

Regenerable Field Emission Cathode for Spacecraft Neutralization

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This research investigates the discharge characteristics of a field emission cathode for use in electric propulsion that has the ability to be regenerated when the emitter tip becomes damaged. Emitter tip regeneration is achieved by taking advantage of Taylor cone formation from an operating liquid–metal ion source. Tip formation is accomplished by solidifying, or quenching, the ion-emitting cone to preserve the sharp protrusion so that it can then be used for electron emission. Electron emission I - V curves were taken after tips were formed by quenching the liquid–metal ion source at ion discharge currents ranging from 1 to 25 μA . Fowler–Nordheim modeling was then used to estimate the emitter tip radii of each quenched liquid–metal ion source. Results of the Fowler–Nordheim modeling were promising, showing the ability to regenerate tips and to control the features of the resulting tips by varying the ion current during the quench process. The set of experiments that are reported demonstrated the regeneration process of emitter tip radii ranging from approximately 30–45 nm from a tip quenched at 2 μA down to tip radii of 15–22 nm when quenched at 25 μA .

Nomenclature

A	=	total emitting area, m^2
a	=	Fowler–Nordheim term [see Eq. (2)]
b'	=	Fowler–Nordheim term [see Eq. (3)]
E_o	=	local electric field, V/m
I	=	discharge current, A
k	=	empirical relation for tip radius and gap spacing
r_t	=	emitter tip radius, m
$V_{\max}$	=	extraction voltage required for 0.5 μA of emission current, V
V_o	=	extraction voltage, V
α	=	Nordheim image-correction term
μ	=	Fowler–Nordheim term
ϕ	=	work function, eV

I. Introduction

INTEREST in the miniaturization of space propulsion has been growing over the past 10 to 15 years. The Darwin infrared space interferometer and the Laser Interferometer Space Antenna (LISA) [1] are examples of missions that require technology capable of producing 0.1 to 1000 μN of thrust with low thrust noise and high thrust precision. Two ideal candidates that could meet the thrust requirements are the colloid microneutron thruster (CMNT) and the field emission electric propulsion (FEEP) thruster [1–3]. CMNT and FEEP thrusters are unique in that they do not require a cathode for propellant ionization. However, a neutralizer is still necessary to maintain spacecraft neutrality, because an operating FEEP thruster will still cause a global charge imbalance on a spacecraft. Because CMNT and FEEP thrusters operate using only a few watts of power and very little propellant, traditional neutralizers cannot be used, due to their relatively massive propellant and power requirements. Most

traditional neutralizers require an inert-gas flow and heater power to thermionically emit electrons [4]. From a propellant consumption and power requirement standpoint, the thruster efficiency for a CMNT or FEEP thruster would be extremely low if a cathode were used that required more propellant and power than the thruster itself. Therefore, a low-power neutralizer with minimal propellant requirements would be ideal.

One solution is the field emission cathode. Field emission cathodes use nanoscale sharpened electrodes with locally enhanced electric fields to stimulate electrons to escape from the surface of the electrode into vacuum via a quantum tunneling effect known as Fowler–Nordheim emission. If the electric field at the sharp electrode is great enough (greater than 10^9 V/m), electrons can essentially leak through the potential barrier at the metal surface by applying a potential between the sharp electrode and an extraction electrode, as shown in Fig. 1 [5]. Because the local electric field is inversely proportional to the electrode tip radius, the sharper the emitter tip, the lower the electric potential needed to obtain electron field emission [6]. A tungsten single-needle field emitter typically has a tip radius on the order of tens of nanometers to a few microns and can produce up to 100 μA of electron emission current [5].

Field emission cathodes are used as neutralizers for space propulsion devices and as electron sources for flat-panel displays, focused electron beams for electron microscopy, and neutralization for spacecraft mass spectrometry [6–9]. The motivation for the research reported here is the limited lifetime of many current microfabricated field emitters, with the exception of carbon nanotube cathodes, which have demonstrated impressive life tests [10]. With most field emission cathodes, as electron discharge is continued for long periods of time, the emitter tip begins to wear and blunt.

In 2007, Makela and King [11] proposed and demonstrated a technique for regenerating emitter tips using a liquid–metal ion source (LMIS) to construct nanoscale metal structures intended for use as electron field emission neutralizers for space applications. Historically, LMISs have found extensive use as ion sources of high brightness in focused-ion-beam materials-processing applications [12] and, more recently, as electric propulsion (EP) thrusters via the FEEP technology mentioned previously [13–15]. In an LMIS or FEEP thruster, an intense electric field is created near the surface of a low-melting-temperature liquid metal, such as indium, by a downstream electrode. A balance between the liquid surface tension and the electrostatic force between the liquefied metal and the downstream electrode causes a structure known as a Taylor cone to form in the liquid, as shown in a micrograph taken from Driesel et al.'s work [16] in Fig. 2. Because the Taylor cone has a very sharp tip, geometric

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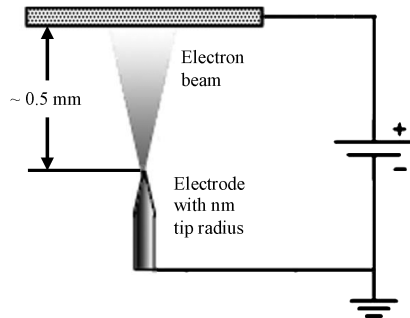


Fig. 1 Field emission cathode schematic.

enhancement of the local electric field at the cone tip is sufficient to extract metal ions directly from the liquid. The ions emerge from a very narrow (few-nanometer diameter) liquid jet at the cone apex and are subsequently accelerated by the electric field to either produce thrust (FEEP) or for materials-processing applications (LMIS). Other applications and areas of interest for the use of focused ion beams include lithography, semiconductor doping, sample preparation for transmission electron microscopy imaging, circuit repair, scanning ion microscopy, and scanning ion mass spectroscopy [17].

The research reported here takes advantage of Taylor cone formation of an LMIS to construct sharp nanoscale structures. By solidifying, or quenching, an operating LMIS, one can preserve the sharp ion-emitting jetlike protrusion for use as a field emission cathode for EP. The resulting metal structure has a tip radius of tens to hundreds of nanometers, depending on the quenching conditions. It then becomes possible to use the emitter tip to obtain Fowler–Nordheim emission of electrons by reversing the polarity of the LMIS extraction electrode. The sharp protrusions are ideal due to the fact they only require extraction voltages of tens to thousands of volts to obtain field emission [6]. The protrusions can then be used as field emission electron sources until the point in time when the tip becomes damaged, causing their performance to degrade. When performance degrades, the emitter tip can once again be operated as an LMIS to form and quench another sharp jetlike protrusion. The process of tip regeneration can be repeated as long as there is a sufficient coating of indium on the tungsten electrode.

Although never applied to EP or space-based applications, the idea to use a liquid–metal Taylor cone as a combined electron/ion source is not new. The earliest documentation of a liquid–metal electron source (LMES) was the work of Swanson and Schwind [18]. Because the formation of a Taylor cone is independent of field polarity, Swanson and Schwind applied electron-extracting fields to a liquid metal in an effort to obtain electron emission from the liquid cone. Their experiments showed that stable electron emission was impossible to achieve from a liquid metal and that the emission current that was recorded from the liquid metal occurred in pulses. They referred to the emission as explosive, because small portions of the liquid metal were expelled as pulsed emission. The phenomena responsible for pulsed emission were supported by Gomer [19] the following

year. Later, using gallium and indium, Rao et al. [20] found that it is possible to obtain dc electron emission if the LMES is first operated as an LMIS and then the Taylor cone is “frozen in” so that electron emission is induced from a solid, rather than liquid, metal tip. It is now understood that during operation as an LMIS, the Taylor cone forms a jetlike protrusion at the cone apex that can be solidified when the cone is quenched by removing heater power. It is the protrusion that is responsible for the stable electron emission when the extraction electrode polarity is changed to emit electrons.

In previous work, Makela and King [11] showed the feasibility of creating field emitting tips from frozen Taylor cones by quenching the ion-emitting jetlike protrusions at emission currents ranging from 0 to 25 μA . It was shown that an indium emitter tip can be regenerated as long as there is a sufficient supply of indium to obtain ion emission. It was also found that the electron I - V characteristics of a field emitter could be altered in two ways. The first is dependent on the amount of heat that is applied to liquefy the indium during ion emission and the second depends on what ion emission current at quench was chosen. It was determined that quenching at higher ion emission current produced sharper emitter tip radii than when quenched at lower currents. Applying the Fowler–Nordheim model to the electron I - V data yielded tip radii ranging from 80 to 230 nm at quench currents of 0 to 25 μA [21].

The research reported here focused on investigating the reproducibility of the jetlike protrusion that is formed when quenching an operating LMIS. The solidified protrusions were used to generate electron emission I - V curves so that the Fowler–Nordheim model could be applied to estimate emitter tip radii. Tip radii were evaluated from protrusions formed at ion quenching currents ranging from 0 to 25 μA . Multiple tests were performed under the same conditions to address the repeatability of forming tips through Taylor cone quenching.

II. Description of Apparatus

It has become common practice to coat electrochemically etched tungsten electrodes with low-melting-temperature metals to use as sites for Taylor cone formation [22]. For the experiments reported here, sharpened tungsten electrodes with desirable geometry and surface features for electron and ion emission were formed using an electrochemical etching reaction in a 200 mL solution of 2 molar concentration NaOH and a 0.25-mm-diam tungsten wire. The tungsten electrodes were then coated with a thin layer of indium.

To electrochemically etch the tungsten, the wire was suspended in the center of a 250 mL cylindrical beaker with a cylindrical stainless-steel mesh placed along the perimeter of the beaker, as shown in the cross-sectional schematic in Fig. 3.

By applying a dc bias between the partially submerged tungsten wire (anode) and the immersed stainless-steel electrode (cathode), a sharpened tungsten electrode with a smooth surface finish and emitter tip radius of tens of nanometers to tens of micrometers is formed [23]. Unfortunately, most liquid-metal coatings on smoothly etched needles tend to pull away from the needle apex in an effort to minimize area and surface energy. Therefore, one additional

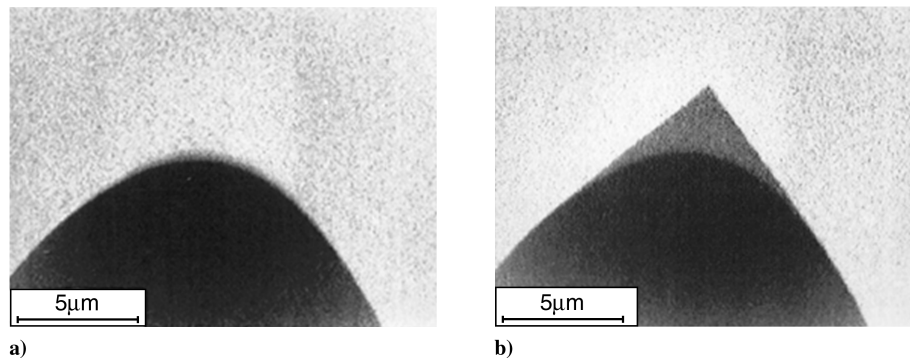


Fig. 2 Image showing an emitter tip a) without and b) with a Taylor cone, courtesy of Driesel [16].

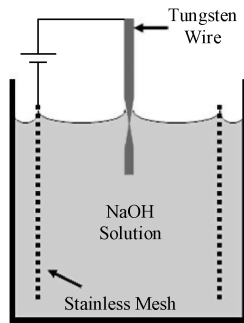


Fig. 3 Electrochemical etching configuration.

electrochemical etch was performed to obtain a surface finish with longitudinal microgrooves on the electrode [24].

The additional etch was performed using a function generator to produce a sinusoidal waveform [24]. For the second etching procedure, the majority of the tungsten electrode must be submerged in the 2 molar concentration NaOH solution. At a minimum, the area that requires indium coating must be submerged. By biasing the electrode using the ac conditions mentioned, the geometry of the microgrooves can be altered by adjusting the amplitude and frequency of the sinusoidal input. The exposure time of the tungsten electrode to the ac conditions also can alter the surface finish. One example of an etched electrode is shown in Fig. 4. The grooves act as capillaries that aid indium flow to the tip of the electrode [24].

The tungsten electrodes were coated by heating sharpened needles and dipping them in a heated crucible of liquefied indium in a vacuum environment of 10^{-6} torr. The vacuum environment is necessary to minimize the oxidation of the indium. The tungsten electrode was then dipped into and removed from the molten indium crucible 5 times. The repeated dipping was done to ensure that an even coating of indium was applied on the surface of the tungsten electrode. The etched and coated tungsten emitter was then cooled, removed from the vacuum environment, and inserted into a Teflon fixture with a planar stainless-steel extraction electrode placed approximately $500\ \mu\text{m}$ away, as shown in the schematic in Fig. 5.

The entire assembly was then placed in an ultrahigh vacuum (UHV) chamber. The UHV chamber is approximately 0.5 m in diameter by 0.5 m deep and has a base pressure of 10^{-9} torr, which is achieved by pumping with a single 280 liter/s turbomolecular pump that is backed by a 110 liter/min dry scroll pump. The tank is also equipped with a 300 liter/s combination ion-sublimation pump to reach ultrahigh vacuum. An operating pressure of 5×10^{-8} torr was maintained while testing the regenerable field emission cathode.

One additional feature of the UHV facility is a trinocular stereo microscope. The microscope is situated outside the front viewing port of the chamber and has a focal length that allows viewing within the chamber. The microscope has an optical magnification up to $90\times$ and it is equipped with a color digital camera. The camera's optical

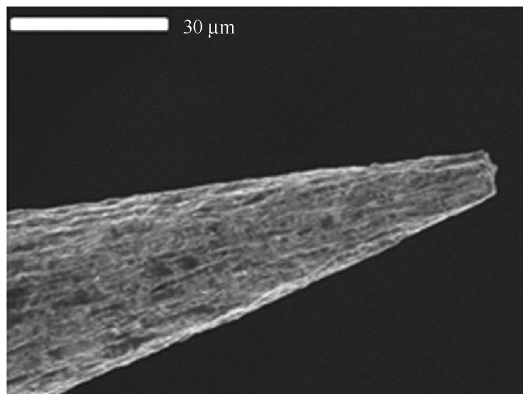


Fig. 4 Electrochemically etched tungsten electrode showing longitudinal microgrooves that act as capillaries. The capillaries supply liquid indium to the electrode tip.

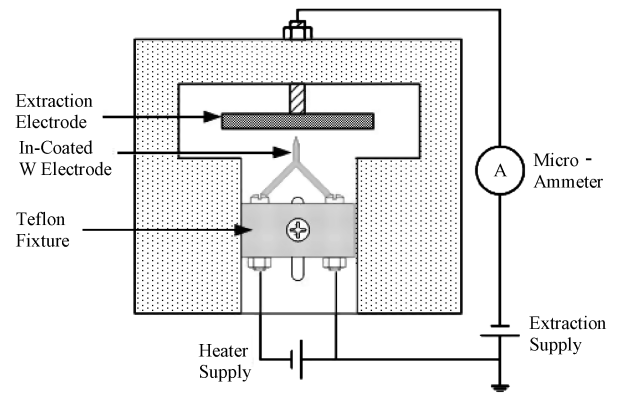


Fig. 5 Dual ion/electron source electric schematic.

magnification provides a limited ability to capture in situ images of an operating LMIS for diagnostic purposes, as well as the ability to record video. However, the optical microscope cannot resolve images at the magnification that is necessary to see or measure the nanoscale emitter tips.

III. Results

To obtain ion emission, it was necessary to first liquefy the layer of In on the W electrode. To adequately liquefy the indium, the emitter heating supply (shown in Fig. 5) was powered and increased to attain a temperature greater than the melting point of indium, which is 156°C . For the experiments reported here, the heater power during ion emission remained between 1 and 1.25 W, which corresponded to 2.4 to 2.5 A of heater current. The heater supplied enough power to keep the In liquefied, without heating it to significant vaporization. The extraction electrode was then biased negatively with a high-voltage power supply and the emitter electrode was grounded. The negative voltage was increased until ion emission was achieved, typically requiring 3 to 4 kV for the onset of emission. At that point, the high-voltage power supply was current-limited at an ion discharge current of $2\ \mu\text{A}$, allowing the voltage to float when necessary to maintain ion-field evaporation. The current-limited operation was maintained for the first 30 min; during this period, ion emission stabilized at constant voltage. After the 30 min period, the ion discharge current was then switched to voltage-limited mode. The extraction voltage could then be adjusted to obtain a desired ion emission current. When the emission current of interest was reached, the emitter heater power was quickly reduced to 0 W, causing the emission current to decrease to $0\ \mu\text{A}$ in 2 to 3 s. Removing the heat source was done to quench a sharp jetlike protrusion, such as the one shown in Fig. 6.

Once a sharp emitter was formed by quenching, the extraction electrode was biased with a positive potential to obtain electron field emission from the cold needle. The extraction voltage was swept between 0 and the voltage necessary to obtain $0.5\ \mu\text{A}$ of emission current, which will be referred to from this point forward as V_{max} . The extraction voltage was swept by using the analog input controls on the high-voltage power supply. A step function was input to sweep the extraction voltage at 25 V intervals every second up to V_{max} while recording 1000 samples/s of the emission current through the analog output of a microammeter. The microammeter was designed

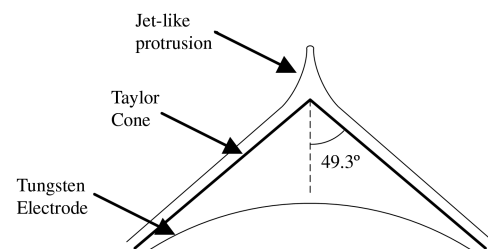


Fig. 6 Taylor cone and jetlike protrusion on an LMIS.

and built in-house to measure a 0 to 100 μA signal floating up to 10 kV and to optically isolate a calibrated output of 0 to 10 V, corresponding to the current. The analog output could then be safely isolated from the extraction voltage and recorded directly into a computer data acquisition system.

Sharp emitters were formed at ion emission currents between 0 and 25 μA to determine what effect quenching current had on the electron emission characteristics. The procedure for the first 25 experiments was to first obtain ion emission, then quench the emitter to solidify and preserve the jetlike protrusion, and then use the quenched protrusion to produce an electron emission I - V curve by sweeping the extraction voltage while recording the emission current. After the electron emission characteristics were established, the emitter heater was increased to 2 W for 25 to 30 s with no applied extraction voltage in an effort to flash heat the emitter tip and, it is hoped, destroy the tip to prepare for reformation in subsequent tests. It was initially thought that melting the indium on the emitter tip in the absence of an electric field would allow the surface tension of the liquefied indium to destroy any sharp protrusions so that additional testing could be done to form new sharp tips at different quenching currents. Upon further investigation using the optical microscope, it was obvious that merely increasing the amount of heat to the emitter wasn't removing the sharpened protrusions: subsequent tests were likely inducing emission from the same protrusion each time. This prevented a study of protrusion shape as a function of ion quench current, and so a new method was conceived to destroy the emission site before regrowth. The new method involved quickly increasing the extraction voltage to approximately 10 to 12 kV. The increase in extraction voltage caused the emitter to briefly arc to the extraction electrode, a process that exploded the protrusion off of the emitter apex, giving off a microscale white flash. An image acquired using the microscope before removing the jetlike protrusion and the instant after removing the protrusion is shown in Fig. 7.

Once the new method of blunting the emitter tips was discovered, a new set of experiments was conducted ranging the ion emission current at quench between 0 and 25 μA . Just as previously done, the heater power was increased to approximately 1 W and then the extraction voltage was increased until ion emission began. Then the ion source was current-limited at 2 μA for 30 min. After the emission stabilized, the ion discharge current was switched to voltage-limited mode. The extraction voltage was then adjusted to achieve the desired emission current and then the heater power was turned off, solidifying the jetlike protrusion. The polarity of the extraction electrode was then reversed to obtain electron field emission and swept from 0 to V_{max} . Multiple electron I - V curves are shown in Fig. 8. Each curve was taken after quenching a jetlike protrusion at a different ion emission current. Between each successive test the tips were exposed to an increased electric field to cause tip explosion, followed by the application of 2 W of heater power in an attempt to smooth out any additional protrusions.

IV. Discussion

Because of the limitations of optical microscopy, the highest magnification of the microscope that was employed during the reported testing wasn't powerful enough to resolve the detail necessary to measure emitter tip radii. Fortunately, using the electron

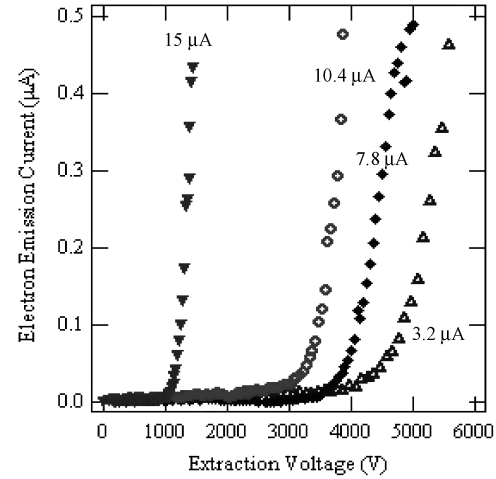


Fig. 8 A sample of electron emission current vs extraction voltage data for emitters quenched at ion currents of 3.2, 7.8, 10.4, and 15 μA .

I - V curves along with the Fowler–Nordheim equation, it was possible to make a theoretical estimate of the emitter tip radius. For tip radius evaluation, Gomer's technique [5] of applying the following Fowler–Nordheim equation was used:

$$\frac{I}{V_o^2} = a \left[\exp\left(\frac{-b'\phi^{3/2}}{V_o}\right) \right] \quad (1)$$

where a and b' are curve fits corresponding to characteristics of the I - V data plotted as $\ln(I/V_o^2)$ versus I/V_o and are introduced as the following:

$$a = A[6.2 \times 10^6 (\mu/\phi)^{1/2} (\mu + \phi)^{-1} (\alpha k r_t)^{-2}] \quad (2)$$

and

$$b' = 6.8 \times 10^7 \alpha k r_t \quad (3)$$

In this series of equations I is the discharge current measured in amperes, V_o is the extraction voltage measured in volts, ϕ is the work function in electron volts, A is the total emitting area, α is the Nordheim image-correction factor, and $k r_t$ is the field voltage proportionality factor [5].

When plotted, the graph of $\ln(I/V_o^2)$ versus I/V_o is linear, as shown in Fig. 9, and has an intercept of $\ln(a)$ and a slope of $b'\phi^{3/2}$. Using Eq. (3) and taking α to be 1 and k equal to 5 for a parabolic tip shape, the tip radius r_t can be approximated [5]. The Fowler–Nordheim model was applied to each of the quench conditions to estimate tip radii and is shown in Fig. 10.

It is clear from looking at Fig. 10 that the emitter tip radius decreases as the ion current at quench is increased. This was expected from an examination of Fig. 8. Sharper protrusions have much lower onset voltages, where onset voltage is defined as the extraction voltage at which field emission begins. Numbers were placed next to each data point in Fig. 10, showing the chronological order in which the data were collected.

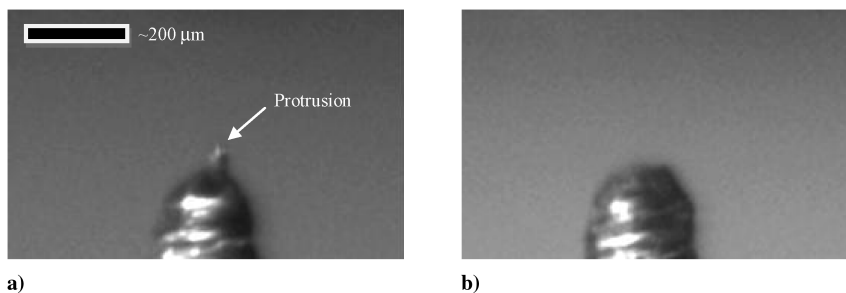


Fig. 7 Microscopic images of an indium coated tungsten electrode with a) jetlike protrusion solidified and b) after the protrusion has been removed.

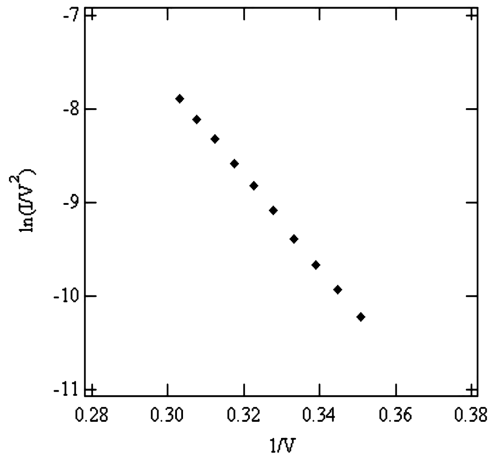


Fig. 9 Fowler-Nordheim plot of electron field emission taken on a cold tip after quenching at a 15 μA ion emission current.

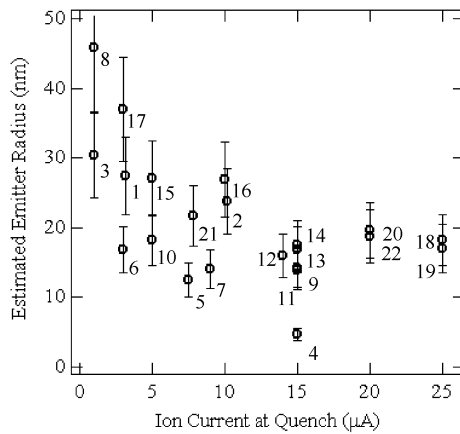


Fig. 10 Estimated electron emitter radius using Fowler-Nordheim modeling at quenching currents ranging from 0 to 25 μA . The number next to each data point shows the sequential order in which the data were collected.

It has been shown that the ion emission current before quenching a jetlike protrusion has a large impact on the electron I - V characteristics when the polarity of the extraction electrode is reversed and the voltage is swept from 0 to a few kilovolts. It is also clear that as the ion current before quench is increased, there is an increase in the electron emission at much lower extraction voltage. Because the local electric field at the emitter apex is approximated as

$$E_o = V_o / kr_t \quad (4)$$

where V_o is the applied potential, r_t is the tip radius, and k is a geometric factor that can be approximated as 5 for most emitters with a parabolic tip shape, it is clear to see that local field enhancement increases as the emitter tip radius decreases [5]. Therefore, it is assumed that as the ion current before quench increases there is a decrease in jetlike protrusion radius, which agrees with the Fowler-Nordheim model. Experimental data taken by Forbes [25] and Driesel et al. [26] using transmission electron microscopy shows the same trend of decreasing tip radius with an increase in emission current; however, the opposite trend was shown by a limited data set and theoretical models by Chen and Wang [27] as well as Knapp et al. [28].

After establishing that a relationship existed between ion quenching current and the emitter tip radius, multiple protrusions were formed at each quench current to determine tip reproducibility. The amount of scatter in the estimated emitter tip radii was approximately 15 nm at each quench current, as shown in Fig. 10. From this limited data set it appears that once ion quenching currents

of 15 μA are exceeded, the emitter tip radius reaches a minimum. This could be due to microdroplet emission causing the tip to break off from the emitter apex at higher emission currents [25].

V. Conclusions

The ability for a field emission electron source to repair itself is advantageous for a number of reasons. The most important reason is to increase the lifetime of the propulsion system. Field emission cathodes are currently being employed with low-power space missions, and their ability to reliably supply electrons lies with maintaining sharp emission electrodes. The experiments that were reported successfully demonstrated the ability for field emission electrodes to be regenerated when they become damaged.

It was found that the ion quenching current has an important role in the geometry of the jetlike protrusion that is formed. By applying the Fowler-Nordheim model to the data that were collected, it is apparent that higher quenching currents form sharper protrusions, which is what was expected when looking at the electron I - V curves after each quench. The electron I - V curves showed that electron emission onsets at much lower extraction voltages from emitters that were quenched at higher currents. Also, it was found that emitter tips could be reproduced to within a range of about 15 nm at each ion quenching current.

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