MICROFABRICATION OF AN ELECTROSPRAY THRUSTER FOR SMALL SPACECRAFT

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Abstract: This paper presents the micro-fabrication and characterization of an electrospray thruster for fuel-efficient propulsion of nano- (10–100 kg mass) and pico- (1–10 kg mass) satellites. The thrusters operate by electrospraying charged particles, ions and/or charged droplets, from ionic liquids, with exit speeds of up to 40 km/s at 1.4 kV. The devices consist of a 100 μm long, 10 μm inner diameter, silicon capillaries centered 45 μm below annular silicon extractor electrodes. The devices are micro-fabricated from two bonded silicon on insulator (SOI) wafers. The divergence of spray from the devices is characterized, and the effect of molecular vapour deposition (MVD) of a hydrophobic coating to control liquid wetting is investigated.

Keywords: Electrospray, ionic liquid, MEMS, satellite, thruster, EMI-BF_4

INTRODUCTION

Electrospray microthrusters are promising high-efficiency electric propulsion systems particularly suited to nano- and pico-satellites. In these devices, thrust is produced by direct extraction and acceleration of charged particles from the surface of ionic liquids contained in a capillary emitter, by applying a large electric field (~10^9 V.m^{-1}) between the emitter and an extractor electrode, as shown in Fig. 1 [1]. Due to interaction of the electric field with the surface tension in the liquid, the shape of the liquid surface changes and eventually forms a conical shape, typically known as Taylor cone, and charged species are ejected, either from the tip of the cone or in form of a jet. The emission may consist of pure ions with very high charge over mass ratio (~10^6 C.kg^{-1}), or of a mixed ion/droplet mode, or of large charged droplets with much lower charge over mass ratio. Depending on the charge over mass ratio of the emitted species, the performance of the thruster varies from very high fuel efficiency (specific impulse ~ 3000–4000 s in pure ion regime) to high thrust mode (~1–100 μN per emitter in droplet mode). Using ionic liquids as fuel rather than liquid metals presents the advantage of room temperature operation and the ability to spray charges of both polarities. The spray property (ion vs. droplet) can be altered onboard the satellite by simply tuning the applied electric drive potential. Thrust can be increased by micro-fabricating arrays of emitters.

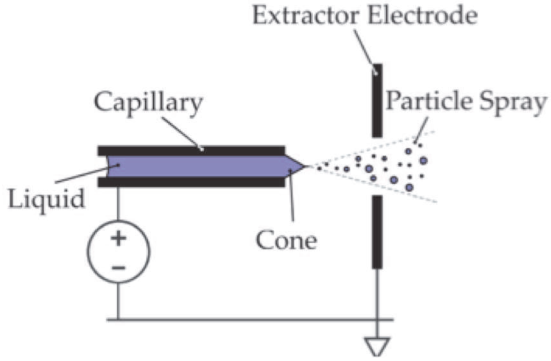

Fig. 1: Schematic of electrospray mechanism

In this paper, the fabrication and latest characterization experiments on the spray divergence from the thrusters are presented. The thrusters are micro-fabricated on SOI wafer, the details of which will be discussed in the next section. The research groups working with ionic liquid electrospray have observed spray over a significantly large solid angle [2]–[4]. For thruster application, determination of the spray divergence is important for many reasons. Spray that is not in the intended direction consumes power but does not contribute to thrust. Also any asymmetry in the spray may lead to overall thrust in a different direction. A large spray angle may lead to damage in the extractor electrode resulting in reduced lifetime of the thruster. A spray-shape characterization set-up has been built to determine the angular spray profile, which will be discussed in subsequent sections. Finally some spray angle measurement results will be discussed.

ELECTROSPRAY DEVICES

The electrospray thrusters are fabricated on SOI wafer. The capillaries and the extractor are fabricated on two different SOI wafers.

Emitter fabrication process

The emitters (capillaries) are fabricated on a wafer with 100/2/500 μm thick device/oxide/handle layer [5]. The process flow for fabricating the emitters is depicted in Fig. 2. It starts with a 2.2 μm thermal oxide layer lithographically patterned on the device layer to create the openings for the capillaries (Fig. 2(a) and Fig. 2(b)) followed by 100 μm Deep Reactive Ion Etch (DRIE) of silicon. This step is the most critical one in the fabrication process due to limited aspect ratio of the DRIE step, which limits the miniaturization of the emitter opening for the 100 μm deep capillaries. In the present devices, the opening in the capillaries is 9 to 11 μm, almost reaching the fabrication limit. A reservoir is created in the handle layer by DRIE (Fig. 2(c)) after lithographic patterning from the back-side. In order to sharpen the emitter tip to minimize unwanted wetting of the outside of the capillary, the tip is first isotropically etched followed by a DRIE step on the outside with another silicon dioxide mask (Fig. 2(d) and Fig. 2(e)). Finally, the devices are released by buffered hydrofluoric acid (BHF) wet-etching of the 2 μm buried oxide layer (Fig. 2(f)) for fluidic continuity between the reservoir and the capillary.

One of the problems of the emitters is liquid spillage during operation, which creates a low impedance path between the emitter and the extractor leading to failure of the devices. In order to reduce this wetting issue and increase the lifetime of the devices, a silane-based "hydrophobic" monolayer is deposited on the exterior of the capillaries in a MVD instrument from Applied Microstructures [6] (Fig. 2(g) to Fig. 2(i)). Previous work ([7], coating MVD A in Figure 15) showed that the application of such a layer on silicon stabilized the contact angle of EMI-BF_4 above 90° (94.2° +/- 2.4°, one sigma). During deposition of the monolayer, the capillary is first filled with photoresist (AZ1518) (Fig. 2(g)) preventing any coating on the interior of the emitter. The resist is later removed by immersion for several hours in an ultrasonic acetone bath, which does not attack the monolayer.

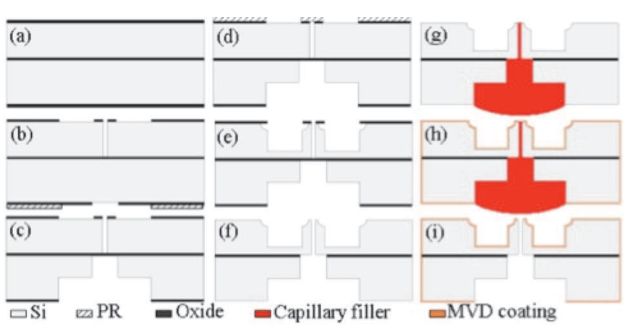

Fig. 2: Emitter process flow

Extractor fabrication process

The extractor (annular electrode) is machined from another SOI wafer with 50/2/400 μm thick device/oxide/handle layer as shown in Fig. 3 [5]. Different extractor aperture diameters between 150 μm and 300 μm with a step of 50 μm are fabricated on the same wafer by lithography followed by DRIE steps. The front-side and the back-side of the wafer are etched separately followed by a BHF buried oxide etch step to open the aperture. For electrical continuity between the two layers, a 200 nm aluminium layer is deposited on both sides of the wafer.

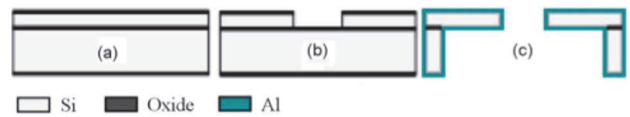

Fig. 3: Extractor process

Wafer level integration

For wafer level integration of the emitter and the extractor wafers, three layers of 15 μm thick DuPont MX5015 laminated dry photoresist are used as an

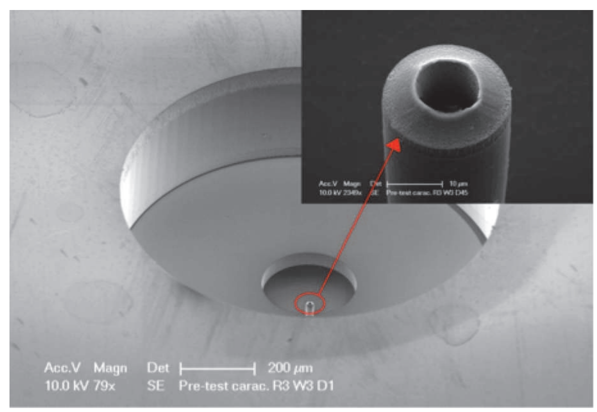

Fig. 4: SEM image of the complete thruster. Emitter in the inset

insulating and high dielectric-strength bonding agent with thicknesses well-suited for the desired thruster configuration [5]. In Fig. 4 a scanning electron microscope (SEM) image of the complete thruster is shown.

SPRAY PROFILE TEST SETUP

The spray tests are performed in a vacuum chamber, which can be pumped down to 10^{-6} mbar with a turbo-molecular pump. The ionic liquid, 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF_4), is reserved in a separate chamber and is supplied to the emitter by hollow silica capillary tube. High voltage (HV) bipolar power supplies for extraction are created using PCB mountable DC-DC converters and high voltage relays. The bipolar power supply is connected to the emitter through HV feed-through while the extractor is grounded through a 1 MΩ resistor for extractor current monitor. In order to detect the spray divergence, a 19-annular-plate detector has been fabricated on a FR4 board as shown in Fig. 5 and a time-multiplexed plate switching

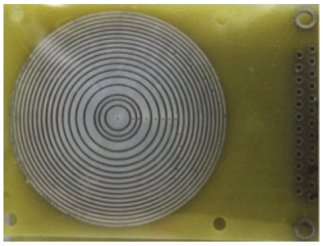

Fig. 5: 19-annular-plate detector for beam shape measurement

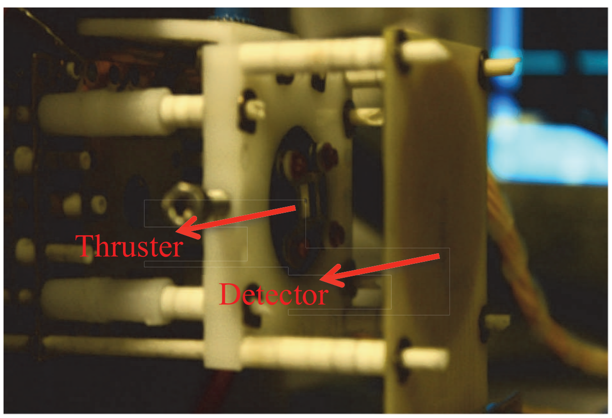

Fig. 6: Beam angle measurement configuration. The detector plate is placed 25 mm away from the emitter.

electronic system has been built to detect the current in each plate in both polarities of operation. The entire system is controlled using data acquisition system and analog output system from National Instruments. The detector is placed at a distance of 25 mm (Fig. 6) from the emitter inside the vacuum chamber and the currents in the plates are sequentially detected across 1 MΩ resistors.

TEST RESULTS AND DISCUSSIONS

The spray shapes of the thrusters with extractor diameter 200 μm and 250 μm have been characterized. The extraction voltage at the emitter is increased in step in both polarities and the currents in the 19 detector plates are monitored for each applied voltage. In Fig. 7 the spray angle for the two types of devices are plotted as a function of the emitter voltage in both polarities. In Fig. 8 and Fig. 9 the current

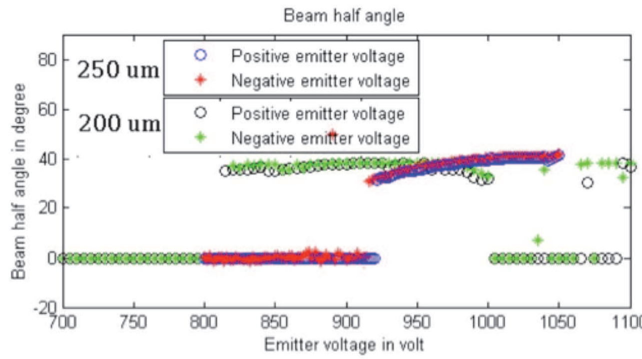

Fig. 7: Beam half angle as a function of extraction voltage (positive and negative) for two extractor diameters.

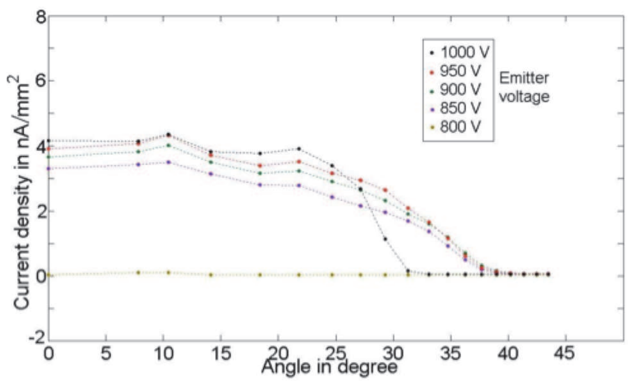

Fig. 8: Evolution of beam half angle with the emitter voltage for a 200 µm extractor diameter device

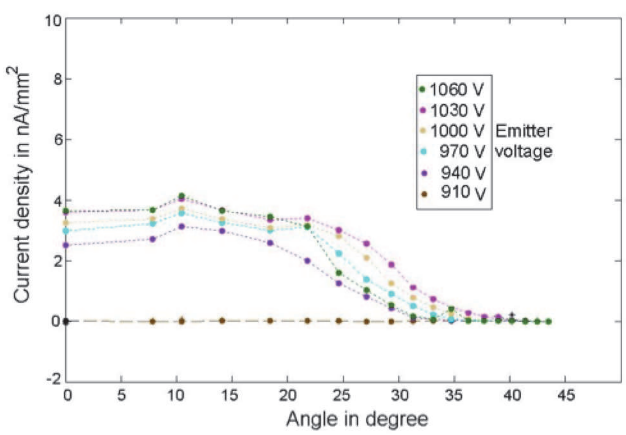

Fig. 9: Evolution of beam half angle with the emitter voltage for the 250 µm extractor diameter device

density distributions as a function of the emission angle from the axis as obtained from the 19 plates are shown for the same two types of devices.

It is observed from Fig. 7 that for larger extractor diameter, the onset of emission takes place at a higher voltage. This is because the distance between the tip of the emitter and the extractor is larger. However the difference in the electric field direction due to the difference in extractor diameter does not affect the total spray angle noticeably. In both cases, the spray angle tends to increase with the extraction voltage slightly (8–10° for a increase of around 100 volt) and saturates nearly at 40°.

It is observed from the spray shape results (Fig. 8 and Fig. 9) that the current density is not highest along the axis of spray. These results have been observed repeatedly for different tested devices and the results conform to previously reported results on purely charged droplet/mixed ion-droplet emission [4]. It can be inferred from these results that the emission from the thrusters is either in droplet or mixed droplet-ion mode. This result is expected from these large emitter diameters of the thrusters, which provide fluidic impedance low enough to allow large droplets to emit along with field emission of ions from the surface of the liquid. A reduced emitter diameter may tend to result in purer ionic emission.

Although not quantitatively analyzed, the MVD coating on the emitters appears to increase the lifetime of the devices (up to 18 hours of continuous operation). Due to the liquid-phobic nature of the coating, the liquid is microscopically observed to accumulate with much smaller droplet sizes on the emitter than in earlier devices and hence provides less chance of creating an electrical short.

CONCLUSIONS

This paper presents the latest micro-fabrication and test procedures on the electrospray microthrusters developed at EPFL. It has been conclusively inferred from several experiments that the emission from the latest micro-fabricated devices do not achieve pure ionic mode and the spray is predominantly in form of charged droplets. The devices in the next run will target 5 μm emitter diameter so that at least one order of magnitude increase in fluidic impedance can be achieved. Detailed spray composition analysis can be performed either by retarded potential analysis or time of flight analysis to find the ion and droplet composition of the spray; results in these directions will be reported in future.

The unique procedure of MVD coating reduces the failure rate of the devices. However, in order to re-use the devices, the emitters are treated in piranha solution after use, which dissolves and removes the ionic liquid; but this removes the MVD coating from the emitter as well.

The spray profile characterization setup has been discussed and test results on two different extractor diameters have been presented. It is observed that the extractor diameter does not strongly affect the spray angle unless inhibiting the spray due to physical boundaries (which can occur for 150 μm diameter extractors). The spray half angle tends to increase as the electric field increases and then saturates to nearly 40° for both the dimensions. Further results on the beam shape for different extractor electrode diameters, for different emitter to extractor distances, and for different ionic liquids will be reported in the future.

ACKNOWLEDGEMENTS

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