Effect of insulating layer on the Field Electron Emission Performance of Nano-Apex Metallic Emitters

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Abstract: This paper deals with the process of electron emission from the surface of metals (before and after coating with controlled layers of dielectric materials) into the vacuum due to an intense applied external electric field. This process is usually called cold field electron emission (CFE). The research work reported here includes the current-voltage (I–V) characteristics presented as Fowler-Nordheim (FN) plots and scanning electron micrographs in addition to the spatial emission current distributions (electron emission images). The process of coating the clean tungsten (W) emitters by layers of dielectric epoxytite resin was easy, and the measurements were performed under UHV ~ 10⁻⁸ mbar. From comparing the results obtained in this work, significant improvement in properties of the emitters after coating are observed.

1. Introduction

Electron emission refers to the release of electrons from the surface of a material into vacuum [1]. Field-induced emission of electrons was explained in 1928, by combining quantum tunneling theory with Fermi-Dirac statistical theory [2]. This was one of the early triumphs of both theories, and a stepping stone towards the modern band theory of solids. The theory of field electron emission from bulk metals was proposed by Ralph H. Fowler and Lothar W. Nordheim [3]. A family of approximate equations, "Fowler–Nordheim-type equations", is named after them. Strictly speaking, these equations apply only to field emission from bulk metals, but the theory is often used – as a rough approximation – to describe field emission from other materials [1]. The material vastly used to carrying out experiments of field electron emission is tungsten [4], due to its superior properties, such as high mechanical strength (hard material due to its weak grain boundaries), high melting point of 3422 °C, and lowest vapor pressure at temperatures above 1650 °C, in addition to a remarkable high density and chemical stability.

Other experiments were carried out using the glass coated conductive materials [5], carbon nanotubes [6, 7], and carbon fibers [8, 9]. There are many improvements and developments that has occurred on the Fowler-Nordheim equations [10-16]. The coating of electron emitters by controlled insulating layer technique was used to improve the properties of electron emitters [2, 5, 17].

2. Experimental techniques

The microprint nano-apex metallic emitters used for such measurements were electrolytically etched from tungsten 0.1mm diameter with 99.95% purity wires using a 1M solution of NaOH. Then the tip is ultrasonically cleaned, its profile recorded using SEM, tested at the home built Field electron microscope (FEM) before being coated with epoxytite resin (Clark Electromedical Instruments). The coating procedure involved firstly very slowly dipping a tip into the resin and then accurately removing it to ensure that only a thin film remained on the tip surface. To make sure that this coating forms a regular film located on the tip surface, the tip is then carefully transferred to an oven and subjected to a curing
cycle of thirty minutes at 100 °C to drive off the solvents, followed by another thirty minutes at 185 °C to complete the curing of the resin [4].

The thickness of such a resin film was measured by comparing the radius of the nano tip-apex before and after coating the tip. The radius of tip Nano-apex was measured at 20 KV Scanning Electron Microscope (SEM). A clean W-tip is presented in fig. 1a while in fig. 1b shown after being coated with 0.01945 μm of epoxylite resin.

The experimental facility used to measure the field electron emission characteristics and the emission image data, are carried out in a simple geometry field emission microscope, where the separation between the cathode and the anode was standardized at ~ 10 mm. The emission images were photographed directly from the phosphor screen. All the experiments were performed under pressure ~ 10⁻⁸ mbar after baking the ultra high vacuum (UHV) system to ~ 200 °C for 12 hours.

![Fig.1: Micrographs of W-tip (a) before coating and (b) after coating with 19.45 nm of epoxylite resin.](image)

3. Experimental findings

The measurements described below include the I-V characteristics and the emission images of the W-tips before and after coating with 0.01945 μm of epoxylite resin by dipping.

3.1 Emission characteristics

The general form of the I-V characteristic acquired from the composite emitters is presented in fig.2. From the trend shown, it can be seen that as the applied voltage is slowly increased across the virgin composite emitter, a point is reached, $V_{sw}$, where the emission current switches-on unawares from an effective zero to a stable saturated value $V_{SAT}$. The saturated region 3 to an upper voltage limit $V_{max}$, marked by the onset of current instabilities and possibly followed by a tip explosion. By slowly decreasing the switching voltage to a lower value the emission current starts to be decreasing until a limit reached, beyond which the emission current falls smoothly to zero as the applied voltage is decreased to the threshold value $V_{th}$. However, as shown in the figure, this part of the characteristics can be routinely divided into a transition region 2, limited by $V_{L}$, and a low-field region 1 where the I-V data gives a linear Fowler-Nordheim (F-N) plot similar to what has been reported elsewhere[4, 17].
Fig.2: The generalized form of the current-voltage (I-V) characteristic of a W-emitter coated with insulating layer.

The characteristics have been presented using two methods. The first one, which provides very useful information about the emission behavior, is the typical simple I-V plot. This plot demonstrates the dependence of the emission current $I$, on the externally applied voltage $V$, between the emitter and anode [4, 17]. In Fig. 3, curves (A) and (B) represent the comparison of the $I$-$V$ characteristics of the tungsten microprint emitter before and after the coating by 19 nm insulating layer, and curve (C) shows the $I$-$V$ characteristics after switching-on of the electron emission current. In Fig.3, curve (A), the characteristics of the emitter is shown for before coating the electron emission initiated at applied voltage $= 540$ V. For the coated emitter, curve (B) shows that the electron emission is initiated at an applied voltage $= 100$ V. Curve (C) demonstrates the electron emission characteristics that is initiated by a high conventional switch-on the voltage $V_{SW}$ of 2800 V, generating a saturation current, $V_{SAT} = 1.1 \times 10^{-5}$ A. On lowering down the applied voltage, the $V_{SAT}$ remained constant to the saturated voltage value of $V_{SAT} = 2100$ V, and then started to fall smoothly to $V_{L}= 500$ V. It then continues to decline to zero as the applied voltage is lowered down to a threshold value $V_{TH} = 100$ V. After that, the electron emission is initiated at an applied voltage of 100 V, with emission current $= 6.7$ nA and reached to $1.1$ $\mu$A emission current at applied voltage $= 500$ V. This refers to a significant improvement in the performance of the electron emitter.
Fig. 3 The $I-V$ characteristics of an uncoated tungsten emitter (curve A), after coating with 19 nm layer of epoxylite resin (curve B), and (curve C) presents the I-V characteristics after switching-on of the electron emission.

The second method gave the Fowler-Nordheim (F-N) plots of the clean tungsten emitter (curve A) and that obtained from the composite emitter (curve B) as shown in Fig. 4., in a similar trend to what has been reported elsewhere [4, 17].
Fig. 4: Fowler-Nordheim plots of the electron emission of clean emitter (curve A), the electron emission of coated emitter (curve B), and (curve C) the electron emission after switch electron emission on of the coated emitter whose $I-V$ characteristics are presented in Fig.3.

3.2 Emission images
The electron emission images were photographed directly from the phosphored conductive screen (anode) of the field emission microscope. The emission was concentrated into a single very bright spot that showed no obvious structure within the image. In order to highlight the deference between the emission of the emitter before and after coating, Fig.5 compares the images obtained at a standard emission current of $4.6\times10^{-7}$ A for the same emitter before and after coating. It is shown that, for a given emission current, the composite electron source is much brighter than the clean uncoated metallic source.

Fig. 5: Projection images obtained (a) a clean tungsten emitter and (b) after coating with 17 nm insulating layer. Both images were recorded with the same distance between the tip and the screen and the same emission current $4.6\times10^{-7}$ A.
The switch-on phenomenon discussed in the previous section and demonstrated in Fig. 3, was recorded and shown in the sequence of four images in Fig. 6. When the applied voltage reaches a value of 2800 V, the emission current reaches the saturated value $I_{SAT} = 1.3 \times 10^{-5}$ A. In this example, the emission image was concentrated in a single bright spot without any apparent structure within the image.

![Image](image.png)

(a) ![Image](image.png) (b) ![Image](image.png) (c) ![Image](image.png) (d) ![Image](image.png)

Fig. 6: Sequence of projection images reproduced at actual size showing how the spot size improve with emission saturated current value.

For the tungsten emitter that was coated with an insulating layer of 17 nm thick, the emission appeared to come from several well defined sub-emission centers. This is shown in Fig. 7. The treatment that produced such effects included repeated thermal treatment of the source, and relaxation process by which the tip was left emitting under vacuum overnight. Such effects and the mechanism behind, can be studied and discussed in a future work.
Fig. 7: A sequence of emission of tungsten emitter coated by 17 nm insulating layer thick.

Table 1: the rsm calculated from the scanning electron microscope for the three samples before and after coating. This shows the minimum voltage needed to start the emission before coating, the thickness of insulating layers on the samples, switch-on voltage (Vs), saturation current (Is), minimum saturation voltage and threshold voltage (Vth) of the emission after coating. Where: rsm: Radius of tip calculated by using scanning electron microscope. dr: the thickness of insulating layer on the tip

| Tip.No | rsm (nm) | Vlow (volt) | rsm (nm) | dr (nm) | Vs (volt) | Is (μA) | Vsat (volt) | Vth (volt) |
|--------|----------|-------------|----------|---------|-----------|--------|-------------|-----------|
| 1      | 102      | 540         | 106.85   | 4.85    | 2800      | 13     | 2100        | 100       |
| 2      | 109.3    | 570         | 126.3    | 17      | 2000      | 9      | 1100        | 100       |
| 3      | 120.2    | 1410        | 140.85   | 20.65   | 4200      | 25     | 3400        | 200       |

4. Conclusion
It has been demonstrated that the field emission characteristics of tungsten electron source are drastically changed by coating the emitter with a layer of insulating material. So, such a composite emitter exhibits a switch on phenomenon with a subsequent smooth and reversible current-voltage characteristic whose threshold field lower than that of the clean tungsten electron emitter. The next table shows the emission data obtained from tungsten emitters before and after coating with dielectric epoxylite resin.
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