Design and fabrication of the thruster heads for the MicroThrust MEMS electrospray propulsion system

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Abstract: Microfabricated electrospray thrusters are widely acknowledged as one of the most promising technologies for the propulsion of small spacecraft. Their relative simplicity, high efficiency ($> 70\%$), low footprint ($M < 500g$, $V < 10cm^3$) and large potential specific impulse ($> 3000s$) enable the creation of a miniature system capable of providing up to 5km/s ΔV to 3U CubeSats.

We report here on our latest efforts in the development of such a thruster system, completed within the MicroThrust (www.microthrust.eu) project. While a companion paper will present early test results of the thrusters, this paper will focus on their design and fabrication.

We use MEMS microfabrication to manufacture internally fed capillary emitters from silicon. This permits the high fluidic impedance required to get the necessary low flow rates associated with pure ionic mode operation, in addition to allowing the fabrication of large arrays of perfectly aligned, nearly identical emitters. We present for the first time the wafer-level integration of an acceleration stage, with individual electrodes operating on up to 127 emitters on a single chip. By adding the accelerator, we increase both the specific impulse and thrust generated by the emitters, while also increasing the thrust efficiency by electrostatic focusing the spray.

We have fabricated chips with varying emitter density (213 and 125 emitters per cm^2) and have successfully tested passively fed emitter arrays, obtaining up to 35 μA of current at +875V for a 91 emitter array.

Nomenclature

$DRIE$	= Deep Reactive Ion Etch
SEM	= Scanning Electron Microscope
SOI	= Silicon-On-Insulator
THC	= Thruster chip

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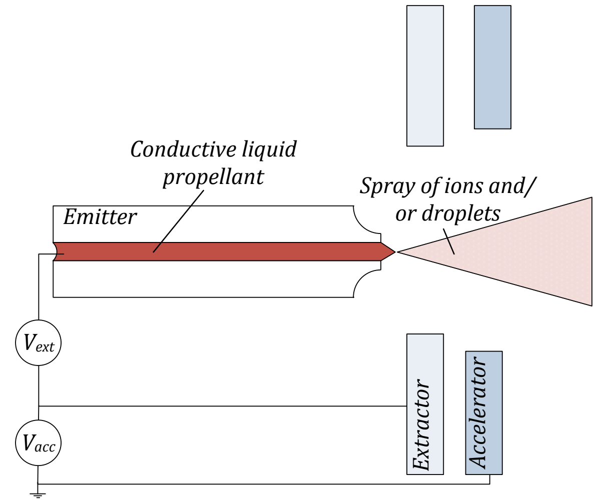


Figure 1. Simplified diagram of electrospray principle with extraction and acceleration electrodes.

I. Introduction

A propulsion system capable of delivering high ΔV ($> 5000 m/s$) while having a low mass (500g), volume ($< 10cm^3$) and power ($< 10W$) footprint could have a profound effect on the space industry by permitting low cost science and exploration missions using small satellites. The MicroThrust[a] project is an European initiative meant to develop such a technology.

We use electrospray microthrusters, where a spray of charged particles is generated from the tip of a cylindrical emitter using an annular extaction electrodes (Figure 1). By adjusting the extraction voltage, the nature of the extracted particles can be changed, from monomer ions[1] to droplets. The specific impulse and thrust are calculated from equations (1) and (2), which show that the q/m ratio of the emitted species is critical.

$$T = I_T \sqrt{2V_b \frac{m}{q}} \quad (1)$$

$$I_{sp} = \frac{1}{g}\sqrt{2V_b \frac{q}{m}} \quad (2)$$

In MicroThrust, we aim to operate in the high specific impulse ($> 3000s$) regime, overcoming the low thrust limitation by using large arrays ($\sim 5000 - 10000$) of emitters thrusting in parallel.

We presented at IEPC 2011[2] the fabrication and test of some early devices with $10\mu m$ inner diameter single emitters. We showed how the devices could be operated, although fully ionic operation could not be reached. We described how back pressure had a large effect on the nature of the emission: higher ion content was observed with the low flow rate resulting from very low back pressure. This was consistent previous observations[3,4] that a high fluidic impedance of the emitters was required to achieve ionic operation. We presented a comparison between our early propellant candidate, $EMI-TF_2N$ and a more performant liquid, $EMI - BF_4$, showing also the wetting properties of these liquids.

We now introduce a new generation of devices, with smaller inner diameters ($\sim 7.9\mu m$) and larger arrays (up to 127 emitters). Additionally, we integrate a second electrode stage capable of accelerating and focusing the spray, simultaneously increasing both thrust, specific impulse and thrust efficiency.

In this paper, we will present the design and fabrication of this new generation of THruster Chip (THC). Companion papers will focus on early test results of the THC (IEPC-2013-146), on the custom designed high voltage driving power board (IEPC-2013-258) and on a new Time of Flight (TOF) setup to be used to characterize the THC (IEPC-2013-413).

[a]www.microthrust.eu

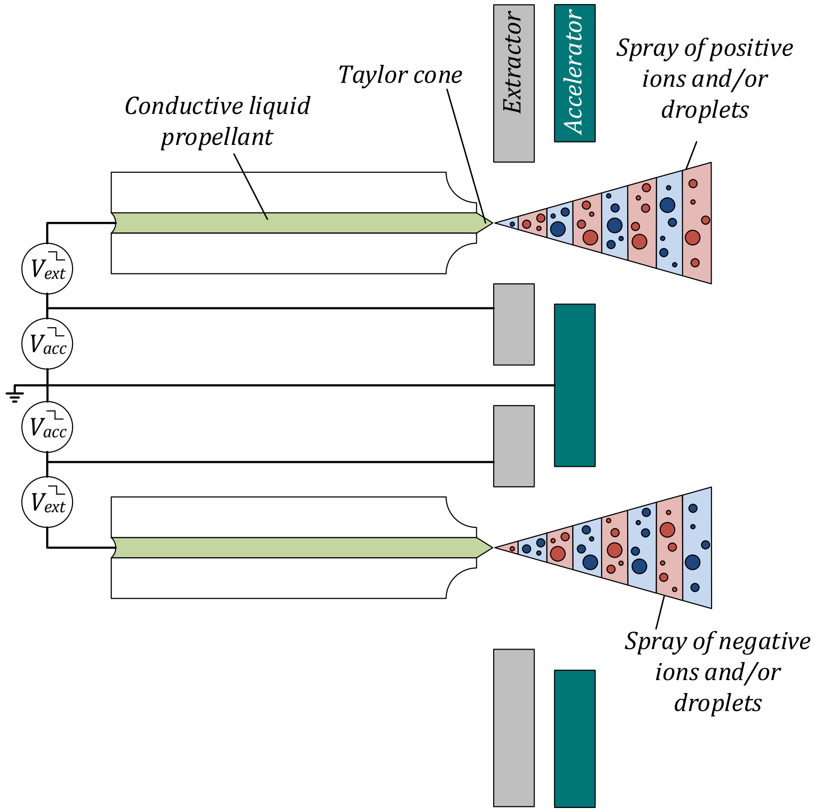


Figure 2. Diagram of electrospray thruster concept, with two emitters spraying in opposite polarity, to keep spacecraft neutrality but also alternating to avoid charge buildup in the reservoir.

II. Thruster configuration

Electrospray thrusters are often classified according to the mechanism used to transport the liquid to the extraction site. Typical methods use external wetting,[5] porous feeding[6] or internal feeding. We use the latter, which allows good control of the fluidic impedance of the device and minimizes propellant exposure to space. Internally fed capillaries can be pressure driven[7] or with passive capillary feeding. While the former offers good control of the nature of the emitted species, it requires additional components such as pressurized reservoirs, precision valves and flow sensors. We use the passive feeding approach[8,9] which does not suffer from these drawbacks, but requires very low tolerances in the fabrication of the emitters. It also leads to a somewhat unstable system, where small changes in extraction voltage can have large consequences in the operation. Nevertheless, the advantages are believed to outweigh the inconveniences.

A further simplification of the system is achieved by using pairs of emitters operating in opposite polarity, which allows spacecraft neutralization without the need of an external neutralizer. Each of the emitter is alternating its emission polarity, so that an individual propellant reservoir will not build up a charge imbalance[10] (Figure 2).

The extraction potential is generally fixed at an optimal value to yield the desired beam composition (in the range of 800 V, depending on extractor design). The acceleration potential can be tuned with little effect on the extraction itself. Using high acceleration, the beam is accelerated and focused, but at the cost of power consumption.

Typically, the accelerator electrode, on the exterior of the spacecraft, is grounded and the high or low potentials applied to the extractor electrode and the reservoir.

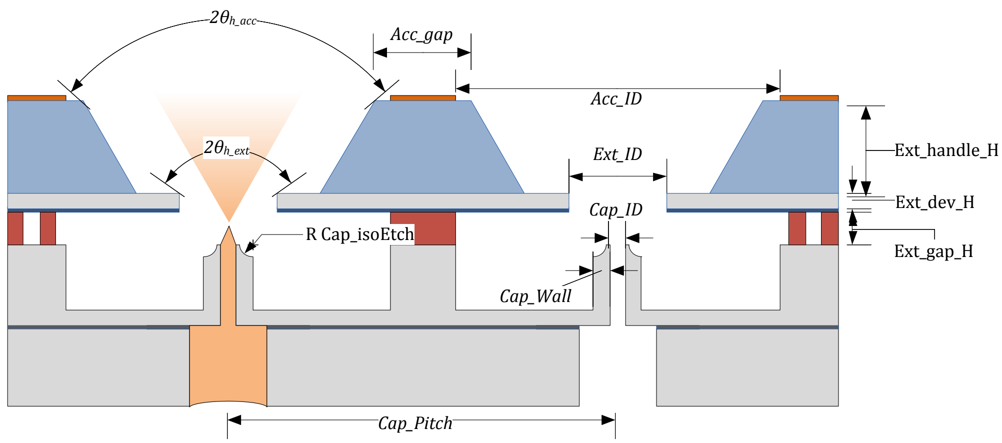


Figure 3. Cross section diagram of thruster stack.

III. Thruster chip design

The MicroThrust emitters are in their simplest description an array of vertically standing micro cylinders. Their fabrication in bulk crystalline silicon ensures very strong mechanical resistance and virtually perfect parallelism. Above the emitters is aligned a matching array of two-level electrodes, designed to extract the flux of particles and accelerate it. Figure 3 is a cross section of the emitters, with dimensions listed in Table 1.

The key dimensions of the emitter are their inner diameter and height. These drive the fluidic impedance of the emitters and consequently the propellant flow.

The packing density is also critical. Since each emitter delivers low thrust (expected in the range of 20 nA), it is necessary to fabricate several thousand emitters to provide acceptable thrust levels ($\sim 100\mu N$). With an available surface in the order of 30 cm^2, it is important to pack the emitters as densely as possible. The packing density is calculated from the emitter pitch, which in turn is driven by the thickness of the electrode stack. Since a certain beam angle must be allowed to clear the accelerator, a thinner electrode will yield to lower pitch. With the current process, a total stack thickness (including the bonding layer) of 350 μm can be fabricated. The two designs shown here differ by their allowed beam clearance (38° and 48°). For these two designs, we achieve respectively 213 and 125 emitters per cm^2.

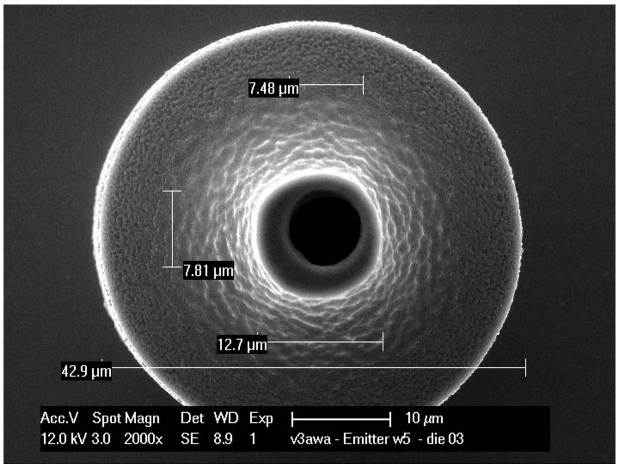
Table 1. Design parameters of MicroThrust electrospray thrusters.

Parameter	Identification	Nominal dimension (μm)
Emitter inner diameter	Cap ID	5
Emitter inner height	Cap H	100
Emitter wall thickness	Cap Wall	20
Emitter pitch	Cap Pitch	737, 963
Emitter isotropic etch radius	Cap isoEtch	15
Extractor electrode diameter	Ext ID	168
Extractor electrode thickness	Ext dev H	50
Extractor-emitter gap	Ext gap H	50
Glass thickness	Ext handle H	250
Accelerator electrode diameter	Acc ID	540, 765
Accelerator to accelerator spacing	Acc gap	150

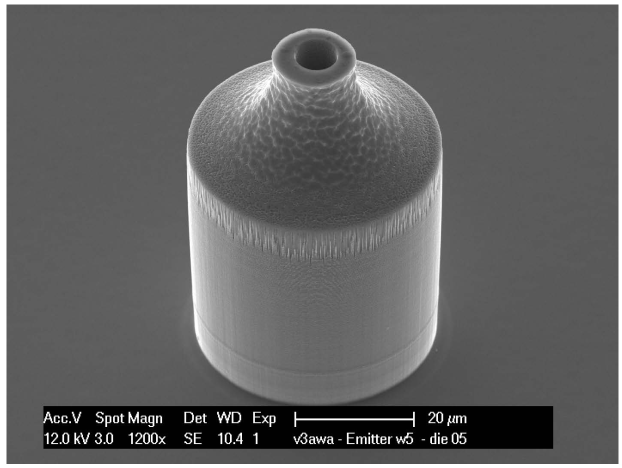
IV. Microfabrication

A. Emitter fabrication

The emitters are micro fabricated from a single Silicon On Insulator (SOI) wafer. Definition of the emitters is achieved through a series of anisotropic and isotropic dry and wet etches, which chemically attack the silicon and oxide layers with a high level of precision and control. Most critical is the first Deep Reactive Ion Etch (DRIE) which defines the interior of the capillaries. On recent devices, an inner diameter of 7.9 +/- 0.5 μm could be achieved for a 100 μm high emitter. Figure 4 shows SEM images of fabricated emitters. More details on this fabrication process can be found in previous publications.[9,11]



(a)



(b)

Figure 4. SEM images of MicroThrust emitters.

B. Electrode fabrication

Electrode fabrication starts with the patterning of the extractor electrodes on a bulk silicon wafer, through standard photolithography and DRIE. Separately, glass wafers are patterned with micro-sandblasting[b]. The silicon and glass wafers are then bonded anodically (Figure 5a) before the silicon is removed from the backside of the wafer by grinding and polishing, revealing the extractor pattern (Figure 5b). Next, silicon dioxide is sputtered on the bottom of the silicon to provide electrical insulation. Metal is finally deposited through a shadow mask on the front side of the glass to create the accelerator electrodes (Figure 5c) and metalize the contact points. Completed electrodes are shown in Figure 6.

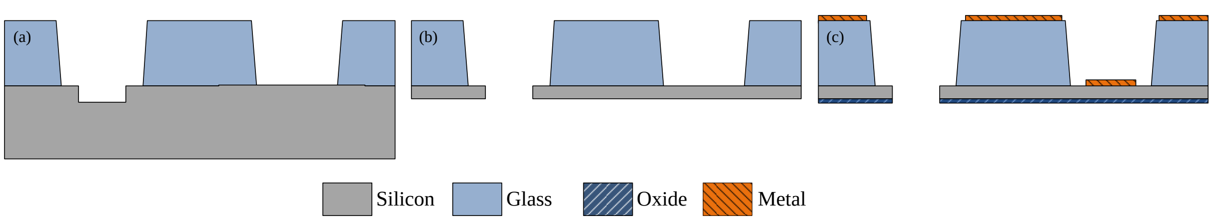
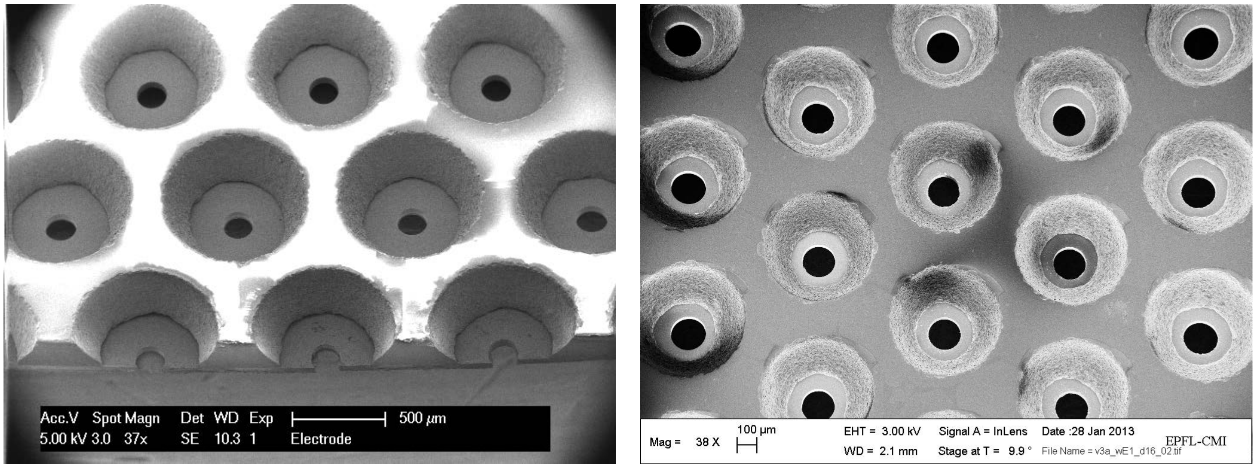


Figure 5. Electrode fabrication process flow

[b] www.icoflex.com



(a) (b)

Figure 6. SEM images of MicroThrust electrodes.

C. Wafer-level assembly

A 50μm thick photopatternable film (MX5050) is used as a bonding layer to assemble the electrode and emitter wafers. The film is applied on the electrode, exposed and developed (Figure 7a-b). Both wafers are then aligned and put in contact in the BA6 bond alignment tool, allowing $< 5\mu m$ alignment. The wafers are then bonded by thermo-compression (3 bar, 150°C, 30 minutes) (Figure 7c). Finally, the wafers are diced with protective tape applied on the front and back. (Figure 7d)

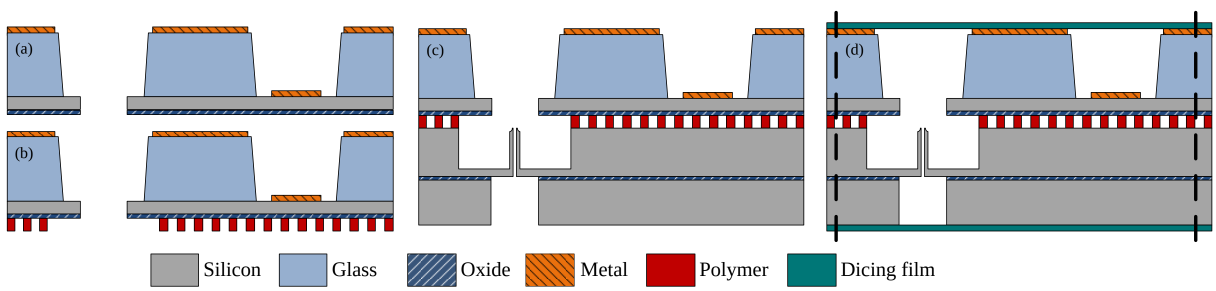


Figure 7. Assembly process flow

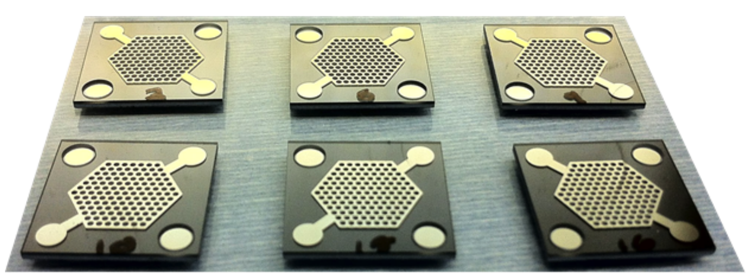
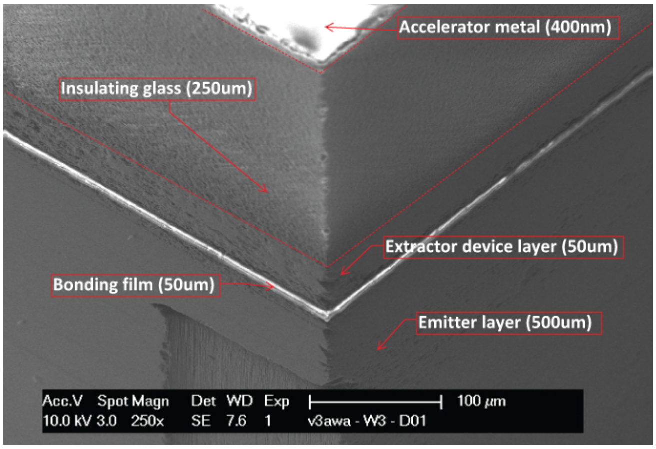
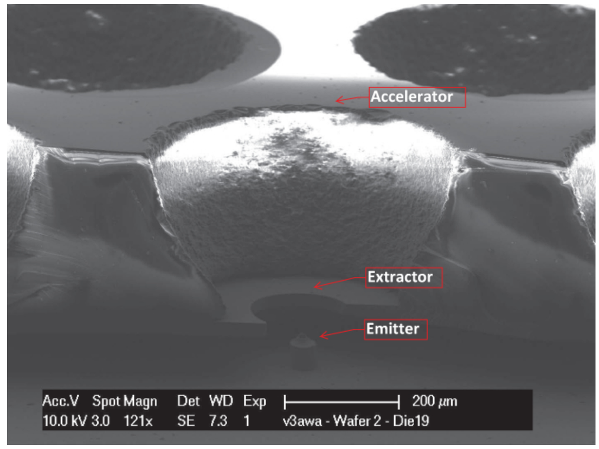


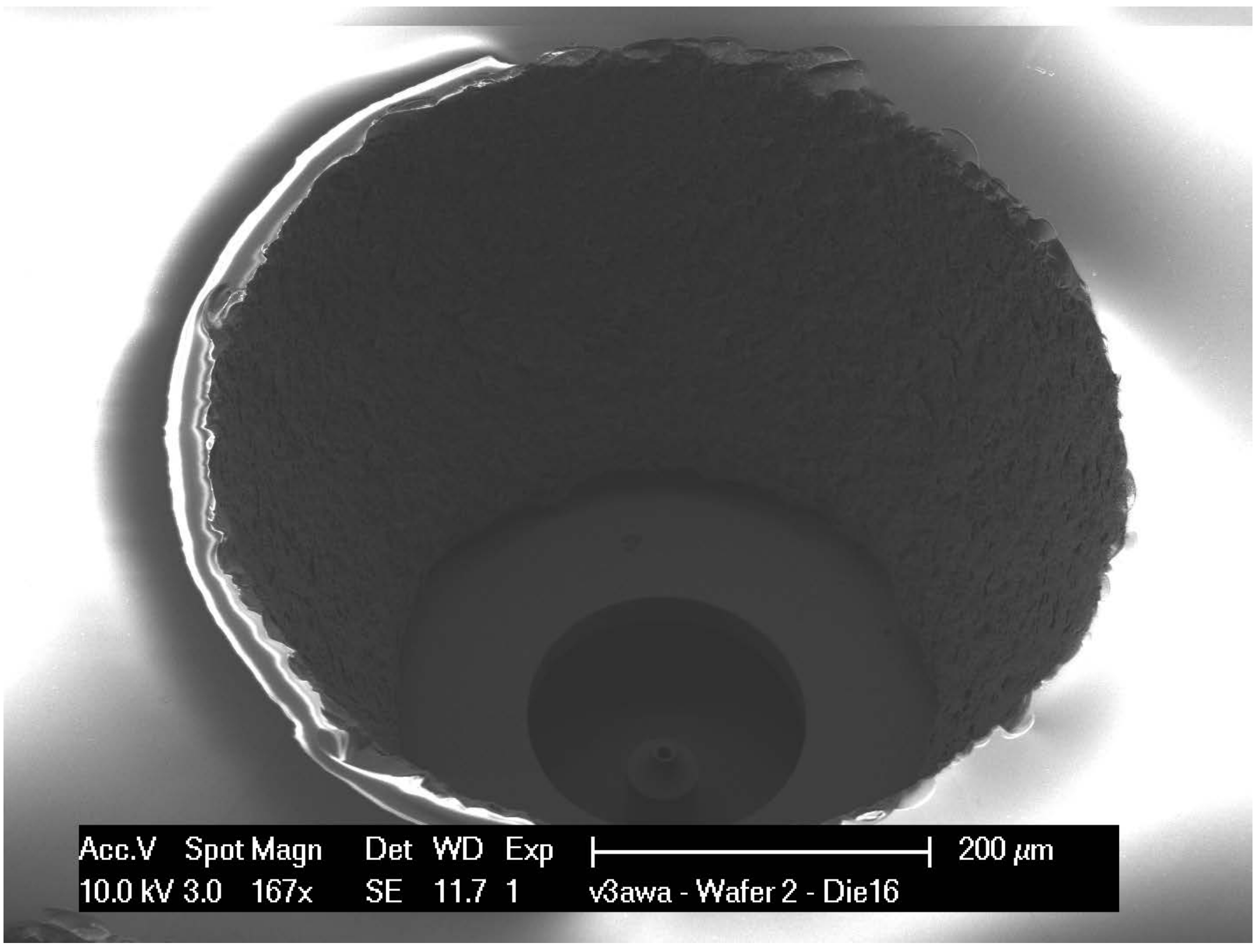
Figure 8. Optical image of several THC ready for test.



(a)



(b)



(c)

Figure 9. SEM images of completed thruster stacks. (a) Corner of die, showing thickness of different layers. (b) Cross section of active area with emitter aligned below cleaved electrode. (c) Close-up of accelerator-extractor-emitter stack.

V. Conclusion

We have presented the design and fabrication of a new generation of MEMS electrospray thrusters to be used for small spacecraft. This technology is unmatched in its ability to combine high deltaV with small footprint, making it a key enabler for small spacecraft missions requiring orbit changes.

Microfabrication is a powerful tool to boost the performance of such devices. In addition to minimizing the physical footprint of the device in terms of mass and volume, it acts on two critical performance aspects. First, it allows the fabrication of high fluidic impedance devices, which is key to achieving high I_{sp} ionic operation. Second, it allows for higher packing of emitters, increasing thrust density.

We have presented how the fabrication process has evolved to include an accelerator level, capable of increasing Isp and Thrust by accelerating the emitter particles. This latest process was used to produce several dozens of THC which were characterized for their performance. Results of these tests are presented in a companion paper (IEPC-2013-146).

Acknowledgments

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References

[1] Romero-Sanz, I., Bocanegra, R., and De La Mora, J. F., "Source of heavy molecular ions based on Taylor cones of ionic liquids operating in the pure ion evaporation regime," *Journal of Applied Physics*, Vol. 94, No. 5, 2003, pp. 3599.

[2] Dandavino, S., Ataman, C., Shea, H. R., Ryan, C., and Stark, J. P. W., "Microfabrication of Capillary Electrospray Emitters and ToF Characterization of the Emitted Beam," *32nd International Electric Propulsion Conference*, 2011, pp. 1–10.

[3] Krpoun, R., Smith, K. L., Stark, J. P. W., and Shea, H. R., "Tailoring the hydraulic impedance of out-of-plane micromachined electrospray sources with integrated electrodes," *Applied Physics Letters*, Vol. 94, No. 16, 2009, pp. 163502.

[4] Garoz, D. and Fernandez de la Mora, J., "Charge emissions from electrosprays in vacuum: Mixtures of formamide with methylammonium formate," *Journal of Applied Physics*, Vol. 113, No. 6, 2013, pp. 064901.

[5] Lozano, P. C. and Martínez-Sánchez, M., "Ionic liquid ion sources: characterization of externally wetted emitters," *Journal of Colloid and Interface Science*, Vol. 282, No. 2, Feb. 2005, pp. 415–21.

[6] Courtney, D. G. and Lozano, P. C., "Development of Ionic Liquid Electrospray Thrusters using Porous Emitter Substrates," *International Conference on Space Technology and Science*, 2009, pp. 1–6.

[7] Lenguito, G., De La Mora, J. F., and Gomez, A., "Design and Testing of Multiplexed Electrospray with Post-Acceleration for Space Propulsion Applications," *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, No. August, 2011, pp. 1–11.

[8] Krpoun, R., Räber, M., and Shea, H. R., "Microfabrication and test of an integrated colloid thruster," *21st International Conference on Micro Electro Mechanical Systems*, 2008, pp. 964–967.

[9] Dandavino, S., Ataman, C., Chakraborty, S., Shea, H. R., Ryan, C., and Stark, J. P. W., "Progress Towards a Miniaturized Electrospray Thruster for Propulsion of Small Spacecraft," *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, No. August, Atlanta, Georgia, 2012, pp. 1–13.

[10] Lozano, P. C. and Martínez-Sánchez, M., "On the dynamic response of externally wetted ionic liquid ion sources," *Journal of Physics D: Applied Physics*, Vol. 38, No. 14, July 2005, pp. 2371–2377.

[11] Ataman, c., Dandavino, S., and Shea, H. R., "Wafer-level Integrated Electrospray Emitters for a Pumpless Microthruster System Operation in High Efficiency Ion-Mode," *IEEE MEMS*, Paris, France, 2012.