Encyclopedia of Barium Tungsten Cathode

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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Appendix

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CTIA GROUP LTD
Barium Tungsten Cathode Introduction

1. Overview of Barium Tungsten Cathode

The Barium Tungsten Cathode is a type of thermionic emission material typically composed of high-purity tungsten as the base, impregnated with barium compounds. Upon high-temperature activation, it emits free electrons and is widely used in vacuum electronic devices. Due to its low work function and high electron emission efficiency, this cathode plays a critical role in high-power electronic equipment. CTIA GROUP LTD specializes in the global flexible customization of tungsten and molybdenum products, offering tailored high-performance barium tungsten cathodes according to customer requirements.

2. Characteristics of Barium Tungsten Cathode

- **High Electron Emission Efficiency:** The low work function of barium enables the cathode to emit a large quantity of electrons even at relatively low temperatures.
- **High-Temperature Resistance:** With a tungsten matrix that has a melting point of 3422° C, the cathode maintains structural stability in high-temperature operating environments.
- **Long Service Life:** Optimized barium compound impregnation techniques help minimize barium evaporation, thereby extending the cathode's lifespan.
- **Low Evaporation Rate:** Compared to other cathode materials, barium tungsten exhibits a lower evaporation rate at high temperatures, reducing contamination within the device.
- **Arc Stability:** Delivers a stable electron flow, making it ideal for high-precision electron beam applications.

3. Applications of Barium Tungsten Cathode

- **HID Lamps:** The cathode's low work function and high current density allow HID lamps to emit bright and stable light, making them suitable for applications that require high brightness and long service life, such as roadway and industrial lighting.
- **Vacuum and Laser Devices:** The low work function makes barium tungsten ideal for use in vacuum electronic and laser components.
- **Stage and Club Lighting Effects:** High-frequency strobe lights made from this material are known for their long lifespan and stable performance.
- **Film Projection and Video Recording:** The film and broadcast industry also relies heavily on this material for projection and recording equipment, where it ensures long-term operational stability and high efficiency.
- **Laser Mercury Pumps:** Its high electron emission capability and low operating temperature contribute to improved laser performance and stability.

5. Procurement Information

Email: sales@chinatungsten.com
Phone: +86 592 5129595; 592 5129696
Website: www.tungsten.com.cn

Preface

Purpose and Significance

Barium Tungsten Cathode, as an efficient thermion-emitting material, occupies a pivotal position in the field of modern electronic technology. Its core properties—low work function, high emission current density, and excellent thermal stability and long lifetime—stem from the ingenious combination of a porous tungsten matrix with a barium compound such as barium-calcium aluminate. This unique design makes barium tungsten cathodes ideal for vacuum electronic devices (such as microwave tubes, X-ray tubes, and photomultiplier tubes), and are widely used in cutting-edge fields such as aerospace, medical imaging, communication systems, scientific instruments, and high-energy physics experiments. Barium tungsten cathodes not only promote the continuous advancement of vacuum electronics technology, but also provide potential support for emerging technologies such as terahertz wave generators and ion thrusters.

This book is designed to provide readers with a comprehensive and systematic reference material for barium tungsten cathodes, covering its material science, manufacturing process, working principle, application fields, and future development trends. We hope to uncover its critical role in high-performance electronics by delving into the technical details of barium-tungsten cathodes, while exploring their potential for innovation in interdisciplinary fields.

Overview of Book Structure

This book has a clear structure, from basic to application, from theory to practice, logical rigor, layer by layer, divided into eight chapters and appendices, fully covering all aspects of barium tungsten cathodes:

- **Chapter 1: Overview of Barium Tungsten Cathodes**
  This chapter lays the foundation for the book, introducing the definition, basic concepts and comparisons of barium and tungsten cathodes and their comparison with other hot and cold cathodes, sorting out the historical context of its evolution from its origin to modern technology, and outlining its wide range of applications in vacuum electronic devices, industry and scientific research.
- **Chapter 2: Material Science of Barium Tungsten Cathodes**
  This chapter delves into the material composition and preparation process of barium tungsten cathodes, analyzes the chemical and physical properties of porous tungsten matrixes, barium compounds and additives, and reveals the internal relationship between microstructure (such as porosity and surface morphology) and emission properties.
- **Chapter 3: Working Principle and Emission Mechanism**
  This chapter starts from the theory of thermionic emission and combines the Richardson-Dushman equation, Schottky effect and quantum mechanics to analyze in detail the formation mechanism of the low work function of barium tungsten cathode, the dynamic

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behavior of the active layer and the environmental factors affecting the emission performance.

- **Chapter 4: Manufacturing and Processing Technology of Barium Tungsten Cathode**
  This chapter focuses on the manufacturing process, covering the powder metallurgy molding of porous tungsten matrix, the impregnation and activation process of barium compounds, and the testing and quality control methods of emission properties, providing technical reference for industrial production.
- **Chapter 5: Application of Barium Tungsten Cathode**
  This chapter systematically sorts out the specific applications of barium tungsten cathode in vacuum electronic devices (such as microwave tubes, X-ray tubes), scientific instruments (such as electron microscopes, mass spectrometers), industrial communications, aerospace and emerging fields, highlighting its cross-field potential.
- **Chapter 6: Optimization and Improvement of Barium Tungsten Cathode Performance**
  This chapter discusses strategies to improve emission efficiency, extend service life, and enhance environmental adaptability, including cutting-edge methods such as novel barium compound formulations, nanotechnology applications, and intelligent design.
- **Chapter 7: Challenges and Future Developments**
  This chapter analyzes current technical bottlenecks (such as material costs, performance consistency) and challenges of competing technologies such as cold cathodes, and looks forward to the future direction of new materials, new processes, and interdisciplinary research (such as artificial intelligence and quantum computing).
- **Chapter 8: Barium Tungsten Cathode Standards**
  This chapter introduces international and industry standards related to barium and tungsten cathodes, covering performance parameter specifications, test methods, manufacturing processes, and environmental safety requirements, providing guidelines for standardized production.
- **Appendices and Indexes**
  Appendices include glossaries, references, test standards, performance data sheets, and supplier information (e.g., CTIA GROUP LTD) for easy reference and in-depth research. The indexing section provides keyword and topic indexes for quick content targeting.

The content design of this book focuses on the combination of theory and practice, with both in-depth discussions on basic science and detailed guidance on engineering applications, aiming to provide readers with a comprehensive and practical knowledge system.

Target Audience

This book is intended for a wide range of readers, including but not limited to:

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- **Materials Scientists**: pay attention to the material composition, microstructure and preparation process of barium tungsten cathodes, and seek breakthroughs in new materials and processes.
- **Electronic Engineer**: Engaged in the design and development of vacuum electronic devices, it is necessary to master the working principle and manufacturing technology of barium tungsten cathode.
- **Vacuum Electronics Technology** researchers: focus on the performance optimization, application expansion and standardization research of thermal cathodes.
- **Industrial Technicians**: apply barium tungsten cathodes in the production and maintenance of microwave tubes, X-ray tubes, radar systems and other equipment.
- **Interdisciplinary Innovators**: Exploring the potential of barium tungsten cathodes in emerging fields such as terahertz technology, ion thrusters, biomedicine, and more.
- **Teachers and Students in Colleges and Universities**: This book can be used as a graduate textbook or reference book for majors in materials science, electronic engineering, vacuum electronic technology, etc., to provide support for academic research and teaching.

Whether you are a newcomer to barium tungsten cathodes or an expert with years of experience in related fields, this book aims to provide you with a clear knowledge framework, in-depth technical insights, and practical application guides.

Write Features and Values

This book focuses on the following features in the writing process to ensure that its academic value and practicality are balanced:

- **Comprehensive and Systematic**
  This book comprehensively covers all dimensions of barium and tungsten cathodes from basic theory to cutting-edge applications, from materials science to industrial standards, and builds a complete knowledge system to ensure that readers can systematically grasp the relevant content.
- **Combining Theory and Practice**
  While in-depth expounding on the theory of thermionic emission and the principles of materials science, this book provides detailed manufacturing processes, performance testing methods and practical application cases, taking into account the needs of academic research and engineering practice.
- **Forward-Looking and Innovative**
  This book not only summarizes the existing technical achievements of barium tungsten cathodes, but also looks forward to its future development direction in nanotechnology, intelligent design and interdisciplinary research (such as artificial intelligence and quantum computing), providing readers with innovative inspiration.
- **Usefulness and Operability**

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Glossary, performance data sheets, test standards, and supplier information (e.g., CTIA GROUP LTD) in the appendix provide readers with convenient reference resources. The index design facilitates quick targeting of key content and enhances its usefulness.

Through this book, readers can not only deeply understand the scientific and technical connotation of barium tungsten cathodes, but also draw inspiration from it to promote innovation and development in vacuum electronics technology and related fields. We believe that barium-tungsten cathodes, as a classic and dynamic technology, will continue to play an important role in future technological waves, providing endless possibilities for high-performance electronic devices and interdisciplinary applications.

Chapter 1: Overview of Barium Tungsten Cathodes

As a highly efficient thermionic emission material, Barium Tungsten Cathode has an irreplaceable position in the field of vacuum electronics and high-tech. Its unique porous tungsten matrix and barium compound impregnated structure give it the characteristics of low work function, high emission current density, excellent thermal stability, and long life, making it a core component of microwave tubes, X-ray tubes, electron microscopes, and other equipment. This chapter aims to provide readers with a comprehensive introduction to barium tungsten cathodes, covering their definition and basic concepts, historical development context, and wide range of application fields, laying the foundation for in-depth discussion in subsequent chapters. By comparing the performance differences between barium tungsten cathodes and other cathode types, we will sort out the key milestones in their technological evolution and look forward to their potential in traditional and emerging fields.

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1.1 Definition and Basic Concept of Barium Tungsten Cathode

1.1.1 Definition of Barium Tungsten Cathode

Barium tungsten cathode is a cathode based on the principle of thermionic emission, and its core structure consists of a porous tungsten matrix with high porosity and impregnated barium compounds such as barium calcium aluminate, Ba-Ca-Aluminate. The porous tungsten matrix is prepared by powder metallurgy technology and has a uniform pore structure, which can effectively adsorb and store barium compounds. Under high-temperature operating conditions, barium compounds release reactive barium atoms through thermal decomposition, which diffuse to the surface through the pores of the porous tungsten matrix, forming a single-atomic layer with a low work function (work function of about 1.1–1.5 eV). This low-power function significantly reduces the energy required for electron escape, allowing barium-tungsten cathodes to provide high emission current density and perform well in high-power, high-frequency, and high-reliability scenarios.

The design of barium tungsten cathodes combines the high melting point of the tungsten matrix (about 3422°C), excellent chemical stability, and the low work function advantages of barium compounds, making them particularly suitable for vacuum electronic devices that require a stable electron source, such as microwave tubes, X-ray tubes, and scientific instruments. Its resistance to poisoning and thermal stability further enhance its suitability in demanding environments, such as high-vacuum or high-radiation scenarios.

1.1.2 Comparison of Hot Cathode and Cold Cathode

Electron emission sources are mainly divided into two categories: hot cathode and cold cathode, and there are significant differences in their working principles, performance characteristics and application scenarios. The following is a detailed comparison:

- **Thermal Cathodes (such as barium tungsten cathodes)**
  The hot cathode heats the material to high temperature, so that the electrons obtain sufficient energy to overcome the surface barrier and achieve thermionic emission. Its main features include:
  - **High Transmit Current Density**: Reaching several amps to tens of amps per square centimeter, suitable for high-power devices such as microwave tubes and X-ray tubes.
  - **Stability and Mature Process**: After nearly a hundred years of development, thermal cathode technology has mature manufacturing processes and high performance consistency, and is widely used in industry and scientific research.
  - **Long Lifespan**: Barium tungsten cathodes can operate for thousands to tens of thousands of hours under the right conditions, meeting high reliability requirements. The limitations are the need for continuous heating, resulting in high energy consumption, high temperatures that can cause thermal stress or material

aging, and high requirements for a vacuum environment (typically 10^{-6} Pa or less) to avoid surface contamination.

- **Cold Cathodes (e.g., field emission cathodes, carbon nanotube cathodes)**
  Cold cathodes induce electron tunneling emission through strong electric fields (usually 10^{7}–10^{9} V/m) without high temperature operation. Its main features include:
  - **Low Power** consumption: No heating required, suitable for low-energy devices such as portable electronics.
  - **Fast Response**: The electron emission has a short response time (nanosecond), making it suitable for high-frequency or pulsed applications.
  - **Miniaturization Potential**: Compact and suitable for miniaturized devices such as field emission displays or micro X-ray sources. However, cold cathodes have low emission current density (usually at the mA/cm² level), extremely high requirements for electric field uniformity and surface cleanliness, are susceptible to contamination or damage, and have a complex manufacturing process and high cost.

The following table summarizes the performance of hot cathodes versus cold cathodes (data based on common technical parameters):

Characteristic	**Thermal Cathodes (E.G., Barium Tungsten Cathodes)**	**Cold Cathode (E.G. Field Emission Cathode)**
How It Works:	Thermionic emission (heated to high temperature)	Field-induced electron tunneling (strong electric field)
Work Function (Ev)	1.1–1.5 (barium tungsten cathode)	4–5 (typical)
Emission Current Density	10–20 A/cm²	0.01–1 A/cm²
Operating Temperature	900–110850°C	room temperature
Life Span	Tens of thousands of hours	Thousands of hours (depending on the environment)
Vacuum Requirements	High (10^{-6} Pa or less)	Extremely high（10^{-8} Pa or less）
Key Benefits	High current density and long life	Low power consumption, fast response
Main Limitations	High energy consumption and high temperature required	Low current density and complex process
Typical Applications	Microwave tubes, X-ray tubes	Field emission display, micro X-ray source

Hot cathodes, such as barium tungsten cathodes, dominate high-power, long-life vacuum electronics, while cold cathodes are better suited for low-power, miniaturized emerging applications. The two complement each other in different scenarios and jointly promote the progress of electronic emission technology.

1.1.3 Comparison of Barium Tungsten Cathodes with Other Thermal Cathodes

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Among the thermal cathode family, barium tungsten cathodes are widely favored for their excellent comprehensive properties. Here's a comparison of it with common thermal cathode types (oxide cathodes, thorium tungsten cathodes, pure tungsten cathodes):

- **Oxide Cathode**
  Oxide cathode is made of barium oxide (BaO), strontium oxide (SrO) and other materials coated on a nickel matrix, with a low work function (about 1–2 eV), an operating temperature of 800–1000°C, and an emission current density of about 1–5 A/cm². Its advantage is its low cost and is suitable for low-power vacuum tubes (such as early radios). However, it has strict requirements for vacuum environments (less than 10^{-7} Pa), is susceptible to oxygen or water vapor contamination leading to reduced emission performance, and usually has a lifetime of hundreds to thousands of hours. In contrast, barium tungsten cathodes have stronger poison resistance and thermal stability, making them suitable for high-power, long-running scenarios.
- **Thorium Tungsten Cathode**
  Thorium tungsten cathode achieves a low work function (about 2.6 eV) by doping thorium oxide (ThO_2) in a tungsten matrix, with an operating temperature of 1700–1900°C and an emission current density of up to 5–10 A/cm², making it suitable for high current density applications such as high-power microwave tubes. However, the radioactivity of thorium poses potential risks to humans and the environment, limiting its application in medical and civilian fields. Barium tungsten cathodes have no radioactive risk, lower operating temperatures, higher energy efficiency, and longer lifespans (up to tens of thousands of hours).
- **Pure Tungsten Cathodes**
  Pure tungsten cathodes are made of tungsten wire or tungsten sheet, have a high work function (about 4.5 eV), and require extremely high temperatures (2000–2500°C) to achieve sufficient emission current (about 0.1–1 A/cm²). Its advantages are strong chemical stability and suitable for extreme environments (such as high vacuum or high temperature), but its high energy consumption and low emission efficiency make it difficult to meet the needs of modern high-performance devices. The low work function and low operating temperature of barium tungsten cathodes make them outperform pure tungsten cathodes across the board in terms of energy efficiency, performance, and longevity.

Barium tungsten cathode has become the preferred thermal cathode material in modern vacuum electronic devices due to its advantages of low work function, high emission efficiency, long life and non-radioactivity, and is widely used in high-reliability and high-power scenarios.

1.2 Historical Development of Barium Tungsten Cathode

1.2.1 Origin and Technical Evolution of Barium Tungsten Cathodes

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The origin of barium tungsten cathodes can be traced back to the rise of thermionic emission technology in the early 20th century. In the early 1900s, hot cathodes began to be applied to early vacuum tubes such as diodes and triodes in radio communications. At that time, pure tungsten cathodes were widely used due to their high melting point and chemical stability, but their high work function (about 4.5 eV) and high operating temperature limited emission efficiency and energy efficiency. In the 20s and 30s of the 20th century, the emergence of oxide cathodes significantly reduced the work function, but their environmental sensitivity and short-lifetime shortcomings prompted researchers to explore better thermal cathode materials.

In the 1950s, with the surge in demand for vacuum electronic devices such as radar, microwave communication, and television picture tubes, the research and development of low-power function and long-life cathodes became a hot topic. In the late 1950s, American scientists first proposed the concept of impregnating barium compounds in a porous tungsten matrix and developed an early prototype of a barium tungsten cathode. This cathode combines the high stability of the tungsten matrix with the low work function characteristics of barium compounds, significantly improving the emission performance. In the 1960s, the powder metallurgy preparation technology of porous tungsten matrix and the impregnation process of barium compounds gradually matured, and barium tungsten cathodes began to be commercially applied in microwave tubes and X-ray tubes.

In the 70s and 80s of the 20th century, barium tungsten cathode technology entered a period of rapid development. The introduction of new compounds such as barium-calcium aluminate optimizes emission properties, and the standardization of activation processes improves production consistency. Since the 90s of the 20th century, with the advancement of aerospace, medical imaging and high-energy physics experiments, the application scope of barium tungsten cathodes has been further expanded. At the beginning of the 21st century, the introduction of nanotechnology, new barium compound formulations and intelligent manufacturing processes has brought the performance and application potential of barium tungsten cathodes to a new level. These technological advances have driven the development of vacuum electronics in the direction of high power, high frequency, and long life.

1.2.2 Key Milestones and Technological Breakthroughs

In the development of barium tungsten cathodes, several key technological breakthroughs have played a decisive role in improving their performance and widespread applications:

- **Breakthrough in Porous Tungsten Matrix Technology (1950–1960s)**
  Advances in powder metallurgy technology have made it possible to prepare high porosity tungsten matrixes. The porous structure increases the storage capacity of barium compounds through capillary action and promotes the diffusion of reactive barium to the surface, thereby improving emission efficiency and stability. This breakthrough laid the foundation for the commercialization of barium tungsten cathodes.

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- **Optimization of Barium Compound Formulation (1970s)**
  Barium calcium aluminate (e.g., $4BaO\cdot CaO\cdot Al_2O_3$) became a key breakthrough in barium tungsten cathodes. This compound decomposes slowly at high temperatures and is able to continuously release reactive barium, ensuring a long cathode life (tens of thousands of hours) and stable emission (current density of 10–20 A/cm²). The optimized formula also improves resistance to poisoning and reduces the impact of surface contamination.
- **Standardization of Impregnation and Activation Processes (1980s)**
  control of impregnation parameters (e.g., solution concentration, impregnation time, temperature) and heat treatment activation process significantly improved the uniformity of the active layer and the consistency of emission properties. This standardized process has promoted the industrial production of barium tungsten cathodes, making them more widely used in microwave tubes, X-ray tubes and other fields.
- **Introduction of Nanotechnology (2000s to Present)**
  exploration of nanoscale porous tungsten matrix and nanobarium coating technology has further improved the emission performance. The nanopore structure increases the surface area and enhances the diffusion efficiency of barium atoms. New doping techniques, such as the addition of rare earth elements such as lanthanum or cerium, optimize the work function and thermal stability. These technologies allow barium tungsten cathodes to show potential in emerging applications such as terahertz wave generators.
- **Intelligent Manufacturing and Testing (2010s to Present)**
  Modern manufacturing has introduced automated impregnation equipment and real-time monitoring technology to ensure the accuracy of the production process. Advanced testing methods (e.g., scanning electron microscopy analysis, emission current density measurement) improve quality control and reduce performance deviations in production.

These technological breakthroughs have not only improved the performance of barium tungsten cathodes, but also promoted the widespread application of vacuum electronic devices in the fields of radar, communications, medical and scientific research.

1.3 Application Fields of Barium Tungsten Cathodes

1.3.1 Vacuum Electronics

The high emission current density, long lifetime, and excellent stability of barium-tungsten cathodes make them the core components of a variety of vacuum electronic devices, including:

- **Microwave Tubes**
  Microwave tubes are high-frequency, high-power electronic devices widely used in radar, communications, and industrial heating. Barium tungsten cathodes play a key role in the following microwave tubes:
    - **Magnetron:** Used in military and civilian radars (e.g., weather radars, air traffic control radars) and microwave heating equipment (e.g., industrial microwave

ovens), its high current density (10–20 A/cm²) supports stable high power output (up to the megawatt level).
  - **Traveling Wave Tube**: used for satellite communication, ground base station amplifier and high-frequency broadcasting, providing broadband and high-gain signal amplification to meet the high-frequency requirements of modern communication systems.
  - **Klystron** tube: used for high-power radars (such as missile guidance systems) and particle accelerators (such as synchrotron radiation sources), supporting high pulse power (hundreds of kilowatts to megawatts). The high stability and aging resistance of barium-tungsten cathodes ensure reliable operation of these devices in high-frequency, demanding environments.
- **X-Ray Tubes**
  X-ray tubes are the core components of medical imaging and industrial non-destructive testing. Barium tungsten cathodes provide a high-brightness, stable electron beam that supports the following applications:
  - **Medical Imaging**: Such as CT scanners and X-ray diagnostic instruments, their high emission efficiency supports high-resolution imaging (resolution up to sub-millimeter level) and fast scanning (second-level resolution), improving diagnostic accuracy and patient experience.
  - **Industrial Non-Destructive Testing**: Used to detect cracks, weld quality and pipeline corrosion of aviation components to ensure industrial safety and product quality. The long life (tens of thousands of hours) and consistency of barium tungsten cathodes reduce equipment maintenance costs and improve operational efficiency.
- **Other Vacuum Devices**
  Barium tungsten cathodes are also used in photomultiplier tubes (for high-sensitivity light detection, such as astronomical observations and nuclear physics experiments), electron beam welding equipment (for precision manufacturing of aerospace components), and vacuum switches (for electronic control of high-voltage power systems). Its high performance meets the stringent requirements of these devices for electronic sources.

1.3.2 Specific Uses in Industry and Scientific Research

Barium tungsten cathodes have a wide range of applications in industrial production and scientific research, including:

- **Electron Microscopy**
  In scanning electron microscopy (SEM) and transmission electron microscopy (TEM), barium-tungsten cathodes provide a high-brightness, stable electron beam that supports nanoscale resolution surface topography and internal structure analysis. Its high emission current density and low noise characteristics make it suitable for materials science (e.g.,

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semiconductor material analysis), biology (e.g., cell structure imaging), and nanotechnology research.

- **Mass Spectrometer**
  As a key component of a high-sensitivity ion source, the barium tungsten cathode plays an important role in environmental monitoring (such as detecting volatile organic compounds in the air), drug development (such as metabolite identification) and geological research (such as isotope ratio analysis). Its high emission efficiency improves the detection sensitivity of the mass spectrometer (up to ppb level).
- **Surface Analysis Equipment**
- In Auger Electron Spectrometer (AES), X-ray Photoelectron Spectrometer (XPS) and Secondary Ion Mass Spectrometer (SIMS), barium tungsten cathode provides a stable electron flow for accurate analysis of the chemical composition and electronic structure of the material surface. These technologies are widely used in the development of new materials (such as high-performance alloys, semiconductor films) and surface engineering (such as coating performance optimization).
- **Radar and Communication Systems**
  Barium tungsten cathodes provide high-power electron sources in military radars (such as missile guidance systems), civilian radars (such as air traffic control) and communication equipment (such as satellite amplifiers, 5G base stations), supporting long-distance signal transmission and anti-interference capabilities. Its high reliability and long life reduce system maintenance costs and meet the high-performance requirements of modern communication systems.
- **Industrial Heating and Processing**
  In electron beam melting, electron beam surface modification, and vacuum heat treatment equipment, barium tungsten cathodes provide high-energy electron beams for metal purification (e.g., titanium alloy production), alloy preparation, and case hardening (e.g., aviation turbine blades), significantly improving material properties and industrial efficiency.

1.3.3 Cross-Domain Potential

With the rapid development of science and technology, the application potential of barium tungsten cathodes is expanding into emerging and interdisciplinary fields, showing promising prospects:

- **New Energy Technology**
  In ion thrusters, barium tungsten cathode serves as a high-current electron source to support the development of spacecraft microthrust systems. Ion thrusters are ideal power sources for deep space exploration (e.g., Mars rover, interstellar missions) with their high specific impulse (up to 3000–9000 seconds) and low fuel consumption. The high stability and long life of barium tungsten cathodes meet the demanding requirements of the space environment.
- **Terahertz Wave Technology**

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Terahertz waves (0.1–10 THz) offer unique advantages in imaging, communication, and spectral analysis. The barium tungsten cathode provides a high-power electron source in a vacuum electron terahertz wave generator that supports terahertz imaging (for security screening, early cancer detection) and high-speed communication (next-generation 6G networks). Its high emission efficiency and stability provide the possibility for the commercialization of terahertz technology.

- **High-Energy Physics Experiments**
  In particle accelerators (such as CERN's LHC) and synchrotron radiation sources, barium-tungsten cathodes provide a high-current electron source to generate high-energy particle beams and explore the properties and structure of elementary particles. Its high emission efficiency and stability support long, high-intensity experimental runs.
- **Biomedical Applications**
  Through high-precision mass spectrometry analysis, barium tungsten cathodes can be used as an ion source for molecular detection in disease diagnosis, such as cancer marker analysis and metabolomics studies. Its high sensitivity and reliability have driven the development of precision medicine. In addition, the application of barium tungsten cathode in electron beam sterilization equipment provides an efficient solution for medical device sterilization.
- **Quantum Technology**
  The potential application of barium tungsten cathodes in quantum computing and quantum communication equipment is being explored. Its high stability and low work function characteristics can be used to develop high-precision electron sources to support the manipulation of quantum bits and the detection of quantum states. Interdisciplinary research (such as the combination of quantum materials and vacuum electronics technology) may bring new breakthroughs in quantum technology.
- **Green Energy and Environmental Protection**
  The application of barium tungsten cathode in plasma generators supports efficient exhaust gas treatment and water purification techniques, such as plasma degradation of organic pollutants through electron beam induction. In addition, its potential applications in nuclear fusion research, such as electron beam heating systems for tokamak devices, provide possibilities for clean energy development.

In summary, barium-tungsten cathodes, with their excellent performance and wide adaptability, not only occupy a core position in traditional vacuum electronic devices, but also show great potential in emerging fields such as new energy, terahertz technology, quantum technology, and biomedicine. This chapter provides readers with a clear framework of knowledge through the definition of barium tungsten cathodes, comparisons with other cathodes, historical developments, and comprehensive introductions to application fields. Subsequent chapters will further delve into its material science, working principles, manufacturing processes, and performance optimization strategies, providing readers with a more comprehensive and in-depth technical perspective.

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Chapter 2: Materials Science of Barium Tungsten Cathodes

The excellence of barium tungsten cathodes stems from their meticulous material composition, precise preparation processes, and the interplay between complex microstructure and performance. As an efficient thermionic emission material, the synergistic effect of the porous tungsten matrix of the barium tungsten cathode and the barium compound achieves low work function, high emission current density and excellent thermal stability, making it a central position in vacuum electronic devices. This chapter delves into the material science basis of barium tungsten cathodes, analyzes in detail the impact of their material composition, preparation process and microstructure on performance, covering the chemical and physical properties of porous tungsten matrixes, the optimization of barium compound ratios, the role of additives, key technologies in the preparation process, and the relationship between microstructure and emission properties.

2.1 Material Composition of Barium Tungsten Cathode

2.1.1 Chemical and Physical Properties of Porous Tungsten Matrix

The porous tungsten matrix is the core structure of the barium tungsten cathode, and its chemical and physical properties directly determine the thermal stability, mechanical strength and electron emission efficiency of the cathode. The porous tungsten matrix is prepared by powder metallurgy technology using high-purity tungsten (purity ≥99.95%), with appropriate porosity and pore size. This porous structure not only provides space for the storage of barium compounds but also facilitates the diffusion of active barium atoms through capillary action, resulting in the formation of a low-work function layer on the surface of the cathode. The following are the main chemical and physical properties of porous tungsten matrix:

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- **Chemical Stability**: Tungsten's high chemical inertness makes it highly resistant to oxygen, water vapor, and residual gases in high-vacuum environments (10^{-6} Pa or less). This stability effectively reduces the risk of surface oxidation or poisoning and extends cathode life. In addition, tungsten has low chemical reactivity to barium compounds, avoiding adverse interactions between the matrix and the active substance.
- **Physical Properties**: Tungsten's high melting point (approximately 3422°C) allows it to withstand the typical operating temperatures (900–1100°C) of barium-tungsten cathodes without structural degradation or deformation. High density (about 19.25 g/cm³) and high mechanical strength (tensile strength about 700–1000 MPa) ensure the stability of the matrix in high-temperature and high-stress environments. The capillary action of the porous structure enhances the adsorption capacity of barium compounds, and the pore network provides an efficient channel for the diffusion of active barium atoms to the surface.
- **Thermal and Electrical Conductivity**: The high thermal conductivity of tungsten (about 173 W/m·K) ensures even distribution of heat during the working process, reducing material degradation caused by local overheating. The high conductivity (approximately 1.82×10^{7} S/m) supports efficient electronic transmission, making it suitable for the needs of high-power electronic devices.
- **Pore Properties**: Porosity and pore size distribution are key parameters for porous tungsten matrix. The 20–30% porosity balances the storage capacity and mechanical strength of the barium compounds, and the pore size range of 1–10 μm ensures the effectiveness of capillary action. The pores need to form a connected network to support the continuous diffusion of barium atoms.

The porosity and pore size distribution of porous tungsten matrix need to be controlled by precise preparation process, too high porosity may lead to insufficient mechanical strength, and too low porosity will limit the storage and diffusion efficiency of barium compounds and affect the emission performance. The microstructure of the matrix is typically analyzed by scanning electron microscopy (SEM) or X-ray tomography (X-CT) to ensure pore uniformity and consistency.

2.1.2 Properties and Ratios of Barium Compounds (such as barium calcium aluminate)

Barium compounds are the key components of barium tungsten cathode to achieve low work function and high emission efficiency, and the commonly used barium compounds are barium calcium aluminate (such as $4BaO\cdot CaO\cdot Al_2O_3$, abbreviated as 4:1:1 ratio). These compounds release free barium atoms by thermal decomposition at high temperatures (900–1100°C) and diffuse to the surface of the porous tungsten matrix, forming a low work function layer (work function of about 1.1–1.5 eV), which significantly reduces the energy required for electron escape. The following are the key properties and ratio optimization of barium compounds:

- **Chemical Properties**: Barium-calcium aluminate decomposes at high temperatures through the following reactions:
  $4BaO\cdot CaO\cdot Al_2O_3 \rightarrow 4Ba + CaO + Al_2O_3 + O_2$

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The released free barium atoms are adsorbed on the surface of the tungsten matrix, forming a single atomic layer or thin film, reducing the work function. The generated by-products (e.g., CaO, Al_2O_3) have high chemical stability and do not interfere with emission performance. The decomposition rate of the compound needs to be moderate to ensure a continuous barium supply during long-term operation while avoiding active layer loss due to excessive evaporation.

- **Physical Properties**: The melting point of barium calcium aluminate is higher than the cathode operating temperature, preventing premature melting or volatilization. The particle size of the compound needs to match the pore size of the tungsten matrix to ensure uniform impregnation and efficient diffusion. The thermal expansion coefficient of the compound is different from that of the tungsten matrix, and the thermal stress needs to be reduced through process optimization.
- **Ratio Optimization**: 4:1:1 ratio ($4BaO \cdot CaO \cdot Al_2O_3$) is standard in industrial applications because it balances barium release rate, chemical stability, and toxicity resistance. Other configurations include 5:3:2 ($5BaO \cdot 3CaO \cdot 2Al_2O_3$) or 6:1:2 ($6BaO \cdot CaO \cdot 2Al_2O_3$) is also explored in specific scenarios. For example, the ratio of 5:3:2 can improve the anti-poisoning ability and is suitable for high residual gas environments; The 6:1:2 ratio increases the barium release rate, which is suitable for high current density needs but may reduce lifetime. The ratio selection should be optimized according to the application scenario, such as high-power microwave tubes or long-life X-ray tubes.
- **Environmental Adaptability**: Barium compounds are sensitive to oxygen and water vapor and need to be stored and handled in a high-vacuum environment to avoid degradation due to oxidation or hydration.

The ratio and particle characteristics of barium compounds directly affect the formation efficiency of the active layer and the long-term stability of the cathode, and need to be optimized experimentally to meet the needs of different applications.

2.1.3 Effect of Additives on Emission Performance

In order to further improve the emission efficiency, thermal stability and anti-poisoning ability of barium tungsten cathodes, additives are often introduced into barium compounds or tungsten matrixes. The following are common additives and their effects:

- **Rare Earth Oxides (e.g., La_2O_3, CeO_2):** Rare earth elements enhance emission efficiency by reducing the work function (up to 1.0 eV or less) while improving the thermal stability of the active layer. For example, doping with 0.5–2 wt% La_2O_3 significantly reduces the work function and enhances oxidation resistance, making it suitable for high-power applications. CeO_2 improves surface hardness and reduces mechanical wear.
- **Calcium (Ca) or Strontium (Sr) Compounds**: control the decomposition rate of barium compounds by adjusting the ratio of CaO or SrO and extend cathode life. For example, increasing the CaO ratio (to a 2:1:1 ratio) can slow down the barium release rate, which is

suitable for long-life applications such as satellite communication devices, but may slightly reduce the transmit current density.

- **Metal Additives (e.g., Os, Ir):** Coating a thin layer of osmium (Os) or iridium (Ir) (about 0.1–1 μm thick) on the surface of the tungsten matrix can enhance the catalysis of the surface, promoting the diffusion of barium atoms and the formation of active layers. OS coatings can reduce the work function to about 1.0 eV, but the cost is higher and there is a trade-off between economics.
- **Silicate or Borate Additives**: Improve resistance to poisoning by forming a protective layer and reduce the effects of oxygen or carbon pollution. However, excess silicate may increase the work function, and the addition ratio (usually < 1 wt%) needs to be controlled.
- **Other Additives**: such as yttrium oxide (Y_2O_3) or zirconia (ZrO_2), which improve thermal stability and mechanical strength, suitable for extreme environment applications (such as space electronics).

The type and ratio of additives need to be accurately optimized through experiments, and excessive addition may lead to uneven active layers or side reactions, reducing emission performance. The choice of additives needs to be designed for specific application scenarios, such as high current density, long life, or anti-poisoning needs.

2.2 Preparation Process of Barium Tungsten Cathode

2.2.1 Preparation of Porous Tungsten Matrix: Powder Metallurgy and Pore Control

The preparation of porous tungsten matrix is a core step in barium tungsten cathode manufacturing, using powder metallurgy technology, and the process includes powder screening, pressing molding, sintering, and pore control. Here are the detailed steps:

- **Tungsten Powder Screening**: Select high-purity tungsten powder (purity ≥99.95%, particle size 1–10 μm) to ensure the chemical stability and uniformity of the matrix. The particle size distribution has a direct impact on the pore structure and needs to be optimized by vibration screening or airflow classification technology. Smaller particle sizes (1–3 μm) increase porosity but may reduce mechanical strength; Larger particle sizes (5–10 μm) enhance strength but reduce porosity.
- **Pressing**: Tungsten powder is placed in a mold and pressed under high pressure (100–500 MPa) to form blanks, usually cylindrical (5–20 mm in diameter) or sheet (1–5 mm thick). The pressing process requires controlling pressure, mold design, and lubricant use to achieve a uniform initial pore structure. Bidirectional pressing or isostatic pressing techniques improve billet density uniformity.
- **Sintering Process**: High-temperature sintering (2000–2500°C) in vacuum (10^{-4}–10^{-6} Pa) or hydrogen atmosphere allows tungsten particles to combine through diffusion to form a porous structure. The sintering time (1–4 hours) and temperature need to be precisely controlled, too high a temperature may lead to pore collapse, and too low a temperature

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will affect the bonding strength of the particles. Hydrogen atmosphere reduces oxide impurities and improves matrix purity.

- **Porosity Control**: Control porosity and pore size by adding temporary fillers (e.g., starch, polymethyl methacrylate) or adjusting the particle size distribution of tungsten powder. The filler volatilizes during the sintering process, creating a uniform pore network. Porosity tests show that 20–30% porosity balances mechanical strength with barium compound storage capacity.

The quality of the porous tungsten matrix directly affects the subsequent impregnation process and cathode performance, and the consistency of the pore structure needs to be verified by SEM, X-CT or specific surface area analysis (BET). The optimized matrix should have a uniform pore distribution, high mechanical strength (compressive strength >500 MPa), and an appropriate pore size (1–10 μm).

2.2.3 Impregnation Process of Barium Compounds: Solution Preparation and Impregnation Parameters

The impregnation process of barium compounds is a key step in uniformly introducing barium compounds into porous tungsten substrates, which directly affects the formation efficiency and emission properties of the active layer. The process includes solution preparation, impregnation, drying and heat treatment as follows:

- **Solution Preparation**: Barium calcium aluminate (such as $4BaO \cdot CaO \cdot Al_2O_3$) is mixed with deionized water or an organic solvent such as ethanol to form a suspension or solution. The viscosity and particle dispersion of the solution need to be optimized by agitation or sonication to ensure uniform penetration into the pores. Adding a small amount of surfactant, such as polyvinyl alcohol, improves the wettability of the solution.
- **Impregnation Process**: The porous tungsten matrix is immersed in a barium compound solution, using vacuum impregnation (10^{-2}–10^{-4} Pa) or pressure impregnation (0.1–1 MPa) techniques to facilitate solution penetration into the pores. Vacuum impregnation removes air from pores and improves filling efficiency; Pressure impregnation enhances the penetration depth of the solution. Conditions such as impregnation temperature and time should be optimized according to the porosity of the matrix and solution concentration, and too long soaking time may lead to pore clogging.
- **Drying and Heat Treatment**: The impregnated substrate is dried at low temperatures (100–300°C) to remove solvents and prevent damage to the pore structure. This is followed by high-temperature heat treatment (1000–1200°C) in a vacuum or inert atmosphere to cure the barium compound and form an initial active layer. Heat treatment should be heated step by step to avoid thermal stress causing cracking of the matrix.

The parameters of the impregnation process have a significant impact on the uniformity and emission properties of the active layer. For example, too high a solution concentration may lead to

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the accumulation of barium compounds on the surface, reducing the emission uniformity; Heat treatment temperatures that are too high may accelerate the evaporation of barium and shorten its life. Process optimization requires experimental validation (e.g., SEM observation or emission testing) to ensure uniform distribution of barium compounds and stable active layers.

2.3 Microstructure and Properties of Barium Tungsten Cathodes

2.3.1 Porosity and Structure Analysis of Porous Tungsten Matrix

The microstructure of the porous tungsten matrix is the basis of the cathode performance of barium tungsten, and its porosity, pore size distribution and connectivity directly affect the storage, diffusion and emission properties of barium compounds. The following are the key structural characteristics and analysis methods:

- **Porosity**: Typical porosity is controlled at 20–30% to balance the storage capacity of the barium compound with its mechanical strength. High porosity may lead to insufficient matrix strength and easy deformation at high temperatures. If it is too low, the barium release rate will be limited and the transmit current density will be reduced. Mercury intrusion or gas adsorption (BET) is commonly used to accurately measure porosity.
- **Pore Structure**: Pores need to form a three-dimensional network to ensure efficient diffusion of barium atoms to the surface through capillary action. The pore size distribution should be uniform, too large a pore size may lead to uneven distribution of barium compounds, and too small a pore size will limit the diffusion efficiency. X-ray tomography (X-CT) reconstructs the three-dimensional structure of the pores and verifies connectivity.
- **Structural Analysis**: Scanning electron microscopy (SEM) is used to observe pore morphology and surface properties, and specific surface area analysis (BET) is used to measure pore surface area. Energy Dispersive Spectroscopy (EDS) analyzes the distribution of impurities in tungsten matrices to ensure high purity. The uniformity and connectivity of the pore structure are critical to the long-term stability of the cathode.

Optimizing the pore structure needs to be achieved by adjusting the particle size, pressing pressure and sintering parameters of tungsten powder. The structural analysis results need to be combined with the emission performance test to verify the effect of pore design.

2.3.2 Relationship Between Surface Morphology and Emission Performance of Barium Active Layer

The barium active layer is the core of the emission performance of barium tungsten cathode, and its surface morphology directly determines the work function, emission current density and emission uniformity. The following are the key features and how they relate to performance:

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- **Surface Morphology**: The active layer consists of a single atomic layer or thin film formed by barium atoms and their oxides on the surface of a tungsten matrix. The ideal active layer should be uniform, continuous with low surface roughness to ensure uniformity of electron emission and low noise characteristics. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) are commonly used to analyze surface topography and verify the flatness and coverage of active layers.
- **Work Function**: The formation of the active layer reduces the work function from 4.5 eV to 1.1–1.5 eV for pure tungsten, significantly increasing the transmit current density. The uniformity of the work function depends on the diffusion rate and surface coverage of the barium atoms, and insufficient coverage (<80%) may lead to local high-work function regions, reducing the emission efficiency.
- **Emission Performance**: The uniform active layer allows for high transmit current density and low noise emission, meeting the needs of high-power microwave tubes or X-ray tubes. Surface defects (e.g., cracks, particle buildup) can trigger localized arcing or uneven emissions, reducing performance. Emission performance is typically evaluated by thermionic emission testing.
- **Influencing Factors**: The performance of the active layer is affected by the following factors:
  - **Operating Temperature**: Excessive temperature accelerates the evaporation of barium, resulting in the loss of the active layer and shortening the life. Too low a temperature limits the diffusion of barium and reduces the emission efficiency.
  - **Vacuum Environment**: Low vacuum (>10^{-6} Pa) may cause surface oxidation or contamination, increasing the work function.
  - **Surface Contamination**: Oxygen, water vapor, or carbon compounds can react with barium to form high-work function compounds (such as BaO_2), reducing emission performance.
  - **Heat Treatment Process**: Step-by-step activation creates a uniform active layer, optimizing emission performance.

By optimizing the impregnation process, heat treatment parameters, and additive formulation, a uniform and stable active layer can be formed, improving the emission performance and lifetime of barium tungsten cathodes. The correlation between surface topography and emission performance needs to be comprehensively analyzed by SEM, AFM and emission test to guide process improvement.

In summary, the material science of barium-tungsten cathodes involves the complex interaction of porous tungsten matrixes, barium compounds and additives, and its preparation process and microstructure have a decisive impact on the emission performance and lifetime. Through a comprehensive analysis of material composition, preparation process and microstructure, this chapter lays a solid foundation for subsequent discussion of working principles, manufacturing technology and performance optimization.

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CTIA GROUP LTD
Barium Tungsten Cathode Introduction

1. Overview of Barium Tungsten Cathode

The Barium Tungsten Cathode is a type of thermionic emission material typically composed of high-purity tungsten as the base, impregnated with barium compounds. Upon high-temperature activation, it emits free electrons and is widely used in vacuum electronic devices. Due to its low work function and high electron emission efficiency, this cathode plays a critical role in high-power electronic equipment. CTIA GROUP LTD specializes in the global flexible customization of tungsten and molybdenum products, offering tailored high-performance barium tungsten cathodes according to customer requirements.

2. Characteristics of Barium Tungsten Cathode

- **High Electron Emission Efficiency:** The low work function of barium enables the cathode to emit a large quantity of electrons even at relatively low temperatures.
- **High-Temperature Resistance:** With a tungsten matrix that has a melting point of 3422° C, the cathode maintains structural stability in high-temperature operating environments.
- **Long Service Life:** Optimized barium compound impregnation techniques help minimize barium evaporation, thereby extending the cathode's lifespan.
- **Low Evaporation Rate:** Compared to other cathode materials, barium tungsten exhibits a lower evaporation rate at high temperatures, reducing contamination within the device.
- **Arc Stability:** Delivers a stable electron flow, making it ideal for high-precision electron beam applications.

3. Applications of Barium Tungsten Cathode

- **HID Lamps:** The cathode's low work function and high current density allow HID lamps to emit bright and stable light, making them suitable for applications that require high brightness and long service life, such as roadway and industrial lighting.
- **Vacuum and Laser Devices:** The low work function makes barium tungsten ideal for use in vacuum electronic and laser components.
- **Stage and Club Lighting Effects:** High-frequency strobe lights made from this material are known for their long lifespan and stable performance.
- **Film Projection and Video Recording:** The film and broadcast industry also relies heavily on this material for projection and recording equipment, where it ensures long-term operational stability and high efficiency.
- **Laser Mercury Pumps:** Its high electron emission capability and low operating temperature contribute to improved laser performance and stability.

5. Procurement Information

Email: sales@chinatungsten.com
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Website: www.tungsten.com.cn

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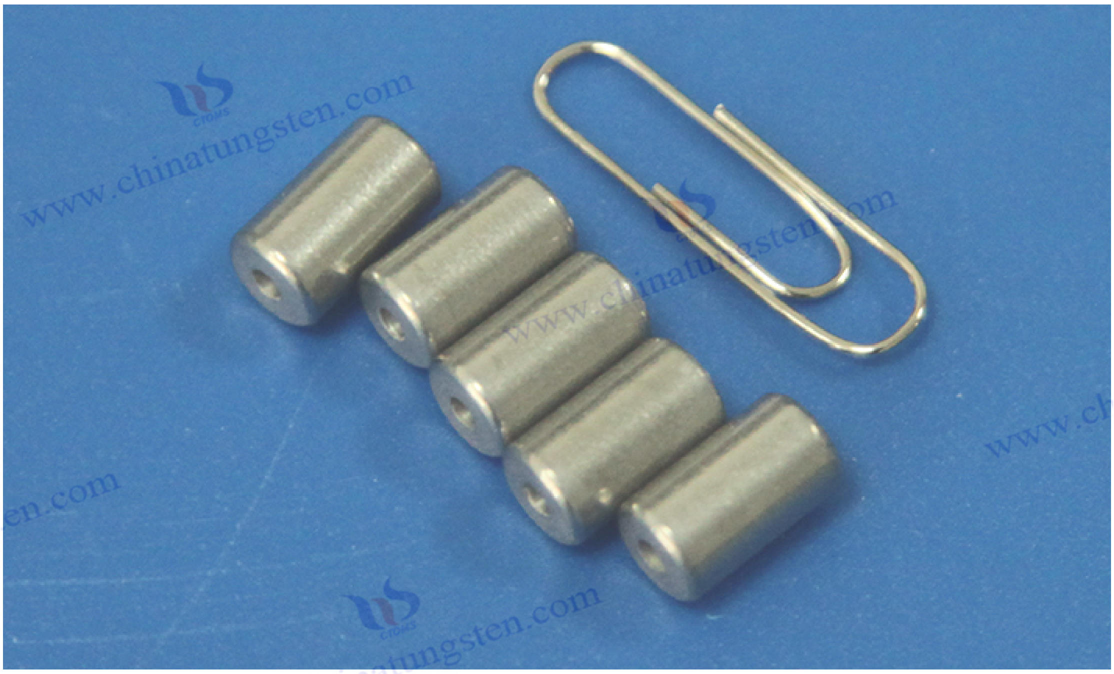

Chapter 3: Working Principle and Launch Mechanism

As a highly efficient thermionic emission material, barium tungsten cathode is derived from its unique working principle and emission mechanism. This chapter delves into the thermionic emission theory, emission characteristics, and various factors that influence the performance of barium tungsten cathodes. Based on the basic principle of thermionic emission, combined with the Richardson-Dushman equation, Schottky effect and quantum mechanics perspective, this paper analyzes the formation mechanism of the low work function of barium tungsten cathode, the dynamic behavior of the active layer and its thermal stability, and elaborates on the effects of working environment, aging and poisoning effects, and failure mode on emission performance.

3.1 Theory of Thermionic Emission

Thermionic emission is the core working principle of barium tungsten cathode, which refers to the process of heating the material to obtain sufficient energy for electrons to overcome the surface barrier and escape into the vacuum. This section analyzes the emission mechanism of barium tungsten cathode from the perspective of classical thermionic emission theory, combined with the Richardson-Dushman equation, Schottky effect and quantum mechanics.

3.1.1 Richardson-Dushman Equation

The Richardson-Dushman equation is a basic theoretical model describing thermionic emission, which expresses the relationship between the emission current density and temperature and work function. For a barium tungsten cathode, its emission current density (J) can be described by the following equation:

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$$J = AT^2 \exp\left(-\frac{\phi}{kT}\right)$$

Thereinto:

- (J): Emit current density (unit: A/cm²);
- (A): Richardson's constant (theoretical value is 120.4 A/cm²· K², the actual value varies depending on the surface properties of the material, usually 50–100 A/cm²· K²）;
- (T): Absolute temperature (unit: K, the typical operating temperature of barium tungsten cathode is 1173–1373 K, i.e. 900–1100°C);
- (exp): exponential function.
- (φ): work function (unit: eV, barium tungsten cathode is about 1.1–1.5 eV);
- (k): Boltzmann constant (8.617×10^{-5} eV/K).

In barium-tungsten cathodes, the low work function (1.1–1.5 eV) significantly increases the exponential term, resulting in an emission current density of 10–20 A/cm² at lower temperatures, much higher than that of pure tungsten cathodes (about 4.5 eV and current density of about 0.1–1 A/cm²). The actual value of the Richardson's constant is affected by surface state, barium active layer coverage and microstructure, and needs to be measured experimentally, such as using thermionic emission test equipment in a high vacuum environment. The application of equations takes into account actual operating conditions, such as temperature uniformity and vacuum environment, to ensure prediction accuracy.

3.1.2 Schottky Effect and Field-Enhanced Emission

The Schottky effect refers to the phenomenon that the surface barrier of the material is reduced under the action of an external electric field, resulting in the enhancement of thermionic emission. In barium tungsten cathodes, the Schottky effect is described by the following modified work function:

$$\phi_{\text{eff}} = \phi - \sqrt{\frac{e^3 E}{4\pi\epsilon_0}}$$

Thereinto:

- (φeff): the effective work function (unit: eV), which represents the work function after being reduced under the action of an applied electric field;
- (φ): Original work function (unit: eV);
- (e): electronic power (1.602×10^{-19} C);
- (E): Applied electric field strength (unit: V/m);
- (ε_0): Vacuum dielectric constant (8.854×10^{-12} F/m).

Under high electric field conditions (e.g., 10^7–10^8 V/m, commonly found in microwave tubes or X-ray tubes), the reduction of the work function can significantly increase the transmitted current density. The Schottky effect is particularly important for high-power devices, as it allows for high

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current output at lower temperatures, reducing energy consumption and thermal stress. In practical applications, the electric field uniformity needs to be optimized through electrode design (such as using smooth circular electrodes) to avoid arcing caused by local excessive electric fields and damage to the cathode surface.

3.1.3 Quantum Mechanics Perspective

Under high field strength or extreme conditions, quantum mechanical effects (such as tunneling effect) have a certain impact on the emission behavior of barium tungsten cathodes. The tunneling effect refers to the escape of electrons into a vacuum through quantum tunneling without completely overcoming the surface barrier. The probability of tunneling effect is described by the Fowler-Nordheim equation:

$$J = \frac{A'E^2}{\phi} \exp\left(-\frac{B\phi^{3/2}}{E}\right)$$

Thereinto:

- (J): tunneling current density (unit: A/cm²), which represents the electron flow intensity per unit area;
- (A'), (B): constant (related to material and geometry, typical values are 1.54×10^{-6} A·eV/V² and 6.83×10^{9} V/m·eV$^{-3/2}$）;
- (E): Electric field strength (unit: V/m);
- (φ): Work function (unit: eV).

In barium-tungsten cathodes, tunneling effects are usually significant at very high electric fields, such as in field-enhanced microwave devices or terahertz wave generators. The low work function reduces the tunneling barrier and improves the tunneling probability. However, since the barium tungsten cathode mainly relies on thermionic emission, the tunneling effect has a small contribution and needs to be considered only in specific high field strength scenarios. The quantum mechanics perspective complements the understanding of complex emission mechanisms and helps optimize cathode design, such as improving the local enhancement effect of the electric field by adjusting the surface topography (e.g., nanoscale protrusions).

3.2 Emission Characteristics of Barium Tungsten Cathodes

3.2.1 Formation Mechanism of Low Power Function

The low work function (1.1–1.5 eV) of the barium-tungsten cathode is the core of its high emission efficiency, which is due to the diffusion and surface action of barium atoms in the porous tungsten matrix. The following is a detailed analysis of the formation mechanism:

- **Diffusion of Barium Atoms**: At operating temperature, barium calcium aluminate (e.g. $4BaO\cdot CaO\cdot Al_2O_3$) releases free barium atoms through a thermal decomposition reaction:

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$$4BaO \cdot CaO \cdot Al_2O_3 \rightarrow 4Ba + CaO + Al_2O_3 + O_2$$

these atoms diffuse to the surface through a pore network of porous tungsten matrix, with a diffusion coefficient of about 10^{-12}–10^{-10} m²/s, which is sufficient to form a uniform surface cover in seconds. Pore connectivity and porosity (20–30%) are critical for diffusion efficiency and need to be optimized by powder metallurgy processes.

- **Surface Action**: Barium atoms are adsorbed on the surface of the tungsten matrix to form a single atomic layer or thin film. The low electronegativity of barium and the high electronegativity of tungsten form a surface dipole layer, which reduces the surface barrier and reduces the work function from 4.5 eV to 1.1–1.5 eV of tungsten. The surface coverage should reach more than 80% to ensure the uniformity of the work function, below which may lead to local high work function regions and reduce the emission efficiency.
- **Chemical and Physical Adsorption**: Barium atoms form strong bonds with the surface of tungsten through chemical adsorption to enhance the stability of the active layer. Physically adsorbed barium atoms provide continuous barium replenishment to maintain dynamic equilibrium. The stability of chemisorption ensures the long-term reliability of the active layer at high temperatures.

The formation of the low work function depends on the decomposition rate of barium compounds, the diffusion efficiency of pore structure and the uniformity of surface morphology. Optimizing these factors results in stable high current density and low noise emission, making them suitable for high-power vacuum electronics such as microwave tubes and X-ray tubes.

3.2.2 Dynamic Behavior and Thermal Stability of Active Layers

The dynamic behavior and thermal stability of the barium active layer directly affect the performance and lifetime of the cathode. Here are the key features:

- **Dynamic Behavior**: The active layer is in dynamic equilibrium during operation, with barium atoms continuously diffusing from the pores to the surface, while some barium atoms are lost due to evaporation. It is necessary to optimize the barium compound ratio to ensure that the replenishment rate matches the loss rate. The active layer coverage fluctuates with time, and the initial formation needs to be optimized through a step-by-step activation process to reduce early losses.
- **Thermal Stability**: The active layer needs to be stable at 900–1100°C, and the evaporation loss of barium is accelerated at too high temperature, resulting in an increase in the work function. Too low temperature limits barium diffusion and reduces emission efficiency. The high thermal conductivity (173 W/m·K) and low coefficient of thermal expansion (4.5×10^{-6} K^{-1}) of the tungsten matrix ensure that thermal stress is minimized and the structural integrity of the active layer is maintained.

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- **Surface Topography**: The surface roughness of the active layer should be kept low to avoid local high-power function regions. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) analysis showed that a uniform active layer reduced emission noise (noise level <1%) and improved current stability. For example, surface defects such as particle buildup can cause local current density fluctuations, increasing noise.

The dynamic behavior and thermal stability of the active layer need to be optimized through precise process control (e.g., impregnation parameters, activation temperature). For example, adding a small amount of rare earth oxides can improve the evaporation resistance of the active layer and extend its life. Regular monitoring of surface topography and emission properties (e.g., by SEM or ammeter) can assess the stability of the active layer.

3.3 Factors Affecting the Emission Performance of Barium Tungsten Cathode

The emission performance of barium tungsten cathodes is affected by a variety of factors, including the operating environment, aging and poisoning effects, and failure modes.

3.3.1 Working Environment

The working environment has a significant impact on the emission performance of barium tungsten cathodes, including temperature, vacuum, surface pollution, external electric field and mechanical stress.

- **Operating Temperature**: The ideal operating temperature for barium-tungsten cathodes is 900–1100°C (1173–1373 K), which allows for high transmit current density for high-power devices. Excessive temperature accelerates the evaporation loss of barium, affects the coverage of the active layer, increases the work function, and reduces the current density. Too low a temperature limits the diffusion of barium atoms and reduces the emission efficiency.
  Influence Mechanism: high temperature accelerates the thermal evaporation of barium atoms and reduces the coverage of the active layer; Low temperature slows down the decomposition and diffusion rate, which affects the stability of the work function.
  Coping Strategies:
    - The temperature uniformity is controlled by a high-precision heating system, and real-time monitoring is carried out using an infrared thermometer.
    - Optimize the ratio of barium compounds to slow down the evaporation loss of barium at high temperature and extend the life of the active layer.
    - Design an efficient heat dissipation structure (such as adding cooling channels to the back of the tungsten matrix) to avoid local overheating.
- **Vacuum Environment**: Barium tungsten cathodes need to be operated under high vacuum to avoid residual gas contamination. The low vacuum causes oxygen, water vapor, or carbon compounds to react with barium to form high-work function compounds that reduce

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the emission current density.

Influence Mechanism: The residual gas reacts chemically with barium atoms to form inert compounds, increasing the surface barrier and reducing the escape efficiency of electrons.

Coping Strategies:

- o Maintain vacuum with a high-efficiency vacuum pump system, such as a turbomolecular or ion pump.
- o Vacuum sealing technology (e.g., metal-ceramic sealing) and pre-vacuum treatment reduce residual gases.
- o Clean the vacuum chamber regularly (e.g., plasma cleaning or high-temperature baking) to remove adsorbed gas molecules.

- **Surface Contamination**: Oxygen, water vapor, carbon compounds, or sulfides react with barium to form high-power function compounds (such as $BaCO_3$), significantly reducing emission efficiency. The pollution rate is generally proportional to the partial pressure of the gas. Common pollutants include:
  - o Oxygen: Forms BaO_2 (work function 2.5 eV).
  - o Water vapor: forms $Ba(OH)_2$ (work function 2.8 eV).
  - o Carbon compounds: Formation of $BaCO_3$ (work function 3.0 eV).

  Influence Mechanism: The pollutant occupies the active site through chemisorption, destroys the low power function layer, and leads to a decrease in emission performance.

  Coping Strategies:

  - o Cleanroom environments are used during cathode manufacturing and installation to reduce initial contamination.
  - o Pre-activation treatment removes surface contaminants.
  - o Anti-toxicants are added to form a protective layer to slow down the rate of pollution reaction.
  - o Periodic surface regeneration (such as ion bombardment or cryogenic activation) restores emission performance.
- **External Electric Field**: The applied electric field enhances the emission performance through the Schottky effect, reducing the work function and increasing the current density. However, excessive electric fields can trigger localized arcing, leading to surface damage or emission instability. Insufficient electric field uniformity may lead to excessive local current, accelerating aging.

  Influence Mechanism: high electric field reduces potential barriers and enhances emission; The uneven electric field triggers local overheating or arcing, damaging the surface structure.

  Coping Strategies:

  - o Optimize electrode geometry (e.g., smooth circular electrode or gate structure) to ensure electric field uniformity.
  - o Use electric field probes to monitor electric field strength in real time to avoid excessive electric fields.
  - o Surface polishing and defect repair (such as laser repair) reduce arcing risk.

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- **Mechanical Stress**: High-temperature operation can induce thermal stress, especially in cases of large temperature gradients, leading to microcracks or pore collapse of the tungsten matrix.
  Influence Mechanism: Thermal stress causes damage to the matrix structure, affecting barium diffusion and active layer stability.
  Coping Strategies:
  - Step-by-step heating is used to reduce thermal stress.
  - Optimize porosity, balance mechanical strength, and diffusion efficiency.
  - Use a high-strength tungsten matrix to improve crack resistance.

Optimizing the working environment requires comprehensive consideration of temperature control, vacuum technology, electrode design, and mechanical stability to ensure consistent high emission performance.

3.3.2 Mechanism of Aging and Toxicity Effects

Aging and poisoning effects are the main reasons for the deterioration of barium tungsten cathode performance, and the mechanism is as follows:

- **Aging Effect**: long-term operation leads to the depletion of barium compounds, the decrease of active layer coverage, and the increase of work function. The life of a barium tungsten cathode is closely related to the amount of barium stored and the working conditions.
  Influence Mechanism: Barium depletion reduces the coverage of the active layer, increases the surface barrier, and reduces the efficiency of electron escape.
  Coping Strategies:
  - Increase porosity or optimize barium compound ratios to increase barium storage and extend life.
  - Regular low temperature activation replenishes the active layer to restore coverage.
  - Real-time monitoring of transmit current, prediction of aging process, and adjustment of operating parameters in advance.
  - High-capacity barium compounds are used to increase initial barium storage for high-power applications.
- **Poisoning Effect**: Residual gases (such as O_2, H_2O, CO_2) react with barium to form high-power function compounds (such as BaO_2, $BaCO_3$), reducing the emission efficiency. The rate of poisoning is directly proportional to the partial pressure of the gas, and common pollutants and their effects include:
  - Oxygen: Forms BaO_2 (work function 2.5 eV).
  - Water vapor: forms $Ba(OH)_2$ (work function 2.8 eV).
  - Carbon compounds: Formation of $BaCO_3$ (work function 3.0 eV).
    Influence Mechanism: The pollutant occupies the active site through chemisorption, destroys the low power function layer, and leads to a decrease in

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emission performance.

Coping Strategies:

- Anti-toxic agents are added to form a protective layer, slowing down the reaction rate and prolonging the performance maintenance time.
- Increasing the vacuum level reduces the probability of contamination, such as using a combination of ion pumps and cryogenic trap pumps.
- Regular surface regeneration (such as ion bombardment or cryogenic activation) removes contaminants and restores current density.
- Optimize electrode design (e.g., add shielding) to reduce contaminant contact with the active layer.

Management of aging and toxicity effects needs to be achieved through material optimization, process improvement, and environmental control.

3.3.3 Failure Mode Analysis

The failure modes of barium tungsten cathodes include the following types, each requiring specific diagnostic methods and improvement strategies:

- **Emission Attenuation Caused by Surface Pollution**: pollutants (such as BaO_2, $BaCO_3$) increase the work function and reduce the current density and its performance.
  Diagnostic Methods:
  - X-ray photoelectron spectroscopy (XPS) analyzes the chemical composition of the surface, detects the Ba/O/C ratio, and confirms the type of contaminant.
  - Thermionic emission tests evaluate current density attenuation.
  - Energy dispersive spectroscopy (EDS) verifies surface element distribution.

  Improvement Strategy:
  - Anti-poisoning additives are used to form an antioxidant protective layer.
  - Use a high-vacuum environment and plasma cleaning to remove contaminants.
  - Optimize the activation process, such as step-by-step heating, to ensure initial surface cleaning.
- **Barium Depletion**: Long-term operation leads to the depletion of barium compounds, the active layer coverage decreases, the work function increases, and the current density decreases.
  Diagnostic Methods:
  - SEM observed the morphology of the active layer and verified the coverage.
  - Work function measurements (such as thermionic emission tests) assess performance degradation.
  - EDS analysis of barium content.

  Improvement Strategy:
  - Increase barium storage.
  - Optimized ratio slows down barium depletion and extends life.

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  - Regular low-temperature activation replenishes the active layer to restore current density.
- **Mechanical Failure**: High-temperature thermal stress may cause cracking or pore collapse of the tungsten matrix, affecting barium diffusion.
  Diagnostic Methods:
  - X-ray tomography analyzes pore structure to detect cracks or collapses.
  - Mechanical tests, such as compressive strength tests, assess matrix integrity.
  Improvement Strategy:
  - Optimize the sintering process (e.g., reduce the sintering temperature) to enhance the strength of the matrix.
  - Step-by-step heating is used to reduce thermal stress.
  - Doping improves crack resistance.
- **Arc Failure**: Surface defects (e.g., particle buildup, cracks) or uneven active layers trigger localized arcing, leading to emission instability or surface damage.
  Diagnostic Methods:
  - The high-frequency emission test detects current fluctuations.
  - SEM analyzes surface defects.
  - Arc monitoring devices (such as oscilloscopes) record abnormal discharges.
  Improvement Strategy:
  - Optimize the impregnation process, such as controlling the solution concentration, to ensure the homogeneity of the active layer.
  - Surface polishing and laser repair to remove defects.
  - Electrode design optimizations (e.g., increasing gate spacing) reduce electric field concentration and reduce arcing risk.

Failure analysis requires a combination of multi-technology diagnostics (e.g., XPS, SEM, X-CT, emission testing) to accurately identify the cause of failure. For example, in X-ray tube applications, regular XPS analysis and activation can reduce failure rates. Improvement strategies include material optimization (e.g., addition of antitoxic agents), process improvements (e.g., step-by-step activation), and environmental control (e.g., high vacuum) to extend cathode life.

In summary, the working principle and emission mechanism of barium-tungsten cathode involve the theory of thermionic emission, the dynamic behavior of the active layer, and the complex interaction of various environmental factors. This chapter provides a comprehensive analysis of the Richardson-Ducman equation, Schottky effect, quantum mechanical perspective, emission characteristics and influencing factors, laying the foundation for the subsequent chapters to discuss manufacturing technology and performance optimization.

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Chapter 4: Manufacturing and Processing Technology of Barium Tungsten Cathode

The manufacturing and processing technology of barium tungsten cathodes is a key link in achieving their high performance and reliability, which directly affects their emission efficiency, lifetime, and stability in vacuum electronic devices. This chapter explores in detail the molding process of porous tungsten matrix, the impregnation and activation process of barium compounds, and quality control and testing methods, covering the complete process from raw material preparation to final performance verification.

4.1 Porous Tungsten Matrix Molding

The porous tungsten matrix is the core structure of the barium-tungsten cathode, providing a network of pores to store barium compounds and channels to support the diffusion of active barium atoms. Its molding process requires precise control of porosity, pore size distribution, and mechanical strength to meet the demands of high-performance cathodes. This section details the screening and pressing processes of tungsten powder, as well as the optimization techniques for porosity and mechanical strength.

4.1.1 Screening and Pressing Process of Tungsten Powder

The screening and pressing of tungsten powder are the basic steps of porous tungsten matrix forming, which determines the initial microstructure and subsequent processing properties of the matrix. The following is the detailed process:

- **Tungsten Powder Screening**:
  - **Raw Material Selection**: High-purity tungsten powder is selected to ensure chemical stability, reducing side reactions or surface contamination caused by

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impurities such as iron, carbon, or oxygen. Excessive impurity content may cause oxidation or degradation of the matrix at high temperatures.
  - **Particle Size Control**: Control the particle size distribution of tungsten powder through screening or airflow classification techniques. The particle size range needs to be optimized according to the pore design. Finer powders create a more uniform pore structure, making them suitable for high current density applications; Coarser powders offer improved mechanical strength and are suitable for long life needs. The particle size distribution is measured by a laser particle size analyzer to ensure consistency.
  - **Powder Pretreatment**: To remove surface oxide layer or moisture, tungsten powder needs to be preheated at low temperature in a vacuum or hydrogen atmosphere. Pretreatment also improves powder flowability for subsequent pressing.
- **Pressing Process**:
  - **Mold Design**: Design cylindrical, sheet, or other geometric molds based on cathodic applications (such as microwave tubes or X-ray tubes). The mold surface needs to be polished to reduce billet defects, and the material is usually high-strength steel or carbide to withstand high pressure.
  - **Pressing Technology**: Tungsten powder is pressed into billets using uniaxial pressing or cold isostatic pressing (CIP) technology. Single-axis pressing is suitable for small batch production; Cold isostatic pressing creates a more uniform billet by applying pressure evenly, making it suitable for high-precision applications. The pressure rate needs to be controlled during the pressing process to avoid cracks in the billet.
  - **Binder Addition**: To improve the green strength of the blank, a small amount of organic binder (such as polyvinyl alcohol or polymethyl methacrylate) can be added. The binder should be completely volatilized in subsequent sintering to avoid residue affecting the pore structure.
  - **Billet Inspection**: The pressed billet needs to be checked for density and surface integrity. Density is measured by the Archimedes method, and surface defects are identified by optical microscopy or ultrasonic inspection, ensuring no cracks or delamination.
- **Process Optimization**:
  - Optimize particle size distribution and compression pressure to create a uniform initial pore structure. Narrow particle size distribution improves pore uniformity but may reduce strength; A wide particle size distribution enhances strength but can lead to uneven porosity.
  - The pressing environment should be controlled in a clean room (ISO level 7 or higher) to avoid dust contamination.
  - Experimentally validate pressing parameters, such as using a microscope to observe the pore distribution of the billet section, to ensure that the initial structure meets the design requirements.

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The screening and pressing process needs to ensure the high purity of the tungsten powder and the structural consistency of the billet to lay the foundation for subsequent sintering and impregnation.

4.1.2 Optimization of Porosity and Mechanical Strength

Porosity and mechanical strength are the key performance parameters of porous tungsten matrix, which need to be optimized through sintering process and pore control technology to balance the storage capacity and structural stability of barium compounds. The following is a detailed optimization process:

- **Sintering Process**:
  - **Sintering Environment**: Sintering is carried out in a vacuum or high-purity hydrogen atmosphere to prevent oxidation of tungsten powder. The hydrogen atmosphere also removes residual binders and surface oxides.
  - **Temperature Control**: The sintering temperature is typically 2000–2200°C, below the melting point of tungsten to preserve the pore structure. The step-by-step heating reduces thermal stress and avoids cracking of the billet. The holding time is optimized according to the size of the billet.
  - **Sintering Equipment**: High-temperature vacuum furnaces or hydrogen protection furnaces are employed, equipped with precise temperature control systems. The atmosphere in the furnace needs to be monitored by a gas analyzer to ensure that there is no oxygen or water vapor contamination.
  - **Pore Formation**: During the sintering process, tungsten particles form strong bonds through surface diffusion and grain boundary bonding, while retaining a three-dimensional connected pore network. Temporary fillers, such as starch or polystyrene microspheres, can volatilize during sintering, creating additional porosity.
- **Porosity Optimization**:
  - **Target porosity**: Control the porosity by adjusting the tungsten powder particle size, pressing pressure, and sintering conditions. The appropriate porosity range needs to be optimized according to the application, and high current density applications need to have a higher porosity to increase barium storage; Long-life applications require lower porosity to improve strength.
  - **Pore connectivity**: Connecting pore networks is crucial for barium diffusion and can be achieved by controlling particle size distribution (mixing fine and larger particles) or adding fillers. X-ray tomography (X-CT) reconstructs the three-dimensional structure of the pores and verifies connectivity.
  - **Measurement method**: Porosity is measured by mercury intrusion or gas adsorption (BET), and typical surface area is assessed by BET method. The pore size distribution is analyzed by microscopy or X-CT to ensure uniform pore size.
- **Mechanical Strength Optimization**:

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  - **Strength target**: The matrix needs to withstand thermal stress and mechanical vibration during high-temperature operation, and the compressive strength is evaluated by testing.
  - **Process Adjustments**: Reducing the sintering temperature or shortening the holding time can preserve more porosity, but the particle bonding strength needs to be ensured. Doping trace additives can enhance grain boundary bonding and improve strength.
  - **Verification Method**: Evaluate the mechanical strength through compressive or tensile tests, and observe the bonding state of the sintered particles in combination with SEM to ensure no microcracks or pore collapse.
- **Process Validation**:
  - X-CT was used to analyze the pore structure of the sintered matrix to verify that the porosity and connectivity met the requirements.
  - Mechanical testing combined with microstructural analysis ensures the stability of the matrix during high-temperature operation.
  - Optimizing the process requires iterative experiments, such as adjusting the sintering temperature and filler ratio to balance porosity and strength.

Optimization of porosity and mechanical strength requires precise process control and multi-technology validation to ensure that the matrix meets the structural and functional requirements of high-performance cathodes.

4.2 Impregnation and Activation of Barium Compounds

The impregnation and activation of barium compounds is the core process of introducing active substances into porous tungsten matrix and forming a low-work function active layer, which directly affects the emission performance and lifetime of the cathode. This section details the formulation and optimization of the impregnation process, as well as the heat treatment techniques during activation.

4.2.1 Impregnation Process: Barium Compound Formulation and Impregnation Conditions

The impregnation process aims to introduce barium compounds uniformly into the pore network of the porous tungsten matrix, ensuring a continuous supply of active barium atoms. The following is a detailed process flow and optimization method:

- **Barium Compound Formulation**:
  - **Material Selection**: Commonly used barium calcium aluminate is widely used due to its excellent thermal decomposition properties and chemical stability. The formulation releases free barium atoms at operating temperature through the following reactions:

$$4BaO \cdot CaO \cdot Al_2O_3 \rightarrow 4Ba + CaO + Al_2O_3 + O_2$$

by-products (e.g., CaO, Al_2O_3) are highly stable and do not interfere with emission properties.

- **Ratio Optimization**: Adjust the ratio according to the application requirements. High current density applications can use high barium content ratio to increase the barium release rate. Long-life applications can increase the ratio of CaO or Al_2O_3 to slow the rate of decomposition. The addition of antitoxic agents such as La_2O_3 or CeO_2 improves antioxidant capacity.
- **Particle Characteristics**: Barium compounds need to be ground to the micron level to match the pore size of the matrix to avoid clogging pores or uneven distribution.

- **Solution Preparation**:
  - **Solvent Selection**: Barium compounds are mixed with deionized water or organic solvents such as ethanol or isopropanol to formulate a suspension. Deionized water is low cost, but it needs to be free of impurities; Organic solvents can improve dispersibility, but volatility and safety are considered.
  - **Dispersion Processing**: High-speed stirring or sonication ensures uniform dispersion of particles to avoid agglomeration. The solution concentration needs to be optimized to balance the permeability efficiency and pore filling.
  - **Additives**: Small amounts of surfactants, such as polyethylene glycol, can improve solution wettability and promote penetration into pores.
- **Impregnation Process**:
  - **Vacuum Impregnation**: A porous tungsten matrix is placed in a vacuum chamber to remove air from the pores and subsequently a barium compound solution is introduced. The vacuum environment enhances solution penetration efficiency and reduces bubble residue. The impregnation time is optimized according to the porosity of the matrix.
  - **Pressure Impregnation**: Applies to high porosity substrates by applying moderate pressure to facilitate solution penetration into pores. The pressure needs to be controlled to avoid deformation of the matrix or clogging of pores.
  - **Process Control**: Impregnation should be carried out in a clean room (ISO class 5 or higher) to avoid dust or impurity contamination. The surface of the matrix needs to be pre-cleaned (e.g., ultrasonic cleaning) to remove grease or oxides.
- **Drying**:
  - The impregnated substrate is dried at low temperature to remove the solvent. Drying should be carried out in a vacuum or inert atmosphere to avoid the reaction of barium compounds with oxygen or water vapor in the air.
  - Step-by-step drying prevents pore clogging caused by rapid volatilization of the solution. After drying, the matrix needs to be checked for weight increments to ensure that the barium compound filling is in line with the design requirements.
- **Process Validation**:

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- SEM and EDS were used to analyze the distribution uniformity of barium compounds to verify pore fill.
- Confirm the amount of filling through gravimetric analysis, and observe the pore section in combination with a microscope to ensure that there are no blockages or voids.
- Optimize impregnation parameters such as vacuum, pressure, and solution concentration to improve filling efficiency and uniformity.

The impregnation process needs to ensure that the barium compounds are evenly distributed across the pore network to provide a stable source of barium for subsequent activation.

4.2.2 Activation Process: Heat Treatment and Surface Active Layer Formation

The activation process decomposes the impregnated barium compound through heat treatment and forms a low-work function active layer on the surface of the tungsten matrix, which is a key step in achieving cathodic emission performance. The following is the detailed process:

- **Heat Treatment**:
  - **Environmental Control**: Activation is performed in a high vacuum or inert atmosphere (e.g., high-purity argon) to prevent oxidation or contamination of barium compounds. Vacuum pump systems, such as turbomolecular pumps, ensure low partial pressure of residual gas.
  - **Temperature Procedure**: Step-by-step heating is employed to avoid cracking of the matrix due to thermal stress. The holding time is optimized according to the ratio of barium compounds. High temperatures prompt the decomposition of barium compounds, releasing free barium atoms and diffusing to the surface through pores.
  - **Equipment requirements**: Use high-temperature vacuum furnace or resistance heating furnace with precise temperature control system. Infrared thermometers monitor substrate temperature in real-time, ensuring uniformity.
- **Surfactant Layer Formation**:
  - **Barium Diffusion and Adsorption**: Free barium atoms diffuse to the surface of the tungsten matrix through a network of pores, forming a single atomic layer or thin film. The chemisorpted barium atoms form a strong bond with the tungsten surface, reducing the work function to 1.1–1.5 eV. The physically adsorbed barium atoms provide continuous replenishment and maintain the dynamic equilibrium of the active layer.
  - **Surface Topography Control**: The active layer should be uniform and continuous, and the surface roughness should be controlled at a low level through polishing. The uneven active layer may lead to local high-power function regions, reducing the emission efficiency.

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- **Additive Effect**: Adding a small amount of rare earth oxides can enhance the thermal stability of the active layer and slow down the evaporation loss of barium.

- **Process Optimization**:
  - The activation temperature and time should be adjusted according to the ratio of barium compounds and the pore structure of the matrix. Too high temperature may accelerate the evaporation of barium and shorten the lifespan; Insufficient activation may lead to low active layer coverage, affecting emission performance.
  - Step-by-step activation can be carried out in stages, stabilizing the barium compound before forming an active layer.
  - After activation, it needs to be cooled to room temperature to avoid surface defects caused by thermal stress.
- **Process Validation**:
  - The emission performance of the active layer is verified using thermionic emission testing to ensure that the current density reaches the target value.
  - AFM and SEM analyze the surface topography to confirm the uniformity and roughness of the active layer.
  - XPS analyzes the chemical composition of the surface to verify the effect of barium atom coverage and work function reduction.

The activation process requires precise temperature and environmental control to form a stable active layer to ensure the high-performance operation of the cathode.

4.3 Quality Control and Testing of Barium Tungsten Cathodes

Quality control and testing are key aspects of ensuring the consistency and reliability of barium tungsten cathode performance, including emission performance testing, conformance assessment, and failure analysis. This section details the methodology and standards.

4.3.1 Test Method for Transmitting Performance

Emission performance testing is designed to evaluate the current density, work function, and emission stability of barium-tungsten cathodes to verify the effectiveness of the manufacturing process. The following is a detailed test method:

- **Thermionic Emission Test**:
  - **Test Conditions**: In a high vacuum environment, heat the cathode to operating temperature, and measure the emission current using an anode collector and a precision ammeter. The test device needs to be equipped with a high-precision power supply and temperature control system.
  - **Test Procedure**: Apply a gradually increasing anode voltage and record the current-voltage characteristic curve (I-V curve). Calculate the work function using the Richardson-Dushman equation:

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$$J = AT^2 \exp\left(-\frac{\phi}{kT}\right)$$

ensure that the work function is in the range of 1.1–1.5 eV and the current density meets the design requirements.

- **Data Analysis**: Assess the stability and noise levels of the transmitted current. Abnormal fluctuations may indicate uneven active layers or surface contamination.

- **Pulse Test**:
  - **Test Purpose**: To simulate transient operating conditions in high-power devices and evaluate the performance of cathodes under high electric fields or high current densities.
  - **Test Process**: Apply a pulse voltage to measure transient current density and response time. Testing detects emitted noise due to surface defects or inhomogeneity.
  - **Equipment Requirements**: Use high-frequency pulse power supplies and oscilloscopes to record current waveforms to ensure measurement accuracy.
- **Life Testing**:
  - **Test Conditions**: Continuous operation for thousands of hours under simulated operating conditions, monitoring current density decay.
  - **Test Process**: Regularly record current density and work function changes, and draw performance decay curves. Tests assess aging rates and active layer stability.
  - **Data Analysis**: Predict cathode life through attenuation curves to ensure application needs are met.
- **Verification Method**:
  - The test results should be compared with the design specifications, such as the current density should reach the target value and the work function should meet expectations.
  - Multiple tests to ensure data reliability, excluding equipment errors or environmental interference.

Emission performance testing is performed in a standardized test environment, combined with multi-parameter analysis, to ensure that cathode performance meets application requirements.

4.3.2 Evaluation Criteria for Consistency And Reliability

Consistency and reliability are key requirements for large-scale production of barium tungsten cathodes and are evaluated by the following criteria:

- **Conformance Assessment**:
  - **Parameter Monitoring**: Statistical analysis of the emission current density, work function and lifetime of multiple batches of cathodes, and calculation of the

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coefficient of variation (standard deviation/mean). The factor of variation needs to be kept low to ensure consistent performance from batch to batch.
    - **Microstructure Verification**: Analyze matrix pore structure and barium compound distribution using SEM and X-CT to ensure consistent porosity and fill volume from batch to batch. Surface roughness is measured by AFM.
    - **Process Control**: Statistical process control (SPC) technology is used to monitor pressing pressure, sintering temperature, and impregnation parameters in real time, and adjust deviations in time. Control charts can be used to track the stability of key parameters.
- **Reliability Assessment**:
    - **Accelerated Aging Testing**: Operates under high temperature or high current density conditions to assess the cathode's performance degradation in extreme environments. The test results are used to calculate the mean time between failures (MTBF) and the probability of failure.
    - **Environmental Adaptability Testing**: Tests under simulated operating conditions to verify the stability of the cathode in different environments.
    - **Standard development**: Reliability indicators are developed based on application requirements (e.g., microwave tubes or X-ray tubes).
- **Verification Method**:
    - Combine multi-batch test data to evaluate the repeatability and stability of the production process.
    - Use statistical software to analyze parameter distributions to ensure that normal distributions or target tolerances are met.
    - Regularly calibrate the testing equipment to ensure measurement accuracy and consistency.

Conformance and reliability evaluation require systematic testing and data analysis to ensure the performance stability of cathodes in production and applications.

4.3.3 Failure Analysis and Improvement

Failure analysis aims to identify the causes of barium tungsten cathode degradation or failure, and to propose targeted improvement measures. The following are common failure modes and analysis methods:

- **Surface Contamination**:
    - **Failure Mechanism**: Oxygen, water vapor, or carbon compounds react with barium to form high-work function compounds (such as BaO_2 or $BaCO_3$), reducing emission performance.
    - **Diagnostic Methods**:

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        - X-ray photoelectron spectroscopy (XPS) analyzes the chemical composition of the surface, detects the Ba/O/C ratio, and confirms the type of contaminant.
        - Thermionic emission testing evaluates current density attenuation to verify contamination effects.
    - **Improvement Measures**:
        - Increase the vacuum level to reduce residual gas contamination.
        - Anti-toxicants such as La_2O_3 are added to form a protective layer.
        - Plasma cleaning is used to remove surface contaminants.
- **Barium Depletion**:
    - **Failure Mechanism**: long-term operation leads to the depletion of barium compounds, the decrease of active layer coverage, and the increase of work function.
    - **Diagnostic Methods**:
        - SEM and EDS analyzed barium content and active layer morphology to verify coverage.
        - Work function measurements (by thermionic emission tests) assess performance degradation.
    - **Improvement Measures**:
        - Optimize the ratio of barium compounds to increase barium storage.
        - Improve porosity to increase filling capacity.
        - Regular low temperature activation to replenish the active layer.
- **Mechanical Failure**:
    - **Failure Mechanism**: Thermal stress or mechanical vibration can cause matrix cracking or pore collapse, affecting barium diffusion.
    - **Diagnostic Methods**:
        - X-CT analyzes pore structure to detect cracks or collapses.
        - Mechanical tests (such as compression tests) assess substrate strength.
    - **Improvement Measures**:
        - Optimize the sintering process to enhance particle bonding.
        - Step-by-step heating is used to reduce thermal stress.
        - Doped with ZrO_2 improves crack resistance.
- **Arc failure**:
    - **Failure Mechanism**: Surface defects or uneven active layers trigger localized arcing, leading to emission instability or surface damage.
    - **Diagnostic Methods**:
        - SEM detects surface defects such as particle buildup or cracks.
        - The high-frequency emission test (frequency 1 kHz) records current fluctuations.
        - The oscilloscope monitors the arc signal.
    - **Improvement Measures**:
        - Optimized impregnation process ensures uniformity of the active layer.

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    - Surface polishing reduces defects.
    - Optimize electrode design to reduce electric field concentration.
- **Failure Analysis Method**:
  - **Fault Tree Analysis (FTA):** Construct a failure cause tree to identify major failure modes (e.g., barium depletion or surface contamination) and their root causes (e.g., process parameter deviations).
  - **Statistical Process Control (SPC):** Analyze failure data, identify process bottlenecks, and optimize key parameters.
  - **Multi-Technique Diagnostics**: Combine XPS, SEM, X-CT, and emission testing to comprehensively analyze failure mechanisms.
- **Improvement Strategy**:
  - Optimize process parameters (e.g., sintering temperature, impregnation pressure) to improve cathodic consistency.
  - Introducing online monitoring systems, such as temperature sensors or gas analyzers, to detect process deviations in real time.
  - Establish a feedback mechanism to apply the failure analysis results to process improvement and reduce the failure rate.

Failure analysis requires a combination of multi-technology diagnostics and systematic analysis methods to ensure that the root cause is identified and effective improvement measures are proposed.

This chapter elaborates on each step of the process from tungsten matrix forming to active layer formation, as well as the key methods of performance testing and failure analysis, providing a solid technical foundation for the production and optimization of high-performance cathodes, and providing process guarantee for subsequent application development and performance improvement.

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CTIA GROUP LTD
Barium Tungsten Cathode Introduction

1. Overview of Barium Tungsten Cathode

The Barium Tungsten Cathode is a type of thermionic emission material typically composed of high-purity tungsten as the base, impregnated with barium compounds. Upon high-temperature activation, it emits free electrons and is widely used in vacuum electronic devices. Due to its low work function and high electron emission efficiency, this cathode plays a critical role in high-power electronic equipment. CTIA GROUP LTD specializes in the global flexible customization of tungsten and molybdenum products, offering tailored high-performance barium tungsten cathodes according to customer requirements.

2. Characteristics of Barium Tungsten Cathode

- **High Electron Emission Efficiency:** The low work function of barium enables the cathode to emit a large quantity of electrons even at relatively low temperatures.
- **High-Temperature Resistance:** With a tungsten matrix that has a melting point of 3422° C, the cathode maintains structural stability in high-temperature operating environments.
- **Long Service Life:** Optimized barium compound impregnation techniques help minimize barium evaporation, thereby extending the cathode's lifespan.
- **Low Evaporation Rate:** Compared to other cathode materials, barium tungsten exhibits a lower evaporation rate at high temperatures, reducing contamination within the device.
- **Arc Stability:** Delivers a stable electron flow, making it ideal for high-precision electron beam applications.

3. Applications of Barium Tungsten Cathode

- **HID Lamps:** The cathode's low work function and high current density allow HID lamps to emit bright and stable light, making them suitable for applications that require high brightness and long service life, such as roadway and industrial lighting.
- **Vacuum and Laser Devices:** The low work function makes barium tungsten ideal for use in vacuum electronic and laser components.
- **Stage and Club Lighting Effects:** High-frequency strobe lights made from this material are known for their long lifespan and stable performance.
- **Film Projection and Video Recording:** The film and broadcast industry also relies heavily on this material for projection and recording equipment, where it ensures long-term operational stability and high efficiency.
- **Laser Mercury Pumps:** Its high electron emission capability and low operating temperature contribute to improved laser performance and stability.

5. Procurement Information

Email: sales@chinatungsten.com
Phone: +86 592 5129595; 592 5129696
Website: www.tungsten.com.cn

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Chapter 5: Application of Barium Tungsten Cathode

Barium tungsten cathodes play a key role as efficient thermionic emission sources in many high-tech fields due to their low work function, high emission current density, and excellent thermal stability. This chapter discusses in detail the specific uses of barium tungsten cathodes in vacuum electronics, scientific instruments, industrial and communications, aerospace and defense, and emerging and cross-field applications, and analyzes their roles and technical requirements in different scenarios.

5.1 Vacuum Electronics

Vacuum electronic devices use the movement of electrons in a vacuum environment to achieve signal amplification, oscillation, or energy conversion, and are widely used in communications, radar, and industrial fields. Barium tungsten cathodes serve as a high-efficiency source of electron emission, providing a steady flow of high-current electrons to these devices, meeting high power and frequency requirements.

5.1.1 Microwave Tube

Microwave tubes are a class of vacuum electronic devices that use electron beams to interact with electromagnetic fields to generate or amplify microwave signals, which are widely used in radar, communications, and scientific experiments. Barium tungsten cathodes are indispensable in microwave tubes due to their high emission efficiency and stability.

5.1.1.1 Magnetron: Used in Radar and Microwave Heating Equipment

- **Equipment Introduction**: Magnetron is a high-power microwave oscillator that excites the resonator cavity to generate high-frequency microwave signals (usually in the GHz range) by moving electrons along a specific orbit under the interaction of electric and magnetic fields. Its core components include a cathode (electron source), an anode resonant cavity, and a magnetic field system. Magnetrons are widely used in radar systems (e.g., weather radars, military target tracking radars) and microwave heating equipment (e.g., industrial microwave ovens, microwave drying equipment) due to their ability to generate high-power (kW to MW) pulses or continuous microwave signals.
  Working principle: The cathode emits electrons, forming a rotating electron cloud under the action of cross-electric and magnetic fields, coupled with the anode resonant cavity to generate a microwave signal of a specific frequency.
- **Barium tungsten cathode function**: The barium tungsten cathode serves as the electron source of the magnetron, providing high current density electron flow and supporting high-power microwave output.
- **Cathode requirements**:

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- **High Current Density**: Magnetrons require high transmit current density to support high power output. Barium tungsten cathodes provide stable emission at high temperatures to meet power demands.
- **Fast response**: Radar pulse operation requires the cathode to respond to high-frequency pulse voltages within microseconds, with low emission noise and a uniform active layer.
- **Vibration resistance**: Mechanical vibration in military radar requires high mechanical strength of the cathode matrix to prevent pore collapse or active layer spalling, and the sintering process and matrix structure need to be optimized.

- **Technical Advantages**: The low work function and high thermal stability of barium tungsten cathodes allow them to operate for extended periods under high power and pulse conditions, meeting the needs of magnetrons for efficient and reliable electron sources.

5.1.1.2 TWTs: High-frequency communications and satellite amplifiers

- **Equipment Introduction**: Traveling Wave Tube (TWT) is a broadband microwave amplifier that amplifies high-frequency signals through the interaction of electron beams with traveling wave fields. Its core components include a cathode, a slow-wave structure, an electron beam focusing system, and a collection electrode. TWTs are widely used in satellite communications (uplink/downstream signal amplification), 5G base stations, and broadcasting systems due to their high gain and broadband characteristics.
  Working principle: The electron beam emitted by the cathode travels synchronously with the input microwave signal in a slow-wave structure (such as a spiral), and the kinetic energy of the electron beam is transferred to the signal to achieve amplification and output.
- **Barium-tungsten cathode action**: The barium-tungsten cathode provides a stable electron beam, supporting the high-frequency signal amplification of the traveling wave tube.
- **Cathode requirements**:
  - **High emission uniformity**: The traveling wave tube needs a stable electron beam to ensure the quality of signal amplification, and the cathode active layer needs to be uniform and has low surface roughness to avoid signal distortion.
  - **Long life**: Satellite communication requires long cathode life, and the ratio of barium compounds needs to be optimized to slow down the evaporation loss of barium.
  - **Anti-toxicity**: There may be trace amounts of residual gases in the space environment, and anti-toxicants need to be added to maintain performance.
- **Technical Advantages**: The high current density and anti-poisoning capabilities of barium tungsten cathodes ensure the signal stability and reliability of traveling wave tubes in high-frequency, long-life operation.

5.1.1.3 Klystron tube: high-power radar and particle accelerator

- **Equipment Introduction**: Klystron is a high-power microwave amplifier or oscillator that generates or amplifies microwave signals through the speed modulation of an electron beam in the resonant cavity. Its core components include a cathode, resonant cavity, drift

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tube, and collection electrode. Klystron tubes are widely used in high-power radars (e.g., air traffic control radars, missile guidance radars) and particle accelerators (e.g., synchrotron radiation sources, CERN's LHCs).

Working principle: The electron beam emitted by the cathode is velocity modulated as it passes through the resonant cavity, forming a density modulation beam, which converts kinetic energy into microwave energy in the subsequent cavity.

- **Barium Tungsten Cathode Action**: The barium tungsten cathode provides a high-current electron beam, supporting the high-power output of the klystron tube.
- **Cathode requirements**:
  - **Ultra-high current density**: The klystron requires extremely high electron flow to support MW-level output, and the cathode needs to be combined with the Schottky effect to enhance emission at high electric fields.
  - **Thermal stability**: Fluctuations in operating temperature require the cathode to maintain stable performance, and the thermal conductivity of the matrix and the heat resistance of the active layer need to be optimized.
  - **High vacuum compatibility**: In ultra-high vacuum cathodes, it is necessary to avoid performance degradation caused by surface contamination.
- **Technical advantages**: Barium tungsten cathodes provide stable electron emission under high power and high electric field conditions, meeting the extreme operating requirements of klystron tubes.

5.1.2 X-ray tubes

X-ray tubes are vacuum devices that generate X-rays by bombarding metal targets with high-energy electrons, widely used in medical and industrial fields. The barium tungsten cathode provides it with a highly efficient electron source.

5.1.2.1 Medical Imaging Equipment (e.g., CT Scanners, X-ray Diagnostic Machines)

- **Equipment Introduction**: X-ray tubes are the core components of medical imaging equipment (such as computed tomography CT, X-ray diagnostic instruments), which generate X-rays by electronically bombarding anode targets (such as tungsten or molybdenum) for human tissue imaging. Its main components include the cathode, anode, and vacuum housing. CT scanners generate three-dimensional images through multi-angle X-ray projections, and diagnostic X-ray machines are used for bone or soft tissue examination.

  How it works: The cathode emits electrons that bombard the anode under the acceleration of a high-voltage electric field, producing characteristic X-rays and continuous spectral X-rays for fluoroscopic imaging.
- **Barium Tungsten Cathode Action**: The barium tungsten cathode provides a high-energy electron beam that generates a high-quality X-ray signal.
- **Cathode requirements**:

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  - **High emission stability**: The imaging quality requires a stable electron flow, and the cathode needs to be evenly emitted to reduce current fluctuations.
  - **Quick start**: The diagnostic equipment needs to start quickly, and the cathode needs to reach the operating temperature and emit stably in a short time.
  - **Long life**: Medical equipment requires long cathode life, and it is necessary to optimize barium storage and anti-poisoning capabilities.
- **Technical Advantages**: The high current density and rapid response capabilities of barium-tungsten cathodes ensure the imaging accuracy and reliability of X-ray tubes, meeting the high standards of medical devices.

5.1.2.2 Industrial non-destructive testing

- **Equipment Introduction**: X-ray tubes are used in industrial NDT to detect internal defects (such as cracks, porosity), weld quality, or electronic component structure. It works similarly to medical X-ray tubes but requires higher X-ray energy to penetrate thick metals or composites. Application scenarios include aviation component inspection, pipeline weld analysis, and semiconductor package inspection.
  How it works: A high-energy electron beam bombards the target to generate X-rays, which are captured by the detector after transmitting the sample, forming an image of the internal structure.
- **Barium Tungsten Cathode Action**: The barium tungsten cathode provides a high-intensity electron beam, supporting high-energy X-ray generation.
- **Cathode requirements**:
  - **High power output**: Industrial inspection requires high-energy X-rays, and cathodes need to provide high current density.
  - **Environmental Adaptability**: Industrial environments may experience vibration or temperature changes, and cathodes need to have high mechanical strength and thermal stability.
  - **Contamination resistance**: Non-ideal vacuum conditions require the cathode to be enhanced against poisoning through additives.
- **Technical Advantages**: The robustness and high emission efficiency of barium tungsten cathodes make them suitable for the demanding conditions of industrial inspection, providing high-quality X-ray signals.

5.1.3 Other vacuum devices

- **Photomultiplier** tube:
  - **Equipment Introduction**: Photomultiplier Tube (PMT) is a high-sensitivity photodetector that converts weak light signals into electrical signals, which are widely used in radiation detectors (such as gamma-ray detection), astronomical observations, and photon counting in scientific experiments. Its core components include a photocathode, an electron multiplier, and an anode.
    Working principle: The photocathode absorbs photons and emits electrons,

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which are amplified by the multiplier and collected by the anode to form a detectable electrical signal.

- **Barium tungsten cathode action**: Provides highly sensitive electron emission and supports the generation of initial photoelectric signals.
- **Cathode requirements**: Extremely low emission noise and fast response time are required to ensure photon detection accuracy.
- **Technical Advantages**: The low noise and high sensitivity characteristics of barium tungsten cathodes make them ideal electron sources for photomultiplier tubes.

- **Electron Beam Welding Equipment**:
  - **Equipment Introduction**: Electron beam welding equipment utilizes high-energy electron beam molten materials for high-precision welding, which is widely used in aerospace, automobile manufacturing, and nuclear industries. Its core components include a cathode, an electron optical system, and a vacuum chamber. **Working principle:** The electron beam emitted by the cathode is accelerated and focused in high vacuum, bombarding the workpiece to generate local high temperature and achieve deep melt welding.
  - **Barium tungsten cathode action**: Provides a high-energy electron beam that supports deep melt welding.
  - **Cathode requirements**: High current density and stable electron beam focusing performance are required, and the operating temperature needs to be precisely controlled to avoid overheating.
  - **Technical** Advantages: The high emission efficiency and stability of barium tungsten cathodes ensure precision and efficiency in welding.

5.2 Scientific instruments

Barium tungsten cathodes serve as high-performance electron sources in scientific instruments, supporting high-resolution imaging and analysis tasks that meet the requirements of high precision and sensitivity.

5.2.1 Electron microscope

- **Equipment Introduction**: Electron microscope uses electron beam imaging and is divided into scanning electron microscopy (SEM) and transmission electron microscopy (TEM). SEM scans the surface of the sample through an electron beam, collects secondary electrons or backscattered electrons to form a surface topography image with a resolution of nanometers; TEM penetrates ultra-thin samples with an electron beam to generate images of internal structures with resolutions down to the sub-angstrom level. Both are widely used in materials science, biology, and nanotechnology research.
  How it works: The electron beam emitted by the cathode is accelerated by an electric field and focused by a magnetic field, scanned (SEM) or penetrated (TEM) and captured by the detector to generate a high-resolution image.

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- **Barium tungsten cathode action**: Provides a high-brightness electron beam and supports sub-nanoscale imaging.
- **Cathode requirements**:
  - **High brightness**: High current density and low emission noise are required to achieve high resolution.
  - **Stability**: Long-term imaging requires low fluctuations in emission current, and the uniformity of the active layer needs to be optimized.
  - **Vacuum compatibility**: Ultra-high vacuum requires strong cathode resistance to contamination.
- **Technical Advantages**: The high brightness and stability of the barium tungsten cathode make it an ideal source of electrons for SEM and TEM.

5.2.2 Mass spectrometer: High sensitivity ion source

- **Equipment Introduction**: Mass spectrometer is an analytical instrument that determines molecular composition and structure by ionizing sample molecules and measuring their mass-to-charge ratio, and is widely used in chemical analysis, environmental monitoring, and biomedical research. Its core components include an ion source, a mass analyzer, and a detector.

  Working principle: The cathode emits electrons to bombard the sample molecules, and after generating ions, they are separated by electric or magnetic fields, and the molecular species are detected according to the mass-to-charge ratio.
- **Barium tungsten cathodic action**: Provides a stable flow of electrons for sample ionization.
- **Cathode requirements**:
  - **High sensitivity**: A steady flow of low-energy electrons is required to improve ionization efficiency, and the cathode needs to be operated at lower temperatures.
  - **Long lifetime**: Analytical tasks need to run for long periods of time, and cathodes need to be extended by optimizing the barium ratio.
- **Technical Advantages**: The low work function and high emission efficiency of the barium-tungsten cathode ensure high sensitivity and long-term stability of the mass spectrometer.

5.2.3 Surface Analysis Equipment

- **Equipment Introduction**: Auger Electron Spectrometer (AES) and X-ray Photoelectron Spectrometer (XPS) are surface analysis instruments used to study the chemical composition and electronic structure of material surfaces. AES generates Auger electrons by exciting the sample with an electron beam to analyze elemental species; XPS excites photoelectrons through X-rays, measuring elements and chemical states. Both are widely used in materials science and semiconductor research.

  How it works: A cathode emitting electron or X-ray source excites the sample and collects the emitted electrons for energy spectral analysis.
- **Barium Tungsten Cathodic Action**: Provides a stable electron beam (AES) to support high-precision surface analysis.

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- **Cathode requirements**:
  - **High precision**: A stable flow of low-energy electrons is required, and the cathode needs to provide uniform emission and low noise characteristics.
  - **Ultra-High Vacuum Compatibility**: The cathode needs to avoid surface contamination.
- **Technical Advantages**: The uniform emission and resistance to contamination of barium tungsten cathodes make them suitable for high-precision surface analysis tasks.

5.3 Industrial and Communication Applications

Barium tungsten cathodes support high-power electronic sources and signal amplification functions in the industrial and communication fields, meeting the needs of high reliability and efficiency.

5.3.1 Radar System

- **Equipment Introduction**: The radar system detects the target position and speed by transmitting and receiving microwave signals, and is divided into military radar (such as air defense radar, missile guidance radar) and civilian radar (such as air traffic control, weather radar). Its core components include a microwave source (such as a magnetron or klystron), an antenna, and a signal processor.
  Working Principle: The electron beam emitted by the cathode generates a high-power microwave signal in the microwave tube, which is reflected back to the detector after being transmitted by the antenna.
- **Barium Tungsten Cathode Action**: Provides high-power electron flow and supports microwave signal generation.
- **Cathode Requirements**:
  - **High Power Output**: High current density is required to support high-power signal transmission.
  - **Vibration Resistance**: Mobile platforms (such as shipboard radars) require high mechanical strength of the cathode matrix.
  - **Fast Response**: The pulse radar needs to be quickly started by the cathode and transmitted stably.
- **Technical Advantages**: The high emission efficiency and robustness of the barium tungsten cathode make it an ideal source of electrons for radar systems.

5.3.2 Communication Equipment

- **Equipment Introduction**: Satellite communication and ground base station amplifiers are used for long-distance signal transmission, relying on traveling wave tubes or solid-state amplifiers to amplify high-frequency signals. Satellite communication supports global communication networks, and terrestrial base stations are used for 5G and broadcasting systems.
  Working Principle: The electron beam emitted by the cathode amplifies the input signal in the traveling wave tube and outputs a high-power signal.

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- **Barium Tungsten Cathode Action**: Provides a stable flow of electrons, supporting signal amplification.
- **Cathode Requirements**:
  - o **High Frequency Stability**: low noise electron flow is required, and the cathode active layer needs to be uniform.
  - o **Long Life**: Satellite communication requires long cathode life, and anti-poisoning and evaporation performance needs to be optimized.
- **Technical Advantages**: Barium tungsten cathodes support high-frequency signal amplification and long-term operation, meeting the high reliability requirements of communication equipment.

5.3.3 Vacuum Switch Tube

- **Equipment Introduction**: Vacuum switch tube is a high-voltage switching device used for circuit breakers, power distribution, and load control in power systems, achieving fast switching through electronic control. Its core components include a cathode, anode, and vacuum housing.
  Working Principle: The cathode emits electrons, forming an arc or on-current at high voltage to realize circuit switching.
- **Barium Tungsten Cathode Action**: Provides high-current electron flow and supports fast switching operation.
- **Cathode Requirements**:
  - o **High Current Density**: Requires support for high-current switching operation.
  - o **Arc Resistance**: It is necessary to avoid arcing caused by surface defects and optimize the surface topography.
- **Technical Advantages**: The high emission efficiency and stability of barium tungsten cathodes make them suitable for high-voltage, high-power switching applications.

5.4 Aerospace and Defense

Barium tungsten cathodes support high-reliability and high-performance electronics in aerospace and defense to meet the demands of extreme environments.

5.4.1 Space Electronic Devices

- **Equipment Introduction**: Space electronic devices include communication modules, propulsion systems and scientific instruments in deep space probes and satellites, which need to operate in extreme vacuum and radiation environments. Typical applications include electronic sources for satellite communication systems (such as GPS satellites) and probes (such as Mars rover).
  Working Principle: The cathode provides electron flow, supporting communication signal amplification or propellant ionization.
- **Barium Tungsten Cathode Action**: Provides a high-reliability electron source to support long-term space missions.

- **Cathode Requirements**:
    - **Adaptability to Extreme Environments**: It needs to operate stably in space vacuum and radiation environments.
    - **Long Life**: The mission cycle is up to several years, and the barium storage needs to be optimized to extend the life.
    - **Low Power Consumption**: Low heating power is required to save energy.
- **Technical Advantages**: The high reliability and low work function of barium tungsten cathodes make them a preferred choice for space applications.

5.4.2 Electronic Countermeasure System

- **Equipment Introduction**: Electronic countermeasures systems use high-power microwave signals to jam or disrupt enemy communications, radars, or electronic equipment, including high-power microwave weapons and jammers. Its core component is a microwave source (such as a clostron or magnetron).
  Working Principle: The electron beam emitted by the cathode generates a high-power microwave signal that emits an interfering target through a directional antenna.
- **Barium Tungsten Cathode Action**: provides ultra-high power electron flow and supports microwave signal generation.
- **Cathode Requirements**:
    - **Ultra-High Power**: Requires extremely high current density to support MW-level output.
    - **Fast Response**: Pulse operation requires fast start-up and stable emission.
- **Technical Advantages**: Barium tungsten cathodes provide a stable flow of electrons under high electric fields and high powers, meeting the needs of counter systems.

5.5 Emerging and Cross-Domain Applications

Barium tungsten cathodes show extensive potential in emerging technology fields, supporting cutting-edge research and interdisciplinary applications.

5.5.1 Terahertz Wave Generator

- **Equipment Introduction**: The terahertz wave generator generates terahertz waves for terahertz imaging (such as security, medical diagnosis) and high-speed communication. Its core components include an electronic source and an oscillator (such as a traveling wave tube or klystron tube).
  Working Principle: The electron beam emitted by the cathode oscillates in a high-frequency field, generating terahertz waves.
- **Barium Tungsten Cathode Action**: provides a high-frequency electron beam and supports terahertz wave generation.
- **Cathode Requirements**:
    - **High Frequency Response**: It is necessary to support high-field strong emission in combination with tunneling effect.

  - **Stability**: Low noise is required at high vacuum and high temperatures.
- **Technical Advantages**: The low work function and high current density of barium tungsten cathodes make them suitable for the high requirements of terahertz wave generators.

5.5.2 Ion Thrusters

- **Equipment Introduction**: Ion thrusters are low-thrust, high-efficiency space propulsion systems that generate ion beams through ionizing propellants (such as xenon) to provide micro-thrust (μN to mN levels) for attitude control of deep space probes or satellites.
  Working Principle: The cathode emits electron ionizing propellant, and the ions are ejected after the electric field accelerates to generate thrust.
- **Barium Tungsten Cathode Action**: provides a high-efficiency electron source and supports propellant ionization.
- **Cathode Requirements**:
  - **High Efficiency**: Efficient electron flow is required to improve ionization efficiency.
  - **Long Life**: Deep space missions require several years of operation.
- **Technical Advantages**: The high emission efficiency and long life of the barium-tungsten cathode support the low power consumption and long-term operation of the ion thruster.

5.5.3 High-Energy Physics Experiments

- **Device Description**: Particle accelerators, such as CERN's LHC, accelerate charged particles through electric and magnetic fields for high-energy physics research. Its electron source is used to generate an initial particle beam or an auxiliary beam.
  Working Principle: The electron beam emitted by the cathode is accelerated and injected into the accelerator to participate in the particle collision experiment.
- **Barium Tungsten Cathode Action**: Provides a high-current electron source to support particle beam generation.
- **Cathode Requirements**:
  - **Ultra-High Current Density**: Need to support high-energy particle beams.
  - **Stability**: It needs to operate for a long time under ultra-high vacuum.
- **Technical Advantages**: The high performance and stability of barium tungsten cathodes meet the extreme conditions of high-energy physics experiments.

5.5.4 Biomedical Applications

- **Equipment Introduction**: High-precision mass spectrometry analysis is used for disease diagnosis (such as early cancer screening, metabolic disease detection) by detecting the mass-to-charge ratio of biomarkers. Its core component is the ion source of the mass spectrometer.
  Working Principle: The cathode emits electrons to bombard biological samples, and the ions are generated and analyzed by mass spectrometry.
- **Barium Tungsten Cathode Action**: Provides a stable electron flow and supports high-sensitivity ionization.

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- **Cathode Requirements**:
  - **High Sensitivity**: requires a stable flow of low-energy electrons.
  - **Low Noise**: Analysis accuracy requires very low emission noise.
- **Technical Advantages**: The high sensitivity and low noise characteristics of barium tungsten cathodes make them ideal electron sources for biomedical mass spectrometry analysis.

In summary, barium tungsten cathodes have shown a wide range of application values in vacuum electronics, scientific instruments, industrial and communications, aerospace and defense, and emerging fields due to their low work function, high current density, and excellent stability. This chapter introduces in detail the equipment principles of each application scenario and their technical requirements for cathodes, clarifies the key role of barium tungsten cathodes in promoting the development of high-tech fields, and provides an application-oriented reference for subsequent performance optimization and interdisciplinary research.

Chapter 6: Optimization and Improvement of Barium Tungsten Cathode Performance

Performance optimization and improvement of barium tungsten cathodes are key to improving their performance in vacuum electronics and high-tech applications, aiming to improve emission efficiency, extend service life, enhance environmental adaptability, and enable intelligent design. This chapter discusses in detail the optimization of pore structure of porous tungsten matrix, the formulation of novel barium compounds, the application of nanotechnology, anti-toxicity processes, thermal and mechanical stability improvements, low-power green manufacturing, and intelligent monitoring technologies, covering a full range of strategies from material design to process optimization.

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6.1 Improve Launch Efficiency

Improving the emission efficiency of barium tungsten cathodes is a core goal of optimizing their performance, involving increasing the emission current density, reducing the work function, and improving the emission uniformity of electrons. This section discusses the optimization of pore structure of porous tungsten matrix, the formulation and doping of novel barium compounds, and the application of nanotechnology.

6.1.1 Optimization of Pore Structure of Porous Tungsten Matrix

The pore structure of the porous tungsten matrix directly affects the diffusion rate of barium atoms and the formation efficiency of the active layer, and the emission efficiency can be significantly improved by optimizing the porosity and connectivity.

- **Porosity Regulation**:
  - **Optimization Goal**: Balance barium compound storage and matrix mechanical strength by adjusting porosity. High porosity increases barium storage, which is conducive to high current density emission. Low porosity enhances strength for long-life applications.
  - **Process Method**: Fine tungsten powder is mixed with larger particles to form a bimodal pore distribution and enhance connectivity. Temporary fillers, such as polystyrene microspheres, volatilize during sintering, creating a uniform pore network.
  - **Sintering Parameter Optimization**: Adjust the sintering temperature, heating rate, and holding duration to ensure that the particles bind while retaining pores. Vacuum or hydrogen atmosphere prevents oxidation.
- **Pore Connectivity Enhanced**:
  - **Technical Means**: By controlling the particle size distribution of tungsten powder and pressing pressure, a three-dimensional connected pore network is formed to promote the diffusion of barium atoms to the surface.
  - **Verification Method**: X-ray tomography (X-CT) reconstructs the pore structure to confirm connectivity; Mercury pressure method measures porosity and pore size distribution.
- **Performance Improvement**: The optimized pore structure can improve the barium diffusion efficiency, increase the coverage of the active surface layer, reduce the work function, and increase the transmit current density.
- **Process Validation**: Scanning electron microscopy (SEM) is used to observe pore cross-sections, combined with thermiontronic emission testing to evaluate emission performance to ensure uniformity and stability.

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Pore structure optimization needs to be achieved through precise powder metallurgy and sintering processes to provide the structural basis for efficient emission.

6.1.2 Formulation and Doping Technology of New Barium Compounds

Novel barium compound formulations and doping techniques optimize the formation and stability of the active layer, reduce the work function and improve the emission efficiency.

- **New Barium Compound Formulation**:
  - **Formula Adjustment**: Traditional barium calcium aluminate ($4BaO \cdot CaO \cdot Al_2O_3$, 4:1:1) increases the barium content by adjusting the molar ratio and accelerates the release rate of free barium, making it suitable for high current density applications. The low barium ratio slows down decomposition and is suitable for long life needs.
  - **Alternative Compounds**: Explore barium silicates (e.g., Ba_2SiO_4) or barium titanates (e.g., $BaTiO_3$) as alternatives due to their more stable thermal decomposition properties over a certain temperature range and reduce by-product interference.
  - **Particle Optimization**: Grind barium compounds to the submicron level to match the pore size of the matrix, improve impregnation uniformity, and enhance active layer coverage.
- **Doping Technology**:
  - **Dopant Selection**: Rare earth oxides (such as La_2O_3, CeO_2, <2 wt%) were added to enhance the thermal stability of the active layer and reduce the work function. La_2O_3 forms Ba-La-O complexes with low work function, and CeO_2 improves antioxidant capacity.
  - **Doping Method**: The dopant is mixed with a barium compound and ground to prepare a suspension, or it is introduced through secondary impregnation after impregnation to ensure uniform distribution. Ultrasonic dispersion prevents agglomeration.
  - **Mechanism of Action**: Dopants reduce the work function by changing the electronic structure of the surface, while inhibiting barium evaporation and prolonging the active layer life.
- **Performance Enhancements**: New formulations and doping techniques reduce the work function, increase the transmit current density, and improve emission uniformity.
- **Process Verification**: X-ray photoelectron spectroscopy (XPS) was used to analyze the chemical composition of the surface and confirm the dopant distribution. Thermionic emission tests verify the increase in work function and current density.

New formulations and doping techniques need to be experimentally optimized to ensure compatibility with the pore structure of the matrix.

6.1.3 Nanotechnology Applications

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Nanotechnology improves the emission efficiency of barium-tungsten cathodes by constructing nanoscale structures, involving nanoscale barium coatings and nanoporous tungsten matrixes.

- **Nanoscale Barium Coating**:
  - **Preparation Method**: Atomic layer deposition (ALD) or chemical vapor deposition (CVD) is used to deposit nanoscale barium oxide coatings on the surface of the tungsten matrix. ALD uses $Ba(C_5H_7O_2)_2$ as a precursor and is deposited layer by layer at a certain temperature to ensure uniformity.
  - **Advantages**: Nanocoatings increase the surface coverage of barium atoms, reduce the work function, and reduce barium evaporation losses. The high specific surface area of the coating improves the efficiency of electron emission.
  - **Process control**: Deposition should be carried out in high vacuum to control the deposition rate and avoid the coating being too thick to block the pores.
- **Nanoporous Tungsten Matrix**:
  - **Preparation Method**: Nanopores are formed on the surface of the tungsten matrix by electrochemical etching or stencil methods (such as anodized aluminum templates). The template method uses an Al_2O_3 template to remove the template after depositing tungsten by plasma-enhanced chemical vapor deposition (PECVD).
  - **Advantages**: Nanopores increase the specific surface area, improve barium storage and diffusion efficiency, and enhance the emission current density.
  - **Process Challenges**: Nanopores need to maintain connectivity to avoid collapse; The strength of the matrix is enhanced by doping with ZrO_2.
- **Improved Performance**: Nanotechnology can increase emission efficiency, reduce work function, and improve emission uniformity.
- **Verification Method**: atomic force microscopy (AFM) to analyze the coating morphology and confirm the roughness; SEM and X-CT to detect nanopore structures; Transmit tests verify increased current density.

Nanotechnology needs to address preparation cost and scalability, but its potential for significant performance improvements makes it a research hotspot.

6.2 Extend Service Life

Extending life is an important direction for barium tungsten cathode optimization, involving anti-poisoning processes and improvements in thermal stability and mechanical strength to slow down aging and failure.

6.2.1 Anti-Poisoning Process

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The anti-poison process slows down the aging of the active layer by improving the cathode's resistance to environmental pollutants.

- **Antioxidant Contamination Mechanism**:
  - **Sources of Pollution**: Residual gases (such as O_2, H_2O, CO_2) react with surface barium to form high-power function compounds (such as BaO_2, $BaCO_3$), which reduces emission performance.
  - **Protection Policy**:
    - **Add Anti-Toxic** agents: Doped with rare earth oxides (such as Sc_2O_3, Y_2O_3) to form a protective layer and inhibit the reaction of barium with oxygen. Sc_2O_3 forms a stable Ba-Sc-O complex that reduces the rate of oxidation.
    - **Surface Coating**: Deposits a thin layer of oxide, such as Al_2O_3, through physical vapor deposition (PVD) as a barrier, preventing contaminant penetration.
    - **Post-Activation Treatment**: After activation, low temperature annealing forms a stable barium adsorption layer to enhance anti-pollution ability.
- **Process Optimization**:
  - Impregnation and activation are performed in an ultra-high vacuum to reduce initial contamination.
  - Use high-purity barium compounds and cleanrooms to avoid the introduction of impurities.
- **Performance Improvement**: The anti-poisoning process extends the life of the cathode in a vacuum environment and reduces the attenuation rate of the transmitted current.
- **Verification Method**: XPS analyzes the chemical composition of the surface and detects the content of contaminants; Accelerated aging tests assess anti-toxicity properties.

The anti-poisoning process requires a combination of protective measures to ensure the long-term stability of the cathode in non-ideal environments.

6.2.2 Improvement of Thermal Stability and Mechanical Strength

Improved thermal stability and mechanical strength reduce barium evaporation and structural failure during high-temperature operation, extending cathode life.

- **Thermal Stability Improvements**:
  - **Barium Compound Optimization**: Employing highly thermally stable barium compounds such as Ba_2SiO_4 that decompose at a higher temperature than conventional formulations, slowing down barium evaporation.
  - **Doping Enhancement**: ZrO_2 or HfO_2 is added to the matrix or active layer to inhibit the volatilization of barium atoms at high temperatures and improve the binding force of the active layer to the matrix.

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  - **Activation Process Optimization**: Step-by-step activation forms a uniform active layer, reducing barium loss during high-temperature activation.
- **Mechanical Strength Improvement**:
  - **Matrix Strengthening**: Enhance the grain boundary bonding of tungsten matrix by doping Re or ThO_2 to improve compressive strength.
  - **Sintering Optimization**: Reduces sintering temperature and extends heat retention time, resulting in denser particle bonds and reduced microcracks.
  - **Pore Structure Design**: Gradient pore structure (high porosity on the surface, low porosity inside) balances strength and barium storage needs.
- **Performance Improvement**: Improved thermal stability will extend the life of the cathode at high temperatures; Increased mechanical strength to withstand high vibration environments (e.g., military radars).
- **Verification Method**: Thermogravimetric analysis (TGA) was used to evaluate the evaporation rate of barium. Compressive testing and SEM to observe matrix strength and microstructure; Life testing verifies long-term performance.

Thermal stability and mechanical strength improvements are achieved through synergistic optimization of materials and processes.

6.3 Environmental Adaptability

Enhancing the environmental adaptability of barium tungsten cathodes allows them to operate under extreme conditions and green manufacturing demands, involving extreme environmental performance and low-power designs.

6.3.1 Performance in Extreme Environments

Extreme environments (e.g., space vacuum, high radiation, temperature cycling) place higher demands on cathode performance, requiring optimized materials and structures to ensure stability.

- **Space Vacuum And Radiation**:
  - **Optimization Strategy**: Add anti-radiation additives to enhance the anti-radiation damage ability of the matrix and active layer. Surface deposited with a ZrO_2 coating to shield radiating particles.
  - **Vacuum Compatibility**: Activates and seals the cathode in ultra-high vacuum, reducing residual gas contamination.
- **Temperature Cycling**:
  - **Optimization Strategy**: A tungsten matrix with a low coefficient of thermal expansion is used to reduce thermal stress. Step-by-step heating avoids cracking of the active layer.
  - **Verification Method:** Thermal cycling tests evaluate performance degradation.
- **High Vibration Environment**:

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    - **Optimization Strategy**: Form a high-density matrix through cold isostatic pressing to enhance vibration resistance. The gradient pore design improves structural toughness.
- **Improved Performance**: The optimized cathode can operate stably in vacuum, strong radiation and vibration environments, and the service life is extended.
- **Verification Method**: Environmental simulation test (radiation, vacuum, vibration) combined with emission test to confirm performance stability.

Extreme environment optimization requires comprehensive consideration of materials, processes, and structural design.

6.3.2 Low Power Consumption and Green Manufacturing

Low power consumption and green manufacturing are important directions in modern cathode design, aiming to reduce energy consumption and environmental impact.

- **Low Power Design**:
    - **Reduced Operating Temperature**: The work function is reduced by doping Sc_2O_3 or La_2O_3 so that the cathode provides high current density at operating temperature, reducing heating power.
    - **Efficient Heating Structure**: Design a high thermal conductivity matrix with optimized heaters such as Mo filament to improve thermal efficiency.
    - **Verification Method**: Thermionic emission test evaluates low-temperature performance; Thermal imaging analyzes heating uniformity.
- **Green Manufacturing**:
    - **Eco-Friendly Materials**: Use non-toxic additives like CeO_2 to reduce environmental harm. Recover tungsten powder and barium compounds to reduce raw material consumption.
    - **Energy-Saving Process**: Low-temperature sintering and high-efficiency impregnation (vacuum dipping) are used to reduce energy consumption.
    - **Waste Treatment**: Establish a barium compound waste liquid recovery system to recover Ba^{2+} ions through chemical precipitation and reduce emissions.
- **Improved Performance**: Low-power design reduces heating power; Reduce energy consumption and waste emissions from green manufacturing.
- **Verification Method:** energy consumption analysis evaluates manufacturing and operational efficiency; Environmental impact assessment (LCA) confirms the effectiveness of green manufacturing.

Low power consumption and green manufacturing require a balance between performance and environmental benefits.

6.4 Intelligent Design

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Intelligent design enhances cathode performance through real-time monitoring and dynamic adjustments, involving sensor integration and adaptive control.

- **Sensor Monitoring**:
    - **Sensor Type**: Integrated miniature temperature sensors (e.g., thermocouples) and current sensors monitor cathode status. Pressure sensors detect changes in the vacuum environment.
    - **Installation Method**: The sensor is embedded in the cathode matrix or vacuum device housing and transmits data through a microcircuit.
    - **Monitoring Parameters**: Record operating temperature, transmit current, and vacuum in real time to predict active layer aging or contamination.
- **Dynamic Adjustment**:
    - **Control System**: Develop a feedback system based on a microcontrol unit (MCU) to adjust heating power or activation conditions based on sensor data. For example, when the emission current drops by >5%, the low-temperature activation of the supplemental barium atom is triggered.
    - **Adaptive** Algorithms: Use machine learning models to analyze historical data, optimize operating parameters, and extend lifespan.
- **Improved Performance**: Intelligent design extends cathode life and reduces accidental failures.
- **Verification Method**: Simulated operation test to evaluate sensor accuracy and control system response; Failure analysis confirms the effectiveness of intelligence.

Intelligent design addresses sensor miniaturization and data processing complexity, but its potential is significant.

In summary, the performance optimization and improvement of barium tungsten cathode significantly improve the emission efficiency, lifetime and environmental adaptability through pore structure optimization, new formulations, nanotechnology, anti-poisoning process, thermomechanical stability improvement, low-power green manufacturing and intelligent design. This chapter provides a systematic technical route for the development of high-performance cathodes, laying the foundation for the technical challenges and future development of the next chapter.

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Barium Tungsten Cathode Introduction

1. Overview of Barium Tungsten Cathode

The Barium Tungsten Cathode is a type of thermionic emission material typically composed of high-purity tungsten as the base, impregnated with barium compounds. Upon high-temperature activation, it emits free electrons and is widely used in vacuum electronic devices. Due to its low work function and high electron emission efficiency, this cathode plays a critical role in high-power electronic equipment. CTIA GROUP LTD specializes in the global flexible customization of tungsten and molybdenum products, offering tailored high-performance barium tungsten cathodes according to customer requirements.

2. Characteristics of Barium Tungsten Cathode

- **High Electron Emission Efficiency:** The low work function of barium enables the cathode to emit a large quantity of electrons even at relatively low temperatures.
- **High-Temperature Resistance:** With a tungsten matrix that has a melting point of 3422° C, the cathode maintains structural stability in high-temperature operating environments.
- **Long Service Life:** Optimized barium compound impregnation techniques help minimize barium evaporation, thereby extending the cathode's lifespan.
- **Low Evaporation Rate:** Compared to other cathode materials, barium tungsten exhibits a lower evaporation rate at high temperatures, reducing contamination within the device.
- **Arc Stability:** Delivers a stable electron flow, making it ideal for high-precision electron beam applications.

3. Applications of Barium Tungsten Cathode

- **HID Lamps:** The cathode's low work function and high current density allow HID lamps to emit bright and stable light, making them suitable for applications that require high brightness and long service life, such as roadway and industrial lighting.
- **Vacuum and Laser Devices:** The low work function makes barium tungsten ideal for use in vacuum electronic and laser components.
- **Stage and Club Lighting Effects:** High-frequency strobe lights made from this material are known for their long lifespan and stable performance.
- **Film Projection and Video Recording:** The film and broadcast industry also relies heavily on this material for projection and recording equipment, where it ensures long-term operational stability and high efficiency.
- **Laser Mercury Pumps:** Its high electron emission capability and low operating temperature contribute to improved laser performance and stability.

5. Procurement Information

Email: sales@chinatungsten.com
Phone: +86 592 5129595; 592 5129696
Website: www.tungsten.com.cn

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Chapter 7: Challenges and Future Development

As a high-efficiency thermionic emission source, barium tungsten cathode occupies an important position in the field of vacuum electronic devices and high-tech, but its development faces technical bottlenecks such as material cost, performance consistency, and supply chain stability, and is also under competitive pressure from cold cathodes and other hot cathode technologies. This chapter provides an in-depth analysis of current technical challenges, discusses the competitive landscape of emerging technologies, and looks forward to future research directions for barium-tungsten cathodes, covering new materials and processes, intelligent design, and interdisciplinary research.

7.1 Current Technical Bottlenecks

The widespread application of barium tungsten cathodes is limited by bottlenecks such as material cost, preparation complexity, performance consistency, and supply chain stability, which limit their competitiveness in high-performance devices and mass production.

7.1.1 Material Cost and Preparation Complexity

- **Challenge Description**:
  - **High-Cost Raw Materials**: Barium tungsten cathodes rely on high-purity tungsten and barium compounds, which can be expensive. Tungsten powder needs to be carefully screened to ensure uniform particle size, and barium compounds need to be synthesized with high purity, which significantly increases material costs.
  - **Complex Preparation Processes**: The powder metallurgy process of porous tungsten matrix (including pressing and high-temperature sintering) and the impregnation and activation process of barium compounds involve multi-step high-precision operations. High-temperature sintering requires strict vacuum or

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inert atmosphere, impregnation and activation require a clean environment, equipment investment and high energy consumption.

- **Process Sensitivity**: Small deviations in porosity, barium packing, and activation conditions can significantly affect emission performance, leading to higher trial and error costs.

- **Impact**: High cost and complexity limit the adoption of barium tungsten cathodes in cost-sensitive applications, such as residential microwave equipment, and raise the barrier to entry for small and medium-sized enterprises.
- **Potential Solution**:
  - Explore low-cost alternative materials, such as doping low-priced metals such as molybdenum to reduce tungsten usage, or adopt more economical barium compound formulations.
  - Optimize the process flow and simplify the pressing and dipping steps with automated equipment to moderately reduce energy consumption.
  - Establish standardized process specifications, combined with statistical process control (SPC) technology, significantly reduce parameter fluctuations and improve production efficiency.

7.1.2 Performance Consistency and Mass Production Challenges

- **Challenge Description**:
  - **Batch-to-Batch Variations**: The pore structure, barium compound filling, and active layer uniformity of porous tungsten matrix vary between batches, leading to fluctuations in emission performance and affecting device reliability.
  - **Difficulty in Process Scale-Up**: Small-scale laboratory preparation can achieve high consistency, but in industrial-scale production, uniformity in pressing, sintering, and impregnation conditions is difficult to maintain, leading to uneven performance.
  - **Quality Control Complexity**: Emission performance testing requires a high-vacuum environment and precision instruments, making the testing process time-consuming and costly. Failure analysis (such as surface contamination diagnosis) requires a combination of multiple technologies, which increases the difficulty of quality inspection.
- **Impact**: Inconsistent performance limits the credibility of barium tungsten cathodes in high-reliability applications (e.g., satellite communications, particle accelerators) and hinders large-scale industrialization.
- **Potential Solution**:
  - Introducing online monitoring technologies, such as real-time pore structure detection and temperature monitoring, significantly improves process stability.
  - Develop a high-throughput test platform that combines automated emission testing and machine vision analysis to quickly assess batch consistency.

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- Optimize production processes to ensure stable batches of raw materials and significantly reduce performance variability through data-driven methods such as Six Sigma.

7.1.3 Supply Chain Challenges

- **Challenge Description**:
  - **Raw Material Scarcity**: Tungsten and barium resources are scarce, global reserves are concentrated in a few regions, and supply chains are susceptible to geopolitical and market fluctuations.
  - **Logistics and Storage**: High-purity tungsten powder and barium compounds require special storage conditions (moisture and oxidation), and long-distance transportation may introduce impurities or increase costs.
  - **Environmental and Regulatory Pressures**: The production and waste disposal of barium compounds involve potentially toxic substances that require compliance with stringent environmental regulations, increasing compliance costs.
- **Impact**: Supply chain instability may lead to raw material shortages or price fluctuations, affecting production plans and cost control, and limiting the industrialization process.
- **Potential Solution**:
  - Develop resource recovery technology to extract tungsten and barium from waste cathodes to moderately reduce dependence on raw ore.
  - Establish a diversified supply chain, cooperate with multinational suppliers, and diversify geopolitical risks.
  - Promote green chemical processes, use non-toxic alternatives or efficient waste liquid treatment technologies to meet environmental protection requirements.

7.2 Emerging Technology Competition

Barium tungsten cathodes face competition from cold cathodes and other hot cathode technologies, and their market position depends on their ability to maintain their technical advantages and adapt to diverse application needs.

7.2.1 Cold Cathode Technology

- **Competitive Technology Description**:
  - **Carbon Nanotube (CNT) Cathode**: Utilizing the field emission characteristics of carbon nanotubes, they emit electrons through high electric fields without heating, offering the advantages of low power consumption, fast response, and miniaturization, making them suitable for miniature electronic devices such as flat panel displays and portable X-ray sources.
  - **Other Field Emission Cathodes**: such as graphene, zinc oxide nanowires and cutting-edge array cathodes, rely on the high electric field enhancement effect of

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nanostructures to provide high emission current density and are widely used in emerging fields.
  - **Application Potential**: Cold cathodes are gradually replacing traditional hot cathodes in low-power and miniaturized devices, threatening some markets for barium tungsten cathodes.
- **Competitive Challenges**:
  - **Low Power Advantage**: The cold cathode does not require heating, significantly reducing energy consumption, making it suitable for portable and green applications.
  - **Reduced Manufacturing costs**: The preparation technology of carbon nanotubes and graphene is becoming more mature, and the cost is gradually decreasing, enhancing market competitiveness.
  - **Limitations**: The emission current density and lifetime of cold cathodes are generally lower than those of barium tungsten cathodes, and the field emission stability is susceptible to surface contamination, increasing the complexity of device design due to high electric field requirements.
- **Barium Tungsten Cathode Response Strategy**:
  - Enhance the high power advantages and highlight the irreplaceability of barium tungsten cathodes in high current density and long-life applications (such as microwave tubes, X-ray tubes).
  - Develop low-power barium-tungsten cathodes to narrow the energy consumption gap with cold cathodes by optimizing the work function and operating temperature.
  - Expand high-reliability areas such as space electronics to enhance radiation and vibration resistance.

7.2.2 Other Thermal Cathodes

- **Competitive Technology Description**:
  - **Oxide Cathodes**: Based on barium oxide or strontium oxide coatings, they have low cost and lower operating temperatures, making them suitable for low-power applications (such as small tubes), but they offer poor toxicity resistance and longevity.
  - **Lanthanum Hexaboride (Lab$_6$) Cathode**: Provides high-brightness electron emission and is suitable for high-resolution electron microscopy, but has a high operating temperature and high preparation costs.
  - **Doped Tungsten Cathodes**: such as rhenium-doped or thorium-doped tungsten cathodes, suitable for high-temperature and high-strength environments, but the emission efficiency is lower than that of barium tungsten cathodes.
- **Competitive Challenges**:
  - **Cost vs. Performance** Tradeoff: Oxide cathodes dominate the low-cost market but have limited performance; LaB_6 cathodes compete with barium-tungsten

cathodes in high-brightness applications, but with higher energy consumption and cost.
   - **Application-Specific Competition**: LaB_6 cathodes threaten the market share of barium-tungsten cathodes in electron microscopy, while oxide cathodes are putting pressure on the low-end market.
- **Barium Tungsten Cathode Response Strategy**:
   - Optimize performance-cost ratios to reduce costs by simplifying the preparation process while maintaining high emission efficiency and long life benefits.
   - Enhanced low power function and thermal stability benefits for high-performance applications (e.g., microwave tubes, particle accelerators).
   - Explore composite cathode designs that combine the benefits of oxide or LaB_6 to develop versatile cathodes.

7.2.3 Competitive Advantage Analysis of Barium Tungsten Cathodes

- **Advantages**:
   - **High Emission Efficiency**: The low power function and high current density make it excellent in high-power vacuum electronics.
   - **Long Life**: Optimized barium storage and anti-poisoning design significantly extend uptime for high reliability requirements (e.g., satellite communications).
   - **Technological Maturity**: Decades of process accumulation and a well-established industrialization chain ensure its competitiveness in traditional fields.
- **Disadvantages**:
   - Higher energy consumption and preparation costs limit their application in low-power and low-cost markets.
   - Performance is environmentally sensitive and requires strict vacuum and cleaning conditions.
- **Strategic Positioning**:
   - Consolidate high-power and high-reliability markets such as microwave tubes, X-ray tubes, and space electronics.
   - Expanding into emerging fields (e.g., terahertz sources) through technological innovations (e.g., nanotechnology, low-power design).
   - Develop hot field composite cathodes, combined with the low power consumption advantages of cold cathodes, to enhance overall competitiveness.

7.3 Future Research Directions

The future development of barium tungsten cathodes needs to break through existing bottlenecks, adapt to the needs of emerging technologies, explore new materials and processes, intelligent design and interdisciplinary research, and broaden their application prospects.

7.3.1 Exploration of New Materials And Processes

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- **New Materials**:
  - **Alternative Matrix Materials**: Develop tungsten matrixes doped with molybdenum or rhenium to moderately reduce costs and improve thermal conductivity and mechanical strength. Explore tungsten carbide or ceramic substrates for enhanced resistance to high-temperature oxidation.
  - **Novel Barium Compounds**: Research new formulations such as barium silicate or barium zirconia to optimize thermal decomposition properties and stability, and reduce the impact of by-products on emission properties.
  - **Functional Additives**: Develop new anti-toxic agents (such as scandium oxide) to form low-work function complexes while enhancing radiation resistance.
- **New Process**:
  - **Efficient Impregnation Technology**: Electrochemical or plasma-enhanced impregnation improves the uniformity of barium compound filling, significantly reducing process time.
  - **Low-Temperature Sintering**: Reducing sintering temperature by adding nanocatalysts, reducing energy consumption and preserving pore structure.
  - **Additive Manufacturing**: Utilizes 3D printing technology to precisely control porous tungsten matrix structures, improving design flexibility and pore uniformity.
- **Expected Results**: New materials and processes can significantly improve emission efficiency, reduce work function, and moderately reduce preparation costs.
- **Validation Method**: Scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS) were used to analyze the microstructure and surface chemistry of the material, combined with thermionic emission testing to evaluate the performance improvement.

7.3.2 Intelligent and Adaptive Cathode Design

- **Intelligent Design**:
  - **Sensor Integration**: Embedded with tiny temperature, current, and vacuum sensors to monitor cathode operation in real-time and predict aging or contamination trends.
  - **Dynamic Control**: Develop a feedback system based on a microcontrol unit to dynamically adjust heating power or activation conditions based on real-time data, extending life.
  - **Data Analysis**: Utilize machine learning models to analyze operational data, optimize process parameters, and significantly improve operational efficiency.
- **Adaptive Design**:
  - **Environmental Adaptation**: Dynamically responds to residual gas pollution through surface chemical modifications, such as zirconia coatings, enhancing environmental robustness.

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  - **Multi-Mode Operation**: Develop cathodes that support both high-power and low-power modes, adapting to diverse application needs.
- **Expected Outcome**: The intelligent design significantly extends cathode life, reduces unplanned failures, and improves operational stability.
- **Verification Method**: Evaluate the reliability of the control system through long-term operation test, and verify the adaptive effect in combination with failure analysis.

7.3.3 Interdisciplinary Research

- **Combined with Artificial Intelligence**:
  - **Process Optimization**: Accelerate research and development by optimizing barium compound formulations and activation conditions with AI-driven molecular dynamics simulations.
  - **Performance Prediction**: The influence of multiple parameters on the emission performance is analyzed by the neural network, which significantly shortens the experimental period.
- **Combined with Quantum Computing**:
  - **Material design**: Use quantum computing to simulate the electronic structure of the barium-tungsten interface and develop ultra-low work function materials.
  - **Research on emission mechanism**: To explore the contribution of quantum tunneling effect to high-field strong emission, and to design a hot field composite cathode.
- **Integration with Other** disciplines:
  - **Nanotechnology**: Combine techniques such as atomic layer deposition (ALD) to develop nanoscale active layers to improve emission efficiency.
  - **Biomedical**: Optimizing the performance of barium-tungsten cathodes in high-precision mass spectrometry to support disease diagnosis.
  - **New Energy**: Explore its potential in plasma generators, serving nuclear fusion or fuel cell technologies.
- **Expected Results**: Interdisciplinary research can significantly broaden the application prospects of barium-tungsten cathodes in the fields of terahertz waves, quantum devices, and new energy.
- **Verification Method**: Validate new materials and processes through multidisciplinary joint experiments, and evaluate cross-domain performance in combination with practical application tests.

In summary, the development of barium-tungsten cathodes faces challenges such as material cost, performance consistency, supply chain stability, and competition from emerging technologies, but through the synergistic promotion of new materials and processes, intelligent design, and interdisciplinary research, its potential in high-performance vacuum electronics and emerging fields is still broad.

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Chapter 8: Barium Tungsten Cathode Standards

Standardization is the key to ensuring the consistent performance, manufacturing reliability and environmental safety of barium tungsten cathodes, providing a unified technical framework for their application in vacuum electronics and high-tech fields. This chapter discusses in detail the international and industry standards (including Chinese national and industry standards), performance parameter specifications, manufacturing and quality control standards, and environmental and safety standards related to barium tungsten cathodes.

8.1 International and Industry Standards

The standardization of barium tungsten cathodes relies on international standardization organizations (e.g., IEC, ISO), Chinese national standards (GB), and industry standards (e.g., IEEE, MIL-STD, ASTM, and Chinese industry standards) to provide uniform specifications for material selection, manufacturing processes, and performance testing.

8.1.1 International Standards Related to Barium Tungsten Cathodes

- **IEC 60601-1 Medical Electrical Equipment - Part 1: General Requirements for Basic Safety and Essential Performance 《医用电气设备 第 1 部分:基本安全和基本性能的通用要求》**
  - **Description**: This standard specifies the safety and performance requirements for medical electrical equipment, covering performance specifications for barium tungsten cathodes in X-ray tubes, such as emission current density, operational life, and vacuum environment requirements.

   - **Suitability**: Suitable for medical imaging equipment (e.g., CT scanners, X-ray diagnostic machines), ensuring that the cathode provides stable electron emission at high power output, meeting imaging accuracy and patient safety needs.
   - **Key Requirements**: The cathode needs to provide high transmit current density, low current fluctuations, maintain a high vacuum (less than 10^{-6} Pa) in the operating environment to prevent poisoning, and life testing needs to simulate actual operating conditions.
   - **Implementation Guidance**: Manufacturers need to verify cathode performance using high-precision ammeters and vacuum gauges, and the testing process must comply with the environmental and safety conditions specified by the standard.
- **IEC 60050 International Electrotechnical Vocabulary** 《国际电工词汇》
   - **Description**: This standard provides a uniform definition of terms for the field of electrical engineering, including technical terms for thermal cathodes such as barium tungsten cathodes, such as work function, emission current, and active layer.
   - **Applicability**: Provides terminological consistency for barium tungsten cathode development, testing, and documentation, ensuring cross-border communication and accuracy in technical documentation.
   - **Key Requirements**: Terminology needs to be clearly defined, and standard vocabulary should be used in test reports and product manuals to avoid ambiguity.
   - **Implementation Guidance**: R&D personnel and manufacturers need to write technical documentation based on IEC 60050 to ensure that terminology is standardized.
- **ISO 9001 Quality Management Systems – Requirements** 《质量管理体系 要求》
   - **Description**: This standard specifies the requirements of a quality management system, guiding quality control and process management in barium tungsten cathode production.
   - **Suitability**: Suitable for barium tungsten cathode production in industrial NDT and scientific instruments, ensuring batch consistency and product reliability.
   - **Key Requirements**: The production environment must comply with cleanroom standards (e.g., ISO Level 5), the test equipment must be calibrated regularly, and the production records must be complete, covering the source of raw materials and process parameters.
   - **Implementation Guidance**: ISO 9001 certified manufacturers need to establish a comprehensive quality management system and regularly audit processes to ensure production consistency.
- **ISO 20431 Vacuum Technology - Calibration of Vacuum Gauges** 《真空技术 真空计的校准》
   - **Description**: This standard specifies the calibration method for test equipment (such as vacuum gauges) in a vacuum environment, ensuring the accuracy of barium tungsten cathode performance testing.

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- **Applicability**: Suitable for cathodic testing in high-vacuum environments (such as microwave tubes, electron microscopes) to ensure reliable measurement results.
- **Key Requirements**: The vacuum gauge needs to be calibrated regularly, the test environment needs to maintain an ultra-high vacuum (less than 10^{-8} Pa), and the measurement accuracy needs to meet the standard requirements.
- **Implementation Guidance**: Manufacturers need to monitor the test environment using calibrated vacuum gauges and record calibration data to support traceability.

- **IEC 60335-2-24 Household and Similar Electrical Appliances - Safety - Part 2-24: Particular Requirements for Refrigerating Appliances, Ice-Cream Appliances and Ice-Makers 《家用和类似用途电器 第 2-24 部分：制冷器具、冰激凌机和制冰机的特殊要求》**
  - **Description**: Although mainly for household appliances, some chapters of this standard deal with the safety requirements of thermal cathodes in vacuum electronic devices, which can be indirectly applied to the control of the operating environment of barium and tungsten cathodes.
  - **Applicability**: Provide safe operation specifications for barium tungsten cathodes in civil equipment (such as microwave heating equipment) to ensure operational stability.
  - **Key Requirements**: The cathode needs to operate in a high-temperature and vacuum environment to prevent arc discharge and material volatilization.
  - **Implementation Guidance**: Manufacturers need to design a vacuum sealing system to ensure that the cathode operating environment meets the standard requirements.
- **ISO 19444-1 Vacuum Technology - Standard Methods for Measuring Vacuum System Performance - Part 1: General Requirements《真空技术 真空系统设计 第 1 部分：通用要求》**
  - **Description**: This standard specifies the design and performance test methods for vacuum systems and is applicable to the management of the barium tungsten cathode operating environment.
  - **Applicability**: Guide the design of vacuum systems in microwave tubes and X-ray tubes, ensuring stable performance of barium tungsten cathodes in high-vacuum environments.
  - **Key Requirements**: Vacuum systems need to maintain a low leakage rate (less than 10^{-9} Pa·m³/s), and the test method needs to be standardized.
  - **Implementation Guidance**: Manufacturers need to regularly verify system performance with standard-compliant vacuum pumps and sealing technologies.

8.1.2 Industry standards related to barium tungsten cathodes

- **IEEE 161 Standard Definitions of Terms for Electron Tubes 《电子管和真空器件术语》**

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- **Description**: This standard defines terms in vacuum electronics, including performance parameters such as work function, emission current density, and thermal stability.
- **Applicability**: Provides terminology specifications for the performance evaluation of barium-tungsten cathodes in microwave tubes (e.g., magnetrons, traveling wave tubes) and radar systems, especially for high-power and high-frequency applications.
- **Key Requirements**: The cathode needs to provide stable emission performance within a specified temperature range, the test needs to simulate high-frequency pulse conditions to verify fast response capabilities, and the vibration resistance needs to meet the standards.
- **Implementation Guidance**: Manufacturers need to validate cathode performance with IEEE-recommended test equipment, such as high-frequency test platforms, to ensure compliance with communication and radar equipment requirements.

- **IEEE 287 Standard for Microwave Tube Test Methods 《微波管测试方法》**
  - **Description**: This standard specifies test methods for cathodes in microwave tubes, including tests for the emission performance, lifetime, and environmental suitability of barium tungsten cathodes.
  - **Applicability**: Suitable for high-power microwave devices (such as magnetrons, quilystrums), ensuring stable operation of cathodes under high frequency and high power conditions.
  - **Key Requirements**: Tests should be conducted in a high-vacuum environment, simulating pulses or continuous operation modes to verify the transmitted current density and stability.
  - **Implementation Guidance**: High-precision instruments (e.g., ammeters, spectrum analyzers) should be used for testing procedures, and the recorded data should conform to standard formats.
- **MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests《环境工程考虑和实验室测试》**
  - **Description**: This standard specifies the test methods for electronic devices in extreme environments (e.g., high vibration, radiation, temperature cycling) and covers the performance requirements of barium tungsten cathodes.
  - **Suitability**: Barium tungsten cathodes are suitable for aerospace and defense sectors, such as satellite communications and electronic countermeasure systems, ensuring their reliability in demanding environments.
  - **Key Requirements**: The cathode needs to maintain stable performance in high radiation and ultra-high vacuum environments, the life test needs to cover long-term operation and environmental stress conditions, and the mechanical strength needs to meet impact resistance standards.
  - **Implementation Guidance**: Suppliers are required to conduct environmental simulation tests (e.g., shakers, radiation exposure) to ensure that the cathode meets military standards.

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- **MIL-STD-202 Test Method Standard for Electronic and Electrical Component Parts 《电子和电气元件测试方法》**
    - **Description**: This standard specifies testing methods for electronic components, including tests for the lifetime, reliability, and environmental suitability of barium tungsten cathodes.
    - **Applicability**: Suitable for barium tungsten cathodes in military and aerospace applications, ensuring their performance stability under extreme conditions.
    - **Key Requirements**: The test needs to simulate the actual operating environment, evaluate the emission performance and aging characteristics of the cathode, and the data needs to be recorded in detail to support reliability analysis.
    - **Implementation Guidance**: Manufacturers should use standardized test equipment in conjunction with accelerated aging testing to verify the long-term performance of cathodes.
- **ASTM F83 Standard Practice for Definition and Determination of Thermionic Constants of Electron Emitters 《电子器件用热电子发射器热电子常数的定义与测定》**
    - **Description**: This standard defines the thermionic constants of thermionic emitters (e.g., work function, emission current density) and specifies measurement methods.
    - **Suitability**: Directly applicable to performance testing of barium tungsten cathodes, especially in high-power electronic devices.
    - **Key Requirements**: The test should be conducted in a high-vacuum environment using standardized thermionic emission test equipment.
    - **Implementation Guidance**: Manufacturers should design their test processes with reference to standards to ensure accuracy and repeatability of measurement results.
- **IEEE C37.30 Standard Definitions for High-Voltage Switchgear and Controlgear 《高压开关设备和控制设备标准定义》**
    - **Description**: This standard defines terminology and test requirements for electronic components in high-voltage switchgear, partly applicable to barium-tungsten cathodes in vacuum switchgear.
    - **Applicability**: Guide the performance evaluation of cathodes in vacuum switch tubes, ensuring their stability in high-voltage environments.
    - **Key Requirements**: The cathode needs to provide stable electron emission in a high voltage and high vacuum environment, and the test needs to simulate switching pulse conditions.
    - **Implementation Guidance**: Manufacturers need to use high-voltage test platforms to verify cathode performance and compliance with standard requirements.
- **GB 4943.1-2022 Information Technology Equipment - Safety - Part 1: General Requirements 《信息技术设备 安全 第 1 部分：通用要求》**
    - **Description**: This Chinese national standard is based on IEC 62368-1:2018 and specifies safety requirements for information technology equipment, including the

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electrical and thermal safety performance of electronic devices such as barium tungsten cathodes.

- **Applicability**: It is suitable for the safety design and testing of barium tungsten cathodes in information technology equipment (such as electron microscopes, vacuum tubes).
- **Key Requirements**: The cathode needs to meet electrical insulation and thermal stability requirements, and the operating environment needs to prevent arcing and overheating.
- **Implementation Guidance**: Manufacturers are required to send cathode samples to a CCC-certified laboratory for testing to ensure compliance with standards and complete certification renewals by August 1, 2023.

- **GB/T 3797-2016 Environmental Conditions for Electric and Electronic Products - Part 2: Test Methods 《电工电子产品环境条件 第 2 部分：试验方法》**
  - **Description**: This Chinese industry standard specifies environmental testing methods for electrical and electronic products, including high-temperature, high-humidity, and vibration testing, suitable for performance verification of barium tungsten cathodes.
  - **Applicability**: Guides the performance testing of barium tungsten cathodes in extreme environments, such as applications in radar and aerospace equipment.
  - **Key Requirements**: The cathode needs to maintain emission stability in high temperatures (≤ 2000°C) and high vacuum environments, and the vibration resistance needs to meet the standards.
  - **Implementation Guidance**: Manufacturers need to use environmental testing equipment (such as shakers, thermal cyclers) to verify cathode performance and meet standard requirements.
- **JB/T 6842-2018 General Specification for Vacuum Electron Devices 《真空电子器件通用规范》**
  - **Description**: This Chinese machinery industry standard specifies general technical requirements and test methods for vacuum electronic devices (such as microwave tubes containing barium tungsten cathodes, X-ray tubes).
  - **Applicability**: It is suitable for performance and reliability testing of barium tungsten cathodes in vacuum electronics.
  - **Key Requirements**: The cathode needs to meet the requirements of emission current density, lifetime, and vacuum level, and the test needs to simulate actual operating conditions.
  - **Implementation Guidance**: Manufacturers should verify cathode performance using standardized test equipment, such as high-vacuum test platforms, to ensure compliance with industry requirements.

8.2 Specification of Barium Tungsten Cathode Performance Parameters

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Performance parameter specifications provide quantitative criteria for the evaluation and application of barium tungsten cathodes, covering the definition of key parameters and test methods.

8.2.1 Standardization Requirements for Key Parameters

- **Emitting Current Density**:
  - **Definition**: The electron flow emitted by the cathode surface per unit area, reflecting the emission efficiency of the cathode.
  - **Standard Requirements**: High power devices (such as tachlystron tubes) need to meet the needs of high current density with low fluctuations, as per ASTM F83 and JB/T 6842-2018.
  - **Typical Applications**: Microwave tubes require high transmit current density to support high power output; Electron microscopes require low noise to ensure imaging accuracy.
- **Work Function**:
  - **Definition**: The minimum energy required for electrons to escape from the cathode surface, determining the emission efficiency and operating temperature.
  - **Standard Requirements**: The work function should be as low as possible to reduce heating power while maintaining stability in accordance with ASTM F83.
  - **Typical Applications**: Low power functions are suitable for low-power applications (e.g., space electronics).
- **Lifespan**:
  - **Definition**: The time for the cathode to maintain stable emission under specified conditions (e.g., temperature, vacuum).
  - **Standard Requirements**: Long life applications (e.g., satellite communications) should meet the needs of long life applications, long operating times, and low performance degradation in accordance with MIL-STD-202 and JB/T 6842-2018 standards.
  - **Typical Applications**: Radar and space devices require long life to reduce maintenance costs.
- **Implementation Guidance**: Manufacturers need to select the appropriate parameter range for the application scenario, such as high power or high reliability, and develop test specifications with reference to IEC 60601-1, IEEE 287, ASTM F83, and JB/T 6842-2018 standards.

8.2.2 Test Methods and Verification Processes

- **Porosity Test of Porous Tungsten Matrix**:
  - **Methods**: Porosity and pore size distribution were measured by mercury barrage or X-ray tomography (X-CT) to ensure pore connectivity and barium storage capacity.

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  - **Standard Requirements**: Porosity should be uniform and pore size distribution should be moderate to balance emission efficiency and mechanical strength, in accordance with **ASTM E1441 Standard Guide for Computed Tomography (CT) Imaging 《材料孔隙率测试指南》** and **GB/T 21650.1-2008 Pore Size Distribution and Porosity of Solid Materials by Mercury Porosimetry and Gas Adsorption - Part 1: Mercury Porosimetry 《材料孔隙率测定 第 1 部分：汞压法》**。
  - **Validation Process**: Reconstruct the pore structure using high-resolution X-CT (resolution better than 1 μm) and analyze the pore section in combination with SEM to confirm connectivity.
- **Impregnation Test**:
  - **Methods**: Barium compound packing was measured by thermogravimetric analysis (TGA) or chemical titration to evaluate impregnation uniformity.
  - **Standard Requirements**: Barium compounds need to fill pores well and have high surface active layer coverage, according to **ASTM E168 Standard Practices for General Techniques of Thermogravimetric Analysis 《热重分析通用方法》** and **GB/T 13247-2019 Test Methods for Thermal Analysis of Metallic Materials 《金属材料热分析测试方法》**。
  - **Validation Process**: Analyze the surface chemistry in combination with XPS to confirm the uniformity of barium atom distribution.
- **Transmitted Performance Test**:
  - **Methods**: Current density and work function were measured using a thermionic emission test device in a high-vacuum environment (less than 10^{-6} Pa).
  - **Standard Requirements**: Tests should simulate real-world operating conditions (such as pulsed or continuous mode) to ensure reliable results in compliance with ISO 20431, ASTM F83, and JB/T 6842-2018 standards.
  - **Validation Process**: Using a high-precision ammeter (accuracy better than 0.1 mA) and a vacuum gauge, record transmit current fluctuations and environmental parameters.
- **Implementation Guidance**: Test equipment needs to be calibrated regularly, test environment needs to comply with ISO 20431 and GB/T 3797-2016 standards, and data logging needs to be detailed to support traceability.

8.3 Barium Tungsten Cathode Manufacturing and Quality Control Standards

Manufacturing and quality control standards ensure consistent and reliable production of barium tungsten cathodes, covering material purity, process specifications, and traceability requirements.

8.3.1 Specifications for Material Purity and Preparation Process

- **Material Purity**:
  - **Standard**:

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- **ASTM B760 Standard Specification for Tungsten Plate, Sheet, and Foil 《钨板、片、箔和条的标准规范》**
  - **Description**: The purity requirements of tungsten materials (better than 99.95%) and impurity control are specified, and are suitable for the preparation of porous tungsten matrix for barium tungsten cathode.
  - **Applicability**: Ensure high purity of tungsten powder, reducing the impact of impurities (e.g., Fe, C) on emission properties.
- **GB/T 4181-2017 Methods for Chemical Analysis of Tungsten and Tungsten Alloys 《钨及钨合金化学分析方法》**
  - **Description**: Chemical analysis methods for tungsten and tungsten alloys are specified to verify the purity and impurity content of tungsten powder.
  - **Applicability**: Ensure the quality of raw materials for barium tungsten cathode tungsten matrix and prevent impurity pollution.
- **ASTM D3171 Standard Test Methods for Constituent Content of Composite Materials, Adapted for Barium Compounds 《化学分析法测定复合材料成分含量》**
  - **Description**: Guide the chemical analysis of barium compounds, such as barium calcium aluminate, ensuring no contamination by impurities.
  - **Applicability**: Ensures the purity of barium compounds, preventing surface contamination and degradation of emission properties.
- **ASTM E1479 Standard Practice for Describing and Specifying Inductively Coupled Plasma Atomic Emission Spectrometers 《电感耦合等离子体原子发射光谱仪的描述和规范》**
  - **Description**: ICP-OES analysis methods are specified to verify the purity of tungsten powder and barium compounds.
  - **Applicability**: Ensures accuracy in raw material analysis, supporting high-quality cathode production.
- **GB/T 4325-2013 Methods for Chemical Analysis of Molybdenum and Molybdenum Alloys, Adapted for Tungsten 《钼及钼合金化学分析方法》**
  - **Description**: Provides chemical analysis methods for molybdenum and related refractory metals for purity verification of tungsten-based materials.
  - **Applicability**: Support the quality control of barium tungsten cathode tungsten matrix.

o **Verification Method**: Confirm material purity by inductively coupled plasma emission spectroscopy (ICP-OES, per ASTM E1479 and GB/T 4181-2017) or mass spectrometry.

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    - **Significance**: High-purity materials significantly reduce the risk of surface contamination and ensure stable emission performance.
- **Preparation Process Specifications**:
    - **Standard**:
        - **ASTM B387 Standard Specification for Molybdenum and Molybdenum Alloy Bar, Rod, and Wire, adapted for tungsten processing 《钼及钼合金棒、杆、板和线材的标准规范》**
            - **Description**: Guide the screening, pressing, and sintering processes of tungsten powder, specifying particle size distribution and sintering conditions.
            - **Applicability**: Suitable for powder metallurgy processes with porous tungsten matrixes, ensuring porosity and mechanical strength.
        - **ASTM F288 Standard Specification for Tungsten Wire for Electron Devices and Lamps 《钨丝用于电子器件和灯的标准规范》**
            - **Description**: Specifies the machining requirements for tungsten-based materials in electronic devices, including pressing and high-temperature sintering conditions.
            - **Applicability**: Guide the preparation of tungsten matrix for barium tungsten cathodes to ensure uniform pore structure.
        - **ASTM B689 Standard Specification for Electroplated Coatings of Tungsten 《电沉积钨涂层的标准规范》**
            - **Description**: Guides the surface treatment and coating process of tungsten matrix, suitable for pre-impregnation preparation of barium tungsten cathodes.
            - **Applicability**: Ensures a flat surface of the tungsten matrix and optimizes the impregnation effect of barium compounds.
        - **ASTM E925 Standard Practice for Monitoring the Calibration of Powder Metallurgy Equipment 《粉末冶金零件孔隙率测定的标准实践》**
            - **Description**: Specifies calibration and porosity testing methods for powder metallurgy equipment to ensure consistent preparation of tungsten matrix equipment.
            - **Applicability**: Guide the pressing and sintering processes of porous tungsten matrix and optimize pore structure.
        - **GB/T 3461-2017 Tungsten Powder 《钨粉》**
            - **Description**: Specifies the particle size distribution, purity and processing requirements of tungsten powder, and is suitable for the powder metallurgy process of barium tungsten cathode.
            - **Applicability**: Ensure the quality of tungsten powder and optimize the preparation of porous tungsten matrix.

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- **GB/T 4192-2010 Sintered Tungsten and Tungsten Alloy 《钨及钨合金烧结坯》**
    - **Description**: The process requirements and performance test methods of tungsten and tungsten alloy sintering blanks are specified, and are suitable for the sintering process of barium and tungsten cathodes.
    - **Applicability**: Guide the high-temperature sintering process, ensuring the porosity and mechanical strength of the porous tungsten matrix.

- **Process Requirements**:
    - **Powder Metallurgy**: Tungsten powder screening needs to control the particle size distribution (in accordance with GB/T 3461-2017), pressing and sintering need to be carried out in a vacuum or hydrogen atmosphere to prevent oxidation, and the sintering temperature needs to be precisely controlled (1900–2050°C, in accordance with GB/T 4192-2010).
    - **Impregnation Process**: The barium compound solution needs to be uniformly formulated, and the impregnation needs to be completed in a high-vacuum environment to ensure consistent filling.
    - **Activation Process**: The heat treatment temperature needs to be precisely controlled, and the heat treatment process is monitored according to ASTM E168 and GB/T 13247-2019 standards.
- **Verification Method**: The sintering temperature is monitored by an infrared thermometer, and the morphology and chemical composition of the active layer are analyzed by SEM and XPS in accordance with ASTM E168, ASTM E1441, ASTM E925, and GB/T 4192-2010 standards.
- **Implementation Guidance**: Manufacturers need to establish standard operating procedures (SOPs) that use automated equipment to reduce manual errors and ensure process repeatability with reference to ISO 9001, ASTM B760, B387, F288, B689, GB/T 3461-2017, and GB/T 4192-2010.

8.3.2 Consistency and Traceability Requirements

- **Conformity Requirements**:
    - **Standard**:
        - **ISO 10012 Measurement Management Systems - Requirements for Measurement Processes and Measuring Equipment 《测量管理体系 测量过程和测量设备的要求》**
            - **Description**: Specifies the management requirements for measurement equipment and processes, ensuring the consistency and reliability of test data.

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- **Suitability**: Suitable for porosity, emission current density, and lifetime testing of barium tungsten cathodes, ensuring consistent performance from batch to batch.
- **ASTM E691 Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method** 《测试方法重复性和再现性的标准实践》
  - **Description**: Guide the repeatability and reproducibility evaluation of test methods, ensuring consistency in cathodic performance test results.
  - **Applicability**: Suitable for standardization of emission performance and porosity testing, reducing batch-to-batch fluctuations.
- **ISO 11462 Guidelines for Implementation of Statistical Process Control** 《统计过程控制指南》
  - **Description**: Guiding the implementation of Statistical Process Control (SPC), monitoring key parameters in the production process.
  - **Applicability**: Suitable for pressing, sintering, and impregnation processes of barium tungsten cathodes, reducing performance fluctuations.
- **ASTM E2782 Standard Guide for Measurement Systems Analysis** 《实验室测试方法精度的标准实践》
  - **Description**: Guide the analysis and optimization of measurement systems, ensuring the consistency and reliability of test data.
  - **Applicability**: Suitable for instrument calibration and data analysis for cathodic performance testing.
- **GB/T 19022-2003 Measurement Management Systems - Requirements for Measurement Processes and Measuring Equipment** 《测量管理体系 测量过程和测量设备的要求》
  - **Description**: Chinese industry standard, equivalent to ISO 10012, specifies management requirements for measuring equipment and processes, ensuring test consistency.
  - **Applicability**: Suitable for instrument management and data verification for barium tungsten cathodic performance testing.

- **Goal**: Ensure consistent porosity, transmit current density, and lifetime across batches of cathodes with low performance fluctuations.
- **Methods**: Statistical process control (SPC, in accordance with ISO 11462 and GB/T 19022-2003) was used to monitor key process parameters (e.g., pressing pressure, sintering temperature) and verify batch performance through high-throughput testing in accordance with ASTM E691 and E2782 standards.

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   - **Verification Process**: Parameter deviations are analyzed using control charts, combined with emission testing to evaluate batch consistency in accordance with IEEE 287, ASTM E691, E2782, and GB/T 19022-2003 standards.
- **Traceability Requirements**:
   - **Standard**:
      - **ISO 9001 Quality Management Systems – Requirements 《质量管理体系 要求》**
         - **Description**: Requires the establishment of a traceable production record system, covering the entire process from raw material procurement to finished product testing.
         - **Applicability**: Ensure traceability of barium tungsten cathode production issues, facilitating quality improvement and failure analysis.
      - **ISO/IEC 17025 General Requirements for the Competence of Testing and Calibration Laboratories 《测试和校准实验室能力的通用要求》**
         - **Description**: Specifies traceability requirements for laboratory tests and calibrations, ensuring the accuracy and reliability of test data.
         - **Suitability**: Suitable for data logging for cathodic performance testing and quality control.
      - **ASTM E2554 Standard Practice for Estimating and Monitoring the Uncertainty of Test Results 《可追溯性数据管理标准实践》**
         - **Description**: Guide uncertainty assessment and data management of test results, ensuring traceability.
         - **Suitability**: Suitable for performance testing and quality record management of barium tungsten cathodes.
      - **GB/T 27025-2019 General Requirements for the Competence of Testing and Calibration Laboratories 《检测和校准实验室能力的通用要求》**
         - **Description**: Chinese industry standard, equivalent to ISO/IEC 17025, specifies data traceability requirements for testing and calibration laboratories.
         - **Applicability**: It is suitable for data management and verification of barium tungsten cathode performance testing.
   - **Goal**: Record the whole process data from raw material procurement to finished product testing, ensuring that problems can be traced.
   - **Method**: An electronic production record system was established, covering raw material batches, process parameters, and test results, in compliance with ISO 9001, ISO/IEC 17025, ASTM E2554, and GB/T 27025-2019 requirements.
   - **Verification Process**: Regularly audit records to ensure data integrity, incorporating barcode or RFID technology to track products.

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- o **Implementation guidance**: Manufacturers need to deploy quality management systems with reference to ISO 9001, ISO/IEC 17025, ASTM E2554, and GB/T 27025-2019 to ensure traceability throughout the entire process.

8.4 Environmental and Safety Standards

The production and use of barium tungsten cathodes involve toxic materials and waste disposal, and strict environmental and safety regulations must be followed.

8.4.1 Safety Treatment and Environmental Protection Specifications for Barium Compounds

- **Safe Handling**:
  - o **Standard**:
    - **EN 374 Protective Gloves Against Dangerous Chemicals and Micro-organisms 《防护手套抗化学品和微生物的性能要求》**
      - **Description**: Specifies the requirements for the permeability of protective gloves to chemicals such as barium compounds, ensuring operator safety.
      - **Suitability**: Suitable for personnel protection during the preparation and impregnation of barium compound solutions.
    - **OSHA 1910.1200 Hazard Communication Standard 《危险化学品通信》**
      - **Description**: Requires identification, training, and safety data sheet (SDS) management of hazardous chemicals such as barium compounds.
      - **Applicability**: Ensure that personnel in barium tungsten cathode production understand the toxicity risks of barium compounds.
    - **OSHA 1910.1450 Occupational Exposure to Hazardous Chemicals in Laboratories 《实验室化学品职业暴露》**
      - **Description**: Specifies the safe handling and protective measures for chemicals (such as barium compounds) in laboratories.
      - **Applicability**: Guide the safe management of laboratory environments in barium tungsten cathode production.
    - **GB 30000.1-2024 Rules for Classification and Labelling of Chemicals - Part 1: General Rules 《化学品分类和标签规范 第 1 部分：通则》**
      - **Description**: This Chinese national standard replaces GB 13690-2009 and specifies the classification, labeling, and safety data sheet (SDS) requirements for hazardous chemicals such as barium compounds.
      - **Applicability**: Guides safety labeling and operational practices for barium compounds in barium tungsten cathode production, with an implementation date of August 1, 2025.

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- **Key Requirements**: Standard-compliant SDS for barium compounds and training for staff.
- **GB/T 16483-2008 Safety Data Sheet for Chemical Products - Content and Order of Sections 《化学品安全技术说明书 内容和项目顺序》**
  - **Description**: Specifies the content and format requirements of the chemical safety data sheet, which is applicable to the safety management of barium compounds.
  - **Applicability**: Ensure transparency in the safety information of barium compounds in barium tungsten cathode production.

- **Requirements**: Barium compounds (e.g., $BaCl_2$) are toxic, and operation must be carried out in fume hoods, and workers are required to wear protective equipment (e.g., gloves, masks) in accordance with EN 374, OSHA 1910.1200, OSHA 1910.1450, GB 30000.1-2024, and GB/T 16483-2008.
- **Method**: A closed system was used to prepare and impregnate a barium compound solution to prevent leakage and volatilization.
- **Verification Process**: Through air quality monitoring (Ba^{2+} concentration below safe limits, refer to **OSHA 1910.1000 Air Contaminants Standard** and **GBZ 2.1-2019 "Occupational Exposure Limits for Hazardous Agents in the Workplace - Part 1: Chemical Hazardous Agents"** ensures a safe operating environment.

- **Environmental Protection Specifications**:
  - **Standard**:
    - **EU RoHS Restriction of Hazardous Substances Directive, 2011/65/EU 《限制使用某些有害物质指令》**
      - **Description**: Restrict the use of hazardous substances (such as barium compounds) in electronic products, requiring waste liquid treatment to meet environmental standards.
      - **Applicability**: Suitable for waste liquid and waste treatment in barium tungsten cathode production.
    - **EU REACH Registration, Evaluation, Authorisation and Restriction of Chemicals, EC 1907/2006 《化学品注册、评估、授权和限制》**
      - **Description**: Requires registration and risk assessment of chemicals such as barium compounds to ensure environmental safety.
      - **Applicability**: Guide the recovery and treatment process of barium compound waste.
    - **ISO 14040 Environmental Management - Life Cycle Assessment - Principles and Framework 《环境管理 生命周期评估 原则与框架》**
      - **Description**: Guiding the environmental impact assessment of the production process, optimizing waste disposal and resource utilization.

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        - **Applicability**: It is suitable for the whole life cycle environmental management of barium tungsten cathode production.
    - **EPA 40 CFR Part 261 Identification and Listing of Hazardous Waste 《危险废物识别标准》**
        - **Description**: Specifies requirements for the identification and disposal of hazardous waste, including barium compound waste.
        - **Applicability**: Guide the classification and treatment process of barium tungsten cathode production waste.
    - **GB 18597-2023 Technical Specification for Pollution Control of Hazardous Waste 《危险废物污染防治技术规范》**
        - **Description**: This Chinese national standard specifies the requirements for the collection, storage, transportation and treatment of hazardous waste, which is suitable for the environmental management of barium compound waste.
        - **Applicability**: Guide the standardized treatment of hazardous waste in the production of barium tungsten cathode.
    - **GB 5085.7-2019 Identification Standards for Hazardous Wastes - General Specifications 《危险废物鉴别标准 通则》**
        - **Description**: Specifies the identification methods and standards of hazardous waste, which are applicable to the classification of barium compound waste.
        - **Applicability**: Ensure proper classification and handling of barium tungsten cathode production waste.
  - **Requirements**: Barium compound waste liquid must comply with EU RoHS, EU REACH, EPA 40 CFR Part 261, GB 18597-2023 and GB 5085.7-2019 regulations, and must not be discharged directly, and the heavy metal content must be lower than the emission standard.
  - **Methods**: Ba^{2+} ions were recovered by chemical precipitation or ion exchange, and waste liquid treatment was required to comply with EU REACH, EPA 40 CFR Part 261, and GB 18597-2023.
  - **Validation Process**: Analysis of waste liquid components using ICP-OES (in accordance with ASTM E1479 and GB/T 4181-2017) to ensure emissions comply with EU RoHS, EU REACH, GB 18597-2023, and GB 5085.7-2019.
  - **Implementation Guidance**: Manufacturers need to train operators, establish waste disposal procedures, undergo regular environmental inspections, and comply with ISO 14001, GB 18597-2023, and GB 5085.7-2019 standards.

8.4.2 Compliance Guidelines in Production and Use

- **Production Compliance**:
  - **Standard**:

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- **ISO 14001 Environmental Management Systems - Requirements with Guidance for Use** 《环境管理体系 要求及使用指南》
  - **Description**: Specifies the requirements of the environmental management system and guides the control of energy consumption and emissions in the production process.
  - **Suitability**: Suitable for barium tungsten cathode production facilities, reducing environmental impact.
- **IEC 62474 Material Declaration for Products of and for the Electrotechnical Industry** 《电子电气产品及其供应链中的材料声明》
  - **Description**: Requires declarations of materials in electronics, such as barium compounds, assessing environmental and safety impacts.
  - **Applicability**: Guiding material compliance management in barium tungsten cathode production.
- **ISO 50001 Energy Management Systems - Requirements with Guidance for Use** 《能源管理体系 要求及使用指南》
  - **Description**: Guidance on energy management, optimizing energy efficiency in production processes.
  - **Applicability**: Suitable for high-temperature sintering and heat treatment processes in barium tungsten cathode production.
- **GB/T 24001-2016 Environmental Management Systems - Requirements with Guidance for Use** 《环境管理体系 要求及使用指南》
  - **Description**: Chinese industry standard, equivalent to ISO 14001, guides environmental management in the production process.
  - **Applicability**: Suitable for environmental compliance management in barium tungsten cathode production facilities.
- **GB/T 23331-2020 Energy Management Systems - Requirements with Guidance for Use** 《能源管理体系 要求及指南》
  - **Description**: Chinese industry standard, equivalent to ISO 50001, guides energy efficiency management in the production process.
  - **Applicability**: Suitable for high-temperature process optimization in barium tungsten cathode production.

o **Requirements**: Production facilities must comply with ISO 14001, ISO 50001, GB/T 24001-2016, and GB/T 23331-2020 standards to reduce energy consumption and emissions, and materials must comply with IEC 62474 declaration requirements.

o **Method**: Energy-saving equipment (such as low-temperature sintering furnaces) and green chemical processes are used to reduce the carbon footprint and comply with ISO 14040 and GB/T 24001-2016 life cycle assessment requirements.

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- Validation Process: Analyze the environmental impact of production through a life cycle assessment (LCA, in accordance with ISO 14040) and optimize the process.

- **Usage Compliance**:
  - **Standard**:
    - **IEC 60601-1 Medical Electrical Equipment - Part 1: General Requirements for Basic Safety and Essential Performance 《医用电气设备 第 1 部分:基本安全和基本性能的通用要求》**
      - **Description**: The cathode operating environment is required to maintain a high vacuum to prevent residual gas contamination and ensure safe use.
      - **Suitability**: Suitable for barium tungsten cathode operation in medical and industrial equipment.
    - **ISO 20431 Vacuum Technology - Calibration of Vacuum Gauges 《真空技术 真空计的校准》**
      - **Description**: Ensure the accuracy of vacuum environment testing equipment and maintain the stability of cathode operation.
      - **Suitability**: Suitable for cathode operating environment management in microwave tubes and electron microscopes.
    - **IEC 60068-2-64 Environmental Testing - Part 2-64: Vibration, Broadband Random and Guidance《环境测试 第 2-64 部分:振动、宽带随机和指导》**
      - **Description**: Specifies the test methods of electronic devices in vibration environments to ensure the stability of the cathode in dynamic environments.
      - **Applicability**: Suitable for the management of the operating environment of barium tungsten cathodes in aerospace and radar systems.
    - **GB/T 3797-2016 Environmental Conditions for Electric and Electronic Products - Part 2: Test Methods 《电工电子产品环境条件 第 2 部分：试验方法》**
      - **Description**: Specifies environmental testing methods for electrical and electronic products, including vibration and high temperature testing, suitable for operational verification of barium tungsten cathodes.
      - **Applicability**: Ensures the stability of cathode operation in harsh environments.
  - **Requirements**: Cathode operation should be carried out in a high vacuum environment (less than 10^{-6} Pa) to avoid residual gas contamination, in accordance with IEC 60601-1, ISO 20431, IEC 60068-2-64 and GB/T 3797-2016 requirements.

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- **Method:** The device design should include a vacuum seal and exhaust system, and regular maintenance should be performed to ensure vacuum and vibration resistance.
- **Verification Process**: The operating environment is monitored using a vacuum gauge, and the vibration test must comply with IEC 60068-2-64 and GB/T 3797-2016, and the maintenance log is recorded.
- **Implementation Guidance**: Manufacturers and users need to follow IEC, ISO, and GB/T guidelines to ensure safe compliance in production and use.

8.4.3 Waste Disposal Specifications

- **Standard**:
  - **EU WEEE Waste Electrical and Electronic Equipment Directive, 2012/19/EU** 《废弃电气电子设备指令》
    - **Description**: Waste electronic equipment (such as devices containing barium tungsten cathodes) is required to be classified, recycled and treated to prevent environmental pollution.
    - **Applicability**: It is suitable for the recycling and disposal of waste barium tungsten cathodes.
  - **UN 1564 UN Recommendations on the Transport of Dangerous Goods, Barium Compound, N.O.S.** 《危险货物运输建议书 钡化合物》
    - **Description**: Specifies the transportation and handling requirements for barium compound waste, ensuring safety and compliance.
    - **Applicability**: Guide the transportation and handling process of waste barium tungsten cathodes.
  - **EPA 40 CFR Part 262 Standards Applicable to Generators of Hazardous Waste** 《危险废物产生者标准》
    - **Description**: Specifies the requirements for the generation, storage and disposal of hazardous waste, applicable to barium compound waste.
    - **Applicability**: Guide the standardized management of barium tungsten cathode production waste.
  - **ISO 14044 Environmental Management - Life Cycle Assessment - Requirements and Guidelines** 《环境管理 生命周期评估 要求与指南》
    - **Description**: Guide the life cycle assessment of waste disposal, optimizing resource recovery and environmental impact management.
    - **Applicability**: Suitable for the recycling and disposal process of barium tungsten cathode waste.
  - **GB 18597-2023 Technical Specification for Pollution Control of Hazardous Waste** 《危险废物污染防治技术规范》
    - **Description**: Specifies the requirements for the collection, storage, transportation and treatment of hazardous waste, and is suitable for the environmental management of barium compound waste.

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        - **Applicability**: Guide the standardized treatment of barium tungsten cathode production waste.
    - **GB 5085.7-2019 Identification Standards for Hazardous Wastes - General Specifications** 《危险废物鉴别标准 通则》
        - **Description**: Specifies the identification methods and standards of hazardous waste, which are applicable to the classification of barium compound waste.
        - **Applicability**: Ensure proper classification and handling of barium tungsten cathode production waste.
- **Requirements**: Waste barium tungsten cathodes and production waste should be sorted and disposed of to avoid environmental pollution, and comply with the requirements of EU WEEE, UN 1564, EPA 40 CFR Part 262, ISO 14044, GB 18597-2023 and GB 5085.7-2019.
- **Methods**:
    - Recover tungsten powder and barium compounds to separate useful materials by high-temperature cracking or chemical extraction.
    - Non-recyclable waste should be stored in a sealed container and disposed of by a professional organization according to hazardous waste standards, complying with UN 1564, EPA 40 CFR Part 262, and GB 18597-2023 requirements.
- **Verification Process**: Confirm recycling efficiency through waste composition analysis (ICP-MS, in accordance with ASTM E1479 and GB/T 4181-2017), document waste disposal flow to comply with EU WEEE, EU REACH, ISO 14044, GB 18597-2023, and GB 5085.7-2019 regulations.
- **Implementation Guidance**: Establish a waste management system and regularly report treatment to environmental protection departments to ensure compliance with ISO 14001, EU WEEE, UN 1564, EPA 40 CFR Part 262, GB 18597-2023, and GB 5085.7-2019 requirements.

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CTIA GROUP LTD
Barium Tungsten Cathode Introduction

1. Overview of Barium Tungsten Cathode

The Barium Tungsten Cathode is a type of thermionic emission material typically composed of high-purity tungsten as the base, impregnated with barium compounds. Upon high-temperature activation, it emits free electrons and is widely used in vacuum electronic devices. Due to its low work function and high electron emission efficiency, this cathode plays a critical role in high-power electronic equipment. CTIA GROUP LTD specializes in the global flexible customization of tungsten and molybdenum products, offering tailored high-performance barium tungsten cathodes according to customer requirements.

2. Characteristics of Barium Tungsten Cathode

- **High Electron Emission Efficiency:** The low work function of barium enables the cathode to emit a large quantity of electrons even at relatively low temperatures.
- **High-Temperature Resistance:** With a tungsten matrix that has a melting point of 3422° C, the cathode maintains structural stability in high-temperature operating environments.
- **Long Service Life:** Optimized barium compound impregnation techniques help minimize barium evaporation, thereby extending the cathode’s lifespan.
- **Low Evaporation Rate:** Compared to other cathode materials, barium tungsten exhibits a lower evaporation rate at high temperatures, reducing contamination within the device.
- **Arc Stability:** Delivers a stable electron flow, making it ideal for high-precision electron beam applications.

3. Applications of Barium Tungsten Cathode

- **HID Lamps:** The cathode's low work function and high current density allow HID lamps to emit bright and stable light, making them suitable for applications that require high brightness and long service life, such as roadway and industrial lighting.
- **Vacuum and Laser Devices:** The low work function makes barium tungsten ideal for use in vacuum electronic and laser components.
- **Stage and Club Lighting Effects:** High-frequency strobe lights made from this material are known for their long lifespan and stable performance.
- **Film Projection and Video Recording:** The film and broadcast industry also relies heavily on this material for projection and recording equipment, where it ensures long-term operational stability and high efficiency.
- **Laser Mercury Pumps:** Its high electron emission capability and low operating temperature contribute to improved laser performance and stability.

5. Procurement Information

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Appendix

A. Glossary

The following are technical terms and definitions for barium tungsten cathodes and related fields, based on international standards (e.g., IEC 60050, IEEE 161) and industry practices.

- **Barium Tungsten Cathode**: A thermally emitting cathode made of a porous tungsten matrix impregnated with barium compounds such as barium-calcium aluminate, which produces high current density electrons through heating and is widely used in vacuum electronics.
- **Thermionic Emission**: The phenomenon of electrons escaping from the surface barrier of a material at high temperatures, following the Richardson-Dushman equation, the core working mechanism of the barium-tungsten cathode.
- **Work Function**: The minimum energy required for electrons to escape from the surface of the material, measured in electron volts (eV), and the barium-tungsten cathode reduces the work function through the barium active layer to improve the emission efficiency.
- **Porous Tungsten Matrix**: A high-purity tungsten porous structure made by powder metallurgy to store and release barium compounds, affecting emission properties and longevity.
- **Barium Compounds**: such as barium-calcium aluminate (Ba-Ca-Aluminate), impregnated in a porous tungsten matrix, through thermal activation to form a low-work function active layer.
- **Emission Current Density**: The electron flow emitted per unit area of the cathode surface, measured in A/cm^2, measures the emission efficiency of the barium-tungsten cathode.
- **Active Layer**: A low-work function layer formed by thermal activation on the surface of the barium tungsten cathode, which is mainly composed of barium atoms or barium oxide, which determines the emission performance.
- **Poisoning Effect**: The phenomenon of reduced emission performance due to contamination of residual gases (such as oxygen and carbon compounds) on the cathode surface.
- **Activation Process:** A process in which barium compounds form an active layer on the surface of a tungsten matrix by controlling the temperature and vacuum environment.
- **Vacuum Electron Device**: A device that uses electronic movement in a vacuum environment, such as microwave tubes and X-ray tubes, with the barium tungsten cathode as its core electron source.
- **Schottky Effect**: Under the applied electric field, the cathode surface barrier is reduced, enhancing thermionic emission, which is common in high-field strength applications.
- **Porosity**: The percentage of pore volume in the porous tungsten matrix to the total volume, affecting the barium storage capacity and emission properties, tested in accordance with ASTM E1441 and GB/T 21650.1.
- **Powder Metallurgy**: A method of preparing porous tungsten matrix by screening, pressing, and sintering tungsten powder, which must comply with GB/T 3461 and GB/T 4192.

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- **Impregnation Process**: The process of filling a barium compound solution into the pores of a porous tungsten matrix is performed in a high-vacuum environment in accordance with ASTM E168.
- **Anti-Poisoning Capability**: The cathode's ability to resist residual gas contamination is improved by optimizing barium compound formulations and surface treatments.
- **Aging Test**: A test that simulates long-term operating conditions to evaluate cathodic emission performance attenuation, in accordance with MIL-STD-202 and JB/T 6842.
- **Failure Mode**: The mechanism of cathode performance degradation, such as surface contamination, barium depletion, or mechanical damage, is analyzed using methods such as fault tree analysis (FTA).
- **High Vacuum Environment**: The low-pressure environment required to operate the barium-tungsten cathode, typically below 10^{-6} Pa, tested in accordance with ISO 20431.

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C. Test Standards and Specifications

The following is a detailed list of international, industry, and Chinese standards related to barium tungsten cathodes, covering performance testing, manufacturing, quality control, and environmental safety specifications.

International Standards

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- **IEC 60601-1 Medical Electrical Equipment - Part 1: General Requirements for Basic Safety and Essential Performance 《医用电气设备 第 1 部分:基本安全和基本性能的通用要求》**
  - o Applicability: Specifies the performance and safety requirements of barium tungsten cathodes in medical X-ray tubes, testing emission current density and vacuum environment.
  - o Key requirements: transmit current fluctuation of less than 5%, vacuum degree less than 10^{-6} Pa.
- **IEC 60050 International Electrotechnical Vocabulary 《国际电工词汇》**
  - o Applicability: Provide definitions of barium tungsten cathode-related terminology to ensure consistency in technical documentation.
  - o Key requirements: Terminology must comply with international standards to avoid ambiguity.
- **ISO 9001 Quality Management Systems – Requirements 《质量管理体系 要求》**
  - o Applicability: Guide quality management systems in barium tungsten cathode production, ensuring batch consistency.
  - o Key requirements: The production environment must comply with ISO Class 5 cleanroom standards.
- **ISO 20431 Vacuum Technology - Calibration of Vacuum Gauges 《真空技术 真空计的校准》**
  - o Suitability: Ensures vacuum gauge accuracy in barium tungsten cathode testing, suitable for microwave tubes and electron microscopy.
  - o Key requirements: The gauge calibration accuracy must be better than 0.1 Pa.
- **ISO 19444-1 Vacuum Technology - Standard Methods for Measuring Vacuum System Performance - Part 1: General Requirements《真空技术 真空系统设计 第 1 部分：通用要求》**
  - o Applicability: Guiding the design of vacuum systems for the barium tungsten cathode operating environment.
  - o Key requirements: The vacuum system has a leakage rate of less than 10^{-9} Pa·m³/s。
- **ISO 16000-6 Vacuum Technology - Vacuum Pumps - Part 6: General Requirements 《真空技术 真空泵性能测量 第 6 部分：通用要求》**
  - o Applicability: Guide vacuum pump performance evaluation in barium tungsten cathode production and testing.
  - o Key requirements: Vacuum pump pumping speed stability is better than 5%.

Industry Standard

- **IEEE 161 Standard Definitions of Terms for Electron Tubes 《电子管和真空器件术语》**
  - o Applicability: Define the performance parameters of the barium tungsten cathode, such as the work function and the emission current density.
  - o Key requirements: The test needs to simulate high-frequency pulse conditions.
- **IEEE 287 Standard for Microwave Tube Test Methods 《微波管测试方法》**

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  - Applicability: Specifies test methods for barium tungsten cathodes in microwave tubes, such as emission performance and life tests.
  - Key requirements: The test environment needs to maintain a high vacuum and the current density test accuracy is better than 0.1 mA/cm².
- **MIL-STD-810 Environmental Engineering Considerations and Laboratory Tests** 《环境工程考虑和实验室测试》
  - Applicability: Suitable for vibration and radiation testing of barium tungsten cathodes in the aerospace field.
  - Key requirements: The cathode needs to maintain stable performance in high radiation environments.
- **MIL-STD-202 Test Method Standard for Electronic and Electrical Component Parts** 《电子和电气元件测试方法》
  - Suitability: Guides the longevity and reliability testing of barium tungsten cathodes.
  - Key requirements: Accelerated aging tests need to simulate actual operating conditions.
- **ASTM F83 Standard Practice for Definition and Determination of Thermionic Constants of Electron Emitters** 《电子器件用热电子发射器热电子常数的定义与测定》
  - Applicability: Specifies the test method for the work function of barium tungsten cathode and the density of the transmitted current.
  - Key requirements: The test should be performed in a high vacuum environment with an accuracy of better than 0.01 eV.
- **ASTM B760 Standard Specification for Tungsten Plate, Sheet, and Foil** 《钨板、片、箔和条的标准规范》
  - Applicability: Specifies the purity requirements of tungsten materials for porous tungsten matrix of barium tungsten cathode.
  - Key requirements: Tungsten purity needs to be better than 99.95%.
- **ASTM E1441 Standard Guide for Computed Tomography (CT) Imaging** 《材料孔隙率测试指南》
  - Applicability: Guides porosity and pore size distribution testing of porous tungsten matrix.
  - Key requirement: X-CT resolution better than 1 μm.
- **ASTM E168 Standard Practices for General Techniques of Thermogravimetric Analysis** 《热重分析通用方法》
  - Suitability: Thermogravimetric analysis (TGA) to guide the amount of impregnation of barium compounds.
  - Key requirement: Thermal analysis accuracy better than 0.1 mg.

Chinese National and Industry Standards

- **GB 4943.1-2022 Information Technology Equipment - Safety - Part 1: General Requirements** 《信息技术设备 安全 第 1 部分：通用要求》

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- Suitability: Suitable for electrical and thermal safety testing of barium tungsten cathodes in information technology equipment.
- Key requirements: The operating temperature should be controlled within a safe range to prevent arc discharge.

- **GB/T 3797-2016 Environmental Conditions for Electric and Electronic Products - Part 2: Test Methods** 《电工电子产品环境条件 第 2 部分：试验方法》
  - Applicability: Guide the performance testing of barium tungsten cathodes in high-temperature, high-humidity, and vibration environments.
  - Key requirements: The cathode needs to be stable at 2000°C and high vacuum.
- **JB/T 6842-2018 General Specification for Vacuum Electron Devices** 《真空电子器件通用规范》
  - Applicability: Specifies the performance and testing requirements of barium tungsten cathodes in vacuum electronics.
  - Key requirements: Transmit current density needs to meet the needs of high-power devices.
- **GB/T 21650.1-2008 Pore Size Distribution and Porosity of Solid Materials by Mercury Porosimetry and Gas Adsorption - Part 1: Mercury Porosimetry** 《材料孔隙率测定 第 1 部分：汞压法》
  - Applicability: Guide porosity testing of porous tungsten substrates.
  - Key requirements: Porosity measurement accuracy must be better than 1%.
- **GB/T 13247-2019 Test Methods for Thermal Analysis of Metallic Materials** 《金属材料热分析测试方法》
  - Suitability: Thermogravimetric analysis (TGA) to guide the amount of impregnation of barium compounds.
  - Key requirement: Thermal analysis accuracy needs to be better than 0.1 mg.
- **GB/T 3461-2017 Tungsten Powder** 《钨粉》
  - Applicability: Specifies the particle size distribution and purity requirements of tungsten powder.
  - Key requirements: The purity of tungsten powder needs to be better than 99.95%.
- **GB/T 4192-2010 Sintered Tungsten and Tungsten Alloy** 《钨及钨合金烧结坯》
  - Applicability: Guide the sintering process of barium tungsten cathode porous tungsten matrix.
  - Key requirement: Sintering temperature controlled at 1900–2050°C.
- **GB/T 4181-2017 Methods for Chemical Analysis of Tungsten and Tungsten Alloys**《钨及钨合金化学分析方法》
  - Applicability: Guide the purity analysis of tungsten powder and tungsten matrix.
  - Key requirement: ICP-OES analysis accuracy is better than 10 ppm.
- **GB 30000.1-2024 Rules for Classification and Labelling of Chemicals - Part 1: General Rules** 《化学品分类和标签规范 第 1 部分：通则》
  - Applicability: Guides safety labeling and operating practices for barium compounds.

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 - Key Requirement: Provide a standards-compliant SDS with an implementation date of August 1, 2025.

- **GB/T 16483-2008 Safety Data Sheet for Chemical Products - Content and Order of Sections** 《化学品安全技术说明书 内容和项目顺序》
  - Applicability: Ensure the standardized management of safety information of barium compounds.
  - Key requirements: SDS needs to include chemical toxicity and handling requirements.
- **GB 18597-2023 Technical Specification for Pollution Control of Hazardous Waste**《危险废物污染防治技术规范》
  - Applicability: Guides the collection, storage, and disposal of barium compound waste.
  - Key requirements: The content of heavy metals in the waste liquid must be lower than the emission standard.
- **GB 5085.7-2019 Identification Standards for Hazardous Wastes - General Specifications** 《危险废物鉴别标准 通则》
  - Applicability: Stipulate the identification and classification requirements of barium compound waste.
  - Key requirements: Waste materials should be disposed of according to hazardous waste standards.
- **GB/T 14815-2008 Vacuum Technology – Vocabulary** 《真空技术 术语》
  - Applicability: Define vacuum technical terms in barium tungsten cathode testing and operation.
  - Key requirements: Terminology needs to be consistent with international standards.
- **GB/T 34590-2017 Vacuum Technology - Methods of Measurement of Vacuum System Performance** 《真空技术 真空系统性能测试方法》
  - Applicability: Guiding vacuum system performance testing for barium tungsten cathode operating environment.
  - Key requirements: The vacuum system has a leakage rate of less than 10^{-9} Pa·m³/s。

D. Suppliers & Resources

- **CTIA GROUP LTD Introduction**

  CTIA GROUP LTD is a leading supplier of barium-tungsten cathode and vacuum electronic materials in China. The products are widely used in microwave tubes, X-ray tubes, radar systems, electron microscopes and aerospace fields. CTIA GROUP LTD specializes in flexible customization of tungsten and molybdenum products, providing high-performance cathode solutions, and can customize and process various specifications, performance, sizes and grades of tungsten and molybdenum products according to customer needs.

  Contact Information:

  邮箱：sales@chinatungsten.com

  Telephone: 0592-5129696, 0592-5129595
- **CTIA GROUP LTD Barium Tungsten Electrode Related Websites**

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E. index

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