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



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Nano Structuring Center

PHYSIK





- 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, H₂O and XeF











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







Ionization

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- 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 \approx 30 μ K
- energy spread $\Delta E = 0.45 \text{ eV}$
- accl. voltage U = 2 16 kV
- ion beam pA to nA





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Ga ion image



Cs ion image



NSC

graphite pen: magnification 10k x



PHYSIK

Ga ion image



Cs ion image



graphite pen: magnification 20k x





PHYSIK

Ga ion image



Cs ion image



graphite pen: magnification 50k





PHYSIK

Ga ion image



Cs ion image









Material contrast

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electron image



Cs @ 16 kV, 1 pA

Cs ion image

| 90 | HV | curr | mode | dwell | mag | WD | ⊷−−−− 4 µm −−−−− |
|----|----------|---------|------|-------|----------|---------|------------------|
| 50 | 16.00 kV | 0.60 pA | SE | 30 µs | 10 000 x | 16.5 mm | T. Loeber NSC |

NSC

cross section of GaAs and AlGaAs layer



Material contrast

PHYSIK

Ga ion image



Cs ion image



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





Material contrast

PHYSIK

Ga ion image



Cs ion image



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





Deposition of platimun

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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 time 2:30 min







Deposition of platimun

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deposition time 2:30 min



deposition time 2:30 min



- deposition area 2 μm x 10 $\,\mu m$
- good results @ 6 pA/ μ m²
- Cs: layers deposited at lower voltages have rounder cross section





Milling in Silicon

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reality



VS.

expectation



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



- 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

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







Polycrystalline materials

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

SE image taken with Ga ions @ 30 kV



SE image taken with electrons @ 2 kV







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/μm²





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

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SRIM simulations





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Ga ion beam: along crystal axis

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- high penetration depth
- very low sputter rate
- dislocations





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Ga ion beam: at an angle to crystal axis

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

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Cs ion beam: along crystal axis

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

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Cs ion beam: at an angle to crystal axis

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- very close to the surface
- very high sputter rate







Milling in Silver

PHYSIK

Ga ion: 30 kV @ 50 pA



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

Cs ion: 16 kV @ 40 pA







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/μm²





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/μm²





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

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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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