

Microfabrication of a Massive Emitter Array for Higher Thrust Density of Ionic Liquid Electrospray Thrusters

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Abstract: As a preliminary experiment, a few 100 μm pitch emitter array was fabricated by conventional MEMS processes and its voltage-current characteristics were measured using ionic liquid of EMI-BF₄ as the propellant. The ion beam was able to be extracted at the applied voltage of ± 1.6 kV for the gap distance of 0.2 mm. Particle-in-cell simulations were also carried out to investigate ion beam trajectories after the ions were extracted. To increase the thrust density, drastically high-density emitter array has been fabricated using field-emitter-array fabrication processes, where the package density was four orders of magnitude higher than that of the conventional emitter array.

I. Introduction

THE number of microspacecraft launched has dramatically increased since 2013, and more than 100 nano/microsatellites (1–50 kg) were launched last year. However, most microspacecraft do not have any propulsion systems because of the limited size and power. Although a 50-kg-class microspacecraft already mounted a unified propulsion system containing an ion thruster and eight gold gas thrusters and was successfully operated in space in 2014,¹ it would be difficult to further reduce the propulsion system as long as the gas propellant was employed. Since most microspacecraft launched recently are less than 10 kg, more compact thrusters are required.

Ionic liquid electrospray thrusters (ILESTs) are one of the candidates for such microthrusters owing to their compactness and possibility of high propulsion efficiency using ionic liquid as the propellant, and many studies were already conducted so far.^{2–9} Ionic liquid consists of only cations and anions and no solvent is included, unlike sodium chloride. Because of strong Coulomb force between cations and anions, the vapor pressure is almost zero,¹⁰ so that ionic liquid is able to exist as liquid even in vacuum. When applying a bipolar pulse voltage, both cations and anions can be extracted as shown in Fig. 1, implying that no neutralizer is required. These facts can significantly contribute to the compactness and light weight of the propulsion system.

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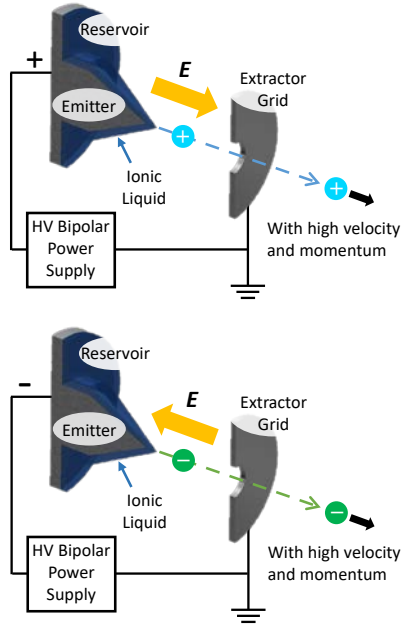


Figure 1. Schematic of the ILEST.⁹
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However, ILESTs need many emitters to deliver the thrust because a single emitter produces only a tiny beam current ($< 1 \mu\text{A}$). The number of emitters is currently less than a few hundred per square centimeter, and thus the thrust density is one order of magnitude lower than that of ion thrusters. To increase the thrust density of ILESTs drastically we have been fabricating much more emitters using the fabrication technique of a field emitter array (FEA),¹¹ after we fabricated emitters by conventional MEMS processes as a preliminary experiment. We have also performed numerical simulations for ion beam extraction to investigate its characteristics.

II. Preliminary Experiment

The preliminary experiment using conventional MEMS processes was recently published in Ref. 9, and thus we briefly summarize the results as below.

A. Fabrication of an Emitter Array

An emitter array was fabricated on a surface of a silicon wafer. Figure 2 shows the fabrication procedure. (a) A positive type photoresist (PMER P-LA900PM) was applied to the silicon wafer and heated. (b) Photolithography transcribed the photoresist from a patterned photomask. (c) Isotropic dry etching was performed using SF_6 to form the cone shape of the emitter tips based on the patterned photoresist layer. (d) The Bosch process was employed to increase the height of the emitter and form the reservoir of ionic liquid. (e) Finally, the photoresist at the tip of the emitter was removed. The emitters were placed as many as possible with 250 and 500 μm pitches inside the reservoir of 8 mm diameter, where there are about 200 emitters on the 500- μm -pitch emitter chip. Figure 3 shows typical examples of the SEM images of the emitter array with a 250 μm pitch. Here, the height of the emitters was 230 μm (160 μm depth for the Bosch process), and the wafer was singulated into a $1 \times 3 \text{ cm}^2$ emitter chip by mechanical dicing.

B. Experimental Setup

Figure 4 shows a schematic of the experimental setup for the current measurement of both the cation and anion beams. Most

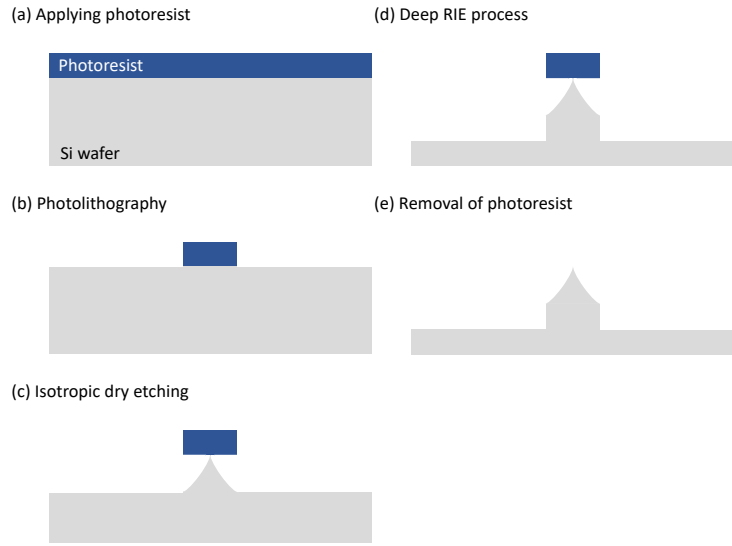


Figure 2. Fabrication procedure of the emitter array.

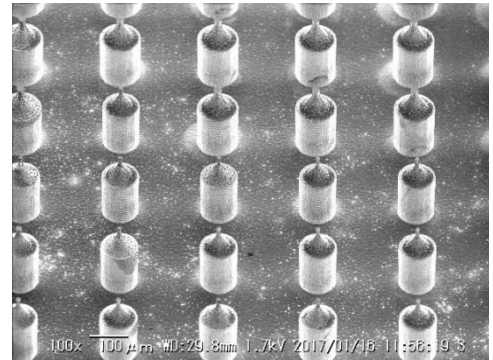


Figure 3. SEM image of the emitter array.⁹
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experimental systems (emitters, extractor, and collector) were in a vacuum chamber evacuated by a rotary pump and a turbomolecular pump at a base pressure lower than 2.0×10^{-3} Pa. Here, the distance between the emitter tip and extractor grid was set at 0.2, 0.3, and 0.4 mm. The ionic liquid employed was 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF₄). The extractor grid was made of 1×3 cm² stainless steel with a thickness of 80 μ m (each grid diameter was set to be 200 and 300 μ m for the 250- and 500- μ m-pitch emitter chips, respectively) and was fabricated by metal etching.

Voltage alternation was employed to prevent the electrochemical decomposition of the ionic liquid and to neutralize the space charge,⁷ where a function generator (Matsusada eK-FGJ) generated a bipolar pulse signal that was amplified by a high voltage amplifier (Matsusada HJOPS-4B10). The beam current of ions passing through the extractor grid was measured with a shunt resistor of 1 k Ω connected to the collector in series using a digital multimeter (Keithley 2110). The current intercepted by the extractor grid was also measured similarly.

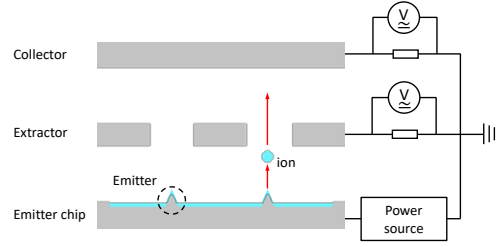


Figure 4. Schematic of the experimental setup.

C. Voltage-Current Characteristics

Figure 5 shows the extractor and collector currents measured by applying a bipolar pulse voltage between the emitter chip and the extractor grid with gap distances of 0.2 mm for the 500- μ m-pitch emitter chip, where the repetition frequency of the bipolar pulse was set at 0.5 Hz. When the absolute applied voltage was more than 1.6 kV, ion beam currents were detected, and the absolute value of the collector current increased with increasing absolute applied voltage. Since the maximum amplitude of the high-voltage amplifier is 4 kV, a higher voltage was also applied. However, stable currents were not obtained in this higher voltage region. A previous study showed that the ion source became unstable and more than one emission site from a single emitter tip was observed at higher applied voltages.¹² Although the starting voltage was almost the same for both cations and anions, more currents were measured for cations than for anions, probably because anion beams contain more dimers (EMI-BF₄)BF₄⁻ or droplets than cations. When increasing the gap distance, the starting voltages of ion extraction increased and the collector current also increased for both cations and anions because of the higher potential drop between the emitter and the extractor grid, while the extractor currents also increased, which resulted in the loss of the thrust. Here, the cation currents were higher than the anion currents at all the gap distances. In spite of careful alignment of the extractor apertures and the emitters, non-negligible currents were observed at the extractor grid because of ion collisions. Figure 6 shows the surface of the extractor grid on the side toward the emitter chip after several times of the experiments. The edge of the grid becomes dark, indicating that ion beams with a relatively large divergence angle collide with the extractor grid.

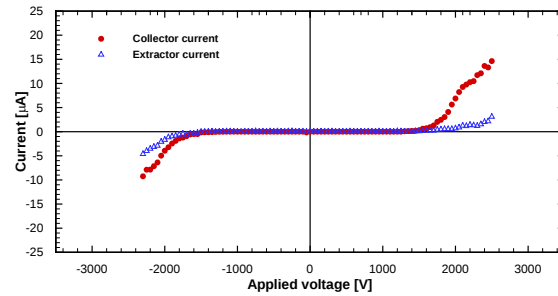


Figure 5. Collector and extractor currents as a function of applied voltage.⁹ Copyright (2017) The Japan Society of Applied Physics.

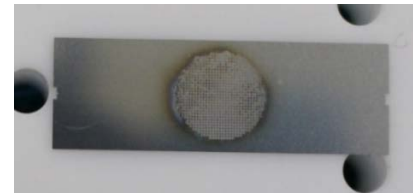


Figure 6. Photograph of the extractor grid after the experiments.

D. Estimation of a Divergence Angle

Etching or deposition may occur when the emitted ions collide against the collector electrode.¹³ During the experiments, a bipolar pulse voltage with an amplitude of up to 4 kV was applied to the emitter chip for more than 30 minutes and a clear footprint was observed. Figure 7 shows the collector plate before and after extracting the ion beam, where the whitish trace, which indicates that ions collide with the collector, can be seen on the plate surface after the experiment and its width is about 18 mm. Since the diameter of aperture region of the extractor grid is 8 mm and the gap length between the extractor and the collector electrodes is 16 mm as shown in Fig. 8, the beam divergence angle

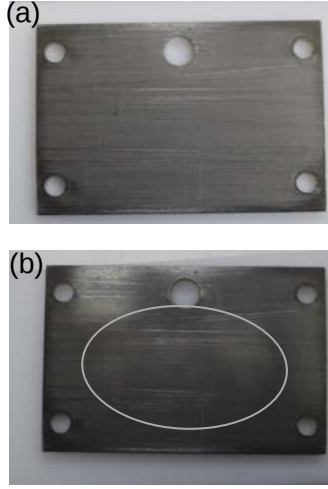


Figure 7. Photograph of the collector (a) before and (b) after the experiments.

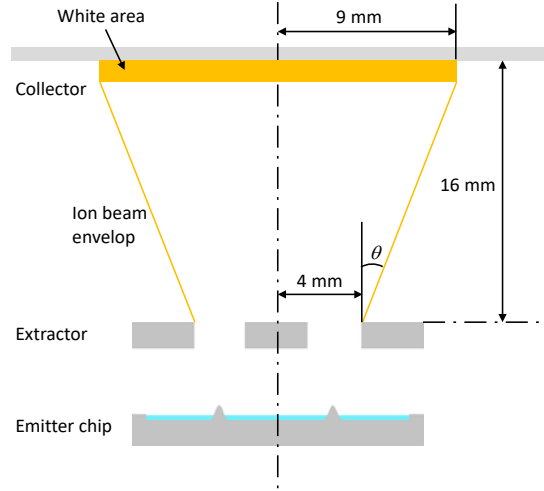


Figure 8. Position relationship between collector and extractor electrodes.

θ was estimated to be about 17° , assuming that the ions in the beam envelope are emitted from the outermost hole of the extractor grid.

III. Numerical Analysis

A. Configuration

Figure 9 shows the calculation model of the electrospray thruster,¹⁴ where the model has a similar size to the experiments. To reduce the calculation time, two-dimensional cylindrical coordinates are employed and a single emitter cone is treated as the calculation target. The emitter shape is the circular cone which is $70 \mu\text{m}$ in radius and height, and the thickness of the extractor grid is $20 \mu\text{m}$. The calculation area is divided into $5 \mu\text{m} \times 5 \mu\text{m}$ cells.

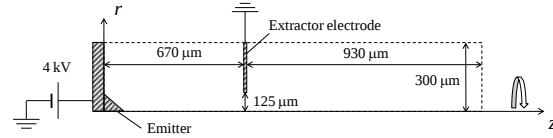


Figure 9. Simulation area of the ion beam extraction.¹⁴ ©JSASS.

B. Assumptions

In this simulation, EMI- BF_4 is employed for the ionic liquid propellant. A molecular of EMI- BF_4 has two ions: a cation EMI^+ and an anion BF_4^- . The ion particles considered in the simulation are assumed to be monomers and dimers, which are measured by Time-of-Flight spectra in experiments: EMI^+ , BF_4^- , $(\text{EMI}-\text{BF}_4)\text{EMI}^+$, and $(\text{EMI}-\text{BF}_4)\text{BF}_4^-$.¹⁵ We also assumed that ions were extracted from the emitter tip at a current of $1 \mu\text{A}$ and extracted ions had the random initial velocities of the Maxwellian distribution at a temperature of 2.6 eV . The ion beam trajectories are calculated using a particle-in-cell method, which is generally employed for plasma simulations.

C. Numerical Results

Figures 10 and 11 show the time-averaged anionic monomer density and energy distributions when the anionic monomer beam is extracted from the emitter tip applied at -4 kV . The maximum value of the anionic monomer density is about 10^{19} m^{-3} near the emitter tip, while the minimum value of that is about 10^7 m^{-3} at the edge of the anionic monomer beam. Here, the difference of the anionic monomer density between the center and the edge of the

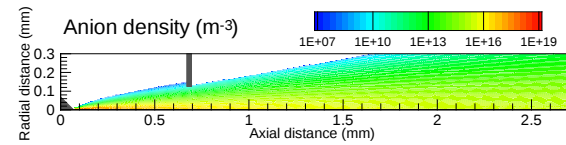


Figure 10. Anionic monomer density distribution (only monomers).

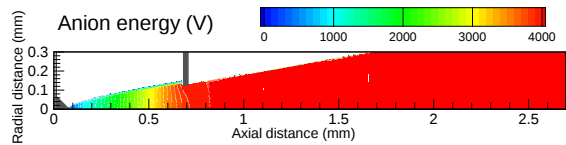


Figure 11. Anionic monomer energy distribution (only monomers).

anionic monomer beam is about 10^5 m^{-3} at the extractor grid. The anionic monomer energy increases immediately as the ions move from the emitter tip to the downstream, and the ion energy at the extractor grid reaches about 4 keV.

The half-angle of the anionic monomer beam is estimated to be 10° when it is assumed that the temperature of the emitter tip is 2.6 eV, and the edge of the anionic monomer beam collides with the extractor grid. This estimated half-angle of the anionic monomer beam is small compared with the value measured in the experiments. However, the anionic monomer beam divergence would be changed when we assumed the different temperature of the ionic liquid at the emitter tip. Therefore, it is necessary to consider the motion of ions at the emitter tip to decide the initial velocity distribution and the emitter current.

IV. Massive Emitter Array Fabrication

A. Fabrication Procedure

Figure 12 shows the fabrication process of the ultra-high-density emitter and extractor electrodes based on the process of FEAs.¹⁶ Here, we employ a minimal wafer 0.5 inch in diameter and 250 μm in thickness in order to partly use a minimal fab system, which is totally different from the conventional semiconductor/MEMS fabrication plants and is suitable for trial and low-volume production of semiconductor/MEMS devices.^{17,18}

The detailed fabrication procedure is as follows:

- (1) A lift-off layer and a photoresist were deposited on an Al thin film, which was also deposited on a Si minimal wafer.
- (2) Photolithography was carried out to form an emitter array pattern and then the lift-off layer was removed using a buffered hydrofluoric (BHF) acid solution.
- (3) A Ni Spindt-type emitter was fabricated using vacuum vapor deposition.
- (4) The photoresist and the lift-off layer were dissolved using wet etchant.
- (5) An insulator SiO_2 and an emitter metal of Nb were deposited by PE-CVD.
- (6) A photoresist was then spin coated.
- (7) Reactive ion etching (RIE) was carried out to remove the photoresist and the Nb electrode on top of the mountain structure.
- (8) The photoresist was dissolved using wet etchant.
- (9) The extractor electrode was fabricated in the same manner as the emitter electrode using the procedure from (5) through (8).
- (10) After the surface was coated by SiO_2 and a photoresist, the minimal wafer was turned over and an Al layer was deposited. The Al layer was then etched using patterned photolithography.
- (11) The Si layer was removed by the Bosch process until the Al layer appeared.

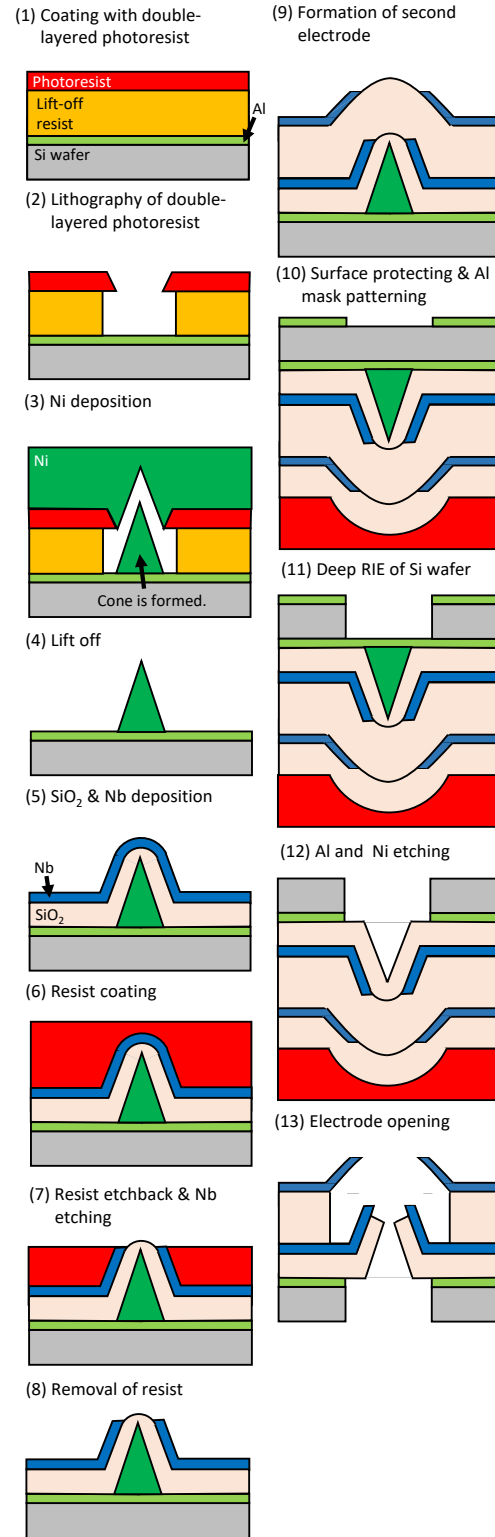


Figure 12. Fabrication procedure of the ultra-high-density emitter array.¹⁶ ©JSASS.

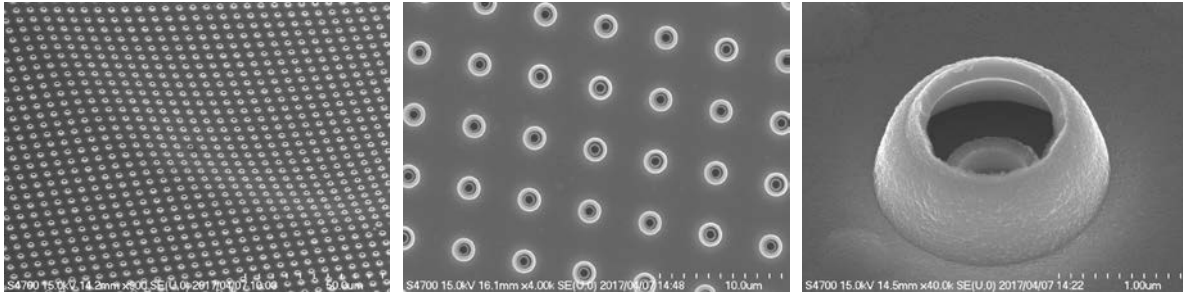


Figure 13. SEM images of an ultra-high-density emitter array.

- (12) The Al and Ni layers were removed using wet etchant.
- (13) The minimal wafer was turned over again and part of the SiO₂ layer was removed using BHF to fabricate the capillary-type emitter electrode and the extractor electrode.

B. Example of a Massive Emitter Array

Figure 13 shows the SEM images of a massive emitter array fabricated using the above process, where different magnifying power is employed from left (low) to right (high). Compared with the conventional emitter array using the top-down process, which normally has a few 100-μm pitch, the pitch is drastically reduced by about two orders of magnitude, and thus the emitter package density is four orders of magnitude higher than that of the conventional emitter array. If the obtainable current per emitter was the same as that of the conventional emitter, the thrust density would also increase by four orders of magnitude. A trial of the ion beam extraction is now underway and will be presented at the conference site.

Acknowledgments

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