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

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Abstract: For improving the thrust density of ionic liquids electrospray thrusters, a high-density emitter array using the fabrication technique of a field emitter array has been fabricated, where the structure consists of sub-µm scale capillary emitters with self-aligned extractor electrodes and ionic liquid reservoirs behind them. The density of the emitter array can reach approximately 4 million/cm^2, which is about four orders of magnitude higher than that of conventional ones. Current measurements have shown that both positive and negative ion currents were detected using EMI-DCA as the propellant, involving leakage of the ionic liquid. For the prevention of leakage, capillary-needle-type emitter electrodes are now under development. Accelerator electrodes are also being fabricated for the ion beam acceleration.

Nomenclature

EMI-BF_4 = 1-ethyl-3-methylimidazolium tetrafluoroborate
EMI-DCA = 1-ethyl-3-methylimidazolium dicyanamide
FEA = field emitter arrays
MEMS = microelectromechanical system
RIE = reactive ion etching
SEM = scanning electron microscope

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I. Introduction

IN recent year, nano/microsatellites (1–50 kg) have been attracting much attention in the space community because they can be developed at low cost and in the short term and the number of nano/microsatellites launched was more than 300 in 2017 already.[1] Most nano/microsatellites are singly used; however, more advanced missions such as constellation and deep-space exploration are also planned and conducted using nano/microsatellites.[2-4] In such advanced missions, high-performance (high Δv and total impulse) small propulsion systems are required.

One of the candidates for such thrusters is ion thrusters, which were already mounted on two 50 kg-class microsatellites and successfully operated in space.[3,5] However, it is difficult to miniaturize ion thrusters so that they can be mounted on even 10 kg-class nanosatellites unless high-pressure gas feeding systems are removed.

On the other hand, electrospray thrusters using ionic liquids as a propellant (Fig. 1) are one of the solutions because they do not require a gas propellant or a neutralizer. Applying a high voltage to the emitter substrate gives the strong electric field at the emitter tips. When the force of the field is larger than the surface tension pressure of the ionic liquid, it forms a conic shape called Taylor cone,[6] ions are emitted from the tip and accelerated by the potential difference between the emitter and extractor, producing the thrust.

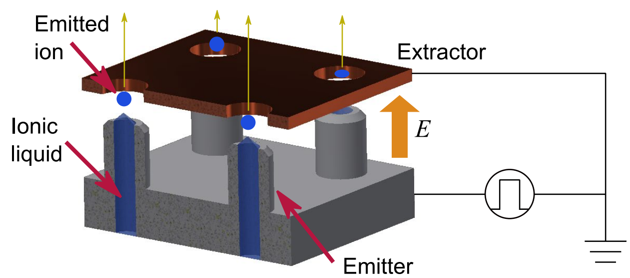

Figure 1. Schematic of an internally fed electrospray thruster.[20] Copyright (2019) The Japan Society of Applied Physics.

Here, ionic liquids consist of only cations and anions, giving negligible vapor pressure owing to the strong Coulomb force between both ions.[7] Since both cations and anions can be extracted by applying bipolar pulse voltages, neutralizers are not required. The molecular weight of anions is similar to that of cations, and thus, not only cations but also anions can deliver the thrust.

Although there have been many studies of electrospray thrusters already,[8-13] the thrust density obtained is still quite low, lower than conventional ion thrusters, because the thrust per single emitter is very tiny (a few tens of nN). For increasing the thrust level, many emitters must be contained. The emitter array can be fabricated with MEMS or electrochemical etching and laser ablation technologies, where the size of emitters is usually on the order of several hundred µm. Since it is difficult to increase the current per emitter, further high-density packaging is required with much smaller emitters.

In this work, for increasing the thruster density, we have developed an electrospray thruster with a high-density emitter array using a fabrication technique of FEAs,[14,15] where sub-µm scale emitters with self-aligned extractor electrodes can be realized. Since the fabrication scale is two orders of magnitude smaller than that of the conventional electrospray thrusters, the emitter density can be four orders of magnitude higher (millions/cm^2). The objective is to demonstrate such high-density emitter fabrication and the ion extraction from the tiny emitters.

II. Concept of the Electrospray Thruster

Figure 2 shows a schematic of the electrospray thruster presented in this work, consisting of capillary emitter, extractor, and accelerator electrodes for the acceleration of ion beams, where the ionic liquid is fed from the backside of the emitter array. As shown in the figure, a single capillary emitter has a sub-µm aperture and the emitter pitch can be set at a few µm, leading to the emitter density of approximately a few million/cm^2, which is about four orders of magnitude higher than that of conventional electrospray thrusters.[8,9]

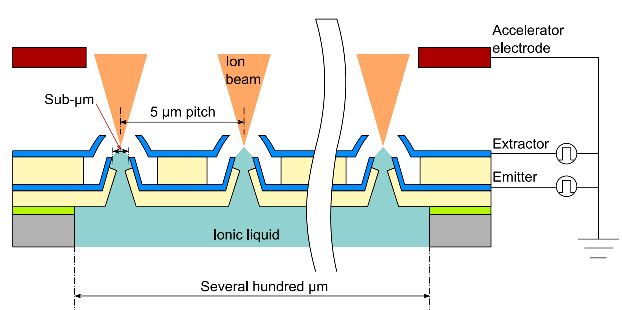

Figure 2. Schematic of a high-density emitter array with extractor and accelerator electrodes.[20] Copyright (2019) The Japan Society of Applied Physics.

In addition to increasing the emitter array density, the sub-µm order diameter of the capillary emitter can increase the fluidic impedance and suppress droplets emission, which contributes to the increase in the specific impulse and the thruster efficiency.[12,16] Although it is difficult to fabricate such a tiny capillary with a very high aspect ratio by conventional MEMS process technologies, a bottom-up process of FEAs enable us to develop the structure presented in Fig. 2.

Since the gap distance between the emitter and the extractor electrodes is approximately 0.5−1 μm, the starting voltage of ion emission is expected to be much smaller. However, it is impossible to operate at a higher voltage (a few kV) owing to the breakdown between the electrodes; no high thrust and specific impulse can be obtained. Thus, we plan to provide an accelerator electrode separately to complement both thrust and specific impulse, where the gap between the accelerator and the extractor is a few hundred μm. Since there is an optimum voltage range for ion beam extraction,[8,17] such separation of ion beam extraction and acceleration can be useful for thrust control.

III.Fabrication a Massive Emitter Array

The fabrication process is mainly divided into two procedures: the top side of the double electrodes (emitter and extractor) and the bottom side of the reservoir. The top double electrodes consist of integrated capillary emitters and extractor electrodes, where the fabrication of the top electrodes is based on that of a volcano-structured double-gate Spindt-type FEA.[14,15] After the formation of the top double electrodes, the back-side reservoir and capillaries of ionic liquid were fabricated, where the Si wafer was etched employing the Bosch process.

In several steps of the fabrication (photolithography and deep-RIE), we used a minimal-fab system,[18,19] which consists of a group of small semiconductor manufacturing equipment for a half-inch wafer eliminating a need of cleanroom environment. The minimal-fab system is suitable for multi-product and low-volume manufacturing, and thus, the system would be the best choice for the fabrication of micro space propulsion. The details of the fabrication process can be seen in our previous paper.[20]

Figure 3 shows SEM images of the 5 μm-pitch emitter array and an enlarged view of the emitter seen from the top side of the electrodes. As shown in the figure, the Ni cones at the center of the electrodes were removed, and the capillary emitter structure could be fabricated, where an approximately 700-nm diameter of the capillary entrance with a through-hole can be seen, and ionic liquid could be supplied from the backside of the emitter array to its tips.

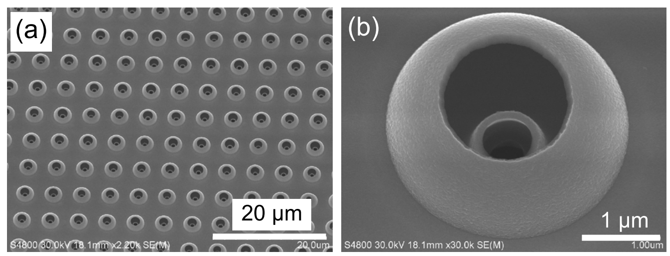

Figure 3. SEM images of (a) the 5 μm pitch emitter array and (b) an enlarged SEM view of the emitter seen from the top of the electrodes.[20] Copyright (2019) The Japan Society of Applied Physics.

IV.Current Measurements

A. Experimental Setup

To confirm whether ions could be extracted from the high-density emitter array, we conducted a preliminary experiment to measure ion currents as shown in Fig. 4. In the measurement, we used an emitter array with approximately 2900 emitters in a reservoir of 300-μm diameter and an ionic liquid of EMI-BF$_4$ or EMI-DCA as the propellant. Since a feeding system of ionic liquid was not developed in this study, a drop of ionic liquid (0.1 μL) was just put on the reservoir (the backside of the emitter array) to be supplied to the emitter array. For the measurement of collect emitted ions, a Si plate deposited with Al layer (collector) was placed 8.5 mm downstream of the emitter array. The emitter was biased by a source meter (Keithley 2657A) through a shunt resistor of 1 MΩ.

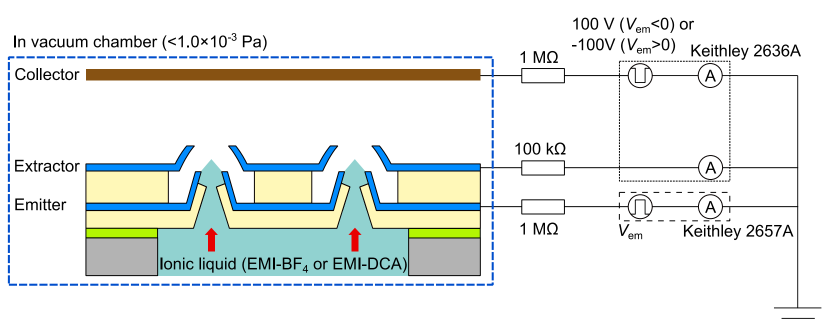

Figure 4. Schematic of the experimental setup for the current measurement of the ion emission.[20] Copyright (2019) The Japan Society of Applied Physics.

We applied 5-Hz bipolar pulse voltages to the emitter chip, the amplitude of which increased by 1 V at each cycle from 0 to 200 V. The extractor and the collector were also connected to another source meter (Keithley 2636A) through 100 kΩ and 1 MΩ resistors, respectively. The voltage output to the extractor was set at 0 V (equivalent to the ground potential), which could detect the ions colliding against the extractor. The collector was also biased by 5-Hz bipolar pulse voltage of 100-V amplitude; its polarity was always opposite to that of the emitter voltage. Note that owing to the high-frequency harmonics, the collector current drastically increased or decreased for the first 10 ms at the time of voltage alternation, showing the capacitor characteristics; therefore, we discarded the data for the first 10 ms and obtained the collector current averaging the rest of data for 90 ms. The experiment was conducted in a vacuum chamber, where the pressure was maintained below 1.0×10^{-3} Pa.

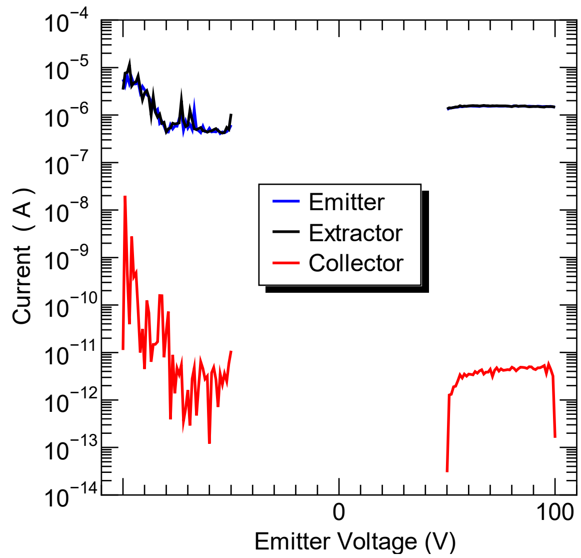

Figure 5. Collector, extractor, and emitter currents as functions of the emitter voltage for the emission of EMI-BF_4. Note that the current is shown as its absolute value for the logarithmic scale.

B. Experimental Results and Discussion

Firstly, we conducted the ion emission experiment of EMI-BF_4, which was often used in previous studies of electrospray thrusters.[8,9,11,12] Figure 5 shows the measured currents of the emitter, extractor, and collector as functions of emitter voltage. When the emitter voltage was lower than −80 V, the collector current began to rise drastically and reached approximately 20 nA at −99 V. However, there was almost no change in the collector current when the positive voltage was applied to the emitter chip, and almost no collector current was observed when the voltages of both polarities were applied again. Since the measured currents of all electrodes were less than 1 pA when there was no ionic liquid in the reservoir, the current of 20 nA would be the anion emission although the current value was much lower than expected. After the measurements, SEM observations were conducted; some Nb double electrodes seemed to disappear probably by electrochemical reaction with EMI-BF_4.

As a next step, we conducted the current measurement using EMI-DCA, which excludes fluorine in its anion. Figure 6 shows the measured currents of the emitter, extractor, and collector as functions of emitter voltage for its

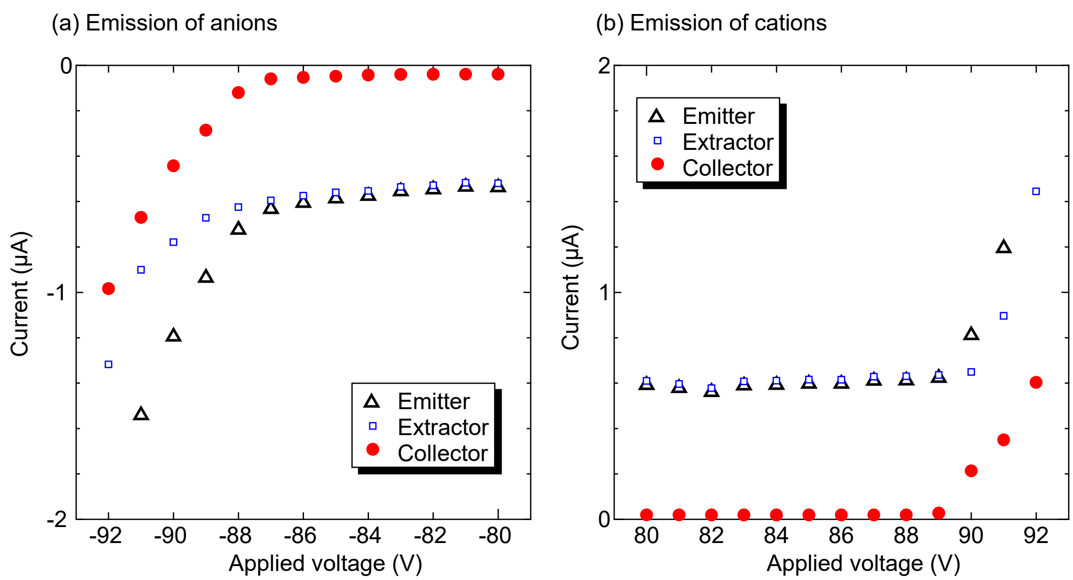

Figure 6. Collector current (solid circles), extractor current (open squares), and emitter current (open triangles) as functions of the emitter voltage for the emission of (a) anions and (b) cations of EMI-DCA.[20] Copyright (2019) The Japan Society of Applied Physics.

amplitude range from 80 to 92 V. When the emitter voltage was lower than −87 V or higher than 89 V, the collector current began to be detected and reached −1.0 μA at −92 V and 0.6 μA at 92 V. Since the starting voltage of ion extraction is a function of the surface tension of the ionic liquid, the curvature radius of the emitter tip, and the distance between the emitters and extractor,[21] the absolute value of the starting voltage is estimated to be approximately equal for both cation and anion extraction, which was true for the present experiments and the previous ones.[8,9,22] We could demonstrate that ions were extracted from the sub-μm scale capillaries of the high-density emitter array when EMI-DCA was utilized as the propellant.

Figure 6 also indicates that the emitter and extractor currents were nonnegligible values and almost the same before ion emission. Since no emitter and extractor currents were observed without ionic liquid, this phenomenon might be due to the slight leakage of the ionic liquid from the capillary emitters into the space between the emitter and the extractor although the resistance value of the ionic liquid was not constant. When the emitter voltage was higher or lower than ±92 V, the emitter and the extractor currents increased or decreased suddenly, exceeding ±50 μA; ion emission was hindered.

As shown in Fig. 6, the current density was determined to be −1.4 mA/cm^2 at an emitter voltage of −92 V and 0.85 mA/cm^2 at 92 V, where the emission area was assumed to be equal to the reservoir area (300 μm in diameter), which is a few times higher current density for both polarities than the conventional electrospray thruster. Since the applied voltage was less than 100 V in the present experiment, our high-density emitter array is expected to deliver at least 10 times higher thrust density when the accelerator electrode is placed; the potential difference between the emitter and accelerator is set at approximately 1 kV. Although the magnitude of the collector current was still lower than that of the extractor current and voltage range that could extract ions was narrow, probably owing to the leakage of the ionic liquid, these issues are expected to be solved when an appropriate feed mechanism of the ionic liquid is developed.

V.Summary and Outlook

In this paper, we have proposed and fabricated a high-density emitter array for electrospray thrusters and conducted current measurements as a preliminary experiment for the demonstration of the thruster operation. To realize high-density packaging, instead of MEMS etching techniques, we have utilized the fabrication technique for FEAs. Since sub-μm scale of capillary electrodes can be fabricated, the emitter pitch is reduced to 5 μm, and thus the emitter density of approximately 4 million/cm^2 is realized, which is four orders of magnitude higher than that of conventional electrospray thrusters. For the current measurements, the collector currents due to the ion emission from both cations and anions were detected at emitter voltages of approximately ±90 V when EMI-DCA was used for the current measurement. We have also demonstrated that ions could be extracted from the sub-μm scale capillaries of the high-density emitter array. Although the absolute value of the detected current was 1.0 μA at the maximum probably owing to the leakage of the ionic liquid, the current density was nonetheless a few times higher than that of the conventional electrospray thrusters using ionic liquids. Since the applied voltage was one-tenth of that of the conventional thruster, the thrust density should be at least one order of magnitude higher when the accelerator electrode is employed for producing the same beam voltage of 1 kV.

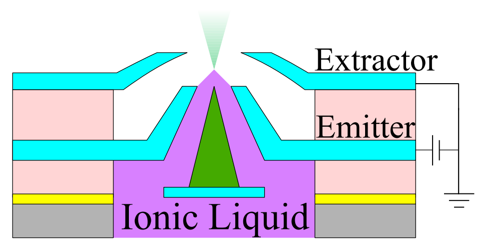

Figure 7. Schematic of an electrospray thruster with capillary-needle-type emitter electrodes.

For the prevention of ionic liquid leakage, capillary-needle-type emitter electrodes are now under development, where a Ni cone at the center of the emitter electrode exists inside the capillary emitter electrode as shown in Fig. 7. We keep the ionic liquid on the surface of the Ni cone and narrow the flow path to increase the fluidic resistance. We could already obtain the structure having the emitter cones at the center of the double electrodes. Ion beam extraction will be performed.

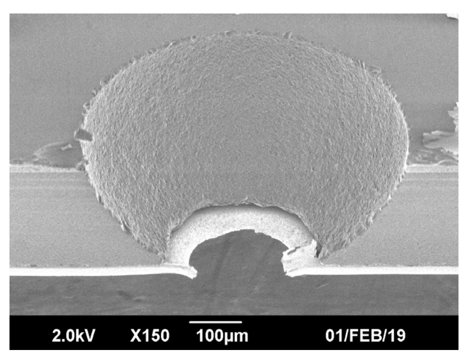

Figure 8. SEM image of the accelerator and extractor electrodes on a glass wafer.

As described in Section II, we plan to provide an accelerator electrode separately to complement both the thrust and specific impulse. For the fabrication of the accelerator electrode, we employed a 300-μm thick glass wafer, where a sandblasting method was utilized for opening patterns.[12] Since we used the combination of the present accelerator electrode and conventional needle-type electrode to demonstrate the accelerator grid electrode,[8] we employed Al for the accelerator electrode and Ni for the extractor electrode, where the Ni has high selectivity for the sandblasting and the patterning was conducted using LIGA process, and both electrodes were fabricated successfully (Fig. 8).

Acknowledgments

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