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University
of Science
and Technology

VACUUM-SEALED ELECTRON BEAM MICROCOLUMN FOR HIGH VACUUM MEMS DEVICES

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OUTLINE

1. Electron beam microcolumns – state-of-the-art
2. MEMS high vacuum micropump
3. MEMS electron beam microcolumn and its application
   A. MEMS scanning electron microscope
   B. MEMS point X-ray source
   C. MEMS electron source
   D. MEMS free electron laser
4. Summary

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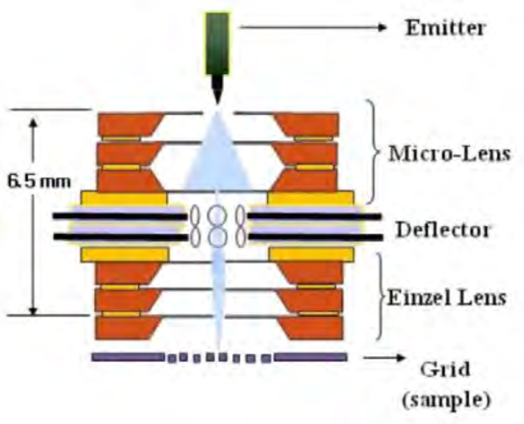
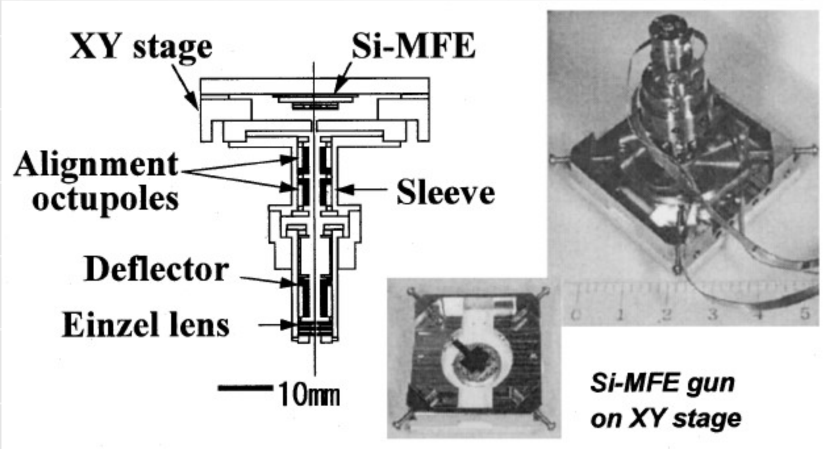
State-of-the-art

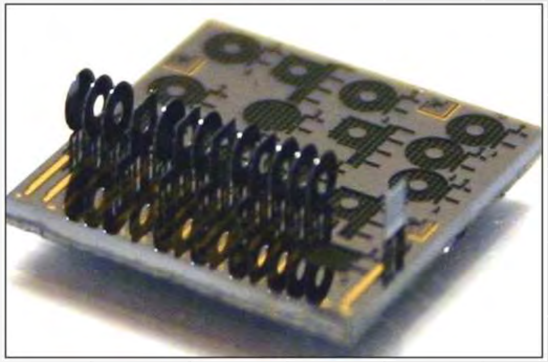
ELECTRON BEAM MICROCOLUMNS



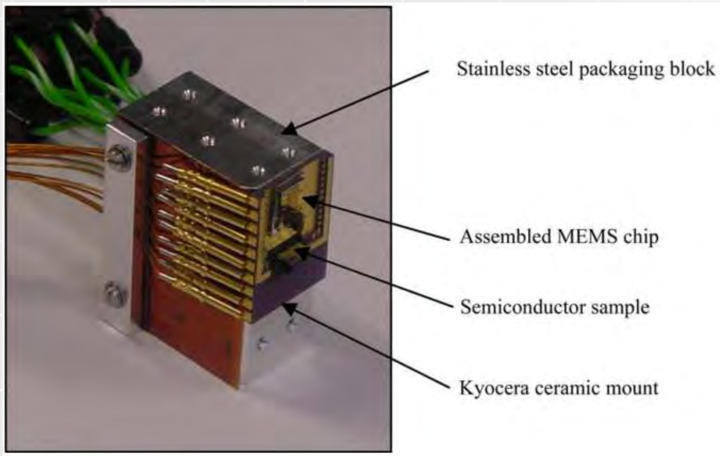
H. S. Kim et al., *The assembly of a fully functional microcolumn and its STEM-Mode operation*, Journal of the Korean Physical Society 43, 5 (2003) 831-835.



I. Honjo et al., *Miniature electron beam column with a silicon micro field emitter*, J. Vac. Sci. Technol. B 15 (1997) 2742-2748.



R. Saini, et al., Manufacturable MEMS miniSEMs, Microelectronic Engineering 83 (2006) 1376–1381



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State-of-the-art

ELECTRON BEAM MICROCOLUMNS

Fabrication methods:

- Precision mechanics
- Microelectronics and microengineering
- MEMS

Applications:

- X-ray sources
- Ion sources
- Lithography tools
- Imaging methods (SEM)

Parameters:

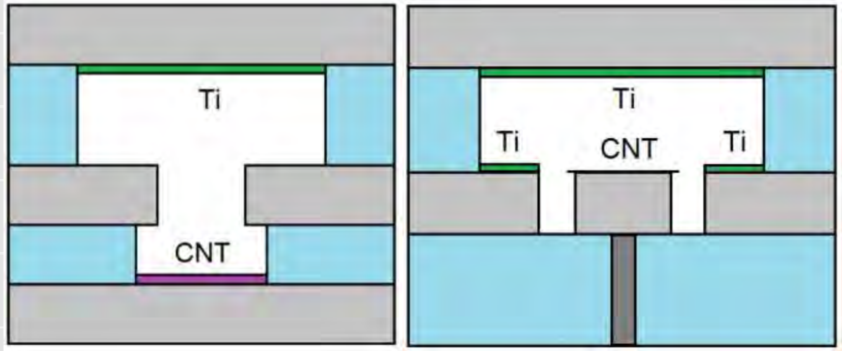
- Resolution <50 nm
- High and stable electron beam
- High precision electron beam scanning

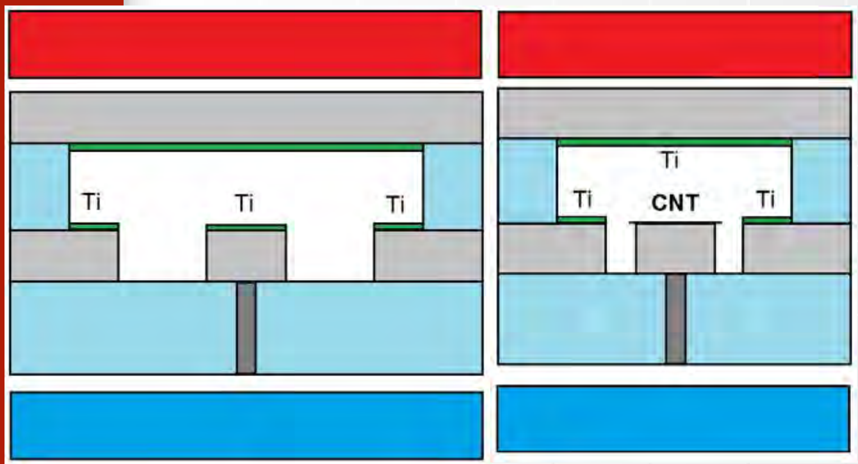
NO PUMPING SYSTEM DEVELOPED

MEMS high vacuum micropump

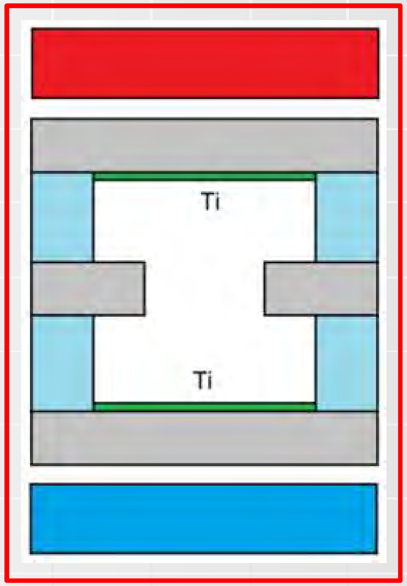
Silicon-glass, anodically bonded ion-sorption vacuum micropumps:

- Gas ionization (electron beam, gas discharge)
- Absorption of ionized particles on getter layer
- Full compatibility and vacuum tightness

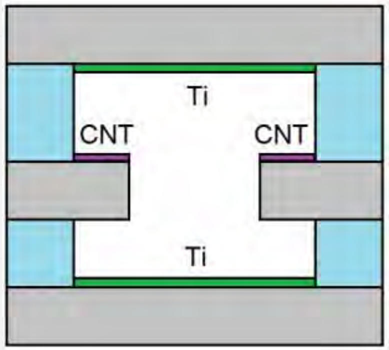




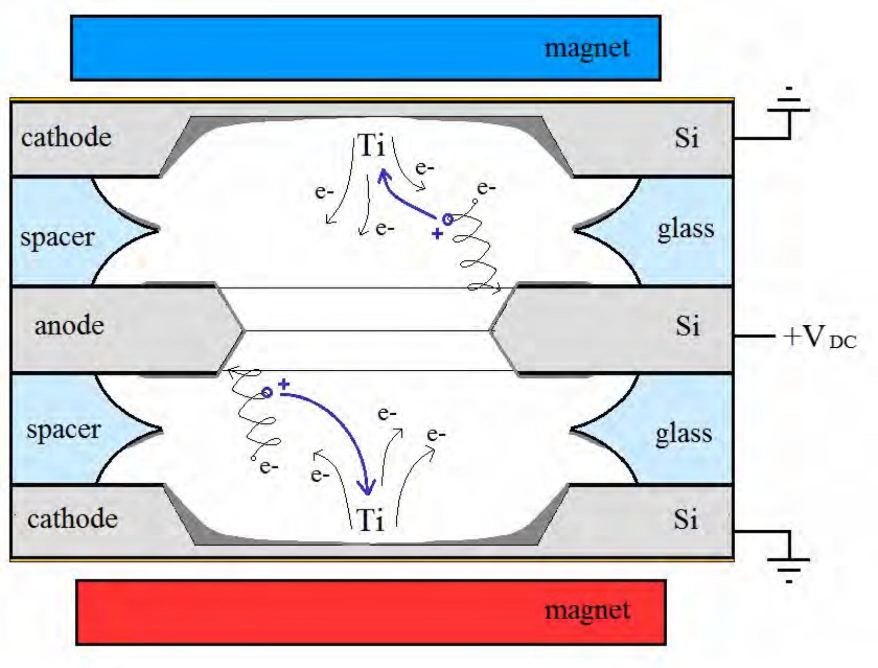
Gas ionization in magnetic field



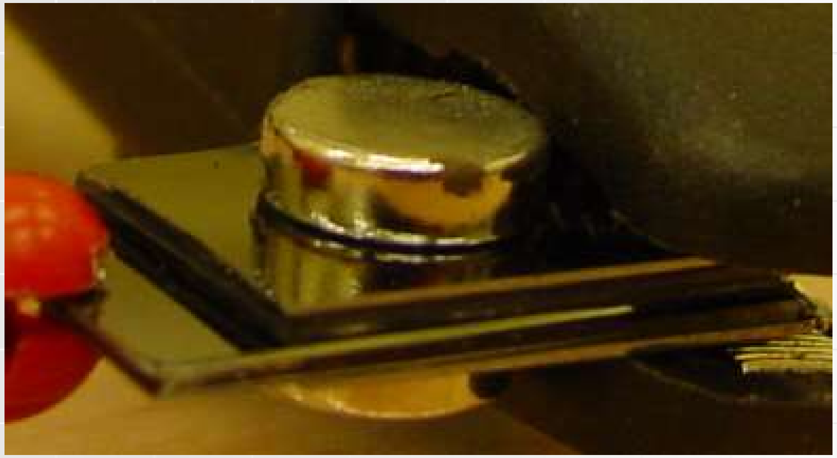
Gas ionization by an electron beam emitted from CNT cathode



MEMS high vacuum micropump



- Silicon- glass sandwich
- Volume < 0.01 cm^3
- 2 Nd magnets
- Thin-film getter (optional)



Operating principle:

Ionization process started by spontaneous electrons
Glow-discharge enhanced by external magnetic field
Attraction and adsorption of ions by Ti thin film

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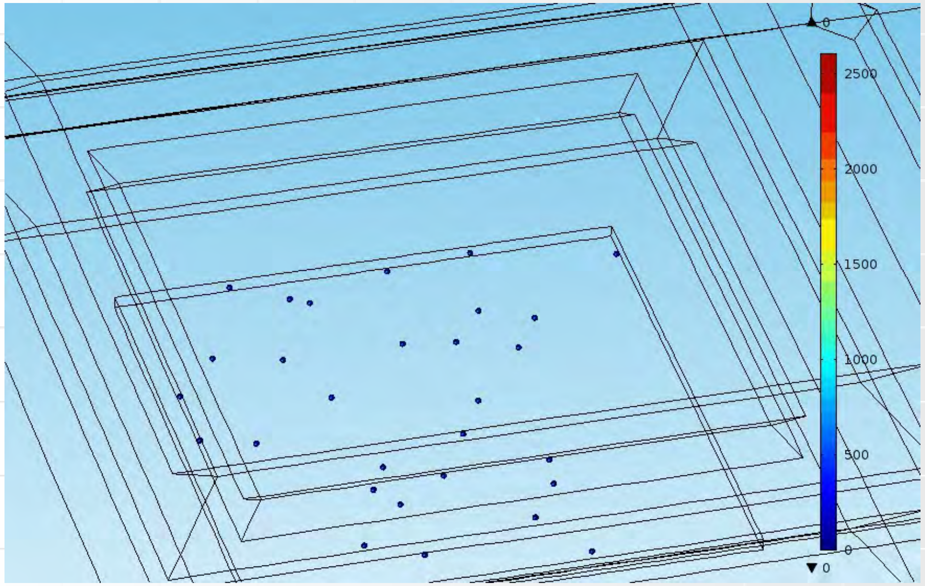
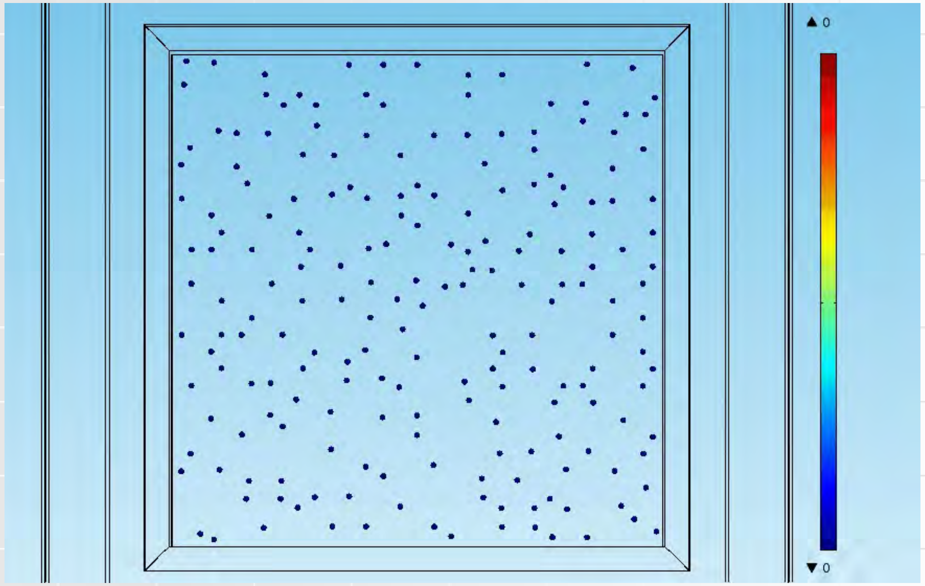
MEMS high vacuum micropump





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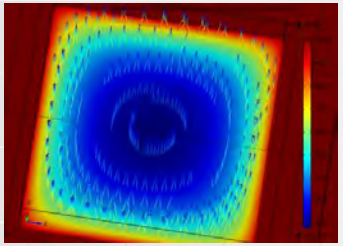
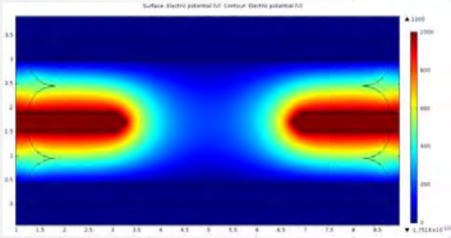
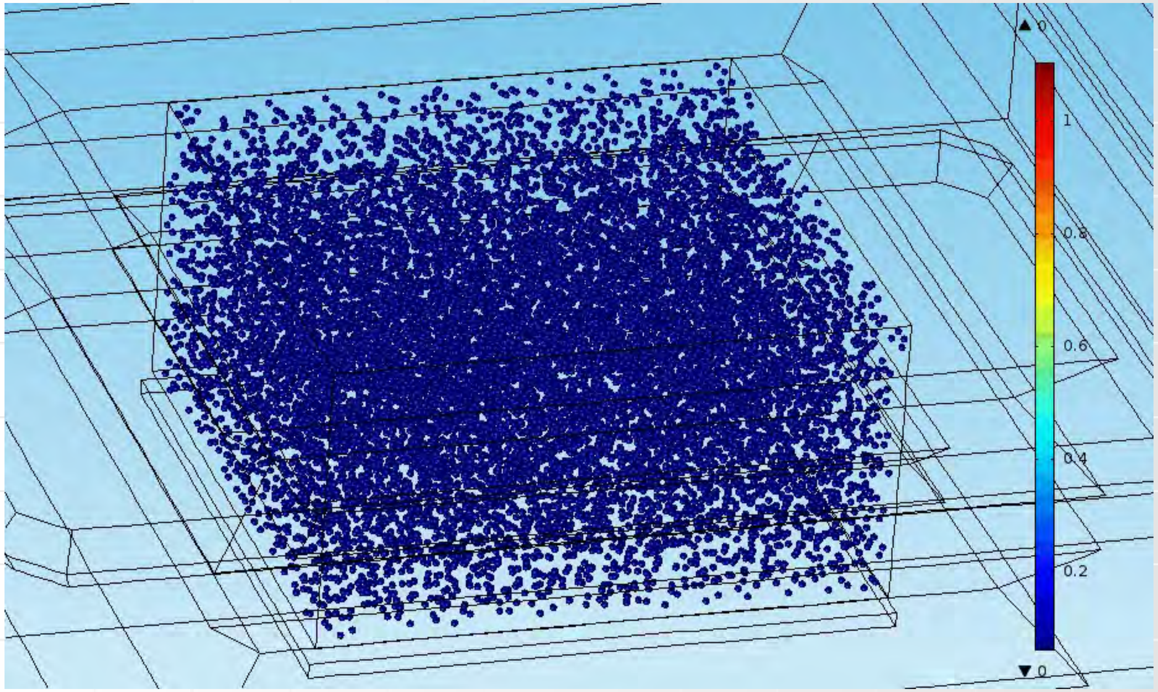
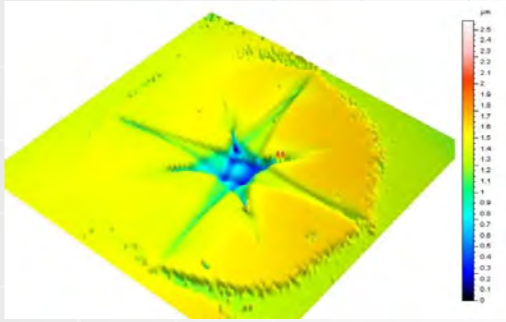
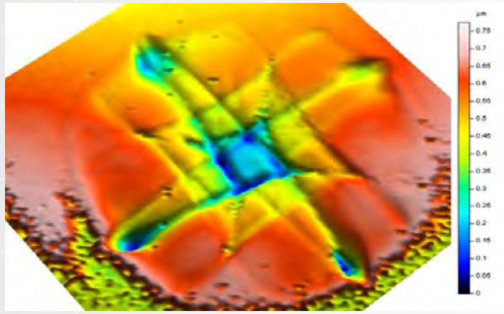


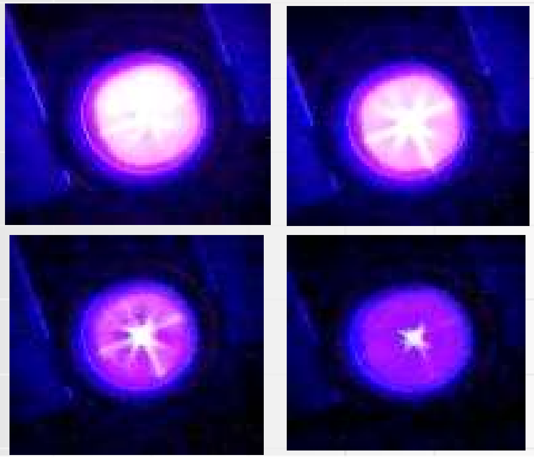


MEMS high vacuum micropump









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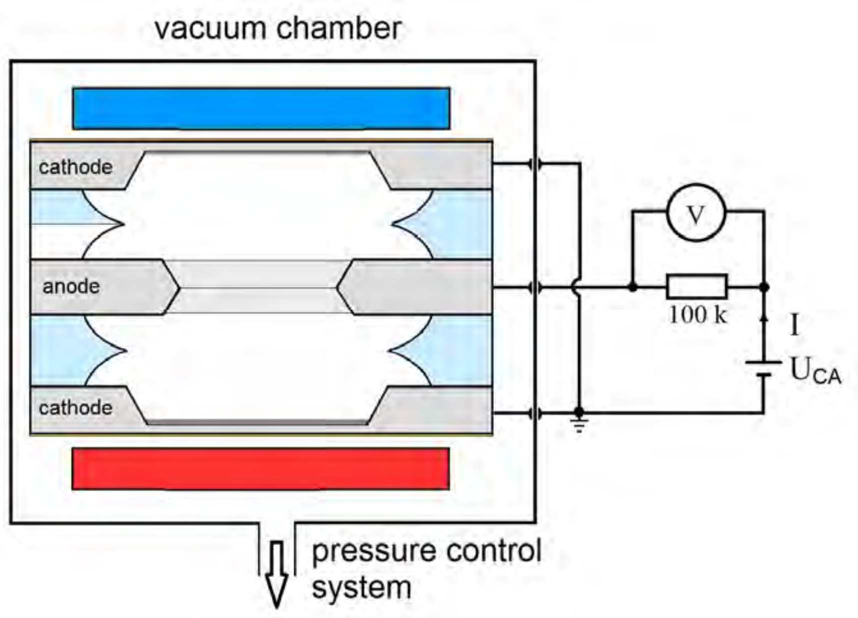
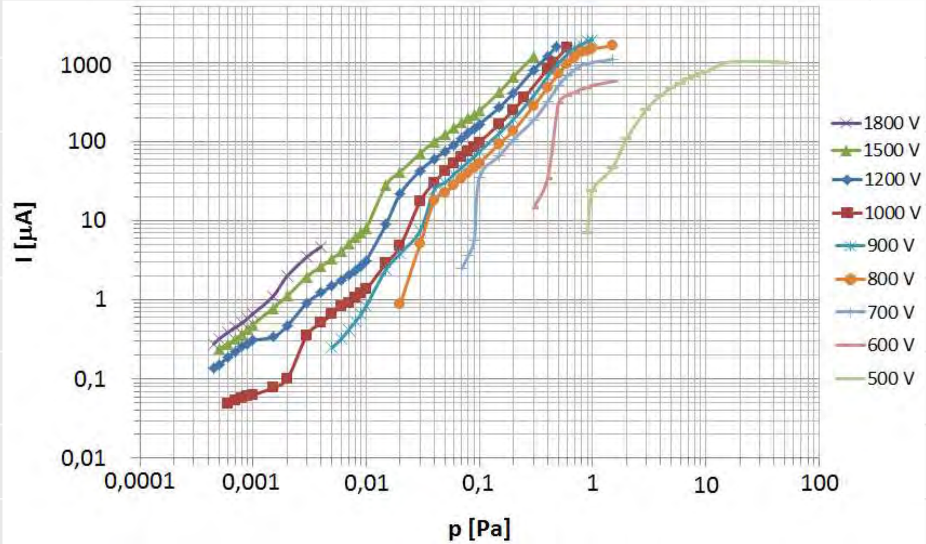
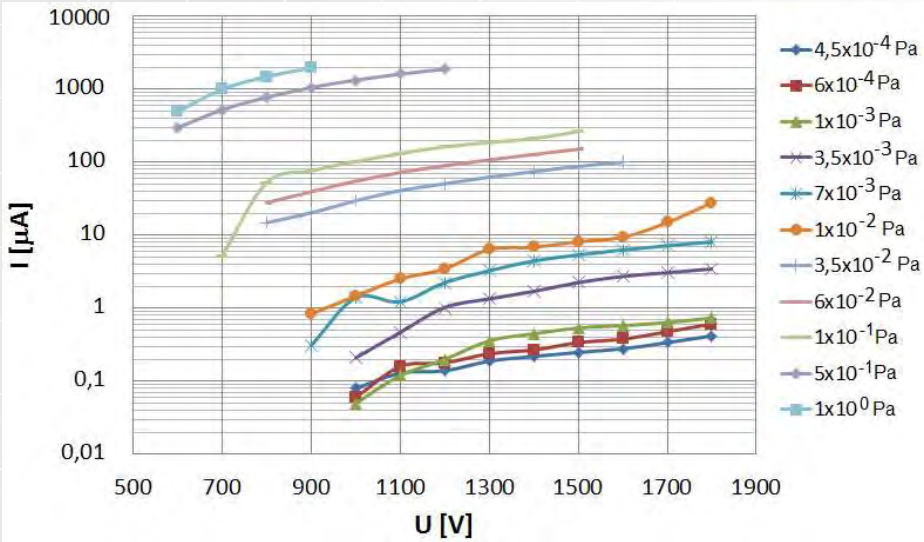
MEMS high vacuum micropump







- Operating pressure range:
  1 hPa -10^{-7} hPa
- Operating voltage:
  500 – 2500 V

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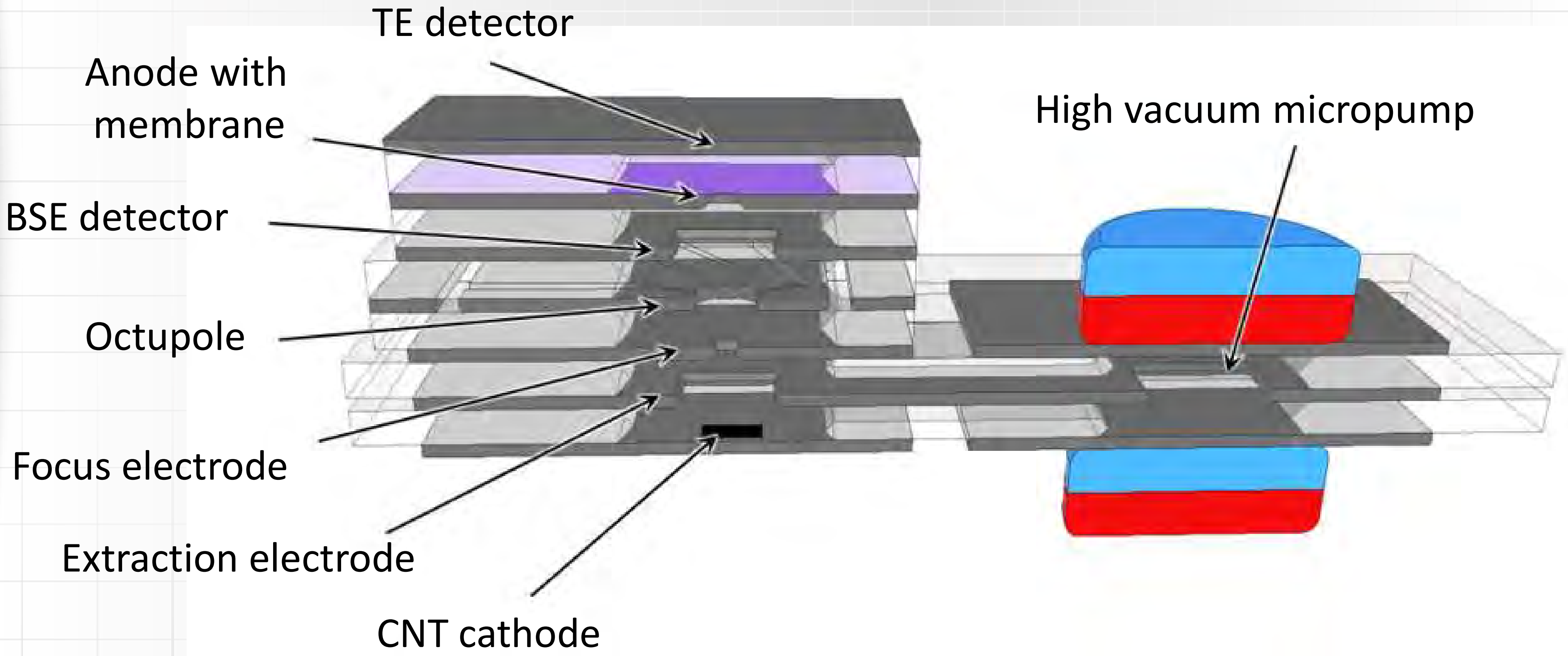
MEMS electron beam microcolumn

Concept of a MEMS scanning electron microscope



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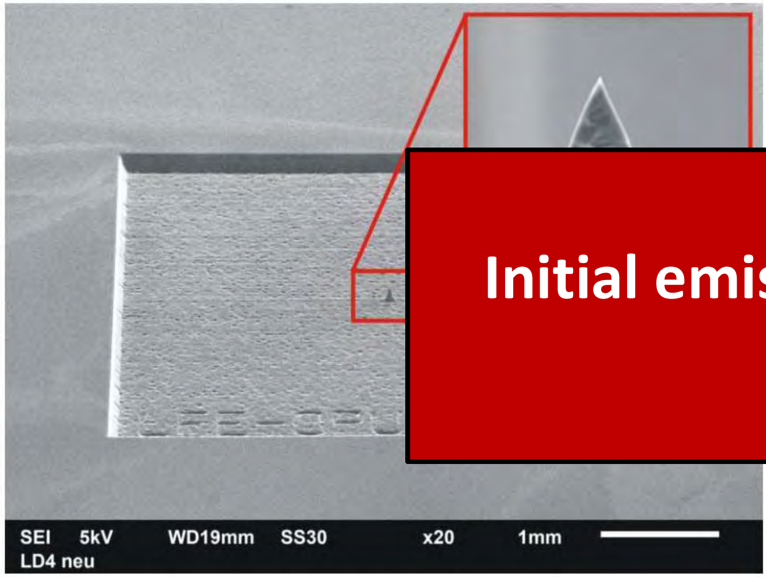
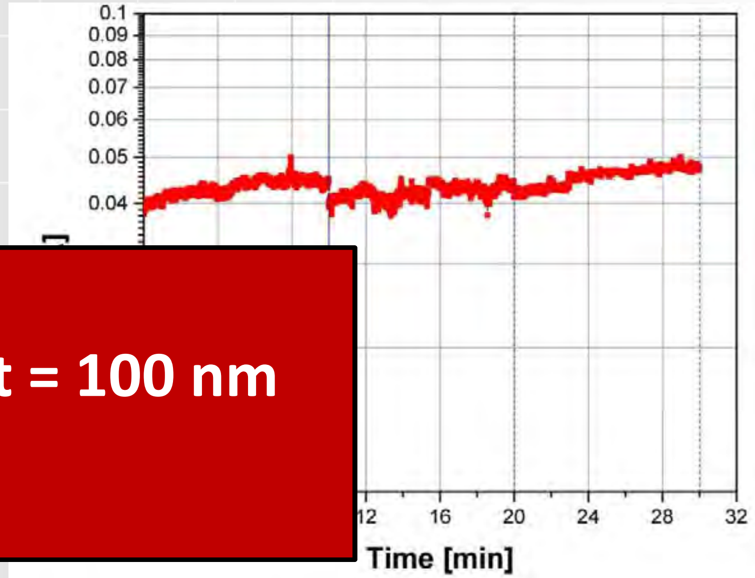
Silicon electron emitter

- Silicon tip fabricated using laser micromachining process (OTH Regensburg)
- Threshold voltage <1500 V
- Small initial spot size (~100 nm)
- Stable current for p-type emitters



P-type silicon tip emitter.

Initial emission spot = 100 nm

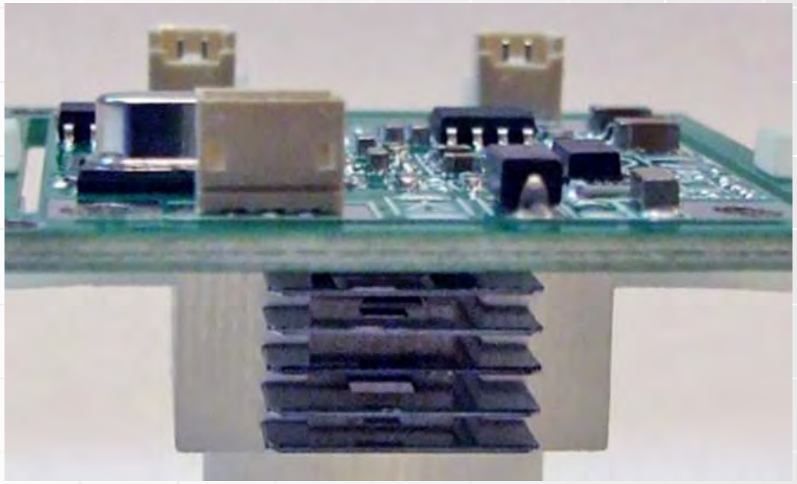


Electron emission current vs. time for p-type silicon emitter

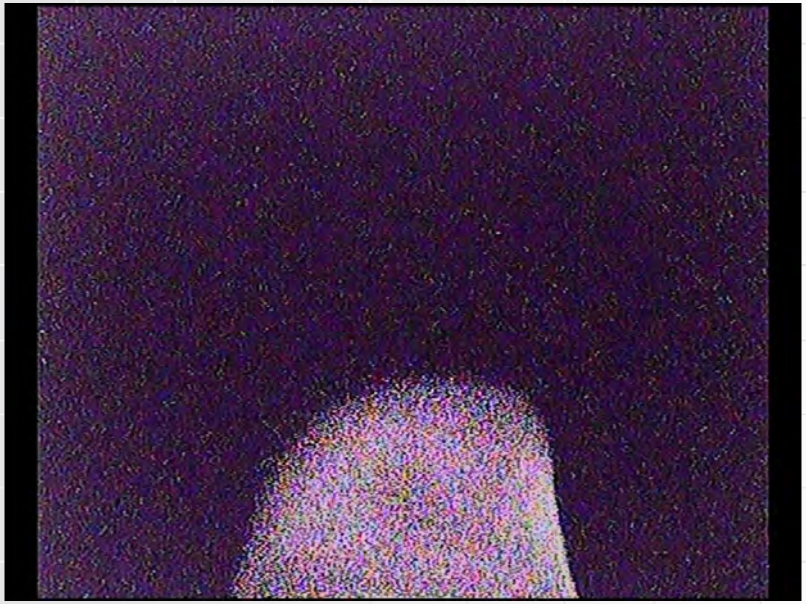
M. Krysztof, P. Urbański, T. Grzebyk, M. Hausladen, R. Schreiner, MEMS X-ray source: electron emitter development, PowerMEMS 2022, Salt Lake City, Utah, USA, 12 - 15 December 2022, (2022) pp. 248–251.

Focusing of electron beam

- MEMS electrostatic lens (Einzel lens)
- Flat CNT cathode (1x1 mm^2)
- Silicon gate (3x3 mm^2)
- LC-1/4 Sony 480TVL Ex-view CCD camera



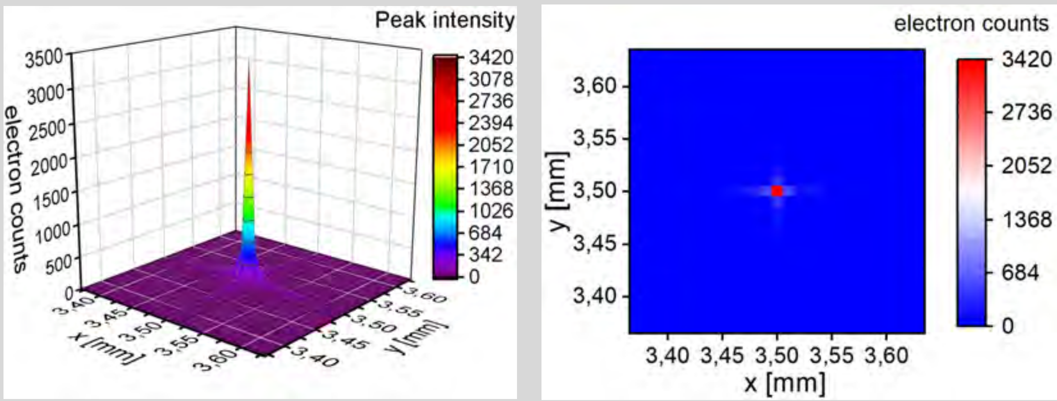
Electron optics column with CCD camera



Focusing of electron beam

- Realistic electron beam 50000 electrons from 40x40 μm^2 area
- 5 different size of Einzel lens were investigated (from 1 to 3 mm)

Sharp silicon/CNT cathode

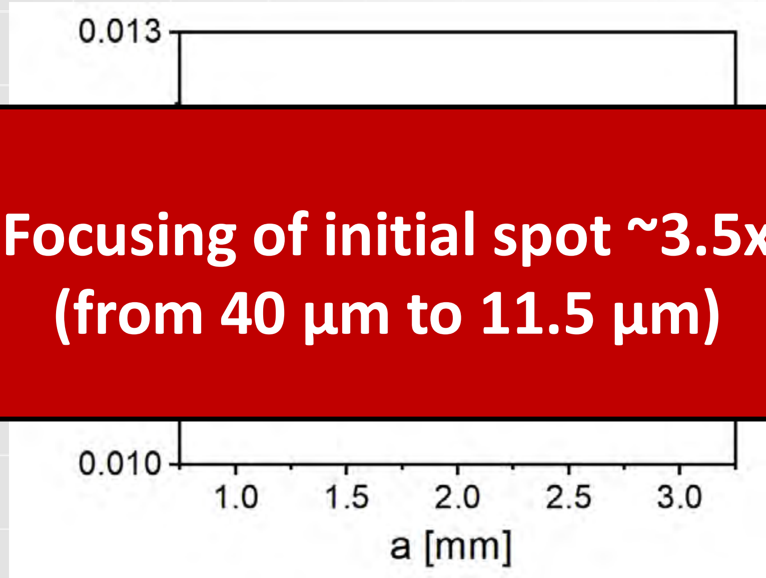


Electron beam spot – 11.5 µm

Einzel lens size – 3 mm

Focusing voltage – 3590 V

E-beam Energy – 2 keV



Focusing of initial spot ~3.5x (from 40 µm to 11.5 µm)

Size of a electron beam spot „D" vs. size of the Einzel lens hole „a"

M. Krysztof, Design of an Einzel Lens with Square Cross-Section, Electronics 2021, 10(19), 2338;

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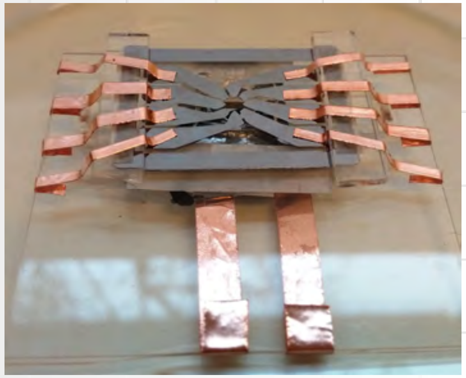
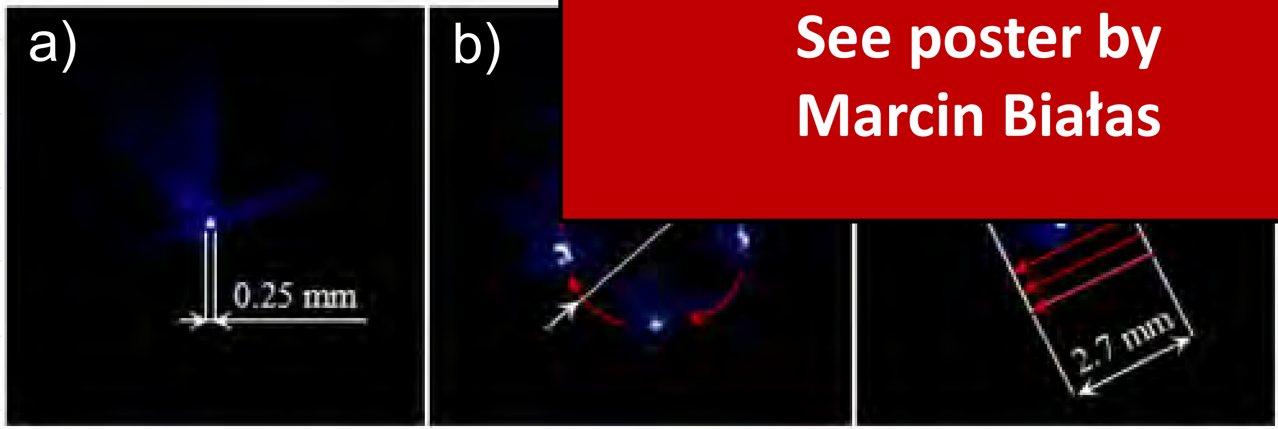
Scanning of the electron beam

- The electron beam is controlled by 8 electrodes (silicon octupole)
- The power supply was designed and made by Marcin Białas
- The **scanning diameter is 3.8 mm**, and the **scanning area is 2.7 x 2.7 mm^2** with the **scanning sensitivity of 15 µm/V**
  (for E = 4 keV, H = 5 mm



Silicon-glass octupole mounted on CNT electron gun

See poster by Marcin Białas



Images of the deflected electron beam: a) starting spot of the electron beam, b) deflection along a circular line (electron beam spot in five different positions), c) scanning line by line (red dashed line indicates the movement of the electron beam spot).

Scanning of the electron beam

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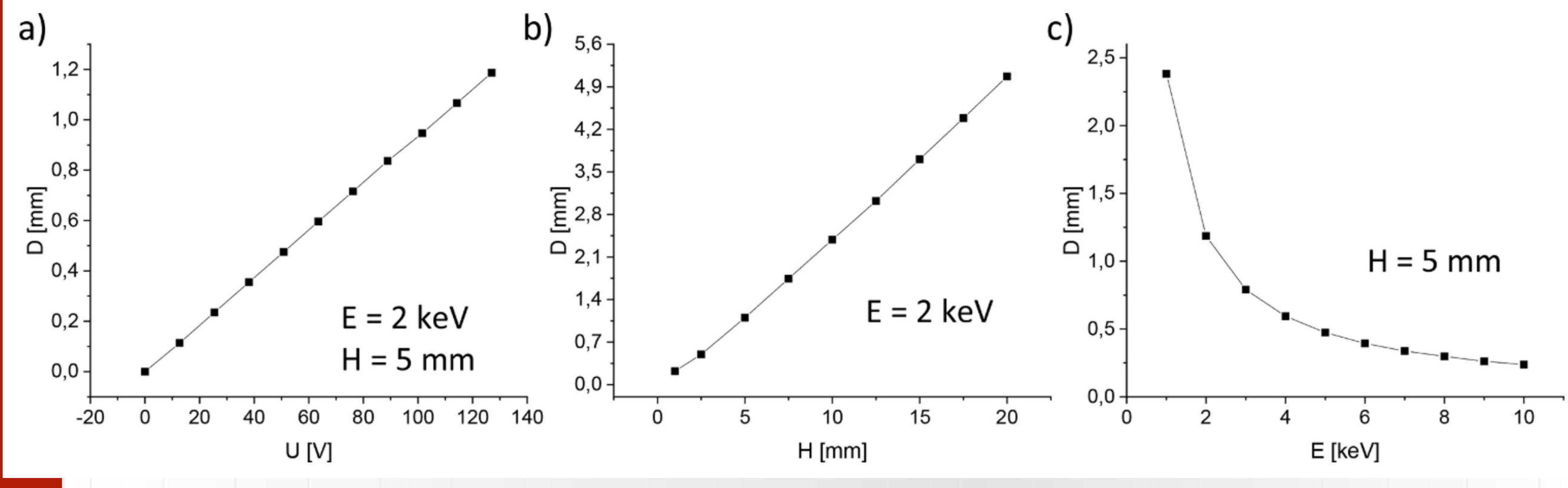
E = 4 keV
H = 1 mm
D = 110 μm
Scanning step = 27 nm

- The scanning area depends on: **octupole voltage; working distance** and **electron beam energy.**



The dimension of scanning area as a function of: a) octupole voltage (± 127 V), b) octupole–observation plane distance, c) electron beam energy

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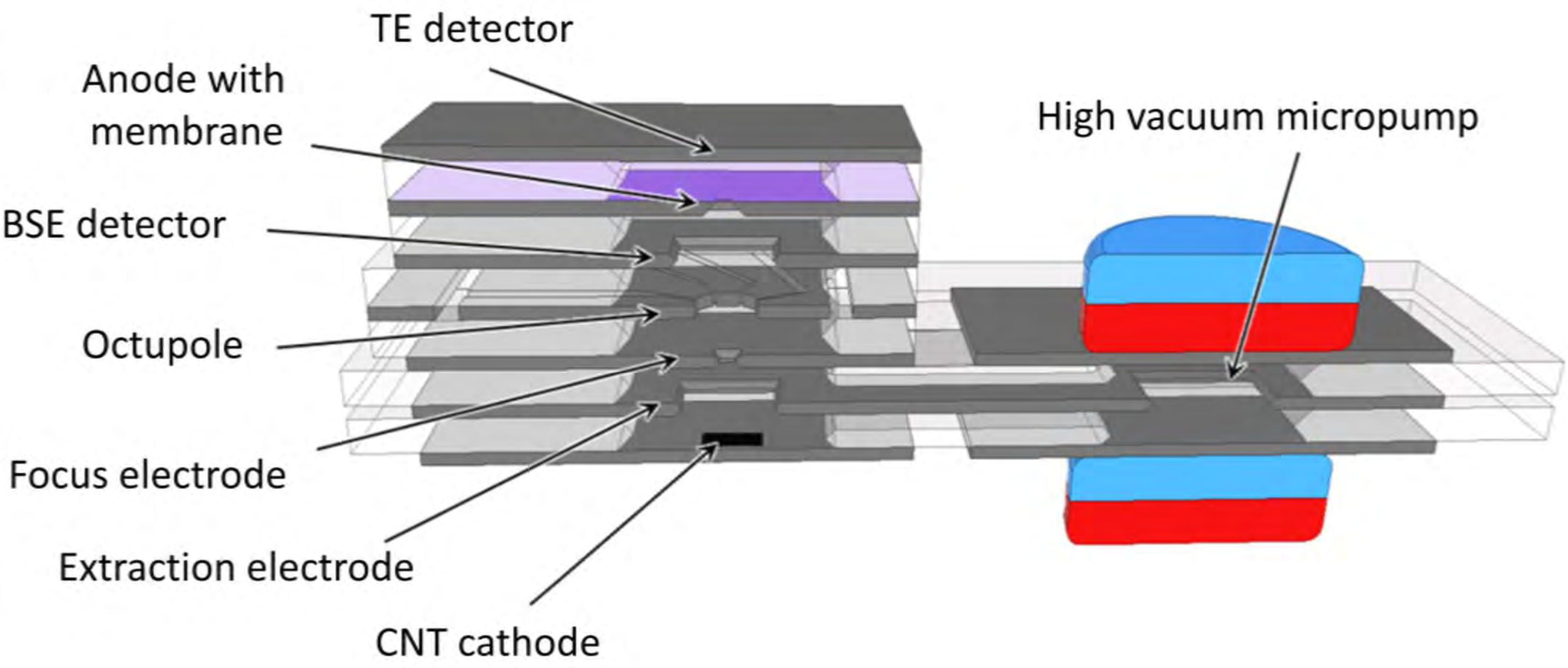
MEMS electron beam microcolumn

Concept of a MEMS scanning electron microscope



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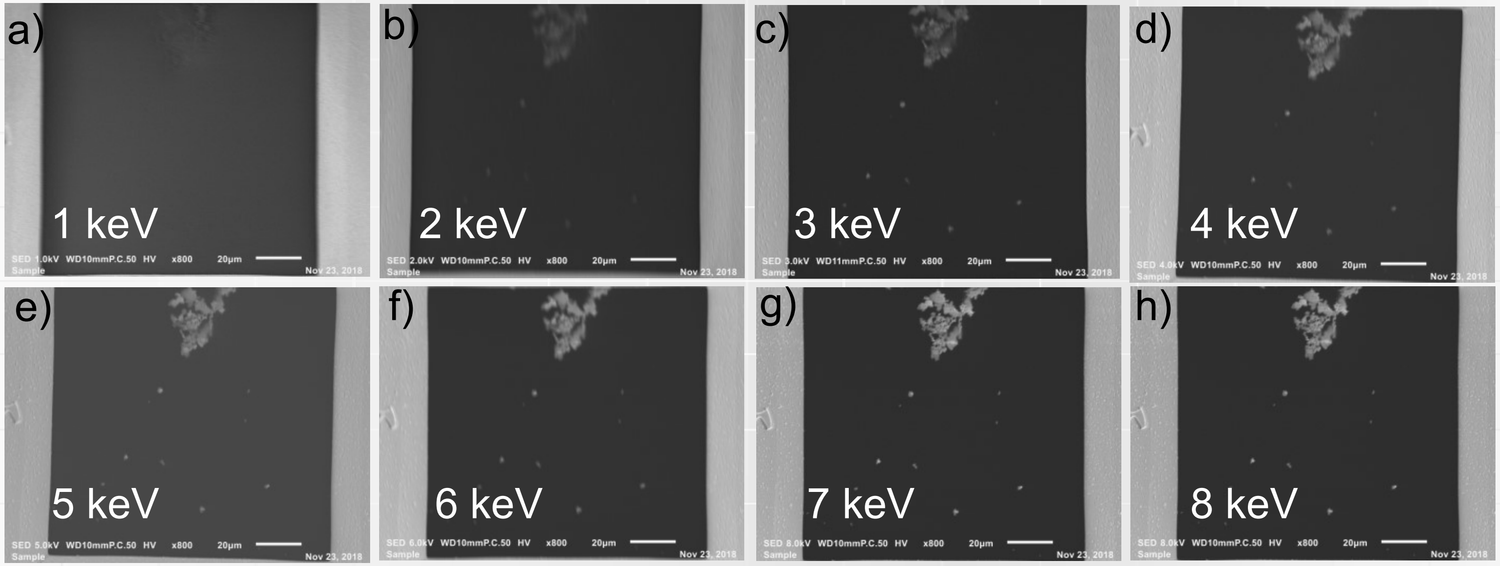
Imaging samples through the Si_3N_4 membrane with low energy electron beam

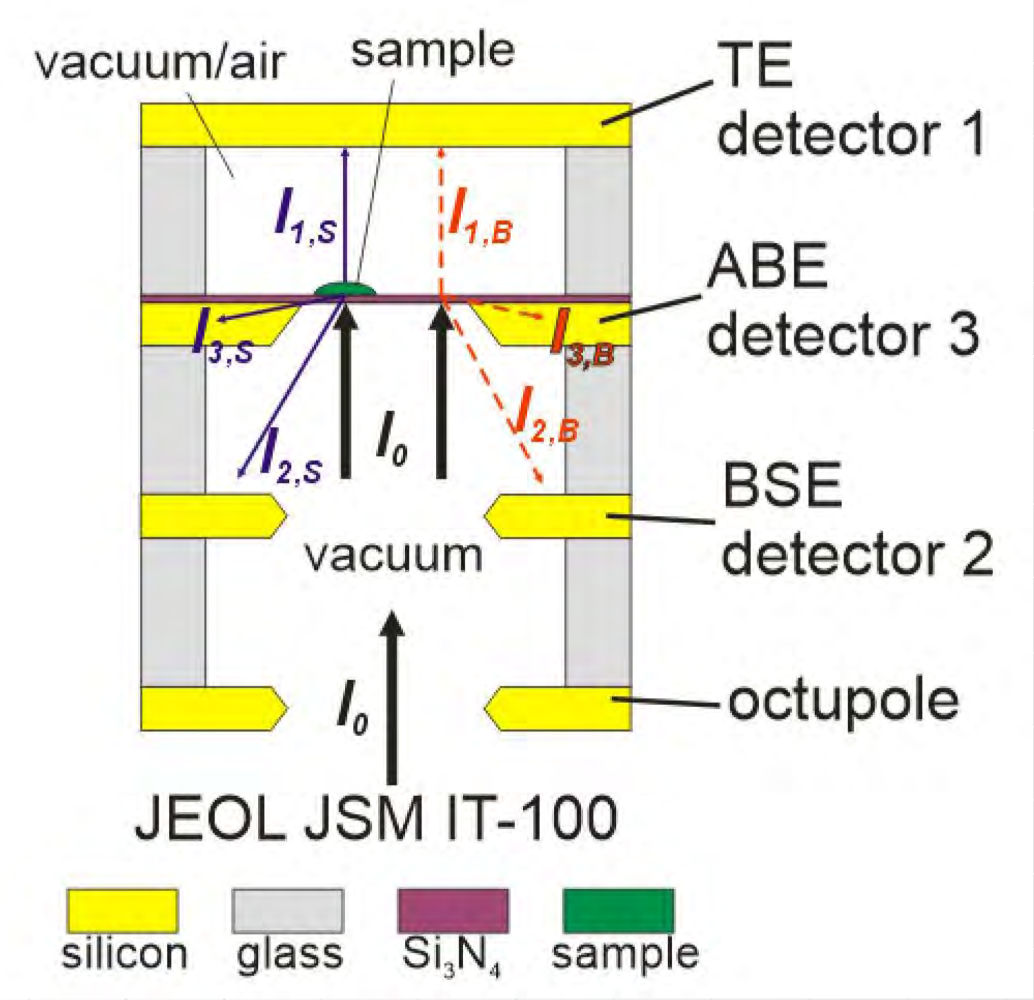
JEOL JSM IT-100

NaCl – salt crystals



Secondary electron images of salt crystals (NaCl) through Si_3N_4 membrane (50 nm thick) for electron beam energies of: a) 1 keV, b) 2 keV, c) 3 keV, d) 4 keV, e) 5 keV, f) 6 keV, ***g) 7 keV, h) 8 keV.***

New detectors for MEMS SEM

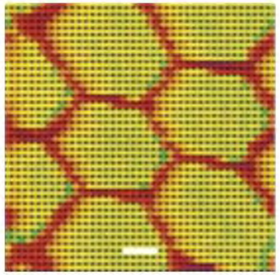
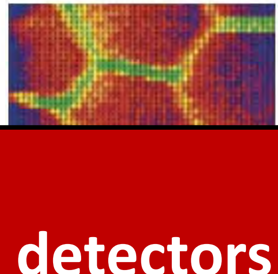
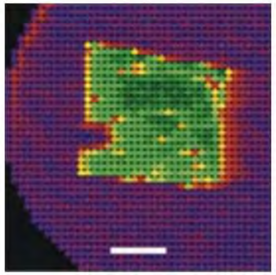
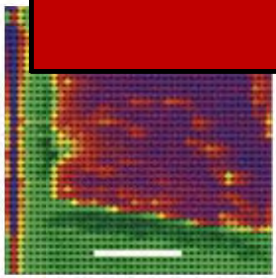
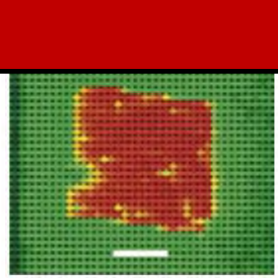
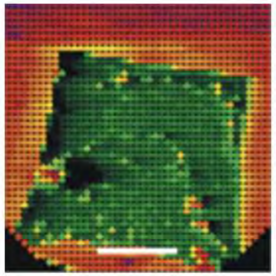
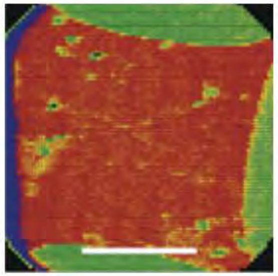
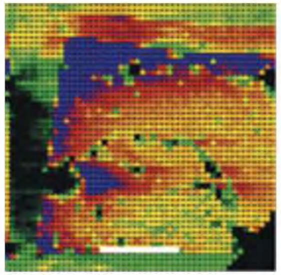


Silicon electron collectors:

- TE – transmitted electrons
- ABE – absorbed electrons
- BSE – backscattered electrons

- **I_S – sample current** (electrons collected at the detector after interacting with the sample)
- **I_B – background current** (electrons collected at the detector with no interaction with the sample)
- **$\Delta I = |I_S - I_B|$ – image contrast**

Testing of the detectors

	Detector 1 Transmitted electrons	Detector 2 Reflected electrons	Detector 3 Absorbed electrons	Sample/conditions
$E_0 = 3$ keV $I_0 = 0.85$ nA				hexagonal grid gh vacuum membrane
$E_0 = 5$ keV $I_0 = 1.09$ nA				particles (5-30 μm) high vacuum membrane
$E_0 = 7$ keV $I_0 = 1.46$ nA				steel particles (5-30 μm) high vacuum/air membrane

All three detectors work

JEOL JSM IT-100 vs. MEMS EM

- The resolution of the MEMS EM for TE detector is comparable with commercial SEM (for low magnification)

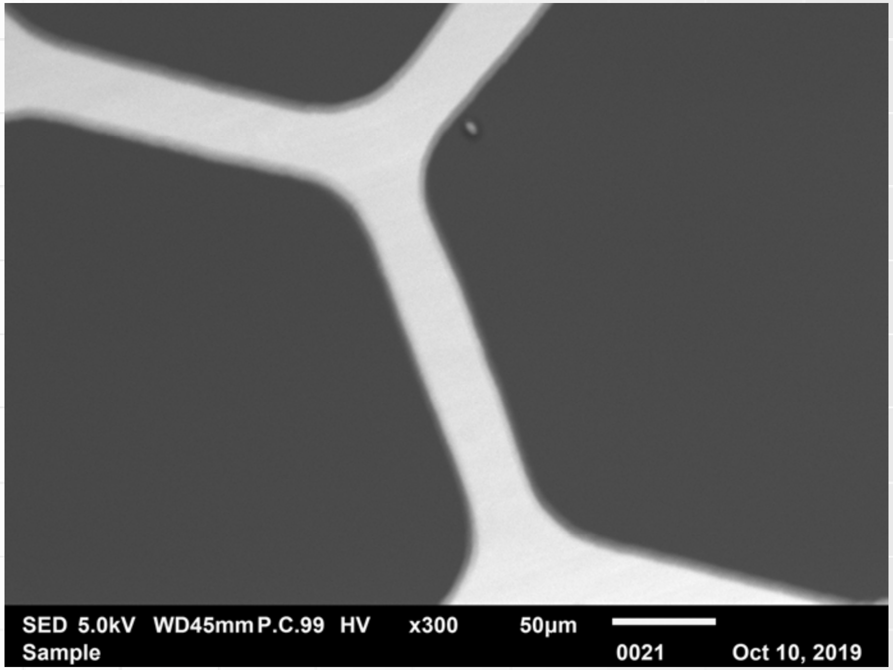


Image of a metal grid with the use of JEOL JSM IT-100

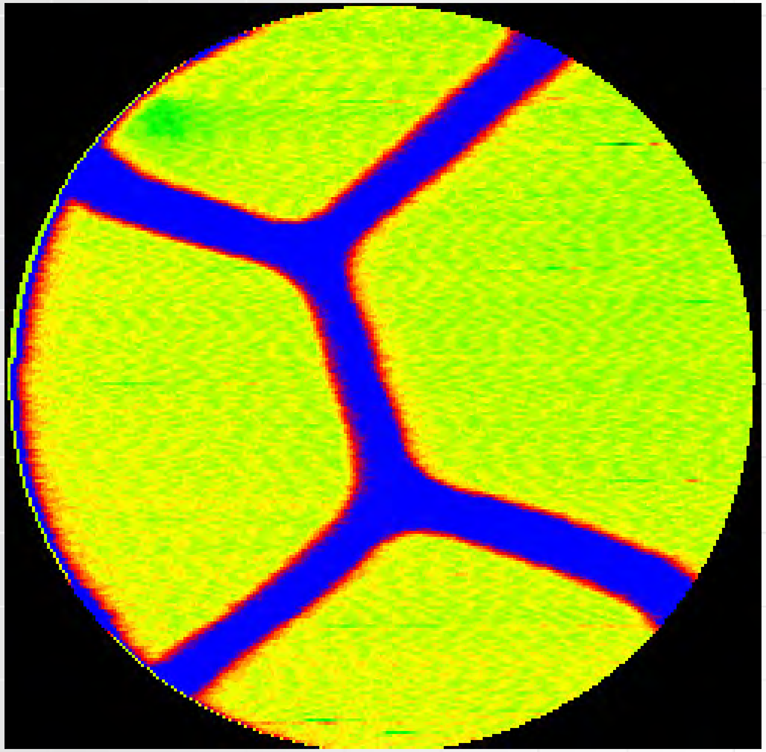
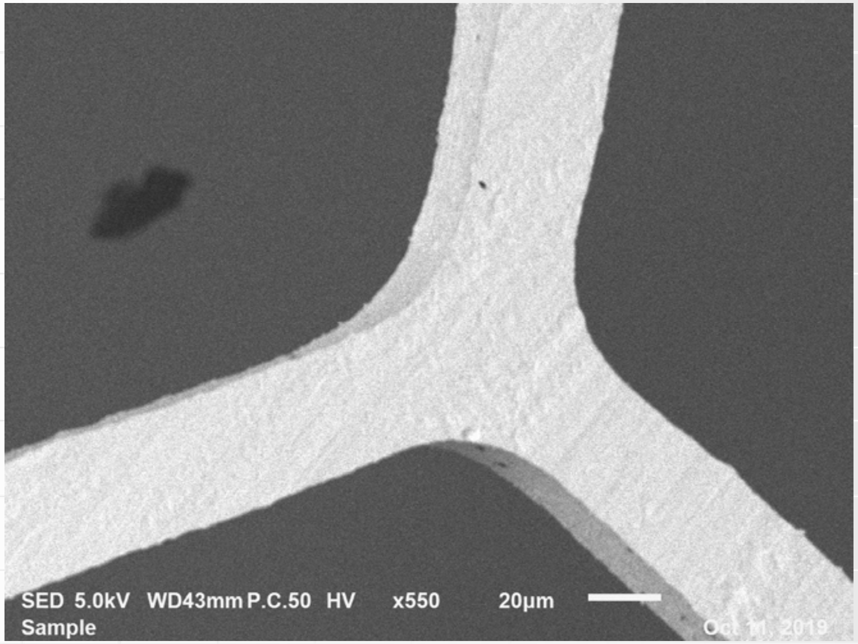


Image of the metal grid with the use of MEMS TEM

JEOL JSM IT-100 vs. MEMS EM

- With higher magnification the resolution and quality is worse due to noise



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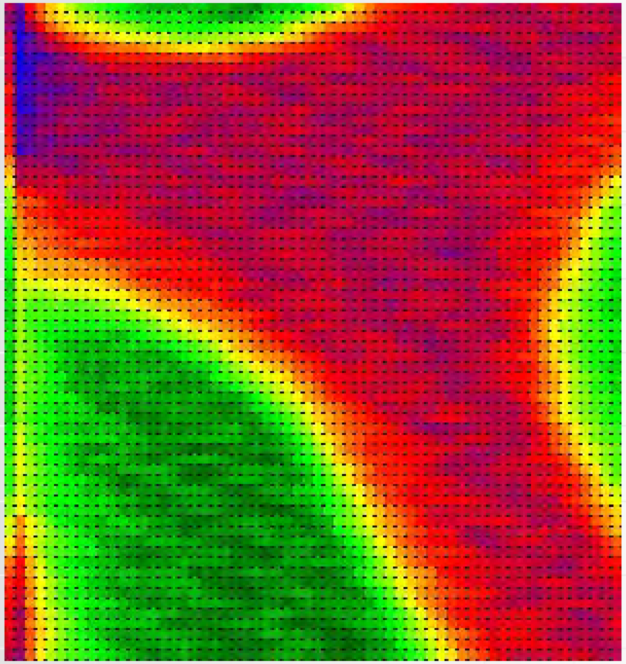

Image of the metal grid with the use of MEMS TEM

JEOL JSM IT-100 vs. MEMS EM

- The field of view of the MEMS TEM is smaller thus the image distortion

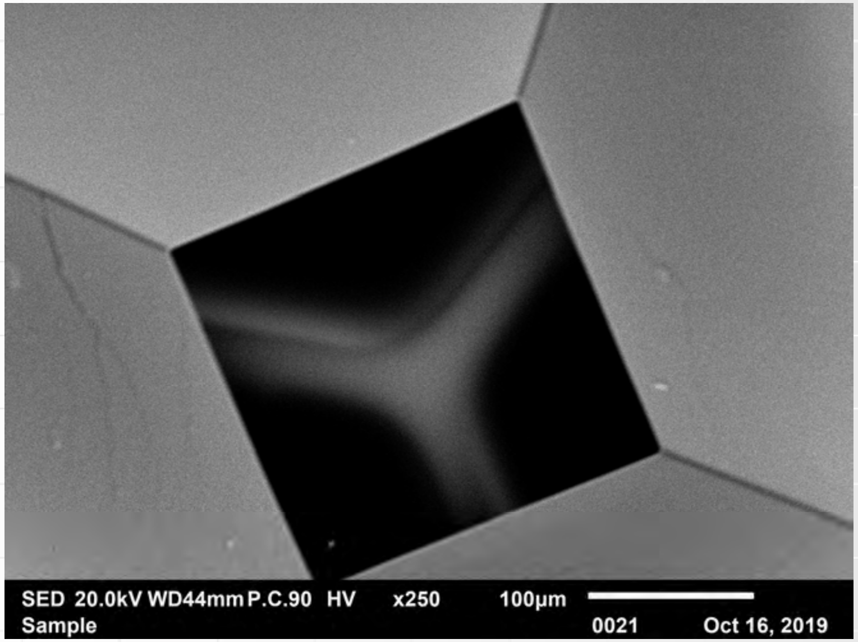

Image of a metal grid through the membrane with the use of JEOL JSM IT-100

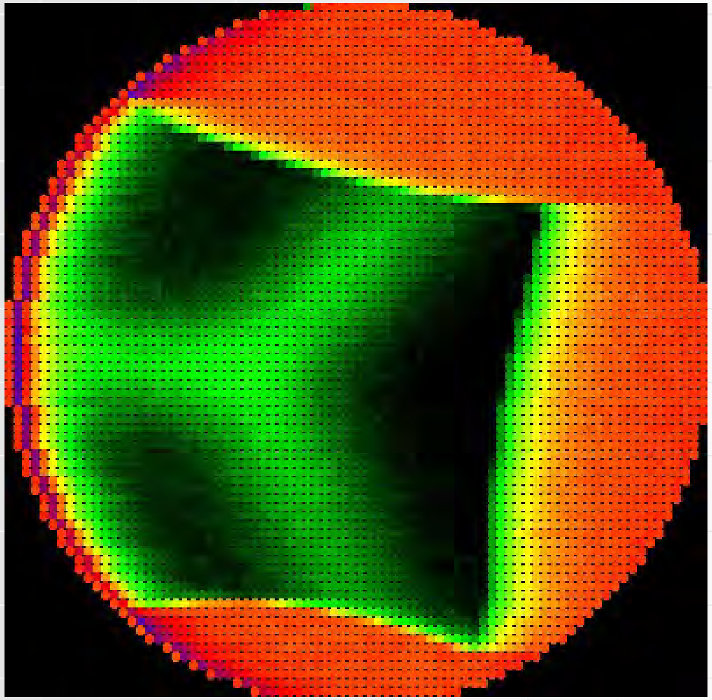

Image of the metal grid through the membrane with the use of MEMS TEM

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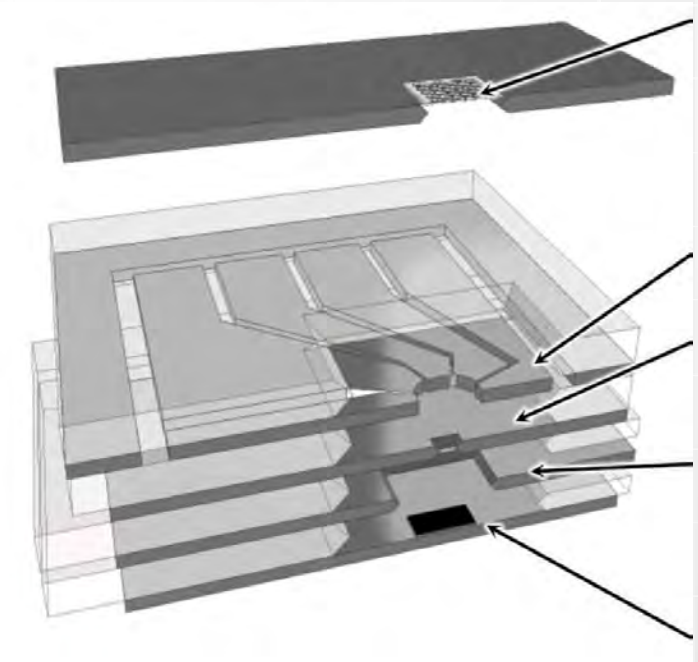
Imaging using MEMS SEM test model

- Test structure inside high vacuum chamber (10^{-5} mbar)
- The metal grid as an electron collector
- High fluctuations of electron emission visible at the image



Metal grid (10 V)

Octupole

Focus electrode (0 V)

Extraction electrode (-1.5 kV)

CNT cathode (-2 kV)

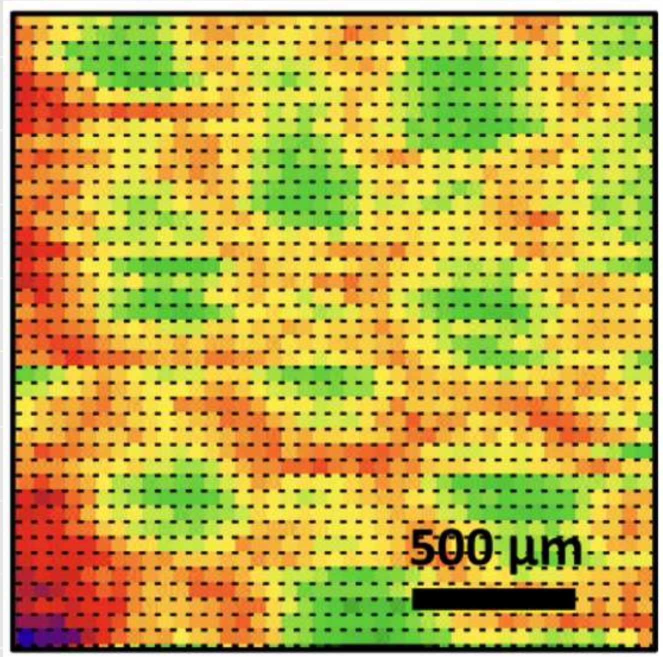
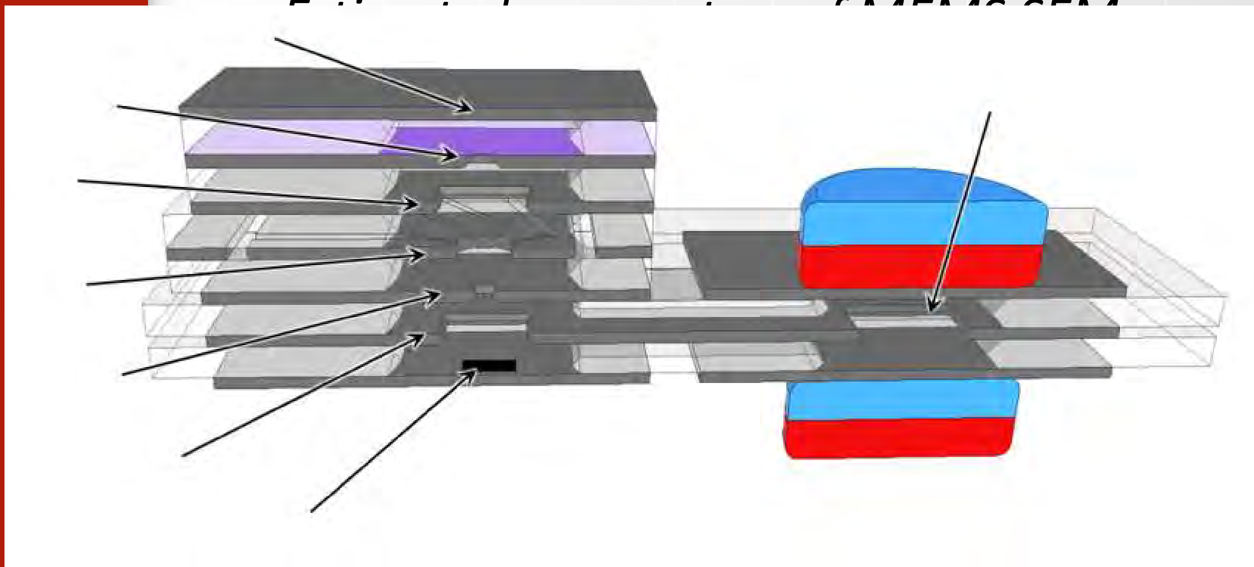
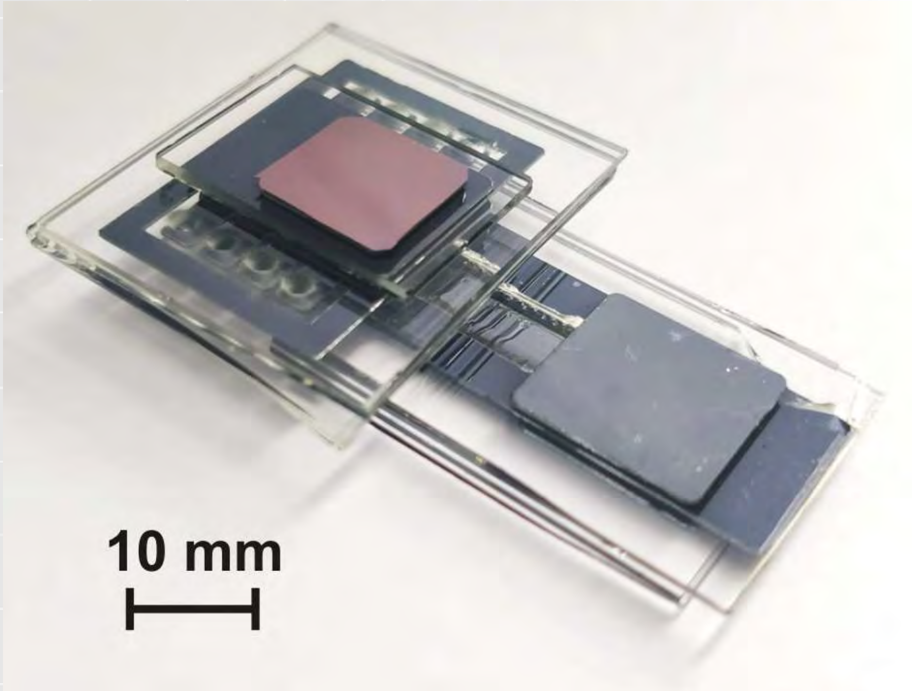


Image of a hexagonal metal grid

First in the world model of MEMS SEM

1. At this point all elements of MEMS SEM are tested and operational
2. New detection methods were developed and tested





*** - assuming 100 nm initial spot and 3.5 times focusing.*

**** - counting external dimensions of the device.*

MEMS electron beam microcolumn

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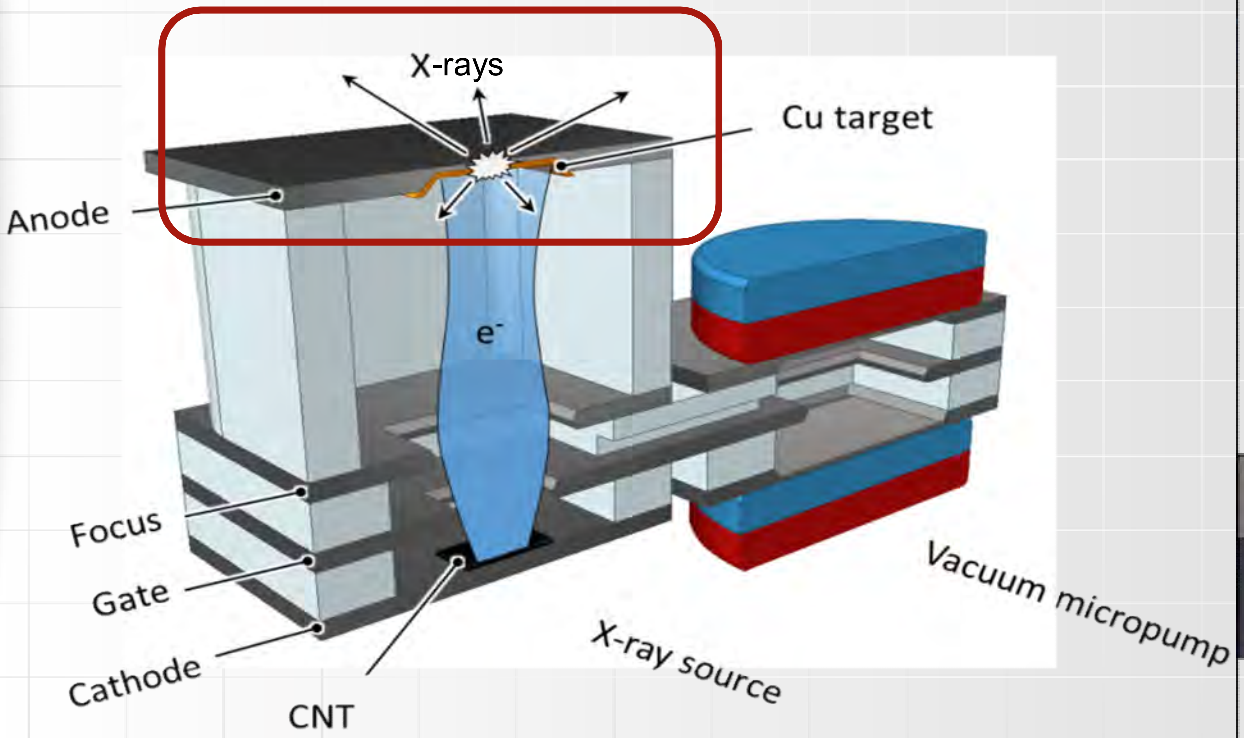
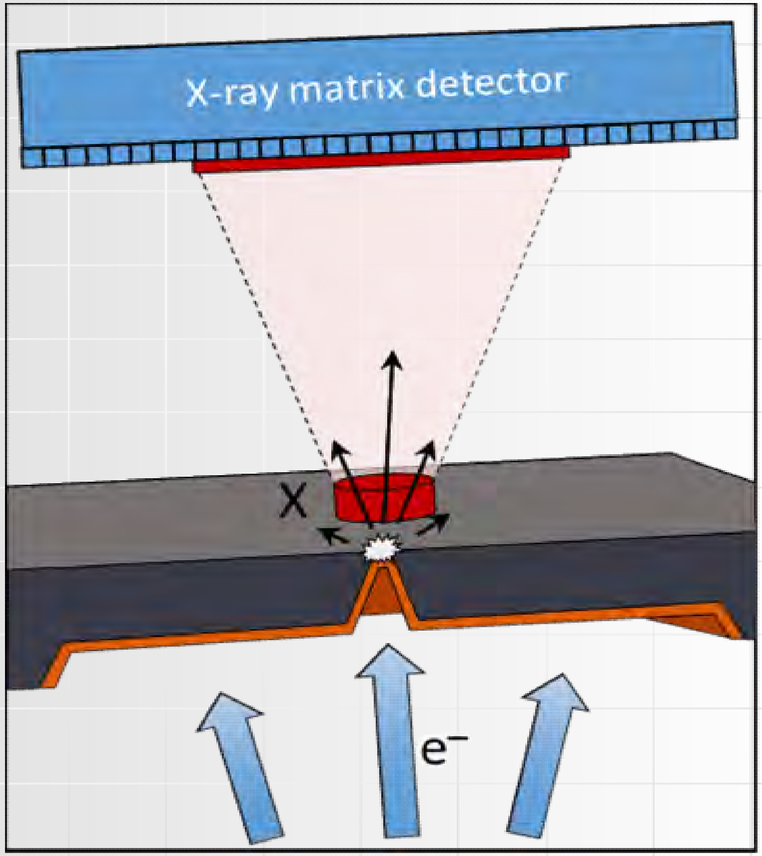
Concept of a MEMS point X-ray source

Integration of: micropump, electron optics column, and thin target on a single chip





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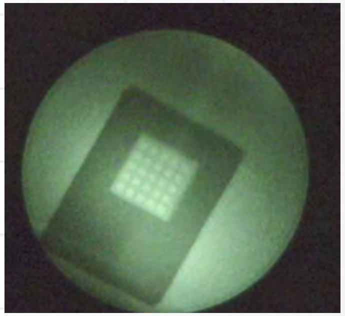
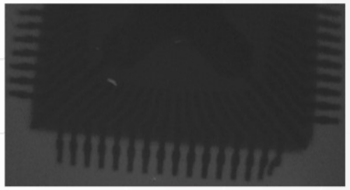
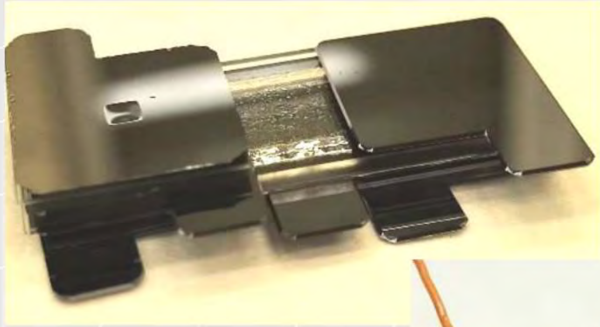
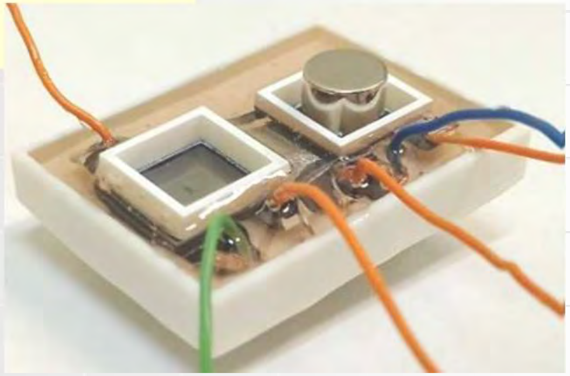
Fully MEMS X-ray source

Inspection of small objects



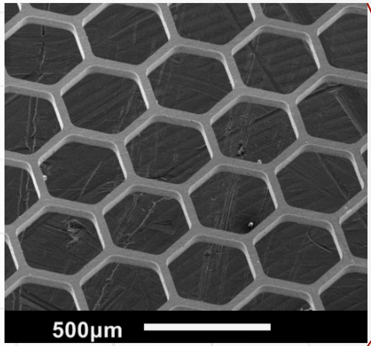


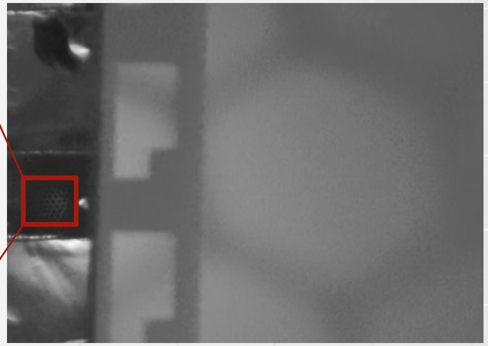


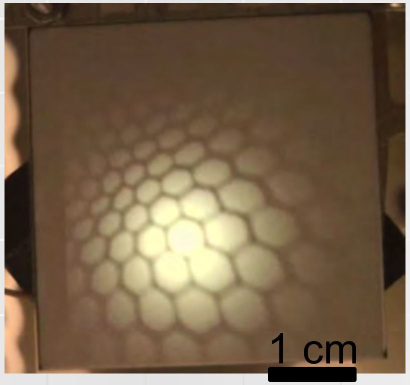


See poster by Paweł Urbański

Object magnification







MEMS electron beam microcolumn

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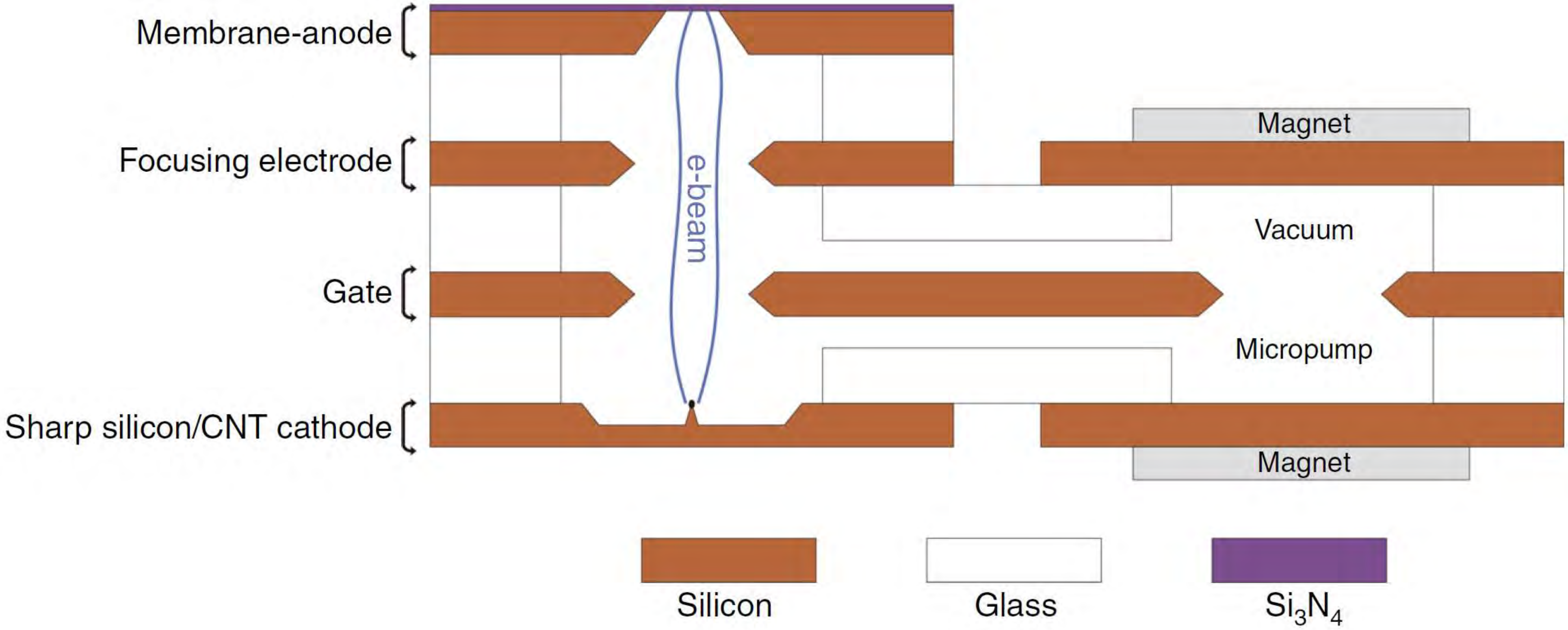
Concept of a MEMS electron source

Structure similar to X-ray source. Anode with thin silicon nitride membrane.



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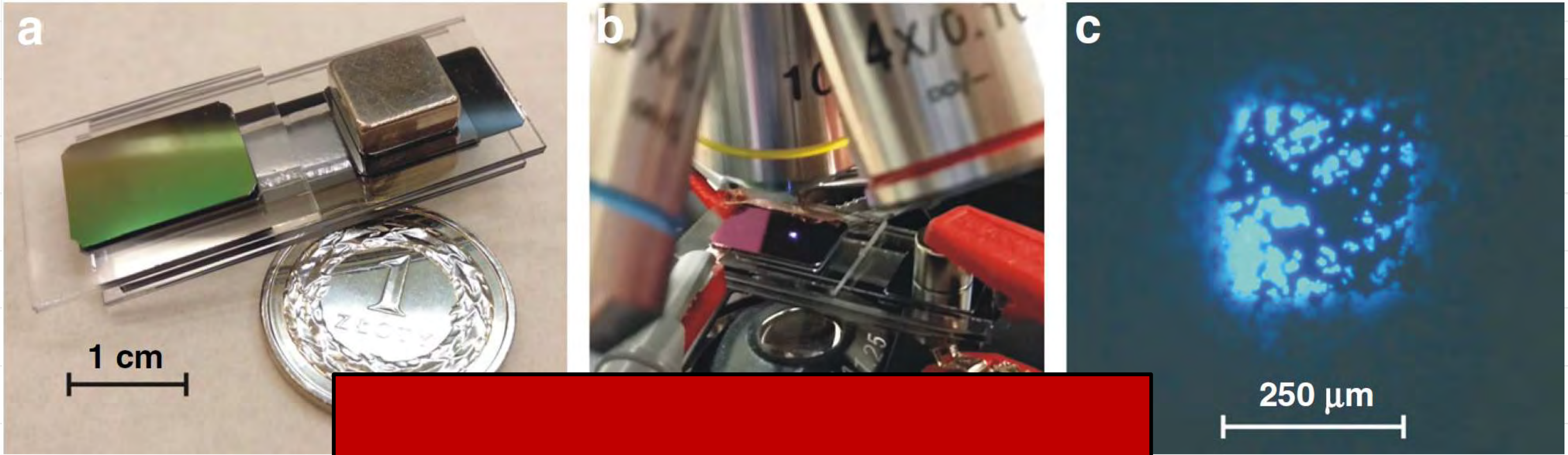
MEMS electron source



See poster by
Michał Zychla and Jan Sobków

- Operates in air
- Generates electron beam that passes to air

- on source for MEMS
- bility sepctrometer
- Cathodoluminescence investigation of materials for pharmaceutical industry/geology
- Studies of electron interactions with biological samples or DNA

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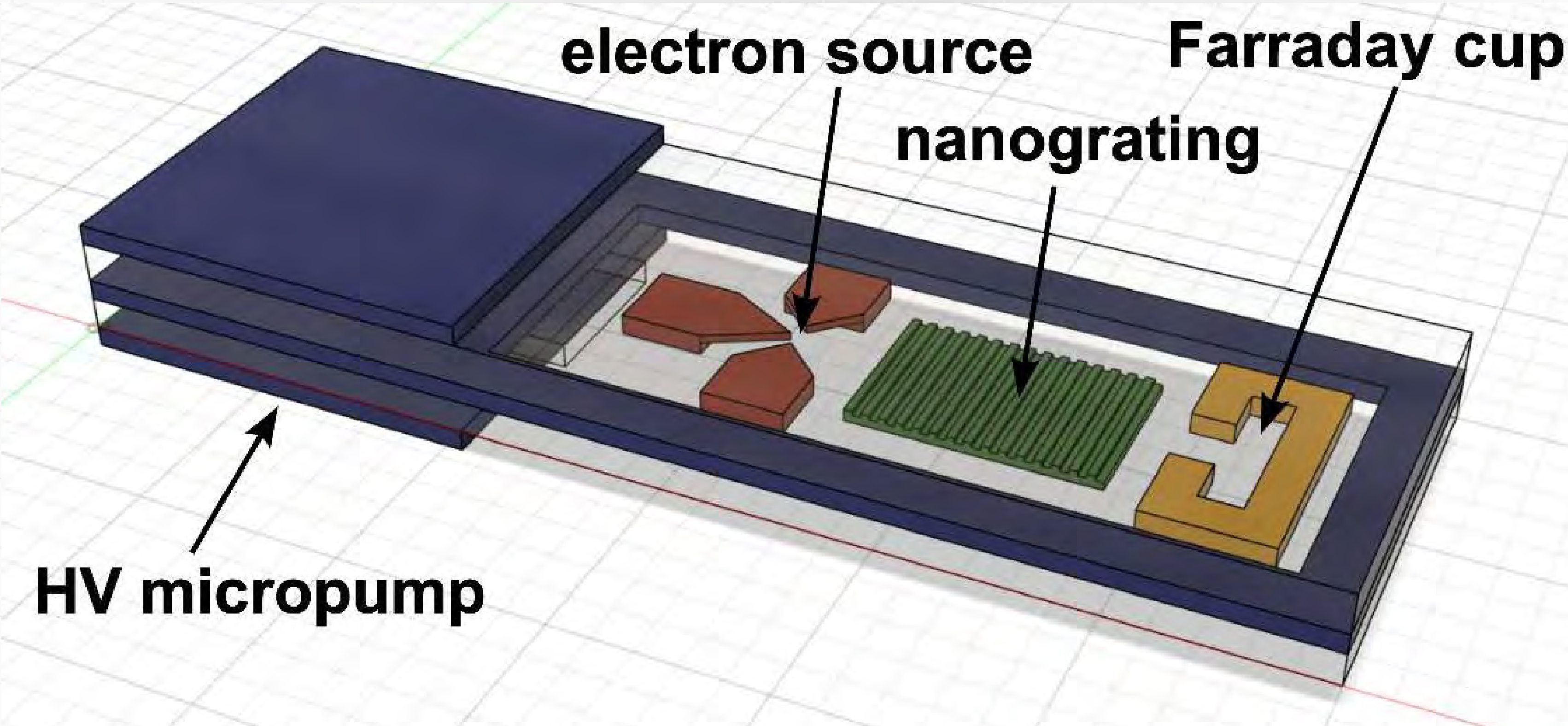
MEMS electron beam microcolumn

Concept of a MEMS free electron laser



Schematic arrangement of MEMS FEL elements inside the HV MEMS packaging.

Diagram of the free electron laser proposed by Hans W.P. Koops (original drawing)

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Summary

VACUUM-SEALED ELECTRON BEAM MICROCOLUMN

1. MEMS technology ideal for inegrating elements of electron optical devices on-chip
2. MEMS high vacuum pump generates up to 10^{-7} mbar vacuum
3. Anodic bonding technique enables vacuum sealing of the device
4. MEMS SEM elements developed and tested
5. MEMS X-ray source operational
6. MEMS electron source operational
7. MEMS FEL – conceptual vision

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Thank you for your attention

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