Study on Influence of Temperature on Field Emission Performance of Metals

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Abstract

The electrons escaping from metal surfaces driven by an external electric field are invariably associated with radio-frequency breakdown of microwave systems, seriously limiting the physical performance of accelerators and electronic devices. In this paper, the influence of temperature on the field emission characteristics of metals has been investigated by using a field emission system. After a heater is installed in the field emission system, the cathode's temperature can be adjusted from room temperature to hundreds of degrees centigrade. It is experimentally revealed that the field emission performance of titanium and oxygen-free copper is greatly improved when the temperature is increased within 100 degrees centigrade. The field-emission current of oxygen-free copper at 105℃ increases to 4.0 times its value at room temperature as the intensity of the applied electric field remains 140 kV/cm, while the field-emission current of titanium at 150℃ is 14.6 times that at room temperature under an electric field strength of 190 kV/cm. These experimental phenomena are not consistent with the traditional metal model. Afterwards, the thermal-field emission theory of dielectric microdot is introduced to reasonably explain the promotion of temperature on the field-emission characteristics of these two metals, indicating that the dielectric microdots on the surface dominate the thermal-field emission of metals. The new discovery can provide theoretical guidance for suppressing vacuum breakdown in microwave devices and accelerators.

Full Text

Study on the Influence of Temperature on Field Emission Performance of Metals

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Abstract

Field electron emission from metal surfaces driven by external electric fields is invariably associated with radio-frequency breakdown in microwave systems, seriously limiting the physical performance of accelerators and electronic devices. In this paper, we investigate the influence of temperature on the field emission characteristics of metals using a dedicated field emission system. By installing a heater in the system, the cathode temperature can be adjusted from room temperature to hundreds of degrees Celsius. Our experiments reveal that the field emission performance of titanium and oxygen-free copper is substantially improved when the temperature is increased within 100°C. Specifically, the field-emission current of oxygen-free copper at 105°C increases to 4.0 times its room-temperature value when the applied electric field intensity remains at 140 kV/cm, while the field-emission current of titanium at 150°C becomes 14.6 times that at room temperature under an electric field strength of 190 kV/cm. These experimental phenomena are inconsistent with the traditional metal model. Subsequently, we introduce the thermal-field emission theory of dielectric microdots to reasonably explain the enhancement of field-emission characteristics with temperature, indicating that dielectric microdots on the surface dominate the thermal-field emission of metals. This new discovery can provide theoretical guidance for suppressing vacuum breakdown in microwave devices and accelerators.

INTRODUCTION

High-gradient radio-frequency (RF) breakdown severely degrades the operational reliability and lifetime of accelerating structures and vacuum electronic devices, representing a major technical bottleneck that limits the physical performance of microwave systems. As microwave systems pursue higher output power and longer pulse duration, the risk of RF breakdown increases enormously. Over the past several decades, the physical mechanisms behind high-gradient RF breakdown and plasma discharge have attracted considerable interest. The prevailing view is that RF breakdown is closely associated with field electron emission (FEE) from metal surfaces. On the one hand, FEE can transform into explosive electron emission (EEE) under a locally intensive electric field, during

which a large amount of energy is absorbed in the cavity, leading to a rapid drop in internal field strength and triggering breakdown. On the other hand, the accumulation of plasma due to concentrated bombardment of structure surfaces by field-emitted electrons may also cause RF breakdown.

The traditional Fowler-Nordheim formula is generally utilized to analyze the field emission characteristics of metals. After obtaining the field-emission current varying with the applied electric field (I-E curve), the equivalent field enhancement factor resulting from protrusions, defects, and grain boundaries can be acquired through mathematical transformation of the Fowler-Nordheim formula. In tests by many researchers on different metallic materials, the equivalent field enhancement factor has been found to range from tens to hundreds, indicating that extremely sharp structural mutations exist on metal surfaces. However, these structures have not been confirmed by material characterization methods, including optical microscopy and scanning electron microscopy (SEM). This contradiction between experimental observations and theoretical calculations implies that the physical mechanism of field emission from metals needs further exploration.

In this work, we experimentally examine the influence of temperature on the field emission performance of titanium and oxygen-free copper. The field current of these two metals is substantially increased by temperature rises of less than 100°C, which differs from the theoretical expectation of the traditional metal model. We reasonably explain these experimental observations using the thermal-field emission theory of dielectric microdots, verifying that the experimental findings result from temperature acting on dielectric microdots. This paper is organized as follows: Section I presents experimental results regarding the influence of temperature on field emission performance of titanium and oxygen-free copper. Section II introduces and discusses the theoretical analysis. Finally, Section IV provides a brief summary and conclusion.

I. EXPERIMENTAL RESULTS

The schematic of the field-emission test system is shown in Fig. 1 [Figure 1: see original paper]. A molecular pump and a sputtered ion pump employed in this system are used to improve the vacuum degree of the test environment. The field-emission test is performed when the vacuum degree is stable below 10^{-5} Pa. When a high voltage is applied between the anode and cathode, the cathode is driven by an intensive electric field to produce field-emitted electrons, which are ultimately collected by the anode.

Fig. 1. Schematic of the field-emission test system loaded with a heating furnace.

To improve the efficiency of electron collection, the anode radius is generally larger than the cathode radius. Under this condition, structural distortion at the cathode edge results in local electric field enhancement, as shown by the blue line in Fig. 2 [Figure 2: see original paper]. The electric field intensity

at the edge is more than 3.6 times that of the uniform electric field at the center when an applied voltage of 5 kV is employed and the distance between the two electrodes is maintained at 0.5 mm. Therefore, field-induced electrons first appear from the cathode edge. The space-charge shielding effect caused by strong edge emission may intensively inhibit field electron emission at the center of the cathode, interfering with measurement of the field emission performance. To avoid this, the cathode edge needs to be chamfered. After field simulation and parameter optimization, the geometric parameters of the anode and cathode are determined. The cathode adopts a replaceable cylindrical structure with a radius of 5 mm, while the anode is made of indium-tin oxide (ITO) with good conductivity and has a radius of 8 mm. Additionally, the chamfer radius of the cathode edge is $r_0 = 2.5$ mm.

The electric field distribution on the cathode surface is displayed by the red line in Fig. 2 while the external conditions remain the same as before chamfering. The edge enhancement effect is significantly suppressed, and the electric field is almost uniformly distributed within a radius of less than 3.5 mm. It should be pointed out that a field-emission current of 10 pA can be detected even when no voltage is loaded between the anode and cathode. We believe this is the inherent leakage current between these two electrodes, which needs to be deducted in the calculation. Beyond electrical design, a heating furnace is placed under the cathode platform to heat the cathode. Additionally, a micro stepper motor with a resolution of 10 m is utilized to control the relative position of the cathode. When the cathode moves downward, it is continuously heated by the heating furnace. The cathode temperature can be adjusted from room temperature to 600°C, which is monitored online by a thermocouple during the experiment.

Fig. 2. Electric field distribution on the cathode surface before and after chamfering with an applied voltage of 5 kV and a distance between the anode and cathode of 0.5 mm.

Different heating powers correspond to different steady-state temperatures of the cathode. At a specific temperature, the applied voltage is progressively increased, and the accompanying emission current is then measured. The cathode samples made of titanium and oxygen-free copper are subjected to three processes prior to experimental operation: mechanical polishing, ultrasonic cleaning, and high-temperature baking. The roughness of the cathode samples is measured as less than 0.2 m by a three-dimensional confocal laser microscope (Olympus Lext OLS4100) after mechanical polishing. At this roughness level, the surface topography has limited influence on field emission performance according to previous studies. The duration of ultrasonic cleaning and high-temperature baking is 1 hour and 3 hours, respectively, with a baking temperature of 125°C. After these pretreatments designed to avoid interference from oil and water vapor on the surface, the field emission characteristics of titanium and oxygen-free copper are acquired and demonstrated in Fig. 3 [Figure 3: see original paper].

As depicted in Fig. 3(a), temperature rising within 100°C significantly promotes the field emission performance of titanium. The field emission current of I = 117

A at 150°C is 14.6 times higher than that at room temperature (25°C) when the applied electric field intensity remains at 190 kV/cm. Similar to titanium, the field emission properties of oxygen-free copper are also greatly enhanced with increasing temperature. When the electric field intensity is maintained at 140 kV/cm, the field emission current of I = 107 A at 105°C is 4.0 times that at room temperature, as shown in Fig. 3(b). The experimental observations indicate that further increasing the electric field significantly elevates the probability of inter-electrode breakdown. Once breakdown occurs, it may lead to vacuum deterioration and structural degradation of the device. This explains the operational protocol of terminating voltage escalation upon detecting emission currents reaching the hundred-microampere range.

Fig. 3. Field emission characteristic curves of titanium (a) and oxygen-free copper (b) with different cathode temperatures.

II. ANALYSIS AND DISCUSSION

First, we attempted to theoretically explain the effect of temperature on the field emission performance of titanium and oxygen-free copper by adopting the thermal-field emission model for metals. Without considering thermal effects, the field emission current density (J_{FN}) satisfies:

$$J_{FN} = \frac{e^3 E_0^2}{8\pi h \phi_w t^2(y)} \exp\left(-\frac{8\pi\sqrt{2m_e}\phi_w^{3/2}}{3heE_0} v(y)\right)$$

where E_0 denotes the normal strength of the electric field (V/cm), β represents the field enhancement factor, ϕ_w presents the work function of metallic materials (eV), and k, h, m_e, and e are Boltzmann's constant, Planck's constant, the electron mass, and the electron charge, respectively. The two elliptic functions of variable y are t(y) and v(y):

$$t(y) = \left(\frac{1}{2} + \frac{1}{2}\sqrt{1-y^2}\right)^{1/2}$$

$$v(y) = \sqrt{1-y^2} - \frac{y^2}{2} \ln \frac{1+\sqrt{1-y^2}}{1-\sqrt{1-y^2}}$$

with

$$y = \frac{e\sqrt{eE_0}}{2\phi_w\sqrt{4\pi\varepsilon_0}}$$

According to the traditional thermal-field emission model, FEE gradually converts to thermo-field emission as temperature increases. The thermo-field emission current density (J_{TFN}) is expressed as:

$$J_{TFN} = J_{FN}\frac{\pi kT/d}{\sin(\pi kT/d)} = \frac{e^3E_0^2}{8\pi h\phi_w t^2(y)}\exp\left(-\frac{8\pi\sqrt{2m_e}\phi_w^{3/2}}{3heE_0}v(y)\right)\frac{\pi kT/d}{\sin(\pi kT/d)}$$

where d represents:

$$d = \frac{heE_0}{2\pi\sqrt{2m_e kTt(y)}}$$

Substituting E_0 = 200 kV/cm (similar to that applied in the experiment), ϕ_w = 4.3 eV (close to titanium's work function), and $\beta = 100$ into the equations, the field emission current density varying with applied temperature is acquired and demonstrated in Fig. 4 [Figure 4: see original paper]. The thermal-field emission current density is mainly determined by the applied electric field when the temperature is lower than 500°C; therefore, the enhancement of temperature on field emission current is negligible under these conditions. In contrast, the effect of temperature on field emission performance of metals progressively begins to appear when the temperature exceeds 600°C, which is inconsistent with the experimental phenomena shown in Fig. 3. Hence, the traditional metal model is difficult to reconcile with the experimental observation that field emission properties of titanium and oxygen-free copper are significantly enhanced when temperature rises within 100°C.

Fig. 4. Field emission current density varying with applied temperature based on the traditional metal model.

Further morphological characterization and energy dispersive spectroscopy (EDS) have yielded notable observations. As demonstrated in Fig. 5 [Figure 5: see original paper], the surfaces of oxygen-free copper and titanium exhibit no adhered particles following ultrasonic cleaning and high-temperature baking, despite displaying residual mechanical processing traces such as scratches and microvoids. EDS analysis reveals that both metal surfaces still contain carbon and oxygen components, even though their contents are less than 3%. These elements predominantly constitute surface oxide layers and adsorbed impurities. Previous studies have shown that dielectric impurities preferentially accumulate at grain boundaries due to irregular atomic arrangement, where their bonding with metallic matrices forms thermodynamically stable configurations resistant to dissolution through regular treatments. Consequently, the role of dielectric impurities at grain boundaries in modulating the field emission properties of titanium and oxygen-free copper deserves further investigation.

Fig. 5. SEM morphology characterization and energy dispersive spectroscopy for titanium (a) and oxygen-free copper (b).

To explain the enhanced field emission performance of titanium and oxygen-free copper, we introduce the thermal-field emission theory of dielectric microdots.

After considering thermal effects, the field emission current density of dielectric microdots (j_d) satisfies:

$$j_d = \frac{e^3 n_0 \mu E_s}{4\pi^2 \hbar^2} \exp\left(-\frac{4\sqrt{2m_e}\phi^{3/2}}{3eE_s}\frac{\pi^2 C k_B T_0}{eE_s \lambda}\right)$$

where $_0$ is the permittivity of free space, ϕ is the work function of dielectric microdots, T_0 is the temperature of dielectric microdots, is the electron mobility, _s is the sound velocity, E_s = E_0/ _r is the internal electric field of the dielectric, and _r is the relative dielectric constant of the dielectric. The equation can be simplified as:

$$j_d = A \exp\left(-\frac{B}{E_0^{0.5}} + \frac{C}{T_0 E_0^{0.5}}\right)$$

where X is a constant determined by the properties of the dielectric:

$$X = \frac{2\pi^2 \varepsilon_0 \varepsilon_r \mu \nu_s}{3}$$

If the temperature of dielectric microdots satisfies T_0 < 500°C and the strength of the applied field satisfies E_0 > 1 kV/cm, we have:

$$\sin\left(\frac{p\pi}{2}\right) \approx \frac{p\pi}{2} \quad \text{for} \quad p < 1$$

Thus, the equation is rewritten as:

$$j_d = A \exp\left(-\frac{B}{E_0^{0.5}} + \frac{C}{T_0 E_0^{0.5}}\right)$$

When the applied electric field satisfies $BE_0^{0.5}$ - ϕ < 0, the thermal-field current density of dielectric microdots increases exponentially with temperature (T_0) on the basis of a quadratic growth relationship with temperature. The field emission area, denoted as S_e, serves as the critical parameter for determining the field emission current:

$$I = j_d S_e = A S_e \exp\left(-\frac{B}{E_0^{0.5}} + \frac{C}{T_0 E_0^{0.5}}\right)$$

Equation (17) is further mathematically transformed:

$$\ln\left(\frac{I}{E_0^2}\right) = \ln[A S_e (k T_0 X)^2] + \frac{B}{k T_0 X}\frac{1}{E_0^{0.5}} - \frac{\phi}{k T_0 X}\frac{1}{E_0}$$

Let y = ln(I/E^2) and x = 1/E$^{0\cdot5}$, we have:

$$y = a_1 + a_2 x + a_3 x^2$$

where a$_1$ = ln[AS_e(kT$_0$X)^2], a$_2$ = B/kT$_0$X, and a$_3$ = -ϕ/kT$_0$X. Different from the linearity of ln(I/E^2)-1/E shown by the Fowler-Nordheim formula, the relationship between ln(I/E^2) and 1/E$^{0\cdot5}$ is quadratic. The field emission curves of titanium and oxygen-free copper with temperature are analyzed based on these equations. The experimental data regarding titanium's field emission characteristic curves (Fig. 3(a)) are processed by plotting the transformed coordinates of ln(I/E^2) versus 1/E$^{0\cdot5}$. The scatter distribution of ln(I/E^2)-1/E$^{0\cdot5}$ is then fitted by a quadratic function. The fitted curves shown in Fig. 6 [Figure 6: see original paper] demonstrate good agreement with the experimental data.

Fig. 6. ln(I/E^2)-1/E$^{0\cdot5}$ fitting curves of titanium at different temperatures.

Consistent with this methodology, the field emission characteristics of oxygen-free copper presented in Fig. 3(b) undergo identical coordinate transformation. The resulting ln(I/E^2)-1/E$^{0\cdot5}$ distribution is similarly analyzed through quadratic fitting, exhibited in Fig. 7 [Figure 7: see original paper]. Notably, these fitted curves maintain strong congruence with the measured results, thereby verifying the universal applicability of the dielectric microdot model across different metallic materials under temperature loading.

Fig. 7. ln(I/E^2)-1/E$^{0\cdot5}$ fitting curves of oxygen-free copper at different temperatures.

Through rigorous analysis of the quadratic fitting results, characteristic coefficients including the quadratic term a$_1$, linear coefficient a$_2$, and constant a$_3$ are quantitatively determined. Correspondingly, the equivalent emission area and maximum emission current density are derived based on the following equations:

$$a_2 = \frac{B}{kT_0X}$$

$$S_e = \frac{\exp(a_1)}{A(kT_0X)^2}$$

$$J_m = \frac{I_m}{S_e}$$

where I_m denotes the maximum emission current recorded at a certain temperature corresponding to the maximum electric field, and J_m represents the local maximum emission current density at a certain temperature.

Fig. 8. Emission area and maximum emission current density of titanium (a) and oxygen-free copper (b) at different temperatures.

As illustrated in Fig. 8 [Figure 8: see original paper], both titanium and oxygen-free copper exhibit emission areas on the order of 10^{-12} cm^2, with copper demonstrating a relatively larger emission area compared to titanium. Notably, the observed temperature-dependent oscillation in emission area reveals a complex thermal activation phenomenon requiring further mechanistic investigation. This thermal effect, combined with temperature-induced variations in work function, likely contributes to the deviation between theoretical prediction and experimental data shown in Figs. 6 and 7. Furthermore, the maximum emission current density on the order of 10^7 A/cm^2 has been derived for both titanium and oxygen-free copper, which is consistent with previous studies showing that field emission stability can be maintained at current densities up to ~10^7 A/cm^2. Considering the significant effect of temperature on field emission performance of metallic materials, the critical role of thermal management in high-power microwave applications must be emphasized. The localized heat accumulation generated during prolonged high-repetition operation could potentially accelerate electron generation and surface degradation, thereby lowering the RF breakdown threshold. Therefore, these insights suggest that surface engineering through advanced pretreatment techniques targeting temperature limitation and reduction of dielectric impurities may offer an effective physical method for enhancing both the breakdown resistance and operational stability of next-generation microwave devices.

III. CONCLUSION

In conclusion, we have studied the influence of temperature on field emission from titanium and oxygen-free copper using a field emission system. Contrary to the effect of temperature on field emission performance predicted by the traditional metal model, our experiments found that temperature increases within 100°C significantly enhance the field emission performance of titanium and oxygen-free copper. The observed phenomena are reasonably explained by introducing the thermal-field emission theory of dielectric microdots. It is verified that the key factor affecting field emission properties of metallic materials is dielectric impurities on the metal surface. Next, we intend to explore possible pretreatments for reducing dielectric impurities on metal surfaces to improve the breakdown threshold of microwave devices.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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