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IONIC LIQUID ELECTROSPRAY THRUSTER WITH TWO-STAGE ELECTRODES ON GLASS SUBSTRATE

Akane Nishimura[1], *Toshiyuki Tsuchiya*[1], *and Yoshinori Takao*[2]
[1]Department of Micro Engineering, Kyoto University, JAPAN and
[2]Division of Systems Research, Yokohama National University, JAPAN

ABSTRACT

This paper reports ion emission of an ionic liquid electrospray thrustor with two-stage electrodes made on glass substrate having through hole for low-cost micro/nano satellites. By using the two electrodes, one for ion extraction and the other for acceleration, high and stable ion emission and propulsion force is obtained. The emitter array was fabricated on a silicon wafer. The electrodes were fabricated on both sides of a glass substrate. The ion emission test was conducted and ion emission current was observed. Almost no ions were collected on the accelerator electrode and reached to the collector electrode, which demonstrates the advantage of the two-stage configuration.

KEYWORDS

Electrospray thruster, ionic liquid, silicon emitter array, glass via hole.

INTRODUCTION

Development of low-cost miniature satellites, such as nano-satellites and CubeSat is actively carried out. Even such a compact satellite, the attitude and orbital controls are demanded. Therefore, for these satellites compact electrical propulsion system is demanded. Among the electrical propulsion systems, ion emission thrusters using ionic liquid as a propellant is attracting more attentions because of its simple propellant supply system, no needs for neutralizer and large propulsion force [1]. There have been several reports on microelectromechanical system (MEMS) based ionic liquid electrospray thrustors (ILESTs) [2-5]. However, the emission stability is one of the major technical issues. The work measured current from silicon made emitters and metal extractor electrodes, but the emission is not stable because of the extraction voltage is too high [5]. The issues are poor alignment between emitters and extractor electrode and complicated fabrication process.

In this study, ILEST was fabricated using microfabrication process, especially the electrodes are fabricated on the glass wafers with via holes using lift-off process with a dry thick photoresist film. In this paper, the fabrication process of both the emitter chips made from a silicon wafer and the electrode chips made from a glass substrate, and an assemble method with good precision to realize stable emission are reported.

OPERATION PRINCIPLE

Figure 1 shows the concept drawing of an ILEST with two-stage electrodes. We employed a glass substrate with via hole for ion emission and two electrodes on both sides for ion extraction and acceleration. By applying voltage between the bottom electrodes, the high concentrated electric field at the tip of the emitter generates the Tayler cone of ionic liquid propellant and the anions and cations are emitted by applying positive and negative voltages. The emitted ions are accelerated by the potential difference between the accelerator and emitter electrodes. By separating the functions of emission and acceleration, the stable and high thrust is expected because the emission requires a high electric field but the acceleration depends on the total voltage. The key is the small gap between extractor electrodes and emitter tip. The low extraction voltage and large gap for accelerator electrodes avoids the electrical discharge. In addition, we can control the propulsion force with stable emission.

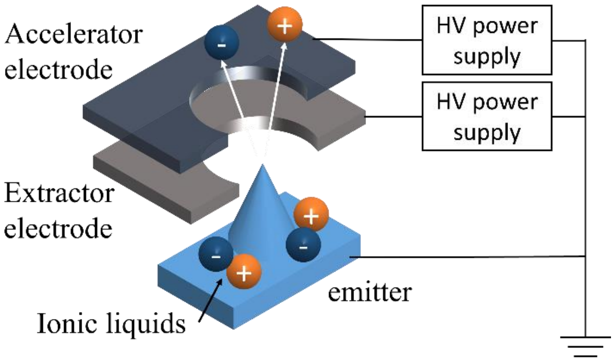


Figure 1: Concept of ionic liquid electrospray thruster with two-stage electrodes.

DESIGN AND FABRICATION

Device structure

Figure 2 shows the schematic design of the two-stage ILEST. The emitter chip is made from a 4-inch silicon wafer of 400 μm thick. The chips is 18 mm square. There are 57 emitters is arranged by 1 mm interval placed in the 12-mm-diameter circular reservoir cavity. The electrode chip is made from a 4-inch glass wafer of 300 μm thick. 57 tapered via holes are arranged at the corresponding positions to the emitters. The diameters of the holes at bottom (emitter side) and top are 200 and 340 μm, respectively. The electrode chip is designed to be placed diagonal direction to the emitter chip to use the chip corners for the alignment described below.

To reduce the extracting voltage and to realize stable and uniform emission, the alignment accuracy between the two chips both horizontal and vertical directions is critically important. The alignment accuracy is ensured by the photolithography precision and the mechanical assembly using beads [2]. The emitter and electrode chips are fabricated with high precision because of semiconductor microfabrication technology. For the mechanical assembly, the four holes are made on the corners of the electrode glass chip and steel beads of 2 mm

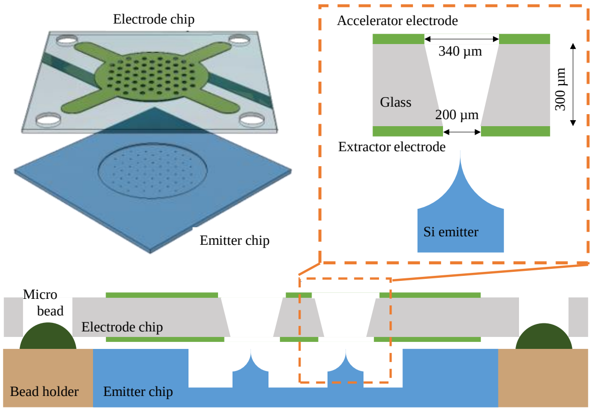


Figure 2: Device structure of ionic liquid electrospray thruster with double-side electrode.

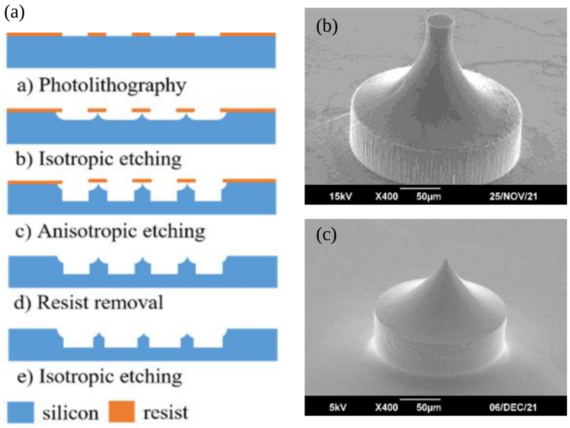


Figure 3: a) Fabrication process of silicon emitter electrodes, b) after deep RIE process and photoresist removal and c) after isotropic etching thinning.

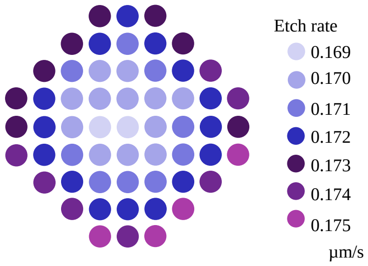


Figure 4: Etching rate distribution in an electrode chip at wafer center.

diameter is fit to the hole. The beads are placed in each bead holder.

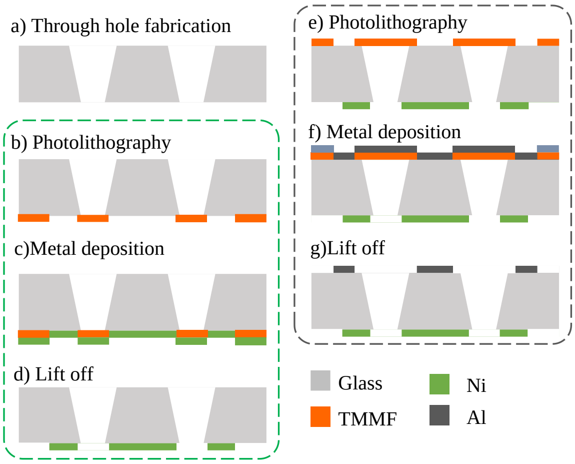


Figure 5: Fabrication process of electrode chip.

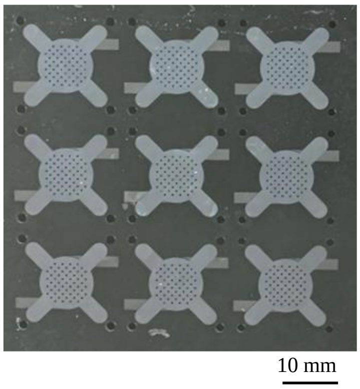


Figure 6: Fabricated electrode chip before dicing.

Emitter chip

Figure 3 shows the fabrication process of the silicon emitter chip. Circular photoresist masks were patterned and SF_6 isotropic dry etching to form conical emitter shapes and then Bosch process to gain height were conducted using ICP-RIE successively. One of the fabricated emitters is shown in Fig. 2b. The diameter of the cylindrical part is 220 μm and the total height is about 150 μm. The diameter of the remained circle plane on the top is 30 μm and there is a variation of about 7 μm in a chip. The difference is caused by the etching rate non-uniformity in each chip and the whole wafer. To sharpen the tip, the additional isotropic dry etching was conducted (Fig. 3c). The tips had sharp but the height of the emitter reduced by 50 μm.

The etching rate nonuniformity is evaluated. Figure 4 shows the etching rate map taken from observation of all the emitters on the chip taken from the wafer center. The rate at the center is 3% higher than the that at the edge. This is caused by the etching gas supply. In addition, the chip at the wafer edge showed higher etching rate of more than 5 % of that at the center. In this study, the insufficient etching shown in Fig. 3c is corrected by the additional isotropic etching. The additional etching make the height of the emitter smaller, which is not good to reduce the extractor voltage and we will consider the compensation by the mask diameter to mitigate the etching rate variation.

Electrode chip

Figure 5 shows the fabrication process of the glass chip. The via holes on the glass wafer were fabricated using laser-assisted chemical etching process. We also had examined dry etching of glass wafer after electrode fabrication. But the dry etching is too slow to make via hole on glass wafer of 300 μm thick. The technical problem for the current process is the deposition and patterning of the electrodes on both sides. To avoid electrical short circuit between electrodes, nickel and aluminum film electrodes were patterned by lift-off process. Dry film photoresist sheets were used to apply the photoresist on wafers with via holes.

Fabricated electrode chips before blade dicing is shown in Fig. 6.

Assembly

The silicon emitter chip, glass electrodes chip, steel beads and bead holders were assembled using polytetrafluoroethylene (PTFE) parts, base plate, and top plate, as shown in Figure 7. The silicon chip was placed on the base plate and aligned by the four bead holders made of polyether ether ketone (PEEK). The alignment between the base and the glass chip is made by four steel beads of 2-mm diameter. The gap between the emitter tips and extractor electrode is controlled by the diameter of the holes on the corner of glass chip. In this experiment, the alignment hole is 1.48 mm in diameter and the gap between chips is designed as 400 μm. The electrode chip is fixed by placing the top plate using spring plungers. The spring plungers are used for electrical connection of accelerator electrode.

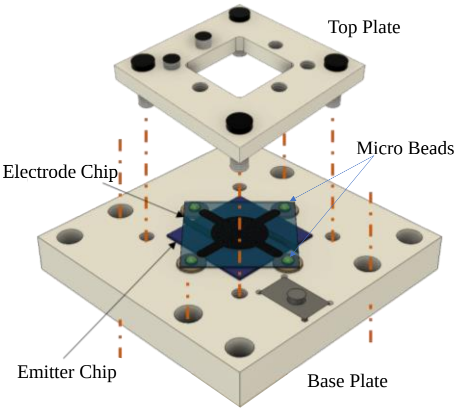


Figure 7: Schematic drawing of ILEST assembly.

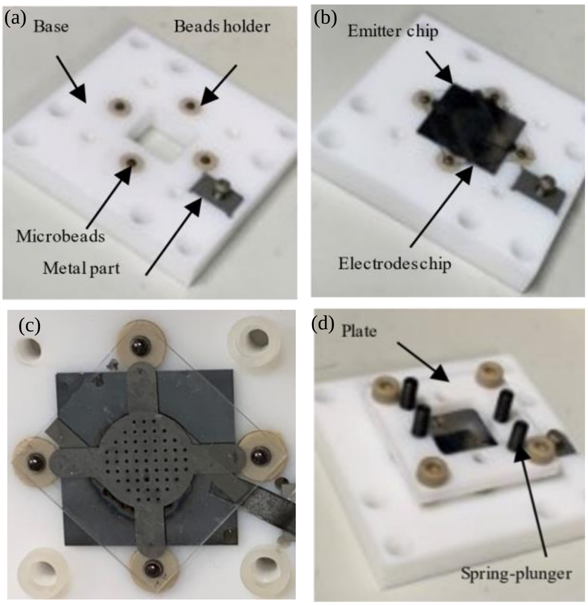


Figure 8: Fabricated jig parts and assembled ILEST.

Figures. 8a-8c show the assembling procedures. The bead holders were inserted to the holes of the base plate and microbeads are put on the base plate (Fig. 8a). The emitter chip was put on the base plate aligned by the edge of the bead holders (Fig. 8b). The electrode chip was put on the microbeads (Fig 8c). The electrical connection of extractor electrode was made using a conductive tape as seen at the bottom left of the figure. The assembled device is shown in Fig. 8d. The top plate is fixed by PEEK screws.

EXPERIMENTS

1-Ethyl-3-Methylimidazolium Dicyanamide (EMI-DCA) was used as an ionic liquid propellant. The properties of EMI-DCA are listed in Table 1 [6, 7]. The propellant of about 1 μL was supplied to the reservoir of emitter chip before assembly. The emitter was processed by helium atmospheric pressure plasma to make the surface wettable to EMI-DCA. The assembled ILEST device was put in a custom-made vacuum chamber. The ion emission experiments were conducted in a vacuum at 3.0×10^{-3} Pa or lower.

The measurement setup was drawn in Fig. 9. To apply voltages to the emitter and extractor, high power source-measure units (SMU; 2657A, Keithley) were used. The currents of the collector and accelerator were measured by a SMU (2612B, Keithley). Bipolar square wave of 1Hz was applied and the emitter voltage was increased by 100V in the range from 0 to 1500 V and 10 V at 1500 V and higher. The extractor voltage was increased by 100 V to 500 V and fixed. Therefore, the voltage between accelerator and extractor was kept at 500 V, while the voltage between emitter and extractor was increased from 0 V to 2500 V.

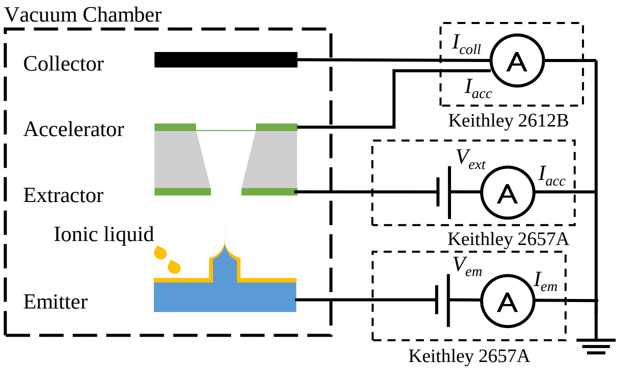
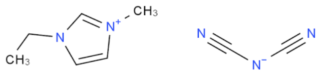


Figure 9: Ion emission test set-ups.

Table 1: Propertiess of EMI-DCA (25 °C, 1 atm)

	
Electrical conductivity	2.8 S/m
Viscosity	0.021 Pa·s
Density	1080 kg/m^3
Surface tension	0.04905 N/m
cation/anion mass	111.2/66 Da

RESULTS AND DISCUSSION

Figures 10 show the measured current at each electrode when the distance between the emitters and extractor is about 400 µm. The horizontal axis indicates the voltage difference between emitter and extractor electrodes. 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, and about 10% of extracted ions were detected on the collector. The accelerator current 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.

We suspect that the main reason of low transmittance thorough via holes would be the misalignment of the electrode chip to the emitter chip. There was a significant rotational misalignment of the emitter chip since the chip position is guided by the edges of the bead holders 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. 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.

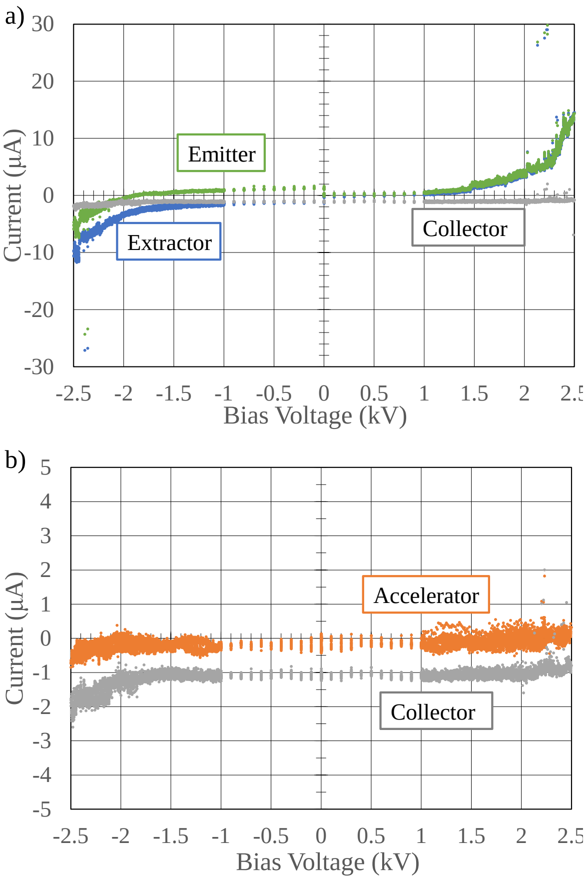


Figure 10: Measured current at each electrode as function of bias voltage between emitter and extractor electrodes. a) Currents at emitter, extractor, and collector electrodes. b) Magnified plots of collector and accelerator electrodes.

CONCLUSION

The two-stage electrode ILEST using glass substrate was designed, fabricated, and tested. We successfully demonstrate ion emission but the emission to collector is small. The assembly methods should be improved to reduce ion corrosion to the extractor electrode and decrease the starting voltage. We also plan to employ a new propellant supply method from the backside of the emitter chip.

ACKNOWLEDGEMENTS

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CONTACT

*T. Tsuchiya, tel: +81-75-383-3690; tutti@me.kyoto-u.ac.jp