6th ESA Round Table on Micro & Nano Technologies

Integrated Electrospray Micropropulsion System

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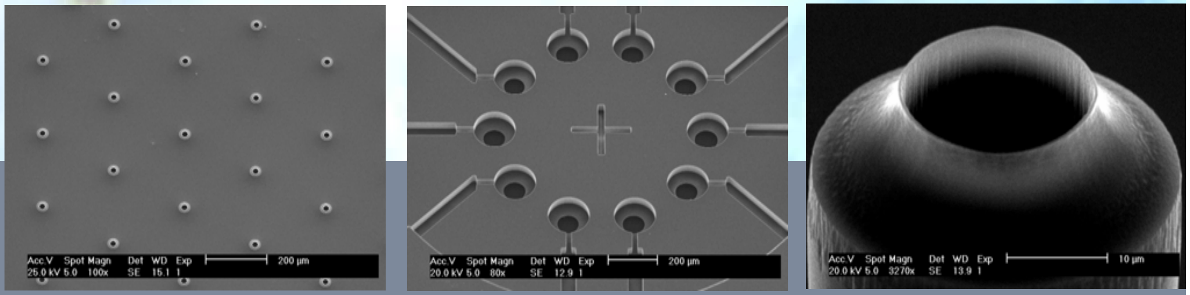


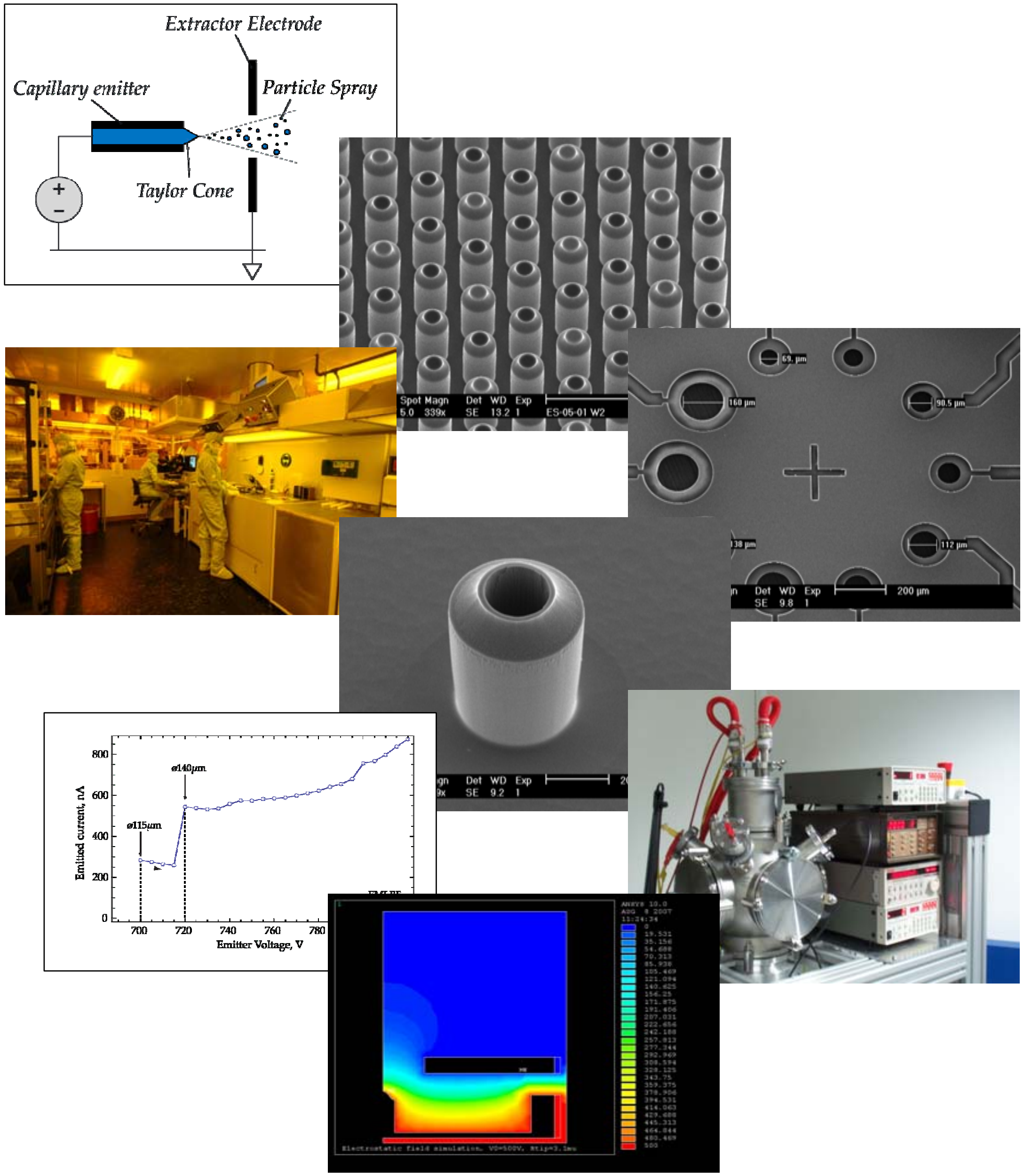
Acknowledgments

The authors would like to thank:

- ESA and Mr. José González del Amo for support (ESA ITI Type A - Contract No 20022/06/NL/PA)
- Katharine Smith & John Stark at Queen Mary, University of London, United Kingdom for very valuable inputs during the development of the thrusters
- the staff of the EPFL-CMI and the University of Neuchâtel COMLAB for their help during device fabrication.

Outline

- Introduction
- Thruster Design
- Microfabrication
- Experimental Details
- First Results
- Conclusion and outlook



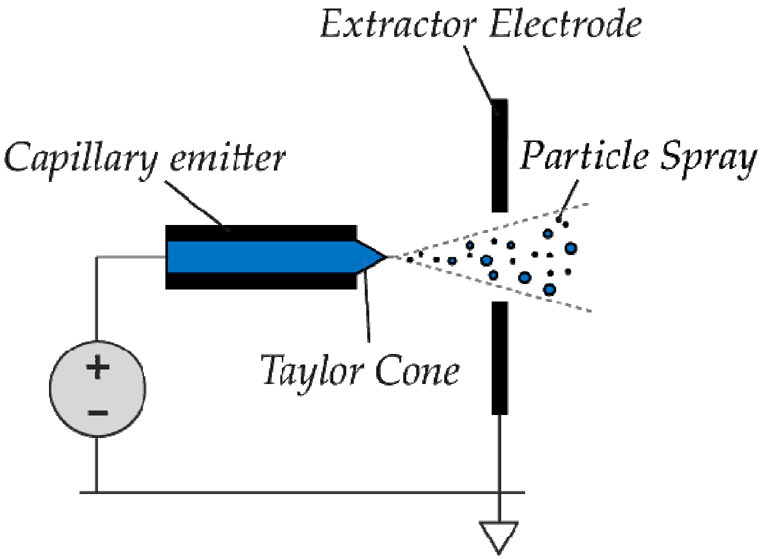
Introduction to Electrospray

Electrosprays

- **Principle of operation**: a liquid at the tip of a capillary is electrically charged to a high voltage. Above a critical threshold the liquid deforms into a cone and a spray of charged droplets or ions is accelerated towards an extractor electrode.

- Several research groups have observed transition from **ions to droplets** in sprays when using ionic liquids as fuel.

- In ionic mode a **large Isp** (> 1000s) can be reached, but thrust is low thus the **motivation of having arrays of emitters**.



$$Isp = \frac{1}{g}\sqrt{2V_a\frac{q}{m}}$$

Specific impulse

$$T = I\frac{m}{q}\sqrt{2V_a\frac{q}{m}}$$

Thrust

q	charge
m	particle mass
V_a	applied voltage
I	current
g	gravitational constant

Propulsion requirements – future ESA missions

Parameter	**Value**
Thrust	**1 μN to 1 mN**
Thrust noise	<0.1 μN / $Hz^{1/2}$
Mass	minimize
Isp	> 4000 s
Thrust resolution	< 0.1 μN
Thrust linearity	< 4 μN ± 4%
Thrust repeatability	< 0.5 μN ± 0.5%
Lifetime	> 10'000 hours
Thrust vector instability	minimize

Introduction

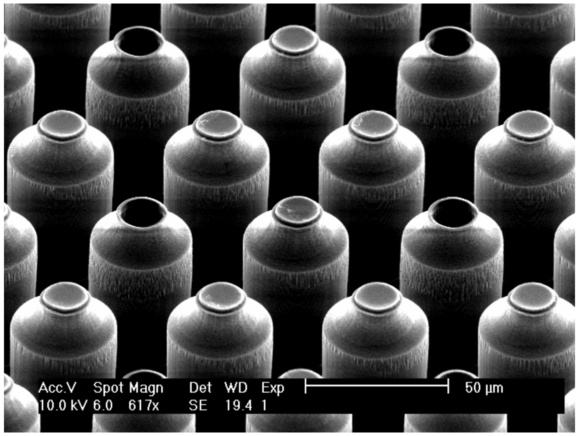
Micro-Fabrication – Advantages (1)

- **Scalability** – with MEMS technology large arrays can be microfabricated (easily covering 100 cm^2) to increase thrust
- **Redundancy**: if a few emitters in an array fail, the thruster continues to operate
- **Low voltage**: the very small spacing l (<25 μm) between ion source and extraction electrodes which, coupled with small capillary diameter d, can decrease to under 500 V the voltage required to spray from a Taylor cone.

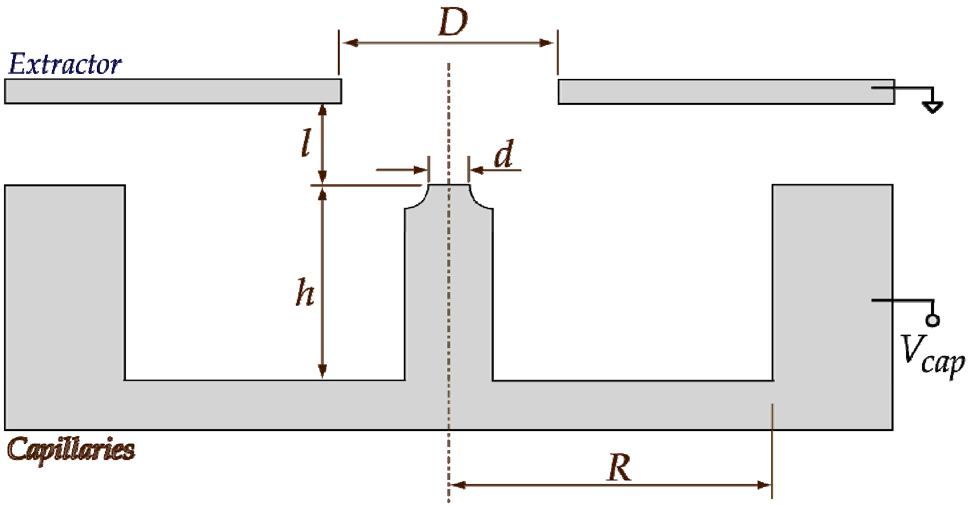
Starting voltage (approximation)

$$V_{oc} \approx \sqrt{\frac{\gamma \cdot d}{2 \cdot \varepsilon_0}} \cdot \ln\left[\frac{2l}{d}\right]$$

[Ref. Martínez-Sánchez, MIT Open Courseware]



Microfabrication test

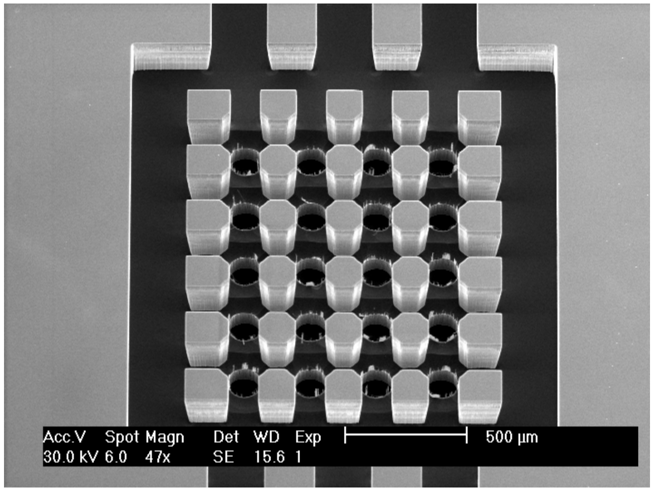


Geometry of prototype thruster

Introduction

Micro-Fabrication – Advantages (2)

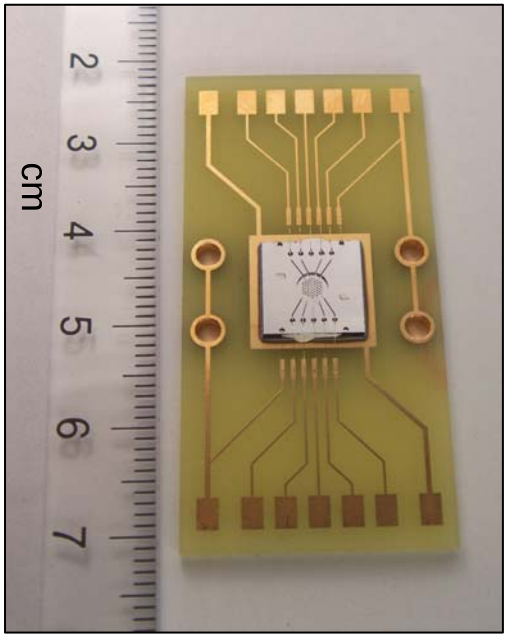
- **No moving parts**: all thrust control is done by changing voltages on extraction and acceleration electrodes.
- **Large thrust range**
  - by continuously going from ionic mode to droplet mode: can choose between high mass or high power efficiency.
  - By emitting only from selectable subset of capillaries
- Fluidic network can be **integrated** in the back of the chip: no pumping



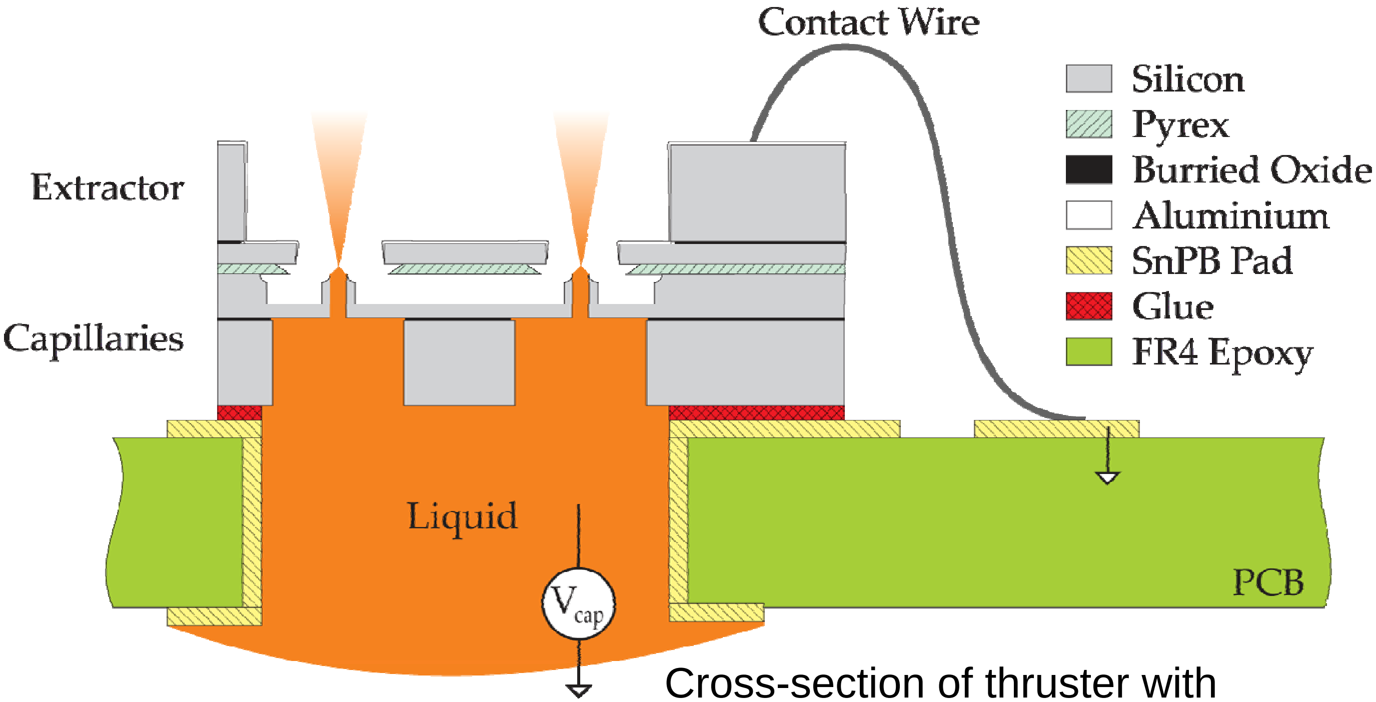
SEM image of a fluid handling system on the back of a capillary chip

Thruster Design: Overview

- Each capillary emitter has an **individual extractor** electrode. Two designs:
  - All extractors in parallel (same voltage on all)
  - Individually addressable extractor electrodes to spray from any given capillary
- For vacuum testing the microfabricated thruster is mounted on a PCB.
- **No active pumping** is necessary, wetting of structures occurs through capillarity.

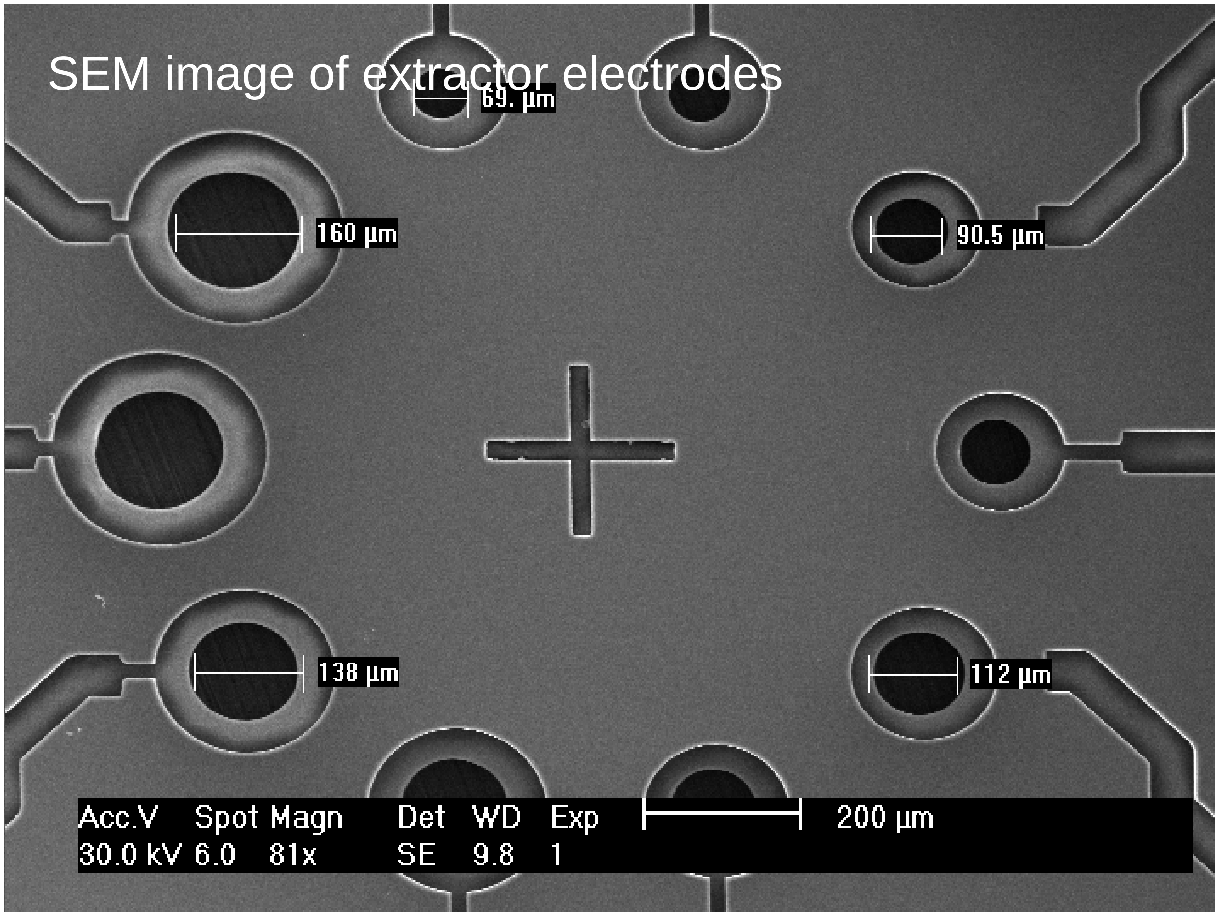


thruster assembly

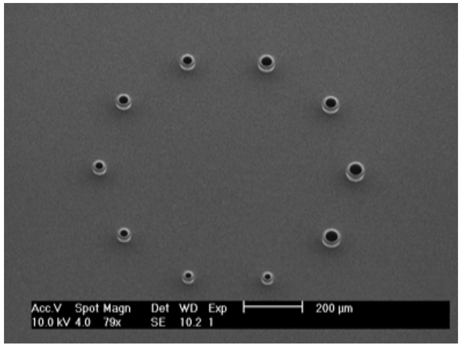


Cross-section of thruster with simultaneous emitting electrodes

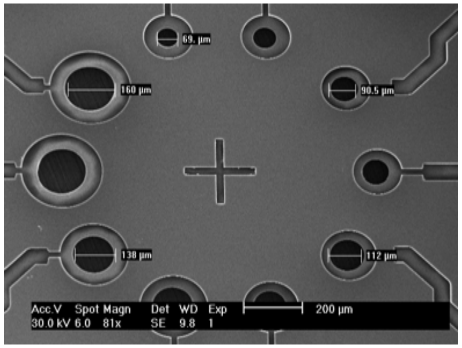
Thruster Design: Geometry and Wafer Layout


SEM image of extractor electrodes

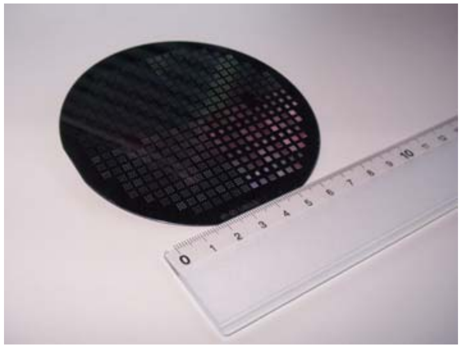
Thruster cross section with standard dimensions



Capillaries, various diameters



Extractors, various diameters

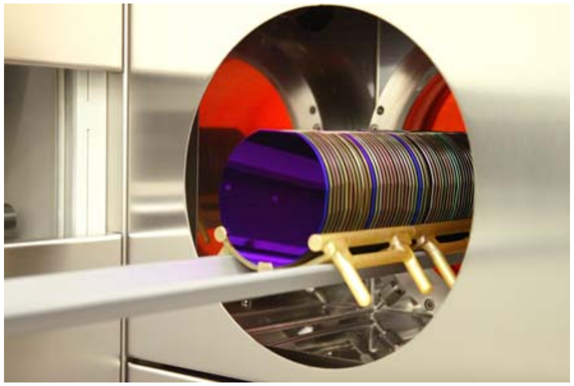


4" wafer

Microfabrication

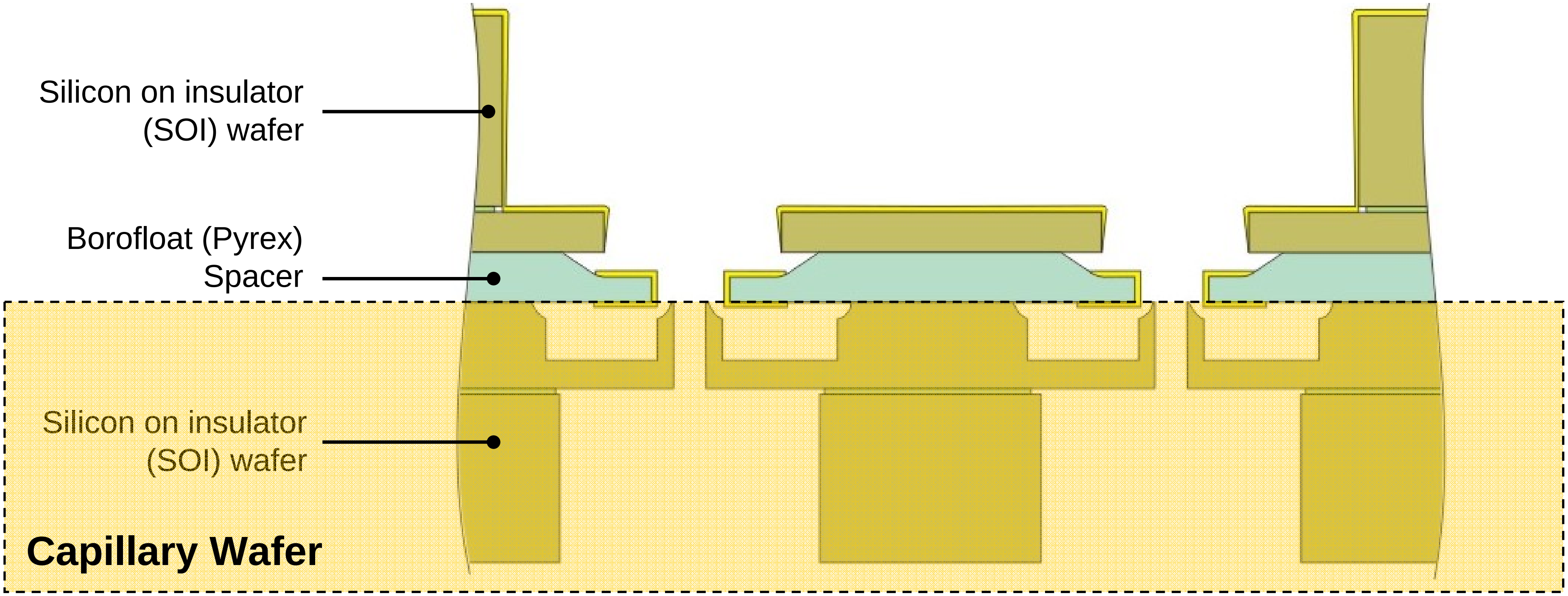
Facilities

- Access to two state-of-the-art MEMS cleanroom facilities:
  - COMLAB (Neuchâtel)
  - CMI/EPFL (Lausanne)
- For quality assurance, debugging and process development, access to the following tools is available (in Neuchâtel and Lausanne):
  - Scanning Electron Microscopes (including ESEM, EDX, BSE …)
  - Transmission electron microscope (including FIB for sample preparation)
  - Various optical microscopes for process control and thin film characterization
  - Etc.



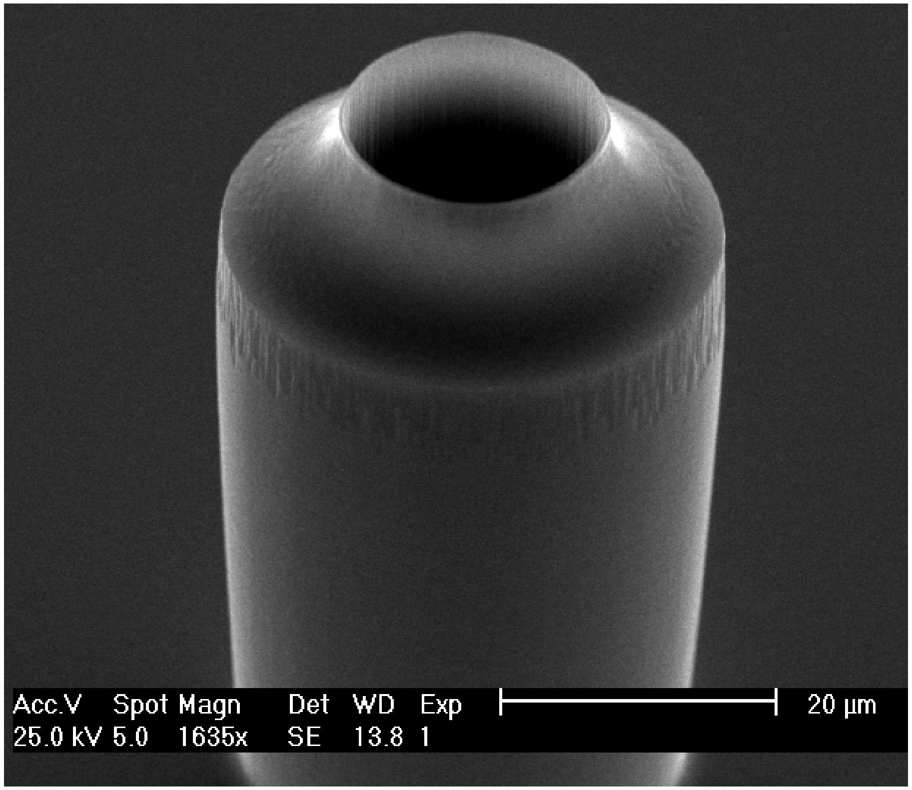
Microfabrication
Process Flow – Capillary Arrays

- Two distinct elements have been developed
  - Capillary Emitters
    (modification of a design by Griss, *et al.*, J. Micromech. Microeng.**12** (2002), pp. 682—687)
  - Extractor electrodes
- The design allows to stack further electrostatic lens components

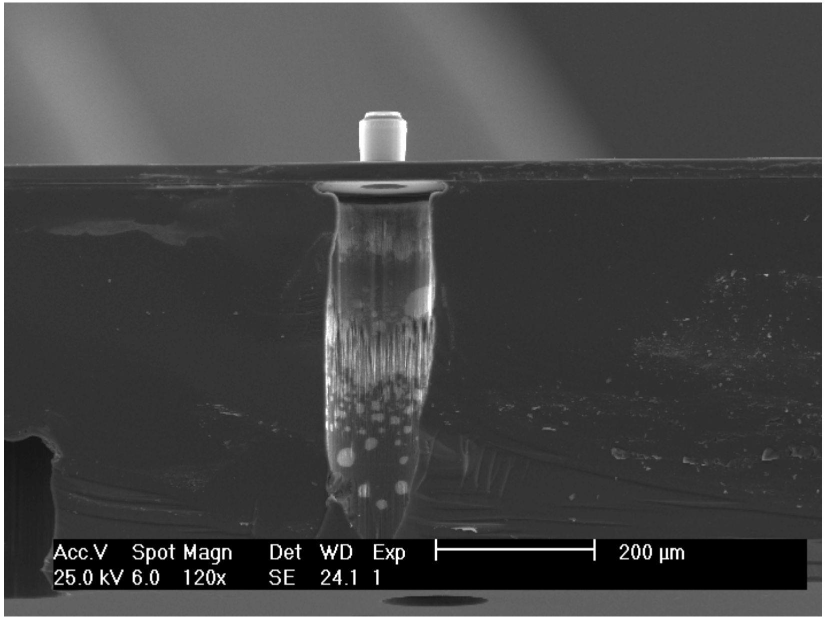


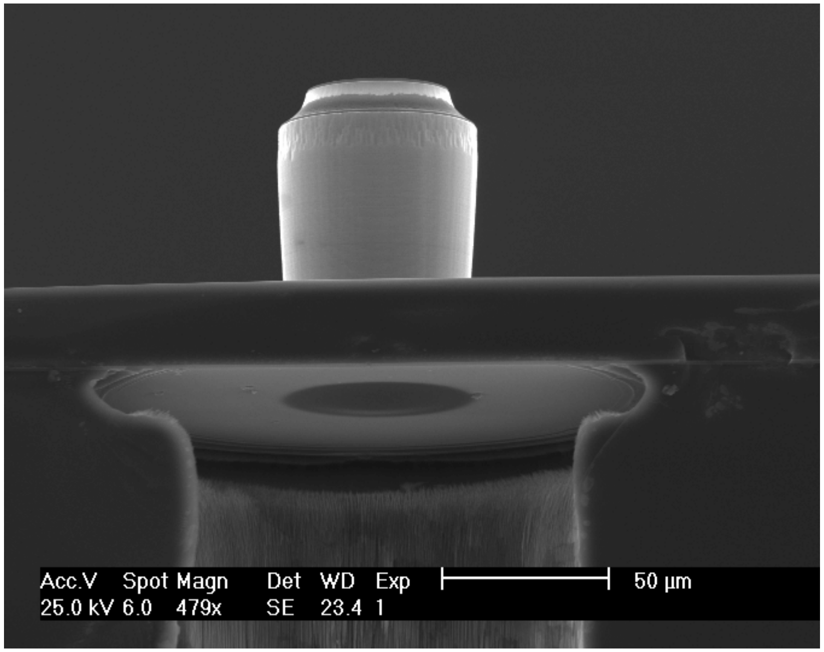
Thruster assembly **with** individually adressable extractor electrodes

Microfabrication
Capillaries



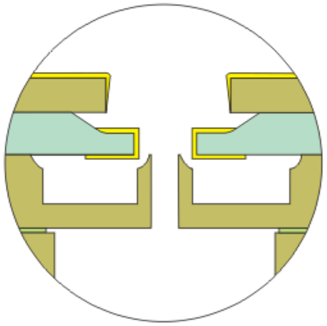
SEM images of a capillary emitter



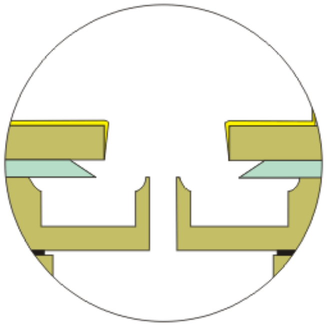


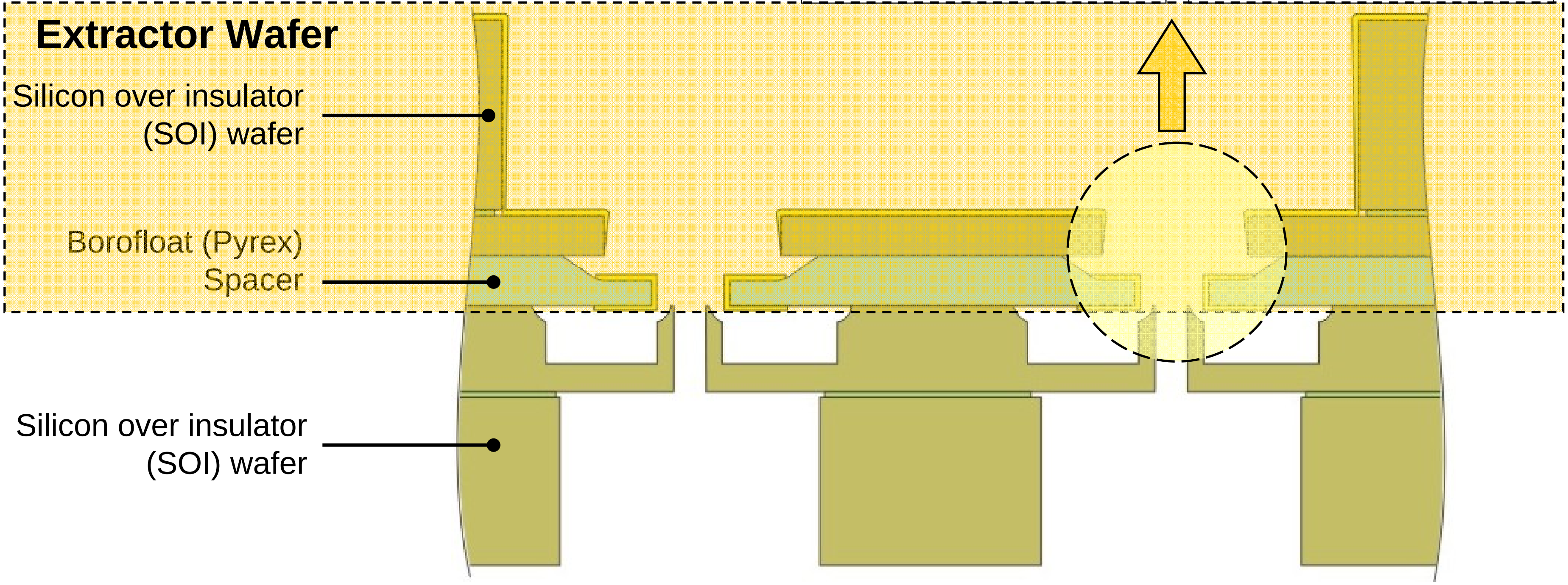
Microfabrication
Process Flow – Extractor Arrays

Design #1
Individual addressing



Design #2
Simult. addressing





Extractor Wafer

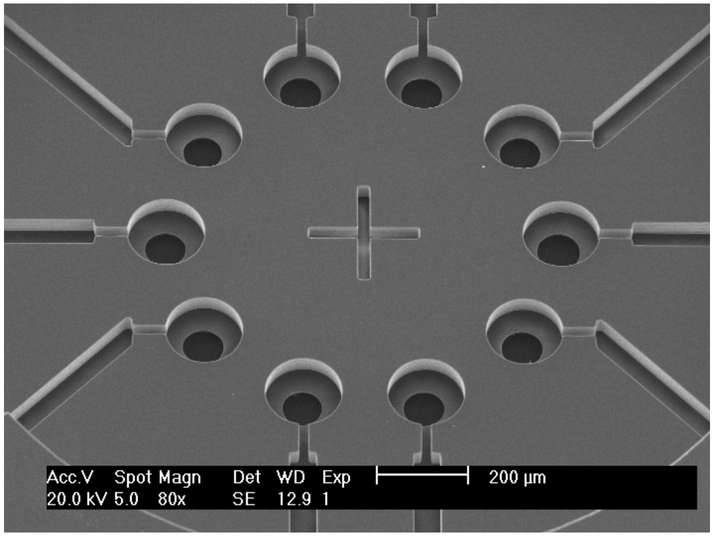
Silicon over insulator (SOI) wafer

Borofloat (Pyrex) Spacer

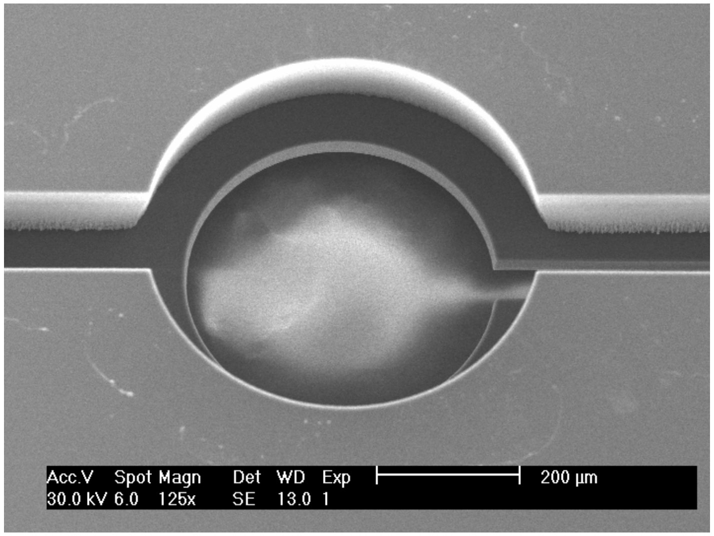
Silicon over insulator (SOI) wafer

Fig. Thruster assembly **with** individually adressable extractor electrodes

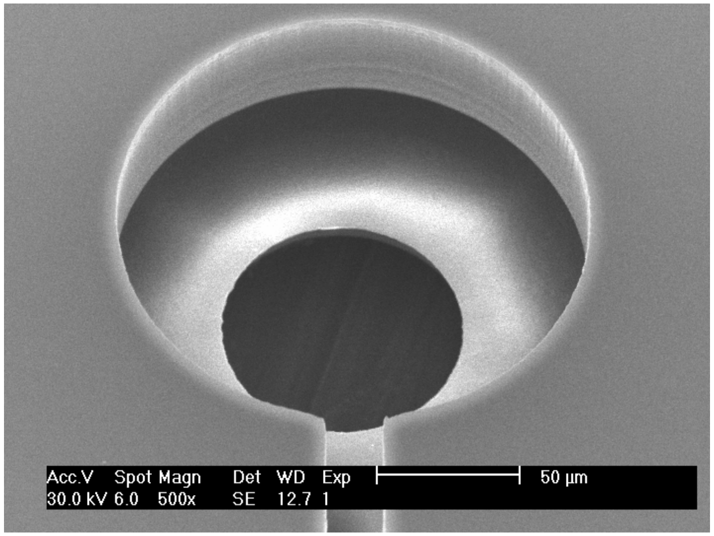
Microfabrication
Extractor



SEM image of extractor electrode array



SEM image of wirebonding pad



SEM image of extractor electrode

Microfabrication
Assembly

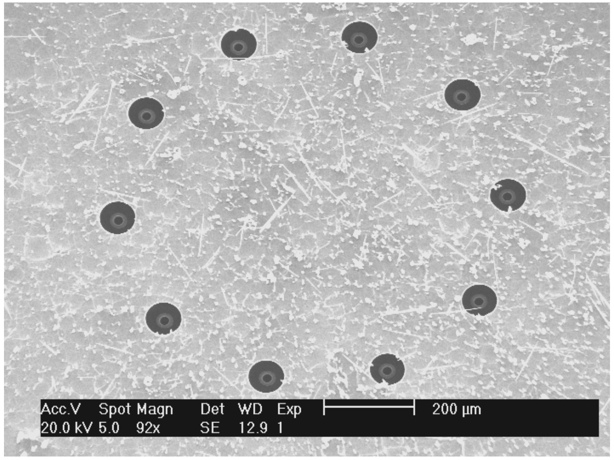


Fig. Assembled thruster with simultaneous addressable electrodes

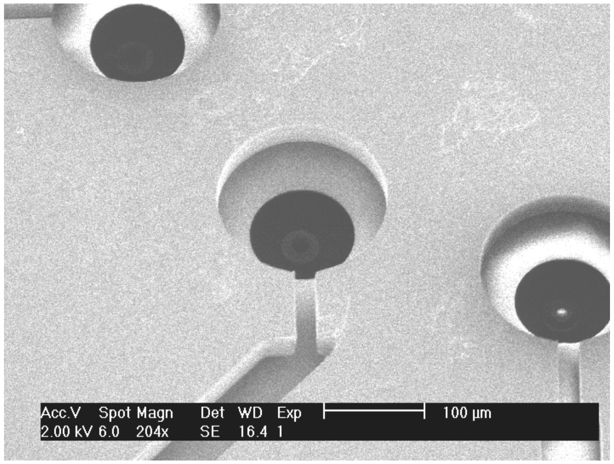


Fig. Assembled thruster with individually addressable electrodes

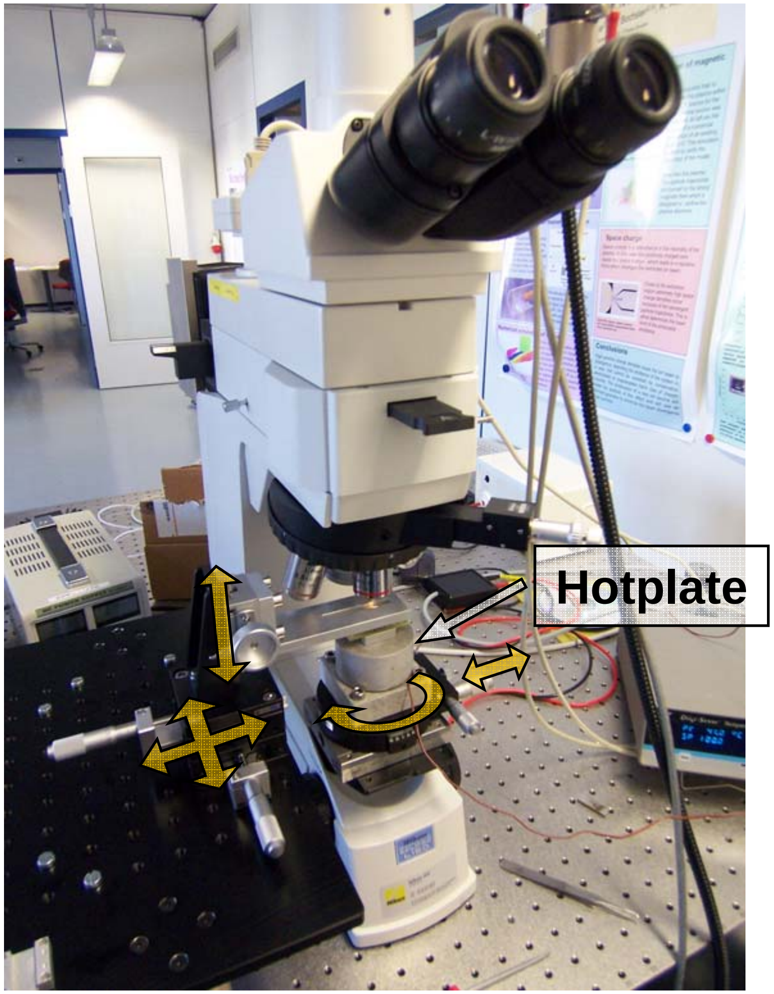
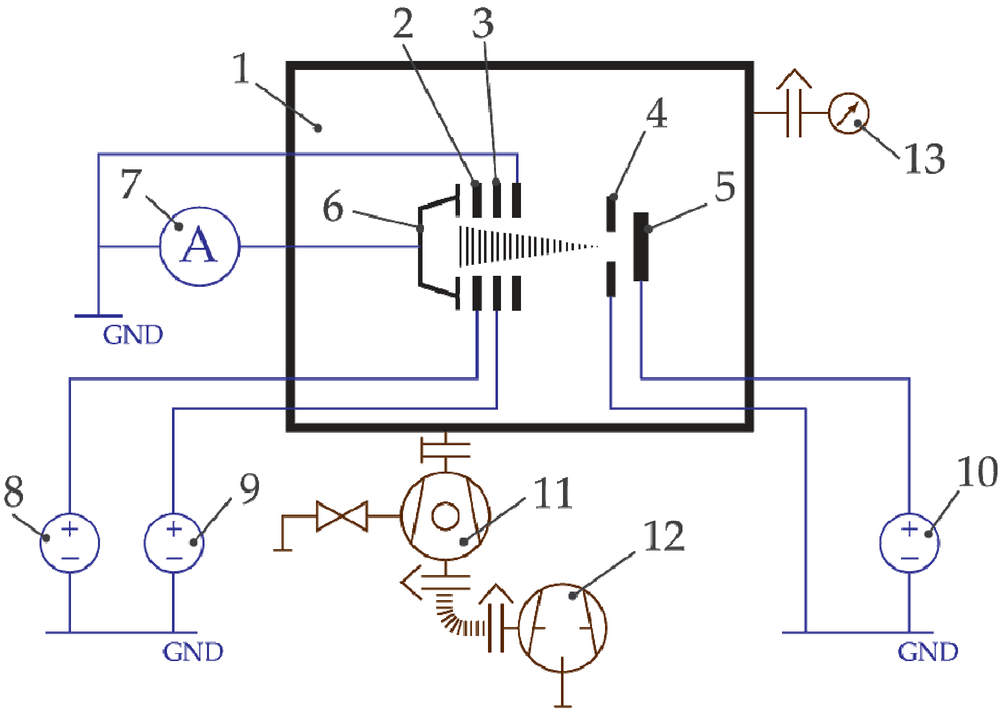


Fig. Setup to assemble individual chips below a microscope

Beam current & energy measurements
Test bench – Overview



Schematic layout of test setup

1	Vacuum chamber
2	Supression Grid
3	Retarding grid
4	Extractor electrode (on chip)
5	Capillary emitter (on chip)
6	Faraday cup
7	Picoammeter
8	Voltage source (supression grid)
9	Voltage source (retarding grid)
10	Voltage source (emitter)
11	Turbomolecular vacuum pump
12	Roughing pump
13	Pressure gauge

Beam current & energy measurements

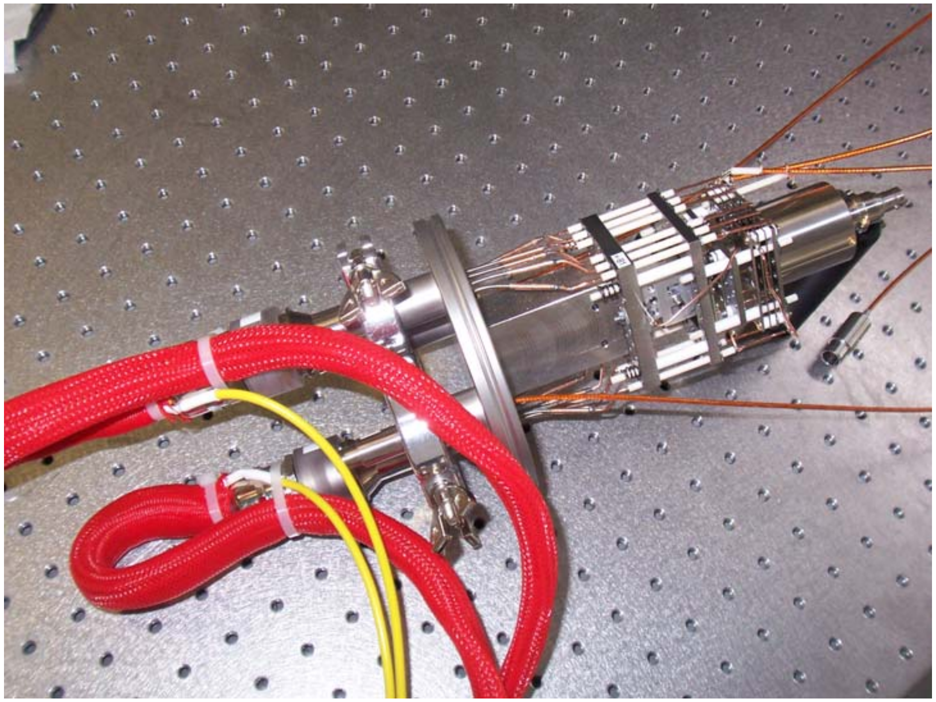
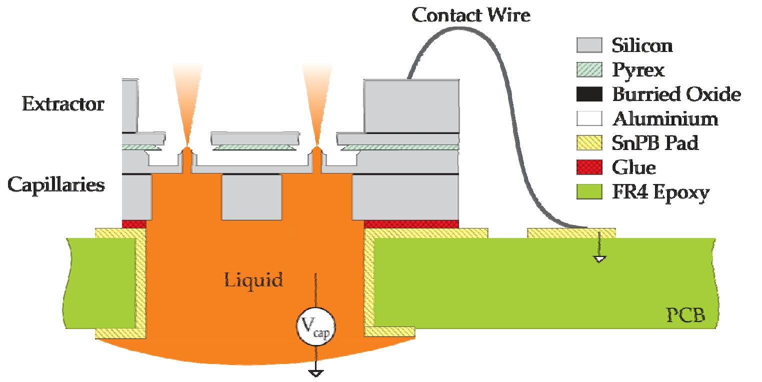


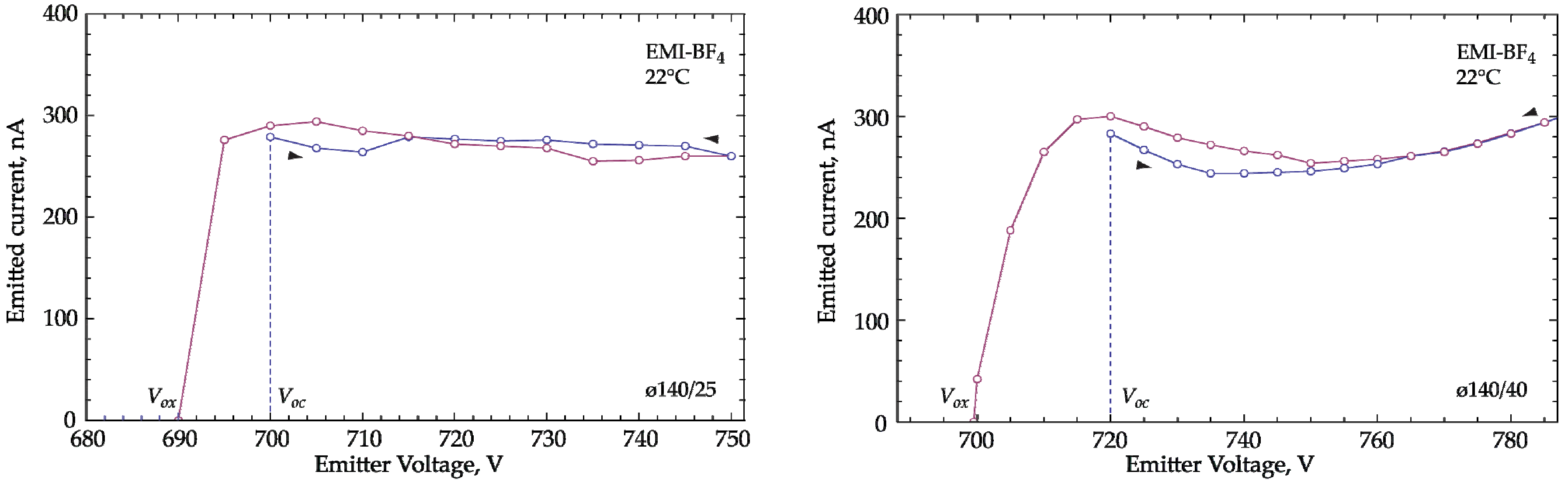
Fig. Ion gun with mounted Faraday cup

Fig. Electrospray test-rig at EPFL-LMTS

Current – voltage characteristics
Effects of capillary tip to extractor distance

- Current-voltage measurements for a single capillary.



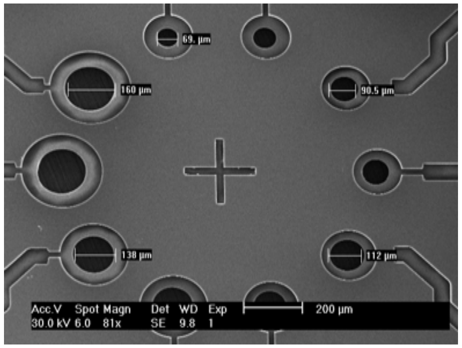


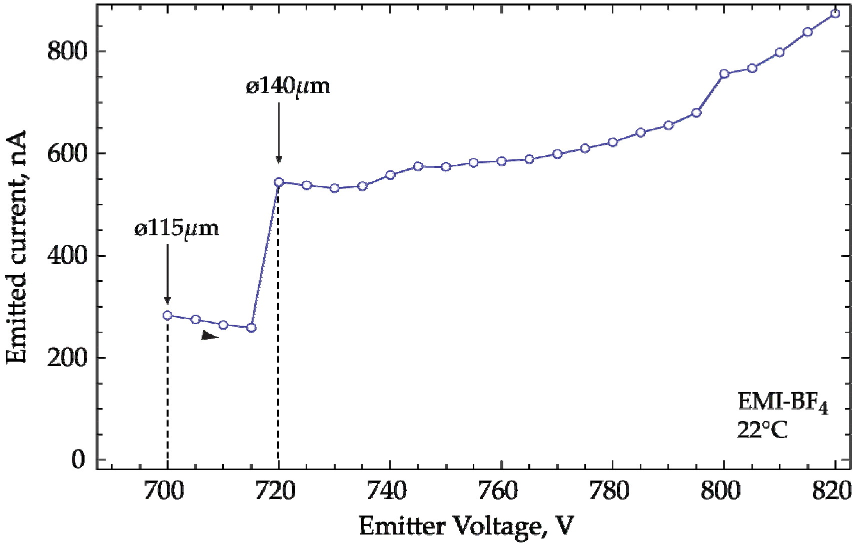
(a) (b)

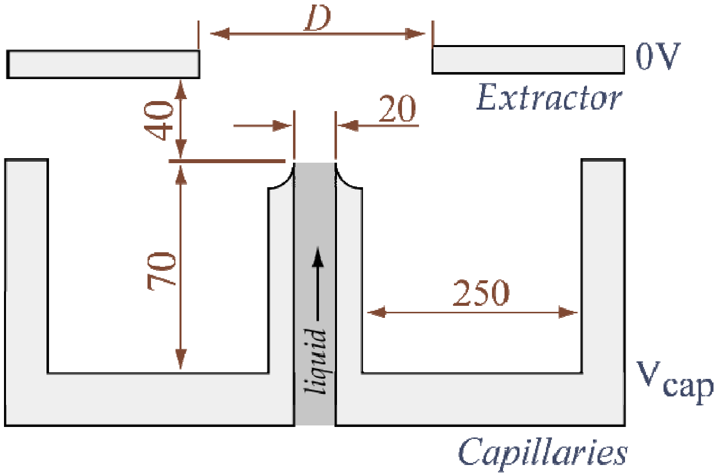
Current-voltage curve for a capillary with a 20μm i.d. and 140μm diameter electrodes spaced at (a) 25μm and (b) 40μm from the emitter

Current – voltage characteristics
Extractor diameter variation

- Thrust modulation can be achieved by varying the extractor diameter



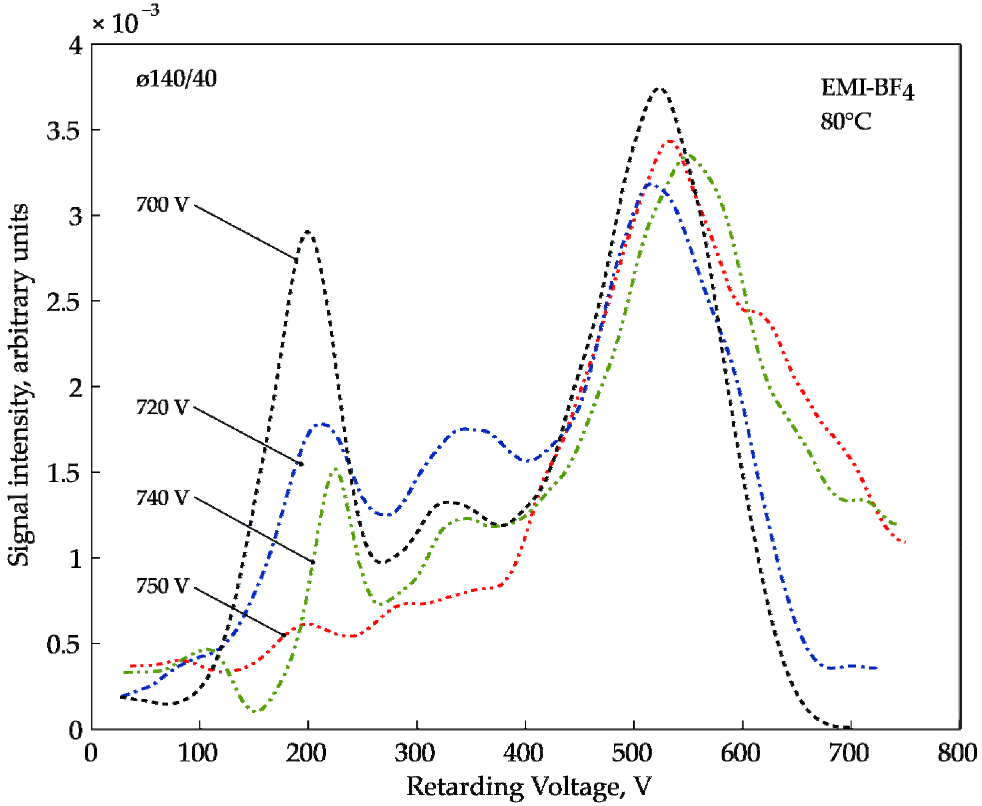




Current-voltage curve for a capillary with a 20µm i.d. capillary and an electrode spaced 40µm from the emitter. Two capillaries with different extractor diameters are tested together.

Retarding potential

- The large energy distribution indicates most likely the presence of a jet and therefore the existence of droplets in the beam.

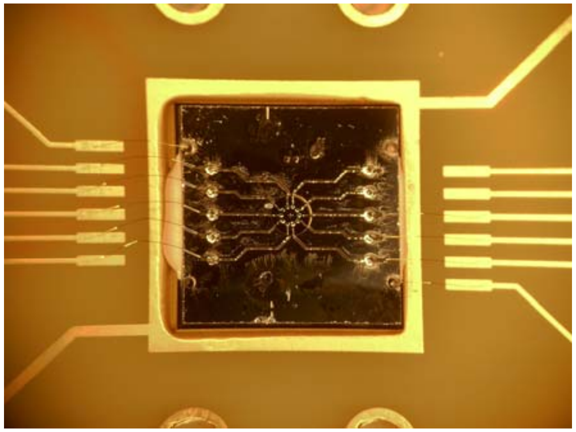


Need to do mass spectrometry to determine different operation modes and hence thrust

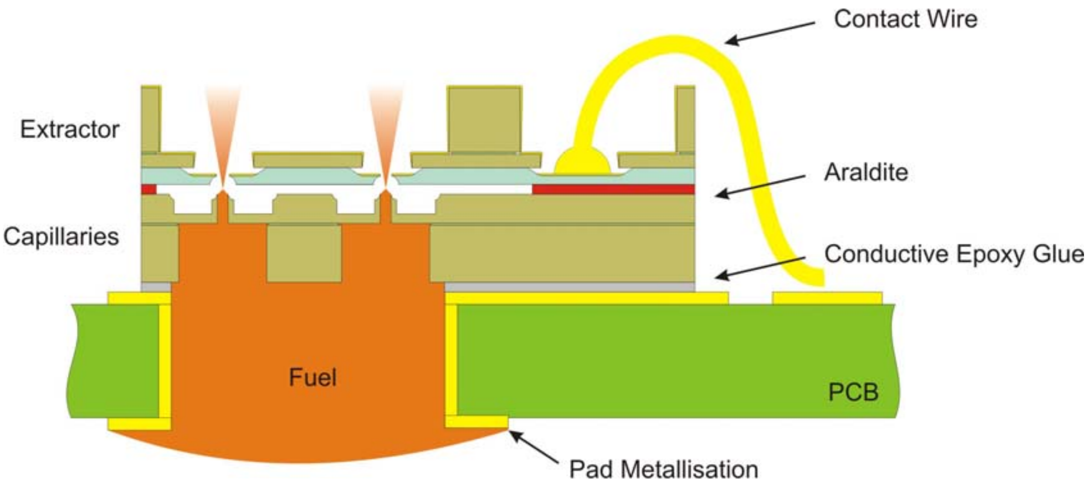
Fig. Retarding potential measurement of a capillary with 140μm extractor electrode at 40μm from the emitter. Measurements were taken for different operation voltages.

Individually addressable chips

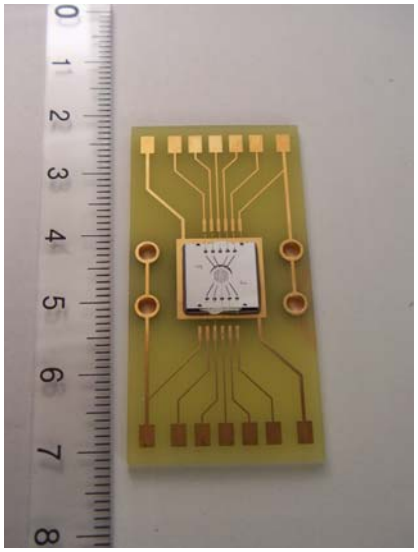
- Stable spraying observed for a few minutes before flooding of the chip.
- Observed current of 150nA for a single emitter at 570V.
- New batch of chips in fabrication to solve identified issues



Detail of assembled thruster



Cross section of a the thruster with individually addressable extractor electrodes



Assembled thruster with PCB support

Technology Readiness Level

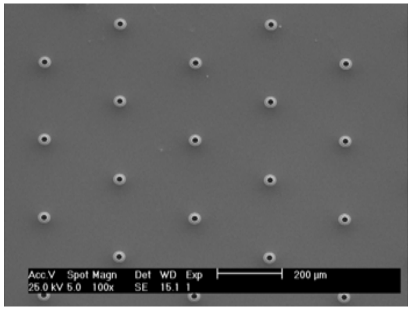
- Current development status is TRL2

Technology Readiness Levels Summary	
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
9	Actual system “flight proven” through successful mission operations

Conclusions

- The microfabrication process for a small integrated MEMS electrospray thruster has been validated
- Thruster operation has been demonstrated for small arrays, including a new way to obtain thrust modulation.
- A FEM based model to predict the starting voltage of the emission shows a good correlation with the obtained results
- Thruster lifetime remains an unexplored issue. Design improvements such as microchannels at the capillary inlet and chip heating are expected to lead to repeatable capillary filing and spraying.
- We are continuing to develop the thruster in collaboration with partners, and are looking for opportunities to test on nanosatellites

Questions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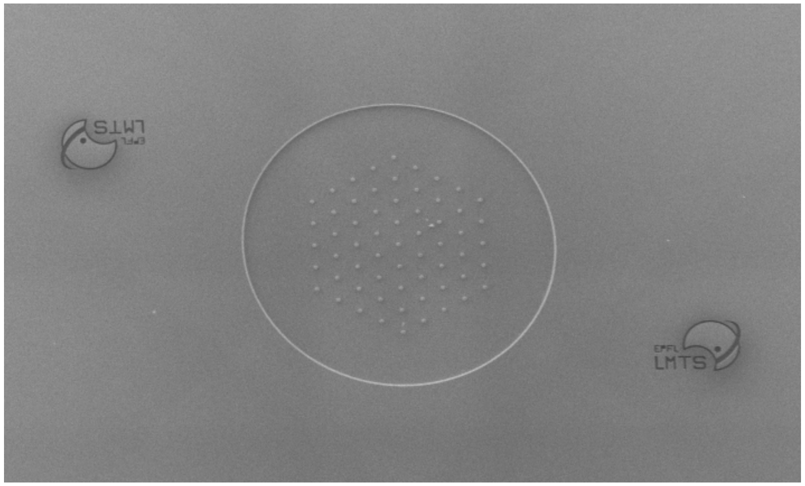
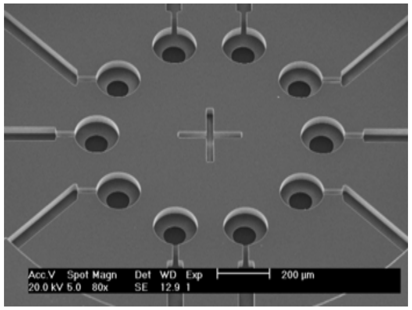
25.0 kV 5.0 100x SE 15.1 1


EPFL LMTS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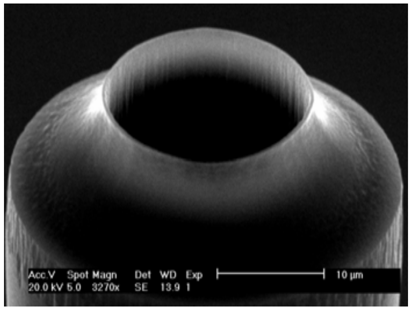
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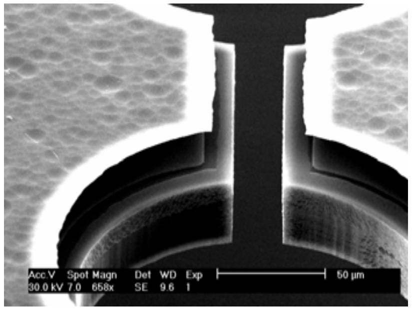
20.0 kV 5.0 3270x SE 13.9 1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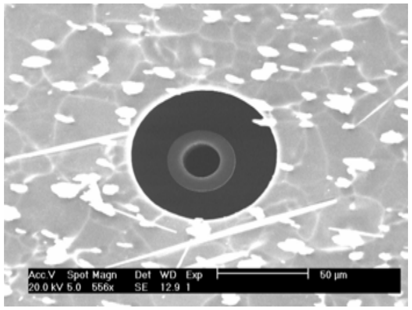
30.0 kV 7.0 658x SE 9.6 1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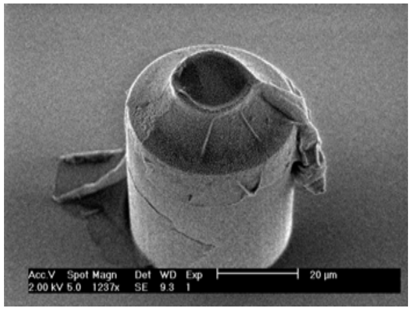
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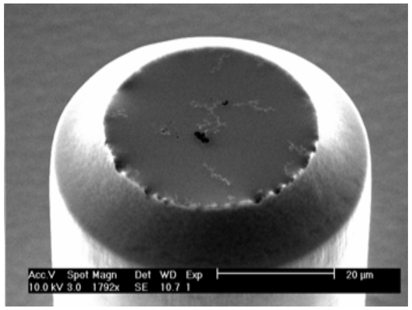
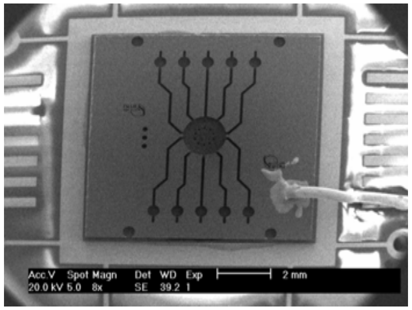

Acc.V Spot Magn Det WD Exp 20 µm
10.0 kV 3.0 1792x SE 10.7 1


Acc.V Spot Magn Det WD Exp 2 mm
20.0 kV 5.0 8x SE 39.2 1

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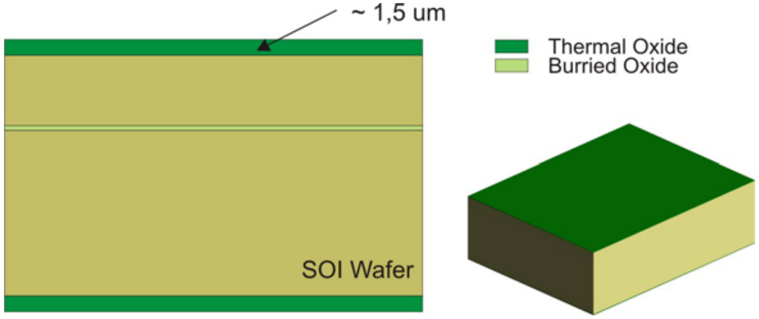
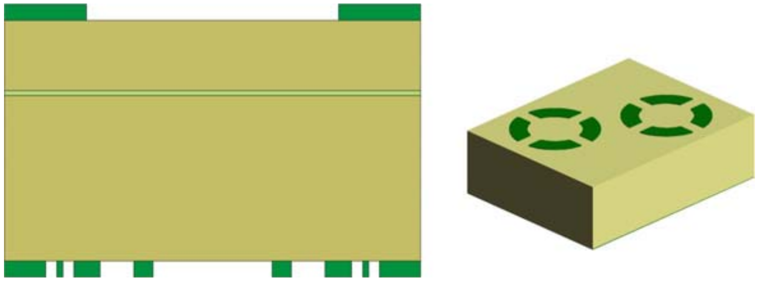
Microfabrication
Capillary Wafer – Process flow (1)

Start with an Silicon-on-Insulator wafer

A thermal oxide layer for standoff structures is grown

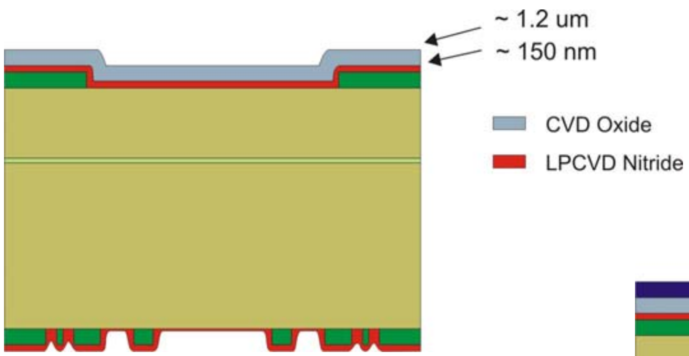


Pattern oxide

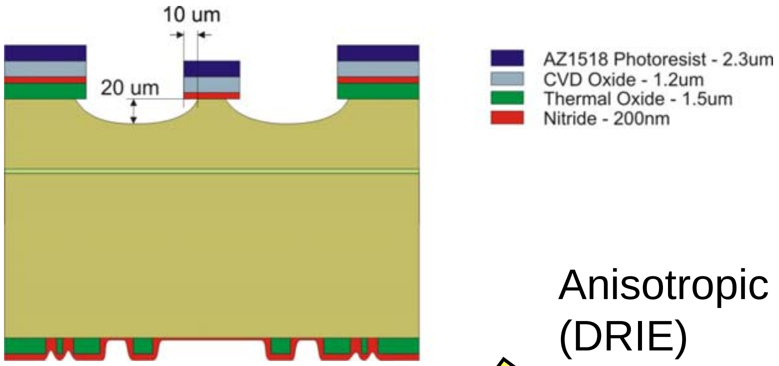


Microfabrication
Capillary Wafer – Process flow (2)

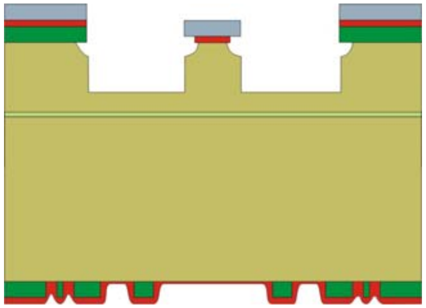
Deposit LPCVD Nitride and CVD Oxide



Isotropic plasma etch



Anisotropic plasma etch (DRIE)



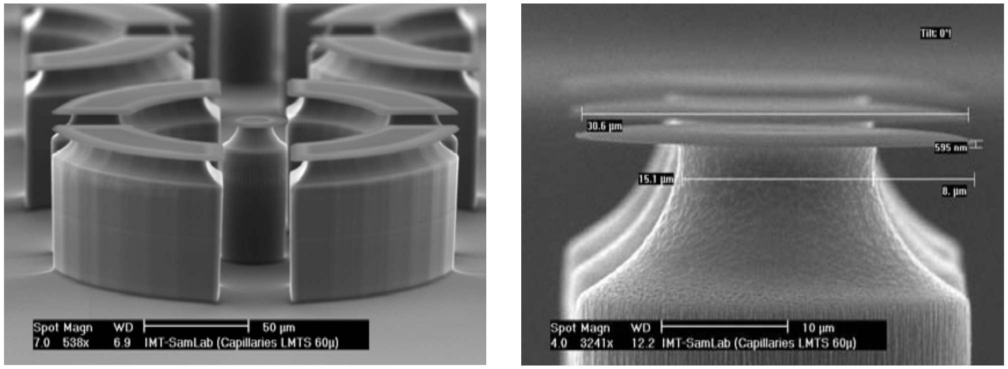
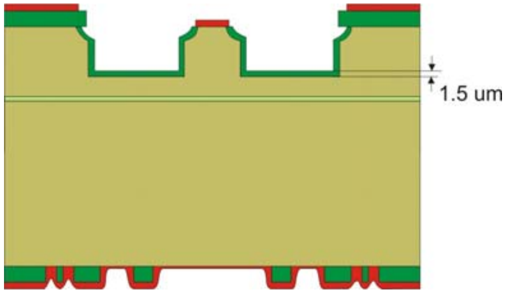
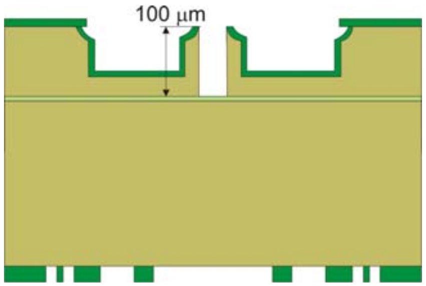


Fig. SEM images of capillaries after isotropic/anisotropic etching

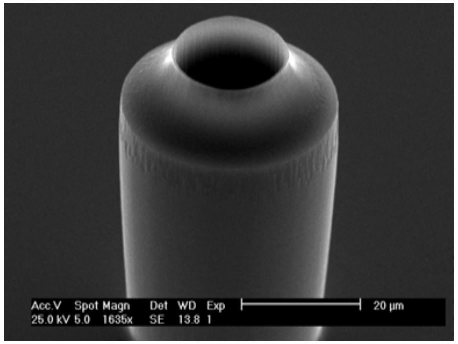
Microfabrication
Capillary Wafer – Process flow (3)



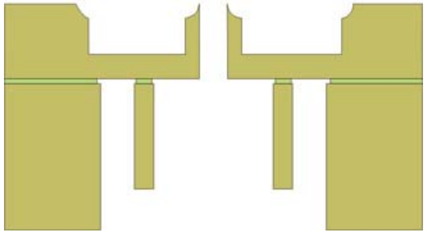
Oxide growth, no oxide will be formed where the silicon is protected by a nitride layer (red)



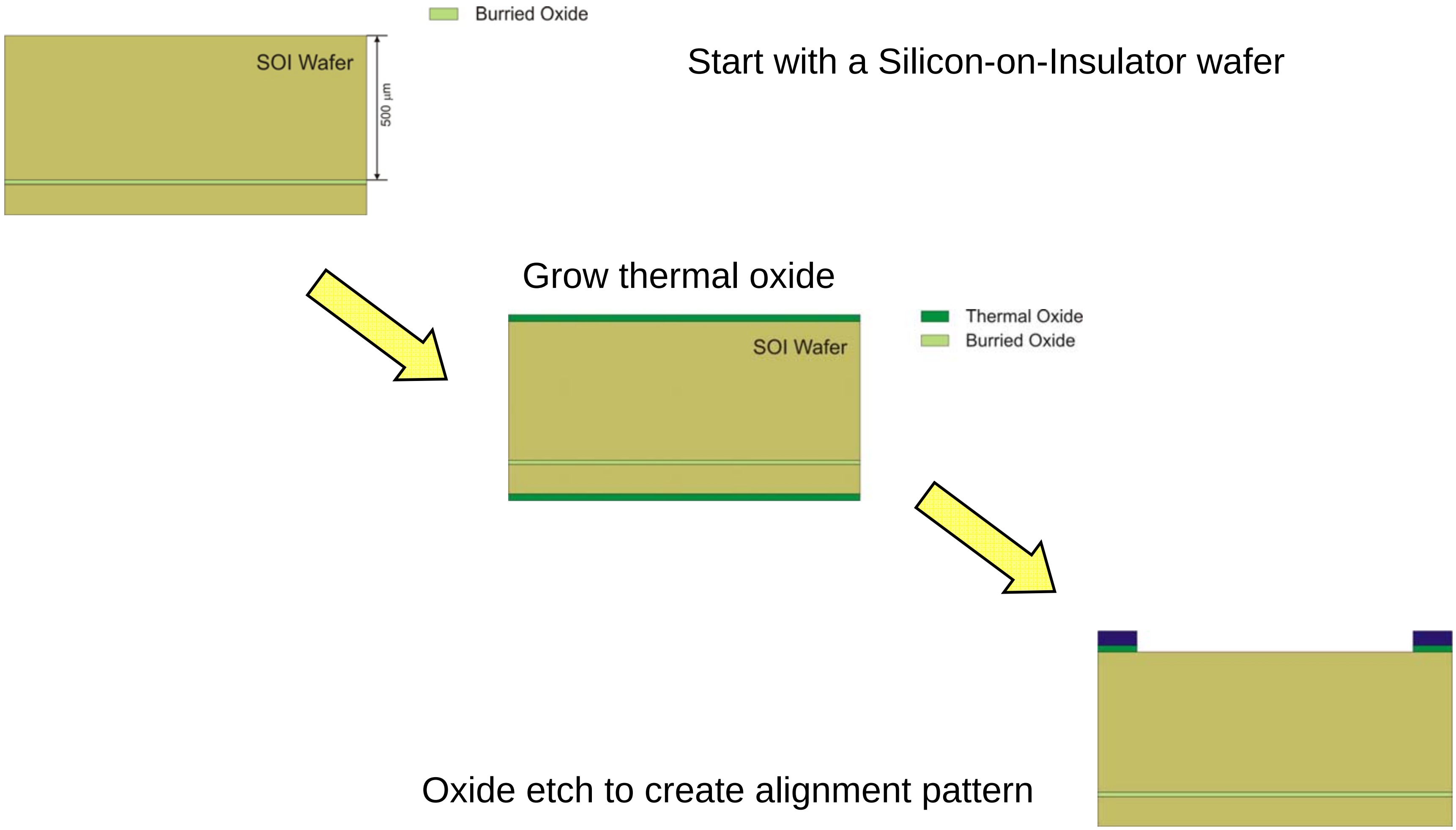
Remove nitride, perform anisotropic plasma etch (DRIE).



Etch backside (DRIE) and remove oxide by HF vapor etching



Microfabrication
Extractor – Process Flow (1)

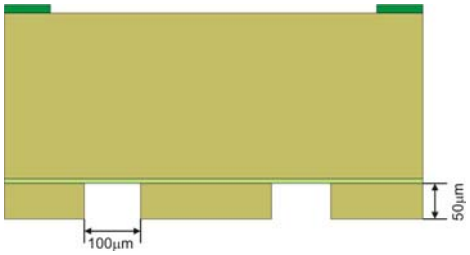


Start with a Silicon-on-Insulator wafer

Grow thermal oxide

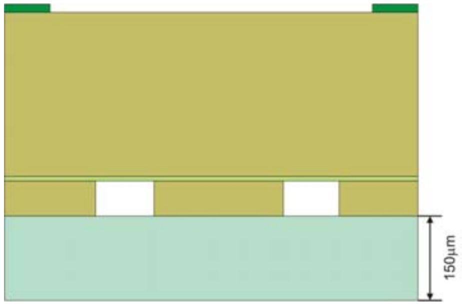
Oxide etch to create alignment pattern

Microfabrication
Extractor – Process Flow (2)



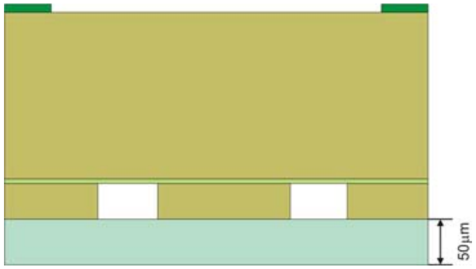
DRIE of shadow mask pattern

Anodic bonding of Borofloat (Pyrex) wafer

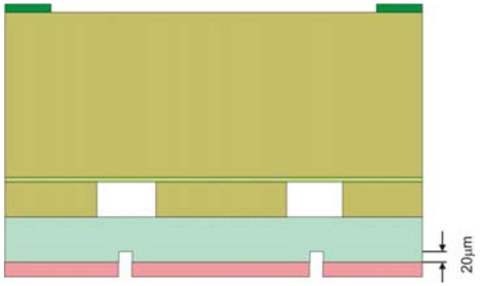


- 🟩 Burried Oxide
- 🟩 Borofloat
- 🟩 Thermal Oxide

Thinning of Borofloat

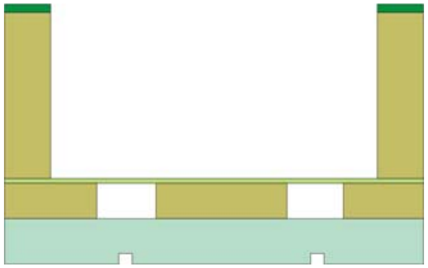


Microfabrication
Extractor – Process Flow (3)



Amorphous silicon deposition, patterning and Pyrex etch **(only executed for individually addressable Electrodes)**

Etch handle layer (DRIE)



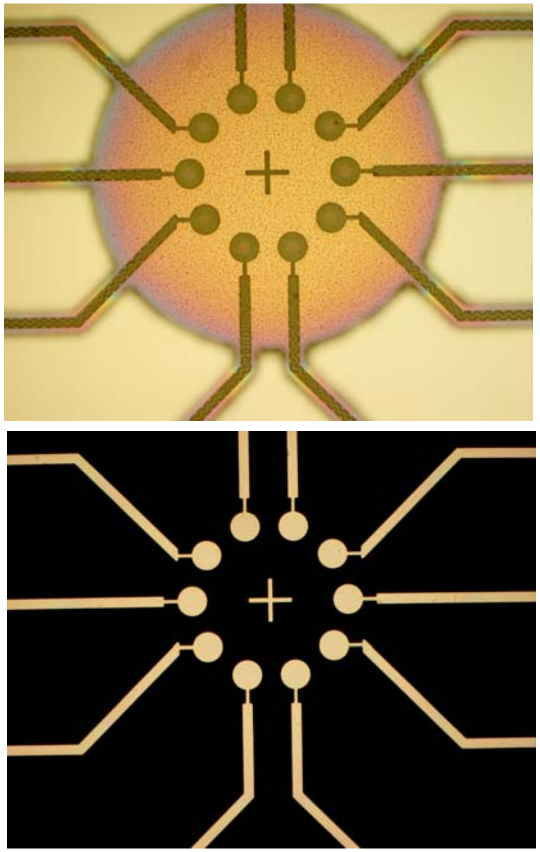


Fig. Image of extractor electrode array

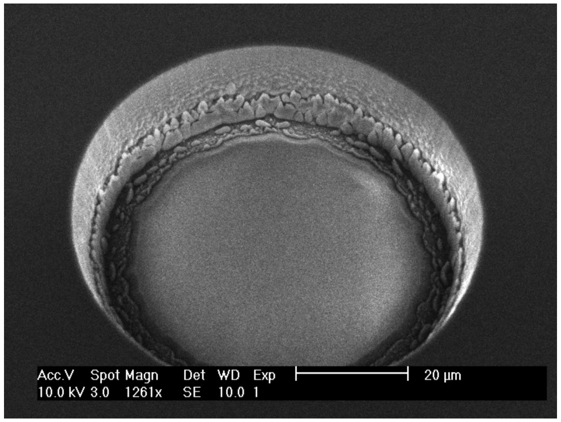
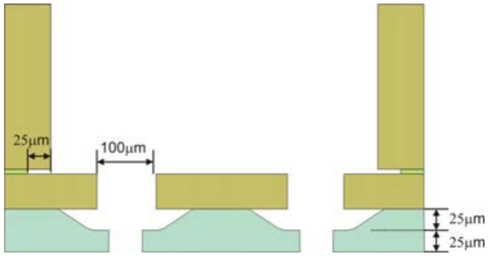


Fig. SEM image of etched Borofloat

HF 20% Pyrex wet etch



Discussion
Starting Voltage - Modelling

- Equilibrium between surface tension and electrical stress

$$\frac{1}{2}\varepsilon_0 E_a(V)^2 = \frac{2\gamma}{r_a}$$

r_a – Radius of the cone apex
γ – Surface Tension
E_a – Electric Field at the apex
V – Voltage
ε_0 – Permittivity of free space

- Linear relation assumed between electric field and applied voltage

$$E_a = \alpha \times V$$

α – Proportionality factor

- Solving for the voltage yields

$$V_{oc} = \frac{1}{\alpha}\sqrt{\frac{4\gamma}{\epsilon_0 r_a}}$$

- The proportionality factor, α, can be determined by FEM analysis

Discussion
Starting Voltage - Correlation

- The proportionality factor, α, was determined for different apex radii
- Conic section on top of capillary modeled using a rational quadratic parametric equation.
- Results for a 20μm capillary with 140μm diameter extractor, spaced at 40μm from the capillary shown in table below (measured value 720V)

Tip radius, nm	Critical Voltage, V	α – factor, m^{-1}
0.6	745	7.56×10^6
2.8	749	3.56×10^6
12.7	751	1.67×10^6
56.8	748	0.79×10^6
254.5	743	0.39×10^6
1140.6	747	0.18×10^6

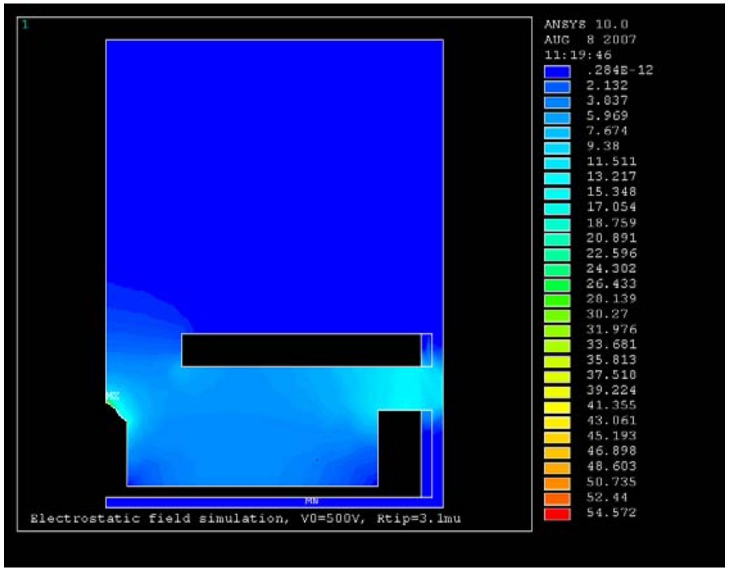


Fig. Example plot of the electric field

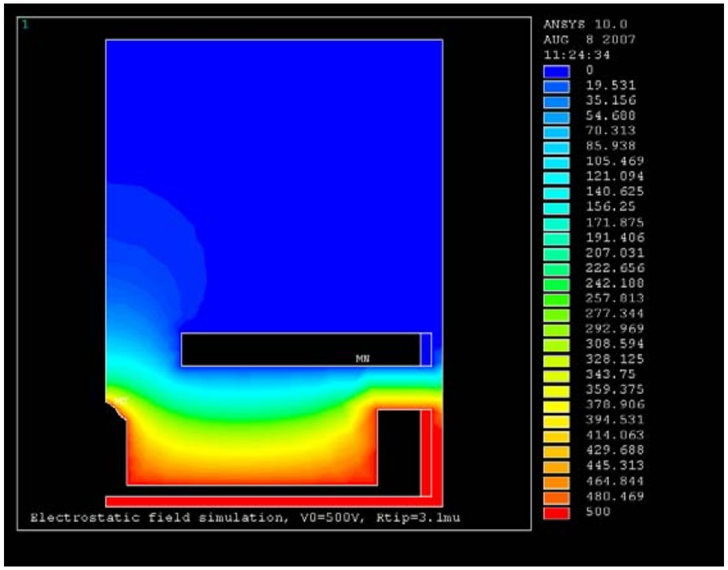


Fig. Example plot of the voltage distribution