

Design and Fabrication of Ionic Liquid Electrospray Thruster with Two-Stage Electrodes

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An ionic liquid electrospray thruster (ILEST) is expected as a propulsion system to control nano-spacecraft attitude and orbit in space. To produce high thrust, we propose a two-stage electrodes thruster which has an accelerator in addition to an extractor. We fabricated emitters on a silicon wafer and the two-stage electrodes on a glass substrate with through holes using microfabrication technologies. We confirmed that the fabricated ILEST emitted ions or droplets from the silicon emitters at near 2.0 kV. The maximum current in single-stage operation was -570 μ A at 3.0 kV. With two-stage operation using the accelerator, ion emission happens at high voltage without conduction between the extractor and the accelerator. The results show the advantage of the fabricated two-stage electrodes. Currently, extracted ions were captured mostly at the extractor because of the poor alignment of the emitter silicon chip to the jig.

Key Words: Electrospray, Ionic Liquid, Silicon Emitter, Two-Stage Electrodes, Nano-Spacecraft

Nomenclature

d	: hole diameter, m
E_a	: electrical field at tip, Vm^{-1}
h	: gap distance between emitter tip and extractor electrode, m
I	: current, A
r_a	: radius of curvature, m^{-1}
V	: voltage, V
γ	: surface tension of propellant, Jm^{-2}
ϵ_0	: electric constant, Fm^{-1}
η	: transmittance of ion
θ_b	: divergence angle of ion beam, rad
θ_{eh}	: aperture angle of emission hole, rad

Subscripts

acc	: accelerator
coll	: collector
em	: emitter
ext	: extractor
start	: at emission start

1. Introduction

More and more nano-spacecraft (less than 100kg) have been launched recently by small companies and universities because their development is low-cost and short-term. These spacecrafts require inexpensive and compact propulsion system to control their attitude and orbit for achieving missions in space. Conventional thrusters mounted on the spacecraft are not for nano-spacecrafts due to the limit of their size, weight and power supply of spacecrafts. So, the miniaturization of the conventional electric thruster and the development of a new thruster for nano-spacecraft have been conducted recently.

An ionic liquid electrospray thruster (ILEST) has attracted attentions for the requirement and has been studied extensively.¹⁾ The ILEST comprises emitters and an electrode. The ILEST generates thrust by electrospraying phenomenon where ions evaporate from the surface of propellant formed conical structure, known as the Taylor cone, at the tip of the emitters by applying a high electrical field.²⁾ The advantage of the ILEST is capability of miniaturization because it does not require a neutralizer and a complicated propellant supply system. The propellant of the ILEST is an ionic liquid which consists of cations and anions and is a liquid at room temperature. Its negligible vapor pressure simplifies the entire propellant supply system, compared with conventional plasma electric thruster with a gas. By applying positive and negative voltage alternatively, the emitters can extract both cations and anions. This enables charge neutralization without a dedicated auxiliary equipment.³⁾ In addition, the use of fabrication techniques of micromechanical systems (MEMS) miniaturizes the emitter and accumulates a number of emitters, which improves the thrust amount, though that of single emitter is very small. The ILEST has the possibility to control the thrust precisely.

In our previous research, we fabricated a single-stage ILEST device consisting of micromachined silicon emitters and a metal plate extractor.⁴⁾ The ion emission of the device became unstable on applying high voltage beyond a threshold. We concluded that an ILEST with single extractor/accelerator electrode was difficult to generate high thrust.

In this research, we have adopted two-stage electrodes adding a second electrode (accelerator) to accelerate ions extracted by a first electrode (extractor) as shown in Fig. 1. Voltage at the accelerator is controlled independently to that at the extractor, which improves the stability of thrust and specific impulse.⁵⁾ By using this advantage, we can increase the thrust

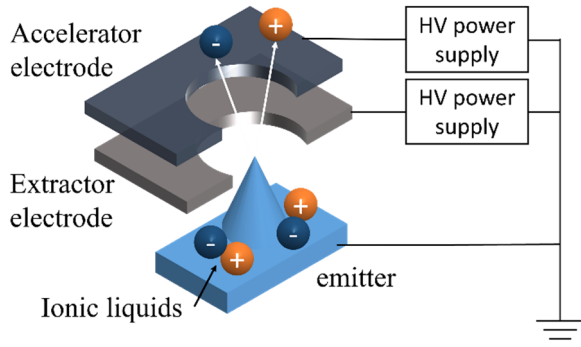


Fig. 1. Concept of ionic liquid electrospray thruster with extractor and accelerator electrodes.

in proportion to the square root of the voltage difference between the accelerator and extractor electrode with stably emitted ions. Moreover, the extracted ion beam half-angle in two-stage is smaller than in the single-stage. This shows that the accelerator also improves efficiency by reducing ion loss at the extractor.

This paper describes the design and fabrication process of chips for the emitter and the two-stage electrodes and a chip alignment jig using microbeads. Then, we explain the details of the experiments and present the experimental results of ion emission as I-V characteristics. Finally, the results of the supply from the back side are reported.

2. Design and Fabrication

2.1. Emitter chip

The emitter chip made of silicon is 18 mm square and contains 57 emitters with the pitch of 1 mm. There are 2 types of the emitter.

One is a pencil shape emitter having a pillar as shown in Fig. 2(a). The chip of this type has 13 mm diameter reservoir at emitter area to prevent ILs from overflowing. Fig. 3(a) shows the fabrication process. First, a conical tip is formed by isotropic dry etching and cylindrical part is then formed by anisotropic dry etching. To sharpen the tip, isotropic dry etching is conducted again after removing the photoresist.⁶⁾ Sharper tip makes electric field enhancement stronger and the starting voltage of the ion emission lower. However, the emitter tip located at is about 100 μm below the wafer surface due to the last isotropic dry etching step.

The other is a conical shape and has holes at the position off the tip center for passing the ionic liquid from the back side as

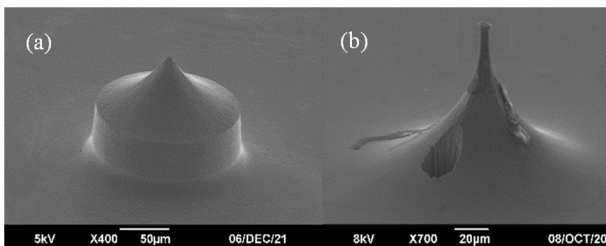


Fig. 2. SEM images of emitter. (a) pencil shape (b) conical shape with propellant supply hole. Propellant is supplied from backside.

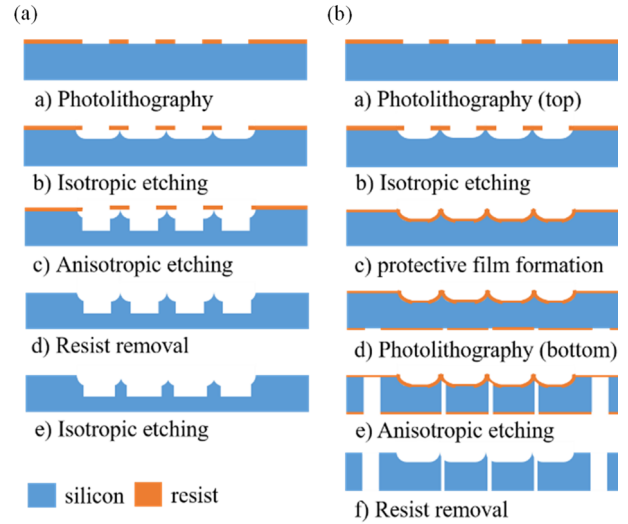


Fig. 3. Fabrication process of emitter chips of (a) pencil shape and (b) conical shape.

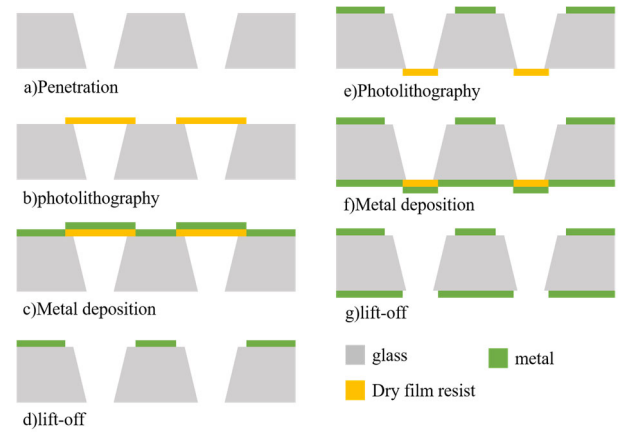


Fig. 4. Fabrication process of electrodes chip.

shown in Fig. 2(b). The reservoir in this design is 10 mm diameter. The fabrication process is shown in Fig. 3(b). First, the conical tips are fabricated by isotropic dry etching. Unlike the pencil type, no additional etching is conducted. Then, the through holes are formed from the back side by anisotropic dry etching while the photoresist film protects the emitters on the front side.

2.2. Electrode chip

The electrode chip is a 20 mm square glass substrate with a thickness of 300 μm and metal films for the electrodes patterned on both sides. Glass is difficult to process using dry etching but has good electrical insulation. The glass substrate has apertures at the positions corresponding with emitters for passing ions. The diameter of the apertures is 200 μm at the extractor side and 340 μm at the accelerator side because extracted ions fly with diverging. At the corner of the glass chip, four holes are placed for using microbeads as described below. The diameter of these holes defines the distance between the emitter and the extractor electrode.

The fabrication process of the electrode chip is shown in Fig. 4. The glass holes are fabricated by laser-assisted chemical etching (NSC Co., Ltd.). These holes are covered with dry-film

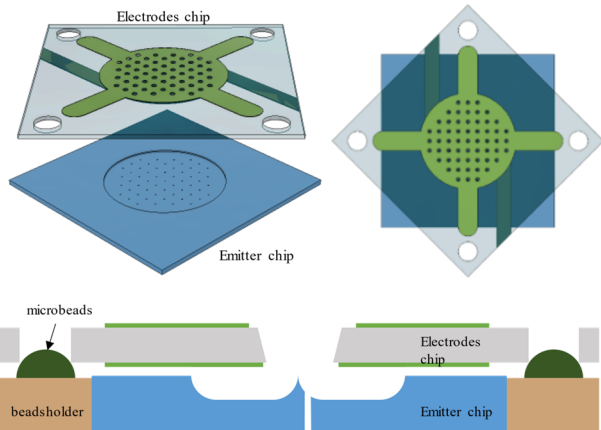


Fig. 5. Schematic diagram showing placement of electrodes and emitter chips and cross-section of emitter assembly.

resist (DFR) to make electrode patterns by metal vacuum deposition. DFR is a negative photosensitive resin film, since a liquid-type photoresist is difficult to apply to substrates with through holes. The hole diameter of electrode pattern is larger than that of the aperture for suspending DFR after each lithography step.

2.3. Device assembly

Jigs were designed to assemble the emitter chip and the electrode chip with a small misalignment. The alignment jigs consist of a base, a plate, microbeads, and bead holders as shown in Fig. 5. The base and the plate were made of polytetrafluoroethylene (PTFE). The polyetheretherketone (PEEK) bead holders that have a cylindrical shape with a hole for putting a microbead, are placed on the base to determine the position of the emitter chip. Four microbeads of a diameter of 2 mm were put in the bead holders and fitted to the holes on the electrode chip to determine the position and the distance between the emitters and electrodes. Because of microfabrication process using photolithography, the accuracy of the dimensions of each chip is in micrometer order. And the alignment accuracy using the microbeads will provide the positional accuracy about a few tenth of micrometers. After alignment, the chips are fixed by pressing with spring-plungers through the screwed plate from top. The spring-plungers also establish electrical connection to the emitter chip and the accelerator electrode. The extractor electrode is connected electrically to the metal part on the base using a double-sided conductive tape.

The assembled device is shown in Fig. 6. For the pencil-shaped emitter, the propellant is supplied on the reservoir on the top side of the emitter chip before assembling the device. For the conical-shaped emitter, the propellant is supplied from the back side of the chip. In this case, a reservoir part having a cavity at the center is attached at the bottom of the assembled device. A sponge soaked with the propellant is put into the cavity and the propellant is supplied into the supply hole by capillary action and electrostatic force. The electrical connection to the sponge is made with a screw at the side of the reservoir.

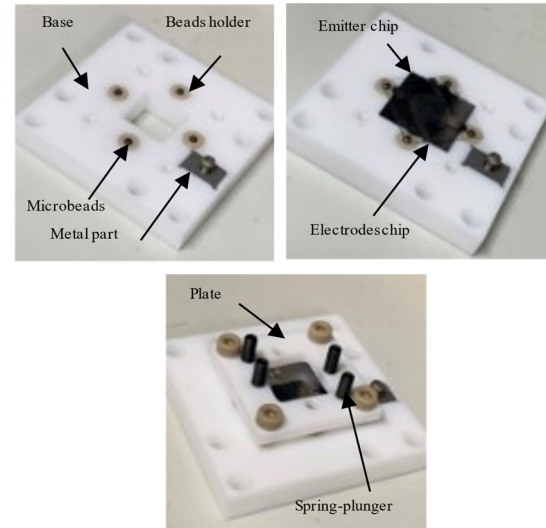


Fig. 6. Fabricated jig parts and assembled ILEST.

3. Experiments

3.1. Single stage mode ion emission

Figure 7(a) shows a schematic of the experimental set-up for applying voltage to emitter and measuring the ion current. The thruster device is placed into a vacuum chamber under 3.0×10^{-3} Pa, evacuated by rotary and turbomolecular pumps. A collector placed upstream is a metal plate to detect extracted ions.

In this experiment, the pencil-shaped emitter chip without the supply holes was used and atmospheric helium plasma treatment on the area of emitters was conducted before assembly to improve wettability and diffusion of the propellant. The contact angle of the IL is small, which prevents the IL from diffusing spontaneously.⁷⁾ This leads to the non-uniform ion emission and conduction. After the surface treatment, the IL ($\sim 1 \mu\text{L}$) was dropped on the reservoir with a micropipette. We used EMI-DCA (1-Ethyl-3-methylimidazolium dicyanamide, $\text{C}_8\text{H}_{11}\text{N}_5$) as an IL propellant. The properties are listed in Table 1.^{8,9)} On repeating experiments for several times with the same emitter chip, the chip is cleaned by acetone using an ultrasonic bath for 5 minutes before the surface plasma treatment.

Table 1. Characteristics of EMI-DCA. (25 °C, 1 atm)

Electrical conductivity (S/m)	2.8
Viscosity (Pa·s)	0.021
Density (kg/m ³)	1080
Surface tension (N/m)	0.04905
± Ion mass (Da)	111.2/66

Source measure units (SMUs) are connected to apply high voltage and measure the currents. The bias voltage between the emitter and the extractor electrodes was from 0 V to 2700 V and 1 Hz bipolar pulse to suppress the formation of a charge double layer, accumulation of one polarity ions in the IL and reverse polarity ions on the emitter chip. The potential difference beyond the potential window of the IL causes electrochemical reaction which produces decomposed chemicals or gas to damage the thruster device.¹⁰⁾ The voltage

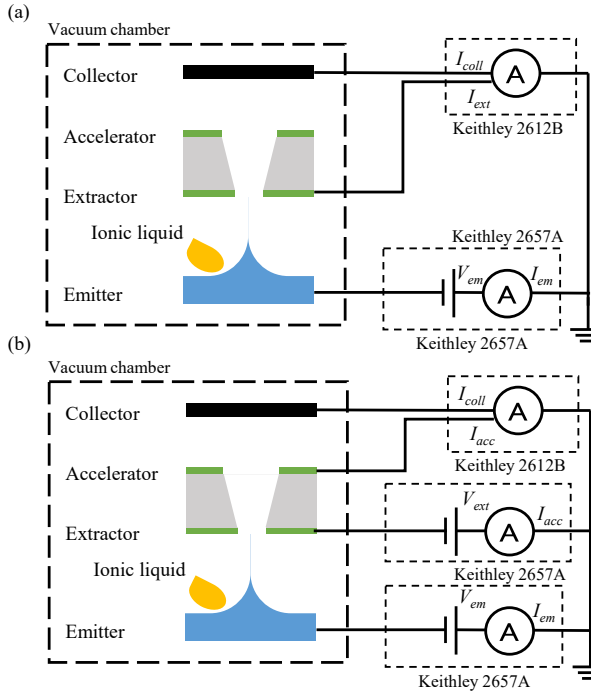


Fig. 7. Schematics of set-up for experiments for ion emission. (a) single-stage mode (b) two-stage mode.

was increased by 100 V in the range from 0 V to 1500 V and 10 V at higher than 1500 V to obtain the onset voltage of the ion emission. The voltage to the extractor, the accelerator, and the collector was 0 V to detect the extracted ions. The SMUs measured the current at 48 points in 0.5 second.

3.2. Two-stage mode ion emission

Figure 7(b) shows experimental set-up for two-stage mode emission with a use of the accelerator. The bias voltage between the emitter and the extractor was changed from 0 V to 2500 V, while the bias voltage between the extractor and the accelerator was fixed at 500 V. The other conditions were the same as Sec. 3.1.

3.3. Single-stage mode with back side IL supply

The experiments described in the previous sections are not feasible for practical system because there is no way to supply additional propellant. A method for supplying the propellant to emitters must be established. The back side supply method should be established using the supply hole. First, 1 μ L droplet of the propellant, EMI-DCA, was applied onto the back side of the emitter chip after the assembly process to check the capillary action supply is feasible. Voltage was applied between the emitter chip and the extractor electrode. Then, the sponge soaked with the propellant was used as described in Sec. 2.3. The electrical connection to the sponge is made with a screw at the side of the reservoir as the distal electrode preventing electrochemical reaction, as described in Sec. 2.3.⁽¹¹⁾ In both experiments, voltage applications were conducted in a vacuum chamber at 2.0×10^{-3} Pa.

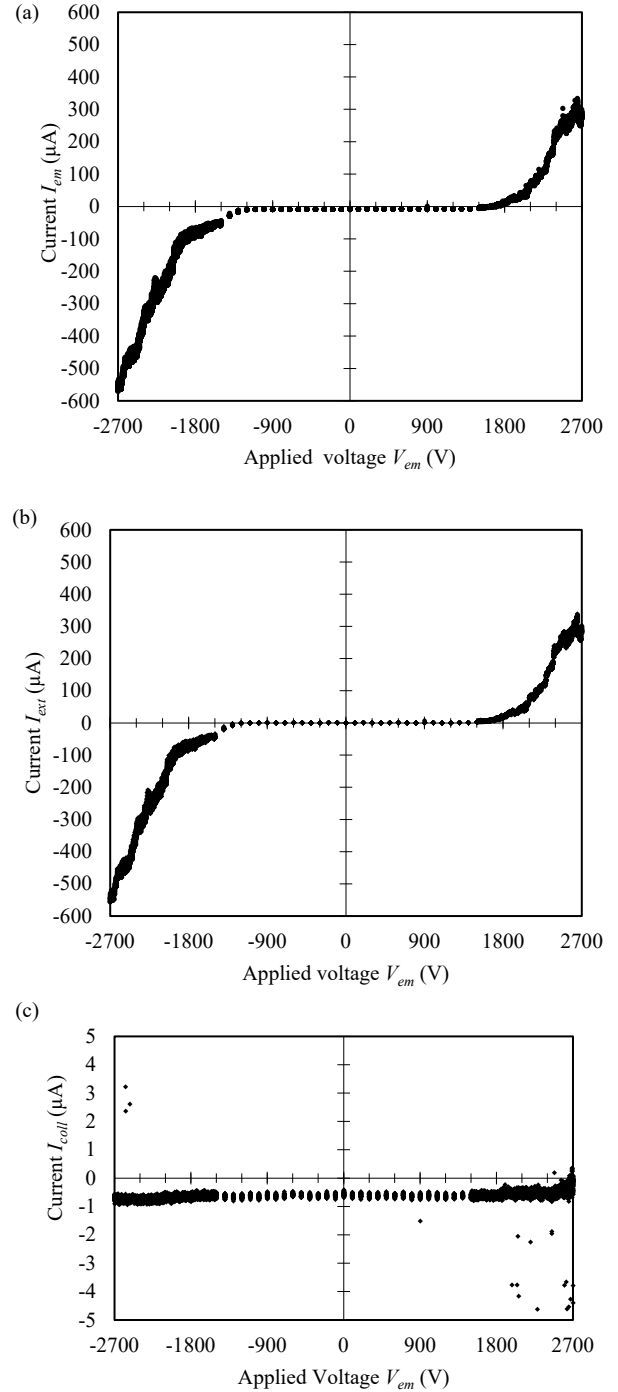


Fig. 8. I-V characteristics of single-stage mode ion emission. (a) emitter, (b) extractor and (c) collector.

4. Results and Discussion

4.1. Ion emission -single-stage mode-

Figure 8 shows results of ion emission using the single-stage mode. The distance between emitters and the extractor is estimated about 600 μ m. The offset current in I_{em} and I_{coll} was observed at the low voltage on repeating the experiments. The voltage-current curve indicates the starting voltages of the extracting cations and anions were 1670 V and -1300 V, respectively. The largest negative ion current was -570 μ A.

An ILEST produces the propulsion force as a reaction force

by the motion of emitting ions. When voltage is applied between the emitter and extractor electrode, the Taylor cone of the liquid is created by the electrical field enhancement at the emitter tip. Electrospray, ion emission from the propellant, occurs when the enhanced field E_a is larger than the inner pressure caused by the surface tension γ of the propellant. The condition of the emission is, ¹²⁾

$$\frac{1}{2} \varepsilon_0 E_a^2 > \frac{2\gamma}{r_a}, \quad (1)$$

The electrical field at the tip is described as,

$$E_a = -\frac{2V_{\text{ext}} / r_a}{\ln(4h/r_a)}. \quad (2)$$

From Eqs. (1) and (2), the starting voltage of ion emission is expressed as,

$$V_{\text{start}} = \sqrt{\frac{\gamma r_a}{\varepsilon_0}} \ln\left(\frac{4h}{r_a}\right). \quad (3)$$

Using Eq (3), the surface tension given in Table 1 and the observed starting voltages of 1670 V and −1300 V for anions and cations, r_a were calculated as 24 μm and 10 μm , respectively. The calculated radii are reasonable considering the tip dimensions and tip radius ($\sim$ a few micrometers).

Assuming that 57 emitters extract ions uniformly, the current per one emitter is about −10 μA . However, the collector current I_{coll} was very small compared with I_{em} and I_{ex} . These results indicate that majority of the extracted ions collided to the extractor because the gap between emitters and the extractor was too large. In the current setup, the gap between the emitter and extractor is too large compared to the diameter of the ion emission hole, as shown in Fig. 9. Assuming that the ion density in the ion beam is uniform, the ion transmittance is expressed by the ratio of cross-sectional area of ion beam and the hole diameter, as follows,

$$\eta_{tr} = \frac{d^2}{4h^2 \tan^2 \theta_b} \quad (4)$$

Assuming ions are emitted uniformly in a beam and the ion beam half-angle is 30° , 8.3% ions can pass 200 μm diameter hole at the extractor 600 μm away from emitters, by considering the area ratio. To measure extracted ions at the collector with better accuracy, we should make the gap smaller while preventing short circuit and electrical discharge. On reducing the gap, the electrical discharge and short circuit may occur on the emitters and reservoir. To avoid them, smaller

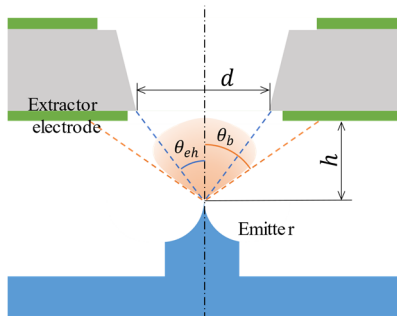


Fig. 9. Schematic of relationship between emitter and extractor electrode.

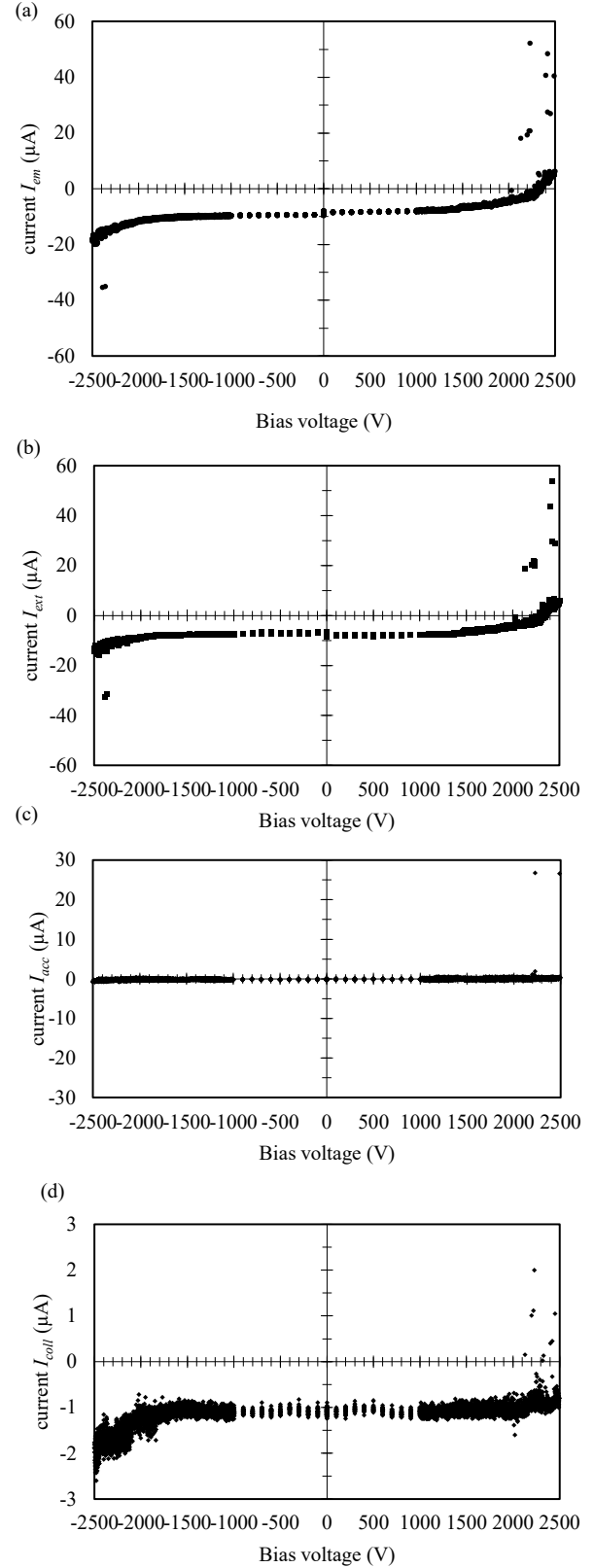


Fig. 10. I-V characteristics of two-stage mode ion emission. (a) emitter (b) extractor (c) accelerator (d) collector.

misalignment of the glass plate and back-side IL supply will be required.

4.2. Ion emission –two stage mode-

Figure 10 shows results of ion emission when the distance between emitters and the extractor is about 400 μm . The starting voltages of extracting cations and anions were 1810 V and -1860 V, respectively. The largest ion currents were 12 μA and -13 μA , respectively, in the stable emission range. Majority of the extracted ions collided to the extractor same as the single-stage mode, and about 10% of extracted ions were detected on the collector. The accelerator current I_{acc} was almost zero, which shows the two-stage electrodes worked adequately.

Unstable large current was detected over ± 2 kV. This would be caused by droplets extraction. The droplets lead to lower specific impulse due to large mass flow rate.

The extraction voltage was high, so we were not able to increase the accelerator voltage higher than 500 V due to upper voltage limit of the SMUs.

In case that the half angle of the ion beam θ_b is 30° , the transmittance of the two-stage electrode was calculated as ~ 0.19 using Eq. 4, since the gap of the electrode are 400 μm , and the hole diameter is 200 μm . Though these values underestimate the transmittance, because the ion beam is not uniform in the cross section, the measured ion transmittance is much smaller than these. The collector current was not significantly increased even when the gap became small. Therefore, we suspect that the main reason of low transmittance would be the misalignment of the glass chip to the silicon emitters. There was significant rotational misalignment of the emitter chip made of silicon wafer since the chip position is guided by the edges of the bead holder and the chip often rotated during the assembly process.

To increase the ion current on the collector, the hole diameter should be larger and the electrode gap should be much smaller. But the former reduces the number of emitters per area and the total emissions will decrease. In order to reduce the gap between the emitter and glass electrode, ionic liquid should be supplied from the back side the chip to avoid unintended discharge during the operation.

When V_{em} is positive, the cations or IL droplets were emitted and detected at the collector. However, the collector current I_{coll} became negative at high positive voltage. This indicates the secondary electrons were emitted when highly energetic particles impacted to the collector. The detection of the electron emission can be eliminated by the negatively biased grid in

front of the collector.¹³⁾

4.3. IL backside supply

When the IL was directly dropped on the backside of the emitter chip, ion extraction was observed at -2.5 kV. Figure 11 shows luminescence above the electrodes chip. This suggests that it is possible to supply the IL using the supply holes at emitters.

After this experiment, there were some chemical traces on the emitter chip and the extractor electrode. This was the result of an electrochemical reaction which happened through the IL between the emitters and the extractor.

Then, the IL soaked sponge was used. However, no emission was observed on some trials. When the amount of IL was little (1 μL), the IL was not observed at the emitter area after the low (<250 V) voltage application. When 2- μL IL was soaked, the propellant flooded from the cavity. In both cases, electric sparks were observed at -3.0 kV. The sparks were caused by unexpected IL flow between the emitter chip and the jigs. The propellant did not get into the supply hole in either case because of the bypass flow. The back-side supply system needs further improvement, for example the jigs should be redesigned so that the IL will not go to the gap and reaches only to the supply holes.

5. Conclusion

We designed and fabricated the ILEST with two-stage electrodes of stable propulsion for nano spacecrafts. We fabricated silicon emitters and glass with double side electrodes using microfabrication technologies. The electrodes were the metal films on both sides of the glass chip having the through holes. These chips are fabricated with good accuracy using semiconductor microfabrication technology.

In ion emission experiments using the pencil-shaped emitters, we confirmed ion current at both positive and negative high voltages. However, most ions did not pass through holes on the electrodes chip but collided to the extractor electrode. The main reason was poor alignment of the emitter chip to the jig.

We tried ion emission using the conical emitters with supplying IL from back side through holes. When we directly dropped the IL the back of the chip, ion emission observed.

In a future work, we will demonstrate the ion emission and improve the emission through the hole with a smaller gap between emitters and the extractor by redesigning the jigs and realizing the back side IL supply. Then, we will discuss the effect of the accelerator.

Acknowledgments

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Fig. 11. Image of ion beams when supplying from back side of emitter chip.

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