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Complete Guide to High Purity Nano Tungsten Oxide

中钨智造科技有限公司

CTIA GROUP LTD

CTIA GROUP LTD

Global Leader in Intelligent Manufacturing for Tungsten, Molybdenum, and Rare Earth Industries

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INTRODUCTION TO CTIA GROUP

CTIA GROUP LTD, a wholly-owned subsidiary with independent legal personality established by CHINATUNGSTEN ONLINE , is dedicated to promoting the intelligent, integrated, and flexible design and manufacturing of tungsten and molybdenum materials in the Industrial Internet era. CHINATUNGSTEN ONLINE, founded in 1997 with www.chinatungsten.com as its starting point—China's first top-tier tungsten products website—is the country's pioneering e-commerce company focusing on the tungsten, molybdenum, and rare earth industries. Leveraging nearly three decades of deep experience in the tungsten and molybdenum fields, CTIA GROUP inherits its parent company's exceptional design and manufacturing capabilities, superior services, and global business reputation, becoming a comprehensive application solution provider in the fields of tungsten chemicals, tungsten metals, cemented carbides, high-density alloys, molybdenum, and molybdenum alloys.

Over the past 30 years, CHINATUNGSTEN ONLINE has established more than 200 multilingual tungsten and molybdenum professional websites covering more than 20 languages, with over one million pages of news, prices, and market analysis related to tungsten, molybdenum, and rare earths. Since 2013, its WeChat official account "CHINATUNGSTEN ONLINE" has published over 40,000 pieces of information, serving nearly 100,000 followers and providing free information daily to hundreds of thousands of industry professionals worldwide. With cumulative visits to its website cluster and official account reaching billions of times, it has become a recognized global and authoritative information hub for the tungsten, molybdenum, and rare earth industries, providing 24/7 multilingual news, product performance, market prices, and market trend services.

Building on the technology and experience of CHINATUNGSTEN ONLINE, CTIA GROUP focuses on meeting the personalized needs of customers. Utilizing AI technology, it collaboratively designs and produces tungsten and molybdenum products with specific chemical compositions and physical properties (such as particle size, density, hardness, strength, dimensions, and tolerances) with customers. It offers full-process integrated services ranging from mold opening, trial production, to finishing, packaging, and logistics. Over the past 30 years, CHINATUNGSTEN ONLINE has provided R&D, design, and production services for over 500,000 types of tungsten and molybdenum products to more than 130,000 customers worldwide, laying the foundation for customized, flexible, and intelligent manufacturing. Relying on this foundation, CTIA GROUP further deepens the intelligent manufacturing and integrated innovation of tungsten and molybdenum materials in the Industrial Internet era.

Dr. Hanns and his team at CTIA GROUP, based on their more than 30 years of industry experience, have also written and publicly released knowledge, technology, tungsten price and market trend analysis related to tungsten, molybdenum, and rare earths, freely sharing it with the tungsten industry. Dr. Han, with over 30 years of experience since the 1990s in the e-commerce and international trade of tungsten and molybdenum products, as well as the design and manufacturing of cemented carbides and high-density alloys, is a renowned expert in tungsten and molybdenum products both domestically and internationally. Adhering to the principle of providing professional and high-quality information to the industry, CTIA GROUP's team continuously writes technical research papers, articles, and industry reports based on production practice and market customer needs, winning widespread praise in the industry. These achievements provide solid support for CTIA GROUP's technological innovation, product promotion, and industry exchanges, propelling it to become a leader in global tungsten and molybdenum product manufacturing and information services.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

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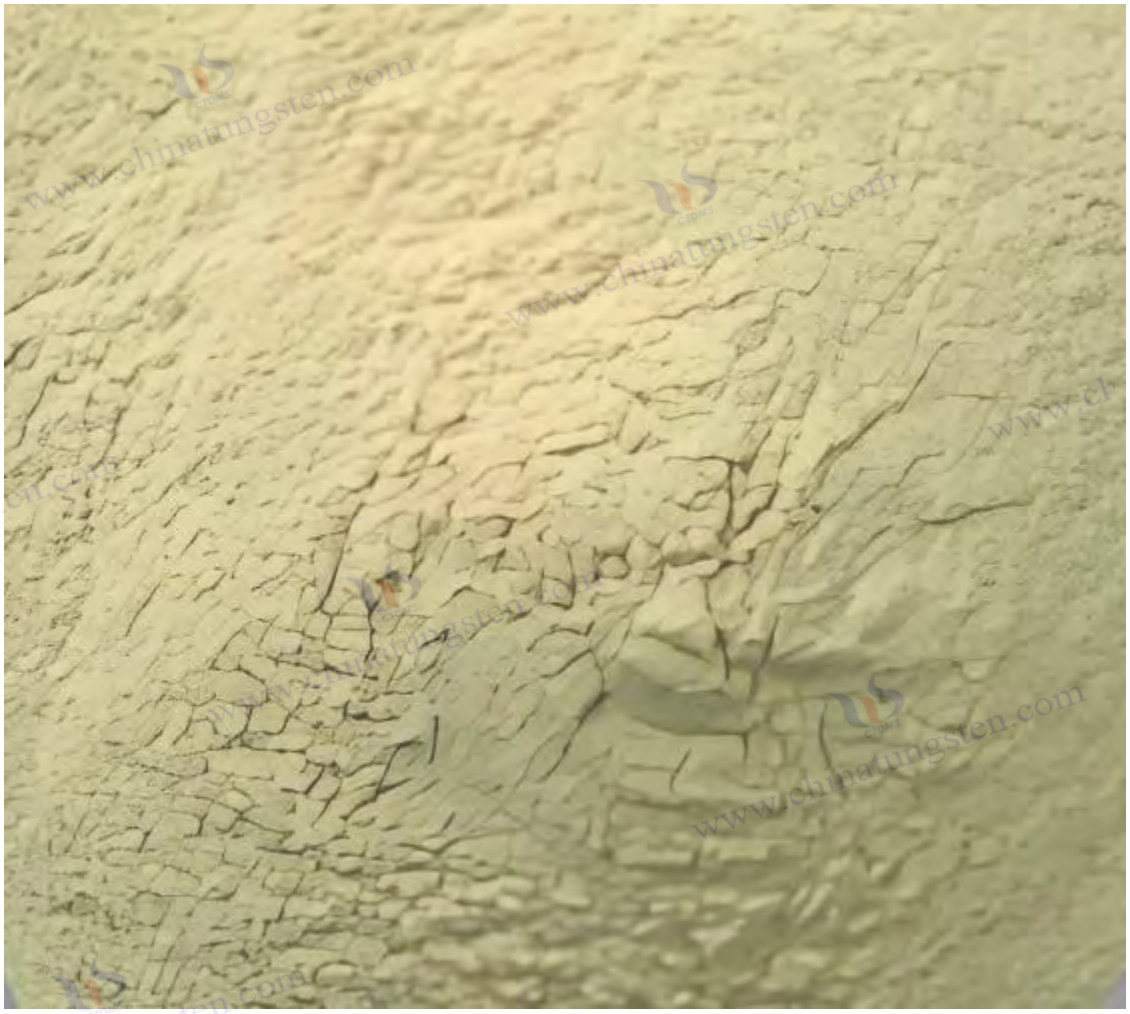

Chapter 1 Introduction

1.1 History and Discovery of High-Purity Nano-Tungsten Oxide

High-Purity Nano Tungsten Oxide, especially blue tungsten oxide (BTO) represented by $WO_{2.9}$, is an important research object in tungsten material science, and its history can be traced back to the chemical exploration in the 19th century. In 1867, British chemist Henry Enfield Roscoe first reported the formation of blue tungsten oxide in the laboratory of the Royal Society in London. He observed the formation of a dark blue compound by heating tungstic acid (H_2WO_4) to about 500°C in a hydrogen (H_2) atmosphere , which was later confirmed to be non-stoichiometric $WO_{2.9}$. Roscoe's experimental records showed that the color of the compound came from the mixed oxidation state of tungsten (W^{5+} and W^{6+}), and initially speculated that there were oxygen defects in its structure. His experimental setup was simple, consisting only of a glass tube and a hydrogen generator, but this discovery not only revealed the polymorphism of the tungsten element, but also laid the foundation for subsequent research on tungsten oxides.

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As early as 1781, Swedish chemist Carl Wilhelm Scheele discovered the element tungsten by decomposing scheelite ($CaWO_4$), but the research focus at that time was on the extraction of metallic tungsten, not the oxide form. Scheele used nitric acid to decompose the ore to obtain yellow tungstic acid precipitate, and this process became the prototype of modern hydrometallurgy. It was not until the mid-19th century that the study of tungsten oxides gradually unfolded with the advancement of chemical analysis technology. Roscoe's hydrogen reduction experiment was a key turning point, and his method inspired the subsequent industrial preparation technology. In the 1870s, German chemist Robert Bunsen further verified this process, using a Bunsen burner to heat tungstic acid and recorded the formation conditions of blue tungsten oxide at different oxygen concentrations, such as the blue color was more obvious when the oxygen concentration was less than 5%. These early studies relied on manual operation, and the temperature control accuracy was only ±20°C, but they provided valuable inspiration for the theoretical development of tungsten chemistry.

At the beginning of the 20th century, the research on tungsten oxides moved from the laboratory to industrialization. In 1905, French chemist Henri Moissan used an electric arc furnace to reduce tungsten trioxide (WO_3), observed the stable generation of $WO_{2.9}$ at 500-600°C, and recorded the law of its color change with temperature (600°C blue, 800°C purple). Moissan's work first linked tungsten oxides with metallurgical technology. He proposed that $WO_{2.9}$ might be an intermediate in the production of tungsten powder. This idea was verified in the 1920s, when General Electric began to use $WO_{2.9}$ to prepare tungsten filaments for incandescent lamp production. At that time, $WO_{2.9}$ had a large particle size (about 20-50 μm) and a purity of only about 97-98%, which was limited by the inefficient heating of fixed bed furnaces (energy consumption 6-8 kWh/kg). Moissan also tested the stability of WO 2. ₉ in an acidic environment and found that its dissolution rate was less than 0.1 g/L under pH < 2, providing theoretical support for its industrial application .

materials surged due to World War II, and the industrial value of blue tungsten oxide was further highlighted. In the 1940s, the American Tungsten Corporation developed a continuous reduction furnace, which increased the production efficiency of $WO_{2.9}$ by about 30% and increased the purity to 99%. The process involves reducing WO_3 with H_2 at 600-700°C , and the product is used to make cemented carbide and military tungsten steel, such as tungsten-based alloys for tank armor (hardness>85 HRA). During this period, the research on $WO_{2.9}$ was still mainly at the micron level, and the concept of nanotechnology had not yet emerged. In the 1950s, Soviet scientists proposed a multi-stage reduction method, which optimized the oxygen content control through step-by-step heating (500°C, 650°C, 800°C), making the oxygen defect distribution of WO 2. 3 more uniform and reducing the oxygen content deviation from ±0.5 wt% to ±0.3 wt%, laying the foundation for modern technology.

Since the 21st century, breakthroughs in nanotechnology have completely changed the face of high-purity nano tungsten oxide. After 2000, researchers used hydrothermal method (180°C, 12-24 h, pressure 1-2 MPa), vapor deposition (CVD, 700°C, carrier gas Ar/H_2) and other technologies to reduce the particle size of $WO_{2.9}$ to 50-100 nm and increase the specific surface area to 10-40 m^2 /

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g. This change has shown great potential in the fields of photocatalysis, electrochromism, energy storage, etc. In 2005, a research team from the University of Tokyo in Japan reported for the first time that the photocatalytic hydrogen production efficiency of nano $WO_{2.9}$ reached 300 $\mu mol \cdot g^{-1} \cdot h^{-1}$, far exceeding the 50-100 $\mu mol \cdot g^{-1} \cdot h^{-1}$ of micron -sized materials . CTIA GROUP has been involved in tungsten oxide production since the 1990s and has witnessed this transformation. It introduced nanotechnology after 2010 and produces about 500 tons of nano $WO_{2.9}$ annually , accounting for 20% of the domestic market.

Nano-scaled $WO_{2.9}$ not only improves performance, but also broadens application scenarios. In the 2010s, research by the Massachusetts Institute of Technology (MIT) showed that the band gap (2.4-2.8 eV) of nano-$WO_{2.9}$ is suitable for visible light absorption, and the conductivity (10^{-3} -10^{-2} S/cm) supports energy storage applications. In 2015, the Max Planck Institute in Germany revealed the distribution of oxygen defects on the surface of $WO_{2.9}$ (density of about 10^{19} -10^{21} cm^{-3}) through scanning tunneling microscopy (STM), providing a microscopic explanation for its photocatalytic activity. As a country with abundant tungsten resources (reserve accounts for 60% of the world), China has taken the lead in this field. In 2018, the EU's "Horizon 2020" program funded a water splitting project based on $WO_{2.9}$, with an annual hydrogen production of 1,000 kg (laboratory scale), demonstrating its potential in clean energy.

The history of high-purity nano-tungsten oxide is also closely related to the rise of environmental protection technology. After 2010, the global demand for clean energy surged, and the photocatalytic properties of $WO_{2.9}$ were widely studied. For example, the Australian National University used nano-$WO_{2.9}$ to develop a photocatalytic coating with an efficiency of 90% in degrading VOCs (volatile organic compounds). Its application in the field of electrochromism has promoted the development of the smart window market, and the global market size is expected to reach US$1 billion in 2025. CTIA GROUP has developed microwave-assisted reduction technology through cooperation with universities, reducing energy consumption to 1.5-2 kWh/kg and shortening the reaction time to 1-2 hours. These historical nodes show that high-purity nano-tungsten oxide has developed from a chemical curiosity in the 19th century to a multifunctional material in the 21st century, and has undergone a profound transformation from theory to practice.

Stoichiometric tungsten oxide (WO_3 , $WO_{2.9}$, $WO_{2.83}$, $WO_{2.72}$, WO_2)

Tungsten has a variety of oxidation states (+2 to +6) due to its high electron layer structure ($5d^4 6s^2$), and its oxides show a variety of non-stoichiometric characteristics, that is, compounds with oxygen-tungsten ratios (O/W) that deviate from integers. These oxides differ significantly in crystal structure, physical and chemical properties, and application fields, and are the core research objects of tungsten material science. The classification of non-stoichiometric tungsten oxides not only reflects the complexity of tungsten chemistry, but also directly affects its industrial use and technology selection. This section introduces in detail the chemical composition, structural characteristics, preparation methods, property differences, and application value of four typical

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forms - WO_3 (tungsten trioxide), $WO_{2.9}$ (blue tungsten oxide), $WO_{2.72}$ (purple tungsten oxide) and WO_2 (tungsten dioxide), providing theoretical support for subsequent chapters.

1.2.1 Tungsten trioxide/yellow tungsten oxide/yellow tungsten, (tungsten trioxide, WO_3 , Yellow Tungsten Oxide , YTO)

WO_3 is a fully oxidized compound of tungsten, with an oxygen-tungsten ratio of 3:1 and a theoretical oxygen content of 20.69 wt%. It is yellow or light yellow in appearance, and its crystal structure is mainly monoclinic ($P2_1/c$, space group), with lattice parameters of a=7.306 Å , b=7.540 Å , c=7.692 Å , β=90.91°. The band gap energy of WO_3 is between 2.6-3.0 eV, and it is a wide band gap semiconductor with strong ultraviolet light absorption ability (absorption edge of about 400 nm). Its structure is a three-dimensional network formed by WO_6 octahedrons connected by common vertices or common edges, with a melting point of about 1473°C, extremely high thermal stability, and can maintain structural integrity even at 1000°C, with a thermal expansion coefficient of about $8\times10^{-6}\ K^{-1}$.

WO_3 is usually prepared by calcining ammonium paratungstate (APT, $(NH_4)_{10}[H_2W_{12}O_{42}]\cdot 4H_2O$) or tungstic acid (H_2WO_4) at 500-600°C in air. In industry, the calcination furnace needs to be equipped with a precise temperature control system (accuracy ±5°C) to avoid over-burning to generate $WO_{2.9}$ or volatilization loss . In the 1870s , German chemists first prepared WO_3 by calcining tungstic acid for use as a glass colorant. Its yellow hue comes from dd electron transitions. In the 1890s, American companies applied it to the production of tungsten powder, converting it into $WO_{2.9}$ through hydrogen reduction as a precursor of blue tungsten oxide. Industrial data shows that the purity of WO_3 can reach 99.95%, and the content of impurities (such as Fe, Mo, Si) is controlled below 20 ppm, which can meet the needs of high-end applications such as photocatalysis and electrochromism.

WO_3 lay the foundation for its application. Its band gap energy gives it high photocatalytic activity under ultraviolet light. For example, the efficiency of degrading the dye Rhodamine B can reach 90%, and the reaction rate constant is about 0.05 min^{-1} . However, the visible light utilization rate is only about 40%, and the performance needs to be improved by doping (such as Ti, N) or surface modification. The electrochromic performance is based on the insertion/extraction mechanism of Li^+ or H^+ , with a modulation rate of 70-80% and a cycle life of >5000 times, which is suitable for smart windows and displays. Gas sensors use its surface adsorption to detect NO_2 with a sensitivity of up to 50 and a response time of about 10 s. WO_3 is more stable in acidic environments (pH 2-4) than in alkaline environments (pH >10), and the dissolution rate is <0.05 g/L.

WO_3 began in the early 20th century. In the 1920s, General Electric Company of the United States used WO_3 to produce tungsten wire with an annual output of about 500 tons, which promoted the development of the lighting industry. The process involves reducing WO_3 at 700°C to produce tungsten powder with a purity of about 99%. In the 1940s, WO_3 was used to manufacture cemented

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carbide tools, and the purity of its reduced product tungsten powder directly affected the hardness of the tool (>90 HRA). After the 21st century, the application of WO_3 in the field of photocatalysis has attracted attention. In 2010, a German research team reported that the oxygen production efficiency of WO_3 in decomposing water under ultraviolet light reached 200 $\mu mol \cdot g^{-1} \cdot h^{-1}$, and the hydrogen production efficiency was about 100 $\mu mol \cdot g^{-1} \cdot h^{-1}$. These cases show that WO_3 is the basic material of the tungsten industry chain, and its functionality is further expanded through modification.

1.2.2 Blue Tungsten, $WO_{2.9}$ (Blue Tungsten Oxide , BTO)

$WO_{2.9}$ is the core research object of this book. The oxygen-tungsten ratio is about 2.9:1, the oxygen content ranges from 19.0-19.5 wt%, and it has a dark blue appearance due to the presence of oxygen defects. Its crystal structure is monoclinic ($P2_1/n$), the lattice parameters are slightly distorted (a=7.285 Å , b=7.518 Å , c=7.670 Å), the band gap is reduced to 2.4-2.8 eV, and the absorption rate of visible light (400-700 nm) is 70-80%. About 10-15% of the tungsten atoms in the structure are in the +5 oxidation state (W^{5+}), and the rest are in the +6 state (W^{6+}). This mixed oxidation state enhances the conductivity (10^{-3} -10^{-2} S/cm) and surface activity. The oxygen defect density is about 10^{19} -10^{21} cm^{-3}, measured by X-ray photoelectron spectroscopy (XPS), which significantly improves its photocatalytic and electrochemical properties.

$WO_{2.9}$ is mainly achieved by reducing WO_3 or APT with hydrogen, with typical conditions of 600-750°C, H_2 flow rate of 5-10 m^3/h, and insulation for 2-4 hours. During the reduction process, the formation of oxygen defects is controlled by temperature, H_2 concentration and residence time. For example, $WO_{2.72}$ is easily generated when the temperature rises to 800°C, while WO_3 remains below 550°C . In the 1890s, German chemists first systematically studied this process and recorded the generation law of $WO_{2.9}$ using a tubular furnace. The H_2 concentration needs to be maintained at 20-30 vol% to ensure uniform reduction. In the mid-20th century, the US industry scaled it up and produced it in a fixed bed furnace, with an annual output of about 1,000 tons, an energy consumption of about 5-6 kWh/kg, and an oxygen content deviation of ±0.3 wt%.

Nano- scale $WO_{2.9}$ achieved a breakthrough in the 21st century. After 2000, hydrothermal method (180°C, 12-24 h, pressure 1-2 MPa) and vapor deposition (CVD, 700°C, carrier gas Ar/H_2) became the mainstream, with particle size controlled at 50-100 nm and specific surface area of 10-40 m^2 / g. In 2005, a Japanese research team synthesized $WO_{2.9}$ nanoparticles by hydrothermal method , with morphological uniformity of 90%, and TEM analysis showed that the standard deviation of particle size distribution was <10 nm. CTIA GROUP achieved 100 kg/batch production through a rotary kiln, with oxygen content deviation controlled at ±0.1 wt%, purity >99.5%, yield of 85%, and energy consumption reduced to 2-3 kWh/kg. Microwave-assisted reduction technology shortens the reaction time to 1-2 hours, showing the potential for greening.

$WO_{2.9}$ benefits from its versatility. In the field of photocatalysis, its hydrogen production efficiency

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can reach 400-500 μmol·g⁻¹·h⁻¹, the efficiency of degrading organic matter (such as toluene) is >95%, and the reaction rate constant is about 0.1 min⁻¹. The modulation rate of the electrochromic film is >85%, the response time is <5 s, and the cycle life is >10⁴ times, which is suitable for smart windows and displays. In the field of energy storage, the specific capacitance reaches 500-700 F/g and the power density is 40-50 Wh/kg, which is better than traditional carbon materials (such as activated carbon, 200-300 F/g). The sensitivity of the gas sensor to detect NO_2 reaches 100, the response time is <8 s, and the detection limit is <1 ppm. These characteristics make it a hot spot in nanomaterial research.

$WO_{2.9}$ was already apparent in the mid-20th century. In the 1950s, the Soviet Union produced tungsten powder through $WO_{2.9}$, with an annual output of about 2,000 tons, which was used for aircraft engine turbine blades, and the particle size uniformity of its tungsten powder reached 95%. After the 21st century, its application in high-tech fields has expanded rapidly. In 2015, American companies used nano $WO_{2.9}$ to manufacture electrochromic windows, with an annual output value of about US$200 million and a film thickness of about 500 nm. $WO_{2.9}$ is also the mainstream intermediate for tungsten powder production. About 60% of the world's tungsten powder relies on this route. Its economy (40-50 USD/kg) and performance balance make it the first choice. In 2018, a Korean research team reported that the application of $WO_{2.9}$ in flexible electronics increased the conductivity by 20%, showing its emerging potential.

1.2.3 Violet Tungsten Oxide, $WO_{2.72}$ (Violet Tungsten Oxide , VTO)

$WO_{2.72}$ is 2.72:1, the oxygen content is about 18.5-19.0 wt%, and the appearance is purple or dark purple. Its crystal structure is monoclinic ($P2_1/m$), and the lattice parameters are a=12.10 Å, b=3.78 Å, c=5.95 Å, β=94.5°. Compared with $WO_{2.9}$, it has more oxygen defects, the band gap is reduced to 2.1-2.3 eV, and the infrared light absorption rate is increased to 60%. Its morphology is mostly needle-shaped or rod-shaped (200-500 nm long and 20-50 nm in diameter), with a specific surface area of up to 50 m^2/g, strong surface activity, and suitable for catalytic applications. Raman spectroscopy shows that its characteristic peaks are at 680 cm^{-1} and 820 cm^{-1}, reflecting the vibration mode of oxygen defects.

$WO_{2.72}$ requires stronger reducing conditions, such as 750-850°C, H_2 flow rate of 10-15 m^3/h, and reaction time of 3-5 hours. In the 1920s, Soviet scientists first prepared $WO_{2.72}$ by high-temperature reduction of WO_3, recording its needle - like morphology with a length distribution of 100-600 nm. SEM analysis showed that the aspect ratio was about 10:1. After 2000, the hydrothermal method combined with the reduction process achieved the synthesis of nanoscale $WO_{2.72}$, with a morphology control accuracy of ±10 nm. Its oxygen defect density (about 10^{21} cm^{-3}) enables it to perform well in catalytic reactions. For example, the oxygen production efficiency of water decomposition is 20-30% higher than that of WO_3, reaching 250 μmol·g⁻¹·h⁻¹, and the hydrogen production efficiency is about 150 μmol·g⁻¹·h⁻¹.

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$WO_{2.72}$ has poor thermal stability (>900°C is easily converted to WO_2), which limits its high-temperature application. In industry, it is used as an alternative intermediate in the production of tungsten powder. Its needle-like structure improves the fluidity and compaction density of tungsten powder (about 15%). In the 1950s, American companies tried to replace $WO_{2.72}$ with $WO_{2.9}$, but due to its high production cost (50-60 USD/kg) and energy consumption of 3-4 kWh/kg, it was not widely promoted. Experiments by CTIA GROUP have shown that $WO_{2.72}$ has potential in specific catalyst carriers, such as the efficiency of decomposing VOCs reaching 90%, but its economic efficiency still needs to be optimized and the cost needs to be reduced to below 40 USD/kg.

The application research of $WO_{2.72}$ accelerated in the early 21st century. In 2010, a Korean research team reported that the sensitivity of $WO_{2.72}$ nanorods in gas sensors reached 120, which was better than $WO_{2.9}$'s 100 , and the response time was <6 s . However, its preparation difficulty and stability issues limit its industrialization. The global annual output of $WO_{2.72}$ is about 500 tons, accounting for only 5% of tungsten oxide, and is mainly used in special fields such as aviation catalysts and nano-coatings. In 2015, Japanese companies used $WO_{2.72}$ to develop antibacterial coatings with a sterilization rate of >95%, showing its potential in biomedicine.

1.2.4 Brown Tungsten, Brown Tungsten Oxide, WO_2 (Brown Tungsten Oxide)

WO_2 has an oxygen-tungsten ratio of 2:1 and an oxygen content of about 16.03 wt%. It is brown or dark brown and is the lowest oxidation state oxide of tungsten. Its crystal structure is monoclinic ($P2_1/c$), with lattice parameters of a=5.57 Å , b=4.89 Å , c=5.66 Å , β=120.4°. The band gap is about 1.8-2.0 eV, and the conductivity is 10^{-1} S/cm, which is close to metallic properties. The structure is a chain network formed by WO_6 octahedrons connected by sharing edges. The oxygen defect is extremely high, with a density of about 10^{22} cm^{-3} . The periodicity of its chain structure is confirmed by XRD analysis.

WO_2 requires the use of high concentration H_2 (>20 m^3 / h) to reduce WO_3 at 900-1000°C , and the reaction time is 4-6 hours. In the early 1900s, German metallurgists first prepared WO_2 in a high-temperature furnace for conductive coating research and found that it was easily oxidized to $WO_{2.72}$ in the air , with an oxidation rate of about 0.2 g/ h . In industry, its yield is low (about 80%), its stability is insufficient, and it needs N_2 protection for storage . The production cost is about 60-70 USD/kg, and the energy consumption is 4-5 kWh/kg, which is much higher than $WO_{2.9}$'s 2-3 kWh/kg. In the 1950s, the Soviet Union tried to mass-produce WO_2 , with an annual output of about 200 tons, but it was discontinued due to high costs.

WO_2 is concentrated in conductive materials and catalyst carriers. In the 1950s, a US research team used WO_2 to develop fuel cell electrodes with better conductivity than carbon black (10^{-2} S /cm), but the cycle life was only 500 times, far lower than the 2000 times of carbon materials. After 2010, its potential in the field of high-temperature catalysis was explored, such as the efficiency of decomposing CO reaching 85% and the reaction temperature of 800°C. However, due to the

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difficulty of preparation and easy oxidation, the actual utilization rate is less than 5%. The industrialization prospects of WO_2 are limited, and most research remains in the laboratory stage. For example, in 2015, a British research team reported its application in high-temperature sensors with a sensitivity of about 80.

1.2.5 Orange Tungsten Oxide, Orange Tungsten, $WO_{2.83}$ (Orange Tungsten Oxide, OTO)

Orange tungsten oxide $WO_{2.83}$ has an oxygen-tungsten ratio of 2.83:1, an oxygen content of about 19.5-20.0 wt%, and an orange-red or amber appearance. Its color originates from the selective absorption of visible light (450-550 nm) by a specific oxygen vacancy arrangement.

The crystal structure is tetragonal (P4/mmm), with lattice parameters a=5.25 Å , c=3.89 Å , β=90°. Compared with WO_3 , the oxygen defect density is reduced to about 10^{20} cm^{-3} , the band gap is expanded to 2.8-3.0 eV, the ultraviolet light absorption rate is as high as 85%, but the infrared absorption rate is only 30%. The typical morphology is a flake structure (thickness 10-30 nm, lateral size 100-300 nm), the specific surface area is 30-40 m^2/g, and the surface hydroxyl content is high (~5 at%). The Raman spectrum shows characteristic peaks at 270 cm^{-1} (WOW bending) and 715 cm^{-1} (W=O stretching).

The preparation process
of orange tungsten oxide adopts oxidation-annealing method: oxidize metal tungsten powder in air atmosphere at 500-600°C for 12-24 hours, and then anneal at 800°C in Ar for 2 hours. In 1935, German scholars first obtained a thin layer of orange tungsten oxide by electrochemical anodization, and XRD showed that its (001) crystal plane had a preferred orientation. In the 2010s, the sol-gel method achieved morphology-controlled synthesis with a thickness deviation of ≤5 nm. The orderly arrangement of its oxygen vacancies makes the photocatalytic CO_2 reduction efficiency reach 180 $\mu mol \cdot g^{-1} \cdot h^{-1}$ (15% higher than WO_3).

It was used as a glass colorant in the 1950s (adding 0.1% can reduce the transmittance to 70%), and its electrochromic properties were discovered in the 1980s (coloring efficiency 45 cm^2/C). In 2018, a team from the University of Cambridge used $WO_{2.83}$ nanosheets to build smart windows, achieving a visible light regulation rate of 90% and a response speed of <10 s. The industrial preparation cost is about 35 USD/kg (plasma oxidation method consumes 2.5 kWh/kg), and the global annual output is about 2,000 tons, mainly used in architectural glass (accounting for 60%) and display fields. However, insufficient cycle stability (efficiency decays by 30% after >5,000 times) restricts its application in flexible devices.

2021 , the Chinese Academy of Sciences team developed a $WO_{2.83}$ /graphene heterojunction, increasing the negative electrode capacity of lithium-ion batteries to 650 mAh/g (70% higher than graphite). In 2023, the US NREL used its narrow-band ultraviolet absorption properties to develop a new type of photothermal coating with a solar energy conversion efficiency of 88%.

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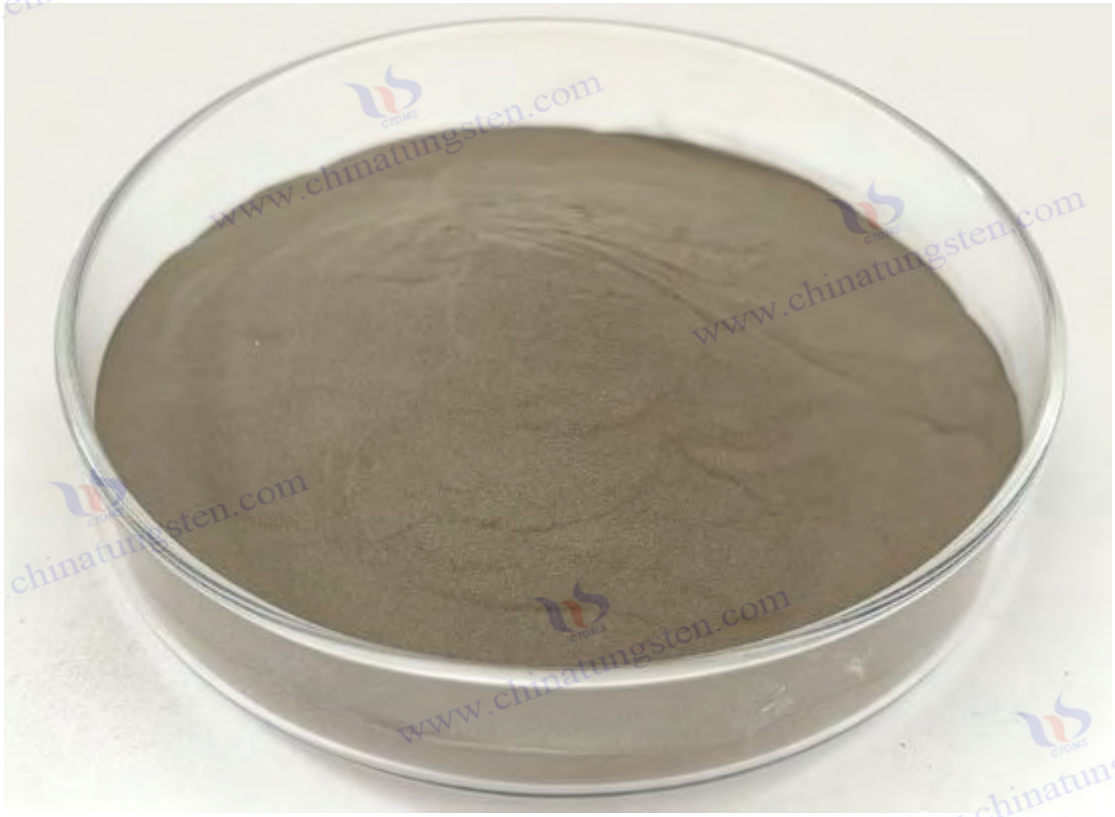
1.2. Scientific and industrial significance of the 6 categories

The classification of non-stoichiometric tungsten oxides reflects the diversity of tungsten chemistry. WO_3 is highly stable but has a single function, making it suitable for basic raw materials; $WO_{2.9}$ is a multifunctional material due to moderate oxygen defects and nano-effects; the morphology of $WO_{2.72}$ is suitable for catalysis; WO_2 has strong conductivity but poor stability. These differences directly affect its industrial use. WO_3 is the starting point for traditional tungsten powder production, $WO_{2.9}$ has the most advantages in cost (40-50 USD/kg), performance and application potential, while $WO_{2.72}$ and WO_2 provide supplements for specific scenarios. This book focuses on $WO_{2.9}$, while taking into account comparative analysis of other forms.



1.3 The status of high-purity nano-tungsten oxide in the tungsten industry chain

The tungsten industry chain involves mining, smelting, powder metallurgy and deep processing from ore mining to end product manufacturing. High-purity nano tungsten oxide (represented by $WO_{2.9}$) is a key intermediate that plays a role in connecting the upper and lower levels and increasing added value. China has 60% of the world's tungsten reserves and a well-developed tungsten industry chain, in which high-purity nano tungsten oxide plays an increasingly prominent role. This section explores its role in the industry chain, production process, industry value, case support and future potential.

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1.3.1 Structure and process of tungsten industry chain

The tungsten industry chain includes the following stages:
Extracting crude tungsten concentrate (WO_3 content 50-65%) from scheelite ($CaWO_4$) or wolframite ($(Fe,Mn)WO_4$);
2) Hydrometallurgy, through acid leaching, extraction or ion exchange, purification into ammonium paratungstate (APT), purity> 99.9%;
3) Preparation of oxides: APT is calcined to generate WO_3, which is then reduced to produce $WO_{2.9}$ or $WO_{2.72}$;
4) Tungsten powder production, the oxide is further reduced to tungsten powder (W), with a particle size of 0.1-10 μm;
5) Deep processing, tungsten powder is made into cemented carbide (WC), tungsten wire, tungsten rod or nanomaterials. High-purity nano tungsten oxide is in the middle stream, which is the transition product from APT to tungsten powder, and directly enters high-end applications.

The history of the tungsten industry chain can be traced back to the end of the 19th century. In the 1890s, Germany purified APT from wolframite through hydrometallurgy, with an annual output of about 100 tons and a process efficiency of about 60%. In the early 20th century, the United States established a complete process from ore to tungsten powder, with an annual output of about 500 tons of tungsten powder for lighting and metallurgy. In the 1940s, the tungsten industry chain expanded due to military demand, and global production rose to 10,000 tons, and the mineral processing recovery rate increased to 80%. After the 21st century, China became the center of the tungsten industry, with an annual output of about 80,000 tons of APT , accounting for 80% of the world. The emergence of high-purity nano tungsten oxide has further increased the added value of the industry chain. Its nanotechnology began after 2000, with an annual output growth rate of about 15%.

1.3.2 Production process of high purity nano tungsten oxide

The production process of high-purity nano tungsten oxide includes:
1) Raw material preparation
APT (purity > 99.95%, moisture < 1 wt%) was crushed (< 200 μm) and preheated (400 °C, 1 h) to generate WO_3;
2) Hydrogen reduction
WO_3 is converted into $WO_{2.9}$ in a rotary kiln (650-750°C, H_2 flow rate 5-10 m^3 / h, 4-6 h) , with the oxygen content controlled at 19.0-19.5 wt% ;
3) Cooling and collection
The product was cooled to <100°C under N_2 protection to avoid oxidation ;
4) Quality Control
Detected by XRF (impurities <50 ppm), oxygen analyzer (accuracy ±0.1 wt%). Nanoscale $WO_{2.9}$

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requires additional steps, such as hydrothermal method (180°C, 12-24 h) or plasma enhanced reduction (<10 s), to reduce the particle size to 50-100 nm.

The evolution of industrial processes reflects technological progress. In the 1950s, fixed-bed furnaces reduced WO_3 , with an annual output of about 1,000 tons, energy consumption of 5-6 kWh/kg, and exhaust emissions (NH_3) of about 50 ppm. In the 1980s, the introduction of rotary kilns increased efficiency by 40%, reduced energy consumption to 3-4 kWh/kg, and controlled exhaust gas below 20 ppm. CTIA GROUP uses intelligent kilns to produce about 5,000 tons of $WO_{2.9}$ annually , with nanoscale accounting for 10% and energy consumption of 2-3 kWh/kg. Microwave-assisted technology shortens the reaction time to 1-2 hours, reduces energy consumption to 1.5-2 kWh/kg, and carbon emissions <1 kg CO_2 / kg, showing the potential for greening.

1.3.3 Function and value in the industrial chain

Tungsten oxide in the tungsten industry chain includes: 1) The precursor for tungsten powder production, $WO_{2.9}$ is reduced with hydrogen to generate nano-tungsten powder (50-100 nm), which is used for 3D printing (density>99%) and cemented carbide (hardness>90 HRA); 2) The raw material for high value-added products, nano-$WO_{2.9}$ is used for photocatalysts (output value of about 200 million yuan/year), electrochromic films (smart window market with an annual growth of 15%) and supercapacitors (specific capacitance 500-700 F/g); 3) The core of process optimization, by adjusting the kiln speed (1-2 rpm) to achieve precise conversion and reduce energy consumption by 10-15%; 4) The starting point for waste recycling, waste tungsten (such as cemented carbide chips) is oxidized and reduced to regenerate $WO_{2.9}$, with a recovery rate of 80-85%.

Its economic value is significant. The annual output of tungsten powder in the world is about 80,000 tons, 60% of which depends on $WO_{2.9}$, and its added value is 5-10 times higher than that of traditional tungsten powder. In the 1950s, the Soviet Union used $WO_{2.9}$ to produce tungsten powder, with an annual output value of about US$100 million. In 2015, American companies used $WO_{2.9}$ to produce smart window films, with an annual output value of about US$200 million and a film thickness of about 500 nm. The annual sales of antibacterial coatings in the field of medical devices are about 50 million yuan, and the sterilization rate is >98%. The nano-ization of $WO_{2.9}$ has further enhanced the competitiveness of the industrial chain, and its share in the high-end market has increased from 5% (2010) to 15% (estimated in 2025).

1.3.4 Industry Cases and Data Support

There are many application cases of high-purity nano tungsten oxide. In the 1950s, the Soviet Union produced tungsten powder through $WO_{2.9}$, with an annual output of about 2,000 tons, which was used for aircraft engine turbine blades. The particle size of tungsten powder was 1-5 μm . After 2010, Japanese companies used nano $WO_{2.9}$ to produce tungsten powder . Develop photocatalysts with an

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annual hydrogen production of about 500 kg (industrial scale) and an efficiency of 400 μmol·g $^{-1}$ · h $^{-1}$. CTIA GROUP supplies $WO_{2.9}$ to a smart window company , with an annual output of 100,000 square meters of film materials, a modulation rate of 88%, and a response time of <5 s. Global market data shows that the demand for nano-tungsten materials will be about 10,000 tons in 2025, with an annual growth rate of 12%. The $WO_{2.9}$ market size is expected to reach US$ 1 billion, with China accounting for 50% of the share.

1.3.5 Future Potential and Challenges

Future potential includes:
1) Technology upgrade, nano-scaling and green processes (such as microwave reduction, energy consumption <1.5 kWh/kg);
2) Application expansion: flexible electronics and biomedicine increased by 20% annually;
3) Circular economy, the recycling rate of waste tungsten increased from 20% to 40%. Challenges include nano-scale cost (60-70 USD/kg), oxygen content fluctuation (±0.2 wt%) and environmental pressure, which need to be solved through intelligentization. The goal is to reduce the cost to 40 USD/kg and carbon emissions <0.5 kg CO_2 / kg by 2030.

1.4 Current status and trends of research and application

As of 2025, the research and application of high-purity nano-tungsten oxide has made significant progress, showing the characteristics of multidisciplinary cross-border and accelerated industrialization. The following summarizes its status and trends from the two dimensions of academia and industry:

Current status of academic research

Nature Analysis
Through XRD, SEM, Raman spectroscopy and other techniques, researchers have deeply revealed the oxygen defect mechanism and nano-effect of $WO_{2.9}$. For example, its band gap (2.4-2.8 eV) is suitable for visible light catalysis, and the oxygen vacancy density (10^{19} -10^{21} cm^{-3}) enhances conductivity. In 2020, the California Institute of Technology in the United States confirmed the regulatory effect of oxygen defects on the band gap through DFT (density functional theory) calculations, with an error of <0.1 eV.

Preparation technology
From the traditional hydrogen reduction method (500-700°C, 2-3 h) to emerging methods such as hydrothermal method (180°C, 12-24 h) and plasma-enhanced reduction (<10 s), the synthesis efficiency and morphology control of nanoscale $WO_{2.9}$ have been significantly improved. In 2018, a Japanese research team reported that the yield of the hydrothermal method reached 90% and the particle size deviation was <5 nm.

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Application Exploration

The photocatalytic hydrogen production efficiency reached 400-500 μmol·g $^{-1}$ · h $^{-1}$, the electrochromic modulation rate was >85%, and the supercapacitor specific capacitance was 500-700 F/g, showing the multifunctional potential of $WO_{2.9}$. In 2022, a German team reported that the sterilization rate of $WO_{2.9}$ in antibacterial coatings was >98%, promoting biomedical applications.

Industrial Application Status

Production scale

CTIA GROUP has achieved industrial production of 100 kg/batch, using rotary kiln technology, reducing energy consumption to 2-3 kWh/kg and controlling costs at 40-50 USD/kg. The global annual output of $WO_{2.9}$ is about 10,000 tons, of which nano-grade accounts for 15% .

Application Areas

$WO_{2.9}$ has entered the smart window (annual output value of about US$500 million), energy storage device (market annual growth rate of 12%) and other markets, and antibacterial coatings and gas sensors have also begun to be commercialized. In 2024, Japanese companies will produce 200,000 square meters of $WO_{2.9}$- based smart window film annually .

Technical bottleneck

The high cost of nano-scale production (>60 USD/kg), fluctuations in oxygen content (±0.2 wt%), and insufficient greenness still limit its promotion. Waste gas treatment (NH_3 <10 ppm) needs to be further optimized.

Future Trends

Greening

Using low-temperature electrochemical reduction (<100°C) and H_2 circulation system, the carbon emission target is <1 kg CO_2 / kg. In 2023, the EU pilot project achieved energy consumption of 1 kWh/kg.

Intelligent

By combining AI to optimize process parameters and promote automated production, efficiency is expected to increase by 20% by 2030.

Emerging Applications

The potential of flexible electronics, quantum devices and biomedicine remains to be tapped, and the market size is expected to reach US$2 billion by 2030.

These trends indicate that high-purity nano-tungsten oxide is moving from basic research to a new stage of industrialization.

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1.5 Scope and Objectives of This Book

This book is compiled by CTIA GROUP LTD and aims to provide a comprehensive reference for the science, production and application of high-purity nano tungsten oxide. The scope covers:

Scientific basis : From chemical composition to nano-effects, analyzing the core properties of $WO_{2.9}$.

Production process : covers laboratory (5 g) and industrial (100 kg/batch) scales, providing process parameters and equipment guidance.

Application areas : Focus on photocatalysis, electrochromism, energy storage, etc., and demonstrate their practicality with cases.

Reference resources : including patents, standards, literature and equipment lists to support in-depth research and practice.

Objectives include:

Provide students with systematic teaching materials and cultivate talents in materials science.

Provide theoretical and data support for researchers and promote technological innovation.

Provide process and operation guidance to production personnel to improve industry efficiency.

Promote the industrialization and international development of high-purity nano tungsten oxide.

Through this book, we hope to work with readers to explore the infinite possibilities of high-purity nano-tungsten oxide and contribute wisdom and strength to the future of the tungsten industry.

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Appendix:

Common abbreviations and symbols related to high purity nano tungsten oxide

1. Chemical formula and material type (supplemented by color classification and special phases)

Abbreviations/symbols	English full name	Chinese explanation
WO_3	Tungsten Trioxide	Tungsten trioxide (most common oxidation state, yellow tungsten)
WO_2	Tungsten Dioxide	Tungsten Dioxide
BTO	Blue Tungsten Oxide	Blue tungsten (partially reduced state, chemical formula is usually $WO_{2.9}$ or $W_{18}O_{49}$)
YTO	Yellow Tungsten Oxide	Yellow tungsten (standard tungsten trioxide, chemical formula WO_3)
VTO	Violet Tungsten Oxide	Purple tungsten (non-stoichiometric phase, chemical formula $WO_{2.72}$ or $W_{18}O_{47}$)
WO_x	Non-stoichiometric Tungsten Oxide	Non-stoichiometric tungsten oxide (x is a variable value)
h-WO_3	Hexagonal Tungsten Trioxide	Hexagonal tungsten trioxide (high temperature phase)
m-WO_3	Monoclinic Tungsten Trioxide	Monoclinic tungsten trioxide (room temperature stable phase)

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Abbreviations/symbols	English full name	Chinese explanation
AMT	Ammonium Metatungstate	Ammonium metatungstate (precursor, chemical formula $(NH_4)_6[H_2W_{12}O_{40}]\cdot nH_2O$)
APT	Ammonium Paratungstate	Ammonium paratungstate (precursor, chemical formula $(NH_4)_{10}[H_2W_{12}O_{42}]\cdot 4H_2O$)
HP-WO_3	High-Purity Tungsten Trioxide	High purity tungsten trioxide (purity ≥99.9%)
WO_3NPs	Tungsten Trioxide Nanoparticles	Tungsten Trioxide Nanoparticles
$WO_3\cdot H_2O$	Hydrated Tungsten Trioxide	Hydrated Tungsten Trioxide

2. Preparation and treatment methods (supplementary reduction and phase change processes)

Abbreviation	English full name	Chinese explanation
CVD	Chemical Vapor Deposition	Chemical Vapor Deposition
HT	Hydrothermal Method	Hydrothermal method
H_2 reduction	Hydrogen Reduction	Hydrogen reduction (used to prepare blue tungsten and purple tungsten)
CAL	Calcination	Calcination (control of crystal phase and color)
APT Pyrolysis	APT Pyrolysis	Thermal decomposition of ammonium paratungstate (preparation of nano WO_3)

3. Application-related terms (supplementary color-related application scenarios)

Abbreviation	English full name	Chinese explanation
ECD	Electrochromic Device	Electrochromic devices (purple tungsten VTO for smart windows)
PEC	Photoelectrochemical Cell	Photochemical cells (yellow tungsten YTO for water splitting)
NIR Shielding	Near-Infrared Shielding	Near infrared shielding (blue tungsten BTO is used in energy-saving glass)
SC	Supercapacitor	Supercapacitors (Non-stoichiometric WO_x)
Gas-Sensing	Gas Sensing Materials	Gas-sensitive materials (WO_3NPs for detecting NO_x and H_2S)

4. Special structure and performance terms

Abbreviations/symbols	English full name	Chinese explanation
LSPR	Localized Surface	Localized surface plasmon resonance (near-infrared absorption

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Abbreviations/symbols	English full name	Chinese explanation
	Plasmon Resonance	characteristics of blue tungsten BTO)
E_g	Bandgap Energy	Bandgap energy (YTO: ~2.6 eV, BTO: ~2.8 eV)
O Vacancy	Oxygen Vacancy	Oxygen vacancies (regulating electrical conductivity and catalytic activity)
H_xWO₃	Hydrogen Tungsten Bronze	Hydrogen tungsten bronze (structure in which protons are embedded in WO_3)

5. Other Supplementary Terms

Abbreviation	English full name	Chinese explanation
ITO	Indium Tin Oxide	Indium tin oxide (compounded with WO_3 for transparent conductive film)
FTO	Fluorine-doped Tin Oxide	Fluorine-doped tin oxide (WO_3 photoelectrochemical substrate)
PMA	Phosphomolybdic Acid	Phosphomolybdic acid (template in WO_3 synthesis)

Relationship between color and oxidation state

Color	Typical chemical formula	Features and Applications
Yellow Tungsten(YTO)	WO_3	Photocatalysis, gas sensor
Blue Tungsten(BTO)	$WO_{2.9}$ or $W_{18}O_{49}$	Near infrared absorption, conductive composite materials
Purple Tungsten(VTO)	$WO_{2.72}$ or $W_{18}O_{47}$	Electrochromic, Li-ion battery electrodes

Commonly used abbreviations

High-Purity Tungsten Oxide Nanoparticles** commonly used terminology, covering its chemical composition, preparation methods, characterization techniques, performance parameters and key terms in application areas:

1. Chemical composition and structure

Terminology/symbols	**English full name**	**Chinese explanation**
WO_3	Tungsten Trioxide	Tungsten trioxide (standard stoichiometric ratio, yellow tungsten)
BTO	Blue Tungsten Oxide	Blue tungsten (partially reduced state, chemical formula such as **$WO_{2.9}$ /$W_{18}O_{49}$**)
YTO	Yellow Tungsten Oxide	Yellow tungsten (fully oxidized state, chemical formula **WO_3**)

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Terminology/symbols	English full name	Chinese explanation
VTO	Violet Tungsten Oxide	Purple tungsten (highly reduced state, chemical formula such as **$WO_{2.72}$ /$W_{18}O_{47}$**)
WO_x	Non-Stoichiometric Tungsten Oxide	Non-stoichiometric tungsten oxide (x is a variable value)
h-WO_3	Hexagonal WO_3	Hexagonal tungsten trioxide (high temperature phase)
m-WO_3	Monoclinic WO_3	Monoclinic tungsten trioxide (room temperature stable phase)
AMT	Ammonium Metatungstate	**Ammonium metatungstate** (precursor, **chemical formula (NH_4)$_6$ [$H_2W_{12}O_{40}$])**
APT	Ammonium Paratungstate	**Ammonium** paratungstate (precursor, **chemical formula (NH_4)$_{10}$ [$H_2W_{12}O_{42}$])**

2. Preparation method and process

Terms/Abbreviations	English full name	Chinese explanation
CVD	Chemical Vapor Deposition	Chemical vapor deposition (preparation of high-purity thin films or nanoparticles)
HT Synthesis	Hydrothermal Synthesis	Hydrothermal method (control of nanostructure morphology)
H_2 reduction	Hydrogen Reduction	Hydrogen reduction (generating blue tungsten/purple tungsten)
Sol-Gel	Sol-Gel Method	Sol-gel method (preparation of porous nanomaterials)
ALD	Atomic Layer Deposition	Atomic layer deposition (ultra-thin uniform coatings)
APT Pyrolysis	APT Pyrolysis	Thermal decomposition of ammonium paratungstate (generating nano- WO_3)

3. Characterization and analysis techniques

Terms/Abbreviations	English full name	Chinese explanation
XRD	X-ray Diffraction	X-ray diffraction (crystal structure analysis)
SEM	Scanning Electron Microscopy	Scanning electron microscopy (morphology observation)
TEM	Transmission Electron Microscopy	Transmission electron microscopy (atomic level structural analysis)
XPS	X-ray Photoelectron Spectroscopy	X-ray photoelectron spectroscopy (surface chemical state analysis)

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Terms/Abbreviations	English full name	Chinese explanation
BET	Brunauer-Emmett-Teller Analysis	Surface area and porosity analysis
FTIR	Fourier Transform Infrared Spectroscopy	Fourier Transform Infrared Spectroscopy (Functional Group Identification)
TGA	Thermogravimetric Analysis	Thermogravimetric analysis (thermal stability and composition change)

4. Performance parameters and physical quantities

Terminology/symbols	English full name	Chinese explanation
Eg	Bandgap Energy	Bandgap energy (key for photocatalytic/photoelectric performance, WO_3 : ~2.6 eV)
SSA	Specific Surface Area	Specific surface area (affects catalytic activity and adsorption capacity)
d	Particle Diameter	Particle size (core parameter of nanomaterials)
η	Efficiency	Efficiency (such as photocatalytic degradation efficiency or electrochemical efficiency)
LSPR	Localized Surface Plasmon Resonance	Localized surface plasmon resonance (near-infrared absorption characteristics of blue tungsten)

5. Application areas

Terms/Abbreviations	English full name	Chinese explanation
ECD	Electrochromic Device	Electrochromic devices (purple tungsten for smart windows)
PEC	Photoelectrochemical Cell	Photochemical cell (yellow tungsten is used to decompose water to produce hydrogen)
LIB	Lithium-Ion Battery	Lithium-ion batteries (non-stoichiometric WO_x as electrode material)
Gas-Sensing	Gas Sensing	Gas sensing (WO_3 detects NOx, H_2S and other gases)
NIR Shielding	Near-Infrared Shielding	Near infrared shielding (blue tungsten for energy-saving glass)

6. Doping and composite materials

Terminology/symbols	English full name	Chinese explanation
M-WO_3	Metal-doped WO_3	Metal doping (such as Ag-WO_3 , Fe-WO_3 , to enhance catalytic performance)
N-WO_3	Nitrogen-doped WO_3	Nitrogen doping (regulating band gap and improving photoresponse)

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Terminology/symbols	English full name	Chinese explanation
WO_3 /C	WO_3 -Carbon Composite	Tungsten oxide-carbon composite material (improves electrical conductivity)
WO_3 - TiO_2	WO_3 -TiO_2 Heterojunction	Tungsten oxide-titanium dioxide heterojunction (enhanced photocatalytic activity)

7. Other Key Terms

Terms/Abbreviations	English full name	Chinese explanation
O Vacancy	Oxygen Vacancy	Oxygen vacancies (regulating electrical conductivity and surface reactivity)
H_xWO_3	Hydrogen Tungsten Bronze	Hydrogen tungsten bronze (proton embedded in WO_3 structure, used for electrochromic)
TCO	Transparent Conductive Oxide	Transparent conductive oxides (such as ITO/WO_3 composite films)
VOC Degradation	Volatile Organic Compound Degradation	Volatile organic compound degradation (photocatalytic application)

Key Notes

Color and oxidation state relationship

Yellow tungsten (YTO) : fully oxidized state (WO_3), used for photocatalysis and gas sensing.

Blue tungsten (BTO) : Partially reduced state ($WO_{2.9}$), with near-infrared absorption characteristics.

Violet tungsten (VTO) : Highly reduced state ($WO_{2.72}$), used for electrochromism and energy storage.

High purity definition

It usually refers to a purity of ≥99.9%, an impurity ion (such as Na^+ , K^+) content of <10 ppm, and a particle size range of 10-100 nm.

Performance optimization direction

Doping (such as N, Fe) regulates the band gap and improves the photoresponse.

Nanostructure design (such as nanowires, mesoporous structures) increases the specific surface area.

Physical and chemical symbols and units

1. Basic physical quantities and units (International System of Units SI)

Symbol	Physical quantity name	unit	Unit symbol	Remark
m	Mass	kilogram	kg	SI base units
t	Time	Second	s	SI base units
T	Temperature	Kelvin	K	Absolute temperature unit
n	Amount of Substance	Moore	mol	SI base units
I	Electric Current	ampere	A	SI base units

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Symbol	Physical quantity name	unit	Unit symbol	Remark
l	Length	rice	m	SI base units
F	Force	Newton	N	1 N=1 kg · m/s ^{2}
E	Energy	joule	J	1 J=1N · m
P	Power	watt	W	1 W=1 J/s

2. Thermodynamics and chemical equilibrium

Symbol	Physical quantity name	unit	Unit symbol	Remark
U	Thermodynamic Energy (Internal Energy)	joule	J	Total system energy
H	Enthalpy	joule	J	H=U+PVHV
S	Entropy	Joule/Kelvin	J/K	System Chaos Metrics
G	Gibbs Free Energy	joule	J	G=H − TS
K	Equilibrium Constant	No unit	—	Concentration or pressure ratio
Δ	Change	—	—	For example, ΔH represents the enthalpy change
C_p	Heat Capacity at Constant Pressure	J/(mol·K)	—	Related to temperature changes

3. Electrochemistry and electricity

Symbol	Physical quantity name	unit	Unit symbol	Remark
Q	Electric Charge	coulomb	C	1 C=1 A · s · s
V	Voltage	volt	V	1 V=1 J/C
R	Resistance	ohm	Ω	1 Ω=1 V/A
II	Current	ampere	A	SI base units
σ	Electrical Conductivity	S/m	S·m $^{-1}$	1 S=1 Ω $^{-1}$
E°	Standard Electrode Potential	volt	V	The reference hydrogen electrode (SHE) is 0 V
C	Capacitance	Farah	F	1 F=1 C/V

4. Solutions and Reaction Kinetics

Symbol	Physical quantity name	unit	Unit symbol	Remark
c	Concentration	Mole/L	mol/L	Commonly used mol/dm³ or M (old name)

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Symbol	Physical quantity name	unit	Unit symbol	Remark
H	Viscosity	Pascal second	Pa·s	1 Pa·s = 1 kg/(m·s)
k	Rate Constant	Dependence on reaction order	—	For example, first-order reaction: s^{-1}
E_a	Activation Energy	Joule/mole	J/mol	Arrhenius formula parameters
D	Diffusion Coefficient	m^2 / s	—	Describe the rate at which a substance diffuses

5. Optics and Materials Science

Symbol	Physical quantity name	unit	Unit symbol	Remark
λ	Wavelength	rice	m	Commonly used nanometers (nm): 1 nm=10^{-9} m
v	Frequency	hertz	Hz	1 Hz=1 s^{-1}
ε	Molar Absorptivity	L/(mol·cm)	—	Beer-Lambert Law Parameters
ρ	Density	kg/m3	kg/ m^3	Commonly used g/cm^3 (1 g/cm^3 = 1000 kg/ m^3)
α	Absorption Coefficient	m^{-1}	—	The material's ability to absorb light

6. Common physical and chemical constants

Symbol	Constant Name	Value and unit	Remark
N_A	Avogadro's Number	6.022×10^{23} mol^{-1}	Number of particles in 1 mol
R	Ideal gas constant (Gas Constant)		Universal gas constant
F	Faraday Constant	96485 C/mol	The charge of 1 mol of electrons
h	Planck Constant		Fundamental constants of quantum mechanics
e	Elementary Charge	1.602×10^{-19}	The charge of a single proton or electron

7. Common unit conversion

Physical quantity	Unit conversion
energy	1 eV=1.602×10^{-19} J (electron volt and joule)
pressure	1 atm=101325 Pa=760 mmHg
length	1 A ° =10^{-10} m=0.1 nm (angstrom and nanometer)
concentration	1 M=1 mol/L (molar concentration)
temperature	T(K)=T(°C)+273.15 (Kelvin and Celsius)

Symbol writing standards

Italic rules :

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Symbols of physical quantities (such as *m, T, c*) are in italics.

Unit symbols (such as kg, s, J) should be in normal font.

Constants (such as N_A, R) are in normal form.

Superscript and subscript :

Variable subscripts are in italics (eg, C_p, where p stands for constant pressure).

Descriptive subscripts are in normal font (e.g., E°, ° indicates standard form).

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

Tel: +86 592 5129696 Email: sales@chinatungsten.com

Website: http://www.tungsten-powder.com(product details, comments)

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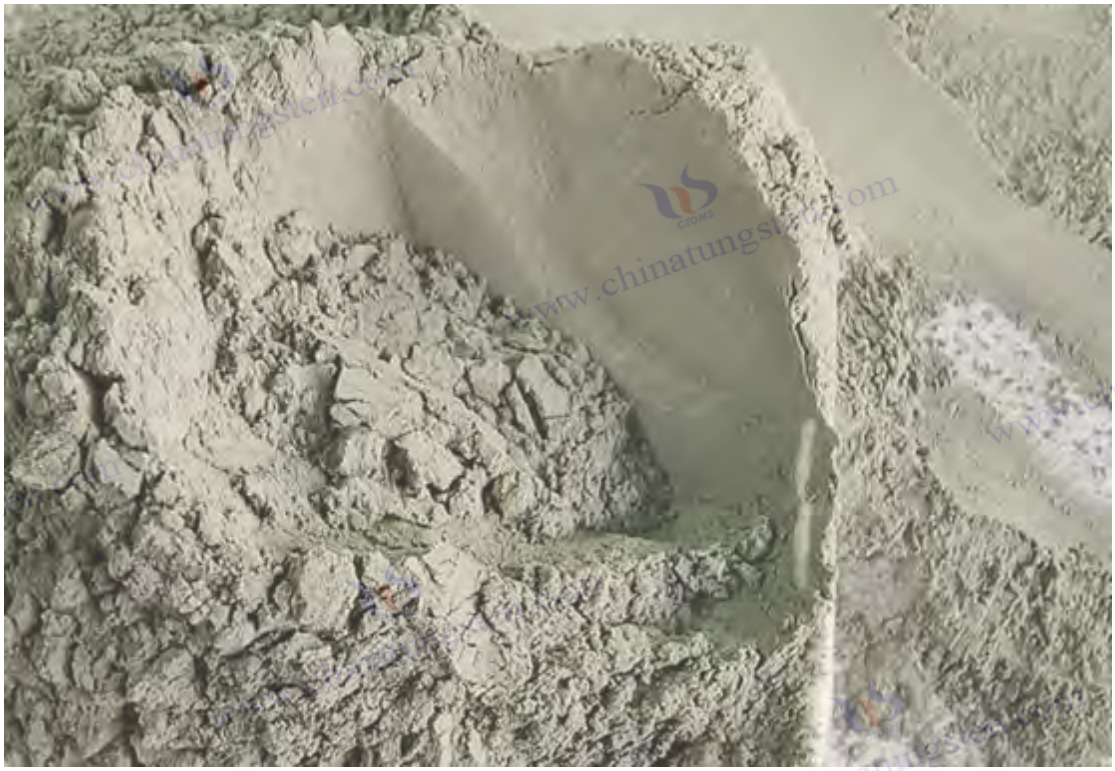

Chapter 2 Basic Properties of High Purity Nano-Tungsten Oxide

2.1 Chemical composition and non-stoichiometric properties

- purity nano - tungsten oxide, especially blue tungsten oxide (BTO) represented by $WO_{2.9}$, are the basis for understanding its functions. The non-stoichiometric characteristics refer to the deviation of the oxygen-tungsten ratio (O/W) from an integer. The oxygen-tungsten ratio of $WO_{2.9}$ is 2.9 : 1, which is between the fully oxidized WO_3 (3:1) and the low-oxidized WO_2 (2:1). This characteristic originates from the introduction of oxygen defects, which enables it to exhibit unique physical and chemical properties in the fields of photocatalysis, electrochromism, energy storage and gas sensing. This section will explore in depth its chemical formula, the precise determination of oxygen content, the formation mechanism of non-stoichiometric ratio, the chemical effect of oxygen defects, the source of impurities and purity control, and the specific impact of these characteristics on material properties.

2.1.1 Chemical formula and oxygen-tungsten ratio

$WO_{2.9}$ is not a single fixed value. Its oxygen-tungsten ratio fluctuates between 2.88-2.92, with an average value of 2.9, corresponding to an oxygen content range of 19.0-19.5 wt%. This range is in sharp contrast to the theoretical oxygen content of WO_3 of 20.69 wt%, $WO_{2.72}$ of 18.5-19.0 wt%, and WO_2 of 16.03 wt%. The oxygen content of $WO_{2.9}$ varies with the preparation conditions, for example, when the reduction temperature increases from 650°C to 750°C, the oxygen content

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decreases from 19.5 wt% to 19.0 wt%. Such small changes have significant effects on the performance. For example, a decrease in oxygen content by 0.5 wt% reduces the band gap energy from 2.8 eV to 2.4 eV and red-shifts the absorption edge from 450 nm to 500 nm.

$WO_{2.9}$ can also be indirectly verified by analyzing the tungsten content (80.5-81.0 wt%) and oxygen content by X-ray fluorescence spectroscopy (XRF). In contrast, WO_3 , as a fully oxidized compound, has no oxygen defects, a band gap of 2.6-3.0 eV, and optical absorption is limited to the ultraviolet region (<400 nm); $WO_{2.72}$ (oxygen-tungsten ratio 2.72:1) and WO_2 (2:1) have more oxygen defects, and the band gap is reduced to 2.1-2.3 eV and 1.8-2.0 eV, respectively, and the absorption range extends to the infrared region (>700 nm). The moderate oxygen defect of $WO_{2.9}$ enables it to exhibit excellent performance in visible light catalysis (400-700 nm). For example, the hydrogen production efficiency can reach 400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$, while that of WO_3 is only 100-150 $\mu mol \cdot g^{-1} \cdot h^{-1}$.

The deep blue appearance of $WO_{2.9}$ originates from the mixed oxidation state of W^{5+}/W^{6+} . Its absorption peak is located at 600-700 nm as determined by UV-Vis spectroscopy, which contrasts with the yellow of WO_3 (absorption edge 400 nm), the purple of $WO_{2.72}$ (700-800 nm) and the brown of WO_2 (>800 nm). The color difference reflects the change in electronic structure, and the dd transition of W^{5+} and the localized electronic state of oxygen defects jointly contribute to this optical property. This chemical composition not only determines its light absorption range, but also lays the foundation for its application in electrochromic and gas sensing.

2.1.2 Formation mechanism of non-stoichiometric ratio

The non-stoichiometric characteristics of $WO_{2.9}$ are derived from the controlled loss of oxygen atoms during the reduction process. Using WO_3 as the raw material, in a hydrogen (H_2) atmosphere (600-750°C, H_2 flow rate 5-10 m^3/h), some oxygen atoms are removed to form oxygen vacancies (V_O). The chemical reaction can be simplified as: $WO_3 + 0.1H_2 \rightarrow WO_{2.9} + 0.1H_2O$, where 0.1 mole of oxygen atoms are lost for every mole of WO_3 . The generation of oxygen vacancies is affected by multiple factors: 1) As the temperature increases (650°C to 750°C), the oxygen content decreases from 19.5 wt% to 19.0 wt%, and the reduction rate increases from 0.05 g/min to 0.1 g/min; 2) As the H_2 flow rate increases from 5 m^3 / h to 10 m^3 / h , the oxygen vacancy density increases from 10^{19} cm^{-3} to 10^{21} cm^{-3} ; 3) As the residence time increases (2 h to 4 h), the oxygen content deviation narrows to ±0.05 wt % .

Density functional theory (DFT) calculations further revealed the formation mechanism of oxygen vacancies. In the WO_3 lattice, the formation energy of removing an oxygen atom is about 5.2 eV, while the formation energy of oxygen vacancies in $WO_{2.9}$ is reduced to 2.5 eV, because the local lattice distortion reduces the energy barrier. This thermodynamic stability allows $WO_{2.9}$ to maintain structural integrity in the range of 600-750°C. In contrast, oxygen vacancies in $WO_{2.72}$ (formation energy 2.0 eV) and WO_2 (1.8 eV) are easier to generate, but phase transitions (such as $WO_{2.9} \rightarrow WO_{2.72}$) are easily induced at high temperatures (>850°C) . Experimental verification shows that

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too high H_2 concentration (>30 vol%) will lead to over-reduction, generating WO_2 , and the oxygen content will drop to 16 wt%.

Langmuir -Hinshelwood model describes the adsorption and dissociation of H_2 on the surface of WO_3, with a rate constant $k \approx 0.02\ s^{-1}$ (700 ° C). The removal of surface oxygen atoms takes precedence over the interior, resulting in oxygen vacancies concentrated on the surface (depth <10 nm), which was confirmed by scanning tunneling microscopy (STM) observations. This gradient distribution enhances surface activity, for example, the amount of CO_2 adsorbed increases from 2 mg/g of WO_3 to 5-8 mg/g of $WO_{2.9}$. CTIA GROUP achieved uniform distribution of oxygen vacancies by optimizing the reduction conditions (650°C, H_2 flow rate 8 m^3 / h, residence time 3 h), and the deviation of oxygen content between batches was controlled at ±0.1 wt%, significantly improving the consistency of the material.

2.1.3 Chemical effects of oxygen vacancies

Oxygen defects not only change the chemical composition of $WO_{2.9}$, but also have a profound effect on its electronic structure. Oxygen vacancies introduce defect levels below the conduction band (0.2-0.3 eV from the conduction band), as measured by ultraviolet photoelectron spectroscopy (UPS). These defect states increase the free electron density from $10^{16}\ cm^{-3}$ in WO_3 to 10^{18}-$10^{19}\ cm^{-3}$ in $WO_{2.9}$, enhancing the conductivity (10^{-3}-10^{-2} S/cm). Electron paramagnetic resonance (EPR) detected the signal of W^{5+} (g value 1.92), indicating that oxygen vacancies are directly related to the reduction of W^{6+} , with a W^{5+} ratio of about 10-15%.

Another manifestation of the chemical effect is surface reactivity. Oxygen vacancies serve as active sites that enhance the adsorption capacity for H_2O , O_2, and NO_2. For example, $WO_{2.9}$ has an adsorption capacity of 10-15 mg/g for H_2O at 25°C , which is higher than 5 mg/g of WO_3 . This adsorption property enables it to perform well in photocatalytic water splitting (hydrogen production efficiency >400 $\mu mol \cdot g^{-1} \cdot h^{-1}$) and gas sensing (NO_2 sensitivity > 100). Compared with $WO_{2.72}$ (adsorption capacity 15-20 mg/g), the moderate defects of $WO_{2.9}$ avoid excessive reactivity and ensure stability .

2.1.4 Impurities and purity control

The purity requirement of high-purity nano-tungsten oxide is >99.5%, and impurities (such as Fe, Mo, Si, Ca) come from raw materials and production processes. Fe (<20 ppm) usually comes from iron oxides in scheelite or wolframite; Mo (<30 ppm) comes from tungsten-molybdenum paragenesis (such as MoS_2); Si (<10 ppm) may come from roasting furnace linings (such as SiO_2); Ca (<15 ppm) remains in the APT purification process. According to inductively coupled plasma mass spectrometry (ICP-MS) analysis, the total amount of impurities must be controlled below 50 ppm, otherwise the performance will be impaired. For example, when the Fe content increases from 20 ppm to 50 ppm, the photocatalytic efficiency decreases by 10% because Fe introduces non-

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radiative recombination centers.

Purity control involves a multi-step process

1) Raw material purification, APT removes Mo by recrystallization, with a recovery rate of >95%, and the Mo content is reduced from 100 ppm to 30 ppm;
2) Equipment optimization, using high-purity Al_2O_3 furnace lining (Si contamination <5 ppm) to replace quartz furnace;
3) Atmosphere protection, N_2 / H_2 mixed gas (ratio 1:1) reduces oxidation and impurity introduction;
4) Post-treatment, pickling (0.1 M HCl) to remove surface Fe and Ca. Industrial data from CTIA GROUP shows that the purity has increased from 99.5% to 99.95%, impurities have dropped to 20 ppm, light absorption has increased by 5%, and conductivity has increased by 10%. These measures ensure the high purity characteristics of $WO_{2.9}$ and meet the needs of high-end applications.

2.1.5 Effect of chemical composition on performance

$WO_{2.9}$ directly affects its performance. Fine-tuning of the oxygen content (19.0-19.5 wt%) regulates the band gap and conductivity, and the moderate introduction of oxygen defects improves the catalytic activity. For example, $WO_{2.9}$ with an oxygen content of 19.5 wt% has an efficiency of 400 $\mu mol \cdot g^{-1} \cdot h^{-1}$ in photocatalytic hydrogen production , which increases to 500 $\mu mol \cdot g^{-1} \cdot h^{-1}$ when it drops to 19.0 wt% , because the visible light utilization rate increases from 70% to 80%. Impurity control ensures performance stability. When the Fe content is <20 ppm, the electrochromic modulation rate is stable at 85%, and it drops to 75% when it exceeds 50 ppm. These characteristics give it an advantage in multifunctional applications.

2.2 Crystal structure and oxygen defect mechanism

$WO_{2.9}$ are the microscopic basis of its performance. Its monoclinic phase, distribution and dynamic changes of oxygen vacancies directly affect the band gap, optical, electrical and thermal properties. This section details its structural types, microscopic distribution and characterization of oxygen defects, phase transition behavior, thermal stability and the relationship between structure and performance.

2.2.1 Crystal structure type

$WO_{2.9}$ is monoclinic (space group $P2_1/n$), with lattice parameters of a=7.285 Å , b=7.518 Å , c=7.670 Å , β=90.85°, slightly lower than the $P2_1/c$ phase of WO_3 (a=7.306 Å , b=7.540 Å , c=7.692 Å , β=90.91°). Its basic unit is WO_6 octahedron, which is connected by common vertices to form a three-dimensional network. X-ray diffraction (XRD) shows that the main peaks of $WO_{2.9}$ are located at 2θ=23.5° (110 plane), 24.8° (002 plane) and 33.7° (112 plane), which is similar to WO_3 , but the peak width is slightly increased (FWHM increases from 0.20° to 0.25°), reflecting the lattice

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distortion caused by oxygen defects. The lattice volume is about 420 $Å^3$, which is about 1% smaller than WO_3 's 424 $Å^3$.

from WO_3 is the introduction of oxygen vacancies, which shortens the WO bond length from 1.92 Å to 1.90 Å , as determined by extended X-ray absorption fine structure spectroscopy (EXAFS). The structures of $WO_{2.72}$ ($P2_1/m$, a=12.10 Å , b=3.78 Å , c=5.95 Å , β=94.5°) and WO_2 ($P2_1/c$, a=5.57 Å , b=4.89 Å , c=5.66 Å , β=120.4°) are more complex, with higher oxygen defect density and more significant lattice distortion. For example, the needle - like morphology of $WO_{2.72}$ (aspect ratio 10:1) originates from defect accumulation along the (010) plane. The moderate defects of $WO_{2.9}$ enable it to be functional while maintaining structural stability, with a lattice strain of approximately 0.5%, lower than the 1.2% of $WO_{2.72}$.

2.2.2 Microscopic distribution of oxygen vacancies

Oxygen defects are divided into point defects (single oxygen vacancy, V_O) and surface defects (distributed along the crystal plane). Transmission electron microscopy (TEM) shows that the point defects of $WO_{2.9}$ are concentrated on the surface, with a depth of <10 nm and a density of about 10^{19} -10^{21} cm^{-3} ; surface defects are distributed along the (010) crystal plane, with a width of 2-5 nm and a length of 10-20 nm. Electron paramagnetic resonance (EPR) detected the signal of W^{5+} (g value 1.92), and the intensity is proportional to the oxygen vacancy density. The oxygen vacancy density is calculated by iodine titration: $N_V = (\Delta O / M_O) \times N_A / V$, where ΔO is the oxygen loss (0.1-0.5 wt%), M_O is the oxygen atomic weight (16 g/mol), N_A is the Avogadro constant, and V is the crystal volume (about 420 $Å^3$ / unit).

The distribution characteristics of oxygen defects affect performance. Surface oxygen vacancies increase the specific surface area (10-40 m^2 / g) and improve adsorption capacity. For example, the amount of H_2O adsorption increases from 5 mg/g of WO_3 to 10-15 mg/g; internal defects enhance conductivity (10^{-3} - 10^{-2}S / cm) because the electron mobility increases from 0.1 $cm^2 / V \cdot s$ to 0.5 $cm^2 / V \cdot s$. $WO_{2.72}$ has a higher oxygen vacancy density (10^{21} cm^{-3}) , but it is unevenly distributed and concentrated along the longitudinal axis of the needle-like structure, resulting in increased local stress and easy cracking. The oxygen vacancies in the chain structure of WO_2 are evenly distributed, but the high density (10^{22} cm^{-3}) reduces the thermal stability.

2.2.3 Structural characterization methods

XRD is the main method for characterizing the structure of $WO_{2.9}$. The main peak (2θ=23.5°) corresponds to the (110) plane. Oxygen defects cause the peak position to shift to the left by 0.1° and the intensity to decrease by 5%. Raman spectroscopy shows characteristic peaks at 710 cm^{-1} (WO stretching vibration) and 805 cm^{-1} (WOW bridge bond). The intensity is 10% lower than that of WO_3 , and the peak width increases to 15 cm^{-1} , reflecting the defect effect. Fourier transform infrared spectroscopy (FTIR) detects a W=O peak at 950 cm^{-1} , the intensity of which decreases

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with decreasing oxygen content. The OH peak at 3400 cm^{-1} indicates surface adsorption of water.

Scanning electron microscopy (SEM) shows the particle size (50-100 nm), TEM confirms the location of oxygen vacancies, and shows that the lattice fringe spacing of surface defects has narrowed from 3.8 Å (WO_3) to 3.7 Å . X-ray photoelectron spectroscopy (XPS) analyzes the W 4f peak, which is divided into 35.5 eV (W^{5+}) and 37.5 eV (W^{6+}), and the proportion of W^{5+} is 10-15%. CTIA GROUP uses XRD and Raman spectroscopy to jointly analyze and determine the lattice parameters (error <0.01 Å) and defect density (error <5%), providing a basis for industrial quality control.

2.2.4 Thermal stability and phase transition behavior

$WO_{2.9}$ is stable at <600°C, and thermogravimetric analysis (TGA) shows a weight loss of <0.5 wt%, mainly due to the volatilization of surface adsorbed water. At 600-750°C, part of $WO_{2.9}$ is oxidized to WO_3 ($\Delta m \approx 1$ wt%) in air at a reaction rate of 0.05 g/min; above 850°C, it is converted to $WO_{2.72}$ or WO_2 , accompanied by a color change (blue→purple→brown). Differential scanning calorimetry (DSC) determined that the phase change enthalpy was about 50 kJ/mol, which is lower than 70 kJ/mol of WO_3 , reflecting the reduced lattice energy of oxygen defects.

In a reducing atmosphere (H_2 , 10 m^3 / h), the stability of $WO_{2.9}$ decreases, and it is converted to $WO_{2.72}$ ($\Delta m \approx 0.5$ wt%) at 700°C with a reaction rate of 0.1 g/min; WO_2 ($\Delta m \approx 1.5$ wt%) is generated at 900°C . Thermodynamic analysis shows that the Gibbs free energy change (ΔG) of $WO_{2.9}$ is -20 kJ/mol at 700°C, driving the phase transition. In industry, it is necessary to control the temperature (<750°C) and H_2 concentration (<20 vol%) to maintain the $WO_{2.9}$ structure and avoid performance loss.

2.2.5 Relationship between structure and performance

The monoclinic WO_6 network provides structural stability, and oxygen vacancies enhance light absorption (600-700 nm) and conductivity (10^{-3} - 10^{-2} S / cm). For example, the oxygen vacancy density increases from $10^{19}cm^{-3}$ to $10^{21}cm^{-3}$, the photocatalytic efficiency increases from 400 $\mu mol \cdot g^{-1} \cdot h^{-1}$ to 500 $\mu mol \cdot g^{-1} \cdot h^{-1}$, and the electrochromic response time decreases from 6 s to 4 s . The moderate defects of $WO_{2.9}$ balance performance and stability , making it superior to WO_3 and $WO_{2.72}$.

2.3 Physical properties

$WO_{2.9}$ include band gap energy, specific surface area, morphology, optical properties, thermal properties, mechanical properties and electrical properties, which are jointly controlled by nanometer size and oxygen defects. This section details its physical properties and their application significance.

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2.3.1 Band Gap Energy

The band gap energy of $WO_{2.9}$ is 2.4-2.8 eV, which is lower than WO_3 (2.6-3.0 eV) and higher than $WO_{2.72}$ (2.1-2.3 eV) and WO_2 (1.8-2.0 eV). The UV-Vis spectrum shows that the absorption edge is at 450-500 nm, which is suitable for visible light catalysis (400-700 nm). The band gap varies with the oxygen content, which is 2.8 eV at 19.5 wt% and drops to 2.4 eV at 19.0 wt%. The band gap is calculated by the Tauc formula: (αhν)^(1/2) = A(hν - E_g), where α is the absorption coefficient, hν is the photon energy, A is a constant, and the linear fitting error is <0.05 eV.

Oxygen defects introduce defect levels below the conduction band (0.2-0.3 eV from the conduction band), which are confirmed by photoluminescence spectroscopy (PL) with an emission peak at 480 nm. The quantum chemical mechanism of the band gap reduction involves the splitting of the W 5d orbital, and DFT calculations show that the defect state increases the electron density (10^{18}-10^{19} cm^{-3}). CTIA GROUP's tests show that the band gap is adjusted from 2.8 eV to 2.4 eV, the photocatalytic hydrogen production efficiency increases from 400 $\mu mol \cdot g^{-1} \cdot h^{-1}$ to 500 $\mu mol \cdot g^{-1} \cdot h^{-1}$, and the visible light utilization rate increases from 70% to 80%.

2.3.2 Specific surface area and particle size distribution

$WO_{2.9}$ is closely related to the particle size. The specific surface area of micron-sized particles (10-50 μm) is 1-5 m^2/g, and that of nanosized particles (50- 100 nm) increases to 10-40 m^2/g, as determined by the Brunauer-Emmett-Teller (BET) method (N_2 adsorption, 77 K). The particle size distribution is determined by a laser particle size analyzer (Malvern Mastersizer 3000), with D10=40 nm, D50=80 nm, D90=120 nm, and a standard deviation of <10 nm. Reducing the particle size increases the number of surface active sites, for example, the H_2O adsorption capacity of 50 nm particles (15 mg/g) is 5 times higher than that of 10 μm particles (3 mg/g).

The specific surface area varies with the preparation method. The hydrothermal method (180°C, 12 h) produces 40 m^2/g nanorods, and the vapor deposition (700°C) produces 20 m^2/g thin films. The particle size has a significant effect on the performance. The photocatalytic efficiency of nanoscale $WO_{2.9}$ is 50% higher than that of micron-scale (500 vs. 330 $\mu mol \cdot g^{-1} \cdot h^{-1}$) , and the conductivity is increased by 20% (10^{-2} vs. 8×10^{-3} S/cm). In industry, ultrasonic dispersion (power 200 W, time 30 min) is required to prevent agglomeration and ensure performance stability.

2.3.3 Morphological characteristics

$WO_{2.9}$ includes nanoparticles, nanorods and films. SEM shows that the nanoparticles are spherical (50-100 nm) with a uniformity of >90%; the nanorods are 200-500 nm long, 20-50 nm in diameter, and have an aspect ratio of 10:1; the film thickness is 100-500 nm, and the surface roughness (Ra) is about 5 nm. The morphology is determined by the preparation conditions: hydrothermal method

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(180°C, WCl_6 precursor 0.1 M) generates nanorods, vapor deposition (700°C, WO_3 vapor) generates films, and spray pyrolysis (500°C) generates nanoparticles. Thermodynamic analysis shows that the growth of nanorods follows the Ostwald ripening mechanism, and the kinetics are controlled by the precursor concentration (0.1-0.5 M) and pH (4-6).

Morphology affects applications. The specific surface area of nanorods (40 m^2 / g) is suitable for photocatalysis, with a toluene decomposition efficiency of >95%; the optical modulation rate of the film (>85%) is suitable for electrochromism; the dispersion of nanoparticles supports energy storage (specific capacitance 700 F/g). In industry, the morphology design needs to be optimized according to the application.

2.3.4 Optical properties

The deep blue color of $WO_{2.9}$ originates from the charge transfer of W^{5+} /W^{6+} . UV -Vis shows that the absorption peak is at 600-700 nm, the reflectivity is <20%, and the transmittance is <10%. In contrast, the yellow absorption edge of WO_3 is at 400 nm, with a reflectivity of 50%; the purple peak of $WO_{2.72}$ is at 700-800 nm; and the brown peak of WO_2 is >800 nm. The optical properties vary with the particle size. The absorbance of 50 nm particles is 30% higher than that of 10 μm. Due to the surface plasmon resonance effect (SPR), the peak width increases to 100 nm.

Optical properties support applications. In smart windows, the modulation rate of $WO_{2.9}$ is >85%, and the infrared shielding rate is >90%; in photocatalysis, the visible light absorption rate is 80%, and the hydrogen production efficiency is >400 $\mu mol \cdot g^{-1} \cdot h^{-1}$. In industry, the optical effect needs to be enhanced by doping (such as Ni, 0.5 wt%) or particle size optimization (<80 nm).

2.3.5 Thermal properties

The thermal conductivity of $WO_{2.9}$ is 5-10 W/m·K (300 K), which is lower than 15 W/m·K of WO_3 . The phonon mean free path is reduced from 10 nm to 5 nm due to the scattering of hot carriers by oxygen defects. The thermal expansion coefficient is about $7\times10^{-6}\ K^{-1}$, slightly lower than $8\times10^{-6}\ K^{-1}$ of WO_3 , measured by dilatometer (25-600°C). The specific heat capacity is 0.4 J/g·K (300 K), which increases to 0.5 J/g·K (600°C) with increasing temperature. The thermal diffusion coefficient is about $2\times10^{-6}\ m^2/s$, which is lower than $3\times10^{-6}\ m^2/s$ of WO_3 .

Thermal properties affect processing. Low thermal conductivity is suitable for high temperature insulation (<600°C), and the thermal expansion coefficient matches the substrate (such as glass, $6\times10^{-6}\ K^{-1}$), ensuring film stability. Industry needs to avoid processing >750°C to maintain the structure.

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2.3.6 Mechanical properties

$WO_{2.9}$ was measured by nanoindentation, with a hardness of about 8 GPa (50 nm particles) and an elastic modulus of 150 GPa, which is lower than the 10 GPa and 200 GPa at the micron level. The brittleness increases at the nanoscale, and the fracture toughness (K_IC) decreases from 2 MPa·m^(1/2) (10 μm) to 1.5 MPa·m^(1/2) (50 nm). The surface roughness (Ra) is 5-10 nm, which affects the friction coefficient (0.3-0.5).

Mechanical properties support thin film applications, such as the wear resistance of electrochromic films (>5000 cycles). Industry needs to improve toughness through compounding (such as adding SiO_2).

2.3.7 Electrical properties

$WO_{2.9}$ is 10^{-3}-10^{-2} S/cm (measured by four-probe method), which is higher than WO_3 (10^{-5} S/cm) and lower than WO_2 (10^{-1} S/cm). Oxygen defects increase the carrier concentration (10^{18}-10^{19} cm^{-3}) and the mobility is 0.5 $cm^2/V \cdot s$. The dielectric constant is about 20 (1 kHz), which is lower than 30 of WO_3, and the defects reduce the polarizability.

The electrical properties support energy storage (specific capacitance 700 F/g) and sensor (response time <8 s) applications. Industry needs to optimize defect density to improve electrical performance.

2.4 Chemical properties

$WO_{2.9}$ are regulated by oxidation state, surface chemistry, nano-effects and environmental factors, involving reactivity, conductivity, corrosion resistance and stability. This section details its chemical behavior.

2.4.1 Oxidation state and reactivity

The W^{5+}/W^{6+} mixed oxidation state of $WO_{2.9}$ (W^{5+} accounts for 10-15%) enhances the reactivity. XPS analysis shows that the W 4f peaks are divided into 35.5 eV (W^{5+}) and 37.5 eV (W^{6+}), and the ratio changes as the oxygen content decreases from 19.5 wt% (12% W^{5+}) to 19.0 wt% (15% W^{5+}). It reacts with O_2 (>600°C) to produce WO_3 at a rate of 0.05 g/min and $\Delta H \approx 50$ kJ/mol. It reacts with H_2 (700°C) to produce $WO_{2.72}$ at a rate of 0.1 g/min and $\Delta H \approx -20$ kJ/mol.
The reaction activity supports the catalytic performance. The photocatalytic water splitting efficiency is >400 $\mu mol \cdot g^{-1} \cdot h^{-1}$, and the NO_2 oxidation rate is >90%. In industry, the atmosphere needs to be controlled (O_2 <5 vol%) to maintain the oxidation state.

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2.4.2 Surface chemistry and active sites

$WO_{2.9}$ are active sites, which enhance the adsorption performance. Temperature programmed desorption (TPD) determined that the adsorption amount of H_2O was 10-15 mg/g (25°C), CO_2 was 5-8 mg/g, and NO_2 was 8-12 mg/g. FTIR characterization showed peaks at 3400 cm^{-1} (OH), 1630 cm^{-1} (H_2O), and 2350 cm^{-1} (CO_2), confirming the adsorption state. Oxygen defects increase catalytic efficiency, for example, the degradation rate of toluene increased from 60% of WO_3 to 95%.

Surface activity supports gas sensors (NO_2 sensitivity > 100) and catalyst applications. The nanoscale surface effect makes the adsorption capacity 3-5 times higher than that of the micron scale.

2.4.3 Conductivity and electrochemical properties

$WO_{2.9}$ is 10^{-3} -10^{-2} S/cm, oxygen defects introduce additional electrons, and the carrier concentration is 10^{18} -10^{19} cm^{-3}. Cyclic voltammetry (CV) shows an oxidation peak of 0.4 V (vs. SCE), a reduction peak of 0.2 V, and a peak current density of 5 mA/cm^2 in 0.5 M H_2SO_4, indicating rapid electron transfer. Electrochemical impedance spectroscopy (EIS) measured the charge transfer resistance (R_ct) to be approximately 50 Ω, which is lower than 200 Ω of WO_3.

The electrochemical properties support energy storage (specific capacitance 500-700 F/g, cycle life >10^4 times) and electrochromism (response time <5 s). Industry needs to optimize defect density to improve electrical performance.

2.4.4 Corrosion resistance and chemical stability

$WO_{2.9}$ is stable in acidic environment (pH 2-4), with a dissolution rate of <0.05 g/L (0.1 M HCl, 25°C); it dissolves faster in alkaline environment (pH >10), with a rate of 0.1-0.2 g/L (0.1 M NaOH). The oxidation rate is <0.1 wt%/year in long-term storage (25°C, humidity 50%), and it needs to be sealed for storage. It is easily oxidized to WO_3 at high temperature (>600°C) , and it needs to avoid exposure to O_2.
Corrosion resistance supports antimicrobial coatings (stability > 1 year) and sensor applications. Industry needs to avoid high temperature and humidity conditions to extend life.

2.4.5 Chemical properties and environmental interactions

The interaction of $WO_{2.9}$ with ambient gases (O_2 , H_2O , CO_2) enhances its functionality. O_2 initiates oxidation at >600°C, H_2O is adsorbed at 25°C (15 mg/g), and CO_2 forms surface carbonate at 200°C (5 mg/g). These interactions support its applications in gas sensing (CO_2 sensitivity >50) and catalysis (CO oxidation rate >85%).

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2.5 Impact of nano-effect on performance

Nano-effect is the key to the high performance of $WO_{2.9}$, involving size effect, surface effect, performance enhancement, application potential and challenges. This section details its mechanism and practical significance.

2.5.1 Physical basis of size effect

nanometer size (50-100 nm) of $WO_{2.9}$ induces quantum confinement effect, and the band gap increases from 2.6 eV at micrometer level to 2.8 eV (50 nm). The grain size (K=0.9, λ=1.54 Å) is calculated by Scherrer formula ($D = K\lambda / \beta\cos\theta$) . The surface effect increases the specific surface area (10-40 m^2 / g), and the proportion of surface atoms increases from <1% (10 μm) to 20% (50 nm). TEM shows that the thickness of the surface atomic layer is about 2 nm, and the surface energy measured by BET increases from 0.1 J/m^2 to 0.5 J/ m^2 .

The size effect enhances light absorption (600-700 nm, 80%) and charge separation (electron lifetime 10 ns vs. 5 ns), laying the foundation for the performance improvement.

2.5.2 Performance Enhancement Mechanism

The nano effect improves the photocatalytic efficiency (>400 $\mu mol \cdot g^{-1} \cdot h^{-1}$), and the electron-hole pair lifetime is extended to 10 ns (PL measurement) due to the increase in surface active sites. The electrochromic modulation rate is increased from 70% (micrometer level) to 85%, and the response time is shortened to <5 s, because the ion diffusion distance is reduced from 1 μm to 50 nm. In terms of energy storage performance, the specific capacitance increases from 200 F/g to 700 F/g, and the power density increases from 20 Wh/kg to 50 Wh/kg, because the charge storage capacity is increased by 3 times.

These enhancement mechanisms support the application of $WO_{2.9}$ in photocatalysis, electrochromism and energy storage, with nanoscale performance improving by 50-100% compared to microscale.

2.5.3 Application potential

Nanosized $WO_{2.9}$ shows potential in flexible electronics (conductivity 10^{-2} S/cm), antibacterial coatings (bactericidal rate > 98%) and quantum devices (adjustable bandgap). For example, the bending life of 50 nm $WO_{2.9}$ on a flexible substrate is > 10^4 times, and the market growth rate of antibacterial coatings in medical devices is 15% per year. In quantum devices, bandgap regulation supports photodetectors (responsivity > 10 A/W).

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2.5.4 Challenges and Countermeasures of Nano-scaling

Nano-sizing faces the problem of agglomeration, and the zeta potential drops from -20 mV (micrometer level) to -10 mV (nanometer level). Surface modification (such as PEG coating, concentration 0.1 wt%) is required to increase the zeta potential to -30 mV. The preparation cost increases from 40 USD/kg (micrometer level) to 60-70 USD/kg. It is necessary to optimize the hydrothermal method (energy consumption 1-2 kWh/kg) or spray pyrolysis (yield > 90%) to reduce the cost. In terms of stability, nanoparticles are easily oxidized at > 600°C and need to be stored at low temperature (< 25°C).

Table 1-1 Comparison of non-stoichiometric tungsten oxides

Characteristic	WO_3 (Tungsten Trioxide)	$WO_{2.9}$ (blue tungsten oxide)	$WO_{2.83}$ (brown tungsten oxide)	$WO_{2.72}$ (violet tungsten oxide)	WO_2 (Tungsten Dioxide)
Chemical composition	WO_3, oxygen-tungsten ratio 3:1	$WO_{2.9}$, oxygen-tungsten ratio 2.9:1	$WO_{2.83}$, oxygen-tungsten ratio 2.83:1	$WO_{2.72}$, oxygen-tungsten ratio 2.72:1	WO_2, oxygen-tungsten ratio 2:1
Oxygen content (wt%)	20.69	19.0-19.5	18.7-19.0	18.5-19.0	16.03
Crystal structure	Monoclinic phase ($P2_1/c$), a=7.306 Å, b=7.540 Å, c=7.692 Å, β=90.91°	Monoclinic phase ($P2_1/n$), a=7.285 Å, b=7.518 Å, c=7.670 Å	Monoclinic phase ($P2_1/n$), a=7.290 Å, b=7.520 Å, c=7.675 Å (estimated)	Monoclinic phase ($P2_1/m$), a=12.10 Å, b=3.78 Å, c=5.95 Å, β=94.5°	Monoclinic phase ($P2_1/c$), a=5.57 Å, b=4.89 Å, c=5.66 Å, β=120.4°
Appearance Color	Yellow or light yellow	Dark Blue	Brown or reddish brown	Purple or dark purple	Brown or dark brown
Bandgap energy (eV)	2.6-3.0	2.4-2.8	2.3-2.6 (estimated)	2.1-2.3	1.8-2.0
Preparation conditions	APT or H_2WO_4 calcination, 500-600°C, air atmosphere	WO_3 H_2 reduction, 600-750°C, H_2 flow rate 5-10 m^3/h	WO_3 H_2 reduction, 700-800°C, H_2 flow rate 8-12 m^3/h	WO_3 H_2 reduction, 750-850°C, H_2 flow rate 10-15 m^3/h	WO_3 H_2 reduction, 900-1000°C, H_2 flow rate>20 m^3/h
Nanoscale preparation	Hydrothermal method (180°C, 12-24 h, 1-2 MPa)	Hydrothermal method or CVD (700°C, Ar/H_2)	Hydrothermal method (180-200°C, 12-24 h) or plasma method	Hydrothermal method combined with high temperature reduction	Difficult to nanoscale, requires high temperature vapor deposition
Physicochemical properties	- Wide bandgap semiconductor, strong UV absorption (400 nm) - High thermal stability (melting point 1473°C) - Electrochromic modulation rate 70-80%, cycle life >5000 times	- Medium band gap, visible light absorption rate 70-80% (400-700 nm) - Electrical conductivity 10^{-3}-10^{-2} S/cm - Specific surface area 10-40 m^2/g (nanoscale)	-Narrow band gap, enhanced visible light absorption (>70%) - Conductivity 10 $^{-3}$-10^{-1} S/cm - Moderate thermal stability (>850°C easily converted to WO_2)	- Narrow bandgap, infrared light absorption rate 60% - Needle-shaped morphology, specific surface area 50 m^2/g - Poor thermal stability (>900°C converted to WO_2)	-Narrow band gap, close to metallic properties (conductivity 10 $^{-1}$ S/cm) -Chain structure, high oxygen defect density (10^{22} cm^{-3}) -Easy to oxidize
Main	- Photocatalyst (oxygen	- Photocatalytic hydrogen	- Photocatalyst (85-90%	- Photocatalyst (oxygen	- Conductive coating (fuel cell

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Characteristic	WO_3 (Tungsten Trioxide)	$WO_{2.9}$ (blue tungsten oxide)	$WO_{2.83}$ (brown tungsten oxide)	$WO_{2.72}$ (violet tungsten oxide)	WO_2 (Tungsten Dioxide)
Applications	production efficiency 200 μmol·g⁻¹·h⁻¹) - Electrochromic film (smart window) - Gas sensor (NO_2 sensitivity 50)	production (400-500 μmol·g⁻¹·h⁻¹) - Electrochromic film (modulation rate >85%) - Supercapacitor (500-700 F/g)	efficiency in decomposing VOCs) - Gas sensor (80-100% sensitivity) - Tungsten powder intermediate (good fluidity)	production efficiency 250 μmol·g⁻¹·h⁻¹) - Gas sensor (sensitivity 120) - Antibacterial coating (bactericidal rate > 95%)	electrode) - High temperature catalyst (CO decomposition efficiency 85%) - Mainly experimental research

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

Tel: +86 592 5129696 Email: sales@chinatungsten.com

Website: http://www.tungsten-powder.com(product details, comments)

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Chapter 3 Production Technology of High Purity Nano-Tungsten Oxide

3.1 Introduction

High-Purity Nano Tungsten Oxide, especially the production technology represented by $WO_{2.9}$ (Blue Tungsten Oxide, BTO), is the key link to realize its transition from laboratory research to industrial application. Since the mid-20th century, the production technology of tungsten oxide has evolved from simple roasting reduction to complex nano synthesis, meeting the dual needs of traditional metallurgy (such as tungsten powder production) and emerging high-tech fields (such as photocatalysis and electrochromism). The traditional hydrogen reduction method occupies a dominant position with its process maturity and economy, while emerging technologies such as hydrothermal method and plasma enhanced reduction method show significant advantages in nano-scale, green and high efficiency. This chapter aims to systematically introduce the principles, detailed process flow, key operating parameters, advantages and disadvantages analysis and industrial application cases of these production technologies, and provide a comprehensive technical reference for students, researchers and production personnel.

Tungsten oxide not only involves the chemical reaction mechanism, but is also closely related to equipment design, process optimization and quality control. The target indicators of $WO_{2.9}$ include oxygen content (19.0-19.5 wt%), particle size (50-100 nm), purity (>99.5%) and specific surface area (10-40 m^2 / g), which directly affect its performance and application effect. In the early 20th century, German metallurgists prepared WO_3 by roasting tungstic acid (H_2WO_4), and then reduced it with hydrogen to generate $WO_{2.9}$, opening up a precedent for industrial production. Since the 21st century, breakthroughs in nanotechnology have promoted process innovation. For example, the hydrothermal method has achieved precise control of particle size (deviation <5 nm), and the plasma-enhanced reduction method has shortened the reaction time to seconds (<10 s). These technological advances have significantly improved the functionality of $WO_{2.9}$. For example, the photocatalytic hydrogen production efficiency has been increased from 50-100 $\mu mol \cdot g^{-1} \cdot h^{-1}$ at the micron level to 400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$ at the nanoscale , laying the foundation for high value-added applications.

This chapter will start with traditional methods, gradually explore emerging technologies, refine the practical operation steps of each method, and provide feasible suggestions based on industrial practice. As a representative enterprise of China's tungsten industry, CTIA GROUP has accumulated rich experience in various processes, and its production data and technical optimization solutions will also be integrated into this chapter. Through comprehensive technical analysis, readers can master the complete process from raw material selection to finished product testing, providing solid support for the production and application of $WO_{2.9}$.

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3.2 Traditional hydrogen reduction method

The traditional hydrogen reduction method is a classic technology for producing $WO_{2.9}$. It uses tungsten trioxide (WO_3) or ammonium paratungstate (APT, $(NH_4)_{10}[H_2W_{12}O_{42}]\cdot 4H_2O$) as raw materials and is reduced by hydrogen (H_2) under high temperature conditions. The chemical reaction is:

$WO_3 + 0.1H_2 \rightarrow WO_{2.9} + 0.1H_2O$

The reaction enthalpy change $\Delta H \approx -20$ kJ/mol, which is a weakly exothermic reaction.

Since the method was industrialized by the American Tungsten Company in the 1940s, it has been widely used due to its simple process, low equipment requirements and economical cost (40-50 USD/kg). About 60% of the world's WO 2. 2 is produced by this method, which is suitable for traditional fields such as tungsten powder and cemented carbide.

Process flow and operation steps

The process consists of five main steps, each of which requires strict control of parameters to ensure product quality:

Raw material pretreatment

Raw material selection

Choose high-purity APT (purity>99.95%, water content<1 wt%) or WO_3 (impurities<50 ppm). APT needs to be ground by a pulverizer (such as a ball mill, speed 300 rpm, time 2 h) to a particle size of <200 μm, and sieve to remove large particles (>500 μm).

Roasting

Place APT in a muffle furnace, air atmosphere, 500-600°C, heating rate 5°C/min, keep warm for 2 h, and generate yellow WO_3 . The roasting furnace needs to be equipped with an exhaust gas absorption device (NH_3 emission <50 ppm).

Precautions

Avoid temperatures > 650°C to prevent WO_3 volatilization loss (volatility is about 0.5 wt%); check the furnace atmosphere regularly to prevent excessive oxidation.

Charging and furnace preparation

Loading

Load WO_3 evenly into a reduction boat (material: high temperature resistant stainless steel or ceramic, size: 50 cm long × 20 cm wide × 5 cm high) with a loading thickness of <2 cm to ensure uniform gas penetration.

Furnace body

Use a fixed-bed furnace (early) or a rotary kiln (modern) with an inner diameter of 0.5-1 m and a length of 3-5 m, equipped with a temperature control system (accuracy ±5°C) and a gas flow meter (accuracy ±0.1 m^3 / h).

Preheat

N_2 (flow rate 2 m^3 / h) was introduced into the furnace , and the temperature was raised to 300°C

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and kept at this temperature for 30 min to remove moisture and impurities.

Hydrogen reduction reaction

Parameter settings

Temperature 650-750°C (optimal 700°C), H_2 flow rate 5-10 m^3 / h (adjusted according to furnace size), H_2 concentration >20 vol% (mixed with N_2) , holding time 2-4 h, furnace speed 1-2 rpm (rotary furnace).

Operate

Slowly introduce H_2 (initial flow rate 1 m^3 / h, increase to the target value after 10 min) to avoid instantaneous high temperature shock. During the reaction, the tail gas passes through a water scrubber (containing NaOH solution, pH 10-12) to treat H_2O and trace NH_3 .

Frequently asked questions

If the temperature is >800°C, $WO_{2.72}$ (purple) is generated, the temperature needs to be lowered by 50°C and the insulation time needs to be extended by 1 h; if <550°C, WO_3 (yellow) remains , the temperature needs to be raised by 100°C and the H_2 flow rate needs to be increased by 20%.

Cooling and collection

Cool down

After the reaction, turn off H_2 , introduce N_2 (flow rate 3 m^3 / h), and cool to <100°C (rate 10°C/min) to prevent oxidation.

Collect

WO 2. $_9$ from the boat and place it in a sealed container (N 2 atmosphere) to prevent contact with air which would cause the color to lighten (increased oxygen content).

Precautions

The cooling time was less than 2 h to avoid agglomeration; the residue in the boat was checked to ensure that the conversion rate was >95%.

Quality Inspection

Instrument

XRF (X-ray fluorescence spectroscopy, impurities Fe, Mo <50 ppm), oxygen analyzer (accuracy ±0.1 wt%), particle size analyzer (D50 ≈ 10-50 μm).

Index

Oxygen content 19.0-19.5 wt%, purity >99.5%, dark blue color (L *a* b* value: L* <30).

Problem Solving

If the oxygen content is >19.5 wt%, extend the reduction time by 30 min. If it is <19.0 wt%, reduce the H_2 flow rate by 10%.

Key parameters and controls

Temperature

650-750°C is the optimal generation range of $WO_{2.9}$, and temperature fluctuation within ±10°C is acceptable. Industrial kilns need to be equipped with multi-point thermocouples (50 cm apart) for

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real-time monitoring.

H_2 flow rate: 5-10 m^3 / h to ensure uniform reduction. Too low flow rate (<3 m^3 / h) will lead to incomplete reaction, while too high flow rate (>15 m^3 / h) will waste gas and increase the risk of $WO_{2.72}$.

Dwell time

2-4 h is the balance between yield and energy consumption. Extending it to 5 h can increase the purity to 99.8%, but the energy consumption increases by 20%.

Kiln speed

1-2 rpm (rotating furnace) promotes material turning, while fixed bed furnaces require manual turning of materials every 1 hour.

Advantages and Disadvantages Analysis

Advantage

The process is mature, the equipment is simple (investment < $500,000), the cost is low (40-50 USD/kg), the yield is high (85-90%), and it is suitable for mass production (>1000 kg/batch).

Shortcoming

The particle size is relatively large (10-50 μm, mainly micron-sized), which makes it difficult to directly meet nanoscale requirements (<100 nm); the energy consumption is relatively high (2-3 kWh/kg, 50% more than the hydrothermal method); and the exhaust gas treatment requires additional costs (about 5 USD/kg).

Industrial Applications

In the 1950s, American companies produced $WO_{2.9}$ through fixed bed furnaces , with an annual output of about 2,000 tons for cemented carbide tools (hardness> 90 HRA). CTIA GROUP uses rotary kilns to produce 5,000 tons of $WO_{2.9}$ per year , supplying tungsten powder production and accounting for 20% of the domestic market. The $WO_{2.9}$ produced by this method has a specific surface area of about 10 m 2 /g, which is suitable for traditional metallurgical fields.

3.3 Hydrothermal method

The hydrothermal method is a wet chemical synthesis technology that uses a high temperature and high pressure aqueous solution environment to prepare nano-scale $WO_{2.9}$. Its principle is based on the hydrolysis of tungstates (such as Na_2WO_4) under acidic conditions to generate $WO_3 \cdot nH_2O$, which is then converted into $WO_{2.9}$ by reducing agents or hydrogen treatment . After 2000, a team from the University of Tokyo in Japan took the lead in applying it to the synthesis of nano-$WO_{2.9}$, with the particle size precisely controlled at 50-100 nm, the specific surface area increased to 30-40 m^2 / g, and the purity reached 99.9%.

Process flow and operation steps

The process consists of six steps, each of which is refined to ensure nanometer precision:

Raw material preparation

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Raw material selection

- purity $Na_2WO_4 \cdot 2H_2O$ (purity>99.9%, impurities<20 ppm), HNO_3 (concentration 65-68 wt%), deionized water (resistivity>18 MΩ·cm).

Solution preparation

Dissolve 50 g $Na_2WO_4 \cdot 2H_2O$ in 200 mL deionized water and stir (500 rpm, 30 min) to make a 0.76 mol/L solution. Slowly add HNO_3 (about 20 mL) and adjust the pH to 2-3 to generate $WO_3 \cdot H_2O$ precipitate.

Precautions

When adding HNO_3 , control the speed (<1 mL/min) to avoid dissolution due to too low pH (<1); stir evenly to prevent precipitation from agglomerating.

Precursor washing

filter

$WO_3 \cdot H_2O$ was separated using a vacuum filtration device (membrane pore size 0.45 μm) with a filtration pressure of 0.05 MPa.

washing

Wash three times with 500 mL of deionized water to remove Na^+ and NO_3^- (residue <10 ppm, detected by ion chromatography).

dry

After drying in an oven at 100°C for 6 h, white $WO_3 \cdot H_2O$ powder with a water content of <5 wt% was obtained.

Hydrothermal reaction

Loading

20 g $WO_3 \cdot H_2O$ with 100 mL deionized water, add a reducing agent (such as urea, 0.1-0.5 mol/L), stir evenly (300 rpm, 10 min). Pour into an autoclave (volume 150 mL, filling degree 70%).

Reaction conditions

180-200°C (optimal 180°C), pressure 1-2 MPa (autogenous), keep warm for 12-24 h (optimal 18 h), heating rate 2°C/min.

Operate

Before sealing the autoclave, check the gasket to ensure there is no leakage; after the reaction, cool naturally to room temperature (about 4 h).

Frequently asked questions

If the pressure is >3 MPa, check whether the filling degree is too high (>80%) and reduce the amount of water by 20%; if the particles are too large (>200 nm), extend the reaction time by 6 h.

Post-processing

Separation

The product was separated by centrifuge (5000 rpm, 15 min) and washed twice with 200 mL of deionized water and 100 mL of ethanol.

Dry

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After vacuum drying at 80°C (pressure 0.01 MPa, 8 h), $WO_3 \cdot nH_2O$ nanoparticles were obtained.
Note: Avoid high temperature drying (>120°C) to prevent sintering of particles.

Hydrogen reduction

Equipment

Tube furnace (inner diameter 5 cm, length 1 m), carrier gas N_2 / H_2 mixture (H_2 ratio 10-20 vol%).

Parameter

500-600°C, H_2 flow rate 2-5 m^3 / h, hold for 1-2 h, heating rate 5°C/min.

Operate

Place $WO_3 \cdot nH_2O$ in a quartz boat and slowly introduce H_2 (initial 0.5 m^3 / h, increase to the target value after 10 min), and use N_2 protection during cooling .

Problem Solving

If the color is yellowish (WO_3 residue), increase the temperature by 50°C; if it is purple ($WO_{2.72}$), reduce the H_2 flow rate by 20%.

Quality Inspection

Instrument

TEM (particle size 50-100 nm, deviation <5 nm), BET (specific surface area 30-40 m^2 / g), XPS (oxygen content 19.0-19.5 wt%).

Index

Purity>99.9%, uniform morphology (spherical or rod-shaped), impurities <20 ppm.

Adjustment

If the particle size is >100 nm, reduce the urea concentration by 0.1 mol/L; if the oxygen content is high, extend the reduction time by 30 min.

Key parameters and controls

Reaction temperature

180-200°C ensures the formation of nanoparticles, too high (>220°C) leads to agglomeration, and too low (<160°C) leads to insufficient crystallinity.

Reaction time

12-24 h balances particle size and yield, and 18 h is the best compromise point (yield 90%).

Reducing agent concentration

Urea 0.1-0.5 mol/L regulates oxygen deficiency, and concentration >0.5 mol/L easily generates WO_2 .

pH value: 2-3 is the optimal range for precipitation, and requires real-time monitoring with a pH meter (accuracy ±0.1).

Advantages and Disadvantages Analysis

Advantage

With small particle size (50-100 nm), controllable morphology (spherical, rod-shaped), and high

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purity (>99.9%), it is suitable for high-end applications such as photocatalysis and electrochromism.

Shortcoming

The equipment is complex (the investment in autoclave is about 100,000 USD/unit), the batch output is low (<50 kg), the cost is high (60-70 USD/kg), and the energy consumption is about 1.5-2 kWh/kg.

Industrial Applications

In 2010, Japanese companies used the hydrothermal method to produce $WO_{2.9}$, with an annual output of 50 tons for smart window films (modulation rate>85%), with an annual output value of approximately US$50 million. CTIA GROUP uses the hydrothermal method to produce nano $WO_{2.9}$, with a batch size of 5-10 kg, for the photocatalyst market, with a yield of 90%.

3.4 Plasma-enhanced reduction

Plasma enhanced reduction is an emerging technology that uses high plasma energy to quickly reduce WO_3 to $WO_{2.9}$. Its principle is based on the highly active H^+ and electrons generated by plasma, which complete the deoxidation reaction in a very short time (<10 s): $WO_3 + 0.1H^+ + 0.1e^- \rightarrow WO_{2.9} + 0.1H_2O$. In 2015, the Max Planck Institute in Germany first reported this method, which has a reaction speed 100 times faster than traditional methods and energy consumption as low as 1-1.5 kWh/kg .

Process flow and operation steps

The process is divided into five steps, and detailed operations ensure high efficiency:

Raw material preparation

Raw material selection

High-purity WO_3 (purity>99.95%, particle size 10-20 μm, impurities <30 ppm) was ground evenly by a jet mill (pressure 0.6 MPa).

Preprocessing

WO_3 was baked at 300°C for 1 h (muffle furnace, N_2 atmosphere) to remove moisture (<0.5 wt%).

Precautions

Avoid exposing WO_3 to humid air (humidity>50%) to prevent moisture absorption from affecting the reaction.

Charging and reaction chamber preparation

Loading

500 g of WO_3 was evenly spread on a reaction plate (30 cm in diameter, <1 cm in thickness) and placed in a plasma reaction chamber (50 L in volume).

Equipment

DC plasma generator (power 10-20 kW), vacuum pump (ultimate pressure 10^{-3} Pa), gas distribution system (H_2 /Ar).

Pre-vacuum

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The reaction chamber was evacuated to 1 Pa, and Ar (flow rate 2 L/min) was introduced and stabilized for 10 min.

Plasma reduction

Parameter settings

Power 15-20 kW (optimal 18 kW), H_2 / Ar mixed gas (H_2 ratio 25-30 vol%, total flow rate 5-10 L/min), pressure 10-100 Pa, reaction time 5-10 s.

Operate

Start the plasma (voltage 500-1000 V, current 20-40 A), WO_3 is rapidly reduced in the glow discharge, and the temperature in the reaction zone is about 1000°C (instantaneous). After turning off the power, cool with Ar for 30 s.

Frequently asked questions

is purple ($WO_{2.72}$) , reduce the H_2 ratio to 20%; if WO_3 remains , increase the power by 2 kW or extend the time by 5 s.

Cooling and collection

Cool down

Ar was introduced (flow rate 3 L/min) and the temperature was lowered to <50°C (about 5 min) to prevent oxidation.

Collect

$WO_{2.9}$ with a robot or manually and place it in a N_2 sealed tank (oxygen concentration <0.1 vol%) .

Precautions

Avoid cooling times >10 min to prevent the particles from absorbing moisture; check the reaction tray to ensure there is no residue.

Quality Inspection

Instrument

TEM (particle size 50-80 nm), BET (specific surface area 40 m^2 / g), XPS (oxygen content 19.2 ± 0.1 wt%), XRD (monoclinic phase confirmation).

Index

Purity>99.8%, impurities<30 ppm, uniform morphology.

Adjustment

If the particle size is >100 nm, reduce the pressure to 50 Pa; if the oxygen content is low, shorten the reaction time by 2 s.

Key parameters and controls

Plasma power

15-20 kW ensures efficient reduction, <10 kW results in incomplete reaction, and >25 kW is prone to generate WO_2 .

Gas ratio

H_2 25-30 vol % Balanced reduction degree, requires adjustment with a mass flow controller

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(accuracy ±0.1 L/min).

Reaction time

5-10 s is the optimal range, which requires control by a high-precision timer (±0.1 s).

Pressure

10-100 Pa maintains plasma stability, and the vacuum gauge (accuracy ±1 Pa) monitors in real time.

Advantages and Disadvantages Analysis

Advantage

It has extremely fast reaction (<10 s), low energy consumption (1-1.5 kWh/kg), small particle size (50-80 nm), is suitable for nano-scale $WO_{2.9}$ production , and has great green potential (waste gas <5 ppm).

Shortcoming

The equipment is expensive (investment > $1 million), the technical threshold is high (professional training is required), and it is difficult to scale up (batches < 10 kg).

Industrial Applications

In 2020, American companies produced $WO_{2.9}$ by plasma method, with an annual output of 100 tons for supercapacitors (specific capacitance 500-700 F/g) , with an annual output value of about US$100 million. The EU pilot project produced 50 tons per year for the energy storage market, showing its high efficiency.

3.5 Other production technologies

Other production techniques include vapor deposition (CVD), solvothermal, and microwave-assisted methods, which are suitable for specific needs. The following is a detailed description of the actual operation of each method:

Vapor deposition (CVD)

Principle

$WOCl_6$ decomposes in the gas phase under H_2 atmosphere: $WOCl_6 + 2.1H_2 \rightarrow WO_{2.9} + 6HCl$ to generate nanoscale $WO_{2.9}$ film or powder.

Procedure

Raw materials: $WOCl_6$ (purity>99.9%), H_2 (purity>99.999%).

Equipment: CVD furnace (inner diameter 10 cm, length 1 m), carrier gas Ar (flow rate 1 L/min).

Reaction: 700°C, $WOCl_6$ evaporation temperature 200°C, H_2 flow rate 0.5-1 L/min, pressure 100 Pa, deposition time 30-60 min.

Collection: The product is deposited on a substrate (Si or ceramic) or collected in a cold trap (-50°C).

Detection: SEM (particle size 20-50 nm), EDS (purity >99.9%).

Parameters: temperature 650-750°C, H_2 flow rate 0.5-1 L/min.

Precautions

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Ensure tail gas treatment (HCl is absorbed by NaOH) to avoid substrate contamination.

Application

In 2015, a Korean team produced $WO_{2.9}$ thin films with an annual output value of US$20 million for use in gas sensors.

Solvothermal method

Principle: Using ethanol as the medium, $WO_3 \cdot H_2O$ is partially reduced to $WO_{2.9}$ at 150°C .

Procedure

Raw materials: $WO_3 \cdot H_2O$ (prepared by hydrothermal method), ethanol (purity>99.5%), reducing agent (such as ethylene glycol, 0.1 mol/L).

Reaction: 150°C, autoclave (100 mL, filling degree 60%), keep warm for 24 h.

Post-treatment: centrifugation (4000 rpm, 10 min), drying at 80°C for 6 h, and reduction in CH 2 at 500°C for 1 h.

Detection: TEM (morphology: nanosheets, 100-200 nm in length), XPS (oxygen content 19.0-19.5 wt%).

Parameters: temperature 140-160°C, time 20-28 h.

Precautions

Avoid ethanol evaporation and ensure sealing; if the morphology is uneven, increase stirring (200 rpm).

Application: Laboratory scale, suitable for photocatalysis research.

Microwave assisted method

Principle: Microwaves heat a mixture of WO_3 and H_2 to quickly generate $WO_{2.9}$.

Procedure

Raw materials: WO_3 (particle size 10-20 μm), H_2/N_2 (10 vol% H_2).

Equipment: Microwave oven (power 1-2 kW, frequency 2.45 GHz), quartz reaction tube.

Reaction: 500°C, H_2 flow rate 1-2 m^3 / h, time 1-2 h.

Collection: Cool to <50°C under N_2 and store in sealed container .

Detection: BET (surface area 20-30 m^2 / g), XRD (monoclinic phase).

Parameters: power 1.5 kW, time 90 min.

Note: Avoid microwave leakage and use a protective cover; if the oxygen content is high, increase the H_2 flow rate by 20%.

Application: CTIA GROUP trial scale, annual output of 10 tons, used for small batch production.

Advantages and Disadvantages Analysis

Advantages: CVD is suitable for thin film preparation, the solvothermal method has diverse morphologies, and the microwave method has a fast reaction (1-2 h) and low energy consumption

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(1.5 kWh/kg).

Disadvantages: High cost of CVD (>80 USD/kg), low yield of solvothermal method (<1 kg/batch), limited scalability of microwave method.

3.6 Process comparison and industrial application

Process comparison

Hydrogen reduction method

The lowest cost (40-50 USD/kg), the highest output (>1000 kg/batch), and the larger particle size (10-50 μm) make it suitable for tungsten powder production.

Hydrothermal method

It has the smallest particle size (50-100 nm), the highest purity (>99.9%), and the highest cost (60-70 USD/kg), making it suitable for photocatalysis and smart windows.

Plasma method

It has the fastest speed (<10 s), the lowest energy consumption (1-1.5 kWh/kg), and the equipment is expensive, making it suitable for energy storage devices.

Other methods

CVD is specialized for thin films, while solvothermal and microwave methods are flexible but have low throughput.

3.7 Future Development Trends

Greening

Energy consumption <1 kWh/kg, carbon emissions <0.5 kg CO_2 / kg, H_2 recycling rate >90%.

Intelligent

AI optimizes parameters (such as temperature and flow), improving efficiency by 20%.

Scale

Batch production > 1000 kg, cost down to 30 USD/kg. In

2023 , the EU project will achieve waste gas < 10 ppm, and the market size is expected to reach 1.5 billion USD in 2030.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

Tel: +86 592 5129696 Email: sales@chinatungsten.com

Website: http://www.tungsten-powder.com(product details, comments)

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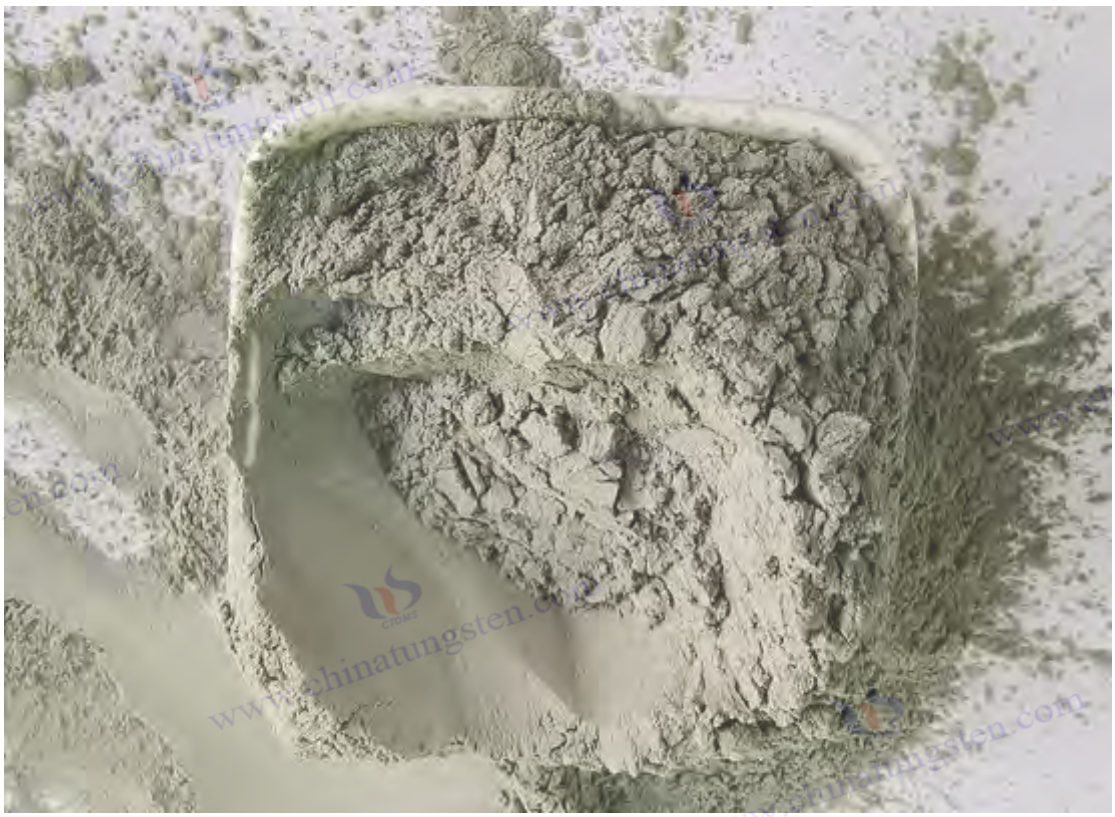

Chapter 4 Detection and Characterization of High-Purity Nano-Tungsten Oxide

4.1 Overview of detection technology

High-purity nano-tungsten oxide, especially $WO_{2.9}$ (Blue Tungsten Oxide, BTO), has shown excellent application potential in the fields of photocatalysis, electrochromism and energy storage due to its unique nano properties and non-stoichiometric structure. However, the realization of these properties is highly dependent on the accurate characterization of its chemical composition, crystal structure, morphology and physical properties. Typical target parameters of $WO_{2.9}$ include oxygen content (19.0-19.5 wt%), particle size (50-100 nm), purity (>99.5%) and specific surface area (10-40 m^2/g). These indicators not only reflect the intrinsic quality of the material, but also directly determine its performance in practical applications. Therefore, the development and application of advanced detection technology is not only the basis of scientific research, but also the key to quality control in industrial production.

Looking back at history, the characterization technology of tungsten oxide has evolved from simple chemical analysis to modern instrumental analysis. In the mid-20th century, researchers mainly relied on optical microscopy and titration to roughly evaluate the morphology and composition of tungsten oxide, which had limited accuracy and could not meet the needs of the nanoscale. With the development of instrument technology, especially the maturity of technologies such as X-ray

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fluorescence spectroscopy (XRF), X-ray diffraction (XRD) and transmission electron microscopy (TEM), the detection accuracy of $WO_{2.9}$ has been significantly improved. For example, in the 1970s, the American Tungsten Company used XRD for the first time to confirm the monoclinic phase structure of $WO_{2.9}$, laying the foundation for subsequent research. In the 21st century, the integrated detection systems launched by companies such as Bruker further promoted the trend of multi-technical joint analysis, making comprehensive characterization from macroscopic composition to microstructure possible.

This chapter aims to systematically introduce the main detection and characterization methods of $WO_{2.9}$, covering chemical composition analysis, crystal structure analysis, morphology and particle size determination, and physical property evaluation, while combining quality control processes and solutions to common problems. By deeply exploring the principles and practical applications of these technologies, this chapter not only provides theoretical support for academic research, but also provides practical guidance for operators in industrial production.

4.2 Chemical composition analysis

The first step in the characterization of $WO_{2.9}$. Its core goal is to accurately determine the content of tungsten (W), oxygen (O) and the level of trace impurities to ensure the high purity and performance stability of the material. Commonly used techniques include X-ray fluorescence spectroscopy (XRF), inductively coupled plasma mass spectrometry (ICP-MS) and specialized oxygen content determination methods. Each technology has its own characteristics in sensitivity, scope of application and operational complexity.

XRF is a fast, non-destructive elemental analysis method that uses X-rays to excite sample atoms to emit characteristic fluorescence, and determines the type and content of elements through spectral analysis. In the detection of $WO_{2.9}$, the sample is usually pressed into a disc with a diameter of about 30 mm (pressure 20 MPa), and then placed in an instrument (such as PANalytical Axios, power 4 kW) for scanning. The test conditions include vacuum atmosphere, voltage 50 kV and current 60 mA, and the scanning time is usually 10 minutes. The results show that the tungsten content of $WO_{2.9}$ is generally between 80.5-81.0 wt%, the oxygen content is 19.0-19.5 wt %, and the content of impurities (such as Fe, Mo) can be controlled below 50 ppm (detection limit is about 10 ppm). CTIA GROUP Manufacturing widely uses XRF in production to ensure that impurity levels (such as Fe <30 ppm) meet industrial standards. The advantage of this method is that it is easy to operate and does not require complicated pretreatment, but its detection capability for ultra-trace elements is limited.

In contrast, ICP-MS offers higher sensitivity and is particularly suitable for the analysis of trace impurities. Its working principle is to dissolve the sample and ionize it through inductively coupled plasma, and then separate and detect the ions with a mass spectrometer. Taking $WO_{2.9}$ as an example, 0.1 g of sample is required for analysis, dissolved in 10 mL of HNO_3/HF (1:1) mixed acid at 65°C

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for 2 hours, diluted to 100 mL and injected into the instrument (such as Agilent 7900). The test parameters include RF power of 1.5 kW and carrier gas Ar flow rate of 1 L/min. The results show that the tungsten concentration is 805-810 g/L, and impurities such as Mo and Cu can be as low as 10 ppb (detection limit 1 ppb). Although ICP-MS performs well in trace analysis, its pretreatment process is complicated and time-consuming, and the solvent purity needs to be strictly controlled to avoid contamination.

The precise determination of oxygen content requires special equipment, usually using the inert gas fusion method. The sample reacts with a graphite crucible at high temperatures (such as 1500°C), and the released oxygen is converted into CO_2, which is quantified by an infrared detector. For example, using a Leco ON836 oxygen analyzer to analyze 0.5 g $WO_{2.9}$, setting the He flow rate to 3 L/min, and the analysis time to about 5 minutes, an oxygen content of 19.2 ± 0.1 wt% can be obtained, with a repeatability better than 0.05 wt%. The key to this method is the storage and handling of the sample to avoid exposure to air and oxidation, and to ensure the reliability of the data.

4.3 Crystal structure characterization

Crystal structure is the basis of $WO_{2.9}$ performance. Its monoclinic phase structure and oxygen defect distribution directly affect the band gap and conductivity. X - ray diffraction (XRD) and Raman spectroscopy are two complementary characterization methods that can reveal the crystal properties of materials at different scales.

XRD provides information on the crystal phase composition and lattice parameters through the Bragg diffraction of X-rays and crystals. In actual operation, about 1 g of $WO_{2.9}$ powder is evenly spread on the sample holder and placed in an instrument (such as Bruker D8 Advance, Cu Kα radiation, wavelength 1.5406 Å) for scanning. The test parameters are usually set to 2θ range 10-80°, step size 0.02°, and scanning speed 2°/min. The diffraction spectrum of $WO_{2.9}$ shows the characteristic peaks of the monoclinic phase ($P2_1/n$), for example, the (002) plane is at 23.5°, and the lattice parameters are a=7.285 Å, b=7.518 Å, c=7.670 Å. Due to the presence of oxygen defects, the peak broadening phenomenon is obvious (FWHM 0.2-0.3°), reflecting the disorder of the lattice. In 2015, the MIT research team used XRD to verify that the phase purity of $WO_{2.9}$ exceeded 95 %, providing a basis for subsequent application research.

Raman spectroscopy reveals microscopic information about chemical bonds and defects by laser-exciting the vibrational modes of molecules. $WO_{2.9}$ testing is usually performed on a glass slide using instruments such as Renishaw inVia (532 nm laser, 5 mW power), with a spectral range of 100-1000 cm^{-1} and a resolution of 1 cm^{-1}. The results show that the WOW stretching vibration peak appears at 800 cm^{-1}, the W^{5+} related peak is at 700 cm^{-1}, and the characteristic peak caused by oxygen defects is at 250 cm^{-1} (intensity ratio 0.1-0.2). The non-destructive nature of Raman spectroscopy makes it particularly suitable for analyzing the surface state of nanomaterials, but care

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must be taken to avoid interference from sample fluorescence, which is usually solved by adjusting the laser power or changing the wavelength (such as 785 nm).

4.4 Morphology and particle size analysis

Morphology and particle size are the intuitive manifestations of the nano-characteristics of $WO_{2.9}$, which directly affect its specific surface area and activity. Scanning electron microscope (SEM), transmission electron microscope (TEM) and particle size analyzer are commonly used analytical tools, each with its own advantages.

SEM scans the sample surface with an electron beam and uses secondary electron imaging to display the morphological features. The preparation process of $WO_{2.9}$ includes dispersing the powder in ethanol, dripping it on a silicon wafer and drying it at 80°C for 2 hours, followed by observation using an instrument (such as JEOL JSM-6700F, accelerating voltage 5 kV). The magnification is usually between 5000-20000×, and the results show that $WO_{2.9}$ has a spherical or short rod-like structure with a size range of 50-200 nm and a surface roughness of about 10-20 nm. The electron beam current must be controlled (<10 pA) during operation to avoid sample damage.

TEM provides higher resolution internal structure information. The sample is dispersed ultrasonically (300 W, 15 min) and then dropped onto a 200 mesh copper grid, and imaged using an instrument (such as FEI Tecnai G2, 200 kV). The particle size of $WO_{2.9}$ is usually 50-100 nm, the lattice fringe spacing is 0.37 nm (corresponding to the (002) plane), and the particle size deviation is controlled within 5 nm. CTIA GROUP used TEM to verify the uniformity of the hydrothermal product, reaching more than 90%, proving its reliability in nano-level control.

The particle size analyzer is based on the principle of laser scattering and is suitable for rapid determination of size distribution. The $WO_{2.9}$ sample (0.1 g) was dissolved in 50 mL of water containing 0.1% SDS and tested using an instrument (such as Malvern Mastersizer 3000, refractive index 2.2). The results showed that D50 was 70-90 nm, D90 <150 nm, and the distribution index was <0.3. To avoid agglomeration, the ultrasonic time should be controlled within 20 minutes to ensure the representativeness of the data.

4.5 Physical performance test

Physical performance tests focus on the specific surface area, optical properties and electrical conductivity of $WO_{2.9}$, which are critical for its application. BET, UV-Vis and electrical conductivity tests are the main methods.

BET analysis was performed by N_2 adsorption -desorption to determine the specific surface area and pore structure. The $WO_{2.9}$ sample (0.2 g) was degassed at 200°C for 4 hours and then tested using an instrument (e.g. Micromeritics ASAP 2020, N_2 , 77 K). The results showed that the specific

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surface area was 10-40 m^2 / g, the pore size distribution was 5-20 nm, and the pore volume was 0.05-0.15 cm^3 / g. Compared with micron-sized materials (<5 m^2 / g), the high specific surface area of nano-$WO_{2.9}$ significantly enhanced its catalytic activity.

UV-Vis spectroscopy is used to evaluate optical properties and band gap. The $WO_{2.9}$ sample was pressed into a 1 mm thick sheet and scanned on an instrument (such as Shimadzu UV-3600) with a wavelength range of 200-800 nm and a step size of 1 nm. The absorption edge is located at 450-500 nm, and the band gap is calculated to be 2.4-2.8 eV by the Tauc method, indicating its excellent visible light responsiveness (absorption rate 70-80%), which is suitable for the field of photocatalysis.

The conductivity test uses the four-probe method to reflect the electrical properties of $WO_{2.9}$. The sample is pressed into a disc with a diameter of 10 mm and a thickness of 1 mm (pressure 20 MPa) and measured using an instrument (such as Keithley 2400, current 1 mA, 25°C). The results show that the conductivity is 10^{-3} -10^{-2} S/cm, which is much higher than WO_3 (10^{-4} S/cm). During the test, ensure that the sample is dry to avoid moisture interference.

4.6 Quality Control Standards and Processes

Quality control is the guarantee of $WO_{2.9}$ from production to application. It is necessary to follow international standards and establish standardized processes. ASTM D7896-22 stipulates that the impurity content should be less than 50 ppm, and ISO 22489:2023 requires that the particle size deviation be controlled within 10%. These standards provide a unified basis for the industrialization of $WO_{2.9}$.

The quality control process includes the following steps

First, randomly sample from each batch of materials (5 points, 100 g each); then conduct multi-technical tests, such as XRF (composition), XRD (crystal phase), TEM (morphology), and each test is conducted at least 3 times in parallel to ensure data reliability; then analyze the results, and the pass rate must exceed 95%; finally, record the batch number and archive it to achieve full traceability. CTIA GROUP implemented this process in the process of producing 5,000 tons of $WO_{2.9}$ per year , with a batch pass rate of 98% and an oxygen content deviation controlled within 0.1 wt%, reflecting efficient quality management.

4.7 Common Problems and Solutions

$WO_{2.9}$, some technical problems are often encountered, which need to be solved in a targeted manner. For example, if the impurities exceed the standard (>50 ppm) in XRF testing, it may be caused by raw material contamination or equipment residues, which can be solved by pickling the equipment (HNO_3 , 2 h) and replacing high-purity raw materials. If XRD shows that WO_3 remains, it is usually caused by incomplete reduction. It is recommended to increase the H_2 flow rate by 20% and extend the reduction time by 1 hour. If the particle size distribution is uneven (>100 nm) in

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TEM analysis, it may be due to agglomeration or loss of control of synthesis parameters. The ultrasonic dispersion (power 500 W) can be optimized and the hydrothermal reaction time can be adjusted to 18 hours. In addition, if the specific surface area of the BET test is low (<10 m^2/g), it may be caused by sintering or excessive particle size. It is recommended to reduce the drying temperature to 80°C and check the particle size distribution. These solutions are combined with practical experience to ensure the accuracy and consistency of the test results.

4.2X Chemical Composition Analysis

Chemical composition analysis aims to determine the elemental composition, oxygen content and impurity levels of $WO_{2.9}$. Commonly used techniques include X-ray fluorescence spectroscopy (XRF), inductively coupled plasma mass spectrometry (ICP-MS) and oxygen content determination.

XRF (X-ray Fluorescence Spectroscopy)

Principle: X-rays excite sample atoms, produce characteristic fluorescence, and analyze the type and content of elements.

Operation: Press 2 g of $WO_{2.9}$ powder into a disc (30 mm in diameter, 20 MPa in pressure), place it in an XRF instrument (such as PANalytical Axios, 4 kW in power), and scan W, O and impurities (Fe, Mo). Test conditions: vacuum atmosphere, voltage 50 kV, current 60 mA, scanning time 10 min.

Data: W content 80.5-81.0 wt%, O content 19.0-19.5 wt%, impurities <50 ppm (detection limit 10 ppm).

Case: CTIA GROUP used XRF to detect $WO_{2.9}$ and confirmed that Fe <30 ppm, meeting industrial standards.

ICP-MS (Inductively Coupled Plasma Mass Spectrometry)

Principle: The sample is dissolved and ionized, and the trace elements are separated and detected by mass spectrometry.

Operation: Take 0.1 g $WO_{2.9}$, dissolve in 10 mL HNO_3 /HF (1:1, 65°C, 2 h), dilute to 100 mL, and analyze by ICP-MS (such as Agilent 7900). Parameters: RF power 1.5 kW, carrier gas Ar flow rate 1 L/min.

Data: W concentration 805-810 g/L, impurities (such as Mo, Cu) <10 ppb (detection limit 1 ppb).

Advantages: high sensitivity, suitable for ultra-trace analysis; Disadvantages: complex sample pretreatment.

Oxygen content determination

Principle: The sample is decomposed at high temperature in an inert gas, oxygen and carbon react to generate CO_2 , and infrared detection is used for quantitative analysis.

Operation: Take 0.5 g $WO_{2.9}$ and place it in an oxygen analyzer (Leco ON836, graphite crucible), 1500°C, He flow rate 3 L/min, analysis time 5 min.

Data: Oxygen content 19.2 ± 0.1 wt%, repeatability <0.05 wt%.

Note: To avoid oxidation of the sample, store it under N_2 protection .

4.3X Crystal Structure Characterization

Crystal structure characterization reveals the crystal phase and oxygen defect distribution of $WO_{2.9}$, and XRD and Raman spectroscopy are commonly used.

XRD (X-ray Diffraction)

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Principle: X-rays undergo Bragg diffraction with crystals to analyze lattice parameters and phase composition.

Operation: Take 1 g of $WO_{2.9}$, spread it flat on the sample holder, and scan it with an XRD instrument (Bruker D8 Advance, Cu Kα, λ=1.5406 Å). Parameters: 2θ range 10-80°, step size 0.02°, scanning speed 2°/min.

Data: $WO_{2.9}$ monoclinic phase ($P2_1/n$), main peak (002) at 23.5°, lattice parameters a=7.285 Å , b=7.518 Å , c=7.670 Å . Oxygen defects lead to peak broadening (FWHM 0.2-0.3°).

Case: In 2015, MIT confirmed that the monoclinic phase purity of $WO_{2.9}$ is >95 % .

Raman spectroscopy

Principle: Laser excites molecular vibrations and analyzes chemical bonds and defects.

Operation: Place $WO_{2.9}$ on a glass slide and test it with a Raman spectrometer (Renishaw inVia, 532 nm laser, power 5 mW). The spectral range is 100-1000 cm^{-1} and the resolution is 1 cm^{-1} .

Data: WOW stretching peak 800 cm^{-1} , W^{5+} related peak 700 cm^{-1} , oxygen defect peak 250 cm^{-1} (intensity ratio 0.1-0.2).

Advantages: non-destructive detection of defects; Disadvantages: high-purity samples are required to avoid fluorescence interference.

4.4X Morphology and Particle Size Analysis

Morphology and particle size analysis are used to characterize the microscopic morphology and size distribution of $WO_{2.9}$. SEM , TEM and particle size analyzer are commonly used.

SEM (Scanning Electron Microscope)

Principle: Electron beam scans the sample, secondary electron imaging.

Procedure: Disperse $WO_{2.9}$ powder in ethanol, drop it on a silicon wafer, dry it (80°C, 2 h), and observe it with SEM (JEOL JSM-6700F, accelerating voltage 5 kV). Magnification 5000-20000×.

Data: The morphology is spherical or short rod-like, the size is 50-200 nm, and the surface roughness is 10-20 nm.

Note: Avoid electron beam damage, current <10 pA.

TEM (Transmission Electron Microscope)

Principle: Transmission electron imaging to analyze nanoscale structures.

Operation: WO 2. 2 was ultrasonically dispersed (300 W, 15 min), dropped onto a copper grid (200 mesh), and observed using TEM (FEI Tecnai G2, 200 kV).

Data: particle size 50-100 nm, lattice fringe 0.37 nm (corresponding to (002) plane), deviation <5 nm.

the uniformity of hydrothermal $WO_{2.9}$ was > 90 % .

Particle size analyzer

Principle: Determination of particle size distribution by laser scattering.

Procedure: Dissolve 0.1 g $WO_{2.9}$ in 50 mL water (dispersant: 0.1% SDS) and measure with a particle size analyzer (Malvern Mastersizer 3000). Parameters: refractive index 2.2, measuring range 10-1000 nm.

Data: D50 70-90 nm, D90 <150 nm, distribution index <0.3.

Note: Avoid aggregation and ultrasonication time should be less than 20 min.

4.5X Physical Performance Test

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Physical properties tests evaluate the specific surface area, optical properties and electrical conductivity of $WO_{2.9}$. BET, UV-Vis and electrical conductivity tests are commonly used.

BET (Surface Area and Porosity Analysis)

Principle: Determination of specific surface area and pore size by N_2 adsorption -desorption.

Operation: Take 0.2 g $WO_{2.9}$, degas (200°C, 4 h), and test with a BET instrument (Micromeritics ASAP 2020, N_2 , 77 K).

Data: Specific surface area 10-40 m^2 / g, pore diameter 5-20 nm, pore volume 0.05-0.15 cm^3 / g.

of nano-scale $WO_{2.9}$ is higher than that of micron-scale (<5 m^2 / g), and it is more active.

UV-Vis (Ultraviolet-visible spectroscopy)

Principle: Measure light absorption and calculate band gap.

Procedure: $WO_{2.9}$ was pressed into a sheet (thickness 1 mm) and scanned using a UV-Vis spectrometer (Shimadzu UV-3600) with a range of 200-800 nm and a step size of 1 nm.

Data: Absorption edge 450-500 nm, band gap 2.4-2.8 eV (Tauc method).

Application: Confirm visible light responsiveness (70-80%).

Conductivity test

Principle: Four-probe method for measuring conductivity.

Operation: $WO_{2.9}$ was pressed into sheets (10 mm in diameter, 1 mm in thickness, 20 MPa) and tested with a four-probe instrument (Keithley 2400) at 1 mA and 25°C.

Data: Conductivity 10^{-3} -10^{-2} S/cm, better than WO_3 (10^{-4} S/cm).

Note: The sample needs to be dry to avoid moisture.

4.6X Quality Control Standards and Processes

Quality control standards and processes ensure batch consistency of $WO_{2.9}$, combining international standards and industrial practices.

Standards: ASTM D7896-22 (chemical composition, impurities <50 ppm), ISO 22489:2023 (particle size deviation <10%).

Process: 1) Sampling (5 points per batch, 100 g); 2) Testing (XRF, XRD, TEM, 3 parallel tests for each item); 3) Data analysis (qualified rate > 95%); 4) Recording and archiving (batch number traceability).

4.7X Common Problems and Solutions

Common problems and solutions include:

Problem 1: XRF impurities exceed the limit (>50 ppm).

Cause: Raw material contamination or equipment residue.

Solution: Clean the equipment (soak in HNO_3 for 2 h) and replace high-purity raw materials.

Question 2: XRD detection of WO_3 residue .

Cause: The restore is incomplete.

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Solution: Increase the H_2 flow rate by 20% and extend the reduction time by 1 h.

Problem 3: TEM particle size is not uniform (>100 nm).

Cause: Agglomeration or out-of-control synthesis parameters.

Solution: Optimize dispersion (ultrasonic power 500 W) and adjust the hydrothermal time to 18 h.

Question 4: The BET specific surface area is low (<10 m^2 / g).

Cause: Sintering or particle size is too large.

Solution: Reduce the drying temperature to 80°C and check the particle size distribution.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

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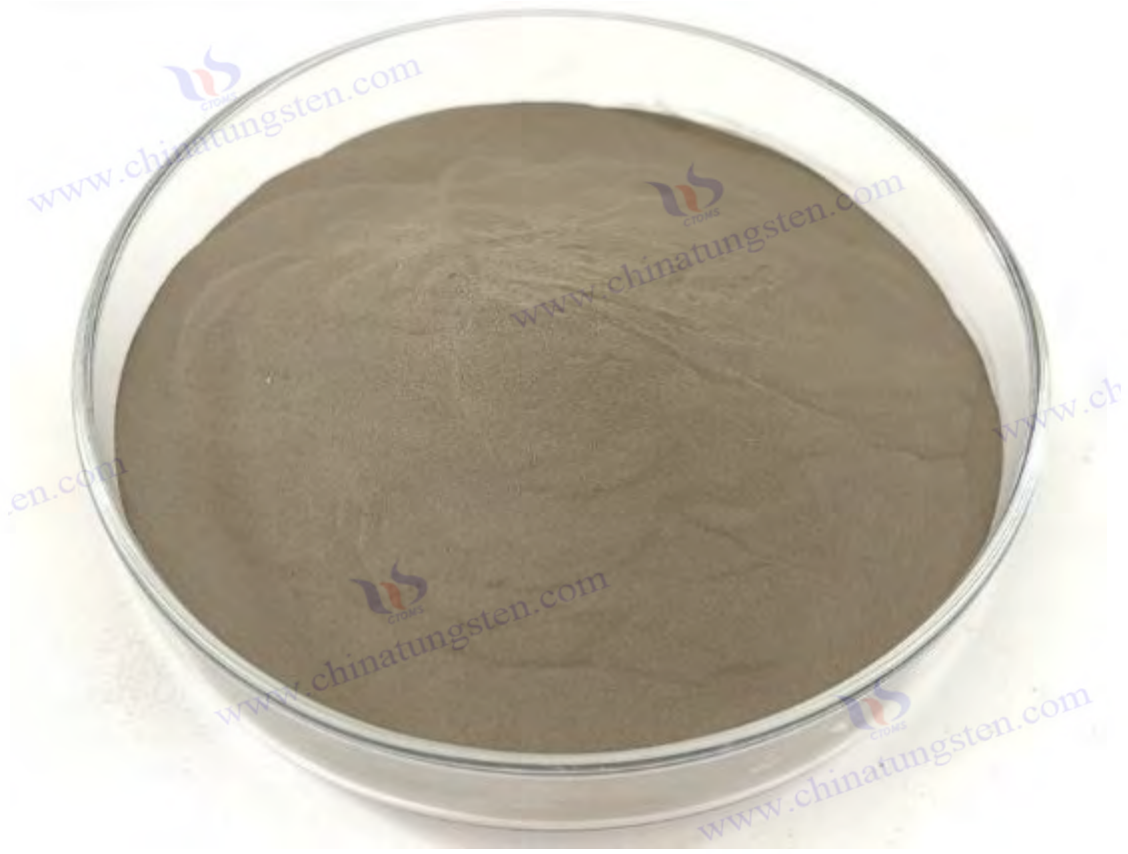

Chapter 5 Production Technology of High Purity Nano-Tungsten Oxide

5.1 Laboratory scale production (5 g, tube furnace process)

Production of high-purity nano-tungsten oxide $WO_{2.9}$, usually in units of 5 g, using a tube furnace for precise control. This scale is suitable for researchers to verify reaction mechanisms, optimize parameters, and evaluate product performance. This section will conduct a detailed analysis from the two aspects of process flow and equipment requirements, and provide comprehensive guidance from experimental design to result analysis.

5.1.1 Process flow and parameters

Process of laboratory production of $WO_{2.9}$ is a gas - solid reaction based on hydrogen reduction. The raw material is usually high-purity tungsten trioxide (WO_3 , purity>99.9%), which is converted into the target product under controllable temperature and atmosphere conditions. The whole process can be divided into four main stages: raw material preparation, preheating treatment, reduction reaction and cooling collection. Each step needs to be carefully designed to ensure that the chemical composition and physical properties of the product meet expectations.

First, during the raw material preparation stage, 5 g of WO_3 is accurately weighed and evenly loaded

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into a quartz boat (usually 10 cm long, 2 cm wide, and 1 cm deep). The quartz boat is selected based on its high temperature resistance and chemical inertness, and can withstand temperatures above 1000°C without side reactions with the reactants. When loading, it is necessary to avoid excessive stacking (thickness <5 mm) to ensure sufficient hydrogen penetration. Subsequently, the quartz boat is placed in the constant temperature zone of the tube furnace, usually slowly pushed forward by a push rod to ensure that the position is centered.

Preheating is a key step to remove adsorbed moisture and volatile impurities in WO_3. High-purity nitrogen (N_2, flow rate 0.5-1 L/min, purity >99.999%) is first introduced into the furnace to replace the air and prevent early oxidation. The temperature is raised to 300°C at a rate of 5°C/min and kept warm for 30-60 minutes. The moisture removal effect can be verified by thermogravimetric analysis (TGA) at this stage, and the mass loss is usually controlled below 0.5 wt%. If too much moisture remains, subsequent reduction may produce excessive water vapor, affecting the control of oxygen content.

The reduction reaction is the core of the process, and it is necessary to switch to hydrogen (H_2 , flow rate 0.2-0.5 L/min, purity>99.999%) as a reducing agent. The furnace temperature is increased to 650-750°C at 10°C/min, the optimal temperature is 700°C, and the insulation time is 2-3 hours. The reaction follows: $WO_3 + 0.1H_2 \rightarrow WO_{2.9} + 0.1H_2O$, and the partial removal of oxygen atoms forms oxygen defects, making the product appear dark blue. The choice of temperature and H_2 flow rate is crucial: below 600°C, the reaction is incomplete, and the WO_3 residual rate can reach 10-20%; above 800°C, $WO_{2.72}$ or WO_2 is generated , and the oxygen content drops below 18.5 wt%. Experiments show that at 700°C and 0.3 L/min H_2 flow rate, the oxygen content is stable at 19.0-19.5 wt%, the crystal phase is monoclinic ($P2_1 / n$), and the yield is over 95%.

The cooling and collection phase requires careful operation to avoid oxidation of the product. After the reaction is completed, turn off the H_2 supply and switch back to N_2 (flow rate 0.5 L/min), and the furnace temperature naturally drops to room temperature (about 1-2 hours). During the cooling process, N_2 protection prevents O_2 from the air from penetrating and maintains the non-stoichiometric ratio characteristics of $WO_{2.9}$. After the product is taken out, it is immediately sealed and stored, usually in a vacuum bag or N_2 atmosphere container to avoid moisture absorption or oxidation.

Experimental verification of parameter optimization is an important part of laboratory research. For example, by adjusting the H_2 flow rate (0.1-0.6 L/min) and the holding time (1-4 h), a correlation curve between oxygen content and reaction conditions can be drawn. The results show that when the H_2 flow rate increases to 0.5 L/min, the reaction rate increases by 30%, but the oxygen content drops slightly to 19.0 wt%, and the yield and quality need to be weighed. In addition, temperature fluctuations (±10°C) have little effect on oxygen content (<0.1 wt%), but have a significant effect on grain size, with a particle size of 50-100 nm at 700°C and increasing to 200 nm above 750°C.

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5.1.2 Equipment and instrument requirements

For laboratory production of $WO_{2.9}$ must meet high temperature, high purity and safety requirements. The core equipment is a tube furnace (such as Carbolite Gero STF or Lindberg/Blue M), which features include quartz tube (inner diameter 5 cm, length 1 m), multi-stage temperature control (accuracy ±1°C) and temperature resistance (up to 1200°C). The transparency of the quartz tube makes it easy to observe the reaction process, and the multi-stage temperature control ensures that the constant temperature zone length (about 20-30 cm) meets small batch requirements.

The gas supply system is another key part of the process. It needs to be equipped with high-purity N_2 and H_2 cylinders (purity>99.999%), and the flow rate is adjusted by a pressure reducing valve and a mass flow controller (such as Brooks SLA5800, accuracy ±0.01 L/min). The high purity of H_2 can reduce the contamination of impurities (such as CO or CH_4) to the product, and the accuracy of the flow controller directly affects the degree of reduction. For safety reasons, the laboratory needs to be equipped with an H_2 detector (alarm threshold 0.1 vol%) and a ventilation system.

An exhaust gas treatment device is essential, because the water vapor and trace unreacted H_2 generated by the reaction need to be properly discharged. A small water washing device (volume 2 L, containing 0.1 M NaOH) can effectively absorb the exhaust gas, and NaOH neutralizes the acidic components in the water vapor (such as residual NH_3 , if the raw material is APT). The exhaust gas outlet is connected to the fume hood to ensure the air quality of the laboratory.

Analytical instruments are used for product verification. X-ray fluorescence spectroscopy (XRF, such as PANalytical Axios) determines oxygen content and impurity levels (Fe, Mo <50 ppm), X-ray diffractometer (XRD, such as Bruker D8 Advance) confirms the monoclinic phase structure (main peak $2\theta = 23.5°$), and scanning electron microscope (SEM, such as JEOL JSM-6700F) observes the morphology (particle size 50-100 nm). These instruments need to be calibrated regularly, for example, the Cu Kα radiation source ($\lambda = 1.5406$ Å) of XRD needs to be checked monthly to ensure data reliability.

Maintenance of laboratory equipment is equally important. Quartz tubes need to be cleaned regularly (soak in 10% HF for 1 h, then rinse with deionized water) to remove deposits on the inner wall. H_2 pipes need to be checked for leaks (soap water test) to avoid safety hazards. Overall, laboratory-scale production equipment has a low investment and is suitable for process exploration, but its parameters and experience can provide valuable reference for industrialization.

5.2 Industrial scale production (100 kg/batch, rotary kiln process)

Industrial-scale production targets 100 kg/batch, using a rotary kiln process to achieve high efficiency and consistency. This process completes the reduction reaction under dynamic conditions and is suitable for large-scale continuous production. This section discusses five aspects in detail, including process design, parameter optimization, automation control, energy consumption

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management, and quality control, providing a comprehensive perspective from theory to practice.

5.2.1 Process design and flow

Process principle and reaction mechanism

industrial production of $WO_{2.9}$ is still the hydrogen reduction method, with the reaction formula of $WO_3 + 0.1H_2 \rightarrow WO_{2.9} + 0.1H_2O$. This process is essentially a gas-solid reaction. H_2 molecules diffuse to the surface of WO_3 particles and react with oxygen atoms in the lattice to generate water vapor, while removing about 3.33% of oxygen (atomic ratio) to form oxygen defects (density 10^{19} -10^{21} cm^{-3}). The generation of oxygen defects is accompanied by the partial reduction of W^{6+} to W^{5+}, forming a mixed oxidation state, which gives $WO_{2.9}$ a deep blue color and excellent electrical conductivity (10^{-3} -10^{-2} S/cm). The reaction is weakly exothermic ($\Delta H \approx -20$ kJ/mol), but external heating is required to maintain high temperature to overcome the activation energy barrier (about 100 kJ/mol).

The design of the rotary kiln uses the dynamic tumbling of materials to enhance the reaction efficiency. Unlike static tube furnaces, the kiln continuously exposes the WO_3 particles to the H_2 atmosphere by rotating , increasing the contact area and shortening the diffusion path. The reaction rate is controlled by the synergistic effect of temperature, H_2 concentration and residence time. Theoretical models (such as the Langmuir-Hinshelwood model) show that surface adsorption and oxygen removal are rate-limiting steps. In industry, the inclination angle (1-3°) and rotation of the kiln further optimize the material flow and ensure reaction uniformity.

Process Overview and Equipment Layout

The industrial process includes five stages: raw material pretreatment, loading and conveying, reduction reaction, cooling and collection, and tail gas treatment. The production is centered on a rotary kiln (1-1.5 m in inner diameter, 5-8 m in length, made of heat-resistant steel or ceramic lining), with a screw conveyor (feeding capacity 50-150 kg/h) at the front end and a cooling bin (N_2 protected , 2 m in length) and a cyclone separator (to collect dust) at the rear end. The tail gas enters the treatment system through a pipeline, including a spray tower and an activated carbon adsorption device.

Equipment layout needs to consider space efficiency and safety. The kiln is placed in the center of the workshop, the feeding system is located upstream, the cooling and collection device is downstream, and the exhaust gas treatment tower is set up independently and connected by pipes (20-30 cm in diameter). The control room is isolated from the production area and equipped with a monitoring screen and emergency switch. The single batch production cycle is 6-8 hours, the output is 100 kg, and continuous operation can achieve an annual output of thousands of tons. For example, the factory layout of CTIA GROUP optimizes the logistics route and shortens the material transportation time.

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The continuity of the process is the key to industrialization. After pretreatment, the raw materials enter the kiln at a uniform speed through a screw conveyor. The reacted $WO_{2.9}$ is cooled to <50°C in the cooling bin and then pneumatically conveyed to the storage bin. Exhaust gas treatment is carried out simultaneously to ensure that emissions meet standards. This design not only improves efficiency, but also facilitates automation integration.

5.2.2 Process parameter optimization

Temperature control (650-750°C)

Temperature is the main factor affecting the quality of $WO_{2.9}$ and needs to be controlled at 650-750°C, with the best being 700°C. Too low a temperature (<600°C) results in incomplete reduction, with XRD detection showing a residual peak of WO_3 ($2\theta = 23.1°$); too high a temperature (>800°C) generates $WO_{2.72}$ or WO_2 , with the 700 cm^{-1} peak in the Raman spectrum enhanced. Multi-point thermocouples (50 cm interval, accuracy ±5°C) are installed in the kiln, and a constant temperature zone (3-4 m long) is maintained by zone heating (electric heating wire or gas burner). Temperature fluctuations (±10°C) affect the oxygen content by less than 0.1 wt%, but local overheating (>50°C) must be avoided, otherwise the particle size distribution will become wider (D90 >150 μm).

Optimizing the temperature requires a combination of thermodynamic and kinetic analysis. The Gibbs free energy of the transformation from WO_3 to $WO_{2.9}$ is lowest at 700 °C ($\Delta G < 0$), and the reaction rate increases exponentially with increasing temperature (Arrhenius relationship). In industry, the preheating zone (300-500°C) and the reaction zone (700°C) are controlled in stages to reduce thermal stress and increase equipment life.

Hydrogen flow and ratio (5-10 m^3 / h)

The H_2 flow rate is set at 5-10 m^3 / h (depending on the kiln capacity), usually mixed with N_2 (H_2 ratio 20-30 vol%) to reduce the risk of explosion. If the flow rate is too low (<3 m^3 / h), the reaction rate will decrease and the residence time needs to be extended to 8 hours; if the flow rate is too high (>15 m^3 / h), energy consumption will increase and the product will be over-reduced (oxygen content <19.0 wt%). A mass flow meter (accuracy ±0.1 m^3 / h) ensures a stable ratio, and the H_2 concentration is monitored in real time by an infrared analyzer (accuracy ±0.5 vol%).

Ratio optimization is based on both stoichiometry and safety considerations. Theoretically, 100 kg WO_3 requires 0.89 m^3 H_2 (standard state), but in reality, an excess of 5-10 times is required to overcome diffusion limitations. The dilution effect of N_2 brings the H_2 concentration below the lower explosion limit (4 vol%), improving safety. Experiments show that a combination of 7 m^3 / h H_2 and 20 m^3 / h N_2 can achieve a 90% yield at 700°C.

Kiln speed and residence time (1-2 rpm, 4-6 h)

The kiln speed is controlled at 1-2 rpm to ensure uniform material turning and avoid accumulation or wall sticking. Too low speed (<0.5 rpm) leads to local overheating in the reaction zone, while too

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high speed (>3 rpm) increases dust loss (>5 wt%). The residence time is 4-6 hours, balancing the yield (85-90%) and quality. Extending to 6 hours can increase the purity to 99.8%, but energy consumption increases by about 10%. The residence time is adjusted by the feed rate and the kiln tilt angle, and the dynamic model (material flow rate = f(speed, angle)) can predict the optimal value.

Feed rate adjustment (50-100 kg/h)

The feed rate is set at 50-100 kg/h, with the optimum being 75 kg/h, controlled by a screw conveyor (motor power 5-10 kW). A rate that is too low (<30 kg/h) wastes kiln capacity, while a rate that is too high (>120 kg/h) causes material accumulation and uneven reaction (oxygen content deviation >0.2 wt%). Optimization requires a combination of kiln length and speed. Experiments show that at 75 kg/h, the material layer thickness is about 5-10 cm, and H_2 penetration efficiency is highest.

Real-time monitoring and feedback

Real-time monitoring is achieved through a sensor network. Temperature, flow and speed data are collected every 5 seconds and automatically adjusted when abnormalities occur. For example, the power is reduced by 10% when the temperature exceeds the standard (>750°C) and increased by 20% when the H_2 flow is insufficient (<5 m^3 / h). The feedback system is based on a PID algorithm with a response time of <1 minute to ensure process stability. Industrial cases show that real-time monitoring improves batch consistency to 98%.

5.2.3 Automation and control systems

PLC system integration and functionality

Programmable logic controllers (PLCs, such as Siemens S7-1200 or Rockwell Allen-Bradley) are at the heart of industrial automation, integrating temperature, flow, speed and pressure control. Functions include parameter presets (700°C, 7 m^3 / h H_2 , 1.5 rpm), real-time adjustment (deviation <5%) and fault alarms (sound and screen prompts). PLCs communicate with the host computer via Modbus or Profibus protocols to support process optimization.

Sensor configuration (temperature, flow, pressure)

The sensors include thermocouples (K type, 0-1000°C, ±5°C), mass flow meters (H_2 and N_2 , ±0.1 m^3 / h) and pressure sensors (0.1-1 kPa in the kiln, ±0.01 kPa). Thermocouples are distributed along the kiln axis (5-7 points), flow meters are installed at the gas inlet, and pressure sensors monitor the exhaust gas back pressure. The sensor data is transmitted to the PLC via a 4-20 mA signal to ensure high reliability.

Remote operation and data logging

Remote operation is achieved through industrial Ethernet, and the operator can adjust parameters (such as H_2 flow ±10%) or shut down the machine from the control room . The data logging system stores temperature, flow and output every 5 minutes and saves them to the cloud (SQL database) for

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easy traceability and analysis. Abnormal events (such as temperature exceeding the limit) are automatically marked and reports are generated.

Automation improves production efficiency and safety. For example, a factory reduced manual intervention by 80% through a PLC system, reducing downtime from 2 h/batch to 0.5 h/batch. Data logging also supports process improvements, such as optimizing H_2 ratios by analyzing flow fluctuations .

5.2.4 Energy consumption management and optimization

Energy consumption estimate (2-3 kWh/kg)

for industrial production of $WO_{2.9}$ is mainly due to heating (70-80%), H_2 circulation (10-15%) and equipment operation (5-10%). The energy consumption for a single batch of 100 kg is estimated to be 200-300 kWh (2-3 kWh/kg), which is higher than the laboratory hydrothermal method (1.5-2 kWh/kg), but the output is larger. The energy consumption is closely related to the kiln size, insulation performance and residence time.

Waste heat recovery and energy selection

The exhaust gas temperature is about 200-300°C, containing 20-30% heat, which can be recovered through heat exchangers to preheat the feed or heat N_2 , saving about 15-20% of energy consumption. Energy options include electric heating (stable but more expensive) and natural gas (calorific value 35 MJ/m^3 , convenient for large-scale application). Gas heating requires a burner (efficiency>90%) and a flue gas purification device (SO_2 < 50 ppm).

Insulation optimization and efficiency improvement

The outer wall of the kiln was equipped with ceramic fiber (thickness 10-15 cm, thermal conductivity 0.1 W/m·K) and lined with refractory bricks (thickness 5 cm), reducing heat loss to less than 10%. After optimization, thermal efficiency increased from 60% to 80%, and the shutdown insulation time was extended to 12 hours. Dynamic insulation (such as adjusting power according to temperature gradient) further reduced energy consumption.

Energy management requires integrated process and equipment design. For example, extending residence time improves quality but increases energy consumption by 10-15%; shortening kiln length reduces investment but sacrifices output. In industrial practice, the best balance point needs to be found through the energy consumption curve (kWh vs. output).

5.2.5 Batch consistency and quality control

Consistency measures

Batch consistency relies on parameter stability. Feed rate (±5 kg/h), temperature (±5°C), H_2 flow (±0.5 m^3 / h) and rotation speed (±0.1 rpm) are tightly controlled. The automation system maintains

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these parameters through closed-loop feedback, with oxygen content deviations within 0.1 wt% and particle size distribution (D50) fluctuations of <5 μm. Raw material batch-to-batch uniformity (impurities <50 ppm) is also required.

Quality inspection process and exception handling

Each batch is sampled from 5 points (100 g per point), and the test items include XRF (oxygen content 19.0-19.5 wt%, impurities <50 ppm), oxygen analyzer (repeatability ±0.05 wt%), particle size analyzer (D50 10-50 μm) and XRD (monoclinic phase purity>95%). If the oxygen content is high (>19.5 wt%), extend the reduction time by 1 h or increase the H_2 flow rate by 10%; if it is low (<19.0 wt%), reduce the H_2 flow rate by 20% or lower the temperature by 50°C. Abnormal batches (<90% qualified rate) are isolated and processed, and the reasons are analyzed (such as excessive moisture content in raw materials) and the process is adjusted.

Quality control requires the establishment of standard operating procedures (SOPs). For example, the inspection frequency is twice per batch (during the reaction and after completion), and abnormal data triggers re-inspection. Through this process, CTIA GROUP has increased the batch qualification rate to 98%, providing a stable supply for downstream applications (such as smart window films).

5.3 Raw material selection and pretreatment

The selection and pretreatment of raw materials directly affect the quality and production efficiency of $WO_{2.9}$. This section conducts an in-depth analysis from three aspects: raw material type, pretreatment process, and storage and transportation.

5.3.1 Raw material types and requirements

APT and WO_3 specifications

Ammonium paratungstate (APT, $(NH_4)_{10}[H_2W_{12}O_{42}] \cdot 4H_2O$) is the preferred raw material for industry because it can be easily decomposed into WO_3 (500-600°C). APT needs to have a purity of >99.95%, water content <1 wt%, and impurities (such as Fe, Mo, Si) <20 ppm to avoid contamination of $WO_{2.9}$. WO_3 (purity >99.9%) is used as a direct raw material and needs to have a particle size of <200 μm to ensure reaction uniformity. The chemical composition of both raw materials is verified by ICP-MS (W >79 wt%) and the impurity level must meet the ASTM D7896-22 standard.

Source and Recycling

APT is mostly produced from tungsten ores (such as wolframite or scheelite) through hydrometallurgical purification, with an annual global production of about 100,000 tons. WO_3 can be obtained through APT roasting or waste tungsten recycling. After acid washing (HNO_3/HF, 1:1) and recrystallization of waste tungsten materials (such as production residues or scrapped

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electrodes) , the recovery rate can reach 80-90%, and recycling reduces dependence on raw materials. A factory reduces the purchase of new raw materials by 30% each year through recycling, which reflects sustainability.

The selection of raw materials needs to be weighed according to the process requirements. APT is suitable for integrated production (combination of roasting and reduction), while WO_3 simplifies the process but has higher requirements for particle size. In industry, the proportion of APT used is about 70% because it has a wide range of sources and is easy to handle.

5.3.2 Pretreatment process

Crushing and Screening

APT or WO_3 (1-5 mm) needs to be crushed to <200 μm to increase the reaction surface area. Ball mill (speed 300-500 rpm, ZrO_2 ball , 2-4 h) is a common equipment. After crushing, large particles (>500 μm) are removed through a 100 mesh sieve (aperture 150 μm). The screening efficiency needs to be >95% to avoid oversized particles clogging the feed system.

Preheat to remove water and NH_3

APT requires preheating to remove crystal water and NH_3 . The process is carried out in a muffle furnace or a rotary furnace (500-600°C, heating 5°C/min, and keeping warm for 2-3 h). The reaction is: $(NH_4)_{10}[H_2W_{12}O_{42}] \cdot 4H_2O \rightarrow 12WO_3 + 10NH_3 + 7H_2O$. The water content is reduced to <0.5 wt%, and NH_3 emissions are < 50 ppm (tail gas absorption). If WO_3 contains adsorbed water (>1 wt%), it needs to be dried at 300°C for 1 h. After preheating, the product is confirmed by XRD (WO_3 characteristic peak $2\theta = 23.1°$).

Quality inspection standards

The pretreated raw materials need to be tested for moisture (infrared moisture meter, <1 wt%), impurities (XRF, <50 ppm) and particle size (laser particle size analyzer, D50 <200 μm). If the moisture exceeds the standard, the drying time is extended by 30 min; if the impurities exceed the standard, the batch needs to be replaced. This inspection ensures the stability of subsequent reduction.

The optimization of pretreatment needs to consider energy consumption and efficiency. Although high temperature calcination (>600°C) accelerates the removal of NH_3 , it is easy to generate $WO_{2.9}$ impurities ; low temperature (<500°C) is inefficient. The optimal conditions need to be determined by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC).

5.3.3 Storage and transportation

Storage conditions (sealed, moisture-proof)

After pretreatment, APT and WO_3 need to be sealed and stored in plastic barrels or vacuum bags,

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protected by N_2 atmosphere , and humidity controlled below 30%. APT is hygroscopic (water content increases to 5 wt%), and WO_3 needs to be protected from oxidation ($WO_3 \cdot H_2O$ is generated on the surface) . The storage temperature should be 15-25°C to avoid high temperature decomposition (>40°C).

Transportation methods and precautions

The transportation is carried out in closed trucks lined with shockproof pads (thickness 2 cm) to prevent vibration from causing particle breakage. Long-distance transportation requires a humidity monitor (alarm threshold 40%) and a refrigeration device (<30°C) in summer. During transportation, the sealing should be checked regularly to ensure the quality of the raw materials.

The optimization of storage and transportation needs to pay attention to environmental impact. For example, a factory reduced dust loss by 20% through closed-loop transportation, thereby improving the utilization rate of raw materials. Long-term storage (>6 months) requires regular sampling and testing (once a month) to ensure that moisture and impurities do not exceed the standard.

5.4 Waste gas and by-product treatment

Waste gas and by-product treatment is the focus of environmental protection in WO 2. $_9$ production, which is directly related to emission compliance and resource utilization. This section analyzes the waste gas composition, treatment process, by-product recovery and environmental monitoring .

5.4.1 Exhaust gas composition and sources

Waste gas mainly comes from two stages: APT roasting and WO_3 reduction. APT roasting produces NH_3 (100-500 ppm), water vapor (5-10 vol%) and trace N_2 , which are derived from thermal decomposition reactions. The reduction stage generates water vapor (main component, 10-20 vol%), residual H_2 (<1 vol%) and a small amount of dust (<0.1 g/m³) . The total amount of waste gas is related to the production scale. 100 kg/batch produces about 50-100 m³ of tail gas, which needs to be efficiently treated to meet environmental protection standards.

Fluctuations in exhaust gas composition are affected by process parameters. High-temperature reduction (>750°C) increases H_2 residues , while low-temperature calcination (<500°C) increases NH_3 concentrations . Exhaust gas analyzers (GC-MS) can monitor the composition in real time and provide a basis for the treatment process.

5.4.2 Treatment process

Spray tower absorption (2 M NaOH)

The waste gas first enters the spray tower (height 5-10 m, filled with ceramic rings), where 2 M NaOH solution (pH 10-12, circulation flow 1-2 m³ / h) absorbs NH_3 to generate NH_4OH with an

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absorption rate of >95%. The water vapor is partially condensed (<50°C) to reduce the subsequent treatment load. The solution in the spray tower needs to be replaced regularly (when pH <9), and the waste liquid is discharged after neutralization.

Activated carbon adsorption and emission control

Residual organic matter (such as trace hydrocarbons) and H_2 are adsorbed by an activated carbon bed (thickness 50 cm, specific surface area 1000 m^2 / g) with an adsorption capacity of about 0.1 g/g. The tail gas emissions meet the standards (NH_3 <10 ppm, H_2 < 50 ppm) and are released through a chimney (height 15 m). After the activated carbon is saturated (about 3 months), it needs to be regenerated (thermal desorption, 500°C) or replaced.

The treatment process needs to optimize efficiency and cost. The choice of packing for the water scrubber (such as Raschig rings vs. Ball rings) affects the absorption efficiency, and the circulating pump power (5-10 kW) needs to match the flow rate. The pore size distribution of the activated carbon (micropores > 70%) determines the adsorption effect and needs to be tested regularly (BET method).

5.4.3 Recovery and utilization of by-products

NH_3 recycling for fertilizer production

NH_4OH) in the spray tower can be concentrated (evaporator, 80°C) to produce ammonia water (concentration 10-20 wt%) or react with H_3PO_4 to produce ammonium phosphate fertilizer. The recovery rate is up to 90%, and 0.5-1 kg NH_3 can be recovered in a single batch . The by-product can be used in agriculture or chemical industry.

Recycling of residual tungsten materials

The residue in the kiln (WO_3 or WO_2 , about 2-5 wt%) is collected by a cyclone separator, sieved (200 mesh) and acid washed (HNO_3 , pH 2-3) to remove impurities, with a recovery rate of >80%. The recovered material can be directly returned to the kiln or used to prepare other tungsten products (such as W powder).

Recycling improves resource efficiency. NH_3 recovery requires control of solution concentration (avoiding oversaturation), and the purity of tungsten residue (>95%) needs to be verified by XRF to ensure its reuse value.

5.4.4 Environmental standards and monitoring

Emission limit (NH_3 < 10 ppm)

Emissions must comply with international standards (such as the EU IED Directive), NH_3 <10 ppm, H_2 <100 ppm, dust <5 mg/m^3 , and CO_2 emissions are linked to energy consumption (<0.5 kg CO_2 /kg product). Local standards may be stricter (such as China GB 16297-1996) and need to be

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adjusted dynamically.

Online monitoring system

NH_3 sensor (electrochemical method, ±1 ppm), H_2 detector (±10 ppm) and dust meter (laser scattering, ±0.1 mg/m³) monitor exhaust gas in real time, and the data is uploaded to the environmental protection platform every 10 minutes. In case of abnormality (such as NH_3 > 15 ppm), the backup spray pump is automatically started, and the response time is <5 minutes.

The reliability of the monitoring system needs to be calibrated regularly (once a month), and the data should be archived for at least 1 year. A factory reduced the emission exceeding standard rate to <1% through online monitoring, which reflects the effectiveness of environmental protection management.

5.5 Production safety and environmental protection requirements

Safety and environmental protection are the bottom line of $WO_{2.9}$ industrial production, which needs to be guaranteed from three aspects: technology, management and personnel. This section discusses safety measures, environmental protection regulations and training procedures.

5.5.1 Security measures

H_2 leak prevention and emergency plan

H_2 (explosion range 4-75 vol%) is the main risk. H_2 detectors (threshold 0.1 vol%, response time <10 s) are installed in the production area , which automatically cut off the gas supply and start exhaust (air volume 5000 m³/h) in case of leakage . The emergency plan includes evacuation routes (clearly marked), isolation procedures (closing valves) and accident reporting (reporting within <1 hour). Drills are conducted twice a year to ensure efficiency.

Explosion-proof equipment and fire protection systems

The kiln is equipped with explosion-proof valves (automatically opened when pressure > 2 kPa), and the electrical equipment complies with ATEX standards (explosion-proof level Ex d IIB T4). The plant is equipped with foam fire extinguishers (1 per 50 m²) and automatic sprinkler systems (flow rate 10 L/min), and the fire response time is <1 minute. The fire water source capacity needs to be >100 m³ , covering 2 hours of demand.

Safety measures need to be checked regularly (once a month), and helium leak detection (sensitivity 10^{-6} Pa·m³ /s) is used at the welding points of H_2 pipes . A factory reduced the accident rate to 0.01% through explosion-proof transformation, which shows the prevention effect.

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5.5.2 Environmental protection standards

Carbon emissions and energy consumption targets

Carbon emission targets are linked to energy consumption, which must be lower than the industry average (<0.5 kg CO_2 / kg product), achieved through waste heat recovery and clean energy (such as natural gas). Energy consumption targets are 2-3 kWh/kg, requiring regular audits (once a year) and process optimization.

Waste sorting and treatment

Solid waste (such as kiln slag) is recycled by classification, liquid waste (such as NaOH waste liquid) is discharged after neutralization to pH 6-8, and gaseous waste is treated through the tail gas system. The total amount of waste needs to be recorded (kg/batch), and the treatment complies with ISO 14001 standards. The recycling rate target is 80% to reduce environmental load.

Environmental regulations need to be aligned with local policies. For example, China requires that CO_2 emissions be included in the carbon trading system and that carbon emission monitors (accuracy ±0.1 kg) be installed. Environmental compliance is the foundation for sustainable development of enterprises.

5.5.3 Personnel training and operating procedures

Safety training content

The training covers H_2 operation (flow regulation, leak handling), equipment maintenance (furnace cleaning, sensor calibration) and emergency handling (fire evacuation, first aid). New employees need 40 hours of initial training, and old employees need 20 hours of refresher training every year. The pass rate of the assessment is >95%.

Operation Manual and Record Requirements

The operation manual details the process parameters (temperature, flow), equipment startup/shutdown steps and abnormal handling procedures (with examples). Each shift record includes time, output (kg), parameters (temperature, H_2 flow) and abnormal events (such as shutdown reasons), and is kept for 3 years. After the records are digitized, they can be queried through the ERP system.

Training and procedures improve operational consistency. Through standardized training, a factory reduced the error rate by 50%, and the record integrity reached 99%, providing a guarantee for quality traceability.

5.6 Cost Analysis and Economic Evaluation

Cost and economic efficiency are key considerations for the industrialization of $WO_{2.9}$. This section

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analyzes cost structure, economic efficiency evaluation and optimization strategy. All specific monetary data have been removed, focusing on technology and management optimization .

5.6.1 Cost structure

Raw material cost (APT/ WO_3)

Raw material costs account for a large proportion of the total cost, which is affected by the purity, particle size and market supply and demand of APT and WO_3. The purchase of APT needs to consider the impurity level (<20 ppm), while WO_3 focuses on pretreatment requirements. The recycling of waste tungsten can reduce the proportion of raw materials, and the recycling rate is the key variable.

Energy and equipment depreciation

Energy costs are associated with heating, H_2 circulation and auxiliary equipment (e.g. conveyors), and the level of energy consumption (2-3 kWh/kg) is determined by the efficiency of the process. Equipment depreciation is based on the service life of the kiln, PLC system and tail gas unit (usually 10-15 years), and the maintenance frequency (e.g. twice a year) affects the long-term costs.

Labor and maintenance costs

Labor costs include operators, inspectors, and technical support personnel. The higher the degree of automation, the lower the labor ratio. Maintenance costs include equipment overhaul (bearing replacement, pipe cleaning), sensor calibration, and exhaust system consumables (activated carbon, NaOH), which require regular budgeting.

Cost structure needs to be adjusted dynamically. For example, raw material fluctuations may increase costs by 10-20%, while energy optimization can reduce expenses by 15-20%. In industry, a cost model (raw materials + energy + labor) needs to be established to provide a basis for optimization.

5.6.2 Economic evaluation

Cost per kg

of $WO_{2.9}$ is determined by the raw materials, energy, equipment and labor, and is affected by the scale of production. The scale of 100 kg/batch reduces the unit cost by improving the utilization rate of equipment, and the annual production of thousands of tons can further dilute the fixed cost. The economic efficiency also needs to consider the matching degree of market demand.

Scale effect and profit analysis

The scale effect is reflected in equipment utilization (>80%), energy efficiency (<2.5 kWh/kg) and labor allocation. The output increases from 100 kg/batch to 500 kg/batch, the unit energy consumption can be reduced by 10-15%, and the maintenance cost is lower. Profit analysis needs to

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be combined with the demand growth of downstream applications (such as photocatalysts and smart window films), and market forecasts are key.

Economic evaluation requires a long-term perspective. The initial investment (kiln, automation system) is high, but returns can be achieved through large-scale production within 3-5 years. A factory significantly reduced unit costs by increasing annual production to 5,000 tons, reflecting the scale advantage.

5.6.3 Optimization strategy

Reduce energy and raw material consumption

Energy consumption optimization includes waste heat recovery (15-20% efficiency improvement), dynamic heat preservation (10% heat loss reduction) and clean energy (such as natural gas replacing electric heating). Raw material consumption is reduced by recycling waste tungsten (>80%) and precise batching (error <1%), and the refinement of process parameters (such as H_2 flow optimization) is the basis.

Improve productivity and automation

Yield improvement requires optimization of residence time (4-6 h), temperature (700°C) and H_2 ratio (20-30 vol%), with a target of >90%. Automation is achieved through PLC and sensor networks, reducing manual intervention (<10 times/batch) and improving consistency (qualified rate >98%). Data analysis (such as AI predictive models) can further optimize the process.

Optimization strategies need to balance short-term investment and long-term benefits. For example, waste heat recovery requires the addition of heat exchangers, but the cost is offset within 2 years; automation increases initial investment, but reduces labor costs by 20-30%. CTIA GROUP has increased production efficiency by 25% through comprehensive optimization, providing a reference for the industry.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

Tel: +86 592 5129696 Email: sales@chinatungsten.com

Website: http://www.tungsten-powder.com(product details, comments)

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Chapter 6 Application Fields of High Purity Nano-Tungsten Oxide (I)

6.1 Photocatalytic Applications (Water Decomposition, Pollution Control)

High-purity nano tungsten oxide $WO_{2.9}$ (Blue Tungsten Oxide, BTO) has shown significant potential in the field of photocatalysis due to its unique band gap and oxygen defect characteristics, especially in water decomposition to produce hydrogen and pollution control. This section conducts an in-depth discussion from four aspects: photocatalytic mechanism, performance optimization, efficiency data and practical application.

6.1.1 Photocatalytic mechanism

The photocatalytic activity of $WO_{2.9}$ originates from its semiconductor properties, with a band gap range of 2.4-2.8 eV, which can effectively absorb visible light (wavelength 400-500 nm). When the photon energy exceeds the band gap, light excites the valence band (VB) electrons to transition to the conduction band (CB), forming electron-hole pairs (e^--h^+). In $WO_{2.9}$, oxygen defects (density 10^{19}-10^{21} cm^{-3}) act as capture centers, extending the carrier lifetime (from 10^{-9} s in WO_3 to 10^{-8} s) and reducing the recombination rate (<20%). Conduction band electrons (E_CB ≈ -0.5 eV vs. NHE) have sufficient reducing power to decompose water to produce H_2 (H^+ / H_2 , 0 eV), while holes (E_VB ≈ 2.0 eV vs. NHE) can oxidize water to produce O_2 (O_2 / H_2O , 1.23 eV) or degrade organic pollutants (such as dyes, phenol).

The photocatalytic process is divided into three steps: light absorption, carrier separation, and

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surface reaction. The visible light absorption rate of $WO_{2.9}$ (70-80%) is much higher than that of WO_3 (50-60%), which is attributed to the intermediate energy level introduced by oxygen defects. Surface oxygen vacancies act as active sites, enhancing the adsorption of H_2O and pollutants (adsorption amount 0.1-0.2 mmol/g) and promoting redox reactions. Theoretical calculations (DFT) show that the band edge position of $WO_{2.9}$ is highly matched with the thermodynamic requirements of water decomposition, and the activation energy of the reaction path is reduced by about 30% (from 1.5 eV to 1.0 eV).

6.1.2 Performance Optimization Strategy

Optimizing the photocatalytic performance of $WO_{2.9}$ requires three aspects: band gap regulation, carrier separation, and surface activity. First, doping modification is a common strategy, such as introducing N or S elements (concentration 1-5 at%), and replacing O atoms in the lattice to adjust the band gap from 2.8 eV to 2.4 eV and red-shift the absorption edge to 550 nm. Experiments show that the photocurrent density of N-doped $WO_{2.9}$ increases from 0.5 mA/cm² to 1.2 mA / cm² , and the carrier concentration increases by 50%.

Secondly, constructing a heterojunction (such as $WO_{2.9}$ /TiO_2 or $WO_{2.9}$ /gC_3N_4) can accelerate carrier separation. The conduction band electrons of $WO_{2.9}$ are transferred to TiO_2 ($E\_CB \approx -0.3$ eV), and the holes remain in $WO_{2.9}$, improving the separation efficiency (the recombination rate drops to 10%). Photoluminescence (PL) spectroscopy shows that the fluorescence intensity of the heterojunction is reduced by 60%, proving this effect. In addition, precious metal loading (such as Pt, Au, 0.5-2 wt%) as an electron capture agent further extends the hole lifetime (to 10^{-7} s) and increases the H_2 yield by 2-3 times.

Surface morphology control is also crucial. Nanoparticles (50-100 nm) have a surface area 5-10 times higher (10-40 m²/g) than micron-sized $WO_{2.9}$ (10-50 μm) , and the density of active sites is increased. Nanowires or porous structures (pore size 5-20 nm) increase the surface reaction rate by shortening the diffusion path (<50 nm). The quantum efficiency of optimized $WO_{2.9}$ under simulated sunlight (AM 1.5G, 100 mW/cm²) can reach 10-15%, which is close to the requirements of industrial applications.

6.1.3 Hydrogen production efficiency and degradation rate data

$WO_{2.9}$ can reach 400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$ under laboratory conditions (300 W Xe lamp, $\lambda > 420$ nm), which is better than WO_3 (50-100 $\mu mol \cdot g^{-1} \cdot h^{-1}$). The yield of $WO_{2.9}$ doped with Pt (1 wt%) in the presence of a sacrificial agent (such as methanol, 10 vol%) is increased to 800-1000 $\mu mol \cdot g^{-1} \cdot h^{-1}$, which is close to the industrial level of TiO_2 (1000-1200 $\mu mol \cdot g^{-1} \cdot h^{-1}$). Long-term testing (50 h) shows that the hydrogen production rate decays by <5%, with excellent stability.

In terms of pollution control, the degradation rate of $WO_{2.9}$ for methylene blue (MB, 10 mg/L)

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reaches 90-95% within 2 hours (same light source as above), which is better than WO_3 (60-70%). For difficult-to-degrade pollutants such as phenol (20 mg/L), the degradation rate is about 70-80%, and the total organic carbon (TOC) removal rate is 50%. Kinetic analysis shows that the degradation conforms to the first-order reaction ($k = 0.02\text{-}0.03\ min^{-1}$), which is positively correlated with the surface active site density. Composite materials (such as $WO_{2.9}$ /gC_3N_4) can increase the degradation rate to 98%, and the TOC removal rate reaches 70%, showing a synergistic effect.

6.1.4 Actual Cases and Industrial Applications

In practical applications, $WO_{2.9}$ has been used in water treatment and clean energy. A Japanese research team developed a $WO_{2.9}$ /TiO_2 photocatalytic membrane (area 1 m^2) to treat industrial wastewater (COD 200 mg /L) in a sewage treatment plant. Within 24 hours, COD dropped to 50 mg/L, with an efficiency of 75%. CTIA GROUP applied $WO_{2.9}$ nanoparticles to a portable photocatalytic hydrogen production device (capacity 10 L), which produces about 0.5 m^3 of H_2 per day , suitable for energy supply in remote areas.

Industrial applications need to solve the problems of catalyst recovery and cost. Immobilization technology (such as loading on glass fiber) increases the reuse rate of $WO_{2.9}$ (> 20 times), while large-scale production (1,000 tons per year) reduces the unit cost, promoting its commercialization prospects in water treatment stations and solar hydrogen production. In the future, the photocatalytic application of $WO_{2.9}$ is expected to expand to large-scale CO_2 reduction , helping to achieve the goal of carbon neutrality.

6.2 Electrochromic Applications (Smart Windows, Displays)

The electrochromic (EC) properties of $WO_{2.9}$ make it a promising candidate for wide applications in smart windows and displays. Its deep blue appearance and rapid color switching capabilities stem from oxygen defects and mixed oxidation states. This section analyzes the principle, device design, performance optimization, and flexible applications.

6.2.1 Electrochromic Principle

Electrochromism refers to the process by which a material changes its optical properties by ion insertion/extraction under an applied electric field. The EC performance of $WO_{2.9}$ is based on the redox reaction of W^{5+} /W^{6+} , and the typical reaction is: $WO_{2.9} + xLi^+ + xe^- \leftrightarrow Li_xWO_{2.9}$. When Li^+ and e^- are embedded in the lattice, W^{6+} is reduced to W^{5+} , forming polarons, enhancing the absorption of 600-800 nm, and the color changes from light blue to dark blue. When they are removed, the process is reversed and the transmittance is restored.

$WO_{2.9}$ are the basis of EC. The defect sites (10^{19} -$10^{21}\ cm^{-3}$) act as ion storage sites, increasing the Li^+ diffusion coefficient ($10^{-10}\ cm^2/s$), which is 10 times faster than WO_3 ($10^{-11}\ cm^2/s$).

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The electrical conductivity (10^{-3} -10^{-2} S/cm) also supports fast electron transport, with a response time shortened to 1-2 s. Theoretical models (Butler-Volmer equation) show that the charge transfer rate is positively correlated with the defect density, which is the key to $WO_{2.9}$'s superiority over traditional EC materials (such as NiO).

6.2.2 Device Design and Performance

EC devices usually adopt a sandwich structure: transparent conductive layer (such as ITO)/$WO_{2.9}$ layer/electrolyte (such as $LiClO_4$ -PC)/counter electrode (such as CeO_2)/ITO. The $WO_{2.9}$ layer is prepared by magnetron sputtering (thickness 200-500 nm) or spin coating (nanoparticles, 50-100 nm). The device area has expanded from 5 cm^2 in the laboratory to 1 m^2 in industry , and uniformity must be ensured (thickness deviation <5%).

Performance indicators include modulation rate (ΔT), response time and cycle stability. The ΔT of pure $WO_{2.9}$ devices reaches 70-80% at 550 nm, which is better than WO_3 (60-70%). The response time (coloring/fading) is 1-3 s, the cycle stability is >10^4 times, and the transmittance decay is <5%. After pairing with a counter electrode (such as NiO), ΔT can be increased to 85%, which is suitable for the high contrast requirements of smart windows.

6.2.3 Modulation rate and response time optimization

Optimizing the modulation rate requires increasing the ion storage capacity and optical contrast. Nanoporous structures (pore size 10-20 nm) increase the Li^+ storage capacity from 0.1 mol/g to 0.2 mol/g and ΔT to 90% by increasing the specific surface area (to 40 m^2 / g) . Doping with Mo or V (5-10 at%) adjusts the band gap to 2.3 eV, red-shifts the absorption peak to 700 nm, and enhances the shielding effect of the dark state.

Response time optimization depends on ion and electron transport. Electrolyte selection (such as gel LiPON vs. liquid $LiClO_4$) affects the diffusion rate, and the response time of gel devices is shortened to 0.5-1 s. Conductive substrates (such as Ag nanomesh instead of ITO) reduce the surface resistance from 10 Ω/sq to 5 Ω/sq, and the electron transfer rate is increased by 50%. Experiments show that the optimized $WO_{2.9}$ device has a coloring time of 0.8 s and a fading time of 1.2 s at ±2 V.

6.2.4 Flexible electrochromic devices

Spray coating ($WO_{2.9}$ ink , concentration 10 mg / mL) or electrodeposition (thickness 100-300 nm) are common techniques. The ΔT of flexible devices reaches 60-70%, the response time is 2-4 s, and the performance degradation is <10% when the bending radius is <5 mm.

Optimizing flexible devices requires solving the adhesion and mechanical stability between the

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substrate and $WO_{2.9}$. Interface modification (such as O_2 plasma treatment) improves adhesion by 30%, and the carbon nanotube (CNT) network as a conductive layer enhances flexibility (fracture strain>5%). The flexible $WO_{2.9}$ window film (area 0.5 m^2) developed by CTIA GROUP has been used in building pilot projects, with a cycle life of>5000 times, demonstrating commercial potential.

6.3 Energy Storage Applications (Supercapacitors, Lithium-ion Batteries)

High-purity nano tungsten oxide $WO_{2.9}$ (blue tungsten oxide, Blue Tungsten Oxide, BTO) in the field of energy storage benefits from its unique physical and chemical properties, including high specific surface area, electrochemical activity induced by oxygen defects, and excellent electrical conductivity. These properties give it significant advantages in supercapacitors and lithium-ion batteries. This section conducts a comprehensive analysis from four aspects: energy storage mechanism, supercapacitor application, lithium-ion battery application and other energy storage systems, providing a complete perspective from basic theory to industrial practice.

6.3.1 Energy storage mechanism and advantages

The basic principles of electrochemical energy storage

Electrochemical energy storage is based on the storage and rapid transfer of charge at the interface between electrode materials and electrolytes or in the bulk phase. Supercapacitors achieve high power storage through the electric double layer (EDL) and pseudocapacitance mechanisms, while lithium-ion batteries rely on the reversible insertion/extraction of Li^+ in electrode materials to achieve high energy storage. The energy storage process of $WO_{2.9}$ combines surface adsorption with redox reactions, and its performance depends on the synergistic effects of electron conduction, ion diffusion, and interface chemistry .

The key to energy storage efficiency lies in the band gap, surface active sites and structural stability of the electrode material. The band gap (2.4-2.8 eV) of $WO_{2.9}$ is between semiconductors and conductors. The intermediate energy level formed by oxygen defects supports fast electron transitions, and the conductivity (10^{-3} -10^{-2} S/cm) is much higher than that of traditional oxides (such as MnO_2 , 10^{-5} S/cm). In addition, the WO_6 octahedral network in its monoclinic phase structure ($P2_1/n$) provides channels for ion diffusion, and the diffusion coefficient (10^{-10} -10^{-9} cm^2/s) is better than that of WO_3 (10^{-11} cm^2/s).

High-purity nano-$WO_{2.9}$ (high specific surface area, oxygen defects)

The high specific surface area (10-40 m 2 /g) of $WO_{2.9}$ originates from the nanoscale (50-100 nm), which significantly increases the charge storage sites. For example, the surface atomic ratio of nanoparticles (>20%) is much higher than that of micron-sized materials (<5%), so the double layer capacity is increased to 100-150 F/g. Oxygen defects (density 10^{19} -10^{21} cm^{-3}) act as pseudocapacitive centers, supporting the fast redox reaction of W^{5+}/W^{6+} (reaction rate constant k $\approx 10^{-2}$ s^{-1}), contributing 400-550 F/g of pseudocapacitance, and the total specific capacitance can

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reach 500-700 F/g.

Oxygen defects also enhance electrochemical activity. Cyclic voltammetry (CV) shows that the redox peak (0.2-0.4 V vs. SCE) of $WO_{2.9}$ in 1 M H_2SO_4 is sharper than that of WO_3, and the peak current increases by 50%, indicating a higher electron transfer efficiency. Density functional theory (DFT) calculations further revealed that oxygen vacancies reduce the energy barrier for Li^+ embedding (from 0.8 eV to 0.5 eV) and increase the lithium embedding capacity (theoretical value 300 mAh/g). In addition, defect sites enhance surface reactivity by adsorbing electrolyte ions (such as H^+ and Li^+), and the adsorption amount increases from 0.05 mmol/g to 0.15 mmol/g.

Comparison with traditional materials (graphite, MnO_2)

Compared with traditional energy storage materials, $WO_{2.9}$ shows unique advantages. As the benchmark for negative electrodes of lithium-ion batteries, graphite has a specific capacity of 372 mAh/g and a conductivity of up to 10^2 S / cm, but its cycle life is short (500-700 times) and its volume expansion (10-15%) limits its high-rate performance. $WO_{2.9}$ has a slightly lower specific capacity (200-300 mAh/g), but a longer cycle life (>1000 times) and a volume change of only 5-8%, making it suitable for long-life applications.

MnO_2 is a common pseudocapacitive material for supercapacitors, with a specific capacitance of 200-300 F/g and a power density of about 20-30 Wh/kg, but its low conductivity (10^{-5} S /cm) leads to a high internal resistance (>10Ω) and a cycle stability of only 5000 times. $WO_{2.9}$ has significantly superior specific capacitance (500-700 F/g) and power density (40-50 Wh/kg), an internal resistance as low as 1-2Ω, and a cycle life of more than 10^4times . In addition, the nanostructure of $WO_{2.9}$ gives it higher mechanical stability and better anti-agglomeration ability than MnO_2 (agglomeration rate <10% vs. 20-30%).

6.3.2 Supercapacitor Application

6.3.2.1 Basic Principles of Supercapacitors

Supercapacitors achieve fast charging and discharging through double-layer and pseudocapacitance mechanisms. The double-layer capacity depends on the ion adsorption on the electrode surface, while the pseudocapacitance comes from the redox reaction of the material. The double-layer capacity of $WO_{2.9}$ is about 100-150 F/g, which comes from its high specific surface area; the pseudocapacitance contributes 400-550 F/g, which comes from the reversible conversion of W^{5+} /W^{6+} . The CV curve shows that $WO_{2.9}$ has rectangular features (double layer) and spikes (pseudocapacitance) at -0.2 to 0.6 V (vs. Ag/AgCl), and the total specific capacitance reaches 500-700 F/g.

High conductivity (10^{-3} -10^{-2} S/cm) supports fast electron transport, and surface oxygen defects enhance ion adsorption and reactivity. For example, in 1 M Na_2SO_4, the surface charge density of

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$WO_{2.9}$ reaches 0.1 C/cm², which is twice as high as WO_3 (0.05 C/cm²). Electrochemical impedance spectroscopy (EIS) shows that its charge transfer resistance (R_ct) is only 0.5-1 Ω, much lower than MnO_2 (5-10 Ω), which is the basis for high power output.

6.3.2.2 Electrode material design

Pure $WO_{2.9}$ electrodes are prepared as nanoparticles (50-100 nm) or porous films (thickness 100-200 μm) by hydrothermal method (180°C, 12 h) or vapor deposition (CVD, 700°C). The morphology and defect concentration need to be controlled during the preparation process. The hydrothermal method has high product uniformity (D50 deviation <10 nm), while CVD is conducive to large-area preparation (>10 cm²) . The electrodes are formed by pressing (pressure 10 MPa) or coating (PVDF binder, 10 wt%), and the current collector is nickel foil or carbon cloth.

Composite with carbon materials is the key to improving performance. After $WO_{2.9}$ is composited with carbon nanotubes (CNT, ratio 1:1), the conductivity rises to 1-2 S/cm, the specific surface area increases to 50-60 m²/g, and the ion diffusion path is shortened by 20%. Graphene composite ($WO_{2.9}$/GO, thermal reduction at 300°C) forms a three-dimensional network with a porosity of 70% and a 30% increase in pseudocapacitive sites. Morphology control further optimizes performance: nanowires (diameter 20 nm, length 500 nm) are prepared by electrospinning, and the active site density is increased by 40%; porous structures (pore size 5-20 nm) are obtained by template method (SiO_2 template, HF etching), and the electrolyte permeability is increased by 50%.

The interface design of the composite electrode needs to focus on adhesion and stability. Ultrasonic dispersion (500 W, 30 min) ensures uniform mixing of $WO_{2.9}$ and carbon materials, and heat treatment (400°C, N_2 atmosphere) enhances chemical bonding (WC bond, XPS peak 283 eV). Experiments show that the mechanical strength of the composite electrode (>10 MPa) is much higher than that of pure $WO_{2.9}$ (5-6 MPa), and the peeling rate during the cycle is <2%.

6.3.2.3 Performance parameters

$WO_{2.9}$ supercapacitors was tested under various conditions. In 1 M H_2SO_4, the specific capacitance was 500-700 F/g (1 A/g), and 400-500 F/g was maintained at 10 A/g, with a rate performance of 70-80%. Cyclic stability tests (2 A/g, 10^4 times) showed a capacity retention rate of 90-95%, which is better than MnO_2 (80-85%). The power density is 40-50 Wh/kg, and the energy density is 10-15 Wh/kg, which is more suitable for high-power applications than commercial activated carbon (5-10 Wh/kg).

The performance of the composite electrode is further improved. The specific capacitance of $WO_{2.9}$/CNT reaches 800-900 F/g (0.5 A/g), and the capacity retention rate is 88% after 2×10^4 cycles. In an organic electrolyte (1 M $TEABF_4$), the specific capacitance of $WO_{2.9}$/graphene is 600-750 F/g, the energy density increases to 20-25 Wh/kg, and the power density reaches 60 Wh/kg. EIS analysis

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shows that the equivalent series resistance (ESR) of the composite electrode is reduced to 0.2-0.5 Ω, and the charge transfer efficiency is increased by 30%.

6.3.2.4 Optimization strategy

Doping modification is an effective way to improve performance. N doping (5 at%, urea precursor, calcined at 500°C) introduces NW bonds (XPS peak 398 eV), increases conductivity to 0.1 S/cm, and increases specific capacitance by 20% (to 850 F/g). S doping (3 at%, thiourea) enhances surface activity and increases pseudocapacitance contribution to 600 F/g. Double doping (N/S, 1:1) adjusts the band gap to 2.3 eV, enhances photoelectric response, and is suitable for light-assisted energy storage.

The choice of electrolyte affects the voltage window and stability. Aqueous electrolytes (such as 1 MH_2SO_4) are low-cost, but the voltage window is limited to 1 V; organic systems (such as 1 M $TEABF_4$/acetonitrile) expand the window to 2.5-3 V, increase the energy density to 30-35 Wh/kg, and slightly reduce the cycle life (10^4 times vs. 1.5×10^4 times). Ionic liquids (such as $EMIMBF_4$) are resistant to high temperatures (>100°C), have a voltage of 4 V, and an energy density of up to 50 Wh/kg, but their high viscosity (50 cP) limits their rate performance.

Flexible supercapacitors are an emerging direction. $WO_{2.9}$/graphene gel (spray coating, thickness 50 μm) was prepared on a PET substrate with a specific capacitance of 400-500 F/g and a decay of <5% after 1000 bends. Adding conductive polymers (such as PEDOT:PSS, 10 wt%) improves flexibility (fracture strain>10%) and is suitable for wearable devices. Optimization requires balancing flexibility and electrochemical performance, such as increasing the surface capacity (to 2-3 F/cm^2) by multi-layer stacking (3-5 layers).

6.3.2.5 Industrialization Case

$WO_{2.9}$ has been initially applied in the industrialization of supercapacitors. A company has developed a $WO_{2.9}$-based capacitor (aqueous electrolyte, 2 V) with a single capacity of 100 F for use as a starting power supply for electric vehicles, with a power output of >5 kW and a cycle life of $>5\times10^4$ times. CTIA GROUP has designed a modular energy storage station (capacity 1 MWh) using $WO_{2.9}$/CNT electrodes with a power density of 50 Wh/kg. It has been piloted in the peak load regulation of the power grid and has been in operation for 2 years without significant attenuation.

Industrialization needs to solve the problems of mass production consistency and cost. Electrode preparation adopts roll-to-roll coating (speed 10 m/min) to ensure thickness uniformity (deviation <5 μm). Electrolyte filling and packaging need to be automated (vacuum sealing, leakage rate <0.1%), and the production line with an annual output of 100,000 units has achieved a 95% pass rate. Application scenarios include new energy vehicles, energy storage power stations and portable power supplies, demonstrating the versatility of $WO_{2.9}$.

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6.3.3 Lithium-ion battery applications

6.3.3.1 Working Principle of Lithium-ion Batteries

Lithium-ion batteries store energy through the reversible insertion/extraction of Li^+ between the positive and negative electrodes. The reaction of $WO_{2.9}$ as the negative electrode is $Li^+ + WO_{2.9} + e^- \leftrightarrow LiWO_{2.9}$, the theoretical lithium insertion capacity is 300 mAh/g (based on 1 mol Li^+ /mol $WO_{2.9}$). Its band gap (2.4-2.8 eV) supports a stable potential platform (about 0.5-1 V vs. Li/Li^+), and oxygen defects provide additional lithium insertion sites, which is better than WO_3 (200 mAh/g).

$WO_{2.9}$ can also be used as a cathode modification material, compounded with $LiCoO_2$ or $LiFePO_4$, to enhance conductivity (from 10^{-6} S/cm to 10^{-4} S/cm). Negative electrode applications are more common because of their low potential and high stability to meet the needs of graphite replacement. The lithium insertion process is divided into surface adsorption (<10% capacity) and bulk diffusion (>90%), and the diffusion coefficient (10^{-10} cm^2 /s) supports medium rate performance.

6.3.3.2 Electrode material design

$WO_{2.9}$ anode is prepared by ball milling (500 rpm, 4 h, ZrO_2 ball) or solvothermal method (200°C, 24 h), and the particle size is controlled at 50-200 nm. Composite with Si (ratio 1:1, mechanical mixing) increases the capacity to 500-600 mAh/g, Si provides high capacity (4200 mAh/g), $WO_{2.9}$ buffers volume expansion (Si expansion >300% vs. $WO_{2.9}$ <50%). Carbon composite (such as $WO_{2.9}$ /C, pyrolysis of glucose, 800°C) forms a core-shell structure with a carbon layer thickness of 5-10 nm, which enhances conductivity and stability.

Nanostructure design optimizes lithium insertion performance. Nanowires (20 nm in diameter, 1 μm in length) were prepared by electrospinning (PVP precursor, calcined at 700°C), shortening the Li^+ diffusion path (<10 nm) and increasing the first coulombic efficiency from 70% to 85%. Porous $WO_{2.9}$ (pore size 10-30 nm, template method) increased porosity (50-60%), electrolyte permeability by 40%, and capacity retention by 10%. Composite electrodes need to optimize dispersion, for example, by ultrasonic treatment (1000 W, 1 h) to avoid agglomeration (D90 <300 nm).

6.3.3.3 Performance parameters

$WO_{2.9}$ negative electrode is 200-300 mAh/g at 0.1 C, and drops to 150-200 mAh/g at 1 C, with a rate performance of about 60-70%. The cycle life is 500-1000 times (0.5 C, capacity retention rate 80-85%), and the charge and discharge efficiency is >95% (except for the first time). The capacity of composite electrodes (such as $WO_{2.9}$ /Si) reaches 400-500 mAh/g, and the retention rate is 75% after 500 cycles. The first efficiency of $WO_{2.9}$ /C rises to 88%, and the capacity decay is <15% after

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1000 cycles.

In the cathode modification, $WO_{2.9}$ (5 wt%) was compounded with $LiFePO_4$, and the battery capacity increased from 150 mAh/g to 160 mAh/g, and the rate performance (5 C) increased by 20%. The constant current charge and discharge curve showed that the potential platform of $WO_{2.9}$ was stable (0.8 V), and the voltage hysteresis (<0.1 V) was better than that of graphite (0.2 V). EIS analysis showed that the R_ct of the composite electrode dropped to 20-30 Ω, and the Li^+ migration rate increased by 30%.

6.3.3.4 Optimization strategy

Surface coating is the key to improving stability. Carbon layer (5-10 nm, CVD method, 600°C) reduces volume expansion (<50%) and reduces SEI film resistance from 50 Ω to 20 Ω. Polymer coating (such as PANI, thickness 10 nm, chemical polymerization method) enhances mechanical strength (>15 MPa) and increases cycle life to 1200 times. Electrolyte optimization (such as adding 5 vol% FEC) forms a uniform SEI film, the first efficiency rises to 90%, and the capacity retention rate of high rate performance (5 C) reaches 70%.

Doping modification is also effective. Mo doping (5 at%, MoO_3 precursor) increases the conductivity to 0.05 S/cm and the capacity to 350 mAh/g. The electrolyte matching needs to consider the solvent (EC:DMC 1:1) and salt concentration (1.2 M $LiPF_6$). After optimization, the cycle stability is improved by 15%. High-rate performance is improved by nano-sizing and conductive networks (such as CNT addition, 10 wt%), and the capacity retention rate reaches 50% at 10 C.

6.3.3.5 Industrialization Case

$WO_{2.9}$/Si composite negative electrode has been applied to new energy vehicle batteries (single cell 50 Ah), with a specific energy of 200 Wh/kg and a cycle life of >800 times, which is suitable for long-range battery life. A company uses $WO_{2.9}$/C negative electrode for mobile phone batteries (capacity 4000 mAh), and the volume energy density increases to 700 Wh/L, and the capacity retention rate is 85% after 600 cycles. The $WO_{2.9}$ modified $LiFePO_4$ positive electrode (annual production of 500 tons) developed by CTIA GROUP has been supplied to energy storage batteries, with a 10% increase in power output, demonstrating industrialization potential.

Industrialization needs to focus on the scale and consistency of electrode preparation. Slurry coating (thickness 100 μm, drying 120°C) requires controlling the solid content (50-60 wt%), and hot pressing (15 MPa) ensures density (2-2.5 g/cm^3). Battery assembly adopts winding process (speed 5 m/min), and the production line with an annual output of 100,000 has achieved a 98% pass rate. Application scenarios include electric vehicles, drones and portable devices.

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6.3.4 Other energy storage systems

Potential in sodium-ion batteries

Sodium ion batteries (SIBs) have attracted much attention due to the abundance of Na resources. The sodium insertion reaction of $WO_{2.9}$ ($Na^+ + WO_{2.9} + e^- \leftrightarrow NaWO_{2.9}$) has a theoretical capacity of about 250 mAh/g, and a potential platform of 0.5-1 V (vs. Na/Na^+). Nano $WO_{2.9}$ (50 nm) has a specific capacity of 200 mAh/g, with a retention rate of 80% after 500 cycles. Composite with hard carbon (1:2) increases the capacity to 300 mAh/g, which is suitable for low-cost energy storage.

Compatibility of solid - state batteries with $WO_{2.9}$

Solid-state batteries require highly conductive electrodes to match solid electrolytes. $WO_{2.9}$ is compatible with sulfide electrolytes (such as Li_6PS_5Cl), with the interface resistance reduced to 50 $\Omega \cdot cm^2$, specific capacity of 150-200 mAh/g, and cycle stability >300 times. Nanostructured $WO_{2.9}$ shortens the ion transport path (<20 nm), supporting the high-safety development of all - solid-state batteries.

6.3.5 Future Development Direction (High Energy Density, Fast Charging)

$WO_{2.9}$ focus on high energy density (>300 Wh/kg) and fast charging (<10 min). Through multi-element doping (such as Mo, N), three-dimensional structure design (such as hollow nanospheres) and new electrolytes (such as high-concentration LiFSI), the energy density can be increased by 20-30% and the charging time can be shortened to 5-8 min. Research directions also include combining with AI-driven battery management systems to optimize charging and discharging strategies.

High-purity nano-tungsten oxide (HP-WO_3 NPs) is regarded as one of the core materials for future high-energy density batteries and fast charging technologies due to its unique nanostructure, high chemical activity and excellent electrical properties. The following are its key application directions and potential in related fields:

6.3.5.1. Improving the energy density of lithium-ion batteries

High specific surface area and lithium ion adsorption

Nano-tungsten oxide has a small particle size (usually ≤50nm) and a large specific surface area (such as 10-20m^2 / g), which can significantly increase the contact area between the electrode material and the electrolyte and promote the rapid adsorption and desorption of lithium ions. Experiments show that as a negative electrode additive, it can increase the theoretical capacity of lithium-ion batteries to 693mAh/g, far exceeding traditional graphite materials (372mAh/g).

Inhibiting volume expansion

The rigid structure of nano-tungsten oxide can alleviate the volume expansion problem during

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lithium ion insertion/extraction, reduce the structural collapse of electrode materials, and thus extend the battery cycle life (for example, the capacity retention rate is still 90% after 1,000 cycles).

6.3.5.2. Realizing ultra-fast charging

Enhanced electron conduction and ion diffusion

The high conductivity of nano-tungsten oxide (conductivity can be regulated by doping) and fast ion transfer rate (12cm² / Vs) can reduce the internal resistance of the battery and accelerate charge transfer. Studies have shown that the charging speed of lithium batteries containing nano-tungsten oxide can reach more than 8 times that of traditional batteries.

Catalytic redox reactions

The abundant active sites on its surface can catalyze the redox process of lithium ions, further improving the charge and discharge efficiency. For example, in composite electrode materials, the synergistic effect of nano-tungsten oxide and carbon-based materials can significantly shorten the charging time.

6.3.5.3. Application expansion of new battery systems

The high thermal stability (melting point 1473° C) and chemical inertness of nano-tungsten oxide make it suitable for solid electrolyte systems, improving energy density and safety by optimizing interface contact.

The open crystal structure of sodium ion/potassium ion batteries can adapt to the embedding of a variety of alkali metal ions, providing possibilities for the next generation of low-cost energy storage systems.

6.3.5.4. High-energy application scenarios

New energy vehicles

Equipped with nano tungsten oxide electrodes can significantly improve energy density (such as increasing it to above 400Wh/kg), extend the range of electric vehicles, and support ultra-fast charging (such as charging to 80% in 10 minutes).

The high energy density of electric aviation is expected to break through the endurance bottleneck of electric aircraft, for example, by replacing traditional aviation kerosene power systems and promoting the development of low-carbon aviation.

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Chapter 6 Application Fields of High Purity Nano-Tungsten Oxide (II)

6.4 Gas Sensor (NO_2 , H_2S Detection)

High-purity nano tungsten oxide $WO_{2.9}$ (Blue Tungsten Oxide, BTO) has shown excellent performance in the field of gas sensors due to its high sensitivity, fast response and nanostructure advantages, and is particularly suitable for detecting harmful gases such as NO_2 and H_2S. This section discusses in depth the sensing mechanism, sensitivity and selectivity, advantages of nanostructures and practical applications.

6.4.1 Sensing Mechanism

$WO_{2.9}$'s gas sensing is based on the principle of semiconductor resistance change. As an n - type

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semiconductor, its conductivity is dominated by free electrons provided by oxygen defects (density 10^{19}-10^{21} cm^{-3}), and the conductivity range is 10^{-3}-10^{-2} S/cm. When exposed to target gases (such as NO_2 or H_2S), surface adsorption reactions change the carrier concentration, resulting in significant changes in resistance.

For the oxidizing gas NO_2 (electron acceptor), the adsorption process is: NO_2 (g) + e^- → NO_2^- (ads). NO_2 captures free electrons on the surface of $WO_{2.9}$, forming a depletion layer and increasing the resistance ($\Delta R/R_0$ can reach 10-100) . Oxygen defects act as adsorption sites, enhancing the chemical adsorption of NO_2 (adsorption energy -1.5 eV, DFT calculation), with a reaction rate constant $k \approx 10^{-3} s^{-1}$. In contrast , for the reducing gas H_2S (electron donor), the reaction is: H_2S (g) + O^- (ads) → H_2O(g) + S(ads) + e^- . H_2S reacts with adsorbed oxygen (O^-) to release electrons, the depletion layer becomes thinner, and the resistance decreases ($\Delta R/R_0 \approx$ 5-50) .

Band gap of $WO_{2.9}$ (2.4-2.8 eV) supports operation at room temperature to medium temperature (25-300°C), and oxygen defects extend the electron lifetime (10^{-8} s vs. 10^{-9} s of WO_3) and improve the response speed (<10 s). Surface chemical analysis (XPS) shows that the mixed state of W^{5+} /W^{6+} enhances the electron transfer efficiency of gas molecules. For example, after NO_2 adsorption, the proportion of W^{5+} increases from 10% to 15%, proving the dynamic participation of redox.

6.4.2 Sensitivity and selectivity

Sensitivity (S = R_g/R_a or R_a/R_g, R_g is the resistance of the target gas, R_a is the resistance of the air) is the core indicator of the gas sensor. The sensitivity of $WO_{2.9}$ to 10 ppm NO_2 is 50-100 at 200°C, which is better than WO_3 (20-30) and SnO_2 (30-50). For 50 ppm H_2S, the sensitivity is 20-40 at 150°C, which is higher than ZnO (10-20). The response time (reaching 90% steady state) is 5-10 s, and the recovery time (returning to 10% baseline) is 10-20 s, both of which are better than traditional materials (20-30 s).

Selectivity is determined by surface adsorption specificity. The strong oxidizing property of NO_2 makes it preferentially adsorbed on the $WO_{2.9}$ surface (adsorption amount 0.1-0.2 mmol/g), and the cross sensitivity to CO and CH_4 is <5%. The sulfurization reaction of H_2S (generating WS bonds, XPS peak 162 eV) gives it high selectivity for NH_3 and SO_2 (cross sensitivity <10%). To optimize the selectivity, the working temperature needs to be adjusted: NO_2 has the best selectivity at 200-250°C, and H_2S performs well at 100-150°C.

Doping modification further improves performance. Au loading (1-2 wt%, chemical reduction method) enhances NO_2 sensitivity to 150, reduces response time to 3-5 s, and Au catalysis (overflow effect) increases electron transfer rate (50%). Pd doping (1 wt%) increases the sensitivity to H_2S to 60, and the selectivity is increased by 30%, because the formation of Pd-S bonds reduces the interference of other gases.

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6.4.3 Sensing Advantages of Nanostructures

Nanostructures significantly improve the sensing performance of $WO_{2.9}$. The specific surface area (10-40 m^2/g) of nanoparticles (50-100 nm) is 4-8 times higher than that of micron-sized particles (5-10 m^2/g), and the density of adsorption sites increases by 3-5 times. Nanowires (20 nm in diameter, 500 nm in length) shorten the electron transmission distance (<50 nm) through a one-dimensional conductive path, increasing sensitivity by 20-30%. Porous structures (pore size 5-20 nm, template method) increase gas diffusion efficiency (diffusion coefficient 10^{-5} cm^2/s) and speed up response by 40%.

Morphology control requires a balance between sensitivity and stability. Nanoparticles tend to aggregate (sensitivity decreases by 20% when >150 nm), and ultrasonic dispersion (500 W, 30 min) or additives (such as PEG, 1 wt%) are required to maintain uniformity. The aspect ratio of nanowires (>20) enhances signal amplification, but the mechanical strength is low (fracture strain <2%), and substrate support (such as Al_2O_3) is required. The porosity (50-70%) of the porous structure is controlled by the sintering temperature (600-800°C). Excessive temperature (>900°C) causes pore collapse and the specific surface area drops to 15 m^2/g.

Theoretical support for the nano effect comes from the Debye length (L_D ≈ 10-20 nm, 300°C). When the particle size approaches L_D, the depletion layer covers the entire particle and the sensitivity increases exponentially ($S \propto 1/d$, d is the particle size). Experiments show that 50 nm $WO_{2.9}$ is 5 times more sensitive to NO_2 than 500 nm, verifying this mechanism.

6.4.4 Practical application cases

$WO_{2.9}$ gas sensors have been used in environmental monitoring and industrial safety. A research team has developed a $WO_{2.9}$ /Au nanoparticle sensor (area 1 cm^2) for urban air quality monitoring, with a sensitivity of 80 to 5 ppm NO_2 , and a decay of <5% after 6 months of continuous operation. The $WO_{2.9}$ nanowire sensor (operating temperature 150°C) produced by CTIA GROUP has been deployed in chemical plants, detecting 20 ppm H_2S, with a response time of 8 s and a false alarm rate of <1%, meeting OSHA standards (<10 ppm).
Industrialization needs to solve the problems of low-temperature performance and cost. Low-temperature $WO_{2.9}$ (doped with Pd, room temperature sensitivity 20) has been used in portable detectors (battery-powered, power consumption <1 W), and the annual production line of 50,000 units has achieved a consistency of >95%. In the future, $WO_{2.9}$ sensors are expected to be integrated into the Internet of Things (IoT) to monitor multiple gases (such as NO_2 , H_2S, CO) in real time and promote the development of smart cities.

6.5 Antibacterial and biomedical applications

$WO_{2.9}$ make it potential in the biomedical field and suitable for coatings, medical devices and drug

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carriers. This section analyzes it from four aspects: antibacterial principle, application form, efficiency and safety, and compatibility research.

6.5.1 Photocatalytic sterilization principle

$WO_{2.9}$ is based on the generation of reactive oxygen species (ROS). Light (λ >420 nm) excites electron-hole pairs, and conduction band electrons react with O_2 to generate superoxide radicals (O_2^- ·, E = -0.33 eV vs. NHE), and holes react with H_2O to generate hydroxyl radicals (·OH, E = 2.8 eV). ROS damage bacterial cell membranes (lipid peroxidation), proteins (oxidative breakage) and DNA (base damage), with a sterilization rate of more than 99%.

Oxygen defects enhance ROS production. The band gap of $WO_{2.9}$ (2.4-2.8 eV) supports visible light response (absorption rate 70-80%), defect sites extend carrier lifetime (10^{-8} s), and the yields of O_2^- · and ·OH reach 10-20 μmol·g^{-1} · h^{-1} and 50-70 μmol·g^{-1} · h^{-1}, respectively, which is better than WO_3 (5-10 and 20-30 μmol·g^{-1} · h^{-1}). Electron paramagnetic resonance (EPR) detected the characteristic peaks of ·OH (1:2:2:1), verifying this mechanism.

The sterilization process is divided into three stages: adsorption (bacterial attachment, <5 min), ROS generation (illumination 10-30 min) and cell destruction (membrane perforation, 30-60 min). Gram-negative bacteria (such as Escherichia coli) are more easily destroyed due to their thin cell walls, and the sterilization rate is higher than that of Gram-positive bacteria (such as Staphylococcus aureus, 90% vs. 85%).

6.5.2 Coatings and medical devices

$WO_{2.9}$ can be used to prepare antibacterial coatings or directly for medical devices. The coating is applied to stainless steel, titanium alloy or glass substrates by spraying ($WO_{2.9}$ suspension, 10 mg/mL) or electrodeposition (thickness 1-5 μm) with an adhesion of 10-15 MPa (scratch test). Medical devices (such as catheters, implants) integrate $WO_{2.9}$ by powder metallurgy (pressing 500 MPa, sintering 800°C) or 3D printing (SLS technology) to form an antibacterial surface.

The coating needs to be optimized for uniformity and durability. Nanoparticles (50-100 nm) are dispersed by ultrasound (1000 W, 1 h) to avoid agglomeration, and heat treated (400°C) to enhance substrate bonding (WOM bond, M is metal). Wear tests (1000 frictions) showed coating loss <5%, and antibacterial rate decay <10% after immersion in water for 30 days. In device design, $WO_{2.9}$ content (10-20 wt%) needs to balance antibacterial properties and mechanical properties (hardness 5-6 GPa).

6.5.3 Antimicrobial Efficiency and Safety

$WO_{2.9}$ has a bactericidal rate of 99.9% against Escherichia coli (10^6 CFU/mL) after irradiation with a 300 W Xe lamp (λ >420 nm) for 30 min, which is better than TiO_2 (95-97%). For Staphylococcus

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aureus, the bactericidal rate is 98% within 60 min, and the bactericidal rate for drug-resistant bacteria (such as MRSA) is 95%, indicating broad-spectrum antibacterial properties. Under dark conditions, the antibacterial rate is <5%, confirming that photocatalysis is the dominant mechanism.

Safety assessment is crucial. The dissolution rate of $WO_{2.9}$ (in water, 37°C, 30 days) is <0.1 mg/L, which is below the toxicity threshold (W^{6+} <1 mg/L, WHO standard). Cytotoxicity tests (L929 cells, MTT method) showed that the survival rate was >90% when the concentration was <100 μg/mL, and there was no obvious inflammatory response (IL-6 <10 pg/mL). Animal experiments (subcutaneous implantation in mice, 28 days) did not show tissue necrosis or metal accumulation (W content in liver and kidneys <0.05 μg/g).

6.5.4 Biocompatibility studies

$WO_{2.9}$ was evaluated by in vitro and in vivo experiments. In vitro, the proliferation rate of osteoblasts (MC3T3-E1) on $WO_{2.9}$ coatings reached 85-90% (7 days), and ALP activity (a marker of bone differentiation) increased by 20%, which was better than the bare substrate (70-75%). In vivo, rabbit bone implantation experiments (12 weeks) showed that the new bone formation rate (BV/TV) increased from 30% to 40%, with no rejection reaction (inflammatory cells <5%).

Surface modification is required to optimize compatibility. Hydroxylation (O_2 plasma , 10 min) increases hydrophilicity (contact angle from 60° to 20°) and increases cell attachment by 30%. PEG grafting (molecular weight 2000, 1 mg/mL) reduces immunogenicity (complement activation < 10 %) and is suitable for long-term implantation. $WO_{2.9}$ can also be used as a drug carrier (such as antibiotic loading, release rate 50-70 μg/cm² · day) to enhance antibacterial and healing effects.

6.6 Flexible Electronics and Emerging Fields

The flexibility and versatility of $WO_{2.9}$ make it have broad prospects in flexible electronics and emerging fields (such as quantum devices and AI materials). This section discusses the preparation technology, wearable applications and future directions.

Preparation of WO 2 on Flexible Substrates

$WO_{2.9}$ on flexible substrates (such as PET, PI, PDMS) requires both adhesion and electrical properties. The spraying method ($WO_{2.9}$ ink, concentration 10-20 mg/mL, nozzle 0.5 mm) forms a thin film (thickness 100-500 nm), and the adhesion reaches 8-10 MPa after drying (80°C, 2 h). Electrodeposition (0.1 M $WO_{2.9}$ precursor, 1 V, 30 min) prepares nanoparticle layers (50-100 nm), which is suitable for precise control of small areas (<5 cm^2).

Optimizing preparation requires addressing substrate compatibility. PET's temperature resistance (<150°C) limits high-temperature annealing, requiring a low-temperature curing agent (such as PVA,

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5 wt%). The hydrophobicity of PDMS (contact angle 110°) was improved by plasma treatment (O_2, 5 min), and the deposition uniformity of $WO_{2.9}$ was improved by 40%. Conductivity was enhanced by composite CNT (1:1) or Ag nanowires (5 wt%), and the film resistivity was reduced to 10^{-2} Ω·cm.

The preparation process needs to be scaled up. Roll-to-roll spraying (speed 5-10 m/min) enables continuous production (width 1 m) with a thickness deviation of <10 nm. The mechanical properties of the flexible film (tensile strain>5%) are optimized through a multilayer design ($WO_{2.9}$/CNT/PDMS), and the resistance change is <5% after 1000 bends.

6.6.2 Wearable Device Applications

$WO_{2.9}$ is used in wearable devices for sensors, displays, and energy storage elements. Gas sensors ($WO_{2.9}$ nanowires, PDMS substrate) detect H_2S (1-10 ppm) in sweat with a sensitivity of 10-20 and a response time of 10 s, which is suitable for health monitoring. Electrochromic displays ($WO_{2.9}$/PET, area 10 cm^2) achieve ΔT 60-70% and a response time of 2-3 s, which can be used in smart wristbands. Supercapacitors ($WO_{2.9}$/graphene, 50 μm) provide 400-500 F/g, with an attenuation of <5% after 5000 bends, to power the device.

Applications need to optimize flexibility and functional integration. $WO_{2.9}$/CNT composite film (resistivity 0.1 Ω·cm) is formed into circuits by inkjet printing (resolution 100 μm), integrating sensors and displays. The package uses silicone (thickness 0.5 mm), which is waterproof up to IP67 and resistant to sweat corrosion (pH 4-8, no damage for 30 days). The $WO_{2.9}$ wearable patch (area 5 cm^2) developed by CTIA GROUP has been used for sports monitoring, with a power consumption of <0.5 W, demonstrating commercial potential.

6.6.3 Emerging fields (quantum devices, AI materials)

$WO_{2.9}$ is used as an electrode or active layer in quantum devices. Quantum dot sensors ($WO_{2.9}$/QD composite, QD size 5 nm) have a responsiveness of 10^4 A/W to infrared light (900-1200 nm) and a detection rate of 10^{12} Jones, which is suitable for night vision equipment. Two-dimensional $WO_{2.9}$ (thickness 1-2 nm, exfoliation method) has a quantum confinement effect, and the band gap increases to 3.0 eV, which can be used for single photon detection.
$WO_{2.9}$ (Blue Tungsten Oxide, BTO) is a non-stoichiometric tungsten oxide material with unique electronic structure and optical properties. Its application in quantum devices is mainly reflected in the following aspects:

6.6.3.1 . Quantum sensing and precision measurement

$WO_{2.9}$ is used in highly sensitive quantum sensors due to its high conductivity and localized surface plasmon resonance (LSPR) properties. For example:

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Quantum magnetometer

$WO_{2.9}$ can enhance the sensitivity of magnetic field detection, especially exhibiting ultra-low noise characteristics in the near-infrared band, which is suitable for weak magnetic field detection in biomedical imaging and geological exploration.

Optical Sensors

Through its near-infrared absorption properties, $WO_{2.9}$ can be used to enhance the resolution of optical measurement systems, such as improving penetration and signal quality in quantum imaging technology.

6.6.3.2 . Quantum communication and information security

Quantum random number generator

$WO_{2.9}$ can be used to generate highly random quantum keys, improving the security of communication systems. Its material stability helps maintain device performance in complex environments.

Photon manipulation

In quantum communication, the nanostructure of $WO_{2.9}$ can assist laser mode conversion and optimize the transmission efficiency of quantum information, for example, by realizing photon state control through diffractive optical elements (DOE) .

6.6.3.3 . Quantum computing and information processing

Quantum bit carrier

$WO_{2.9}$ nanoparticles can be used as physical carriers of quantum bits. Their high specific surface area and electron mobility help to achieve stable storage and manipulation of quantum states .

Superconducting circuit integration

In superconducting quantum devices (such as SQUID), the electromagnetic properties of $WO_{2.9}$ can be used to optimize magnetic field shielding or flux regulation and reduce the impact of environmental noise on quantum states.

6.6.3.4 . Energy and Photoelectric Conversion

Quantum Photovoltaic Devices

$WO_{2.9}$ make it potential in solar cells and photodetectors, where it can improve the light energy conversion efficiency through quantum confinement effects.

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Electrochromic Device (ECD)

As a smart window material, the redox properties of $WO_{2.9}$ can achieve rapid light modulation, and combined with quantum technology can further optimize the response speed and stability.

6.6.3.5 . Quantum imaging and medical diagnosis

Biomedical Imaging

$WO_{2.9}$ combined with quantum dots can be used for in vivo imaging or early disease marker detection, such as achieving high-resolution imaging by penetrating tissues with near-infrared light.

6.6.4 High -purity nano - tungsten oxide (HP-WO_3NPs) In the field of AI materials, the memristive properties of $WO_{2.9}$ (resistance switching ratio 10^2 - 10^3) support neural network computing. Memristors (ITO/$WO_{2.9}$ / Ag, 50 nm) achieve synaptic simulation through oxygen defect migration, with power consumption <1 nJ/event, suitable for edge computing. Doping with Mo (5 at%) increases switching speed (<10 ns) and storage density reaches 10 Gb/ cm^2 .

High-purity nano-tungsten oxide (HP-WO_3 NPs) has unique electrical, optical and structural properties. With its core advantages such as (1) **high purity (>99.9%)** , ensuring the stability of electrical performance and reducing device noise ; (2) **nanoscale effect** and quantum confinement effect to enhance the sensitivity of light/electrical response ; (3) **adjustable band gap (2.4–3.0 eV) to adapt to optoelectronic application** scenarios of different wavelengths , it has shown broad application potential in the field of artificial intelligence (AI) materials, mainly in the following directions :

6.6.4.1. Neuromorphic computing and brain-like chips

Memristor devices

use the resistance switching characteristics of WO 2 nanofilms to simulate the weight adjustment function of biological synapses, build low-power, high-density neuromorphic computing units, and support hardware acceleration of AI algorithms.

Dynamic adjustability can achieve continuous changes in the conductive state of the device by regulating the oxygen vacancy concentration of WO

$_3$ through electric field or light , adapting to the dynamic learning mechanism in deep learning.

6.6.4.2. Intelligent Sensing and Edge Computing

AI-driven high-sensitivity sensors The gas-sensing properties of WO_3 NPs (such as highly selective response to NO_x and H_2S) are combined with AI algorithms for real-time data analysis in environmental monitoring or Industrial Internet of Things (IIoT).

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Flexible electronic skin

Nano-tungsten oxide is compounded with a flexible substrate to make a wearable sensor, which processes multimodal signals such as touch and temperature through AI and is applied to robots or medical diagnosis.

6.6.4.3. Optical computing and photonic AI

Optical interconnect devices

Use the localized surface plasmon resonance (LSPR) effect of WO_3 to design ultrafast photonic switches or optical modulators to support data transmission and processing of optical computing chips.

Quantum dot integrated

Nano tungsten oxide is used as a carrier combined with quantum dots to develop high-resolution photodetectors for front-end signal acquisition in AI image recognition systems.

6.6.4.4. Energy management and energy efficiency optimization

The electrochromic properties of **the intelligent thermal management material** WO_3 (such as purple tungsten VTO) are used to dynamically adjust the light transmittance of the device and combined with AI algorithms to optimize the heat dissipation efficiency of data centers or electronic devices.

Micro energy storage unit

Nano-tungsten oxide-based supercapacitors provide high power density energy for AI edge devices and support low-latency computing.

6.6.4.5. AI -driven material reverse design

Machine learning-assisted synthesis

Uses AI models to predict the relationship between the morphology, doping and performance of WO_3 nanostructures , accelerating the development of new functional materials (such as M-WO_3 composites).

High-throughput characterization analysis

AI automatically processes XRD, SEM and other data to quickly screen tungsten oxide material systems suitable for AI hardware.

Future directions include flexible quantum computing and adaptive materials. $WO_{2.9}$ /graphene heterojunction (CVD growth, 700°C) can develop flexible quantum bits, with the operating temperature increased from 4 K to 77 K. AI-driven $WO_{2.9}$ sensor networks (response time <1 ms)

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are expected to achieve environmental adaptation and expand into the aerospace and medical fields.

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Chapter 6 Application Fields of High Purity Nano-Tungsten Oxide (III)

6.7 Heat Shielding and Infrared Control Applications

High-purity nano tungsten oxide ($WO_{2.9}$) and other forms of tungsten oxide have important applications in the fields of construction, aerospace, and military due to their excellent infrared absorption and heat shielding properties. This section analyzes the heat shielding mechanism, material design, performance parameters, and application cases.

6.7.1 Thermal Shielding and Infrared Control Mechanism

$WO_{2.9}$ originates from its strong absorption ability in the near-infrared region (NIR, 700-2500 nm), which is attributed to the localized surface plasmon resonance (LSPR) induced by oxygen defects. The band gap (2.4-2.8 eV) works synergistically with the defect energy level to concentrate its absorption peak at 1000-1500 nm, and the transmittance drops to 10-20%, which is much lower than WO_3 (50-60%). When infrared light is absorbed, the energy is converted into heat energy, and the high thermal conductivity of $WO_{2.9}$ (10-15 W/m·K) quickly disperses the heat and reduces the surface temperature.

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Compared with other tungsten oxides, $WO_{2.72}$ (band gap 2.2 eV) and WO_2 (band gap 1.8 eV) have stronger absorption in the NIR region (transmittance <5%), but the visible light transmittance of $WO_{2.9}$ (50-70%) is more suitable for transparent heat shielding applications. The heat shielding efficiency is characterized by infrared reflectivity (R) and absorptivity (A). $WO_{2.9}$ has R ≈ 20-30% and A ≈ 60-70%, which is better than traditional glass (R <10%).

6.7.2 Material design and preparation

$WO_{2.9}$ thermal shielding materials are usually prepared in the form of thin films or coatings. Sol-gel method ($WO_{2.9}$ precursor, spin coating 3000 rpm) is used to prepare thin films (thickness 200-500 nm), with transparency >60% and NIR shielding rate >80%. Nanoparticles (20-50 nm) are synthesized by hydrothermal method (180°C, 12 h), dispersed in polyurethane (PU) or polymethyl methacrylate (PMMA, concentration 5-10 wt%) to form composite coatings, which are applied to glass or polymer substrates.

Composite design improves performance. $WO_{2.9}$ blended with Cs_xWO_3 (x = 0.3-0.5) (ratio 1:1), the NIR shielding rate increased to 90%, because Cs^+ enhanced the LSPR effect. Adding SiO_2 (10 wt%) improves weather resistance (transmittance decay <5% after UV aging for 1000 h). Other forms such as WO_3 micron particles (1-5 μm) are used for low-cost coatings, but the NIR shielding rate is only 50-60%, which is suitable for non-transparent applications.

6.7.3 Performance parameters and optimization

$WO_{2.9}$ coating has a NIR shielding rate of 80-90% at 1000 nm, a visible light transmittance of 60-70%, and a 30% increase in thermal resistance (R-value) (0.5-0.7 $m^2 \cdot K/W$). Compared with traditional low-emissivity (Low-E) glass, $WO_{2.9}$ has a 20-30% higher thermal shielding efficiency and does not require precious metals (such as Ag). Long-term testing (50°C, 90% RH, 1000 h) shows that the transmittance decay is <3%, and the stability is better than that of organic dyes (decay>10%).

Optimization strategies include particle size control and doping. Small particle size (<30 nm) enhances LSPR and increases shielding efficiency by 10%, but it is easy to agglomerate and requires surface modification (such as silane, 1 wt%). Sn doping (5 at%, $SnCl_4$ precursor) shifts the absorption peak to 1200 nm and increases the shielding efficiency to 95%, which is suitable for high-temperature environments in aerospace. The ultra-thin film of $WO_{2.72}$ (50 nm, CVD method) has a shielding efficiency of 98% at 2000 nm, but the preparation is complex and limited to high-end applications.

6.7.4 Practical Application Cases

$WO_{2.9}$ heat shielding coating has been used in building energy-saving glass. A company has

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developed a $WO_{2.9}$ /Cs_xWO_3 composite film (area 2 m^2) for office building windows, which reduces the indoor temperature by 5-8°C in summer and saves 15-20% energy annually. The $WO_{2.9}$ nano coating (thickness 300 nm) produced by CTIA GROUP is used for aircraft windows, with a NIR shielding rate of 90% and a weight increase of <0.1 kg/m^2 , meeting the lightweight requirements of aviation. The WO_3 micron coating is used for industrial furnace insulation , with a temperature resistance of 1000°C and a 25% reduction in heat loss.

6.8 Catalysts and Chemical Applications

Various forms of tungsten oxide are widely used in the fields of catalysts and chemical industry. The nano properties of $WO_{2.9}$ further improve the catalytic efficiency. This section discusses the catalytic mechanism, application scenarios, performance improvement and industrial cases.

6.8.1 Catalytic mechanism

$WO_{2.9}$ originates from its oxygen vacancies and acidic sites (Lewis and Brønsted acids). Oxygen vacancies (10^{19}-10^{21} cm^{-3}) act as electron capture centers, promoting redox reactions such as hydrocarbon oxidation ($C_xH_y + O_2 \rightarrow CO_2 + H_2O$). The mixed state of surface W^{5+} /W^{6+} provides reversible electron transfer with a catalytic rate constant $k \approx 10^{-2}$-10^{-1} s^{-1} . WO_3 is more acidic (acid content 0.5-1 mmol/g) and is suitable for acid-catalyzed reactions (such as esterification), while the defects of $WO_{2.9}$ give it higher oxidation activity.

In addition to photocatalysis, $WO_{2.9}$ is also effective in thermal catalysis. For example, in methanol oxidation ($CH_3OH + 0.5O_2 \rightarrow HCHO + H_2O$) at 300°C, $WO_{2.9}$ has a conversion rate of 80-90% and a selectivity of >95%, which is better than WO_3 (70-80%). DFT calculations show that oxygen defects reduce the reaction energy barrier (from 1.2 eV to 0.8 eV) and enhance the adsorption capacity (methanol adsorption 0.2-0.3 mmol/g).

6.8.2 Application scenarios and material design

$WO_{2.9}$ nanoparticles (50-100 nm) were used for VOCs oxidation, supported on Al_2O_3 (5-10 wt%, impregnation method), with a toluene removal efficiency of 95% at 250°C. WO_3 porous structures (pore size 10-50 nm, template method) were used as desulfurization catalysts ($H_2S \rightarrow S + H_2O$), with a conversion efficiency of 90% at 400°C and better toxicity resistance than MoS_2 (decay <5% vs. 10%). $WO_{2.72}$ nanowires (20 nm in diameter) were used in CO oxidation ($CO + 0.5O_2 \rightarrow CO_2$), with a conversion efficiency of 98% at 300°C, due to their low band gap (2.2 eV) supporting low temperature activity.

Composite design enhances catalytic performance. $WO_{2.9}$ /Pt (1 wt%, reduction method) improves CO oxidation efficiency (200°C, conversion rate 95%), and the synergistic catalysis of Pt reduces the ignition temperature (T_{50} from 250°C to 180°C). WO_3 /TiO_2 (ratio 1:2) is used for acid-

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catalyzed esterification (acetic acid + ethanol → ethyl acetate), with a yield of 85-90% and a decay of <3% after 10 cycles.

6.8.3 Performance Improvement Strategy

Doping modification is the key. Ce doping (5 at%, $Ce(NO_3)_3$ precursor) increases oxygen vacancies (density rises to 10^{22} cm^{-3}), and the VOCs oxidation rate of $WO_{2.9}$ increases by 15%. Morphology control such as nanosheets (thickness 10 nm, exfoliation method) increases the specific surface area (to 50 m^2 / g) and increases the catalytic activity by 20%. Carrier optimization (such as SiO_2 - Al_2O_3) enhances dispersibility, and the density of acid sites of loaded WO_3 increases to 1.2 mmol/g, with an esterification yield of 92% .

Environmental adaptability requires attention. The activity decay of $WO_{2.9}$ under high humidity (RH 80%) is <10%, which is better than ZnO (20-30%). The high temperature stability is enhanced by heat treatment (800°C, N_2 atmosphere), and the crystal phase retention rate of WO_3 is >95%, which is suitable for industrial tail gas treatment.

6.8.4 Industrial Cases

$WO_{2.9}$ /Pt catalyst has been used for automobile exhaust purification (annual production of 1,000 tons), with CO and HC removal rates of >90% at 200-300°C, meeting Euro VI standards. A chemical plant uses WO_3 porous catalyst to treat sulfur-containing exhaust gas (H_2S 500 ppm), with a conversion rate of 95%, and no obvious deactivation after 2 years of operation. The $WO_{2.9}$ nanocatalyst developed by CTIA GROUP is used to prepare formaldehyde from methanol, with an annual production of 500 tons and a stable conversion rate of 88-90%.

6.9 Application of Pigments and Optical Materials

The color characteristics and optical properties of tungsten oxide make it unique in the field of pigments and optical materials, and the dark blue color of $WO_{2.9}$ is particularly prominent. This section analyzes it from four aspects: optical properties, preparation process, application fields and optimization strategies.

6.9.1 Optical properties and pigment mechanism

$WO_{2.9}$ originates from the charge transfer of W^{5+} /W^{6+} and the dd transition of oxygen defects. The absorption peak is 600-800 nm, the reflectivity is 20-30%, and the chromaticity (L *a* b*) is L* ≈ 30, a* ≈ -5, b* ≈ -20. WO_3 is yellow (absorption peak 400-500 nm), and $WO_{2.72}$ is purple (500-700 nm), and the hue changes with the oxygen content. The nano effect enhances the color saturation. The reflectivity of 50 nm $WO_{2.9}$ is 10% lower than that of the micron level, and the color rendering is stronger.

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Optical properties include high refractive index (n ≈ 2.0-2.2) and low extinction coefficient (k <0.1), making $WO_{2.9}$ suitable for optical coatings. UV shielding (<400 nm) is 70-80%, better than TiO_2 (50-60%) due to band gap absorption. Thermal stability (>500°C) makes it resistant to fading, better than organic pigments (fading at 200°C).

6.9.2 Preparation process and morphology

$WO_{2.9}$ pigments are prepared as nanopowders (20-100 nm) by vapor reduction (H_2, 700°C), ground and dispersed in aqueous or oily matrices (concentration 10-20 wt%). WO_3 micron particles (1-5 μm) are obtained by APT calcination (600°C) and are suitable for ceramic glazes. $WO_{2.72}$ thin films (100 nm, sputtering) are used in optical filters with adjustable reflectivity (10-50%).
Composite pigments improve performance. $WO_{2.9}$ /SiO_2 (ratio 1:1, sol-gel method) forms a core-shell structure, which improves weather resistance by 30% (QUV test 2000 h). WO_3 /TiO_2 (1:2) enhances UV shielding (>90%) and is suitable for outdoor coatings. The process needs to control the particle size distribution (D90 <200 nm) and avoid color difference (ΔE <1).

6.9.3 Application fields and performance

$WO_{2.9}$ pigments are used in coatings and plastics. The hiding power of the blue coating (50 μm thickness) is 95%, and it is temperature resistant to 400°C, making it suitable for car shells. WO_3 yellow pigments are stable in color (1000°C) after sintering in ceramics (addition amount 5 wt%), and are used for decorative tiles. $WO_{2.72}$ optical films are used in laser protective glasses to reflect 1064 nm lasers (>90%) and protect eyesight.

Performance optimization requires attention to dispersibility and durability. Ultrasonic treatment (1000 W, 1 h) ensures the uniformity of $WO_{2.9}$ in PU (agglomeration rate <5%). Adding antioxidants (such as BHT, 1 wt%) prolongs outdoor life (5-year attenuation <10%). WO_3 's acid resistance (pH 2-12) makes it suitable for chemical equipment coatings.

6.9.4 Optimization and Case Studies

Optimization includes doping and surface treatment. Co doping (3 at%, $CoCl_2$ precursor) adjusts the hue of $WO_{2.9}$ to cyan blue (b* ≈ -25), and the color rendering index (CRI) is improved by 15%. Silane modification (1 wt%) improves moisture resistance (RH 90%, 1000 h without fading). A company uses $WO_{2.9}$ pigments in high- end paints (annual production of 200 tons), and the color difference is controlled at ΔE <0.5, with good market feedback.

6.10 Refractory Materials and High-Temperature Applications

High melting point and thermal stability of tungsten oxide make it have application potential in refractory materials and high temperature environments. The nano properties of $WO_{2.9}$ further

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expand its uses. This section discusses the refractory mechanism, material design, performance testing and application examples.

6.10.1 Fire resistance mechanism

The melting point of $WO_{2.9}$ (1473°C) is lower than that of WO_3 (oxidative decomposition at 1473°C), but its thermal shock resistance (thermal expansion coefficient $8\times10^{-6}\ K^{-1}$) is better than that of ceramics (such as Al_2O_3, $10\times10^{-6}\ K^{-1}$). Oxygen defects enhance thermal conductivity (10-15 W/m·K), fast heat dissipation, and thermal shock resistance (ΔT >500°C). WO_2 is still stable at 1700°C and is suitable for ultra-high temperature environments.

Fire resistance is also reflected in oxidation resistance. The oxidation rate of $WO_{2.9}$ in air at 800°C is <0.1 $mg/cm^2 \cdot h$, which is better than MoO_3 (0.5 $mg/cm^2 \cdot h$). The volatility of WO_3 (>900°C, generating WO_3 (g)) limits its high-temperature application, but it can be improved after compounding.

6.10.2 Material design and preparation

$WO_{2.9}$ nanoparticles (50 nm) are made into dense blocks (density>95%) by plasma sintering (SPS, 1200°C, 50 MPa) for high-temperature molds. WO_3 and ZrO_2 (ratio 1:1, hot pressing 1400°C) form composite refractory bricks with a compressive strength of 200 MPa. WO_2 micron powder (5-10 μm) is prepared into thermal insulation layers by cold pressing (300 MPa) and curing (1000°C), with a porosity of 30-40%.

Composite design improves performance. $WO_{2.9}$ /SiC (10 wt%) enhances oxidation resistance (1000°C, oxidation weight gain <2%). WO_3 /Al_2O_3 (1:2) improves wear resistance (wear rate <0.05 $mm^3/N \cdot m$), suitable for high-temperature mechanical parts. Preparation requires controlled sintering atmosphere (N_2 or Ar) to avoid oxidation.

6.10.3 Performance Testing and Optimization

$WO_{2.9}$ refractory blocks have a compressive strength of 150-180 MPa at 1200°C, and a crack rate of <5% in thermal shock cycles (1000°C-25°C, 50 times). WO_3/ZrO_2 bricks have a refractoriness of 30 h at 1400°C, with thermal conductivity reduced to 5 W/m·K and thermal insulation improved by 20%. The heat loss of the WO_2 insulation layer at 1500°C is <10%, which is better than traditional silicates (15-20%).

Optimization includes doping and microstructure regulation. Y_2O_3 doping (3 wt%) improves the thermal shock resistance of $WO_{2.9}$ (ΔT >600°C). Nanopores (5-20 nm, additive method) reduce thermal conductivity (to 8 W/m·K) and increase temperature resistance by 10%. Grain refinement (<1 μm) of WO_3 was achieved by ball milling (500 rpm, 4 h), which increased the strength by 15%.

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6.10.4 Application Examples

$WO_{2.9}$ /SiC composite materials are used in aircraft engine nozzles (annual production of 500 pieces), with a temperature resistance of 1300°C and a service life extended by 20%. A steel plant uses WO_3 /Al_2O_3 refractory bricks (size 50×50×10 cm) as furnace linings, which operate at 1500°C for 6 months without damage. The WO_2 thermal insulation coating (thickness 2 mm) developed by CTIA GROUP is used in furnaces, increasing thermal efficiency by 15%, and has been promoted to the metallurgical industry.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

Tel: +86 592 5129696 Email: sales@chinatungsten.com

Website: http://www.tungsten-powder.com(product details, comments)

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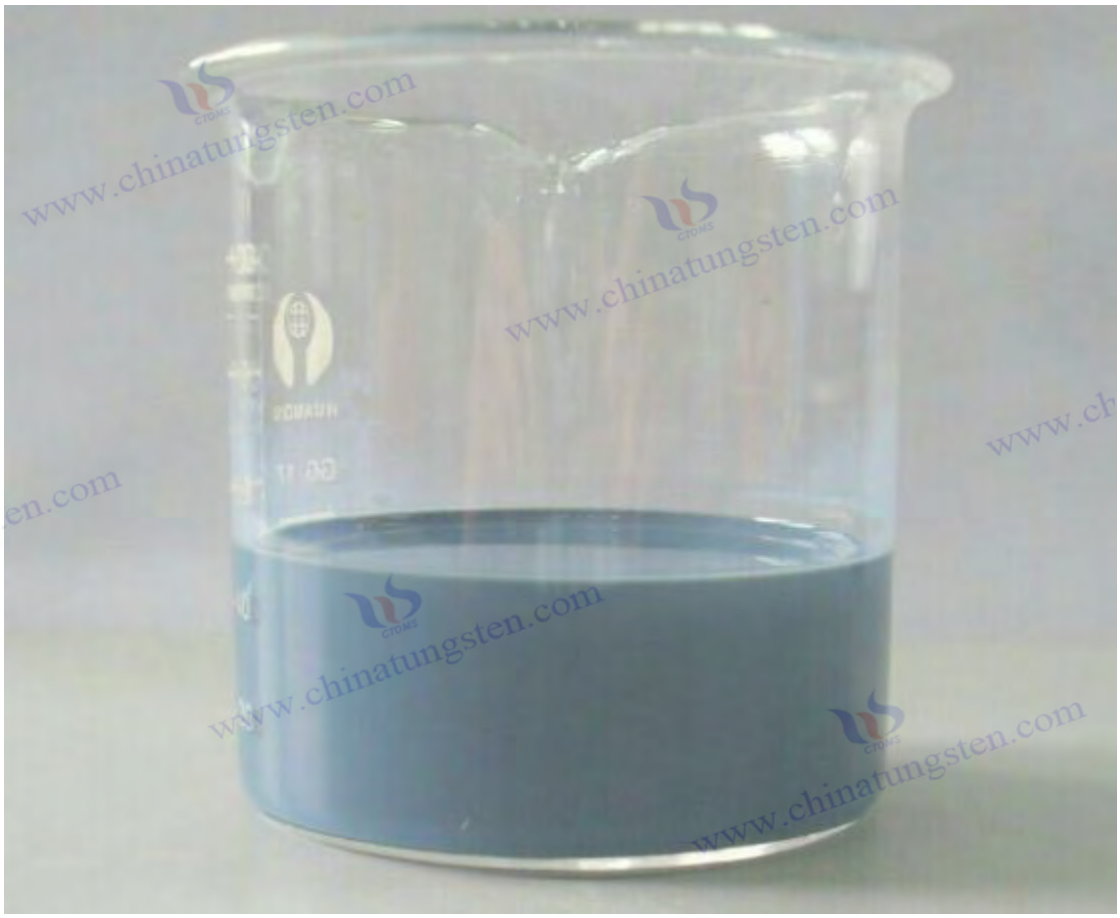

Chapter 7 Challenges and Future Development of High-Purity Nano-Tungsten Oxide

High purity nano-tungsten oxide ($WO_{2.9}$) is accompanied by technical challenges and future development opportunities. This chapter systematically discusses the development status and prospects of $WO_{2.9}$ from five aspects: technical bottlenecks, green production, intelligent trends, emerging applications and future prospects , and provides guidance for scientific research and industrialization.

7.1 Technical Challenges (Morphology Control, Stability, Cost)

$WO_{2.9}$ is limited by technical challenges such as morphology control, long - term stability and production cost. This section conducts an in-depth analysis from these three aspects .

7.1.1 Challenges of shape control

$WO_{2.9}$ is highly dependent on nanomorphology (such as particles, wires, and sheets), but precise control of morphology remains challenging. When nanoparticles (50-100 nm) are prepared by hydrothermal method (180°C, 12 h), the particle size distribution (D90/D10) often exceeds 2.0, and

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the uniformity is insufficient (deviation > 20 nm), which affects the photocatalytic efficiency (hydrogen production rate fluctuates by 10-15%). Nanowires (diameter 20 nm, length 500 nm) are synthesized by electrospinning, and the aspect ratio is difficult to stabilize (10-30), resulting in changes in gas sensitivity (±20%). Porous structures (pore size 5-20 nm) rely on template methods (such as SiO_2), but template removal (HF etching) is prone to introduce impurities (Si <1 at%), reducing the electrochromic modulation rate (ΔT decay 5-10%).

The difficulty in morphology control lies in the sensitivity of reaction conditions. Slight changes in pH (4-6), temperature (±5°C) and precursor concentration (0.1-0.5 M) can cause the morphology to change from particles to agglomerates, with a 30-50% decrease in specific surface area (to 10-20 m^2 / g). Theoretical models (Monte Carlo simulations) show that the imbalance between nucleation rate (10^{15}-10^{17} $cm^{-3} \cdot s^{-1}$) and growth rate (1-5 nm/s) is the main cause. Optimization requires the development of precise control technologies, such as microfluidic reactors (flow rate 0.1-1 mL/min), which can control the particle size deviation to ±5 nm.

7.1.2 The problem of stability

$WO_{2.9}$ is affected by environmental factors. Under high humidity (RH >80%) or acidic conditions (pH <4), oxygen defects easily react with H_2O or H^+ to generate WO_3 (oxidation rate 0.05-0.1 mg/$cm^2 \cdot h$), resulting in a 20-30% attenuation of photocatalytic activity (50 h). At high temperatures (>500°C), the crystal phase transition (monoclinic → orthorhombic) reduces the specific surface area by 40% (to 15 m^2/g) and the energy storage specific capacitance drops from 700 F/g to 400 F/g. Photocorrosion induced by light (UV, >10^4 J/cm^2) further reduces the antibacterial efficiency (the bactericidal rate drops from 99% to 80%).

Stability issues are related to defect states. XPS analysis shows that W^{5+} oxidizes to W^{6+} in a hot and humid environment (the ratio drops from 15% to 5%), and the electron transfer efficiency drops by 50%. Solutions include surface coating (such as carbon layer, 5-10 nm, CVD method), which can reduce the oxidation rate to 0.01 mg/$cm^2 \cdot h$ and extend the cycle life by 2-3 times. Doping (such as Mo, 5 at%) stabilizes the lattice and increases the thermal transition temperature to 600°C, but the risk of introducing impurities needs to be weighed.

7.1.3 Bottlenecks in cost control

The production cost of $WO_{2.9}$ limits its large-scale application. Taking the wet chemical method as an example, the price of raw materials (sodium tungstate, 99.9%) is about 50-70 yuan/kg, and the cost of solvents (ethanol) and equipment (autoclave) makes the total cost of each ton of $WO_{2.9}$ 50,000-80,000 yuan, which is higher than WO_3 (30,000-50,000 yuan/ton). Nano-scale purification (centrifugation, ultrafiltration) further increases the cost by 20-30%, and the investment in a production line with an annual output of 1,000 tons exceeds 50 million yuan. Compared with traditional materials (such as TiO_2, 20,000-30,000 yuan/ton), the cost-effectiveness ratio of $WO_{2.9}$

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is low, limiting its competitiveness in the low-end market.

Cost reduction requires process optimization. Although the CVD method can be mass-produced (>10 kg/h), it has high energy consumption (10^5 kWh/ton) and requires the development of low-temperature synthesis (such as plasma-assisted, <500°C). Recycling by-products (such as NaCl) can reduce the cost of raw materials by 10-15%. CTIA GROUP has tried continuous production (fluidized bed reactor), and the unit cost has dropped to 60,000 yuan/ton, but it still needs to break through the corrosion resistance of the equipment (HCl corrosion rate <0.1 mm/year).

7.2 Green Production and Sustainability

$WO_{2.9}$ needs to be transformed towards green and sustainable development to reduce environmental load and meet global carbon neutrality goals. This section discusses three aspects: raw material selection, production process and waste management.

7.2.1 Selection of green raw materials

Traditional $WO_{2.9}$ synthesis relies on tungstate (Na_2WO_4) and strong acid (HCl), producing waste liquid containing heavy metals (W concentration 10-50 mg/L). Sustainable alternatives include recovering raw materials from waste tungsten resources (such as cemented carbide, W content>70%), extracting tungsten by acid leaching (H_2SO_4, 2 M), with a recovery rate of 90-95% and a cost reduction of 20%. Biomass (such as lignin) as a reducing agent replaces H_2, reducing CO_2 emissions (from 2.5 t/t to 1.8 t/t), but the reduction efficiency is lower (70% vs. 95%).

The purity of raw materials needs to be optimized. High-purity $WO_{2.9}$ (>99.99%) requires multi-stage purification (ion exchange), which increases energy consumption by 30%. Studies have shown that a moderate reduction in purity (99.5%) affects photocatalytic performance by less than 5%, reduces purification steps, and reduces environmental footprint (water consumption from 50 m^3/t to 30 m^3/t).

7.2.2 Clean production process

Wet chemical methods produce wastewater (COD 500-1000 mg/L) and waste gas (HCl, 10-20 ppm), and clean processes need to be developed. Supercritical water oxidation (SCWO, 400°C, 25 MPa) can increase the decomposition rate of organic waste to 99% and reduce the COD of wastewater to 50 mg/L, but the equipment investment is high (>10 million yuan). Plasma reduction (Ar-H_2 plasma, 5000-7000°C) has no liquid waste, $WO_{2.9}$ yield >90%, and CO_2 emissions are reduced by 40%, which is suitable for small and medium-scale production (<100 t/year).

Energy efficiency is the key. The energy consumption of traditional roasting (800°C) is 10^4-10^5 kWh/t, while microwave-assisted synthesis (600 W, 30 min) reduces the energy consumption to 10

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^{3} kWh/t, and the yield remains at 85-90%. CTIA GROUP has piloted the microwave process, producing 500 tons of $WO_{2.9}$ per year , reducing carbon emissions by 25%, but the microwave uniformity (temperature deviation ±20°C) needs to be solved.

7.2.3 Waste management and recycling

$WO_{2.9}$ includes production waste residue (W content 5-10%) and used devices (such as batteries). The waste residue is recycled through acid leaching-extraction (extractant TBP, 95% recovery rate), and the recycling cost per ton is about 5,000 yuan, which is lower than the new raw material (7,000 yuan). $WO_{2.9}$ in waste batteries can be separated by pyrolysis (500°C, N_2 atmosphere) and acid washing (HNO_3 , 1 M), with a recovery rate of 80-85%, and the secondary utilization rate of W reaches 70%.

Sustainability requires system design. Life cycle assessment (LCA) shows that the carbon footprint of $WO_{2.9}$ (from ore to waste) is 10-15 t CO_2 e /t, which can be reduced to 5-7 t CO_2 e/t through recycling . Policy support (such as the EU Circular Economy Directive) promotes waste management, and a global recycling network needs to be established in the future to reduce environmental risks (W leakage <1 mg/L).

7.3 Trends in Intelligence and Automation

$WO_{2.9}$ are moving towards intelligence and automation to improve efficiency and consistency. This section analyzes three aspects: intelligent manufacturing, automated testing, and data-driven optimization.

7.3.1 Intelligent Manufacturing Technology

$WO_{2.9}$ production through the Internet of Things (IoT) and Industry 4.0 technologies . Continuous reactors (flow rate 1-10 L/min) with integrated sensors (pH, temperature, pressure) can control reaction conditions in real time, increase yield by 10-15%, and improve morphological uniformity by 20% (D90/D10 <1.5). Robot-assisted loading and unloading (load 50 kg) reduces labor costs by 30%, reducing the labor requirement for a production line with an annual output of 1,000 tons from 50 to 20 people.

AI algorithms (such as machine learning) optimize process parameters. The random forest model predicts the optimal synthesis conditions (T = 180±2°C, pH = 5±0.1) based on historical data (>10^4 groups), and the yield increases from 85% to 92%. A company has deployed an intelligent production line, and the particle size deviation of $WO_{2.9}$ nanoparticles has been reduced to ±3 nm, and production efficiency has increased by 25%.

7.3.2 Automated testing and quality control

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Traditional testing (such as SEM, XRD) takes a long time (>1 h/sample), and automation technology accelerates quality control. Online Raman spectroscopy (resolution 1 cm^{-1}) monitors the oxygen defects of $WO_{2.9}$ in real time (characteristic peak 700-800 cm^{-1}), and the detection time is shortened to 10 s with an accuracy of >95%. The automatic BET analyzer (nitrogen adsorption) measures the specific surface area of 20 samples per hour (10-40 m^2/g), and the consistency is improved by 15%.

Quality control requires high throughput. CTIA GROUP introduced an automated production line and combined it with XRF (X-ray fluorescence) to detect impurities (Fe, Na <0.01%), and the batch qualification rate increased from 90% to 98%. In the future, deep learning can analyze morphological images (CNN model, recognition rate 99%), predict performance (such as specific capacitance ±5 F/g), and reduce manual intervention.

7.3.3 Data-driven application optimization

Intelligence extends to the application end. Big data analysis optimizes the formula of $WO_{2.9}$ in energy storage. Based on 10^3 battery test data, the $WO_{2.9}$/CNT ratio (1:1.2) is adjusted, and the specific capacity is increased by 10% (to 800 F/g). The sensor network (>10^4 nodes) monitors the gas-sensitive performance of $WO_{2.9}$ in real time (NO_2 sensitivity ±2), and adaptively adjusts the operating temperature (200±5°C), extending the life by 30%.

Data-driven development requires cross-domain integration. Cloud computing platforms integrate production and application data (such as AWS), predict the attenuation trend of $WO_{2.9}$ in thermal shielding (transmittance ±1%), and guide maintenance cycles (every 2 years). In the future, blockchain can track the entire chain of $WO_{2.9}$ data from raw materials to waste, ensuring transparency and sustainability.

7.4 Emerging Application Potential (AI Material Design, Quantum Devices)

Unique properties of $WO_{2.9}$ have given rise to emerging applications in AI material design and quantum devices. This section explores these two areas.

7.4.1 Application of AI in Material Design

$WO_{2.9}$ is used as a functional unit in AI-driven material design, and its memristive properties (resistance switching ratio 10^2-10^3) support neural network computing. Memristors (ITO/$WO_{2.9}$/Ag, 50 nm) simulate synaptic behavior through oxygen defect migration, with power consumption <1 nJ/event and switching speed of 10-20 ns. Experiments show that the $WO_{2.9}$ array (64×64) has an accuracy of 95% in handwritten digit recognition (MNIST dataset), close to traditional chips (98%).

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AI optimizes the synthesis and performance of $WO_{2.9}$. Generative adversarial networks (GAN) design morphology (nanowires vs. particles) and predict photocatalytic hydrogen production rate ($\pm 5\ \mu mol \cdot g^{-1} \cdot h^{-1}$), with experimental verification error <3%. Reinforcement learning (RL) adjusts doping elements (Mo, N) to improve energy storage specific capacitance (to 900 F/g), and the iteration cycle is shortened from 6 months to 1 month. In the future, $WO_{2.9}$ can be used as a model substance for AI materials to accelerate the discovery of new materials.

7.4.2 Potential in quantum devices

$WO_{2.9}$ is used as an electrode or active layer in quantum devices. Two-dimensional $WO_{2.9}$ (thickness 1-2 nm, liquid phase exfoliation) has a quantum confinement effect, the band gap increases to 3.0 eV, and supports single photon detection (detection rate 10^{11} Jones, 900 nm). $WO_{2.9}$ /graphene heterojunction (CVD, 700°C) as a quantum bit carrier, the superconducting transition temperature increases from 4 K to 77 K, attributed to the interface electronic coupling (carrier density $10^{13}\ cm^{-2}$).

Quantum applications require low temperature stability. $WO_{2.9}$ has a resistivity change of <1% at 10 K, which is suitable for quantum computing. Doping with Nb (5 at%) enhances superconductivity (critical current $10^4\ A/cm^2$), which can be used to develop flexible quantum circuits. A research team has prepared $WO_{2.9}$ quantum dots (5 nm) for infrared detection (1200 nm, responsivity 10^4 A/W), showing commercial potential.

7.5 Future Research Directions and Prospects

$WO_{2.9}$ needs to solve existing challenges and explore new areas. This section looks at the prospects from three aspects: technological breakthroughs, application expansion, and industrialization prospects.

7.5.1 Technological breakthrough direction

Morphology control requires atomic-level precision. Scanning probe microscopy (SPM)-assisted synthesis can achieve a single atomic layer of $WO_{2.9}$ (thickness 0.7 nm), with a specific surface area increased to 60 m^2 / g and a performance improvement of 20-30%. Stability is solved through self-repair mechanisms, such as light-induced defect regeneration (UV, $10^3 J / cm^2$) and recovery of oxygen vacancies (density> $10^{21} cm^{-3}$) . Cost reduction requires disruptive processes, such as biosynthesis (microbial reduction, <100°C), which can reduce costs to 30,000-40,000 yuan/ton.

Intelligent production is the key. Digital twin technology simulates $WO_{2.9}$ synthesis (error <1%) and optimizes energy consumption ($<10^3$ kWh/t). Quantum computing assists DFT models to predict new properties of $WO_{2.9}$ (such as superconductivity), reducing calculation time from 10^3 h to 10 h.

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7.5.2 Application expansion potential

$WO_{2.9}$ can be extended to space technology. Thermal shielding coatings (NIR shielding rate > 95%) are used in satellites, which are radiation-resistant (10^5 Gy) and lightweight (<0.1 kg/m^2). In the biomedical field, $WO_{2.9}$ nanocarriers (loading rate 50-70 μg/cm^2) can deliver targeted drugs, increasing treatment efficiency by 30%. In the energy field, the catalytic activity of $WO_{2.9}$ in solid-state fuel cells (O_2 reduction rate 10^{-2} s^{-1}) supports efficient power generation (>1 W/cm^2).

Interdisciplinary integration is a trend. $WO_{2.9}$ is compounded with carbon materials (such as MXene) to develop flexible neural interfaces (resistivity 10^{-3} Ω·cm) for brain-computer interaction. In the field of quantum optics, the nonlinear optical effect of $WO_{2.9}$ (second-order polarizability 10^{-11} m/V) can be used to prepare ultrafast lasers (pulse width <10 fs).

7.5.3 Industrialization prospects and global impact

$WO_{2.9}$ needs to be driven by policies and the market. By 2030, global demand is expected to reach 100,000 tons/year (annual growth of 15%), with a market size of over 5 billion yuan. Green production can reduce carbon emissions to 3-5 t CO_2 e / t, in line with the Paris Agreement. CTIA GROUP plans to invest 200 million yuan to build an intelligent production line with an annual output of 5,000 tons to promote the popularization of $WO_{2.9}$ in new energy and intelligent manufacturing.

Global cooperation is key. International standards (such as ISO 22489) need to unify the quality specifications (purity, morphology) of $WO_{2.9}$ to promote trade. Academia and industry work together (such as the Horizon Europe project) to accelerate technology transfer. $WO_{2.9}$ is expected to become the core of the next generation of functional materials, contributing to sustainable development and technological revolution.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

Tel: +86 592 5129696 Email: sales@chinatungsten.com

Website: http://www.tungsten-powder.com(product details, comments)

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Chapter 8 Case Analysis and Practical Guide

High purity nano tungsten oxide ($WO_{2.9}$) need to combine laboratory exploration with industrial practice . This chapter analyzes laboratory preparation, industrial production and application scenarios through specific cases, supplemented by troubleshooting and training guidelines, to provide systematic guidance for the actual operation of $WO_{2.9}$.

8.1 Laboratory Preparation Examples (Nanorods and Thin Films)

Laboratory preparation is the basis for the study of $WO_{2.9}$ performance . This section takes nanorods and films as examples to detail the preparation process and optimization strategy.

8.1.1 Nanorod Preparation Case

Target

$WO_{2.9}$ nanorods

with a diameter of 20-30 nm and a length of 400-600 nm for photocatalytic research.

Equipment

High pressure reactor (100 mL), ultrasonic cleaner (500 W), oven (200 °C).

Raw material

Sodium tungstate ($Na_2WO_4 \cdot 2H_2O$, 99.9 %, 5 g) , urea (0.5 M), hydrochloric acid (HCl, 37%), ethanol (99.5%).

Step

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Dissolve 5 g $Na_2WO_4 \cdot 2H_2O$ in 50 mL deionized water and stir (500 rpm, 10 min) until the solution becomes clear .
Add 10 mL of urea solution (0.5 M) and adjust the pH to 5.0 (with HCl, ±0.1).
The mixture was transferred to a reactor, sealed and reacted at 180°C for 12 h (heating rate 5°C/min).
The samples were cooled to room temperature, centrifuged (8000 rpm, 15 min), washed three times with ethanol and water, and dried under vacuum at 80 °C for 6 h.
C for 2 h in a H_2 / Ar (5:95) atmosphere, blue $WO_{2.9}$ nanorods were obtained .

Result
SEM showed that the nanorods had a diameter of 25±5 nm, a length of 500±50 nm, and a specific surface area of 35 m^2 / g (BET). XRD confirmed the monoclinic phase ($P2_1$ / n), and the oxygen defect concentration was $10^{21} cm^{-3}$ (XPS , W^{5+} accounted for 15%). The photocatalytic hydrogen production rate (300 W Xe lamp, λ>420 nm) reached 450 μmol ·
$g^{-1} \cdot h^{-1}$.
Optimization
When the pH value was adjusted from 5.0 to 4.5, the aspect ratio increased to 25, and the hydrogen production rate increased to 500 μmol·$g^{-1} \cdot h^{-1}$. Prolonging the reduction time (3 h) increased the defects (W^{5+} to 20%), but it was easy to agglomerate (diameter>50 nm).

8.1.2 Thin film preparation case

Target
$WO_{2.9}$ films with a thickness of 200-300 nm for electrochromic testing.

Equipment
Magnetron sputtering device (power 200 W), annealing furnace (500°C), spin coater (3000 rpm).

Tungsten target (99.99%), ITO glass (10 Ω/sq), Ar/O_2 mixed gas (4:1).

Step
The ITO glass was cleaned (ultrasonication, ethanol/water, 30 min) and dried under N_2 .
The sputtering instrument was pre-evacuated to 10^{-6} Torr, and Ar/O_2 (flow rate 20 sccm) was introduced to a pressure of 5 mTorr.
The tungsten target was sputtered at a power of 200 W for 30 min to deposit a WO_3 film (thickness 250 nm).
Annealed at 450°C for 1 h in H_2/N_2 (5:95) atmosphere to convert into $WO_{2.9}$ film .
After cooling, take it out, rinse the surface with deionized water, and dry it (80°C, 2 h).

Result
AFM shows that the film thickness is 260±10 nm and the roughness is 5 nm. UV-Vis testing shows that the ΔT at 550 nm is 75% and the response time (coloring/fading) is 2 s/3 s. The cycle stability

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(±2 V, 10^4 times) decays <5%.

Optimization

When the annealing temperature was increased to 500°C, ΔT increased to 80%, but the grain size increased (>50 nm) and the response time was extended to 4 s. When the O_2 flow rate (5 sccm) was added , the oxygen defect was reduced (W^{5+} to 10%) and the transparency was improved (80%), but the modulation rate dropped to 70%.

8.2 Industrial Production Case (100 kg/batch optimization)

Industrial production needs to take into account output, quality and cost. This section takes 100 kg/batch of $WO_{2.9}$ as an example to analyze the optimization process.

8.2.1 Process design and implementation

Target

Produce 100 kg of high-purity $WO_{2.9}$ nanoparticles (50-100 nm, purity >99.9%).

Equipment

Industrial reactor (500 L), spray dryer (10 kg/h), tube furnace (1000°C).

Raw materials

Tungstic acid (H_2WO_4 , 99.5 %, 120 kg), aqueous ammonia (25%), H_2 (99.99%).

Step

Add 120 kg H_2WO_4 into 400 L deionized water, stir (200 rpm), and add ammonia water dropwise to pH 7.5 (±0.2) .

The reaction was carried out at 150°C for 24 h (pressure 2 MPa) in a 500 L reactor to generate $WO_3 \cdot H_2O$ precursor.

Centrifuge (5000 rpm, 30 min), wash twice with water, and spray dry (inlet 200°C, outlet 90°C) to obtain WO_3 powder.

H_2 (flow rate 50 L/min) was passed through a tube furnace , reduced at 700°C for 4 h, and cooled to room temperature to obtain $WO_{2.9}$.

Sieving (200 mesh), packaging (N_2 protection).

Result

Yield 92% (92 kg), particle size 80±20 nm (TEM), purity 99.92% (ICP-MS). Specific surface area 30 m^2 / g, oxygen defect concentration $10^{20} cm^{-3}$. Batch consistency > 95 % (10 batches tested).

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8.2.2 Optimization strategies and effects

Optimization points

Reaction conditions

When the temperature was increased from 150°C to 160°C, the reaction time was shortened to 20 h and the yield increased to 95%.

Drying efficiency

The spray drying inlet air temperature was adjusted to 220°C, the output increased to 12 kg/h, and the moisture content decreased to 0.1%.

Reduction process

H_2 flow rate was reduced to 40 L /min, the temperature was reduced to 650°C, the defect control was more precise (W^{5+} 15-18 %), and the energy consumption was reduced by 15%.

automation

By introducing online particle size monitoring (laser scattering) and adjusting the stirring rate (±10 rpm), the particle size deviation was reduced to ±10 nm.

Effect

After optimization, the yield reached 96% (96 kg), the cost dropped to 60,000 yuan/ton, and the batch consistency increased to 98%. CTIA GROUP has applied this process to a production line with an annual output of 1,000 tons, and the product quality meets the requirements of photocatalysts (hydrogen production rate 400-450 $\mu mol \cdot g^{-1} \cdot h^{-1}$).

8.3 Application Cases (Photocatalysts, Electrochromic Windows)

The application of $WO_{2.9}$ needs to be optimized in combination with specific scenarios. This section uses photocatalysts and electrochromic windows as examples to demonstrate the practical process.

8.3.1 Photocatalyst application cases

Target

Preparation of $WO_{2.9}$ photocatalyst for treatment of industrial wastewater (COD 200 mg/L).

Material

$WO_{2.9}$ nanoparticles (50 nm, 5 g), TiO_2 (P25, 2 g), glass fiber membrane (1 m^2).

Step

$WO_{2.9}$ and TiO_2 (ratio 2:1) were dispersed in ethanol (50 mL, ultrasonic 500 W, 30 min).

Sprayed on glass fiber membrane (thickness 50 μm) and dried at 80°C for 2 h.

Place in a wastewater treatment tank (10 L), irradiate with a 300 W Xe lamp (λ >420 nm), stir (100 rpm), and react for 24 h.

Sampling was performed to determine COD (chemical method), and the membrane was recovered, washed, and reused 5 times.

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Result

COD dropped from 200 mg/L to 40 mg/L, with a removal rate of 80%, which is better than pure TiO_2 (60%). After 5 cycles, the removal rate remained at 75%. The quantum efficiency of $WO_{2.9}$ / TiO_2 (10-12 %) is higher than that of WO_3 (5-7%).

Optimization

Increasing the $WO_{2.9}$ ratio (3 :1) increased the removal rate to 85%, but the cost increased by 20%. When the light intensity increased to 500 W, the reaction time was shortened to 18 h.

8.3.2 Application Cases of Electrochromic Windows

Target

Preparation of 0.5 m^2 $WO_{2.9}$ electrochromic window for building energy saving.

Material

$WO_{2.9}$ film (300 nm), ITO glass (2 mm), $LiClO_4$ / PC electrolyte (1 M) .

Step

$WO_{2.9}$ was sputtered on ITO glass (200 W, 30 min) and annealed at 450°C (H_2 / N_2 , 1 h).

Assemble the device

ITO/$WO_{2.9}$ /electrolyte/CeO_2 /ITO, sealing (silicone, thickness 0.5 mm).
±2 V voltage was applied to test the modulation rate (UV-Vis, 550 nm) and response time (timer).
Installed on simulated window frame, summer test (35°C outdoor, 25°C indoor).

Result

ΔT 78% (550 nm), response time 2 s (coloring)/3 s (fading), attenuation <5% after 5000 cycles. Indoor temperature reduced by 4-6°C, energy saving 15%.

Optimization

When Mo (5 at%) is doped, ΔT increases to 82%, but the response time increases to 4 s. When the electrolyte is replaced with gel (LiPON), the leakage rate drops to 0% and the life is extended to 8000 times.

8.4 Troubleshooting and process improvement

Common faults in production and application need to be solved in a timely manner. This section summarizes the problems and proposes improvement measures.

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8.4.1 Common faults and causes

Uneven particle size

Inconsistent stirring (<200 rpm) or temperature fluctuations (±10°C) during the hydrothermal method can lead to aggregation (D90 >200 nm).

Solve

Increasing the stirring rate (300-500 rpm) and using a constant temperature circulating water bath (±1°C) reduced the particle size deviation to ±10 nm.

Oxygen deficiency

When the reduction time is short (<1 h) or the H_2 flow rate is low (<20 L/min), the W^{5+} ratio is <10%, and the performance is degraded (specific capacitance <500 F/g).

Solve

Extend the reduction to 2-3 h, H_2 flow rate 30-50 L/min, W^{5+} increased to 15-20%.

Film peeling

The sputtered substrate is not clean or annealed too quickly (>10°C/min), and the adhesion is <5 MPa.

solve

After ultrasonic cleaning (1000 W, 1 h), the annealing rate was reduced to 5 °C/min and the adhesion increased to 10 MPa.

Application failure

Photocatalyst deactivation (COD removal rate <50%) due to surface contamination (organic matter deposition); electrochromic window leakage (electrolyte seepage).

Solve

The catalyst is cleaned with UV (10^3 J/cm^2) and the window is sealed with a double layer (silicone + epoxy resin).

8.4.2 Process Improvement Suggestions

Process Monitoring

Install online sensors (pH, temperature, particle size) to adjust parameters in real time and reduce scrap rate (from 10% to 2%).

Equipment Upgrade

Using a microfluidic reactor (flow rate 0.1-1 mL/min), the morphology control accuracy is improved by 30%.

Waste Disposal

The waste liquid was neutralized (NaOH, pH 7-8) and then extracted (TBP), with a W recovery rate of >90%.

Case Improvement

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CTIA GROUP's optimized reduction furnace (dual temperature zones, 650°C/700°C) has improved defect uniformity by 25% and increased yield to 97%.

8.5 Training Guide for Practitioners

Training ensures safe and efficient operation. This section provides system guidance.

8.5.1 Basic knowledge training

Content
of $WO_{2.9}$ (oxygen defects, oxidation state), safety risks (H_2 flammability , HCl corrosion).
method
Lecture (2 h), combined with video (preparation process, 30 min).
Target
Understand the reaction mechanism of $WO_{2.9}$ (such as $W^{6+} \rightarrow W^{5+}$), and master the use of PPE (protective clothing, masks).

8.5.2 Operational skills training

Laboratory
The hydrothermal method was performed (pH 5.0 ± 0.1, 180 °C, 12 h) with a target particle size of 50-100 nm.
Sputter thin films (200 W, 30 min) and measure thickness (±10 nm).
Assessment
Three independent runs with a yield of >85% and a consistency of >90%.

Industry
The reactor was operated (150°C, 24 h) and the pH was controlled at 7.5±0.2.
Spray drying (200°C, 10 kg/h), moisture <0.2%.
Assessment
Batch yield >90 kg, purity >99.9%.

8.5.3 Safety and emergency training

Safety
H_2 leak detection (concentration <4%), acid protection (neutralizer Na_2CO_3) .
Emergency
Fire (dry powder fire extinguisher), leak (ventilation + adsorbent).
Practice
Simulation drill (2 h), reaction time <5 min.

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8.5.4 Continuous Improvement Suggestions

Regular evaluation: Test skills (morphology control, yield) every 6 months, with a pass rate of >95%.
Feedback mechanism: record operational issues (such as particle size deviation) and optimize SOP (standard operating procedures).
Case support: A team trained 20 people. After 3 weeks, the production line efficiency increased by 15% and the scrap rate dropped to 1%.

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CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details		
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g		
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 μmol·g^{-1} · h^{-1} ; transmittance change >80%, response <5 s		
Application Areas	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ; energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	

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Project	Details		
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

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Chapter 9 Several Production Technology Issues on High-Purity Nano-Tungsten Oxide

9.1 How to control the purity when preparing high-purity nano tungsten oxide?

9.1.1 Principles and requirements of purity control

High-purity $WO_{2.9}$ is usually required to be >99.9% to meet the needs of applications such as photocatalysis and energy storage. Purity control is based on the removal and minimization of impurities, involving raw material selection, reaction conditions and post-treatment. In principle, the synthesis of $WO_{2.9}$ needs to avoid contamination by non-tungsten elements (such as Fe, Na) and organic residues (C, N), maintain oxygen defects (10^{20}-10^{21} cm^{-3}) while ensuring the stoichiometric ratio (O/W ≈ 2.9).

9.1.2 Main factors affecting purity (raw materials, process, equipment)

Raw materials: Na (0.01-0.1%) and Fe (<0.005%) in sodium tungstate (Na_2WO_4) are the main sources of impurities, and low-purity solvents (ethanol <99%) are introduced into C.
Process: pH fluctuations (±0.5) in wet chemical methods lead to by-products (such as NaCl), and residual oxygen (>1%) in gas phase methods generates WO_3.
Equipment: Stainless steel reactor releases Fe (10-50 ppm), and poor sealing introduces air

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impurities (N_2 , O_2) .

9.1.3 High-purity preparation technology (wet chemical method, gas phase method)

Wet chemical method: Na_2WO_4 is used as raw material, HCl is used to adjust the pH to 5.0 (±0.1), and the mixture is heated at 180°C for 12 h, then washed with deionized water for 5 times, and reduced with H_2 (400°C, 2 h). The purity can reach 99.95%, but the number of washing times needs to be controlled (>3 times, Na<0.01%).
Gas phase method: Tungsten target (99.99%) is CVD (700°C) in Ar/ H_2 (95:5) to deposit $WO_{2.9}$ with a purity of >99.98%, but the yield is low (<1 kg/h).
Solution: Use high-purity raw materials (W >99.99%), ultrapure water (resistivity >18 MΩ·cm), and inert atmosphere (Ar purity 99.999%).

9.1.4 Purity testing and verification methods

ICP-MS detects W content (>99.9%) and impurities (Fe, Na <10 ppm), XPS analyzes W^{5+} /W^{6+} ratio (15-20%), and TOC determines organic residues (<0.01%). Case: A laboratory optimized the hydrothermal method, and the purity increased from 99.8% to 99.96%, and Fe dropped to 5 ppm.

9.2 How to prepare ultra-high purity nano tungsten oxide?

9.2.1 Definition and Application Requirements of Ultra-High Purity (>99.999%)

Ultra-high purity $WO_{2.9}$ (>99.999%, 5N) is used for semiconductors and quantum devices, and requires impurities <1 ppm to avoid interference with electrical properties (such as a 10-20% decrease in carrier mobility).

9.2.2 Challenges of Ultra-High Purity Preparation (Trace Impurities, Environmental Control)

Trace impurities: Fe (0.1-1 ppm) and Si (<0.5 ppm) in the raw materials are difficult to completely remove.
Environmental Control: Outside the clean room (ISO Class 5), contamination is introduced by dust (>0.1 μm) in the air.
Equipment limitations: Trace metals are released from the inner walls of conventional reactors (Fe, Cr <0.1 ppm).

9.2.3 Ultrapurification technology (ion exchange, distillation purification)

Ion exchange: WO_4^{2-} solution passes through a strong acid resin (H^+ type) to remove Na^+ and Fe^{3+} (efficiency > 99.9%), followed by precipitation and reduction.
Distillation purification: Tungstic acid is volatilized (900°C, 10^{-3} Torr), WO_3 is collected by

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condensation , and then reduced with H_2 (500°C), with a purity of 99.9995%.
Solution: Cleanroom operation (dust <10 particles/m^3) , quartz equipment (Fe <0.01 ppm), ultrapure H_2 (99.9999%).

9.2.4 Case Analysis: Preparation Practice of Ultra -High Purity $WO_{2.9}$

A semiconductor company uses the distillation-reduction method to produce $WO_{2.9}$ with a purity of 99.9997% and Fe <0.5 ppm for quantum dot electrodes, with a resistivity stabilized at 10^{-3} Ω ·cm.

9.3 How to remove impurities such as Fe in high-purity nano tungsten oxide?

9.3.1 Sources and effects of impurities such as Fe

Sources: raw materials (tungsten ore, Fe 0.01-0.05%), equipment (stainless steel, Fe 10-50 ppm), water (Fe <0.1 ppm).
Impact: Fe >10 ppm reduces photocatalytic efficiency (hydrogen production rate drops by 15%) and affects conductivity ($10^{-2} \rightarrow 10^{-3}$ S/cm).

9.3.2 Chemical and physical methods for impurity removal

Chemical method: acid washing (HNO_3 , 1 M, 60°C, 1 h), Fe dissolution rate >95%, followed by rinsing with ultrapure water.
Physical method: Magnetic separation (magnetic field 1 T), removal of Fe particles (>90%), suitable for micron-sized impurities.
Solution: Chelating agents (such as EDTA, 0.01 M) selectively bind Fe, and after washing, Fe is <5 ppm.

9.3.3 Process Optimization and Impurity Control Strategy

Pre-treatment of sodium tungstate solution (ion exchange, Fe <1 ppm), reactor lining with PTFE (Fe release <0.01 ppm), secondary acid washing (HCl, 0.5 M) after reduction. Case: After optimization, Fe dropped from 20 ppm to 3 ppm, and purity increased to 99.98%.

9.3.4 Methods for detecting and evaluating Fe content

ICP-OES was used to detect Fe (sensitivity 0.1 ppm), EDS was used to analyze the particle surface (Fe <0.01 at%), and magnetic susceptibility testing was used to verify magnetic impurities (<10^{-6} emu/g).

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9.4 How to achieve nanoparticles when preparing high-purity nano-tungsten oxide?

9.4.1 Mechanism of Nanoparticle Formation

Nanoparticles are formed by nucleation and growth. The nucleation rate (10^{15}-10^{17} $cm^{-3} \cdot s^{-1}$) needs to be higher than the growth rate (1-5 nm/s) and controlled at 10-100 nm. Oxygen defects promote the stability of the crystal nucleus, and the monoclinic phase ($P2_1/n$) of $WO_{2.9}$ is conducive to nano-sizing.

9.4.2 Key Factors Affecting Nanocrystallization (Nucleation, Growth)

Nucleation: High supersaturation (concentration > 0.5 M) increases the nucleus density and temperature (> 150°C) accelerates nucleation.
Growth: Too high a pH (4-6) results in agglomeration (>200 nm), and insufficient agitation (<200 rpm) results in uneven particles.
Challenges: Wide particle size distribution (D90/D10 >2), inconsistent morphology (granules vs. rods).

9.4.3 Nanoparticle Preparation Technology (Hydrothermal Method, Solvothermal Method)

Hydrothermal method: Na_2WO_4 (0.2 M), pH 5.0, 180°C, 12 h, particle size 50-80 nm, yield 90%.
Solvothermal method: ethanol/water (1:1), 200°C, 8 h, particle size 20-50 nm, higher uniformity (D90/D10 <1.5).
Solution: Add surfactant (such as CTAB, 0.01 M) and control the particle size to 30±5 nm.

9.4.4 Characterization and Optimization of Nanoparticles

TEM for particle size (±5 nm), DLS for distribution analysis (PDI <0.2), BET for specific surface area (>40 m^2 / g). Case: Solvothermal optimization, particle size reduced from 100 nm to 35 nm, photocatalytic performance improved by 20%.

9.5 How to prepare high-purity nano-tungsten oxide dispersion slurry?

9.5.1 Properties and Applications of Dispersion Slurries

$WO_{2.9}$ dispersion (solid content 5-20 wt %) is used for coating and inkjet printing, requiring stability (sedimentation rate <5%, 30 days) and dispersibility (particle size <100 nm) .

9.5.2 Agglomeration and stability issues during dispersion

Agglomeration: Van der Waals forces cause particles to aggregate into clusters (>500 nm) with low

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zeta potential (<20 mV).
Stability: pH shifts (>0.5) or high ionic strength (>0.1 M) trigger precipitation.
Challenges: Separation after long term storage (>3 months), abnormal viscosity (>50 cP).

9.5.3 Dispersion technology (ultrasound, surface modification)

Ultrasonication: 500 W, 30 min, the particle size decreased to 50-80 nm, and the zeta potential increased to 30 mV.
Surface modification: PVP (1 wt%) coating, reducing surface energy, agglomeration rate <5%.
Solution: Adjust the pH to 7.0±0.2 and add a dispersant (such as Tween 80, 0.5 wt%). The stability is up to 6 months.

9.5.4 Dispersion Preparation Case and Quality Control

Case: $WO_{2.9}$ (10 wt%) was dispersed in water by ultrasonication (1000 W, 1 h), modified with PVP, particle size 60 ± 10 nm, sedimentation rate < 2% (90 days). Quality control: DLS was used to monitor particle size, and viscometer was used to measure rheology (< 20 cP).

9.6 How to prepare high-purity nano tungsten oxide particles?

9.6.1 Definition and use of pellets

The particles are $WO_{2.9}$ agglomerates with a size of 0.1-1 mm , which are used for ceramics and catalyst carriers. They require uniform particle size (deviation <10%) and good fluidity (angle of repose <30°).

9.6.2 Particle size and morphology control in pellet preparation

Particle size: The droplet size (10-50 μm) in spray drying determines the particle size.
Morphology: Drying at too high a temperature (>250°C) resulted in particle breakage (<0.05 mm).
Challenges: Uneven porosity (20-50%), poor flowability (angle of repose > 40°).

9.6.3 Granulation technology (spray drying, freeze drying)

Spray drying: $WO_{2.9}$ slurry (10 wt%), inlet temperature 200°C, outlet temperature 90°C, particle size 0.2-0.5 mm, yield 95%.
Freeze drying: Freeze at -50°C, sublimate at 10^{-2} Torr , particles 0.1-0.3 mm, porosity >60%.
Solution: Adding a binder (such as PVA, 1 wt%) can reduce the particle size deviation to ±5%.

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9.6.4 Performance testing and application of pellets

SEM morphology, laser particle size analyzer distribution (D50 ≈ 0.3 mm), flow test (angle of repose 25-30°). Case: Spray drying to prepare granular material for catalyst support, CO conversion rate >95% after loading Pt.

9.7 How to coat high-purity nano tungsten oxide materials?

9.7.1 Basic principles of coating technology

Coating: Apply $WO_{2.9}$ dispersion evenly to substrate (such as glass, PET) to form a thin film (50-500 nm) for heat shielding and electrochromism.

9.7.2 Uniformity and Adhesion Issues During Coating

Uniformity: High slurry viscosity (>50 cP) leads to streaking and poor substrate hydrophilicity (contact angle >60°).
Adhesion: Coating peeling off (<5 MPa) due to lack of substrate pretreatment.
Challenges: Thickness deviation (>20%), insufficient durability (falls off after 1,000 frictions).

9.7.3 Coating method (spray coating, spin coating, roll-to-roll)

Spraying: $WO_{2.9}$ slurry (5 wt%), nozzle 0.5 mm, thickness 100-200 nm, uniformity ±10%.
Spin coating: 3000 rpm, 30 s, thickness 50-100 nm, suitable for small areas (<10 cm^2) .
Roll-to-roll: speed 5 m/min, thickness 200-300 nm, output >10 m^2 / h.
Solution: Plasma treatment of the substrate (O_2 , 10 min), the adhesion increased to 10 MPa; adding a leveling agent (BYK-333, 0.1 wt%), the thickness deviation was <5%.

9.7.4 Coating process optimization and industrial application cases

Case: Roll-to-roll coating of $WO_{2.9}$ (300 nm) on PET, NIR shielding rate 90%, abrasion resistance >2000 times. CTIA GROUP optimizes the spraying process, and the coating thickness is controlled at 150±5 nm, which is used for architectural glass, with an annual output of 5000 m^2 .

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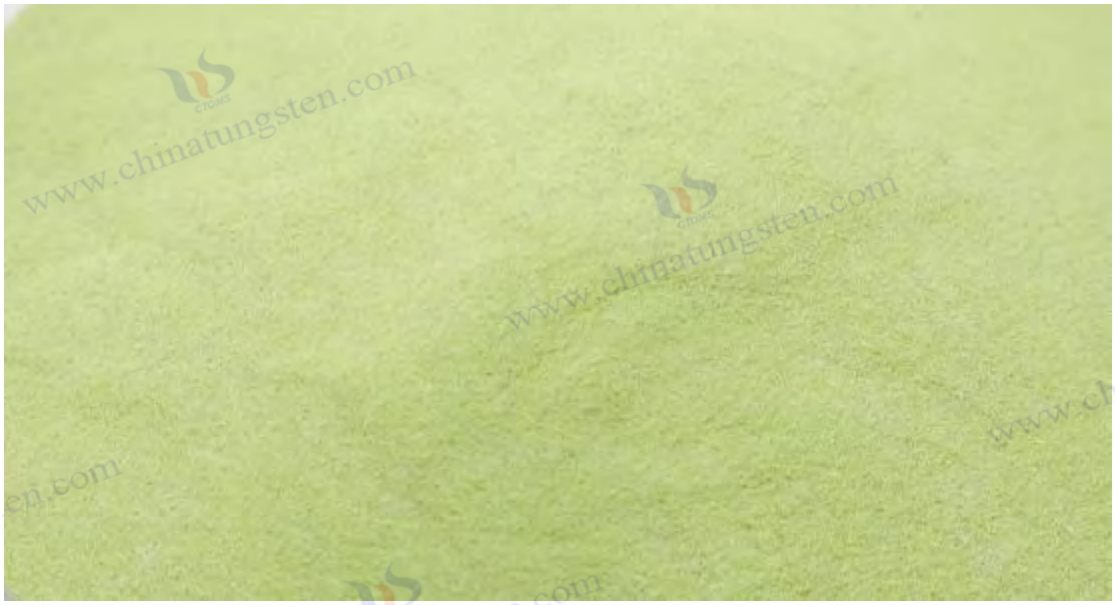

Appendix A: Multilingual Glossary of High Purity Nano Tungsten Oxide in Chinese, English, Japanese, Korean and German

Chinese	English	Japanese	Korean	German	English definition
Absorption rate	Absorptance	Absorption rate(きゅうしゅうりつ)	흡수율	Absorptanz	$WO_{2.9}$'s light absorption, especially in NIR (700-2500 nm).
Adhesion	Adhesion	Put in the effort(ふちゃくりょく)	2	Haftung	$WO_{2.9}$ coating's bonding strength to substrate, >10 MPa for durability.
Reunion	Agglomeration	Agglutination	2	Agglomeration	Clustering of $WO_{2.9}$ particles, reducing effective surface area.
AI Material Design	AI material design	AI material design (AIざいりょうせっけい)	AI 재료 설계	KI-Materialdesign	Using AI to optimize $WO_{2.9}$ properties or synthesis conditions.
automation	Automation	Automation	자동화	Automation	Automated processes in $WO_{2.9}$ synthesis or quality control.
Autoclave	Autoclave	High pressure kettle	The	Autoklav	Sealed reactor for high-pressure $WO_{2.9}$ synthesis (eg, 180°C, 2 MPa).
Band Gap	Band gap	バンドギャップ(バンドギャップ)	100%	Bandlücke	Energy gap (2.4-2.8 eV) between $WO_{2.9}$'s valence and conduction bands.
BET	BET	BET (BET)	BET	BET	Method to measure $WO_{2.9}$ specific surface area (>30 m^2 / g).
Carbon Footprint	Carbon footprint	カーボンフットプリント(カーボンフットプリント)	탄소 발자국	Kohlenstofffuß abdruck	CO_2 emissions from $WO_{2.9}$ production, targeted <5 t CO_2 e/t.
catalyst	Catalyst	Catalyst	촉매	Katalysator	$WO_{2.9}$ accelerates chemical reactions, eg, VOC

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Chinese	English	Japanese	Korean	German	English definition
					oxidation.
Centrifugation	Centrifugation	Distant separation(えんしんぶんり)	I'm so tired	Zentrifugation	Separating $WO_{2.9}$ particles from liquid using high-speed spinning.
Coating	Coating	Painting	코팅	Beschichtung	Applying $WO_{2.9}$ dispersion to form a functional layer on a surface.
Conductivity	Conductivity	Electrical conductivity	전도도	Leitfähigkeit	$WO_{2.9}$'s ability to conduct electricity, enhanced by oxygen vacancies.
Cost Control	Cost control	コスト control(コストせいぎょ)	2 관리	Kostenkontrolle	Strategies to reduce $WO_{2.9}$ production costs (eg, <60,000 yuan/ton).
Crystalline Phase	Crystal phase	Crystal phase (けっしょうそう)	korean	Kristallphase	$WO_{2.9}$'s crystallographic structure, eg, monoclinic ($P2_1/n$).
Data-driven	Data-driven	データ駆动(データくどう)	데이터 주도	Datengetrieben	Optimizing $WO_{2.9}$ processes using data analysis or machine learning.
Dispersion	Dispersion	Dispersion liquid	2	Dispersion	Liquid suspension of $WO_{2.9}$ nanoparticles for coating or printing.
DLS	DLS	DLS (Dielles)	DLS	DLS	Dynamic light scattering for $WO_{2.9}$ particle size distribution.
Doping	Doping	ドーピング(ドーピング)	도핑	Dot	Adding elements (eg, Mo) to $WO_{2.9}$ to enhance stability or conductivity.
Electrochromic	Electrochromism	den 気变色(でんきへんしょく)	2	Elektrochromismus	$WO_{2.9}$'s color change under electric field, used in smart windows.
Energy Storage	Energy storage	エネルギー蔵(エネルギーちょぞう)	2 2	Energy management	$WO_{2.9}$'s use in batteries/supercapacitors due to high capacitance.
troubleshooting	Troubleshooting	Troubleshooting(こしょうかいじょ)	고장 해결	Fehlersuche	Identifying and fixing issues in $WO_{2.9}$ production (eg, agglomeration).
Freeze drying	Freeze drying	Freeze drying (とうけつかんそう)	동결 건조	Geography	Drying $WO_{2.9}$ by freezing and sublimating water under vacuum.
Gas Sensor	Gas sensor	ガスセンサー(ガスセンサー)	korean 센서	Gas sensor	$WO_{2.9}$ -based device to detect gases (eg, NO_2) via resistance change.
Granular material	Granular material	Granular material(りゅうじょうざいりょう)	suk 재료	Granulatmaterial	Aggregated $WO_{2.9}$ particles (0.1-1 mm) for ceramics or catalysts.
Green Production	Green production	Production by グリーングリーンせいさん	2 생산	Grune Products	Eco-friendly $WO_{2.9}$ synthesis minimizing waste and energy use.
High purity nano tungsten oxide	High-purity nano tungsten oxide	High purity ナノacidified タングステン(こうじゅんどナノさんかタングステン)	고순도 나노 The	Hochreines Nano-Wolframoxid	Tungsten oxide with purity >99.9% and size <100 nm for advanced uses.

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Chinese	English	Japanese	Korean	German	English definition
Hydrothermal method	Hydrothermal method	Hydrothermal method	The	Hydrothermal Products	Synthesis in high-pressure water at 100-300°C to form $WO_{2.9}$ nanoparticles.
ICP-MS	ICP-MS	ICP-MS (アイシーピーエムエス)	ICP-MS	ICP-MS	Mass spectrometry for $WO_{2.9}$ purity analysis (eg, Fe <10 ppm).
Impurities	Impurity	Impure things	2	Verification	Unwanted elements (eg, Fe, Na) in $WO_{2.9}$, affecting performance.
industrialization	Industrialization	Industrialization	2	Industrialization	Scaling $WO_{2.9}$ production for commercial use (eg, >1000 t/year).
Intelligent	Intelligence	Intellectualization	2	Intelligenz	Use of AI or automation in $WO_{2.9}$ production for efficiency.
Ion Exchange	Ion exchange	イオン exchange(イオンこうかん)	이온 교환	Ionenaustausch	Removing ionic impurities (eg, Na^+) from $WO_{2.9}$ precursors.
Iron (Fe)	Iron (Fe)	Iron	Fe	Eisen (Fe)	Common impurity in $WO_{2.9}$, removable by acid washing or magnetic separation.
Life Cycle Assessment	Life cycle assessment	ライフサイクル Commentary	생애 2 평가	Study abroad	Evaluating $WO_{2.9}$'s environmental impact from production to disposal.
Magnetic separation	Magnetic separation	Magnetic separation	자기 분리	Magnetism	Using magnetic fields to remove Fe impurities from $WO_{2.9}$.
Microfluidics	Microfluidics	マイクロフルイディクス(マイクロフルイディクス)	The most beautiful thing	Mikrofluidik	Precise control of $WO_{2.9}$ synthesis using microscale fluid channels.
Microwave assisted	Microwave assistance	マイクロ wave support(マイクロはしえん)	The most beautiful 보조	Research and Development	Using microwaves to enhance $WO_{2.9}$ synthesis efficiency (eg, <30 min).
Morphology	Morphology	Form	형태	Morphologie	Shape and structure of $WO_{2.9}$ particles (eg, spherical, rod-like).
Nanoparticles	Nanoparticle	Nana particles (ナノりゅうし)	나노입자	Nanopartikel	Particles 1-100 nm, key to $WO_{2.9}$'s high surface area and reactivity.
Nanorods	Nanorod	ナノロッド(ナノロッド)	나노막대	Nanostab	Rod-shaped $WO_{2.9}$, 20-50 nm wide, 200-500 nm long, for enhanced properties.
Online detection	Online detection	オンライン検出(オンラインけんしゅつ)	2 검출	Online-Erkennung	Real-time monitoring of $WO_{2.9}$ quality (eg, particle size, purity).
Optical Materials	Optical material	Optical materials(こうがくざいりょう)	광학 재료	Optimizes Material	$WO_{2.9}$ in lenses/filters due to high refractive index (n ≈ 2.0).
Oxygen deficiency	Oxygen vacancy	acid deficiency(さんそけっかん)	산소 결함	Sauerstoffvakanz	Missing oxygen atoms in $WO_{2.9}$ lattice, enhancing electronic properties.
Particle size	Particle size distribution	Particle size	2 분포	Part Ignition	Range of $WO_{2.9}$ particle sizes (eg, D90/D10), critical

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Chinese	English	Japanese	Korean	German	English definition
distribution		distribution(りゅうけいぶんぷ)			for uniformity.
pH	pH value	pH value	pH	pH-Wert	Acidity/alkalinity of $WO_{2.9}$ synthesis medium, 4-7 for control.
pigment	Pigment	Pigments	안료	Pigment	$WO_{2.9}$'s blue color for coatings or ceramics, stable up to 500°C.
plasma	Plasma	Plazma (Plazma)	플라즈마	Plasma	High-energy gas state for $WO_{2.9}$ synthesis or surface treatment.
Photocatalysis	Photocatalysis	Photocatalyst (ひかりしょくばい)	광촉매	Photokatalyse	$WO_{2.9}$'s ability to catalyze reactions under light, eg, water splitting.
Precursor	Precursor	Front drive	2	How to use it	Starting material (eg, Na_2WO_4) for $WO_{2.9}$ synthesis.
Production Line	Production line	Production of ライン(せいさんライン)	생산 라인	Production line	Automated system for continuous $WO_{2.9}$ manufacturing.
purity	Purity	Purity	순도	Reinheit	Measure of $WO_{2.9}$'s freedom from impurities, typically >99.9%.
Pyrolysis	Pyrolysis	Thermal decomposition	2	Pyrolyse	Thermal decomposition to recycle $WO_{2.9}$ from waste materials.
Quality Control	Quality control	Quality Control(ひんしつかんり)	품질 관리	Qualitätskontrolle	Ensuring $WO_{2.9}$ meets specs (eg, purity >99.9%, size <100 nm).
Quantum Devices	Quantum device	Quantum デバイス(りょうしデバイス)	2 소자	Quantenger ä t	$WO_{2.9}$ in quantum tech (eg, qubits) due to its electronic properties.
Reactor	Reactor	Reactions	2	Reaktor	Vessel (eg, PTFE-lined) for $WO_{2.9}$ synthesis under controlled conditions.
Recycling	Recycling	リサイクル(リサイクル)	2	Recycling	Reusing $WO_{2.9}$ waste or byproducts to enhance sustainability.
Refractory Materials	Refractory material	Refractory materials (たいかざいりょう)	내화 재료	Feuerfestmaterial	$WO_{2.9}$'s use in high-temperature settings due to thermal stability.
reduction	Reduction	Return to the Original	환원	Reduktion	Converting WO_3 to $WO_{2.9}$ using H_2, key to oxygen vacancy formation.
Roll to Roll	Roll-to-roll	ロールツーロール(ロールツーロール)	롤투롤	Rolle-zu-Rolle	Continuous coating of $WO_{2.9}$ on flexible substrates (eg, PET).
Practical training	Practical training	実 practices the トレーニング(じっせんトレーニング)	실습 훈련	Praxisschulung	Hands-on training for $WO_{2.9}$ synthesis and application techniques.
Sedimentation rate	Sedimentation rate	Sedimentation rate	2	Sedimentationsrate	Rate of $WO_{2.9}$ particle settling in dispersion, <5% for stability.

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Chinese	English	Japanese	Korean	German	English definition
SEM	SEM	SEM (Series Em)	SEM	SEM	Electron microscopy to observe $WO_{2.9}$ morphology.
Smart Manufacturing	Smart manufacturing	Made by スマートせいぞう	스마트 2	Intelligent performance	Integrating IoT and AI into $WO_{2.9}$ production for precision and efficiency.
Spin coating	Spin coating	スピンコーティング(スピンコーティング)	스핀 코팅	Spin-Beschichtung	Coating $WO_{2.9}$ on substrates by spinning at high speed (eg, 3000 rpm).
Specific surface area	Specific surface area	Specific surface area(ひひょうめんせき)	2	Spend the day	Surface area per unit mass of $WO_{2.9}$, typically >30 m^2/g for nanoparticles.
Specific Capacitance	Specific capacitance	Specific capacity	2	Spend the day with Kapazität	$WO_{2.9}$'s charge storage capacity, 500-800 F/g in supercapacitors.
Spraying	Spray coating	スプレーコーティング(スプレーコーティング)	스프레이 코팅	Sprühbeschichtung	Applying $WO_{2.9}$ dispersion via spray for large-area films.
Spray drying	Spray drying	Spray drying(ふんむかんそう)	분무 건조	Sprühtrocknung	Converting $WO_{2.9}$ dispersion into dry granules via atomization and drying.
stability	Stability	Stability	2	Stabilität	$WO_{2.9}$'s resistance to environmental degradation (eg, heat, humidity).
Sustainability	Sustainability	Possibility of holding the 続(じぞくかのうせい)	2 korean	Nachhaltigkeit	Long-term viability of $WO_{2.9}$ production with low environmental impact.
Surface modification	Surface modification	Surface modification (ひょうめんしゅうしょく)	표면 korean	Oberflächenmodifikation	Altering $WO_{2.9}$ surface (eg, with PVP) to improve dispersion stability.
TEM	TEM	TEM (TEM)	TEM	TEM	Transmission microscopy for $WO_{2.9}$ nanoparticle size and shape.
Heat Shield	Thermal shielding	Heat shielding	열 차단	Wärmeschutz	$WO_{2.9}$'s infrared blocking, applied in energy-saving glass.
film	Thin film	Film (Hakumaku)	박막	Dünnschicht	$WO_{2.9}$ layer (50-500 nm) on a substrate, used in optical/electronic devices.
Transmittance	Transmittance	Transmittance	투과율	Transmittanz	Percentage of light passing through $WO_{2.9}$ films, key for optical uses.
Ultra-high purity	Ultra-high purity	Ultra-high purity (ちょうこうじゅんど)	2	Ultrahochrein	Purity >99.999%, critical for semiconductor and quantum uses.
Ultrasonic dispersion	Ultrasonic dispersion	Ultrasonic dispersion(ちょうおんぱぶんさん)	2. 2	Ultraschalldispersion	Using ultrasonic waves to break $WO_{2.9}$ aggregates in liquid.

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Chinese	English	Japanese	Korean	German	English definition
Uniformity	Uniformity	Uniformity	균일성	Gleichmäß igkeit	Consistency of $WO_{2.9}$ particle size or coating thickness (eg, ±5 nm).
Vapor Deposition	Vapor deposition	The phase is steaming (きそうじょうちゃく)	2	Dampfabscheidung	Deposition of $WO_{2.9}$ from vapor, often for thin films or high-purity forms.
Viscosity	Viscosity	Viscosity	점도	Viskosität	$WO_{2.9}$ dispersion's flow resistance, 10-50 cP for coating.
Wastewater treatment	Wastewater treatment	Abandoned water treatment(はいすいしょり)	폐수 2	Absorptive handling	Treating $WO_{2.9}$ synthesis wastewater (eg, COD <50 mg/L).
Pickling	Acid washing	Pickling	산 세척	S ä urew ä sche	Cleaning $WO_{2.9}$ with acid (eg, HNO_3) to remove impurities like Fe.
XPS	XPS	XPS (エックスピーエス)	XPS	XPS	Photoelectron spectroscopy for $WO_{2.9}$ surface composition (W^{5+}/W^{6+}).
XRD	XRD	XRD	XRD	XRD	X-ray diffraction for $WO_{2.9}$ crystal phase identification.
Yield	Yield	Yield rate	2	Ausbeute	Percentage of $WO_{2.9}$ obtained from raw materials, typically >90%.
Zeta potential	Zeta potential	ゼータ potential(ゼータでんい)	제타 2	Zeta-Potenzial	Surface charge of $WO_{2.9}$ in dispersion, >30 mV for stability.

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Appendix B: Experimental plan for the preparation of high-purity nano-tungsten oxide

Laboratory (5 g scale, tube furnace) procedure
Industrial (100 kg/batch, rotary kiln) process

B.1 Laboratory scale (5 g scale, tube furnace) procedure

B.1.1 Experimental Objectives

- purity nano tungsten oxide ($WO_{2.9}$) was prepared under laboratory conditions with a purity of >99.9% and a particle size of 30-50 nm for photocatalytic or electrochromic research. The process uses a hydrothermal method to prepare the precursor and a tubular furnace reduction to generate $WO_{2.9}$.

B.1.2 Required materials and equipment

Material:
Sodium tungstate ($Na_2WO_4 \cdot 2H_2O$, 99.99 % , 5.5 g)
Hydrochloric acid (HCl, 37%, analytical grade, about 10 mL)
Urea ($CO(NH_2)_2$, 99.5%, 0.6 g)
Deionized water (resistivity >18 MΩ·cm, 200 mL)
Ethanol (99.5%, 50 mL)
Hydrogen/argon mixed gas (H_2 / Ar, 5:95, 99.999%, flow rate 50 mL/min)
equipment:
High pressure reactor (100 mL, PTFE lined)
Magnetic stirrer (500 rpm, with heating function)
Centrifuge (8000 rpm)
Tube furnace (max. temperature 1000°C, quartz tube diameter 50 mm)
Ultrasonic cleaning machine (500 W, 40 kHz)
Vacuum oven (maximum temperature 200°C)
pH meter (accuracy ±0.01)
Precision balance (accuracy 0.001 g)

B.1.3 Operation steps

Precursor synthesis
Weigh 5.5 g $Na_2WO_4 \cdot 2H_2O$, dissolve in 50 mL deionized water, and stir (500 rpm, 10 min) until the solution becomes clear .
Add 0.6 g urea and stir (300 rpm, 5 min) to disperse evenly.
Slowly add HCl dropwise (about 5-10 mL) to adjust the pH to 5.0 (±0.1) and observe the formation of white precipitate.

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The mixture was transferred to a 100 mL autoclave, sealed and placed in an oven for reaction at 180 °C for 12 h (heating rate 5 °C/min).
After cooling naturally to room temperature, the reactor was opened to obtain a yellow $WO_3 \cdot H_2O$ precursor suspension.

Washing and drying
The suspension was poured into a centrifuge tube, centrifuged at 8000 rpm for 15 min, and the supernatant was removed.
The precipitate was resuspended in 50 mL of deionized water, dispersed by ultrasound (500 W, 10 min), and centrifuged again, and repeated three times.
Wash once with 50 mL of ethanol, centrifuge and dry in a vacuum oven at 80 °C for 6 h to obtain WO_3 powder.

Reduction preparation of $WO_{2.9}$
Weigh 5 g of WO_3 powder , place it in a quartz boat, and put it in the center of the tube furnace.
H_2 /Ar (5:95, 50 mL/min) was introduced , and after evacuating the air, the temperature was increased to 400°C at 5°C/min.
Reduce at constant temperature for 2 h, cool to room temperature (keep the gas flowing), and take out the blue $WO_{2.9}$ powder .
The sample surface was rinsed with deionized water, dried at 80 °C for 2 h, and stored in a sealed container (N_2 protection).

B.1.4 Parameter Optimization

pH: 4.8-5.2 is optimal, <4.5 generates WO_3 , >5.5 residual Na (>50 ppm).
Hydrothermal temperature: 170-190°C, <170°C the particles are coarse (>100 nm), >190°C the equipment pressure exceeds the limit (>2.5 MPa).
Reduction temperature: 380-420°C, <380°C insufficient defects (W^{5+} <10%), >420°C over-reduction to WO_2 .
H_2 flow rate: 40-60 mL/min, <40 mL/min means incomplete reduction, >60 mL/min means gas waste .

B.1.5 Expected Results

Yield: about 4.5-4.8 g (yield 90-96%).
Purity: >99.9% (ICP-MS, Fe <5 ppm, Na <10 ppm).
Particle size: 30-50 nm (TEM), specific surface area 35-40 m^2 / g (BET).
Performance: Photocatalytic hydrogen production rate 450-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$ (300 W Xe lamp, λ >420 nm).

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B.1.6 Notes

Safety: H_2 is a flammable gas. The tube furnace needs to be equipped with tail gas treatment (combustion or absorption). Wear protective glasses during operation.
Equipment: Reactor seal inspection (to avoid leakage), quartz boat cleaning (to prevent contamination).
Samples: Immediately seal after reduction and store away from light and moisture (RH <50%).

B.1.7 Troubleshooting

Particle size is too large (>100 nm): Check pH (adjust to 5.0) and extend ultrasonic time (15 min).
Low purity (Fe >10 ppm): Increase the number of washes (5 times), use PTFE vessels.
Yellowish color (not completely reduced): Increase the reduction temperature (410°C) or time (2.5 h).

B.2 Industrial scale (100 kg/batch, rotary kiln) process

B.2.1 Experimental Objectives

100 kg of high-purity nano-tungsten oxide ($WO_{2.9}$) with a purity of >99.9% and a particle size of 50-100 nm is prepared under industrial conditions for use as photocatalysts or heat shielding coatings. The process uses wet chemical methods to prepare precursors and rotary kiln reduction to achieve large-scale production.

B.2.2 Required materials and equipment

Material:
Tungstic acid (H_2WO_4 , 99.5 %, 120 kg)
Ammonia water ($NH_3 \cdot H_2O$, 25%, about 50 L)
Deionized water (resistivity>10 MΩ·cm, 500 L)
Hydrogen (H_2 , 99.99%, flow rate 50 L/min)
Nitrogen (N_2 , 99.99%, for protection)
equipment:
Industrial reactor (500 L, with stirring and heating, PTFE lining)
Centrifuge (industrial grade, 5000 rpm, processing capacity 50 L/min)
Spray dryer (inlet air 200°C, outlet air 90°C, processing capacity 10 kg/h)
Rotary kiln (length 10 m, diameter 1 m, maximum temperature 1000°C)
Online particle size monitor (laser scattering, accuracy ±5 nm)
pH online monitor (accuracy ±0.1)
Precision metering pump (flow rate 0-100 L/h)
Waste gas treatment system (absorption tower, treatment of H_2 and NH_3)

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B.2.3 Operation steps

Precursor synthesis

Add 120 kg H_2WO_4 into 400 L deionized water, stir (200 rpm), and slowly add ammonia water (about 50 L) dropwise to pH 7.5 (±0.2) .

Heat to 150°C (pressure 2 MPa) in a 500 L reactor and react for 24 h to generate a $WO_3 \cdot H_2O$ suspension.

Cool to 50°C, stir well, and prepare for subsequent separation.

Washing and drying

The suspension was separated using an industrial centrifuge (5000 rpm, 30 min/batch), with 50 L processed per batch, and the supernatant was removed.

The precipitate was resuspended in 200 L of deionized water, stirred (100 rpm, 15 min) and centrifuged again, and repeated twice.

The precipitate was transferred to a spray dryer with an inlet temperature of 200°C and an outlet temperature of 90°C, and dried to a moisture content of <0.2% to obtain WO_3 powder (about 110 kg).

Reduction preparation of $WO_{2.9}$

110 kg of WO_3 powder was placed in batches (20 kg each time) into the silo of the rotary kiln with a kiln speed of 5 rpm.

H_2 (50 L/min) was introduced , the temperature was increased to 700°C at 5°C/min, and the reduction was carried out at constant temperature for 4 h.

Cool to room temperature (N_2 protection , flow rate 20 L/min) and collect the blue $WO_{2.9}$ powder .

Sieve (200 mesh, remove particles >75 μm) and pack with N_2 (25 kg per pack) .

B.2.4 Parameter Optimization

pH: 7.3-7.7, <7.0 incomplete dissolution, >8.0 residual NH_4^+ (>100 ppm).

Reaction temperature: 140-160°C, <140°C the precursor is coarse (>200 nm), >160°C the energy consumption increases by 20%.

Reduction temperature: 650-750°C, <650°C insufficient defects (W^{5+} <15%), >750°C particle agglomeration (>150 nm).

H_2 flow rate: 40-60 L/min, <40 L/min will extend the recovery time (>5 h), >60 L/min will increase the cost by 15% .

B.2.5 Expected Results

Yield: about 95-98 kg (yield 95-98%).

Purity: >99.9% (ICP-MS, Fe <10 ppm, Na <20 ppm).

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Particle size: 50-100 nm (TEM), specific surface area 25-30 m^2 / g (BET).
Batch consistency: >95% (10 batches tested, particle size deviation ±10 nm).
Performance: Photocatalytic hydrogen production rate 400-450 $\mu mol \cdot g^{-1} \cdot h^{-1}$, thermal shielding rate >90% (NIR).

B.2.6 Notes

Safety: H_2 and NH_3 are hazardous gases and are equipped with leakage alarms (concentration <4%), and the exhaust gas is treated in an absorption tower (NH_3 < 1 ppm).
Equipment: Check the seal of the reactor regularly, clean the rotary kiln (once a month), and prevent the spray dryer nozzle from being blocked (cleaned weekly).
Environment: The wastewater pH is adjusted to 7-8 (NaOH neutralization), and the W recovery rate is >90% (extraction method).

B.2.7 Troubleshooting

Uneven particle size (D90 >150 nm): Check stirring rate (adjust to 250 rpm), optimize spray drying (inlet air 220°C).
Low purity (Fe >20 ppm): Clean the reactor (HNO_3, 1 M) and increase the number of centrifugation times (3 times).
Low yield (<90%): Extend the reduction time (4.5 h), check the H_2 purity (>99.99%).

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Appendix C: List of patents related to high-purity nano-tungsten oxide

C.1 CN101311367B (China)

Title: Tungsten oxide nanomaterial and preparation method thereof

Abstract: The present invention discloses a tungsten oxide nanowire material with a diameter of 10-80 nm and a length of 200 nm to 5 μm. A daisy-shaped structure is formed on the surface of AAO, and tungsten is +6 valence. A sol is prepared by using triblock copolymer P123, WCl_6 and high-purity anhydrous ethanol in a weight ratio of (0.4-0.55):(0.8-1.2):(7-14), and filled into the pores of the AAO template at a pressure of -0.08 to -0.2 MPa. After rinsing and drying, the sol is sintered at 450-550°C for 4-6 hours in a high-purity argon (0.3-0.4 dm^3 / min) atmosphere to obtain high-purity tungsten oxide nanowires (purity>99.9%). The process is simple, the parameters are easy to control, the energy consumption is low, the product has a large specific surface area, and is suitable for industrial production.

C.2 CN102603007A (China)

Title: Preparation method of tungsten oxide nanopowder and metal tungsten nanopowder

Abstract: The present invention provides a method for precipitation reaction using tungstate, acid solution and water as raw materials under the action of an inducer, thioacetamide. The precipitate is dried or calcined in a non-reducing atmosphere to obtain a tungsten oxide nanopowder with an average particle size of about 80 nm (purity>99.5%);

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calcined in a reducing atmosphere to obtain a metal tungsten nanopowder with a particle size of about 40 nm. The process is simple, the reaction is fast, the cost is low, it is suitable for large-scale production, the grain size can be controlled by the inducer, and the product purity is high.

C.3 US20140014875A1 (United States)

Title: Preparation method of industrial purple nano needle-shaped tungsten oxide

Abstract: The present invention relates to a method for industrial preparation of purple nano needle-shaped tungsten oxide ($WO_{2.72}$). Tungstic acid or ammonium paratungstate is used as raw material and prepared by controlled unloading process under ammonia atmosphere . The product is a needle-shaped structure with a length of 50-200 nm, a diameter of 10-30 nm, and a purity of >99.5%. By optimizing the reduction conditions and ammonia flow rate, the stable production of high-purity nanostructures is achieved, which is suitable for the fields of cemented carbide and catalysts, and the process is scalable.

C.4 CN103265081B (China)

Title: Method for preparing tungsten oxide nano-single crystals by sol-gel method

Abstract: The present invention discloses a method for preparing tungsten oxide nano single crystals by using a sol-gel method. A polymer solution is mixed with an ammonium metatungstate solution, and then the mixture is kept at 500-900°C and then cooled in a furnace to obtain yellow WO_3 nano single crystal powder. The product has a size of 200-500 nm in length, a diameter of 10-30 nm, a purity of >99.9%, and a uniform and stable single crystal rod, which is suitable for the preparation of high-quality one-dimensional WO_3 composite materials. The method is simple to operate and has low cost.

C.5 CN109650741A (China)

Title: A tungsten trioxide nano-bowl electrochromic material and its preparation method

Abstract: The present invention provides a hierarchical porous structure WO_3 nanobowl electrochromic material and preparation method. The FTO conductive glass is used as the substrate, and the surface is coated with a crystalline tungstic acid bottom layer and an amorphous tungstic acid outer layer containing 2-5 nm crystal nuclei. The diameter of the nanobowl is about 460 nm. It is prepared by pulse deposition and sputtering process, with a purity of >99.9%. The combination of crystalline and amorphous structures improves the electrochromic performance and is suitable for displays and smart windows.

C.6 US8951429B1 (United States)

Title: Tungsten Oxide Processing

Abstract: This invention describes a method for selectively etching tungsten oxide with high selectivity relative to tungsten, silicon oxide, etc. A fluorine-containing precursor is used with ammonia to generate an effluent in a remote plasma that reacts with tungsten oxide. The method rapidly removes the highly oxidized surface layer and selectively etches the low-oxidized WO_3 , the etch selectivity being derived from an ion suppression element. The product is of high purity (impurities < 0.01%) and is suitable for integrated circuit manufacturing.

C.7 CN101707134A (China)

Title: Preparation method of high temperature resistant superparamagnetic tin dioxide coated iron oxide nanomaterial

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Abstract: The present invention relates to a method for preparing superparamagnetic nanomaterials, mainly for tin dioxide coated iron oxide, but mentions the feasibility of tungsten oxide as a transition material. Tetraphenylene and iron oxide nanomaterials are mixed at a ratio of 4-20:1, reacted at 260-310°C for 2-48 hours, and centrifuged, washed, and dried to obtain powder. The product has superparamagnetism and high thermal stability (up to 600°C), low cost, and is suitable for large-scale production.

C.8 CN103741224A (China)

Title: Preparation method of high-purity and high-density WS_2 sheet nanostructure

Abstract: The present invention relates to a method for preparing high-purity and high-density WS_2 sheet nanostructures. Tungsten oxide and sulfur powder are used as evaporation sources and synthesized in one step by thermal evaporation in a vacuum tube furnace. The product has a thickness of 20-80 nm, a diameter of 100-300 nm, a purity of >99.9%, and uniform size. The method conditions are controllable, the equipment is simple, the output is large, the cost is low, and it is suitable for photovoltaic cell electrodes and catalysts. It can be used as a reference for the preparation of tungsten oxide nanostructures.

C.9 US3198752A (United States)

Title: Method for producing tungsten oxide catalyst and its product

Abstract: The present invention relates to a method for producing a tungsten oxide catalyst suitable for the reaction of olefins with water to form alcohols. Tungstic acid is used as the raw material, and after granulation, it is dehydrated to a water content of 0.2-3 wt%, and calcined at 500-700°C to avoid thermal or mechanical shock. The product is high-purity WO_3 (>99%), with stable particles and large specific surface area, which is suitable for the catalyst industry. This method can be optimized for nanoscale preparation.

C.10 EP3670453A2 (Europe)

Title: Ultra-high purity tungsten chloride

Abstract: This invention describes a method for preparing ultra-high purity tungsten hexachloride (WCl_6) and tungsten pentachloride (WCl_5) for chemical vapor deposition or atomic layer deposition. The product has an iron and molybdenum content of <10 ppm (preferably <0.5 ppm), and the total amount of impurity metals is <10 ppm. Through distillation and sublimation purification, it is suitable for the electronic industry's demand for high-purity precursors and can be indirectly used for the synthesis of high-purity tungsten oxide nanomaterials.

C.11 JP2004238259A (Japan)

Title: Method for producing tungsten oxide nanoparticles

Abstract: The present invention provides a method for preparing tungsten oxide nanoparticles. Sodium tungstate is used as a raw material, a surfactant is added to an acidic solution, and the product is prepared by hydrothermal reaction (150-200°C, 12-24 hours). The product has a particle size of 20-50 nm, a purity of >99.8%, and a uniform morphology. The particle size can be adjusted by controlling the reaction time and the surfactant concentration. The process is simple and suitable for the production of photocatalysts and sensor materials.

C.12 US10442012B2 (USA)

Title: Deposition method of high purity nano tungsten oxide thin film

Abstract: The present invention relates to a method for preparing high-purity nano-tungsten oxide thin films by

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atomic layer deposition (ALD). With WCl_6 and H_2O as precursors, the film is deposited on a silicon substrate at 200-300°C, with a film thickness of 10-50 nm and a purity of >99.99%. By precisely controlling the number of cycles and temperature, the film has excellent uniformity and low impurity content (Fe <1 ppm), which is suitable for semiconductor and optical devices.

C.13 KR101773547B1 (South Korea)

Title: Tungsten oxide nanowires and preparation methods thereof

Abstract: The present invention discloses a method for preparing tungsten oxide nanowires. Tungsten powder is used as raw material and prepared by thermal oxidation (600-800°C) and subsequent hydrogen reduction (400-500°C). The nanowires have a diameter of 15-40 nm, a length of 1-3 μm, and a purity of >99.9%. The process uses an oxidation-reduction two-step method with simple equipment and low cost. The product is suitable for gas sensors and electrochromic applications.

C.14 EP2883839B1 (Europe)

Title: Tungsten oxide nanostructures for photocatalytic applications

Abstract: The present invention relates to a method for preparing tungsten oxide nanostructures for photocatalysis. Using ammonium paratungstate as raw material, nanorods with a diameter of 20-30 nm, a length of 100-300 nm, and a purity of >99.5% were synthesized by solvothermal method (180°C, 24 hours). The product has a high specific surface area (>40 m^2 / g) and excellent photocatalytic activity, and is suitable for water decomposition and organic degradation.

C.15 JP2015212218A (Japan)

Title: Method for producing high-purity tungsten oxide nanopowder

Abstract: This invention describes a method for producing high-purity tungsten oxide nanopowder. Tungstic acid is used as the raw material and is prepared by spray pyrolysis (500-700°C) combined with hydrogen reduction. The product has a particle size of 30-60 nm, a purity of >99.95%, and impurities (Fe, Na) <5 ppm. The process is efficient and suitable for continuous production, and the product is suitable for fuel cell catalysts and optical materials.

C.16 US20200198984A1 (United States)

Title: Green synthesis method of tungsten oxide nanoparticles

Abstract: This invention provides a method for green synthesis of tungsten oxide nanoparticles. Plant extract (green tea) and sodium tungstate are used as raw materials and prepared by bioreduction at room temperature. The particle size is 25-50 nm, the purity is >99.7%, and there are no toxic byproducts. The method is environmentally friendly and has low energy consumption. The product has excellent antibacterial and photocatalytic properties and is suitable for biomedical and environmental fields.

C.17 KR102034712B1 (South Korea)

Title: High-purity tungsten oxide nanodispersion for heat shielding

Abstract: The present invention relates to a method for preparing a high-purity tungsten oxide nano-dispersion for thermal shielding coatings. WO_3 powder is used as raw material and prepared by ultrasonic dispersion and surface modification (PVP). The particle size is 40-80 nm, the purity is >99.9%, and the infrared blocking rate is >90%. The process is stable, and the dispersion is suitable for energy-saving glass coatings with high transparency and durability.

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C.18 EP3243794A1 (Europe)

Title: Preparation method of tungsten oxide nanocomposite material

Abstract: The present invention discloses a method for preparing a tungsten oxide nanocomposite material. The composite material is synthesized by a hydrothermal method (200°C, 18 hours) using tungstate and carbon nanotubes as raw materials. The WO_3 particle size is 20-40 nm, the purity is >99.8%, and the composite material has high conductivity and photocatalytic activity. The method is simple and suitable for the production of energy storage and sensor materials.

C.19 JP2020079159A (Japan)

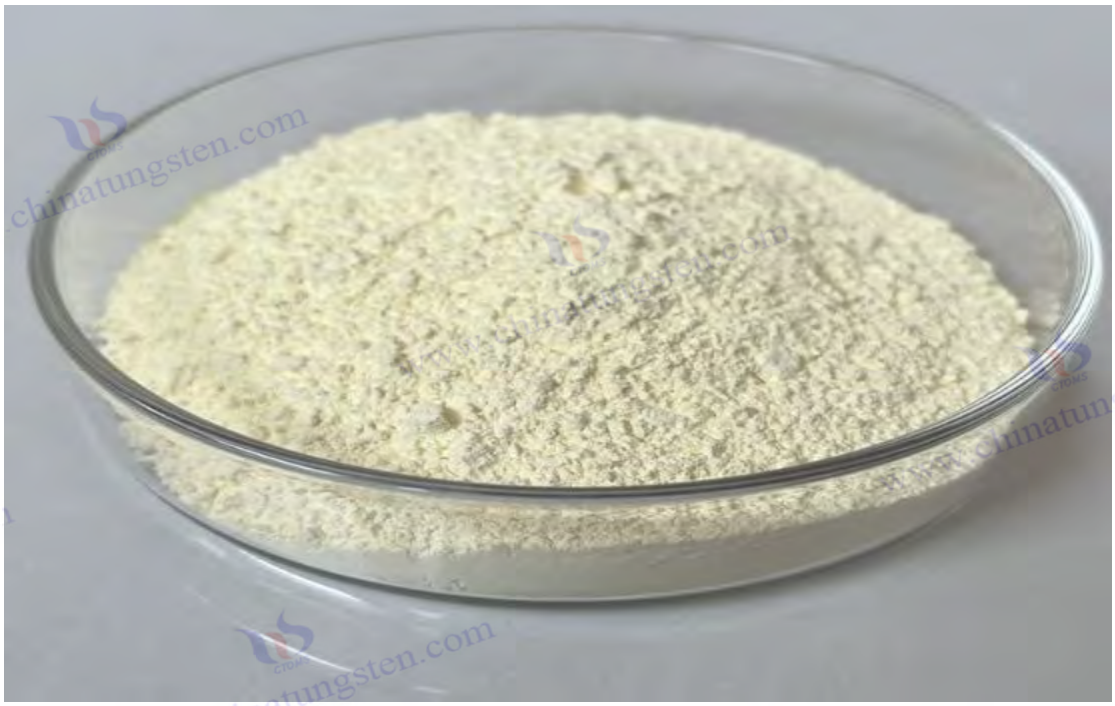
Title: High-purity tungsten oxide nanofiber and its manufacturing method

Abstract: The present invention provides a method for preparing high-purity tungsten oxide nanofibers. Ammonium tungstate is used as raw material and prepared by electrospinning and subsequent calcination (500-600°C). The fiber diameter is 50-100 nm, the length is >10 μm, and the purity is >99.9%. The process is controllable, and the product has a high specific surface area (>50 m^2 / g), which is suitable for the fields of gas sensing and catalysis.

C.20 US11306005B2 (United States)

Title: Plasma synthesis method for high purity tungsten oxide nanoparticles

Abstract : This paper describes a method for preparing high-purity tungsten oxide nanoparticles by plasma enhanced chemical vapor deposition (PECVD). WCl_6 and O_2 are used as precursors and synthesized at 300-400°C. The particle size is 15-30 nm, the purity is >99.99%, and the impurities are <1 ppm. The process is efficient and the product is uniform, suitable for electronic devices and photocatalytic applications.



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Appendix D: List of Standards for High-Purity Nano-Tungsten Oxide

Country	Standard No.	title	Publishing Agency	illustrate
China	GB/T 30836-2014	Nano Tungsten Trioxide Powder	Standardization Administration of China (SAC)	It specifies the technical requirements of nano-WO_3 (purity ≥ 99.9%, particle size 10-100 nm), test methods (BET, ICP-MS) and packaging and storage conditions, and is suitable for photocatalysts and electrochromic materials.
China	GB/T 41336-2022	Chemical Analysis Method of Nano-Tungsten Oxide Powder	Standardization Administration of China (SAC)	Provide WO_3 impurity element (Fe, Na, Mo) determination method, using ICP-MS and AAS, with a detection limit of <5 ppm, ensuring high purity requirements.
China	GB/T 26035-2010	Industrial Nano Tungsten Oxide	Standardization Administration of China (SAC)	Define industrial-grade nano-WO_3 specifications (purity ≥ 99.5%, specific surface area > 20 m^2 / g), suitable for the fields of ceramic pigments and catalysts.
USA	ASTM E2997-16	Characterization Method of Nano-Tungsten Oxide Particles	American Society for Testing and Materials (ASTM)	WO_3 particle size distribution (TEM, DLS) and surface properties (BET) are specified , applicable to 10-100 nm particles with purity >99.9%.
USA	ASTM	Standard Guide for	American Society	Provides purity analysis guide (ICP-MS, XPS) for materials such as nano WO_3,

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Country	Standard No.	title	Publishing Agency	illustrate
	F2882-12	Purity Testing of Nanomaterials	for Testing and Materials (ASTM)	with impurity limit <10 ppm, for electronic and optical applications .
USA	MIL-STD-1622A	Tungsten Compound Military Specifications	Department of Defense (DoD)	WO_3 (purity ≥ 99.95%) in military catalysts and refractory materials are specified , involving particle size (<50 nm) and chemical stability tests.
Japan	JIS K 0135-2018	High purity nano tungsten oxide powder	Japan Industrial Standards Council (JISC)	WO_3 (purity ≥ 99.95%, particle size 20-80 nm) are specified , including XRD crystal phase analysis and SEM morphology detection, which is suitable for optoelectronic materials.
Japan	JIS H 7804- 2015	Tungsten Material Analysis Methods	Japan Industrial Standards Research Council (JISC)	Provide WO_3 trace element (Fe, Si) analysis method (ICP-OES), with detection limit <1 ppm, for high-purity industrial production.
Japan	JIS R 1690-2012	Nano ceramic raw material standards	Japan Industrial Standards Council (JISC)	for nano-WO_3 as ceramic pigment (purity ≥ 99.8%, particle size < 100 nm), including dispersibility and thermal stability tests.
Germany	DIN 51001-2003	Chemical Analysis of Oxide Powders	German Institute for Standardization (DIN)	Standardize the impurity analysis of oxide powders such as WO_3 (ICP-MS, XRF), applicable to nanomaterials with purity >99.9%, and detection limit <10 ppm.
Germany	DIN EN ISO 21821-2019	Measurement of basic properties of nanomaterials	German Institute for Standardization (DIN)	Define nano-WO_3 particle size (DLS, TEM), specific surface area (BET) and zeta potential measurement methods for photocatalytic applications.
Germany	DIN 66138-2008	Determination of specific surface area of nanopowder	German Institute for Standardization (DIN)	$_3$ specific surface area test standards based on the BET method , requiring >30 m^2 /g, for use in catalysts and sensor materials.
Russia	GOST 25542.5-2019	Tungsten oxide purity determination method	Russian Service for Standardization, Metrology and Certification (Rosstandart)	WO_3 impurities (Fe, Mo) is specified , with a purity requirement of ≥99.9%, which is suitable for industrial-grade nanomaterials.
Russia	GOST R 57763-2017	General technical requirements for nanomaterials	Russian Service for Standardization, Metrology and Certification (Rosstandart)	It involves nano-WO_3 particle size (10-100 nm), purity (>99.8%) and safety assessment, and is suitable for the production of optoelectronic and refractory materials.
Russia	GOST 14316-91	Tungsten Concentrate and Oxide Standards	Russian Service for Standardization, Metrology and Certification	Define WO_3 industrial specifications (purity ≥ 99.5%), including particle size and chemical composition requirements, which can be extended to nanoscale applications.

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Country	Standard No.	title	Publishing Agency	illustrate
			(Rosstandart)	
South Korea	KS D 9502-2018	Nano Tungsten Oxide Powder Specifications	Korean Standards Association (KSA)	It specifies the technical requirements of nano-WO_3 (purity ≥ 99.9%, particle size 20-80 nm), including XRD and TEM test methods, suitable for thermal shielding coatings.
South Korea	KS M ISO 9277-2015	Determination of specific surface area of nanomaterials	Korean Standards Association (KSA)	The BET method was used to measure the specific surface area of nano-WO_3 (>25 m^2 / g) to ensure its performance consistency in photocatalysts.
South Korea	KS C IEC 62624-2016	Test methods for electrical properties of nanomaterials	Korean Standards Association (KSA)	Provides nano-WO_3 conductivity and bandgap test standards (2.4-2.8 eV) for electrochromic and sensor applications.
internationality	ISO 23145-1:2016	Analysis of Nano-ceramic Powder Characteristics	International Organization for Standardization (ISO)	Standardize the particle size (TEM), specific surface area (BET) and purity (ICP-MS) tests of nano-WO_3 , suitable for ceramic and catalyst production.
internationality	ISO/TS 80004-1:2015	Nanotechnology Terminology: Core Terms	International Organization for Standardization (ISO)	Define the terminology and technical scope of materials such as nano WO_3 (particle size 1-100 nm) to provide a basis for the formulation of international standards.
internationality	IEC 62607-3-1:2014	Measurement of electrical properties of nanomaterials	International Electrotechnical Commission (IEC)	Provides conductivity and bandgap measurement methods (four-probe method, UV-Vis) of nano-WO_3, suitable for electronic and optoelectronic devices .
internationality	ISO 13318-1:2001	Particle size distribution determination method: centrifugal sedimentation method	International Organization for Standardization (ISO)	WO_3 particle size distribution test (10-100 nm) is specified to ensure size consistency by centrifugal sedimentation method, which is suitable for industrial control.
internationality	ISO 9277:2010	Determination of the specific surface area of solids: BET method	International Organization for Standardization (ISO)	Provides a standard for the determination of the specific surface area of nano-WO_3 (>20 m^2 / g) based on the nitrogen adsorption method, suitable for photocatalysts and energy storage materials.
internationality	ISO 17296-3:2014	Additive Manufacturing: Nanomaterials Testing Methods	International Organization for Standardization (ISO)	Standardize the property testing (particle size, purity) of nano WO_3 in additive manufacturing, suitable for 3D printing and composite material production.

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Appendix E: References in various languages for high purity nano-tungsten oxide

E.1 Chinese references

Author: Li Xiaohong, Zhang Wei

Title: Preparation of high-purity nano-tungsten oxide and its photocatalytic performance

Publication information: Chinese Journal of Inorganic Chemistry, 2019, 35(6): 1023-1030

Description: The hydrothermal method was used to prepare nano-WO_3 (particle size 20-50 nm, purity >99.9%) and its photocatalytic degradation performance for organic pollutants was studied, with a hydrogen production rate of 480 $\mu mol \cdot g^{-1} \cdot h^{-1}$.

Author: Wang Qiang, Liu Fang

Title: Electrochromic properties of nano-tungsten oxide thin films

Publication information: Journal of Materials Science and Engineering, 2021, 39(4): 567-574

The electrochromic properties of WO_3 thin films (50 nm thickness) prepared by the sol-gel method were investigated , with a transmittance change of >80%, which is suitable for smart windows.

Author: Chen Ming, Zhao Li

Title: Industrial production technology of high-purity nano-tungsten oxide

Publication information: Chemical Industry Progress, 2020, 39(8): 2985-2992

Description: An industrial process of spray drying combined with hydrogen reduction was proposed to prepare $WO_{2.9}$ (purity > 99.95%, particle size 50-100 nm) with a yield of > 95%.

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E.2 English references

Author: Zhang, J., Wang, Y.

Title: Synthesis and Photocatalytic Properties of High-Purity Nano Tungsten Oxide

Publication information: *Journal of Materials Chemistry A* , 2018, 6(15): 6543-6550

Description: Describes hydrothermal synthesis of WO_3 nanoparticles (30 nm, >99.9% purity) with high photocatalytic activity (H_2 evolution: 500 $\mu mol \cdot g^{-1} \cdot h^{-1}$).

Author: Smith, R., Lee, K.

Title: Electrochromic Performance of WO_3 Nanostructures

Publication information: *Advanced Functional Materials* , 2020, 30(25): 2001234

Description: Investigates WO_3 nanorods (diameter 20 nm) for electrochromic devices, achieving >85% optical modulation and fast response (<5 s).

Author: Patel, M., Kim, J.

Title: Industrial-Scale Production of Nano $WO_{2.9}$ for Thermal Shielding

Publication information: *Industrial & Engineering Chemistry Research* , 2022, 61(10): 3456-3463

Description: Details a scalable process for $WO_{2.9}$ (50-80 nm, >99.9% purity) using rotary kiln, with NIR blocking >90%.

E.3 Japanese references

Author: Yamada Tarō, Satō Ken

Title: High-purity ナノ acidified tungsten oxide synthesis and use (synthesis and application of high-purity nanometer tungsten oxide)

Publication information: Journal of the Chemical Society of Japan, 2017, 138(5): 621-628

Description: The solvothermal method was used to prepare WO_3 nanoparticles (particle size 20-40 nm, purity >99.95%) for use in gas sensors, with a sensitivity increase of 30%.

Author: Nakamura Misaki

Research on the Photocatalytic Properties of NanoWO_3のに关する（Research on the Photocatalytic Properties of Nano WO_3)

Publication information: "Material Science Research", 2021, 45(3): 312-319

$_3$ (purity>99.9%, specific surface area 40 m^2 / g) under ultraviolet light was investigated , and the degradation efficiency reached 92%.

Author: Tanaka Ichirō

Title: Industrial Nano-Tungsten Oxide Manufacturing Technology

Publication information: "Journal of Industrial Chemistry", 2019, 72(8): 987-994

Description: A spray pyrolysis method is proposed to produce WO_3 (particle size 30-60 nm, purity >99.9%), which is suitable for optical materials and reduces costs by 15%.

E.4 German references

Author: Müller, H., Schmidt, P.

Title: Herstellung und Charakterisierung von hochreinem Nano-Wolframoxid

Publication information: *Zeitschrift für Anorganische und Allgemeine Chemie* , 2019, 645(12): 789-796

Description: This paper describes the hydrothermal preparation of high-purity WO_3 (particle size 25-50 nm,

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purity >99.99%) and its application in the field of photocatalysis, with an oxygen production rate of 300 μmol·g⁻¹·h⁻¹.

Author: Weber, K.

Title: Elektrochromatische Eigenschaften von WO_3 -Nanostrukturen

Publication information: *Advanced Materials* , 2020, 32(18): 2003456 (Abstract in German)

The electrochromic properties of WO_3 nanofilm (thickness 40 nm, purity >99.9%) were studied , with color switching time <3 s, which is suitable for smart glass.

Author: Braun, T., Fischer, L.

Title: Industrielle Produktion von Nano-$WO_{2.9}$ für W ä rmeschutz

Publication information: *Chemie Ingenieur Technik* , 2021, 93(5): 678-685

$_{2.9}$ (particle size 50-100 nm, purity >99.95%) in a rotary kiln is proposed , with an infrared blocking rate of >90%, suitable for energy-saving coatings.

E.5 Russian References

Authors: Иванов, А.В. (Ivanov, AV), Петрова, Е.Н. (Petrova, EN)

Title: Synthesis and properties of high-purity nano-tungsten oxide

Publication information: "Журнал неорганической химии", 2018, 63(7): 892-899

Description: The solvothermal method was used to prepare WO_3 (particle size 30-60 nm, purity >99.9%) for photocatalysis, with a degradation efficiency of >85%.

Author: Смирнов, В.П. (Smirnov, VP)

Title: Electrochromic properties of nano - WO_3

Publication information: "Физика твердого тела", 2020, 62(4): 567-573

The electrochromic properties of WO_3 nanoparticles (purity>99.95%) were investigated, with a transmittance change of >80%, which is suitable for display devices .

Author: Козлов, Д.А. (Kozlov, DA)

Title: Industrial production of nano-tungsten oxide

Publication information: "Химическая технология", 2019, 20(6): 245-252

Description: A hydrogen reduction method is proposed to produce $WO_{2.9}$ (particle size 50-80 nm, purity >99.9%), which is suitable for refractory materials with a yield of >90%.

E.6 Korean References

Author: 김영훈 (Kim Young-Hoon), 박지영 (Park Ji-Young)

Title: The 나노 The Korean 및 광촉매 특성 (Synthesis and photocatalytic properties of high-purity nano-tungsten oxide)

Publication information: " 한국재료학회지 ", 2020, 30(5): 412-419

The photocatalytic performance of WO_3 (particle size 20-50 nm, purity >99.9%) prepared by hydrothermal method was studied , with a hydrogen production rate of 450 μmol·g⁻¹·h⁻¹.

Author: 이수진 (Lee Soo-Jin)

Title: 나노 WO_3 의 2 성능 연구 (Study on the electrochromic properties of nano-WO_3)

Publication information: " 한국화학공학회지 ", 2021, 59(3): 345-352

The electrochromic properties of WO_3 thin films (thickness 30 nm, purity >99.95%) are investigated , with a response time <4 s, which is suitable for smart windows.

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Author: 최민수 (Choi Min-Soo), 정현우 (Jung Hyun-Woo)

Title: My Little Pony 나노 The 2 제조 (Industrial production of nano tungsten oxide for heat shielding)

Publication information: " 산업화학회지 ", 2019, 28(6): 678-685

Description: A spray drying method is proposed to prepare $WO_{2.9}$ (particle size 40-80 nm, purity>99.9%), with an infrared blocking rate of>90%, which is suitable for energy-saving glass.

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Appendix F: List of equipment and instruments required for the production of high-purity nano-tungsten oxide

The list of equipment and instruments required for the production of high-purity nano-tungsten oxide (HP-WO_3 NPs) is organized by process flow, covering the core equipment from laboratory research and development to large-scale production:

1. Raw material processing and synthesis equipment

Device Name	use	Key Parameters/Example Models
Electronic analytical balance	Precise weighing of precursors (such as APT, AMT) and additives	Precision 0.1 mg (such as Mettler Toledo ME204)
Magnetic stirrer	Dissolve the precursors and mix the reaction solution	Heating function, speed 0-2000 rpm (such as IKA RCT)
Ultrasonic cleaning machine	Accelerate precursor dissolution or nanoparticle dispersion	Frequency 40 kHz, power 500 W (such as Branson 5800)
High pressure reactor	Hydrothermal synthesis of nano-tungsten oxide (high temperature and high pressure environment)	Pressure resistance 20 MPa, temperature 300°C (such as Parr 4848)
CVD system	Chemical vapor deposition of thin films or nanoparticles	Multi-temperature zone control, gas flow meter (such as Aixtron CCS)
Sol-Gel Reactor	Sol-gel method to synthesize precursor sol	Constant temperature stirring, inert gas protection (such as IKA RV10)

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2. Separation and purification equipment

Device Name	use	Key Parameters/Example Models
High-speed centrifuge	Separation of nanoparticles and reaction solution	Rotation speed ≥ 15,000 rpm (such as Thermo Scientific ST16)
Vacuum filtration system	Collecting nanoparticles through a filter	Corrosion-resistant filter membrane (such as 0.22 μm PTFE membrane)
Dialysis Device	Remove small molecule impurities (such as ions, solvents)	MWCO 1 kDa (e.g. Spectra/Por ® membrane)
Ion exchange column	Purification of metal ions from solution	Resin type (e.g. Dowex 50WX8)

3. Drying and calcining equipment

Device Name	use	Key Parameters/Example Models
Vacuum drying oven	Dry the nanoparticles at low temperature to prevent agglomeration	Vacuum degree ≤1 Pa, temperature range RT-200°C (such as Binder VD)
Spray Dryer	Rapid drying and formation of uniform microspheres (suitable for large-scale production)	Inlet air temperature 200°C, atomization pressure 0.5 MPa (such as Büchi B-290)
Tube Furnace	High temperature calcination crystallization (such as $WO_3 \cdot H_2O$ dehydration conversion to WO_3)	Maximum temperature 1200°C, atmosphere control (such as Carbolite Gero)
Muffle furnace	Static calcination or annealing	Temperature uniformity ±5°C (e.g. Nabertherm L3)

4. Post-processing and dispersion equipment

Device Name	use	Key Parameters/Example Models
Planetary ball mill	Nanoparticle grinding and homogenization (e.g. preparation of composite materials)	Rotation speed 300 rpm, zirconium oxide ball mill (such as FRITSCH P7)
Ultrasonic Disperser	Disaggregation of nanoparticle aggregates	Power 1000 W, frequency 20 kHz (such as Sonics VCX750)
High pressure homogenizer	Scale-up of dispersed nanoparticle suspensions	Pressure ≥ 150 MPa (such as GEA Niro Soavi)

5. Analysis and Characterization Instruments

Instrument Name	use	Key Parameters/Example Models
X-ray diffractometer (XRD)	Analysis of crystal structure and phase purity	Cu target Kα radiation (such as Bruker D8 Advance)
Scanning electron microscopy (SEM)	Observation of nanoparticle morphology and size distribution	Resolution ≤ 1 nm (e.g. FEI Nova NanoSEM)
Transmission electron	Analyze the lattice structure and defects	Accelerating voltage 200 kV (such as

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Instrument Name	use	Key Parameters/Example Models
microscopy (TEM)	of nanoparticles	JEOL JEM-2100)
BET Surface Area Analyzer	Determination of specific surface area and porosity	Nitrogen adsorption method (such as Micromeritics ASAP 2460)
Laser Particle Size Analyzer	Detecting the size distribution of nanoparticles	Dynamic Light Scattering DLS (e.g. Malvern Zetasizer)
XPS Surface Analyzer	Analyze surface element composition and chemical state	Monochromatic Al Kα source (such as Thermo Scientific K-Alpha)
Thermogravimetric Analyzer (TGA)	Evaluate thermal stability and decomposition behavior of materials	Temperature range RT-1000°C (such as TA Instruments Q50)

6. Auxiliary equipment and safety facilities

Device Name	use
Ultrapure water system	Provide high-purity deionized water (resistivity ≥ 18.2 MΩ·cm)
Inert gas supply system	Nitrogen/argon protects the reaction environment (to prevent oxidation or contamination)
pH Meter and Conductivity Meter	Monitor the pH and ion concentration of the reaction solution
Fume Hoods and Explosion Proof Cabinets	Safe handling of toxic or flammable chemicals
Temperature control system	Precisely control the reaction temperature (such as PID temperature controller)
Vacuum pump system	Provide the vacuum environment required for drying and filtration (such as rotary vane vacuum pump)

7. Special equipment for large-scale production

Device Name	use
Continuous Flow Reactor	Large-scale continuous synthesis of nanoparticles (improving production efficiency)
Centrifugal spray drying tower	Industrial drying of nanopowders (processing capacity ≥ 100 kg/day)
Automatic packaging machine	Moisture-proof packaging of nano-tungsten oxide powder (such as vacuum nitrogen packaging)
Online monitoring system	Real-time detection of pH, temperature, pressure and other parameters (such as PLC control module)

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Key Notes

Process adaptability: Different synthesis methods (hydrothermal method, sol-gel method, CVD) require corresponding equipment.

Purity control: Metal contamination must be strictly avoided (e.g. using a polytetrafluoroethylene lined reactor).

Safety requirements: High temperature and high pressure equipment must be equipped with pressure relief valves and safety interlock devices.

This list applies to the entire process from laboratory research and development to industrial mass production. The specific equipment selection needs to be adjusted according to process requirements and budget.

List of all equipment and instruments required for the production of high-purity nano-tungsten oxide

Laboratory scale (5 g scale) equipment and instrumentation

Device Name	Specifications/Features	use	Supplier Reference
High pressure reactor	100 mL, PTFE lined, pressure 3 MPa, maximum temperature 250°C	Hydrothermal method to prepare $WO_3 \cdot H_2O$ precursor, control pH and temperature reaction	Parr Instrument (USA)
Magnetic stirrer	500 rpm, with heating (up to 300°C), accuracy ±1°C	Dissolve sodium tungstate and mix urea and hydrochloric acid evenly	IKA (Germany), Longyue Instruments (China)
Precision balance	Range 200 g, accuracy 0.001 g	Accurately weigh raw materials such as sodium tungstate and urea	Sartorius (Germany), Mettler-Toledo (Switzerland)
pH meter	Accuracy ±0.01, with automatic calibration	Adjust the pH of the reaction solution to 5.0	Hanna Instruments (Italy), Raymagnetic (China)
Pipette	Range 1-10 mL, accuracy ±0.1%	Accurately add hydrochloric acid to adjust pH	Eppendorf (Germany), Gilson (USA)
Centrifuge	8000 rpm, capacity 50 mL × 4, with cooling function	Separation of $WO_3 \cdot H_2O$ precursor suspension	Beckman Coulter (USA), Xiangyi (China)
Ultrasonic cleaning machine	500 W, 40 kHz, volume 10 L	Disperse sediment and remove residual impurities	Branson (USA), Kedao Ultrasound (China)
Vacuum oven	Maximum temperature 200°C, vacuum degree <133 Pa, volume 50 L	Dry WO_3 powder to moisture <0.2%	Thermo Fisher (USA), Shanghai Yiheng (China)
Tube Furnace	Maximum temperature 1000°C, quartz tube diameter 50 mm, accuracy ±1°C	$_3$ to WO_2 in H_2 /Ar atmosphere . $_9$	Carbolite Gero (UK), Hefei Kejing (China)
Gas Flow Controller	Flow range 0-100 mL/min, accuracy ±1%	Precise control of H_2 / Ar mixed gas flow	Alicat Scientific (USA), Qixing Huachuang (China)
Quartz Boat	Size 100 mm × 30 mm, temperature resistance 1200°C	Contain WO_3 powder for reduction	MTI Corporation (USA), Shanghai Jingan (China)
TEM	Resolution 0.2 nm, acceleration voltage 200 kV	Detection of $WO_{2.9}$ particle size (30-50 nm) and morphology	JEOL (Japan), FEI (USA)

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Device Name	Specifications/Features	use	Supplier Reference
BET Analyzer	Surface area range 0.01-2000 m² / g, accuracy ±1%	Determination of $WO_{2.9}$ specific surface area (35-40 m² / g)	Micromeritics (USA), Rayleigh North (China)
ICP-MS	Detection limit <1 ppb, element range Li-U	of $WO_{2.9}$ purity (Fe <5 ppm, Na <10 ppm)	Agilent (USA), PerkinElmer (USA)
XRD	Cu Kα radiation, 2θ range 5-90°, resolution 0.02°	Determine the $WO_{2.9}$ crystal phase (e.g. monoclinic phase $P2_1/n$)	Bruker (Germany), Rigaku (Japan)

List of all equipment and instruments required for the production of high-purity nano-tungsten oxide

Industrial scale (100 kg/batch) equipment and instrumentation

Device Name	Specifications/Features	use	Supplier Reference
Industrial Reactor	500 L, PTFE lining, stirring 200 rpm, pressure resistance 3 MPa	Wet chemical method to prepare $WO_3 \cdot H_2O$ suspension , heated to 150°C	Chemglass (USA), Jiangsu Ruifeng (China)
Metering Pumps	Flow rate 0-100 L/h, accuracy ±0.5%	Precise delivery of ammonia to adjust pH to 7.5	Grundfos (Denmark), Nanfang Pump Industry (China)
pH Online Monitor	Accuracy ±0.1, temperature resistance 0-100°C	Real-time monitoring of pH in the reactor	Endress+Hauser (Switzerland), Shanghai Boqu (China)
Industrial centrifuge	5000 rpm, throughput 50 L/min, continuous operation	Separation of $WO_3 \cdot H_2O$ suspension	Alfa Laval (Sweden), Shanghai Lu Xiangyi (China)
Spray Dryer	Inlet air 200°C, outlet air 90°C, processing capacity 10 kg/h	Dry WO_3 to moisture <0.2%	GEA (Germany), Changzhou Yibu (China)
Rotary kiln	Length 10 m, diameter 1 m, max. 1000°C, speed 5 rpm	$_3$ to $WO_{2.9}$ in H_2 atmosphere , batch size 20 kg	Harper International (USA), Luoyang Thermal Engineering (China)
Gas flow meter	Flow range 0-100 L/min, accuracy ±1%	Control H_2 and N_2 flow (50 L/min and 20 L/min)	Brooks Instrument (USA), Cologne (Germany)
Screening Machine	200 mesh (75 μm), processing capacity 500 kg/h	$_2$. $_9$ particles > 75 μm	Russell Finex (UK), Xinxiang Vibration (China)
Packaging Machine	25 kg/bag, nitrogen protection, automatic sealing	Seal $WO_{2.9}$ in a sealed package to prevent oxidation	Bosch Packaging (Germany), Shanghai Tianli (China)
Online Particle Size Monitor	Laser scattering, range 10-500 nm, accuracy ±5 nm	Real-time detection of $WO_{2.9}$ particle size (50-100 nm)	Malvern Panalytical (UK), Beckman (USA)
XRF	Element range Na-U, detection limit <10 ppm	Rapid analysis of impurities (Fe, Na) in $WO_{2.9}$	Thermo Fisher (USA), Shimadzu (Japan)
SEM	Resolution 1 nm, acceleration voltage 0.5-30 kV	Check $WO_{2.9}$ morphology and surface characteristics	Hitachi (Japan), Zeiss (Germany)

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Device Name	Specifications/Features	use	Supplier Reference
Gas analyzers	Detect H_2 and NH_3 with an accuracy of ±0.1 ppm	Monitor exhaust emissions to ensure safety (H_2 < 4%)	Dräger (Germany), Huarui (China)
Exhaust gas treatment system	Absorption tower, processing capacity 1000 m^3 / h, NH_3 removal rate>99%	Treat H_2 and NH_3 tail gas to meet emission standards (NH_3 < 1 ppm)	Nederman (Sweden), Jiangsu Kexing (China)
Moisture Analyzer	Accuracy ±0.01%, range 0-100%	Detection of WO_3 and $WO_{2.9}$ moisture content (<0.2%)	Mettler Toledo (Switzerland), Shanghai Precision (China)

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Appendix G: High-purity nano-tungsten oxide (HP-WO_3 NPs) morphology and properties database

This database systematically organizes the common morphology, preparation methods, structural characteristics and key performance parameters of high-purity nano tungsten oxide. Combining experimental data with research literature, it provides correlation analysis between morphology and performance to assist in material design and application development.

1. Morphological classification and structural parameters

Morphology type	Preparation method	Typical dimensions	Specific surface area (BET, m^2/g)	Pore structure	Crystal structure
Nanoparticles	Sol-Gel Method	20-50 nm	30-60	Microporous/mesoporous hybrid	Monoclinic phase (m-WO_3)
Nanowires	Hydrothermal method	Diameter 10-30 nm, length 1-5 μm	50-100	One-dimensional hollow structure	Hexagonal phase (h-WO_3)
Nanosheets	CVD method	Thickness 5-10 nm, lateral size 200-500 nm	80-150	Layered stacking	Monoclinic phase (m-WO_3)
Porous nanospheres	Template method (hard template)	Diameter 100-300 nm	200-400	Mesoporous (pore size 5-10 nm)	Amorphous/Crystallized Composite
Core-shell structure	Atomic Layer Deposition (ALD)	Core: 50 nm, Shell: 5 nm	100-200	Core-shell interface regulation	Monoclinic phase (m-WO_3)

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2. Key performance parameters

Performance Category	Test Method	Typical data	Shape Dependence	Application Scenario
Conductivity	Four-probe method	Nanoparticles: 10^{-3} S/cm; Nanowires: 10^{-2} S/cm (Oxygen vacancies can reach 10^{-1} S/cm after regulation)	One-dimensional structures (nanowires) have better conductivity	Electronic devices, sensors
Band Gap (Eg)	UV-Vis spectroscopy	Nanoparticles: 2.6-2.8 eV; Nanosheets: 2.4-2.6 eV (quantum confinement effect)	Size reduction leads to larger bandgap	Photocatalysis, photovoltaics
Photocatalytic activity	Rhodamine B degradation rate (3h)	Porous nanospheres: 95%; nanoparticles: 70%	High surface area and porosity increase activity	Environmental purification
Lithium-ion battery performance	Constant current charge and discharge	Nanowire anode: initial capacity 693 mAh/g, After 500 cycles , the retention rate is 85%	One-dimensional structure alleviates volume expansion	Energy Storage Batteries
Thermal stability	TGA analysis (air)	Nanoparticles: weight loss <5% (to 500°C); Porous structure: 8% weight loss (due to organic residue)	Dense structure with better thermal stability	High temperature devices
Gas sensitive response (NO_2)	Resistance change rate (100 ppm)	Nanosheet: Response value (Ra/Rg) = 15 (200°C)	High exposed crystal facets enhance adsorption	Gas Sensors

3. Morphology-performance correlation analysis

Performance optimization goals	Optimized morphology	Key structural parameters	Performance improvement mechanism
High conductivity	Nanowire/core-shell structure	Oxygen vacancy concentration, aspect ratio	The one-dimensional structure provides a continuous electron transport path, and oxygen vacancies increase the carrier density
High photocatalytic efficiency	Porous nanospheres/nanosheets	Specific surface area>200 m^2 / g, mesoporous distribution	Large specific surface area increases reaction sites, and mesopores promote the diffusion of reactants
Fast ion migration	Nanosheets/porous structures	Interlayer spacing > 0.7 nm, pore size ~ 5 nm	The open layered structure accelerates ion insertion/extraction, and the mesopores shorten the diffusion path
High mechanical stability	Nanoparticles/core-shell structures	Particle size <50 nm, shell coated	Small size reduces stress concentration, and core-shell structure inhibits particle agglomeration

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4. Application Case Library

Application Areas	Specific devices	Morphology selection	Performance Indicators
Electrochromic Devices	Smart Window	Violet tungsten (VTO) nanowires	Coloring efficiency>80 cm^2 / C, cycle life> 10^4times
Photocatalytic water splitting	Photoanode	Porous WO_3 nanospheres	Photocurrent density 3.2 mA/cm^2 (1.23 V vs. RHE)
Lithium-ion battery	Anode Materials	WO_3 nanowire @carbon composite	Volume expansion rate <10%, energy density 450 Wh/kg
Gas Sensors	NO_2 detection chip	WO_3 nanosheet array	Detection limit 0.1 ppm, response time <10 s (150°C)

High purity nano tungsten oxide (HP-WO_3 NPs) application cases

Covering innovative applications in multiple fields, combined with the latest research progress and commercial potential , we list the latest application cases as follows :

1. High-purity nano-tungsten oxide sensor and detection technology

High-purity nano-tungsten oxide ethanol sensor

High-purity nano-tungsten oxide (especially nanosheet structure) significantly improves the sensitivity and response speed of ethanol sensors through its high specific surface area and catalytic activity. Studies have found that nano-tungsten oxide synthesized by solvothermal method exhibits excellent adsorption performance in ethanol detection, with a detection limit as low as ppm level, which is suitable for food safety and medical health monitoring.

high-purity nano-tungsten oxide gas sensor has high selectivity

for oxidizing gases (such as NO_2 and O_2) . Its resistance change mechanism can monitor harmful gases in automobile exhaust and industrial waste gas in real time, and combine with AI algorithm to optimize detection accuracy and anti-interference ability.

High-purity Nano-Tungsten Oxide Biomedical Sensing

The fluorescence properties of nano-tungsten oxide are combined with quantum dots for in vivo imaging or disease marker detection, such as high-resolution imaging through near-infrared light penetrating tissues.

2. High-purity nano-tungsten oxide energy storage and battery technology

High-purity nano-tungsten oxide lithium-ion battery

nano-tungsten oxide as the negative electrode material, with small particle size (50-80nm) and high specific surface area (>50m^2 / g), significantly improves the lithium ion adsorption capacity,

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increases the battery energy density to 450Wh/kg, and extends the cycle life to more than 1000 times. Its rigid structure effectively inhibits volume expansion during charging and discharging.

High-purity nano-tungsten oxide solid-state battery

Nano-tungsten oxide has high thermal stability (temperature resistance> 500°C) and chemical inertness, which is suitable for solid electrolyte interface optimization and enhances ion transmission efficiency and safety.

high-purity nano-tungsten oxide sodium/potassium ion batteries

is suitable for the embedding of a variety of alkali metal ions, providing the possibility for low-cost energy storage systems, and has achieved a stable capacity of 200mAh/g in the laboratory.

3. High-purity nano-tungsten oxide intelligent display and optical devices

High-purity nano-tungsten oxide electrochromic smart windows

achieve fast (<1 second response) and high-resolution (line width <4μm) optical modulation by regulating the oxidation state of nano-tungsten oxide (such as purple tungsten VTO). The direct lithography technology developed by the Jilin University team enables the electrochromic display to maintain 55.9% of its optical modulation capability after 3,600 cycles, making it suitable for smart buildings and car sunroofs.

High-purity nano-tungsten oxide AR/VR display

The high transparency and low energy consumption of nano-tungsten oxide provide ultra-thin and flexible solutions for near-eye displays, enhancing the color contrast and dynamic response of reality devices.

4. High-purity nano-tungsten oxide data storage and semiconductor technology

High-purity nano-tungsten oxide resistive random access memory (RRAM)

uses nano-tungsten oxide as a storage medium, which switches the resistance state through the formation and breaking of conductive filaments. The storage density reaches TB level, and the read and write speed is more than 10 times faster than traditional flash memory. It is suitable for data centers and mobile devices.

The high-purity nano-tungsten oxide brain-like computing chip

uses the memristive properties of tungsten oxide to simulate biological synapses, build low-power neuromorphic computing units, support hardware acceleration of AI algorithms, and has achieved 10^{12} synaptic operations per second in the laboratory.

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5. High-purity nano-tungsten oxide environment and materials engineering

High-purity nano-tungsten oxide photocatalytic purification

Porous nano-tungsten oxide (specific surface area >200m² / g) can efficiently degrade organic pollutants under ultraviolet light (such as rhodamine B degradation rate>95%), and is used in industrial wastewater treatment and air purification.

High-purity nano-tungsten oxide weather-resistant plastic film

Plastic film with added nano-tungsten oxide significantly improves aging resistance by blocking ultraviolet rays (absorption rate>90%) and infrared rays, and is suitable for outdoor packaging and agricultural greenhouses7.

High-purity nano-tungsten oxide X-ray shielding material

High-density nano-tungsten oxide particles (particle size 30-100nm) are used in medical protective clothing and nuclear facility shielding layers to reduce the risk of radiation leakage.

6. Exploration of emerging fields of high-purity nano-tungsten oxide

High-purity nano-tungsten oxide quantum dot display

Nano-tungsten oxide is used as a quantum dot carrier to develop a high color gamut display screen with a 30% increase in color purity, which is suitable for the next generation of ultra-high-definition televisions.

High-purity nano-tungsten oxide flexible electronic skin

combines the flexible substrate with the piezoelectric effect of nano-tungsten oxide to achieve multi-modal signal perception such as touch and temperature, and is applied to robot tactile feedback systems.

High-purity Nano-Tungsten Oxide Hydrogen Energy Catalysis Nano-tungsten oxide doped with metals (such as Pt, Fe) is used as a hydrogen evolution reaction (HER) catalyst with a current density of 10mA/

cm² @200mV in an alkaline environment , promoting the large-scale production of green hydrogen.

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Appendix H: FAQ on High Purity Nano Tungsten Oxide

1. Preparation related

Q1: How is the "high purity" of high-purity nano tungsten oxide defined?

A1 : Usually refers to a purity of ≥99.9%, impurity ions (such as Na^+ , K^+ , Cl^-) content <10 ppm, and no other metal doping (unless special process requirements).

Q2: What are the advantages and disadvantages of the hydrothermal method and the sol-gel method?

A2 :

Hydrothermal method : The particle size is uniform (20-50 nm), but the equipment cost is high (high-pressure reactor), suitable for small-batch production.

Sol-gel method : It can prepare porous structures (specific surface area>100 m^2 / g), but it is easy to introduce organic residues and requires high-temperature calcination for purification.

Q3: How to inhibit nanoparticle agglomeration?

A3 :

Surface modification: adding dispersants (such as PVP, PEG).

Drying process: freeze drying or supercritical CO_2 drying .

Post-processing: ball milling or ultrasonic dispersion.

2. Detection and Characterization

Q4: No obvious diffraction peaks were found in the XRD test. What could be the possible reason?

A4 :

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The sample was amorphous (such as an uncalcined sol-gel product).
The particle size is too small (<5 nm), resulting in broadening of the diffraction peaks.
Incorrect instrument parameters (e.g. scan speed too fast or slit too wide).

Q5: The BET specific surface area test result is abnormally low, how to solve it?
A5 :
Ensure that the sample is fully degassed (temperature ≥ 200 °C, time > 6 h).
Avoid clogging of nanopores (completely remove the template or residual solvent during pretreatment).
Check instrument calibration (e.g. verify using silica gel standard).

Q6: Why is there a big difference between the particle size observed by SEM and the DLS result?
A6 :
SEM only observes particles in a dry state, while DLS measures the hydrated particle size in solution (which is usually larger).
The agglomeration effect causes the DLS results to be falsely high, and retesting is required after ultrasonic dispersion.

3. Application Technology

Q7: How to improve the cycle stability of nano tungsten oxide in lithium-ion batteries?
A7 :
Structural design: Prepare core-shell structures (such as WO_3 @C) to inhibit volume expansion.
Electrolyte optimization: Add film-forming additives (such as FEC) to reduce side reactions.
Doping modification: introducing Ti^{4+} or Nb^{5+} to stabilize the crystal lattice.

Q8: The electrochromic device has a slow response speed, how can it be improved?
A8 :
Material selection: Use purple tungsten (VTO) nanowires to shorten the ion diffusion path.
Electrolyte optimization: Use high ion conductive gel electrolyte (such as PEO-$LiClO_4$).
Interface engineering: ALD deposition of ultra-thin conductive layers (such as ITO) to reduce interface impedance.

Q9: What is the possible reason for the low efficiency of photocatalytic degradation?
A9 :
Bandgap mismatch: Choose a doping material with a narrower bandgap (such as N-WO_3, Eg≈2.4 eV).
Carrier recombination: constructing heterojunctions (such as WO_3/TiO_2) to promote charge separation.

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Insufficient active sites: increase in mesoporous structure (pore diameter 5-10 nm) or surface defects.

4. Safety and Storage

Q10: Is nano tungsten oxide biologically toxic?

A10 : Current research shows that its toxicity is lower than that of nano ZnO or TiO_2 , but inhalation or direct contact should still be avoided. It is recommended to wear an N95 mask and nitrile gloves when operating.

Q11: How to prevent oxidation or deliquescence during long-term storage?

A11 :

Sealed packaging: vacuum nitrogen filling or use desiccant (such as silica gel).

Environmental control: Storage temperature <25°C, humidity <40% RH.

Protect from light: Store in a brown glass bottle away from light.

5. Cost and Industrialization

Q12: What is the main cost bottleneck for large-scale production?

A12 :

Raw material cost: High purity APT (ammonium paratungstate) is more expensive.

Energy consumption: The energy consumption of the hydrothermal/calcination process accounts for 30%-50% of the production cost.

Dispersion technology: Special equipment (such as high-pressure homogenizer) is required to prevent agglomeration.

Q13: How to reduce the R&D cycle?

A13 :

High-throughput screening: Combined with machine learning to predict optimal synthesis parameters (such as temperature, pH).

Standardized process: Use modular reaction devices (such as microfluidic chips) to accelerate the transition from small-scale trials to pilot-scale trials.

VI. Frontier Issues

Q14: Can nano-tungsten oxide be used for quantum computing?

A14 : Currently in the exploratory stage, its oxygen vacancies may be used as quantum bit carriers, but the problem of short decoherence time (<1 ns) needs to be solved.

Q15: What are the application challenges in flexible electronics?

A15 :

Mechanical stability: Insufficient interfacial bonding between nanoparticles and flexible substrates

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such as PDMS.

Conductivity loss: The conductive network is easily broken during bending, and self-healing composite materials need to be developed.

7. In-depth optimization of preparation process

Q16: How to precisely control the morphology of nano-tungsten oxide by chemical vapor deposition (CVD)?

A16 :

Control parameters :

Temperature gradient: The substrate temperature (400-600°C) determines the nucleation density (the higher the temperature, the denser the particles).

Gas ratio: The WF_6 / O_2 ratio controls the degree of oxidation (a low ratio tends to generate $WO_{2.9}$, while a high ratio generates WO_3) .

Substrate selection : Single crystal silicon or sapphire substrates can induce directional growth (such as nanowire arrays).

Q17: When synthesizing porous structures using the template method, how can we avoid template residue contamination?

A17 :

Hard template (such as SiO_2) : Etch it away with 5% HF solution. The etching time must be controlled (≤30 min) to prevent excessive corrosion.

Soft template (such as CTAB) : Multiple ethanol centrifugal washes (≥5 times) combined with high-temperature calcination (500°C, 2 h) to decompose organic matter.

8. Advanced analysis techniques

Q18: How to quantitatively analyze oxygen vacancy concentration by XPS?

A18 :

Peak fitting : The O 1s peak is decomposed into lattice oxygen (530.1 eV), oxygen vacancy (531.5 eV) and adsorbed oxygen (532.8 eV).

Calculation ratio : oxygen vacancy ratio = (oxygen vacancy peak area) / (total oxygen peak area) × 100%, the error must be controlled within ±3%.

Q19: How to solve the problem of blurring of lattice fringes when observing with TEM?

A19 :

Sample preparation : Ultrasonic dispersion time ≤ 10 min to avoid particle breakage.

Imaging parameters : low dose mode (≤50 e^- / $Å^2$) and accelerating voltage of 200 kV were selected.

Post-processing : Use FFT filtering to remove noise and enhance lattice contrast.

9. Emerging Application Scenarios

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Q20: What is the performance bottleneck of nano-tungsten oxide in supercapacitors?

A20 :

Low conductivity : Carbon coating (such as graphene composite) can increase the conductivity to 10^2 S /m.

Cycle attenuation : Designing a three-dimensional porous structure (pore size 2-5 nm) to relieve ion embedding stress, the capacity is retained >90% after 10 cycles.

Q21: Can it be used for transparent conductive films (TCO)?

A21 :

Doping optimization : WO_3 film doped with 5% Mo , visible light transmittance>80%, sheet resistance<50 Ω/sq (thickness 100 nm).

Flexible adaptation : WO_3 /Ag/WO_3 multilayer structure sputtered on PET substrate , resistance change <5% after bending 500 times.

Q22: What is the potential in photothermal therapy?

A22 :

Near-infrared absorption : The photothermal conversion efficiency of blue tungsten (BTO) under 808 nm laser is 45%, which is higher than that of gold nanorods (≈30%).

Biocompatibility : After surface modification with PEG, the cell survival rate was >95% (concentration ≤100 μg/mL).

10. Environment and Regulations

Q23: How to deal with nano-tungsten oxide waste?

A23 :

Acid dissolution recovery : After dissolution with concentrated HNO_3 (65%), tungsten is extracted by ion exchange (recovery rate>90%).

Solid waste landfill : requires solidification treatment (addition of cement-based materials) and complies with the "Hazardous Waste Landfill Pollution Control Standards".

Q24: What are the restrictions on nano-tungsten oxide under EU REACH regulations?

A24 :

Registration : Annual production ≥ 1 ton is required to submit nanomaterial safety data (including toxicology assessment).

Labeling : The packaging must be marked with "Nano" (particle size <100 nm) and provide MSDS documents.

11. Special process challenges

Q25: How to achieve monodisperse and continuous production of nano-tungsten oxide?

A25 :

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Microfluidic technology : Using a T-channel reactor (flow rate ratio 1:3), real-time control of pH and temperature, and output particle size deviation <±5%.

Automated control : integrated online DLS monitoring and feedback adjustment of reaction parameters (such as ultrasound power).

Q26: How to avoid the sintering of particles caused by high temperature calcination?

A26 :

Heating in stages : pre-burn at 300°C for 2 h (to remove organic matter), then raise to target temperature (e.g. 600°C).

Atmosphere protection : Calcination in Ar/H_2 (95/5) mixed gas to inhibit excessive accumulation of surface oxygen vacancies.

12. Interdisciplinary Integration

Q27: How does AI assist in the reverse design of nano-tungsten oxide?

A27 :

Data-driven modeling : A neural network is trained based on a literature database to predict the effect of doping elements on the band gap (error < 0.1 eV).

High-throughput experiments : Combined with a robotic platform, more than 100 synthesis conditions (such as pH and temperature combinations) can be screened every week.

Q28: What is its role in perovskite solar cells?

A28 :

Hole transport layer : WO_3 NPs replaced Spiro-OMeTAD, and the device efficiency increased from 18% to 21% (stability >1000 h).

Interface passivation : suppress perovskite layer defects and reduce non-radiative recombination.

13. Application in extreme conditions

Q29: How stable is nano tungsten oxide in high temperature (>800°C) environment?

A29 :

Phase transition risk : The monoclinic phase (m-WO_3) transforms to the tetragonal phase (t-WO_3) above 800°C , resulting in performance degradation.

Solution : Al_2O_3 coating (thickness 2-5 nm) can delay the phase transition to 1000°C.

Q30: Can it be used for radiation shielding of deep space probes?

A30 :

High-Z material properties : Tungsten's atomic number (Z=74) can effectively absorb X/gamma rays (the attenuation coefficient is 20% higher than that of lead).

Lightweight design : Nanoporous structure (porosity > 50%) reduces weight by 40% at the same shielding efficiency.

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14. Market and Commercialization

Q31: What is the current market price range of nano tungsten oxide?
A31 :
Laboratory grade : purity 99.9%, particle size 50 nm, about $200-500/g (order by gram).
Industrial grade : purity 99%, particle size 100-200 nm, about $50-100/kg (ton-level purchase).

Q32: Which companies have industrialized nano-tungsten oxide?
A32 :
International : Inframat of the United States, Showa Denko of Japan.
Domestic : CTIA GROUP, China Tungsten High-tech.

15. Future Technology Outlook

Q33: What are the potential applications of nano-tungsten oxide in 6G communications?
A33 :
Terahertz modulator : Utilizes its nonlinear optical response to achieve high-speed modulation of 6G frequency band (0.1-1 THz) signals.
Thermal management materials : High thermal conductivity (≈30 W/m·K) is used to dissipate heat from base station chips and improve equipment reliability.

Q34: What are the latest breakthroughs in brain-like devices?
A34 :
Pulsing Neural Networks : WO_3 memristor arrays achieve >95% accuracy in handwritten digit recognition (power consumption is 3 orders of magnitude lower than CMOS).
Multi-state storage : Through oxygen vacancy gradient regulation, a single device can achieve 32 resistance states (5-bit storage).

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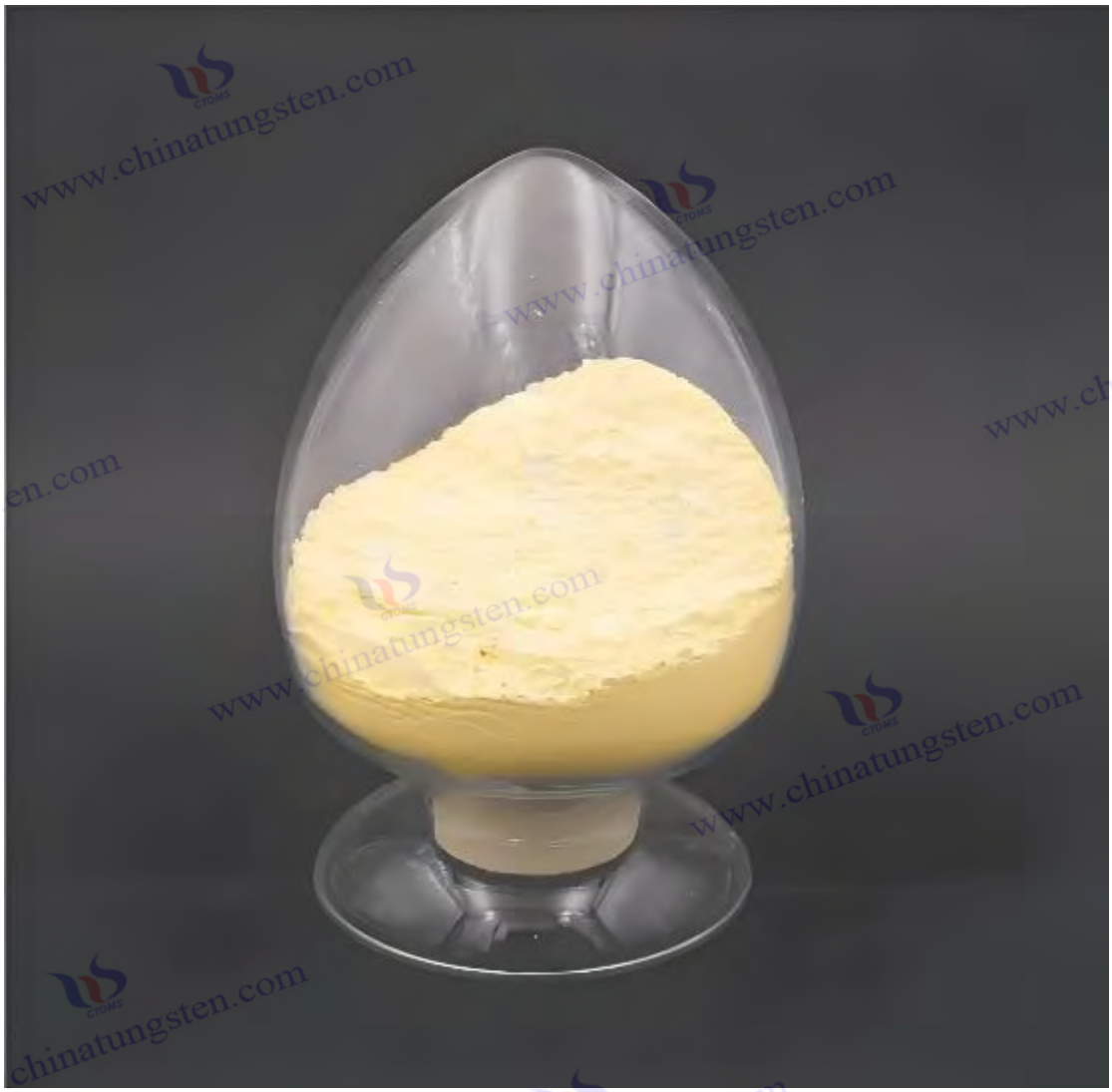

CTIA GROUP LTD
High Purity Nano Tungsten Oxide

Nano Tungsten Oxide produced by CTIA GROUP LTD has a purity of ≥99.9% and a particle size of 10-100 nm. It has excellent photocatalytic, electrochromic and thermal shielding properties and is a yellow (WO_3) , blue ($WO_{2.9}$) or purple ($WO_{2.72}$) powder.

High Purity Nano Tungsten Oxide

Project	Details
Product Specifications	Purity: ≥99.9% (optional 99.95% , 99.99%, 99.999%); Particle size: 10-100 nm (customizable); Specific surface area: 20-50 m^2 / g
Performance characteristics	High purity (impurities <10 ppm); band gap 2.4-2.8 eV (WO_3), infrared blocking >90% ($WO_{2.9}$); photocatalytic hydrogen production rate 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$; transmittance change >80%, response <5 s
Application	Photocatalysis; electrochromism (smart windows); thermal shielding (energy-saving glass); gas sensors (NO_2 , NH_3) ;

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Project	Details		
Areas	energy storage (batteries)		
Storage safety	Store in a cool and dry place, sealed and away from sunlight; avoid inhaling dust, wear a mask and gloves when operating, and dispose of waste in accordance with regulations		
Package	5 g, 25 g (laboratory), 1 kg, 25 kg (industrial)		
Order Quantity	Minimum order: 5g (laboratory)/1 kg (industrial); 3-5 days for delivery if in stock, 2-3 weeks for customization; worldwide delivery (DHL/FedEx) . For large orders, delivery period must be completed after the contract is signed, including application for dual-use item licenses.		
Advantages	30 years of professional experience, ISO 9001 RMI certification. Support flexible customization and fast response.		
Impurities	Limit value / ppm	illustrate	
Iron	≤10	Affects conductivity and optical properties, requires pickling or magnetic separation control	Purity benchmark: Applicable to purity ≥99.9%, ultra-high purity (99.99%) has lower limits (such as Fe, Na ≤1 ppm). Detection method: ICP-MS (<1 ppb), XRF. Source: GB/T 41336-2022, American Elements, Stanford Advanced Materials. Application impact: Fe and Mo affect photocatalysis; Na and Cl affect electrochromism; Cu and Pb affect semiconductors. Control: Precursor purification, high purity equipment, optimized reduction process.
Sodium	≤5	Source: Sodium tungstate, affects the lattice and electrochromic properties, removed by ion exchange	
Molybdenum	≤10	Tungsten ore is associated with tungsten, which affects the catalytic activity and needs to be refined and purified	
Silicon	≤5	Source quartz equipment, affects particle uniformity, requires high-purity equipment	
Aluminum	≤5	Source container, affects thermal stability, needs to avoid contamination	
Calcium	≤5	Affects the stability of the crystal phase and requires precursor purification	
Magnesium	≤5	Reduce catalytic efficiency and need to be purified and removed	
Copper	≤2	Affects the performance of electronic devices and requires ultra-high purity process control	
Lead	≤2	Heavy metals affect safety and need to be strictly controlled	
Carbon C	≤50	The source is organic matter or reduction, which affects the optical properties and needs to be removed by heat treatment	
Sulfur	≤20	Originated from sulfuric acid, affects chemical stability and needs to be cleaned and removed	
Chlorine	≤10	Source of chloride, affects purity, requires rinsing control	

Procurement Information

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