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Miniaturization of an electron gun with cold field emitter for a scanning electron microscope:

Concept and current status

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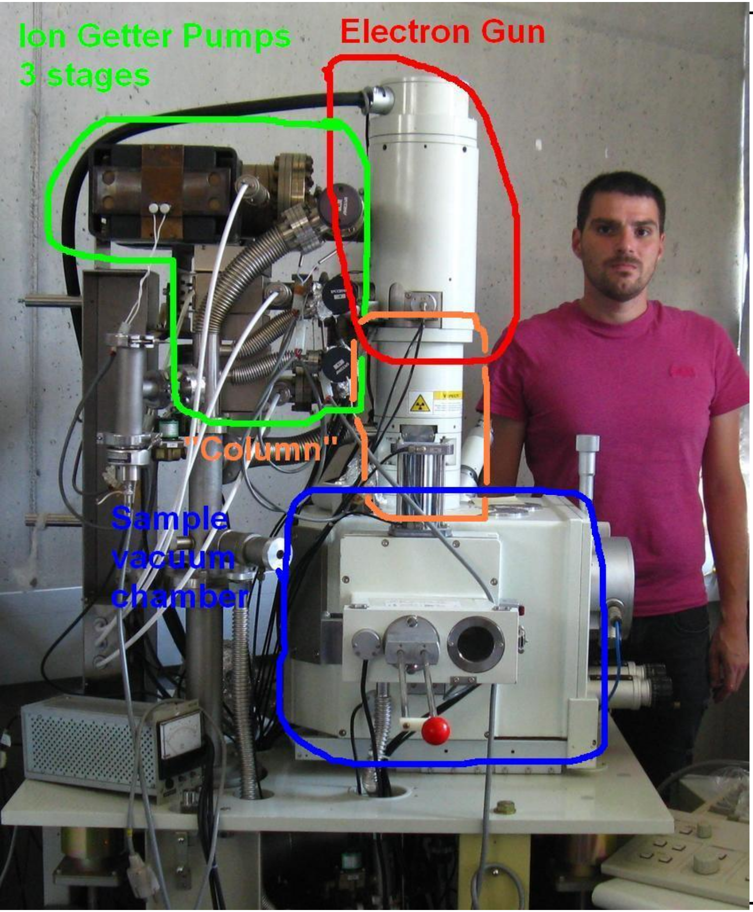
Our Motivation:

- Reduce size of a SEM
- Reduce cost of a SEM

JEOL 6400F
Cold Field emission SEM
(JEOL`s former „flagship“)



How to reduce electron gun size and cost:

-> use MEMS technology instead of established standard W-CFE emitter construction

Concerning the SEM UHV system:

installed volume of SEM UHV system:
approx. 1 to 2 dm^3

necessary SEM UHV volume:
few μm^3 at the cold field emitter tip surface

The aim of our project:

- Development of a cold field emission MEMS gun, to replace any standard cold field emission W gun in a SEM
- Integration as many electron optical elements from the SEM column into the MEMS gun as possible
- Replace the bulky ion getter pumps by a MEMS type ion getter micro pump (-> M. Krysztof, Th. Grzebyk et al, Wroclaw University of Science and Technology)

*MEMS: micro electro mechanical system

Recapitulation: working principle of a scanning electron microscope

- a (primary) electron beam with very small lateral extension is generated by several electron optical components to produce a tiny beam spot on the sample surface
- the beam spot is scanned over the sample surface point by point
- at each point of impact (secondary) electrons (and X-rays) are generated and leave the sample surface in direction to an electron detector
- the detector collects these electrons (or X-rays), producing an electrical signal which holds information about the sample surface properties at the point of impact
- the detector signals are put together point by point by a computer, forming an image which displays the sample surface
- the resolution of the image is directly related to the size of the electron beam spot at the sample surface

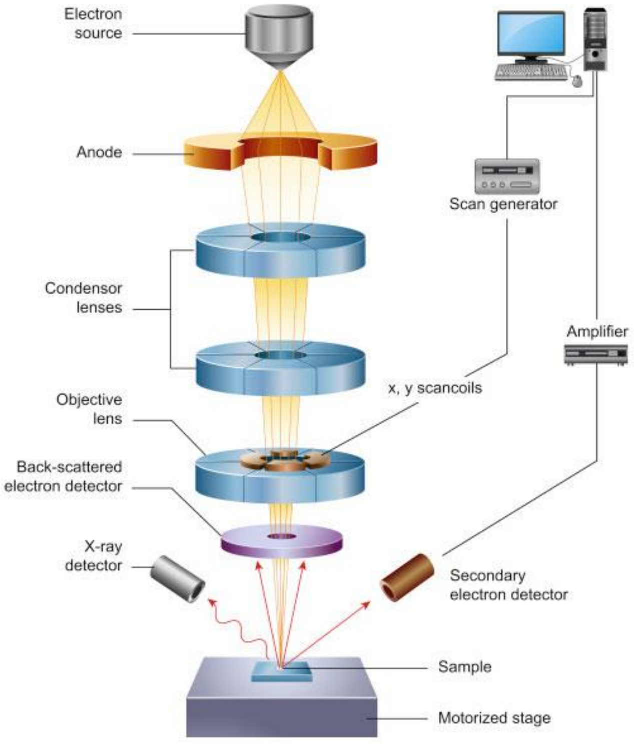


Figure of merit for a SEM electron beam: normalized („reduced“) brightness B_r

B_r = electron current / (spot area * solid angle * beam voltage)

high B_r is necessary for high resolution and less noise in the SEM images, the higher B_r the smaller the useful electon beam focal spot size

B_r is determined by electron emitter properties, it cannot be improved by electron optical components in a SEM (Liouvilles theorem)

The quality of a SEM is based on the type of its electron emitter

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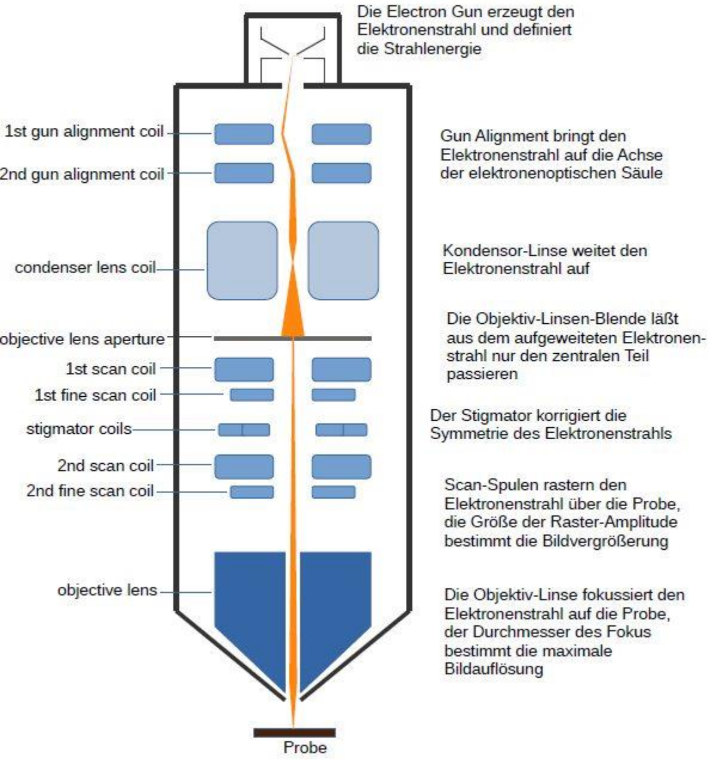
Comparison of standard electron emitters used in a SEM:

Type	W hairpin thermal emitter	LaB6 thermal emitter	Schottky ZrO/W field emitter	Cold W(310) field emitter
Relative B_r	1	10	1000	2000
Vacuum require-ment [mbar]	1e-5 Normal vacuum	1e-7 Good high vacuum	1e-9 moderate UHV	1e-10 UHV

Elektronenoptische Komponenten des JEOL-6510 Raster-Elektronenmikroskops



A detailed view into the interior of a SEM electron optical column:

The main tasks of the electron optical column are:

- Adjust electron beam spot size (-> image resolution)
- Adjust electron beam intensity (-> image noise)
- Minimize electron beam distortions (-> image resolution)
- Adjust scan parameters of the electron beam (-> field of view, speed of image acquisition)

Purpose of Gun Alignment:

move the electron beam to the center of the electron optical column
and make it going down the optical axis

Technology of gun alignment:

- 2 independent electron beam alignment units at 2 different distances from the source
- Each of the alignment unit consists of 2 dipole deflection structures (X und Y-direction)
- Minimum number of alignment elements is 4 per alignment unit

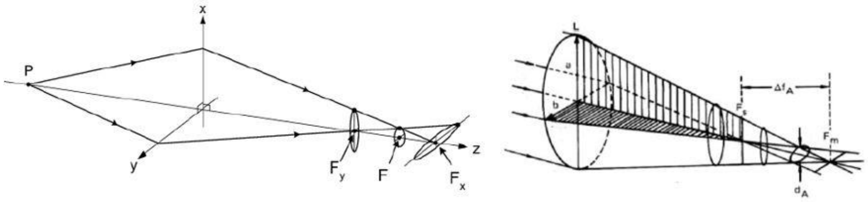
-> MEMS technology favours electrostatic beam deflection by flat metallic structures on the surface of the MEMS chip

we take the beam alignment out of the SEM column and place it into our MEMS electron gun

Purpose of Stigmator:

correct electron beam focus asymmetry

due to imperfections in the column the electron beam usually is distorted:



- minimum number ot independent correction elements to The correct the lowest order is 8
- consists of one quadrupole deflection structur
- can be placed anywhere in the electron beam path

we take the stigmator out of the SEM column and place it into our MEMS electron gun

Elements of our gun design:

Electron beam generation:

Type of electron emitter: -> cold field emission from Si tip
Type of emitter-extractor MEMS geometries, 2 possibilities:
- a) integrated gate on emitter chip
- b) emitter and extractor on separate chips

Our choice -> b) for less risk of leakage current and voltage breakdown

Electron beam alignment:

Electrostatic alignment by flat metallic structures (2 options for the arrangement):
- a) as chip stack on 2 different chips, separated by some distance in beam line direction
- b) both alignment structures on the same chip surface, having different action ranges

Our choice -> b) for smaller size and easier fabrication

Electron beam stigmation:

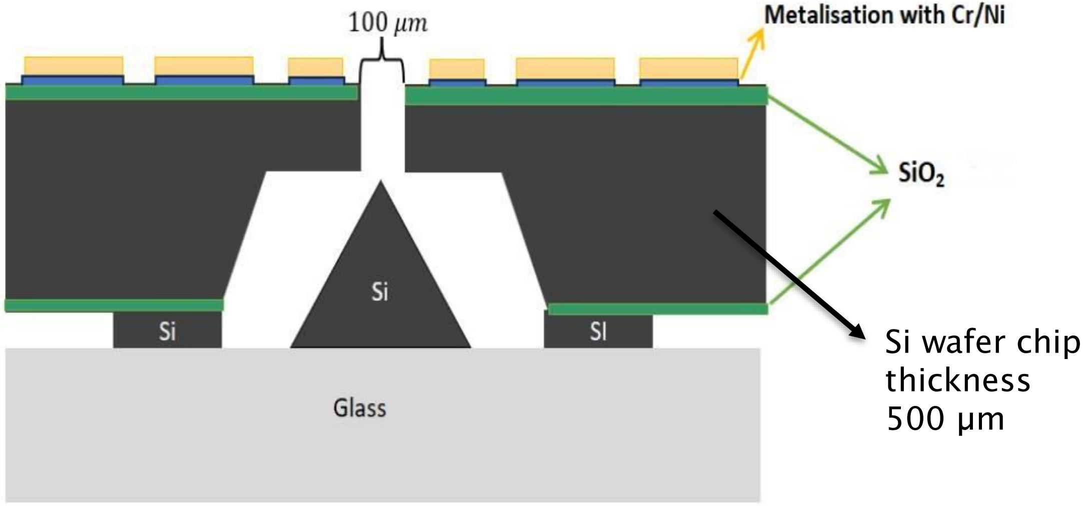
Type of stigmator: electrostatic octupole
Geometry: octupole, flat metallic structures (fields) on chip surface
Advantage: can use the same metallic fields as the beam alignment (if beam alignment is made out of 8 fields each)

Vacuum connections and electrical feedthroughs:

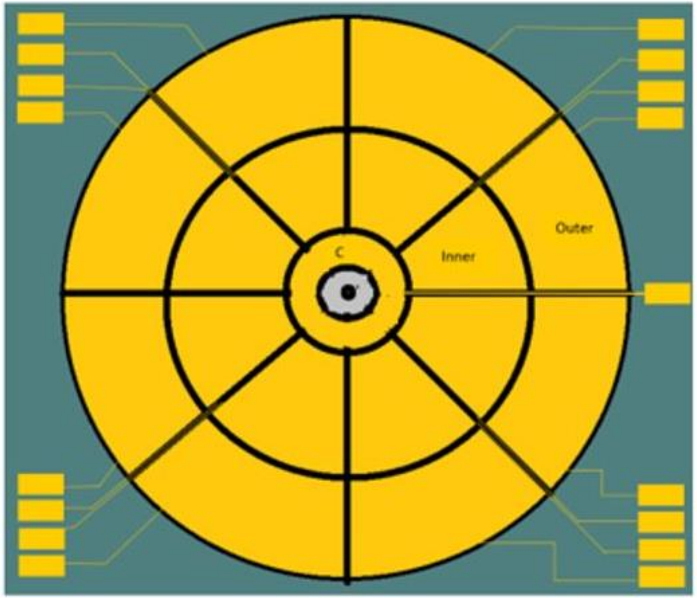
emitter chip vacuum mount: anodic bonding or UHV compatible glue
emitter electrical feedthrough: hole drill through anodically bonded glass chip (-> M. Krysztof)
alignment structure feedthrough: electrically insulation UHV glue on top surface of chip

Our design:

Electron beam alignment and stigmation can be easily integrated onto one MEMS chip:



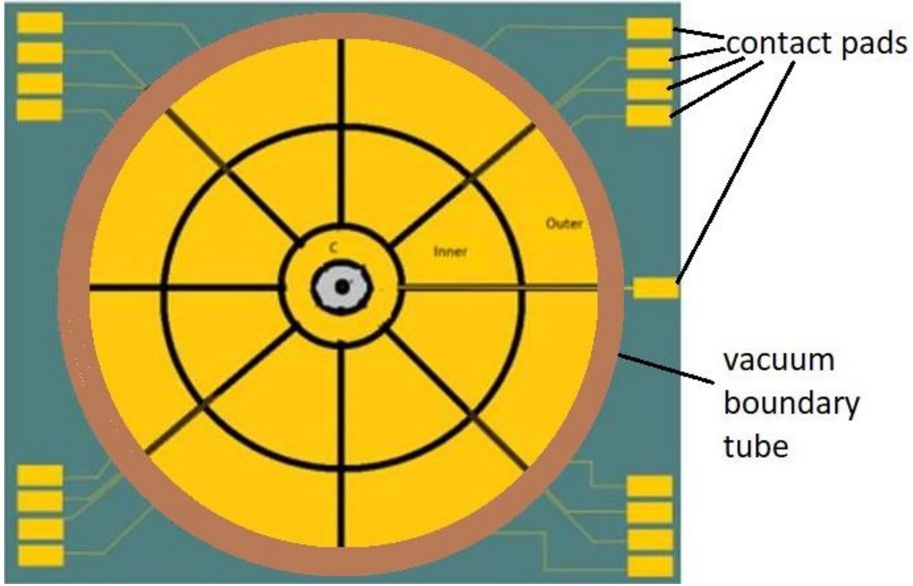
Design side view



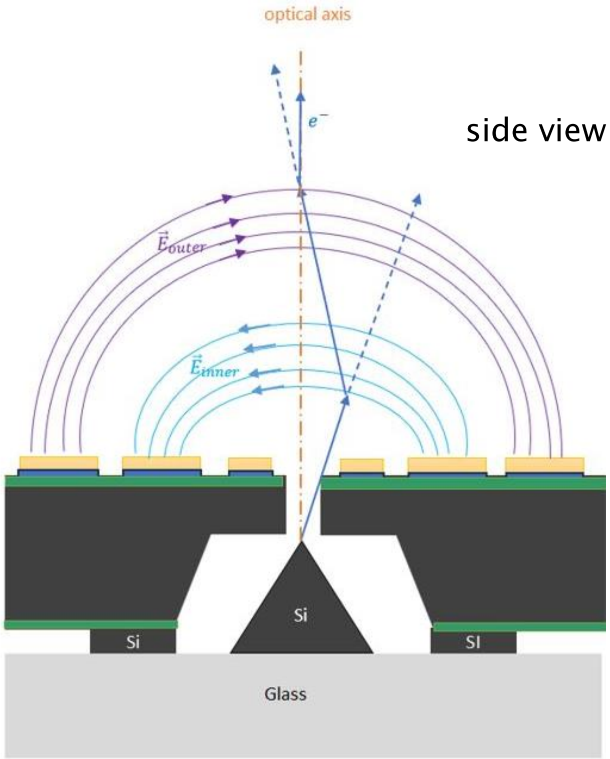
Top view

alignment and stigmation functionality:

top view



side view



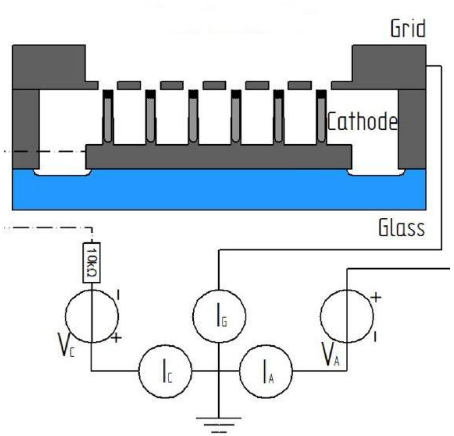
N.B.: stigmation functionality is provided by dividing alignment structures into 8 sector fields instead of 4

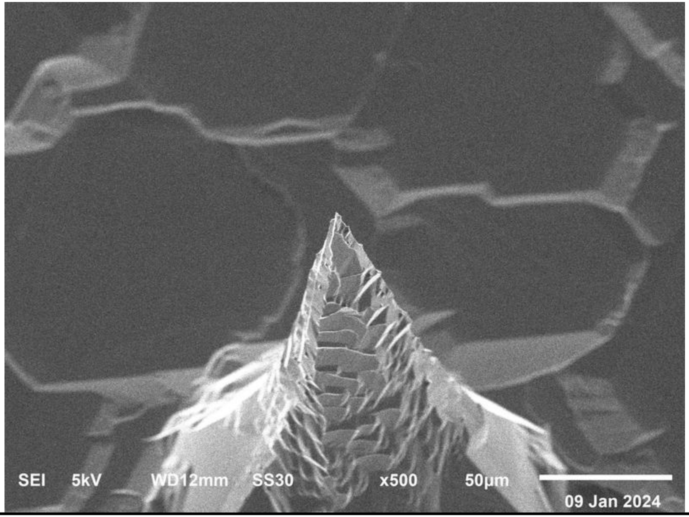
Si emitter production methods established at OTH Regensburg:

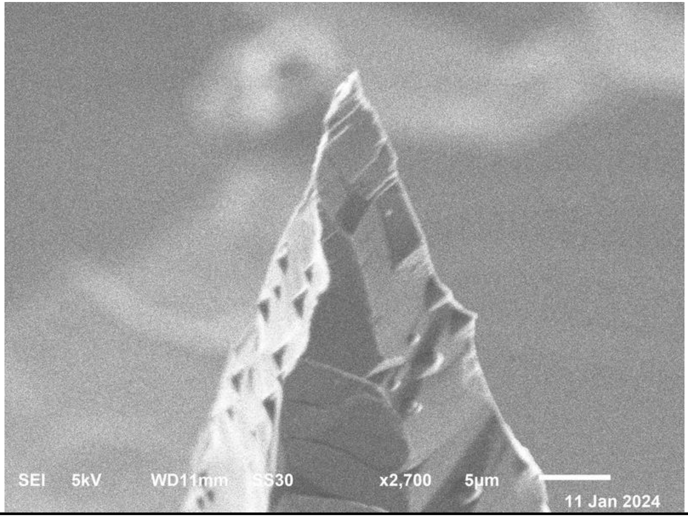
a) Laser ablation for pyramidal shape Si tips with consecutive chem. sharpening:
M. Hausladen et al, Vac. Sci. Technol. B 42, 012201 (2024)

b) Si pillar etching („Bosch“ process) with consecutive nanotip etching:
Ph. Buchner et al, Vac. Sci. Technol. B 42, 022208 (2024)

c) and some more

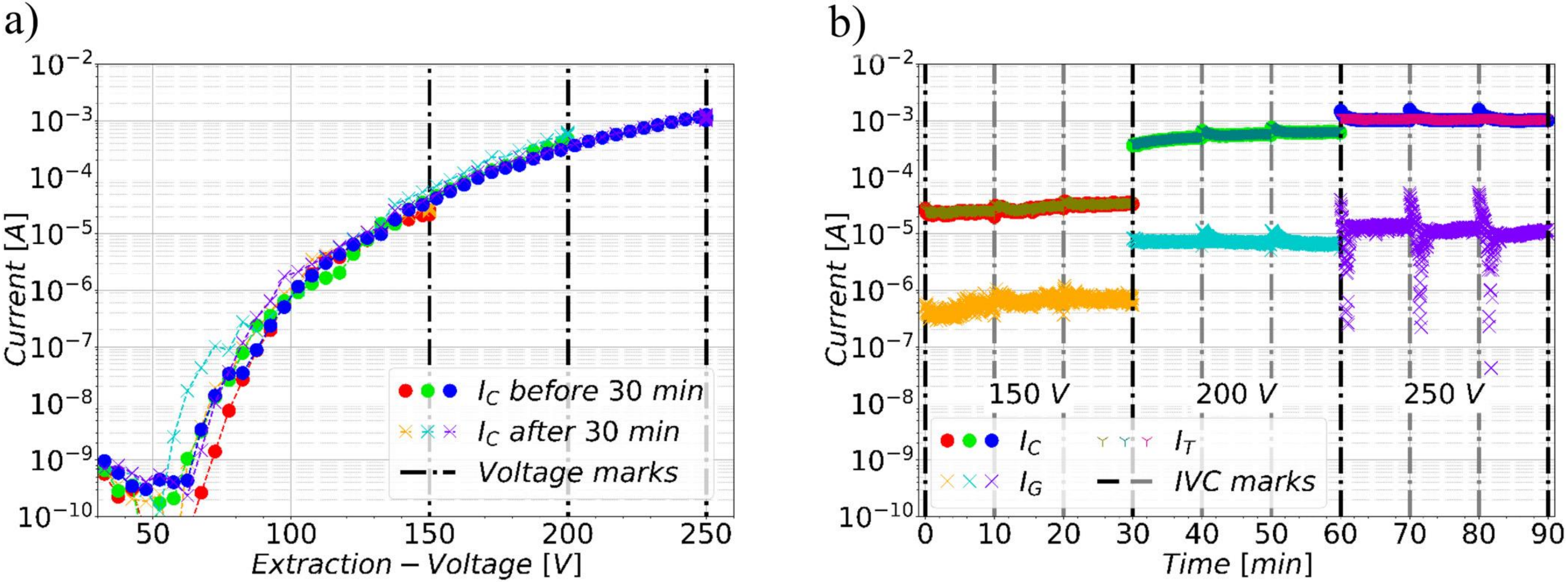






Emission measurement of laser ablated 21x21emitter tip array – extraction grid array (M. Hausladen):

Onset voltage approx. 50 to 70 V at 1 nA
Operating emission current per tip approx. 2 – 3µA at 250V
-> with same production technology chips containing just one single emitter can be produced as well

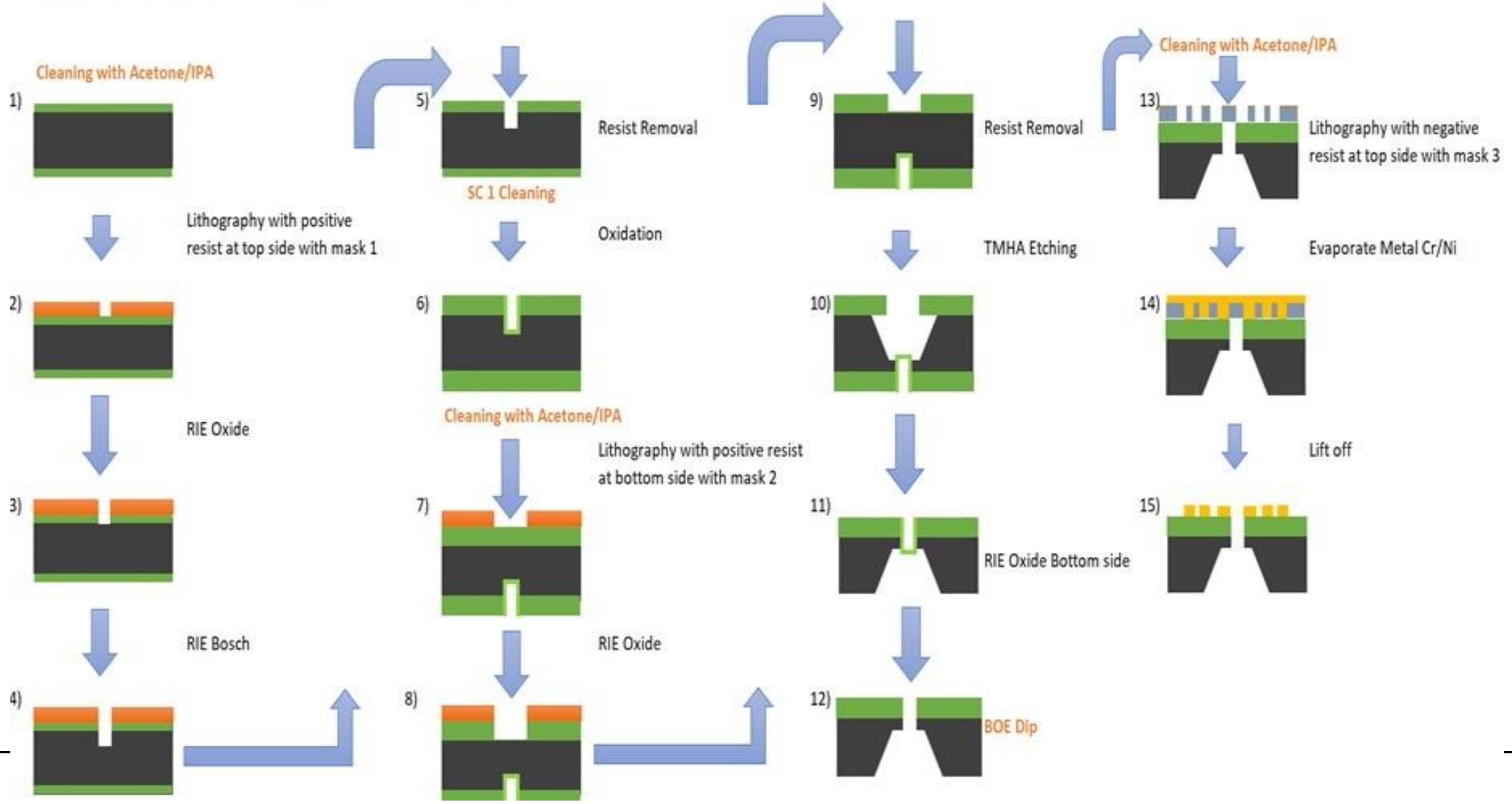


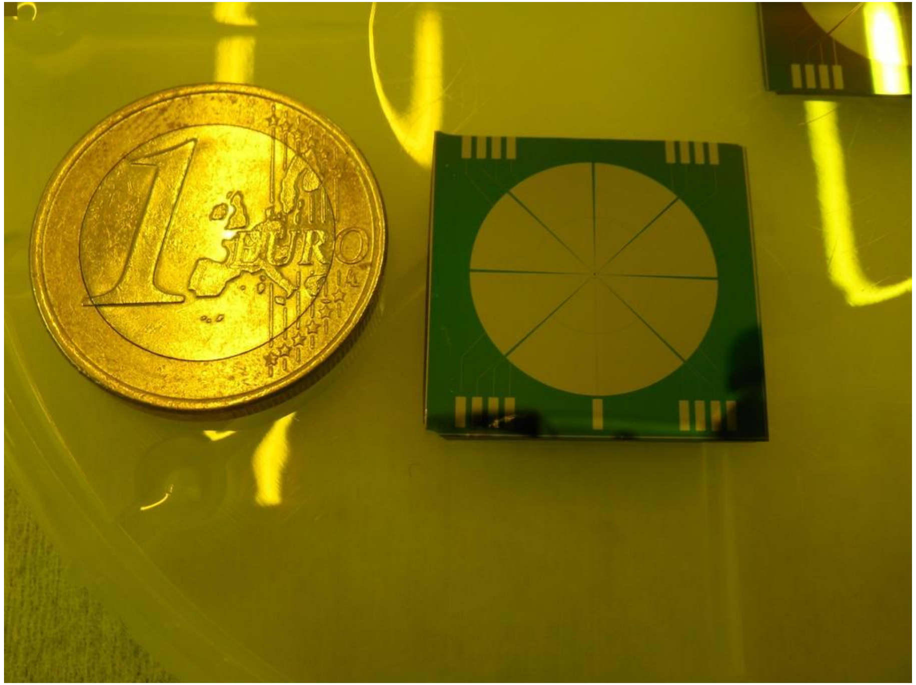
Alignment chip production method (master thesis Ch. Sapannarat):

Use of standard MEMS process technology:

- Start with double sided oxidized Si-wafer (electrical conductor plus electrical insulation)
- In-house Mask production for optical lithography (0.5µm precision masks)
- Structuration of wafer surfaces with thin film resist (approx. 2µm thick):
  - Silicon etching by TMAH
  - Silicon oxide etch by BOE
  - Metallisation (100nm Cr-Ni) by lift-off
- Both front side an back side need to be processes separately

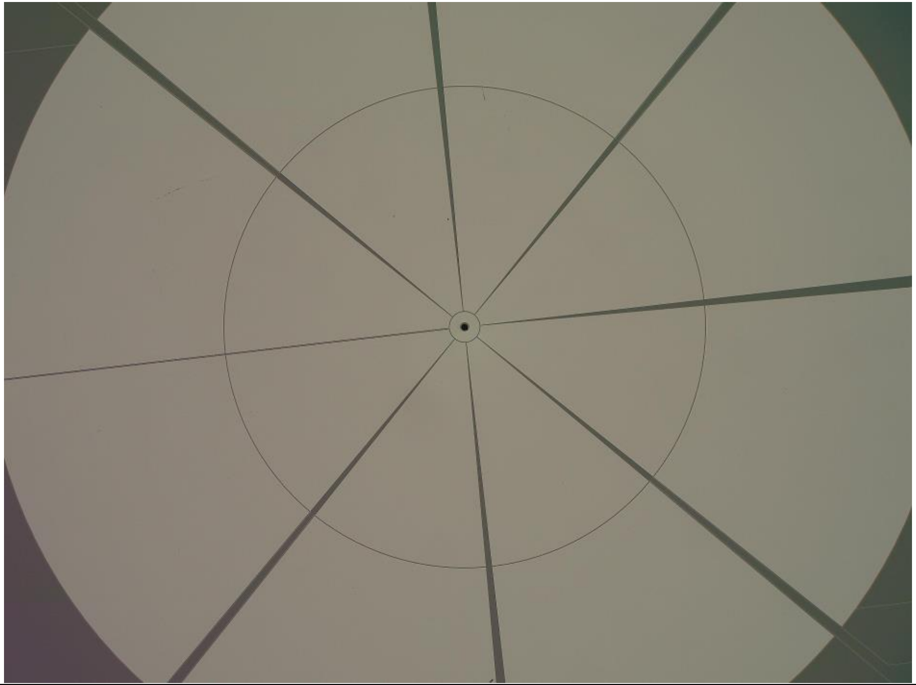
Even when using standard MEMS process technology, care must be taken to provide compatibility from one process step to all other following steps:
-> 15 process steps necessary for final chip structure


Cleaning with Acetone/IPA
1)
Lithography with positive resist at top side with mask 1
2)
RIE Oxide
3)
RIE Bosch
4)
5)
Resist Removal
SC 1 Cleaning
Oxidation
6)
Cleaning with Acetone/IPA
Lithography with positive resist at bottom side with mask 2
7)
RIE Oxide
8)
9)
Resist Removal
TMHA Etching
10)
11)
RIE Oxide Bottom side
12)
BOE Dip
Cleaning with Acetone/IPA
13)
Lithography with negative resist at top side with mask 3
Evaporate Metal Cr/Ni
14)
Lift off
15)



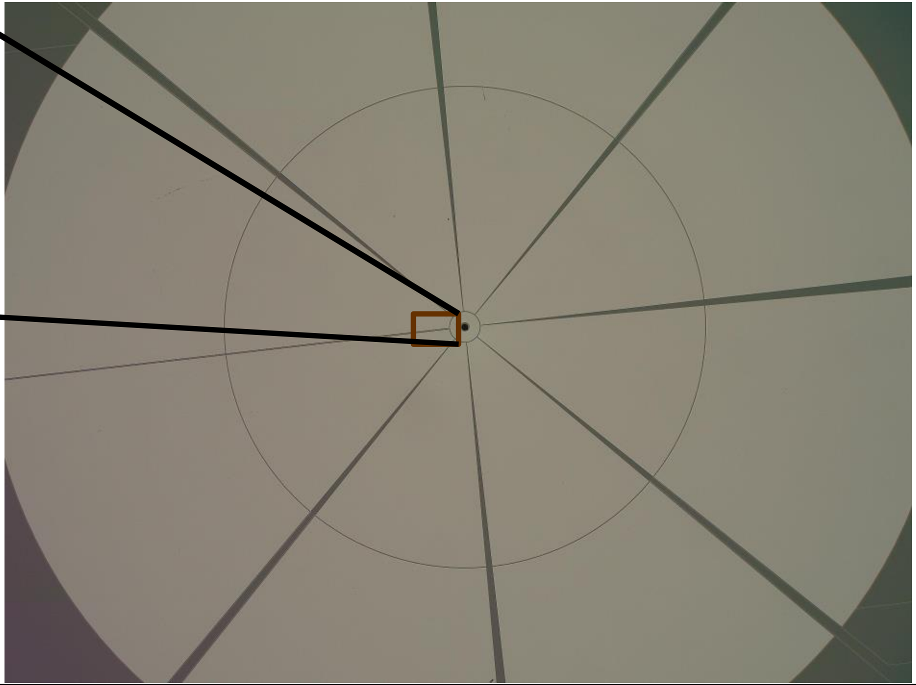
MEMS chip, for size comparison

flat metallic deflection structures (fields), comprising extraction, alignment and stigmation:



High magnification of a central part:
metallic conduction line width 10µm

Alignment and stigmation fields, surview



Dimensional chip structure layout:

extraction hole opening diameter: 100µm

centering of emitter tip to extraction hole by optical microscope easily done
extraction electrical field at the tip still defined by tip radius rather than extraction hole diameter
-> no increase in extraction voltage

diameter of metallic extraction field: 500µm

centering of emitter tip to extraction hole by optical microscope easily done
extraction electrical field at the tip still defined by tip radius rather than extraction hoe diameter

metallic conduction line width: 10µm

minimal influence on symmetry of electrical fields
Can be easily produced by „lift off technology“ (preferred)

distance between metallic conduction lines and adjacent metallic structures: 10µm

good enough for voltages up to max. 100V

size of alignment metallic structures: approx. 4mm

not optimised, but good enough for the beginning

size of contact pads for power supply connection : 0.6mm x 3mm

foreseen for contacting with usual FFP-connectors

How to produce UHV condition in the emitter region:

- Pumping unit must have close distance to the MEMS gun:
  - pumping efficiency is (partly) defined by geometry (connection tube diameter, inner volume, shape of volume, …)

- Differential pumping with very small aperture holes for the electron beam allows moderate pumping speed

- Pumping unit must be free of vibrations
  - Gun vibrations directly transform into SEM image distortions

- Possible pumping technology under consideration:
  - MEMS micropump
  - Non evaporable getter (NEG)
  - Commercial small sized ion getter pump (Varian)
  - Differential pumping with several MEMS pumping stages
  - A combination of some of these
  - More solutions? Ideas welcome!

- Our preferred solution: MEMS micropump
  (T. Grzebyk et al: MEMS ion sorption high vacuum pump, Journal of Physics: Conference Series 773 (2016) 012047)

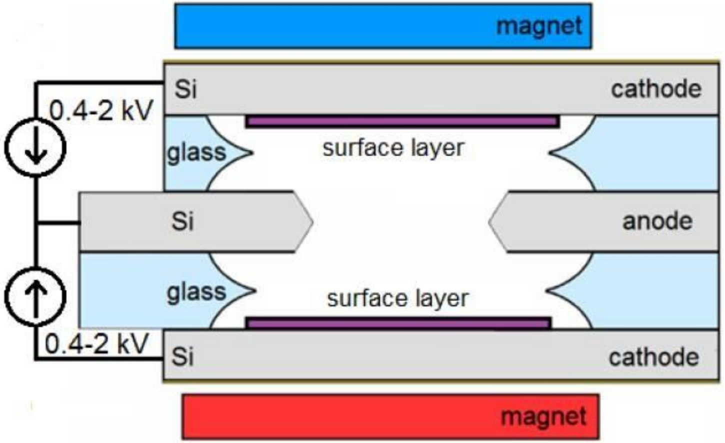
A MEMS micropump:

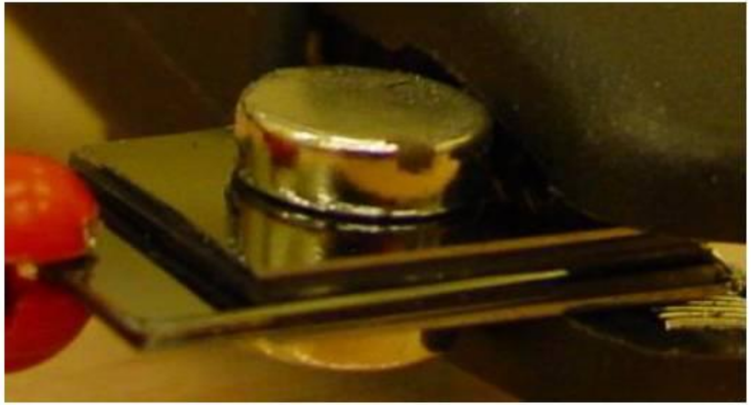
(T. Grzebyk et al: „MEMS ion sorption high vacuum pump“, Journal of Physics: Conference Series 773 (2016) 012047)

Operation similar to a diode type ion getter pump

- very small size (footprint ~1 cm²), yet high percentual inner surface
- made out of UHV compatible materials
- fabricated by anodic bonding (UHV compatible)
- low power consumption
- vibrational free
- can be combined with other non-evaporable getters
- prototype has been fabricated and tested

However:
- MEMS micropump integration to the MEMS gun not yet defined
- electron emission stability under MEMS micropump vacuum not yet investigated
- shielding of magnetic stray field may become necessary





Next steps to be envisaged:

- Connection of MEMS gun to MEMS micropump
- Measurement of alignment and stigmation efficiency
- Measurement of electron beam energy spread
- Measurement of emission current stability
- Connection of the MEMS gun to a SEM column vacuum tube
- Electronics for MEMS gun operation

Summary and outlook:

- Prototype MEMS emitter chip can be fabricated in-house (OTH) similar to existing MEMS Si emitters, however
  - emission properties still to be investigated with respect to SEM image acquisition requirements (stability, lifetime, energy spread, …)
- Prototype MEMS extraction and alignment chip is fabricated, however
  - efficiency of alignment and stigmation still to be investigated
  - inter-electrode voltage capability still to be confirmed
  - electrical feedthrough capabilities not yet tested
  - vacuum connection to SEM column not yet tested
- Integration of MEMS micropump:
  - prototype of MEMS pump is available (Wroclaw Univ. of Sci. and Tech.)
  - tests of implementation and operation details still to be defined
- Vacuum bonding connection methods are available, but still to be tested
- Electronics for beam extraction, beam alignment and stigmator are available (OTH), yet to be adopted to specific requirements

Thank you for your attention, looking forward to interesting discussions