Preliminary Testing of Flat-panel Pixel Electrospray Thrusters for Increased Reliability and Efficiency

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Electrospray thrusters are a promising form of electric propulsion due to their high specific impulse, making them advantageous in deep space satellite and other spacecraft missions. These thrusters operate through the dispersion of an electrically-conductive liquid from a capillary or sharp emitter through the application of a potential difference between the emitter and downstream extractor electrode. This emission is most efficient and advantageous when operated in the purely-ionic regime (PIR), with recent designs utilizing sharp porous emitters to direct emission, though these are often difficult to manufacture precisely to guarantee PIR emission. Electrospray thrusters also suffer in their reliability due to monolithic extractor design causing full array failure upon the shortage of a single emitter. These issues can be solved through the novel electrospray thruster design manufactured and tested in this paper. This design utilizes (1) a flat-panel array design to resolve issues associated with the current emitter tip design to ensure consistent manufacturing and PIR operation, and (2) a series of fuses interconnecting individual extractor rings for each emitter which would break upon shortage, protecting the rest of the extractors in an array in case of a single emitter shortage. Through this research, a design is properly fabricated in a scale required for PIR emission, the required starting voltage for a test is simulated, and preliminary long-duration and IV curve tests of individual capillary emitters using a non-integrated extractor are completed.

Nomenclature

\[ Z_{PIR} \] = PIR impedance
\[ \mu \] = Viscosity
\[ L_c \] = Capillary length
\[ R_c \] = Capillary radius
\[ Z_c \] = Capillary impedance
\[ Z_s \] = Substrate impedance
\[ A_s \] = Substrate cross-sectional area
\[ k_s \] = Porous substrate permeability
\[ L_s \] = Substrate length

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I. Introduction

Electrospray thrusters are efficient electric propulsion devices that can produce high specific impulse and low thrust, making them advantageous in satellite and deep space missions.\(^1\) These thrusters consist of a capillary or sharp geometry from which propellant is expelled due to a voltage differential applied between the propellant source and a downstream electrode. These components are denoted as the emitter and extractor respectively. The efficiency of these devices is optimized when operated in the purely-ionic regime (PIR), in which the propellant is expelled on an ion-basis, due to maximization of the charge to mass ratio of the particles causing a high specific impulse. Recently, electrospray thrusters have been designed using precise tip geometries constructed from porous substrates, allowing propellant to be passively fed to a micron-scale point, which provides the necessary impedance and geometry for PIR emission.\(^2\)–\(^4\) In order to produce a more sizable amount of thrust while still operating in the PIR, hundreds of emitters are constructed from a single substrate as an array, generally using a single extractor electrode to allow for the generation of an electric field and emission.

This current electrospray thruster design is flawed for several reasons, resulting in the decreased lifetime and reliability of the devices. Generally, the extractor electrode used to generate the electric field for all of the emitters is a single component, and therefore a short circuit stemming from a single emitter causes the shortage of the entire extractor array, thus resulting in full array failure.\(^5\) Further, the design of electrospray emission sites currently consists of a sharp cone geometry, generally stemming from a porous substrate, to allow propellant uptake into a fine point that is small enough to enhance the electric field at the meniscus for PIR emission. These tips can be difficult to manufacture and ensure that they are consistently manufactured in the size constraints necessary for PIR emission. Further, it can be challenging to ensure that there are no alignment issues between the emitter and extractor that can cause overspray and backstreaming of secondary electrons, which degrades the thruster over time.\(^6\)

The solution to these problems coalesces into the design previously documented and manufactured, that is now tested in this study, and shown in Figure 1.\(^7\) To first resolve the issue of premature full array failure due to extractor shortage, individualized extractors can be manufactured around each emitter, and can be connected to one another through a series of fuses. These fuses can be manufactured from a material and with a geometry that will allow it to fuse when a current generally experienced during a shortage, 1 mA, attempts to pass through it, thus preventing the shortage from propagating to the rest of the extractors. Further, the issue of emission site geometry and precision can be ameliorated through replacing the emitter tips with capillaries instead, that can be more consistently manufactured on a scale generating sufficient impedance for PIR emission, as shown in previous studies.\(^8\)

This paper seeks to provide an update on preliminary testing data collected from this thruster design. In particular, current-voltage (IV) curves and long-duration tests were completed on single emitter thruster samples fabricated based off of the capillary design using SU-8, an epoxy photoresist, to determine design viability and initial performance metrics. This preliminary test aimed to verify that single capillary emitters can function using this fabrication method, and does not yet employ the integrated extractor design shown in the CAD model.

![Figure 1. CAD model of (a) cross-sectional side view of a single emitter and (b) full view of a full array using proposed design.](image-url)
II. Sizing and Material Selection

Using the assumption that the necessary capillary impedance can be assumed to be 2-3 times PIR impedance to ensure the impedance is sufficiently high, dimensions for the necessary emitter capillary geometry can be found using Equation 1.9

\[
2Z_{PIR} = Z_c + Z_g = \frac{8\mu L_c}{\pi R_c^4} + \frac{\mu L_s}{k_s A_s}
\]  

This equation takes into account the impedance generated by both the capillary \(Z_c\) beneath it, which must be greater than the PIR impedance \(Z_{PIR}\), which has been recorded to be on the order of \(10^{17}\) Pas/m³.\(^{10}\) The capillary impedance equation includes the length \(L_c\) and radius \(R_c\) of the emitter capillary, as well as the propellant viscosity \(\mu\), and the porous glass impedance equation includes the length \(L_s\) and cross-sectional area \(A_s\) of the substrate, as well as substrate permeability \(k_s\), which was assumed to be governed using the Kozeny–Carman approximation for the permeability of a porous media, and Darcy’s law which uses this permeability to find the impedance of the porous media.\(^{11,12}\) Further material choices were previously reported and determined for the base to be a porous material, to allow for passive propellant uptake into the capillaries, and a low dielectric constant material that can be fabricated on the micron-scale for the emitter material and extractor base. This material was chosen to be SU-8, though polydimethylsiloxane (PDMS) or other similar materials may be good options for future work. This was due to its ability to be easily manufactured at the desired scale using photolithography, and was later confirmed as a viable option as other studies were able to make emitters from the same material, though not on porous substrates.\(^{13}\) The extractor/fuse material was determined to be a material that could fuse when fabricated on the micron-scale and is conductive, with nickel-chromium 80-20 (NiCr) being found to be the best option.

This study used a silicon dioxide porous glass with 100 nm pores (Varapor100), manufactured by Advanced Glass and Ceramics, as the base for the thruster. The samples used were 1 mm thick and either 10 mm squares or 10-14 mm diameter discs. The volatile organic compound (VOC) used was fluorene (98+%, Sigma Aldrich), which was used to fill the porous glass substrates prior to manufacturing to ensure that the photoresist spun on the surface did not enter the pores of the substrate. The VOC was removed post-manufacturing using a hot plate and a desiccator. The SU-8 used was SU-8 2005 from Kayaku Advanced Materials, and was spun using a CEE Apogee manual spin coater. The SU-8 was exposed using an MLA 150 Advanced Maskless Aligner with a 375 nm laser (Heidelberg Instruments), developed using propylene glycol methyl ether acetate (PGMEA), and rinsed with isopropanol (IPA) in order to form the emitter. Lift-off was completed using AZoneLOF-2020 (MicroChemicals), which was exposed and patterned using the same MLA 150, and developed with AZ 300K (MicroChemicals). The NiCr and polytetrafluoroethylene (PTFE/Teflon) depositions were completed using an ATC Orion 5 sputter system (AJA International, Inc.). The liftoff material was removed using acetone. The liftoff process was completed with NiCr to pattern on a layer to the edges of the chip with cross-hairs that could allow the extractor to be aligned using a stage controller, which will be described later. The PTFE liftoff process was completed to create hydrophobic regions on the surface of the SU-8 and the glass substrate to prevent excessive propellant wetting and pooling.

Imaging of the films was completed using a Keyence VHX microscope, a Hitachi TM3030Plus tabletop scanning electron microscope (SEM), and an Oxford Instruments MICSF+ energy dispersive x-ray analysis microscope (EDX).

Firing tests were completed using the Sputnik chamber in the Space Propulsion Lab, which uses a Varian DS 102 wet roughing pump and a Varian Turbo-V 70LP turbopump to reach vacuum. The chamber was also equipped with three M-111 compact linear stages controlled using three C-863 Mercury Stage Controllers, both from Physik Intrumente, used to move the extractor electrode above various emitters to generate emission. The potential for emission was generated from a Matsuda Precision Inc AP-3B1-L2 high voltage power supply, with the data collected on a National Instruments DAQ and read using LABVIEW software.

III. Results and Discussion

A. Manufacturing Process

The manufacturing of the tested device was successfully completed on a porous glass substrate through the use of photolithography and sputtering techniques. The substrate was first dipped into molten fluorene for 2
minutes to ensure VOC saturation of the pores, then the substrate was removed and allowed to cool. Next, large excess pieces of VOC were removed with a razor blade, and the substrate was held in a desiccator with a vacuum pump running for 7 minutes to sublimate a small amount of fluorene from the surface. The substrate was then spun with a layer of 8 µm of SU-8, and exposed and developed to form the ring region constituting the emitter. It has been previously reported that exposing large areas of SU-8 on glass can result in excessive cross-linking beyond the desired cured areas, which caused early iterations to begin experiencing cross-linking within the emitter region, effectively blocking off propellant uptake. To mitigate this, smaller rings around the emitter were exposed and developed, and the surrounding surfaces of the chip were coated in a thick sputtered layer of PTFE. Before PTFE sputtering, the SU-8 was hard-baked at 105 °C for 2 hours. Usual SU-8 hard-bake protocol requires a 30 minute bake at 250 °C, but this temperature would cause the fluorene to melt out from the substrate. To prevent this, a cooler and longer hard-bake was used to ensure the SU-8 would be stable enough to endure later sonic baths in acetone, without prematurely removing the fluorene.

Following SU-8 hard-baking, the PTFE deposition was controlled through the use of a liftoff layer. A thin, 1-2 µm layer of AZnLOF 2020 liftoff was spun onto the surface, then exposed and developed to leave only regions of AZnLOF 2020 covering the emitters, leaving the rest of the substrate exposed. The entire substrate was then sputtered with 80 nm of PTFE, and placed in an acetone sonic bath for 10 s to remove the remaining AZnLOF material and any PTFE that had been sputtered on top of it.

The last material deposited was NiCr, which was deposited to form a conductive region on the edge of the chip with crosshairs to allow for substrate alignment with the extractor, which will be described later. The NiCr was sputtered as a 40 nm thick layer, and was patterned using the same AZnLOF liftoff technique described above.

The final step in thruster preparation involved the removal of the fluorene and bonding to a testing frame. The fluorene was removed from the substrate through heating at 150 °C while held in a desiccator with a pump drawing vacuum for approximately 2 hours. To ensure the removal of any remaining fluorene, the substrate was then placed in an acetone sonic bath for an additional 5 minutes. The thruster was then bonded to a frame using a low-outgassing epoxy, and allowed to cure for 24 hours before wetting with 1-ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF4) for 72 hours to ensure complete substrate and capillary wetting. An image of one of these completed single emitters prior to propellant wetting is shown in Figure 2.

Figure 2. Microscope image of an SU-8/PTFE emitter manufactured on porous glass, following fluorene removal.

B. Simulation Results

Prior to thruster testing, the extractor configuration was simulated to ensure that emission would be able to start at a reasonable applied voltage, preferably less than 2.5 kV as this was the maximum output voltage of the power supply used. Additionally, the smallest reasonable distance that the extractor could be above the substrate surface was determined to be approximately 50 µm, as this would account for potential error
in the alignment and stepping of the motor used to place the extractor of approximately 10 µm, and also account for space occupied by the meniscus once it began firing, to prevent the meniscus from potentially reaching the extractor. A diagram showing the emitter/extractor COMSOL simulation window is included in Figure 3.

![Figure 3. COMSOL 2D axisymmetric simulation window of electric field generated between emitter and ball extractor electrodes.](image)

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![Figure 4. COMSOL simulation results for the electric field generated on a 10 µm diameter (a) concave, (b) flat, and (c) convex capillary meniscus from a grounded ball extractor for various applied voltages and extractor heights, and (d) a comparison of the meniscus cases for 2500 V applied to the emitter.](image)

Figure 4. COMSOL simulation results for the electric field generated on a 10 µm diameter (a) concave, (b) flat, and (c) convex capillary meniscus from a grounded ball extractor for various applied voltages and extractor heights, and (d) a comparison of the meniscus cases for 2500 V applied to the emitter.
The resulting electric field generated at the center of the meniscus was compared with the required starting field for an electrospray plume, which is governed by Equation 2.

\[ E_{\text{start}} = \sqrt{\frac{4\gamma}{\varepsilon_0 r}} \]  

In this equation, \( E_{\text{start}} \) is the required starting field, \( \gamma \) is the surface tension of the propellant, \( \varepsilon_0 \) is the permittivity of vacuum, and \( r \) is the radius of the meniscus, which can be assumed to be the emitter radius. It is plotted as the solid black line in the graphs in Figure 4, which shows the resulting field generated for various extractor heights and applied voltages in the case of a flat, convex, and concave meniscus.

The main variables tested were the extractor height and voltage applied, though an important variable that was accounted for in the testing of different geometries was the shape of the meniscus prior to voltage application. Depending on the back pressure within the porous glass, the capillary may have a concave, flat, or convex meniscus, which would greatly affect the starting voltage required to produce emission. This is shown in the plot in Figure 4 (d), where the convex meniscus clearly generates a much higher electric field for the same applied voltage, and therefore requires a lower starting voltage to hit the electric field firing threshold.

Based on these simulation results, it becomes clear that it is important that the extractor be as close as possible to the emitter, but it will be possible to generate enough electric field to start emission from an applied voltage below 2.5 kV even in the worst-case meniscus shape scenarios.

C. Testing Results

Testing was completed in the Sputnik vacuum chamber operating at approximately 1E-5 to 1E-6 Torr. An electrode was applied to the base of the porous substrate, connected through wetted filter paper and wiring. The extractor electrode was built as a grounded floating ball, as described in the simulation and shown in the operation diagram in Figure 5, and was used to generate the necessary voltage differential and field to begin thruster operation.

![Figure 5. Diagram of single emitter test set-up using stage controller and non-integrated ball extractor electrode.](image)

To orient the extractor with each emitter, the extractor ball was first calibrated by aligning it with NiCr crosshairs patterned on the surface of the substrate. This calibration was completed by using the
stage controller to move the extractor ball to the surface of the cross hair, with the extractor ball and cross hairs being connected through a multimeter. A DinoCam camera was placed in the chamber to allow visual confirmation of alignment between the extractor ball and the crosshairs on the thruster chip. Once a resistance was read across the multimeter, contact was determined and the location coordinates on the stage controller were marked. A simple MATLAB script was used to determine the correct stage position for the extractor above each emitter using the crosshair positions and the manufactured spacing of the emitters.

Once the alignment was completed, the DinoCam camera was removed and the chamber was pumped down. While under vacuum, the thruster was operated by increasing the emitter electrode voltage from 0V to approximately 2000 V, or until a current was read through the extractor/emitter. Following the onset of emission, the voltage was either increased linearly in the positive and negative modes until unstable emission behavior occurred, or the voltage was flipped between set positive and negative voltages to collect long-duration test data at a constant magnitude, lower, more stable voltage. Because the extractor was placed directly above the emitter, and the extractor was much larger than the emitter, nearly all of the current produced by the plume from the emitter was collected by the extractor. IV curves of a single 10 µm emitter were taken at various extractor heights, and is shown in Figure 6.

![IV Curves for 10 µm emitter with various extractor heights](image)

**Figure 6.** IV curve of a 10 µm diameter emitter fired with the extractor placed at varying heights.

As shown in Figure 6, as the extractor height increases, so does the starting voltage required for emission. As the voltage increases further from the starting voltage for that specific extractor height, it increases relatively linearly, until hitting a point at which the voltage is too high and instability begins to occur in the capillary, possibly resulting in larger droplet or mixed-regime emission as the high electric field pulls more of the propellant out of the emitter capillary more quickly. This increase happens rather quickly, and at the highest extractor distance of 125 µm the emission very quickly becomes unstable, and it is possible that a discharge is being read here rather than true emission.

Further, the starting voltage of this set-up can be compared to the simulated start-up voltage in the previous section. In this case, for the 50 µm extractor height, the starting voltage is approximately 600 V, and increases to approximately 1700 V when the extractor is 100 µm above the emitter. However, in
the simulation, the starting voltage for the 50 µm extractor height in the best case where the meniscus is convex results in a starting voltage between 1000 to 1500 V. Further, as the extractor height increases in the simulations to 75 and 100 µm, the starting voltage increases to approximately 2000 and 2500 V respectively, which is also much higher than the experimental starting voltage. In general, it appears as though the simulated starting voltage is approximately 700 V higher than the actual required starting voltage. This is likely due to small errors in the positioning of the extractor, as the stage controller could only reliably complete steps of approximately 10 µm. This would explain the difference in the starting voltage, as the simulated starting voltage for an extractor placed 40 µm above the emitter is below 1000 V, which corresponds well with the experimental starting voltage seen when the extractor was placed 50 µm above the emitter.

It is important to note that this set-up is not ideal. As shown in the imaging in Figure 7, the surface of the array became degraded over time likely due to secondary electron emission from the extractor, making the emitters quickly become non-functional after a couple of hours of operation.

Figure 7. Microscope images of a 6 µm diameter emitter (a) post-fabrication, (b) post-wetting with EMI-BF4, and (c) post-firing.

Though the emitter does not survive well using this extractor set-up, it is able to visibly properly wet, showing that the fluorene loaded into the substrate during manufacturing must have been nearly entirely if not completely removed from the glass, as fluorene is very hydrophobic and would prevent the propellant from wetting the porous glass and the capillary. It was also shown that the propellant is able to stay within the confines of the capillary relatively well.

Longer duration tests were also completed on these single emitters in order to see if a steady current could be emitted over a longer period of time. The longest test that was properly recorded on an emitter is shown in the plot in Figure 8 (b), which lasted approximately an hour, where the voltage switches between the positive and negative modes in a 60 s period at a low current.

Figure 8. Current reading and alternating voltage applied for (a) short-term 9 µm diameter emitter with +/- 1500 V applied and (b) long-term 10 µm diameter emitter with +/- 850 V applied.

Figure 8 (a) shows a shorter test done on a 9 µm emitter, displaying the current behavior as the voltage
switches from the positive to the negative mode. When it flips, a spike is seen in the current, that eventually tapers and levels out. This behavior is generally consistent with the behavior seen in other single emitter tests completed. In Figure 8 (b), a longer duration test that runs for approximately an hour is displayed. In this case, the negative mode appears to result in a slightly lower emission current than in the positive mode, and there is also a drop that occurs approximately 15 minutes into the test in the positive mode, and it is unclear as to why this occurred. However, these results display the ability for the emitters to function for relatively long periods of time while emitting a relatively consistent current. It is important to note though that even at such a low current, the emitter still became very degraded and could only operate for an hour before stopping in the best case.

IV. Conclusion

This paper presents a manufacturing process and preliminary test results for a novel electrospray thruster design. Electrospray thrusters have a large potential for their use in spacecraft applications, but are greatly disadvantaged due to their lifetime issues and difficulty in producing reliable PIR emission. These problems stem from the monolithic design of conventional electrospray thruster extractors, where the shortage at a single emitter shorts the extractor for the entire array, as well as the difficulty in manufacturing porous emitter tips consistently and uniformly for proper extractor alignment and PIR emission. By using the thruster design presented, consisting of reliable and easily reproducible capillary emitters with an integrated extractor array with fuses connecting individualized extractors, these issues can be largely resolved. This paper works to take the next step in the actualization of this design, by testing the ability of these capillary emitters to generate emission. Single capillary emitters were successfully tested using a grounded extractor ball set-up, allowing for low voltage IV curves to be collected as well as long-duration test data. Due to the extractor set-up, these emitters were not able to fire for a very long period of time as the emitter site began to degrade rapidly, possibly due to secondary electron emission from the extractor. Though this occurred, the emitters were still able to operate for a short period of time, verifying the capillary emitter design’s viability for further testing and the implementation of the final integrated extractor array. This project will require significant further research to determine the viability of an integrated extractor and its ability to isolate shortages through the use of fuses.

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References


