Optimization of High-Performance Field Emission Rare Earth Tungsten Alloy Cathodes

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Abstract

As the electron emission source for various electronic vacuum devices and spacecraft potential control systems, cathode performance not only affects the overall equipment efficiency but also constitutes one of the most critical factors limiting system longevity and high reliability. In the field of space propulsion, electron emission from conventional cathodes primarily operates through thermal emission and field emission mechanisms. Therefore, based on first-principles calculations using density functional theory, this study constructs atomic models of W cathode surfaces doped with different rare earth atoms. Using a (2$×2×1)W(001)surfacemodel,1MLofOatomsisadsorbedatthetopsitesofthesurface,followedbydopingrare
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and working temperature of 2000°C, the projected lifetime of rare earth tungsten alloy cathodes exceeds 2000 hours.

Full Text

Preamble

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Cathodes serve as the electron emission source for electronic vacuum devices and spacecraft potential control systems, where their performance

not only affects overall equipment efficiency but also represents the most critical factor limiting system longevity and reliability. In space propulsion, conventional cathode electron emission relies primarily on thermionic and field emission mechanisms. This study employs first-principles calculations based on density functional theory to construct atomic models of W cathode surfaces doped with different rare earth atoms. Using a $(2\$\times 2\times 1)W(001)surfacemodel, 1MLofOatomsisadsorbedatthetopsiteofthesurface, followedbydopingofrar$
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m^{-3} and working temperature of 2000 K, the projected lifetime of rare earth tungsten alloy cathodes exceeds 2000 hours.

Keywords: Field emission cathode, Rare earth tungsten alloy, First-principles calculations, Work function

Introduction

Cathodes function as the primary and neutralizing electron source for various electronic vacuum devices and spacecraft potential control systems. Their performance not only influences overall system efficiency but also constitutes the most important factor limiting long service life and high reliability [1,2]. In the 1960s, cathodes were first applied to electric propulsion at the Lewis Research Centre and Houston Research Laboratory in the USA. After decades of development, cathode technology has advanced significantly, encompassing characterization of cathode working plume modes, sputtering corrosion properties of cathode components, emitter working mechanisms, and validation of cathode operational lifetime [3-7].

Compared with conventional thermal cathodes, field emission cathodes offer numerous advantages including fast startup, room temperature operation, no preheating delay, and high current density. These benefits have led to their application in electron beam lithography, vacuum diodes, space propulsion systems, and other fields [8]. Currently, commonly used cathode materials in vacuum devices include Ba-W cathodes, lanthanum hexaboride (LaB_6), dodecacalcium heptaaluminate ($C_{12}A_7$) cathode materials, and new cathode materials developed from these foundations, with different emitter materials offering distinct advantages [9-12]. The Ba-W cathode consists of sintered porous tungsten impregnated with barium oxide, calcium oxide, and alumina, where porous tungsten serves as the substrate and the mixture as the raw material. The Ba-W cathode has a work function of approximately 2.1 eV and an operating temperature of about 1300 K, but imposes stringent requirements on the working medium. LaB_6 is typically fabricated through mechanical processing of powder-pressurized and sintered polycrystalline rods, with a work function of about 2.7 eV and operating temperature exceeding 1800 K, where prolonged high-temperature service leads to substantial power consumption. In recent years, theoretical studies have shown that $C_{12}A_7$ compounds possess lower work functions (theoretically 0.6 eV) and operating temperatures (theoretically 900 K), and although experimental verification remains inconclusive, their excellent performance has attracted considerable attention from researchers worldwide.

Future cathode research will continue to focus on the electron work function of cathode emitters and cathode operating temperature [13,14]. However, in Magneto Plasma Dynamic Thrusters (MPDT), the cathode serves as a core component located at the center of the high-energy plasma plume, experiencing instantaneous ignition voltages up to several thousand volts, operating temperatures exceeding 1500 K, and extremely harsh working environments, which impose stringent requirements on cathode materials and structure [15].

Metallic materials represent the earliest researched and most widely used field emission materials, primarily including W, Mo, Ta, etc. However, pure tungsten exhibits high electron work function and is prone to difficult arc initiation and breakdown at low voltage. Since rare earth elements such as La, Ce, and Y possess lower work functions and higher melting points, studies have demonstrated that adding rare earth oxides with lower work functions to tungsten can significantly improve cathode ablation resistance.

In recent years, North American researchers have prepared E^3 ternary electrodes with ZrO_2 as an additive, with main components of W-La_2O_3-Y_2O_3-ZrO_2. Zhu Wenguang et al. compared the arc initiation performance of E^3 electrodes with traditional multielement electrodes, and after 5 hours of ablation at 200 A current, E^3 electrodes showed the smallest ablation loss, good dimensional stability, and weak recrystallization. Therefore, based on traditional cathode electron emission theory and conventional cathode material types, this study employs high-melting-point tungsten as the cathode substrate, doped with different types and contents of rare earth elements, and completes various performance tests and ground prototype experiments for verification [16–18].

Atomic models were constructed for tungsten (W)-O surfaces doped with various rare earth atoms (La, Ce, Y) using first-principles calculations and density functional theory (DFT). Work function calculations were conducted for models with 0.5 ML and 1.0 ML doping levels. The results demonstrated that doping rare earth elements significantly lowered the work function of the alloy cathode, improving electron emission performance, and that 0.5 ML doping in W-O lattice sites yielded the lowest work function.

In the present study, nano-doped rare earth tungsten cathode materials were prepared using liquid-phase synthesis and plasma discharge sintering techniques. A series of ignition tests on thruster prototypes were conducted along with microstructural characterization experiments to evaluate the electron emission performance, ignition characteristics, and efficiency of tungsten alloy cathodes doped with various elements and proportions.

Additionally, based on the working principle of cathodes for various vacuum devices and considering existing experimental constraints, full-system lifetime testing faces significant limitations. Therefore, this study independently conducted lifetime assessment experiments for cathodes, performing mass-loss-based life prediction through a self-developed cascade arc plasma generator. The results show that nano rare-earth tungsten alloy cathodes exhibit better electron emission performance than conventional cathodes, where lanthanum oxide-doped tungsten alloys with different mass fractions significantly reduce the cathode material work function. After independent cathode lifetime testing, preliminary predictions indicate that rare-earth tungsten alloy cathode lifetime reaches 2000 hours.

Electron Emission Principle of Field Emission Cathode

The emission of cathodes used in thruster systems primarily relies on thermionic emission and field emission principles [19]. Thermionic emission follows the Richardson equation:

$$j_0 = [AT^{2K}] \exp(-\phi_k / kT_K)$$

As shown in Equation (1), j_0 represents the zero-field emission current density, A is the theoretical value of the material' s emission constant, T_K is the cathode operating temperature, and ϕ_k represents the material' s work function [20].

Similar to the theoretical derivation of the thermionic emission equation, Fowler and Nordheim developed field emission theory for metals based on the following assumptions: (1) the distribution of band electrons conforms to the Fermi-Dirac distribution; (2) a smooth, planar metal surface is considered, ignoring atomic-scale irregularities; (3) classical image forces affecting electrons are taken into account; and (4) the work function distribution is uniform. Under these assumptions, the following equation holds:

$$1.54 \times 10^{-6} \xi^2 \left[\frac{6.83 \times 10^7 \phi_k}{\theta(y_0)} \right]$$

In Equation (2), ξ represents the electric field strength measured in V/cm, where $\theta(y_0)$ is a slow-variable function of ξ:

$$(3.79 \times 10^{-4})$$

According to the electron emission equations above, the zero-field emission current density j_0 is closely related to parameters such as the material' s work function, temperature, and electric field strength. Theoretically, the lower the work function of the cathode material, the more readily electrons within the material can overcome the surface potential barrier to emit from the cathode surface. Additionally, the operating temperature T_K and electric field strength ξ are directly proportional to the zero-field emission current density j_0 of the cathode. At lower temperatures, thermionically emitted electrons that overcome the barrier contribute negligibly to the emission current, with emission consisting primarily of field-emitted electrons near the Fermi level [21].

Regarding the work function of cathode materials, the periodic arrangement of lattice ions is interrupted at the metal-vacuum boundary, thereby disrupting the periodicity of the potential field [22]. The potential energy increases in a specific manner and approaches zero at infinity, forming the surface potential barrier of the metal. When electrons move to the metal surface and attempt to escape, they are hindered by this surface barrier, which is defined as the material' s work function:

$$\phi_k = E_V - E_F$$

All electrons attempting to escape from the metal must have energy at least equal to the Fermi level plus the work function value and follow a statistical distribution. Their average energy equals $\frac{3}{2}KT$, with each degree of freedom contributing an average energy of $\frac{1}{2}KT$, consistent with kinetic molecular theory results [23].

On the other hand, the cathode evaporation rate increases sharply with rising cathode operating temperature. Cathode evaporation directly impacts cathode lifespan, grid emission, and inter-electrode insulation performance. Ideally, a cathode should have high emission capability, requiring a low work function and minimal evaporation. Considering these two requirements, a quality factor F can be used to represent performance:

$$F = \phi_k \times 10^3 / T_e \ (\mathrm{eV/K})$$

where T_e is the temperature (K) at which the material' s vapor pressure reaches 10^{-5} mmHg. To ensure thruster performance, the cathode temperature should not exceed its "vapor pressure temperature" T_e [24].

Therefore, the selection and optimization of cathode emitter materials require balancing electronic emission performance with thermodynamic properties. Higher electron emission performance can enhance cathode discharge efficiency and overall thruster efficiency, while better thermodynamic properties extend cathode service life under extreme operating conditions. This research primarily focuses on simulation and experimental optimization of cathode material components to reduce emitter work function, verifying key cathode material parameters such as electron emission performance, lifetime, and ablation characteristics to advance research on high-performance field-emission space propulsion cathodes.

Building upon traditional field emission cathode research, new field emission cathodes have become a current research focus. Researchers at the National University of Defense Technology prepared a carbon fiber composite graphite cathode and tested its electron emission performance, which showed that the field emission threshold electric field of the 40% (mass fraction) carbon fiber composite graphite cathode was reduced from 143 kV/cm to 119 kV/cm, a decrease of approximately 16.8%. Due to the structural stability characteristics of carbon fibers during electron emission, carbon fiber conformity also favors improved cathode service life [25]. Maksim A. Chumak et al. from the Ioffe Research Institute in St. Petersburg, Russia, used atomic layer deposition (ALD) to produce field-emission cathodes with carbon nanotube (CNT) arrays coated with ultrathin nickel oxide (CNT/NiO). They proposed for the first time to reduce the figure of merit of the field-emission nanocomposite CNT/NiO cathode by altering the chemical composition of the oxide coatings. According to secondary electron cut-off energy measurements, the work function of pure CNTs is 4.95 eV, and the work function of the NiO layer deposited on CNTs decreases after heat treatment [26].

First-Principles Study on the Surface Work Function of Rare Earth Tungsten Alloy Cathode

Quantum mechanics forms an important foundation of modern physics and represents one of the greatest discoveries of the 20th century. Using quantum mechanics, it is possible to explain and predict the physicochemical properties of a wide range of systems and quantitatively analyze the laws of electronic motion. First-principles calculation is a computational method based on quantum mechanics that studies material properties from the perspective of electron motion. The wave function contains all information of the computational system, which greatly limits its practical applications, and the establishment of density functional theory solves the problem of wave function complexity. The basic idea of density functional theory is to transform characteristics based on orbital wave functions, using the particle density function to express each physical quantity of the system' s ground state, representing system energy through the electron density function [27,28].

Materials Studio simulation software incorporates various three-dimensional scale simulation calculation methods, enabling cross-scale scientific research from microscopic electronic structure to macroscopic performance prediction [29]. Based on this advantage, the current work modeled atomic-scale emission structures using Materials Studio. Geometric optimization was performed for tungsten alloy models doped with various rare earth elements, followed by surface atom relaxation and work function calculations under convergence conditions. The pseudopotential method was employed to solve the Schrödinger equation, while work function computations were performed using LDA functional and PBE-GGA functional. The work function of the (001) crystal plane for tungsten was calculated to assess the possible effect of doped elements on cathode emission current density [30].

The models primarily include: adsorption of O atoms and La atoms on a tungsten surface, adsorption of O atoms and Ce atoms on a tungsten surface, and adsorption of O atoms and Y atoms on a tungsten surface.

The current work utilized the CASTEP density functional calculation module of Materials Studio, which is based on a plane-wave basis set. Among the well-known classical algorithms in CASTEP, the main approach is the plane-wave pseudopotential method. By moving the tungsten atomic structure model and performing geometric optimization, it was possible to find the ground state with the lowest energy. We used the default maximum number of steps, while the cut-off energy was 278.0 eV. The calculation method was set to "Fine" and remaining parameters were kept at their default values. Under the ultrasoft pseudopotential, GGA was applied, and the functional from Perdew-Burke-Ernzerhof was selected to describe electron exchange-correlation interactions [31].

An O atomic layer was adsorbed on the surface of the supercell W(2$×2×$1). According to related computational literature, larger adsorption energy indicates a more stable adsorption system. The adsorption energies of O atoms on the top site, bridge site, and hollow site of the W supercell are approximately 9.11 eV, 7.40 eV, and 8.20 eV, respectively, indicating that O atoms are preferentially adsorbed at the top site shown in Figure 1 [32].

On the W-O (top-site) surface, rare earth atoms with varying coverages were adsorbed. Similar to O atoms, rare earth atoms on the (2$×2×$1) W(001)-O (top-site) surface have three possible adsorption positions. Due to the larger atomic radius of rare earth elements, adsorption at top and bridge sites causes significant lattice distortion in the W lattice. Computational results indicate that rare earth atoms are more likely to adsorb at hollow sites on the W-O (top-site) surface. The formula for calculating the adsorption energy of rare earth atoms is as follows:

$$E_{ad} = -(E_{La+W(001)-O(top)} - NE_{La} - E_{W(001)-O(top)})$$

As shown in Figures 2a to 2c, the work function for rare earth atoms in the W-O crystal with a coverage of 0.5 ML was calculated using Equation (6). Because rare earth atoms readily lose their two outermost valence electrons, transferring them to the inner O atoms, the electron density of the coverage layer is lower than that of the substrate surface layer. This results in a dipole layer with positive charge on the outside, raising the surface potential and reducing the barrier height.

Similarly, this study further calculated the work function of W-O crystals with a rare earth atom coverage of 1.0 ML, meaning that rare earth atoms fully occupy the hollow sites in the W crystal, as shown in Figures 2d to 2f.

Table 1 . Work Function of W-O (Top-Site) Doped with Different Rare Earth Atoms.

W(001)-O Top-Site Doping	Work Function (eV)
1.0 ML Y atoms	

As marked in Table 1, the computational results of work function for W-O (top-site) doped with 0.5 ML and 1.0 ML of different rare earth atoms show that the large atomic radius of rare earth elements results in substantial lattice distortion when fully occupying the hollow sites in the W crystal, making such systems unstable. When the number of adsorbed atoms increases above optimal coverage, interactions between dipoles increase gradually, where middle atoms become depolarized by the electric field of adjacent dipoles. This reduction of dipole moment increases the work function.

Comparing the data in the table, doping rare earth atoms into the W crystal reduces the surface work function in all cases, validating the feasibility of this study' s approach to optimize cathode electron emission performance by doping tungsten with rare earth elements, thereby enhancing the efficiency of magneto-plasma thrusters. Additionally, the calculation results show that doping 0.5 ML La or Ce atoms at the W-O (top-site) achieves the greatest reduction in work function. Due to the relatively smaller radius of Y atoms, full Y atom doping into the hollow sites of the tungsten crystal results in minimal lattice distortion, and its work function is slightly reduced compared to 0.5 ML Y doping.

Experimental Study on Cathode of Rare Earth Tungsten Alloy

A. Synthesis and Processing of Rare Earth Tungsten Alloy Cathodes

For various vacuum electronics and space propulsion systems, the primary requirements for cathodes are superior electron emission capability and high ablation resistance to withstand impacts from high-energy particles. Experimental research indicates that the electron emission performance, melting point, and ablation resistance of rare earth tungsten alloy cathodes are closely related to the chemical properties, physical dispersion, and percentage content of the nano-doped phase. We synthesized W-La_2O_3 alloy cathodes with different doping levels and studied their electron emission performance at various temperatures and voltages for different W-La_2O_3 doping concentrations [33].

Figure 3a shows the flow process for preparing nano rare earth tungsten alloy cathodes. In this study, nano rare-earth tungsten alloy cathode raw material mixed powders were produced by two methods: liquid-phase synthesis reduction and ball milling, then molded with reference to the processing method of LaB_6 cathode emitters. The liquid-phase synthesis method involves mixing tungstate, lanthanate, and complexing reagent in deionized water according to measured ratios, reacting for approximately 8 hours at appropriate temperature, then spray-drying to obtain homogeneous raw material powders. The ball milling method uses a planetary ball mill to mill mixed powders for 4 hours at 240 rpm under argon gas at room temperature, with a ball-to-powder weight ratio of 8:1. After mixing, powders were pressed into rods with 16 mm diameter by cold isostatic pressing at 150 MPa, then sintered at 2600 K for 4 hours in a dry hydrogen atmosphere. Finally, to remove oxide layers and obtain smooth surfaces, rods were ground to 9.0 mm diameter using computer numerical control (CNC) machining. Densities of the W-La samples were obtained using the Archimedes method, with theoretical densities calculated based on component fractions. The densities of W-La cathodes prepared in this study ranged from 98.5% to 99.5%. Figure 3b shows the physical diagram of the W-La cathode prepared according to the above process [34–36].

After cathode processing, actual density was measured using the Archimedes drainage method and compared with theoretical density to obtain homogeneity parameters, as shown in Table 2. Densities higher than 98% proved that the sintered cathodes obtained by this method are dense and uniform, enabling completion of subsequent tests and experiments.

Table 2 . Actual Density and Homogeneity of Different Types of Cathodes.

Type of Cathode	DA (g/cm^3)	DT (g/cm^3)	Homogeneity (%)
W-Y10 cathode			
W-La10 cathode			
W-La15 cathode			
W-La20 cathode			

The series of rare earth tungsten alloy cathodes designed and processed in this study targets the extreme working environment of vacuum equipment and space thrusters. By optimizing emitter composition, we aim to balance high electron emission performance with ablation resistance for extended service life. Figure 3c shows electron emission performance data for W cathodes doped with various mass fractions of W-La_2O_3. As W-La_2O_3 content increases, the overall electron emission performance of the cathode improves significantly, confirming that adding low work function components to optimize emitter performance is feasible. Additionally, we tested electron emission properties of different doping types of cathodes at 1450°C, 1500°C, and 1600°C, as shown in Figures 3d to 3f. The results show that emission current densities of the four tested cathodes increase to varying degrees with increasing test voltage and temperature, with the W-La15 cathode showing the largest increase. The pure W cathode no longer increases in emission current density when test voltage reaches the threshold value due to its higher electron work function.

Furthermore, we prepared W-Ce and W-Y rare earth tungsten alloy cathodes with different doping ratios using the same processing method and made preliminary predictions of their properties [37,38]. During sintering of W-Ce cathodes, volatilization of CeO_2 affects hollow cathode discharge stability, requiring strict process control and insulated sintering preparation [39].

B. Independent Service Life Experiment Using Cascade Arc Plasma Source

Under existing experimental constraints, verification of cathode service life is a lengthy and expensive process, with thruster-integrated life validation tests being even more costly. As space missions demand longer lifetimes from electric propulsion systems, full-life ground testing has become increasingly impractical. For instance, the ground-tested ion thruster for NASA' s *Deep Space 1* mission lasted 30,352 hours—more than five years [40]. In comparison, the JIMO mission would have used six nuclear-powered ion thrusters as main propulsion, each requiring 83,000-hour lifetimes. Assuming 75% efficient test duration, a 1.5-times redundancy life test would require approximately 19 years [41]. The extended life test of the U.S. NEXT ion thruster for subsequent deep space exploration began in 2005, accumulating 51,184 hours of life testing until 2017 and consuming 918 kg of xenon gas. Therefore, under existing experimental conditions, we employ a rapid life test method to evaluate cathode life in combination with relevant experimental parameters, which greatly reduces life test time and cost [42].

We developed a cascade arc plasma source to simulate the real working environment of rare earth tungsten alloy cathodes, consisting of a vacuum system, power supply system, superconducting magnet system, plasma generation device, gas supply system, water cooling system, and Langmuir probe system, as shown in Figure 4. This study considers that cathode tip morphology changes significantly when cathode mass loss reaches 10–15%. This reduces the effectiveness of small-hole current limitation and leads to inability to maintain stable discharge when propellant flow rate exceeds the set operating range, preventing achievement of cumulative operating time under rated conditions. Beyond this point, the cathode is considered functionally degraded and at the end of its service life.

Therefore, as shown in Figures 4c to 4e, we used our custom cascade arc plasma source to simulate the thruster' s experimental environment by placing the cathode within the plasma source and setting specific plasma density and temperature parameters. Material ablation and service life predictions were conducted based on mass loss over specified experimental duration. This study performed independent lifetime experiments and comparisons for W-La cathodes, W-Ce cathodes, and pure W cathodes [43].

The mass loss of three experimental cathode materials under conditions of 3-hour experimental duration, plasma density up to 1.0$\times10^{19}$ m^{-3} (measured by Langmuir probe), and temperature up to 1300°C (measured by bottom plate temperature probe) is shown in Figure 4b. Based on parameters such as gas flow rate, input current, magnetic field strength, and plasma density, the service life of the W-La cathode is estimated at approximately 3000 hours, and about 1100 hours for the W-Ce cathode. This reduction is attributed to decreased thermal resistance of the cathode matrix as rare earth element content increases, leading to higher mass loss under extreme operating conditions and consequently reduced service life.

Thus, in optimizing cathode performance, it is essential to ensure both excellent electron emission performance and high ablation resistance.

C. Microstructural Characterization of Rare Earth Tungsten Alloy Cathodes

The melting, sputtering, and eventual deposition on the cathode material surface due to the W matrix are critical factors affecting cathode lifespan and efficiency. Preliminary analysis of deposits shows no new elements, consisting solely of tungsten oxides that exhibit valence changes at high temperatures [44].

The rare earth tungsten alloy cathode prepared in this study was severely ablated after prolonged ignition experiments. The cathode surface was characterized and analyzed by SEM before and after the experiment, as shown in Figure 5. Figures 5a to 5c show morphological characterization analysis of the W-La15 cathode before the ignition experiment, where La_2O_3 particles are uniformly distributed on the smooth W substrate, with elemental content distribution shown in Figures 6a to 6d. This indicates that low work function components in the rare earth tungsten alloy cathode prepared by our ball milling and liquid-phase synthesis methods are uniformly dispersed, providing favorable conditions for improved cathode electron emission performance. Figures 5c to 5e show morphological characterization of the cathode after ignition experiments, clearly revealing severe shrinkage of the cathode tip hole due to prolonged ignition and plasma sputtering during operation, which also leads to more difficult arc initiation under the same ignition power and propellant flow rate. This result suggests that to obtain the same or greater propulsive efficiency, ignition voltage must be increased to break through the cathode and complete ignition, causing greater damage during the ignition instant. As shown in the figure, the cathode surface exhibits inhomogeneous holes from La_2O_3 particle depletion, demonstrating the feasibility of improving cathode electron emission performance through addition of low work function components to the W matrix. Therefore, our cathode study must balance ablation performance with optimization of ignition conditions.

The W-La cathodes before and after the experiment were further analyzed by energy dispersive spectroscopy, as shown in Figure 6. Figures 6a to 6d show atomic energy spectra and elemental analysis results of the W-La cathode before the experiment, where the dark-colored area corresponds to La_2O_3 particle locations, highly overlapping with point-scan elemental analysis results in this region. Face-scan elemental analysis results indicate that the main material of the entire cathode is tungsten, with La_2O_3 particles uniformly dispersed on the

W substrate surface. Figures 6e to 6h show atomic energy spectra and elemental analysis results of the W-La cathode after the experiment. Surface-scanning elemental analysis results show W content as high as 65.7%, followed by O element, with rare earth La content as low as 1.6%. This indicates that La is doped into the W matrix in the form of W-La_2O_3 and is consumed during discharge to complete electron emission. Analysis of particulate matter on the cathode surface in Figure 6g shows it to be tungsten oxide. Melting and recrystallization of the W matrix at high temperatures changes the valence state to form different tungsten oxides.

The characterization results demonstrate that rare earth oxide W-La_2O_3, due to its low work function, allows electrons near the Fermi level of La to overcome the surface barrier and emit from the material under high voltage between cathode and anode. This results in pore formation that can be distributed very unevenly on emitter surfaces, also demonstrating that low work function provided by rare earth elements has been widely added to improve total emitter performance and efficiency. Moreover, the density, size, and uniformity of such pores on the surface depend on many factors, including second-phase particle size, doping mass fraction, and raw material mixing methods.

Results and Discussion

The cathode represents one of the crucial components of various electronic vacuum devices and space propulsion systems, where electron emission performance and ablation resistance against high-energy particle impacts directly affect overall system efficiency, performance, and lifetime [45]. Therefore, future cathode research must consider how doping elements affect the electron work function of cathode materials, thereby influencing electron emission performance. Additionally, the ratio of doping elements to W matrix affects the overall alloy melting point, which impacts cathode sputtering resistance. Furthermore, cathode preparation methods greatly affect performance, and optimization of the cathode preparation process enables the dopant phase to form nanoscale dispersion in the W matrix, where better dispersion yields better improvement in cathode emission performance.

This paper investigates optimization of high-performance field emission rare earth tungsten alloy cathodes through both simulation and experimental verification. Atomic models were built with Materials Studio for rare earth elements adsorbed onto the W-O (top-site) surface, with relevant surface work functions calculated based on density functional theory. The calculated work function values were 2.645 eV, 2.924 eV, and 2.908 eV for 0.5 ML of Ce, La, and Y adsorbed on the W-O top site, and 2.770 eV, 3.356 eV, and 2.555 eV for 1.0 ML of Ce, La, and Y, respectively. These results reflect that doping rare earth atoms effectively reduces the surface potential barrier of the cathode, confirming that rare earth atom doping is an effective method to enhance cathode electron emission performance.

Some related studies have shown that adding 1% La_2O_3 to W can improve its cutting performance and recrystallization temperature, further optimizing W-La cathode sintering and processing. Based on Materials Studio simulation results, this paper prepared W-La, W-Ce, and W-Y cathodes with different treatment methods and designed and performed a series of ignition tests. Results indicate that compared with pure tungsten cathodes, rare earth tungsten alloy cathodes operate more stably with lower ignition voltage.

A custom-developed cascade arc plasma source was also employed to simulate the real working environment faced by tungsten alloy cathodes. Based on identical operational parameters including gas flow rate, input current, magnetic field strength, and plasma density, service lives for the considered rare earth tungsten alloy cathodes were estimated. Regarding cathode theoretical life prediction research, more mature research programs exist for Hall thrusters and low-power ion thrusters, with less research on cathodes for high-power, high-specific-impulse magnetic plasma thrusters. The HET-80 Hall thruster underwent life verification tests at the Shanghai Institute of Space Propulsion (SISP) and Beijing University of Aeronautics and Astronautics (BUAA). The full life test was conducted in the VF-6 vacuum chamber of SISP with cumulative working time of 9240 hours, while a 1:1 working life test was performed in the DT-2.5 vacuum chamber of BUAA’ s Space Plasma and Electric Propulsion Laboratory with cumulative working life of 8241 hours [46]. Certainly, due to the more severe working environment and higher operating temperatures of high-power magnetic plasma thrusters, cathode life will be greatly reduced. Therefore, factors such as cathode emitter material selection, ablation mechanism research, and cathode processing technology will impact cathode life, and future cathode life optimization research must balance various factors. Long-life, high-performance cathodes for magnetic plasma thrusters will remain a research focus.

Optical microscopy, SEM, and EDS were conducted on cathodes before and after experiments. Experimental results show that the role of rare earth doping in tungsten alloy cathodes is to excite outer valence electrons at high voltage and break down propellant to form plasma. During continuous electron emission, rare earth atom consumption is gradual. However, with increasing rare earth doping ratio, high-temperature resistance of the cathode declines to a certain extent and serious ablation occurs. Thus, by changing the ratio of doping atoms in the cathode, optimization of the trade-off between excellent electron emission performance and good ablation resistance can be achieved.

Based on the above research on different rare earth tungsten alloy cathodes, we believe that high-performance field emission rare earth tungsten alloy cathodes will have great application prospects in vacuum devices, space propulsion, and other fields, where the excellent electron emission performance of tungsten-lanthanum cathodes can greatly improve cathode emission efficiency. The ablation mechanism of rare earth tungsten alloy cathodes and development of longer-life cathodes will be the next research focus.

Bibliography

[1] D.R. Lev, I.G. Mikellides, D. Pedrini et al., Recent progress in research and development of hollow cathodes for electric propulsion. Reviews of Modern Plasma Physics 3(1), 6 (2019). doi: 10.1007/s41614-019-0026-0

[2] Y. Guo, Z. Nie, X. Xi et al., Advances in research on tungsten cathode materials. J. Rare Earths 29(2), 200–205 (2005). doi: 10.13373/j.cnki.cjrm.2005.02.017

[3] M. Mandell, I. Katz, Theory of hollow cathode operation in spot and plume modes. 30th AIAA (ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit, 1994). doi:10.2514/6.1994-3134

[4] I. Katz, M. Mandell, M. Patterson, M. Domonkos, Sensitivity of hollow cathode performance to design and operating parameters, in 35th Joint Propulsion Conference and Exhibit (1999), p. 2576. doi:10.2514/6.1999-2576

[5] M.T. Domonkos, A.D. Gallimore, M.J. Patterson, An evaluation of hollow cathode scaling to very low power and flow rate, in Proceedings of the 25th International Electric Propulsion Conference (IEPC Cleveland, Ohio, USA, 1997), pp. 97–189

[6] J. Hendry, Investigation of efficient designs of hollow cathodes, in 57th International Astronautical Congress (2006), pp. C4–P. doi:10.2514/6.IAC-06-C4.P.4.07

[7] J. Polk, D. Goebel, R. Watkins, K. Jameson, L. Yoneshige, Characterization of hollow cathode performance and thermal behavior, in 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (2006), p. 5150. doi:10.2514/6.2006-5150

[8] C. Huo, F. Liang, A.b. Sun, Review on development of carbon nanotube field emission cathode for space propulsion systems. High Voltage 5(4), 409–415 (2020). doi: 10.1049/hve.2019.0257

[9] J. Zheng, J. Qin, K. Lu et al. Recent progress in chinese fusion research based on superconducting tokamak configuration. The Innovation 3(4) (2022). doi: 10.1016/j.xinn.2022.100269

[10] D.M. Goebel, E. Chu, High-current lanthanum hexaboride hollow cathode for high-power hall thrusters. Journal of Propulsion and Power 30(1), 35–40 (2014). doi: 10.2514/1.B34870

[11] D.M. Goebel, K.K. Jameson, R.R. Hofer, Hall thruster cathode flow impact on coupling voltage and cathode life. Journal of Propulsion and Power 28(2), 355–363 (2012). doi: 10.2514/1.B34275

[12] J. Yanhui, Z. Tianping, Latest development of space-borne lab6 hollow cathode. Chinese Journal of Vacuum Science and Technology 36(6),690–698 (2016). doi: 10.13922/j.cnki.cjovst.2016.06.15

[13] D.M. Goebel, R.M. Watkins, K.K. Jameson, Lab6 hollow cathodes for ion and hall thrusters. Journal of Propulsion and Power 23(3), 552–558 (2007). doi:10.2514/1.25475

[14] C. Drobny, J. Wulfkühler, K. Wätzig, M. Tajmar, Detailed work function measurements and development of a hollow cathode using the emitter material c12a7 electride. SP2018-92, Seville, Spain (2018)

[15] J. Zheng, H. Liu, Y. Song et al., Integrated study on the comprehensive magnetic-field configuration performance in the 150 kw superconducting magnetoplasmadynamic thruster. Scientific Reports 11(1), 20706 (2021). doi: 10.1038/s41598-021-99999-w

[16] Z. Tian-Ping, T. Fu-Jun, T. Hua-Bing, Foreign technique status of hollow cathode for electric propulsion. Aerospace Shanghai (2008). doi:10.19328/j.cnki.1006-1630.2008.01.009

[17] L. Pengfei, F. Jinglian, H. Yong, Z. Man, T. Jiamin, Toughening mechanisms and interfacial bonding of w-zrc composites. RARE METAL MATERIALS AND ENGINEERING 48(3), 751–757 (2019)

[18] W. Yinhe, Y. Jiancan, C. Ran, G. Yinchen, Research rare earth tungsten electrode on erosion resistance of in electric propulsion. RARE METAL MATERIALS AND ENGINEERING 51(10), 3892–3899 (2022). doi:10.26935/d.cnki.gbjgu.2022.000326

[19] S. Wang, X. Zhang, N. Liu, et al., Recent Advances in Research and Development of Emissive Materials for Hollow Cathodes of Electric Propulsion Systems. Chinese Journal of Vacuum Science and Technology 43(12), 993-1002 (2023). doi: 10.13922/j.cnki.cjvst.202306004

[20] F. Peng, Z. Qin, T. Chen et al., Intrinsic emittance of thermionic cathode with work function variation. Acta Electronica Sinica 47(3), 643–648 (2019). doi: 10.3969/j.issn.0372-2112.2019.03.018

[21] C. Spindt, I. Brodie, L. Humphrey et al., Physical properties of thin-film field emission cathodes with molybdenum cones. Journal of Applied Physics 47(12), 5248–5263 (1976). doi: 10.1063/1.322600

[22] D.A. Shiffler, M. Ruebush, D. Zagar et al., Emission uniformity and emittance of explosive field-emission cathodes. IEEE Transactions on Plasma Science 30(4), 1592–1596 (2002). doi: 10.1109/TPS.2002.804172

[23] S.-K. Qi, X.-X. Wang, J.-R. Luo et al., A novel Y2O3-Gd2O3-HfO2 impregnated w base direct-heated cathode in magnetron tube. Acta Physica Sinica 65(5) (2016). doi: 10.7498/aps.65.057901

[24] K.L. Jensen, Y. Lau, N. Jordan, Emission nonuniformity due to profilimetry variation in thermionic cathodes. Applied Physics Letters 88(16) (2006). doi: 10.1063/1.2197605

[25] F. Dong, H. Ye, W. Zhen, G. Jinyu, W. Hong, Preparation and electron emission properties of carbon fiber composited graphite cathodes. Journal of Materials Engineering 51(8), 149–154 (2023). doi:10.11868/j.issn.1001-4381.2023.000135

[26] M.A. Chumak, E.O. Popov, S.V. Filippov, A.G. Kolosko, D.A. Kirilenko, N.A. Bert, E.V. Zhizhin, A.V. Koroleva, I.S. Yezhov, M.Y. Maximov, Reducing and tuning the work function of field emission nanocomposite cnt/nio cathodes by modifying the chemical composition of the oxide. Nanoscale 16(21), 10398–10413 (2024). doi:10.1039/D4NR00908H

[27] E. Wimmer, Computational materials design with first-principles quantum mechanics. Science 269(5229), 1397–1398 (1995). doi: 10.1126/science.269.5229.139

[28] M. Xia, P. Boulet, M.C. Record, Influence of biaxial and isotropic strain on the thermoelectric performance of theory pbsntese high-entropy alloy: A density-functional study. Materials Today Physics 49, 101590 (2024). doi: 10.1016/j.mtphys.2024.101590

[29] X.H. Fan, B. Xu, Y. Xu et al., Application of materials studio modeling in crystal structure. Advanced Materials Research 706, 7–10 (2013). doi: 10.4028/www.scientific.net/AMR.706-708.7

[30] D. Jennison, P. Schultz, D. King et al., Bao/W(100) thermionic emitters and the effects of Sc, Y, La, and the density functional used in computations. Surface Science 549(2), 115–120 (2004). doi: 10.1016/j.susc.2003.10.027

[31] A. Knizhnik, A. Safonov, I. Iskandarova et al., First-principles investigation of the wc/ hfo2 interface properties. Journal of Applied Physics 99(8) (2006). doi: 10.1063/1.2189209

[32] Q. Zhang, F. Tang, Z. Zhao et al., Surface modification of tungsten oxide by oxygen vacancies for hydrogen adsorption. Journal of Materials Science & Technology 117, 23–35 (2022). doi: 10.1016/j.jmst.2021.10.048

[33] C. Wei, J. Fan, H. Gong, Tungsten adsorption on la2o3 (001) surfaces. Materials Letters 161, 313–316 (2015). doi: 10.1016/j.matlet.2015.08.115

[34] W. Peng, W. Yibai, L. Yong et al., Cathode erosion site distributions in an applied-field magnetoplasmadynamic thruster. Plasma Science and Technology 22(9), 094008 (2020). doi: 10.1088/2058-6272/ab9172

[35] M. Vilémová, K. Illková, F. Lukáč et al., Microstructure and phase stability of w-cr alloy prepared by spark plasma sintering. Fusion Engineering and Design 127, 173–178 (2018). doi: 10.1016/j.fusengdes.2018.01.012

[36] C. Wenge, Z. Hui, D. Bingjun, Advances in study on w-la2o3 electrode materials. Ordnance Material Science and Engineering 25(4), 55 (2002). doi: 10.14024/j.cnki.1004-244x.2002.04.015

[37] Z. Dong, Z. Ma, L. Yu et al., Achieving high strength and ductility in ods-w alloy by employing oxide@ w core-shell nanopowder as precursor. Nature Communications 12(1), 5052 (2021). doi: 10.1038/s41467-021-25283-2

[38] J. Xu, Z. Gu, X. Xi et al., Loss mechanism and lifetime estimation of ce–w cathode in high temperature thermionic emission electrostatic precipitation. Journal of Electrostatics 72(4), 336–341 (2014). doi: 10.1016/j.elstat.2014.06.003

[39] C. Cao, C. Wang, J. Ma, et al., Research on sintering technics by hollow cathode discharge for tungsten and its alloy. Hot Working Technology 38(10), 22–24,28 (2009). doi: 10.14158/j.cnki.1001-3814.2009.10.038

[40] A. Sengupta, Destructive physical analysis of hollow cathodes from the deep space 1 flight spare ion engine 30,000 hr life test (Pasadena, CA: Jet Propulsion Laboratory, National Aeronautics and Space, 2005)

[41] A. Sengupta, J. Brophy, K. Goodfellow, Status of the Extended Life Test of the DS1 Flight Spare Ion Engine after 30,352 Hours of Operation, in 40th Joint Propulsion Conference, Fort Lauderdale, FL (2004). doi: 10.2514/6.2003-4558

[42] J.T. Yim, G.C. Soulas, R. Shastry, M. Choi, J.A. Mackey, T.R. Sarver-Verhey, Update of the NEXT ion thruster service life assessment with post-test correlation to the long duration test, in International Electric Propulsion Conference (IEPC) 2017 (2017), IEPC-2017-061

[43] G.A. Csiky, Langmuir probe measurements in a discharge from a hollow cathode. Journal of Spacecraft and Rockets 7(4), 474–475 (1970). doi: 10.2514/3.29966

[44] W.G. Seo, J.W. Kuk, H. Kim et al., Micro/Nano Scale Emission Tip Fabrication for Field Emission Electric Propulsion, in 2023 IEEE 22nd International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS) (IEEE, 2023), pp. 252–255. doi: 10.1109/PowerMEMS59329.2023.10417347

[45] C.M. Marrese, A review of field emission cathode technologies for electric propulsion systems and instruments, in 2000 IEEE Aerospace Conference. Proceedings (Cat. No. 00TH8484), vol. 4 (IEEE, 2000), pp.85–98. doi: 10.1109/AERO.2000.878369

[46] L. Xin, W. Xuan, T. Hai-bin, Z. Zhe, K. Xiao-lu, Beam characteristics of het-80 hall thruster with 700 watts. Journal of Propulsion Technology 39(6), 1426. doi:10.13675/j.cnki.tjjs.2018.06.028

Note: Figure translations are in progress. See original paper for figures.