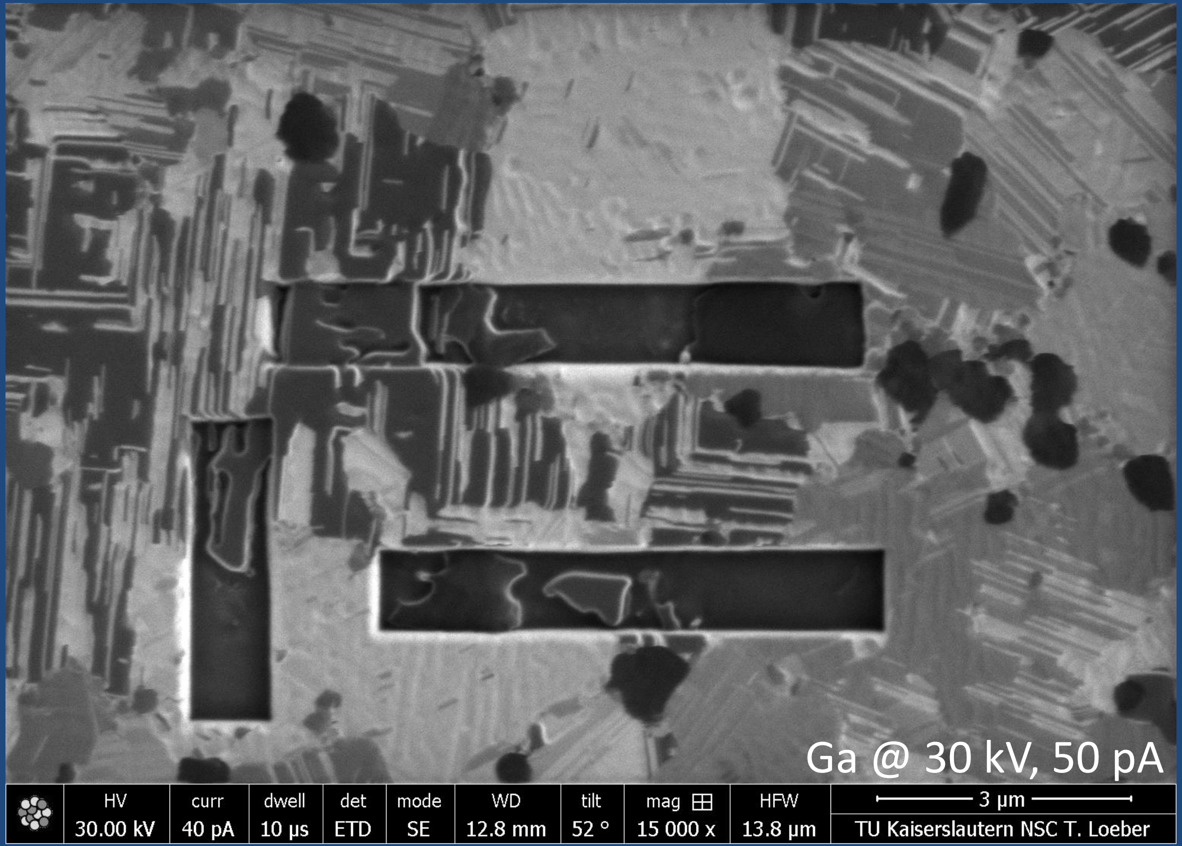
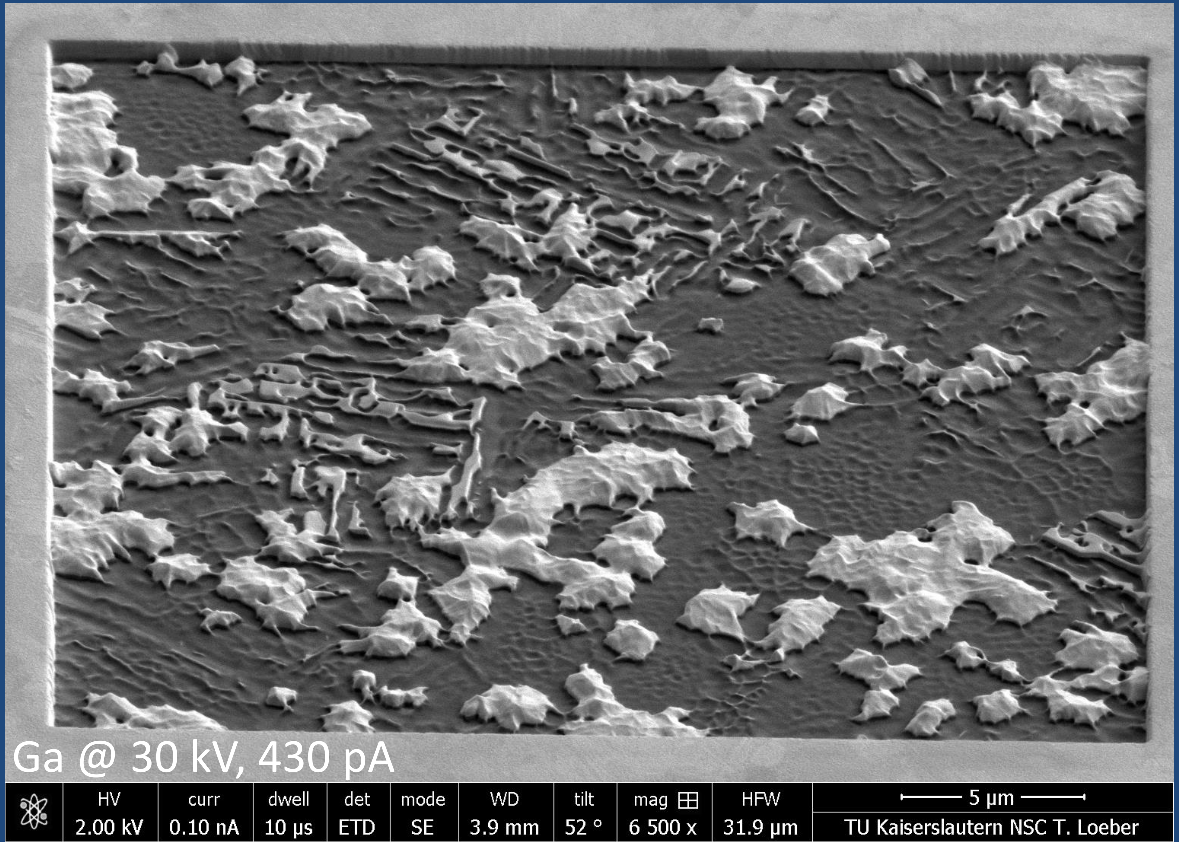
Investigation of different focused ion beam systems and milling strategies for structuring crystalline semiconductors and polycrystalline metal layers





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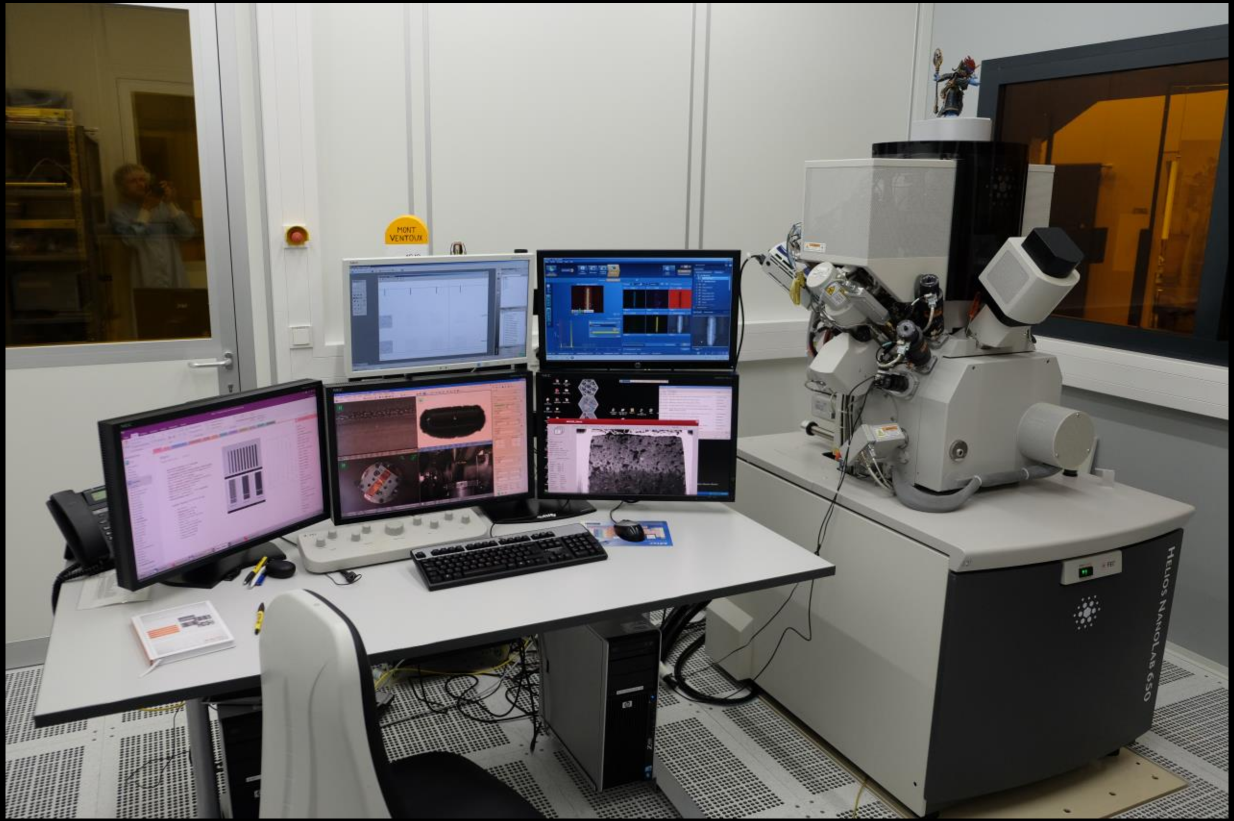
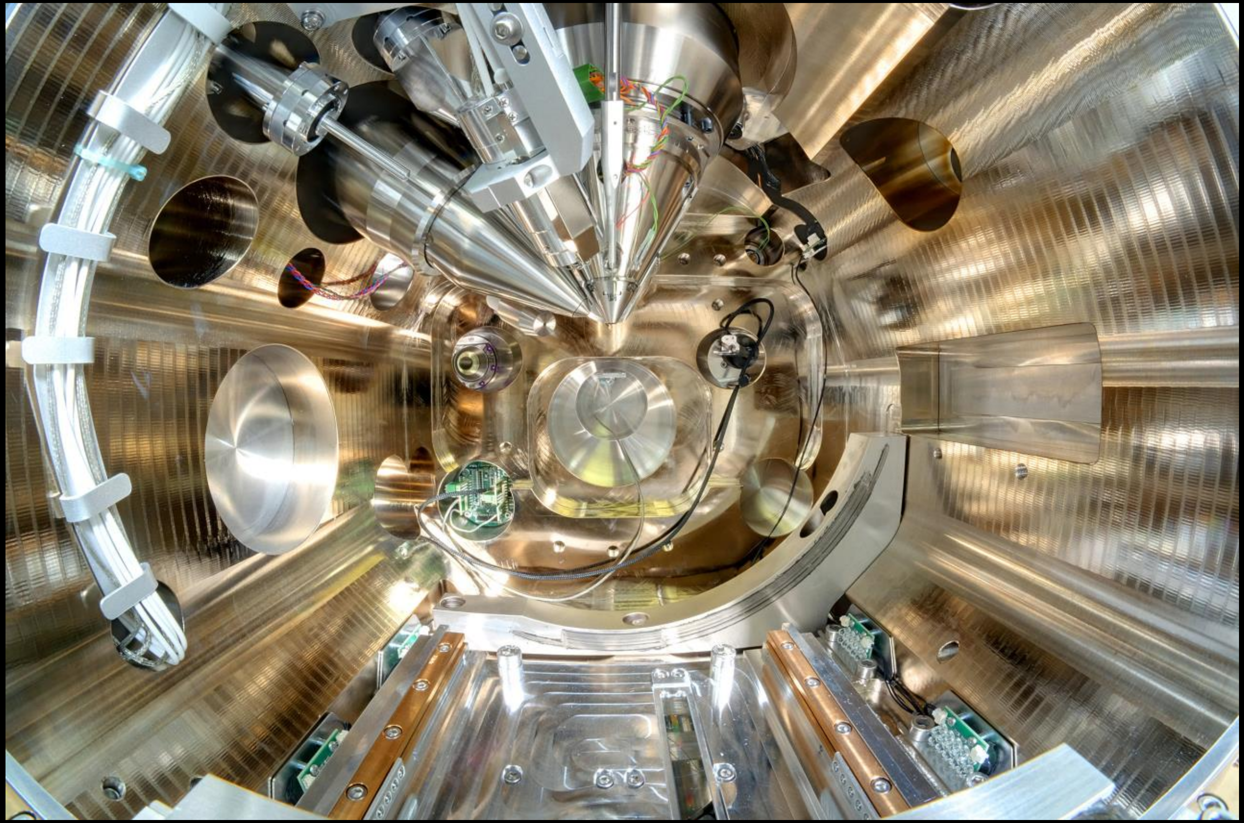
Technische Universität
Kaiserslautern
Landau

Nano Structuring Center

- core facility of the university
- micro and nano structuring
- developing processes
- supporting students
- training on machines

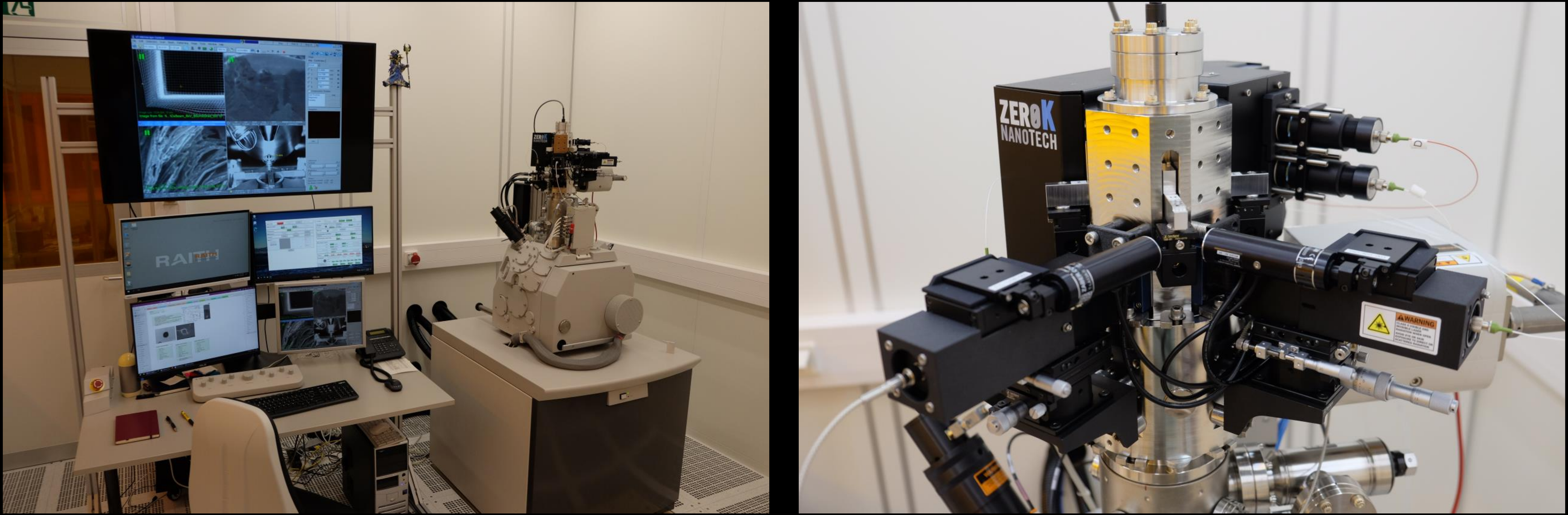
Helios 650 Dualbeam: Ga FIB + SEM





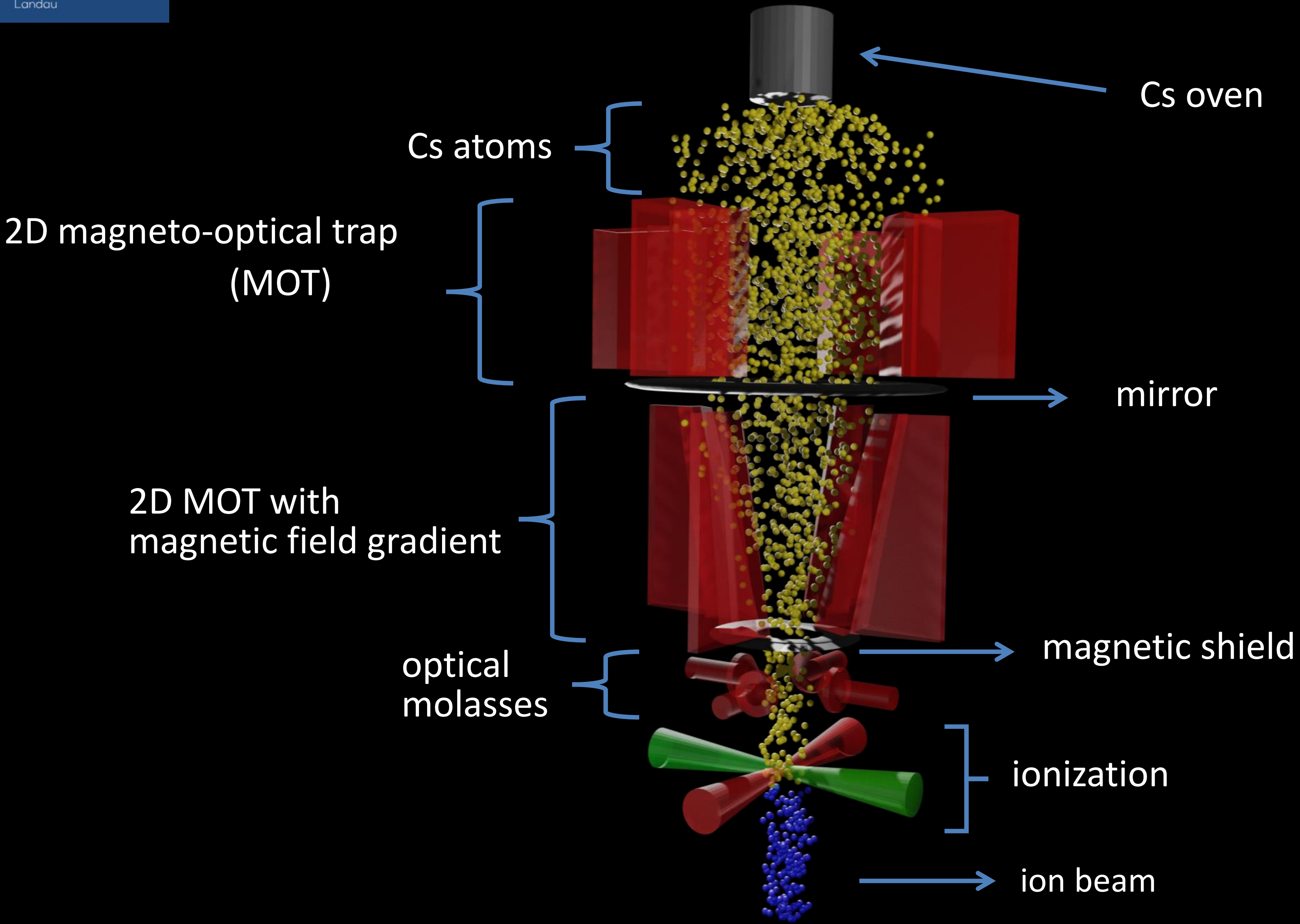
- acceleration voltage: Ga ions 16 and 30 kV; SEM from 1 to 30 kV
- ion beam current: from 1 to 47000 pA
- standard mono GIS with Pt and MultiGIS with C, Pt, H_2O and XeF

Cs FIB



- acceleration voltage: 2, 5, 8 and 16 kV
- ion beam current: from 1 to 1000 pA
- standard mono GIS with Pt
- manufactured by ZeroK

Cs ion source



Cs oven

Cs atoms

2D magneto-optical trap (MOT)

mirror

2D MOT with magnetic field gradient

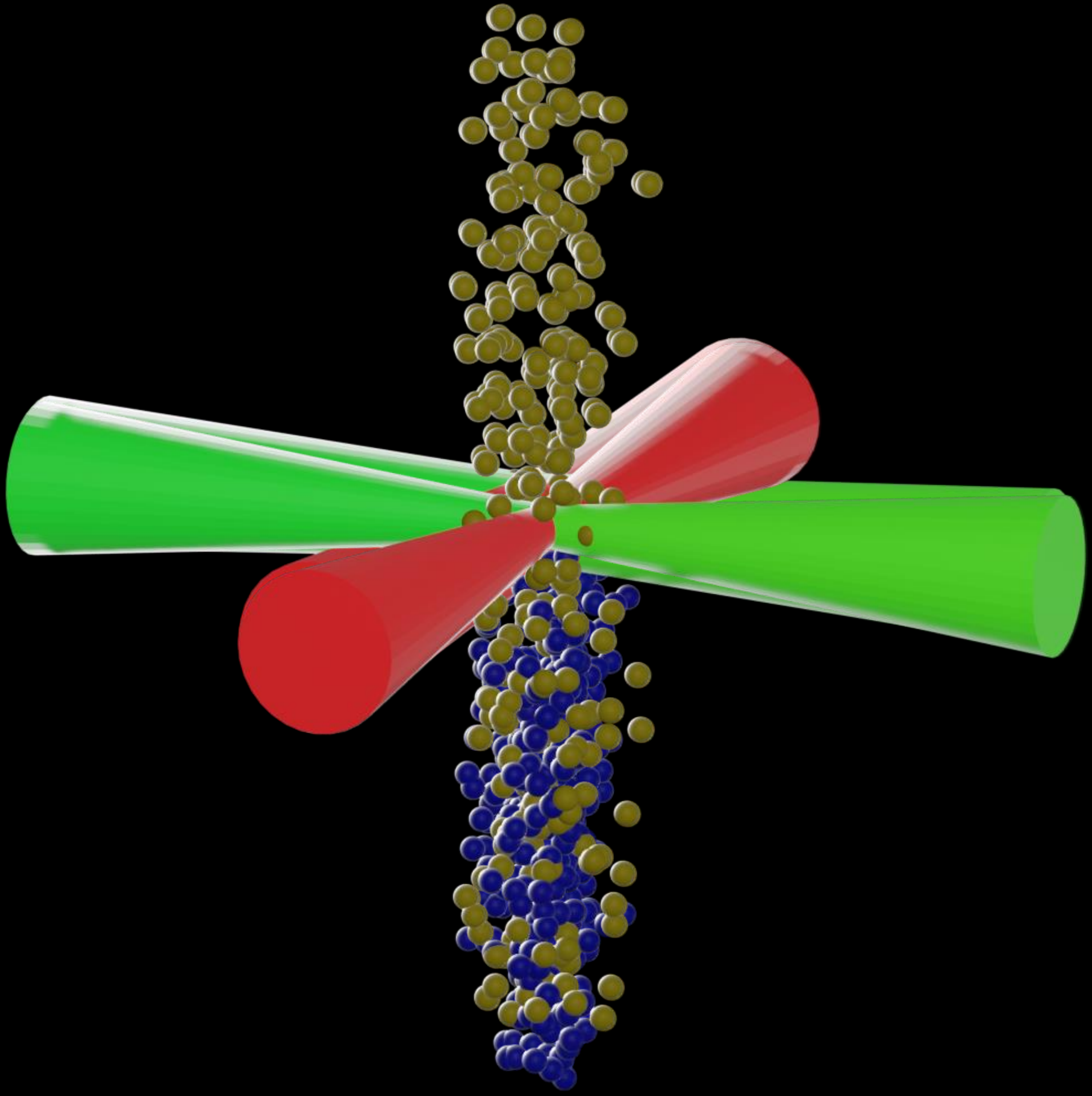
magnetic shield

optical molasses

ionization

ion beam

Ionization

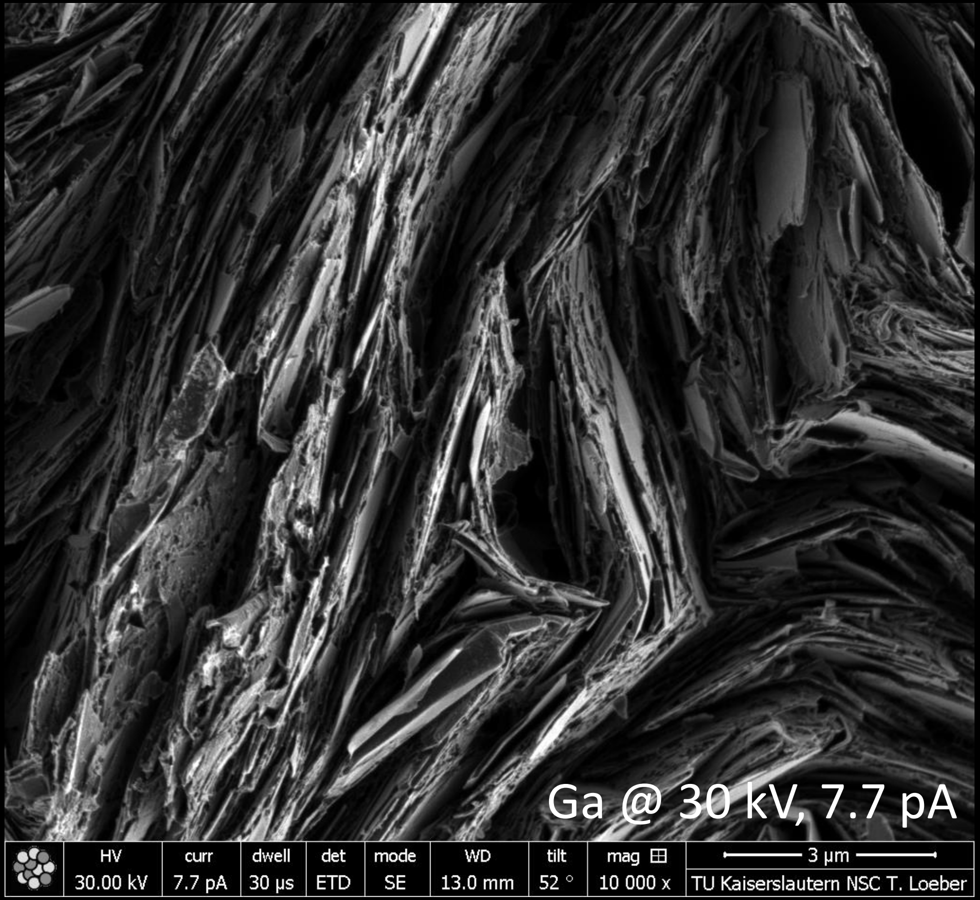


- 2 step ionization
- only in focus of both lasers
- laser power can be changed
- laser beam diameter can be changed
- ion beam can be changed continuously
- no aperture needed

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

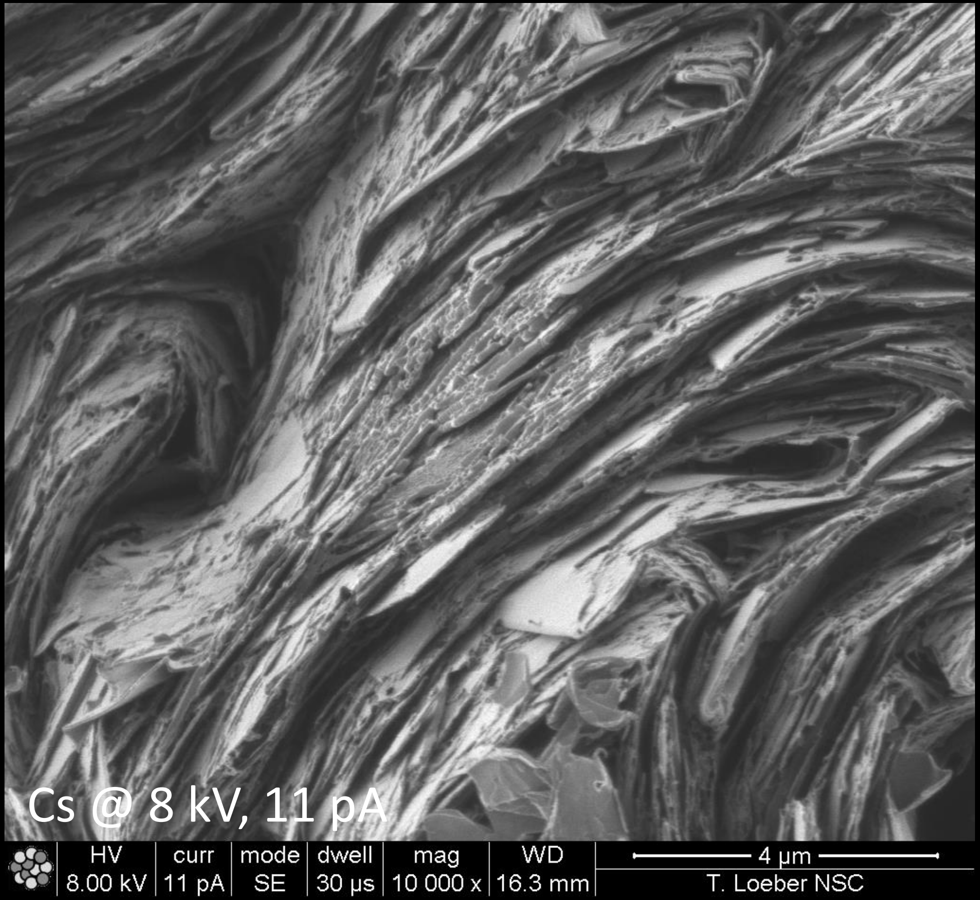
Resolution

Ga ion image


Ga @ 30 kV, 7.7 pA

HV	curr	dwell	det	mode	WD	tilt	mag ⊞	3 µm
30.00 kV	7.7 pA	30 µs	ETD	SE	13.0 mm	52 °	10 000 x	TU Kaiserslautern NSC T. Loeber

Cs ion image

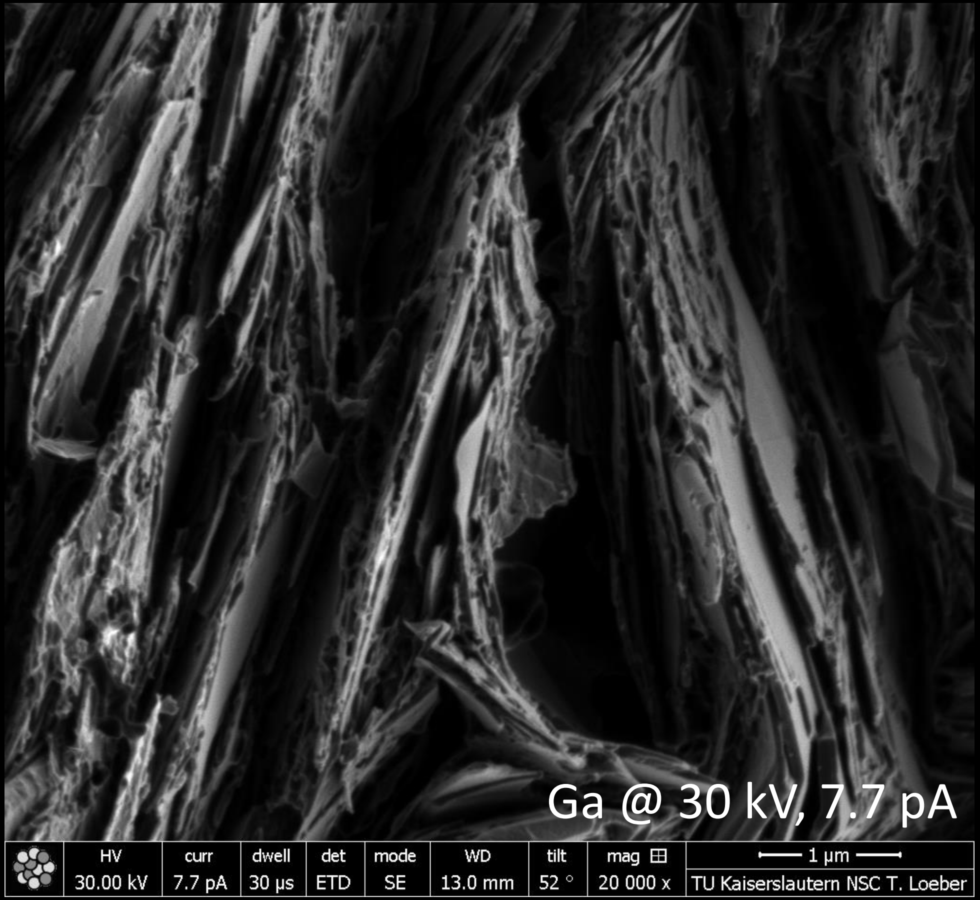

Cs @ 8 kV, 11 pA

HV	curr	mode	dwell	mag	WD	4 µm
8.00 kV	11 pA	SE	30 µs	10 000 x	16.3 mm	T. Loeber NSC

graphite pen: magnification 10k x

Resolution

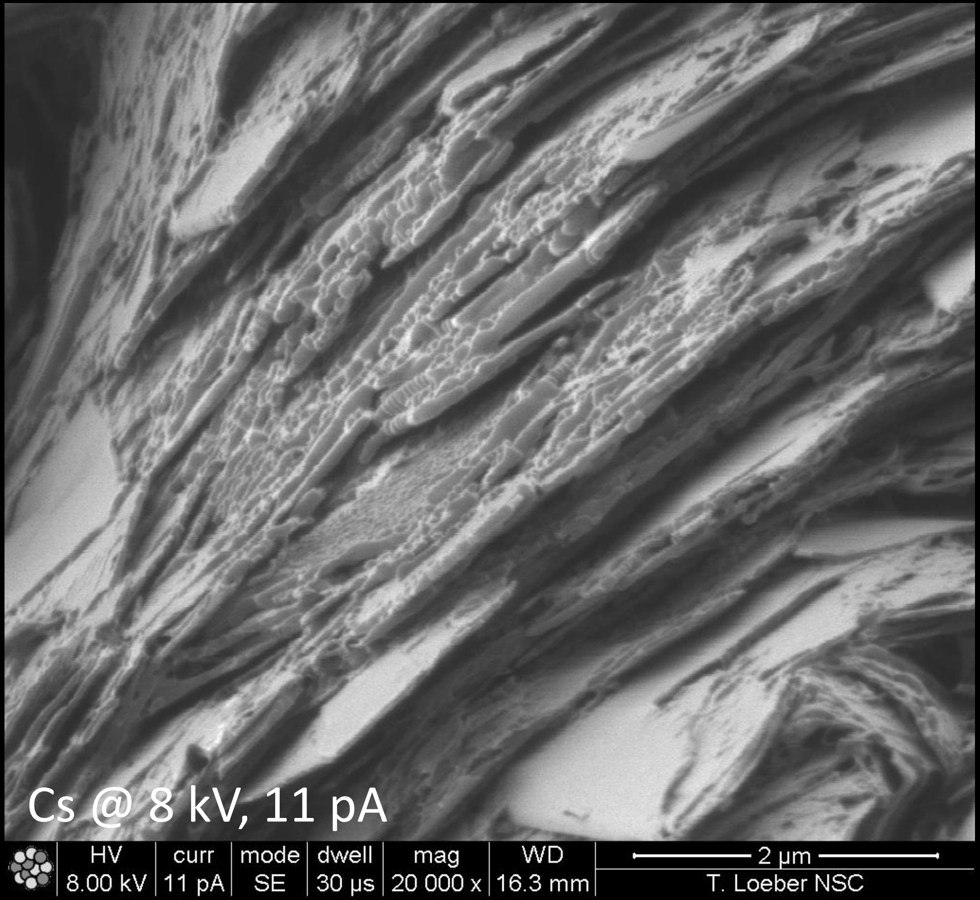
Ga ion image



Ga @ 30 kV, 7.7 pA

HV	curr	dwell	det	mode	WD	tilt	mag ⊞	1 µm
30.00 kV	7.7 pA	30 µs	ETD	SE	13.0 mm	52 °	20 000 x	TU Kaiserslautern NSC T. Loeber

Cs ion image



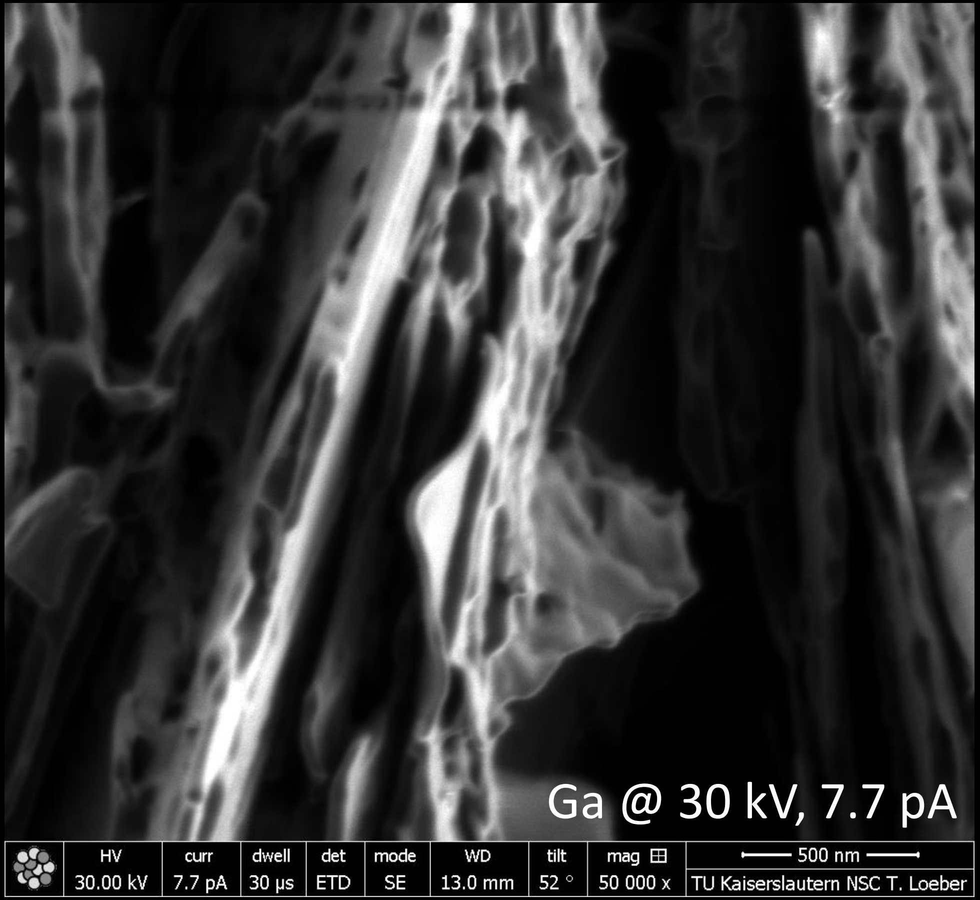
Cs @ 8 kV, 11 pA

HV	curr	mode	dwell	mag	WD	2 µm
8.00 kV	11 pA	SE	30 µs	20 000 x	16.3 mm	T. Loeber NSC

graphite pen: magnification 20k x

Resolution

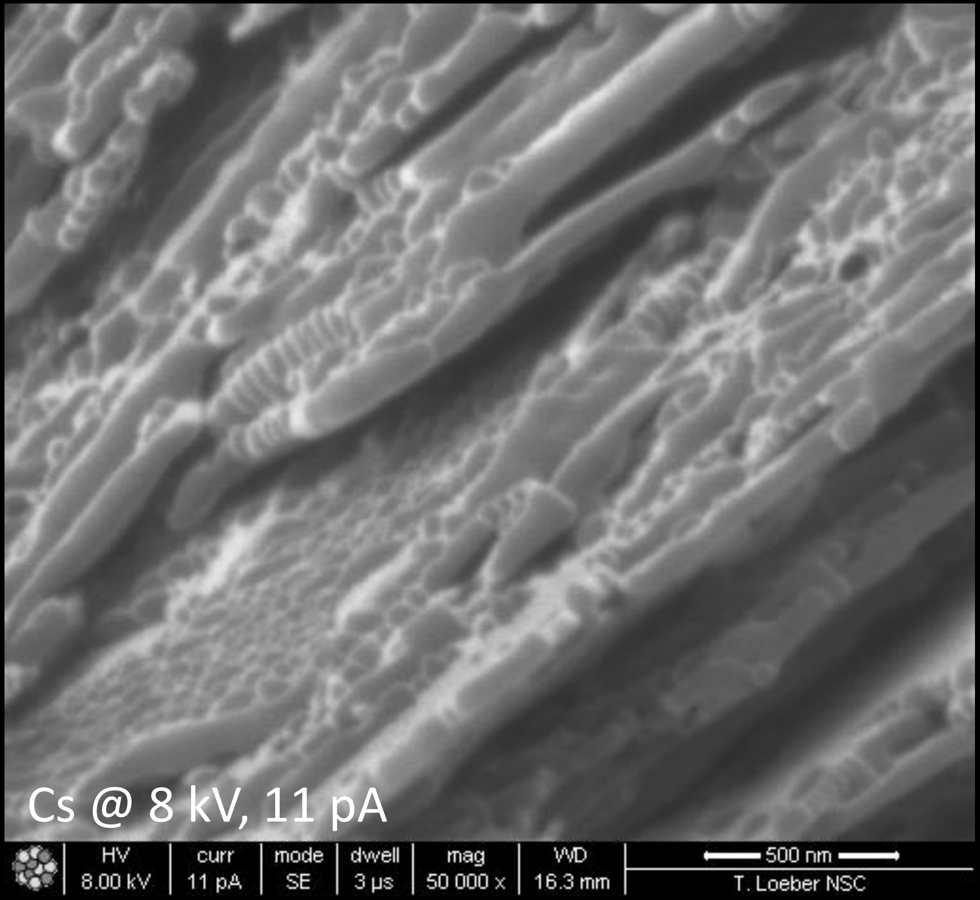
Ga ion image



Ga @ 30 kV, 7.7 pA

HV	curr	dwell	det	mode	WD	tilt	mag ⊞	500 nm
30.00 kV	7.7 pA	30 µs	ETD	SE	13.0 mm	52 °	50 000 x	TU Kaiserslautern NSC T. Loeber

Cs ion image



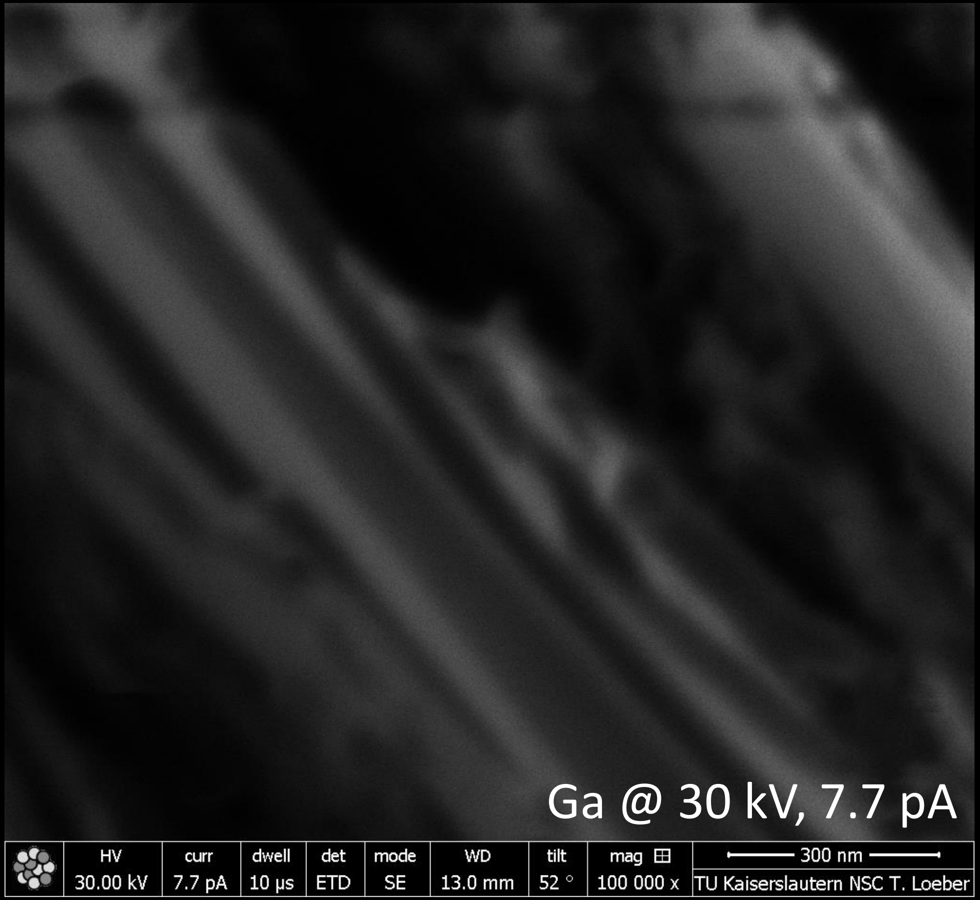
Cs @ 8 kV, 11 pA

HV	curr	mode	dwell	mag	WD	500 nm
8.00 kV	11 pA	SE	3 µs	50 000 x	16.3 mm	T. Loeber NSC

graphite pen: magnification 50k

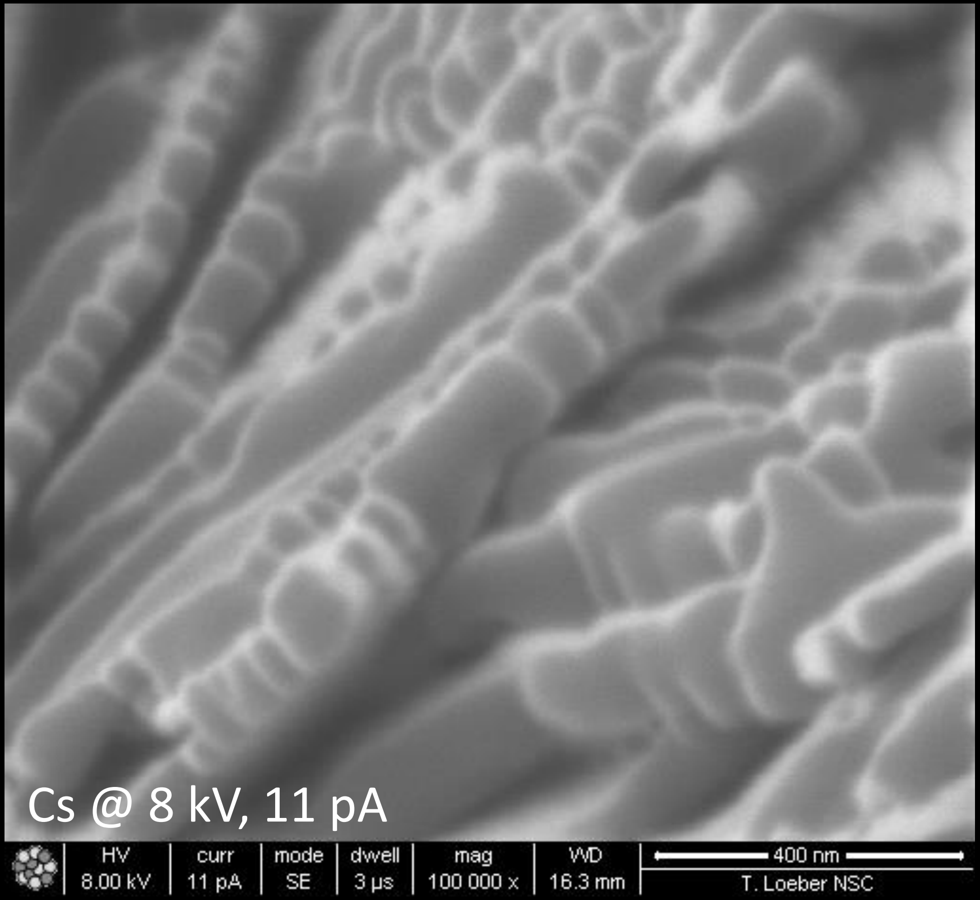
Resolution

Ga ion image


Ga @ 30 kV, 7.7 pA

HV	curr	dwell	det	mode	WD	tilt	mag ⊞	300 nm
30.00 kV	7.7 pA	10 µs	ETD	SE	13.0 mm	52 °	100 000 x	TU Kaiserslautern NSC T. Loeber

Cs ion image

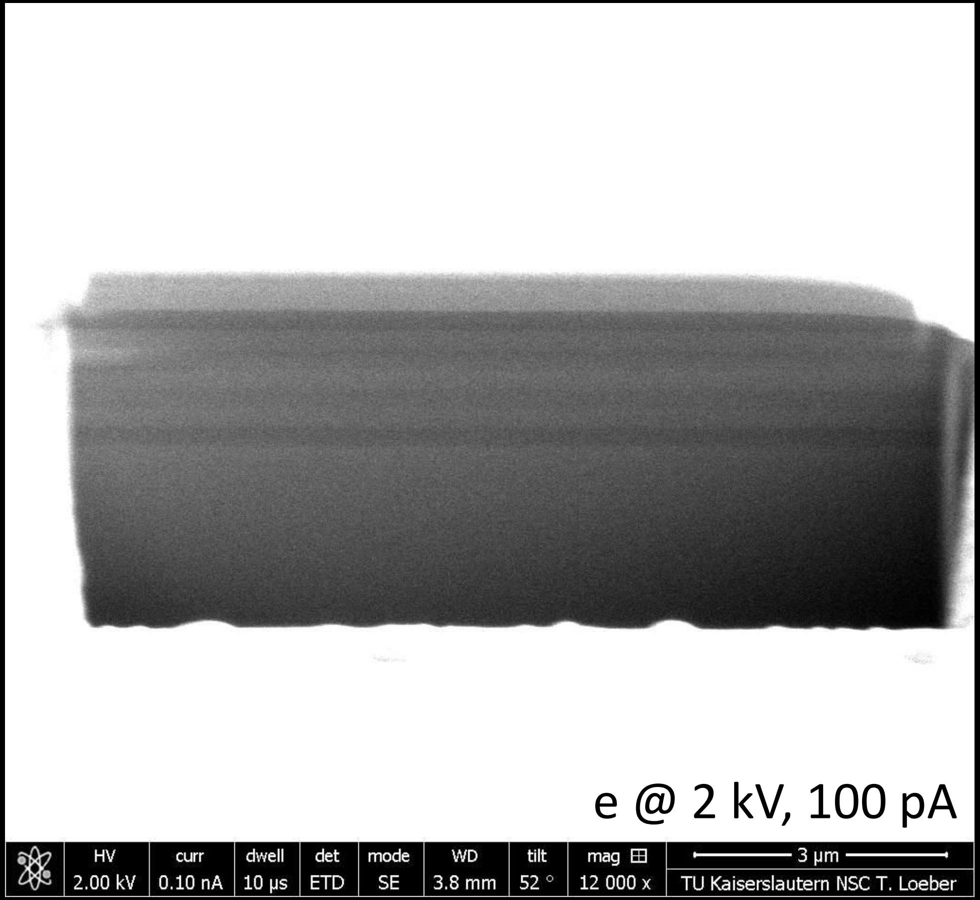

Cs @ 8 kV, 11 pA

HV	curr	mode	dwell	mag	WD	400 nm
8.00 kV	11 pA	SE	3 µs	100 000 x	16.3 mm	T. Loeber NSC

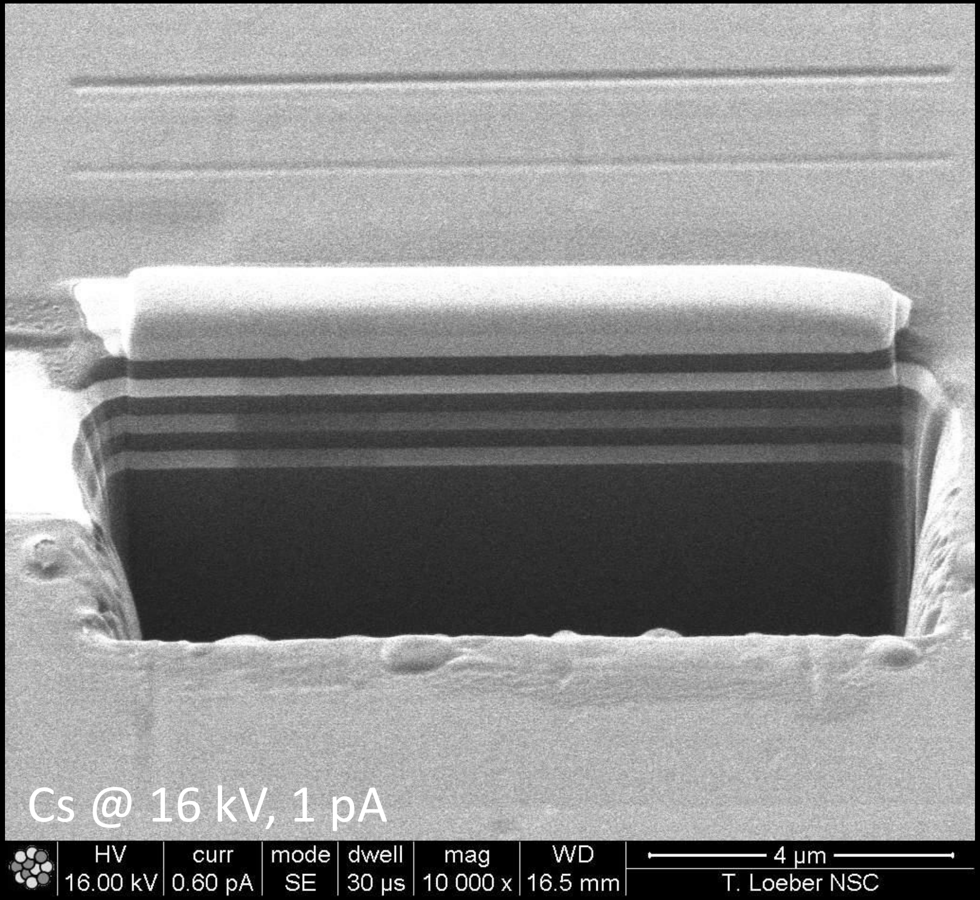
graphite pen: magnification 100k

Material contrast

electron image



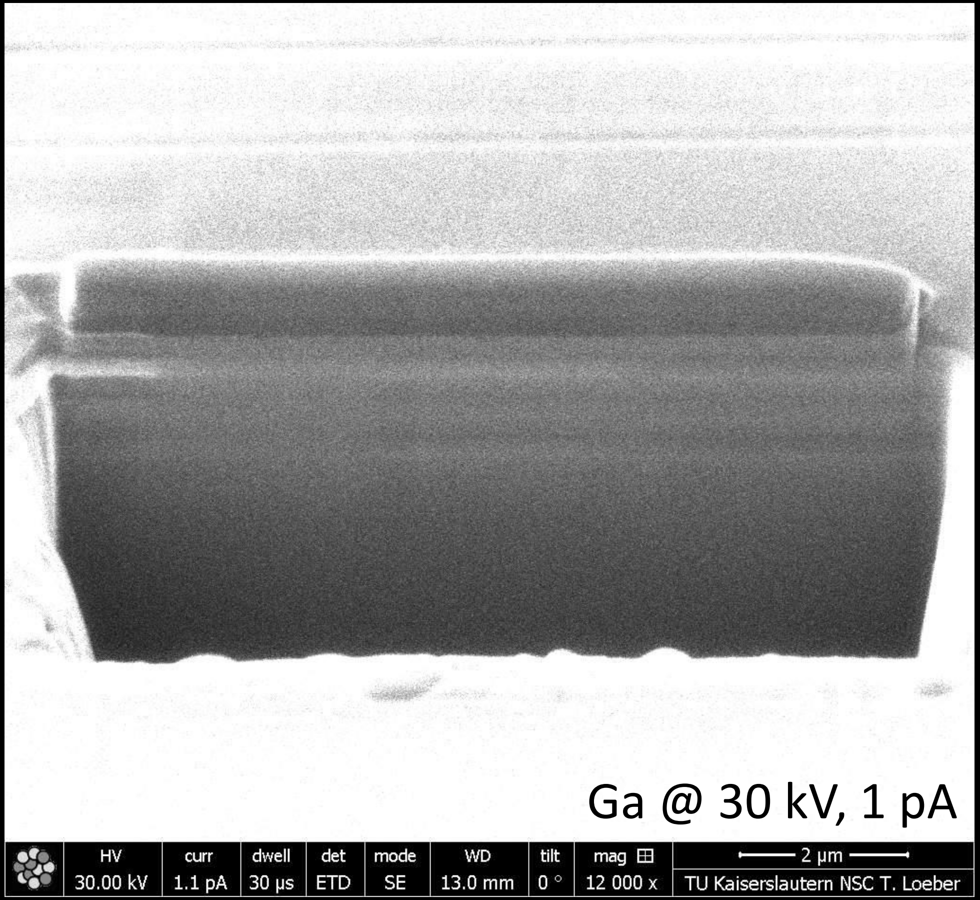
Cs ion image



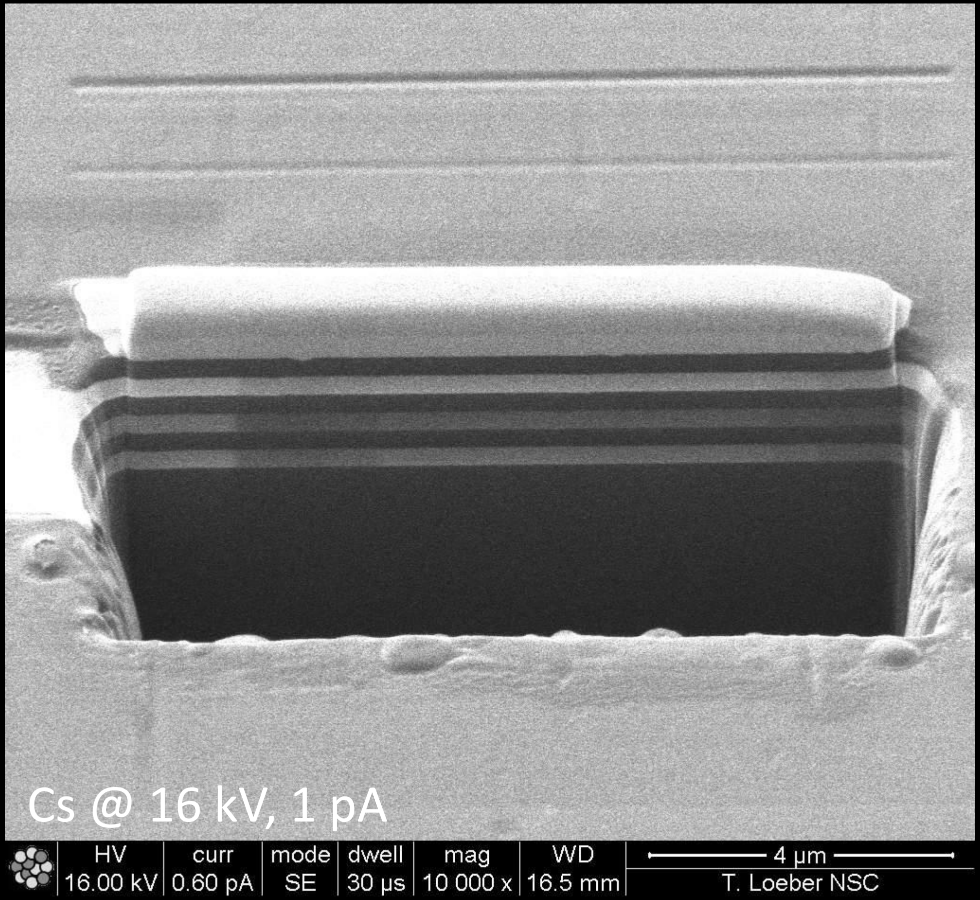
cross section of GaAs and AlGaAs layer

Material contrast

Ga ion image



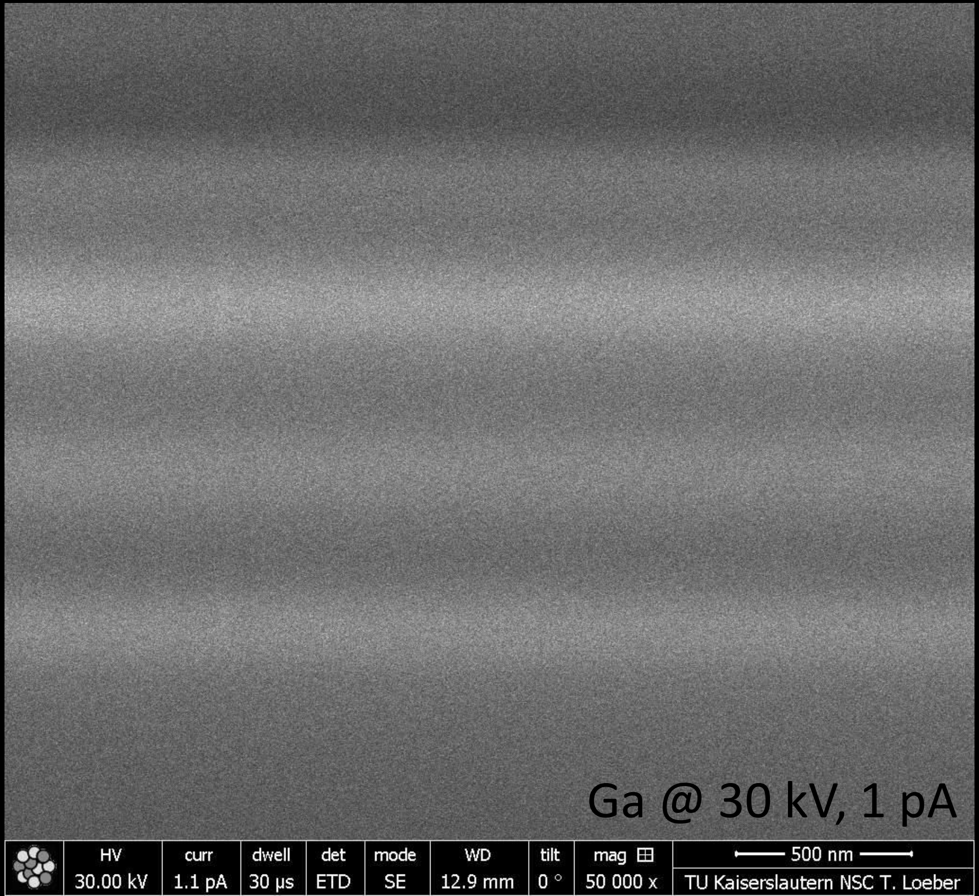
Cs ion image



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

Material contrast

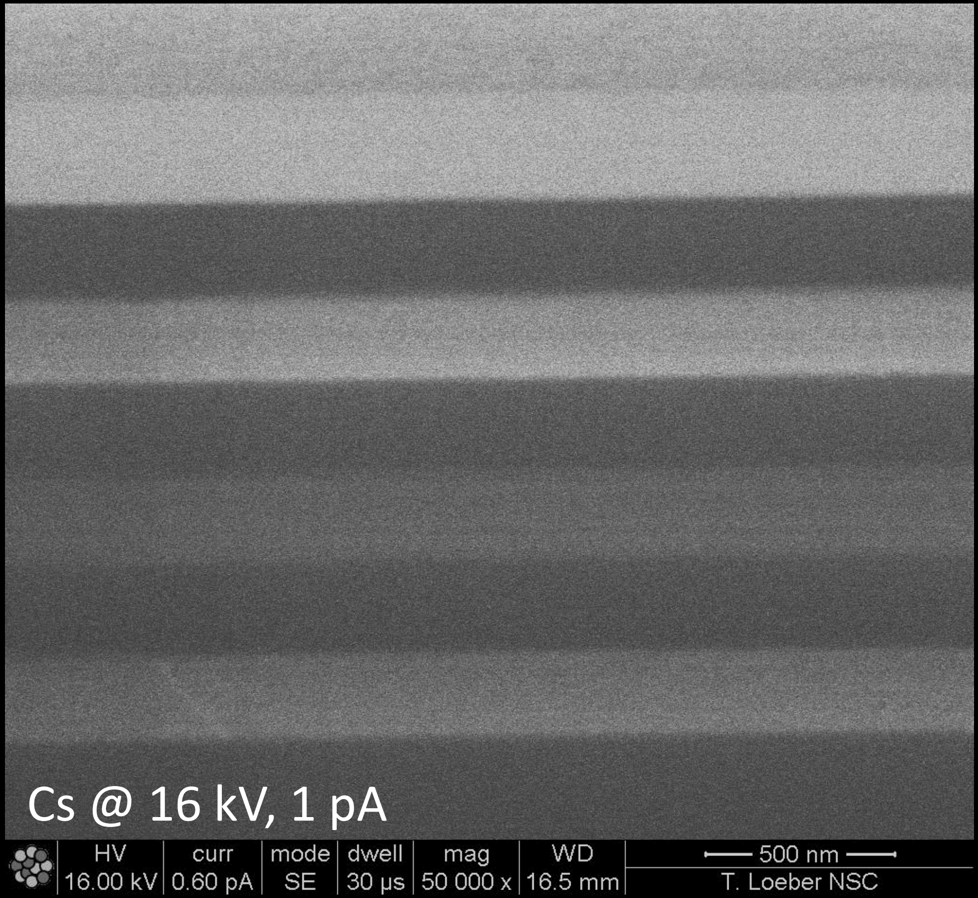
Ga ion image



Ga @ 30 kV, 1 pA

HV	curr	dwell	det	mode	WD	tilt	mag ⊞	500 nm
30.00 kV	1.1 pA	30 µs	ETD	SE	12.9 mm	0 °	50 000 x	TU Kaiserslautern NSC T. Loeber

Cs ion image



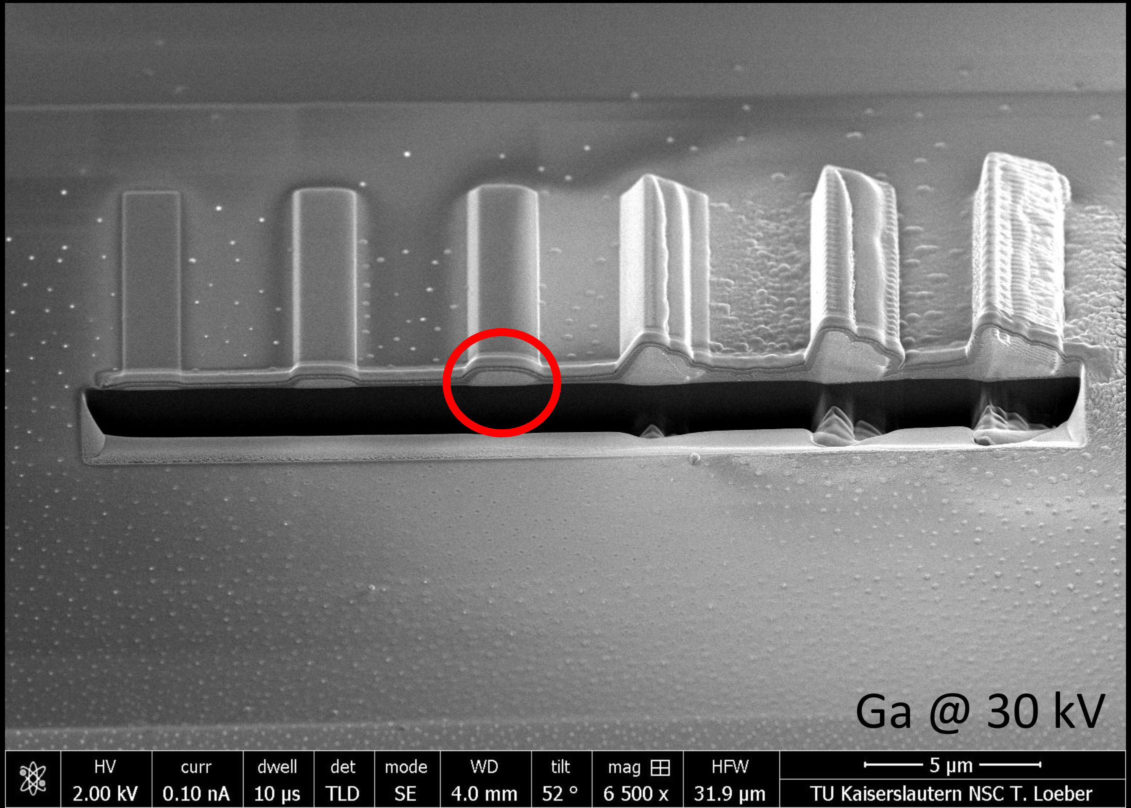
Cs @ 16 kV, 1 pA

HV	curr	mode	dwell	mag	WD	500 nm
16.00 kV	0.60 pA	SE	30 µs	50 000 x	16.5 mm	T. Loeber NSC

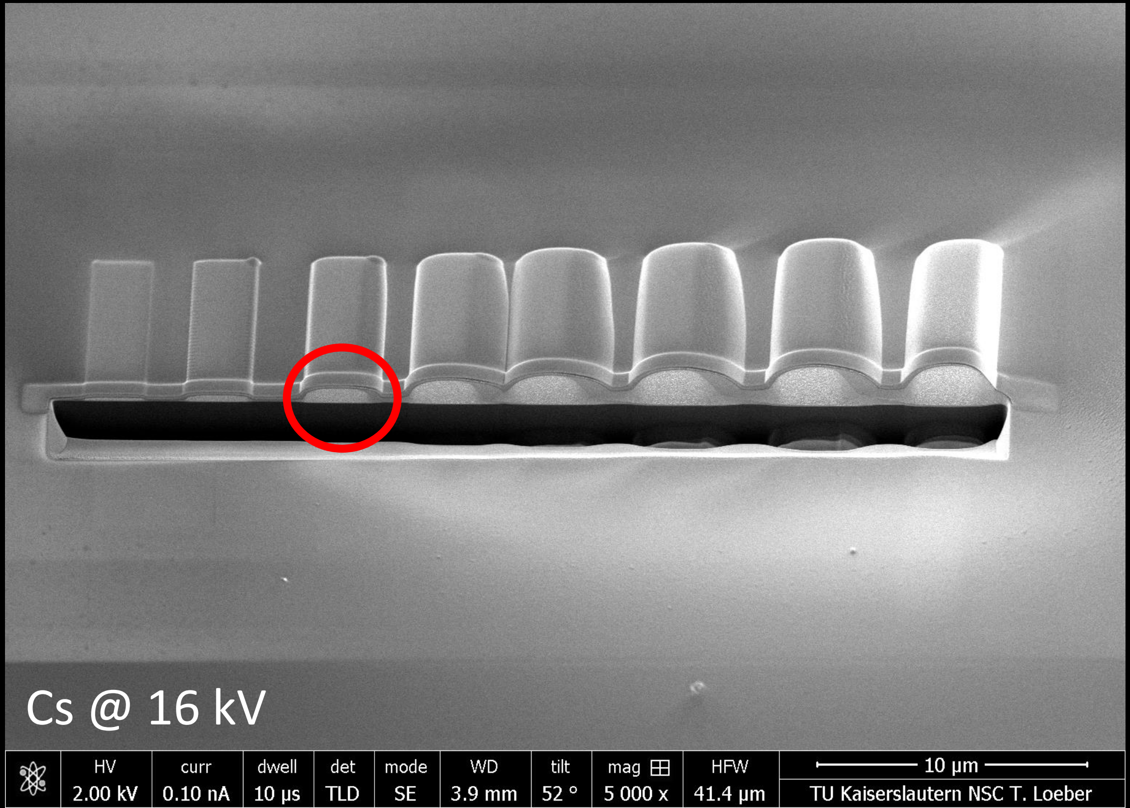
different composition of AlGaAs layers can been seen in different grey values

Deposition of platimun

deposition time 2:30 min



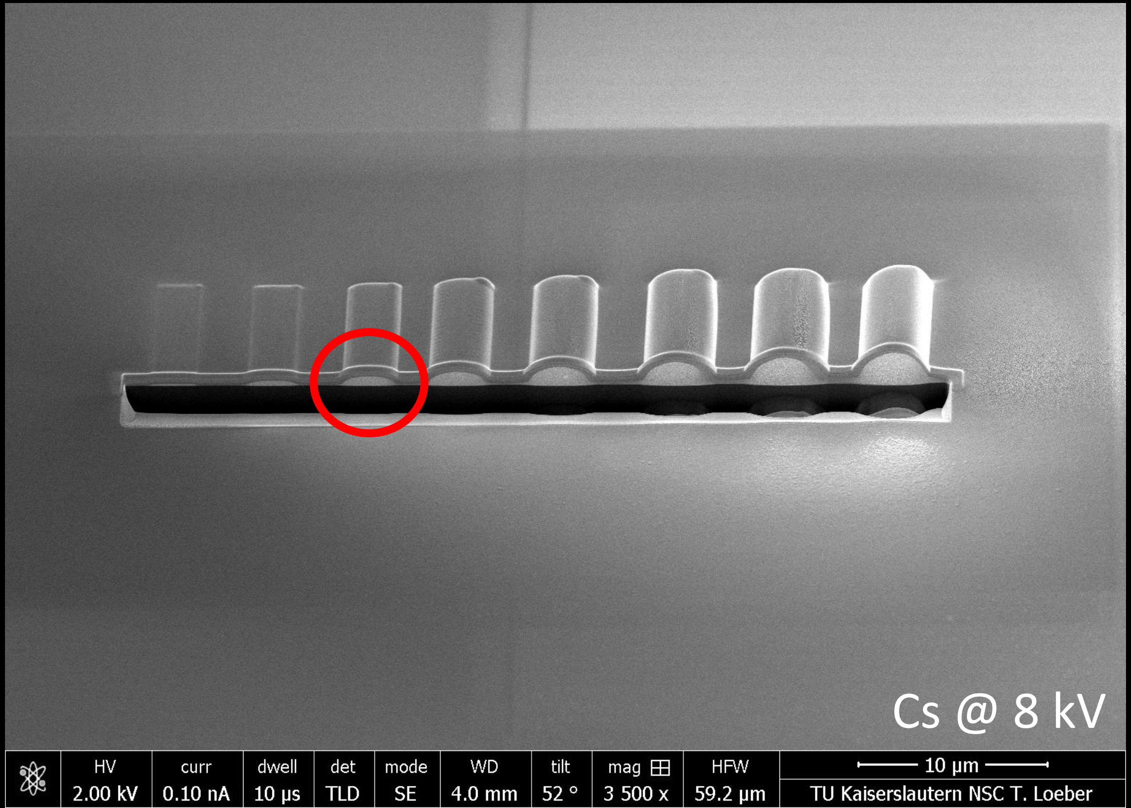
deposition time 2:30 min



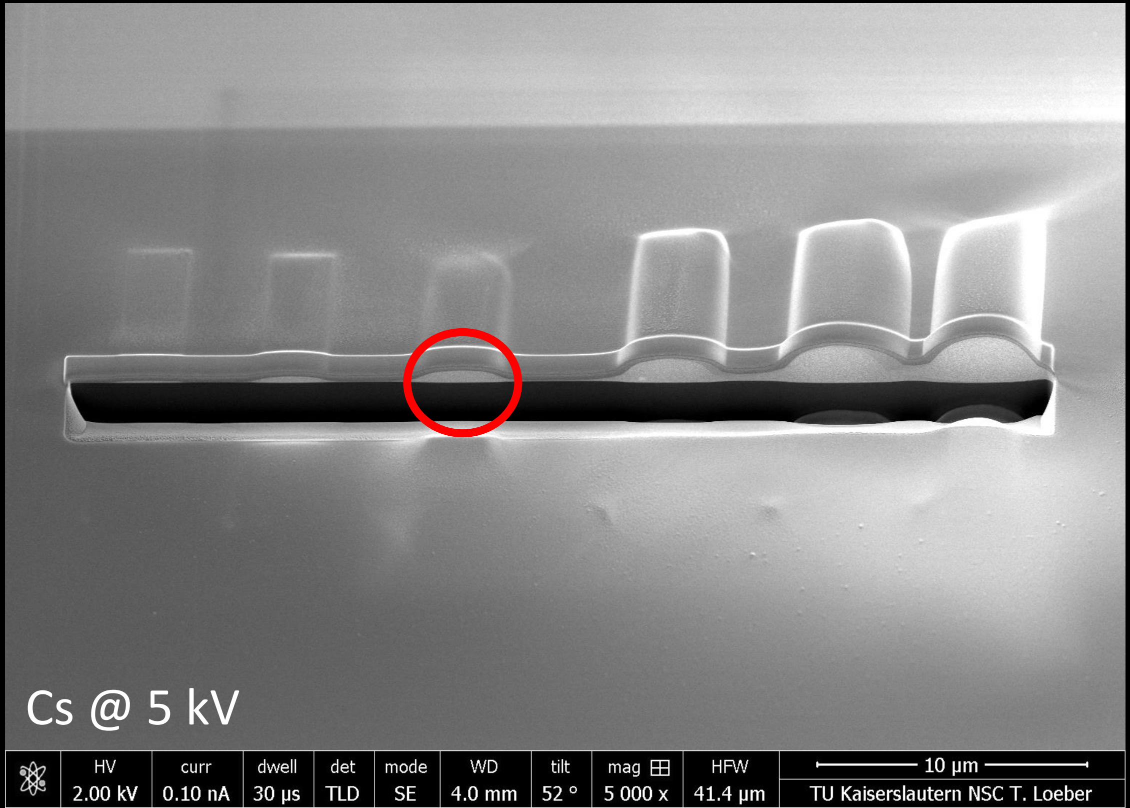
- electron image of cross section
- capping layer on top, deposited with e Beam
- increasing current density from left to right

Deposition of platimun

deposition time 2:30 min

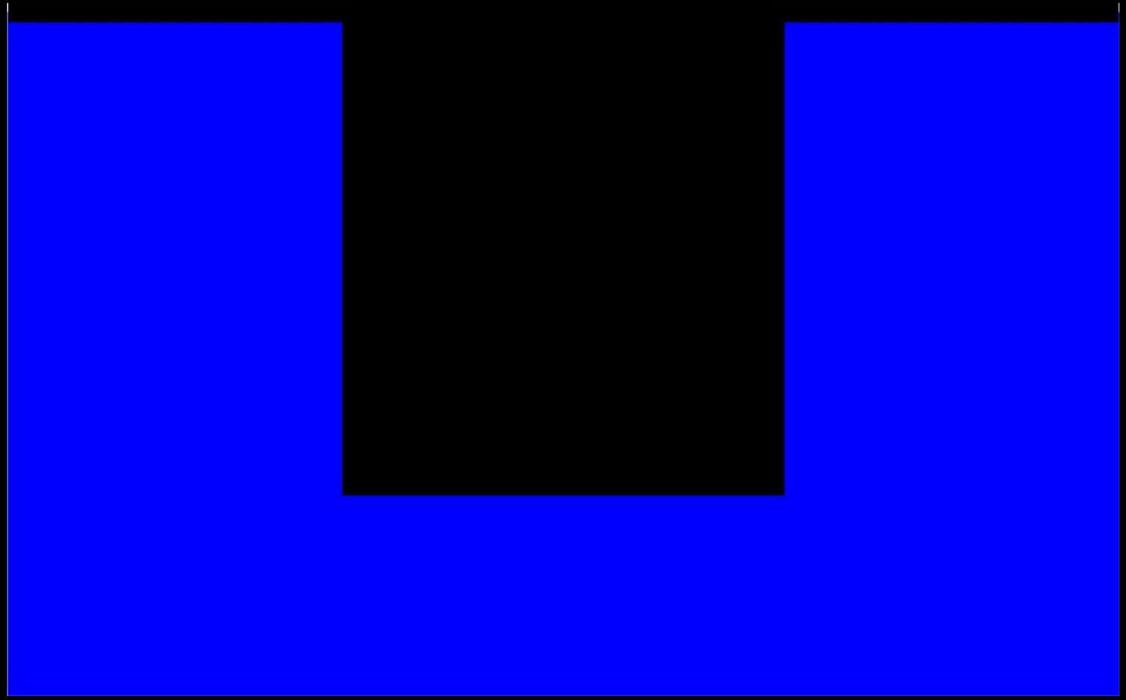


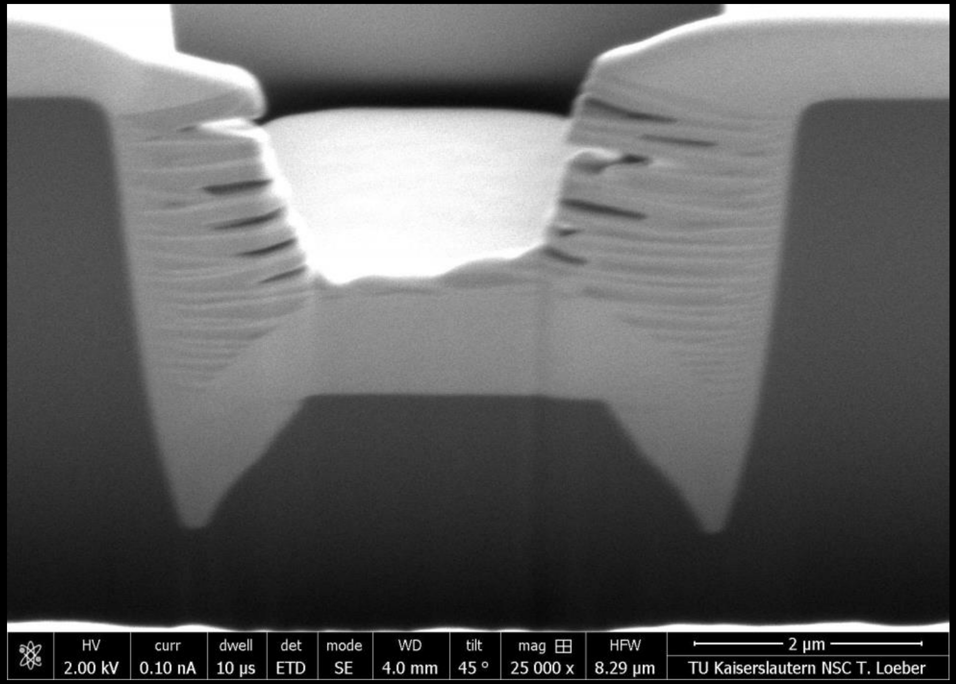
deposition time 2:30 min



- deposition area 2 µm x 10 µm
- good results @ 6 pA/µm^2
- Cs: layers deposited at lower voltages have rounder cross section

Milling in Silicon

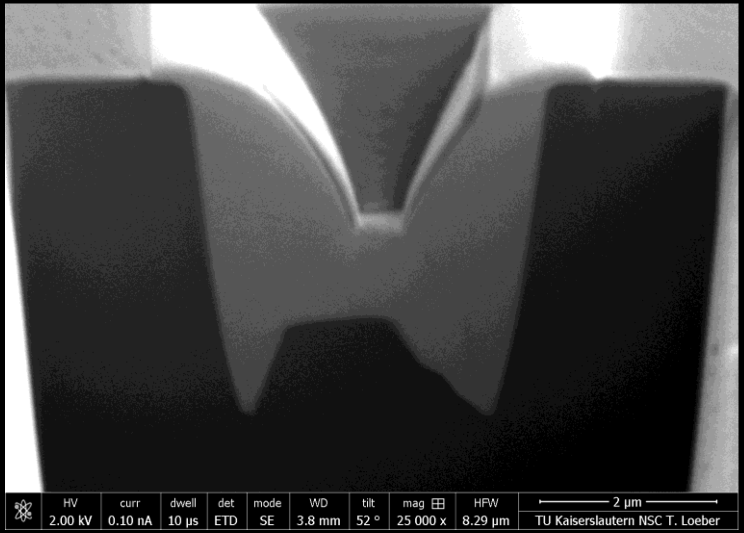




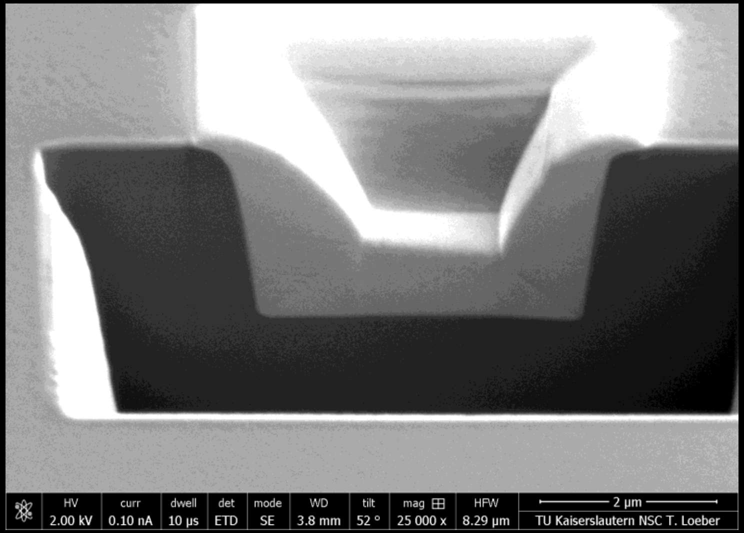
expectation vs. reality

Milling in Silicon

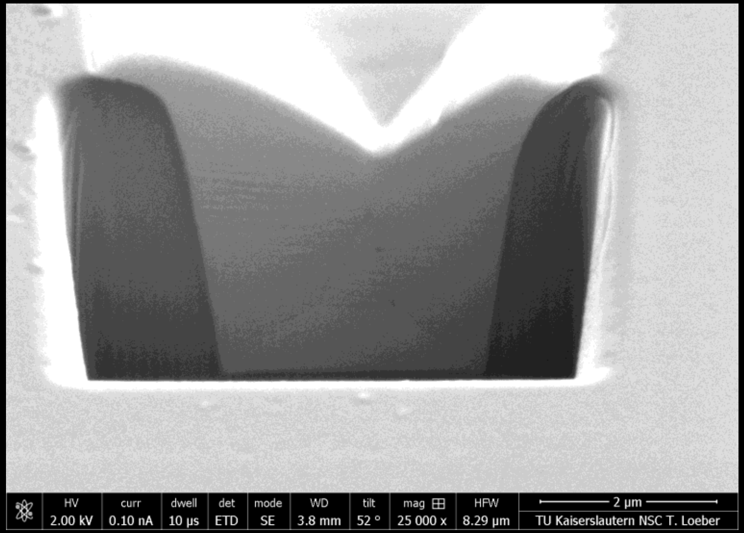
Ga ion: 30 kV @ 348 pA
depth 3.36 µm



Ga ion: 16 kV @ 260 pA
depth 2.41 µm



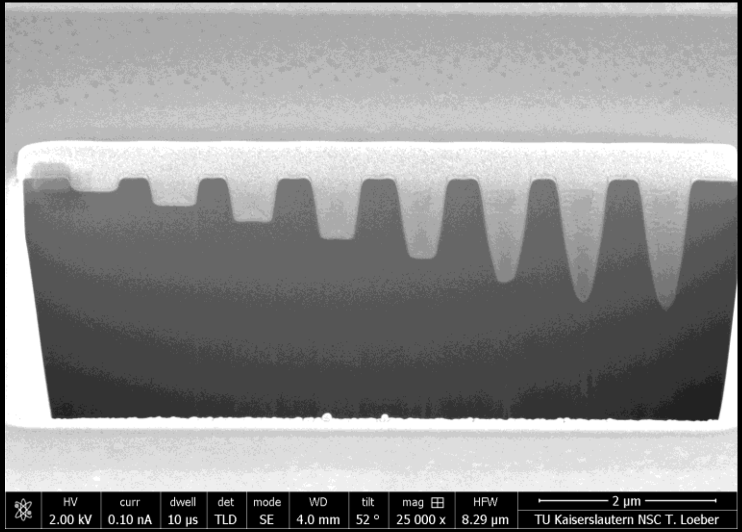
Cs ion: 16 kV @ 265 pA
depth 4.19 µm



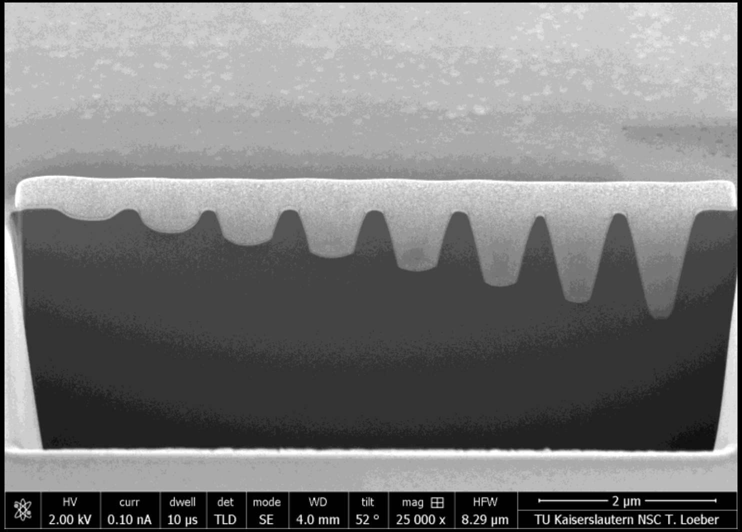
- rectangle 4 µm x 4 µm
- milling time 10 min
- Ga @ 30 kV: uneven bottom
- Ga @ 16 kV: low milling rate
- Cs @ 16 kV: best result

Milling in Silicon

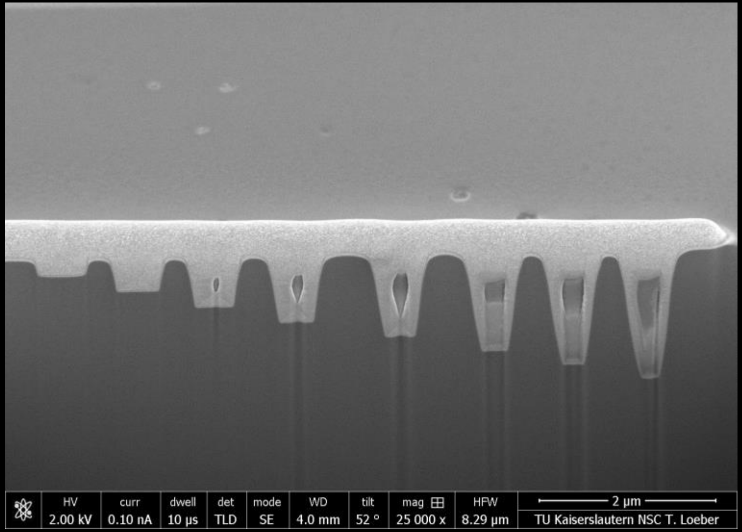
Ga ion: 30 kV @ 22 pA
depth from 0.18 to 1.87 µm



Ga ion: 16 kV @ 19 pA
depth from 0.18 to 1.58 µm

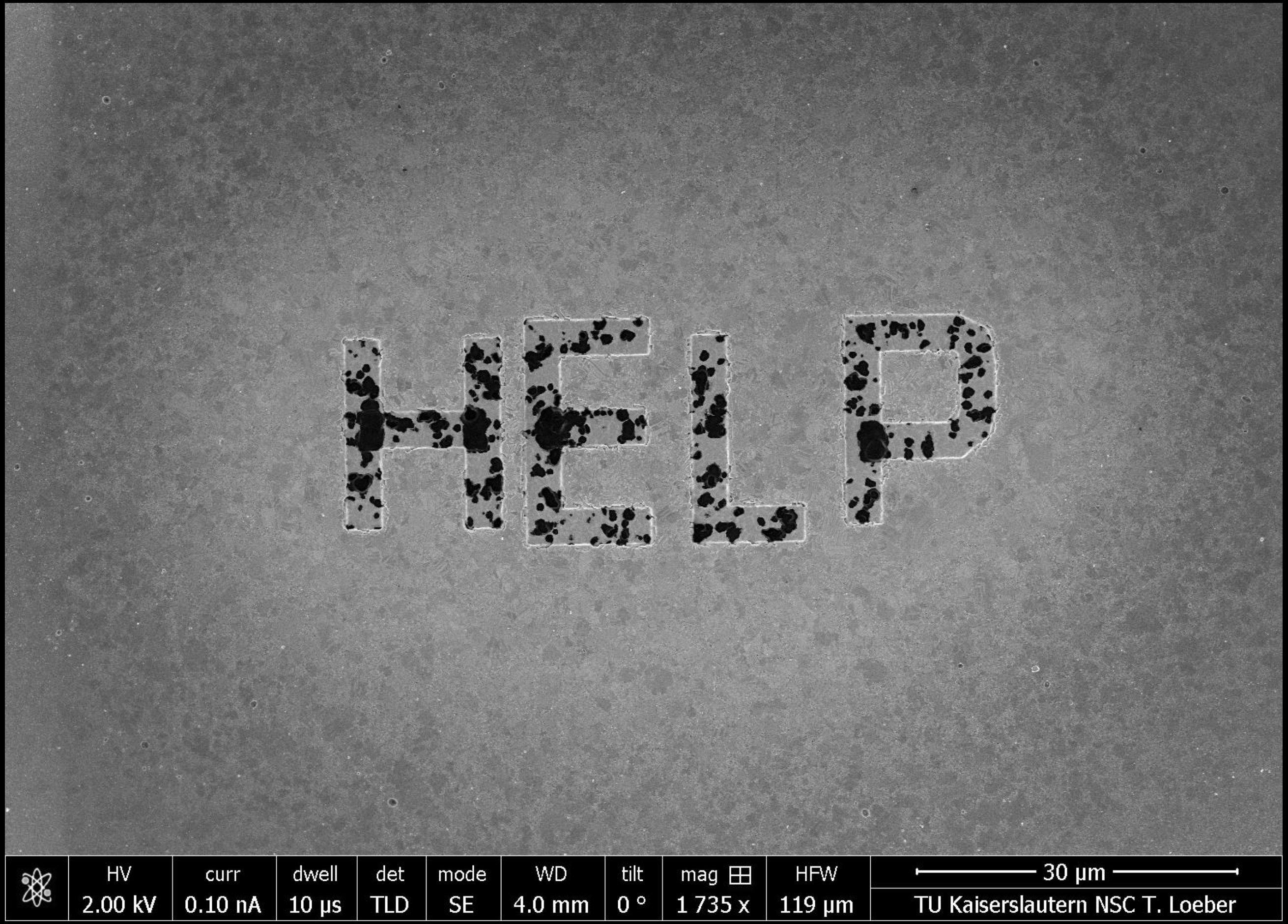


Cs ion: 16 kV @ 22 pA
depth from 0.23 to 1.86 µm



- low ion beam currents
- rectangle 0.5 µm x 0.5 µm
- milling time from 9 s to 1 min
- Ga @ 30 kV: deeper holes have V shape
- Ga @ 16 kV: rounded bottoms
- Cs @ 16 kV: best result

Polycrystalline materials



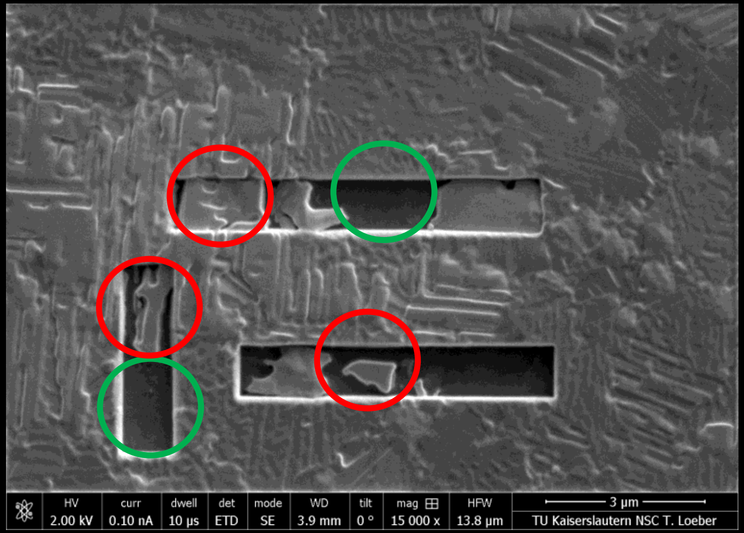
- sputtered polycrystalline metal layer
- often used for plasmonic structures
- ion channeling effect
- inhomogeneous sputter rate
- “nightmare” using a Ga FIB

Ion channeling effect

SE image taken with Ga ions
@ 30 kV

SE image taken with Ga ions
@ 30 kV

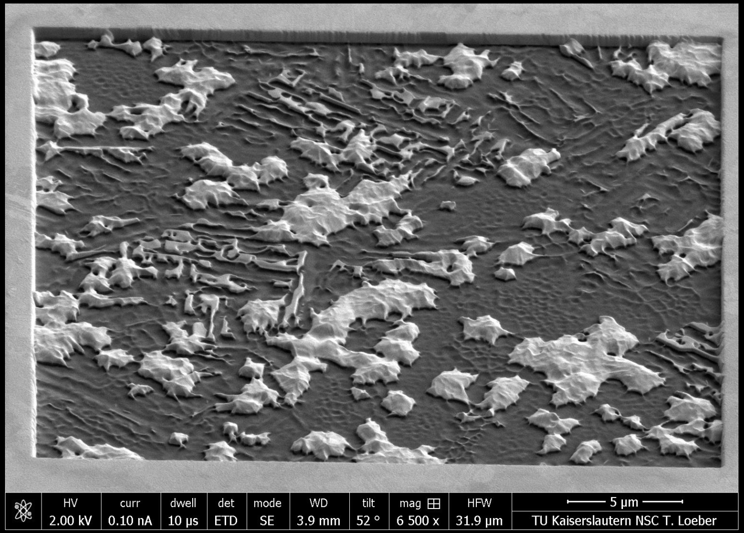
SE image taken with electrons
@ 2 kV



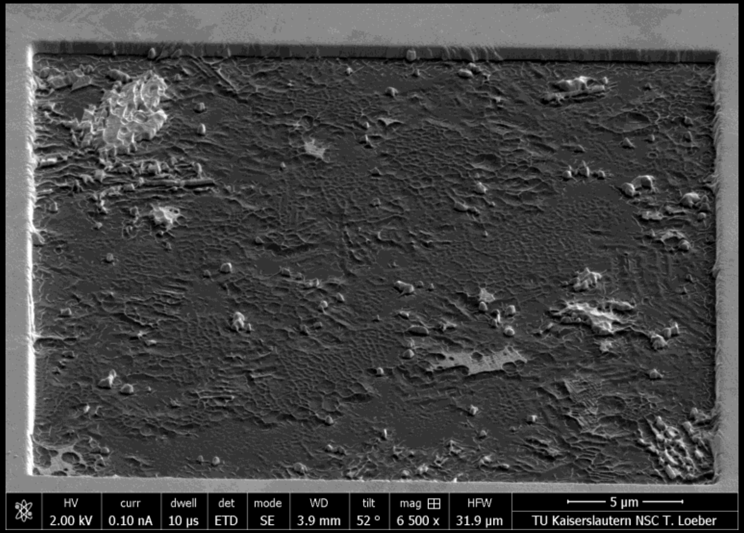
- SE have low escape depth
- dark area:
  - less are emitted SE
  - higher ion penetration depth
  - lower milling rate

Milling in Silver

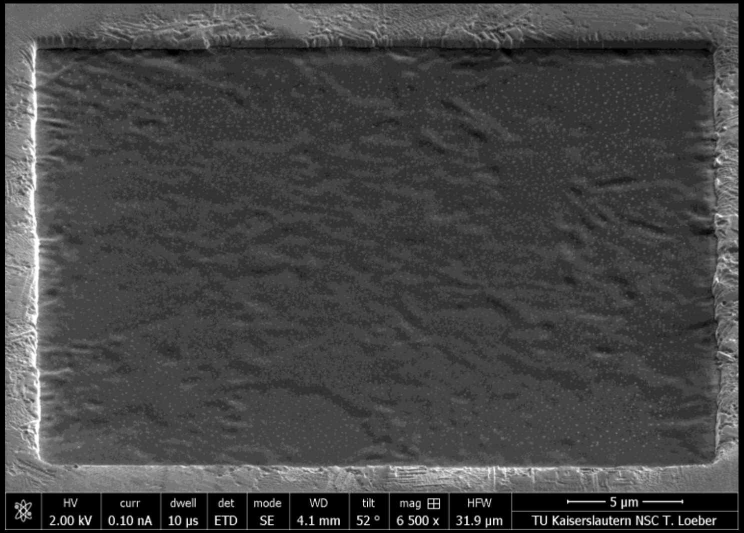
Ga ion: 30 kV @ 460 pA



Ga ion: 16 kV @ 430 pA



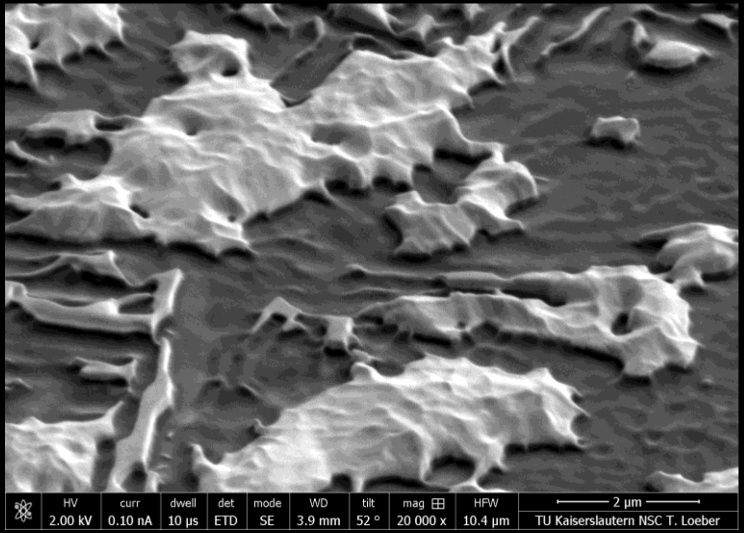
Cs ion: 16 kV @ 460 pA



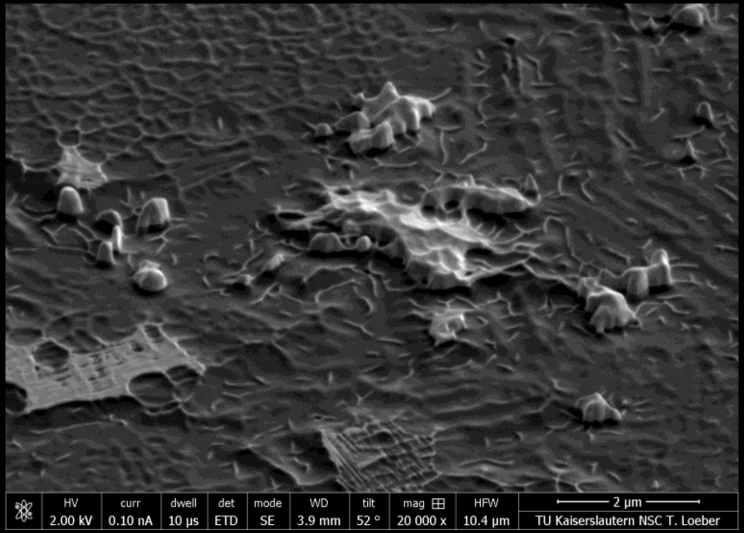
- sputtered Silver layer on Silicon
- layer thickness 535 nm
- rectangle 30 µm x 30 µm
- milling time about 16 min
- dose 500 pC/µm^2

Milling in Silver

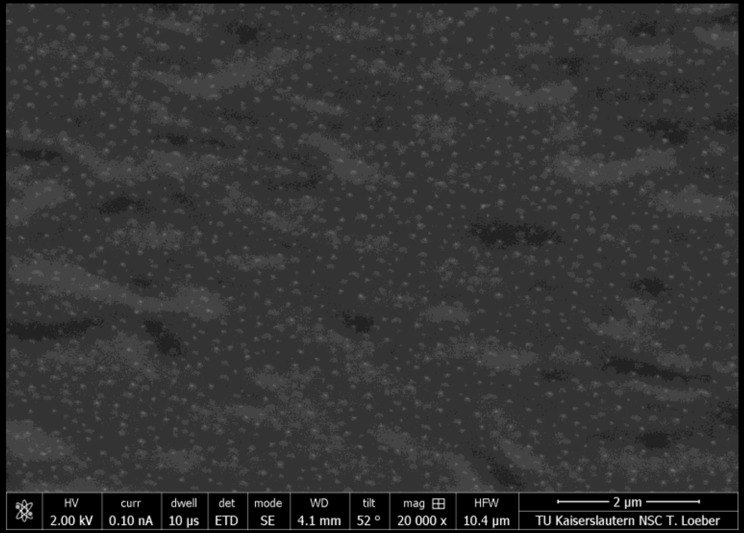
Ga ion: 30 kV @ 460 pA



Ga ion: 16 kV @ 430 pA

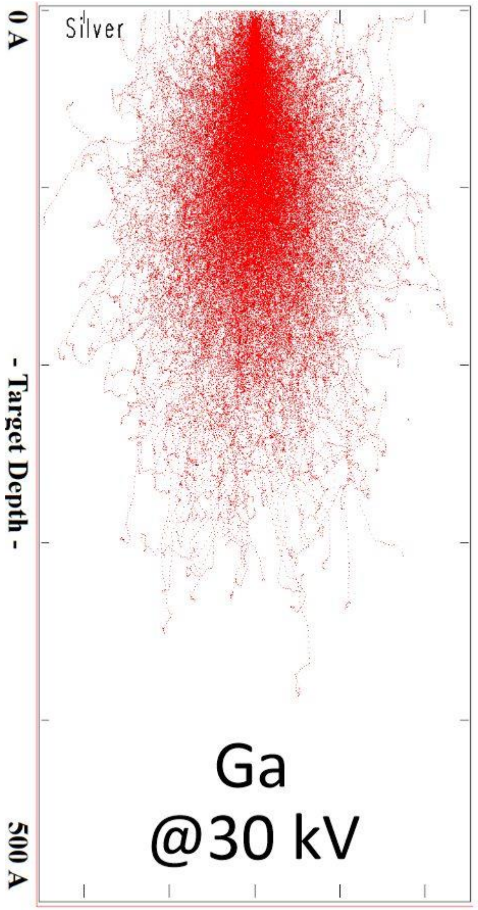


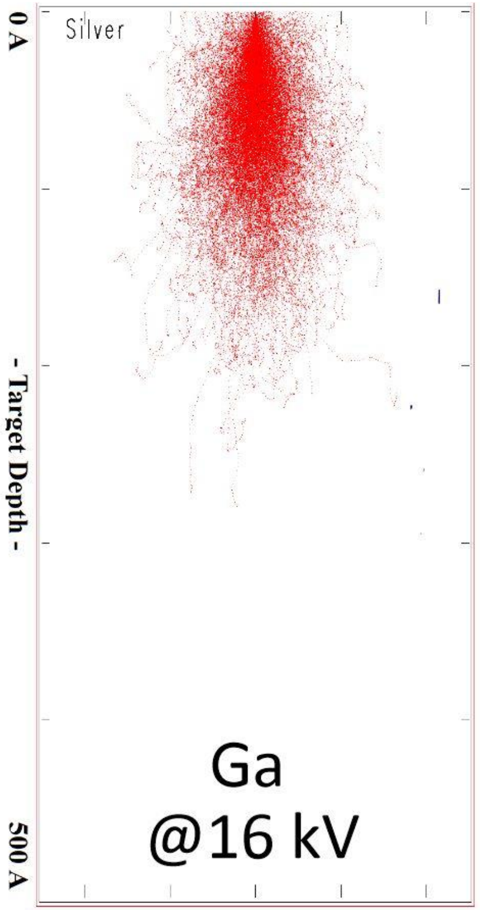
Cs ion: 16 kV @ 460 pA

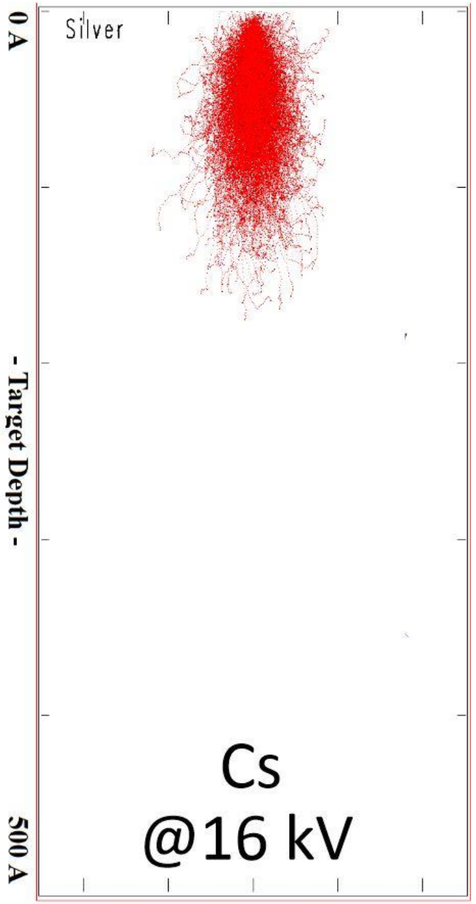


- Ga @ 30 kV: a lot of Silver remaining, while parts of the Silicon are already milled
- Ga @ 16 kV: some Silver remaining, ripples in Silicon
- Cs @ 16 kV: no Silver left , smooth bottom

Penetration depth in amorphous Silver



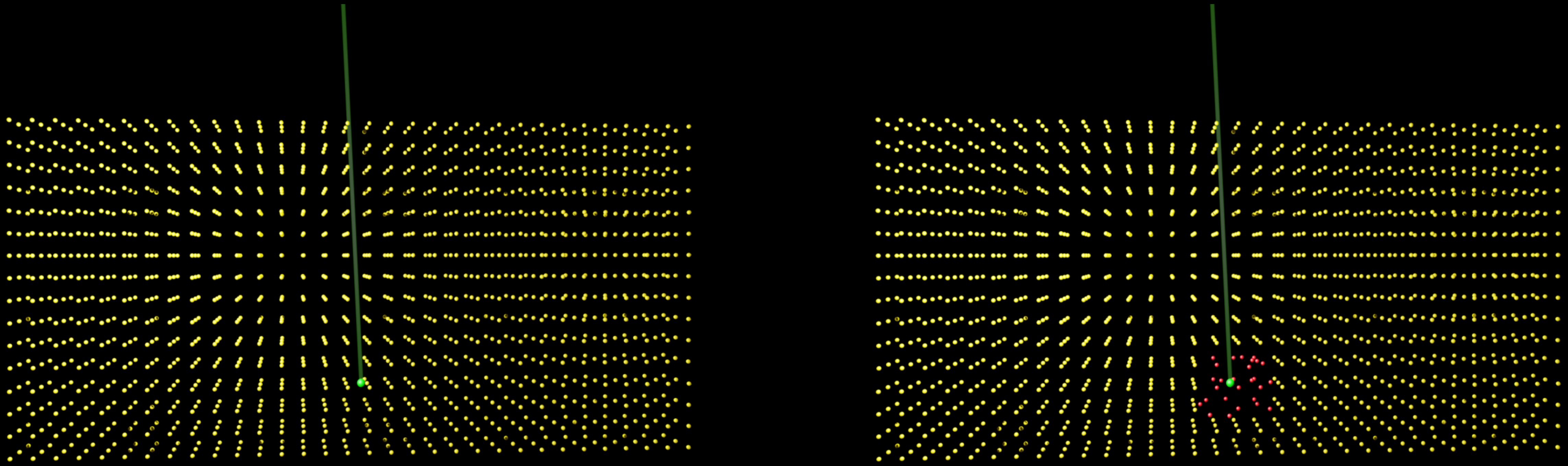




SRIM simulations

Ion channeling

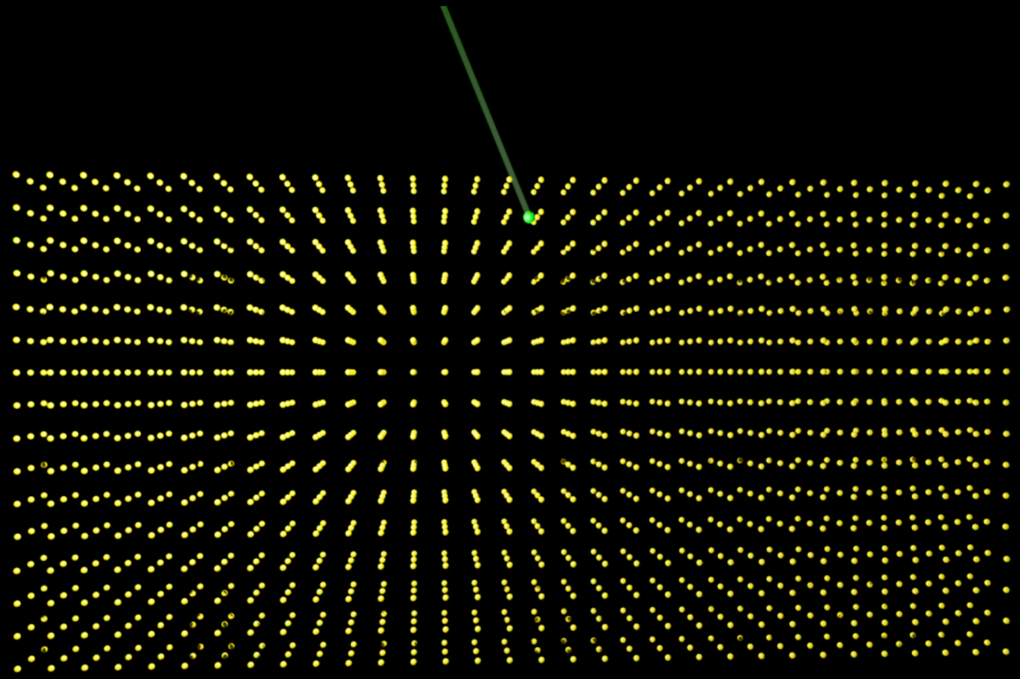
Ga ion beam: along crystal axis

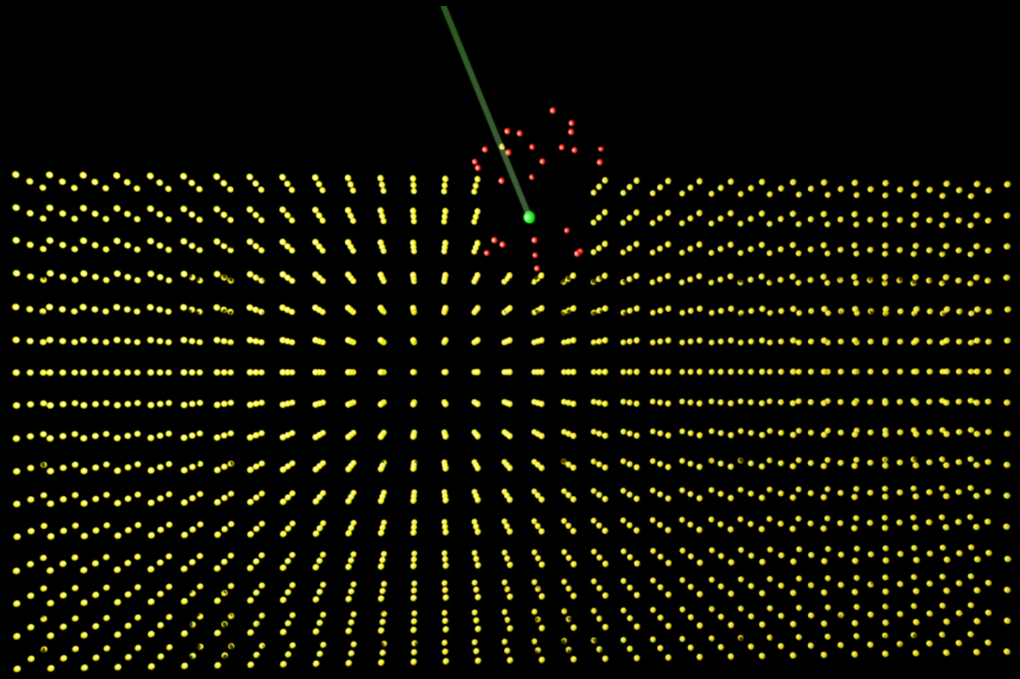


- high penetration depth
- very low sputter rate
- dislocations

Ion channeling

Ga ion beam: at an angle to crystal axis

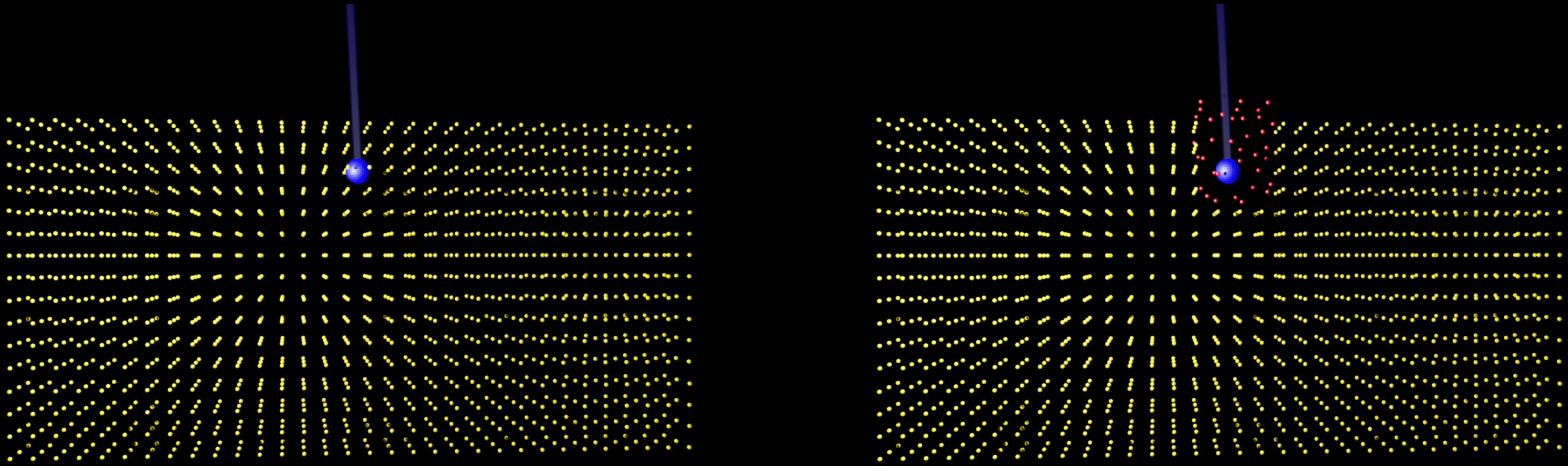




- lower penetration depth
- high sputter rate
- closer to the surface

Ion channeling

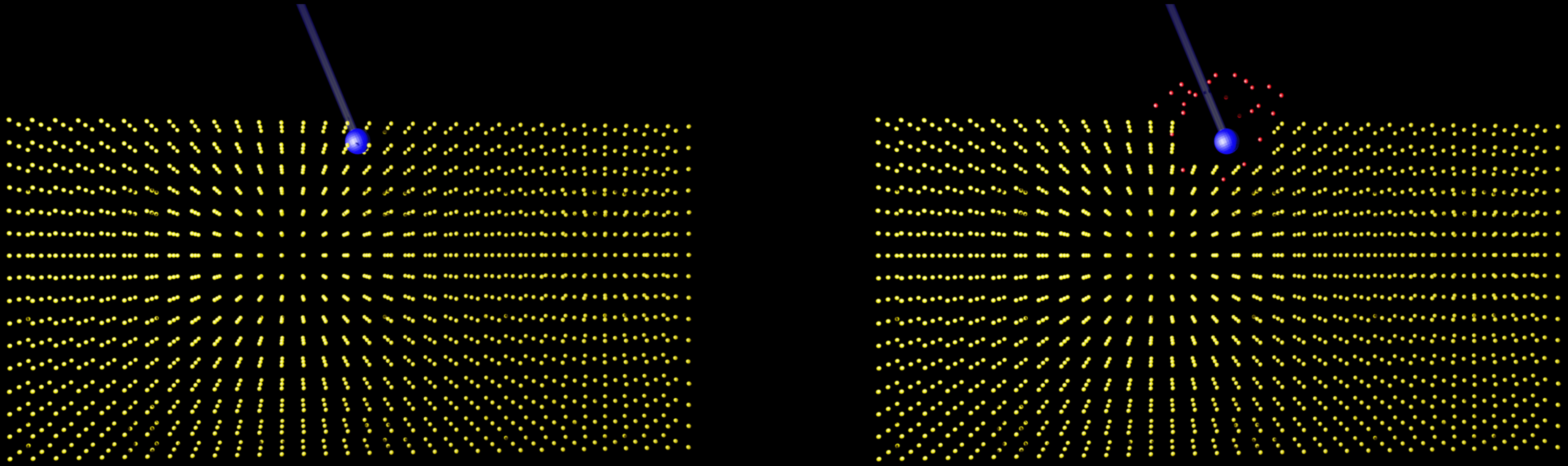
Cs ion beam: along crystal axis



- Cs almost double atomic mass of Ga
- lower penetration depth
- high sputter rate

Ion channeling

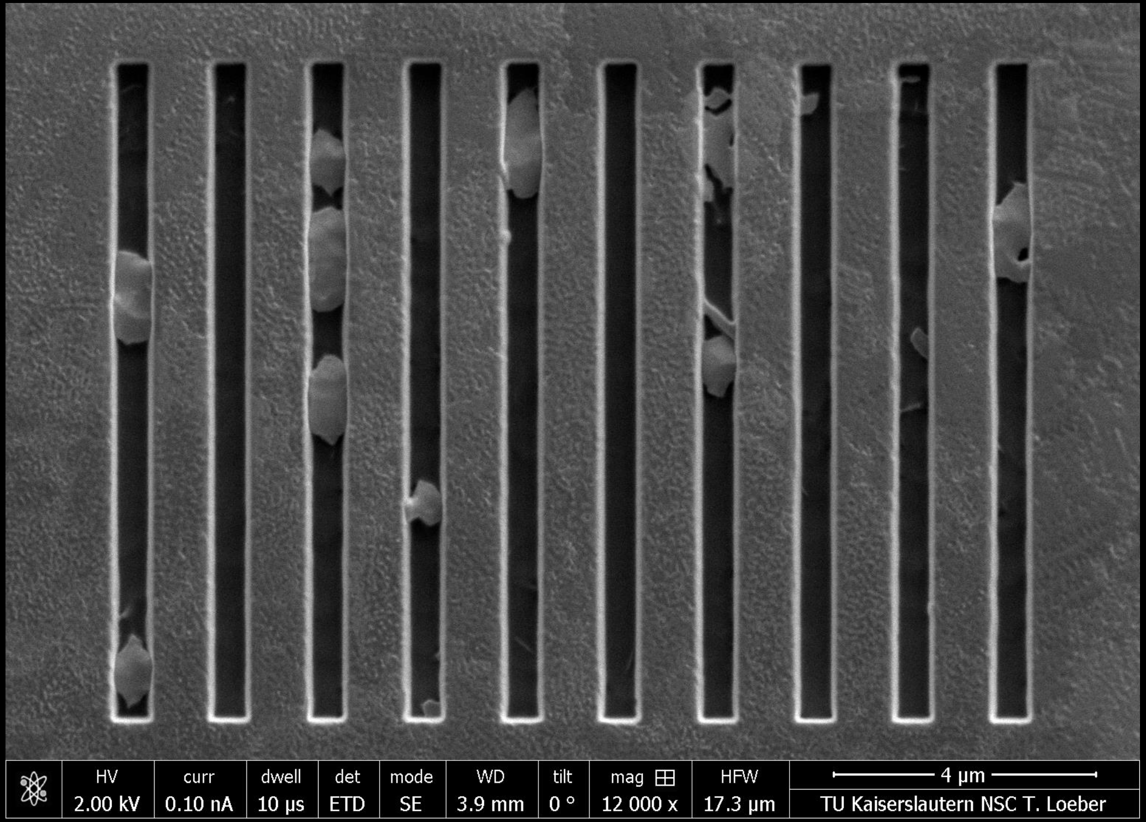
Cs ion beam: at an angle to crystal axis



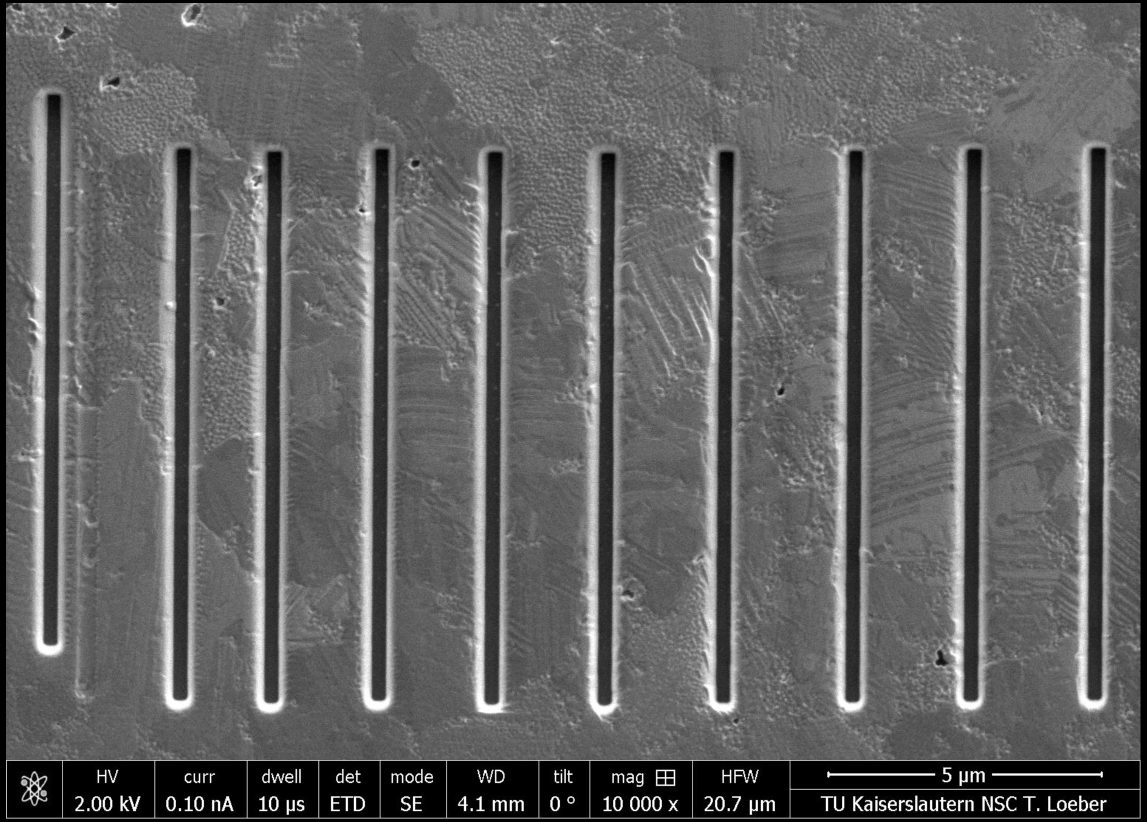
- very close to the surface
- very high sputter rate

Milling in Silver

Ga ion: 30 kV @ 50 pA



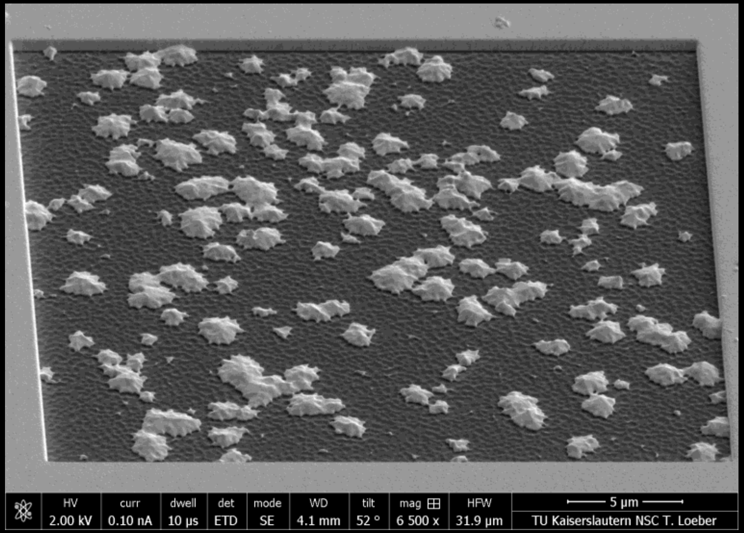
Cs ion: 16 kV @ 40 pA



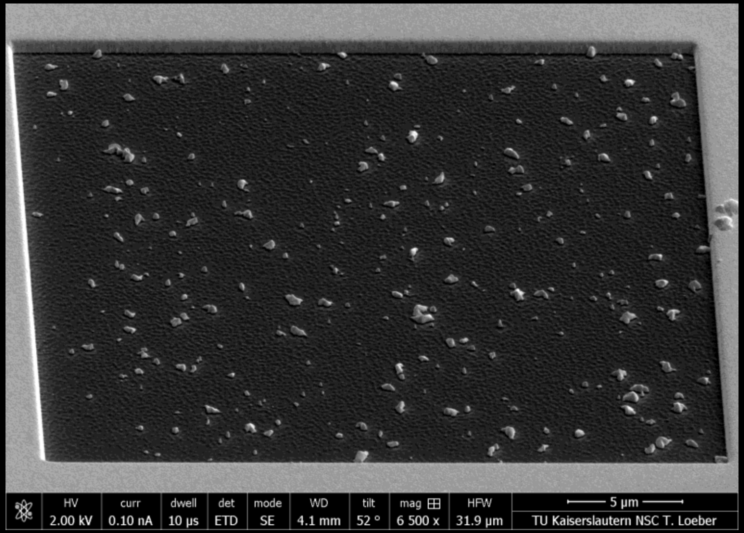
- plasmonic structures in 500 nm thick Silver layer
- Ga: very inhomogeneous milling in polycrystalline Silver
- Cs: “clean” lines, independent from crystalline structure

Milling in Gold

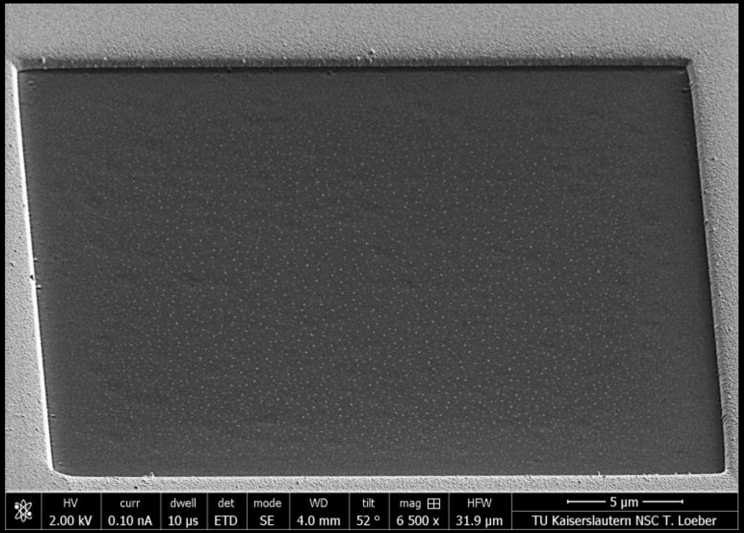
Ga ion: 30 kV @ 467 pA



Ga ion: 16 kV @ 430 pA



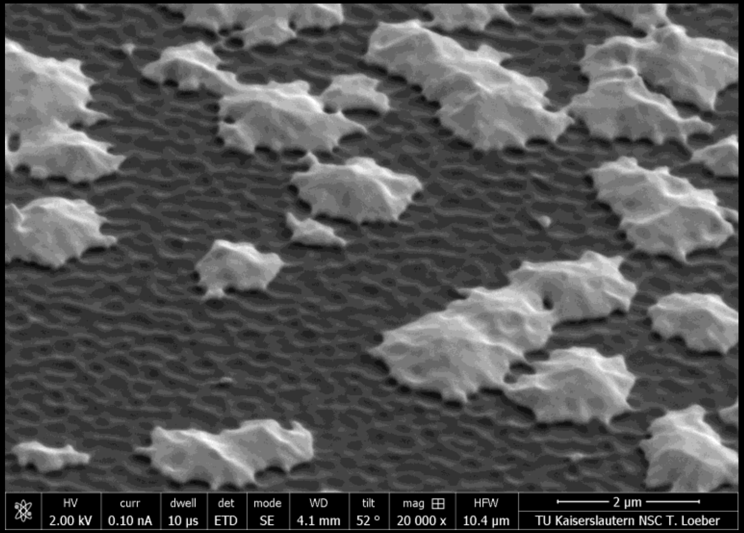
Cs ion: 16 kV @ 430 pA



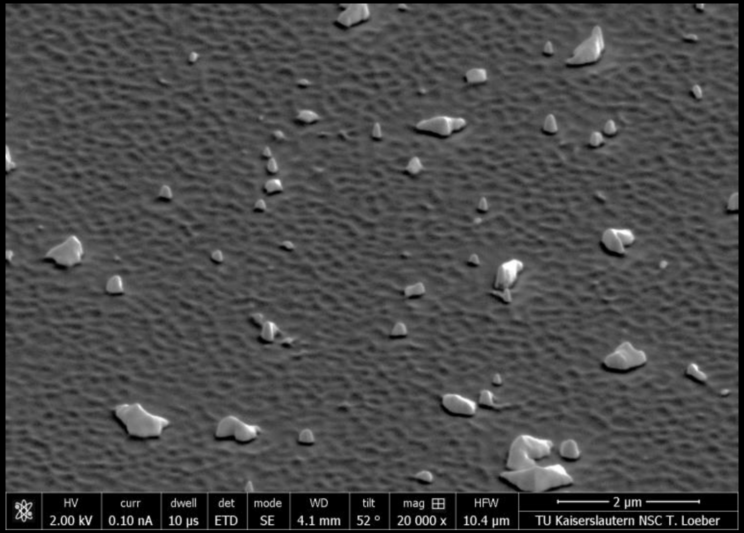
- sputtered Gold layer on Silicon
- layer thickness 520 nm
- rectangle 30 µm x 30 µm
- milling time about 10 min
- dose 300 pC/µm^2

Milling in Gold

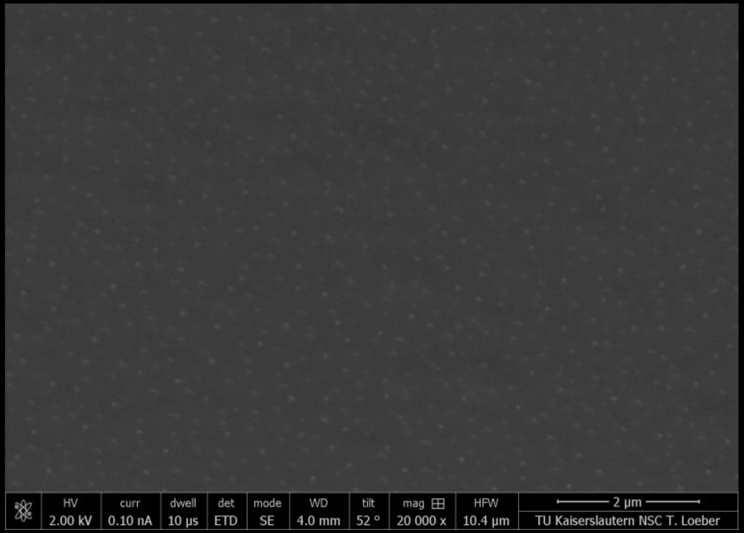
Ga ion: 30 kV @ 460 pA



Ga ion: 16 kV @ 430 pA



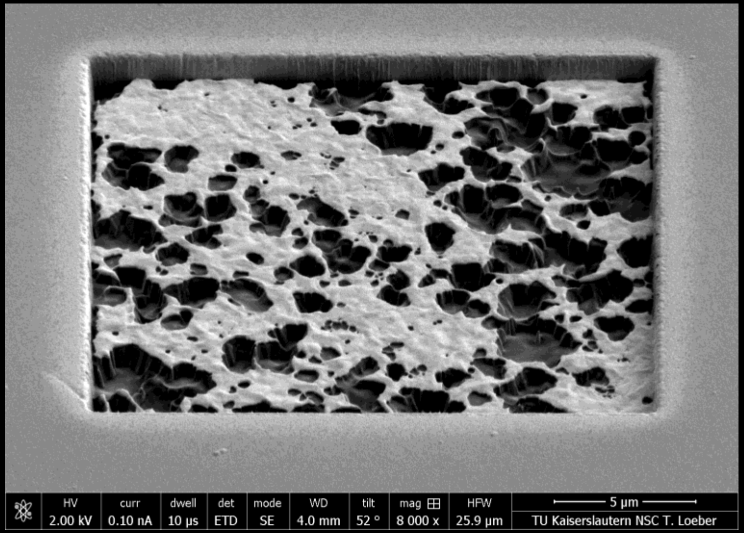
Cs ion: 16 kV @ 460 pA



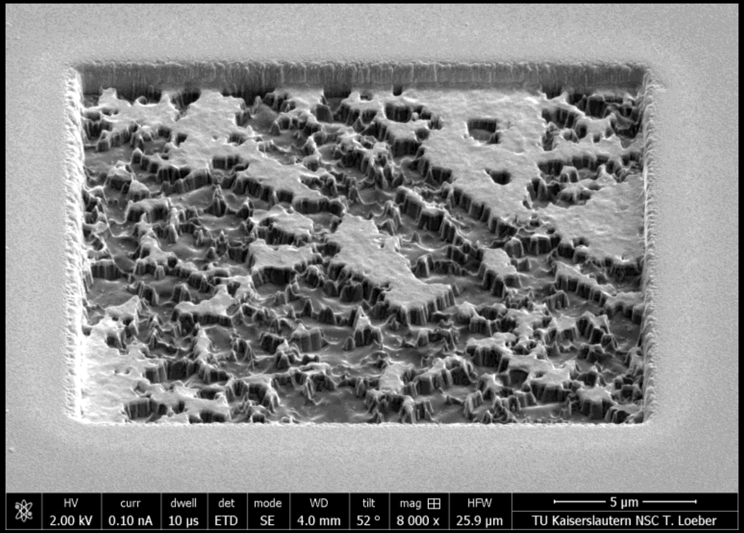
- Ga @ 30 kV: a lot of Gold remaining, while parts of the Silicon are already milled
- Ga @ 16 kV: some Gold remaining, dents in Silicon
- Cs @ 16 kV: no Gold left, smooth bottom

Milling in Copper

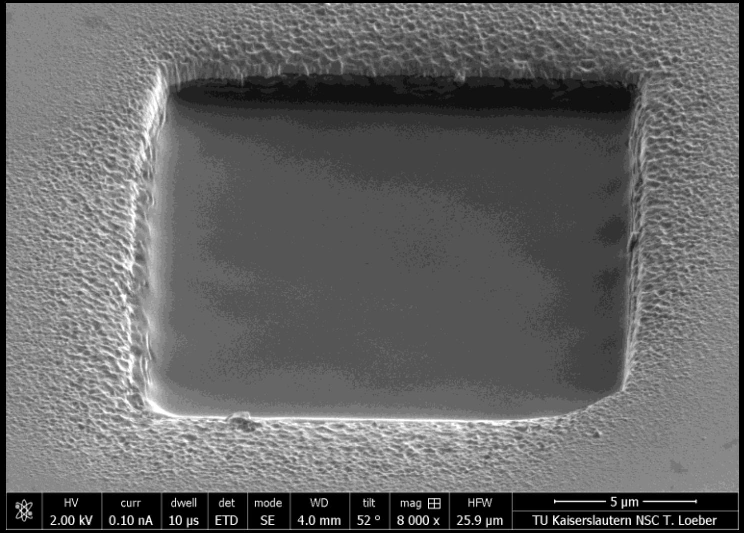
Ga ion: 30 kV @ 2640 pA



Ga ion: 16 kV @ 1440 pA



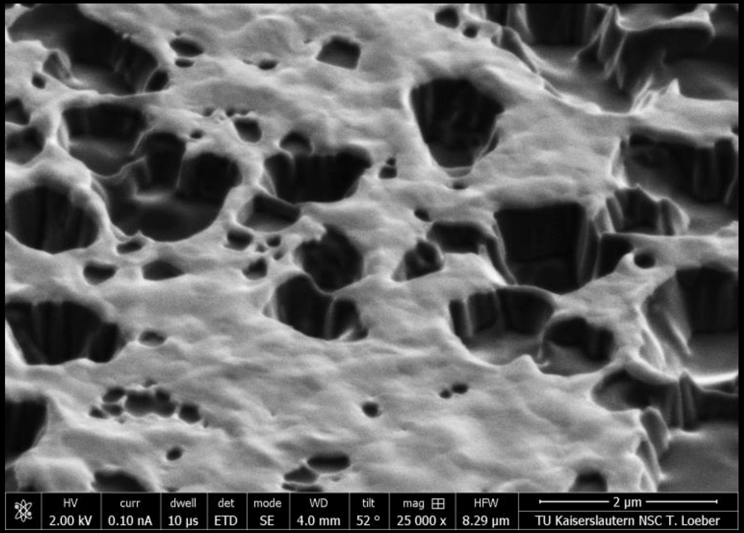
Cs ion: 16 kV @ 1070 pA



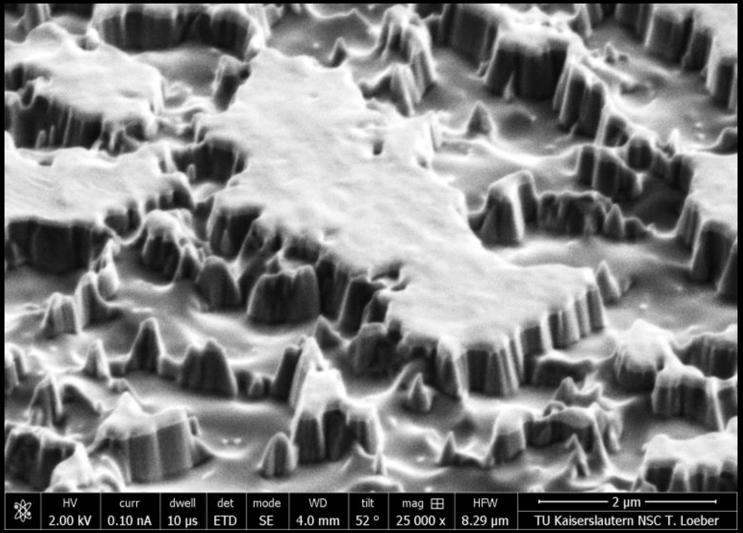
- sputtered Copper layer on Silicon
- layer thickness 1150 nm
- rectangle 20 µm x 20 µm
- milling time about 20 min
- dose about 4500 pC/µm^2

Milling in Copper

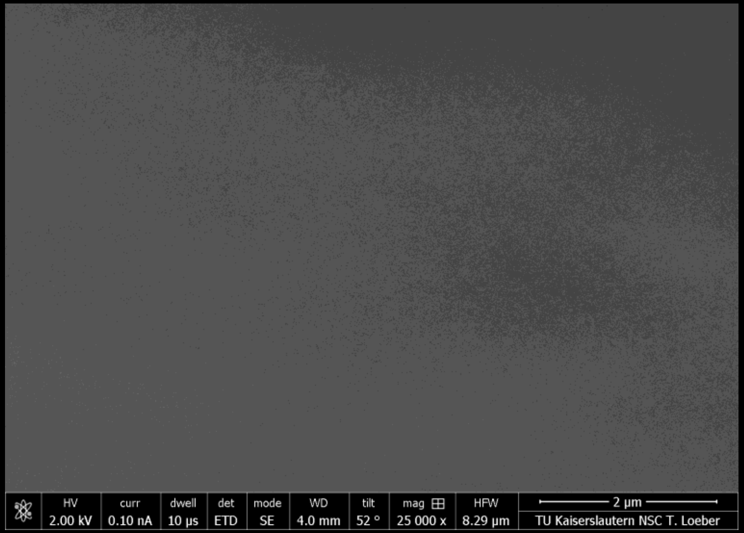
Ga ion: 30 kV @ 2640 pA



Ga ion: 16 kV @ 1440 pA

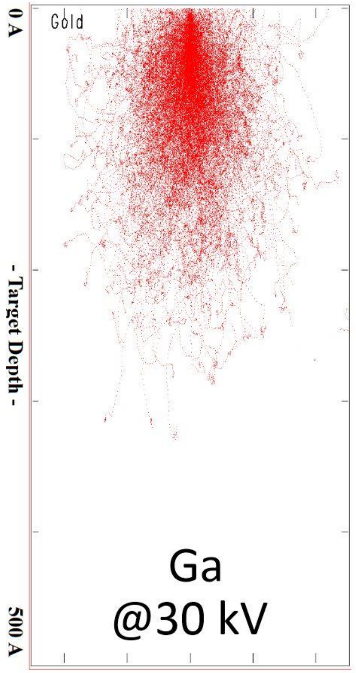


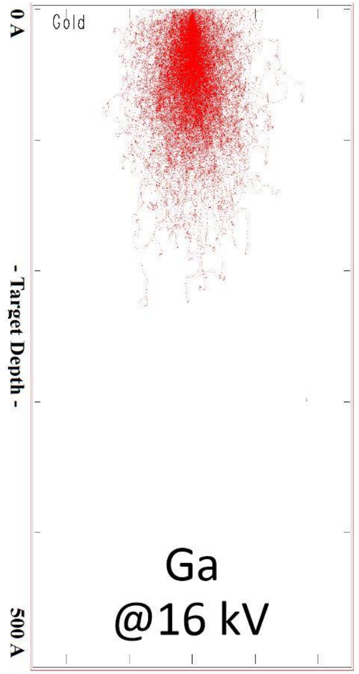
Cs ion: 16 kV @ 1070 pA

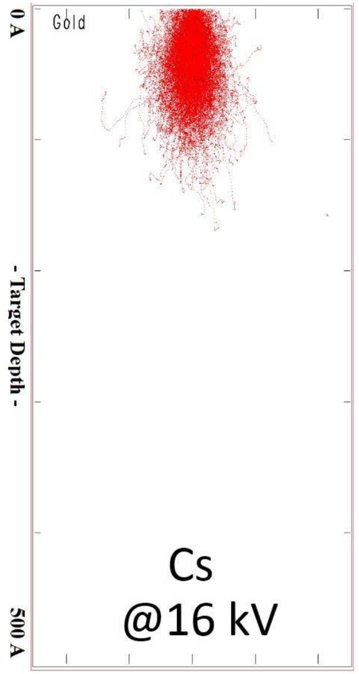


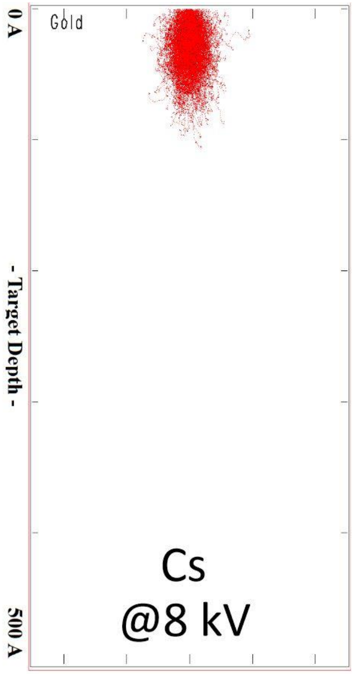
- Ga @ 30 kV and Ga @ 16 kV:
  a lot of Copper remaining, while parts of the Silicon are already deeply milled
- Cs @ 16 kV: no Copper left,
  very smooth bottom

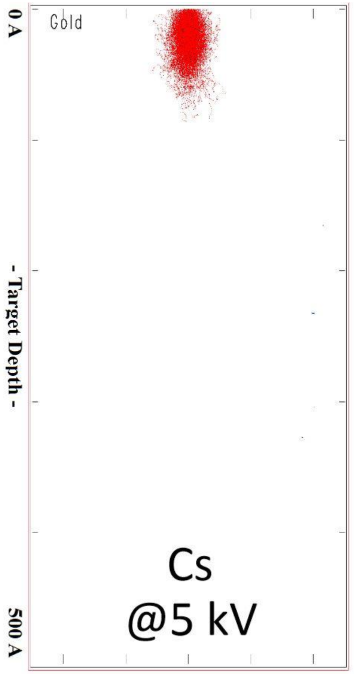
Outlook

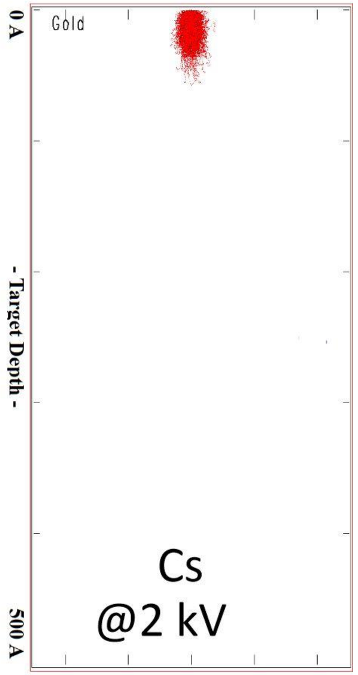












- SRIM simulations
- lower acceleration voltage
- lower penetration depth
- more homogenous sputter rate ???

Summary

Summary

- higher resolution imaging and milling
- Pt deposition
- milling with Cs in Si is different compared to Ga
- polycrystalline layers can have channeling effect
- Ag, Au and Cu can be milled more homogenously

Outlook

- milling further materials
- implementing pattern generator
- open for cooperation

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Thank you
for your
attention