Development and Characterization of Indium Field Emission Electric Propulsion Thruster

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Abstract: Due to the advantage of high specific impulse, low thrust, high precision and high efficiency, field emission electric propulsion (FEEP) is regarded as a promising propulsion technology in ultraprecise attitude and orbit control. The field emission electric propulsion (FEEP) thruster is developed, and the core component---the tip with a radius of only several microns is fabricated by the electrochemical etching method. The tip is roughened by AC and then wetted in vacuum. To determine the characteristics of FEEP the effect experiments of the radius of the tip, the emitter-extractor distance and the diameter of the extractor on the I-V curves are conducted. The plume divergence half-angle is determined by the propellant deposition method. Lastly, a method of improving the ion current by increasing the depth of grooves is proposed and the ignition experiment shows the effectiveness of the method.

I. Introduction

THE development of the micro satellite promotes the requirement of ultraprecise attitude and orbit control. The field emission electric propulsion (FEEP) thrusters offer low thrust noise and high controllability combined with a very high specific impulse (up to 8000 s) enabling ultra high precision pointing capabilities. Such thrusters are required for scientific drag-free and constellation missions such as LISA, GOCE and SMART-2.

The indium needle-type FEEP is stemmed from the development of the liquid metal ion source (LMIS): a sufficiently high electric potential is applied between the emitter and the extractor; the equilibrium between the surface tension and the electric field force forms a so-called Taylor cone with a protruding jet on the needle tip; Atoms are then ionized at the tip of the jet and accelerated out by the same field that created them; the expelled ions are replenished by the hydrodynamic flow of the liquid metal along the micro grooves on the needle surface.

The most researches of indium needle-type FEEP thrusters were developed in ARCS (and subsequent Austrian Institute of Technology and FOTEC) in Austria. Based on the successfully flying of the In LMIS, researchers of ARCS developed the In FEEP thruster. They performed lots of experiments on the testing of thrust, specific impulse, [1]divergence angle of the plume,[2,3] mass efficiency[4] and lifetime.[5] In order to improve the thrust level, on one hand, the FEEP thrusters were clustered,[5] and on the other hand, the porous crown FEEP thruster which combines the advantages of the needle and capillary FEEP thrusters was developed in recent years.[6,7] Now the porous crown FEEP thruster is studied in FOTEC[8] and Technische Universität Dresden[9] and a 10000 h lifetime had been

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conducted in FOTEC by 2016[10]. In this paper, the indium FEEP experimental prototype is developed and the characteristic experiments are conducted and a method of improving the ion current is proposed.

II. Development of indium FEEP experimental prototype

A. Design of the FEEP thruster

The indium FEEP thruster prototype is composed of the tungsten needle tip, the extractor, the reservoir, the ceramic heater and some appurtenances, as shown in Fig. 1. The size of the thruster is Φ28×49 mm and the mass is about 60 g. The extractor is made of stainless with a circular aperture in the middle. The molybdenum reservoir is filled with the propellant indium. The ceramic heater is used to melt the indium so that the liquid propellant could flow to the tip.

Figure 1. In-FEEP experimental prototype.

B. Fabrication of the needle tip

In order to generate a high electric field the radius of the needle tip is usually in micrometer order. The tip is manufactured by the following two processes. Firstly, a smooth tip is formed at the end of the needle by electrochemical etching technology. The electrolyte is 5 M/L NaOH solution contained in a beaker. The anode is a drawn tungsten rod with a diameter of 0.5 mm vertically immersed in the solution. A 40 mm diameter stainless steel circle is horizontally placed in the electrolyte as the cathode. A 5 V DC voltage is applied between the electrodes. During the reaction process, the immersed part of the needle in the electrolyte drops off due to its own weight and a sharp tip with smooth surface is formed as shown in Fig. 2. In addition, the tip should be roughened to decrease the flow impedance of the liquid metal thus promoting continuous ion emission. The manufactured smooth tip is roughened with 0-3 V AC in NaOH solution for a few seconds to form grooves on the surface as shown in Fig. 3.

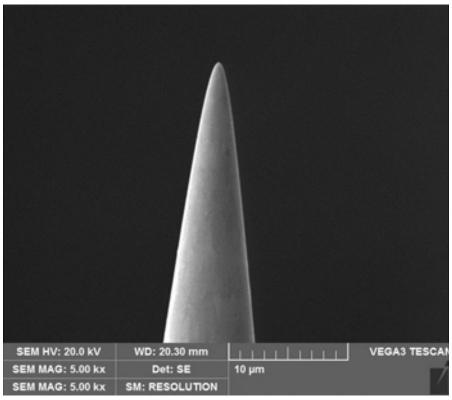


Figure 2. SEM image of the micro-tip.

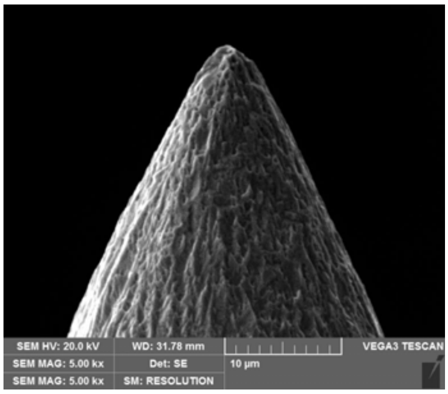


Figure 3. SEM image of the roughened tip.

C. Wetting of the needle tip

Wetting which means adhering a film of indium to the surface of the needle is an important technology of FEEP. Before wetting, the tip should be cleaned because there are lots of NaOH particles and a layer of tungsten oxides on the tip surface after the electrochemical etching processing. The tip is immersed in the hydrochloric acid to remove the NaOH particles then in the hydrofluoric acid to remove the tungsten oxides[11] for a few minutes.

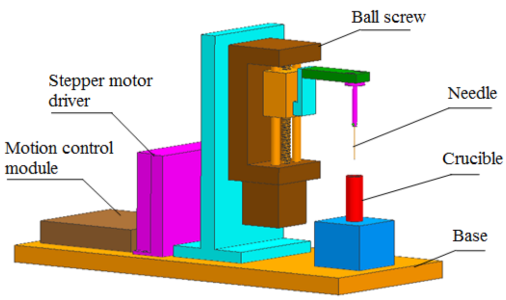


Figure 4. Device for tip wetting.

Because indium is easily to be oxidized in the atmospheric environment, the wetting process must be proceeded in the vacuum chamber. An automatically wetting device is developed as shown in Fig. 4. The clean tip is installed on the wetting device then the indium in the crucible is heated until melted when the vacuum degree reaches to 10^{-3}

Pa. The tip is then dipped in and out of the liquid indium repeatedly under the motion control module until a film of indium is adhered to the surface of the tip.

D. Ignition of the FEEP thruster

The ignition experiment is conducted in a vacuum chamber with a diameter of 0.3 m and a length of 0.6 m. After assembling the needle tip into the thruster and heating the indium in the reservoir above the melting point, the voltage applied between the emitter and the extractor is gradually increased until ions are ejected. The In needle-type FEEP behaves a blue point-like shape during operation as shown in Fig. 5.

Figure 5. In-FEEP thruster during operation.

III. Characteristic Experiments

A. Effect of the tip radius on the I-V curve

Figure 6 shows the effect of the tip radius on the I-V curve. In the experiments the extractor diameter is 4 mm and the emitter-extractor distance is 250 µm. From Fig. 6, the starting voltages are highly dependent on the tip radii and the smaller tip radius shows lower starting voltage. The starting voltages are 4700 V and 6100 V respectively for the tip radius of 1.36 µm and 6.47 µm. This is because the smaller radius leads to higher electric field thus field emission easily.

B. Effect of the emitter-extractor distance on the I-V curve

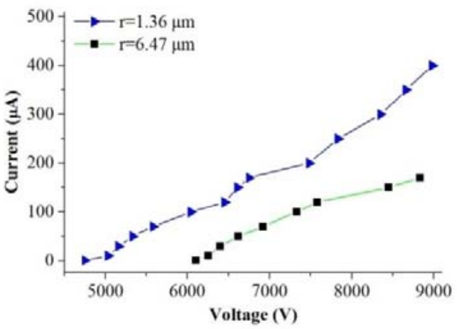


Figure 6. I-V characteristic of needle tips with different radii.

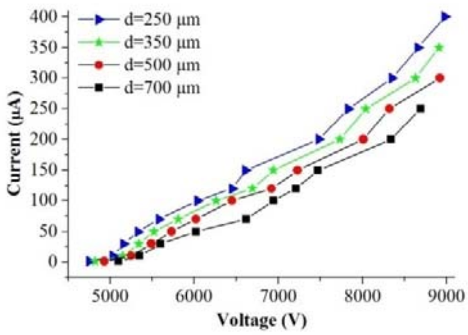


Figure 7. I-V characteristic of needle tips with different emitter-extractor distances.

Figure 7 shows the effect of the emitter-extractor distance on the I-V curve. In the experiments the extractor diameter is 4 mm, the tip radius is 1.36 µm and the emitter-extractor distances are 250 µm, 350 µm, 500 µm and 700 µm respectively. From Fig. 7, the starting voltages are highly dependent on the emitter-extractor distance. The smaller emitter-extractor distance shows lower starting voltage and the ion current is lower for the same voltage as the emitter-extractor distance increases. This is because the smaller emitter-extractor distance leads to higher electric field thus field emission easily.

C. Effect of the extractor diameter on the I-V curve

Figure 8 shows the effect of the extractor diameter on the I-V curve. In the experiments the tip radius is 1.36 µm, the extractor diameter is 4 mm, the emitter-extractor distance is 250 µm and the extractor radii are 4 mm, 6 mm, 8 mm respectively. From Fig.8, the starting voltages are highly dependent on the extractor diameter. The smaller extractor diameter shows lower starting voltage and the ion current is

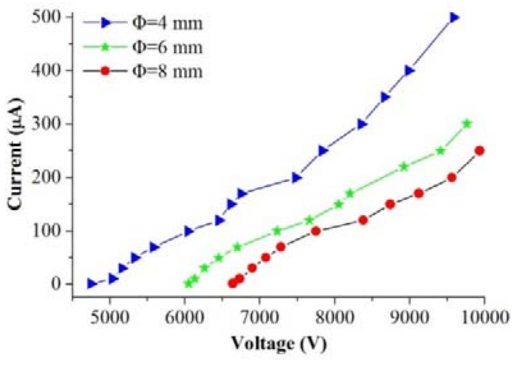


Figure 8. I-V characteristic of needle tips under different extractor radii.

lower for the same voltage as the extractor diameter increases. This is because the smaller extractor diameter leads to higher electric field thus field emission easily. The extractor with 2 mm radius is also tested and sparking occurs sometimes because ions would bombard the inwall of the extractor.

D. Ion plume divergence half-angle

The plume divergence angle is an important performance parameter of FEEP. M. Tajmar developed an ion plume distribution equipment which uses wire probes that can move either in X or Y direction. The probes consist of a 1.6-mm-diam tungsten wire and are moved using Phytron stepper motors[2]. However, for the confine of condition, the propellant deposition method is used to determine the divergence angle which is a simple and convenient way without using any control circuits or instruments. It is found that the indium ejected from the thruster could deposit on the inwall of the vacuum chamber and form a black signet. So a Teflon plate is placed horizontally at a certain distance from the FEEP thruster. The ion divergence half-angle φ can be calculated by the equation (1) where h is the vertical distance between and the tip and d is the horizontal distance between the tip and the vertex of parabolic plume deposition as shown in Fig. 9. The indium deposition on the Teflon plate is shown in Fig. 10. Figure 11 shows the ion plume divergence half-angles for currents from 10 μA to 400 μA and the plume divergence half-angle increases with the ion current.

$$\varphi = \arctan(h/d) \quad (1)$$

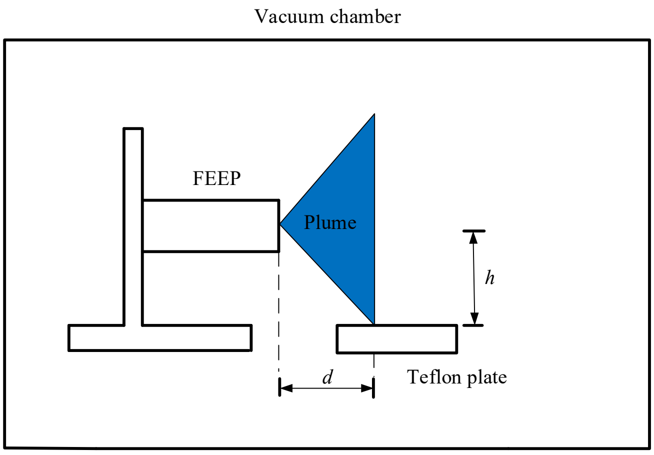


Figure 9. The geometrical relationship between the deposited indium and the position of the FEEP thruster.

Figure 10. The plume deposition on the Teflon plate.

E. A method to improve the ion current

Mair presented that the flow impedance was decreased as the depth of the grooves on the needle tip was increased.[12] Thus, the increased depth and number of the axial grooves is capable of decreasing the flow impedance of the liquid metal thus promoting continuous ion emission. Here, the dependences of roughening parameters including the etching voltage and the processing time on the radius and the surface texture of the needle tip are investigated and presented. In addition, an effective method to fabricate tips with deeper grooved texture thus improving the ion current is also proposed. [13]

To investigate how the AC electrochemical etching parameters affect the tip radius and the texture, the smooth tips shown in Fig. 2 are roughened in the 2.5 M/L NaOH solution under different voltages for different time. It is found that a deeper grooved tip can be obtained under longer etching time at a low roughening voltage (0.5 V) without varying the radius of the tip as illustrated in Fig. 12.

In order to validate the performances of the method, a smooth tip is etched under 1.5 V AC for 20 s to form a tip with 1.25 μm radius. Then the tip is roughened under 0.5 V AC for 2 min, 5 min and 10 min respectively. As shown in Fig. 13, when the roughening time is extended to 5 min and 10 min, the depths of the grooves are increased obviously.

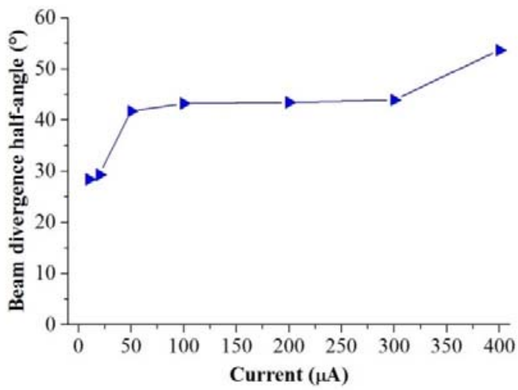
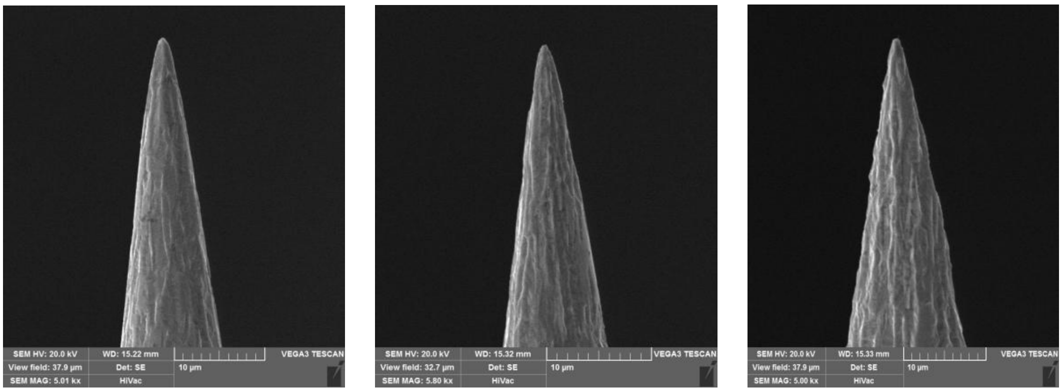
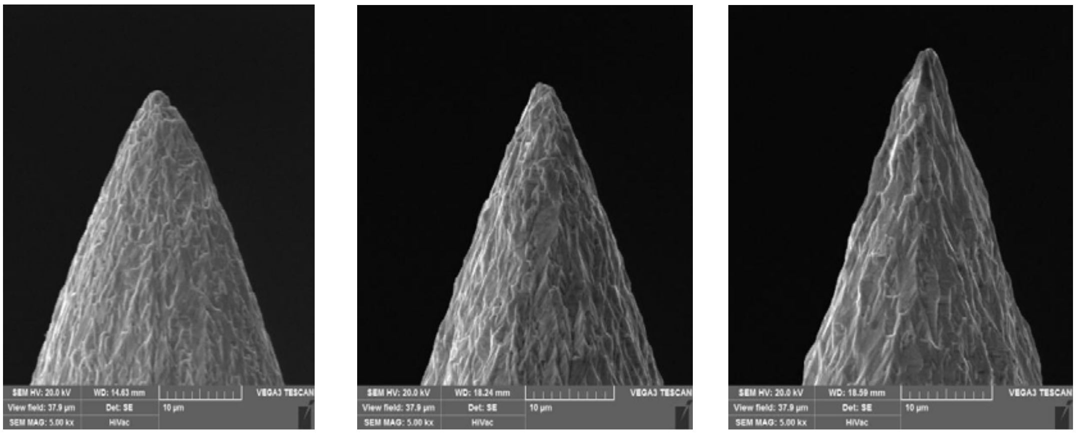


Figure 11. Ion plume divergence half-angles for currents from 10 μA to 400 μA.



a) b) c)

Figure 12. Ac erosion under 1.5 V for 20 s then 0.5 V for different time: (a) 2 min; (b) 5 min; (c) 10 min.



a) b) c)

Figure 13. Ac erosion under 1.5 V for 20 s then 0.5 V for different time: a) 2 min; b) 5 min; c) 10 min.

The I-V characteristics are presented to demonstrate the performances of the tip fabrication method. Figure 14 shows the I-V curves of the two tips created respectively under 1.5 V-20 s+0.5 V-5 min, 1.5 V-20 s+0.5 V-10 min (for simplicity, 1.5 V-20 s+0.5 V-5 min represents the AC etching condition of 1.5 V for 20 s then 0.5 V for 5 min). In the experiment, the extractor diameter is 4 mm and the emitter-extractor distance is 250 µm. The result indicates that the tip with deeper grooves have sharp increases in I-V curves. Further, the roughening time is extended to 30 min and the I-V curve is shown in Fig. 15. Comparing the ignition voltage at the ion currents of 100 µA, 200 µA and

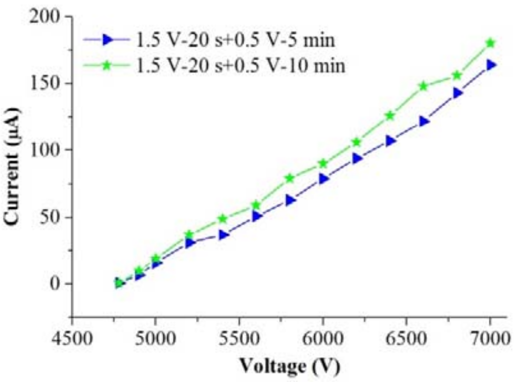


Figure 14. I-V characteristics of two tips formed under the condition of 1.5 V AC for 20 s then 0.5 V AC for 5 min and 10 min.

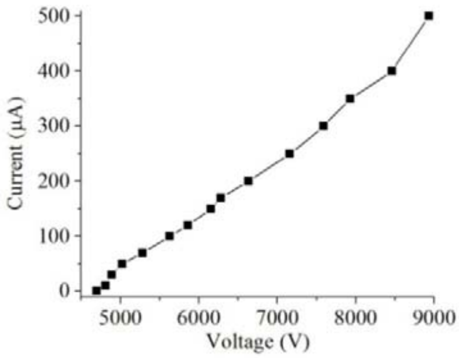


Figure 15. I-V characteristic of the tip formed under the condition of 1.5 V AC for 20 s then 0.5 V AC for 30 min.

300 μA with the tip formed under 1.5 V AC for 20 s, the ignition voltages are 410 V, 850 V and 760 V lower respectively. That is to say, higher ion currents can be reached under the same applied voltage.

IV. Conclusions

A FEEP experimental prototype is developed and the tip with a radius of only several microns which is the core component of the thruster is fabricated, roughened and wetted in vacuum. The characteristic experiments including the effects of the tip radius, the emitter-extractor distance and the extractor diameter on the I-V curves are conducted. The FEEP thruster with small radius tips, short emitter-extractor distances or small diameter extractors show low starting voltages. The ion plume divergence half-angle is tested with the propellant deposition method. The plume divergence half-angle increases with the ion current. Lastly, a method of improving the ion current by increasing the depth of grooves is proposed. The I-V characteristic of the tip fabricated with this method shows higher ion currents can be reached under the same applied voltage.

Acknowledgments

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