

ADSORBATE EFFECTS ON FIELD EMISSION

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by

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Abstract

If a metallic surface is subjected to a sufficiently large electric field (about 1 volt/nanometer), then electrons at the top of the conduction band can readily escape into the vacuum by tunneling through a small barrier. This process is known as field emission and can be described in fairly simple terms. The result, which relates the emission probability to the strength of the electric field and the work function of the metal, is described by what is known as the "Fowler-Nordheim" equation [1]. The effects of adsorbates on the emission properties are, however, not well understood. In the present experiments, the effects of gas adsorbates on the emission properties of Spindt-type molybdenum cathode field emitter arrays were studied. The emission was characterized for an emitter that had been exposed to conditions at atmospheric pressure and then compared to that from a clean metallic surface in an ultrahigh vacuum (about 10^{-9} torr). Adsorbates were removed from the molybdenum tips of the field emitter by using electron-stimulated desorption so as to remove residual adsorbates in a non-destructive manner. After the emitter had been exposed to the atmosphere, the initial cleaning process resulted in a slight increase in emission from baseline levels. Further cleaning, however, proved to reduce emission to below baseline levels indicating that adsorbate coverage has a significant and complex effect on emission properties. We offer an explanation for both observations.

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1. Introduction

1.1 Electron Emission

Electron emission is the process by which electrons near the top of the conduction band of a metal escape the metallic surface. An electron occupying one of these states sees a barrier produced by coulomb interactions from neighboring electrons. In order for one of these electrons to escape the surface it must either be excited into a higher energy level that exceeds the energy of the barrier potential (the work function for the metal) or tunnel through this finite barrier. The first process described is known as thermionic emission and the latter is a cold cathode emission. Both techniques have been pursued in the electronics display industry.

In thermionic emission the temperature of the cathode is high (about 1000 Kelvin) and the relative field strength is low (about 0 volts). As the cathode temperature increases, more electrons are excited beyond the Fermi level, E_F , until eventually, when the temperature is high enough, the energy of the highest occupied electron state exceeds the Fermi energy by an amount comparable to the work function of the metal. This total energy will then exceed that of the barrier potential keeping the electron confined to the metal. The electron is then free to escape from the metal into the vacuum. Figure 1 shows the process by which this emission takes place, with $e\mathbf{j}$ representing the work function of the metal, E representing the energy level of a particular electron, E_F as the Fermi level of the metal, $E=0$ as the ground state electron on the surface, and the lines in between as the occupied electron states. Thermionic emission is used, for example, in cathode ray tubes where a tungsten filament, which is held at several thousand Kelvin

and a low potential, ejects electrons that are then guided with different steering potentials to a phosphorus screen maintained at a higher potential.

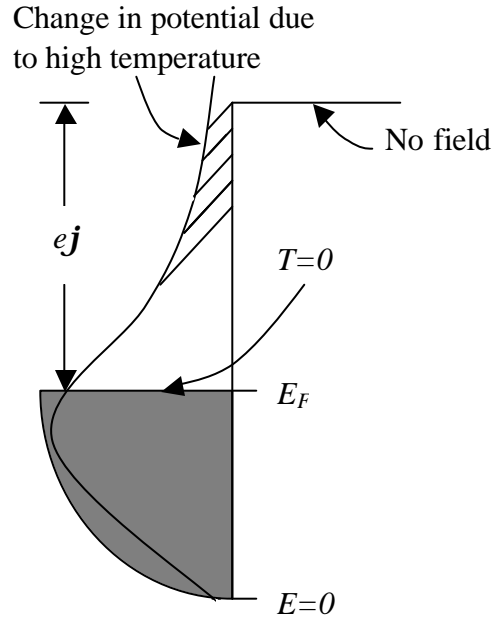


FIG. 1. Energy diagram for thermionic emission with energy plotted as a function of distance from the metallic surface. As the temperature (T) of the cathode increases, electrons are excited to beyond the Fermi level (E_F) and higher until their energies are comparable to the work function of the metal ($e\phi$), allowing them to escape the metallic surface.

Cold cathode emission describes an electron leaving the surface of the metal by quantum mechanically tunneling through the barrier potential. In this process the cathode temperature is low while the relative field strength is high. This mechanism of field emission was first described in the seminal work of Fowler and Nordheim around the inception of quantum mechanics [1]. Cold cathode field emission was proposed as a more efficient type of electron emission and it was believed that it would heavily influence the market in the electronics display industry.

The field emission properties of a metal that has been covered with an adsorbate has, however, not been studied extensively. When an atom is adsorbed onto the surface of a metal, an extra bound and vacant electronic state may be created. For example, the adsorption of oxygen onto molybdenum demonstrates this behavior and has been summarized previously [2]. The binding energy between a single oxygen atom and molybdenum (Mo) is greater than the binding energy between the two oxygen atoms in an oxygen molecule (O_2). The O_2 will therefore dissociatively adsorb so that the individual oxygen atoms will occupy sites on the metallic surface [2]. On the surface the “unoccupied” orbital for an extra electron on the oxygen atom lies below the Fermi level and hence the atom will reside on the metallic surface as O^- . The energy diagram for a clean cathode surface with a strong extraction field is shown in Figure 2 as a function of z , the distance from the metal. The schematic for a surface covered with an adsorbate, such as oxygen, is also illustrated. The new state for O^- creates a gap in the previous barrier potential known as the Schottky barrier (“Field + Surface” in Figure 2) of the metal and provides a tunneling electron with a decreased thickness through which to travel (“Field + Surface + Atom” in Figure 2). It has been shown that oxygen coverage on a molybdenum substrate has a significant effect on the secondary emission of electrons caused by impacting ions [2]. It was anticipated that adsorbate coverage of the surface would be strongly correlated to the emission characteristics of Spindt type field emission cathode arrays [3].

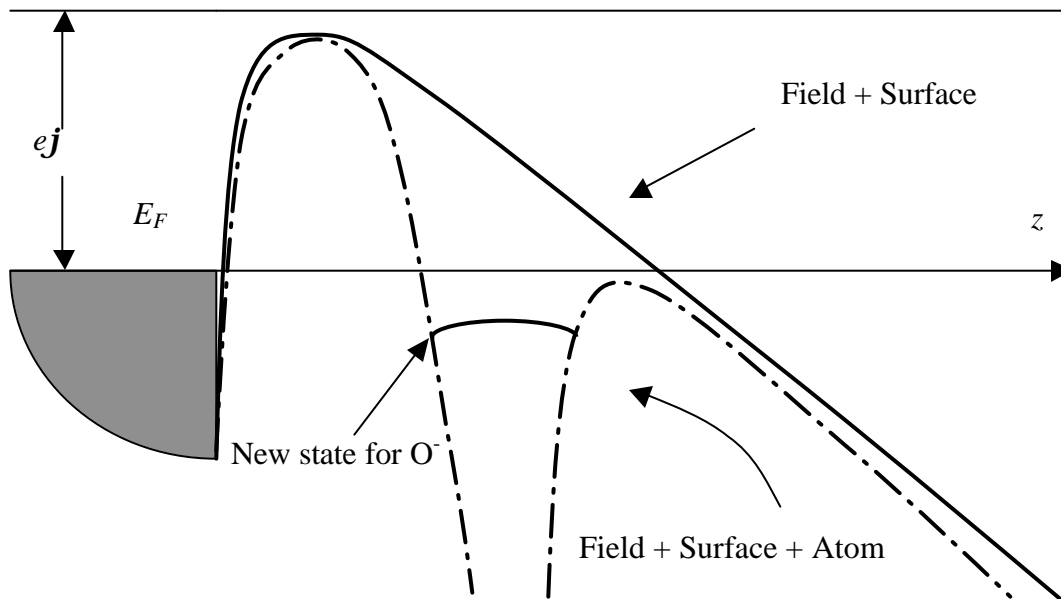


FIG. 2. Energy diagram for field emission with energy plotted as a function of distance from the metallic surface. “Field + Surface” indicates the lowering of the potential barrier created by the applied electric field. “Field + Surface + Atom” indicates the potential seen by an electron residing on an adsorbate covered metallic surface, with an extra electronic state for O^- existing below the Fermi energy.

1.2 Description of Field Emitter Array

Dr. Capp Spindt and co-workers at Stanford Research Institute (SRI) have used techniques in thin-film technology and electron beam microlithography to fabricate cathode arrays of cones [3]. The technique used to produce these field emitter arrays (FEAs) has been refined to make them with significantly more cones packed into a smaller area. A schematic of the field emission cathode is illustrated in Figure 3; it consists of a molybdenum gate film, molybdenum cone, and a silicon substrate. The molybdenum cones described are each about 1.5 microns tall with a tip radius of about 500 angstroms. They rest on the silicon substrate and a molybdenum gate film surrounds each one. The cones are exposed through holes in the gate film with a diameter of about 1.5 microns. The gate film and the silicon substrate are isolated from each other via the silicon dioxide insulating layer [3].

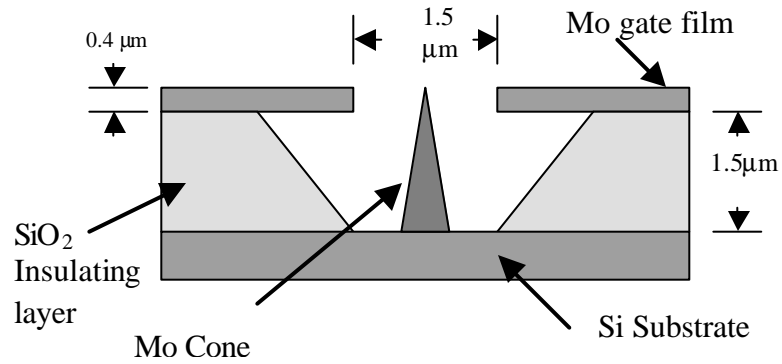


FIG. 3. Schematic diagram of a Spindt-type field emission cathode

The schematic diagram in Figure 3 illustrates the conductor-insulator-conductor configuration that is used in the present FEA. The cathodes can be arranged in arrays of different sizes with varying densities. A scanning electron microscope picture of the array of tips for this type of cathode is shown in Figure 4.

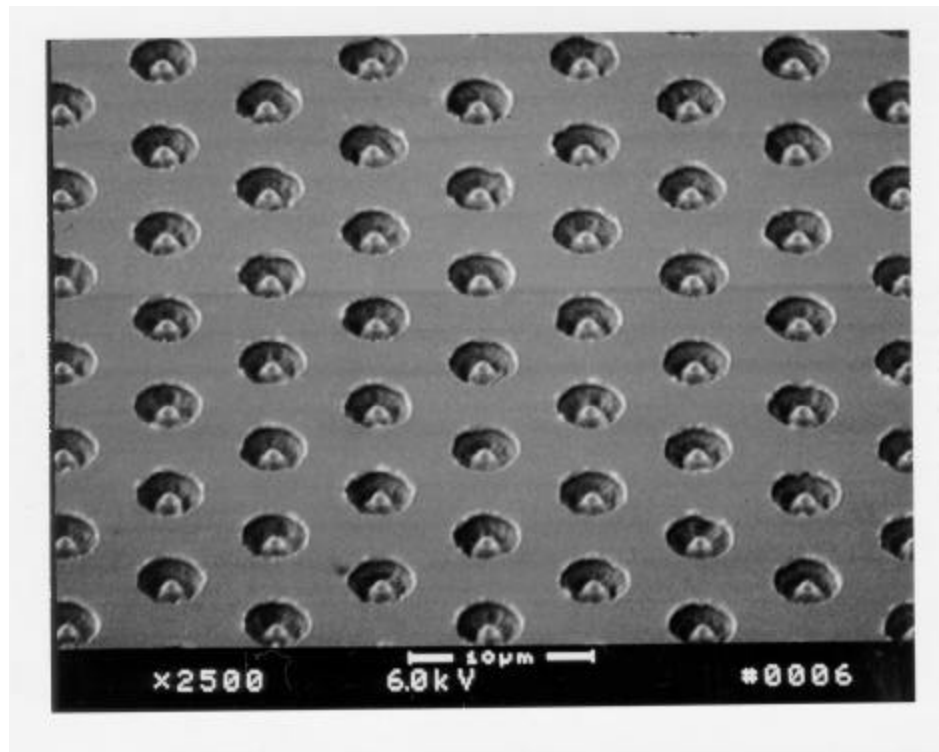


FIG. 4. Scanning electron microscope picture of the array of tips on the FEA.

Previously used field emitters required a high voltage for operation; the Spindt-type FEAs operate at a rather low voltage, which provides several advantages. The lower voltage (of order 100 volts) exposes the FEAs to a lower risk of damage from the ionization of ambient gas, creating a positive ion that then impacts the tip, in the vacuum [4]. This means that the FEAs can be used at a higher pressure with a longer operating lifetime. The FEAs are also reported to have a current density per useful lifetime greater than that of thermionic cathodes [5]. FEA technologies have been researched in the display industry as a more efficient alternative to cathode ray tubes (which utilize thermionic emission) as well as liquid-crystal displays (LCDs) [6]. It is anticipated that FEAs can function at a lower power than current LCDs and also at a thinner depth than current flat panel technology [3]. These advantages are very important for technical applications.

The described geometry of the FEAs is partially responsible for the emission characteristics. The sharp tips on the cones and the close proximity of the gate allows for large electric fields to be generated with fairly small voltages. The electrons from the tips of the cones, where the electric field is the largest, tunnel through the surface barrier of the metal. The Fowler-Nordheim prediction for emission from the pristine metallic substrate yields a result that is significantly *lower* than the observed field emission. It has been proposed that the enhancement factor is due to adsorbed molecules/atoms on the surface [3]. Such suggestions, apparently, have not been experimentally examined.

The tips on the surface of the FEAs are highly sensitive and very susceptible to damage. They cannot be easily heated to temperatures necessary for desorbing residual molecules from the surface. Research to date does not specify a non-destructive manner

in which to clean the tips on the FEAs. Previous experiments have used ion bombardment with an incident argon ion (Ar^+) beam to sputter clean the surface. It is suspected that this keV ion bombardment may lead to defect formation on the surface of the tips. After this cleaning, it is supposed that the surface then slowly anneals to the original topology and thus restores to baseline emission [7]. For the present experiment, electron-stimulated desorption was used to non-destructively remove adsorbates on the surface. The electrons, being much less massive than the argon ions, produced less of an impact that could potentially lead to this defect formation. The ultimate goal of the experiment was to employ this cleaning technique to characterize the effects that adsorbate coverage has on the emission characteristics of the FEA.

2. Theory

2.1 Fowler-Nordheim

Fowler-Nordheim theory describes the field emission from an adsorbate free cathode. The equation relates the field emission current density, J (Amperes per square centimeter), to the electric field at the surface, E (volts per centimeter), and the work function of the metal, f (electron volts), by

$$J = \frac{AE^2}{f t^2(y)} \exp\left(-B \frac{f^{3/2}}{E} v(y)\right) \text{ A/cm}^2, \quad (1)$$

where

$$A = 1.54 \times 10^{-6} \frac{\text{A} \cdot \text{eV}}{\text{V}^2}, \quad (2)$$

$$B = 6.87 \times 10^7 \frac{\text{V}}{\text{cm} \cdot \text{eV}^{3/2}}, \quad \text{and} \quad (3)$$

$$y = \left(3.79 \times 10^{-4} \sqrt{\frac{\text{cm}}{\text{V}}} \cdot \text{eV} \right) E^{1/2} / \mathbf{f}. \quad (4)$$

Both A and B are constant coefficients and y is the Schottky lowering of the work-function barrier. The lowering and curving of the barrier is due to the image force felt by an emitted electron near the metal surface. The two functions $t(y)$ and $v(y)$ are elliptic functions with no units that have been approximated by Spindt [3] to be,

$$t^2(y) = 1.1, \quad \text{and} \quad (5)$$

$$v(y) = 0.95 - y^2. \quad (6)$$

Values for y , $t(y)$, and $v(y)$ have been determined as corrections to the previous work done by Nordheim [7, 8]. To develop a known expression for Fowler-Nordheim theory, it is noted that

$$J = I / \mathbf{a}, \quad \text{and} \quad (7)$$

$$E = \mathbf{b}V / d, \quad (8)$$

where I is current measured in Amperes, a is the emitting area in units of square centimeters, β is a unitless field enhancement factor due to the geometry, V is the applied voltage measured in volts, and d is the gap dimension in centimeters. Substituting these values into Eq. (1) and redefining constants yields

$$I = aV^2 \exp\left(-\frac{b}{V}\right), \quad (9)$$

where

$$a = \frac{\mathbf{a}A\mathbf{b}^2}{1.1\mathbf{f}d^2} \exp\left(\frac{Bdf^{3/2}(1.44 \times 10^{-7})}{\mathbf{b}V}\right) \quad \text{and} \quad (10)$$

$$b = \frac{0.95Bdf^{3/2}}{\mathbf{b}}.$$

In Eq. (9) a depends on the emitting surface area and b depends on the shape and radius of the tips [3]. Eq. (9) can be rearranged to yield

$$\ln\left(\frac{I}{a \cdot V^2}\right) = -\frac{b}{V} \quad (11)$$

which shows a linear relationship between the natural logarithm of (I/V^2) and $(1/V)$. This relation, known as a Fowler-Nordheim plot, yields a straight line while experimental data varies slightly from the model both when the field emitter just begins to emit and at the high end of emission. The Fowler-Nordheim plot for the cathode used in this experiment is shown in Figure 5.

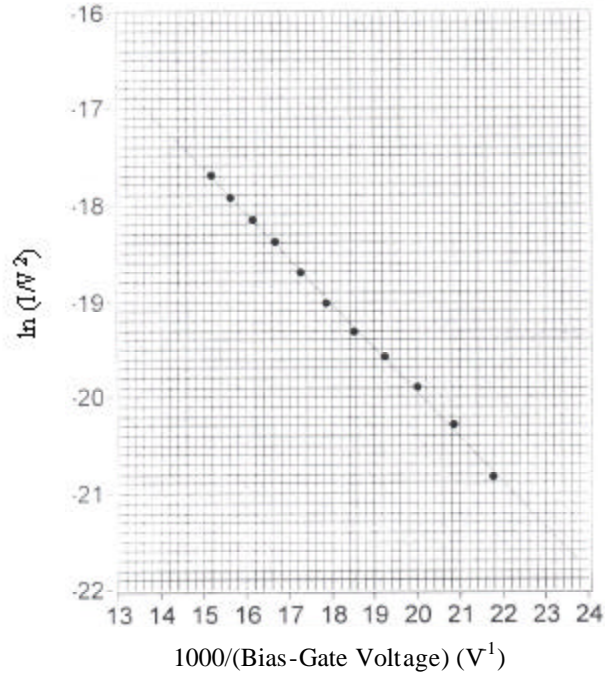


FIG. 5. Fowler-Nordheim plot provided with FEA from SRI International. This plot shows the linear relationship between the inverse of the Bias-Gate Voltage and the natural logarithm of (emission current/ Bias-Gate Voltage²).

2.2 Electron-Stimulated Desorption

The cleaning of the tips for this experiment was facilitated by electron-stimulated desorption (ESD). In this process, an electron impact results in the excitation of an adsorbed atom or molecule on the surface of a metal. This new species can be formed in an anti-bonding state, as illustrated in Figure 6, and will have a different interaction energy with the metallic surface than the former adsorbed species. Desorption occurs as the excited species moves away from the surface and gains kinetic energy from the potential energy loss. This process is seen in Figure 6 with energy plotted as a function of distance from the metallic surface [9].

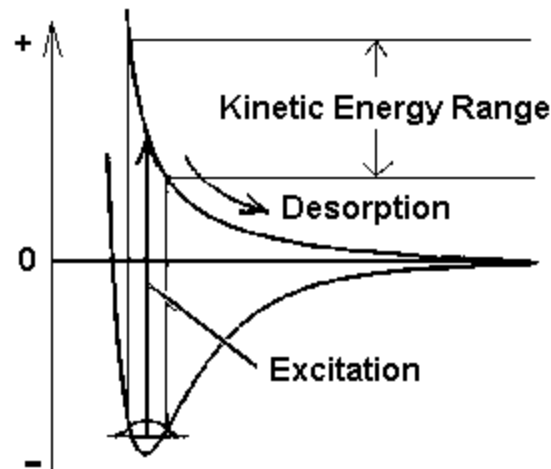


FIG. 6. Energy diagram showing the ESD process with energy plotted as a function of distance from the metallic surface. An incident electron impacting the metal excites an adsorbed species residing on the surface. The energy transfer involved results in the desorption of the adsorbate.

If the desorption of adsorbates on the surface is due solely to ESD, the decrease in the desorption density, dN , is directly proportional to the number of incident electrons per

unit area and time, n , the amount of adsorbate per unit area, N , and the time, dt . The proportionality constant is usually called the cross section and is denoted by \mathbf{s} .

Hence,

$$\frac{dN}{N} = -\mathbf{s}ndt . \quad (12)$$

This differential equation for the adsorbate coverage can be solved to yield

$$N = N_0 \exp(-t / \mathbf{t}) , \quad (13)$$

where the decay rate is denoted by

$$\mathbf{t} = \frac{1}{\mathbf{s}n} . \quad (14)$$

Previous experiments with ESD have yielded results for the desorption cross section, \mathbf{s} , to be on the order of 10^{-17} square centimeters or 0.1 square angstroms [10]. The adsorbate coverage after cleaning can therefore be estimated from Eq. (13) given the initial coverage, number of electrons per unit area and time, and the time of exposure.

3. Experimental Procedure

The chamber for the experiment is an ultrahigh vacuum (UHV) operating in the range of about 10^{-9} torr. This high vacuum was necessary for this experiment so that the state of the surface could be more precisely controlled. The specific cathode used in this experiment also requires a UHV environment for operation. An apparatus was set up in the chamber with the cathode, consisting of the FEA and a TO-5 header, mounted onto a moveable armature in the center as shown by the dotted lines in Figure 7. The moving armature allowed for the cathode to be positioned on the horizontal, facing the electron gun for cleaning, as well as rotated 45 degrees from the horizontal to face a

collector plate used in emission trials.

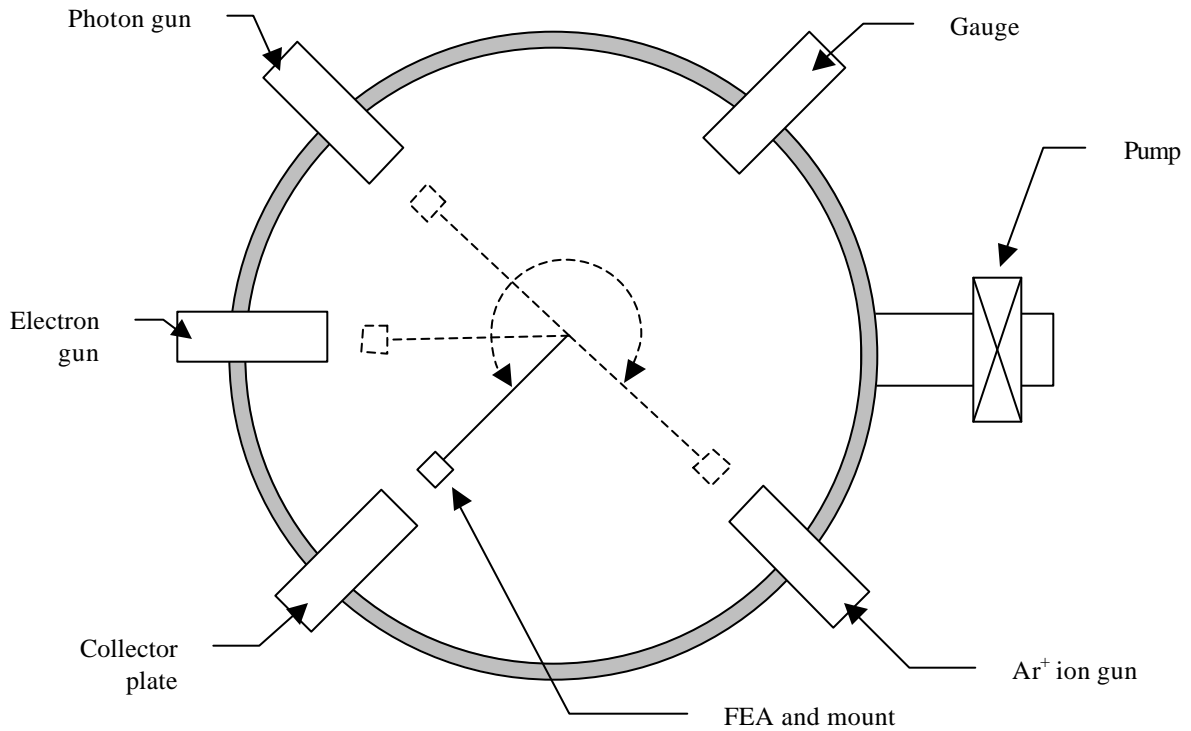


FIG. 7. Schematic of experimental apparatus inside UHV

The cathode itself is an array of approximately 50,000 Spindt-type molybdenum tips in an active area of about 1square millimeter. During emission trials, the gate voltage on the cathode was kept at a constant +20 volts (provided by a Lambda power supply) while the tip voltage was varied from 0 to -70 volts relative to the gate (using the LabView computer program with a Kepco programmable power supply). The voltage difference between the gate and tips (measured by a Keithley 175 multimeter) had a delay for each step of 5 seconds to allow the emission at that voltage to stabilize before taking measurements. The emission current was measured two different ways for the experiment. Previous experiments done in this lab used a collector plate that sat opposite the FEA at a +50 volt bias (powered by a Hewlett Packard power supply). The collector

plate was 1-inch by 1-inch and slightly curved up towards the FEA to improve the accuracy of the measurement. Due to the different cleaning mechanisms used for this experiment, a brass shield was later added to the FEA, surrounding the active emitting area. The shield acted as a new collector plate, also biased at a +50 volts, for early trials in this experiment. Later trials utilized both the old collector plate and the new shield as a combined new collector. The current to the collector and shield arrangement was determined for each voltage step between the gate and tips (amplified by an SRS model SR570 low-noise current preamplifier and measured by a Fluke 45 dual display multimeter). An example of a typical curve for the combined current measured at both collector and shield plotted as a function of the relative gate-tip voltage is shown in Figure 8. This figure shows that emission begins in the range of 35-40 volts and increases exponentially from there.

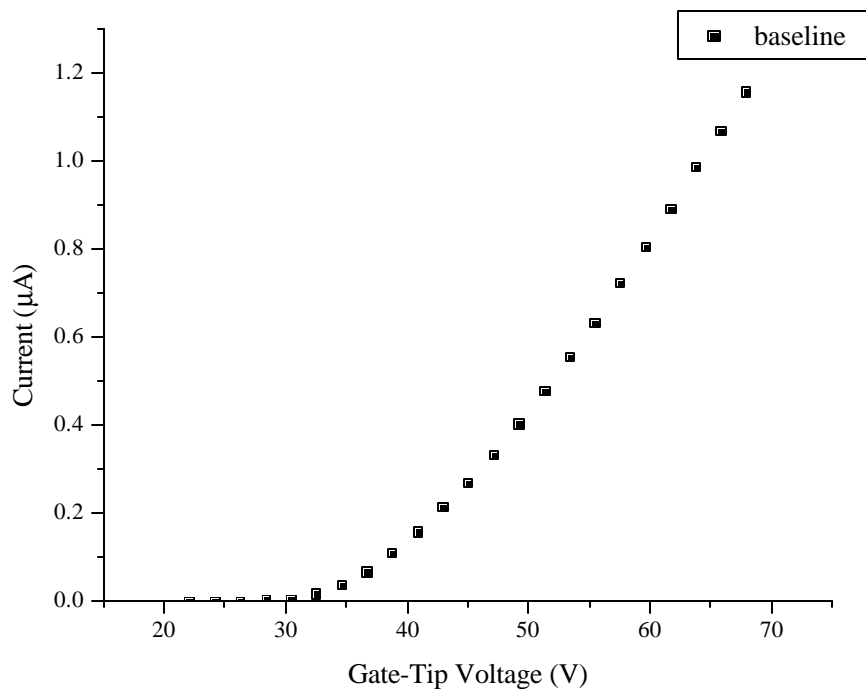


FIG. 8. Collector current as a function of gate-tip voltage

The cleaning procedure consisted of directing a beam of electrons at the tips of the cathode to facilitate the ESD process. With the right conditions the interaction of the electrons with the FEA surface caused the removal of the adsorbates on the tips. To employ ESD, an electron gun was used to direct a beam of electrons with energy of 1 keV to the tips to deliver a current of approximately – 0.1 microamperes.

The design of the FEA and TO-5 header is such that it is not possible to electrically isolate either the tips or the gate. The tips are connected to the TO-5 header, which is connected to the casing for the mount. This aspect of the design proved to be a problem for this experiment in particular where it is necessary to measure the current delivered solely to the tips in the cleaning process. A brass shield 1-inch in diameter with a circular hole comparable to the square millimeter active emitting area on the FEA was attached to - but electrically isolated from - the TO-5 header so that the hole coincided with the active emitting area, as illustrated in Figure 9. This acted as a shield so that when measuring current delivered to the tips, current from the casing would not also be taken into account. This new shield provided a way to accurately measure the current delivered to the tips and was also used in the collector arrangement for measuring emission current from the FEA.

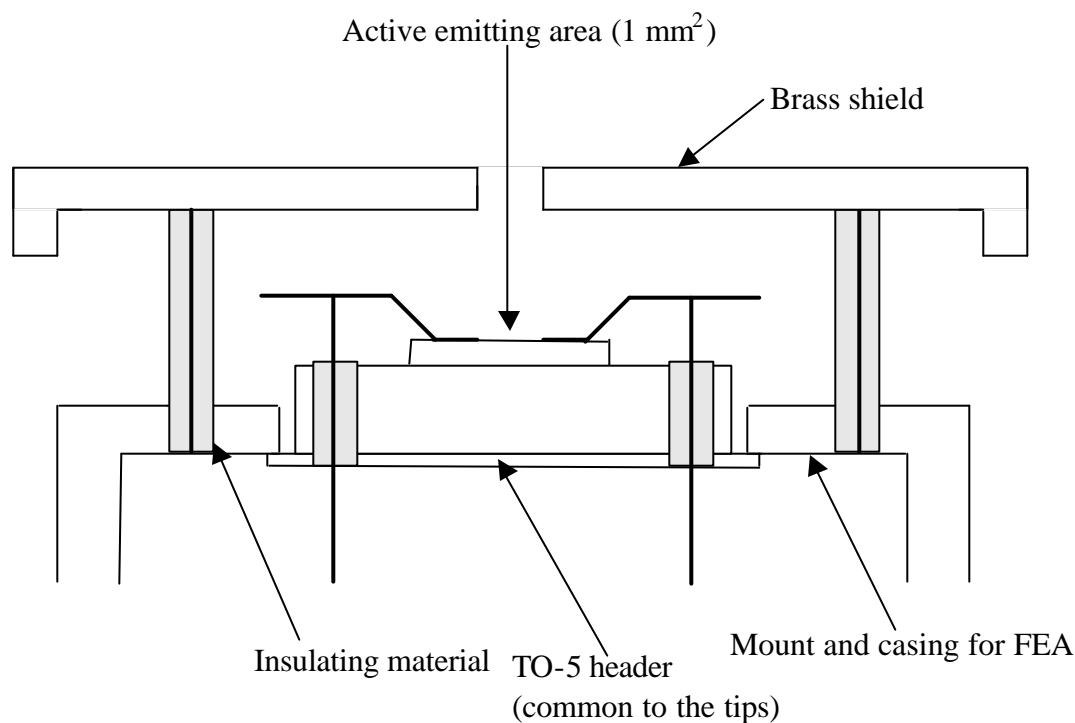


FIG. 9. Schematic of FEA, TO-5 header, mount for FEA, and added brass shield

The experimental procedure described was used to first measure the emission of the FEA, clean the surface, and again measure the emission. It was anticipated that this process would result in a change in the emission characteristics after cleaning, possibly reducing field emission, indicating that an adsorbate on the surface is responsible for the emission characteristics. This experimental procedure was repeated many times and the data showed this hypothesis to be accurate.

4. Results and Discussion

4.1 Cleaning Trials

The FEA and mount was placed into the vacuum chamber, first under technical vacuum conditions. The experiment was carried out once an ideal pressure of about 10^{-9} torr was established. Early experiments were carried out to determine safe operating

voltages to the tips and gate on the FEA as well as to the collector plate arrangement. Initial emission tests showed the baseline curve that is characteristic of the FEA. Once this curve was established, proper cleaning intervals were determined. The first successful cleaning trial was found to be with an electron beam energy of 1 keV delivering a current of -0.1 microamperes to the tips of the FEA for one hour. This data was taken with only the shield surrounding the emitting area acting as the collector plate. This current and time can be used to find the total number of electrons impacting the tips by

$$0.1 \text{ mA} \times \frac{1 \text{ C / sec}}{10^6 \text{ mC / sec}} \times \frac{1 e}{1.6 \times 10^{-19} \text{ C}} \times 3600 \text{ sec} = 2.25 \times 10^{15} e. \quad (15)$$

Noting that there are a total of 50,000 tips on the FEA, the number of electrons impacting each tip is found to be 4.5×10^{10} . The specifications of the FEA indicate that the opening in the gate film to one of the tips has a diameter of about 1.5 microns [3]. The area is thus determined to be

$$\text{Area} = 1.8 \times 10^8 \text{ C}^2/\text{opening}. \quad (16)$$

Using Eqs. (15) and (16) and the total number of tips as 50,000, the number of electron impacts per area in one hour is found to be approximately 250 electrons per square angstrom.

Given this cleaning interval and an initial adsorbate coverage, the resulting coverage can be solved for by first noting from Eqs. (15) and (16) that $n = 0.069$ electrons per second per square angstrom. If $s = 0.1$ square angstroms, as experimental results have shown [10], then the characteristic decay rate from Eq. (14) will be

$$t \cong \frac{1}{sn} \cong 144 \text{ sec}. \quad (17)$$

If the ESD occurs for a time $t = 3600$ seconds, $t / \tau = 25$, which when substituted into Eq. (13) yields

$$\frac{N}{N_0} = \exp(-t / \tau) = \exp(-25) = 1.4 \times 10^{-11}, \quad (18)$$

indicating that the adsorbate concentration on the surface should be substantially reduced. This simple analysis for determining coverage after cleaning does not take into account the readsorption of adsorbates to the surface during cleaning and after cleaning has ended. The unit of gas exposure is called a Langmuir (L) and it corresponds to 10^{-6} torr-seconds of exposure. An exposure of 1L would result in approximately one monolayer of coverage (i.e., $\sim 10^{15}$ per square centimeter) if all impacting molecules/atoms stuck to the surface. Hence if the probability of that adsorbate sticking to the surface is known, the amount of adsorbate coverage can be determined. With a background pressure of about 5×10^{-9} torr as in this experiment, assuming unit sticking probability, the time to acquire one monolayer is about 500 seconds.

We can modify Eq. (12) to approximately account for adsorption:

$$dN = -Nnsdt + \left[\frac{N_0 - N}{N_0} \right] N_0 psdt . \quad (19)$$

The additional term contains the adsorption rate, $N_0 ps$, where p is expressed in units of 10^{-6} torr and s is the sticking probability for the surface ($0 \leq s \leq 1$). The term in brackets represents the fraction of the sites available for adsorption to occur. Full coverage is designated by N_0 . The solution to Eq. (19) is

$$\frac{N(t)}{N_0} = \left(1 - \frac{ps}{ps + \mathbf{b}} \right) \exp[-(ps + \mathbf{b})t] + \frac{ps}{ps + \mathbf{b}} , \quad (20)$$

where

$$\mathbf{b} = n\mathbf{S} . \tag{21}$$

For our experiment, $\mathbf{b} \cong 0.0069$ and $p \cong 0.005$. For molybdenum the sticking probability has been determined to be $s = 0.1$ [2], thus the asymptotic coverage, $N(4)/N_0$, is found from Eq. (20) to be about 7%. In this experiment, species re-adsorption is clearly important, but at the same time Eq. (20) indicates that the ESD process should undoubtedly clean the surface of the FEA to a significant extent (about 93%).

The first cleaning of an FEA exposed to atmospheric pressure resulted in a slight increase in the emission from baseline levels as seen in Figure 10 (for this particular data set the shield acted as the collector). The increase in emission can be explained by noting that cleaning the emitter after it has been exposed to the atmosphere will possibly remove top layer(s) of adsorbates from the surface. The tips are now cleaner but residual adsorbates still exist on the surface. After this preliminary adsorbate removal, the cathode was allowed to relax for a period of 30 minutes. During this interval, it can be seen that the emission started to return to the baseline level as the species cleaned from the surface once again adsorbed to the tips, thus inhibiting emission.

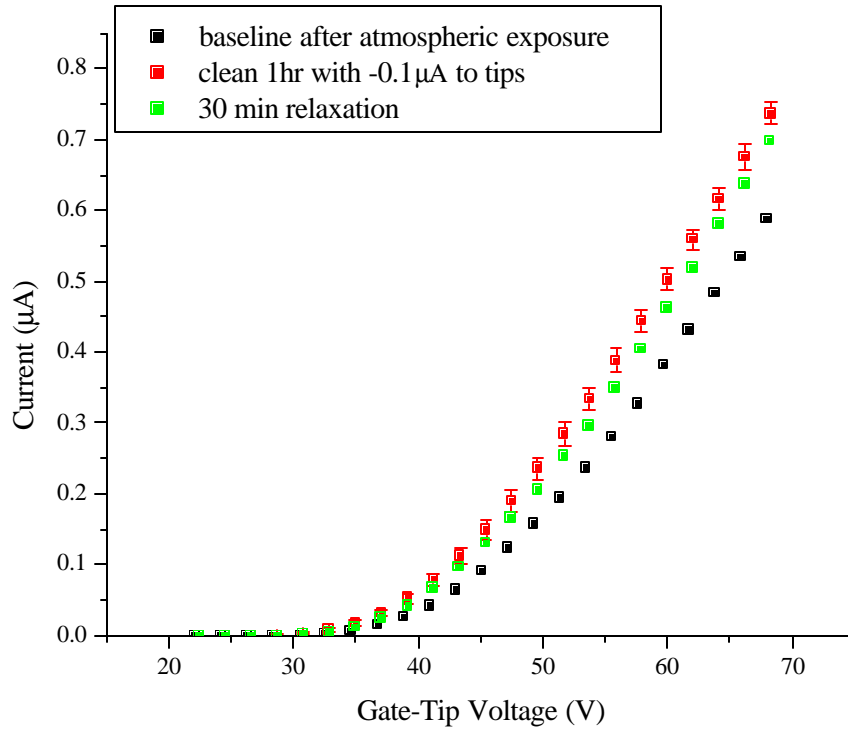


FIG. 10. Voltage versus collector current for initial cleaning trial. The black curve indicates the emission curve upon first placing the FEA into UHV conditions. The red curve shows an increase in emission after using ESD to clean the tips for one hour with a current of $-0.1\mu\text{A}$ to the tips. The green curve shows a slow return to baseline levels after a 30-minute period of relaxation. This indicates that initial cleaning of the surface removed adsorbates that inhibit emission which then re-adsorb to the surface after cleaning bringing the emission back down to near baseline levels.

Once this relationship had been established, further adsorbate removal was accomplished via a second stage of electron-initiated ESD. The initial stage of cleaning facilitated the removal of adsorbates that inhibited emission; the second stage removed additional adsorbates from the surface and the emission was seen to *decrease* as illustrated in Figure 11. A characteristic baseline curve was taken for the FEA after stage one cleaning and once again a 1 keV electron beam was directed at the tips so as to provide a current of about -0.1 microamperes. A one-hour cleaning interval with these conditions resulted in a decrease in emission shown in Figure 11.

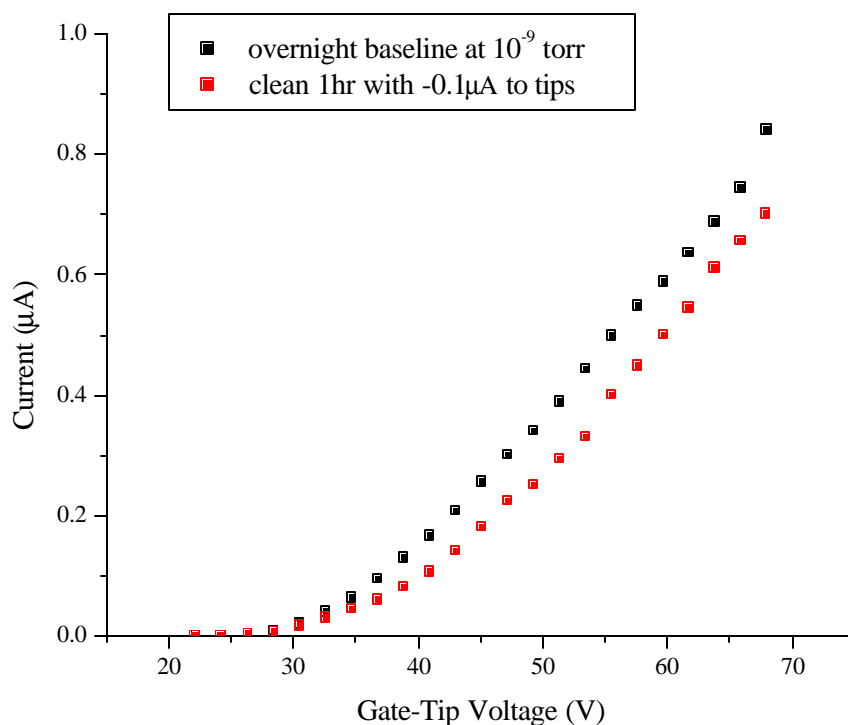


FIG. 11. Voltage versus collector current for next cleaning trial. The black curve shows the characteristic emission after initial cleaning had been performed. The red curve shows the reduction in emission after further cleaning of tips, indicating the removal of the adsorbate responsible for the high emission properties.

The decrease in emission from baseline levels is presumably due to the removal of the emission enhancing adsorbates from the surface as discussed in section 1.2. The red curve shows the emission from a relatively clean cathode surface. After relaxation of the cathode, the desorbed species re-adsorb to the surface, once again restoring emission.

4.2 Cathode Failure

During this investigation of the emission properties of the FEA, two separate cathodes were used. The experimental procedure was refined in an attempt to ensure that the cathode was not damaged during operation. Although precautions were taken with each step of the process, two different cathodes failed catastrophically during the

investigation. The first cathode failure occurred after a period of dormancy in the vacuum; it is not known what precisely caused this failure. All of the data in this analysis was taken from the second cathode used. During the last cleaning trial, the second cathode was subjected to a voltage exceeding its limit (about 70 volts in this experiment) due to a faulty power supply. Once a cathode fails to function properly, a resistance on the order of a megaohm can be detected between the tips and the gate structure. The first cathode showed a resistance of about 6 megaohms after failure while the second had a resistance of 1.5 megaohms. A scanning electron microscope (SEM) was used to examine the array structure of each cathode after the failures occurred to verify the failures.

The first cathode failed in early October before the experimental procedure had been tested. With the SEM, the cathode showed the usual array of cones in the active area, however several of the cones appeared to be missing as seen in Figure 12. Further analysis of the structure showed one of these displaced cones from the array, which can be seen in Figure 13. It is not clear what caused this damage, as the cathode was not in operation for a period of two weeks prior to discovery of the failure. Before this inactive period, the cathode was fully operational.

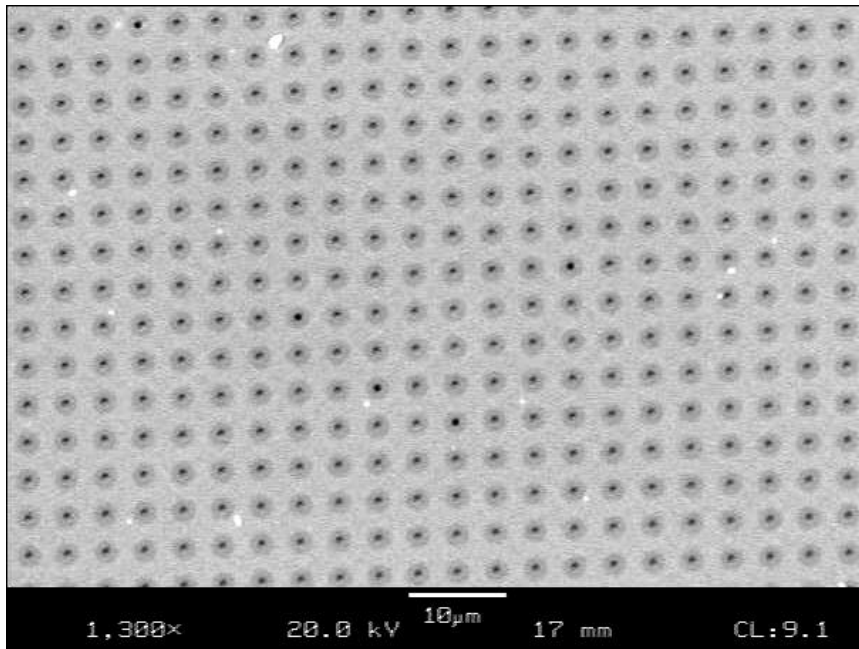


FIG. 12. SEM picture of array of first cathode used in the experiment. This shows the array of cones in the gate structure, however many of the cones appear to be missing, indicated by the dark holes.

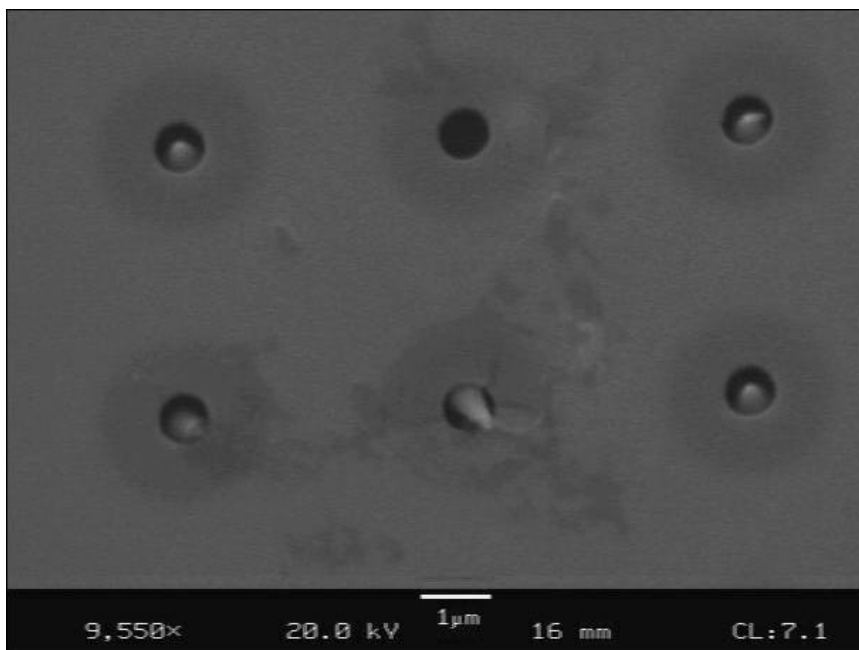


FIG. 13. SEM picture of damage on first cathode.

The second cathode that was used failed in early April during a cleaning trial. A small voltage (about 10 volts) was applied to the tips during this last cleaning trial, however when the power supply to the tips was first turned on, the voltage it provided exceeded the limit for the FEA. Inspection of the surface with the SEM showed a normal cathode structure in the active area as seen in Figure 14. Further examination, however, showed small excoriations outside of the emitting area that can be seen in Figure 15. These structures could be products of the high voltage supplied to the tips.

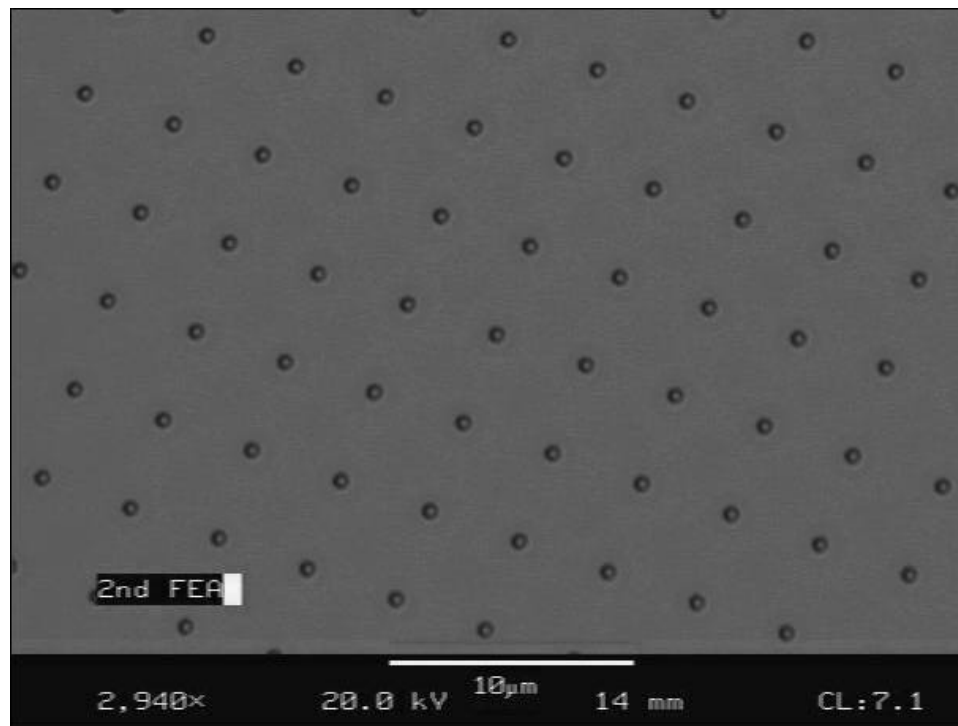


FIG. 14. SEM picture showing array of tips on the second cathode.

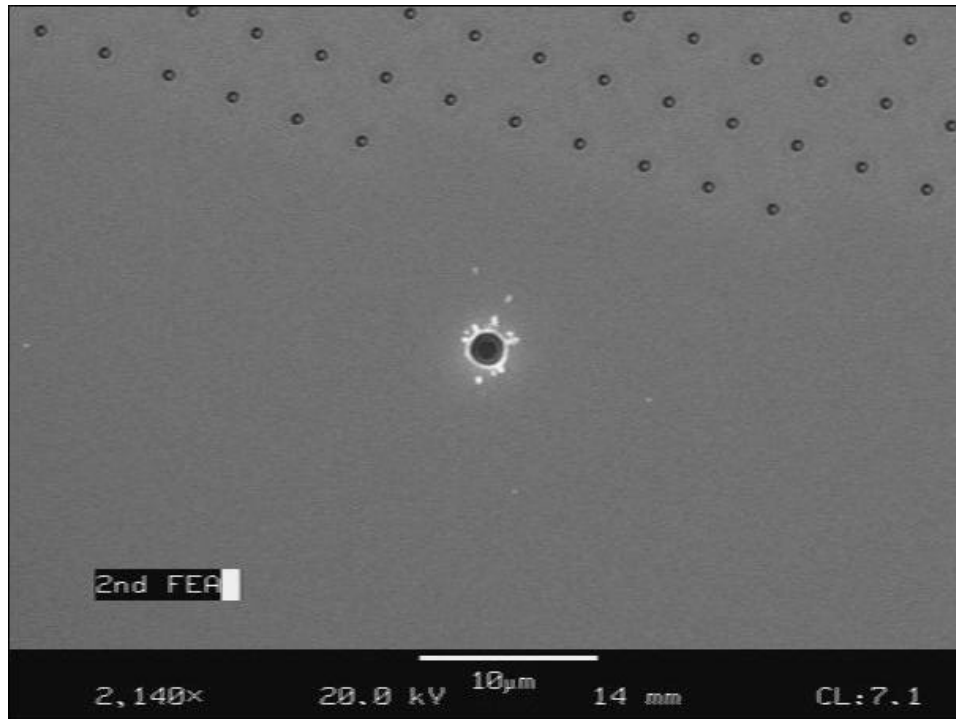


FIG. 15. SEM picture of a small excoriation found outside of the emitting area on the second cathode.

5. Conclusions and Future Work

The goal of this experiment was to determine the correlation between adsorbate coverage and emission properties of a Spindt-type molybdenum cathode FEA. To determine this relationship, the emission properties of an adsorbate free surface had to be characterized. ESD was employed as the cleaning technique to accomplish a non-destructive removal of adsorbates from the tips of the FEA. Ultimately, it was found that initial ESD cleaning of the tips proved to enhance the emission characteristics from beyond the baseline level while further cleaning reduced emission to below baseline levels, showing that adsorbates have a significant effect on emission properties. Relaxation periods after cleaning trials showed that the cathode slowly returned to

baseline levels, indicating that there is a gradual readsorption to the surface from previously removed adsorbates.

Once this relationship had been established, the results were compared to the Fowler-Nordheim model given in Eq. (11). Taking a curve of the emission characteristics after initial cleaning results in a Fowler-Nordheim plot as seen in Figure 16. The Fowler-Nordheim equation shows the emission from just one of the cones on the FEA. It does not apply to each cone, as it does not take into account that the cones may vary slightly in size and some may have sharper tips than others. The specifications are for the average of the properties of all of the 50,000 tips. This is likely to be why the Fowler-Nordheim plot for this situation deviates from what is predicted to be a straight line.

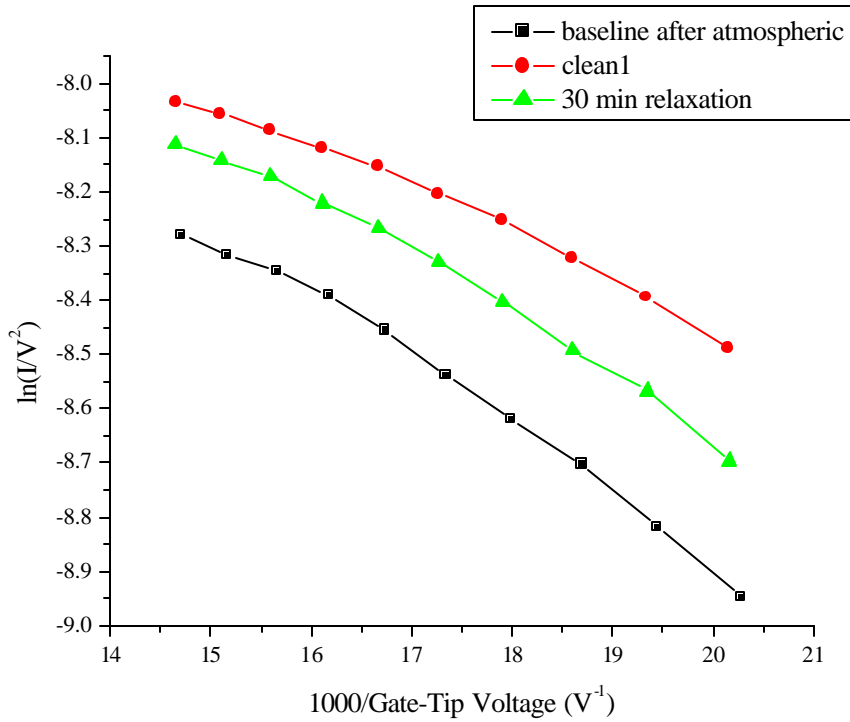


FIG. 16. Fowler-Nordheim plot for initial cleaning of cathode. The black curve shows the baseline level after being exposed to the atmosphere, the red curve shows emission after using ESD to clean the cathode for 1 hour delivering 0.1 μ A to the tips. The green curve shows the emission after a 30-minute period of relaxation after cleaning the tips. Clearly, the emission increases after initial cleaning and then decreases back to baseline levels after the removed adsorbates reattach to the surface.

The specified experiment shows that a clean cathode surface has different emission characteristics than that of an adsorbate-covered surface. Certain adsorbates on the surface reduce emission while others serve to enhance emission. A possible model demonstrating this behavior could be that a surface with multiple layers does not produce much emission, a surface with a monolayer of coverage shows an enhancement in emission, and a clean cathode surface produces emission that is characteristic of the Fowler-Nordheim model. Further work in this area can be done to determine the correctness of this model. Now that a non-destructive cleaning procedure has been established, the types of adsorbates that inhibit and promote field emission can be determined. Trace gases that exist in the vacuum chamber that should be tested include oxygen, hydrogen, methane, carbon dioxide, and water. After cleaning the surface, various exposures of the trace gases could be utilized to determine what effects, if any, they have on the emission. If the tested adsorbate enhances the field emission, the characteristic curve should return to pre-cleaning baseline levels.

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