Progress on Re-generable Field Emission Cathodes for Low-Power Electric Propulsion

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The research reported here explores the possibility of field-emission cathodes for use in EP that have the ability to be re-generated when the emitter tip becomes damaged. The method for re-generation takes advantage of Taylor cone formation in an effort to solidify, or quench, an operating liquid-metal-ion-source (LMIS) to preserve the sharp Taylor cone tip for use as a field-emission cathode. Electron emission I-V curves were taken after Taylor cones were formed by quenching the LMIS at different discharge currents. It is shown that quenching the LMIS at as low as 2 μA produced an increase in electron discharge current as compared with the unquenched emitter, 53 nA as compared with 25 nA at an extraction voltage of 2.7 kV. When the ion emission current at quench was increased to 3 μA and then 25 μA, the discharge that was measured increased to 210 nA for the 3 μA emitter and 1.02 μA for the 25 μA emitter at an extraction voltage of 2.7 kV. Fitting the electron emission I-V characteristics using Fowler-Nordheim theory indicated tip radii as small as 80 nm were formed during the LMIS quenching process.

Nomenclature

a	=	Fowler-Nordheim term (see Equation 2)
b'	=	Fowler-Nordheim term (see Equation 3)
I	=	discharge current (I)
k	=	empirical relation relating tip radius and gap spacing
V	=	extraction voltage (V)
r	=	emitter tip radius (m)
α	=	Nordheim image-correction term
ϕ	=	work function (eV)
μ	=	Fowler-Nordheim term

I. Introduction

LIQUID-METAL ion sources (LMIS) have found extensive use as ion sources of high brightness in focused ion beam materials processing applications[1] and, more recently, as EP thrusters via a technology commonly known as field-emission electric propulsion (FEEP).[2,3,4] In an LMIS or FEEP thruster, an intense electric field is created near the surface of a low melting-temperature liquid metal, such as In, by a downstream electrode. A balance between the liquid surface tension and electrostatic forces causes a structure known as a Taylor cone to form in the liquid. The mechanisms of Taylor cone formation are by now well understood.[5] Because the Taylor cone has a very sharp tip, geometric enhancement of the local electric field at the cone tip is sufficient to extract metal ions directly from the liquid.[2] 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

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(LMIS). Other applications and areas of interest for the use of focused ion beams include lithography, semiconductor doping, sample preparation for TEM imaging, circuit repair, scanning ion microscopy, and scanning ion mass spectroscopy.[6]

The research reported here takes advantage of Taylor cone formation in an effort to solidify, or quench, an operating LMIS to preserve the sharp Taylor cone tip for use as a field-emission cathode for EP. The resulting metal structure will have a tip radius of 10's to 100's of nanometers, which is ideal for Fowler-Nordheim emission. By reversing the polarity of the LMIS, the solid-metal tip will then function as a cold electron emitter. The motivation for this is due to the limited lifetime of current micro-fabricated field emitters. As electron discharge is continued for long durations, the emitter tip begins to wear and blunt. As the sharpness of the emitter tip decreases, the local electric field decreases. This circumstance is unfavorable and eventually renders the emitter tip useless as an electrode source. Where current field emitters would be destroyed at this point, the process described here of applying heat to re-melt the In and switching the polarity back to obtain ion emission allows for the re-generation of a sharp Taylor cone. Another advantage the In coating has is that tips coated with In have a lower work function than W, 3.5 eV for In as opposed to W at 4.5 eV.[7] So once a sharp tip has been formed, it can once again be used for electron emission.

While 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.[8] 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 coax electron emission from the (nonsolidified) cone. Their early paper reports repetitive pulsed electron emission from liquid Ga-In Taylor cones formed on the tip of a W needle electrode with current pulses as high as 250 A for 10 msec at ~50,000 pulses-per-second. A field-emission-initiated explosive emission process during which a small portion of the liquid metal is expelled was proposed to describe the behavior. The phenomena responsible for pulsed emission were supported by Gomer the following year.[9] Later on, using Ga and In, Rao et. al. 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."[10] It is now understood that, during operation as an LMIS, the Taylor cone forms a jet-like protrusion at the cone apex that solidifies when the cone is quenched by removing heater power. It is the protrusion that is responsible for the stable electron emission when the polarity is changed to emit electrons. Formation of the protrusion was determined to be reversible and reproducible.

This research focuses on using a single field emitter that can function as both an ion and an electron source in an attempt to solve the problem of tip degradation by allowing for the possibility of tip re-generation. The primary goal of the research reported here was to determine if it was possible to use a quenched Taylor cone from an ion emitting tip to obtain electron emission. Further testing of different quenching conditions and emitter heating currents was also investigated to determine what type of effect both have on electron discharge I-V characteristics.

II. Description of Apparatus

Sharp W needles were formed by electrochemically etching W wires in a 2M NaOH solution. The etching procedure utilized was similar to the method used and described in further detail by Ekvall.[11] Using this etching technique it was possible to obtain reproducible tip diameters from the 100's of nanometers range up to a few microns, depending on the etch conditions. A typical W needle post-etch is shown in Figure 1.

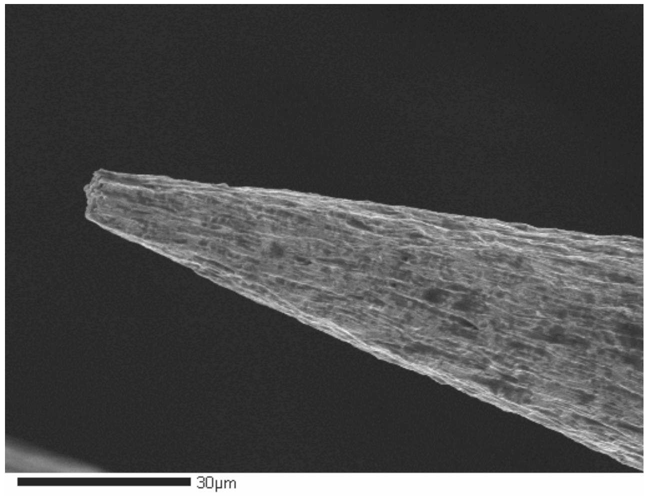

Figure 1. SEM image of an electrochemically etched W wire.

The sharpened W tips were then coated with In by dipping the heated filament in a crucible of liquid In. The etched and coated tips were then inserted into a fixture that served as both a heater as well as an In reservoir and is shown in the SEM image in Figure 2. This fixture was then placed in an LMIS housing with an adjustable extraction electrode. The entire housing schematic can be seen in Figure 3. A planar stainless-steel extraction electrode was positioned downstream of the tip. Typical gap spacing between emitter tip and extraction electrode was 1.0 to 1.5 mm.

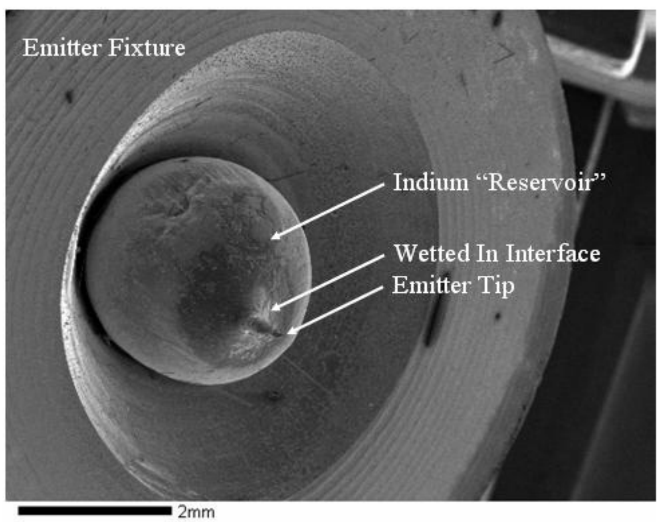

Figure 2. SEM image of a typical emitter fixture.

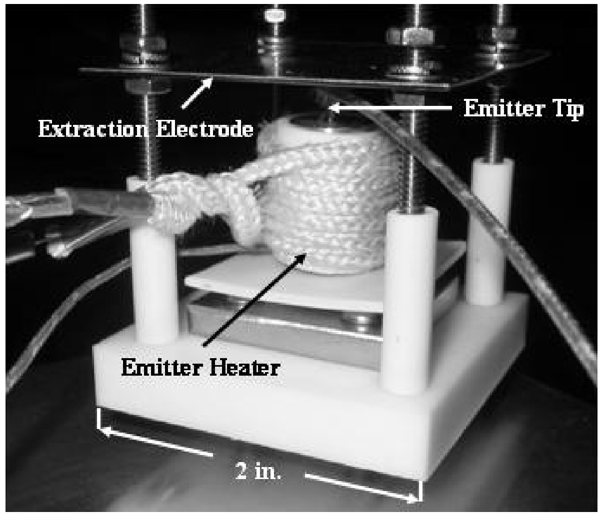

Figure 3. LMIS/electron emitter housing.

To operate the tip as an LMIS, the emitter heater was used to maintain the In reservoir above the melting temperature of In, which is 156.6 deg. C. For electron emission the emitter heater was un-powered, solidifying the In in the reservoir as well as on the emitter tip. The experimental setup for ion and electron emission is shown in Figures 4 and 5, respectively. A current amplifier with gain of 10^5 V/A was used to amplify the discharge signal so that the discharge current could be easily recorded on an oscilloscope.

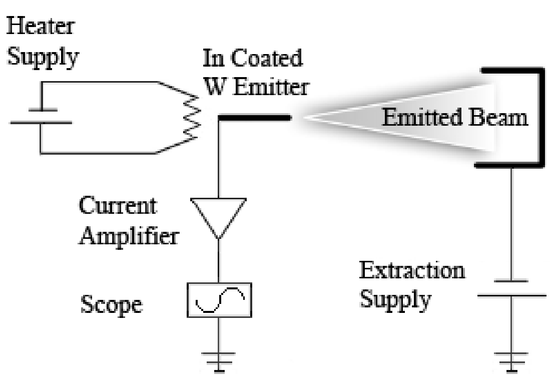

Figure 4. Electrical schematic of a single needle LMIS emitter electrode.

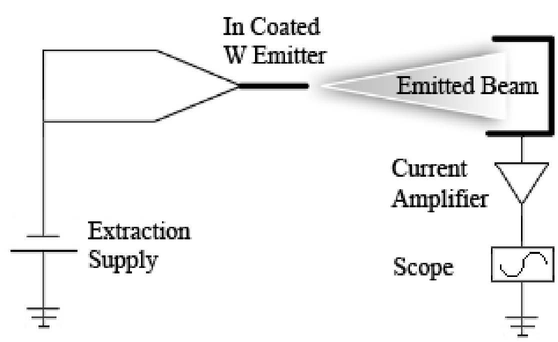

Figure 5. Electric schematic of a single needle field emission electron source.

All of the testing reported here was performed in a UHV chamber at Michigan Technological University's Yoke Khin Yap Research Lab. Research was performed in a 24"-diameter by 8"-deep vacuum chamber. The tank was evacuated using a single turbo-molecular pump and backed by a mechanical pump. Vacuum pressure of 10^{-7} Torr could be achieved in approximately 24 hours.

III. Results

To achieve ion emission, the emitter heating supply was enabled and increased to attain a suitable temperature for the indium to melt. The heater current was held constant for 45 minutes to allow the fixture to reach thermal equilibrium prior to attempting ion emission. The extraction electrode was then biased with a negative voltage and the emitter was grounded to obtain ion emission. Once ion emission was achieved and stabilized (which sometimes took up to several minutes), discharge I-V characteristics were taken at various emitter heating currents, as shown in Figure 6. To solidify the Taylor cone, the emission was quenched by turning off the heater. For this experiment, quenching occurred over 90 seconds when the emission was 2 µA and approximately 200 seconds when emission was 25 µA. A characteristic quenching curve is presented in Figure 7.

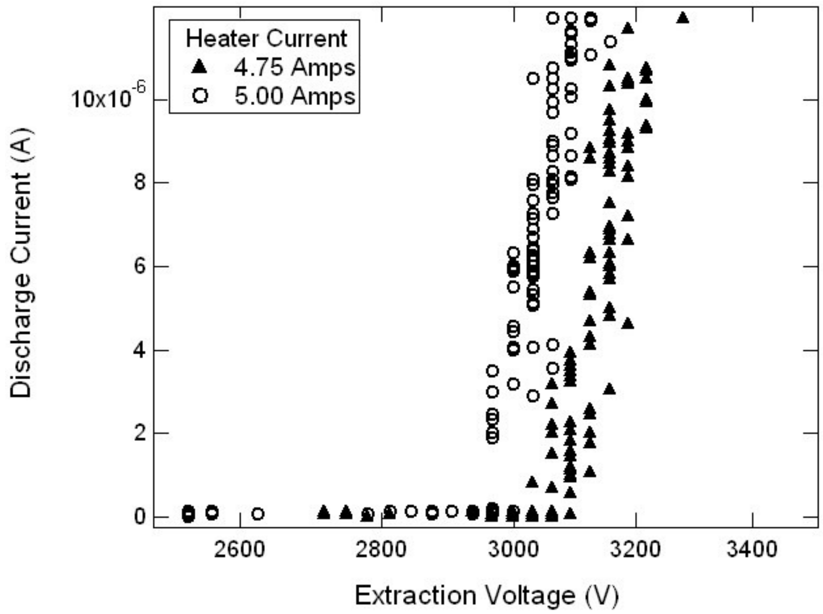

Figure 6. Ion emission current vs extraction voltage at two heater currents.

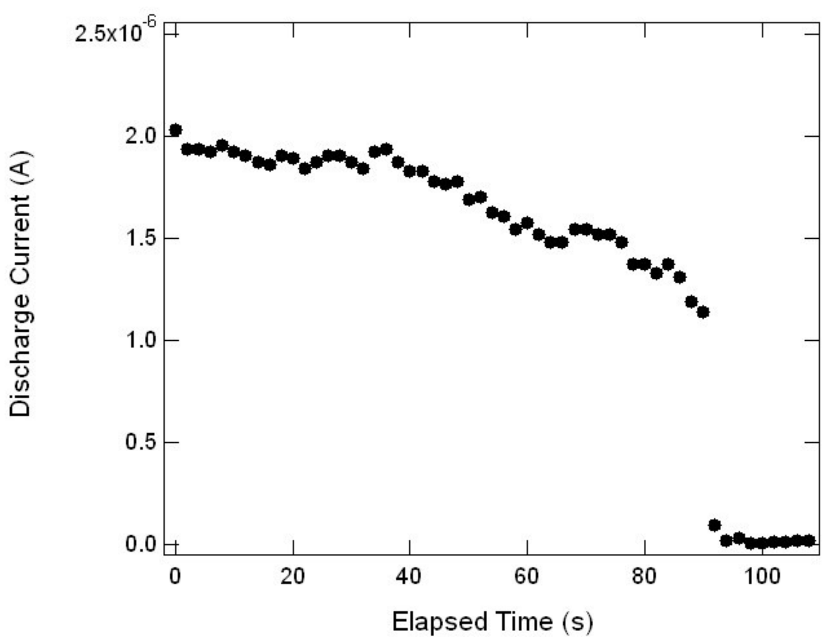

Figure 7. Typical quenching curve for Taylor cone formation from a 2 μA discharge after the emitter heater has been disabled at time t=0.

The Taylor cones were quenched at three different discharge currents and then used to obtain electron I-V characteristics. As shown in Figure 8, the most electron emission that was achieved was from the emitter tip that had been quenched at 25 μA. The next greatest emission was from the emitter tip quenched at 3 μA, and the least amount of electron discharge current from a quenched LMIS was from the tip quenched at 2 μA. It should be noted that while quenching the LMIS at 3 μA, the emission current was unstable and may account for the irregular trace in Figure 7: it is unknown whether the ion emission ceased because the cone solidified or if some other mechanism was responsible, such that the In solidified under a much lower emission current.

The electron emission characteristics from the quenched ion sources are compared in Figure 8 with an electron I-V curve that was obtained from the needle before any ion emission/Taylor cone formation was performed. This was done so that a baseline could be established for electron I-V characteristics with the as-etched needle for comparison with the frozen Taylor cone configurations. It is clear from Figure 8 that the quenching process greatly enhanced the electron field emission when compared to the blunt as-etched needle behavior.

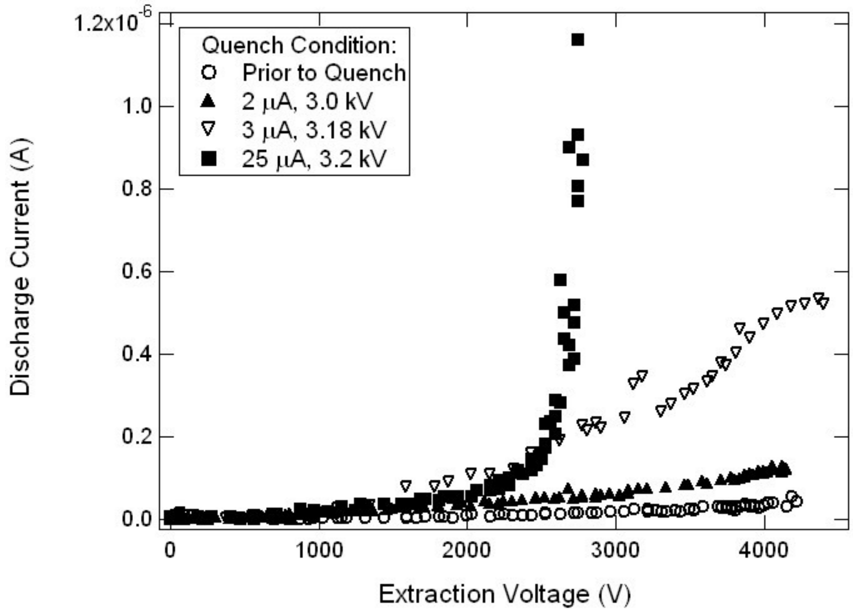

Figure 8. Electron I-V characteristics prior to quenching a Taylor cone, quenching at 2 μA, 3 μA and quenching at 25 μA.

IV. Discussion

It was found that by operating an In field emitter as an LMIS and quenching the tip to form a Taylor cone by removing the emitter heat while leaving the extraction electrode at a constant voltage it was possible to obtain an increase in electron discharge. The data show that quenching at as low as 2 μA produced an increase in electron discharge current as compared with the unquenched emitter. When the current at quench was increased to 3 and 25 μA, the discharge that was measured increased greatly. A trend can be noticed that quenching at higher ion emission currents yields increased electron emission at lower extraction voltages.

Using the electron I-V curves along with the Fowler-Nordheim equation, a theoretical estimate of the emitter tip radius can be made. For tip radius evaluation, Gomer's technique of applying the following Fowler-Nordheim equation was used,

$$\frac{I}{V^2} = a\exp\left(\frac{-b'\phi^{3/2}}{V}\right), \qquad \text{Equation [1]}$$

where *a* and *b'* are introduced as the following,

$$a = A6.2\times10^{6}(\mu/\phi)^{1/2}(\mu+\phi)^{-1}(\alpha kr)^{-2}, \qquad \text{Equation [2]}$$

$$b' = 6.8\times10^{7}\alpha kr. \qquad \text{Equation [3]}$$

In this series of equations I is the discharge current measured in amperes, V is the extraction voltage measured in volts, ϕ is the work function in eV, A is the total emitting area, α is the Nordheim image-correction factor, and a and b' are curve fits corresponding to characteristics of the I-V data plotted as $\ln(I/V^2)$ versus $1/V$.[12]

When plotted, the graph of $\ln(I/V^2)$ versus $1/V$ is linear and according to Gomer's derivation has an intercept of $\ln(a)$ and a slope of $b'\phi^{3/2}$. Using Equation 3 and taking α to be 1 and k equal to 5 as instructed by Gomer, the tip radius, r, can be approximated to within 20%.[12] Table 1 shows the estimated magnitude of the tip radius corresponding to each electron discharge I-V curve.

Current at Quench (µA)	Voltage at Quench (kV)	Tip Radius (nm)
N/A	N/A	230
2	3.0	220
3	3.2	102
25	3.2	80

Table 1. Estimations of emitter tip radii at various quenching currents using Gomer's Fowler-Nordheim analysis.

V. Additional Work – Scaling Up

As described in this paper, the maximum electron discharge current from a single emitter is roughly 1µA. For use with a moderately low-Hall thruster or ion thruster, it is necessary for the cathode to emit ~1 amp. Knowing this, it would take a 1000 x 1000 array of emitters to acquire one amp of electron discharge current. Applying this technology will require development of parallel arrays of regenerable emitter tips. Apart from the fabrication difficulties associated with massively parallel array, it will be necessary to address tip-to-tip variability issues including the uniformity of electron current within the array, the turn-on and quench I-V necessary to form the tips, and the relative lifetime of one tip vs. the population. Before attempting to create an array that is 1000 x 1000, it was determined that much could be learned by taking measurements with small arrays of emitters. In particular, we set out to determine the difficulty associated with building a 4 x 4 array.

Fabrication of a ~1000 x 1000 tip array will undoubtedly rely on some type of batch-formation protocol that does not resemble the electrochemical etch of W wires reported here. However, to separate the tip-to-tip variability issues from those arising from a new fabrication strategy, researchers have set out to build small arrays using the same processing techniques as the single needle. To this end, a 4 x 4 array was built to perform some of the preliminary experiments mentioned and is shown in Figure 9. The procedure for constructing this array was tedious. A 1.5mm thick molybdenum plate was micro-machined using a 0.020" endmill. A pocket was recessed 0.5mm into the plate and an array of holes were milled through the plate 0.020" in diameter. All of this machining was done in the Michigan Technological University Micro-fabrication Facility and tolerances were maintained so that the tungsten needles could be press fit into the moly wafer.

After the molybdenum plate was machined, each tungsten needle was individually electrochemically etched using the technique described earlier. These needles were then "threaded" one-by-one into the Mo alignment plate. They were then mechanically fastened into place.

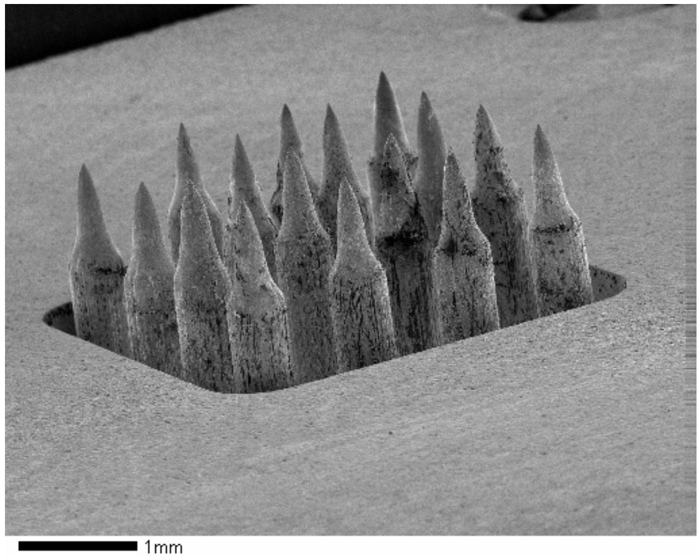

Figure 9. SEM image of the 4x4 array of tungsten needles in a molybdenum plate.

After the sixteen tungsten needles were fixed to the moly plate, the array had to be prepared for indium coating. This consisted of immersing the 4 x 4 wafer in a series of five chemical baths, coating the assembly with W via sputter deposition, followed by an In coating with electron beam evaporation. Approximately six microns of indium were deposited on the array in five consecutive fifteen minute deposition periods. The indium coated array is shown in Figure 10.

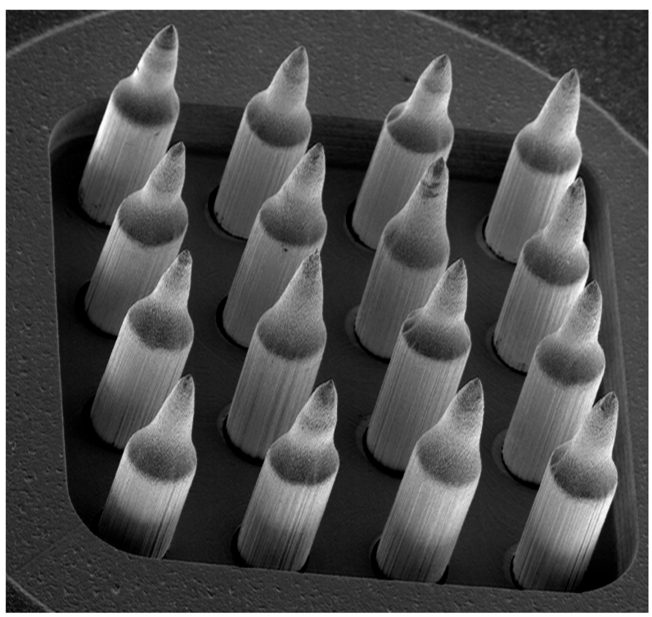

Figure 10. SEM image of the indium coated 4x4 array.

At the time of this writing the array had not been tested for ion or electron emission. Results are anticipated during the winter of 2008 with data to be presented at the 2008 AIAA Joint Propulsion Conference.

VI. Conclusions

In conclusion, it was determined that an In emitter tip can be regenerated as long as there is a sufficient supply of In to form a Taylor cone. Also, the I-V characteristics of the field emitter can be altered depending on which heating and quenching currents are chosen. It was shown that quenching at higher ion emission current produced larger electron emission at lower extraction voltages than when quenched at lower current, implying that the emitter tip radius is reduced when quenching occurs at higher ion emission current.

Since each tip can supply ~1µA of discharge current, applying this technology will require scaling up to very large arrays. Aside from the manufacturing difficulties associated with building massive arrays of emitters, many other operating characteristics can be investigated using smaller arrays. For this reason, a 4 x 4 array was built and will be experimented with in the near future to determine such characteristics.

Future work that is planned with single emitters is to perform long duration tests of electron discharge to determine how often emitter tips must be regenerated. Also, operating the emitters in different levels of vacuum will be experimented with, as well as in low-density ambient plasma environments that would be expected in the vicinity of EP thrusters.

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