INTRODUCTION

Developing electron sources with better characteristics and lifetimes is a very important task for applied electronics. This paper is about novel forms of field electron emission (FE) source, and continues work previously reported by the Mutah University field emission group (Alnawasreh et al., 2015; Mousa et al., 2012).

The first observation of what appears to be an FE-initiated electric discharge was made by Winkler (1744). The first clear review of experimental FE phenomena (then called “autoelectronic emission”) was given by Lilienfeld (1922). Many modern emitters operate in the so-called “cold field electron emission (CFE)” regime, which is a regime where (i) the electrons in the emitting region are effectively in local thermodynamic equilibrium and (ii) most electrons escape by deep tunneling from states close to the emitter’s Fermi level (Forbes, 2012; Forbes et al., 2015). The first scientist to attempt a presumptive theory for the CFE regime was Schottky (in 1923). Fowler and Nordheim (in 1928) developed the first appropriate theory for explaining field emission related phenomena. This theory was later improved by Murphy and Good (1956) and many others. CFE from a bulk emitter is described by approximate equations known as Fowler-Nordheim-type (FN-type) equations (Forbes, 2012; Forbes et al., 2015). The technically complete (generalized) FN-type equation for the local emission current density $J_L$ can be written in the form (Forbes, 2012; Lilienfeld, 1922).

$$J_L=\lambda_L a \phi^{-1} F^2 \exp \left[-\nu_F b \phi^{3/2}/F \right]$$

Where, $a$ and $b$ are the first and second Fowler-Nordheim constants, respectively. The barrier form correction factor $\nu_F$ accounts for the particular shape of the potential barrier model to be used, and the local pre-exponential correction factor $\lambda_L$ formally takes into account all other factors that influence the emission. Of course, these two correction factors also depend on the applied field $F$, as well as material parameters. This equation has been called the “technically complete FN-type equation for $J_L$ in terms of $\phi$ and $F$” (Forbes, 2012). For the Schottky-Nordheim (SN) barrier (Forbes,
2012), the barrier form correction factor is given by a well-defined special mathematical function $v_F$, sometimes called the "principal SN-barrier function".

General aims when manufacturing composite micropoint cathodes have been to avoid degradation of the electron emitter tip due to ion sputtering processes during emission, to obtain an electron emitter with long lifetime, and improve the emission characteristics (Mousa, 1990; Mousa & Al Share, 1999; Mousa et al., 2001).

The objective of the present investigation is to study the impact of dielectric coatings, using two different forms of resin: (1) Clark Electromedical Instruments Epoxylite resin ("CEI resin") and (2) Epidian 6 epoxy resin (based on bisphenol A) ("E6 resin"). We examine the effects on the characteristics and emission stability of tungsten and carbon-fiber micro-emitters coated with these resins. Observations made include current-voltage ($I-V$) characteristics, plotted using FN plots, and electron emission images, observed in a field electron microscope (FEM).

**MATERIALS AND METHODS**

Procedures for coating a tungsten (W) tip have been described elsewhere (Al-Qudah et al., 2015; Latham & Mousa, 1986; Madanat et al., 2015; Mousa et al., 2015). The micropoint emitters used were electrolytically etched from 0.1 mm diameter tungsten wires (99.95% purity), using a 2 M solution of NaOH and for carbon fiber tip were using a 0.1 M solution of sodium hydroxide solution (Mousa et al., 2015). Then the tips were ultrasonically cleaned. The coating procedure involves slowly dipping the tip into the dielectric, and then carefully removing it to ensure that only a thin film remains 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 curing of the resin.

The coated tips were studied in evacuated FEMs with a diffusion pump system having an additional liquid nitrogen trap. Base pressures of $10^{-6}$ Pascal ($10^{-8}$ mbar) have been reached.

**Fig. 1.1.** (A) The current-voltage ($I-V$) characteristics of a clean tungsten tip, taken as voltage increases; (B) related Fowler-Nordheim (FN) plot. The applied voltage is in the range of 430 to 980 V. The FN-plot slope is $-3.059$ decade V.

**Fig. 1.2.** Images of field emission from clean tungsten tip are distributed in several spots, when increasing the voltage. The emission current was getting brighter. As can be seen from the emission images, emission spots start to become brighter or bigger as the voltage was increased. Image details are: (A) 780 V, 51 nA; (B) 870 V, 100 nA; (C) 960 V, 5.50 nA.
reached after baking the system at a temperature of 200°C for 12 hours with liquid nitrogen added to the trap. The separation between the tip apex (cathode) and the screen (anode) was standardized at ~10 mm using a current limiting resistor of 20 MΩ. The images presented were taken by a digital camera through the window of the vacuum system. An electric high tension power supply is used to apply a negative voltage to the cathode. The emission current is measured with a Keithley 485 auto-ranging pico-ammeter (Madanat et al., 2015; Moran Meza et al., 2015).

**RESULTS AND DISCUSSION**

As indicated above, tungsten and carbon-fiber microemitters with two types of dielectric coating, namely “CEI resin” and “E6 resin”, have been analyzed. Results are compared below with those obtained with clean uncoated tungsten and carbon-fiber microemitters.

**Composite Tungsten/CEI-Resin Emitter**

Voltage was applied to the clean tungsten tip and the $I-V$ characteristics were recorded. The emission started at 430 V with current 8.8 pA. Increasing the applied voltage very slowly caused an increase in the emission current; voltages applied in the range 430 to 980 V gave currents in the range 8.8 pA to 690 nA, as shown in Fig. 1.1A; Fig. 1.1B shows the related FN plots. Fig. 1.2 shows how the emission image depends on the emission current.

**Composite Tungsten/CEI-Resin Emitter**

Voltage was applied to the clean tungsten tip and the $I-V$ characteristics were recorded. The emission started at 430 V with current 8.8 pA. Increasing the applied voltage very slowly caused an increase in the emission current; voltages applied in the range 430 to 980 V gave currents in the range 8.8 pA to 690 nA, as shown in Fig. 1.1A; Fig. 1.1B shows the related FN plots. Fig. 1.2 shows how the emission image depends on the emission current.
For the composite tungsten/CEI-resin tip, the voltage across a new (untested) emitter is slowly increased until a “switch-on voltage” $V_{sw}$ is reached. At this point the emission current switches on abruptly from an effectively zero value to a stable apparently saturated value, namely the “switch-on current” $I_{sat}$. At this point, $V_{sw}$ is 2,300 V and $I_{sat}$ is 3.3 μA. If the voltage is then reduced, the emission current reduces gradually. Fig. 1.3A shows the $I-V$ characteristics for the first such decreasing scan, which takes place over the voltage range 2,300 V down to 200 V and the corresponding current range 3.3 μA to 32 pA. When the voltage is increased again, there is no abrupt “switch-on phenomenon”, but the current increases steadily.

**Fig. 1.5.** For the composite tungsten/CEI-resin emitter, these images show that emission is relatively stable in one high brightness spot. Measurement details were: (A) 2,300 V, 3.3 μA; (B) 2,100 V, 3.3 μA; (C) 1,700 V, 3.2 μA; the time separation between adjacent images is 15 minutes.

![Graph](image)

**Fig. 2.1.** (A) The current-voltage ($I-V$) characteristics for a clean carbon-fiber tip, taken as voltage increases; (B) related Fowler-Nordheim (FN) plot. The applied voltage is in the range of 200 to 700 V. The FN-plot slope is $-1,313$ decade V.

![Images](image)

**Fig. 2.2.** Images of field emission of carbon-fiber tip, when increasing the voltage. The emission current was increasing. As can be seen from the emission images, emission spots start to become brighter or bigger as the voltage was increased. Image details are: (A) 660 V, 1.0 μA; (B) 680 V, 1.5 μA; (C) 700 V, 2.2 μA.
as shown in Fig. 1.4A. As the voltage increases from 200 V to 900 V, the current increases from 10 pA to 2.2 μA. The right parts of Fig. 1.3 and Fig. 1.4 show the related FN plots. The emission images, Fig. 1.5, which are taken at 15-minute intervals, show that the emission current distribution is relatively stable.

**Composite Carbon-Fiber/CEI-Resin Emitter**

Voltage was applied to the clean carbon-fiber tip and the \( I-V \) characteristics were recorded. Emission started at 220 V with current 5.5 pA. Increasing the applied voltage very slowly caused an increase in the emission current; voltages applied in range 220 to 700 V gave currents in the range 2.2 pA to 2.2 μA, as shown in Fig. 2.1A; Fig. 2.1B shows the related FN plots.

Fig. 2.2 shows the relationship between emission current and the emission images for the clean carbon-fiber tip. With the composite carbon-fiber/CEI-resin tip, there was no “switch-on” phenomenon. Fig. 2.3A shows the \( I-V \) characteristics for the first increasing voltage scan, for the voltage range 260 to 550 V and current range 4.5 pA to 1.4 μA; Fig. 2.4A shows the immediately following voltage scan, with voltage decreasing from 550 V down to 150 V and current from 1.6 μA to 1.2 pA. The right parts of Fig. 2.3 and Fig. 2.4 show the related FN plots.

Fig. 2.2 shows the relationship between the emission image and emission current for the clean carbon-fiber tip; Fig. 2.5 shows similar information for the composite carbon-fiber/CEI-resin tip.

---

**Fig. 2.3.** (A) The current-voltage \( (I-V) \) characteristics of composite carbon-fiber/CEI-resin, during the first increasing-voltage scan; (B) related Fowler-Nordheim (FN) plot. The applied voltage is in the range of 260 to 550 V. The FN plot slope is \(-2,333\) decade V.

---

**Fig. 2.4.** (A) The current-voltage \( (I-V) \) characteristics of composite carbon-fiber/CEI-resin, during the first decreasing-voltage scan; (B) related Fowler-Nordheim (FN) plot. The applied voltage is in the range 550 V down to 150 V the FN plot slope is \(-768\) decade V.
Composite Tungsten/E6-Resin Emitter

As above, voltage was applied to the clean tungsten emitter (before coating) and the $I-V$ characteristics were recorded. The emission started at 640 V with current 8.3 pA. Increasing the applied voltage very slowly caused an increase in the emission current; voltages in the range 640 to 1,550 V gave currents in the range 8.3 pA to 1.1 μA, as shown in Fig. 3.1A; Fig. 3.1B shows the related FN plots. Fig. 3.2 shows how the emission image relates to emission current.

With the composite tungsten/E6-resin tip, a "switch-on" effect...
again occurred. At the switch-on voltage \(V_{sw}\), the emission current turns on from an effectively zero value to an apparently stable saturated value, namely the “switch-on current” \(I_{sat}\). Switch-on values were \(V_{sw}=12,300\) V and \(I_{sat}=12\) μA.

Fig. 3.3A shows the \(I-V\) characteristics for the first decreasing voltage scan, with voltage decreasing from 12,300 V down to 4,500 V and current from 12 μA down to 5.7 pA. Fig. 3.4 then shows part of a subsequent increasing-voltage scan, from 500 to 5,300 V, with currents from 13 pA to 1.8 μA. The right parts of Fig. 3.3 and Fig. 3.4 show the related FN plots. Fig. 3.5 shows how emission images relate to emission current.

**Composite Carbon-Fiber/E6-Resin Emitter**

As above, voltage was applied to the clean carbon-fiber tip before coating, and the \(I-V\) characteristics were recorded. Emission started at 400 V, with current 1.1 pA. Increasing the applied voltage very slowly caused an increase in the emission current; voltages in the range 400 to 750 V gave currents in the range 1.1 pA to 1.9 μA, as shown in Fig. 4.1A; Fig. 4.1B shows the related FN plots. Fig. 4.2 shows the related emission images.

With the composite carbon-fiber/E6-resin emitter, a switch-on phenomenon was again observed with the previously untested emitter. At the switch-on voltage \(V_{sw}\), the current jumps from an effectively zero value to an apparently stable, saturated value, namely the “switch-on value” \(I_{sat}\). Values were \(V_{sw}=1,300\) V and \(I_{sat}=5.3\) μA. Fig. 4.3A shows the \(I-V\) characteristics for the subsequent first decreasing voltage scan: as voltage decreases from 1,300 V down to 500 V, current decreases from 5.3 μA to 3.0 pA. In a subsequent voltage-

![Fig. 3.3](image1)

![Fig. 3.4](image2)
increasing scan Fig. 4.4, voltage increase from 400 to 790 V caused current increase from 1.1 pA to 1.0 μA. The right parts of Fig. 4.3 and Fig. 4.4 show the related FN plots. Fig. 4.5 shows related emission images.

**CONCLUSIONS**

Composite emitters, consisting of clean tungsten and carbon fiber tips with known profile, coated by dielectric materials, were investigated. It is found that the field emission
characteristics of these micro-emitters are intrinsically changed by coating the emitters with a thin layer of dielectric material, this is in line with the results from previous investigations (Al-Qudah et al., 2015; Bajic et al., 1989; Latham & Mousa, 1986; Moran Meza et al., 2015; Mousa, 1987, 1988, 1992, 1994, 2007; Mousa & Kelly, 2003; Mussa et al., 2012). By comparing
the effects of different coating materials, we find the following effects. Clark Electromedical Instruments Epoxylite resin improves the characteristics of the tungsten emitter more than those of the carbon-fiber emitter. Likewise, Epipan 6 epoxy resin (based on bisphenol A) improved the characteristics of the tungsten emitter more than the characteristics of the carbon-fiber emitter, Table 1 shows the extent of changes on the I-V characteristics of the nanoemitters after being coated with dielectric layer. The composite samples reported in this work could be considered as a potential powerful electron source for technical uses. The produced electron beam can be employed in many applications such as been reported by Lee et al. (2015) where the beam was used in transmission electron microscopy for sample preparation of Ge2Sb2Te5.

| Tip                                      | Clean tip characteristic | Composites tip characteristic |
|------------------------------------------|--------------------------|-------------------------------|
|                                         | Applied voltage range (V) | Emission current range (nA) | Switch-on voltage (V) | Switch-on current (μA) | Applied voltage range (V) | Emission current range (nA) |
| Composite tungsten/CEI-resin emitter     | 430~980                  | 0.0088~690                   | 2,300                 | 3.3                     | 2,300~200                  | 330~0.0032                  |
| Composite carbon-fiber/CEI-resin emitter | 220~700                  | 0.0022~2,200                 | -                    | -                      | 260~550                   | 0.0045~1,400                |
| Composite tungsten/E6-resin emitter      | 640~1,550                | 0.0083~1,100                 | 12,300                | 12                     | 12,300~4,500               | 12,000~0.0057               |
| Composite carbon-fiber/E6-resin emitter  | 400~750                  | 0.0011~1,900                 | 1,300                 | 5.3                    | 1,300~500                 | 5,300~0.003                 |

**REFERENCES**

Alnawasreh SS et al.

Table 1. The extent of changes on the current-voltage (I-V) characteristics of the nano emitters (nanotips) after being coated with epoxylite resin layer of different thickness Clark Electromedical Instrument (CEI)

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGMENTS

Ala’a M. Al-Qudah, Emad S. Bani Ali and Ayman Almasri would like to express gratitude to the Scientific Research Support Fund SRSF in the Hashemite Kingdom of Jordan for financial support that enabled completing this research work.
using metal, carbon fiber and composite field emission sources modulated by a laser beam. *Ultramicroscopy* **89**, 129-135.

Mousa M S, Fischer A, and Mussa K O (2012), Metallic and composite micropoint cathodes: aging effect and electronic and spatial characteristics. *Jo. J. Phys.* **1**, 21-26.

Mousa M S and Kelly T F (2003) Stabilization of carbon-fiber cold field-emission cathodes with a dielectric coating. *Ultramicroscopy* **95**, 125-130.

Murphy E L and Good R H (1956) Thermionic emission, field emission and the transition region. *Phys. Rev.* **102**, 1464-1473.

Mussa K O, Fischer A, and Mousa M S (2012) Characterizing a new composite material: effect of NaOH coating of variable thickness on the properties of a tungsten microemitter. *Jo. J. Phys.* **5**, 27-31.

Winkler J H (1744) *Gedanken von den Eigenschaften, Wirkungen und Ursachen der Elektrizität nebst Beschreibung zweier electricer Maschinen* (Verlag B. Ch. Breitkopf, Leipzig).