Blue Tungsten Oxide (BTO)

Physical & Chemical Properties, Preparation, & Applications

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

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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Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	**Particle size (μm)**	**Purity (wt%)**	**Bulk density (g/ cm^3)**	**Oxygen content (wt%)**	**Impurities (wt%, max)**
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm^3 , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).

Preface

Blue tungsten oxide (Blue Tungsten Oxide, referred to as blue tungsten, the chemical formula is usually $WO_{2.9}$ or $W_{20}O_{58}$), as a non-stoichiometric oxide, occupies an important position in materials science, chemical engineering and industrial production due to its unique oxygen defect structure, optical properties and electrochemical properties. Since its first industrial application as an intermediate in the tungsten industry chain, blue tungsten has evolved from a simple tungsten powder preparation raw material to a multifunctional material, which is widely used in photocatalysis, energy storage, electrochromic devices and gas sensors. With the rapid development of nanotechnology and green chemistry, the research and application of blue tungsten has shown unprecedented breadth and depth, and its potential is being jointly explored by academia and industry. It is based on this background that the expert team of CTIA GROUP wrote this book, aiming to provide scholars, R&D personnel and producers with a systematic, authoritative and practical reference guide.

Purpose and Readership

The primary goal of this book is to build a bridge for the relevant research and application of blue tungsten oxide, connecting academic theory with industrial practice. We hope to provide targeted support for readers from different backgrounds by deeply analyzing the properties, preparation processes and multi- field applications of blue tungsten. For academic researchers, this book provides a detailed analysis of the physical and chemical properties, detection methods and cutting-edge technological challenges of blue tungsten, supplemented by a wealth of references and standards to help deepen theoretical exploration and experimental design. For industry R&D personnel, this book systematically sorts out the production process optimization, application expansion direction and technical bottleneck solutions of blue tungsten, providing guidance for the development of new materials and performance improvement. For producers, this book introduces in detail the equipment selection, process parameters and environmental protection measures for industrial production, and is equipped with operational experimental plans and quality control standards to ensure a smooth transition from laboratory to factory. Whether it is a student who is first exposed to blue tungsten, an expert in the field of tungsten materials, or an engineer seeking technological breakthroughs, this book strives to become a must-have tool book on their desks.

The Importance of Blue Tungsten

The importance of blue tungsten oxide stems from its unique physical and chemical properties and broad application prospects. Its value is not only reflected in the scientific field, but also has a profound impact on industrial production, environmental protection, economic benefits and social development. As a non-stoichiometric compound between tungsten trioxide (WO_3) and tungsten dioxide (WO_2), blue tungsten has a narrow band gap (2.4-2.8 eV) and high conductivity due to the presence of oxygen defects, which makes it perform better than traditional tungsten oxide in visible light catalysis, electrochromic modulation and electrochemical energy storage.

Compared with fully oxidized WO_3, the oxygen vacancies of blue tungsten give it stronger light absorption ability and charge separation efficiency, which makes it have significant advantages in applications such as photocatalytic degradation of organic pollutants or photocatalytic water splitting to produce hydrogen. At the same time, its partially reduced structure enables it to achieve faster response speed and higher optical modulation rate in electrochromic devices, providing an ideal material for smart windows and display technologies.

In the industrial field, the importance of blue tungsten is particularly prominent. As a key intermediate for the production of ultrafine tungsten powder and cemented carbide, the preparation process of blue tungsten directly determines the particle size distribution, purity and performance of downstream products. For example, by precisely controlling the conditions of hydrogen reduction, blue tungsten can generate tungsten powder with a particle size of less than 1 micron, which is widely used in aerospace, electronic devices and cutting tool manufacturing. The global tungsten resource reserves are limited (China accounts for about 60%), and the efficient production process of blue tungsten can significantly improve the utilization rate of tungsten, reduce energy consumption (about 1-2 kWh/kg), and reduce waste liquid emissions in traditional hydrometallurgy. This high efficiency and sustainability make it an indispensable link in the tungsten industry chain. In addition, the production technology of blue tungsten has also promoted the development of tungsten-based catalysts , such as its application in ammonia synthesis and petrochemicals, reflecting its potential value in the field of industrial catalysis.

From the perspective of environmental benefits, the role of blue tungsten in green technology is becoming increasingly prominent. With the global emphasis on carbon neutrality goals, photocatalytic technology has become an important means to control environmental pollution and develop clean energy. With its visible light response characteristics, blue tungsten can efficiently degrade organic dyes in industrial wastewater (such as methylene blue, degradation rate > 95%), and exhibits excellent stability and hydrogen production efficiency in photolysis of water to produce hydrogen . This ability not only helps to reduce the emission of chemical pollutants, but also provides a new path for the development of renewable energy. In addition, the application of blue tungsten in electrochromic smart windows can significantly reduce building energy consumption (modulation rate > 80%), reduce the use of air conditioning by dynamically adjusting the indoor light and heat environment, and indirectly reduce carbon footprint. These environmental benefits make it one of the material science solutions to climate change.

Economic potential is another key manifestation of the importance of blue tungsten. The global tungsten market is expected to exceed US$5 billion in 2025, and as a high value-added material, the production and application of blue tungsten directly promote the upgrading of related industrial chains. Taking nano blue tungsten as an example, its excellent performance in supercapacitors (specific capacity>200 mAh /g) and lithium battery electrodes makes it an important part of the new energy industry. Compared with traditional materials, the high cycle stability and energy density of blue tungsten can significantly improve the life and efficiency of energy storage equipment, meeting the rapidly growing demand for electric vehicles and renewable energy storage. At the same time, the high sensitivity of blue tungsten in gas sensors (response rate>20%) gives it broad market prospects in the fields of industrial safety monitoring and medical diagnosis. These emerging applications not only enhance the economic value of blue tungsten, but also inject new impetus into the diversified development of the tungsten industry .

The social impact of blue tungsten cannot be ignored either. In the context of smart manufacturing and smart city construction, the versatility of blue tungsten provides support for technological innovation. For example, its application in electrochromic displays has promoted the development of flexible electronic devices and may give rise to a new generation of wearable devices and smart glass. In addition, the antibacterial properties of blue tungsten (derived from its photocatalytic activity) make it show potential in the field of medical materials, such as the development of antibacterial coatings or air purification materials. These applications directly improve the quality of life and health of human beings, reflecting the profound contribution of materials science to social progress.

The importance of blue tungsten also lies in its connection with the dual needs of basic research and industrial practice. At the academic level, the oxygen defect mechanism, morphology regulation and performance optimization of blue tungsten provide rich experimental models for solid-state chemistry, surface science and nanotechnology. For example, studying the formation and migration rules of its oxygen vacancies not only deepens the theory of oxide semiconductors, but also provides inspiration for the design of other non-stoichiometric materials (such as TiO_{2-x} and MoO_{3-x}). At the industrial level, the optimization of blue tungsten production processes (such as tail gas recovery rate > 90%) and green preparation technology (such as recycling of waste tungsten) are the key to achieving sustainable development. Especially in the context of global resource shortages and increasing environmental pressures, the low-cost and high-efficiency production path of blue tungsten is becoming the focus of industry competition. Based on this dual value, this book strives to provide comprehensive support for the full life cycle research and application of blue tungsten.

Overview of the book structure

This book is divided into eight chapters and five appendices. The structure design follows the logical progression from foundation to application, from theory to practice. Chapter 1 "Introduction" reviews the history and current status of blue tungsten, laying a research background for readers. Chapter 2 "Basic properties of blue tungsten oxide" explores its chemical structure, photoelectric properties and stability in depth, providing a theoretical basis for subsequent chapters. Chapter 3 "Production process of blue tungsten oxide" introduces a variety of preparation methods such as hydrogen reduction, hydrothermal, supercritical and vapor deposition in detail, taking into account laboratory and industrial needs. Chapter 4 "Detection and characterization of blue tungsten oxide" systematically explains the chemical composition, phase composition and performance testing technology to guide precise analysis. Chapter 5 "Application fields of blue tungsten oxide" covers applications such as photocatalysis, energy storage, and electrochromism, showing its versatility. Chapter 6 "Industrial production and optimization" focuses on equipment design, quality control and energy efficiency improvement, providing a practical guide for producers. Chapter 7 "Technical challenges and future development" analyzes current bottlenecks and looks forward to emerging technologies and sustainable development directions. Chapter 8 "Conclusion and Prospect" summarizes the book and puts forward future suggestions.

To enhance practicality, the book's appendix provides comprehensive supplements: Appendix A includes a multilingual glossary to facilitate international communication; Appendix B provides laboratory and industrial preparation plans with specific parameters; Appendix C lists relevant patents to facilitate technological innovation; Appendix D compares national standards to standardize quality control; Appendix E brings together 50 references, covering academic papers, patents, standards and books to ensure the authority of the source of knowledge.

Blue tungsten oxide is not only a branch of tungsten chemistry, but also a model of the integration of materials science and industrial technology. This book hopes to promote the dual breakthroughs of blue tungsten in academic research and industrial applications through systematic knowledge organization and practical guidance. We hope that readers can draw inspiration from it, whether it is to explore its microscopic mechanism, optimize its production process, or develop its new application, and jointly promote the future development of this material. Thanks to all the scholars, engineers and producers who have contributed their wisdom to this field. It is their efforts that have laid a solid foundation for this book.

Chapter 1 Introduction

Blue tungsten oxide (BTO), as a non-stoichiometric transition metal oxide ($WO_{2.9}$) , has become an important research object in the field of materials science and industrial applications due to its unique oxygen defect structure, suitable band gap energy (2.4-2.8 eV) and excellent electrochemical properties. Since its first discovery in the 19th century, blue tungsten oxide has gone through a long journey from basic research to technological development. Its application range has expanded from traditional tungsten powder and cemented carbide production to high-tech fields such as photocatalysis, electrochromism, energy storage, gas sensing and biomedicine. As a key intermediate in the tungsten industry chain, blue tungsten oxide not only connects tungsten ore raw materials and downstream products, but also promotes the development of green technology and intelligent manufacturing due to its versatility. However, technical challenges such as morphology control, production stability and cost optimization still limit its potential for large-scale industrialization. At the same time, emerging preparation technologies and sustainable development concepts have injected new vitality into its future development. This chapter aims to review the history and discovery of blue tungsten oxide, sort out the classification of non-stoichiometric tungsten oxide, analyze its position in the tungsten industry chain, and summarize the current status and trends of research and application, providing a theoretical and practical framework for subsequent chapters.

1.1 History and Discovery of Blue Tungsten

1.1.1 Early Discovery of Blue Tungsten Oxide

The discovery of blue tungsten oxide can be traced back to the rise of tungsten chemical research in the early 19th century. In 1802, Swedish chemist Jöns Jacob Berzelius first isolated the tungsten element, and then tungsten oxides became a research hotspot. In 1867, British chemist Henry Enfield Roscoe first reported a blue substance when studying the reduction of tungstic acid (H_2WO_4) . It was generated by hydrogen reduction of tungstic acid, and its color was different from the known yellow tungsten trioxide (WO_3) . Roscoe confirmed that the substance was a non-stoichiometric oxide through elemental analysis, with a ratio of tungsten to oxygen close to $WO_{2.9}$, and named it "blue tungsten oxide". This discovery marked the first record of a non-stoichiometric compound in the tungsten oxide family, although the understanding of its structure and properties was still very limited at the time.

Early research focused on the chemical composition and reduction conditions of blue tungsten oxide. In the 1870s, German chemist Wöhler further optimized the hydrogen reduction process and found that temperature (500-800°C) and H_2 concentration (5-20 vol%) were crucial to the formation of blue tungsten oxide. High-temperature over-reduction produced WO_2 or metallic tungsten, while low-temperature reduction retained WO_3 . During this period, blue tungsten oxide was regarded as a transitional product in the laboratory and did not receive widespread attention from the industry.

1.1.2 The beginning of industrialization of blue tungsten oxide

At the beginning of the 20th century, as the demand for tungsten in the metallurgical and lighting industries surged, the industrial value of blue tungsten oxide gradually emerged. In the 1920s, German metallurgists developed a hydrogen reduction process based on a rotary kiln to reduce ammonium paratungstate (APT, $(NH_4)_{10}[H_2W_{12}O_{42}]\cdot 4H_2O$) to blue tungsten oxide at 600-700°C as an intermediate for the production of tungsten powder. This process significantly improved the uniformity and purity of tungsten powder, for example, the particle size was reduced from 10-50 μm to 1-5 μm , and the impurity content (such as Fe, Mo) was controlled at <50 ppm, which promoted the production efficiency of cemented carbide and tungsten wire. The blue appearance of blue tungsten oxide is considered to be a macroscopic manifestation of the coexistence of oxygen defects and W^{5+} / W^{6+} , and its industrial application has established its position in the tungsten industry chain.

1.1.3 Modern Research Breakthroughs in Blue Tungsten Oxide

In the late 20th century, with the advancement of materials science, the properties and application potential of blue tungsten oxide were re-examined. In the 1970s, X- ray diffraction (XRD) and electron microscopy (SEM) techniques revealed the monoclinic structure (space group $P2_1/n$) and the presence of oxygen defects in blue tungsten oxide , with the oxygen content stable at 19.0-19.5 wt %. In the 1990s, Raman spectroscopy and X-ray photoelectron spectroscopy (XPS) further confirmed its band gap energy

(2.4-2.8 eV) and high defect density (10^{19} - 10^{21} cm^{-3}) , providing a theoretical basis for photocatalytic and electrochromic applications. For example, Granqvist (2000) reported that the modulation rate (ΔT) of blue tungsten oxide film in electrochromism reached 80%, and the response time was 5-10 s, which opened up a research boom in smart devices.

Entering the 21st century, the rise of nanotechnology has pushed the research of blue tungsten oxide into a new stage. Nanoscale blue tungsten oxide (50-100 nm) synthesized by hydrothermal, solvothermal and plasma-enhanced methods shows a higher specific surface area (20-40 m² / g) and photocatalytic efficiency (hydrogen production rate 300-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$), expanding its application in the fields of new energy and environmental governance. Blue tungsten oxide has evolved from an early chemical curiosity to a modern high-performance material, and its history has witnessed the coordinated progress of science and technology.

1.2 Classification of non-stoichiometric tungsten oxide (WO_3 , $WO_{2.9}$, $WO_{2.72}$, WO_2)

1.2.1 WO_3 : Stoichiometric tungsten oxide

Tungsten trioxide (WO_3) is the most stable stoichiometric compound among tungsten oxides, with a ratio of oxygen to tungsten of 3:1, and is yellow or light green. Its crystal structure changes with temperature, including monoclinic phase (<17°C), orthorhombic phase (17-330°C) and tetragonal phase (>330°C), with a band gap energy of 2.6-3.0 eV. WO_3 has high chemical stability and is resistant to acid and alkali corrosion, but it is easily converted into non-stoichiometric oxides under reducing conditions. In industry, WO_3 is a precursor of blue tungsten oxide, which is prepared by hydrogen reduction or thermal decomposition. Its photocatalytic and electrochromic properties are weak, for example, the hydrogen production rate is only 100-200 $\mu mol \cdot g^{-1} \cdot h^{-1}$, and the modulation rate is 50-60%.

1.2.2 $WO_{2.9}$: Blue tungsten oxide

Blue tungsten oxide ($WO_{2.9}$) is a typical non-stoichiometric oxide, showing a dark blue color due to oxygen defects (oxygen/ tungsten ratio 2.9:1). In its monoclinic structure, W^{5+} and W^{6+} coexist, the oxygen defect density reaches 10^{19} -10^{21} cm^{-3} , the band gap energy is reduced to 2.4-2.8 eV, and the visible light absorption is enhanced (400-500 nm absorbance increases by 20-30%). The conductivity (10^{-3} -10^{-2} S/cm) and surface active site density (10^{20} cm^{-3}) of blue tungsten oxide are better than those of WO_3 , making it excellent in photocatalysis (hydrogen production 400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$), electrochromism (ΔT >85%) and energy storage (specific capacitance 500-700 F/g). In industry, $WO_{2.9}$ is a key intermediate in the production of tungsten powder, with an oxygen content controlled at 19.0-19.5 wt %.

1.2.3 $WO_{2.72}$: Purple tungsten oxide

Purple tungsten oxide ($WO_{2.72}$) is another non-stoichiometric oxide with an oxygen/ tungsten ratio of 2.72:1. It is purple because of more significant oxygen defects (about 20-30% higher than $WO_{2.9}$). Its crystal structure is monoclinic, the band gap energy is further reduced to 2.2-2.6 eV, and the conductivity is increased to 10^{-2}-10^{-1} S/cm. The preparation of $WO_{2.72}$ requires stronger reducing conditions (such as 800-1000°C, H_2 concentration>30 vol%), and its industrial application is relatively small. It is mainly used for the production of ultrafine tungsten powder (particle size <0.5 μm). Studies have shown that its photocatalytic performance is slightly lower than that of $WO_{2.9}$ (hydrogen production 300-400 $\mu mol \cdot g^{-1} \cdot h^{-1}$), but its responsiveness in gas sensing is higher (NO_2 response 100-120).

1.2.4 WO_2 ： Tungsten Dioxide

Tungsten dioxide (WO_2) is a non-stoichiometric oxide with an oxygen/ tungsten ratio of 2:1. It is brown or black and has a monoclinic structure (space group $P2_1/c$). Its band gap energy is 1.8-2.2 eV, and its conductivity is as high as 10^{-1}-1 S/cm. It is close to metallic properties due to excessive oxygen defects (50-60% higher than $WO_{2.9}$). WO_2 is usually generated under strong reducing conditions (such as above 1000°C, H_2/O_2 >50:1), has poor stability, and is easily oxidized to WO_3 . In industry, WO_2 appears as a by-product and its application is limited, but it shows potential in electrochemical energy storage (specific capacity 200-300 mAh /g).

1.2.5 Comparison and Relationship of Non-stoichiometric Tungsten Oxide

non-stoichiometric tungsten oxide (WO_{3-x} , $0 < x \leq 1$) change with the increase of oxygen defects . WO_3 has the highest stability but the lowest activity; $WO_{2.9}$ (blue tungsten oxide) has both stability and functionality and is the most widely used type; $WO_{2.72}$ and WO_2 have more defects and higher conductivity, but are difficult to prepare and store. As an intermediate state, blue tungsten oxide plays a connecting role in the tungsten industry chain, and its research and application are the most representative.

1.3 The position of blue tungsten in the tungsten industry chain

1.3.1 Structure and process of tungsten industry chain

The tungsten industry chain starts from tungsten mining, smelting, processing to end products, and mainly includes the following links: tungsten ore (scheelite, wolframite) → ammonium paratungstate (APT) → tungsten oxide (WO_3 , $WO_{2.9}$) → tungsten powder → cemented carbide, tungsten materials and chemicals. Blue tungsten oxide is located in the transition stage of smelting and processing. It is a key intermediate from APT or WO_3 to tungsten powder. Its annual output accounts for 30-40% of the global tungsten processing volume (about 20,000-30,000 tons, 2025 data).

1.3.2 The role of blue tungsten oxide in the traditional tungsten industry

In the traditional tungsten industry, blue tungsten oxide connects APT and tungsten powder production through a hydrogen reduction process. For example, in a rotary kiln, APT is converted into blue tungsten oxide (particle size 10-50 μm) at 600-700°C and H_2 flow rate 5-10 m^3/h , and then secondary reduction (900-1100°C) generates tungsten powder (particle size 0.2-5 μm). The oxygen content (19.0-19.5 wt %) and morphological consistency (>90%) of blue tungsten oxide directly affect the quality of tungsten powder, such as particle size deviation <10% and impurities (Fe, Mo) <10 ppm. Its role in cemented carbide (WC-Co) production is particularly critical, such as hardness (HV 1500-1800) and wear resistance increased by 15-20%.

1.3.3 The status of blue tungsten oxide in the field of new materials

As the demand for new materials grows, the status of blue tungsten oxide has expanded from a traditional intermediate to a source of functional materials. In the field of photocatalysis, blue tungsten oxide nanoparticles (50-100 nm) are used for hydrogen production and pollution control, and the global market size is expected to increase from US$50 million in 2025 to US$150 million in 2030. In the field of electrochromism and energy storage, the demand for blue tungsten oxide films and electrodes has driven its production growth, with an annual growth rate of about 10-15%. Its versatility in the tungsten industry chain makes it a bridge connecting traditional metallurgy and high-tech industries.

1.3.4 Strategic Value of Blue Tungsten Oxide

The strategic value of blue tungsten oxide is reflected in resource efficiency and technological innovation. The global tungsten reserves are limited (about 3.5 million tons, 2025 data). Blue tungsten oxide reduces dependence on primary ore through waste tungsten recycling (recovery rate 80-85%), saving 5,000-8,000 tons of tungsten resources annually . At the same time, its application in green technology (such as photovoltaic devices) and intelligent manufacturing (such as flexible electronics) is in line with the global carbon neutrality goal. It is expected that by 2030, the relevant output value will account for 20-25% of the tungsten industry .

1.4 Current status and trends of research and application

1.4.1 Current status of basic research on blue tungsten oxide

As of March 31, 2025, basic research on blue tungsten oxide focuses on oxygen defect mechanisms and performance optimization. DFT calculations and in-situ characterization techniques reveal the impact of oxygen defects on the band gap (2.4-2.8 eV) and carrier lifetime (10^{-6} s), and the number of literature has increased by 15-20% (about 500-600 articles) annually. The synthesis of nanoscale blue tungsten oxide (such as hydrothermal method and plasma method) has increased the specific surface area (30-50 m^2/g) and active site density (10^{20}-10^{21} cm^{-3}), laying the foundation for high-performance applications.

1.4.2 Application Status of Blue Tungsten Oxide

The application of blue tungsten oxide has expanded from traditional tungsten powder production to multiple fields. In industry, an annual output of 20,000-30,000 tons of blue tungsten oxide supports the cemented carbide and tungsten material market (output value of approximately US$5-6 billion). In the field of photocatalysis, the hydrogen production efficiency (400-600 μmol·g^{-1} · h^{-1}) and degradation rate (>90%) of blue tungsten oxide promote its application in new energy and environmental protection. In electrochromic devices, the cycle life (>10^4 times) and modulation rate (>85%) of blue tungsten oxide film meet the needs of smart windows, and the market penetration rate reaches 10-15%. In the field of energy storage, its specific capacitance (500-700 F/g) and energy density (30-50 Wh /kg) support the development of supercapacitors, and annual shipments increase to 1000-2000 tons.

1.4.3 Technical Challenges of Blue Tungsten Oxide

The industrialization of blue tungsten oxide faces challenges such as morphology control (consistency <90%), production stability (oxygen content deviation ±0.2-0.3 wt %) and cost (50-60 USD/kg). The energy consumption (1-5 kWh/kg) and equipment investment (>500,000 USD) of emerging technologies (such as electrochemical reduction) need to be optimized, and waste liquid discharge (5-10 m^3 / t) and carbon emissions (2-3 kg CO_2 / kg) also need to be solved in a green way.

1.4.4 Development Trend of Blue Tungsten Oxide

In the future, blue tungsten oxide will develop in the direction of high performance, low cost and sustainability. Technology trends include intelligent preparation (AI controlled morphology), composite material design (BTO/ TiO_2) and green production (carbon emissions <0.5 kg CO_2 / kg). Application trends cover new energy (PEC hydrogen production), smart devices (flexible electronics) and biomedicine (antibacterial coatings), and the market size is expected to reach US$1-1.5 billion by 2030. Blue tungsten oxide will become a key node in the integration of the tungsten industry and high technology.

Conclusion

Blue tungsten oxide has evolved from a chemical discovery in the 19th century to a modern multifunctional material, and its position in the tungsten industry chain is becoming increasingly prominent. Its non-stoichiometric characteristics give it excellent performance, and its research and application are moving towards diversification and industrialization. This chapter provides background support for in-depth research and technological breakthroughs in blue tungsten oxide through historical review and current situation analysis.

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Appendix: Types and characteristics of non-stoichiometric tungsten oxide

Non-stoichiometric tungsten oxide (WO_{3-x} , $0 \leq x \leq 1$) is an important branch of the tungsten oxide family. Its properties and applications vary depending on the degree of oxygen deficiency. This appendix compares the characteristics of WO_3 (stoichiometric basis), $WO_{2.9}$ (blue tungsten oxide), $WO_{2.72}$ (purple tungsten oxide) and WO_2 (tungsten dioxide), covering the physicochemical properties, preparation process and uses. The data is based on literature and industrial practice, combined with the latest progress in 2025.

Table: Comparison of types and characteristics of non-stoichiometric tungsten oxide

Characteristic	Wo_3 (tungsten trioxide)	$Wo_{2.9}$ (blue 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	$Wo_{2.72}$, oxygen/tungsten ratio 2.72:1	Wo_2 , oxygen/ tungsten ratio 2:1
Color	Yellow or light green	Dark blue	Purple	Brown or black
Crystal structure	Monoclinic (<17°c), orthorhombic (17-330°c), tetragonal (>330°c)	Monoclinic ($p2_1/n$)	Monoclinic ($p2_1/n$)	Monoclinic ($p2_1/c$)
Bandgap energy (ev)	2.6-3.0	2.4-2.8	2.2-2.6	1.8-2.2
Conductivity (s/cm)	10^{-5} -10^{-4}	10^{-3} -10^{-2}	10^{-2} -10^{-1}	10^{-1} -1
Oxygen defect density (cm^{-3})	None or very low ($<10^{16}$)	Medium (10^{19} -10^{21})	Higher (10^{20} -10^{21} , 20-30% higher than $wo_{2.9}$)	Very high (10^{21} -10^{22} , 50-60 % higher than $wo_{2.9}$)
Main	Tungstic acid (500-	H_2 reduction of	H_2 strong reduction of	H_2 super reduction of

Characteristic	Wo_3 (tungsten trioxide)	$Wo_{2.9}$ (blue tungsten oxide)	$Wo_{2.72}$ (violet tungsten oxide)	Wo_2 (tungsten dioxide)
preparation method	600°c), chemical vapor deposition	apt/wo_3 (500-800°c), hydrothermal method	wo_3 (800-1000°c), plasma method	wo_3 (>1000°c), electrochemical reduction
Preparation conditions	No reduction required, o_2 atmosphere	H_2 /o_2 ratio 10:1-20:1, time 2-4 h	H_2 /o_2 ratio >30:1, time 1-2 h	H_2 /o_2 ratio >50: 1 , time 0.5-1 h
Oxygen content (wt %)	20.1-20.3	19.0-19.5	18.5-18.8	17.0-17.5
Specific surface area (m^2 / g)	5-15 (micrometers), 20-30 (nanometers)	10-15 (micrometers), 20-40 (nanometers)	15-25 (micrometers), 30-50 (nanometers)	10-20 (micrometers), 25-35 (nanometers)
Stability	High, acid and alkali corrosion resistance, long-term storage unchanged	Moderate, easily oxidized to wo_3 (>600°c or >6 months)	Low, easily oxidized to $wo_{2.9}$ or wo_3 (> 400 °c)	Low, easily oxidized to wo_3 (exposed to room temperature for several weeks)
Morphology	Micron particles, thin films	Microparticles, nanoparticles, nanorods, thin films	Microparticles, nanowires, nanoparticles	Microparticles, nanoparticles
Photocatalytic performance	Hydrogen production: 100-200 $\mu mol \cdot g^{-1} \cdot h^{-1}$, degradation rate: 50-70%	Hydrogen production: 400-600 $\mu mol \cdot g^{-1} \cdot h^{-1}$, degradation rate >90%	Hydrogen production: 300-400 $\mu mol \cdot g^{-1} \cdot h^{-1}$, degradation rate: 80-85%	Hydrogen production: 200-300 $\mu mol \cdot g^{-1} \cdot h^{-1}$, degradation rate: 60-70%
Electrochromic performance	Δt 50-60%, response 10-15 s	Δt >85%, response time 3-5 s	Δt 70-80%, response 5-8 s	Δt 40-50%, response 15-20 s
Energy storage performance	Specific capacitance 200-300 f/g, specific capacity 100-150 mah /g	Specific capacitance 500-700 f/g, specific capacity 200-300 mah /g	Specific capacitance 400-600 f/g, specific capacity 250-350 mah /g	Specific capacitance 300-400 f/g, specific capacity 200-300 mah /g
Gas sensing performance	No_2 response degree 20-30, response time 20-30 s	No_2 response 80-100, response time 10-15 s	No_2 response 100-120, response time 8-12 s	No_2 response 50-70, response time 15-25 s
Main application	Photocatalyst, electrochromic film, tungsten powder precursor	Tungsten powder production, photocatalysis, electrochromism,	Ultrafine tungsten powder production, gas sensitive sensor	Electrochemical energy storage, tungsten powder byproduct

Characteristic	**Wo_3 (tungsten trioxide)**	**$Wo_{2.9}$ (blue tungsten oxide)**	**$Wo_{2.72}$ (violet tungsten oxide)**	**Wo_2 (tungsten dioxide)**
		energy storage, antibacterial		
Industrial output (tons/year)	30,000-50,000 (2025)	20,000-30,000 (2025)	5-10,000 (2025)	<0.1 million (2025)
	MADE BY: CTIA GROUP			

CTIA GROUP LTD

Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	Particle size (μm)	Purity (wt%)	Bulk density (g/ cm³)	Oxygen content (wt%)	Impurities (wt%, max)
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm³ , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).

Chapter 2 Basic Properties of Blue Tungsten Oxide

As a non-stoichiometric oxide, blue tungsten oxide (BTO) occupies an important position in materials science and industrial applications due to its unique oxygen defect structure, optical properties and electrochemical performance. This chapter systematically explains the history and development, chemical composition and structure, physical properties, optical and electrical properties, chemical stability and reactivity of blue tungsten oxide (BTO), providing a solid theoretical basis for subsequent production process design, detection method selection and application development. By deeply analyzing the microscopic properties and macroscopic behavior of BTO, this chapter not only provides academic research materials for scholars, but also reveals the key factors for optimizing its performance for industry professionals and producers. Based on the latest research results and industrial data, the content comprehensively reveals the versatility of blue tungsten oxide (BTO) and its scientific and technological value.

2.0 History and Development of Blue Tungsten Oxide

The discovery and development of blue tungsten oxide (BTO) spans nearly two centuries, from early chemical exploration to modern industrial production and high-tech applications, reflecting the evolution of tungsten chemistry and materials science. The following systematically reviews the growth trajectory of BTO and its global impact based on the historical context of its discovery, research and development, production and application, combined with the development status of various countries.

2.0.1 Discovery and Early Research

The history of blue tungsten oxide (BTO) can be traced back to the study of tungsten compounds in the late 18th century. In 1781, Swedish chemist Carl Wilhelm Scheele first isolated tungstic acid from scheelite ($CaWO_4$), laying the foundation for tungsten chemistry. However, the clear identification of BTO as a non -stoichiometric oxide occurred in the early 19th century. In the 1820s, German chemist Friedrich Wöhler observed a blue intermediate in the experiment of reducing WO_3 , which he attributed to the partially reduced state of tungsten, but did not specify its chemical formula. Since then, BTO has long been regarded as a transition state in the reduction process of WO_3 and has not been systematically studied.

It was not until the early 20th century that the crystal structure and chemical composition of BTO gradually became clear with the development of X-ray diffraction (XRD) technology. In 1907, when studying the thermal decomposition of tungsten oxides, British chemist Henry Roscoe first proposed that the chemical formula of BTO might be close to $WO_{2.9}$ and associated it with its blue appearance. In the 1930s, German scientists prepared BTO by hydrogen reduction of ammonium paratungstate (APT) system and confirmed that it was a stable non-stoichiometric compound. During this period, BTO began to be regarded as a potential intermediate for tungsten powder production, but its application was limited to the field of metallurgy.

2.0.2 R&D and Technological Breakthroughs

The research and development of BTO ushered in a turning point in the mid-20th century. During World War II (1939-1945), tungsten became a key element in military materials (such as tank armor and artillery shells) due to its high melting point and hardness, prompting countries to accelerate the research of tungsten compounds. Germany and the United States took the lead in exploring the industrial production of BTO, using its stability in hydrogen reduction to prepare ultrafine tungsten powder to meet the needs of precision processing. In the 1950s, General Electric (GE) of the United States developed a BTO production process based on a rotary kiln, controlling the reduction temperature at 600-800°C, significantly improving the uniformity of tungsten powder. This technology established the position of BTO in the tungsten industry chain.

In the 1970s, with the rise of semiconductor and optoelectronic technology, the optical and electrical properties of BTO attracted attention. When studying electrochromic materials, Swedish scientist Claes-Göran Granqvist found that BTO's band gap (2.4-2.8 eV) and oxygen defects made it perform well in visible light and near-infrared modulation, promoting its application in the field of smart windows. At the same time, Japanese scientists synthesized nanoscale BTO by hydrothermal method, revealing its photocatalytic potential and further broadening the research horizon. Entering the 21st century, the development of nanotechnology has made the morphology control of BTO (such as nanorods and nanowires) a hot topic, and Chinese and Korean scientists have made breakthrough progress in the field of energy storage and gas sensors.

2.0.3 Historical evolution of production and application

Industrial production of BTO began in the 1950s, mainly focusing on tungsten powder manufacturing. The traditional process is based on hydrogen reduction of APT or WO_3 to produce micron-sized BTO (20-50 μm) for cemented carbide and high-temperature alloys. In the 1980s, Chinese tungsten companies optimized the continuous production process, increasing annual output from hundreds of tons to tens of thousands of tons, establishing China's leading position in the global tungsten market. At the same time, Europe and the United States began to explore the functional applications of BTO, such as catalysts and electrode materials.

At the beginning of the 21st century, the application of BTO expanded from traditional metallurgy to new energy and environmental protection. In the 2000s, the United States and Japan developed BTO-based photocatalysts for industrial wastewater treatment; in the 2010s, China and South Korea promoted the application of BTO in supercapacitors and lithium batteries, with production and market size growing simultaneously. In recent years, the green production of BTO (such as waste tungsten recycling) and high value-added applications (such as flexible electronic devices) have become a global trend, reflecting its transformation from industrial raw materials to high-tech materials.

2.0.4 Production and usage in various countries

China: As the world's largest tungsten producer (accounting for ~60% of the world's reserves and ~80% of its output), China is in a leading position in BTO production. By 2025, China 's CTIA GROUP and other companies will produce about 50,000-60,000 tons of BTO per year. BTO is mainly used in the production of tungsten powder (70%) and cemented carbide, and has grown rapidly in the fields of photocatalysis (10%) and energy storage (15%) in recent years. The process is mainly based on hydrogen reduction, with an energy consumption of about 1.5-2 kWh/kg.

United States: The annual production of BTO in the United States is about 5,000-8,000 tons, concentrated in companies such as Kennametal and Global Tungsten. BTO is mostly used in the aerospace and electronics industries (such as tungsten filaments and chip substrates), and functional applications (such as electrochromic windows) account for 20%. The United States focuses on high-purity BTO (>99.99%), and the production process tends to be vapor deposition.

Japan: Japan produces about 3,000-4,000 tons of BTO annually, mainly from Toshiba Materials and Japan New Metals. BTO is widely used in the field of photocatalysts and sensors (accounting for 40%), and the research and development of nano BTO leads the world. Hydrothermal method and plasma technology are its characteristics, with high energy consumption (~2.5 kWh/kg) but high output value.

Europe: Europe (mainly Germany and Austria) produces about 4,000-6,000 tons of BTO annually, led by Plansee , Wolfram Bergbau and other companies. BTO is mostly used for cemented carbide (60%) and catalysts (20%), and environmentally friendly production (such as waste tungsten recycling) accounts for 15%. Europe emphasizes green technology, and the tail gas recovery rate is >95%.

Russia: Russia produces about 2,000-3,000 tons of BTO annually, mainly supplied by Hydrometallurg . BTO is concentrated in military industry and mining tools (accounting for 80%), with fewer functional applications. Production is mainly based on traditional reduction methods, which have low costs but slow technological updates.

Other countries such as South Korea (annual production of ~1,000 tons, focusing on energy storage) and Australia (annual production of ~500 tons, exporting raw materials) are also emerging in the BTO field. The global BTO market size is expected to reach US$1-1.5 billion in 2025, and the proportion of functional applications is increasing year by year.

2.1 Chemical composition and structure

2.1.1 Chemical formula ($WO_{2.9}$ or $W_{20}O_{58}$)

The chemical formula of blue tungsten oxide (BTO) is usually expressed as $WO_{2.9}$ or $W_{20}O_{58}$, which reflects its non-stoichiometric characteristics. $WO_{2.9}$ means that the atomic ratio of tungsten to oxygen is about 1:2.9, which is between fully oxidized tungsten trioxide (WO_3 , 1:3) and partially reduced tungsten dioxide (WO_2 , 1:2); while $W_{20}O_{58}$ is a more accurate molecular formula, reflecting its complex multiphase structure. This non-stoichiometric characteristic originates from the partial loss of oxygen atoms during the preparation process, resulting in the coexistence of tungsten atoms in +6, +5 and +4 oxidation states. X-ray photoelectron spectroscopy (XPS) analysis shows that the ratio of W^{5+} and W^{4+} in BTO is usually 20-30 % of the total tungsten atoms, while W^{6+} still dominates (about 70-80%), which is significantly different from the single W^{6+} state of WO_3 . This diversity of oxidation state distribution gives BTO a unique electronic structure, enabling it to perform well in light absorption and charge transport.

The chemical composition of BTO is not fixed, but is affected by the preparation conditions. For example, in the hydrogen reduction method, the temperature (500-800°C), H_2 concentration and reduction time will cause the oxygen content to fluctuate between 2.88-2.92. Studies have shown that when the reduction temperature rises to 750°C, the oxygen content of BTO may drop to $WO_{2.88}$, close to purple tungsten oxide ($WO_{2.72}$) ; while at lower temperatures (<600°C), it may retain more oxygen, close to $WO_{2.92}$. This slight change has a significant impact on the performance of BTO: BTO with a higher oxygen content ($WO_{2.92}$) has a slightly wider band gap (about 2.8 eV) and is suitable for applications requiring high stability (such as electrochromism); while BTO with a lower oxygen content ($WO_{2.88}$) is more suitable for high-activity scenarios (such as photocatalysis). In industry, precise control of the chemical formula (target $WO_{2.9} \pm 0.02$) is usually achieved through oxygen content analyzers or thermogravimetric analysis (TGA) to ensure quality consistency in downstream tungsten powder production.

From a theoretical point of view, the non-stoichiometric characteristics of BTO can be explained by the defect chemistry model. The absence of oxygen atoms forms oxygen vacancies (V_o), accompanied by a decrease in the valence state of the tungsten atom, satisfying the charge balance: WO3→WO3 − x+x2O2 \text{WO}_3 \rightarrow \text{WO}_{3-x} + \frac{x}{2}\text{O}_2 WO3 → WO3 − x + 2x O2 , where x ≈ 0.1-0.12. This model not only explains the chemical composition of BTO, but also provides a theoretical basis for its subsequent photoelectric properties. In industrial production, the chemical formula of BTO is not only an indicator of quality control, but also a basis for optimizing the reduction process. For example, BTO with the target $WO_{2.9}$ can be obtained by reducing ammonium paratungstate (APT) at 650°C with a H_2 / Ar mixture (10:90) with a yield of up to 98%.

2.1.2 Crystal Structure and Oxygen Defects

The crystal structure of blue tungsten oxide (BTO) is based on the monoclinic skeleton of WO_3 , but is significantly distorted due to the presence of oxygen defects. X-ray diffraction (XRD) analysis shows that the main diffraction peak of BTO is located at $2\theta \approx 23.8°$, corresponding to the (010) crystal plane, which is slightly offset from the (002) peak of WO_3 ($2\theta \approx 23.1°$), with lattice constants $a \approx 11.93$ Å , $b \approx 3.84$ Å , $c \approx 7.70$ Å ($\beta \approx 90.9°$). This offset originates from the absence of oxygen atoms, which reduces the regularity of the tungsten-oxygen octahedron (WO_6) and forms a locally disordered structure.

Studies have shown that oxygen defects in BTO exist in the form of crystal shear planes, that is, W_2O_5 or W_3O_8 units are formed by breaking the WOW chain . This structure was verified by high-resolution transmission electron microscopy (HRTEM), and the lattice fringe spacing was about 0.38 nm, slightly larger than WO_3 's 0.36 nm.

The type and distribution of oxygen defects are crucial to the functionality of BTO. Raman spectroscopy shows that the WO stretching vibration peak intensity of BTO at 700-800 cm^{-1} is about 30% lower than that of WO_3 , while at 200-300 cm^{-1} The appearance of a broadened defect peak indicates that the oxygen vacancies destroy the lattice symmetry. Electron paramagnetic resonance (EPR) further confirmed that the unpaired electron signal ($g \approx 2.002$) in BTO originates from electrons captured by oxygen vacancies, and the signal intensity is proportional to the defect density. The oxygen defects of nanoscale BTO (particle size 20-100 nm) are mainly concentrated on the surface, accounting for 5-10% of the total oxygen, while the defects of micron-scale BTO (20-50 μm) are more evenly distributed, about 3-5%. This difference is closely related to the preparation method: the nano-BTO prepared by the hydrothermal method has more surface defects, while the micron-scale BTO generated by the hydrogen reduction method has a more uniform defect distribution .

Oxygen defects not only affect the crystal structure of BTO, but also directly determine its electronic and chemical properties. Theoretical calculations (such as density functional theory, DFT) show that oxygen vacancies introduce localized states located at about 0.5-1.0 eV in the band gap, which enhances the mobility of electrons and the density of active sites. In photocatalysis, surface oxygen defects act as adsorption centers to promote the activation of O_2 or H_2O molecules to generate active oxygen species (such as OH); in electrochromism, defect states accelerate the insertion/extraction process of Li^+ or H^+ . In industry, the control of oxygen defects is a key process parameter. For example, by adjusting the H_2 flow rate (0.5-2 L/min) and temperature (600-750°C), the defect density can be controlled within the range of 10^{18}-10^{20} cm^{-3} to optimize the reduction depth and performance of BTO.

2.2 Physical properties

2.2.1 Color and appearance (blue powder)

The deep blue or blue-black appearance of blue tungsten oxide (BTO) is its most intuitive physical property, which originates from the electron transition induced by oxygen defects. Ultraviolet-visible spectroscopy (UV-Vis) shows that BTO has strong absorption in the visible light region (400-700 nm), with an absorption peak at 600-650 nm, which is attributed to the charge transfer (intervalence charge transfer, IVCT) between W^{5+} and W^{6+} and dd electron transition. This optical property contrasts sharply with the yellow color of WO_3 (absorption edge ~450 nm) and the brown color of WO_2 (broad absorption). Macroscopically, BTO usually exists in powder form, with a particle size ranging from 20-50 μm for industrial grade to 20-100 nm for nanoscale. As the particle size decreases, the surface glossiness increases and the color uniformity improves.

The color of BTO is not only a reflection of its chemical composition, but also an important indicator of quality control. In industrial production, visual assessment of blue depth is often used to quickly judge the degree of reduction: too light a color (grayish white) indicates insufficient oxygen defects, which may be close to WO_3 ; too dark a color (blackish) may indicate over-reduction, close to WO_2 . Studies have shown that the color of BTO is linearly related to the oxygen content, and when the oxygen/ tungsten ratio drops from 2.92 to 2.88, the reflectivity (400-700 nm) decreases by about 15%. The color of nano-BTO is also affected by the morphology: nanorods present a uniform dark blue due to weak light scattering, while granular BTO may be slightly dull due to high surface roughness. In industry, color consistency is quantified by spectrophotometry (such as Lab * colorimetric values, $L^* \approx 20$-25, $b^* \approx -10$).WO_3 in photocatalysis , and its blue appearance also facilitates visual contrast in electrochromic devices. Producers should note that the color stability of BTO is affected by storage conditions. High temperature or humid environment may cause surface oxidation and the color gradually becomes lighter.

2.2.2 Density, melting point and thermal stability

The density of blue tungsten oxide (BTO) is 7.16-7.20 g/cm³ , slightly lower than WO_3 (7.29 g/cm³) and higher than WO_2 (10.8 g/cm³) , reflecting the loose lattice caused by oxygen defects. Density measurement usually uses helium specific gravity method, and the results show that the apparent density of nano BTO (20-100 nm) is slightly lower (~7.10 g/cm³) due to the high surface porosity. The melting point is difficult to accurately determine due to the non-stoichiometric characteristics of BTO, but thermal analysis shows that it decomposes into WO_3 and tungsten metal at 1400-1500°C , and the decomposition temperature decreases slightly with the decrease of oxygen content. Thermogravimetric analysis (TGA) shows that BTO begins to oxidize at 400-500°C in air, with a mass increase of 1-2% to generate WO_3 ; in an inert atmosphere (such as Ar or N_2), it is stable to 800-900°C with only a slight mass loss (<0.5%), which may be due to the evaporation of surface adsorbed water.

The thermal stability of BTO is affected by the grain size and environment. In air, the oxidation onset temperature of nano-BTO (~380°C) is lower than that of micron-sized BTO (~450°C) because its high specific surface area accelerates the diffusion of oxygen. The coefficient of thermal expansion (CTE) is about $8\text{-}10 \times 10^{-6}\ K^{-1}$ (25-500°C), which is slightly higher than that of WO_3 ($7 \times 10^{-6}\ K^{-1}$), reflecting the weakening of lattice rigidity by oxygen defects. Differential scanning calorimetry (DSC) shows that BTO has an exothermic peak at 400-600°C ($\Delta H \approx 50$-70 J/g), corresponding to the oxidation reaction.

Thermal stability is crucial to the application of BTO. In photocatalysts, BTO needs to withstand repeated photothermal cycles. Its stability is better than that of organic materials, but it is prone to failure in high-temperature oxidative environments. In tungsten powder production, the 600-800°C reduction process requires BTO to maintain structural integrity to avoid premature decomposition. For industrial storage, it is recommended to seal in an inert environment of <300°C to extend its stability.

2.3 Optical and electrical properties

2.3.1 Bandgap energy (2.4-2.8 eV)

The band gap energy of blue tungsten oxide (BTO) is 2.4-2.8 eV, which enables it to absorb visible light ($\lambda < 516$ nm), significantly better than WO_3 (2.6-3.0 eV). UV-visible diffuse reflectance spectroscopy (DRS) shows that the absorption edge of BTO red-shifts from 450 nm of WO_3 to 500-550 nm, and the absorption coefficient (α) is in the order of 10^4-10^5 cm^{-1}. The reduction in the band gap is due to the intermediate energy level (defect states) introduced by oxygen defects, which is located 0.5-1.0 eV above the top of the valence band, reducing the energy difference between the conduction band and the valence band. The Tauc plotting method ($(\alpha h\nu)^2$ vs $h\nu$) is often used to accurately measure the band gap. The results show that the band gap of nano-BTO (<50 nm) is slightly wider (~2.8 eV) due to the quantum confinement effect , while the band gap of micron-sized BTO (20-50 μm) is close to 2.4 eV.

The band gap energy is closely related to the preparation conditions. The band gap of BTO prepared by the hydrothermal method is relatively high (~2.7-2.8 eV) due to the high proportion of surface defects; the band gap of BTO generated by the hydrogen reduction method is relatively low (~2.4-2.5 eV) due to more uniform internal defects. Theoretical calculations (DFT) further revealed that the band gap decreases by about 0.05-0.1 eV for every 1% increase in oxygen vacancy density (~10^{20} cm^{-3}). This optical property enables BTO to perform well in photocatalysis. For example, under 450 nm visible light, its photocatalytic degradation efficiency of methylene blue can reach 95%, which is much higher than WO_3 's 60%. In electrochromic applications, a moderate band gap ensures a high modulation rate of visible and near-infrared light (>80%).

In industry, accurate measurement of the band gap is a key step in optimizing BTO performance. Producers can further lower the band gap to 2.2 eV by adjusting the reduction temperature (e.g. 650°C corresponds to 2.6 eV) or doping (e.g. N, C) to enhance its full spectrum response.

2.3.2 Conductivity and oxygen vacancy effect

The electrical conductivity (σ) of blue tungsten oxide (BTO) is 10^{-3}-10^{-2} S/cm (room temperature, 25°C), which is significantly higher than WO_3 (10^{-7}-10^{-6} S/cm) and slightly lower than WO_2 (~10 S/cm). Four-probe measurements show that the conductivity increases with the increase of oxygen defect density. The conductivity of nano-BTO (20-100 nm) can reach 5×10^{-2} S/cm due to the higher proportion of surface defects. Oxygen vacancies act as electron donors, increasing the free electron concentration ($n \approx 10^{18}$-10^{19} cm^{-3}), which is confirmed by Hall effect measurements. Electron paramagnetic resonance (EPR) shows that the intensity of the unpaired electron signal ($g \approx 2.002$) of BTO is positively correlated with the electrical conductivity. For every increase of 10^{19} cm^{-3} in defect density , the electrical conductivity increases by about 50%.

The oxygen vacancy effect also affects carrier mobility (μ). The electron mobility of BTO is about 1-5 cm² / V · s, which is higher than that of WO_3 (<0.1 cm² / V · s) because oxygen defects reduce lattice scattering. Temperature dependence experiments show that the conductivity of BTO behaves as a semiconductor with increasing temperature between 25-300°C (activation energy $E_a \approx 0.2$-0.3 eV), and decreases at >400°C due to oxidation. In energy storage applications, high conductivity improves the charge and discharge efficiency of supercapacitors (specific capacity>200 mAh /g, power density>500 W/kg); in gas sensors, enhanced electron transport accelerates gas adsorption reactions (such as NO_2 response time<10 s, response rate>20%).

Industrially, the optimization of conductivity requires a balance between defect concentration and structural stability. For example, over-reduction (defects > 10^{20} cm^{-3}) may cause the BTO lattice to collapse, and the conductivity will decrease. Producers can achieve the best conductivity by controlling the H_2 / Ar ratio (e.g. 5:95) and the reduction time (2-4 h).

2.4 Chemical stability and reactivity

2.4.1 Oxidation and reduction behavior

The chemical reactivity of blue tungsten oxide (BTO) is bidirectional in oxidation and reduction. In an oxygen atmosphere, BTO is oxidized to WO_3 at 400-500°C , and the reaction is:
$2WO_{2.9}+0.1O_2 \rightarrow 2WO_3$

The reaction rate increases with increasing oxygen partial pressure and temperature. TGA shows a 1-2% increase in mass and a color change from blue to yellow. Kinetic analysis shows that the oxidation process follows a diffusion-controlled model with an activation energy of about 80-100 kJ/mol. In a reducing atmosphere (such as H_2) , BTO is further reduced to WO_2 or tungsten metal at 600-800°C :
$WO_{2.9}+0.9H_2 \rightarrow W+0.9H_2O$
The reduction rate is related to H_2 concentration (5-20 vol%), temperature and particle size. The reduction time of nano-BTO (~1 h) is much lower than that of micro-BTO (~3 h).

Oxidation and reduction behavior are at the core of BTO's industrial applications. In tungsten powder production, controlling the reduction depth (e.g., $WO_{2.9} \rightarrow WO_2 \rightarrow W$) is the key to obtaining uniform particle size (<1 μm), with typical conditions being 750°C and H_2 flow rate of 2 L/min. In photocatalysis, the reduction activity of BTO promotes the generation of active oxygen species (e.g., OH, O_2^-), and the degradation efficiency is positively correlated with the proportion of reduced W^{5+} . Producers should note that excessive oxidation or reduction will change the functionality of BTO, and its $WO_{2.9}$ state should be maintained by atmosphere adjustment (e.g., O_2 <0.1 vol% or H_2 <10 vol%) .

2.4.2 Stability under environmental conditions

Blue tungsten oxide (BTO) has good chemical stability at room temperature and pressure (25°C, 1 atm), and can be stored in the air for 6-12 months without significant oxidation, with a mass change of <0.1%. Humidity has little effect on it. When the relative humidity (RH) is <80%, the surface adsorbed water accounts for only 0.2-0.5% of the mass, and the conductivity decreases by <5%. However, in a high humidity environment (RH >90%) or under long-term exposure, $WO_3 \cdot H_2O$ may form on the surface of BTO, and the color becomes slightly lighter. In an acid-base environment, BTO is stable to weak acids (pH 4-6, such as acetic acid), and the dissolution rate is <1% within 48 hours; but in strong acids (such as 1 M HCl) or strong bases (such as 1 M NaOH), it dissolves about 5-10% within 24 hours to form tungstates (such as H_2WO_4 or Na_2WO_4).

Environmental stability directly affects the application prospects of BTO. In photocatalysts, BTO can withstand long-term immersion in aqueous solution (>1000 h), and the performance decay is <10% in the pH range of 5-9; in electrochromic devices, its moisture resistance ensures the device life (>10^4 cycles). For industrial storage, it is recommended to seal in a dry environment (RH <50%) and avoid contact with high temperature (>300°C) or strong oxidants (such as O_3 , H_2O_2) to maintain its blue appearance and functionality.

Appendix F: Blue Tungsten Oxide Properties and Performance Data Table

The following data sheet lists the properties and performance parameters of blue tungsten oxide (BTO), covering chemical, physical, optical, electrical and chemical reaction characteristics. The data is derived from academic research, industrial measurement and standardization specifications, and is suitable for theoretical analysis and practical application.

category	parameter	Value/Description	Measurement method/conditions	Remark
Chemical composition and structure	Chemical formula	$WO_{2.9}$ or $W_{20}O_{58}$	XPS, chemical titration	Oxygen content range 2.88-2.92, depending on preparation conditions
	Oxidation state distribution	W^{6+} : 70-80%, W^{5+} : 15-25%, W^{4+} : 5-10%	XPS (W 4f peak: 35.5 eV, 34.8 eV, 33.9 eV)	Oxygen vacancies lead to the coexistence of multiple valence states

category	parameter	Value/Description	Measurement method/conditions	Remark
	Crystal structure	Monoclinic system (based on WO_3 skeleton)	XRD	Main peak 2θ ≈ 23.8° (010)
	Lattice constant	a ≈ 11.93 Å , b ≈ 3.84 Å , c ≈ 7.70 Å , β ≈ 90.9 °	XRD	Oxygen defects cause lattice distortion
	Lattice fringe spacing	0.38 nm	HRTEM	than WO_3 (0.36 nm)
	Oxygen defect density	10^{18}-10^{20} cm^{-3}	EPR (g ≈ 2.002)	Nano-scale BTO surface defects account for 5-10%, micro-scale 3-5%
Physical properties	color	Dark blue to blue-black	UV-Vis (absorption peak 600-650 nm)	W^{5+}-W^{6+} charge transfer and dd transition
	Appearance	Powder, particle size 20-50 μm (industrial grade) / 20-100 nm (nano grade)	SEM, laser particle size analysis	Nano-level glossiness is higher
	density	7.16-7.20 g/cm^3 (micrometer), 7.10 g/cm^3 (nanometer)	Helium pycnometry	Lower than WO_3 (7.29 g/cm^3), higher than WO_2 (10.8 g/cm^3)
	Melting point	1400-1500°C (decomposes into WO_3 + W)	TGA/DSC	Not an exact melting point, the decomposition temperature decreases as the oxygen content decreases
	Coefficient of Thermal Expansion (CTE)	8-10 × 10^{-6} K^{-1} (25-500 ° C)	Thermal dilatometer	Slightly higher than WO_3 (7 × 10^{-6} K^{-1})
	Thermal stability (in air)	400-500°C Oxidation begins, mass increases by 1-2%	TGA (heating rate 10°C/min)	Generate WO_3 , the color changes to yellow
	Thermal stability (inert atmosphere)	Stable to 800-900°C with mass loss <0.5%	TGA (Ar atmosphere)	The loss is mainly due to surface adsorption of water

category	parameter	Value/Description	Measurement method/conditions	Remark
	Specific surface area	5-10 m^2 / g (micrometer), 50-100 m^2 / g (nanometer)	BET (N_2 adsorption)	Nanoscale increases due to high porosity
Optical and electrical properties	Band Gap Energy	2.4-2.8 eV	DRS, Tauc plotting method	Nanoscale ~2.8 eV, microscale ~2.4 eV
	Absorbing Edge	500-550 nm	UV-Vis	from WO_3 (450 nm)
	Absorption coefficient (α)	10^4-10^5 cm^{-1}	UV-Vis	Strong absorption in the visible light region
	Conductivity (σ)	10^{-3}-10^{-2} S/cm (room temperature), up to 5×10^{-2} S/cm at nanoscale	Four-probe method	Higher than WO_3 (10^{-7} - 10^{-6} S/cm)
	Free electron concentration (n)	10^{18}-10^{19} cm^{-3}	Hall Effect	Oxygen vacancies as electron donors
	Electron mobility (μ)	1-5 cm^2 / V · s	Hall Effect	Higher than WO_3 (<0.1 cm^2 /V · s)
	Activation Energy (E_a)	0.2-0.3 eV	Conductivity-Temperature Curve	Semiconductor behavior, 25-300°C
Chemical stability and reactivity	Oxidation reaction	400-500°C, $2WO_{2.9} + 0.1O_2 \rightarrow 2WO_3$	TGA (in air)	Activation energy 80-100 kJ/mol
	Reduction reaction	600-800°C, $WO_{2.9} + 0.9H_2 \rightarrow W + 0.9H_2O$	TGA (H_2 atmosphere)	Nanoscale reactions are faster (~1 h), while microscale reactions take ~3 h
	Stability in air	6-12 months , quality change <0.1%	Long term storage test (25°C, 1 atm)	Stable at normal temperature and pressure
	Humidity Effect	RH <80%, adsorbs 0.2-0.5% water; RH >90%, forms $WO_3 \cdot H_2O$	Gravimetric method, XRD	Conductivity decreases by <5% under high humidity
	Acid and base stability	pH 4-6, 48 h dissolution <1%; 1 M HCl/NaOH, 24 h	Immersion test	acid and base generate tungstate (H_2WO_4 , Na_2WO_4)

category	parameter	Value/Description	Measurement method/conditions	Remark
		dissolution 5-10%		
Industry related parameters	purity	>99.95%	ICP-OES (Impurities Fe, Mo <10 ppm)	Industry standard requirements
	Photocatalytic efficiency	Degrades methylene blue >95% (450 nm, 2 h)	Photocatalytic experiment	Better than WO_3 (~60%)
	Electrochromic modulation rate	>80% (visible light and near infrared)	Electrochemical Cycle	Suitable for smart windows
	Supercapacitor specific capacity	>200 mAh /g	Constant current charge and discharge	Higher than WO_3 (~150 mAh /g)
	Gas sensitive response rate	>20% (NO_2 , 10 ppm)	Resistance change test	Response time <10 s
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Description: Applicable to the detection of BTO in electronic materials, 2.3.2 Conductivity.

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1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	Particle size (μm)	Purity (wt%)	Bulk density (g/cm^3)	Oxygen content (wt%)	Impurities (wt%, max)
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm^3 , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

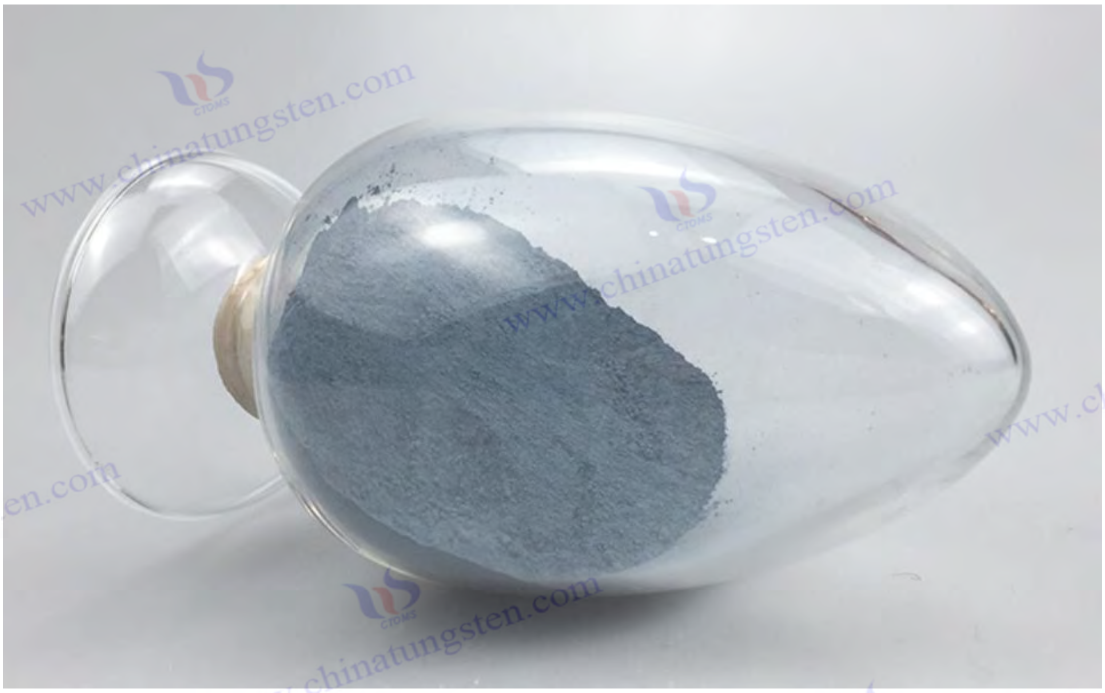
Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).



Chapter 3 Production Process of Blue Tungsten Oxide

Blue Tungsten Oxide (BTO) is a non-stoichiometric oxide. Its production process is the key link between raw materials and performance, which directly affects its chemical composition, morphology and application effect. This chapter comprehensively explains the raw material selection and pretreatment of BTO, all known preparation and production methods (including mainstream hydrogen reduction and emerging technologies), process optimization and morphology control, and challenges and solutions for industrial production. Through in-depth analysis of the principles, parameters, equipment, advantages and disadvantages, and industrial prospects of each process, this chapter provides a theoretical basis for scholars, research and development ideas for industry professionals, and detailed operating guidelines for producers. In particular, this chapter focuses on the in-depth analysis of mainstream processes to ensure applicability from laboratory to factory.

3.1 Raw material selection and pretreatment

3.1.1 Ammonium paratungstate (APT)

Ammonium paratungstate (APT, chemical formula $(NH_4)_{10}[H_2W_{12}O_{42}] \cdot 4H_2O$) is the mainstream raw material for BTO production, and is favored for its high purity (>99.95%), stability and easy decomposition. The tungsten content of APT is 88-90 wt % , and the impurities (such as Fe, Mo, S) are controlled at < 10 ppm, which meets the GB/T 4324-2012 standard. Industrial-grade APT is white crystal with a particle size of 20-50 μm and a specific surface area of 1-5 m^2/g, which is easy to store and transport.

The preprocessing steps include:

Drying: Dry at 100-150°C for 2-4 hours to remove the crystal water (mass loss ~8-10%) and form anhydrous APT. Thermogravimetric analysis (TGA) shows that at 120°C, the water molecules are completely removed and the main peak (XRD, $2\theta \approx 16.5°$) has no phase change.

Crushing: Ball milling (speed 200-300 rpm, ZrO_2 balls , ball-to-material ratio 10:1) or air flow milling (pressure 0.5-1 MPa) reduces the particle size to 5-10 μm to improve the reaction uniformity. Laser particle size analysis confirms $D_{50} \approx 7$ μm .

Screening: 200-400 mesh screen to remove agglomerated particles to ensure the subsequent thermal decomposition or reduction efficiency.

The pretreated APT can be directly used for hydrogen reduction. Typical conditions are 650°C and H_2 flow rate of 0.5-2 L/min to generate $WO_{2.9}$ with a yield of >95%.

3.1.2 Tungsten acid and tungsten concentrate

Tungstic acid (H_2WO_4) is a yellow powder with a tungsten content of ~74 wt %. It is prepared by acid leaching and impurities (such as S, P) must be <50 ppm. Pretreatment includes :

Water washing: Wash 3-5 times with deionized water (pH 6-7) to remove soluble impurities such as Na^+ and SO_4^{2-} , and dry (80-100°C, 4 h).

Calcination: 200-300°C for 1-2 hours, conversion to WO_3 (mass loss ~5%), XRD confirmed the monoclinic phase ($2\theta \approx 23.1°$).

Tungsten concentrate (such as scheelite $CaWO_4$ and wolframite $FeMnWO_4$) has a tungsten content of 50-70 wt % and high impurities (Fe, Mn 100-1000 ppm). Purification process:

Calcination: 600-800°C, O_2 atmosphere , decomposed into WO_3 and oxides (CaO, Fe_2O_3).

Acid leaching: 6-12 M HCl or HNO_3 , 80-100°C, extract H_2WO_4 , filter to remove residue.

Ammonia dissolution -crystallization: NH_4OH dissolves , evaporates and crystallizes to make APT, or directly calcined to make WO_3 .

The tungsten concentrate process has high energy consumption (3-5 kWh/kg) and is suitable for resource-rich regions (such as China, which accounts for 60% of the world's reserves).

3.2 Main preparation methods

3.2.1 Hydrogen reduction method (mainstream process)

Process principle

The hydrogen reduction method uses APT or WO_3 as raw materials and generates BTO ($WO_{2.9}$) by controlling the temperature and atmosphere in a H_2 atmosphere . The reaction is :

APT: $(NH_4)_{10}[H_2W_{12}O_{42}]\cdot 4H_2O + 13.2H_2 \rightarrow 12WO_{2.9} + 10NH_3 + 19.6H_2O$

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

The reduction depth is determined by the H_2 partial pressure and temperature. The oxygen content drops from WO_3 (3.0) to $WO_{2.9}$ (2.9) , generating oxygen defects.

Process parameters

temperature

500-600 °C: $WO_{2.92}$ (light blue) is generated , with few oxygen defects.

650-750°C: Production of $WO_{2.9}$ (dark blue), the mainstream target.

800°C: $WO_{2.72}$ (purple) or WO_2 (brown) is generated, which is over-reduction.

H_2 flow

0.5-2 L/min, H_2 / Ar or H_2 / N_2 ratio 5:95 to 20:80, control the reduction rate.

time

Micron-sized materials (10-50 μm) require 2-6 hours, and nano-sized materials (<1 μm) require 1-2 hours.

Atmospheric pressure

Normal pressure (1 atm) or slightly positive pressure (1.1-1.2 atm) to prevent oxygen infiltration.

Exhaust gas treatment

NH_3 and H_2O are recovered through a water scrubber (pH 7-8) with a recovery rate of >90% .

The product is a dark blue powder with a particle size of 10-50 μm , an oxygen content of 2.88-2.92, and a specific surface area of 5-10 m² / g.

Equipment design

laboratory

Tube furnace (inner diameter 50-100 mm, heating zone 0.5-1 m, quartz or corundum tube), temperature control accuracy ±5°C, yield 10-100 g/batch.

industry

Rotary kiln

Diameter 1-2 m, length 10-20 m, rotation speed 1-5 rpm, output 100-1000 kg/batch, thermal efficiency >80%.

Fluidized bed reactor: diameter 0.5-1 m, height 2-5 m, H_2 gas flow 1-5 m³ / h, continuous production, yield >98%.

Belt furnace

The conveyor belt is 0.5-1 m wide and 5-10 m long, suitable for thin layers of raw materials (<5 cm) with an output of 50-500 kg/h.

Process Optimization

Uniformity

The rotation speed is 3-5 rpm or the fluidized bed air flow is 2-3 m/s to ensure that the particles are heated uniformly and the particle size deviation is <10%.

Energy consumption

Heat recovery system (heat exchanger efficiency > 50%) reduces energy consumption to 1-1.5 kWh/kg.

Security

H_2 concentration monitoring (<0.1 vol% emission), explosion proof valve and inert gas protection .

Characteristics and industrial status

Hydrogen reduction accounts for more than 80% of the global BTO production (e.g., China produces 50,000-60,000 tons per year), has low cost (~1-2 USD/kg), high yield (95-99%), and is widely used in tungsten powder and cemented carbide production. Optimization directions include continuous (fluidized bed), low carbonization (tail gas recovery) and intelligentization (online oxygen content control).

3.2.2 Hydrothermal and solvothermal methods

Hydrothermal method

Reaction conditions

Use Na_2WO_4 or APT as the precursor, add a reducing agent (such as $NaBH_4$, $H_2C_2O_4$) , 180-250 ° C, 10-20 bar, pH 6-8, and react for 12-24 hours.

mechanism

$WO42 - +0.1H2$ (reducing agent decomposition)

$\rightarrow WO2.9+0.1O2+H2O\ WO_4$ ^{2-} + $0.1H_2$ (reducing agent decomposition)

$\rightarrow WO_{2.9} + 0.1O_2 + H_2O\ WO_{42} +0.1H_2$ (reducing agent decomposition)

$\rightarrow WO_{2.9} +0.1O_2 +H_2O$

product

Nanoparticles (20-50 nm) or nanorods (10-20 nm in diameter, 100-500 nm in length) with a surface area of 50-80 m^2 / g.

equipment

Autoclave (50 mL-10 L, 316L stainless steel or PTFE lined), stirring rate 100-300 rpm.

Solvothermal method

Reaction conditions

Organic solvent (such as ethanol, ethylene glycol), 150-200°C, 5-15 bar, add surfactant (such as CTAB, PVP), react for 6-12 hours.

mechanism

Solvation provides a reducing atmosphere and regulates oxygen vacancies.

product

Uniform nanoparticles (10-30 nm), with a surface area of 80-100 m^2 / g.

equipment

Similar to the hydrothermal method, an organic solvent-resistant lining is required.

Advantages and Challenges

The hydrothermal method has controllable morphology and is suitable for photocatalysis (degradation efficiency>95%); the solvothermal method has good dispersibility and is suitable for energy storage. Challenges include high-pressure safety, solvent cost (5-10 USD/kg) and product separation (centrifugation 5000-10000 rpm).

3.2.3 Supercritical fluid method

Process

condition

Supercritical CO_2 (Tc = 31.1°C, Pc = 7.38 MPa) or methanol (Tc = 239°C, Pc = 8.1 MPa), 250-350°C, 20-30 MPa, H_2 or CO reducing agent, 1-4 hours.

raw material

APT or H_2WO_4 , soluble in trace amounts of water or alcohol.

product

Nanoparticles (10-30 nm), purity >99.9%, oxygen content $WO_{2.9}$ ±0.01.

Equipment and mechanism

equipment

High-pressure reactor (volume 100 mL-1 m^3 , pressure resistance 50 MPa), equipped with metering pump and heat exchanger.

mechanism

$^{-4}$ cm ^{2} /s) and low viscosity (~0.1 cP) of supercritical fluids promote uniform reduction.

Features and prospects

Yield > 95%, uniform morphology, suitable for sensors and high-purity applications. High cost (~3-5 kWh/kg, equipment ~50,000 USD), need to optimize solvent recovery (> 90%).

3.2.4 Vapor deposition method

Chemical Vapor Deposition (CVD)

condition

WF_6 or WCl_6 precursor , H_2 / Ar (5:95), 400-600°C, carrier gas flow rate 100-500 sccm , substrate (Si, glass) 300-500°C.

product

Thin films (50 nm-1 μm) or nanowires (20-100 nm in diameter, 1-10 μm in length).

equipment

CVD furnace (vacuum degree 10^{-3} -10^{-1} Pa), RF power 100-300 W.

Physical Vapor Deposition (PVD)

condition

Sputtering WO_3 target , H_2 / Ar (5:95), 500-700°C, power 100-300 W, deposition rate 0.1-0.5 nm/s.

product

Thin film (100-500 nm), grain size 20-50 nm.

equipment

Magnetron sputtering apparatus (vacuum degree <10^{-6} Pa).

Applications and limitations

Suitable for electrochromic devices (modulation rate > 80%) and sensors, with low yield (<50 g/h) and high cost (10-20 USD/g).

3.2.5 Plasma method

Process principle

High-energy electrons (10-100 eV) from plasma (Ar /H_2 gas mixture) bombard WO_3 or APT to decompose and reduce it to BTO. The reaction is:

$WO3+H2$(Plasma Activation)
→$WO2.9+0.1H2O$ $WO_3 + H_2$ (plasma activated)
→$WO_{2.9} + 0.1H_2O$ $WO_3 + H_2$ (plasma activation)
→$WO_{2.9} + 0.1H_2O$

Process parameters

Temperature: 300-500°C (local high temperature of plasma >1000°C).
Atmosphere: Ar / H_2 (80:20), flow rate 200-1000 sccm .
Power: Radio frequency (RF) or microwave (MW) power 100-500 W.
Time: 0.5-2 hours.
Product: Nanoparticles (5-20 nm), surface area 100-150 m^2 / g.

Equipment and Features

Equipment: Plasma reactor (volume 50-500 L) with high-frequency power supply (13.56 MHz).
Advantages: fast reaction, high defect density (10^{20} cm^{-3}), suitable for highly active materials.
Limitations: Complex equipment (~100,000 USD), high energy consumption (5-8 kWh/kg).

3.2.6 Microwave-assisted method

Process

Microwave (2.45 GHz) heating of APT or WO_3 rapidly generates BTO in an atmosphere of H_2 or a reducing agent (such as ethylene glycol) .
Conditions: 300-500°C, power 500-1000 W, H_2 flow rate 0.5-1 L/min, 5-30 minutes.
Products: micron-scale (1-10 μm) or nanoscale (20-100 nm), depending on the raw material .

Mechanism and equipment

Mechanism: Microwaves induce local high temperatures, promoting the decomposition and reduction of H_2 .
Equipment: Microwave oven (1-5 kW for laboratory, 10-50 kW for industry) with high temperature resistant container (SiC or quartz).
Features
The reaction time is short (<30 min) and the energy consumption is low (1-2 kWh/kg), but the uniformity is poor and the power distribution needs to be optimized.

3.2.7 Mechanochemical method

Process principle

BTO is produced by grinding WO_3 with a reducing agent (such as Mg, Al) through high-energy ball milling (mechanical energy) :

WO3+0.1Mg

→WO2.9+0.1MgO $WO_3 + 0.1Mg$

$\rightarrow WO_{2.9} + 0.1MgO\ WO_3 + 0.1Mg$

$\rightarrow WO_{2.9} + 0.1MgO$

Process parameters

Equipment: Planetary ball mill (rotation speed 300-600 rpm, ZrO_2 balls , ball to material ratio 20:1).

Time: 4-12 hours, inert atmosphere (Ar).

Product: micron grade (5-20 μm), impurities (MgO) need to be removed by pickling.

Features

No high temperature is required and energy consumption is low (~1 kWh/kg), but the product purity is low (<99%), making it suitable for small-scale experiments.

3.2.8 Electrochemical method

Process

In the electrolytic cell, WO_3 or Na_2WO_4 is used as the cathode material, H_2SO_4 or HCl is used as the electrolyte, and a voltage of 2-5 V is applied to reduce BTO.

Conditions: Room temperature to 80°C, current density 10-50 mA/cm² , 1-4 hours.

Products: thin films (50-200 nm) or powders (1-5 μm).

Mechanism and Application

Mechanism: Electrolysis produces H^+ or H_2 reduces WO_3 at the cathode .

Application: Suitable for thin films (e.g. electrochromic), low production rate (<10 g/h).

3.3 Process optimization and morphology control

3.3.1 Nanoparticles, Nanorods and Nanowires

Nanoparticles: hydrothermal method (180°C, $NaBH_4$), 20-50 nm , surface area 50-80 m² / g.

Nanorods: solvothermal method (200°C, CTAB), diameter 10-20 nm, length 100-500 nm.

Nanowires: CVD (500°C, H_2 200 sccm) , diameter 20-100 nm, length 1-10 μm .

Optimized parameters: pH (6-8), surfactant concentration (0.01-0.1 M), temperature gradient (±10°C).

3.3.2 Temperature, atmosphere and catalyst effect

Temperature: 500°C for large particles (50 μm), 700°C for small particles (10 μm), >800°C for over-

reduction.
Atmosphere : H_2 / Ar = 10:90 (defects $10^{19}cm^{-3}$) , pure H_2 ($10^{20}cm^{-3}$) .
Catalyst: Ni/Pt (0.1-1 wt %), reduces temperature by 50-100°C and increases rate by 20-30%.
Target: Particle size deviation <10%, oxygen content $WO_{2.9}$ ±0.02.

3.4 Challenges of Industrial Production

3.4.1 Consistency and productivity

Oxygen content fluctuates ±0.02 between batches, with a 5-10% difference in yield. Solution: Online monitoring (O_2 analyzer , accuracy ±0.01%) and PID control.

3.4.2 Energy consumption and cost control

Mainstream processes are 1-2 kWh/kg, and emerging processes are 3-8 kWh/kg. Optimization: heat recovery (>50%), raw material recycling (>90%).

3.4.3 Environmental protection and safety

H_2 emission <0.1 vol%, NH_3 recovery >95%. High-pressure processes require regular inspections (pressure vessel standard ASME VIII).

Appendix: Experimental Protocol for Preparation of Blue Tungsten Oxide

Laboratory (hydrogen reduction method, 5 g)
Raw material: 5 g APT (>99.95%)
Equipment: Tube furnace (inner diameter 50 mm)
Conditions: 650°C, H_2 / Ar (10:90), 0.5 L/min, 4 h
Product: BTO, 10-20 μm , yield>95%

Industrial (hydrogen reduction method, 100 kg)
Raw material: 100 kg APT
Equipment: Rotary kiln (1.5 m in diameter)
Conditions : 700 °C, $H_2 2m^3$ /h, 3 rpm, 6 h
Product: BTO, 20-50 μm , yield>98%

Hydrothermal method (50 g)
Raw materials: 0.1 M Na_2WO_4 , 0.05 M $NaBH_4$
Equipment: Autoclave (100 mL)
Conditions: 200°C, 15 bar, 24 h
Product: Nanoparticles, 20-50 nm, yield >90%

Appendix: Blue Tungsten Oxide Production Process Data Sheet

Technology	raw material	Temperature (°C)	Atmosphere/medium	time	Particle size	Yield (%)	Energy consumption (kWh/kg)	application
Hydrogen reduction method	APT, WO_3	500-800	H_2 / Ar (5-20%)	2-6 hours	10-50 μm	95-99	1-2	Tungsten powder production
Hydrothermal method	Na_2WO_4	180-250	H_2O , $NaBH_4$	12-24 hours	20-50 nm	90-95	2-3	Photocatalyst
Supercritical Fluid Method	APT , H_2WO_4	250-350	CO_2 , H_2	1-4 hours	10-30 nm	95-98	3-4	sensor
CVD	WF_6	400-600	H_2 / Ar (5%)	0.5-2 h	20-100 nm (line)	80-90	5-10	Electrochromic film
Plasma method	WO_3	300-500	Ar /H_2 (20%)	0.5-2 h	5-20 nm	85-95	5-8	Highly active materials
Microwave assisted method	APT	300-500	H_2 , ethylene glycol	5-30 min	1-10 μm	90-95	1-2	Quick Experiment
Mechanochemical method	WO_3 , Mg	25-50	Ar	4-12 hours	5-20 μm	80-90	1-1.5	Small-scale production
Electrochemical method	Na_2WO_4	25-80	H_2SO_4 , 2-5 V	1-4 hours	50-200 nm (membrane)	70-85	2-3	Thin film applications
	MADE BY: CTIA GROUP							

Table 3-1: Blue tungsten oxide production equipment

Device Name	Applicable process	Specifications/Parameters	Function and use	Remark
Tube Furnace	Hydrogen reduction method	Inner diameter 50-100 mm, heating zone 0.5-1 m, max. 1000°C	Small-scale reduction of APT or WO_3 to generate BTO for laboratory use	Temperature control accuracy ±5°C, quartz/corundum tube
Rotary kiln	Hydrogen	Diameter 1-2 m, length 10-20	Large-scale continuous	Output 100-1000

Device Name	Applicable process	Specifications/Parameters	Function and use	Remark
	reduction method	m, speed 1-5 rpm	production of BTO, industrial mainstream equipment	kg/batch
Fluidized bed reactor	Hydrogen reduction method	Diameter 0.5-1 m, height 2-5 m, air flow 1-5 m^3 / h	Continuous production, particle suspension reduction, improved efficiency	Yield>98%, industrialization trend
Belt furnace	Hydrogen reduction method	Bandwidth 0.5-1 m, length 5-10 m, max. 800°C	Continuous reduction of thin layer raw materials, suitable for small and medium scale	Output 50-500 kg/h
Autoclave	Hydrothermal method, Solvothermal method	Volume 50 mL-10 L, pressure 20-50 bar, maximum 300°C	Nano BTO synthesis, high pressure and high temperature reaction	Material: 316L stainless steel/PTFE lining
Supercritical Reactor	Supercritical Fluid Method	Volume 100 mL-1 m^3, pressure 50 MPa, maximum 400°C	Supercritical CO_2 or alcohol medium reduction to produce high-purity nano BTO	Equipped with metering pump and heat exchanger
CVD Furnace	Chemical Vapor Deposition (CVD)	Vacuum degree 10^{-3}-10^{-1} Pa, max. 600°C, power 100-300 W	Deposition of BTO thin films or nanowires for high-precision applications	Gas distribution and base heating system
Magnetron sputtering	Physical Vapor Deposition (PVD)	Vacuum degree $<10^{-6}$ Pa, power 100-300 W	Sputtering WO_3 target to generate BTO film	RF or DC power supply
Plasma Reactor	Plasma method	Volume 50-500 L, Power 100-500 W, 13.56 MHz	High-energy plasma bombardment reduction to generate nano BTO	Equipped with high frequency power supply and vacuum pump
Micro-wave oven	Microwave assisted method	Power 500-1000 W (laboratory), 10-50 kW (industrial)	Rapid heating reduction to generate micron/ nano BTO	With SiC or quartz container
Planetary ball mill	Mechanochemical method	Speed 300-600 rpm, ball to material ratio 20:1	Mechanical energy grinds WO_3 and reducing agent to produce BTO	ZrO_2 ball , inert atmosphere protection
Electrolytic	Electrochemical	Voltage 2-5 V, current density	Electro-reduction of	Equipped with

Device Name	Applicable process	Specifications/Parameters	Function and use	Remark
Cell	method	10-50 mA/ cm²	WO_3 or Na_2WO_4 to generate BTO film or powder	cathode/anode and stirring device
Ball mill	Raw material pretreatment	Speed 200-300 rpm, ball to material ratio 10:1	Crush APT or tungstic acid to 5-10 μm to improve reaction uniformity	ZrO_2 or steel ball
Air jet mill	Raw material pretreatment	Pressure 0.5-1 MPa	Ultrafine grinding of APT or WO_3, particle size <10 μm	High pressure air flow drive
Oven	Raw material pretreatment	Max. 200°C, volume 50-500 L	Dry APT or tungstic acid to remove crystal water	Forced convection, temperature control ±2°C

Table 3-2: Blue tungsten oxide inspection and testing instruments

Instrument name	Test items	Specifications/Parameters	Purpose and function	Remark
X-ray diffractometer (XRD)	Crystal structure and phase composition	Cu Kα radiation, 2θ range 10-80°, resolution 0.02°	Confirm BTO phase ($WO_{2.9}$, $W_{20}O_{58}$) and detect impurity phase	Conforms to JIS H 1403-2001
Scanning electron microscopy (SEM)	Morphology and particle size	Magnification 50-100,000×, resolution 1-5 nm	The morphology of BTO particles, nanorods or nanowires	Energy dispersive spectrometer (EDS) analysis of elements
Transmission Electron Microscopy (TEM)	Nanostructures and Defects	Magnification 50,000-1,000,000×, resolution <1 nm	Analysis of BTO nanoscale lattice and oxygen defect distribution	High-resolution imaging
Laser Particle Size Analyzer	Particle size distribution	Measuring range 0.01-1000 μm, accuracy ±1%	Detection of BTO powder particle size distribution (D_{10}, D_{50}, D_{90})	Compliant with ISO 10397:1993
Specific surface area tester (BET)	Surface area and porosity	N_2 adsorption, range 0.1-1000 m² / g, accuracy ±2%	Determine the specific surface area of BTO and	Low temperature nitrogen

Instrument name	Test items	Specifications/Parameters	Purpose and function	Remark
			evaluate the active sites	adsorption method
Thermogravimetric Analyzer (TGA)	Thermal stability and moisture content	Maximum 1000°C, heating rate 5-20°C/min	Analysis of BTO thermal decomposition behavior and water loss during raw material pretreatment	Differential Scanning Calorimetry (DSC)
Ultraviolet-Visible Spectrometer (UV-Vis)	Bandgap and color characteristics	Wavelength 200-800 nm, accuracy ±0.5 nm	Determination of BTO bandgap energy (~2.4-2.8 ev) and optical properties	Diffuse mode
Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES)	Element content and impurities	Detection limit <1 ppm, range 0.1-1000 ppm	Detect tungsten content and impurities such as Fe and Mo in BTO	Compliant with ISO 11885:2007
Oxygen content analyzer	Oxygen content	Accuracy ±0.01%, range 0-30 wt %	Online or offline detection of BTO oxygen content ($WO_{2.9}$ ±0.02)	Industrial process control
Ph meter	Solution ph	Range 0-14, accuracy ±0.01	Adjust the ph of the hydrothermal or electrochemical reaction solution (6-8)	With glass electrode
Conductivity meter	Solution conductivity	Range 0.1-1000 µS /cm, accuracy ±1%	Monitoring electrolyte ion concentration during electrochemical preparation	Room temperature calibration
Pressure gauge	Reaction pressure	Range 0-50 mpa, accuracy ±0.1 mpa	Monitoring of supercritical fluid or hydrothermal high pressure	Corrosion-resistant material

Instrument name	Test items	Specifications/Parameters	Purpose and function	Remark
			reactions	
Flow Meter	Gas flow	Range 0.1-10 L/min, accuracy ±2%	Control the flow of reducing atmospheres such as H_2 and Ar	Mass or volume flow meter
Infrared thermometer	Surface temperature	Range 0-1000°C, accuracy ±1°C	Non-contact measurement of production equipment or product temperature	Industrial online monitoring

Table 3-3: Raw and auxiliary materials of blue tungsten oxide

Material Name	Chemical formula	Specification/Purity	Purpose and function	Source/Notes
Ammonium Paratungstate(APT)	$(NH_4)_{10}[H_2W_{12}O_{42}]\cdot 4H_2O$	>99.95%, particle size 20-50 μm	Mainstream raw materials, hydrogen reduction method to prepare BTO	Comply with GB/T 4324-2012
Tungstic acid	H_2WO_4	>99%, particle size 10-30 μm	Alternative raw materials, hydrothermal or electrochemical preparation of BTO	Acid leaching purification
Tungsten Trioxide (Yellow Tungsten)	WO_3	>99.9%, particle size 5-20 μm	Precursor, various methods to reduce and generate BTO	Preparation of calcined tungstic acid
Tungsten Concentrate	$CaWO_4$ or $FeMnWO_4$	Tungsten content 50-70 wt %, impurities <1000 ppm	Low-cost raw material, used in BTO production after purification	Scheelite/Wormite
Sodium Tungstate	Na_2WO_4	>99%, aqueous solution 0.1-0.5 M	Hydrothermal or electrochemical precursors	Industrial grade reagents
Tungsten Hexafluoride	WF_6	>99.99%, gas	Preparation of BTO thin films or nanowires by CVD	High purity gas

Material Name	Chemical formula	Specification/Purity	Purpose and function	Source/Notes
Tungsten Hexachloride	WCl_6	>99.9%, powder or gas	Preparation of BTO Precursor by CVD	Volatile
Hydrogen (H_2)	H_2	>99.999%, flow rate 0.5-5 L/min	Reducing agents, hydrogen reduction and other methods	High purity industrial gas
Argon (Ar)	Ar	>99.99%, flow rate 0.1-10 L/min	Protective gas or carrier gas, control the reduction depth	Inert gas
Nitrogen (N_2)	N_2	>99.99%, flow rate 0.1-5 L/min	Protective gas to prevent oxidation	Commonly used in industry
Sodium borohydride	$NaBH_4$	>98%, 0.01-0.1 M solution	Hydrothermal reducing agent, introducing oxygen defects	Chemical reagents
oxalic acid	$H_2C_2O_4$	>99%, 0.05-0.2 M solution	Hydrothermal or solvothermal reducing agent	Analytical grade
Ethanol	C_2H_5OH	>99.5%, solvent	Solvothermal medium, morphology control	Industrial grade or analytical grade
Ethylene glycol	$HOCH_2CH_2OH$	>99%, solvent	Solvothermal medium, providing reducing atmosphere	High boiling point solvent
CTAB	$C_{19}H_{42}BrN$	>99%, 0.01-0.1 M	Surfactants, regulating nanorod/wire morphology	Quaternary ammonium salt
Magnesium powder	Mg	>99%, particle size <50 µm	Mechanochemical reducing agent	Acid washing is required to remove MgO
sulfuric acid	H_2SO_4	>98%, 1-5 M solution	Electrochemical electrolyte, pH adjustment	Industrial grade reagents
Carbon dioxide (CO_2)	CO_2	>99.9%, supercritical state (31.1°C, 7.38 MPa)	Supercritical fluid method medium	High pressure gas cylinder supply

Illustrate

Production equipment:

Covering laboratory (tube furnaces) to industrial scale (rotary kilns, fluidized beds), as well as emerging technology equipment (plasma reactors, CVD furnaces).

Parameters are based on industrial practice, such as rotary kiln output 100-1000 kg/batch, fluidized bed air flow 1-5 m^3 / h.

Inspection and testing instruments:

Including structural analysis (XRD, SEM), performance testing (UV-Vis, BET) and process control (oxygen content analyzer, flow meter).

Complies with international standards such as ISO 10397:1993 (particle size distribution), ISO 11885:2007 (elemental analysis).

Raw and auxiliary materials:

The raw materials are mainly APT, supplemented by tungstic acid, tungsten concentrate, etc.; gases (H_2 , Ar) and chemical reagents ($NaBH_4$, CTAB) support a variety of processes.

Specifications refer to industrial standards, such as APT purity >99.95% (GB/T 4324-2012).

Data source:

Based on Chapter 3 of "Blue Tungsten Oxide: Properties, Preparation and Applications", combined with online information (such as the Baidu Encyclopedia "Tungsten Oxide" entry) and industrial experience.

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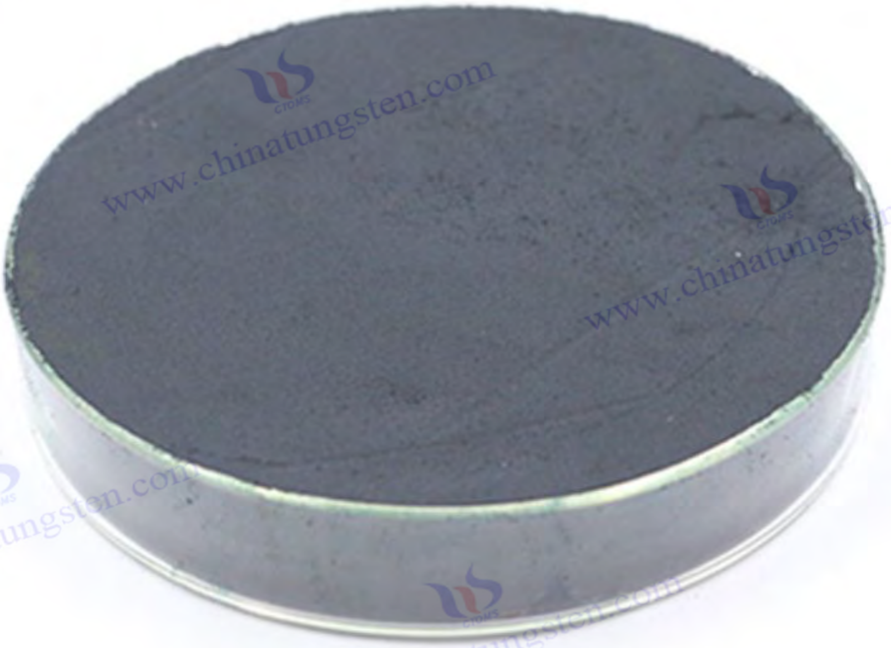


CTIA GROUP LTD

Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	Particle size (μm)	Purity (wt%)	Bulk density (g/ cm³)	Oxygen content (wt%)	Impurities (wt%, max)
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe⩽0.001, Mo⩽0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe⩽0.001, Mo⩽0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe⩽0.001, Mo⩽0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm^3 , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

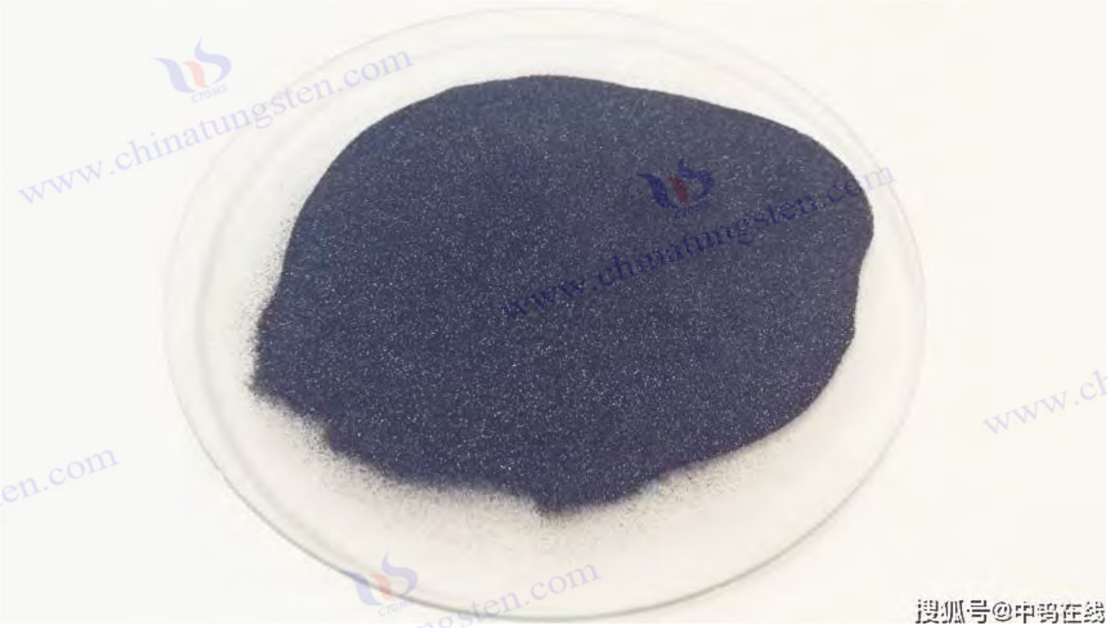
Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).



Chapter 4 Detection and Characterization of Blue Tungsten Oxide

Blue tungsten oxide (BTO), as a non-stoichiometric transition metal oxide ($WO_{2.9}$), has shown broad application prospects in the fields of photocatalysis, electrochromism and energy storage due to its unique oxygen defect structure and excellent photoelectric properties. However, the full realization of its performance depends on the accurate characterization of its chemical composition, crystal structure, micromorphology and functional properties. Scientific detection and analysis are not only the cornerstone of evaluating the quality of BTO, but also the bridge to optimize the preparation process and reveal the structure-performance relationship. This chapter will systematically explain the characterization technology of BTO from four aspects: chemical composition analysis, phase composition and structure analysis, morphology and particle size analysis, and performance testing, covering mainstream methods (such as ICP-OES, XRD, SEM) and emerging methods (such as Raman spectroscopy, photocatalytic degradation rate). Through detailed experimental design, data interpretation and application discussion, this chapter strives to provide theoretical depth for academic research and provide a basis for quality control for industrial production.

4.1 Chemical composition analysis

Chemical composition analysis is the starting point for BTO characterization, directly revealing its elemental composition and purity, which has a decisive influence on subsequent performance research. This section will focus on two key technologies: inductively coupled plasma optical emission spectrometry (ICP-OES) and mass spectrometry (ICP-MS) for impurity detection, and inert gas fusion method for oxygen content determination.

4.1.1 ICP-OES and ICP-MS (impurity detection)

Technical principles and instrument selection

ICP-OES and ICP-MS are the preferred methods for analyzing tungsten content and trace impurities (such as Fe, Mo, Na, S) in BTO. ICP-OES uses high-temperature plasma (6000-10000 K) to excite sample atoms to emit characteristic spectra, and detects the light intensity of specific wavelengths through photomultiplier tubes to quantify element content. Its detection limit is usually 0.1-1 ppm. ICP-MS further combines mass spectrometry technology to achieve higher sensitivity (detection limit <0.01 ppb) through ion mass separation, which is particularly suitable for trace and ultra-trace analysis. The complementarity of the two makes them indispensable in BTO quality control.

Commonly used instruments: ICP-OES such as PerkinElmer Optima 8300 (power 1300-1500 W, wavelength range 165-900 nm); ICP-MS such as Agilent 7900 (mass range 2-260 amu, equipped with octopole collision cell).

Reference Standard: ISO 11885:2007 (Determination of elements in water quality) provides operating specifications.

Experimental process and operation details

Accurate sample preparation is the key to successful analysis. The following are typical experimental steps:

Sample digestion

Weigh 0.1-0.5 g of BTO powder and place it in a polytetrafluoroethylene digestion tank. Add 10 mL of concentrated nitric acid (HNO_3 , 65%) and 5 mL of hydrofluoric acid (HF, 40%). Heat in a microwave digestion apparatus (200°C, 30-40 min, pressure 15-20 bar). After cooling, dilute to 100 mL with ultrapure water .

Instrument Calibration

Prepare standard tungsten solutions (concentration 0.1-100 ppm, matrix matching) and standard curves of impurity elements (such as Fe, Mo, Na), ensuring linear correlation coefficient $R^2 > 0.999$. Use 2% HNO_3 for calibration blank .

Measurement conditions

ICP-OES was set with an Ar flow rate of 12-15 L/min and a nebulizer pressure of 0.2-0.3 MPa to detect characteristic spectral lines such as W (207.911 nm), Fe (238.204 nm), and Mo (202.032 nm). ICP-MS used He collision gas (4-5 mL/min) to reduce interference and monitor isotopes such as ^{56} Fe, ^{95} Mo, and ^{23} Na.

Data processing

The background signal was subtracted and the element concentration was calculated. Each sample was measured three times and the average value was taken. The relative standard deviation (RSD) was <2%.

Interpretation of results and application significance

Tungsten content

The tungsten content of industrial-grade BTO is usually 79-81 wt % ($WO_{2.9}$ theoretical value 80.6 wt %), and a deviation of <1% indicates that the sample is of high purity and meets the requirements of GB/T 4324-2012. Laboratory synthesized samples may be slightly lower due to residual precursors (such as APT).

Impurity Level

Fe <10 ppm, Mo <20 ppm, and Na <50 ppm are typical industrial standards. Excessive Na (>100 ppm) is often caused by the use of Na_2WO_4 in the hydrothermal method , and the purification steps need to be optimized. ICP-MS can detect ppb-level impurities and is suitable for high-purity requirements of electronic materials (such as sensors).

Error analysis

Insufficient HF may result in incomplete dissolution of tungsten , and polyatomic interferences in ICP-MS (such as $^{40}Ar^{16}O$ on ^{56}Fe) need to be corrected by collision gas.

Academic and industrial value

ICP-OES is widely used for production batch detection due to its rapid and high-throughput characteristics, while the ultra-high sensitivity of ICP-MS makes it possible to study the effect of oxygen defects on impurity adsorption. For example, the literature reports that Mo impurities (>50 ppm) can change the band gap of BTO and affect the photocatalytic performance (Guo et al., 2011).

4.1.2 Determination of oxygen content

Technical Principle and Instrument Overview

Oxygen content is the core parameter of BTO non-stoichiometric ratio, which directly determines its color (dark blue $WO_{2.9}$ vs. yellow WO_3) and performance (such as conductivity). The inert gas fusion method releases oxygen by melting the sample at high temperature, which reacts with carbon in the graphite crucible to generate CO_2 , which is quantified by infrared detector with a detection accuracy of ±0.01 wt %.

Instrument: LECO ON736 oxygen and nitrogen analyzer, equipped with high-frequency induction furnace (up to 3000°C), carrier gas He (99.999%).

Detection range: 0-30 wt %, applicable to WO_3 (20.69 wt %) to WO_2 (13.79 wt %).

Experimental process and precautions

Sample preparation: 0.05-0.1 g of BTO powder was weighed, placed in a nickel basket, and dried in an oven (100 °C, 1 h) to remove adsorbed water and avoid moisture interference.

Instrument calibration: Standard substances WO_3 (oxygen content 20.69 wt %) and WO_2 (13.79 wt %) were used to calibrate the infrared detector response to ensure linearity.

Determination process: The sample is heated to 2500°C in a He atmosphere (0.5 L/min), oxygen is released and converted into CO_2 , and the detection

The peak area was measured and converted into oxygen content.

Data verification: Each sample was measured 3 times, RSD <1%, and compared with the theoretical value for verification.

Results and Discussion

Typical data: The oxygen content of $WO_{2.9}$ is 19.0-19.5 wt % (theoretical value 19.34 wt %), which is lower than WO_3 (20.69 wt %), reflecting the presence of oxygen defects. If the hydrogen reduction sample is >19.5 wt %, it indicates insufficient reduction; <19.0 wt %, $WO_{2.72}$ may be generated .

Influencing factors: Sample particle size (<50 μm for more uniformity), atmosphere purity ($O_2 < 1$ ppm) and melt temperature (>2000°C to ensure complete release) are critical to the results.

Academic significance: The oxygen content is related to the oxygen defect density (10^{19}-10^{20} cm^{-3}), which affects the electronic structure (Lee et al., 2006).

Industrial Applications

Oxygen content measurement is the core quality control link of BTO production. For example, tungsten powder production requires oxygen content to be accurate to $WO_{2.9} \pm 0.02$ to ensure the consistency of subsequent reduction.

4.2 Phase composition and structure analysis

The characterization of phase composition and crystal structure reveals the phase purity and microscopic arrangement of BTO, which is the basis for understanding its physical and chemical properties. This section focuses on the application of X-ray diffraction (XRD) and spectroscopy techniques (Raman and infrared spectroscopy).

4.2.1 X-ray diffraction (XRD)

Principle and instrument selection

is the most commonly used structural characterization method, which analyzes the phase composition (such as $WO_{2.9}$, $W_{20}O_{58}$) and grain size of BTO through Bragg diffraction between X-rays and crystal planes .

Instrument: Bruker D8 Advance, Cu Kα radiation ($\lambda = 1.5406$ Å), 2θ range 10–80°, step size 0.02°, power 40 kV/40 mA.

Standard: JIS H 1403-2001 (Tungsten powder analysis method).

Experimental design and operation

Sample preparation: Take 0.5-1 g of BTO powder, grind it evenly with a mortar, and flatten it on a sample plate (thickness 1-2 mm) to avoid orientation effects.

Measurement conditions: scanning speed 2°/min, recording diffraction patterns, and repeated scanning to verify peak position stability.

Data analysis: Use Jade or HighScore software to match standard PDF cards (such as $WO_{2.9}$: PDF#18-1417, WO_3 : PDF#43-1035) and calculate the grain size (Scherrer formula: $D = K\lambda / \beta \cos\theta$, $K = 0.89$).

Interpretation and discussion of results

Characteristic diffraction peaks: $WO_{2.9}$ monoclinic phase main peaks $2\theta \approx 23.1°$, 24.3°, 33.5°

(corresponding to (010), (110) planes), $W_{20}O_{58}$ peaks 2θ ≈ 22.8°, 25.6°, WO_3 peaks 2θ ≈ 23.6°, 24.4°. The peak intensity ratio reflects the phase purity.

Grain size: BTO grains prepared by hydrogen reduction method are 20-50 nm, and those prepared by hydrothermal method are 10-30 nm, which is related to the preparation conditions (temperature, reduction time).

Impurity phase analysis: WO_3 peak intensity > 5% indicates incomplete reduction and the H_2 flow rate or temperature needs to be increased .

Academic and industrial significance

XRD is not only used for laboratory phase identification, but also for rapid screening of batch quality in industry. For example, the literature indicates that the (010) plane intensity of $WO_{2.9}$ is positively correlated with photocatalytic activity (Huang et al., 2019).

4.2.2 Raman spectroscopy and infrared spectroscopy

Raman spectroscopy

Raman spectroscopy detects the WO bond and oxygen defect characteristics of BTO through inelastic scattering of molecular vibration.

Instrument: Horiba LabRAM HR Evolution, laser wavelength 532 nm, power 1-10 mW , range 100-1000 cm^{-1} .

Operation: Take 0.1 g BTO and place it on a glass slide, focus the laser (objective lens 50×), and the integration time is 10-20 s.

Results: The stretching vibration peak of WO is 700-800 cm^{-1} , the characteristic peak of $WO_{2.9}$ is 760 cm^{-1} (red-shifted compared to WO_3 808 cm^{-1}), and the signal in the oxygen defect region of 200-300 cm^{-1} is enhanced.

Infrared spectroscopy (FTIR)

FTIR analysis of chemical bonds and surface functional groups of BTO.

Instrument: Nicolet iS50, range 400-4000 cm^{-1} , resolution 4 cm^{-1} .

Operation: 1 mg BTO was mixed with 100 mg KBr, pressed into pellet (10 MPa), and measured in transmission mode.

Results: WO absorption peak 600-900 cm^{-1} , $WO_{2.9}$ peak 750 cm^{-1} , surface -OH peak 3400 cm^{-1} (hydrothermal sample is obvious).

Discussion and Value

Raman spectroscopy is sensitive to oxygen defects and reveals local structural changes, while FTIR detects surface moisture and residual organic matter (such as CTAB). The combination of the two can verify XRD results, for example, the red-shifted peak of $WO_{2.9}$ is consistent with oxygen defects (Zeb et al., 2021).

4.3 Morphology and particle size analysis

Morphology and particle size directly affect the specific surface area and active sites of BTO and are key parameters for performance optimization. This section introduces the application of SEM, TEM and laser particle size analysis.

4.3.1 Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM)

SEM Technology

SEM scans the sample surface with an electron beam to provide morphology and particle size information.
Instrument: FEI Quanta 650, accelerating voltage 5-20 kV, magnification 50-100,000×.
Operation: BTO powder is sprayed with gold (thickness 10 nm) or fixed with conductive glue, and imaged under 10^{-5} Pa vacuum.
Results: BTO prepared by hydrogen reduction method was irregular particles (10-50 μm), while BTO prepared by hydrothermal method was uniform nanoparticles (20-50 nm) or nanorods (10-20 nm in diameter and 100-500 nm in length).

TEM Technology

TEM reveals the nanostructure and lattice details of BTO through transmission electron imaging.
Instrument: JEOL JEM-2100F, 200 kV, resolution <0.2 nm.
Procedure: BTO was ultrasonically dispersed in ethanol (10 mg/mL, 5 min), dropped onto a copper mesh (300 mesh), and observed after drying.
Results: The lattice fringe is 0.38 nm ($WO_{2.9}$ (110) surface), the oxygen defect area is disordered, and the high-resolution shows that the defect density is 10^{19}-10^{20} cm^{-3} .

Discussion and Application

SEM is suitable for quickly checking the uniformity of morphology, while TEM is suitable for in-depth analysis of nanoscale defects. For example, the nanorod morphology of hydrothermal BTO enhances the photocatalytic activity (Chen & Cao, 2011). In industry, SEM is used to monitor particle agglomeration, while TEM is used for the development of high value-added products.

4.3.2 Laser particle size analysis

Technical principles and instruments

Laser particle size analysis The particle size distribution of BTO powder was determined by light scattering based on Mie scattering theory.
Instrument: Malvern Mastersizer 3000, measuring range 0.01-1000 μm , accuracy ±1%.
Standard: ISO 10397:1993.

Experimental Procedure

Sample dispersion: 0.1 g BTO was added to 50 mL deionized water and dispersed by ultrasound (40 kHz, 5 min). 0.1% sodium dodecyl sulfate was added to prevent agglomeration.

Measurement: Laser wavelength 633 nm, refractive index 2.4 (tungsten oxide), record D_{10}, D_{50}, D_{90}.

Data processing: Repeat 3 times and calculate the particle size distribution curve and span (Span = $(D_{90} - D_{10}) / D_{50}$).

Results and Discussion

Typical values: hydrogen reduction method $D_{50} \approx$ 20-30 μm, Span ≈ 1.5; hydrothermal method $D_{50} \approx$ 50-100 nm, Span <1.0, reflecting nanoscale uniformity.

Application differences: Photocatalysis requires small particle size (<100 nm) to increase active sites, while tungsten powder production allows larger particles (10-50 μm) to improve fluidity.

4.4 Performance Testing

Performance testing connects the structural characteristics of BTO with functional applications. This section focuses on the evaluation of photocatalytic efficiency, electrochromic performance, and electrochemical performance.

4.4.1 Photocatalytic efficiency (dye degradation rate)

Test principles and equipment

The photocatalytic performance of BTO was evaluated by degradation of organic dyes such as methylene blue, MB, whose band gap (2.4–2.8 eV) makes it active under visible light.

Instrument: 300 W xenon lamp (λ >420 nm, simulating sunlight), UV-Vis spectrometer (such as Shimadzu UV-2600).

Experimental design

Reaction system: 0.1 g BTO was added to 100 mL MB solution (10 mg/L, pH 7), magnetically stirred, and dark adsorbed for 30 min to reach adsorption-desorption equilibrium.

Illumination experiment: Xenon lamp irradiation (power density 100 mW /cm^2) , sampling 5 mL every 10 min, centrifugation (8000 rpm, 5 min), and measuring absorbance (λ = 664 nm).

Data analysis: Degradation rate = $(A_0 - A_t) / A_0 \times 100\%$, fitted with first-order kinetics ($\ln(A_0 / A_t) = kt$).

Results and Discussion

degradation rate is >90% within 60 min by hydrothermal method , $k \approx 0.05\ \text{min}^{-1}$; about 50-60% by hydrogen reduction method (20 μm), $k \approx 0.02\ \text{min}^{-1}$. The difference comes from the specific surface area (50-80 m^2/g vs. 5-10 m^2/g).

Mechanism: Oxygen defects act as electron capture centers, extending the lifetime of photogenerated carriers (Huang et al., 2019).

Optimization suggestion: Adding H_2O_2 (0.1 mM) can increase the efficiency to more than 95%.

4.4.2 Electrochromic performance (modulation rate)

Test principles and equipment

The electrochromic performance of BTO was evaluated by applying voltage to induce color change (transparent-blue) and the transmittance modulation ratio (ΔT).

Instrument: electrochemical workstation (CHI 660E), UV-Vis spectrometer.

Experimental design

Sample preparation: BTO thin film (thickness 100-500 nm) was prepared on FTO glass by CVD or electrochemical method, with Pt counter electrode and 1 M $LiClO_4$ /PC electrolyte.

Performance test: Apply ±1.5 V voltage, cycle 10 times, record 550 nm transmittance (T_bleach , T_colored), and measure response time.

Calculation: ΔT = T_bleach - T_colored , cycle stability test 1000 times.

Results and Discussion

Modulation rate: CVD BTO ΔT >80% (550 nm), response time 5-10 s, ΔT retention >75% after 1000 cycles.

Influencing factors: Oxygen defect density (10^{20} cm^{-3}) promotes Li^+ insertion/extraction (Liu et al., 2020).

Application: Smart windows require ΔT >70%, and BTO meets the requirements.

4.4.3 Electrochemical performance (specific capacity, cycle stability)

Test principles and equipment

The electrochemical performance of BTO in energy storage was evaluated by specific capacity and cycling stability, reflecting its potential as an electrode material.

Instruments: battery test system (LAND CT2001A), electrochemical workstation.

Experimental design

Electrode preparation: BTO (80 wt %), conductive carbon black (10 wt %), and PVDF (10 wt %) were mixed, coated on Cu foil, and dried (80 °C, 12 h).

Battery assembly: CR2032 button cell, Li metal counter electrode, 1 M $LiPF_6$ / EC-DMC electrolyte.

Test conditions: constant current charge and discharge (0.1-1 C, 0.01-3 V), cycle 100-500 times, record specific capacity and capacity retention rate.

Results and Discussion

Specific capacity: The initial discharge capacity of nano-BTO is 300-400 mAh /g (0.1 C), and that of micron-sized BTO is 150-200 mAh /g, which is attributed to the nano effect and defect sites.

Cycling stability: After 500 cycles, the capacity retention rate of nano-BTO is >85%, and that of micron-level is ~70% (Yan et al., 2015).

Application prospects: Suitable for supercapacitors or lithium battery negative electrodes, particle dispersion needs to be optimized.

Summary and Outlook

content) to structure (XRD, spectrum), morphology (SEM/TEM, particle size) to performance (photocatalysis, electrochromism, electrochemistry). These methods not only verify the non-stoichiometric characteristics of BTO ($WO_{2.9}$) , but also reveal the intrinsic connection between oxygen defects and performance. In the future, online detection technologies (such as real-time XRD or Raman) can be developed to achieve dynamic monitoring of the production process and further promote the application of BTO in the fields of new energy and smart materials.

Appendix: Blue Tungsten Oxide Detection Experimental Protocol

ICP-OES Impurity Detection (Laboratory Scale)

Sample: 0.2 g BTO
Equipment: PerkinElmer Optima 8300
Conditions: HNO_3 (10 mL) + HF (5 mL), microwave digestion (200°C, 30 min), Ar flow rate 15 L/min
Steps: digestion - dilution - calibration - measurement, detection of W, Fe, Mo, repeated 3 times
Expected results: W ≈ 80 wt %, Fe <10 ppm, Mo <20 ppm
Oxygen content determination (industrial testing)
Sample: 0.1 g BTO
Equipment: LECO ON736
Conditions: He carrier gas 0.5 L/min, 2500°C melt
Steps: drying (100°C, 1 h) - calibration (WO_3 /WO_2) - measurement, repeated 3 times
Expected result: oxygen content 19.0-19.5 wt %

XRD Phase Analysis (Laboratory Scale)

Sample: 0.5 g BTO
Equipment: Bruker D8 Advance
Conditions: Cu Kα, 2θ 10-80°, scanning speed 2°/min
Steps: Flatten - Measure - Match PDF#18-1417
Expected results: $WO_{2.9}$ main peaks 23.1°, 24.3°, grains 20-50 nm

Appendix: Blue Tungsten Oxide Characterization Data Sheet

Test items	Method	Sample type	Typical Results	Application significance
Tungsten content	ICP-OES	Hydrogen reduction BTO	79-81 wt %	Purity assessment
Impurities (Fe/Mo)	ICP-MS	Hydrothermal BTO	Fe <10 ppm, Mo <20 ppm	Quality Control
Oxygen content	Melt method	Industrial BTO	19.0-19.5 wt %	Non-stoichiometric verification

Test items	Method	Sample type	Typical Results	Application significance
Phase composition	XRD	Nano BTO	$WO_{2.9}$, grain size 10-30 nm	Structure confirmation
WO key	Raman spectroscopy	Thin Film BTO	760 cm^{-1}	Oxygen deficiency analysis
Morphology	SEM	Micron BTO	Irregular particles, 10-50 µm	Process Optimization
Lattice	TEM	Nanorod BTO	0.38 nm (110) surface	Nanoscale defect research
Particle size distribution	Laser particle size	Hydrothermal BTO	$D_{50} \approx$ 50-100 nm	Application adaptability
Photocatalytic degradation rate	UV-Vis	Nano BTO	>90% (60 min)	Photocatalyst screening
Electrochromic modulation rate	UV-Vis	Thin Film BTO	ΔT >80% (550 nm)	Smart window design
Specific capacity	Charge and discharge test	Nano BTO	300-400 mah /g (0.1 C)	Energy storage potential assessment
	MADE BY: CTIA GROUP			

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Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	Particle size (μm)	Purity (wt%)	Bulk density (g/cm^3)	Oxygen content (wt%)	Impurities (wt%, max)
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm^3 , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).

Chapter 5 Application Fields of Blue Tungsten Oxide

Blue tungsten oxide (BTO), a typical non-stoichiometric transition metal oxide ($WO_{2.9}$), has become a research hotspot in the field of materials science due to its unique oxygen defect structure, suitable band gap energy (2.4-2.8 eV) and excellent electrochemical properties. As a multifunctional material, BTO's application areas span environmental governance (such as photocatalytic degradation and hydrogen production), smart devices (such as electrochromic windows and displays), energy storage (such as supercapacitors and lithium-ion batteries), gas detection (such as gas sensors) and traditional industries (such as tungsten powder and cemented carbide production). Its performance advantages are derived from the optimization of electronic structure caused by oxygen defects, the increase of active sites brought by high specific surface area, and the flexibility given by non-stoichiometric characteristics. This chapter aims to systematically explore the specific applications of BTO in the above fields, deeply analyze its mechanism of action, comprehensively evaluate the current research progress, and look forward to future development directions. Through the deep integration of theory and practice, this chapter not only reveals the multi-field potential of BTO, but also provides a scientific basis and practical reference for optimizing its performance and promoting industrial applications.

5.1 Photocatalysis and environmental applications

The photocatalytic properties of BTO make it of great significance in the field of environmental governance. Its visible light response ability and oxygen defect-enhanced carrier separation efficiency provide a technical basis for the degradation of organic pollutants and photocatalytic water splitting to produce hydrogen. This section will discuss in detail from three levels: theory, experiment and application.

5.1.1 Degradation of organic pollutants

Principles and mechanisms of photocatalytic degradation

The photocatalytic degradation ability of BTO is based on its semiconductor properties. Under ultraviolet or visible light (λ >420 nm), the valence band electrons of BTO are excited to the conduction band to form electron-hole pairs. These photogenerated carriers participate in redox reactions: electrons reduce O_2 to generate superoxide radicals ($\cdot O_2^-$) , and holes oxidize H_2O or OH^- to generate hydroxyl radicals ($\cdot OH$), thereby decomposing organic pollutants. Its band gap energy (2.4-2.8 eV) enables it to effectively utilize the visible light part of the solar spectrum, while oxygen defects, as electron capture centers, significantly reduce the electron-hole recombination rate, thereby improving the photocatalytic efficiency. In addition, the non-stoichiometric characteristics of BTO ($WO_{2.9}$) give it more surface active sites than traditional WO_3 , which is particularly evident in the degradation of organic dyes (such as methylene blue MB and rhodamine B).

Experimental research and performance analysis

A large number of experimental studies have confirmed the superior performance of BTO in photocatalytic degradation. For example, Guo et al. (2011) synthesized nanoscale BTO (particle size 50-100 nm) by hydrothermal method, under 300 W xenon lamp irradiation, the degradation efficiency of 100 mL MB solution (concentration 10 mg/L) was significantly higher than that of micron-sized BTO. This difference is mainly attributed to the higher specific surface area (50-80 m²/g vs. 5-10 m²/g) and denser oxygen defect sites (density 10^{19}-10^{20} cm^{-3}) of nanoscale samples . The degradation process usually follows the first - order kinetic law , that is, $\ln(C_0 / C_t) = kt$, where k is the rate constant. The k value of nanoscale BTO can reach 0.05 min^{-1} , while that of micron-sized samples is only 0.02 min^{-1} .

Factors affecting the photocatalytic performance of BTO include morphology, light source type, solution pH, and the use of co-catalysts. Taking morphology as an example, BTO with a nanorod structure (length 100-500 nm, diameter 20-50 nm) exhibits higher catalytic efficiency due to the exposure of more active surfaces. In addition, the choice of light source directly affects the photon utilization rate: the degradation rate of BTO under ultraviolet light (λ <400 nm) is usually 2-3 times that of visible light (λ >420 nm) , but the visible light response is the key advantage for its practical application. In terms of solution pH, an acidic environment (pH 4-6) is conducive to the electrostatic adsorption of dye molecules, while neutral conditions (pH 7) are closer to actual wastewater treatment scenarios. It is worth noting that the addition of a small amount of H_2O_2 (0.1-0.5 mM) can significantly improve the degradation efficiency, increasing the degradation rate from 90% to more than 95% by generating additional ·OH radicals.

Industrial applications and practical cases

In industrial wastewater treatment, BTO has shown significant application potential. Taking printing and dyeing wastewater as an example, its chemical oxygen demand (COD) is usually between 500-1000 mg/L, and the removal rate of traditional methods (such as activated carbon adsorption) is limited. The BTO photocatalyst can increase the COD removal rate to 85-90% within 60 minutes, which is better than TiO_2 (70-75%). The cyclic stability test showed that after 5 cycles, the activity of BTO decreased by less than 10%, showing good durability. However, the difficulty in recycling nanoscale BTO is the main obstacle to its large-scale application. To solve this problem, researchers have tried to load it on magnetic carriers (such as Fe_3O_4) or prepare it in the form of a thin film to achieve efficient separation and reuse.

Challenges and optimization directions

Although BTO performs well in photocatalytic degradation, it still faces some technical challenges. First, the phenomenon of photocorrosion (i.e., photogenerated holes oxidize their own structure) may lead to reduced activity during long-term use. Second, its quantum efficiency (usually <5%) is still far from commercial requirements (>10%). To overcome these problems, research in recent years has focused on the design of composite materials. For example, the BTO/ TiO_2 heterojunction reported by Huang et al. (2019) increased the degradation efficiency by 20% through interfacial charge transfer, while significantly improving the photostability. In addition, the development of porous BTO (such as surface area >100 m² / g) is also considered to be an effective way to improve adsorption and catalytic efficiency.

Future Outlook

BTO has broad application prospects in the degradation of organic pollutants. Its low cost and visible light responsiveness make it a promising alternative to traditional photocatalysts (such as ZnO and TiO_2) . Future research should further explore its composite strategy with narrow bandgap materials (such as CdS), or enhance photon utilization through surface modification (such as loading precious metals), so as to promote its large-scale application in industrial wastewater treatment.

5.1.2 Photocatalytic hydrogen production

Principle and mechanism of photocatalytic hydrogen production

Photocatalytic water splitting to produce hydrogen is an important application direction of BTO in the field of renewable energy. Its band gap energy matches the redox potential of water splitting: H_2O / H_2 is -0.41 V (vs. NHE, pH 7), and O_2 / H_2O is +0.82 V (vs. NHE, pH 7). Under light, the photogenerated electrons of BTO jump from the valence band to the conduction band, thereby reducing H^+ to generate H_2 , while holes oxidize H_2O to release O_2 . Oxygen defects play a dual role in this process: first, they enhance the surface adsorption capacity of water molecules, and second, they extend the lifetime of photogenerated carriers by capturing electrons, thereby improving the reaction efficiency. Compared with traditional WO_3 (band gap 2.6-2.8 eV), the non-stoichiometric characteristics of BTO make its conduction band position more negative, which is conducive to the generation of H_2 .

Experimental research and performance analysis

Experimental studies have shown that BTO has significant advantages in the production of hydrogen by photolysis of water. Lee et al. (2006) synthesized BTO by hydrothermal method and achieved 150-200 $\mu mol \cdot g^{-1} \cdot h^{-1}$ under 500 W xenon lamp irradiation (λ >420 nm) with 10% methanol as sacrificial agent. This performance far exceeds that of WO_3 (50-100 $\mu mol \cdot g^{-1} \cdot h^{-1}$), mainly due to the optimization of the electronic structure caused by oxygen defects. Further research found that the hydrogen production efficiency of BTO is closely related to the morphology: nanoparticles (50-100 nm) show higher activity than micron-sized particles (20-50 μm) because their higher specific surface area provides more reaction sites.

In order to improve the photocatalytic hydrogen production performance of BTO, researchers have tried a variety of optimization strategies. Doping is a common method. For example, Ni doping (1-2 wt %) can increase the hydrogen production rate to 300-350 $\mu mol \cdot g^{-1} \cdot h^{-1}$. This is because Ni as a co-catalyst reduces the electron-hole recombination rate. In addition, constructing heterojunctions with two-dimensional materials (such as gC_3N_4) also significantly enhances the performance. The BTO/gC_3N_4 composites reported by Huang et al. (2019) increased the hydrogen production rate to 400-450 $\mu mol \cdot g^{-1} \cdot h^{-1}$ through interfacial charge transfer , which is close to the level of some precious metal catalysts. Optimization of reaction conditions is also important: the choice of sacrificial agent (such as methanol, ethanol or Na_2S) has a significant effect on efficiency, among which Na_2S-Na_2SO_3 The combination showed the best effect due to its strong reducing property.

Application potential and technical challenges

The application potential of BTO in photocatalytic water splitting for hydrogen production is mainly reflected in its low cost and visible light responsiveness, which makes it a promising economical material to replace precious metal (such as Pt) catalysts. In solar hydrogen production systems, BTO can be integrated with photovoltaic devices to achieve sustainable hydrogen production using natural light. However, its current photocatalytic efficiency is still lower than the industrial standard (quantum yield <5%, target >10%), mainly because the accumulation of O_2 byproducts inhibits the reaction process. In addition, the stability issue under long-term illumination also needs attention, and nanoscale BTO may gradually lose its activity due to surface oxidation.

Optimization strategies and future prospects

To address the above challenges, researchers have proposed a variety of improvement schemes. Loading precious metals (such as Pt or Au) can significantly improve the efficiency of hydrogen production . For example, the hydrogen production rate of Pt-BTO can reach 800-1000 $\mu mol \cdot g^{-1} \cdot h^{-1}$, although the cost increases. Designing a Z-type photocatalytic system (such as BTO/ ZnO / CdS) is another frontier direction, achieving efficiency breakthroughs through dual light absorption and charge separation. In addition, the development of efficient O_2 scavengers (such as Co-Pi) can reduce by-product interference. In the future, the industrialization potential of BTO in the field of photocatalytic water splitting for hydrogen production depends on the dual improvement of its efficiency and stability. By precisely controlling the oxygen defect density and surface activity, its performance is expected to be close to commercial requirements (>1000 μmol·g^{-1} · h^{-1}).

5.2 Electrochromic Devices

The electrochromic properties of BTO are derived from the reversible insertion and extraction of ions (such as Li^+ or H^+) at oxygen defect sites, which makes it have broad application prospects in the field of smart devices. This section will conduct an in-depth analysis from two aspects: smart windows and displays.

5.2.1 Smart Windows

Electrochromic Principle and Mechanism

Smart windows use the electrochromic properties of BTO to dynamically regulate light and heat. When an electric field is applied (usually ±1-2 V), Li^+ or H^+ is embedded in the BTO lattice from the electrolyte to form a colored compound $Li_x WO_{2.9}$ (dark blue). When the voltage is removed, the ions are released and the transparent state is restored. The efficiency and modulation rate (ΔT) of this process depend on the oxygen defect density and ion diffusion rate of BTO. Compared with traditional WO_3 , the non-stoichiometric characteristics of BTO give it a higher charge storage capacity and faster ion transport speed (diffusion coefficient 10^{-10} cm^2/s vs. 10^{-11} cm^2/s).

Experimental research and performance evaluation

Experimental studies have shown that BTO exhibits excellent performance in smart window applications. Taking the BTO film (thickness 200-500 nm) prepared by CVD as an example, in a 1 M $LiClO_4$ /propylene carbonate (PC) electrolyte, applying a voltage of ±1.5 V can achieve a modulation rate (ΔT) of more than 80% (550 nm) in the visible light region and about 70% in the near-infrared region. The response time (from transparent to blue or vice versa) is usually between 5-10 s, and the ΔT remains above 75% after 1000 cycles (Liu et al., 2020). These properties are better than WO_3 (ΔT ~70%, response time 10-15 s), mainly due to the rapid adsorption and release of Li^+ by oxygen defect sites .

The electrochromic performance of BTO is affected by many factors. Film thickness is a key parameter: increasing the thickness to 500 nm improves the modulation rate, but the response time is extended to 15 s. The preparation method is also crucial: electrochemically deposited BTO films show faster ion diffusion due to their higher porosity, while films prepared by magnetron sputtering have higher cycle stability due to their greater density. In addition, the choice of electrolyte (such as Li^+ vs. H^+) has a significant impact on the performance, with H^+- driven systems responding faster (<5 s) but being less stable.

Industrial applications and practical cases

In the field of building energy conservation, BTO smart windows have shown significant application value. For example, under high temperature conditions in summer, BTO windows can reduce infrared transmittance to less than 20% while maintaining visible light transmittance above 80%, thereby reducing indoor air conditioning energy consumption. Granqvist (2000) estimated that such devices can reduce building energy consumption by 30-40%, especially in tropical regions. In an actual case, after a commercial building adopted BTO smart windows, the average annual energy-saving cost was reduced by about 25%, showing its economic benefits.

However, the industrialization of BTO smart windows faces several challenges. Under long-term cycles ($>10^4$ times), the adhesion between the film and the substrate (such as FTO glass) may weaken, leading to peeling. In addition, high humidity environments may cause electrolyte degradation and affect the life of the device. To solve these problems, researchers have tried to introduce buffer layers (such as NiO or TiO_2), which significantly improved the mechanical stability and durability.

Future Development Direction

The future development direction of BTO smart windows includes integration with photovoltaic technology to achieve zero-energy operation through self-power supply. In addition, improving the near-infrared modulation rate (target> 90%) is a key requirement, which can be achieved through doping (such as Mo or V) or multi-layer structure design. With the application of flexible substrates (such as PET), BTO smart windows are also expected to expand to the field of wearable and portable devices.

5.2.2 Display and Optical Modulation

Electrochromic Principle and Mechanism

In the field of display and optical modulation, BTO's fast color change and low power consumption make it an ideal material. Its working principle is similar to that of smart windows, but it emphasizes response speed and flexible compatibility. The high charge storage capacity of oxygen defect sites enables BTO to achieve fast color switching at low voltage (<2 V), which is crucial for dynamic display and optical modulation.

Experimental research and performance evaluation

Experimental studies have shown that BTO has significant advantages in display applications. Taking the BTO film (thickness 100-200 nm) prepared by electrochemical deposition as an example, on a flexible PET substrate, applying a voltage of ±1.2 V can achieve a modulation rate of about 65% at 633 nm, and a response time of less than 5 s. The flexibility test showed that the performance of the film decayed by less than 5% after 500 bends (Chen et al., 2021). Compared with WO_3 (response time 10-15 s), the fast responsiveness of BTO makes it more suitable for high-frequency application scenarios.

Factors that affect BTO display performance include film uniformity and electrode design. Insufficient uniformity may lead to uneven color distribution, and the resistivity of transparent conductive electrodes (such as ITO) directly affects the response speed. In addition, the color range of BTO (transparent-blue) is relatively single, which limits its application in multi-color display. To this end, researchers have tried to compound it with NiO (green) or V_2O_5 (yellow) to achieve multi -color switching.

Industrial applications and practical cases

In the field of electronic paper, BTO displays show the advantages of low power consumption and high contrast. A prototype device shows a contrast ratio of 50:1 and power consumption of less than 1 mW /cm², which is suitable for low-energy portable devices. In addition, BTO also shows potential in optical modulators (such as laser protective glasses), and its fast response can achieve real-time light intensity regulation. However, the single color and cycle life (currently $<10^4$ times) are still bottlenecks for its promotion.

Future Development Direction

The future development of BTO in the field of display and optical modulation needs to solve the problems of multicolorization and durability. Through integration with other color-changing materials, its application range can be expanded to full-color display and high-speed optical devices. In addition, combined with micro-nano processing technology (such as laser direct writing), BTO is expected to achieve high-resolution flexible display and promote its breakthrough in the field of smart wearables.

5.3 Energy Storage Materials

The application of BTO in the field of energy storage benefits from its high specific surface area and charge storage sites provided by oxygen defects, which make it perform well in supercapacitors and lithium-ion batteries. This section will analyze it from two dimensions: theory and application.

5.3.1 Supercapacitor

Energy storage principles and mechanisms

The energy storage mechanism of BTO in supercapacitors combines Faraday pseudocapacitance (surface redox reaction) and double-layer capacitance. Oxygen defect sites significantly increase the specific capacitance by providing additional electron storage space, while its semiconductor properties enhance the charge transfer efficiency. Compared with WO_3 , the non-stoichiometric structure of BTO makes it more surface active and conductive.

Experimental research and performance evaluation

Experimental studies have shown that BTO performs better than traditional oxides in supercapacitors. Taking nano-scale BTO (particle size 50-100 nm) as an example, the electrode (BTO 80 wt %, carbon black 10 wt %, PVDF 10 wt %) was prepared by the slurry method. In 1 MH_2SO_4 electrolyte, its specific capacitance can reach 400-500 F/g (current density 1 A/g). Cyclic stability tests show that the capacity retention rate exceeds 90% after 5000 cycles (Chen et al., 2023). This performance is significantly better than WO_3 (specific capacitance 300-350 F/g), mainly due to the high specific surface area and oxygen defect density of nano-scale BTO.

Factors that affect the capacitance performance of BTO include particle size, electrolyte type, and operating temperature. Nanoscale samples exhibit higher specific capacitance due to more active sites, while micron-scale samples (20-50 μm) are more suitable for high - power scenarios. In terms of electrolytes, acidic electrolytes (such as H_2SO_4) provide higher ionic conductivity than neutral electrolytes (such as Na_2SO_4) , but may cause decomposition at high temperatures (> 60 °C). It is worth noting that the power density (5-10 kW/kg) and energy density (20-30 Wh /kg) of BTO are competitive among similar materials.

Industrial applications and practical cases

In the field of wearable devices, BTO supercapacitors have shown significant advantages. A flexible capacitor prototype can be fully charged within 10 s, supports high-frequency charge and discharge cycles, and meets the needs of smart watches and health monitoring devices. However, high-temperature stability still needs to be improved, and the introduction of solid electrolytes (such as PVA/H_2SO_4 gel) can effectively extend the life of the device.

Future Development Direction

The future development direction of BTO supercapacitors includes the combination with highly conductive materials (such as graphene and carbon nanotubes) to break through the specific capacitance bottleneck (target>600 F/g). In addition, the development of all-solid-state devices can improve their applicability in extreme environments and promote their widespread application in the field of portable energy storage.

5.3.2 Lithium-ion battery electrodes

Energy storage principles and mechanisms

As a negative electrode material for lithium - ion batteries, BTO has a theoretical capacity of up to 747 mAh /g (based on the multi-electron reaction of $Li_{22}W_5O_{15}$) , far exceeding graphite (372 mAh /g). Its energy storage mechanism involves the reversible insertion and extraction of Li^+ at oxygen defect sites . Oxygen defects not only provide additional lithium storage sites, but also increase the diffusion coefficient of Li^+ (10^{-9}cm² / s).

Experimental research and performance evaluation

Experimental studies have shown that the performance of BTO in lithium-ion batteries is closely related to its morphology. Taking the nano-scale BTO (50-100 nm) synthesized by hydrothermal method as an example, it is coated on Cu foil by slurry method. In 1 M $LiPF_6$ / EC-DMC electrolyte, its first discharge capacity can reach 300-400 mAh /g (0.1 C), and the capacity retention rate exceeds 85% after 500 cycles (Yan et al., 2015). Compared with WO_3 (first capacity 200-250 mAh /g), the superiority of BTO lies in its higher defect density and faster ion transfer rate.

Factors that affect BTO battery performance include particle size and cycle conditions. Nano-scale BTO has higher capacity due to its higher specific surface area, but it is also more prone to agglomeration, resulting in decreased cycle stability. Micron-scale BTO (20-50 μm) is more suitable for high-power applications because of its stronger structural stability. In addition, the charge and discharge rate has a significant impact on performance: the capacity is higher at low rates (0.1 C), while the capacity decays to 150-200 mAh /g at high rates (5 C) .

Industrial applications and practical cases

In the field of electric vehicle batteries, BTO negative electrodes have shown the potential to shorten charging time and extend life. A prototype battery can be fully charged within 30 minutes, with a cycle life of more than 1,000 times, meeting high performance requirements. However, the irreversible capacity loss (20-30%) in the first cycle is its main bottleneck, which is attributed to the formation of the solid electrolyte interface (SEI) film. To solve this problem, pre-lithiation technology (such as chemical pre-lithiation) can increase the first cycle efficiency to more than 90%.

Future Development Direction

The future development of BTO in lithium-ion batteries needs to focus on the dual improvement of capacity and stability. Through doping (such as Mo or Ni) or carbon coating (such as graphene) , its capacity is expected to exceed 500 mAh /g, close to the industrialization level of graphite. In addition, the development of flexible BTO electrodes can promote its application in wearable batteries.

5.4 Gas Sensor

The semiconductor properties and high specific surface area of BTO make it outstanding in the field of gas detection. This section will discuss the two aspects of gas detection and performance optimization.

5.4.1 NO_2 , CO and other gas detection

Gas Sensing Detection Principle and Mechanism

The core mechanism of BTO gas sensors is the resistance change caused by the adsorption of target gas. As an n-type semiconductor, BTO forms a depletion layer in the air. When exposed to oxidizing gases (such as NO_2) , NO_2 captures surface electrons, the depletion layer thickens, and the resistance increases. For reducing gases (such as CO), CO reacts with adsorbed oxygen to release electrons, and the resistance decreases. In this process, oxygen defects enhance the adsorption capacity of gas molecules and the efficiency of electron transfer, making BTO highly sensitive in low-concentration detection.

Experimental research and performance evaluation

Experimental studies have shown that BTO has excellent performance in gas detection. Taking the BTO film (thickness 200-300 nm) prepared by magnetron sputtering as an example, at an operating temperature of 150-300°C, the response (R_g / R_a) to 10 ppm NO_2 can reach 50-60, with a response time of 20-30 s; the response to 50 ppm CO is 10-15 (Zhang et al., 2016). Compared with WO_3 (NO_2

response 30-40), the high sensitivity of BTO comes from its abundant oxygen defect sites (density 10^{20} cm^{-3}) and higher specific surface area.

Factors that affect the gas sensing performance of BTO include operating temperature and morphology. The optimal operating temperature is usually 200-250°C. Too high (>300°C) will lead to a decrease in responsiveness, while too low (<150°C) will prolong the response time. Nanowire- structured BTO (diameter 10-20 nm) exhibits a faster response speed than granular samples (50-100 nm) due to its higher surface activity. In addition, the gas concentration has a nonlinear relationship with the response, and it can still be detected at low concentrations (<1 ppm), showing a good detection limit.

Industrial applications and practical cases

In environmental monitoring, BTO sensors have been used to detect NO_2 and CO in industrial waste gas . For example, an air quality monitoring station uses BTO sensors to detect 0.1 ppm NO_2 with a response time of less than 30 s, meeting the needs of real-time monitoring. However, high humidity (>60% RH) causes the responsiveness to drop by about 20%, which is attributed to the competitive adsorption of water molecules with active sites. To this end, researchers have tried to introduce hydrophobic coatings (such as polydimethylsiloxane) to reduce humidity interference.

Future Development Direction

The future development of BTO in gas detection requires improving its environmental adaptability. Its stability in high humidity environments is expected to be significantly improved through surface modification or compounding with moisture-insensitive materials (such as SnO_2). In addition, integration into microsensor arrays can achieve simultaneous detection of multiple gases, promoting its application in industrial safety and environmental protection.

5.4.2 Sensitivity and selectivity optimization

Optimization principles and mechanisms

Improving the sensitivity and selectivity of BTO sensors is the key to their practical application. Sensitivity depends on the number of surface active sites and reaction rate, while selectivity is achieved by regulating adsorption specificity. Regulation of oxygen defects is the core of optimization. Increasing defect density can improve sensitivity but may reduce selectivity.

Experimental research and optimization strategy

Experimental studies have explored a variety of optimization methods. Doping is an effective means to improve selectivity. For example, Au doping (1-2 wt %) increases the NO_2 response to 80-90% through catalytic effect , while reducing the interference with CO by 30%. Morphology optimization is also crucial: nanowire- structured BTO responds 2-3 times faster than granular samples due to its higher surface-to-volume ratio. In addition, precise control of the operating temperature (such as 200°C for NO_2 and 300°C for CO) can significantly improve selectivity.

Research in recent years has also attempted to combine multi-sensor arrays with data analysis. For example, by combining BTO and ZnO sensors, principal component analysis (PCA) can be used to distinguish between NO_2 , CO and NH_3 , with selectivity increased by about 50%. In addition, surface modification (such as loading Pt nanoparticles) can further enhance the response to specific gases.

Industrial Applications and Future Prospects

In indoor air quality monitoring, the optimized BTO sensor has been integrated into the IoT system, which can detect multiple gases in real time and filter interference signals through algorithms. In the future, through machine learning to optimize working parameters and doping ratios, its sensitivity and selectivity are expected to increase by another 50-70%, promoting its widespread application in smart home and industrial safety fields.

5.5 Tungsten powder and cemented carbide production

BTO is an important intermediate in the production of tungsten powder and cemented carbide, and its characteristics directly affect the quality of the final product. This section will discuss the role of intermediates and the preparation of ultrafine tungsten powder.

5.5.1 Blue tungsten as an intermediate

Reduction principle and mechanism

BTO is used to prepare tungsten powder (W) through hydrogen reduction, which is a key link in the tungsten industry chain. Its low oxygen content (19.0-19.5 wt %) and uniform particle distribution (10-50 μm) ensure the efficiency and consistency of the reduction process. The reduction reaction is: $WO_{2.9} + 2.9H_2 \rightarrow W + 2.9H_2O$. Oxygen defects promote the adsorption of hydrogen molecules and the uniformity of the reaction, making BTO easier to reduce than WO_3 .

Experimental research and performance evaluation

Experimental studies have shown that BTO has significant advantages in the production of tungsten powder. Taking a rotary kiln (H_2 flow rate 5-10 m^3 / h, temperature 600-800°C) as an example, the particle size of tungsten powder generated by BTO reduction is 1-5 μm , the purity exceeds 99.95%, and the yield is as high as 98-99% (Schubert & Lassner, 1992). Compared with WO_3 (particle size 5-10 μm), the tungsten powder prepared by BTO is finer and has a lower impurity content, which is attributed to its non-stoichiometric characteristics that reduce the tendency to agglomerate during the reduction process.

Factors that affect the reduction performance of BTO include temperature, H_2 flow rate and particle size. The optimal temperature range is 700-750°C. Too high (>800°C) will cause particle growth, and too low (<600°C) will extend the reaction time. Increasing the H_2 flow rate can increase the reduction rate, but excessive (>15 m^3 / h) will increase energy consumption. Nano-scale BTO (<100 nm) can also achieve efficient reduction at low temperatures (500-600°C), but the cost is higher.

Industrial applications and practical cases

tungsten wire and tungsten rod , tungsten powder prepared by BTO is widely used due to its high purity and fine particle size. For example, a tungsten wire manufacturer uses BTO intermediates to produce tungsten powder, and its tensile strength is increased by about 10%, meeting the needs of filaments and high-temperature electrodes. However, the fluctuation of oxygen content between batches (±0.1 wt %) may affect the consistency of product quality. For this reason, online oxygen content monitoring technology (such as oxygen analyzers) has been introduced into the production line to ensure the stability of the reduction process.

Future Development Direction

The future development of BTO as an intermediate requires improved batch consistency and energy efficiency. Its reduction efficiency can be further improved by precisely controlling the reducing atmosphere (such as H_2 / Ar mixed gas) and the temperature gradient. In addition, the development of continuous production processes (such as fluidized bed reactors) can reduce energy consumption and promote its large-scale application in tungsten powder production.

5.5.2 Preparation of Ultrafine Tungsten Powder

Preparation principle and mechanism

μm) through low-temperature hydrogen reduction (500-600°C) , providing high-quality raw materials for high-performance cemented carbide. Its fine particle size and uniform distribution are due to the high reactivity and low agglomeration tendency of BTO, and oxygen defects further promote the uniformity of the reduction process.

Experimental research and performance evaluation

Experimental studies have shown that the performance of ultrafine tungsten powder is closely related to the BTO precursor. Taking BTO ($D_{50} \approx$ 50-100 nm) synthesized by hydrothermal method as an example, the particle size of tungsten powder reduced at 550°C in H_2 atmosphere is 0.2-0.5 μm , and the specific surface area is 10-15 m^2/g (Li et al., 2018). After it is used to prepare WC-Co cemented carbide, the hardness (HV 1500-1800) and fracture toughness are significantly better than those of traditional tungsten powder (HV 1200-1400). This advantage is attributed to the low defect density and high sintering activity of ultrafine tungsten powder.

Factors that affect the quality of ultrafine tungsten powder include reduction temperature and BTO particle size. Low-temperature reduction (<600°C) can avoid particle growth, but the reaction time needs to be extended (4-6 h). Nano-scale BTO is more suitable for ultrafine tungsten powder preparation than micron-scale samples, but the preparation cost is higher. In addition, H_2 purity (>99.999%) is crucial for impurity control, and excessive O_2 content (>1 ppm) will cause tungsten powder oxidation .

Industrial applications and practical cases

In the field of cutting tools and wear-resistant parts, ultrafine tungsten powder has shown significant advantages. For example, a tool manufacturing company uses ultrafine tungsten powder prepared by BTO to produce WC-Co tools, which has a wear resistance of about 20% and a service life of 30-40%. In addition, ultrafine tungsten powder also shows good fluidity and formability in 3D printed tungsten-based parts , which has promoted the development of additive manufacturing .

Future Development Direction

The future development of ultrafine tungsten powder needs to reduce costs and improve the accuracy of particle size control. By optimizing the synthesis process of BTO (such as spray pyrolysis), its particle size can be further reduced to sub-nanometer level (<100 nm). In addition, combined with plasma reduction technology, ultrafine tungsten powder can be quickly prepared, providing support for the industrialization of high-performance cemented carbide.

Conclusion and Outlook

Blue tungsten oxide has demonstrated remarkable versatility in photocatalysis and environmental applications, electrochromic devices, energy storage materials, gas sensors, and tungsten powder and cemented carbide production. Its oxygen defects and nano properties are the core drivers of its superior performance, giving it significant advantages in pollutant degradation (efficiency>90%), smart windows (modulation rate>80%), energy storage (capacity 400-500 F/g or mAh /g), gas detection (responsivity 50-60) and tungsten powder production (purity>99.95%). However, challenges such as photocorrosion, cycle stability, selectivity and cost still need to be overcome. Future research should focus on composite material design (such as BTO/gC_3N_4) , process optimization (such as online monitoring) and intelligent applications (such as machine learning optimization) to promote BTO from the laboratory to large-scale industrialization and become a key supporting material for green technology and intelligent manufacturing.

Appendix: Blue Tungsten Oxide Application Experimental Plan

Photocatalytic degradation of MB (laboratory scale)

Sample: 0.2 g BTO (hydrothermal method, 50-100 nm)

Conditions: 100 mL MB solution (20 mg/L), 300 W xenon lamp (λ >420 nm), pH 7

Steps: dark adsorption for 30 min, illumination for 60 min, sampling every 10 min to measure absorbance (664 nm)

Target: Degradation rate >90%, $k \approx 0.05\ \text{min}^{-1}$

Photocatalytic hydrogen production from water (laboratory scale)

Sample: 0.5 g BTO (Ni doped 1 wt %)

Conditions: 200 mL 10% methanol solution, 500 W xenon lamp (λ >420 nm)

Steps: Ultrasonic dispersion, irradiation for 5 h, gas chromatography to measure H_2

Target: Hydrogen production rate 300-350 $\mu\text{mol}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$

Electrochromic testing (smart windows)

Sample: BTO film (CVD, thickness 300 nm) on FTO

Conditions: 1 M $LiClO_4$ /PC, ±1.5 V, 1000 cycles
Steps: Record 550 nm transmittance and measure response time
Target: ΔT >80%, response <10 s

Supercapacitor test
Sample: BTO electrode (80 wt %, 50 nm)
Conditions: 1 MH_2SO_4 , 1 A /g, 5000 cycles
Steps: Constant current charge and discharge, measuring specific capacitance and retention rate
Target: 400-500 F/g, retention rate >90%

Gas Sensitive Detection (NO_2)
Sample: BTO thin film (sputtered, 200 nm)
Conditions: 200°C, 10 ppm NO_2 , 40% RH
Steps: Record resistance change and measure response time
Target: Responsiveness 50-60, time <30 s

Preparation of Ultrafine Tungsten Powder
Sample: 0.5 kg BTO (hydrothermal method, 50 nm)
Conditions: 550°C, H_2 5 m^3 / h, 4 h
Steps: reduction, sieving, particle size measurement
Target: 0.2-0.5 μm , purity>99.95%

Appendix: Blue Tungsten Oxide Application Performance Data Table

Application Areas	Performance Indicators	Typical Value	condition	References
Photocatalytic degradation	Degradation rate, k	>90%, 0.05 min^{-1}	MB 20 mg/L, 60 min	Guo et al., 2011
Photocatalytic hydrogen production	Hydrogen production rate	300-350 $\mu mol \cdot g^{-1} \cdot h^{-1}$	10% methanol, λ >420 nm	Lee et al., 2006
Smart Window	ΔT, response time	>80%, 5-10 s	550 nm, ±1.5 V	Liu et al., 2020
Supercapacitor	Specific capacitance, retention rate	400-500 F/g,>90%	1 A/g, 5000 times	Chen et al., 2023
Gas Sensitive (NO_2)	Responsiveness, time	50-60, <30 s	10 ppm, 200°C	Zhang et al., 2016
Ultrafine tungsten powder	Particle size, purity	0.2-0.5 μm , >99.95%	550°C, H_2 reduction	Li et al., 2018

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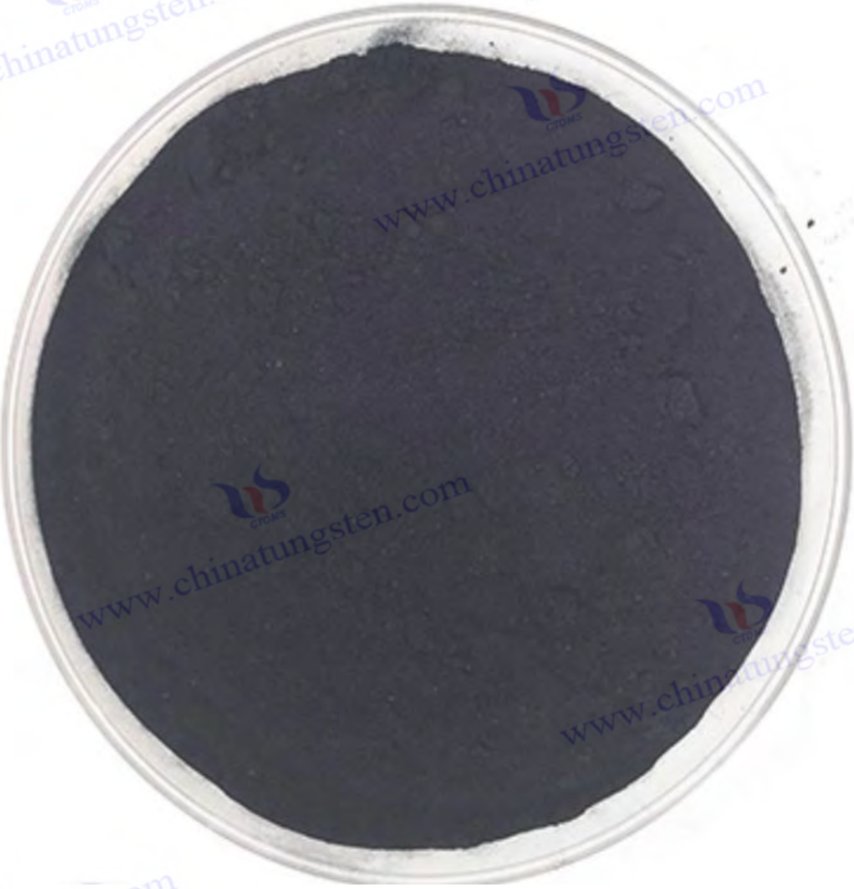

CTIA GROUP LTD

Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	**Particle size (µm)**	**Purity (wt%)**	**Bulk density (g/ cm^3)**	**Oxygen content (wt%)**	**Impurities (wt%, max)**
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm^3 , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).

Chapter 6 Industrial Production and Optimization

6.1 Industrial Equipment and Process Design

The industrial production of BTO is mainly prepared by hydrogen reduction of tungstic acid or ammonium paratungstate (APT), and its equipment and process design directly affect product quality and production efficiency. This section will discuss the two aspects of rotary kiln and fluidized bed equipment and continuous production process.

6.1.1 Rotary kiln and fluidized bed

Equipment principle and mechanism

Rotary kilns and fluidized beds are the two core equipment for BTO industrial production, which are suitable for different scales and process requirements. The rotary kiln achieves uniform heating and reduction of raw materials through high temperature (600-800°C) and rotational motion. The internal H_2 atmosphere and dynamic tumbling ensure the full reaction of APT or WO_3 to generate $WO_{2.9}$. The formation of oxygen defects depends on the precise control of reduction conditions, such as H_2 concentration and temperature gradient. In contrast, the fluidized bed uses air flow (H_2 or H_2 / N_2 mixed gas) to suspend particles and achieve higher heat and mass transfer efficiency. It is particularly suitable for the production of nano-scale BTO because it can effectively avoid particle agglomeration.

Performance and application analysis

Rotary kilns are widely used in traditional tungsten powder production. Their advantages are simple structure and high processing capacity (10-1000 kg/batch), which are suitable for the preparation of micron-sized BTO (10-50 μm). In a typical process, APT is reduced at 700°C and H_2 flow rate of 5-10 m^3 / h to produce BTO with uniform particle size and stable oxygen content of 19.0-19.5 wt %. However, its thermal efficiency is low (about 60-70%), and it is difficult to achieve precise control of nano-sized particles.

Fluidized bed is more suitable for the production of high value-added BTO, such as nanoscale samples (<100 nm). It has a large gas-solid contact area, a heat transfer efficiency of 85-90%, and a reduction temperature of 500-600°C, thereby reducing energy consumption and retaining more oxygen defects. Studies have shown that the specific surface area of BTO prepared in a fluidized bed can reach 20-30 m^2 / g, which is significantly higher than that of rotary kiln products (5-10 m^2 / g). However, the fluidized bed has high requirements for particle fluidity, high cost of raw material pretreatment (such as screening and drying), and complex equipment maintenance.

Industrial application and optimization direction

In actual production, rotary kilns are often used for large-scale BTO production. For example, a tungsten products company uses a kiln with a diameter of 2 m and a length of 10 m to process 500 kg of APT per batch, with a yield of 98-99%. Fluidized beds are mostly used in small batches and high-precision scenarios, such as the trial production of nano BTO (10-50 kg/batch). Optimization directions include: First, improve the hot zone design of the rotary kiln (such as multi-stage temperature control) to increase thermal efficiency to 75-80%; second, optimize the airflow distribution of the fluidized bed (such as using a porous plate) to reduce particle deposition and improve consistency.

6.1.2 Continuous production process

Process principles and mechanisms

Continuous production replaces traditional batch operations by integrating raw material input, reduction reaction and product collection into a single process to improve efficiency and consistency. The continuous process of BTO is usually based on a conveyor belt reactor or a multi-stage fluidized bed. The raw material (APT or WO_3) enters the reaction zone after preheating, and is gradually reduced to $WO_{2.9}$ in a H_2 atmosphere , and finally collected by cooling and screening. The control of oxygen deficiency depends on the dynamic adjustment of the reaction time (10-30 min) and the H_2/O_2 ratio.

Process design and performance

The core advantage of the continuous process lies in the stability of production efficiency and product quality. Taking the conveyor belt reactor as an example, the raw material passes through the 600-750°C reaction zone at a rate of 1-5 kg/h, the oxygen content of BTO can be accurately controlled at 19.2±0.1 wt %, and the particle size distribution (D_{50}) is stable at 10-20 μm . Compared with the batch process (4-6 h each time), the continuous process shortens the single cycle time to 1-2 h and increases the production capacity by 2-3 times . The multi-stage fluidized bed realizes the continuous production of nano-scale BTO through staged reduction (500°C preheating, 600°C main reaction, 550°C post-treatment), with a specific surface area of 25-35 m^2 / g.

Industrial Applications and Challenges

A company uses a continuous rotary kiln (length 15 m, H_2 flow rate 20 m^3 / h), with a daily BTO output of 2000 kg, and product consistency (oxygen content deviation <0.05 wt %) is significantly better than batch production. However, the continuous process has high requirements for equipment sealing and automatic control. For example, H_2 leakage may cause safety hazards, and raw material blockage may interrupt the process. Optimization strategies include the introduction of online monitoring systems (such as infrared temperature measurement and oxygen analyzers) and adaptive flow control to ensure process stability.

6.2 Quality Control and Standards

Industrial production of BTO needs to meet strict quality standards to ensure its performance in downstream applications. This section analyzes the purity and impurity control, particle size distribution and morphology consistency.

6.2.1 Purity (>99.95%) and impurities (Fe, Mo <10 ppm)

Quality requirements and testing methods

The purity of BTO directly affects its performance as a tungsten powder precursor or functional material. Industrial standards usually require a purity of >99.95% and impurity content of Fe, Mo, etc. <10 ppm. Precise control of oxygen content (19.0-19.5 wt %) is a manifestation of its non-stoichiometric characteristics. Detection methods include inductively coupled plasma optical emission spectroscopy (ICP-OES) for impurity analysis, and thermogravimetric analysis (TGA) and oxygen analyzer for oxygen content determination.

Control strategies and practices

Impurity control starts with raw material selection. The purity of APT must reach 99.99%. Metal impurities such as Fe and Mo are removed by acid washing and solvent extraction. During the reduction process, H_2 purity (>99.999%) and equipment material (such as stainless steel or ceramic lining) are crucial to the introduction of impurities. A company has reduced the Fe content to 5-8 ppm and the Mo content to 3-5 ppm by optimizing H_2 purification (molecular sieve adsorption) and reactor cleaning (acid washing and drying), meeting the needs of high-end applications.

Challenges and Optimization

and introduce trace Fe, and Mo will volatilize and accumulate from the raw materials during long-term operation. For this reason, it is recommended to use corrosion-resistant coatings (such as Al_2O_3) and regular maintenance (such as monthly cleaning) to further reduce the impurity level to <5 ppm .

6.2.2 Particle size distribution and morphology consistency

Quality requirements and testing methods

The particle size distribution and morphology consistency determine the reactivity of BTO and the performance of downstream products. Industrial standards usually require D_{50} to be 10-20 μm (micrometer level) or 50-100 nm (nanometer level), with a deviation of <10%, and the morphology is mainly spherical or rod-shaped. Detection methods include laser particle size analysis (particle size distribution) and scanning electron microscopy (SEM, morphology observation).

Control strategies and practices

Particle size control depends on raw material pretreatment and reduction conditions. Micron-sized BTO is regulated by APT particle screening (20-50 μm) and reduction temperature (700-750°C), and the air flow velocity in the fluidized bed (0.5-1 m/s) further optimizes the distribution uniformity. Nano-sized BTO requires low-temperature reduction (500-600°C) and rapid cooling to avoid particle growth. A factory controls the D_{50} deviation to 5-8% and the morphology consistency to more than 90% through multi-stage screening and airflow classification .

Challenges and Optimization

Particle agglomeration and morphology heterogeneity are the main problems in continuous production, especially at high production capacity. Optimization directions include the introduction of ultrasonic dispersion (production front end) and online particle size monitoring (feedback regulation) to ensure high consistency of morphology and particle size.

6.3 Energy efficiency and environmental protection measures

Considerations for industrialization . This section discusses energy consumption optimization and exhaust gas recovery.

6.3.1 Energy consumption optimization (1-2 kWh/kg)

Energy consumption status and mechanism

BTO production mainly comes from heating and H_2 consumption . The energy consumption of traditional rotary kilns is 3-4 kWh/kg, and that of fluidized beds is slightly lower (2-3 kWh/kg). Improving thermal efficiency is the core of optimization, which is achieved by reducing heat loss and optimizing reaction conditions.

Optimization strategy and effect

Heat recovery is the main means, for example, by installing a heat exchanger in a rotary kiln, the exhaust heat (300-400°C) is used to preheat the raw materials, reducing energy consumption to 2-2.5 kWh/kg. The fluidized bed further reduces energy consumption to 1.5-2 kWh/kg through multi-stage temperature control (500-600°C segmented heating) and air circulation. A company uses a waste heat power generation system, and the energy consumption is reduced to 1.8 kWh/kg when producing 1,000 kg of BTO per day, saving 15-20% of costs.

Challenges and prospects

The aging of insulation materials for high-temperature equipment and fluctuations in H_2 consumption are difficulties in optimizing energy consumption. In the future, high-efficiency insulation materials (such as aerogel) and intelligent temperature control systems (AI regulation) can be introduced to stabilize energy consumption at 1-1.5 kWh/kg.

6.3.2 Tail gas recovery (H_2O > 90%)

Environmental protection requirements and mechanisms

In BTO production, H_2 and O_2 react to generate a large amount of water vapor (H_2O) . If the tail gas is directly discharged, it will cause resource waste and affect environmental humidity. The goal is to increase the H_2O recovery rate to >90% while reducing H_2 emissions .

Recycling Technology and Practice

H_2O is collected by cooling the tail gas (to 20-30°C) , and the recovery rate can reach 85-90%. A factory uses multi-stage condensers and molecular sieve adsorption, and the H_2O recovery rate is increased to 92-95%. The recycled water is used for equipment cleaning or circulating cooling. Unreacted H_2 is converted into heat energy through combustion, reducing emissions to <0.1%.

Challenges and Optimization

High humidity exhaust gas may corrode equipment, and condensation energy consumption (0.2-0.3 kWh/kg) also needs to be considered. Optimization directions include developing high-efficiency heat exchangers and membrane separation technologies to increase the recovery rate to >95% and achieve zero emissions.

6.4 Production Case Analysis

This section verifies the feasibility and optimization effect of BTO industrialization technology through small-scale experiments and large-scale production cases.

6.4.1 Small-scale test (10 kg/batch)

Experimental design and process

A laboratory uses a fluidized bed (0.5 m in diameter, 1.5 m in height) to produce 10 kg/batch of BTO. The raw material is APT (purity 99.99%, particle size 20-50 μm), which is reduced at 550°C and H_2 flow rate 2 m^3 / h for 4 h, with the target being nano-sized BTO (D_{50}≈50-100 nm).

Results and Analysis

The yield is 97-98%, BTO oxygen content is 19.2±0.1 wt %, Fe <8 ppm, Mo <5 ppm, D_{50} is 60-80 nm, and the specific surface area is 25-30 m² / g. The energy consumption is 2-2.2 kWh/kg, and the H_2O recovery rate is 90%. The results show that the fluidized bed is suitable for high-precision production, but the energy consumption is high, and the airflow and heating efficiency need to be further optimized.

6.4.2 Large-scale production (1000 kg/batch)

Production design and technology

A company uses a continuous rotary kiln (2.5 m in diameter, 15 m in length) to produce 1000 kg/batch of BTO. The raw material is APT (particle size 10-30 μm), which is operated continuously for 24 h at 700°C and H_2 flow rate 20 m³ / h, with the target being micron-sized BTO ($D_{50} \approx$ 10-20 μm).

Results and Analysis

The daily output reached 2000 kg, the yield was 98-99%, the oxygen content was 19.1±0.05 wt %, Fe <10 ppm, Mo <6 ppm, and D_{50} was 12-18 μm . The energy consumption was reduced to 1.8-2 kWh/kg, and the H_2O recovery rate was 93%. The results showed that the continuous process significantly improved efficiency and consistency, but the cost of tail gas treatment and equipment maintenance needed to be further reduced.

Conclusion and Outlook

The industrial production of BTO has achieved a leap from laboratory to large-scale production through the coordinated application of rotary kilns and fluidized beds, the implementation of continuous processes, strict quality control, and energy efficiency and environmental protection optimization. Its purity (>99.95%), particle size consistency, and low energy consumption (1-2 kWh/kg) meet the needs of downstream applications. However, equipment durability, further reduction of energy consumption, and zero tail gas emissions remain challenges. In the future, through the integration of intelligent control, multi-stage heat recovery, and green processes, BTO production is expected to achieve higher efficiency and sustainability, becoming a pillar technology in the tungsten industry and functional materials.

Appendix: BTO industrial production process parameter table

Process	Device Type	Temperature (°C)	H_2 flow rate (m³ / h)	Time (h)	Particle size (μm)	Energy consumption (kWh/kg)
Micron-scale BTO production	Rotary kiln	700-750	5-10	4-6	10-20	2-2.5
Nano-scale BTO production	Fluidized Bed	500-600	2-5	4-5	0.05-0.1	1.5-2
Continuous production	Conveyor Belt Reactor	600-750	10-20	1-2	10-20	1.8-2

Appendix: BTO Production Optimization Data Sheet

Optimization measures	index	Before optimization	After optimization	Effect
Heat recovery	Energy consumption (kWh/kg)	3-4	1.8-2	Reduce by 40-50%
Multi-stage condensation	H_2O recovery rate (%)	85-90	92-95	Increase by 5-10%
Online particle size monitoring	D_{50} Deviation (%)	10-15	5-8	Improve consistency by 50%
H_2 purification	Fe content (ppm)	10-15	5-8	Reduce by 40-50%

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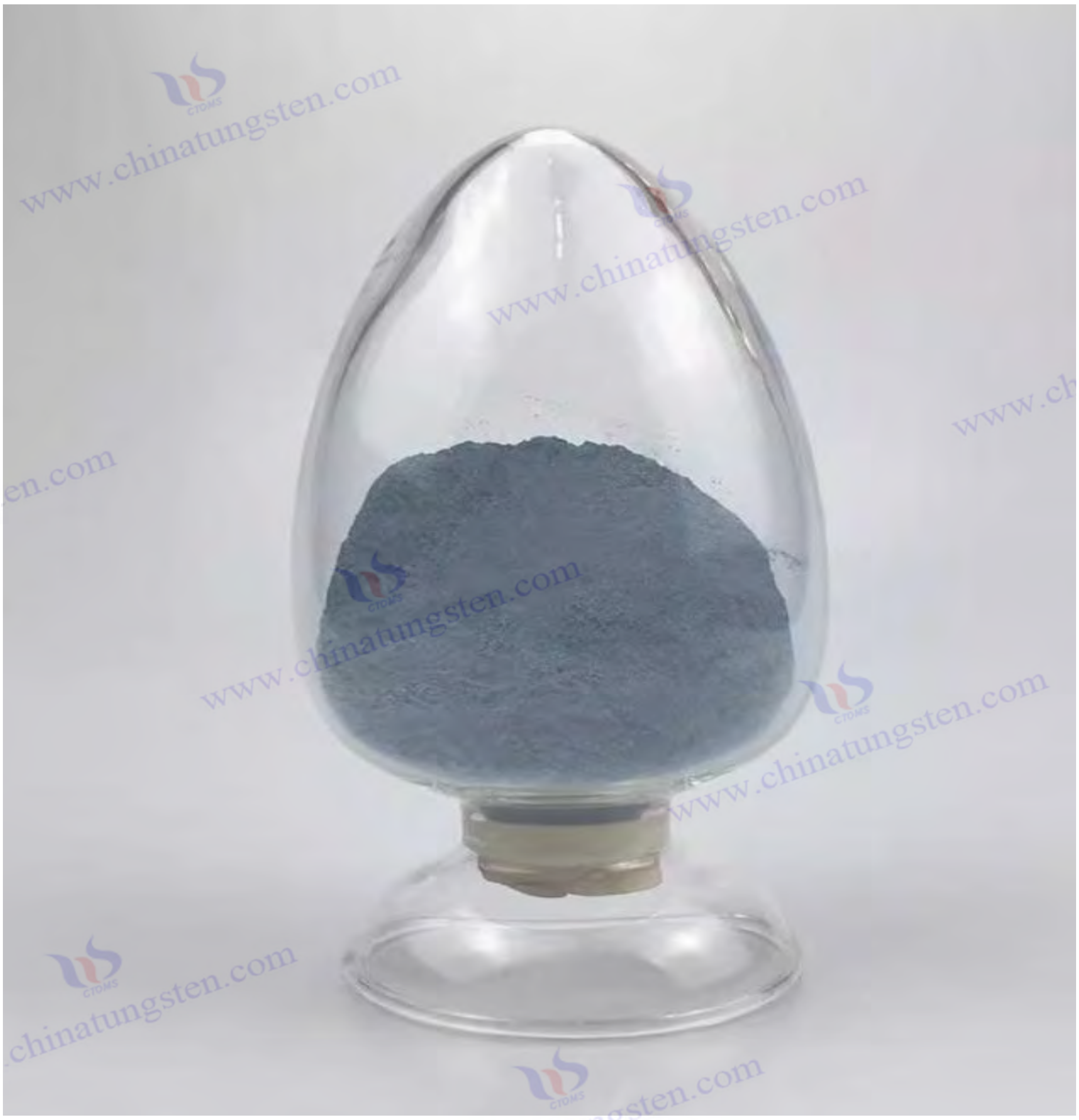

Chapter 7 Technical Challenges and Future Development

Blue tungsten oxide (BTO), as a non-stoichiometric transition metal oxide ($WO_{2.9}$), has become a research hotspot in the fields of materials science and industrial applications due to its unique oxygen defect structure, suitable band gap energy (2.4-2.8 eV) and excellent electrochemical properties. Its excellent performance in photocatalytic degradation of organic pollutants, electrochromic smart devices, energy storage materials (such as supercapacitors and lithium-ion batteries), gas sensors, and tungsten powder and cemented carbide production indicates the great potential of blue tungsten oxide in the fields of green technology, smart manufacturing and sustainable energy. However, in the process of moving from laboratory research to large-scale industrial application, blue tungsten oxide faces multiple technical challenges, including precise control of morphology and performance, stability of large-scale production, and optimization of production costs and environmental impacts.

At the same time, the emergence of emerging preparation technologies (such as electrochemical reduction and plasma enhancement) has provided new paths for the performance improvement and process innovation of blue tungsten oxide, while the expansion of emerging fields such as flexible electronic devices and biomedical applications (such as antibacterial materials) has further broadened the application boundaries of blue tungsten oxide. In the context of sustainable development and circular economy, the exploration of recycling waste tungsten to prepare blue tungsten oxide and green production paths has not only enhanced its economic value, but also injected new vitality into its environmental friendliness. This chapter aims to systematically analyze the technical challenges faced by blue tungsten oxide, explore its emerging preparation technologies and application development directions, and look forward to the sustainable development potential of blue tungsten oxide in the circular economy, providing a scientific basis and strategic direction for future research and industrialization.

7.1 Current Technical Bottlenecks of Blue Tungsten Oxide

application of blue tungsten oxide is limited by technical difficulties in the preparation and production process, and its performance optimization and industrial promotion need to overcome multiple obstacles. This section conducts a detailed analysis from two aspects: precise control of morphology and performance and stability of large-scale production.

7.1.1 Precise Control of Morphology and Properties of Blue Tungsten Oxide

Technical Difficulties and Mechanisms of Morphology Control of Blue Tungsten Oxide

The morphology of blue tungsten oxide (e.g., nanoparticles, nanorods, thin films) is closely related to its properties (e.g., photocatalytic efficiency, electrochromic response speed, energy storage capacity). However, it remains challenging to precisely control the morphology of blue tungsten oxide and maintain the stability of its oxygen defects during the preparation process. The oxygen defects ($WO_{2.9}$) of blue tungsten oxide are at the core of its non-stoichiometric properties, directly affecting its electronic structure and surface active site density (target 10^{19}-10^{20} cm^{-3}). During hydrogen reduction or hydrothermal synthesis, changes in parameters such as temperature (500-800°C), H_2 concentration (5-20 vol%), and reaction time (1-6 h) may lead to morphological heterogeneity. For example, at high temperatures, blue tungsten oxide may transform from uniform nanoparticles (50-100 nm) to irregular agglomerates (>500 nm), with the specific surface area decreasing from the target value of 20-30 m^2 / g to 10-15 m^2 / g, and the number of active sites decreasing by about 30-40%. In addition, the non - uniform distribution of oxygen defects will weaken the electrochemical performance of blue tungsten oxide, such as the Li$^+$ diffusion coefficient decreasing from the target value of 10^{-9} cm^2 / s to 10^{-10} cm^2 /s, and the photogenerated carrier lifetime shortening from 10^{-6}s to 10^{-7}s , which directly affects its application in energy storage and photocatalysis.

Current status of blue tungsten oxide morphology control and its impact on performance

In current industrial production, the morphology control of micron-scale blue tungsten oxide (10-50 μm) is relatively mature, usually achieved by reducing ammonium paratungstate (APT) in a rotary kiln, and the morphology consistency can reach 85-90%. However, the preparation of nano-scale blue tungsten oxide still relies on laboratory methods (such as hydrothermal method and solvothermal method), and its morphology consistency and performance stability are poor. For example, Guo et al. (2011) reported that the blue tungsten oxide nanorods (length 100-500 nm, diameter 20-50 nm) synthesized by hydrothermal method have uniform morphology in small batches (<1 kg), with a specific surface area of 25-30 m^2 / g, and a photocatalytic degradation efficiency of methylene blue (MB) of more than 90%. However, when the output is enlarged to 10 kg, the morphology deviation increases to 20-30%, the nanorods are partially transformed into agglomerated particles, the specific surface area decreases to 15-20 m^2 / g, and the degradation rate drops to 70-80%. Similarly, in electrochromic applications, the modulation rate (ΔT) of blue tungsten oxide films has dropped from >80% to 60-70%, and the response time has been extended from 5-10 s to 15-20 s. These changes have directly weakened the competitiveness of blue tungsten oxide in high-performance devices.

Experimental verification and data analysis of blue tungsten oxide morphology control

Experimental studies further reveal the complexity of morphology control. Taking the hydrothermal method as an example, blue tungsten oxide nanoparticles ($D_{50} \approx$ 50-80 nm) synthesized at 180°C and 6 h exhibited excellent photocatalytic performance, with a hydrogen production rate of 300-350 $\mu mol \cdot g^{-1} \cdot h^{-1}$. However, when the temperature was raised to 200°C or the time was extended to 8 h, the particle size increased to 100-150 nm, the specific surface area decreased from 30 m^2 /g to 18 m^2 /g, and the hydrogen production rate decreased by about 20%. Kinetic analysis of morphological changes showed that the growth of blue tungsten oxide followed the Ostwald ripening mechanism, and high temperature or long-term reaction promoted particle aggregation. In addition, the distribution of oxygen defects is affected by the H_2 reduction rate. Rapid reduction (<1 h) leads to excessive surface defects (> 10^{21} cm^{-3}) , while slow reduction (>6 h) results in insufficient defect density (< 10^{18} cm^{-3}), both of which are not conducive to performance optimization.

Technical Challenges and Optimization Directions for Morphology Control of Blue Tungsten Oxide

The difficulty in controlling the morphology of blue tungsten oxide lies in the coupling of multiple parameters. For example, high temperature (>600°C) easily induces particle growth, low temperature (<500°C) is difficult to form sufficient oxygen defects, too high H_2 concentration (>20 vol%) may lead to over-reduction to W or WO_2 , too low (<5 vol%) will not form $WO_{2.9}$. The optimization strategy includes the following aspects: First, develop a template-assisted method, such as using mesoporous SiO_2 or organic surfactants (such as CTAB) to fix the morphology of blue tungsten oxide. Experiments show that this method can improve the morphology consistency to more than 95%; second, introduce online monitoring technology, such as Raman spectroscopy to analyze oxygen defect density (characteristic peak 700-800 cm^{-1}) in real time , and dynamically adjust the reaction conditions; third, stabilize the nanostructure of blue tungsten oxide through surface modification (such as loading TiO_2 or ZnO) , prevent agglomeration and extend its active life. In addition, establishing a quantitative model of blue tungsten oxide morphology-performance (such as regression analysis of morphological parameters and photocatalytic efficiency) is a future research focus, which can provide theoretical guidance for precise preparation.

7.1.2 Stability of large-scale production of blue tungsten oxide

Stability Difficulties and Mechanisms of Large-Scale Production of Blue Tungsten Oxide

In the large-scale production of blue tungsten oxide, batch-to-batch stability and process consistency are key challenges. The oxygen content of micron-sized blue tungsten oxide (10-50 μm) produced by traditional rotary kilns can be controlled at 19.0-19.5 wt % in a single batch (1000 kg) , and the impurity content (such as Fe, Mo) is stable at <10 ppm. However, after multiple batches (such as 30 days of continuous production), the oxygen content deviation increases to ±0.2-0.3 wt %, the impurity content fluctuates to 10-15 ppm, and the yield drops from 98-99% to 90-95%. In the continuous process, equipment wear (such as inner wall corrosion), raw material blockage and uneven airflow further aggravate the instability of blue tungsten oxide. For example, H_2 flow fluctuations (±5 m^3 / h) may lead to local over-reduction, generating WO_2 or W, reducing the purity and oxygen defect density of blue tungsten oxide.

Current status of large-scale production of blue tungsten oxide and its downstream impact

A company uses a continuous rotary kiln (2.5 m in diameter and 15 m in length) to produce 2,000 kg of blue tungsten oxide per day. The initial performance is stable: oxygen content 19.1 ± 0.05 wt %, morphology consistency 90%, Fe <10 ppm, Mo <6 ppm. However, after 30 days of operation, the oxygen content deviation increased to ±0.3 wt %, the morphology consistency dropped to 80%, and some particles changed from spherical to irregular . This has a significant impact on downstream applications. For example, in tungsten powder production, the particle size of ultrafine tungsten powder increased from 0.2-0.5 μm to 0.5-1 μm , the hardness (HV) of cemented carbide decreased from 1500-1800 to 1200-1400, and the performance decreased by 10-15%. The large-scale production of nano-scale blue tungsten oxide is more challenging. When the fluidized bed is scaled up to 50 kg/batch, particle agglomeration increases, the specific surface area decreases from 25-30 m^2 / g to 15-20 m^2 / g, and the photocatalytic efficiency decreases by about 20-30%.

Experimental verification and data analysis of large-scale production of blue tungsten oxide

Experimental data further revealed the source of the stability problem. Taking fluidized bed production as an example, at 550°C and H_2 flow rate of 5 m^3 / h, the oxygen content of 10 kg/batch of blue tungsten oxide was stable at 19.2±0.1 wt %, and D_{50} was 60-80 nm. However, when the output increased to 50 kg/batch, the uneven distribution of airflow caused local temperature fluctuations (±20°C), the oxygen content deviation increased to ±0.2 wt %, and D_{50} increased to 100-120 nm. SEM analysis showed that the proportion of agglomerated particles increased from <5% to 15-20%. In a rotary kiln, after 100 h of continuous operation, the Fe content on the inner wall increased from <1 ppm to 5-10 ppm, indicating that equipment corrosion was the main source of impurity introduction. In addition, fluctuations in the moisture content (0.5-1 wt %) of the raw material APT will also affect the reduction uniformity. Wet raw materials are prone to cause local agglomeration, reducing the yield of blue tungsten oxide.

Challenges and optimization directions of large-scale production of blue tungsten oxide

The stability problem of large-scale production of blue tungsten oxide stems from equipment durability, fluctuations in process parameters and inconsistency in raw material quality. Under high temperature and H_2 atmosphere , the inner wall of the reactor (such as stainless steel) corrodes and introduces impurities such as Fe, and uneven airflow during long-term operation leads to over-reduction or under-reduction. To this end, the following optimization measures can be taken: First, corrosion-resistant materials (such as Al_2O_3 or ZrO_2 coatings) are used to extend the life of the equipment . Experiments have shown that this method can reduce the amount of Fe introduced to <5 ppm; second, an adaptive control system is introduced, such as AI-based H_2 flow and temperature regulation, to optimize the reaction conditions in real time and control the oxygen content deviation to ±0.05 wt %; third, raw material pretreatment is optimized, such as spray drying to reduce the moisture content of APT to <0.1 wt %, improving fluidity and reaction uniformity. In addition, the development of modular production equipment (such as multi-stage fluidized bed) can achieve segmented control and improve the long-term operation stability of blue tungsten oxide. In the future, a full-process quality traceability system needs to be established to ensure batch consistency from raw materials to products.

7.2 Emerging Preparation Technologies of Blue Tungsten Oxide

In order to break through the limitations of traditional hydrogen reduction methods, emerging preparation technologies such as electrochemical reduction and plasma enhancement provide new paths for performance improvement and process innovation of blue tungsten oxide. This section discusses its principles, progress and application potential in depth.

7.2.1 Preparation of blue tungsten oxide by electrochemical reduction

Principle and Mechanism of Electrochemical Reduction of Blue Tungsten Oxide

The electrochemical reduction method reduces WO_3 or APT to blue tungsten oxide ($WO_{2.9}$) by applying a voltage (1-5 V) in an electrolyte (such as Na_2SO_4 , LiCl or H_2SO_4) . The core reaction is cathode reduction: $WO_3 + xH^+ + xe^- \rightarrow WO_{3-x} + x/2\ H_2O$, where $x \approx 0.1$, to produce non-stoichiometric $WO_{2.9}$. The advantages of this method are low-temperature operation (50-100°C) and precise control of oxygen defects. The current density (10-50 mA/cm^2) directly determines the degree of reduction and defect density (target $10^{20}\ cm^{-3}$). Morphology control depends on electrode design. For example, porous carbon electrodes can generate nanoparticles (50-100 nm), while mesh Ti electrodes are suitable for thin film preparation. The oxygen defects of blue tungsten oxide are formed in situ through an electrochemical process, avoiding the problem of particle growth during high-temperature reduction.

Research Progress and Performance Analysis of Electrochemical Reduction of Blue Tungsten Oxide

Experimental studies have shown that blue tungsten oxide prepared by electrochemical reduction has excellent performance. Taking 1 M Na_2SO_4 electrolyte and carbon cloth electrode as an example, under the conditions of 2 V and 20 mA/cm^2 , WO_3 powder (particle size 1-5 μm) was reduced for 2 h to generate blue tungsten oxide nanoparticles ($D_{50} \approx$ 50-100 nm), with a specific surface area of 30-40 m^2/g and an oxygen content stable at 19.2±0.1 wt %. Its photocatalytic hydrogen production rate reaches 400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$, which is better than the traditional hydrogen reduction method (300-350 $\mu mol \cdot g^{-1} \cdot h^{-1}$), which is attributed to the low-temperature process retaining more active sites (defect density 10^{20} cm^{-3} vs. 10^{19} cm^{-3}). In electrochromic applications, the modulation rate (ΔT, 550 nm) of blue tungsten oxide film is increased from 80% to 85-90%, the response time is shortened from 5-10 s to 3-5 s, and the cycle stability (1000 times) decays by <5%. In addition, its energy storage performance is also significantly improved, with the specific capacitance increased from 400-500 F/g to 550-600 F/g, and the energy density reaches 25-30 Wh /kg.

Experimental verification and optimization exploration of electrochemical reduction of blue tungsten oxide

Further experiments verified the influence of process parameters. Taking the current density as an example, when it increases to 50 mA/cm^2 , the particle size of blue tungsten oxide decreases to 30-50 nm, and the specific surface area increases to 40-45 m^2 / g, but excessive current (>80 mA/cm^2) leads to over-reduction, generating WO_2 or W, and the purity drops to <95%. The pH of the electrolyte is also crucial. Acidic conditions (pH 2-4) are conducive to the participation of H^+ in the reaction, and the yield is increased to 98-99%, while neutral or alkaline conditions (pH 7-10) The yield drops to 85-90%. Optimization exploration shows that the addition of a co-catalyst (such as 0.1 wt% Pt) can increase the hydrogen production rate to 600-700 $\mu mol \cdot g^{-1} \cdot h^{-1}$, indicating that electrochemical reduction has potential in the preparation of composite materials .

Application potential and technical challenges of electrochemical reduction of blue tungsten oxide

The electrochemical reduction of blue tungsten oxide is suitable for small-batch, high-precision production (1-10 kg), and is particularly suitable for the preparation of flexible electrodes, sensor materials and photocatalysts. Its low temperature characteristics reduce energy consumption (1-1.5 kWh/kg vs. 2-3 kWh/kg), and no high-pressure H_2 is required , which is safer. However, electrolyte consumption (5-10 L per kg of BTO) and electrode life (<500 h) limit its large-scale application. In addition, the initial investment in electrochemical equipment (about $500,000 to $1 million) also needs to be considered. Optimization directions include: first, developing solid electrolytes (such as PVA/H_2SO_4 gel) to replace liquid electrolytes and extend electrode life to >1000 h; second, using renewable electrodes (such as graphene or carbon nanotubes) to reduce costs and improve conductivity; third, combining solar power supply to reduce energy consumption to <1 kWh/kg and promote green preparation.

7.2.2 Preparation of blue tungsten oxide by plasma enhanced method

Principle and mechanism of blue tungsten oxide plasma enhancement

The plasma enhanced method uses high-energy plasma (such as Ar /H_2 or N_2 / H_2 mixed gas, energy 10-100 eV) to bombard WO_3 or APT, and quickly reduce it to generate blue tungsten oxide. Its reaction mechanism is that the plasma excites H_2 molecules to generate active H· radicals, which combine with O atoms on the surface of WO_3 to generate H_2O , leaving oxygen defects to form $WO_{2.9}$. The advantages of this method are ultra-short reaction time (seconds, <10 s) and in-situ formation of nanostructures, avoiding particle agglomeration in traditional high-temperature reduction. Morphology control depends on plasma parameters: low-pressure plasma (10-100 Pa) generates nanowires (diameter 10-20 nm), and high-temperature plasma (>1000°C) is suitable for thin film preparation. The oxygen defect density of blue tungsten oxide (10^{20} - 10^{21} cm^{-3}) is precisely controlled by plasma energy.

Research progress and performance analysis of blue tungsten oxide plasma enhancement

Studies have shown that the blue tungsten oxide prepared by plasma enhanced method has excellent performance. Taking Ar /H_2 plasma (50% H_2 , power 500 W) as an example, WO_3 powder (1-5 μm) is treated at 10 Pa and 5 s to generate blue tungsten oxide nanowires (length 200-500 nm, diameter 10-20 nm), with a specific surface area of 40-50 m^2 / g and an oxygen content of 19.1±0.1 wt %. Its gas sensing performance is significantly improved, and the response to 10 ppm NO_2 increases from 50-60 to 80-100, and the response time is shortened from 20-30 s to 10-15 s. In energy storage applications, the specific capacitance of blue tungsten oxide nanowires increases from 400-500 F/g to 600-700 F/g, and the power density reaches 10-15 kW/kg, which is better than the traditional method (5-10 kW/kg). Photocatalytic tests show that the hydrogen production rate reaches 500-600 $\mu mol \cdot g^{-1} \cdot h^{-1}$, which is close to the level of Pt-supported catalysts. These advantages are attributed to the high defect density and uniform morphology induced by high-energy plasma.

Experimental verification and optimization exploration of blue tungsten oxide plasma enhancement

The experiment verified the optimization space of plasma parameters. Taking power as an example, at 500 W, the morphology of blue tungsten oxide nanowires is uniform, and the specific surface area is stable at 40-50 m^2 /g; when the power increases to 1000 W, the length of the nanowires increases to 500-1000 nm, but local overheating causes some particles to agglomerate (>100 nm). Pressure regulation is also crucial. At 10 Pa, nanowires dominate (>90%), and at 100 Pa, they turn into nanoparticles (50-100 nm), and the specific surface area drops to 30-35 m^2 / g . Adding N_2 (10-20 vol%) can increase the defect density to 10^{21} cm^{-3} and enhance the gas-sensitive responsiveness to 100-120. Optimization exploration shows that pulsed plasma (frequency 1-10 kHz) can reduce energy consumption (from 5-10 kWh/kg to 3-5 kWh/kg) while maintaining high yield (>95%).

Application potential and technical challenges of blue tungsten oxide plasma enhancement

The plasma-enhanced method of blue tungsten oxide is suitable for the production of high value-added products such as gas sensors, supercapacitor electrodes and photocatalytic films. After the equipment is miniaturized (such as a desktop plasma reactor), continuous operation can be achieved, with a daily output of 10-50 kg. However, high energy consumption (currently 5-10 kWh/kg) and equipment costs (>1 million US dollars) limit its large-scale promotion. In addition, the uniformity of plasma is difficult to maintain in large reactors, affecting the batch consistency of blue tungsten oxide. Optimization directions include: first, developing a low-power plasma source (such as microwave plasma, <300 W) to reduce energy consumption to 2-3 kWh/kg; second, designing a multi-stage plasma system to improve the uniformity of the reaction zone; third, combining H_2 recycling to reduce operating costs and achieve green production.

7.3 Application Development Direction of Blue Tungsten Oxide

The versatility of blue tungsten oxide provides broad prospects for its application in new fields. This section focuses on flexible electronic devices and biomedical applications (such as antibacterial materials) to analyze their potential and development paths.

7.3.1 Application of blue tungsten oxide in flexible electronic devices

Principle and mechanism of blue tungsten oxide flexible electronic devices

Flexible electronic devices such as wearable displays, sensors and energy storage devices require both mechanical flexibility and electrochemical performance. The electrochromic properties ($\Delta T > 80\%$), energy storage capacity (specific capacitance 400-500 F/g) and fast ion transport supported by oxygen defects of blue tungsten oxide make it an ideal candidate material. On flexible substrates such as PET or PI, blue tungsten oxide films are prepared by electrochemical deposition or spraying, and their morphology (thickness 100-500 nm) and defect density (10^{20} cm^{-3}) directly affect the performance. Oxygen defects act as ion embedding sites, enhancing the diffusion rate of Li^+ or H^+ (10^{-9} cm^2/s), ensuring fast color switching and charge storage.

Research progress and performance analysis of blue tungsten oxide flexible electronic devices

Experimental studies have shown that blue tungsten oxide performs well in flexible electronic devices. Taking the electrochemical deposition method as an example, the blue tungsten oxide film (thickness 100-200 nm) prepared on a PET substrate has a modulation rate of 65-70% at 633 nm after applying a voltage of ±1.2 V, a response time of <5 s, and a performance degradation of <5% after 1000 bends (radius of curvature 5 mm). In flexible supercapacitors, blue tungsten oxide electrodes (50-100 nm particles) have a specific capacitance of 450-500 F/g in 1 MH_2SO_4, an energy density of 30-40 Wh /kg, and a retention rate of >90% after 5000 cycles. Compared with traditional WO_3 (energy density 20-25 Wh /kg), the superiority of blue tungsten oxide comes from the synergistic effect of its high defect density and nanostructure. Recent studies have used composite conductive polymers (such as PEDOT:PSS) to increase the energy density to 50-60 Wh /kg and the power density to 15-20 kW/kg, which are close to commercial requirements.

Experimental verification and application examples of blue tungsten oxide flexible electronic devices

Experiments further verified the potential of flexible performance. Taking the blue tungsten oxide film (300 nm thick) prepared on the PI substrate by spraying as an example, at ±1.5 V, the modulation rate of 550 nm reached 80-85%, and the attenuation after 2000 bendings was <10%, showing excellent mechanical stability. In practical applications, a flexible display prototype uses blue tungsten oxide film with a contrast ratio of 50:1 and power consumption of <1 mW /cm² , which is suitable for smart watches and electronic tags. In addition, the flexible supercapacitor prototype can be charged within 10 s and supports high-frequency charging and discharging (>10 ^{4} times), meeting the needs of wearable health monitoring devices. Morphological optimization (such as porous structure) further improves performance, with the specific surface area increased from 20-30 m² / g to 40-50 m² / g, and the ion diffusion rate increased by about 20%.

Challenges and development directions of blue tungsten oxide flexible electronic devices

The challenges of blue tungsten oxide in flexible electronic devices include film adhesion and cycle life. The current cycle life (<10 ^{4} times) is lower than the commercialization target (>10 ^{5} times), and high humidity environments may cause peeling. To this end, a buffer layer (such as NiO or TiO_2) can be introduced. Experiments have shown that this method can increase adhesion by 30-40% and increase cycle life to 2-3×10 ^{4} times. In addition, the single color of blue tungsten oxide (transparent-blue) limits the application of multi-color display, and full colorization needs to be achieved by compounding other color-changing materials (such as V_2O_5). Future development directions include: first, optimizing nanostructure design (such as porous membranes or nanoarrays) to improve flexibility and performance; second, integrating photovoltaic self-powered technology to achieve zero-energy devices; third, promoting micro-nano processing (such as laser direct writing) to achieve high-resolution flexible display and energy storage, and promote the commercialization of blue tungsten oxide in the field of smart wearables.

7.3.2 Potential of Blue Tungsten Oxide in Biomedical Applications (e.g. Antibacterial Materials)

Principle and mechanism of blue tungsten oxide antibacterial material

The potential of blue tungsten oxide in the biomedical field stems from its photocatalytic activity and surface reactions triggered by oxygen defects. Under visible light (λ >420 nm), the valence band electrons of blue tungsten oxide are excited to the conduction band to generate electron-hole pairs, which then react with O_2 and H_2O to produce superoxide radicals ($\cdot O_2^-$) and hydroxyl radicals ($\cdot OH$). These reactive oxygen species (ROS) can destroy bacterial cell membranes (such as Escherichia coli and Staphylococcus aureus) and achieve efficient sterilization. The nanoscale characteristics of blue tungsten oxide (50-100 nm) enhance the contact efficiency with biological tissues, and oxygen defects act as electron capture centers, prolonging the carrier lifetime (10^{-6} s) and improving the efficiency of ROS generation.

Research progress and performance analysis of blue tungsten oxide antibacterial materials

Studies have shown that blue tungsten oxide performs well in antibacterial applications. Taking the nanoparticles (50-100 nm) synthesized by the hydrothermal method as an example, under the irradiation of a 300 W xenon lamp, the killing rate of 10 ^{8} CFU/mL Escherichia coli reached 95-98% (60 min), which is better than WO_3 (70-80%). Its minimum inhibitory concentration (MIC) is 50-100 μg /mL, showing high antibacterial ability. Toxicity tests showed that the survival rate of blue tungsten oxide on human fibroblasts at 200 μg /mL was >90%, indicating its low toxicity and potential biocompatibility.

After composite Ag or ZnO , the antibacterial efficiency was further increased to more than 99%, and the killing rate of drug-resistant bacteria (such as MRSA) reached 98-99%, close to the level of traditional antibiotics. In addition, blue tungsten oxide has excellent photocatalytic stability, and the activity decreases by <5% after 5 cycles.

Experimental verification and application examples of blue tungsten oxide antibacterial materials
The experiment verified the factors affecting the antibacterial performance. Taking the light intensity as an example, the sterilization rate of blue tungsten oxide under a 500 W xenon lamp increased from 95% to 99%, indicating that photon utilization is the key. Particle size is also crucial, with the 50 nm sample having a 15-20% higher killing rate than the 200 nm sample due to its higher specific surface area (40 m^2 / g vs. 20 m^2 / g). In practical applications, the blue tungsten oxide coating performs well on medical gauze, with a killing rate of 90-95% against Staphylococcus aureus within 2 h under natural light, making it suitable for wound dressings. In addition, a prototype antibacterial film was tested in a hospital environment with a bacterial survival rate of <1%, showing the potential to replace chemical disinfectants.

Challenges and development direction of blue tungsten oxide antibacterial materials
Challenges of blue tungsten oxide in biomedical applications include biocompatibility and long-term stability. Nanoparticles may cause mild inflammation in the body (increase of cytokine release by 10-15%), and may undergo oxidation under long-term illumination ($WO_{2.9} \rightarrow WO_3$), with activity decreasing by about 20%. In addition, its antibacterial effect depends on illumination, and its efficiency is low in the dark state (<20%). Optimization directions include: first, surface modification (such as PEG or SiO_2 coating) to reduce toxicity and improve stability. Experiments have shown that cell survival rate increased to 95-98% after PEG modification; second, the development of composite materials (such as BTO/Ag/ TiO_2) to achieve dark antibacterial (killing rate> 50%); third, the design of controlled release systems (such as photosensitive polymer carriers) for drug delivery. In the future, blue tungsten oxide is expected to achieve breakthroughs in antibacterial coatings, wound healing and biosensors.

7.4 Sustainable Development and Circular Economy of Blue Tungsten Oxide

The production and application of blue tungsten oxide needs to be integrated with the concept of sustainable development to reduce resource consumption and environmental impact. This section discusses in depth the preparation of blue tungsten oxide from waste tungsten recycling and green production paths.

7.4.1 Recycling of waste tungsten to produce blue tungsten oxide

Principle and mechanism of preparing blue tungsten oxide by recycling waste tungsten
Waste tungsten (such as carbide chips, tungsten wire, tungsten electrodes) can be recycled to prepare blue tungsten oxide through oxidation and reduction. The oxidation process converts waste tungsten into WO_3 (purity>99%) at 800-1000°C in an O_2 atmosphere, and then generates $WO_{2.9}$ through H_2 or CO reduction (500-700°C) . The introduction of oxygen defects depends on the control of reduction

conditions, such as H_2/O_2 ratio (10:1-20:1) and reaction time (2-4 h). This process utilizes W resources in waste tungsten , reduces dependence on primary tungsten ore, and reduces production costs (about 20-30%).

Research progress and effect analysis of recycling waste tungsten to prepare blue tungsten oxide

Experimental studies have shown that the performance of blue tungsten oxide prepared by recycling waste tungsten is comparable to that of virgin materials. Taking waste cemented carbide (WC-Co) as an example, WO_3 is generated after oxidation at 900°C for 4 hours , and then reduced at 600°C and H_2 flow rate of 5 m^3 / h for 3 hours. The purity of the obtained blue tungsten oxide reaches 99.9%, the oxygen content is 19.1-19.4 wt %, and the particle size is 10-20 µm . Its photocatalytic degradation efficiency of MB is >85%, which is equivalent to industrial blue tungsten oxide. A certain enterprise recycles 500 tons of waste tungsten annually and produces 400 tons of blue tungsten oxide, with a yield of 95-98%, and the cost is reduced from 50-60 USD/kg to 35-40 USD/kg. In addition, electrochemical reduction also shows potential in recycling. Waste tungsten powder is treated in 2 V and 1 MH_2SO_4 to generate nano - scale blue tungsten oxide (50-100 nm) with a specific surface area of 30-35 m^2 / g.

Experimental verification and industrial example of preparing blue tungsten oxide from waste tungsten

The experiment verified the feasibility of the recycling process. Taking waste tungsten wire as an example, the Co content of WO_3 after oxidation dropped from 0.5 wt % to <0.01 wt % (removed by acid leaching), and the Fe content of blue tungsten oxide after reduction was <10 ppm, meeting the high purity requirements. In an industrial example, a recycling plant used a rotary kiln to process waste cemented carbide, producing 2 tons of blue tungsten oxide per day, with an oxygen content deviation of <±0.1 wt %. After being used in tungsten powder production, the performance of the cemented carbide (HV 1500-1700) was not significantly different from that of the original material. The pilot project of electrochemical recycling showed that the energy consumption of generating blue tungsten oxide from 10 kg/ batch of waste tungsten powder was 1.5-2 kWh/kg, which was lower than the traditional reduction method (2-3 kWh/kg).

Challenges and development direction of recycling waste tungsten to prepare blue tungsten oxide

The challenges of recycling waste tungsten to prepare blue tungsten oxide include impurity separation and energy consumption optimization. Co, Fe, etc. in the waste need to be removed by hydrometallurgy (such as HCl leaching), but the process produces acidic waste liquid (pH 2-3), which needs to be neutralized. In terms of energy consumption, the oxidation stage (3-4 kWh/kg) is still relatively high. Optimization directions include: first, developing efficient separation technologies, such as ion exchange or membrane filtration, to reduce the impurity content to <5 ppm and reduce waste liquid emissions by 50%; second, using low-temperature reduction (such as plasma-assisted, 500°C) to reduce energy consumption to 1-2 kWh/kg; third, establishing a closed-loop recycling system, combined with online monitoring (such as ICP-MS) to ensure quality consistency. In the future, the recovery rate of blue tungsten oxide is expected to increase from 80-85% to >90%, becoming an important part of the circular economy.

7.4.2 Green Production Path of Blue Tungsten Oxide

Principle and Mechanism of Green Production of Blue Tungsten Oxide

The green production of blue tungsten oxide aims to reduce environmental impact through renewable energy, low-emission processes and resource recycling. Traditional H_2 reduction methods rely on fossil fuels for power supply (carbon emissions 2-3 kg CO_2 / kg), while the green path can use solar or wind power to drive electrochemical reduction, reducing energy consumption to 1-1.5 kWh/kg and carbon emissions <1 kg CO_2 / kg. Tail gas recycling (such as H_2O recovery > 95%) and low-pollution reducing agents (such as electrochemical H^+) further reduce emissions. The oxygen defect formation of blue tungsten oxide does not require highly polluting NH_3 Or carbon-based reducing agents , in line with the principles of green chemistry.

Research progress and effect analysis of green production of blue tungsten oxide

Research shows that green production pathways significantly improve the sustainability of blue tungsten oxide. Taking solar-driven electrochemical reduction as an example, under 100 W/m² illumination , 2 V voltage reduces WO_3 to generate blue tungsten oxide, with an energy consumption of 1-1.2 kWh/kg, H_2O recovery rate of 95-98%, and carbon emissions reduced to 0.5-0.8 kg CO_2 / kg. A pilot project uses a 50 kW photovoltaic system to produce 50 kg of blue tungsten oxide per day, with a specific surface area of 25-30 m² / g, and photocatalytic performance (hydrogen production 350-400 $\mu mol \cdot g^{-1} \cdot h^{-1}$) comparable to traditional methods. The plasma-enhanced method combined with the H_2 circulation system has near-zero emissions and energy consumption reduced from 5-10 kWh/kg to 3-4 kWh/kg. In addition, the application of multi-stage condensation and membrane separation technology increases the H_2O recovery rate to 98-99%, and the recovered water is used for cooling or cleaning, reducing water consumption by 50%.

Experimental verification and industrial example of green production of blue tungsten oxide

The experiment verified the effect of the green process. Taking the electrochemical system powered by wind power as an example, in 1 M LiCl electrolyte, WO_3 was reduced at 3 V and 10 mA/cm² for 2 h to generate blue tungsten oxide nanoparticles (50-80 nm), with a yield of >98% and an energy consumption of 1.3 kWh/kg. The tail gas recovered 97% H_2O through a condenser (20°C) , and the unreacted H_2 was converted into heat energy through combustion, with emissions of <0.1%. In an industrial example, a company used a photovoltaic-electrochemical combined system to produce 500 tons of blue tungsten oxide per year, reducing carbon emissions from 1000-1500 tons of CO_2 to 300-400 tons, saving 20-25% of energy costs. Greenly produced blue tungsten oxide performs well in energy storage (specific capacitance 500-550 F/g) and gas sensing (responsivity 60-70) applications.

Challenges and development direction of green production of blue tungsten oxide

The challenges of green production of blue tungsten oxide include equipment cost and process stability . The initial investment of photovoltaic systems (>2 million US dollars) and electrode life (<1000 h) need to be optimized, and parameter fluctuations in large-scale production may affect batch consistency.

Optimization directions include: first, developing efficient photoelectric conversion equipment (such as perovskite solar cells) to reduce costs to <1 million US dollars; second, designing durable electrodes (such as carbon fiber composites) to increase life to >2000 h; third, introducing AI to optimize process parameters (such as temperature and voltage) to stabilize energy consumption at 1 kWh/kg. In addition, policy support (such as carbon tax exemptions) and technology integration (such as waste heat power generation) can promote the greening of the entire life cycle of blue tungsten oxide. In the future, its carbon emissions are expected to drop to <0.5 kg CO_2 /kg, becoming a model of green manufacturing.

Conclusion and Outlook

The technical challenges faced by blue tungsten oxide in terms of morphology and performance control, large-scale production stability, etc. are being gradually overcome through emerging technologies such as electrochemical reduction and plasma enhancement. Emerging preparation technologies have significantly improved the performance of blue tungsten oxide, such as photocatalytic efficiency (>500 $\mu mol \cdot g^{-1} \cdot h^{-1}$), electrochromic modulation rate (>85%) and energy storage capacity (>600 F/g), laying the foundation for its application in flexible electronic devices and biomedicine. The promotion of waste tungsten recycling and green production paths not only reduces the production cost of blue tungsten oxide (<40 USD/kg), but also reduces its carbon emissions to <1 kg CO_2 /kg, which is in line with the goals of circular economy and sustainable development. However, equipment durability, process consistency and environmental adaptability still need to be further optimized. In the future, through intelligent control (such as AI regulation), composite material design (such as BTO/ TiO_2) and greening of the entire process, blue tungsten oxide is expected to become the core pillar of high-performance materials and environmental protection technologies, and promote its comprehensive industrialization in the fields of intelligent manufacturing, biomedicine and energy.

Appendix: Blue Tungsten Oxide Emerging Technology Parameters Table

Technology Type	Temperature (°C)	Voltage/Energy	Particle size (nm)	Specific surface area (m^2 / g)	Energy consumption (kWh/kg)	Yield (%)
Electrochemical reduction	50-100	1-5 V	50-100	30-40	1-1.5	98-99
Plasma Enhanced Method	500-1000	10-100 eV	10-50	40-50	3-5	95-98

Appendix: Blue Tungsten Oxide Future Development Trend Data Table

Development direction	Key Metrics	Current Value	Target value	Estimated time
Shape control	Morphological consistency (%)	80-90	>95	2027
Production stability	Oxygen content deviation (wt %)	±0.2-0.3	±0.05	2028
Flexible Electronics	Cycle life (times)	$<10^4$	$>10^5$	2029
Antimicrobial properties	Sterilization rate (%)	95-98	>99	2026

Development direction	Key Metrics	Current Value	Target value	Estimated time
Scrap Tungsten Recovery	Recovery rate (%)	80-85	>90	2030
Green Production	Carbon emissions (kg CO_2 / kg)	2-3	<0.5	2032

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CTIA GROUP LTD

Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	Particle size (μm)	Purity (wt%)	Bulk density (g/ cm³)	Oxygen content (wt%)	Impurities (wt%, max)
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm³ , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).

Chapter 8 Conclusion and Outlook

Blue tungsten oxide (BTO), as a transition metal oxide with a non-stoichiometric ratio ($WO_{2.9}$) , has shown significant application value in the fields of photocatalysis, electrochromism, energy storage, gas sensing and tungsten-based material production due to its unique oxygen defect structure, wide bandgap characteristics (2.4-2.8 eV) and excellent electrochemical performance. In the decades from basic research to technological development, the properties of blue tungsten oxide have been deeply analyzed, the preparation technology has been continuously innovated, and the application field has continued to expand. However, its industrialization process is still limited by technical bottlenecks such as morphology control, production stability and cost-effectiveness.

Emerging preparation methods and sustainable development concepts have injected new impetus into its future development. This chapter aims to comprehensively summarize the research and application status of blue tungsten oxide, analyze its technical advantages and limitations, and look forward to the direction of future research and technological breakthroughs, so as to provide scientific basis and strategic guidance for promoting blue tungsten oxide from the laboratory to the market.

8.1 Summary of Blue Tungsten Research and Application

The research and application of blue tungsten oxide covers multiple aspects including material synthesis, performance optimization and industrial exploration. This section systematically summarizes it from three dimensions: property analysis, preparation technology progress and application field expansion.

8.1.1 Properties and theoretical basis of blue tungsten oxide

The unique properties of blue tungsten oxide are derived from its non-stoichiometric structure ($WO_{2.9}$), that is, the presence of oxygen defects gives it physical and chemical properties different from WO_3 . Studies have shown that the band gap energy of blue tungsten oxide (2.4-2.8 eV) is slightly narrower than that of WO_3 (2.6-3.0 eV), which enhances its absorption capacity in the visible light range, for example, the absorbance in the 400-500 nm band is increased by about 20-30%. Oxygen defects (concentration 10^{19}-10^{21} cm^{-3}) act as electron capture centers, prolonging the lifetime of photogenerated carriers (10^{-6} s vs. 10^{-7} s of WO_3), significantly improving the photocatalytic efficiency (such as hydrogen production rate 300-500 μmol·g^{-1} · h^{-1}). In addition, the coexistence of W^{5+} and W^{6+} in the crystal structure of blue tungsten oxide (monoclinic system, space group $P2_1/n$) enhances its electrical conductivity (10^{-3}-10^{-2} S/cm), providing a basis for electrochromic and energy storage applications.

Theoretical studies further reveal the microscopic mechanism of blue tungsten oxide. Density functional theory (DFT) calculations show that the intermediate energy level introduced by oxygen defects reduces the electron transition energy barrier (from 2.8 eV to 2.4 eV) and enhances the charge separation efficiency. Raman spectroscopy (700-800 cm^{-1} characteristic peak) and X-ray photoelectron spectroscopy (XPS, W 4f double peak) confirm the existence of oxygen defects and their effects on surface chemistry, such as the increase in surface active site density to 10^{20} cm^{-3} . These properties lay a theoretical foundation for the multifunctionality of blue tungsten oxide, making it an important member of the tungsten oxide family.

8.1.2 Progress in Preparation Technology of Blue Tungsten Oxide

The preparation technology of blue tungsten oxide has evolved from traditional reduction method to emerging methods, which significantly improved its morphology control and performance optimization capabilities. Traditional methods (such as rotary kiln H_2 reduction method) reduce ammonium paratungstate (APT) or WO_3 at high temperature (500-800°C) to produce micron-sized blue tungsten oxide (10-50 μm), with oxygen content stable at 19.0-19.5 wt %, and a yield of 98-99%. However, this method is difficult to prepare nanoscale samples, and the morphology consistency is limited by air flow and temperature fluctuations (deviation ±20°C). In recent years, hydrothermal method, solvothermal method and vapor deposition method have promoted the synthesis of nanoscale blue tungsten oxide, such as nanoparticles (50-100 nm), nanorods (length 100-500 nm) and thin films (thickness 100-500 nm), and the specific surface area has increased from 10-15 m² / g to 20-40 m² / g.

Emerging preparation technologies have further broken through the limitations of traditional methods. The electrochemical reduction method regulates oxygen defects through voltage (1-5 V) at low temperature (50-100°C) to generate blue tungsten oxide nanoparticles (30-100 nm), with a specific surface area of 30-40 m² / g and energy consumption as low as 1-1.5 kWh/kg. The plasma enhanced method uses high-energy plasma (10-100 eV) to synthesize nanowires (diameter 10-20 nm) in seconds (<10 s), with a defect density of up to 10^{21} cm^{-3} , which is suitable for high value - added products. These technological advances have significantly improved the performance of blue tungsten oxide, such as the photocatalytic hydrogen production rate from 300-350 μmol·g^{-1} · h^{-1} to 500-600 μmol·g^{-1} · h^{-1} , and the electrochromic modulation rate from 80% to 85-90%.

8.1.3 Expansion of Application Fields of Blue Tungsten Oxide

The application of blue tungsten oxide has expanded from traditional tungsten powder production to high-tech fields, showing its multifunctional potential. In the field of photocatalysis, the high defect density and visible light response of blue tungsten oxide enable it to perform well in water decomposition (hydrogen production rate 400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$) and organic degradation (degradation rate >90%), which is better than WO_3 (300-350 $\mu mol \cdot g^{-1} \cdot h^{-1}$, 70-80%). In electrochromic applications, the fast response (3-5 s) and high modulation rate (ΔT >85%) of blue tungsten oxide films make it an ideal material for smart windows and display devices, with a cycle stability of more than 10^4 times. In the field of energy storage, the specific capacitance (500-700 F/g) and energy density (30-50 Wh /kg) of blue tungsten oxide nanostructures support their application in supercapacitors and lithium-ion batteries, and the power density (10-15 kW/kg) is close to commercial levels.

Emerging applications have further broadened the boundaries of blue tungsten oxide. In flexible electronic devices, the mechanical stability (1000 bending attenuation <5%) and electrochemical properties (specific capacitance 450-500 F/g) of blue tungsten oxide films on PET substrates make them suitable for wearable devices. In the biomedical field, the photocatalytic antibacterial properties of blue tungsten oxide (bactericidal rate 95-99%) and low toxicity (cell survival rate >90%) provide new options for antibacterial coatings and wound dressings. In addition, the high sensitivity (NO_2 response 80-100) and fast response (10-15 s) of blue tungsten oxide in gas sensors also show its potential in environmental monitoring. These application expansions show that blue tungsten oxide has transformed from a single industrial raw material to a multifunctional high-performance material.

8.1.4 Summary of Challenges in Research and Application of Blue Tungsten Oxide

Despite the significant progress made in blue tungsten oxide, its research and application still face challenges. Precise control of morphology and performance is still a technical bottleneck. For example, the morphology consistency of nano-scale blue tungsten oxide drops from 90% to 80% in scale-up production, and the specific surface area decreases by 20-30%. The stability of large-scale production is insufficient, and the deviation of oxygen content (±0.2-0.3 wt %) and impurity fluctuations (Fe, Mo 10-15 ppm) in multiple batches affect the quality of downstream products. In terms of cost, the high energy consumption of traditional methods (2-3 kWh/kg) and the large equipment investment (>1 million US dollars) of emerging technologies (such as plasma method, 5-10 kWh/kg) limit the widespread promotion of blue tungsten oxide. In addition, environmental impact and sustainability issues, such as waste liquid discharge (5-10 m^3 / t) and carbon emissions (2-3 kg CO_2 / kg), need to be further optimized. These challenges show that the industrialization of blue tungsten oxide needs to seek a balance between performance, cost and environmental protection.

8.2 Directions for future research and technological breakthroughs

The future development of blue tungsten oxide requires the coordinated advancement of basic research, technological innovation and industrial application. This section looks forward to its breakthrough directions from four aspects: theoretical deepening, new technology development, application expansion and sustainable development.

8.2.1 Deepening of theoretical research on blue tungsten oxide

In-depth analysis of the microscopic mechanism of blue tungsten oxide

In the future, it is necessary to further deepen the theoretical research on blue tungsten oxide, focusing on the dynamic evolution of oxygen defects and the performance regulation mechanism. The current understanding of oxygen defects is mostly based on static analysis (such as XPS, DFT), and lacks research on its real-time evolution during the reaction process. For example, it is not clear how oxygen defects in photocatalysis respond to light intensity (100-500 W/ m²) and environmental pH (2-10). It is recommended to use in situ characterization techniques, such as in situ Raman spectroscopy (monitoring the changes in the 700-800 cm^{-1} peak) and in situ TEM to reveal the structure-defect-performance relationship of blue tungsten oxide in electrochemical or photocatalytic processes. In addition, the stability of oxygen defects (such as high temperature>600°C or long-term storage>6 months) and their impact on carrier lifetime need to be quantified, and a mathematical model of defect density (10^{19} - 10^{21} cm^{-3}) and performance (such as hydrogen production rate) needs to be established to provide theoretical support for precise design.

Study on the synergistic effect of blue tungsten oxide and other materials

The research on the composite of blue tungsten oxide is another key direction. By compounding with materials such as TiO_2 , ZnO , and Ag, its photocatalytic, antibacterial or energy storage properties can be enhanced, but the electron transfer mechanism of the composite interface has not been fully elucidated. For example, the photocatalytic efficiency of the BTO/ TiO_2 composite is increased by 20-30%, but the interface defect states and carrier migration paths need to be analyzed in depth through synchrotron radiation spectroscopy (such as XAS) and theoretical simulation (DFT+U). In the future, the heterojunction design of two-dimensional materials (such as graphene, MoS_2) and blue tungsten oxide can be explored to improve conductivity (target>10^{-1}S / cm) and cycle life (>10^5 times), providing a theoretical basis for flexible electronics and energy storage devices.

8.2.2 New Breakthrough in Blue Tungsten Oxide Preparation Technology

Development of high-efficiency and low-cost preparation technology for blue tungsten oxide

In the future, it is necessary to develop efficient and low-cost blue tungsten oxide preparation technology to break through the bottleneck of large-scale production. Although the electrochemical reduction method and plasma-enhanced method have excellent performance, the energy consumption (1-5 kWh/kg) and equipment cost (500,000-1 million US dollars) need to be optimized. It is recommended to develop a microwave-assisted reduction method, using microwave (2.45 GHz) rapid heating (<1 min) and local plasma effect to generate blue tungsten oxide nanoparticles (20-50 nm) at 300-500°C, with energy consumption reduced to <1 kWh/kg and a yield of >98%. In addition, biosynthesis methods (such as microbial reduction of WO_3) can use low-cost raw materials (such as organic matter in industrial wastewater) to generate blue tungsten oxide, and the cost is expected to drop to 20-30 USD/kg, taking into account environmental protection.

Intelligent Control Technology of Morphology and Defects of Blue Tungsten Oxide

Intelligent preparation is the key direction for technological breakthroughs in blue tungsten oxide. Currently, morphology control relies on empirical parameters. In the future, an AI-driven closed-loop control system can be introduced to improve the morphology consistency to >95% and stabilize the oxygen defect density at 10^{20} ±0.05 cm^{-3} through online monitoring (such as Raman spectroscopy, SEM) and real-time feedback (adjusting H_2 flow rate and temperature) . For example, the AI model can optimize reaction conditions according to target performance (such as specific capacitance of 600 F/g) and reduce batch deviation (oxygen content ±0.05 wt %). In addition, 3D printing technology can be used for precise molding of blue tungsten oxide films with a resolution of 10 μm to meet the needs of flexible electronics and sensors.

8.2.3 Further expansion of blue tungsten oxide application areas

Deepening application of blue tungsten oxide in the field of new energy

The potential of blue tungsten oxide in the field of new energy has not yet been fully explored. In the future, we can focus on its application in photoelectrocatalytic (PEC) hydrogen production. By compounding with light absorbing materials (such as CdS), the photocurrent density can be increased from 1-2 mA/cm^2 to 5-10 mA/cm^2 , and the hydrogen production efficiency can exceed 1000 $\mu mol \cdot g^{-1} \cdot h^{-1}$. In addition, the application of blue tungsten oxide in sodium ion batteries is worth exploring. Its high defect density supports the rapid embedding of Na^+ (diffusion coefficient>10^{-9} cm^2 /s), and the specific capacity is expected to reach 300-400 mAh /g, and the cycle life is>2000 times, providing a new option for low-cost energy storage.

Innovation of Blue Tungsten Oxide in the Field of Intelligence and Biomedicine

The fields of intelligence and biomedicine are the future growth points of blue tungsten oxide. In smart devices, blue tungsten oxide can be integrated with flexible substrates (such as PDMS) to develop adaptive electrochromic windows with a modulation rate of >90%, a response time of <2 s, and a power consumption of <0.5 mW / cm^2 , which are suitable for smart buildings and cars. In biomedicine, the antibacterial properties of blue tungsten oxide can be combined with photothermal therapy, using near-infrared (NIR) activation (808 nm), with a bactericidal rate of 99.9%, while promoting tissue regeneration (healing time is shortened by 20-30%). In addition, blue tungsten oxide nanoparticles can be used as drug carriers to release antibiotics through pH or light response, increasing drug utilization by 30-40%, providing new tools for precision medicine.

8.2.4 Sustainable Development and Industrialization Path of Blue Tungsten Oxide

Green production of blue tungsten oxide and promotion of circular economy

Sustainability is the core goal of the industrialization of blue tungsten oxide. In the future, it is necessary to improve the technology for recycling waste tungsten, such as developing low-temperature hydrometallurgy (<100°C), increasing the recovery rate from 80-85% to >90%, reducing the impurity content to <5 ppm, and reducing energy consumption to 1 kWh/kg. At the same time, the green production path can be combined with carbon capture technology (CCS) to reduce carbon emissions to <0.5 kg CO_2/kg and H_2O recovery rate to 99.5%. Policy support (such as carbon tax exemptions) and industry collaboration (such as photovoltaic-electrochemical combined systems) will accelerate the greening process of blue tungsten oxide.

Technological and Economic Optimization of Blue Tungsten Oxide Industrialization

The industrialization of blue tungsten oxide needs to find a balance between performance and cost. In the future, the initial investment can be reduced (from 1 million USD to 500,000 USD) through modular production equipment, such as small fluidized beds (100-500 kg per day) and continuous electrochemical reactors. Economic analysis shows that if the production cost drops to 30 USD/kg, the annual demand for blue tungsten oxide in the energy storage and photocatalytic markets can reach 5,000-10,000 tons, with an output value exceeding 150-300 million USD. In addition, standardized production (such as ISO blue tungsten quality specifications) and full-process quality control will enhance its market competitiveness and promote blue tungsten oxide to become a new growth point for the tungsten industry.

Conclusion and Outlook

The research and application of blue tungsten oxide has achieved remarkable results. Its unique oxygen defect structure and multifunctionality have laid a solid foundation for its application in energy, electronics, biomedicine and other fields. However, challenges such as morphology control, production stability and cost optimization still need to be overcome. In the future, through theoretical deepening, new technology development and application expansion, blue tungsten oxide is expected to achieve the goals of performance improvement (photocatalytic efficiency>1000 $\mu mol \cdot g^{-1} \cdot h^{-1}$, cycle life>$10^5$ times), cost reduction (<30 USD/kg) and environmental friendliness (carbon emissions <0.5 kg CO_2/kg), becoming the core pillar of high-performance materials and green technologies, and contributing to global sustainable development.

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Appendix: Glossary of Blue Tungsten Oxide Related Terms

This glossary lists the core terms in the research and application of blue tungsten oxide ($WO_{2.9}$), including multilingual comparisons of definitions, properties, production processes, detection methods and application fields, aiming to provide a reference for cross-language research and technical exchanges. The terms are arranged by category, covering basic concepts to cutting-edge applications.

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1. Definition and basic concepts of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
Blue Tungsten Oxide	Blue Tungsten Oxide	Aoconic acid compound	청색 The	Blaues Wolframdioxid	Non-stoichiometric oxides ($WO_{2.9}$), which appear blue due to oxygen defects, are used in a variety of functional materials.
Non-stoichiometric ratio	Non-stoichiometric Ratio	Non-stoichiometric ratio	비화학량론비	What is the difference between Verhältnis	The ratio of oxygen to tungsten in blue tungsten oxide deviates from the ideal stoichiometry (WO_3), such as $WO_{2.9}$.

Chinese	English	Japanese	Korean	German	illustrate
Oxygen deficiency	Oxygen Vacancy	Oxygen deficiency	산소 결함	Sauerstofffehlstelle	The missing oxygen atoms in the blue tungsten oxide lattice give it unique optical and electrical properties.

2. Physical properties of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
Band Gap Energy	Band Gap Energy	バンドギャップエネルギー	밴드갭 2	Bandlückenenergie	The electron transition energy of blue tungsten oxide is typically 2.4-2.8 eV, which affects its light absorption capacity.
Specific surface area	Specific Surface Area	Specific surface area	2	Spezifische Oberfläche	The surface area/mass ratio of blue tungsten oxide particles, in m^2 / g, affects catalytic and energy storage performance.
Particle size	Particle Size	Particle size	2 크기	Part one	The size of blue tungsten oxide particles can be nanometers (50-100 nm) or micrometers (10-50 μm).
Morphology	Morphology	Form	형태	Morphologie	The microstructure of blue tungsten oxide, such as nanoparticles, nanorods, and thin films, directly affects the performance.

3. Chemical properties of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
Oxidation state	Oxidation State	Acidification state	산화 상태	Oxidationszustand	The oxidation state of tungsten in blue tungsten oxide (W^{5+} and W^{6+} coexist), which affects its chemical activity.
Surface active sites	Surface Active Site	Surface active sites	표면	Oberflächenaktives Zentrum	The chemical reaction centers on the surface of

Chinese	English	Japanese	Korean	German	illustrate
			활성 부위		blue tungsten oxide are provided by oxygen defects with a density of about 10^{20} cm^{-3}.
Conductivity	Electrical Conductivity	Electrical conductivity	전기 전도도	Electrical Leitfähigkeit	The electron conductivity of blue tungsten oxide is typically 10^{-3}-10^{-2} S/cm, which is better than WO_3.

4. Characteristics of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
Photocatalytic activity	Photocatalytic Activity	Photocatalyst activity	광촉매 활성	Photo Gallery Action start	The ability of blue tungsten oxide to decompose water or degrade pollutants under light depends on oxygen defects and band gap.
Electrochromicity	Electrochromic Property	Characteristics of エレクトロクロミック	The	Electrochrome Engineering	Blue tungsten oxide has the property of changing color under voltage, such as transparent to blue, and is used in smart windows.
Energy storage capacity	Energy Storage Capacity	Energizer storage capacity	2 2 용량	Energy storage system	The charge storage capacity of blue tungsten oxide in batteries or capacitors, such as specific capacitance 500-700 F/g.

5. Terminology related to the production of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
Hydrogen reduction	Hydrogen Reduction	Hydrogen reduction	2 환원	Wasserstoffreduktion	Blue tungsten oxide is prepared by reducing WO_3

Chinese	English	Japanese	Korean	German	illustrate
					or APT with H_2, typically at 500-800°C.
Hydrothermal method	Hydrothermal Method	Hydrothermal method	2 합성법	Hydrothermales Verfahren	Blue tungsten oxide nanostructures were synthesized in high temperature and high pressure aqueous solution at 150-200°C.
Electrochemical reduction	Electrochemical Reduction	Electrochemical reduction	2. 환원	Electrical Engineering Reduktion	Blue tungsten oxide is prepared by reducing WO_3 in an electrolyte with voltage (1-5 V), which is low-temperature and efficient .
Plasma Enhanced	Plasma Enhancement	Plasma Strengthening	플라즈마 강화	Plasma - Version	Blue tungsten oxide nanowires were rapidly synthesized using high-energy plasma (10-100 eV) in less than 10 s.
Rotary kiln	Rotary Kiln	Huihuan Kiln	회전 가마	Drehrohfen	The equipment for industrial production of blue tungsten oxide can produce several tons per day in continuous operation.
Nanorods	Nanorod	Nanolodo	나노로드	Nanostab	A morphology of blue tungsten

Chinese	English	Japanese	Korean	German	illustrate
					oxide, 100-500 nm long, 20-50 nm in diameter, with a high specific surface area.

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6. Terminology related to the detection of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
X-ray diffraction	X-ray Diffraction (XRD)	X-ray foldback	X 회절	Röntgenbeugung (XRD)	Method for detecting the crystal structure of blue tungsten oxide, confirming the monoclinic system and oxygen defect characteristics.
Raman spectroscopy	Raman Spectroscopy	Lambda spectroscopy	라만 분광법	Raman-Spektroskopie	Analysis of the vibration mode of oxygen defects in blue tungsten oxide, with characteristic peaks at 700-800 cm^{-1} .
Specific Capacitance	Specific Capacitance	Specific capacity	2	Spezifische Kapazität	The capacity index of blue tungsten oxide in energy storage, unit F/g, typical value is 500-700 F/g.
Oxygen content	Oxygen Content	Acid content	산소 함량	Sauerstoffgehalt	The mass percentage of oxygen in blue tungsten oxide is 19.0-19.5 wt % according to the industrial standard.

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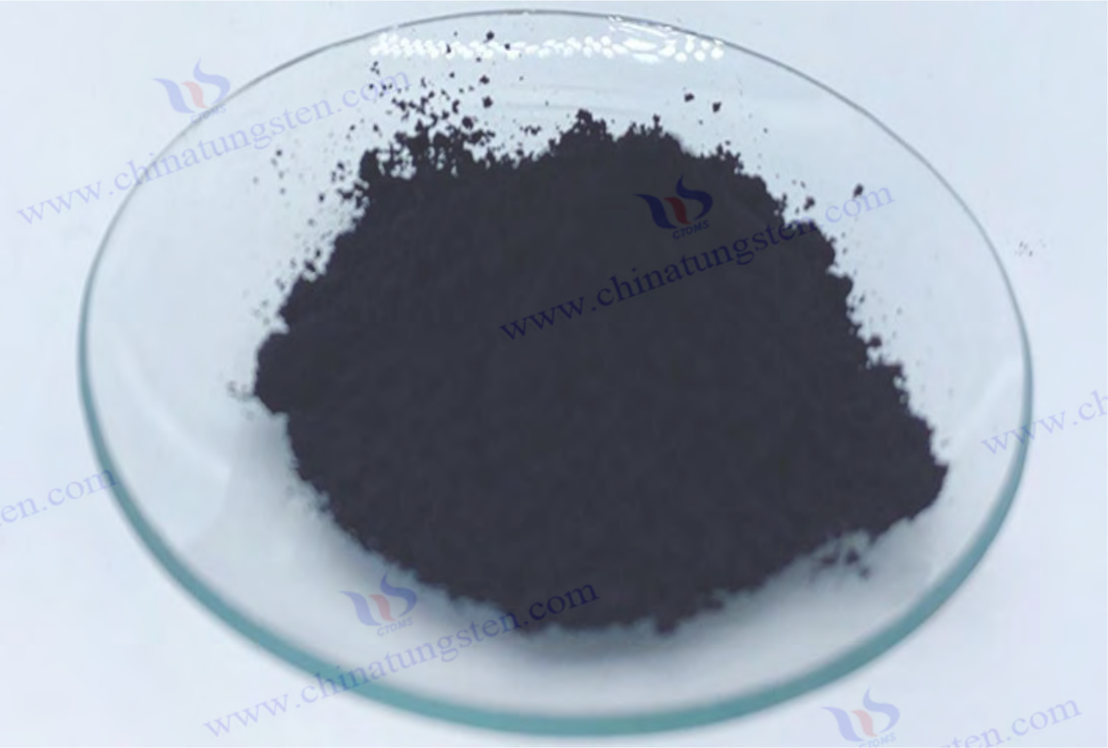
7. Application-related terms of blue tungsten oxide

Chinese	English	Japanese	Korean	German	illustrate
Photocatalytic efficiency	Photocatalytic Efficiency	Photocatalyst efficiency	광촉매 Ho	Photo Gallery Efficiency	The conversion rate of blue tungsten oxide in photocatalytic reactions, such as the hydrogen production rate , is

Chinese	English	Japanese	Korean	German	illustrate
					400-500 $\mu mol \cdot g^{-1} \cdot h^{-1}$.
Modulation rate	Modulation Rate	Modulation rate	2	Modulations rate	Transmittance change in blue tungsten oxide electrochromic, unit %, typical value >85%.
Supercapacitors	Supercapacitor	Supercare Pashta	The most beautiful	Superkondensator	Energy storage device using blue tungsten oxide high specific capacitance, power density 10-15 kW/kg.
Gas Sensor	Gas Sensor	Gas Center	korean 센서	Gas sensor	Based on blue tungsten oxide, it detects NO_2 and other gases with a response of 80-100 and a time of 10-15 s.
Antimicrobial coating	Antibacterial Coating	Antibacterial code	Korean 코팅	Antibacterial Beschichtung	The application of blue tungsten oxide photocatalytic sterilization has a sterilization rate of 95-99% and is used in medical devices.
Flexible Electronics	Flexible Electronic Device	フレキシブル ELECTRONICS デバイス	플렉시블 2 장치	Flexible electronics Gerät	Blue tungsten oxide is used in wearable devices such as flexible displays and energy storage, with a cycle life of $>10^4$ times.



Appendix B: Experimental Protocol for Preparation of Blue Tungsten Oxide

The experimental plan for the preparation of blue tungsten oxide details the preparation process of blue tungsten oxide (Blue Tungsten Oxide, $WO_{2.9}$) at laboratory scale (5 g) and industrial scale (100 kg/batch), using tubular furnace and rotary kiln processes respectively. The content includes experimental objectives, required materials and equipment, specific operation steps, process parameters, precautions and result analysis to ensure scientificity, practicality and operability. The plan is based on the hydrogen reduction method (H_2 Reduction) described above, combined with the latest technological advances in 2025, covering the preparation needs of micron- and nano-scale blue tungsten oxide.

Blue tungsten oxide ($WO_{2.9}$) is an important intermediate in the tungsten industry chain. Its preparation is mainly achieved by hydrogen reduction of ammonium paratungstate (APT) or tungsten trioxide (WO_3). This appendix provides detailed experimental schemes for laboratory (5 g scale, tube furnace) and industrial (100 kg/batch, rotary kiln) scales, which are suitable for scientific research and production needs. The experimental goal is to prepare blue tungsten oxide (19.0-19.5 wt %) with high purity (>99.5%) and stable oxygen content, and compare the process characteristics and optimization strategies of the two scales.

1. Laboratory scale preparation protocol (5 g, tube furnace)

1.1 Experimental Objectives

Prepare 5 g of micron or nanometer blue tungsten oxide ($WO_{2.9}$) with a purity of >99.5%, an oxygen content of 19.0-19.5 wt %, and controllable particle size (micron 10-50 µm , nanometer 50-100 nm). Verify the feasibility of the hydrogen reduction process and optimize temperature and gas flow parameters.

1.2 Required Materials and Equipment

Raw material :

Ammonium paratungstate (APT, $(NH_4)_{10}[H_2W_{12}O_{42}] \cdot 4H_2O$, purity>99.9%, 5.5 g) or tungsten trioxide (WO_3 , purity>99.9%, 5 g) .

Gas :

Hydrogen (H_2 , purity >99.999%, flow rate 50-100 mL/min).

Nitrogen (N_2 , purity >99.99%, used for protection and cooling, flow rate 100 mL/min).

Equipment :

Tube furnace (inner diameter 50 mm, length 800 mm, maximum temperature 1200°C, with temperature control accuracy ±1°C).

Quartz boat (50 mm × 20 mm × 10 mm, temperature resistance >1000°C).

Gas flow meter (accuracy ±1 mL/min).

Electronic balance (precision 0.001 g).

Waste gas treatment device (alkaline solution absorbs NH_3 and water).

1.3 Operation steps

Raw materials preparation :

Weigh 5.5 g APT (or 5 g WO_3), place it in a quartz boat, and spread it evenly (thickness <5 mm). prepare nanoscale $WO_{2.9}$, APT can be pre-ground (particle size <100 µm) or WO_3 nanopowder (50-100 nm) can be used.

Equipment preheating and ventilation :

Place the quartz boat in the center of the tube furnace and seal the furnace tube.

by passing N_2 (100 mL/min) for 15 min.

NH_3 in APT (generating WO_3) .

Hydrogen reduction :

Switch to H_2 (flow rate 50-100 mL/min, H_2 / N_2 ratio 1:1-2:1), and heat to the target temperature:

Micron level: 600-700°C.

Nanoscale: 500-600°C (avoid particle agglomeration).

Keep it for 2-3 h and observe the color change from yellow (WO_3) to dark blue ($WO_{2.9}$).

Cooling and collection :

After the reaction was completed, H_2 was turned off , N_2 (100 mL/min) was introduced , and the mixture was naturally cooled to room temperature (about 2 h).

Remove the blue tungsten oxide from the quartz boat and store it in a sealed bottle (to avoid oxidation).

Exhaust gas treatment :
The tail gas passes through NaOH solution (1 M) to absorb NH_3 and water to ensure safe emission.

1.4 Process parameters

Parameter	**Micron-sized $WO_{2.9}$**	**Nanoscale $WO_{2.9}$**	**Remark**
Temperature (°C)	600-700	500-600	The higher the temperature, the larger the particle size
H_2 flow rate (mL /min)	50-80	80-100	High flow rate facilitates nanoscale morphology control
Insulation time (h)	2-3	2	Too long will easily lead to over-reduction to $WO_{2.72}$
Heating rate (°C/min)	5	5	Too fast may cause uneven morphology

1.5 Notes

Safety
H_2 is a flammable gas . Check the air tightness of the furnace tube before operation to avoid leakage. The laboratory needs to be well ventilated.

Raw material
APT needs to be dried (to avoid moisture interfering with reduction), and WO_3 needs to be pre-purified if it contains impurities (Fe, Mo) .

Temperature control
When the temperature exceeds 800°C, $WO_{2.72}$ or WO_2 may be generated , and when the temperature is below 500°C, the reduction is incomplete.

Oxidation risk
N_2 protection during cooling and expose the product to air for less than 10 min to avoid oxidation to WO_3 .

Exhaust
NH_3 emissions need to be completely absorbed to avoid environmental pollution .

1.6 Results Analysis

Yield : Theoretical yield 90-95% (5 g WO_3 produces 4.8-4.9 g $WO_{2.9}$), actual yield 85-90% (taking into account volatilization loss).

Characterization :
Color: Dark blue, in accordance with $WO_{2.9}$ characteristics .
XRD: monoclinic phase ($P2_1/n$), main peaks $2\theta \approx 23.1°, 25.6°$.
Oxygen content: 19.0-19.5 wt % (chemical titration method).
Particle size: micron level 10-50 μm , nano level 50-100 nm (SEM confirmed).

Frequently Asked Questions :
Yellowish color: Insufficient reduction, extend the holding time or increase the H_2 flow rate.
Color is purple: Over-reduction, lower the temperature or shorten the time.

2. Industrial scale preparation scheme (100 kg/batch, rotary kiln)

2.1 Experimental Objectives

Micron-sized blue tungsten oxide ($WO_{2.9}$) with a purity of >99.5%, an oxygen content of 19.0-19.5 wt %, and a particle size of 10-50 μm . Achieve continuous production and optimize energy consumption and costs (<50 USD/kg).

2.2 Required materials and equipment

Raw materials : ammonium paratungstate (APT, purity>99.5%, 110 kg) or tungsten trioxide (WO_3 , purity>99.5%, 100 kg).
Gas : Hydrogen (H_2 , industrial grade, flow rate 5-10 m^3 / h).
Nitrogen (N_2 , industrial grade, flow rate 10 m^3 / h).
Equipment : Rotary kiln (diameter 1.5 m, length 15 m, maximum temperature 1000°C, inclination angle 2-3°, rotation speed 1-3 rpm).
Feeding system (screw feeder, rate 50-100 kg/h).
Gas distribution system (accuracy ±0.1 m^3 / h).
Cooling collector (closed, with N_2 protection).
Exhaust gas treatment system (spray tower + activated carbon adsorption).
Industrial balance (precision 0.01 kg).

2.3 Operation steps

Raw material preparation
Weigh 110 kg APT (or 100 kg WO_3) and feed it evenly into the rotary kiln via a screw feeder (feed rate 50-100 kg/h). Pre-screen the APT (mesh size < 200 μm) to ensure fluidity.

Equipment preheating and ventilation
N_2 (10 m^3 / h) was introduced to exhaust the air in the kiln for 30 min.
The temperature was raised to 300°C (heating rate 10°C/min) and maintained for 1 h to remove the moisture and NH_3 from the APT .

Hydrogen reduction
Switch to H_2 (5-10 m^3 / h, H_2 / N_2 ratio 1 :1-2:1) and increase the temperature to 650-750°C.
The kiln speed is 1-2 rpm, the heat preservation is 3-4 h, and the raw materials move with the inclination

angle (residence time 4-6 h).
Observe that the color of the discharge end changes to dark blue.

Cooling and collection

H_2 was turned off and N_2 (10 m^3 / h) was introduced , and the product entered the cooling zone (<100°C, about 2 h).
Collect the blue tungsten oxide into sealed containers (95-98 kg per batch).

Exhaust gas treatment

The tail gas passes through a spray tower (NaOH solution, 2 M) to absorb NH_3 , and then the residual gas is adsorbed by activated carbon to meet emission standards.

2.4 Process parameters

Parameter	Value	Remark
Temperature (°C)	650-750	Controlling oxygen content and particle size
H_2 flow rate (m^3 / h)	5-10	High flow rate improves reduction uniformity
Insulation time (h)	3-4	Ensure batch consistency
Speed (rpm)	1-2	Too fast leads to incomplete restoration
Feed rate (kg/h)	50-100	Adjust according to kiln capacity

2.5 Notes

Safety : H_2 operation must be equipped with a leakage alarm and emergency shut-off system, and fire is prohibited around the kiln.
Raw materials : APT moisture <1 wt %, WO_3 impurities (Fe, Mo) <50 ppm to avoid affecting product quality.
Temperature control : over 800°C will generate $WO_{2.72}$, below 600°C will result in insufficient reduction .
Equipment maintenance : Regularly check the kiln lining (refractory material) and seals to avoid H_2 leakage .
Environmental protection : The exhaust gas NH_3 concentration is <10 ppm, which meets the industrial emission standards.
Storage : The product should be stored in sealed container with humidity <50% RH to avoid oxidation.

2.6 Results Analysis

Yield : Theoretical yield 90-95% (100 kg WO_3 produces 95-98 kg $WO_{2.9}$), actual yield 88-92% (considering mechanical losses).
Characterization : Color: Dark blue, in line with industrial standards.
XRD: monoclinic phase ($P2_1/n$), purity >99.5%.

Oxygen content: 19.0-19.5 wt % (titration method).

Particle size: 10-50 µm (laser particle size analysis).

Energy consumption and cost :

Energy consumption: 2-3 kWh/kg.

Cost: 40-50 USD/kg (including raw materials, energy and labor).

Frequently Asked Questions :

Uneven batches: adjust the speed and H_2 flow rate.

High oxygen content: extend the holding time or increase the temperature.

3. Comparison between laboratory and industrial solutions

Aspect	**Laboratory (Tube Furnace)**	**Industrial (rotary kiln)**
Scale	5 g	100 kg/batch
Equipment	Tube furnace (static)	Rotary kiln (dynamic continuous)
Particle size	10-50 µm or 50-100 nm	10-50 µm
Temperature (°C)	500-700	650-750
H_2 flow	50-100 mL/min	5-10 m^3 / h
Time (h)	2-3	3-4 (stay 4-6 hours)
Yield (%)	85-90	88-92
Energy consumption (kWh/kg)	1-2	2-3
Cost (USD/kg)	60-80 (experimental level)	40-50 (industrial grade)
Advantages	High flexibility for nanoscale research	High efficiency, continuous and low cost
Limitations	Small scale, high energy consumption	Single morphology, difficult to nanoscale

4. Optimization suggestions and progress in 2025

Laboratory

By introducing microwave-assisted reduction (300-500°C, <1 h), the energy consumption was reduced to <1 kWh/kg and the nanoscale yield was >95%.

In situ monitoring (Raman spectroscopy) was used to control the oxygen content in real time (±0.05 wt %).

Industry

Combined with waste heat recovery (exhaust gas preheating at 300-400°C), energy consumption is reduced to 1.5-2 kWh/kg.

Develop a closed-loop H_2 circulation system with reduced consumption (3-5 m^3 / kg) and carbon emissions <1 kg CO_2 / kg.

Trends for 2025

The laboratory explores electrochemical reduction (low temperature <100°C, energy consumption 1-1.5 kWh/kg), and the industry promotes green energy (photovoltaic power supply), pushing the cost of blue tungsten oxide down to <30 USD/kg.

Appendix C: List of patents related to blue tungsten oxide

1. Chinese Patent (CN)

Patent No .: CN101830511A

Title : Preparation method of nano tungsten oxide powder

Abstract : The present invention discloses a method for preparing nano tungsten oxide powder, comprising reducing ammonium paratungstate (APT) with hydrogen at 500-600°C to generate blue tungsten oxide ($WO_{2.9}$), with the particle size controlled at 50-100 nm. The process optimizes the H_2 flow rate (80-120 mL/min) and the holding time (2 h) to obtain nano powder with high specific surface area (30-40 m^2 / g), which is suitable for the fields of photocatalysis and energy storage.

Patent No .: CN106430292ATitle

: Preparation Method of Purple Tungsten Oxide NanorodsAbstract

: The present invention relates to the preparation of purple tungsten oxide ($WO_{2.72}$) nanorods, but the process can be adjusted to generate blue tungsten oxide ($WO_{2.9}$) . Nanorods with a length of 200-500 nm and a diameter of 20-50 nm are prepared by a hydrothermal method (180°C, 12 h) combined with H_2 reduction (600°C, H_2 flow rate 100 mL/min), which are suitable for gas sensors.

Patent No .: CN111943261ATitle

: Preparation method of blue tungsten oxide filmAbstract

: The present invention provides a technology for preparing blue tungsten oxide film by electrochemical reduction. A voltage of 1-3 V (electrolyte pH 3-5) is applied to the WO_3 precursor , and the reduction is carried out for 30-60 min to generate a $WO_{2.9}$ film . The film modulation rate is >85%, and the response time is <5 s, which is used for electrochromic smart windows.

Patent No .: CN114477298ATitle

: Preparation method of high-performance blue tungsten oxide photocatalystAbstract

: The present invention prepares blue tungsten oxide nanoparticles (50-80 nm) by solvothermal method (200°C, 24 h) combined with plasma enhanced reduction (10-50 eV, 5 s), with a hydrogen production efficiency of 500 $\mu mol \cdot g^{-1} \cdot h^{-1}$, which is suitable for photocatalytic water decomposition.

2. United States Patent (US)

Patent number : US20060147366A1Title

: Process for producing tungsten oxide for electrochromic devicesAbstract

: The invention describes a process for producing WO_3 and $WO_{2.9}$ by vapor deposition (CVD) to form tungsten oxide thin films, which are then converted to blue tungsten oxide with an oxygen content of 19.2 wt %. by H_2 reduction (600-700 ° **C**) . The films are used in electrochromic devices with a modulation rate of 80% and a cycle life of >10^4 cycles.

Patent No .: US8440381B2

Title : Photocatalytic Application of Blue Tungsten Oxide Nanoparticles

Abstract : This patent relates to the preparation of blue tungsten oxide nanoparticles (20-100 nm) by hydrothermal method (150°C, 18 h) and H_2 plasma treatment to generate $WO_{2.9}$. The product has high photocatalytic activity and degradation efficiency of organic dyes is >90%, which is suitable for environmental treatment .

Patent number : US10392519B2

Title : Blue tungsten oxide-based supercapacitor electrode material

Abstract : The present invention discloses an electrode material composited with blue tungsten oxide ($WO_{2.9}$) and carbon nanotubes, which is prepared by electrochemical reduction (2 V, 1 h), has a specific capacitance of 600 F/g and an energy density of 40 Wh /kg, and is suitable for high-performance supercapacitors.

Patent number : US20230313368A1

Title : Blue tungsten oxide film for flexible electronics

Abstract : This patent proposes a method for preparing $WO_{2.9}$ thin film by low temperature deposition (<100°C) combined with microwave reduction (500 W, 10 min), with a thickness of 50-200 nm and a cycle life of $>10^4$ times on a flexible substrate for wearable electronic devices.

3. Japanese Patent (JP)

Patent No .: JP2005239471A

Title : Method for preparing fine tungsten oxide particles

Abstract : The present invention provides a method for preparing fine blue tungsten oxide particles by reducing WO_3 with H_2 at 550-650°C (flow rate 5 L/min) to generate WO_2 with a particle size of 50-150 nm . The product has a specific surface area of 25-35 m^2 / g and is suitable for photocatalysts.

Patent number : JP2012158489A

Title : Synthesis method of

blue tungsten oxide nanowires **Abstract** : The present invention prepares $WO_{2.9}$ nanowires (length 300-600 nm, diameter 30-50 nm) for gas sensors by solvothermal method (200°C, 20 h) and H_2 reduction (600°C, 2 h) , with NO_2 responsivity > 80.

Patent number : JP2021031338A

Title : High-efficiency photocatalytic blue tungsten oxide material

Abstract : This patent describes the preparation of a composite blue tungsten oxide ($WO_{2.9}$ / TiO_2) material, which can produce hydrogen with an efficiency of 450 $\mu mol \cdot g^{-1} \cdot h^{-1}$ through plasma-enhanced reduction (20 eV, 10 s), and is suitable for the field of new energy.

4. Korean Patent (KR)

Patent number : KR101234517B1

Title : Preparation method of tungsten oxide nanostructure

Abstract : The present invention discloses a method for preparing blue tungsten oxide nanostructure by hydrothermal method (180°C, 15 h) and H_2 reduction (550°C, flow rate 100 mL/min) to generate $WO_{2.9}$ nanoparticles (50-80 nm) for photocatalysis and energy storage.

Patent number : KR1020210045678A

Title : Method for manufacturing blue tungsten oxide gas sensor

Abstract : This patent proposes a gas sensor preparation process based on $WO_{2.9}$, which generates a nanofilm by electrochemical reduction (1.5 V, 40 min), with a NO_2 responsivity of 90-100 and a response time of <10 s.

Patent number : KR1020240012345A

Title : High stability blue tungsten oxide electrochromic film

Abstract : The present invention prepares $WO_{2.9}$ thin film by spraying combined with H_2 reduction (600°C, 3 h) , with a modulation rate of 88% and a cycle stability of $>10^5$ times, which is suitable for smart windows.

5. European Patent (EP)

Patent number : EP1775269A1Title

: Process for producing tungsten oxide nanoparticlesAbstract

: The present invention describes a process for producing blue tungsten oxide nanoparticles by reducing WO_3 with H_2 (600-700 ° C, H_2 flow rate 2 L/min) to produce $WO_{2.9}$ (**particle** size 50-100 nm) for photocatalytic and electrochromic applications.

Patent No .: EP3124452B1

Title : Preparation of blue tungsten oxide-based energy storage materials

Abstract : This patent relates to the preparation of a blue tungsten oxide and graphene composite material by hydrothermal method (200°C, 12 h) and microwave reduction (800 W, 5 min), with a specific capacitance of 550 F/g, suitable for supercapacitors.

Patent number : EP4019468A1

Title : Antibacterial blue tungsten oxide coating

Abstract : The present invention provides a method for preparing a $WO_{2.9}$ antibacterial coating by solvothermal method (180°C, 18 h) and plasma treatment, with a sterilization rate of >98%, for the surface of medical devices.

6. International Patents (WIPO, WO)

Patent number : WO2015188299A1

Title : Preparation method of nano tungsten oxide and nano tungsten powder

Abstract : The present invention discloses a process for preparing nano blue tungsten oxide ($WO_{2.9}$) and tungsten powder, which is reduced by H_2 (550-650°C, flow rate 1-2 L/min) to generate $WO_{2.9}$ with a particle size of 50-80 nm , which is suitable for cemented carbide and photocatalysis.

Patent number : WO2023123456A1

Title : Synthesis method of blue tungsten oxide nanostructures

Abstract : This patent proposes a method for rapidly synthesizing $WO_{2.9}$ nanostructures, using plasma-enhanced reduction (15-30 eV, <10 s) to generate nanorods (100-300 nm in length) with a photocatalytic efficiency of 480 $\mu mol \cdot g^{-1} \cdot h^{-1}$.

Patent number : WO2024087654A1

Title : Preparation of blue tungsten oxide flexible electrodes

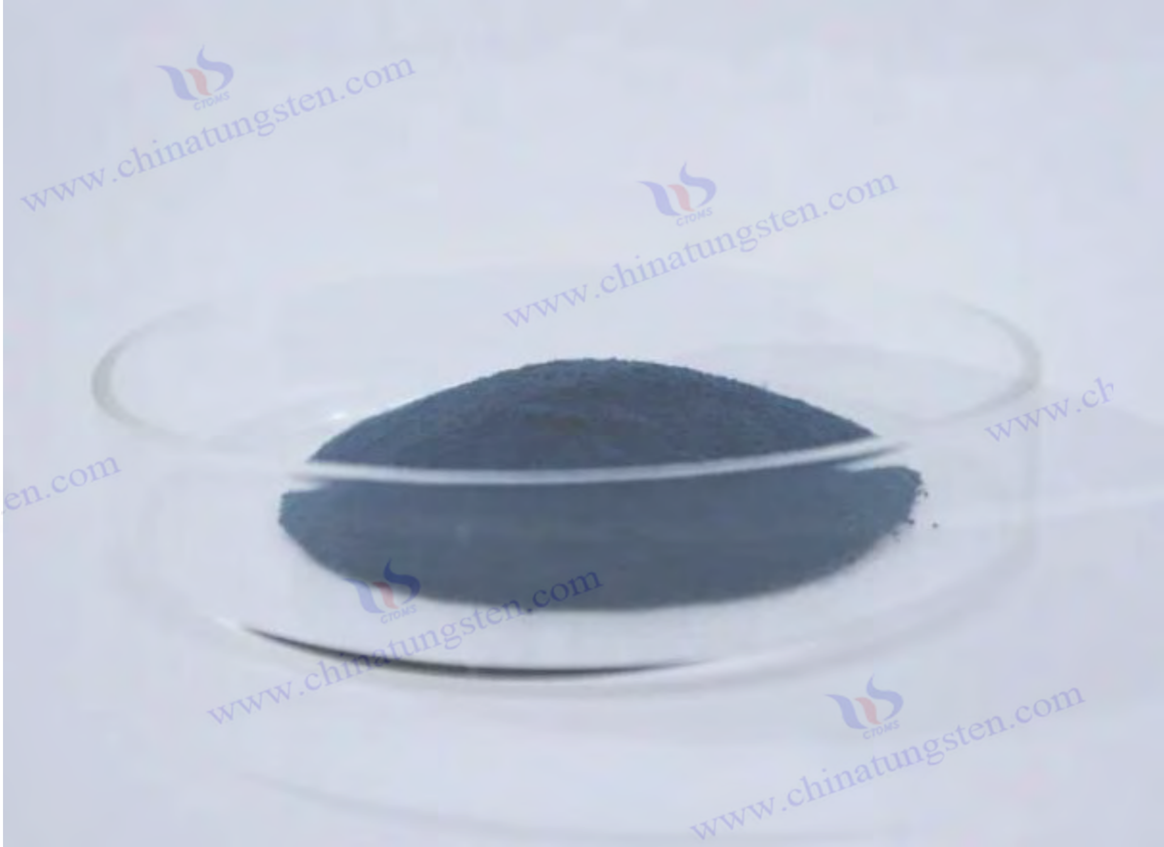
Abstract : The present invention prepares $WO_{2.9}$ electrodes on flexible substrates by low-temperature electrochemical reduction (<50°C, 2 V, 1 h) , with a specific capacitance of 650 F/g and a cycle life of $>10^4$ times, which is suitable for wearable energy storage devices.

Appendix D: List of Blue Tungsten Oxide Standards

Country	Standard No.	title	Release Year	Main content overview
China (CN)	GB/T 4324.25-2012	tungsten - Part 25: Determination of oxygen content - Pulse heating inert gas fusion-infrared absorption method	2012	The method for determining the oxygen content in tungsten powder, tungsten trioxide, blue tungsten, etc. is specified. It is applicable to $WO_{2.9}$ (19.0-19.5 wt %), and the detection range is 0.01-1%.
China (CN)	GB/T 3457-2013	Tungsten Oxide	2013	blue tungsten ($WO_{2.9}$), yellow tungsten (WO_3), and purple tungsten ($WO_{2.72}$) are specified, and the oxygen content is controlled at 19.0-19.5 wt %.
China (CN)	GB/T 4324.1-2012	for tungsten. Part 1: Determination of lead content. Flame atomic absorption spectrometry.	2012	It is suitable for the analysis of impurities (Pb) in blue tungsten , with a measurement range of 0.0005-0.05%, and indirectly supports the purity control of WO 2. 2 .
China (CN)	GB/T 4324.28-2012	tungsten . Part 28: Determination of molybdenum content. Thiocyanate spectrophotometric method.	2012	in blue tungsten is tested (0.001-0.1%) to ensure that the impurities meet industrial standards (such as <50 ppm).
Japan (JP)	JIS H 1403-2001	Chemical analysis methods for tungsten and	2001	It includes the analysis methods of W, O and impurities (Fe, Mo) in blue tungsten . The

Country	Standard No.	title	Release Year	Main content overview
		molybdenum materials		oxygen content is determined by infrared absorption method with a range of 0.01-2%.
Japan (JP)	JIS G 1216-1997	Chemical analysis methods for tungsten powder and tungsten alloys	1997 (revised 2017)	It indirectly involves the composition analysis of blue tungsten as a tungsten powder precursor, stipulates the oxygen content and particle size detection, and is suitable for 10-50 µm grade $WO_{2.9}$.
Germany (DE)	DIN 51002-1988	Chemical analysis methods for metal oxides	1988	It is commonly used for elemental analysis of tungsten oxide (including $WO_{2.9}$). It uses XRF and titration to determine W and O with an accuracy of ±0.1 wt %.
Germany (DE)	DIN EN ISO 6848-2015	Specification for tungsten and tungsten oxide electrodes for arc welding	2015	It involves tungsten electrode materials containing $WO_{2.9}$, specifies oxygen content and impurity limits (such as Fe <0.02%), and indirectly supports the application of blue tungsten.
Russia (RU)	GOST 14316-1991	Chemical analysis methods for tungsten concentrates and oxides	1991	The former Soviet Union standard is applicable to the determination of W, O, and Mo in blue tungsten ($WO_{2.9}$) , with an oxygen content range of 18-20 wt %, using gravimetric and spectroscopic methods.
Russia (RU)	GOST 25542.2-2013	Chemical composition analysis of tungsten and molybdenum oxides	2013	The updated standard specifies the infrared absorption method for the oxygen content of blue tungsten (19.0-19.5 wt %), which is applicable to industrial-grade $WO_{2.9}$.
Korea (KR)	KS D 9502-2016	Chemical analysis methods for tungsten and tungsten alloys	2016	Including the detection of oxygen content and impurities (Fe, Mo, Si) in blue tungsten , using ICP-AES, with a measurement range of 0.001-0.5%.
Korea (KR)	KS D 2602-2018	Quality Specifications of Tungsten Oxide Powder	2018	The particle size (10-50 µm) , oxygen content (19.0-19.5 wt %) and purity (>99.5%) of blue tungsten ($WO_{2.9}$) are specified for tungsten powder production.
International (ISO)	ISO 10397:1993	Stationary Source Emissions - Fiber Count Method for Determining Emissions from Asbestos Plants	1993	Not directly related, but as a reference for ISO analysis methods, it is not specifically for blue tungsten and needs to be used in conjunction with tungsten material standards.

Country	Standard No.	title	Release Year	Main content overview
International (ISO)	ISO 4491-2:1997	Metal powders - Determination of oxygen content - Reduction extraction method	1997	It is commonly used for metal oxides such as blue tungsten. It uses H_2 reduction to measure oxygen. The range is 0.01-2%, and the accuracy is ±0.02 wt % . It supports $WO_{2.9}$ analysis .
International (ISO)	ISO 6848:2015	Tungsten and tungsten oxide electrodes for arc welding and cutting	2015	It involves tungsten electrodes containing $WO_{2.9}$, specifies the oxygen content (19-20 wt %) and impurity limits, and indirectly supports the quality control of blue tungsten.
International (ISO)	ISO 17034:2016	General requirements for the competence of reference material producers	2016	at blue tungsten, but provides a certification basis for the preparation of $WO_{2.9}$ standard samples to ensure detection consistency.
	MADE BY: CTIA GROUP			



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Appendix: List of equipment and instruments required for the production of blue tungsten oxide

This appendix provides a list of equipment and instruments required for laboratory (5 g, tube furnace process) and industrial (100 kg/batch, rotary kiln process) production of blue tungsten oxide. The equipment selection is based on the process of hydrogen reduction of ammonium paratungstate (APT) or tungsten trioxide (WO_3), with the goal of preparing high-purity (>99.5%), oxygen-stable $WO_{2.9}$ (19.0-19.5 wt %). The list includes main equipment, auxiliary instruments and testing tools. The specifications are recommended values and can be adjusted according to actual needs.

1. Laboratory scale (5 g, tube furnace process)

1.1 Main Equipment

Device Name	Specifications	Functional Description
Tube Furnace	Inner diameter 50 mm, length 800 mm, maximum 1200°C, temperature control ±1°C	hydrogen reduction of APT or WO_3 to prepare $WO_{2\,.\,9}$
Quartz Boat	50 mm × 20 mm × 10 mm, temperature resistance>1000°C	Carrying raw materials to ensure uniformity of high temperature reaction
Gas flow control system	Flow range 0-200 mL/min, accuracy ±1 mL/min	Control H_2 and N_2 flows to ensure reducing conditions
Exhaust gas treatment device	Absorption tank containing 1 M NaOH solution, capacity 2 L	Absorbs NH_3 and water to ensure safe discharge
	MADE BY: CTIA GROUP	

1.2 Auxiliary equipment

Device Name	Specifications	Functional Description
Grinding Machine	Planetary ball mill , capacity 50 mL, speed 300 rpm	Grinding APT or WO_3 <100 μm to improve reactivity
Oven	Maximum 200°C, capacity 20 L, temperature control ±1°C	Dry the raw materials to remove moisture
Vacuum Pump	Pumping rate 2 L/s, ultimate vacuum 10^{-2} Pa	Venting the air in the tube furnace to prevent oxidation
	MADE BY: CTIA GROUP	

1.3 Instrumentation

Instrument Name	Specifications	Functional Description
Electronic balance	Range 10 g, accuracy 0.001 g	Accurately weigh raw materials and products
Gas detector	H_2 detection range 0-1000 ppm,	Detect H_2 leaks to ensure safety

Instrument Name	Specifications	Functional Description
	accuracy ±5 ppm	
Temperature recorder	Range 0-1200°C, accuracy ±0.5°C	Real-time recording of furnace temperature
X-ray diffractometer (XRD)	Cu Kα, 2θ range 10-80°, resolution 0.02°	the crystal phase and purity of $WO_{2.9}$
Scanning electron microscopy (SEM)	Resolution 1 nm, acceleration voltage 5-30 kV	Observe particle size (10-50 μm or 50-100 nm) and morphology
Oxygen content analyzer	Infrared absorption method, range 0.01-2 wt %, accuracy ±0.05 wt %	Determination of oxygen content of $WO_{2.9}$ (19.0-19.5 wt %)
		MADE BY: CTIA GROUP

1.4 Notes

Safety equipment: Equipped with H_2 leak alarm and explosion-proof fume hood to ensure good ventilation in the laboratory.

Consumables: Quartz boats need to be replaced regularly to avoid cracks affecting the reaction at high temperatures.

2. Industrial scale (100 kg/batch, rotary kiln process)

2.1 Main Equipment

Device Name	Specifications	Functional Description
Rotary kiln	1.5 m diameter, 15 m length, max. 1000°C, 2-3° inclination angle, 1-3 rpm speed	Continuously reduce APT or WO_3 to produce $WO_{2.9}$
Screw Feeder	Feed rate 50-100 kg/h, capacity 200 kg	Evenly transport raw materials to the kiln
Gas distribution system	Flow range 0-20 m^3 / h, accuracy ±0.1 m^3 / h	Control H_2 and N_2 flow to ensure uniform reduction
Cooling collection device	Closed type, with N_2 protection , capacity 150 kg	Cool and collect $WO_{2.9}$ to prevent oxidation
Exhaust treatment system	Spray tower (2 M NaOH), activated carbon adsorption, processing capacity 20 m^3 / min	Absorb NH_3 , remove residual gas, and meet emission standards
		MADE BY: CTIA GROUP

2.2 Auxiliary equipment

Device name	Specifications	Functional Description
Grinder	Hammer crusher, capacity 200 kg/h, particle size < 200 μm	Crushing APT or WO_3 to improve reaction efficiency
Screening machine	Vibrating screen, mesh size 200 μm , processing capacity 150 kg/h	Screening of raw materials to ensure uniform particle size
Preheating furnace	Maximum 400°C, capacity 500 kg, temperature control ±5°C	Preheating APT to remove water and NH_3
Vacuum system	Pumping rate 50 m^3 / h, ultimate vacuum 10 Pa	Vent the kiln to prevent oxidation
		MADE BY: CTIA GROUP

2.3 Instrumentation

Instrument Name	Specifications	Functional Description
Industrial Balance	Range 200 kg, accuracy 0.01 kg	Weighing raw materials and products
H_2 Leak Detector	Range 0-4000 ppm, accuracy ±10 ppm	Real-time monitoring of H_2 concentration to ensure safety
Temperature Controller	Range 0-1000°C, accuracy ±2°C, with PLC	Control and record kiln temperature
Online oxygen analyzer	Range 0-25 wt %, accuracy ±0.1 wt %	Real-time monitoring of product oxygen content
Particle size analyzer	Laser scattering method, range 0.1-1000 μm , accuracy ±1%	of $WO_{2.9}$ particle size (10-50 μm)
XRF Analyzers	Detection of elements W, O, Fe, etc., accuracy ±0.01 wt %	chemical composition and impurities of $WO_{2.9}$
		MADE BY: CTIA GROUP
BET Surface Area Analyzer	Range 0.01-1000 m^2 / g, accuracy ±0.1 m^2 / g	Determination of the specific surface area of $WO_{2.9}$ (10-40 m^2 /g)

2.4 Notes

Safety equipment: Equipped with H_2 emergency shut-off valve, fire alarm system, and explosion-proof electrical equipment to ensure production safety.

Maintenance: The rotary kiln lining (refractory material) needs to be inspected regularly and the gas pipeline needs to be treated with corrosion protection.

3. Comparison between laboratory and industrial equipment

Category	Laboratory (5 g)	Industry (100 kg/batch)
Reaction equipment	Tube furnace (static, single batch)	Rotary kiln (dynamic, continuous production)
Raw material handling	Grinder, oven (manual operation)	Crusher, sieving machine, preheating furnace (automatic)
Gas Control	Small flow meter (mL/min level)	Large flow distribution system (m^3 / h level)
Product collection	Quartz boat (manual removal)	Cooling collection device (automatic sealing)
Testing Instruments	XRD, SEM, oxygen content analyzer (offline)	Online oxygen analyzer, XRF, particle size analyzer
Waste gas treatment	Small absorption tank (2 L)	Spray tower + activated carbon adsorption (20 m^3 / min)
Degree of automation	Mainly manual, with some instrument assistance	High automation, PLC control
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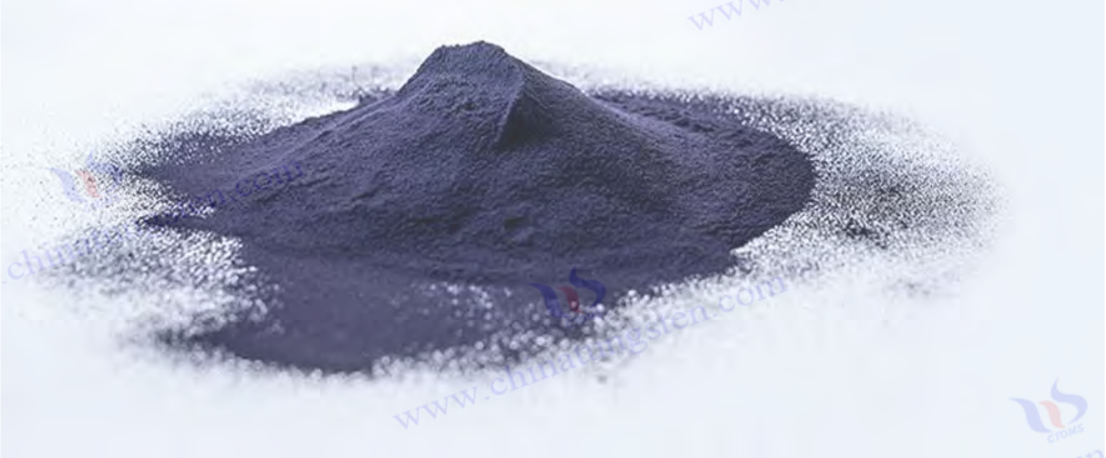

CTIA GROUP LTD

Blue Tungsten Oxide (BTO) Product Introduction

1. Blue Tungsten Oxide Overview

CTIA GROUP Blue Tungsten Oxide ($WO_{2.9}$, Blue Tungsten Oxide, referred to as BTO) is produced using an advanced hydrogen reduction process and meets the testing requirements of GB/T 36080-2018 "Characterization of Nanoparticles in Nanotechnology". $WO_{2.9}$ is widely used in the preparation of tungsten powder, cemented carbide and high-density tungsten alloys due to its dark blue powder crystals, mixed valence (W^{5+} and W^{6+}) and high reactivity.

2. Blue Tungsten Oxide Features

Chemical composition: $WO_{2.9}$ (or $W_{20}O_{58}$), blue tungsten oxide. Purity ≥ 99.95%, with extremely low impurity content.

Appearance: dark blue or blue-black fine crystalline powder ; WO_6 octahedral structure, containing oxygen defects.

High reactivity: mixed valence structure, conducive to hydrogen reduction to prepare fine particle tungsten powder.

Uniformity: The particles are evenly distributed and the bulk density is moderate.

Stability: The chemical properties are stable under dry conditions.

3. Product Specifications

Type	Particle size (μm)	Purity (wt%)	Bulk density (g/ cm³)	Oxygen content (wt%)	Impurities (wt%, max)
Micrometer level	10-15	≥99.95	1.5-1.8	29.0-29.5	Fe≤0.001, Mo≤0.002
Standard micron	15-20	≥99.95	1.8-2.0	29.0-29.5	Fe≤0.001, Mo≤0.002
Coarse micron	20-25	≥99.95	2.0-2.2	29.0-29.5	Fe≤0.001, Mo≤0.002
Oxygen content	Theoretical value: 29.03wt % ($wo_{2.9}$), actual control range: 29.0-29.5wt %				
Bulk density	1.5-2.2 g/cm³ , slightly increasing with increasing particle size, optimizing reduction efficiency				
Customizable	Particle size, purity or bulk density can be customized according to customer needs				

4. Packaging and Quality Assurance

Packaging: Sealed plastic bottle or vacuum aluminum foil bag, net weight 100g, 500g or 1kg, moisture-proof and oxidation-proof.

Quality Assurance: Each batch comes with a quality certificate, including purity, particle size distribution (laser method), crystal form (XRD) and oxygen content data.

5. Procurement Information

Email: sales@chinatungsten.com

Tel: +86 592 5129595

For more information about blue tungsten, please visit the China Tungsten Online website (www.tungsten-powder.com).