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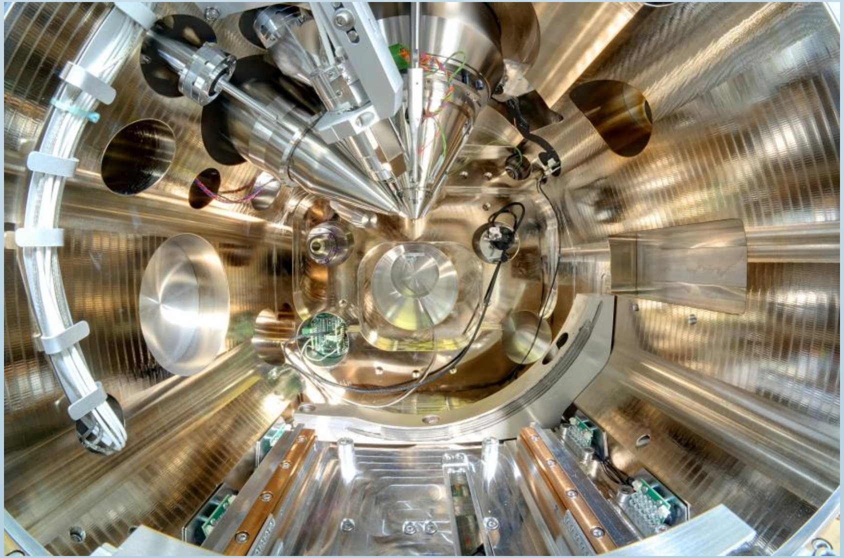
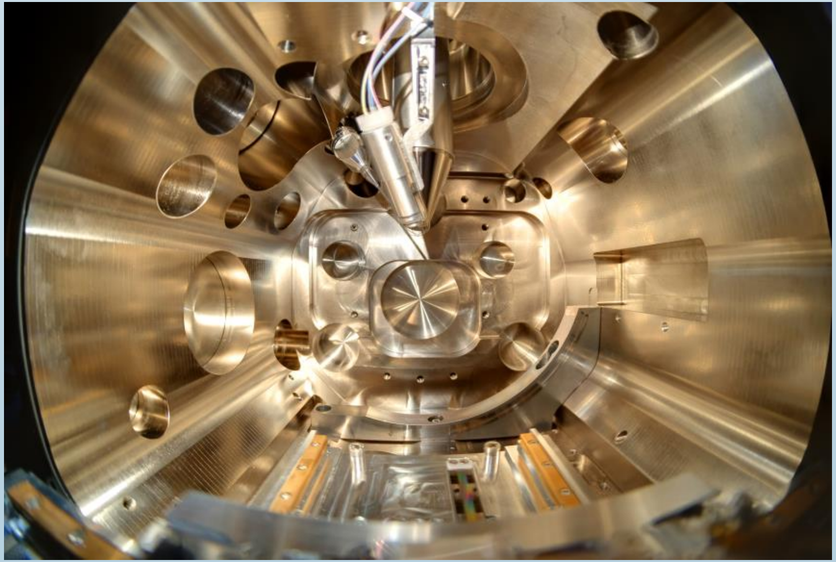
Benefits of a Cs FIB with a low temperature ion source compared to a standard Ga FIB



chamber Ga FIB

vs.



chamber Cs FIB

Thomas Löber, Nano Structuring Center,

Department of Physics, Technische Universität of Kaiserslautern

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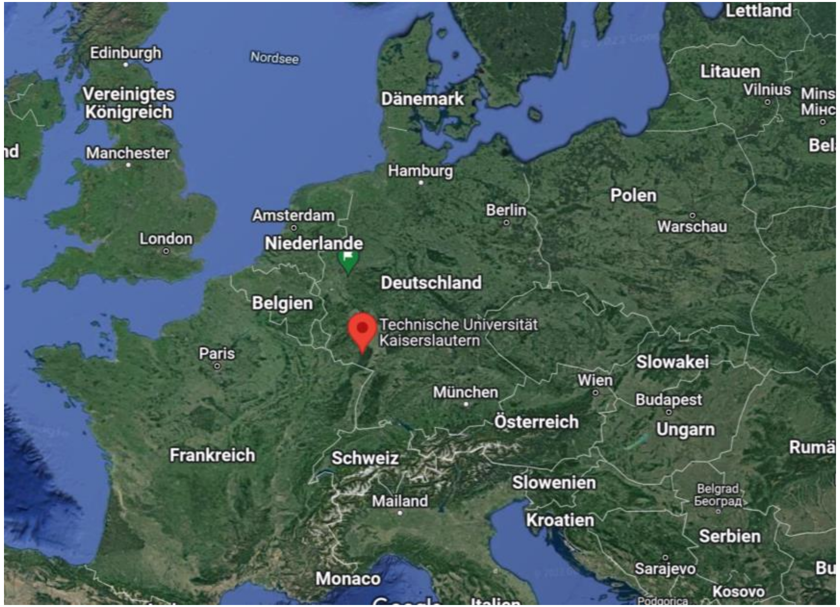

www.google.com/maps

Technische Universität Kaiserslautern

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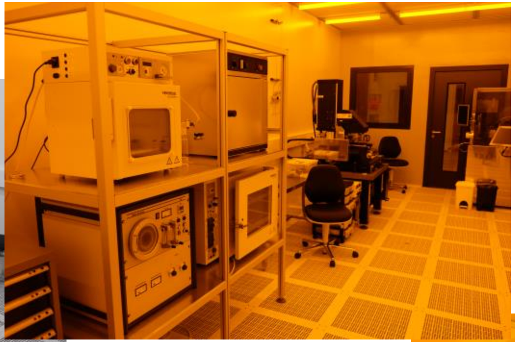

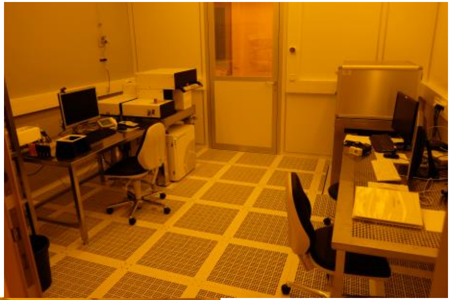

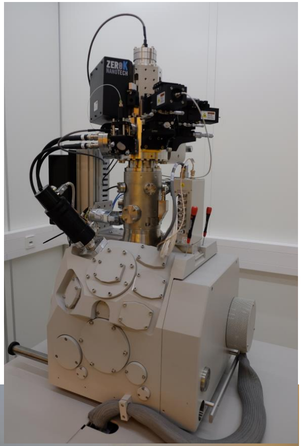

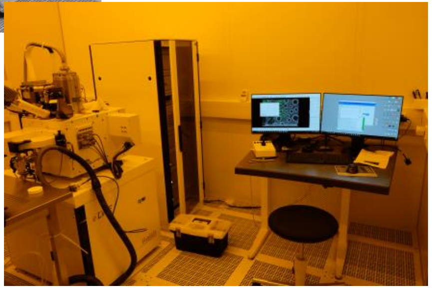

- core facility of the TUK
- electron, ion, photo lithography
- sputtering, e-beam deposition, …
- dry and wet etching, analytic, …

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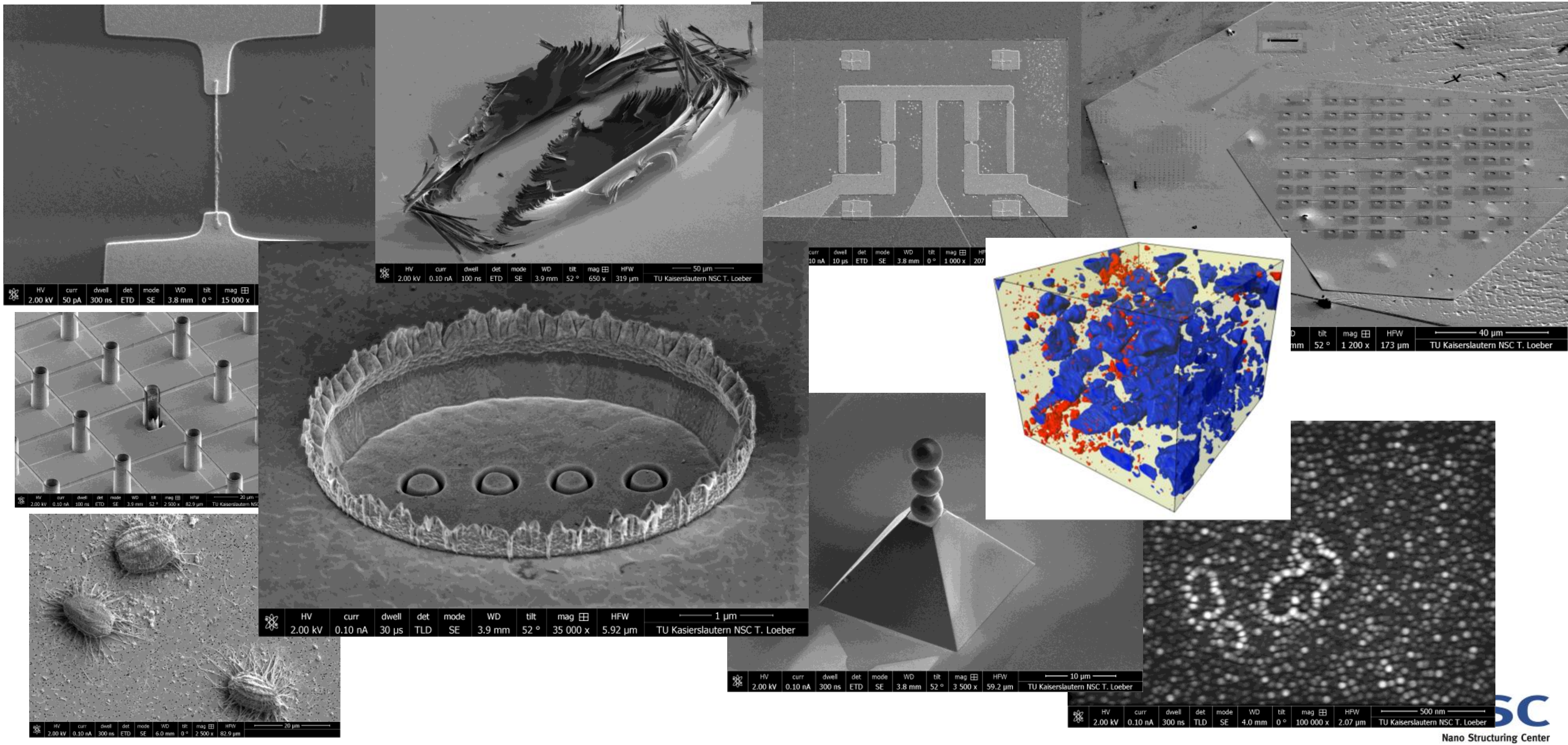


Nano Structuring Center

what we DO

- micro and nano structuring
- developing processes
- supporting students
- training on machines

what we DO NOT DO

- developing machines
- modifying systems

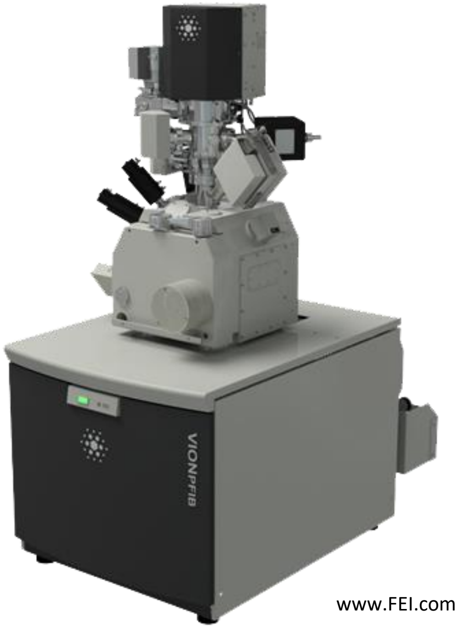
Commercially available FIB systems

www.raith.com

- Ga FIB
- many applications possible
- often combined with SEM

- LMIS with Eutectic
- Ga, Si, Ge, Au, Li, Bi, …
- dedicated ion writer

Commercially available FIB systems



- Xe plasma FIB
- higher currents -> high sputter rates
- large volumes can be milled

- helium or neon ions
- high image quality, small SPL
- low sputter rate

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Low Temperature Cs FIB

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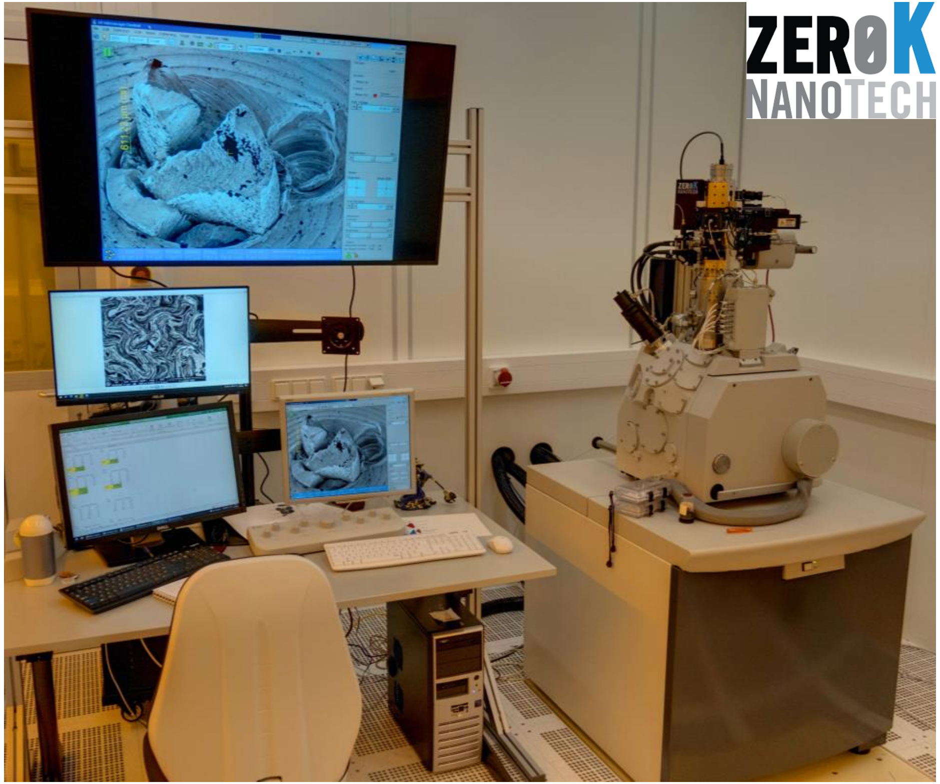

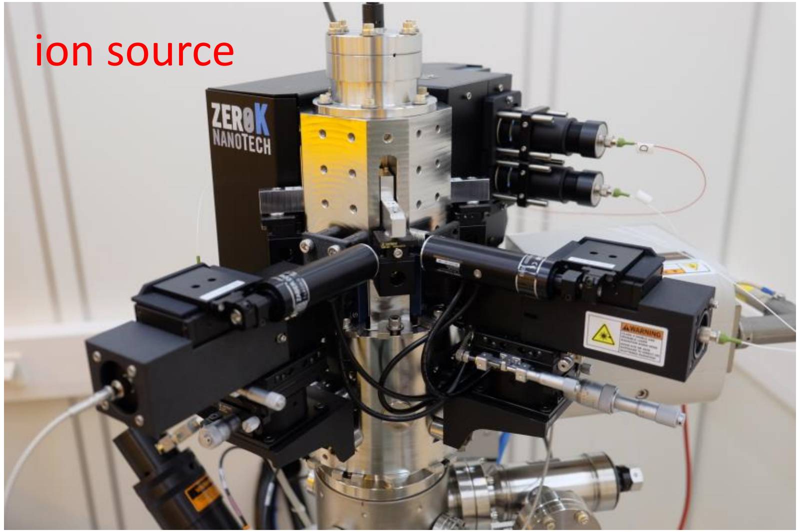

- unique ion source
- uses laser to cool ions
- chamber like FEI Ga FIB
- acceleration voltage 2 – 16 kV

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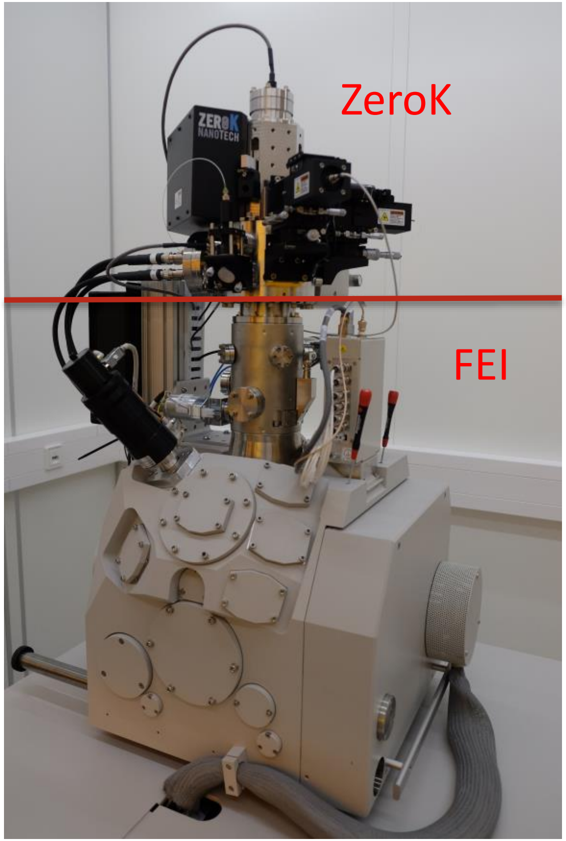
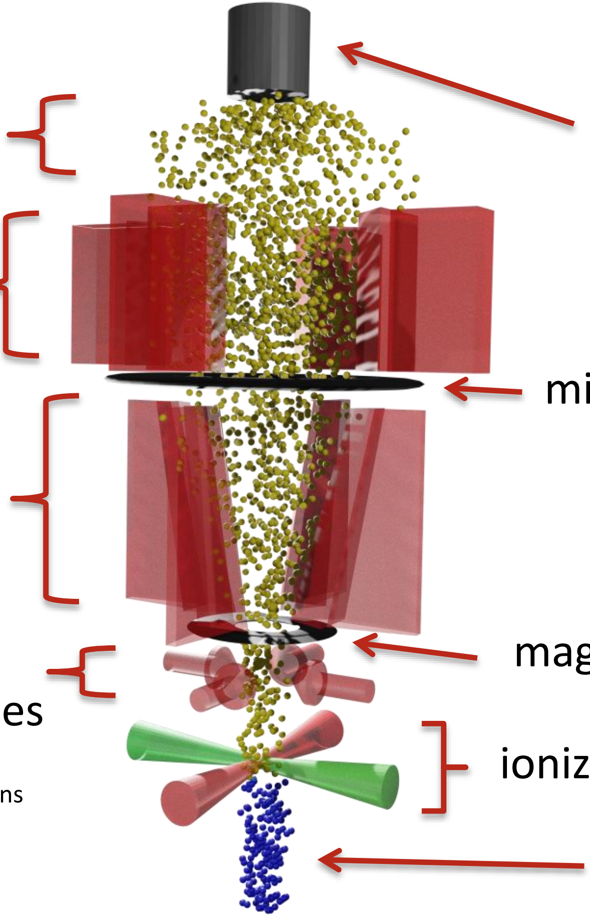
Low Temperature Cs FIB



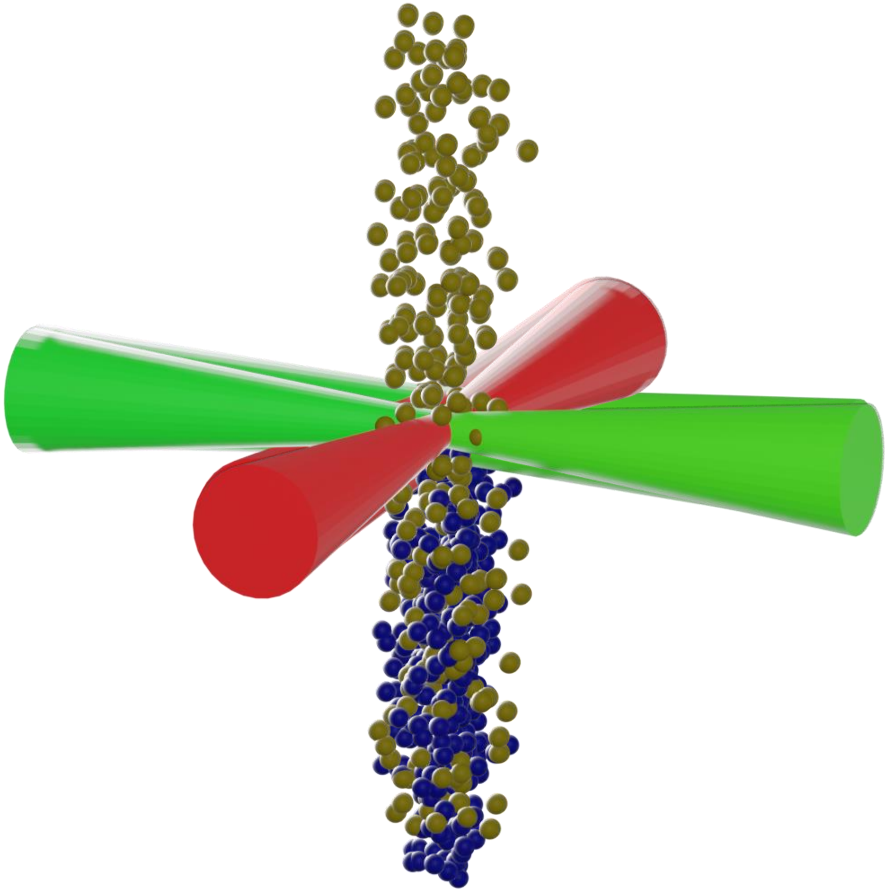
additional
laser rack

LOw Temperature Ion Source LOTIS



Cold atomic beam ion source for focused ion beam applications
Journal of Applied Physics 114, 044303 (2013)
https://doi.org/10.1063/1.4816248
B. Knuffman, A. V. Steele, and J. J. McClelland

Ionization



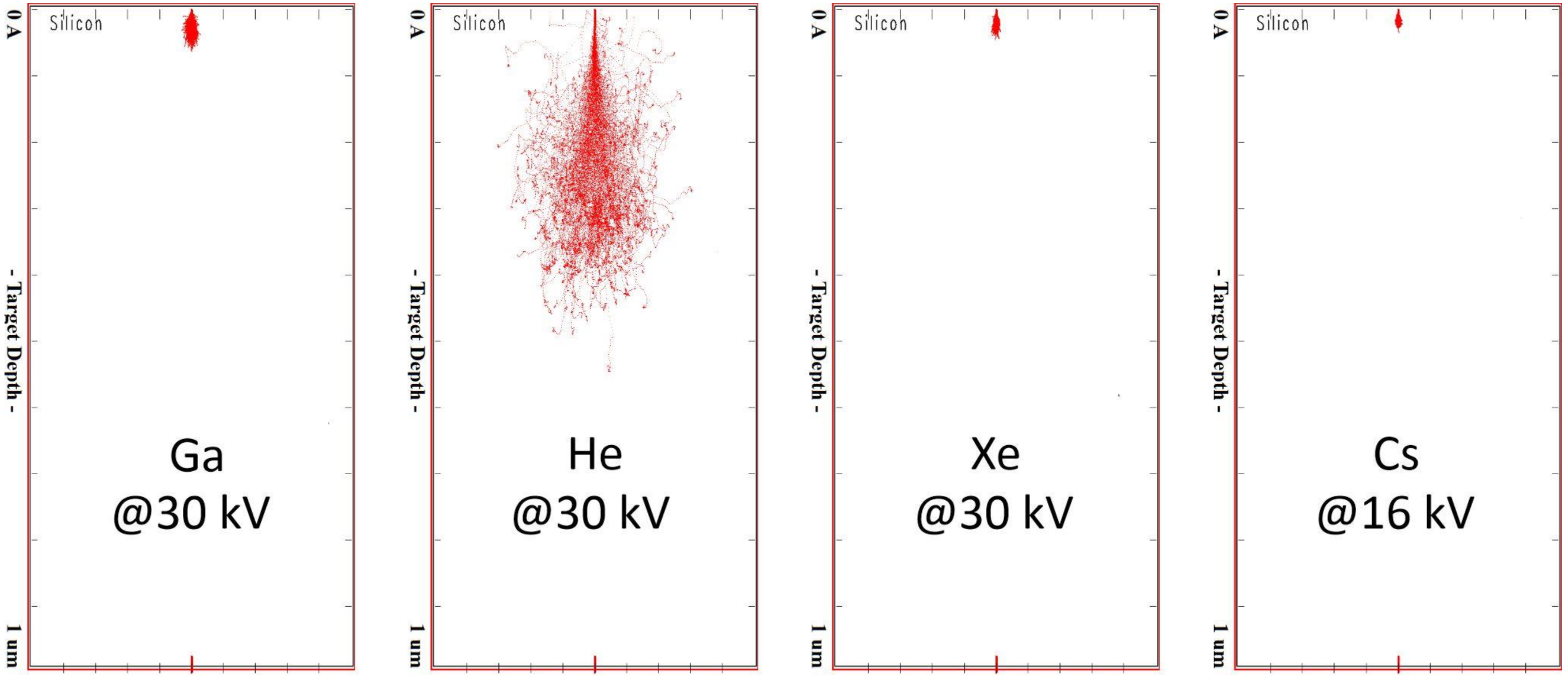
- 2 step ionization
- only in focus of both lasers
- laser power can be changed
- laser beam diameter can be changed
- ion beam can be changed continuously
- no aperture needed

- minimal T ≈ 30 µK
- energy spread ΔE = 0.45 eV
- accl. voltage U = 2 - 16 kV
- ion beam pA to nA

Comparison

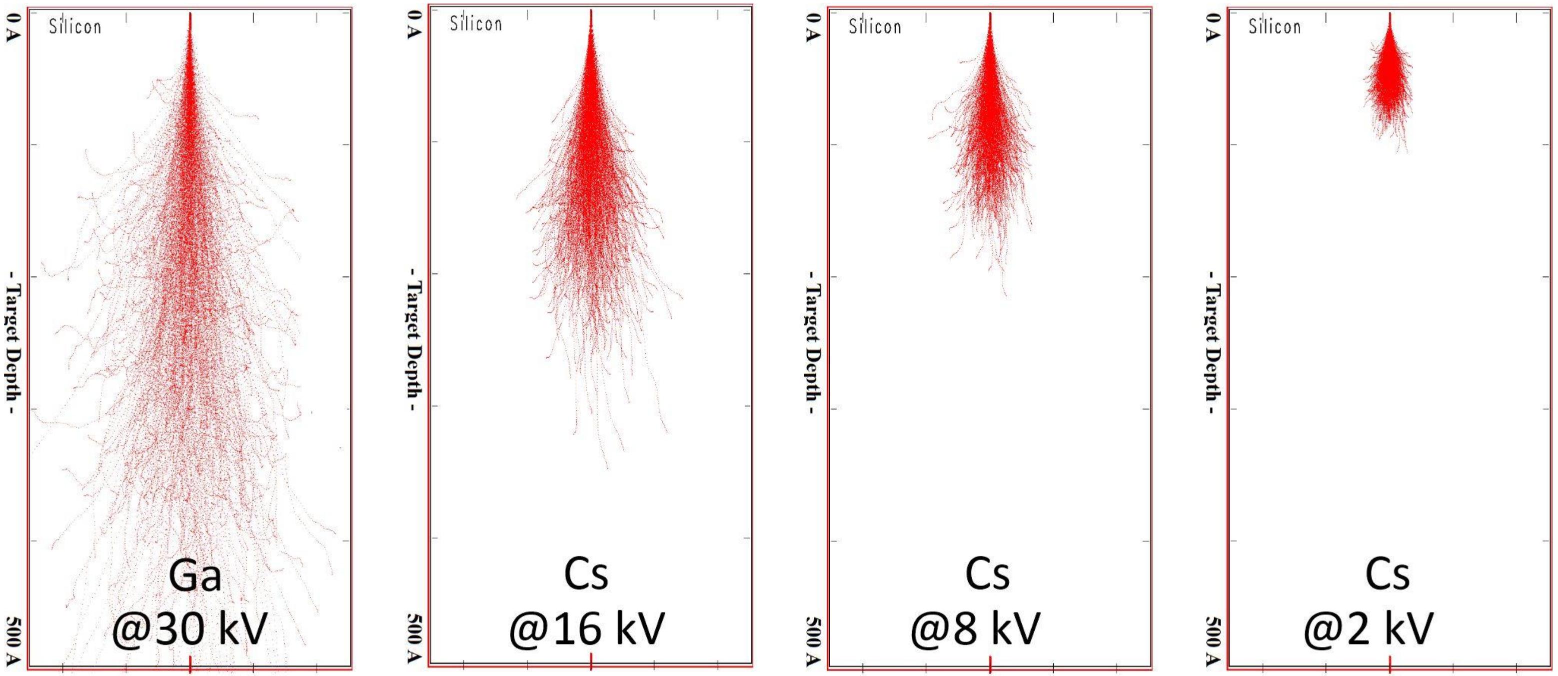
	Ga FIB	Helium FIB	Plasma FIB	Cs FIB
energy spread [eV]	3 - 5	1	3.5	0.45
accelleration voltage [kV]	30	30	30	2 - 16
brightness [10^6 A m^{-2} sr^{-1} eV^{-1}]	1	1000	0.01	20
ion beam	pA - nA	pA	nA	pA - nA
sputter rate	medium	low	high	medium
single pixel line [nm]	40	4	250	~ 10
penetration depth Si [nm]	28	283	23	6

Penetration depth in silicon



SRIM simulations

Penetration depth in silicon



SRIM simulations

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FIB systems @ NSC

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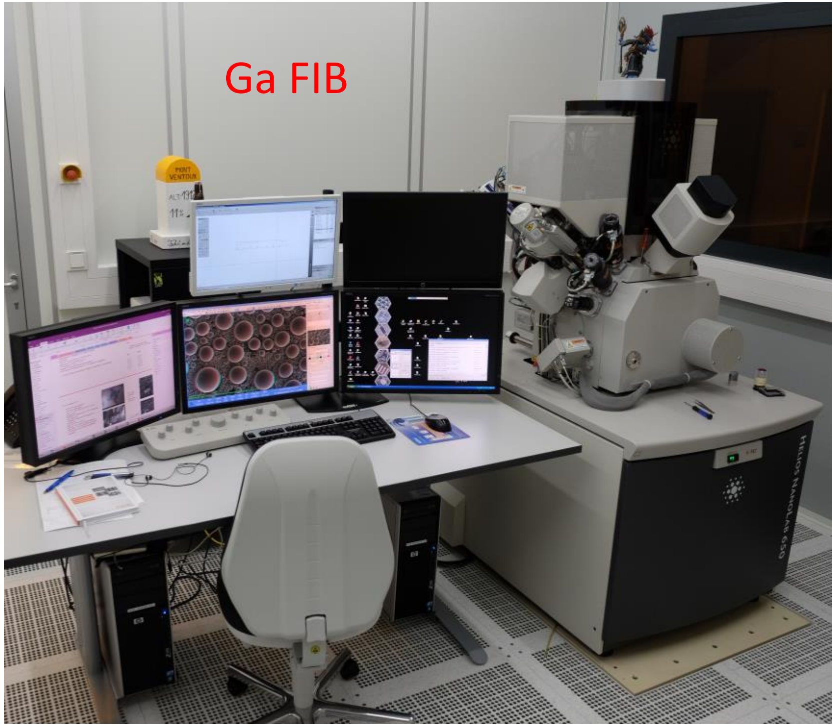
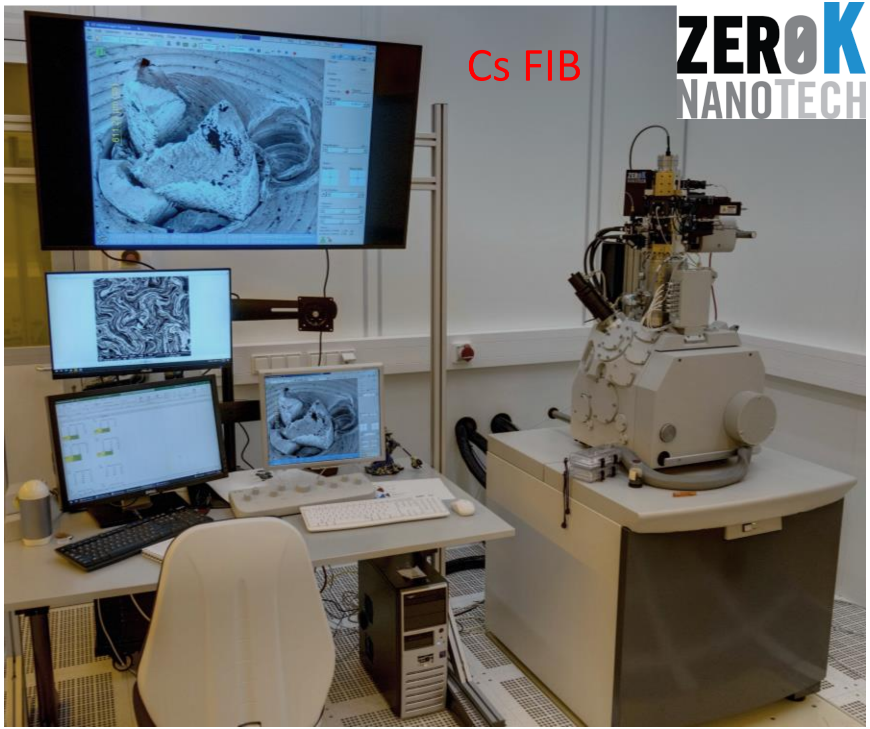


FEI Helios 650 NanoLab DualBeam



ZEROK NANOTECH

ZeroK Cs LOTIS

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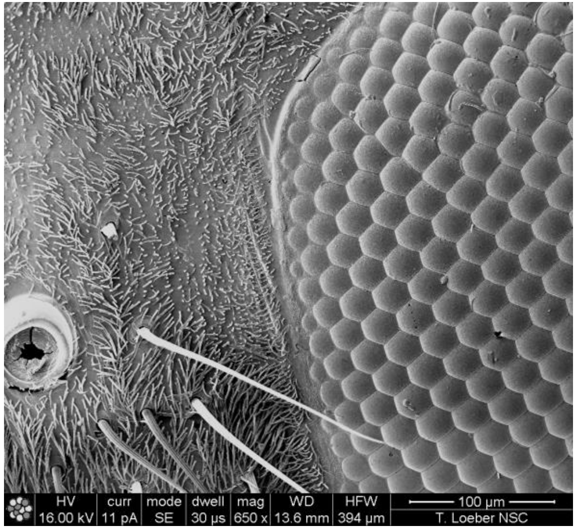
Outline

comparing Ga FIB and Cs FIB

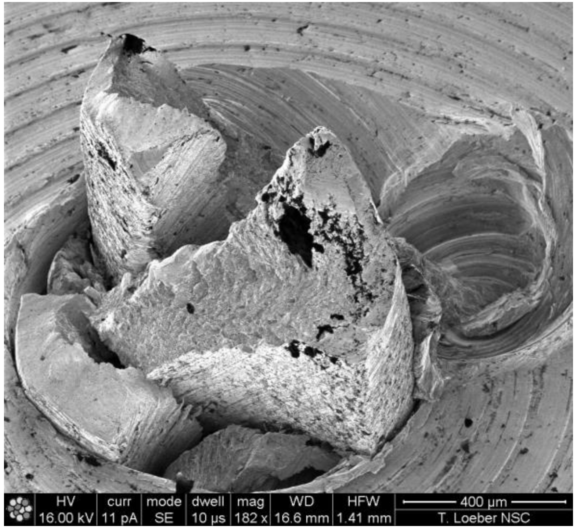
- imaging
  - resolution
  - depth of focus
  - material contrast
  - crystal orientation contrast
- deposition of platinum
- milling
  - silicon
  - silver

Imaging

SE images taken with Cs ion beam @ 16 kV



eye of a fly

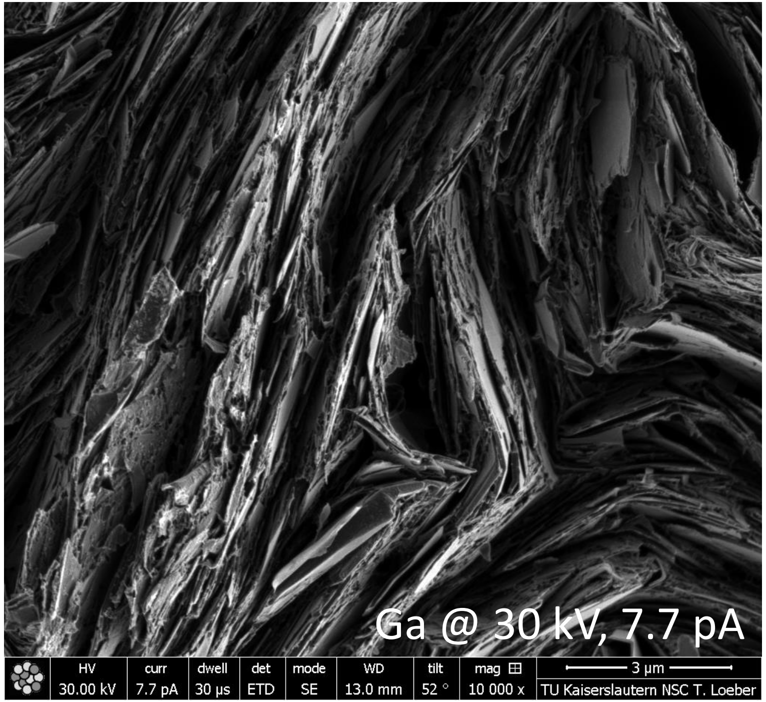


broken drill

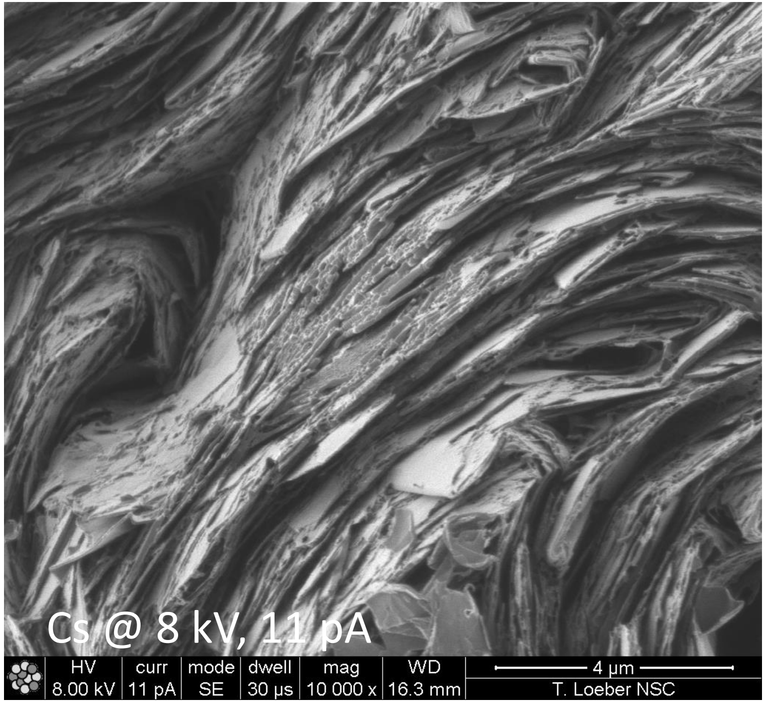
graphite pen

Resolution

Ga ion image



Cs ion image

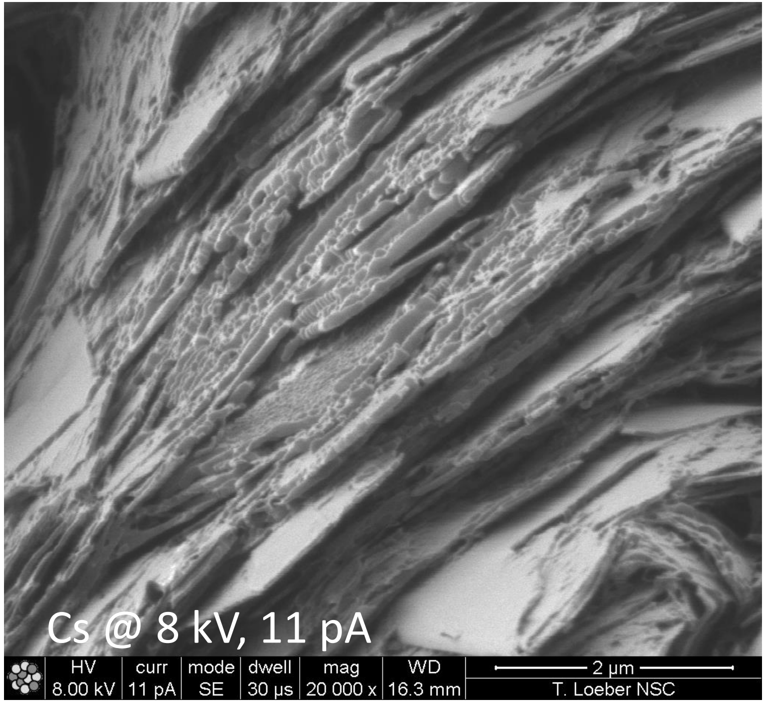


graphite pen: magnification 10k x

Resolution

Ga ion image

Cs ion image



graphite pen: magnification 20k x

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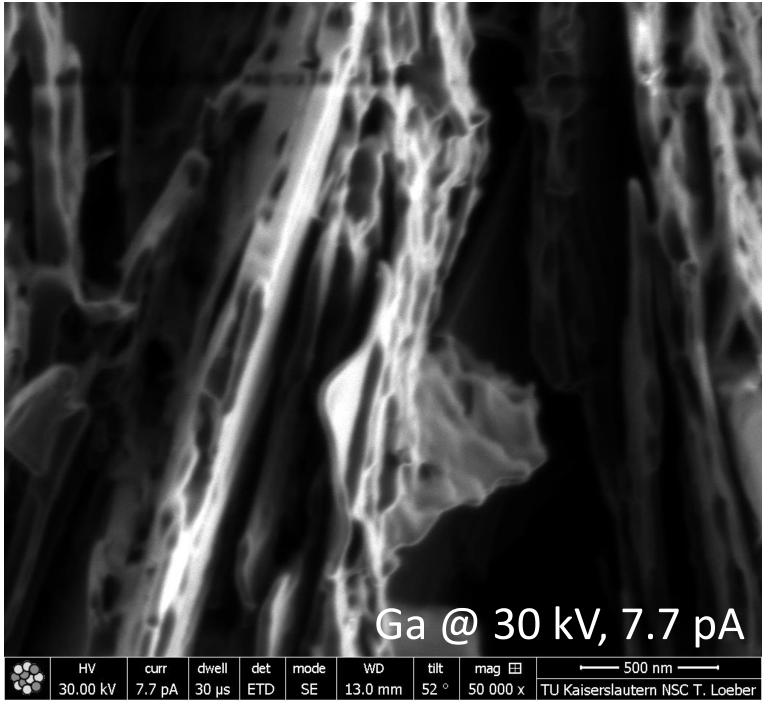
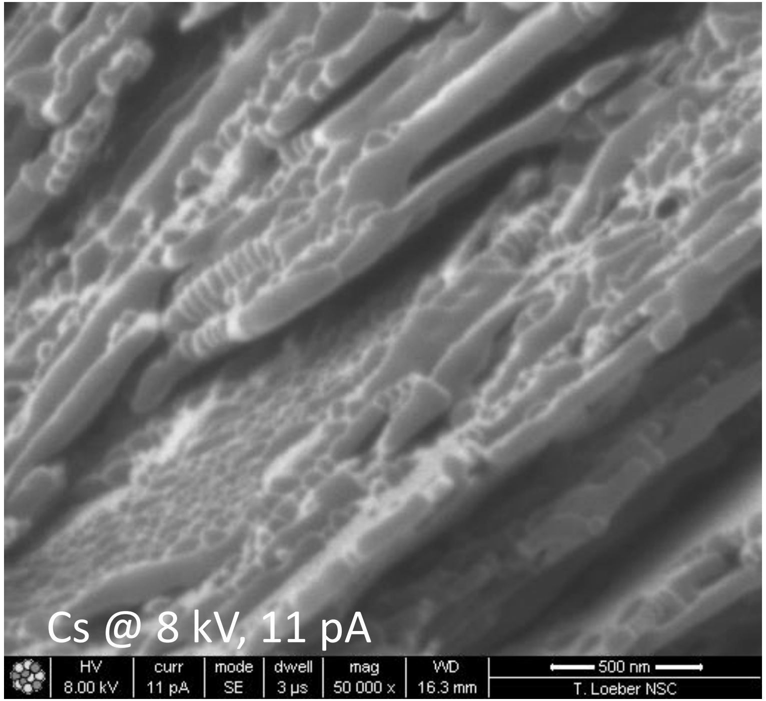
Resolution

Ga ion image



Cs ion image



graphite pen: magnification 50k x

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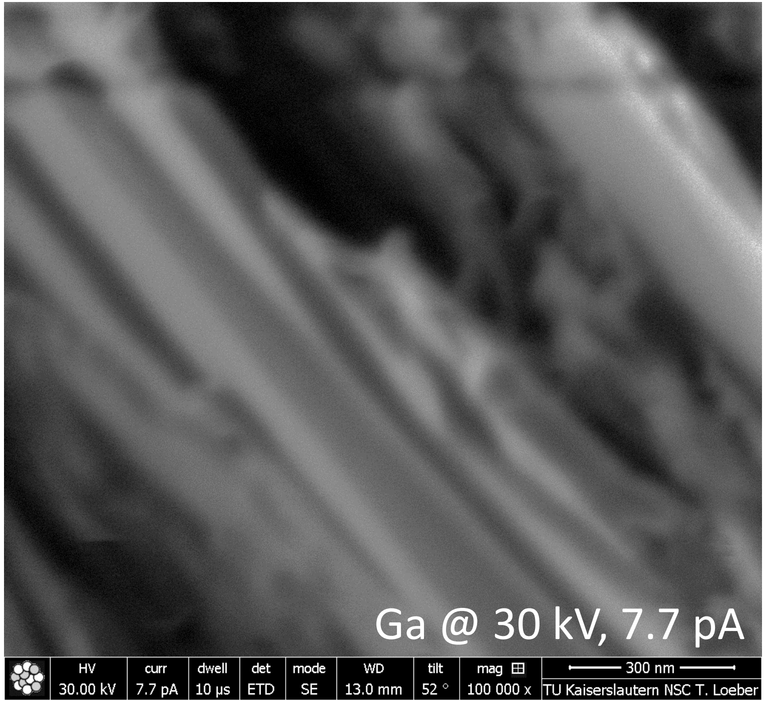
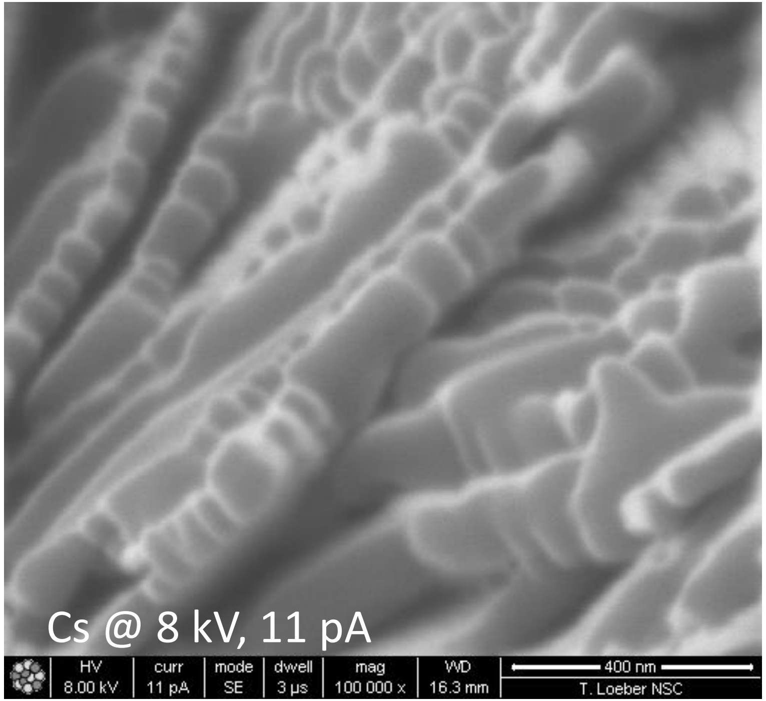
Resolution

Ga ion image



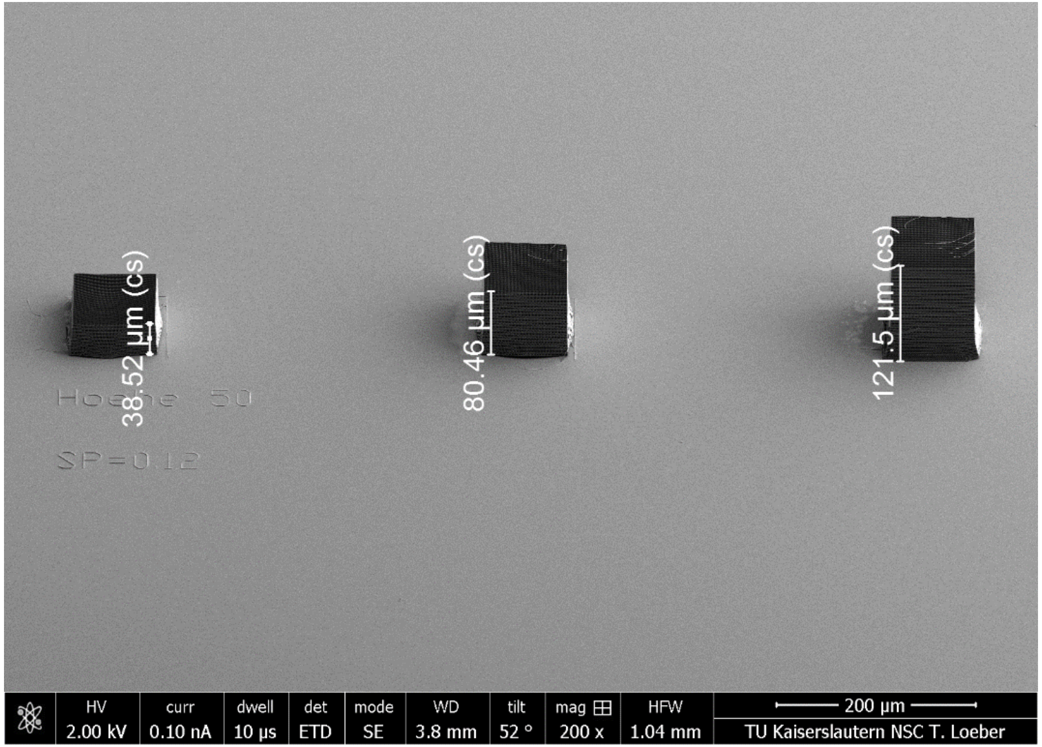
Cs ion image



graphite pen: magnification 100k x

Depth of focus

SEM image: woodpile made of photo resist acrylate



height 40, 80, and 120 µm

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Depth of focus

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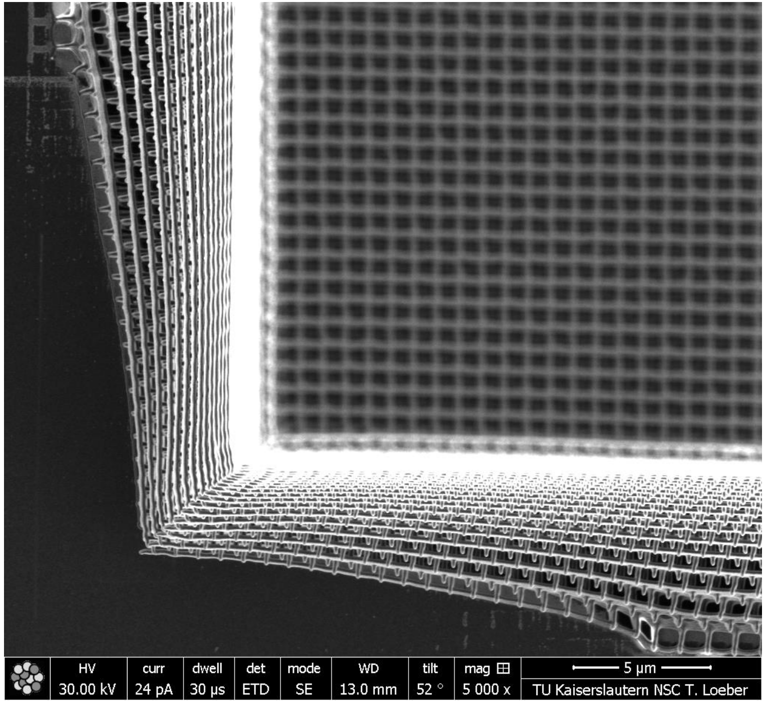
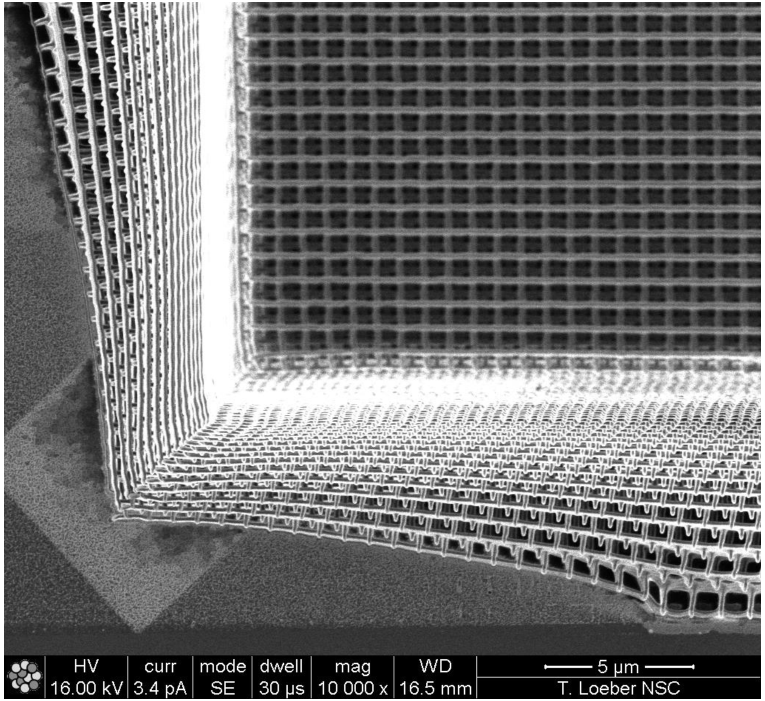
Ga ion image



Cs ion image



wood pile height 120 µm

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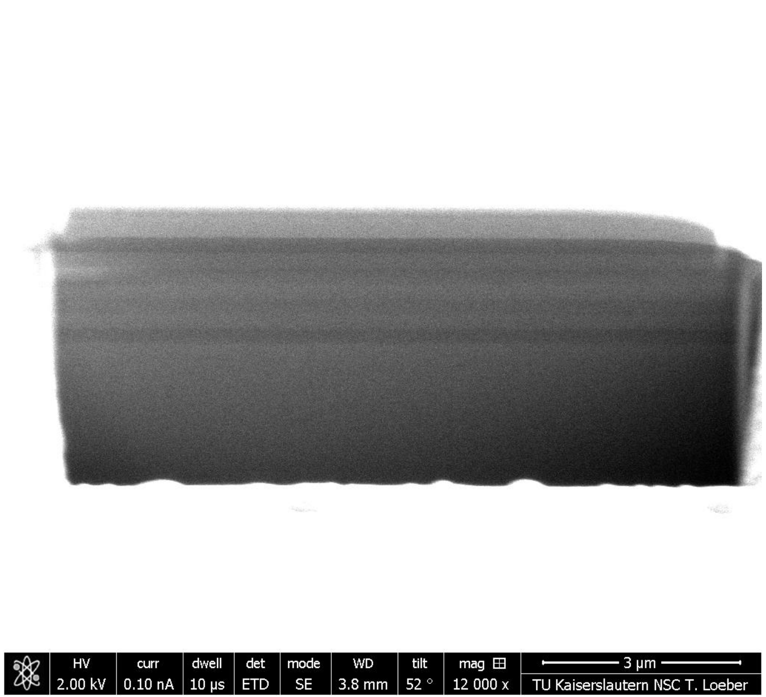
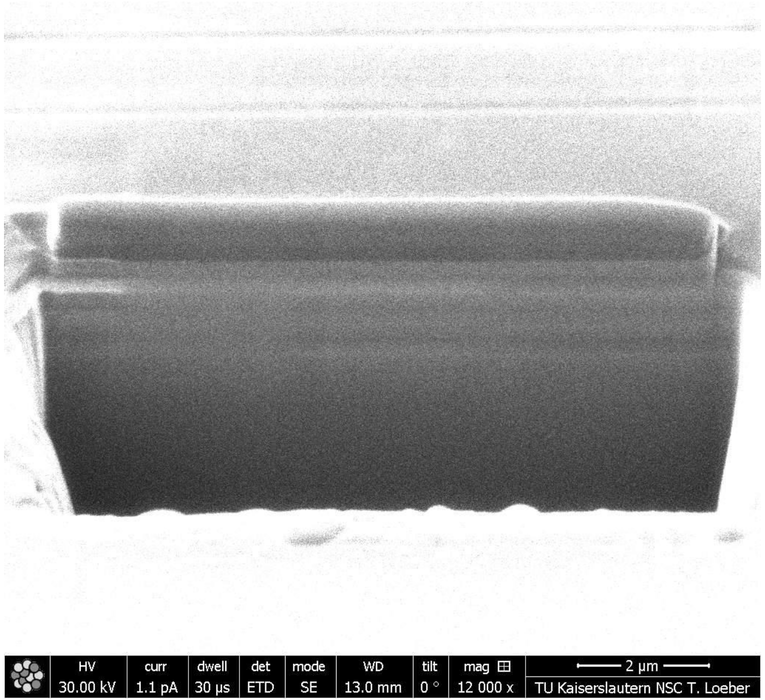
Material contrast

electron image



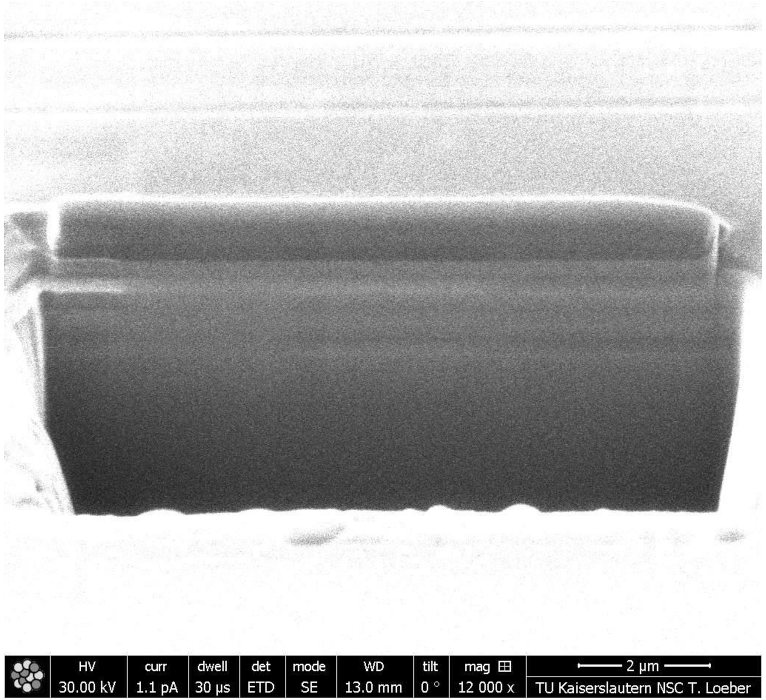
Ga ion image



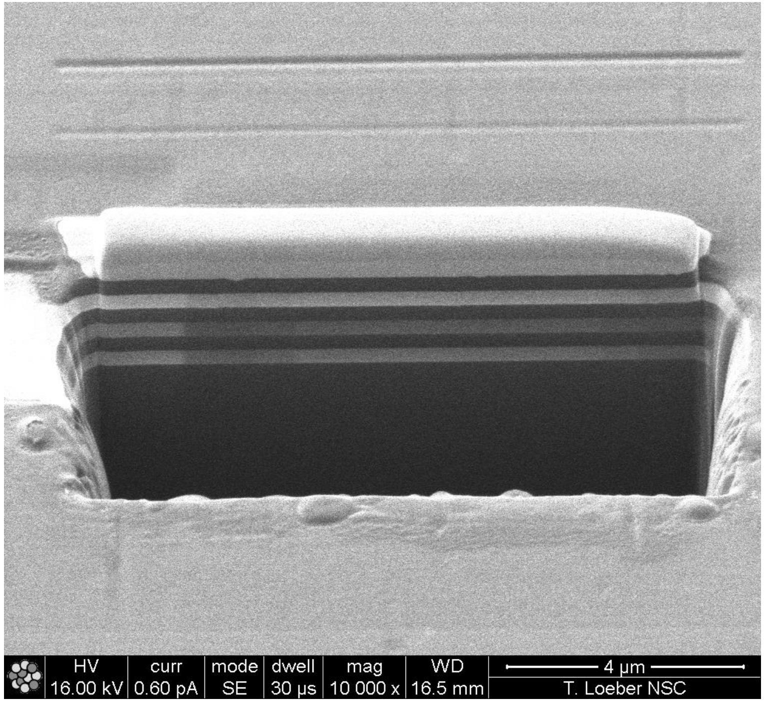
cross section of GaAs and AlGaAs layer

Material contrast

Ga ion image



Cs ion image



Pt layer: contrast of Ga negative of Cs: dark <-> light

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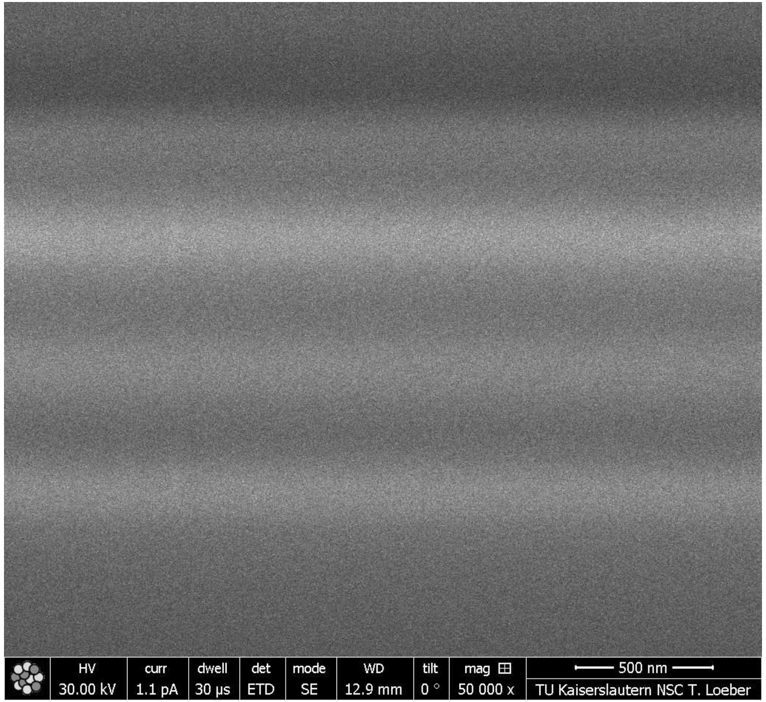
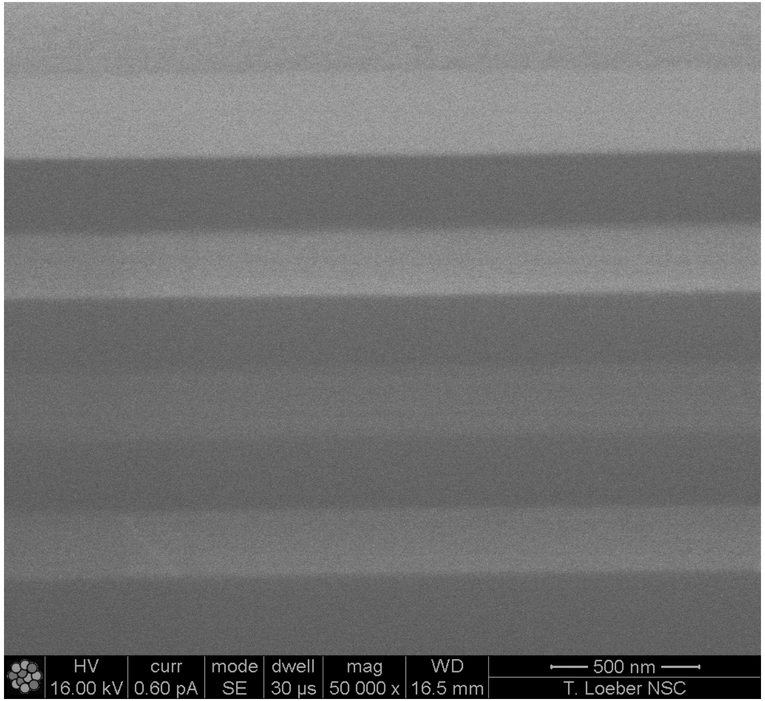
Material contrast

Ga ion image



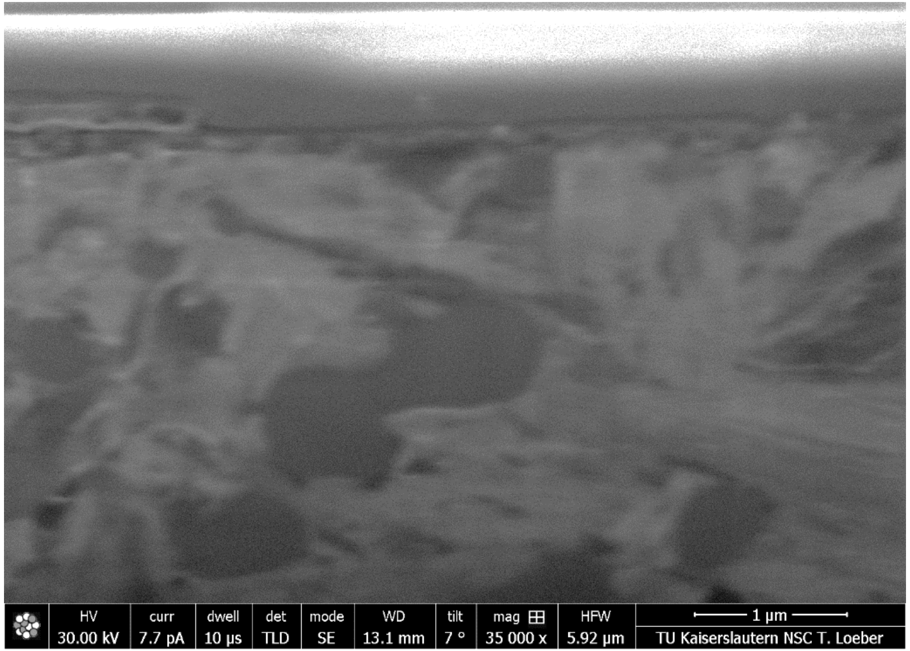
Cs ion image



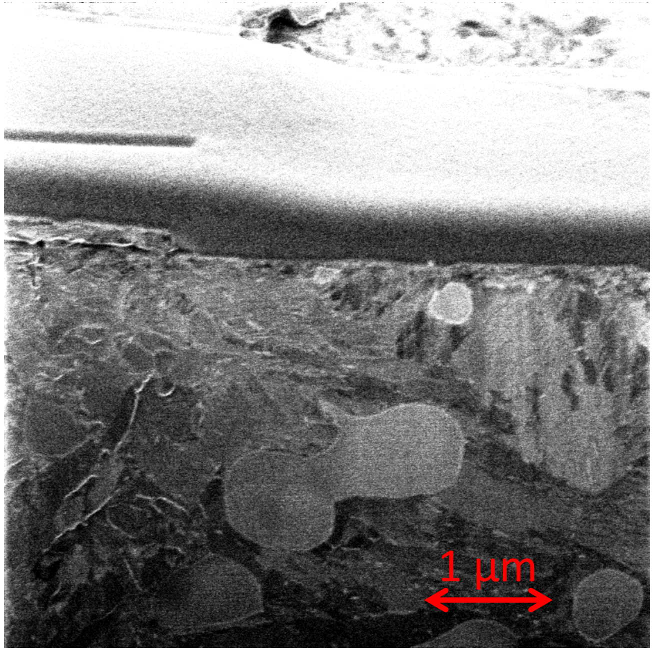
Pt layer contrast of Ga inverted to Cs: dark <-> light

Crystal orientation contrast

Ga ion image



Cs ion image



unpolished cross section of a piece of steal: 100Cr6

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Deposition of platinum

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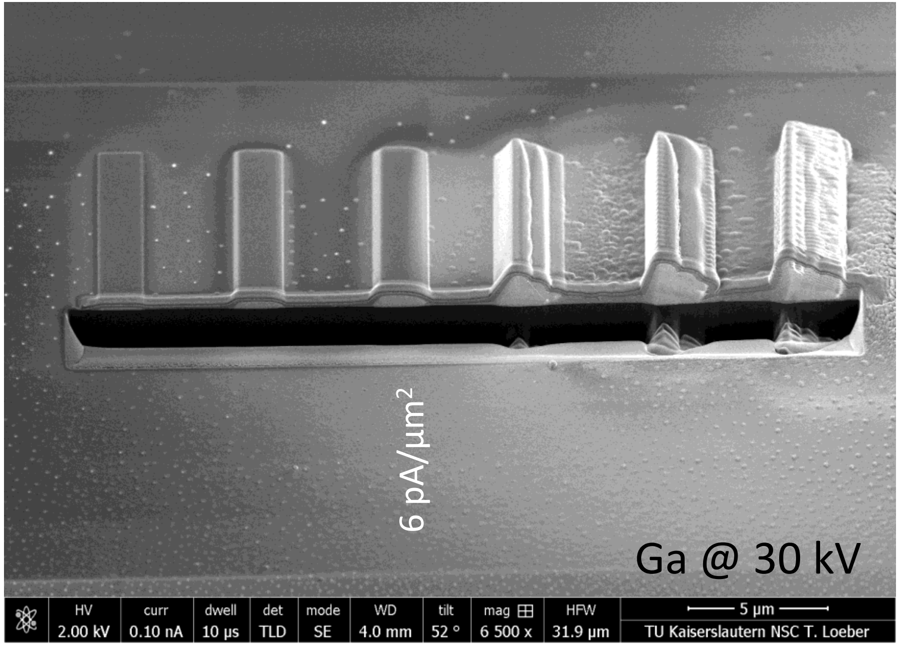

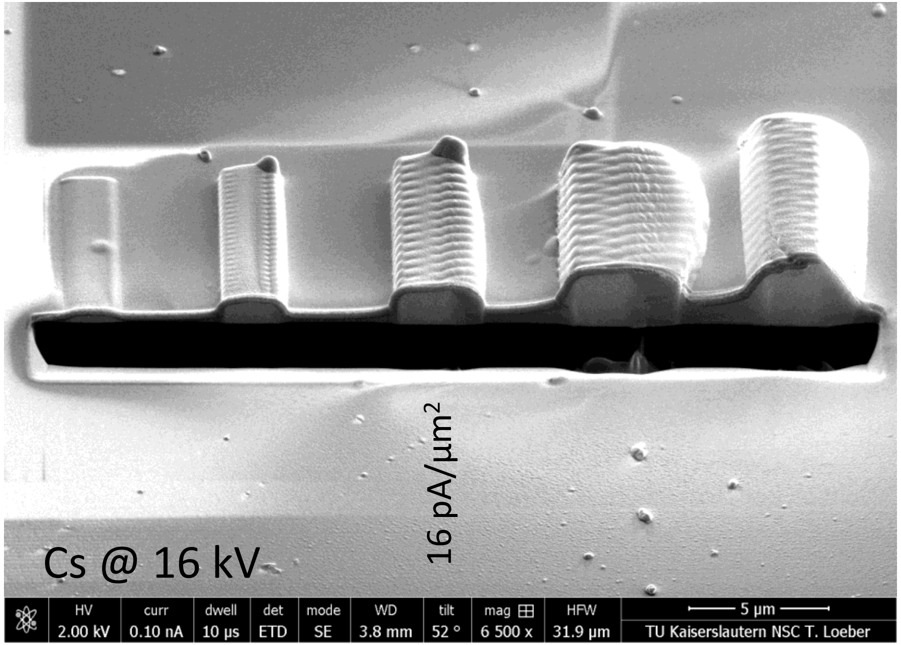

- platinum deposition on Si @ different current densities
- rectangle 1.5 µm x 10 µm
- cross section of the deposited layers

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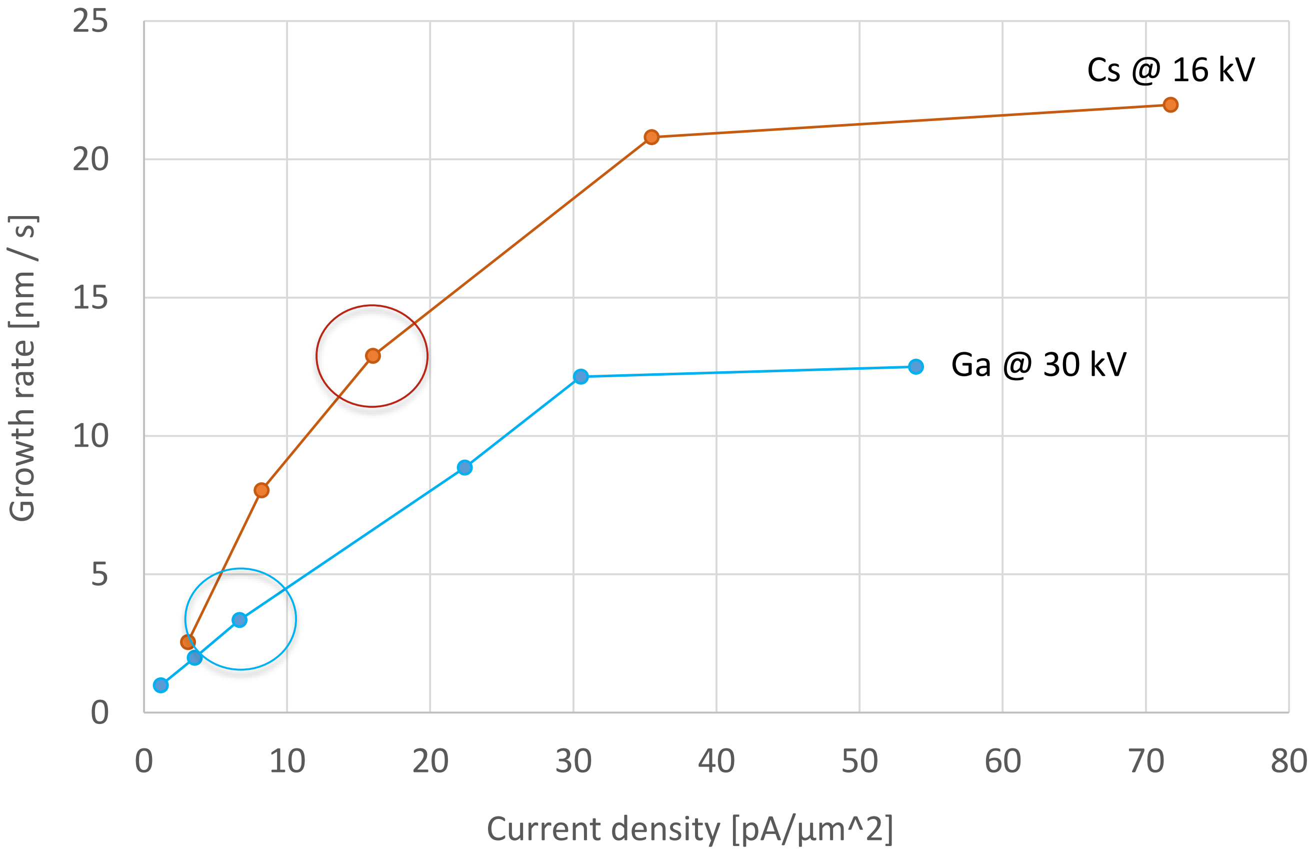
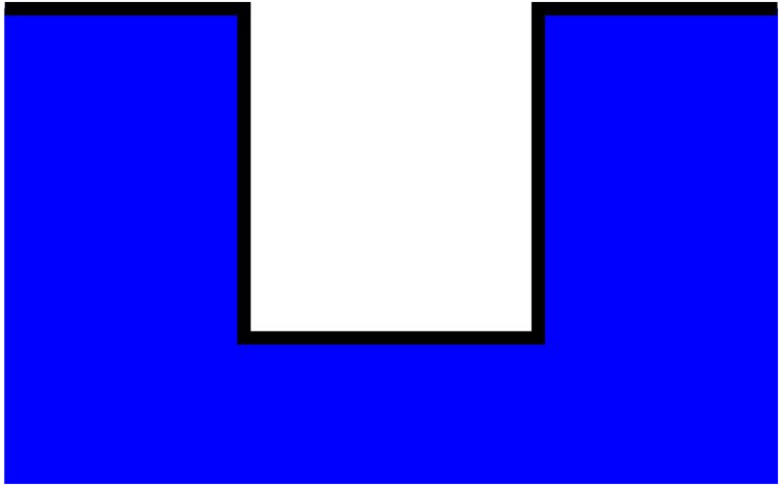
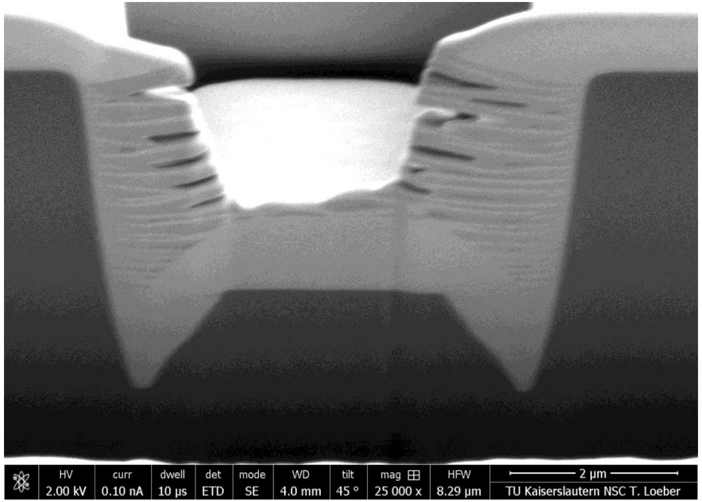
Deposition of platinum



- Cs has a higher growth rate:
- best current density
- Ga: 6 pA/µm^2
- Cs: 16 pA/µm^2

Milling in silicon





expectation vs reality

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Milling in silicon

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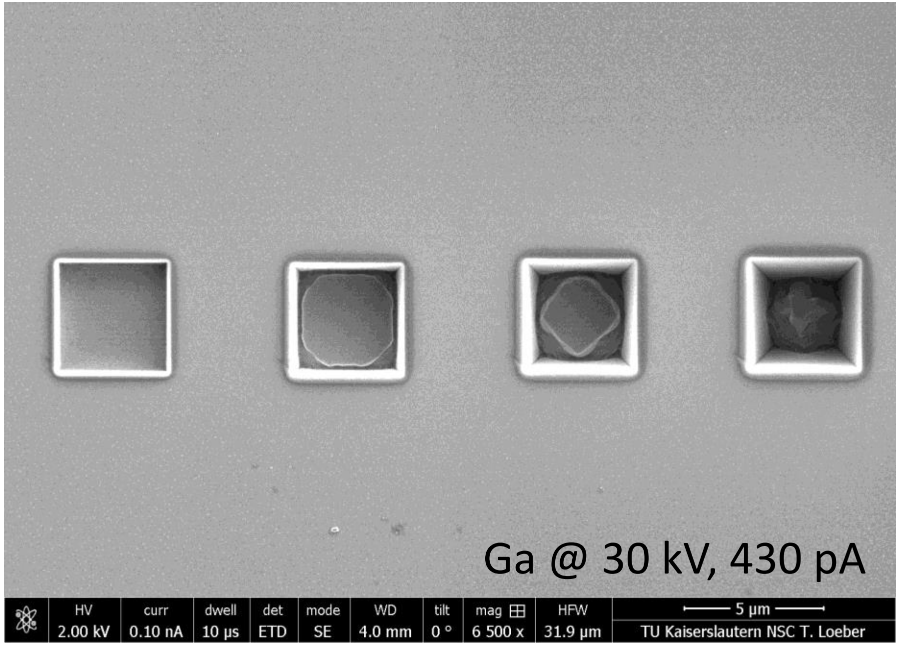

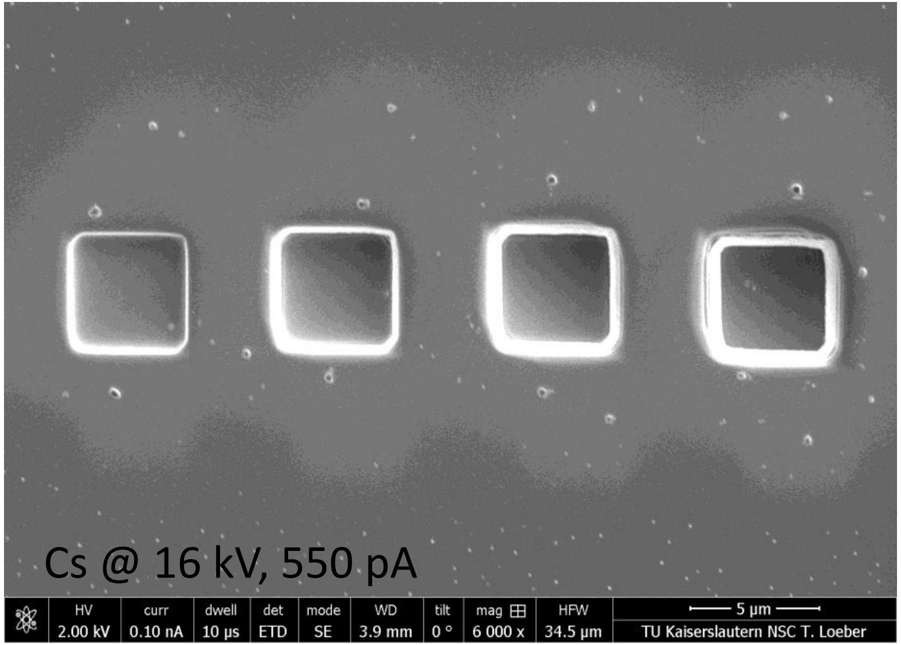

- dose test with Ga and Cs ions
- increasing depth from left to right
- rectangle 4 µm x 4 µm

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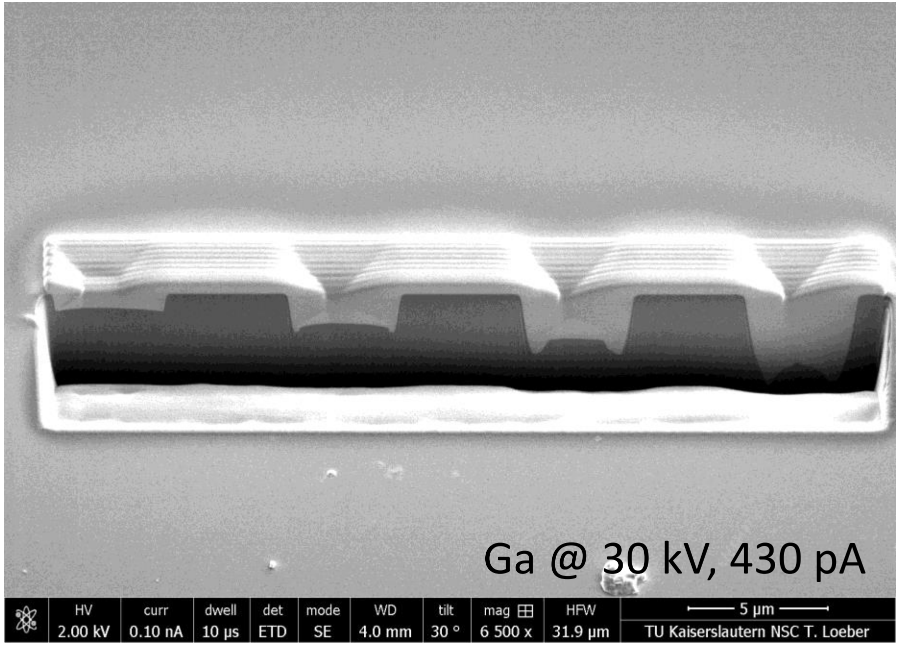
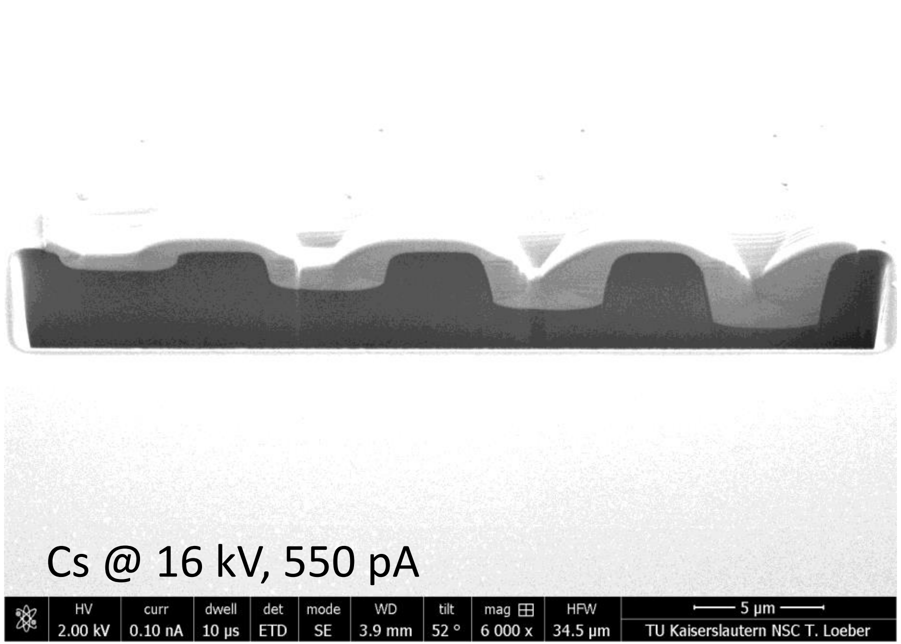
Milling in silicon





- milling time almost the same: over all 20 min
- Ga: increasing depth uneven bottom
- Cs: almost flat bottom in the holes for all depth

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Milling in silicon

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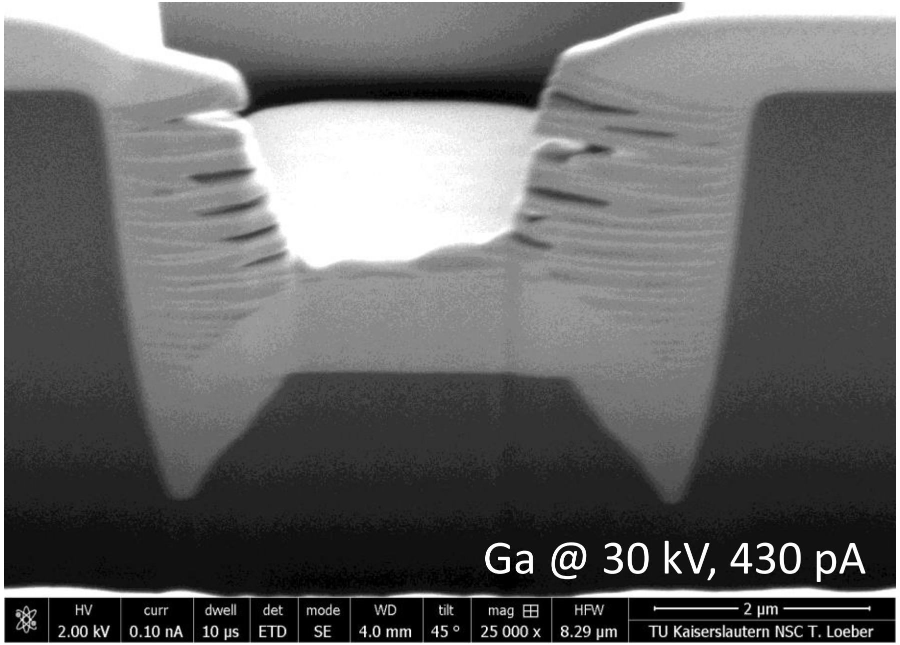

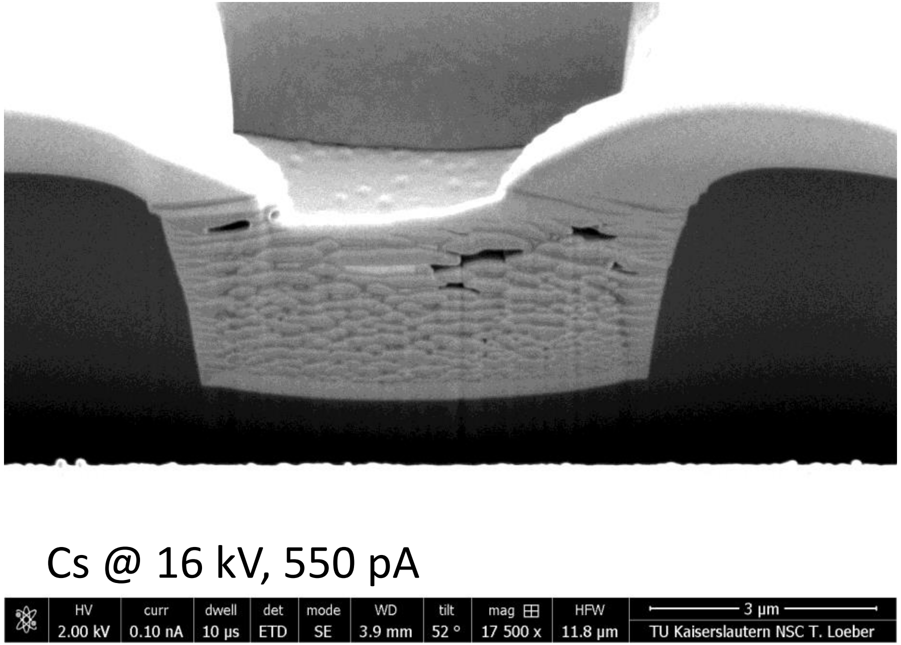

- angle of sidewalls almost the same: around 8°
- Cs: rounder edges at the surface
- Cs: slightly larger as expected

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Milling in silver

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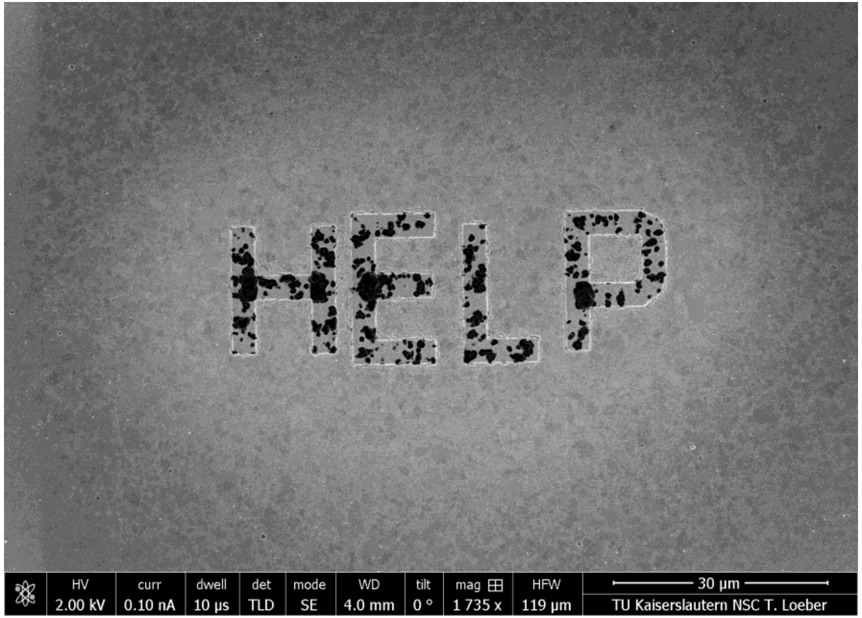

- polycrystalline silver layer
- often used for plasmonic structures
- “nightmare” using a Ga FIB

Ga FIB

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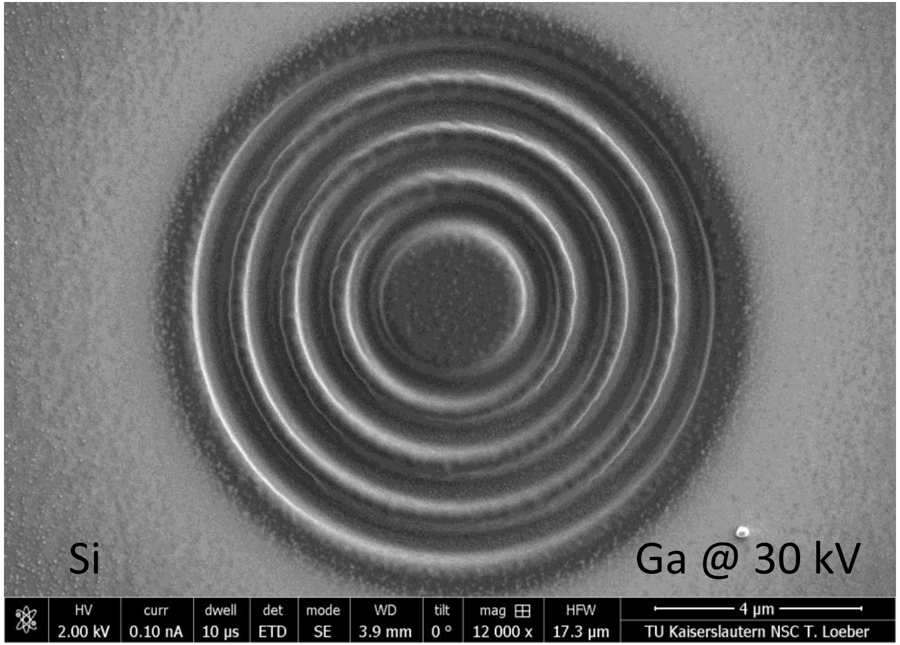
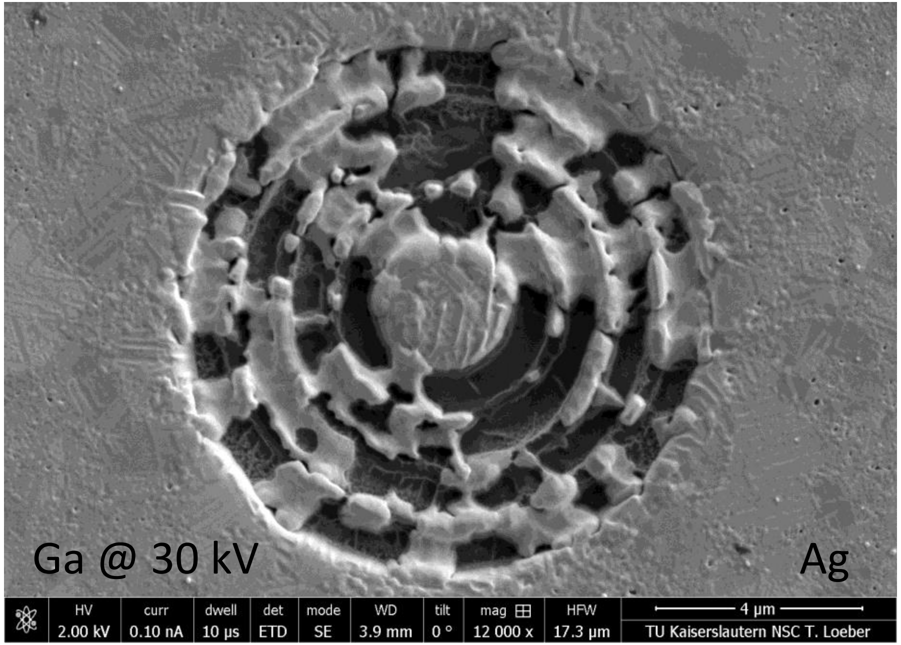
Milling in silver





- demonstration: plasmonic ring structures
- no problem in silicon
- inhomogeneous milling in polycrystalline silver

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Penetration depth in silver

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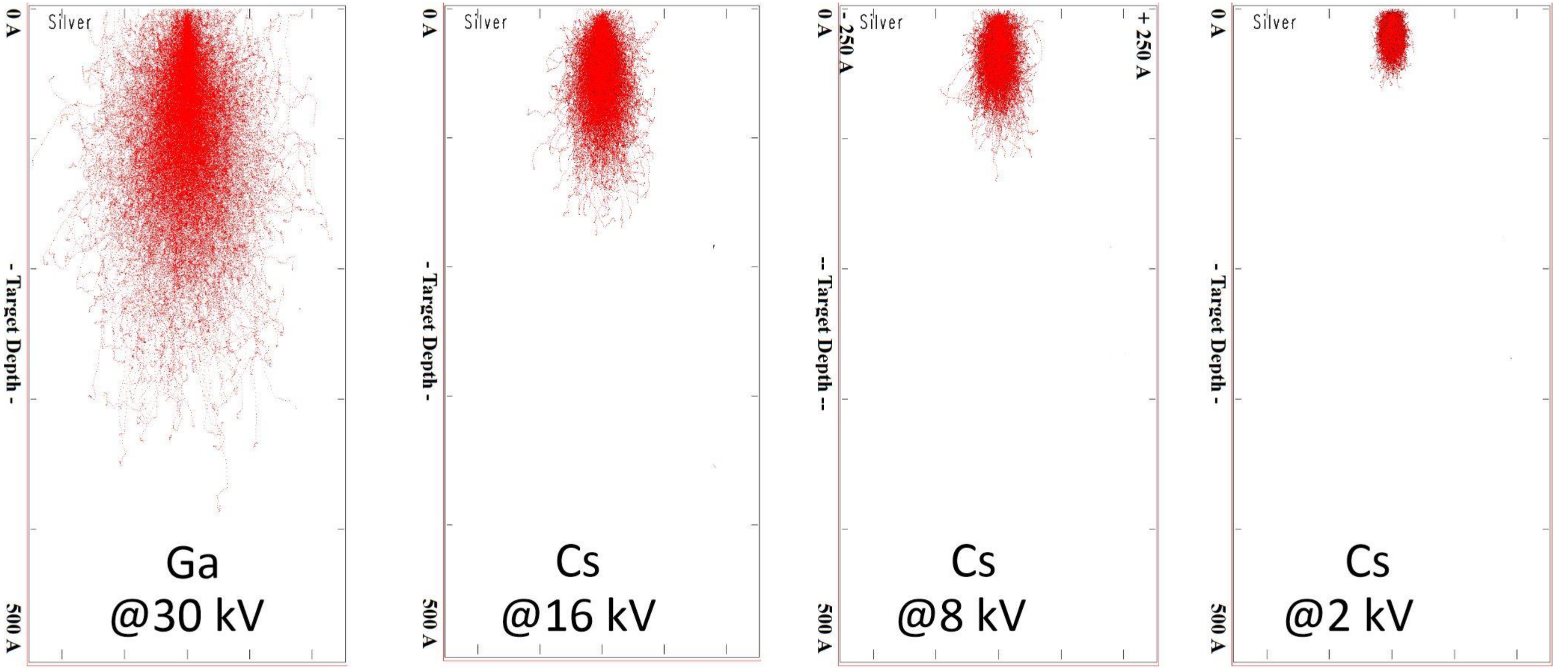

SRIM simulations

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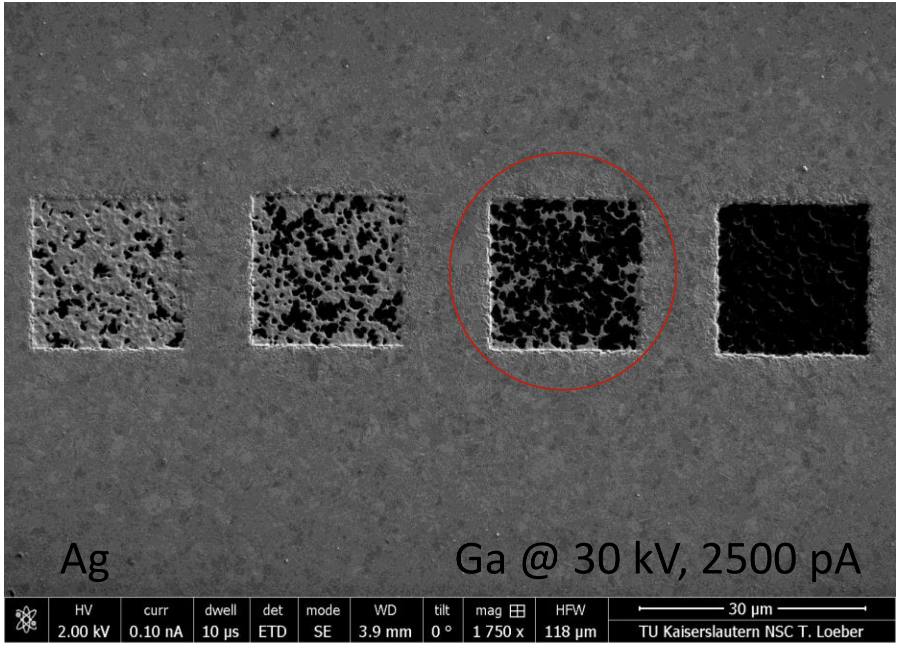
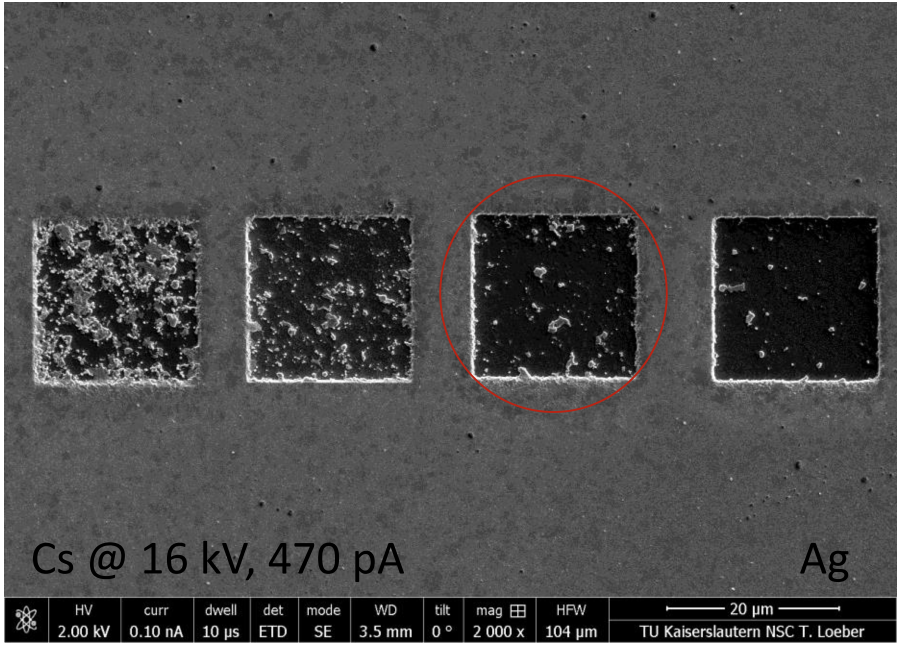
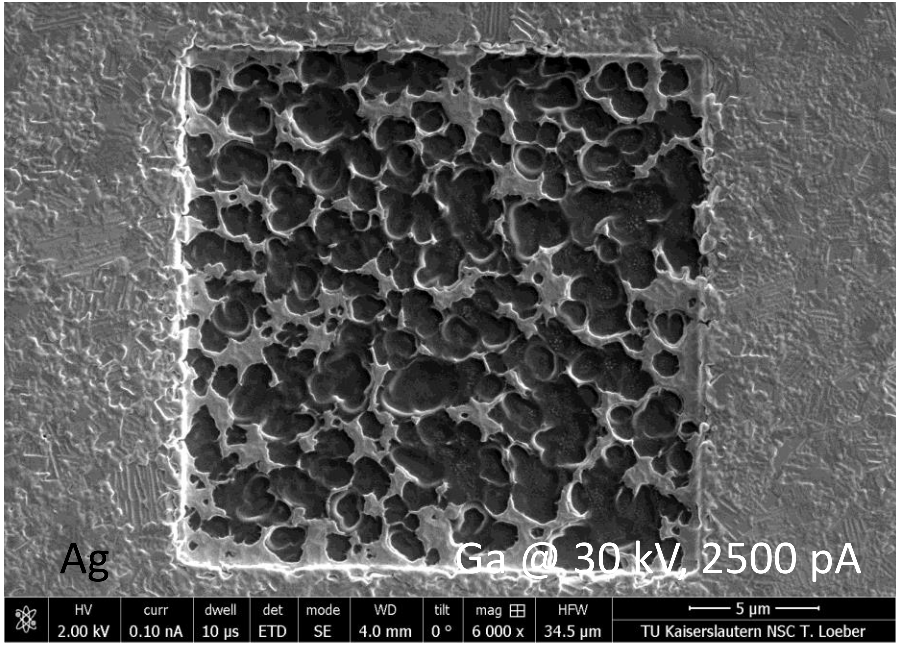
Milling in silver

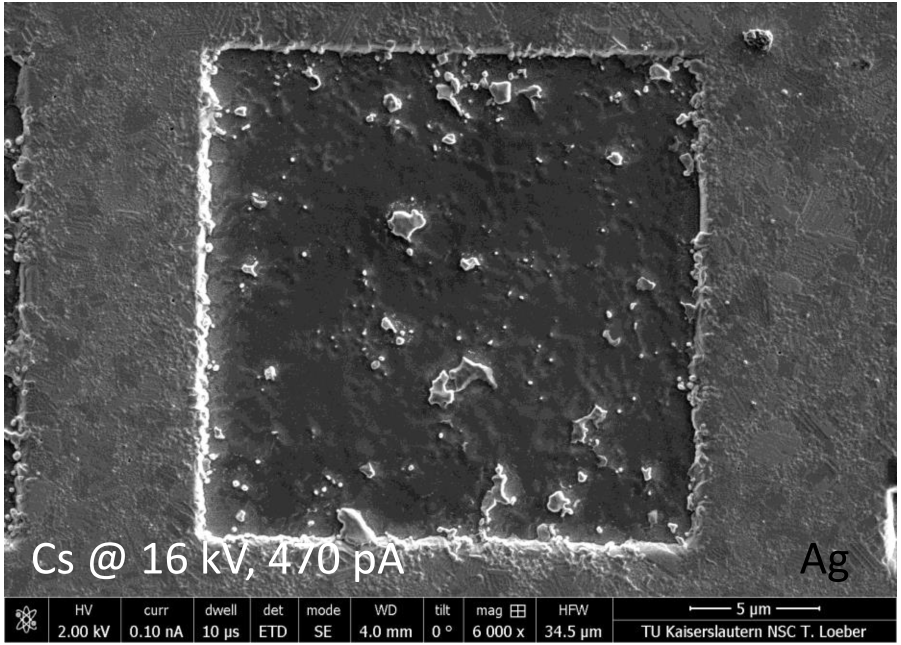




- dose test with Ga and Cs ions in 1100 nm silver layer on silicon
- increasing dose from left to right
- rectangle 20 µm x 20 µm

Milling in silver





- second highest dose: some silver left
- milling time almost the same: over all 20 min
- Ga current 5 times higher than Cs current

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Milling in silver

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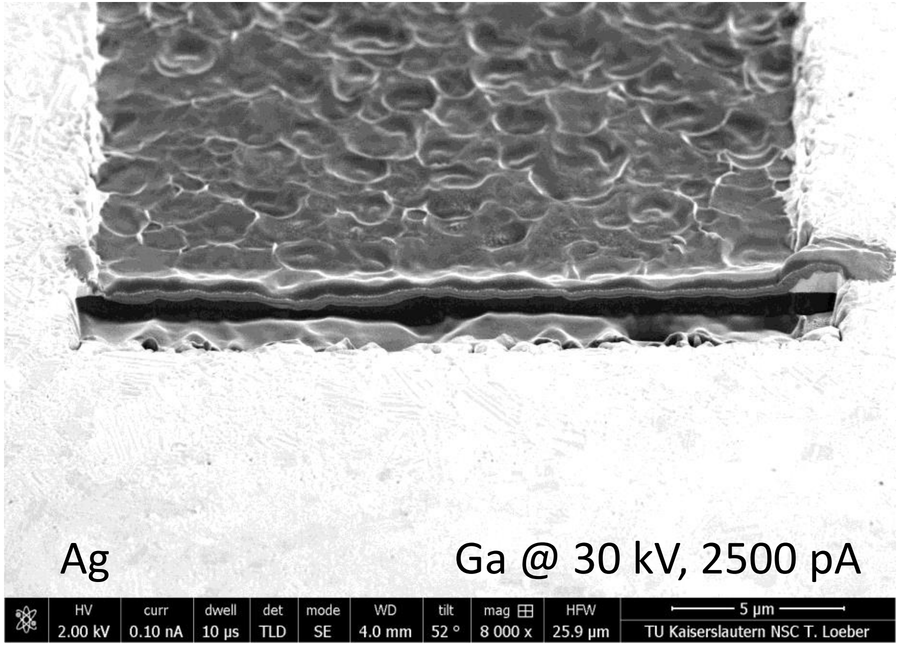

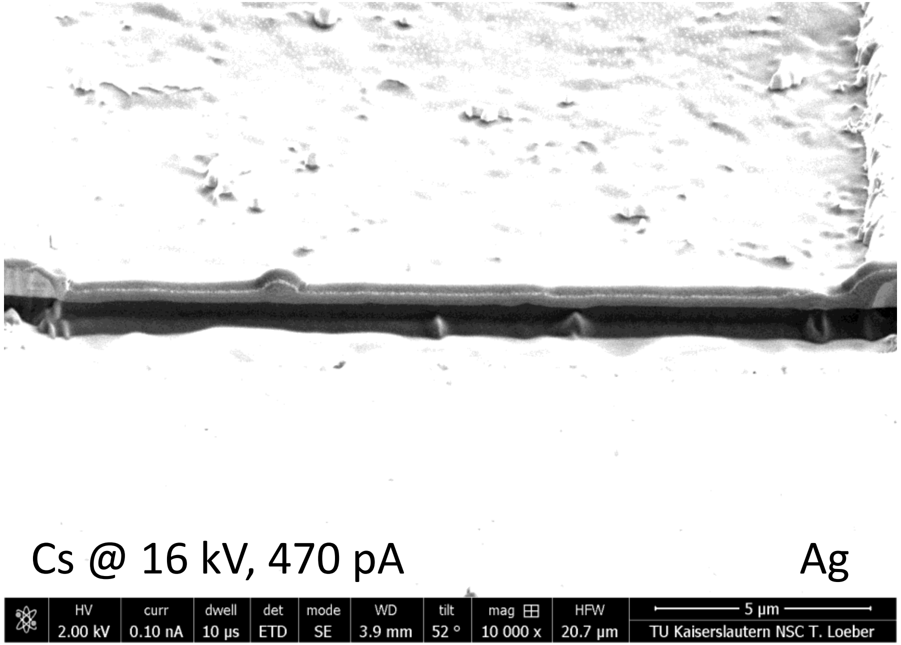

- cross section of area wit highest dose
- Ga: bottom is very uneven
- Cs: bottom almost flat

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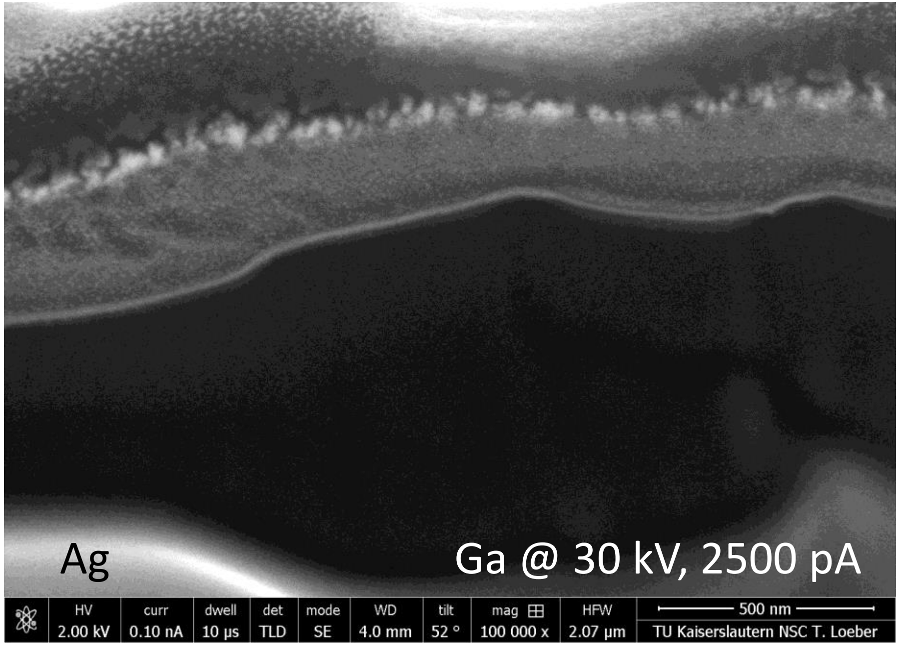
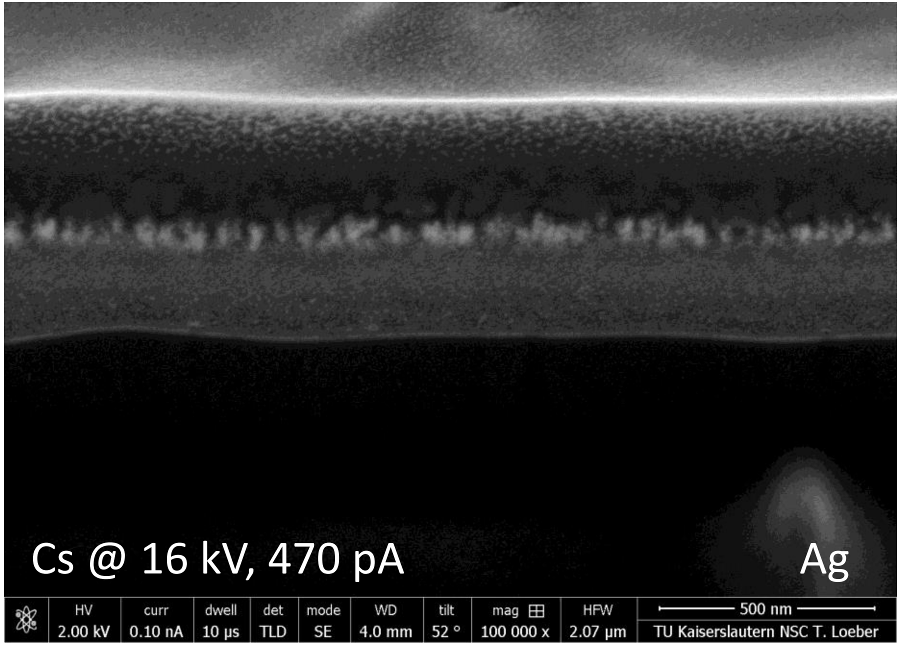
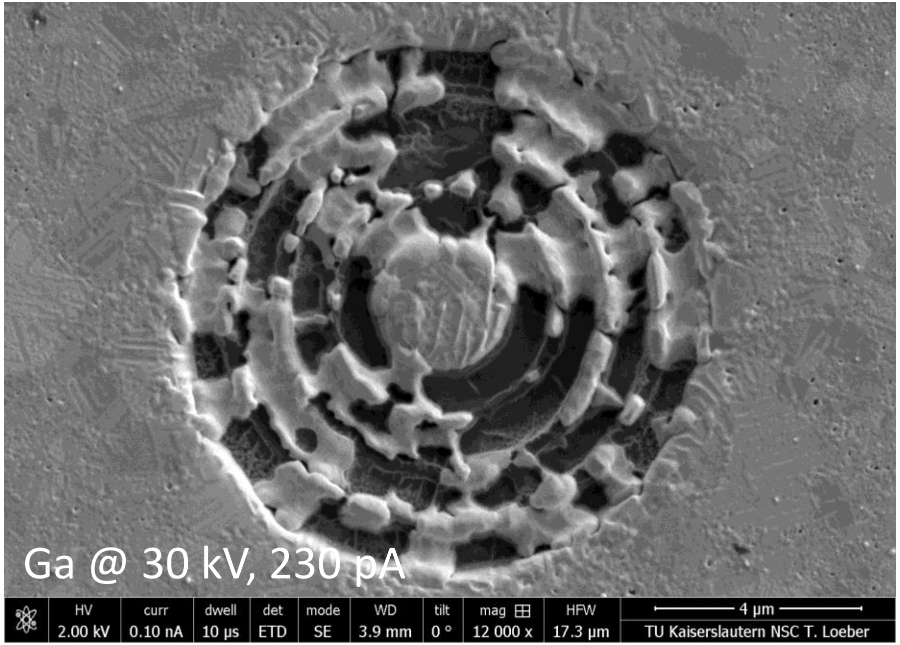
Milling in silver

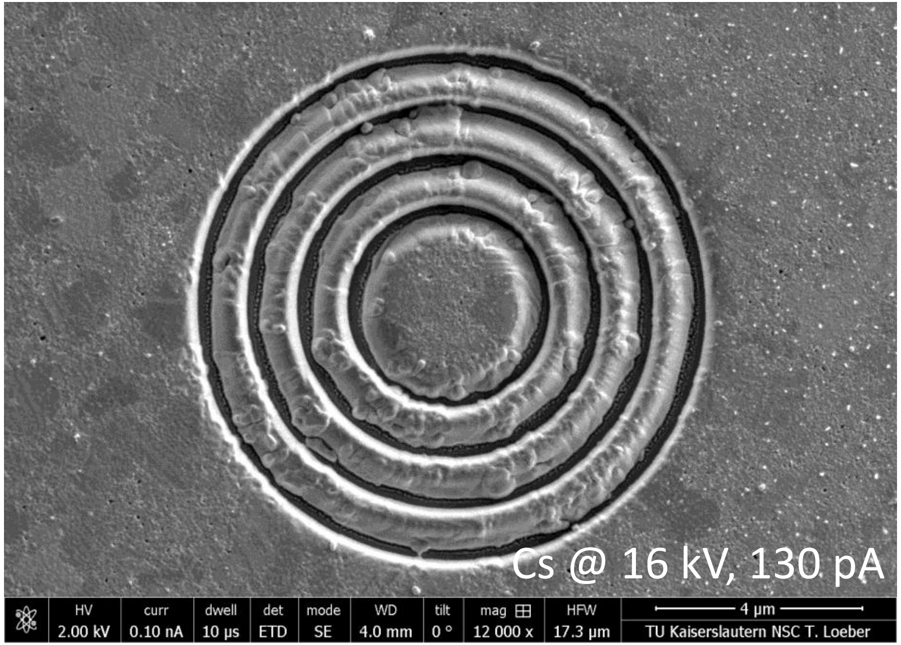




- cross section of area wit highest dose
- Ga: bottom is very uneven
- Cs: bottom almost flat

Milling in silver





- plasmonic structures
- Ga: inhomogeneous milling in polycrystalline silver
- Cs: significant better rings

Summary and Outlook

Summary

- higher depth of focus
- better material contrast
- milling in Si and Ag is different compared to Ga

Outlook

- testing different materials
- milling and measure “real” plasmonic structures
- optimizing the Cs FIB
    - size scaling
    - milling and deposition parameters
    - getting rid of teething problems
- implementing pattern generator
- open for cooperation


Thank you
for your
attention

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Material contrast

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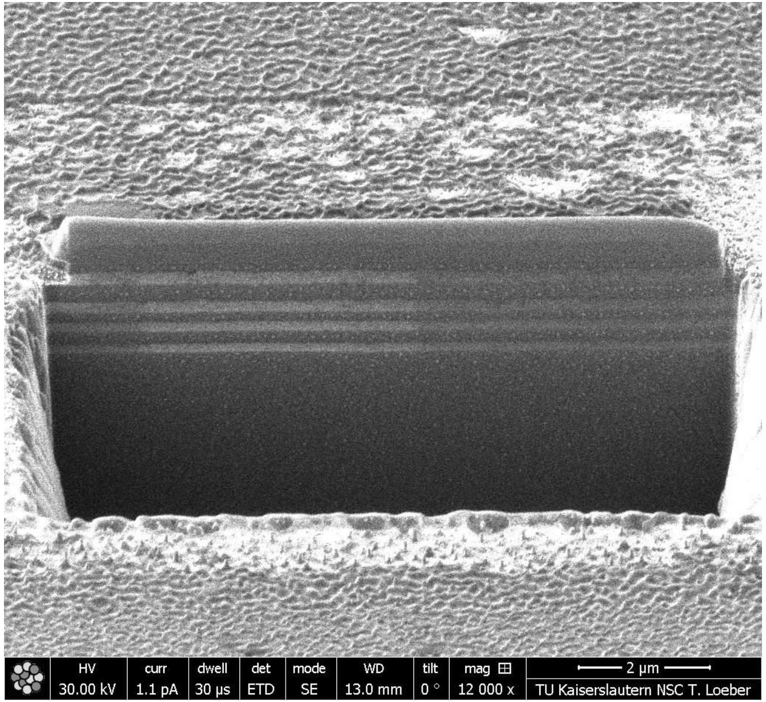
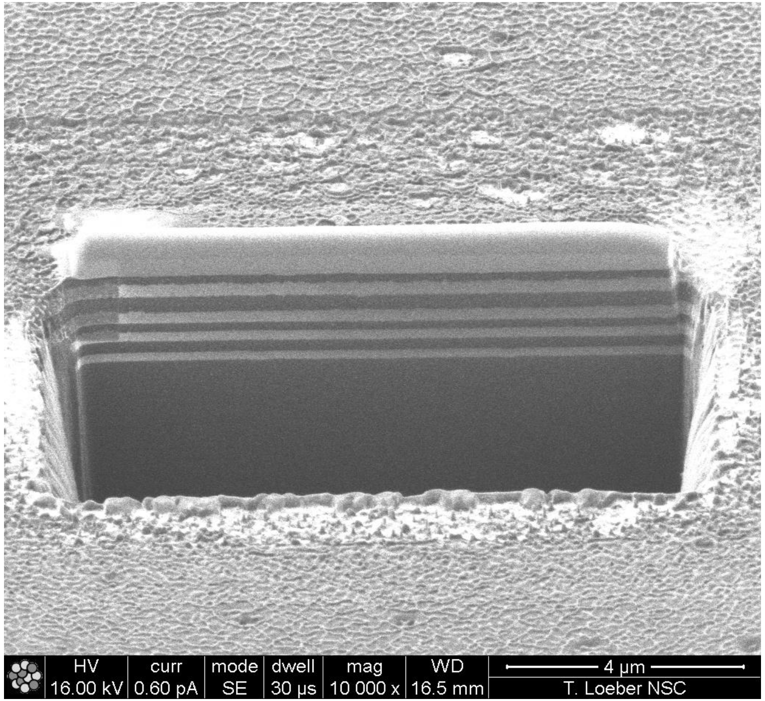
Ga ion image



Cs ion image



cross section of InAs and AlSbAs layer

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Material contrast

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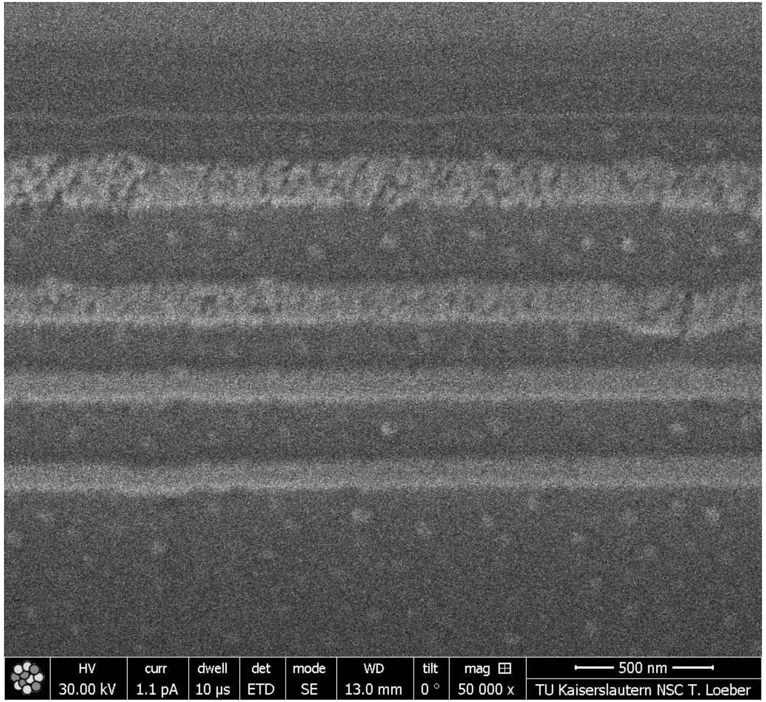
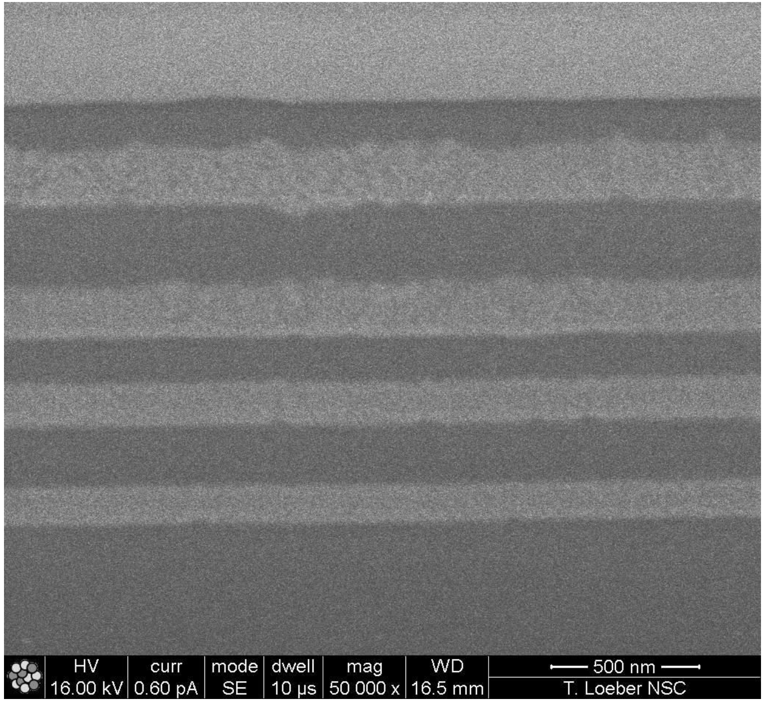
Ga ion image



Cs ion image



cross section done with Ga: not “clean”, dots, layers damaged

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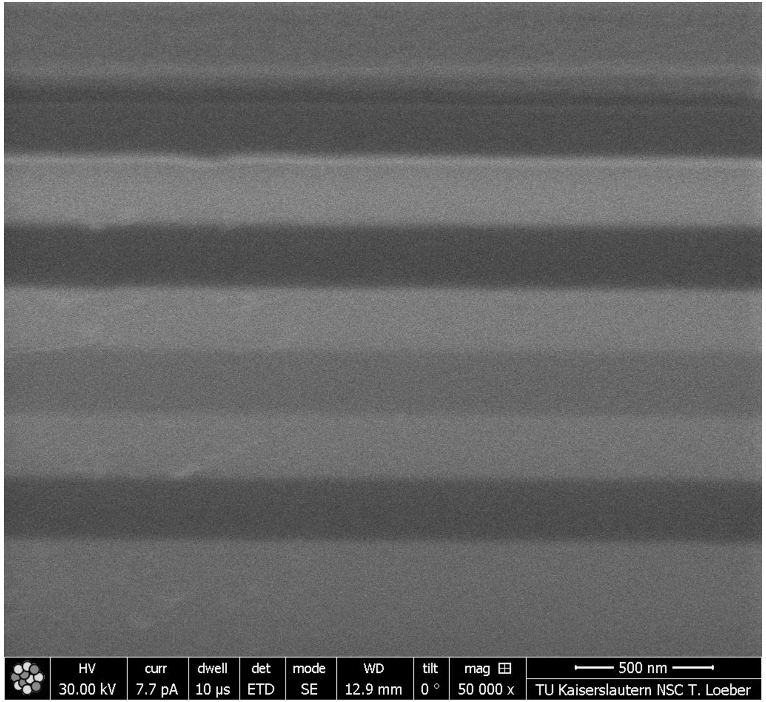
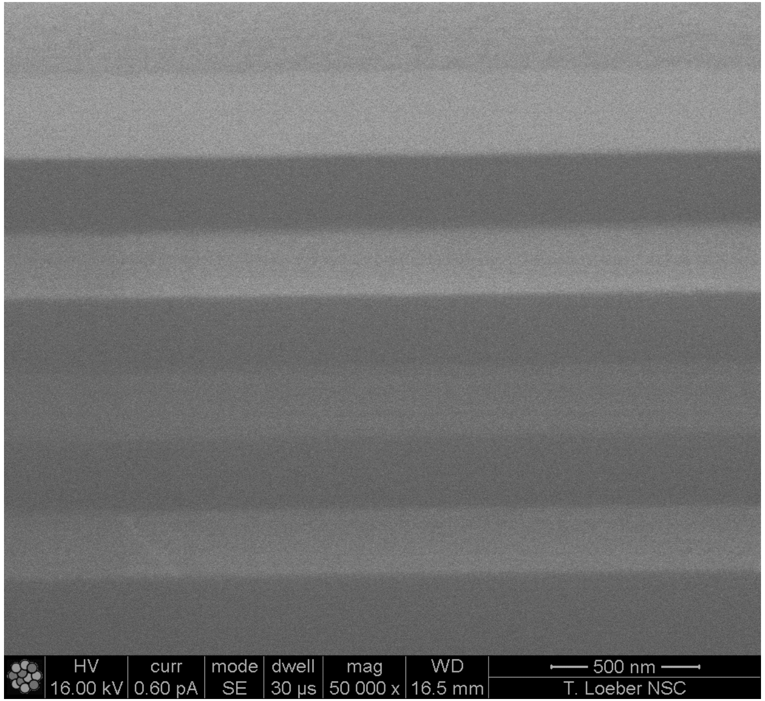
Ga ion image



Cs ion image



GaAs/AlGaAs layer: higher Ga beam better contrast, destroying cross section

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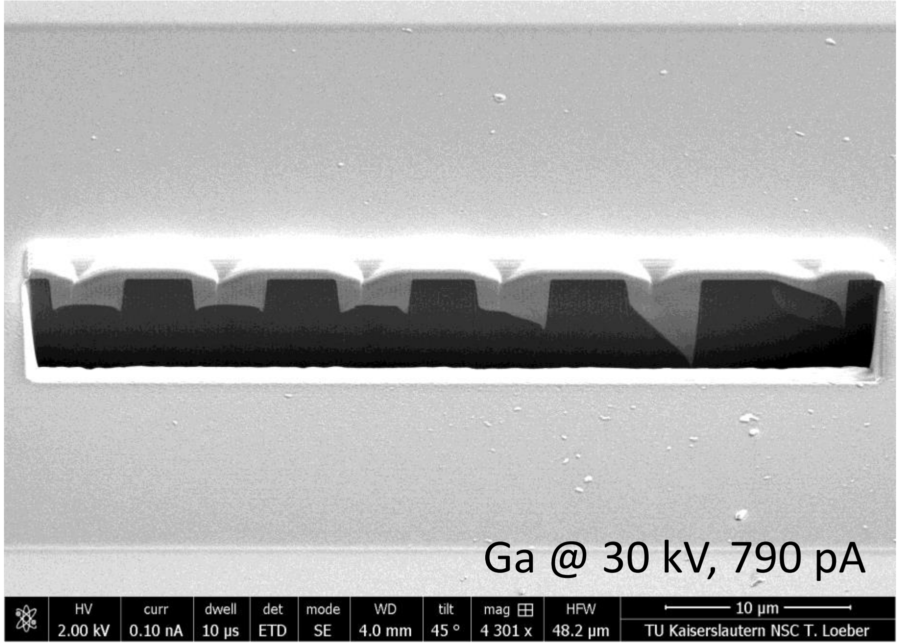
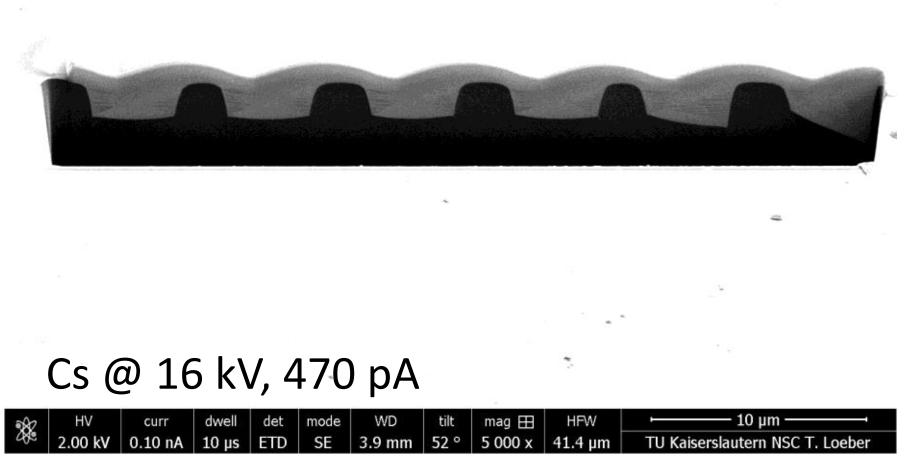
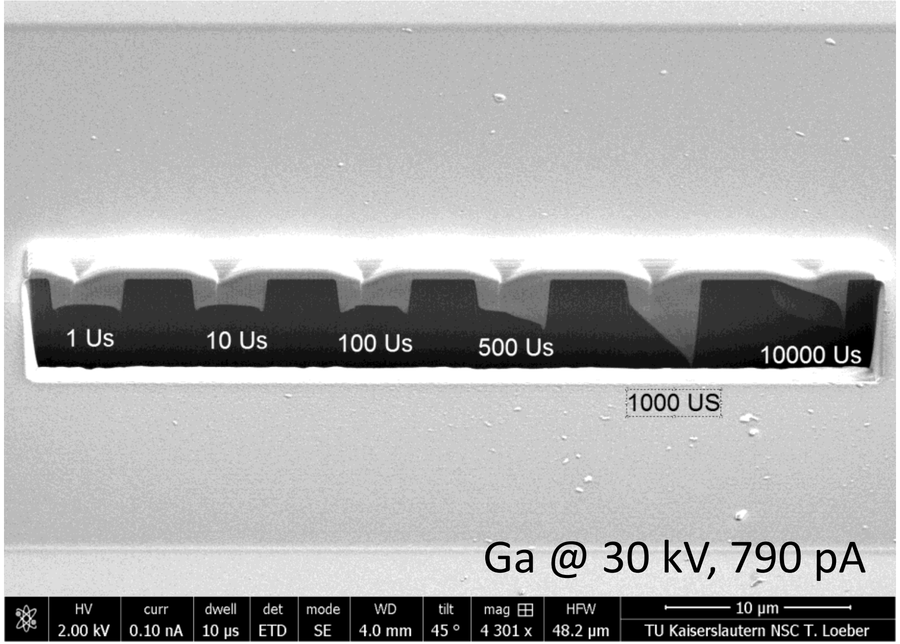
Milling in silicon

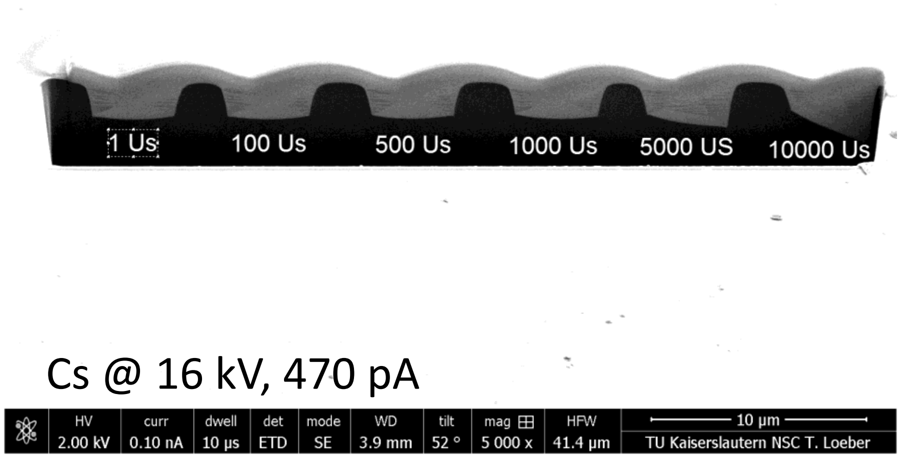




- milling time: Ga over all 12 min, Cs over all 24 min
- dwell time increasing from left to right
- number of loops decreasing -> total dose equal

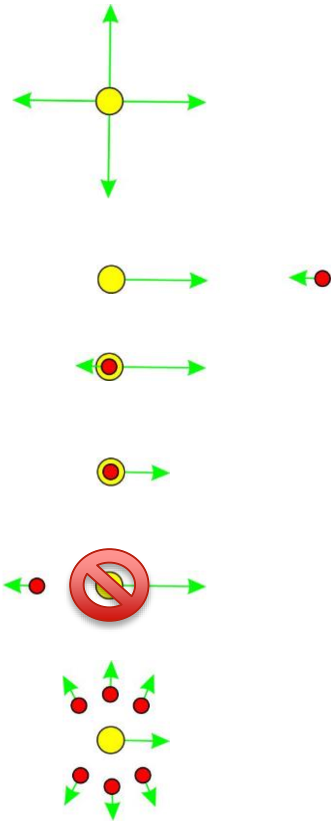
Milling in silicon



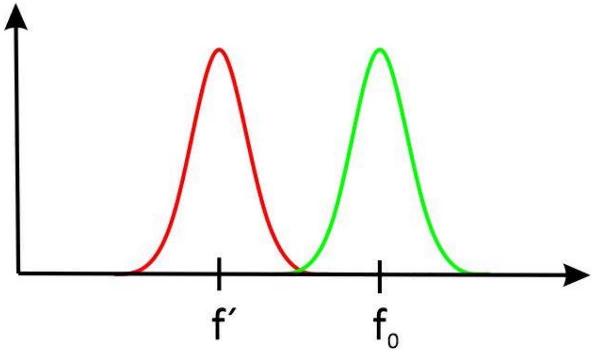


- scan direction left to right
- Ga: 500 µs; Cs: 5000 µs uneven bottom
- dwell time stronger influence on Ga than Cs

Laser cooling



- $p = \frac{h}{\lambda} = \frac{hf}{c}$
- photon absorbed at resonance frequency
- doppler effect: frequency is lower
- atom is slowed down in one direction



Cold atomic beam ion source for focused ion beam applications
Journal of Applied Physics 114, 044303 (2013)
https://doi.org/10.1063/1.4816248
B. Knuffman, A. V. Steele, and J. J. McClelland