# Sample interactions during FIBbing

Hugo Bender
Chris Drijbooms, Patricia Van Marcke,
Paola Favia, Olivier Richard, Jef Geypen, Koen Marrant,
Eveline Verleysen

Leuven, Belgium

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# Outline

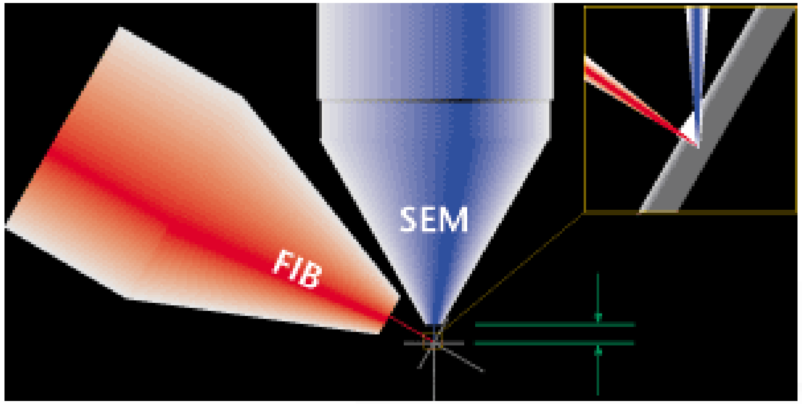
- Introduction : FIB and application

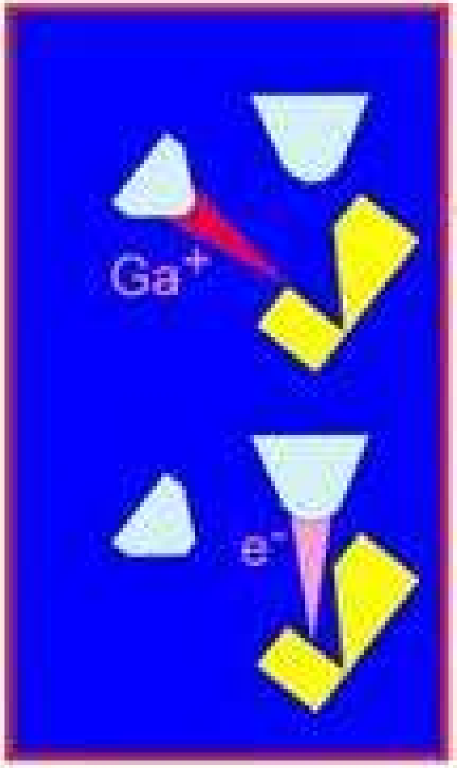
- Ion beam effects
  - image quality
  - curtaining
  - redeposition
  - discharges
- Ion beam interactions with
  - Si
  - metals
  - Al
  - Ni

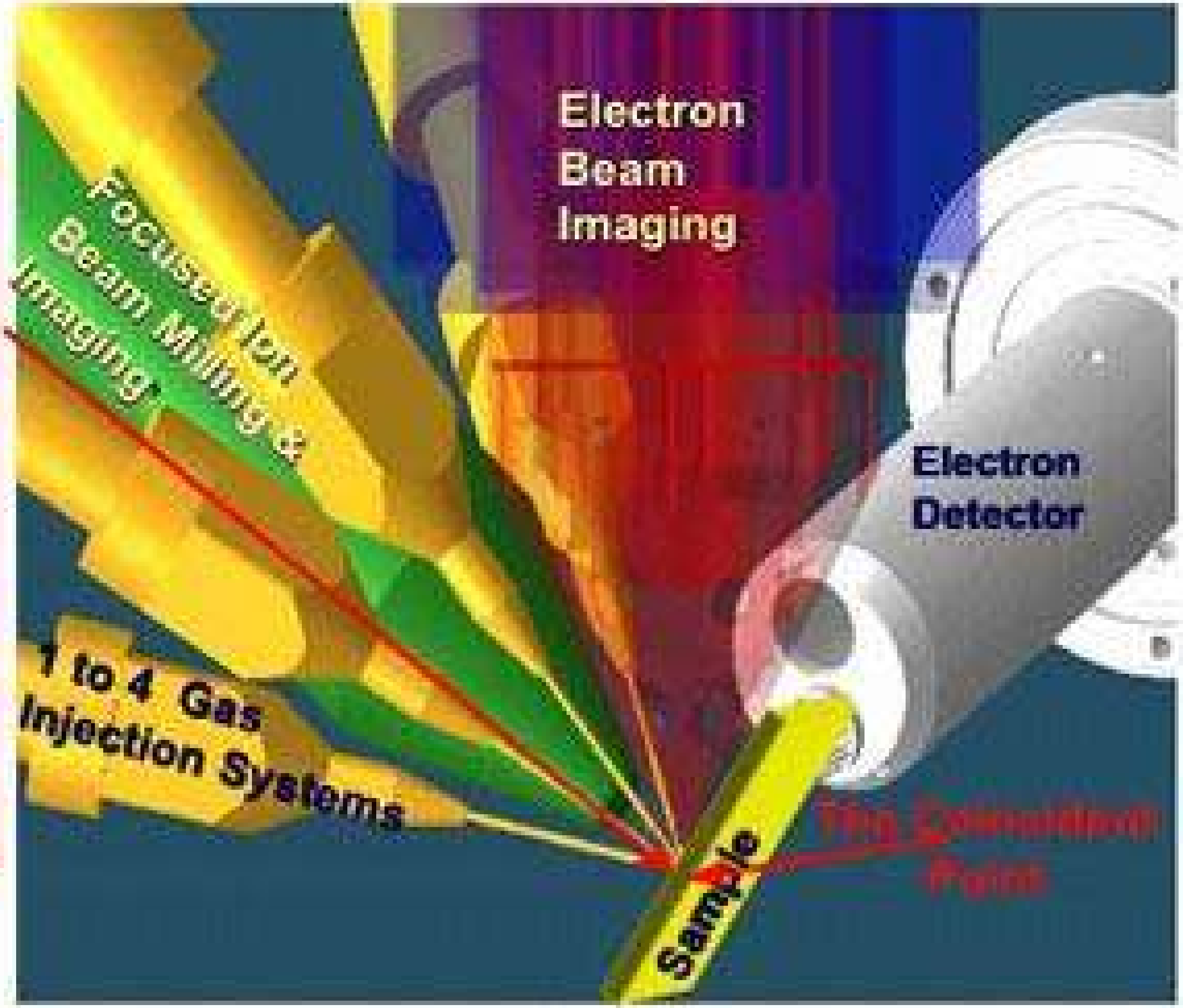
- Conclusions

# FIB/SEM configuration

- “Dual beam”
- “CrossBeam”
- “MultiBeam”

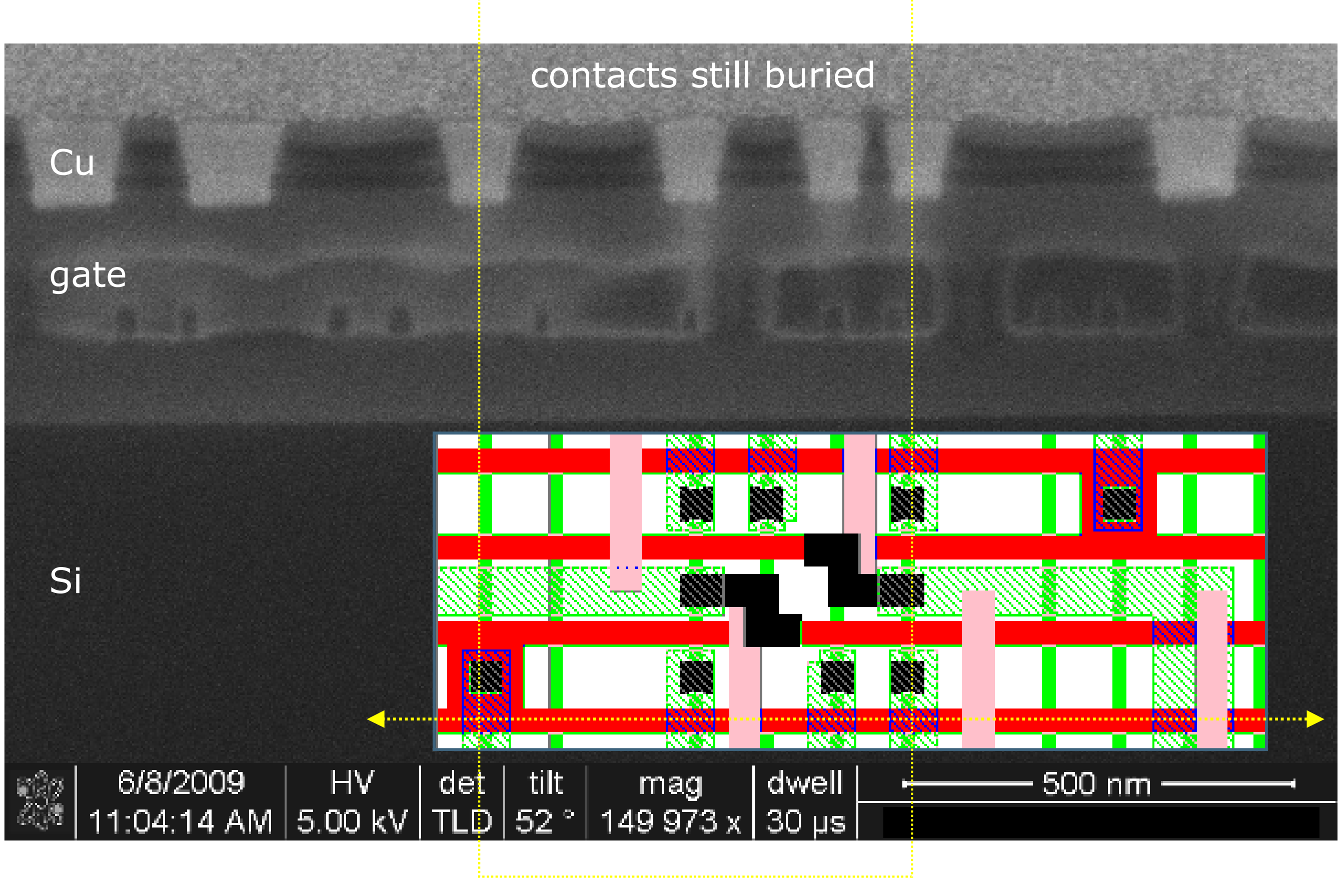






Figures ©FEI

# FIB applications – Cross-section imaging



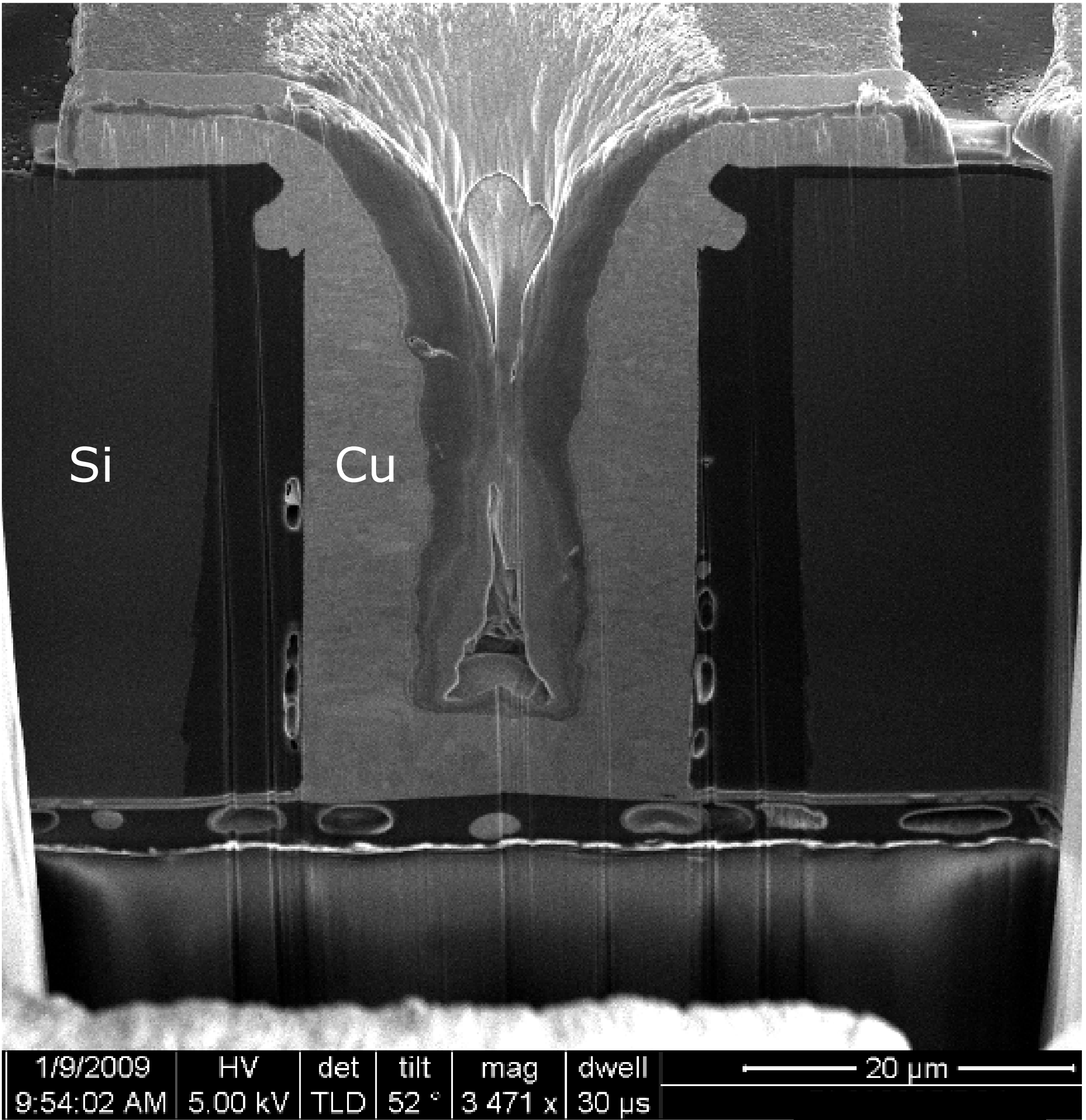
small structures
(3D dimensions : 10-20 nm )

# FIB applications – Cross-section imaging

huge structures :
TSV's, stacked dies, …
(50 µm dimensions)

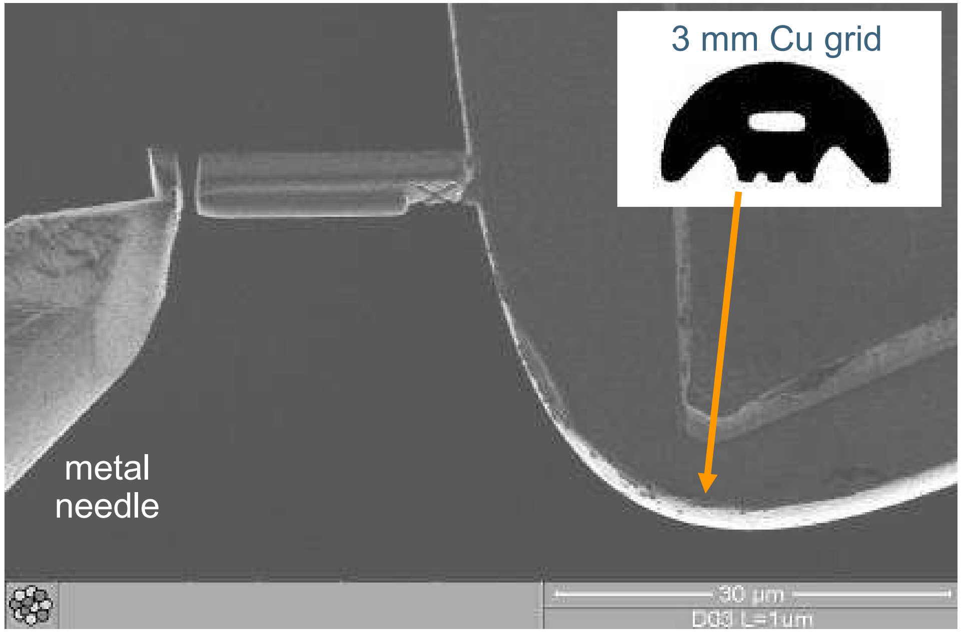
4 to 10 h milling in
classical Ga-FIB !

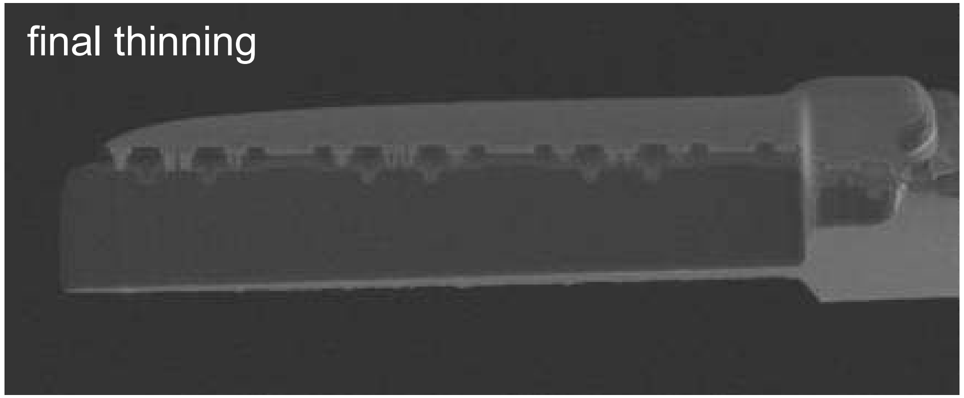
faster FIB's needed !



# FIB applications – TEM preparation

Internal lift-out





# FIB applications - Other

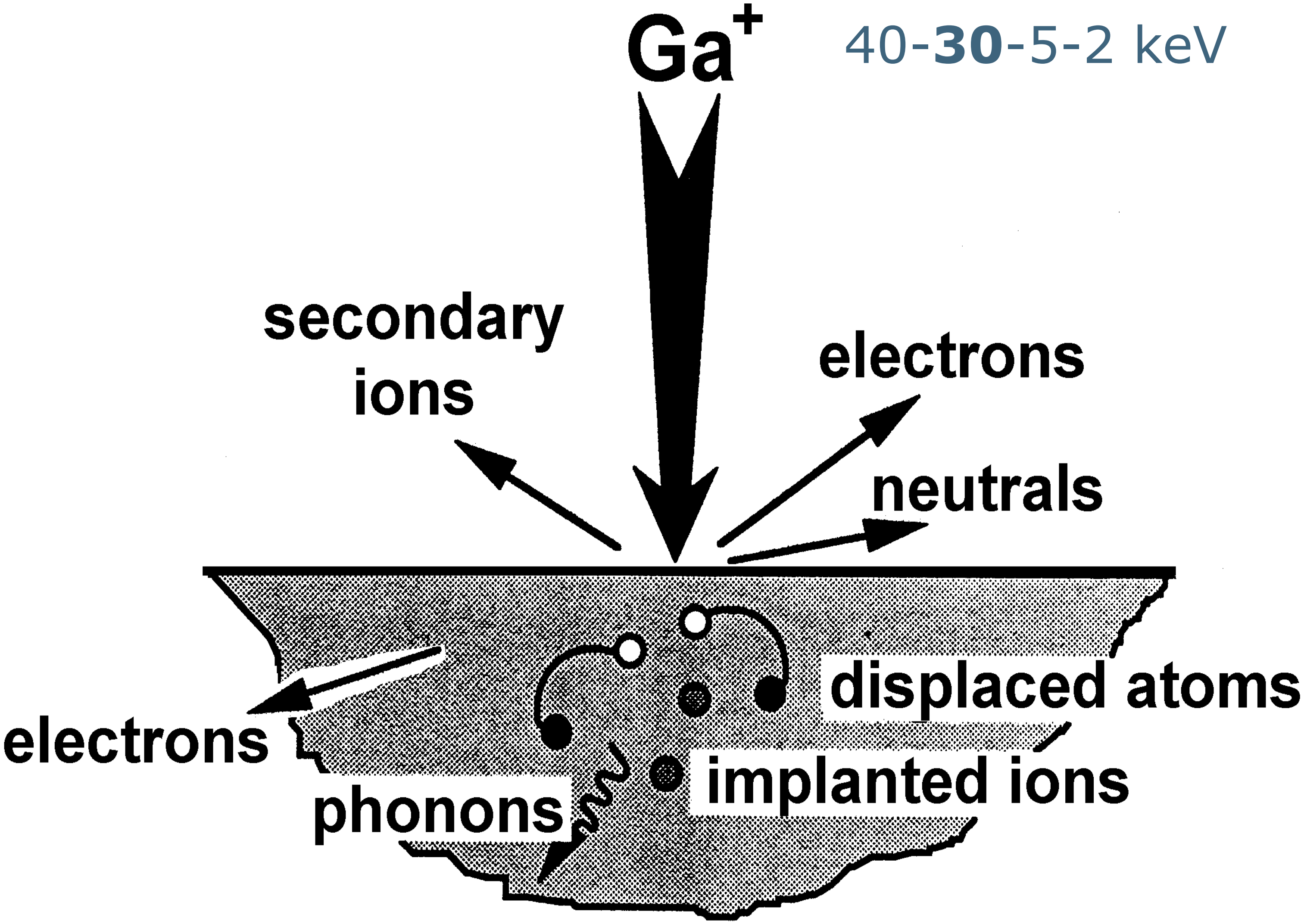
other applications at IMEC:

- Atom probe tips
- Back-contacting for SSRM
- Marking

general:

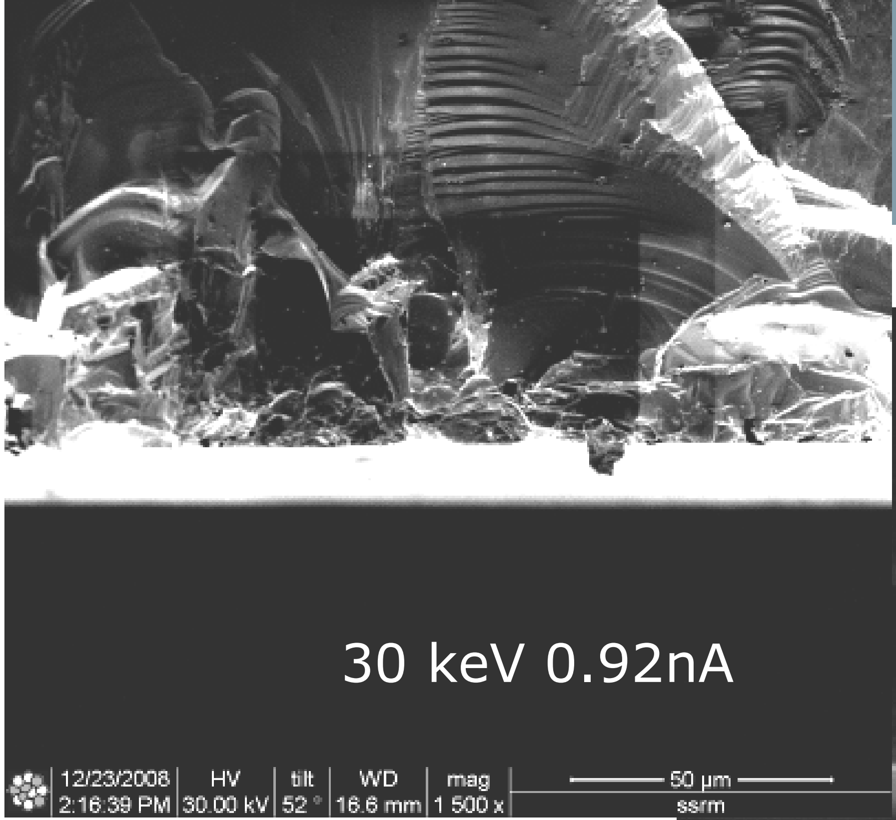
- Ion-beam lithography
- Device modification
- Micro-machining
- Biological

# Interactions with the substrate

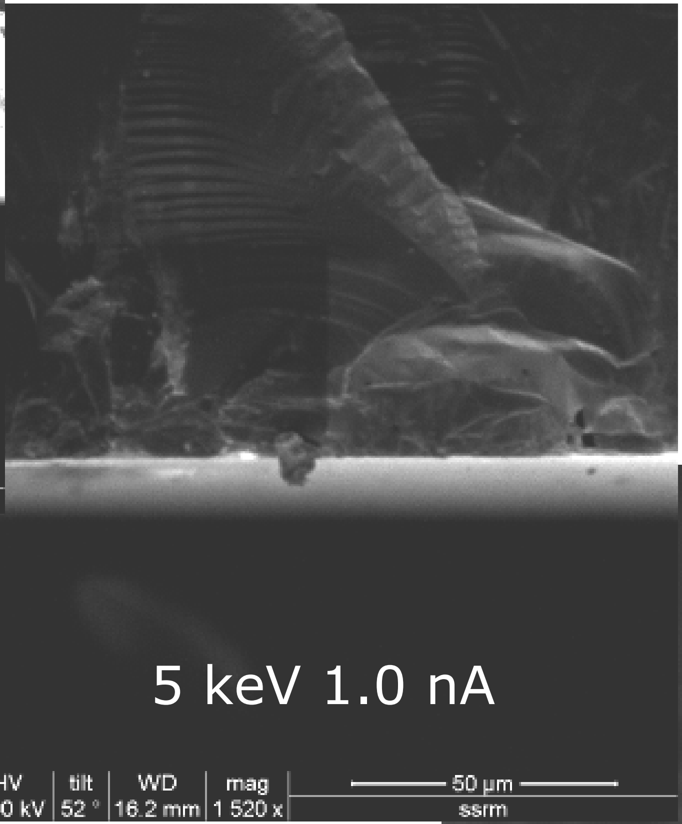


40-**30**-5-2 keV

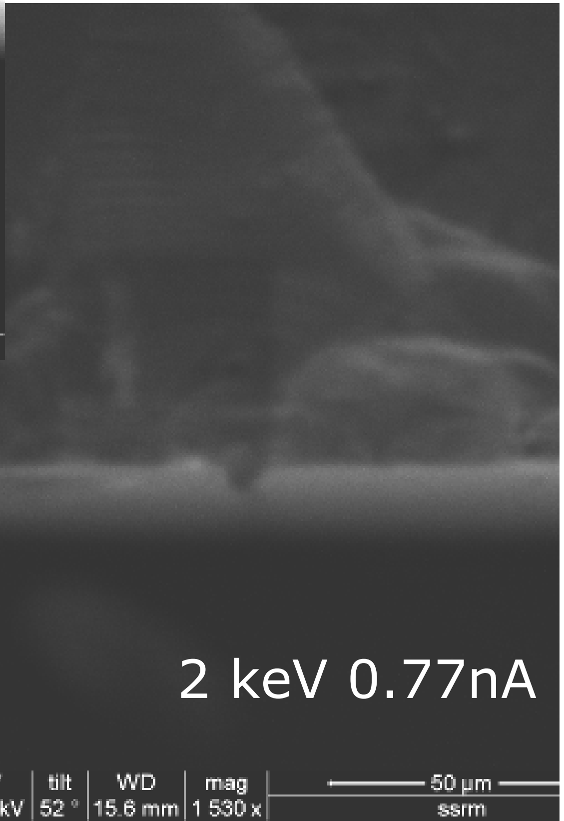
# Ion beam image quality



30 keV 0.92nA

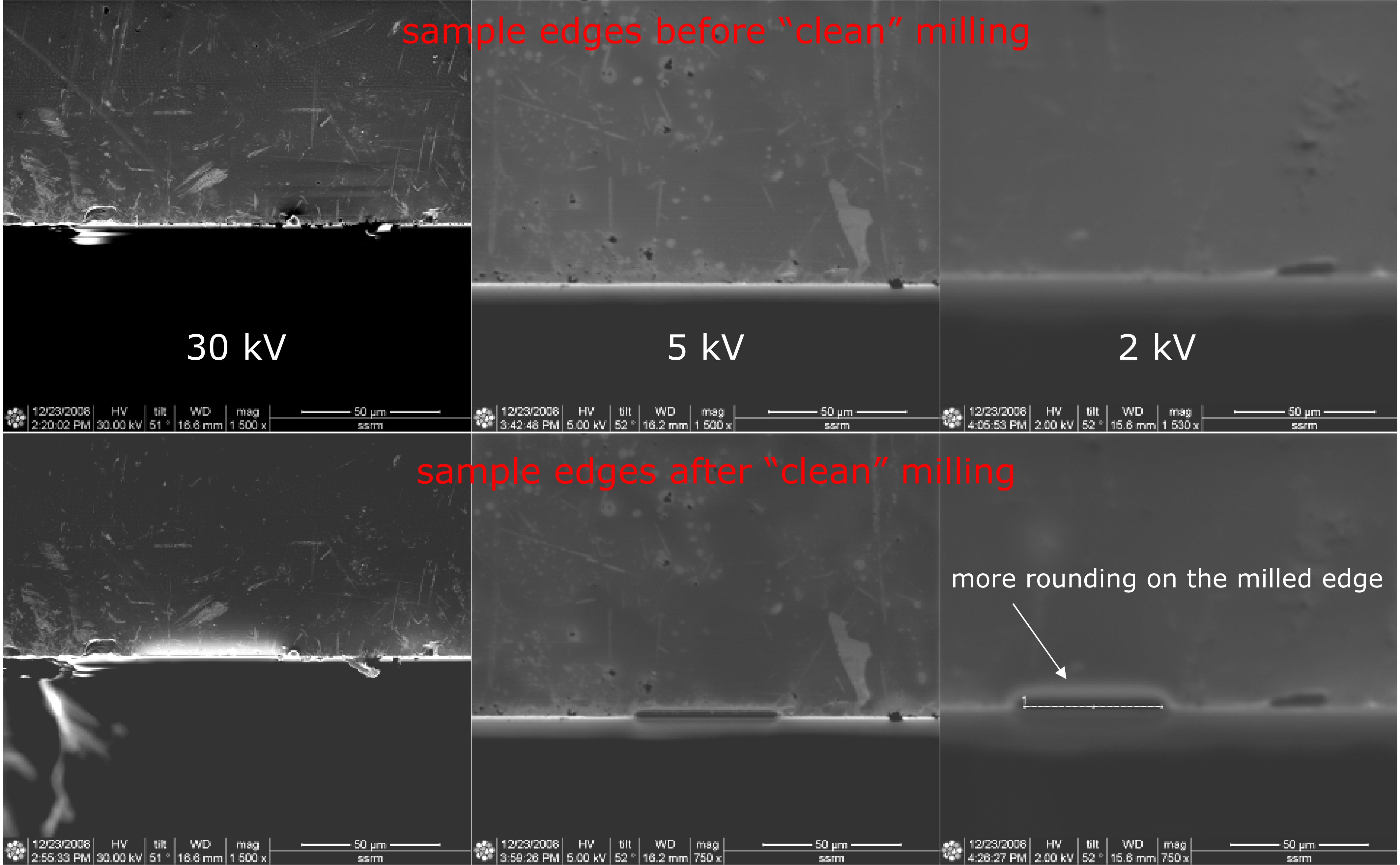


5 keV 1.0 nA



2 keV 0.77nA

# Ion beam image quality



sample edges before “clean” milling

30 kV

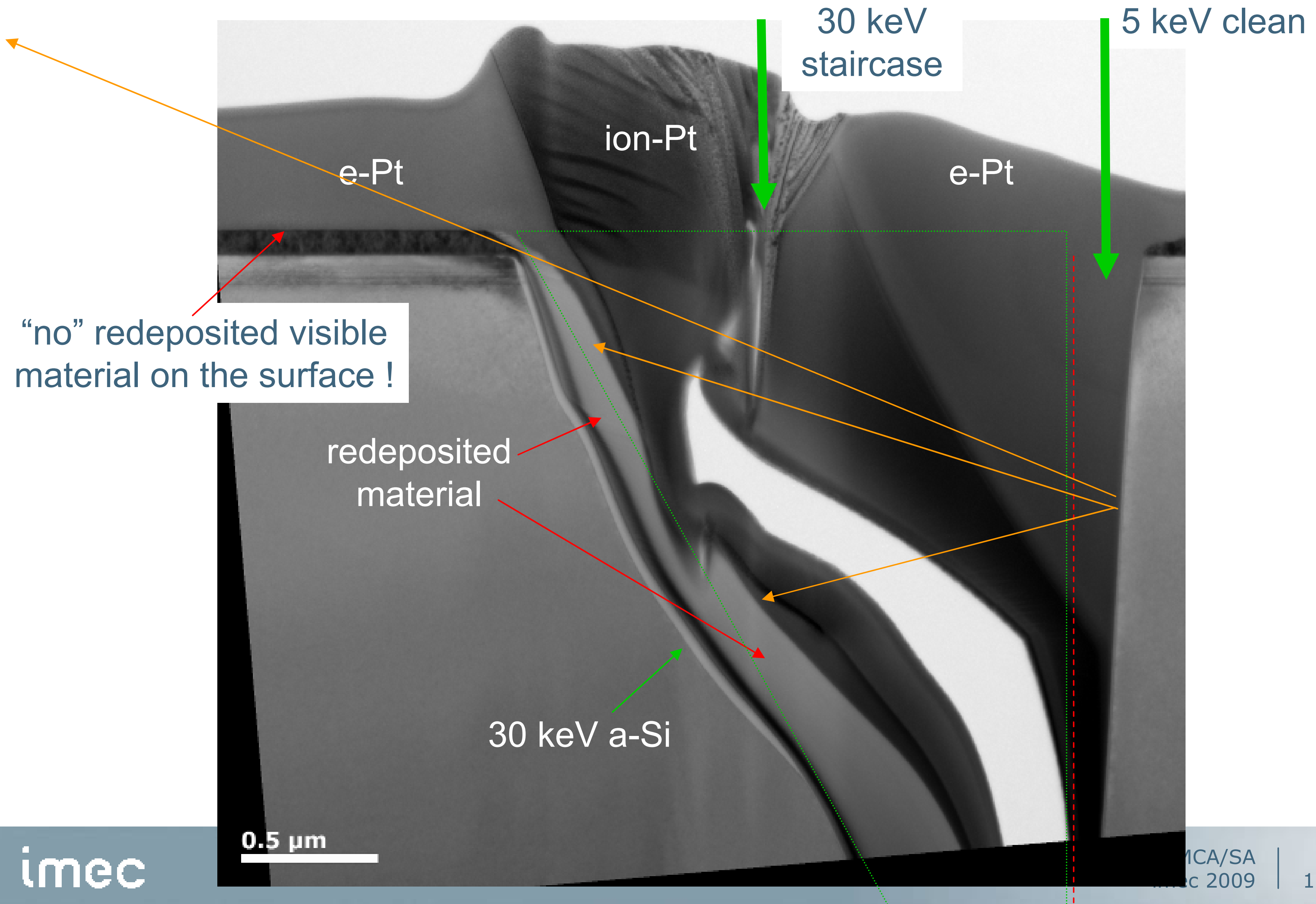
5 kV

2 kV

sample edges after “clean” milling

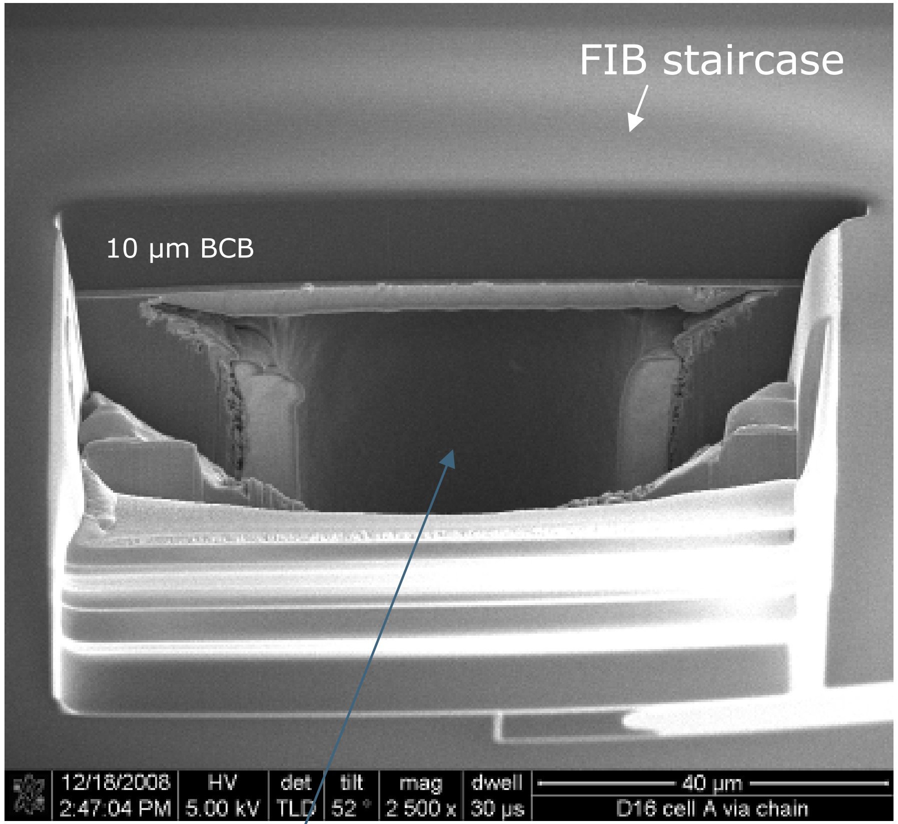
more rounding on the milled edge

# Redeposition

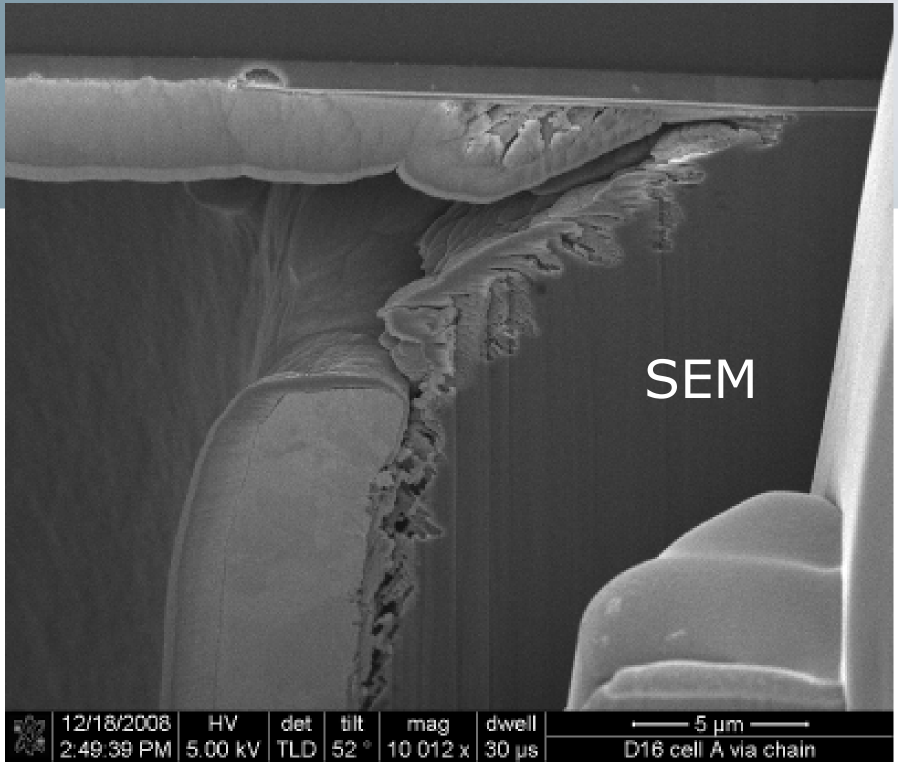


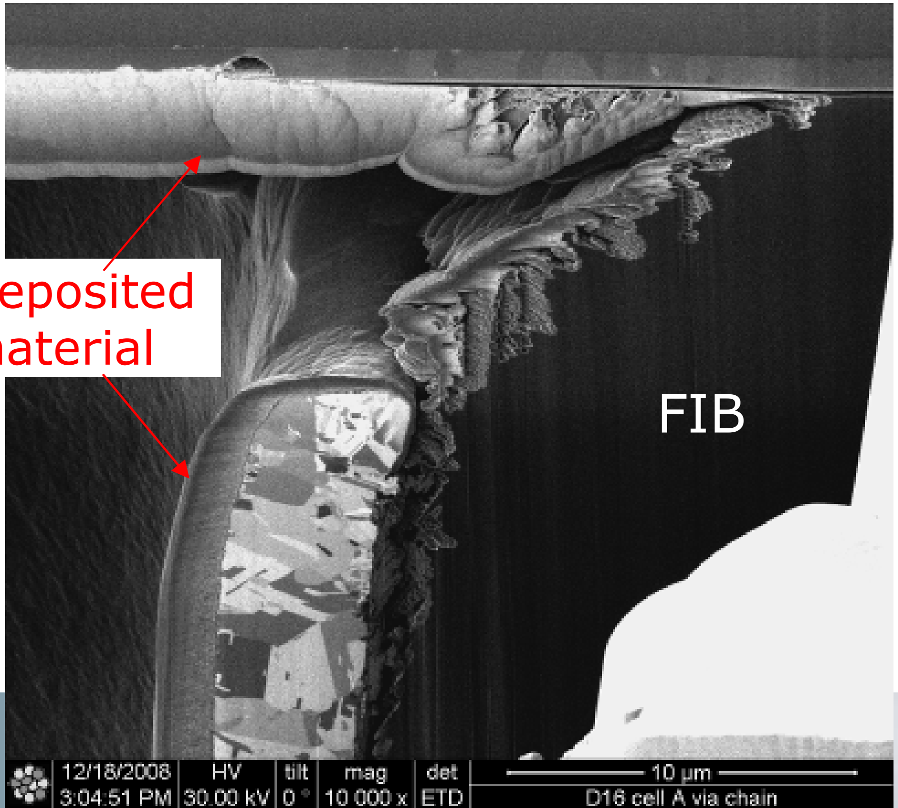
“no” redeposited visible material on the surface !

# Redeposition



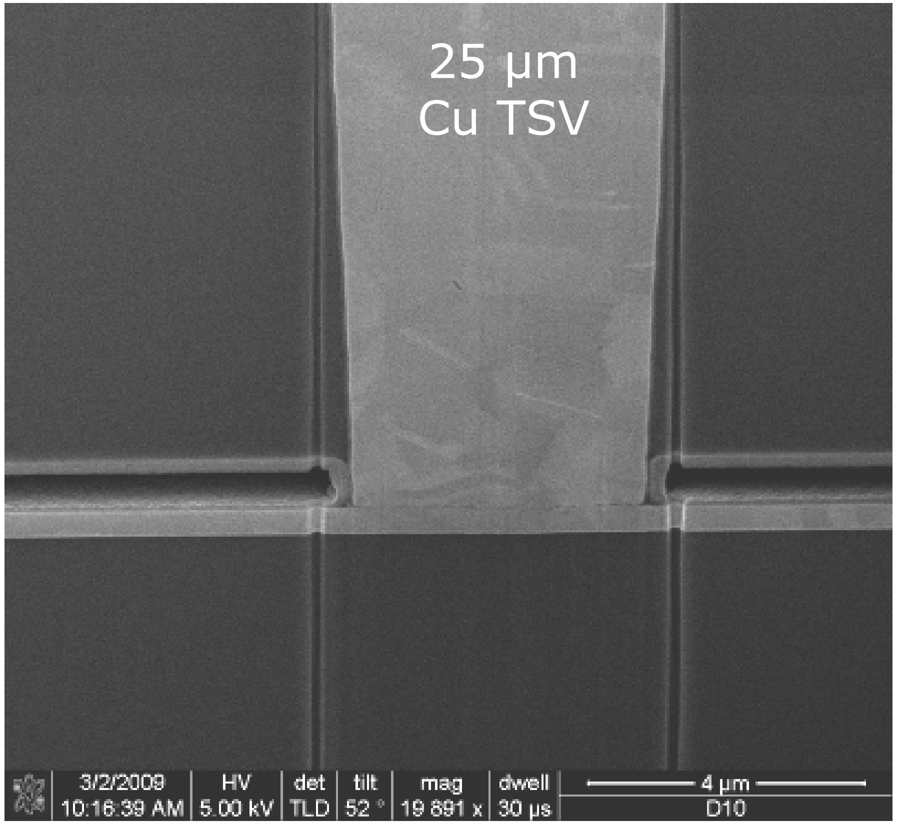
via etched from the backside through 50 µm Si



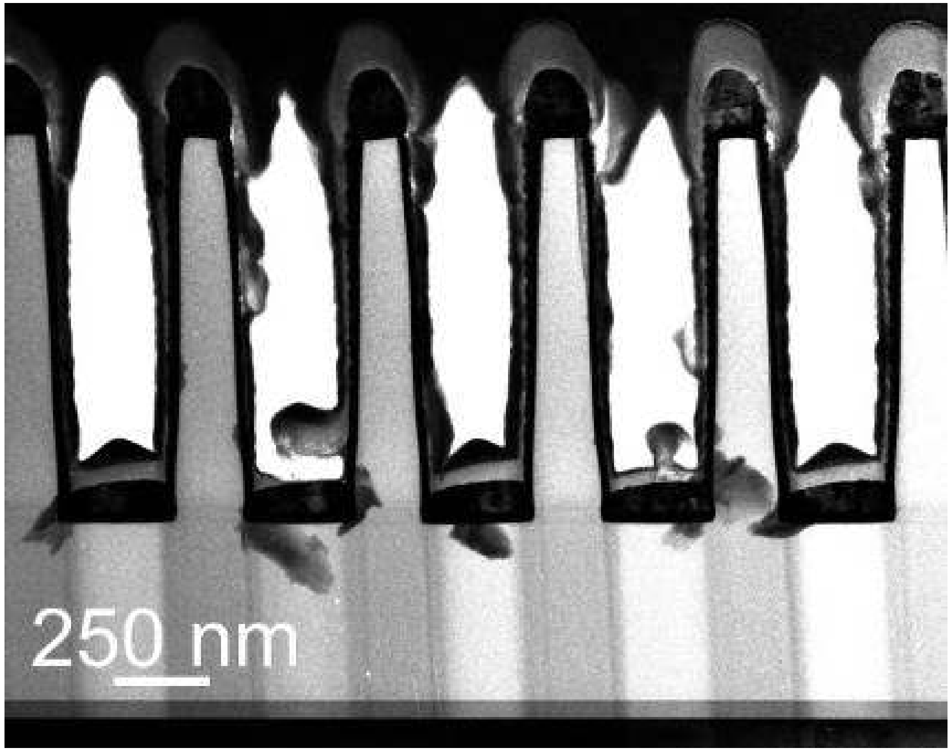


major redeposition occurs strongest on top side of open structures

# Curtaining

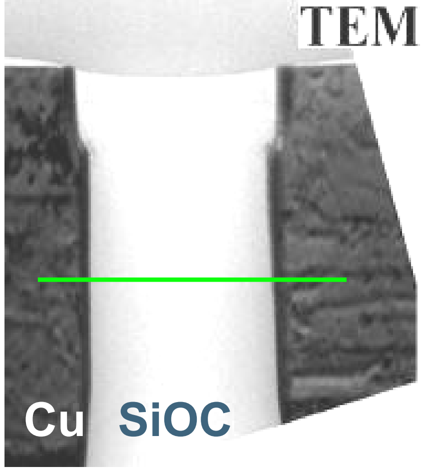


trenches with barrier/Cu seed layer only

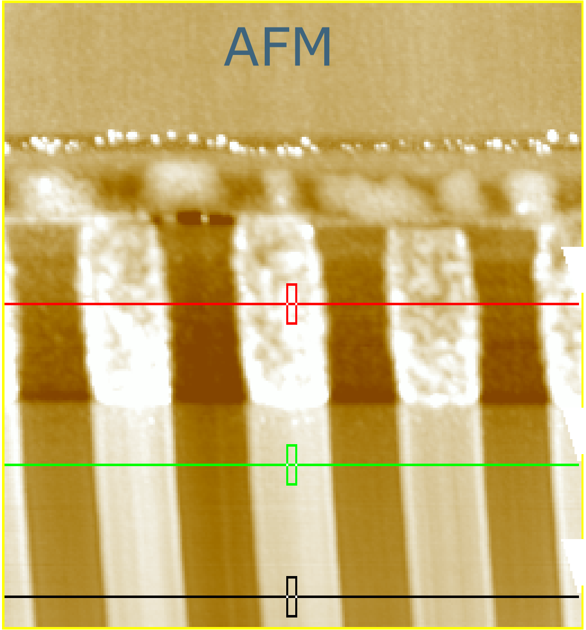


- related to beam tails : worse at lower keV
- induced by differences in milling rate or topography
- can be “avoided” for TEM preparation : backside milling

# Curtaining : low-k/Cu



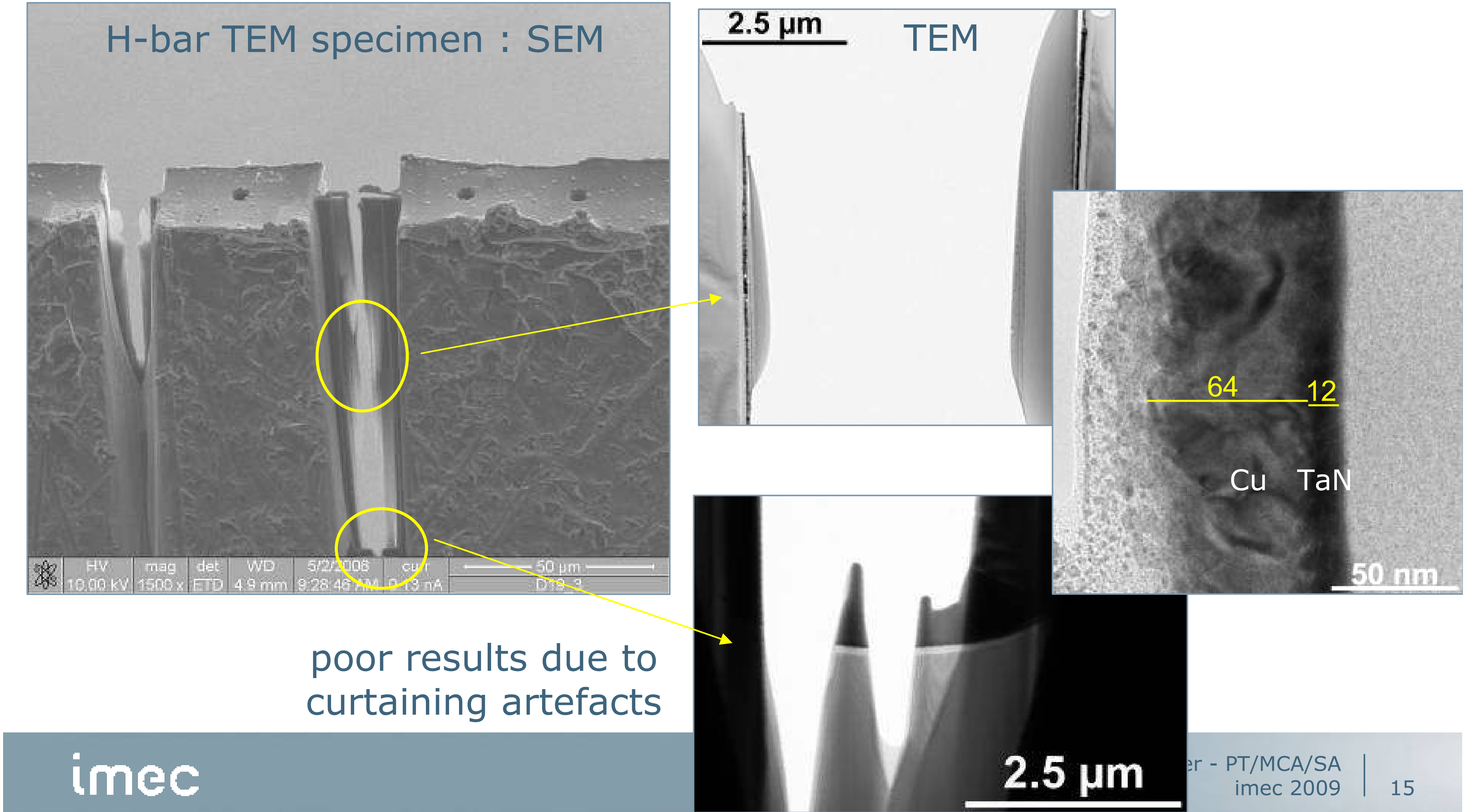
| | | | EFTEM | AFM | | |
|---|---|---|---|---|---|---|
| | | k | low k/Cu relative thickness % | step from Cu/lowk nm | step below the lines in oxide nm | step below the lines in Si nm |
| 7 | $N_2/O_2$ | lowest | 40 | 7.6 | 4.9 | 3.4 |
| 4 | in situ $O_2$ | medium | 60 | 5.2 | 4.0 | 2.6 |
| 11 | $N_2/O_2$ | highest | 80 | 6.4 | 4.4 | 3.5 |



S. Hens et al, Phys. Conf. Ser. 169, 415-418 (2001).

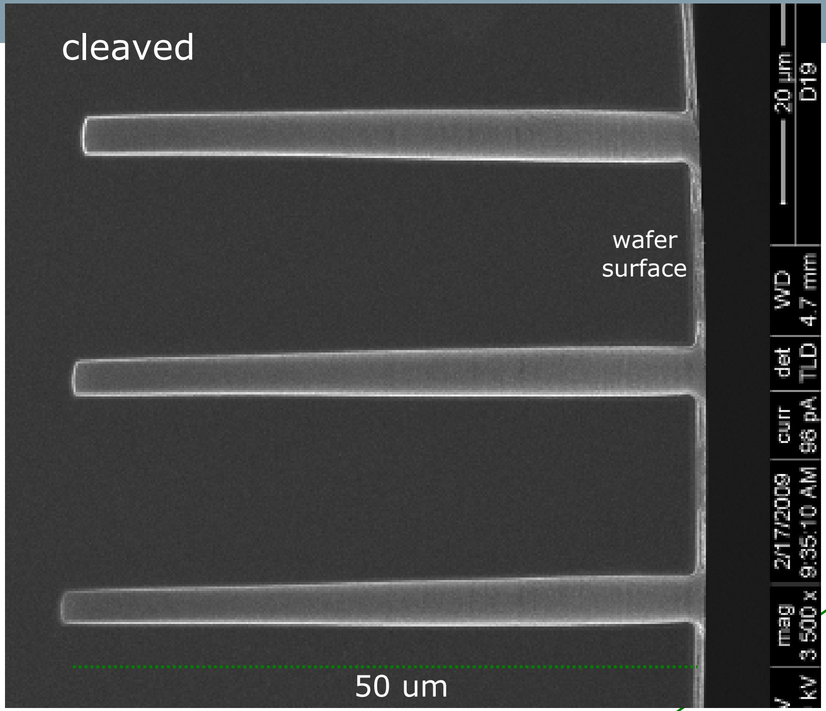
# Curtaining : 50µm open TSV – TEM preparation

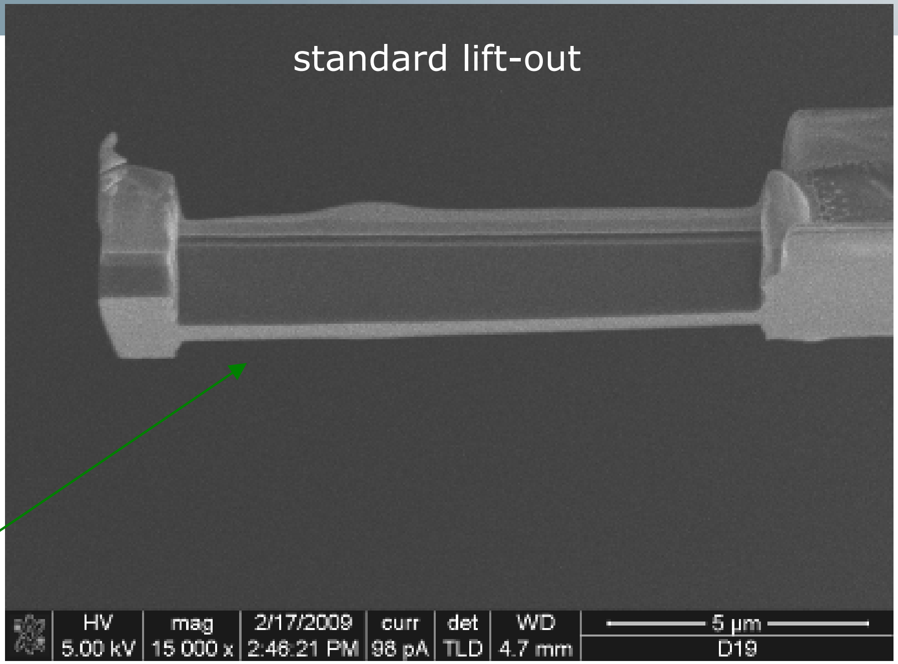
- Deep structures : mounting orthogonal
- Very high aspect ratio structures are difficult to fill with Pt

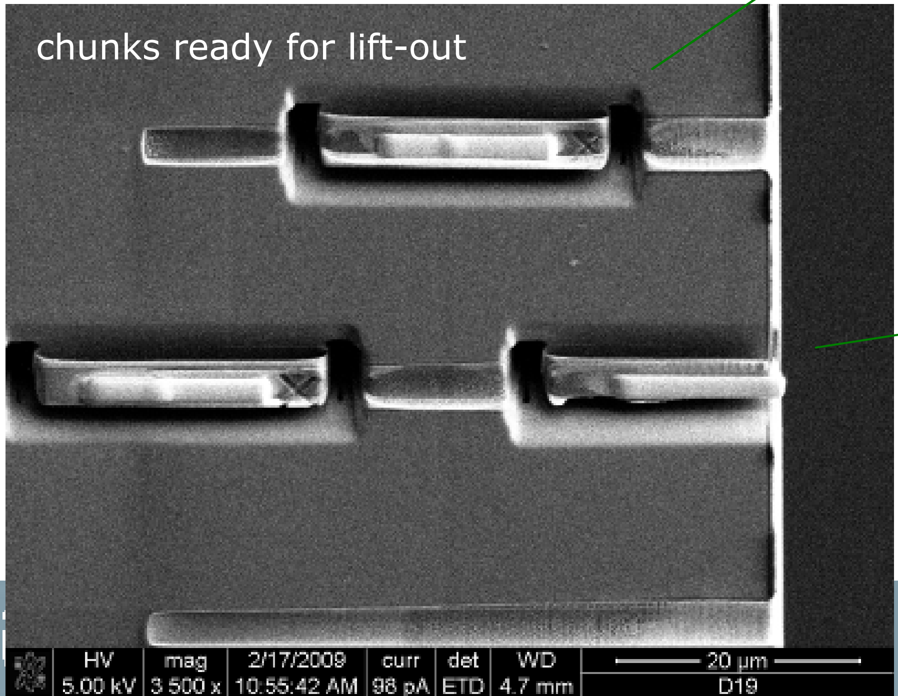


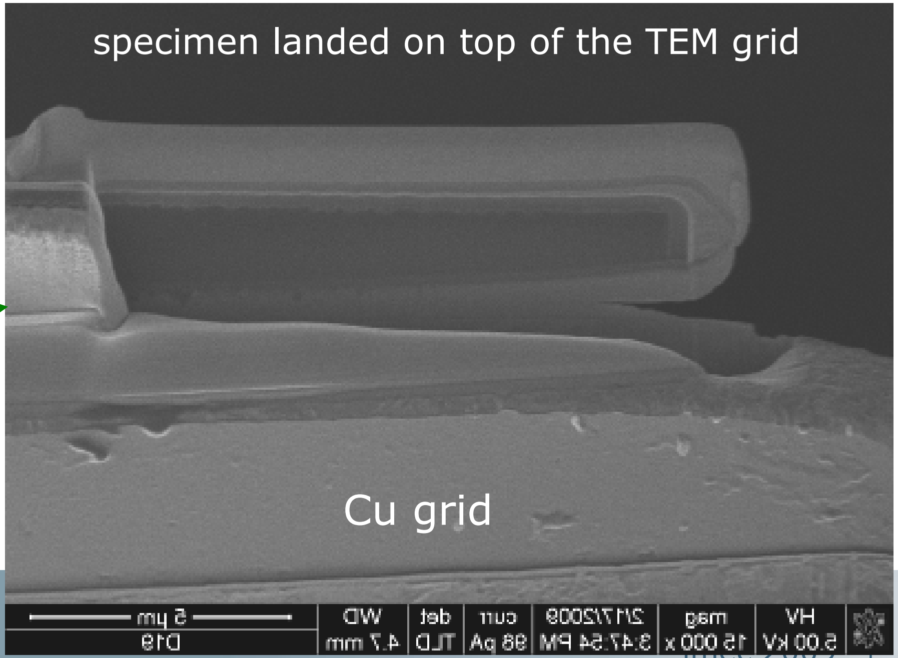
poor results due to
curtaining artefacts

# Curtaining : 50µm open TSV – TEM preparation





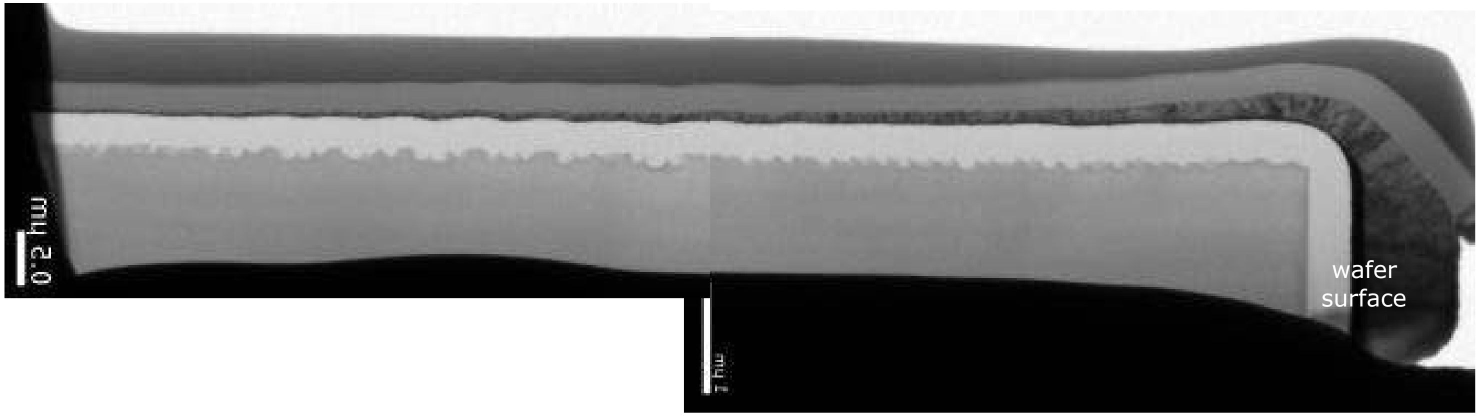




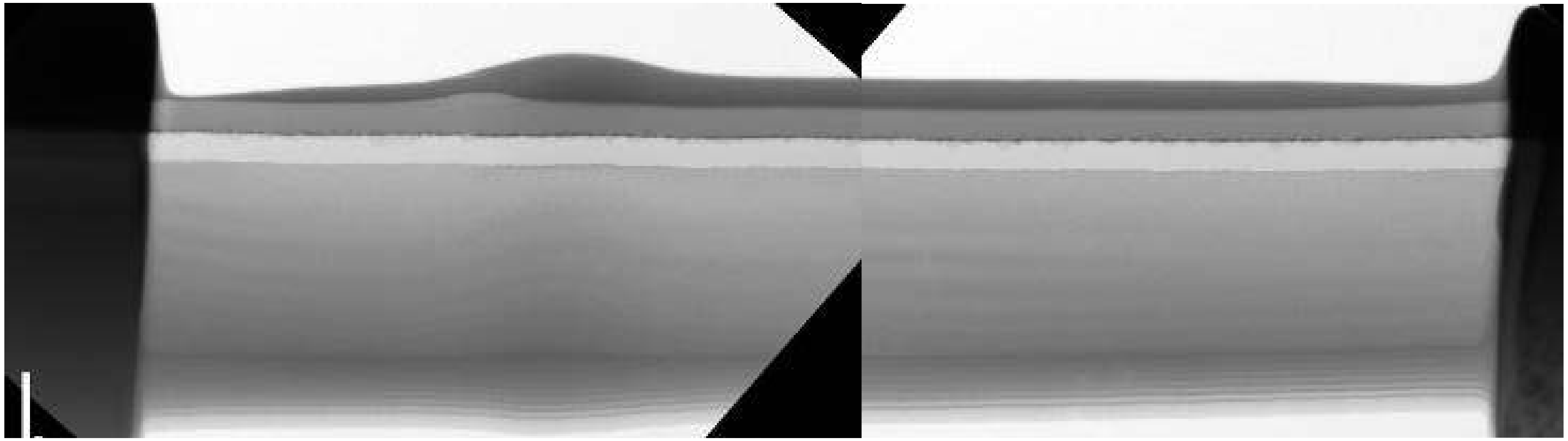
# Curtaining : 50µm open TSV – TEM preparation

curtaining
problem
avoided

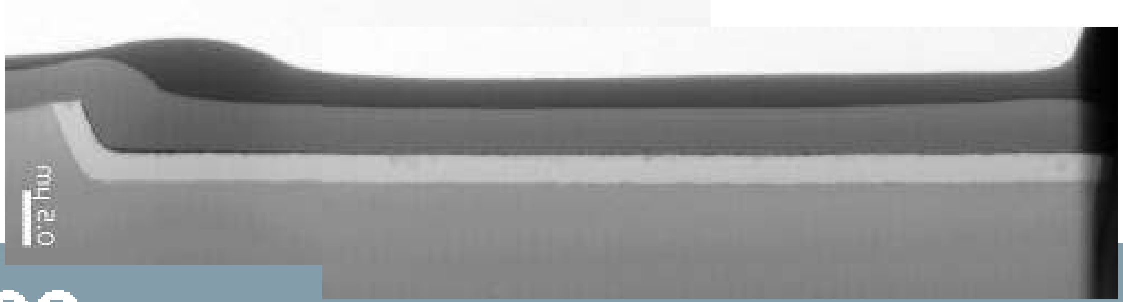
top



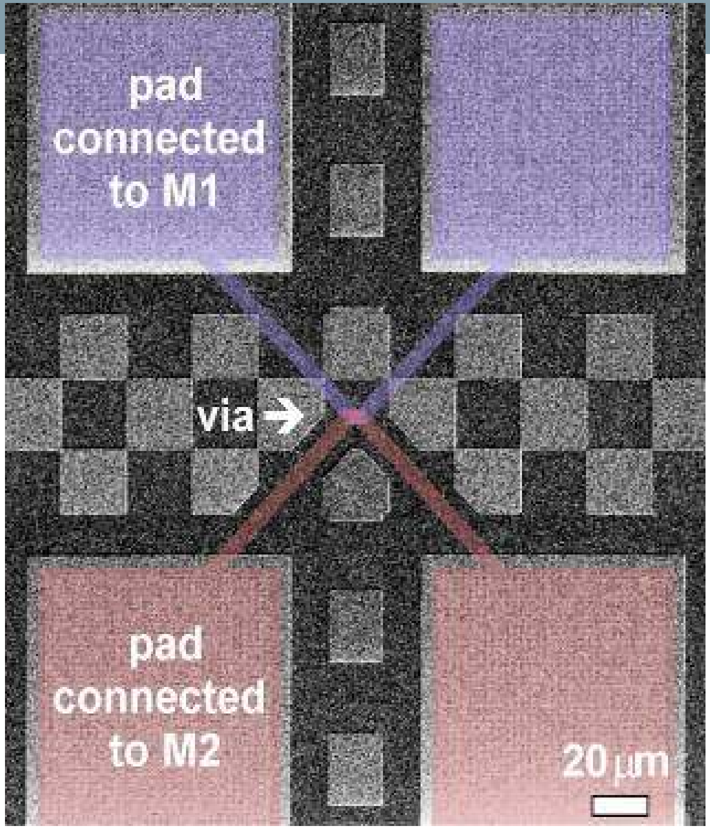
middle

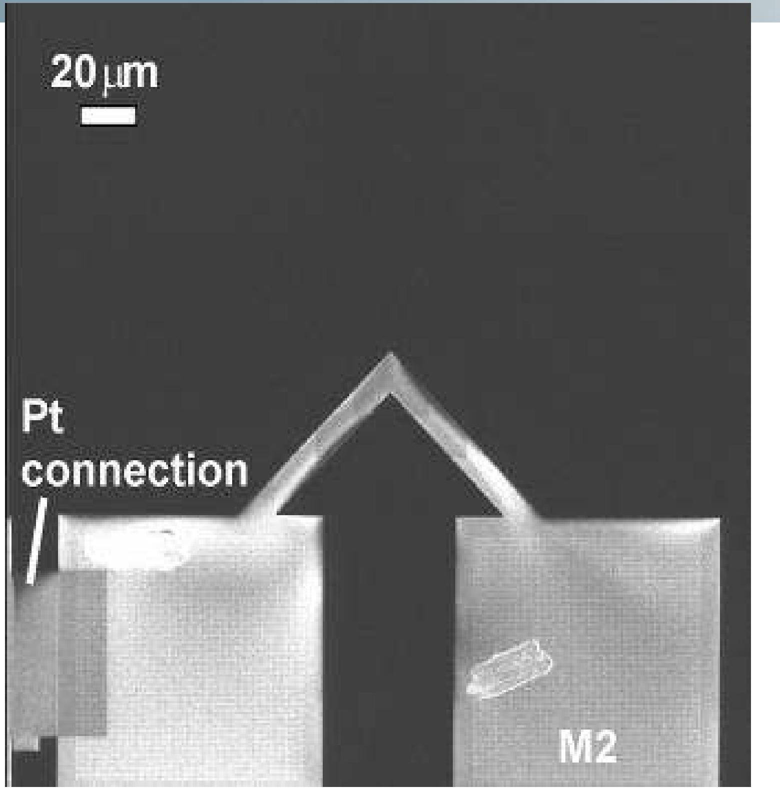


bottom



# Discharge damage : breakdown charge





$$V = \frac{Q_{FIB}}{C_{ox}}$$

$$Q_{FIB} = (E \times t_{ox}) \times (\varepsilon_o \times \varepsilon_r \times S/t_{ox})$$
$$= E \times \varepsilon_o \times \varepsilon_r \times S$$

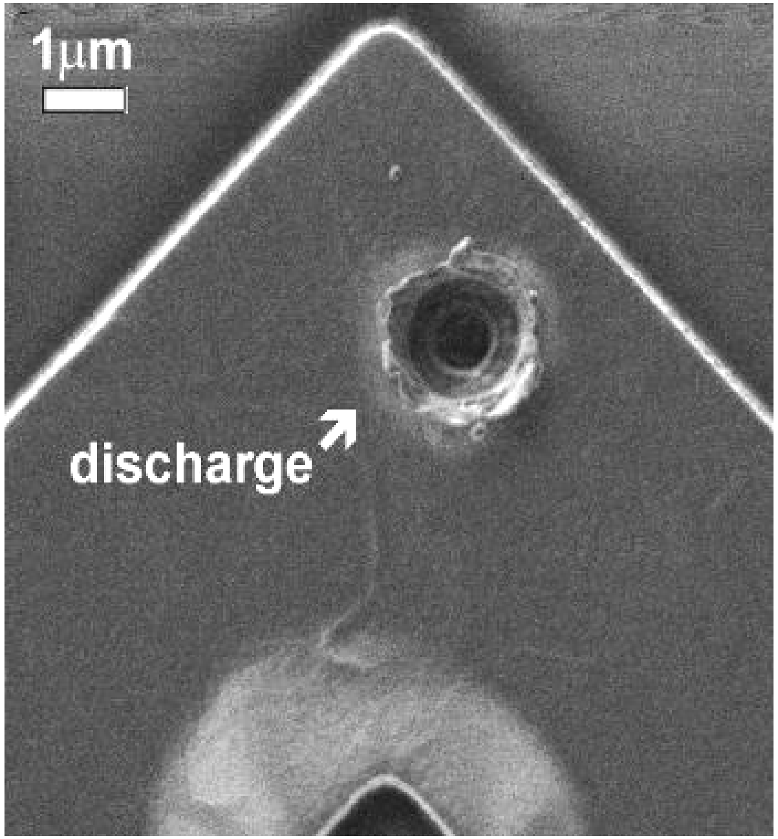
- Kelvin structure : area S ~ 20000 $\mu m^2$
- Breakdown field for CVD oxide ~ 10 MV/cm
- breakdown charge ~ 0.7 nC

imaging 1-4 pA : 700-175 s

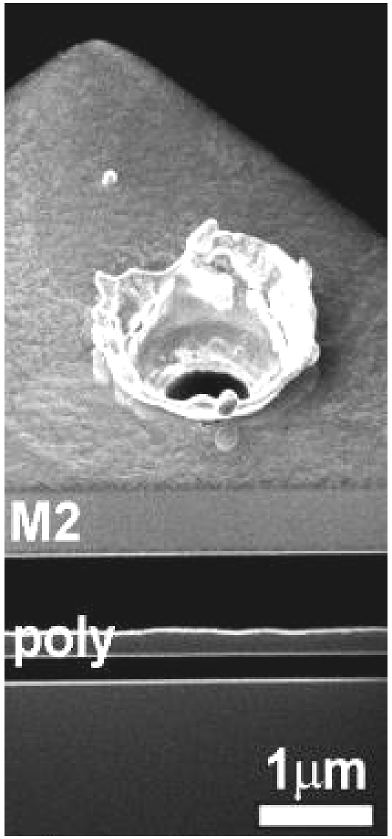
crater with 2700 pA : **0.26 s**

i.e contacting in advance necessary !

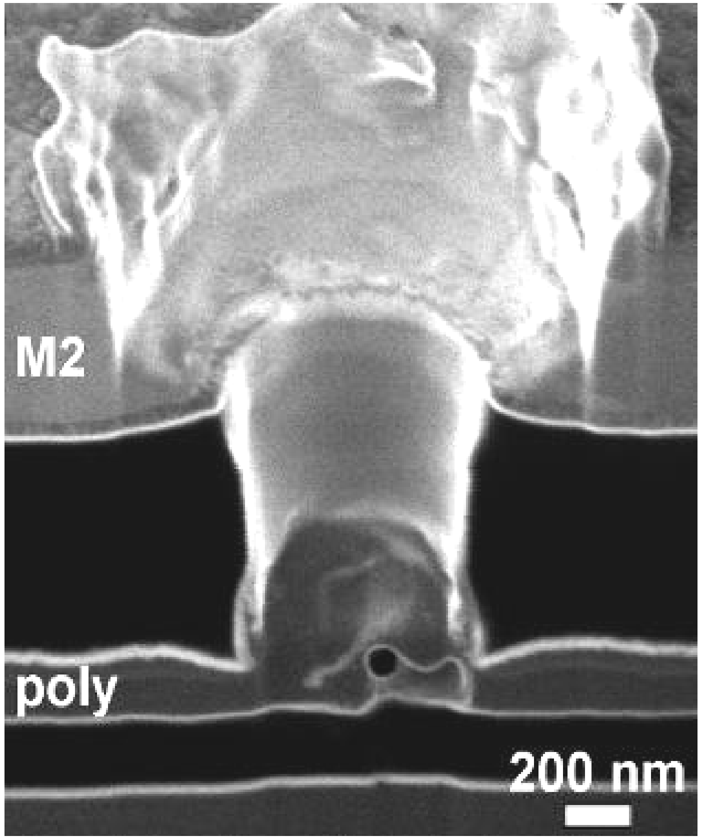
# Discharge damage in Kelvin structure



top view



tilted



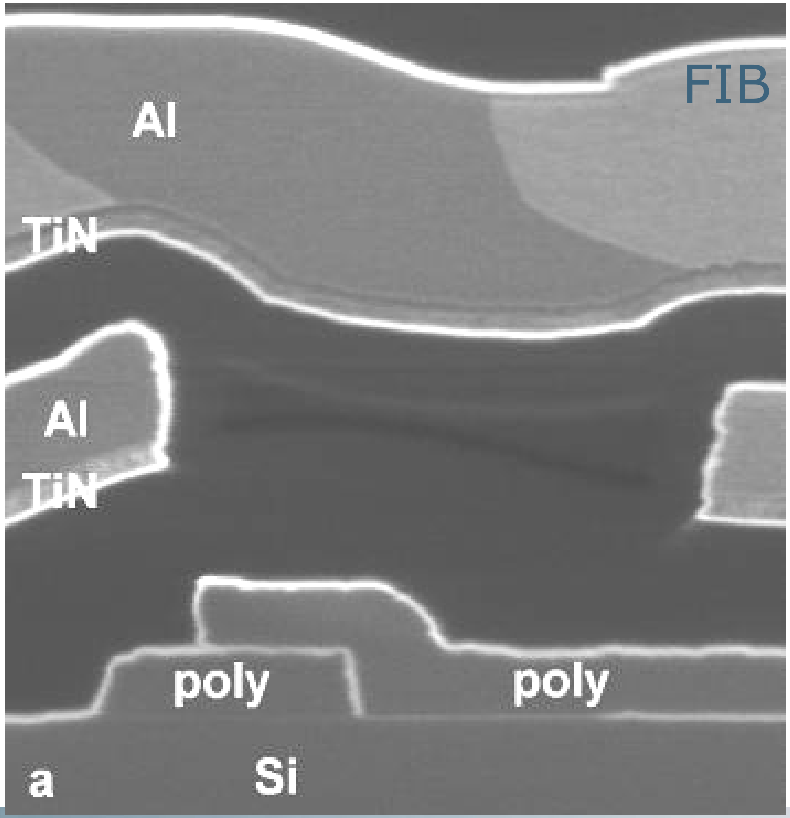
cross-section

through damage

# Ion beam interactions : Si

- many materials are completely amorphized by the ion beam
  - Si, Ge, III-V, …
  - silicides
  - many oxides

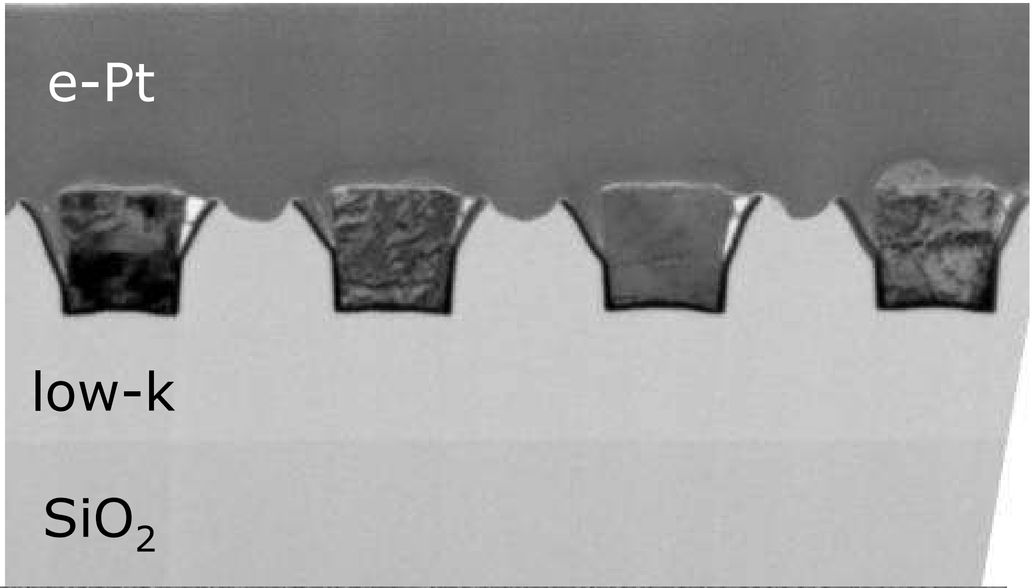
- indication for amorphisation : absence of channeling contrast

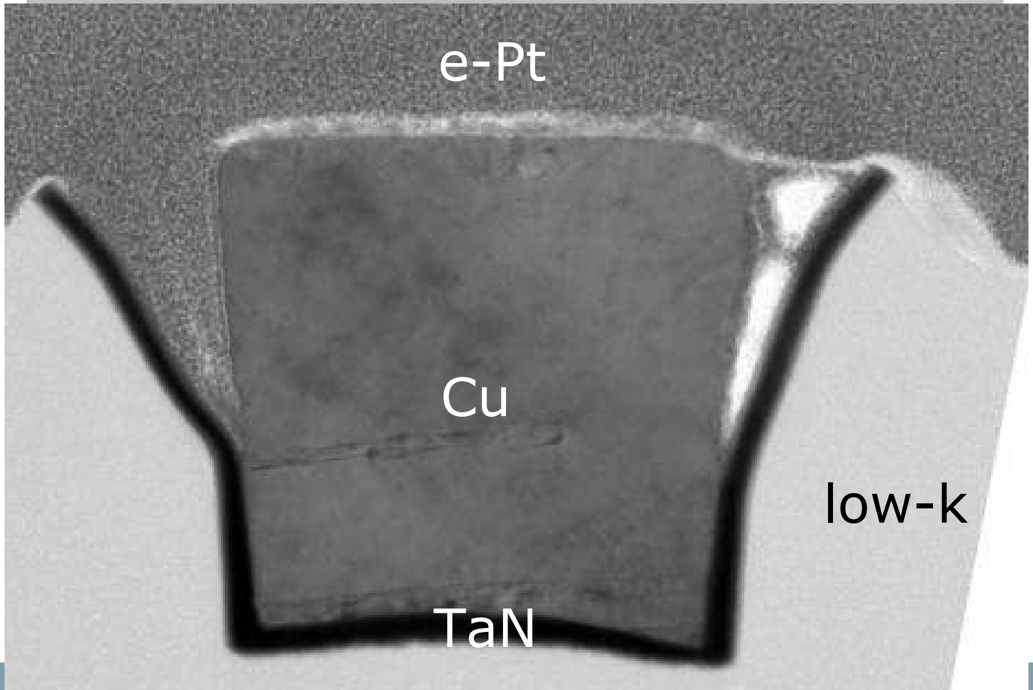


# Surface protective layers

- properties
  - > 150 nm
  - not reacting with the top layer
  - contrast in TEM with top layer, preferably amorphous, light elements
  - not planarising the topography
  - stress free
- options
  - wafer process line : a-Si, poly-Si, stress-free nitride, …
  - low-T CVD glass
  - sputtered glass
  - sputtered/evaporated Al or Ni
  - e-beam Pt or W

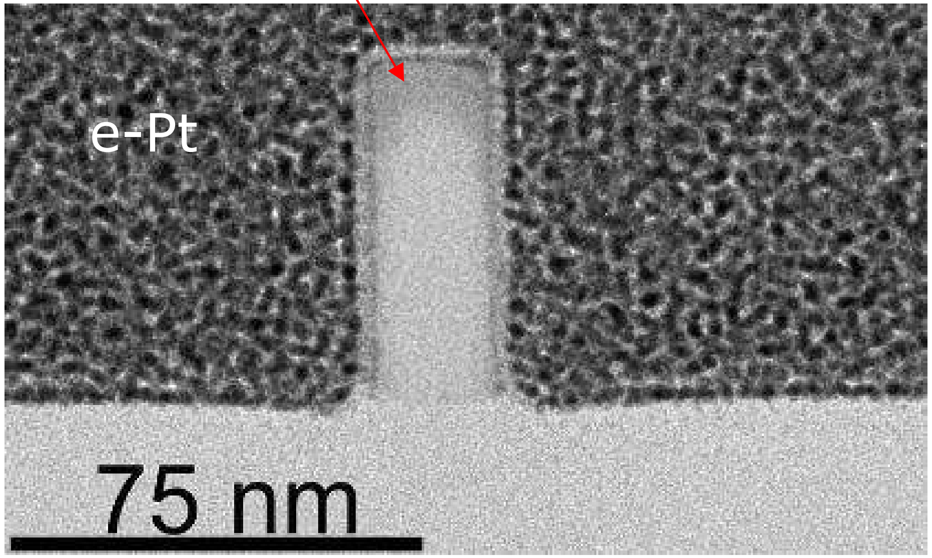
# e-Pt capping





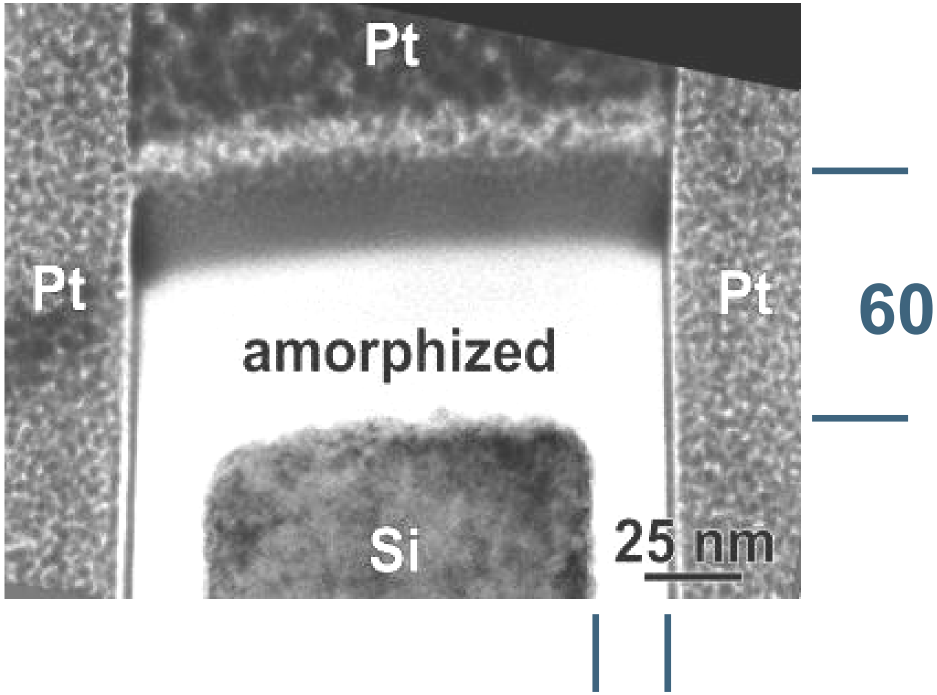
- shrinkage of the low-k and collapse of the barrier

- Pt diffusion in a-Si



# Si sidewall damage

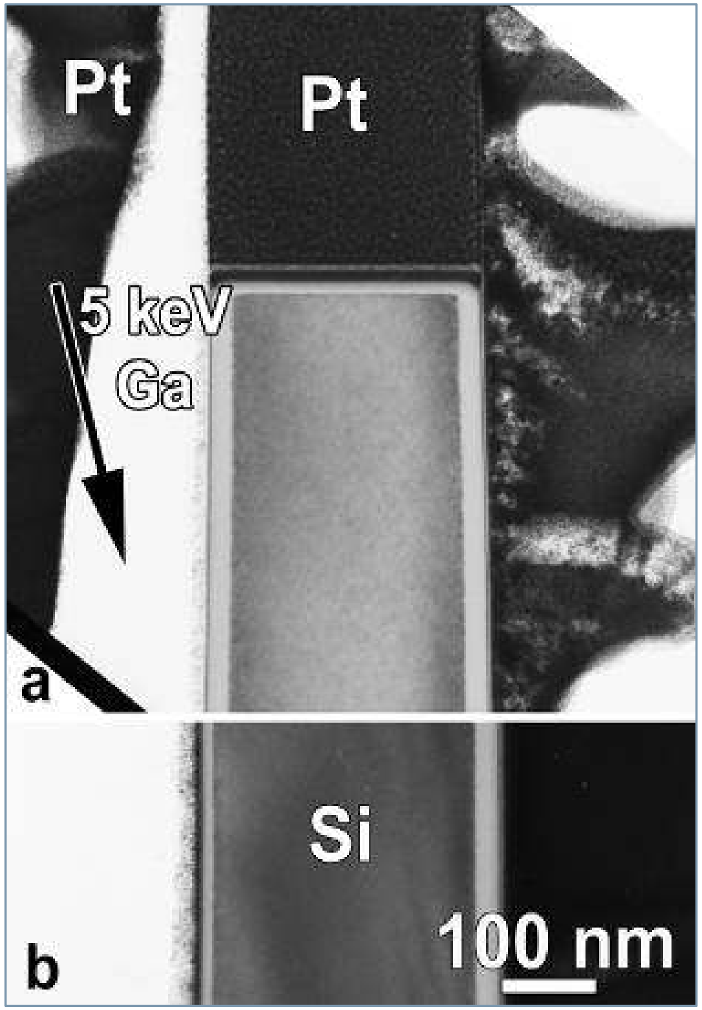
30 keV Ga



60-65 nm

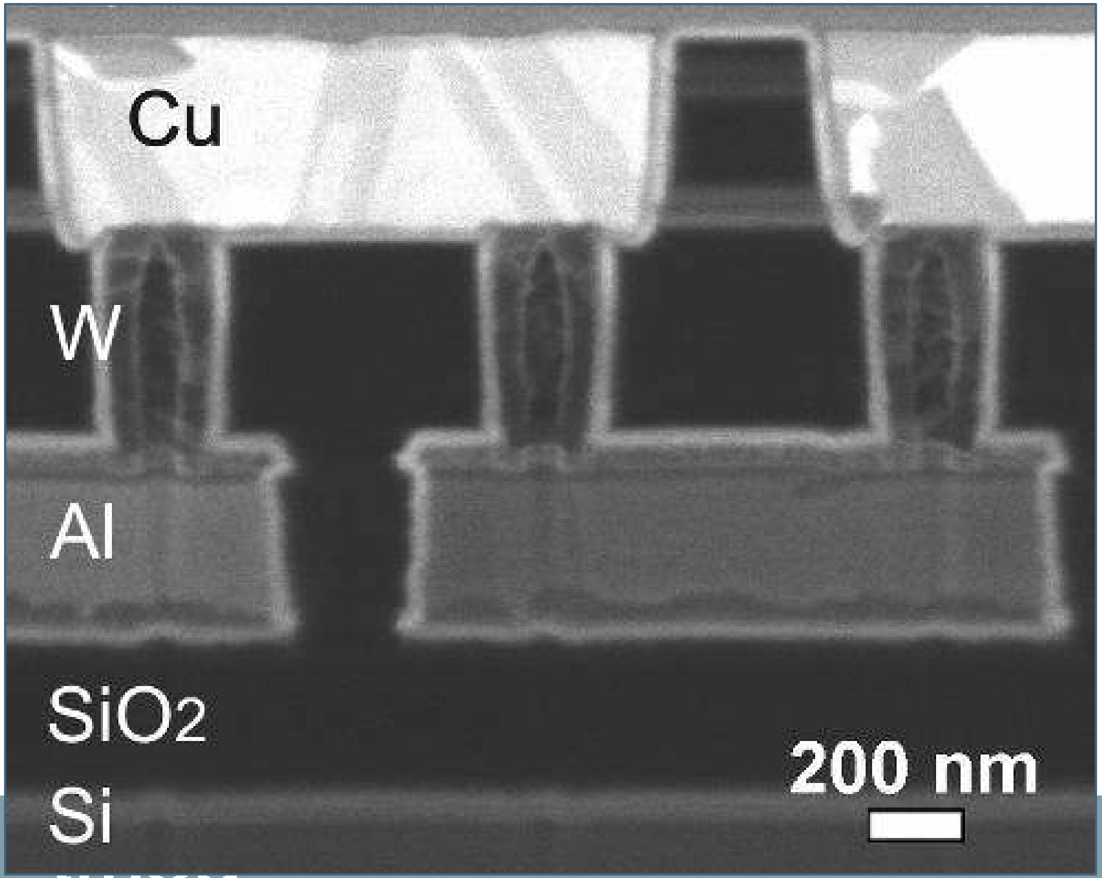
20-23 nm

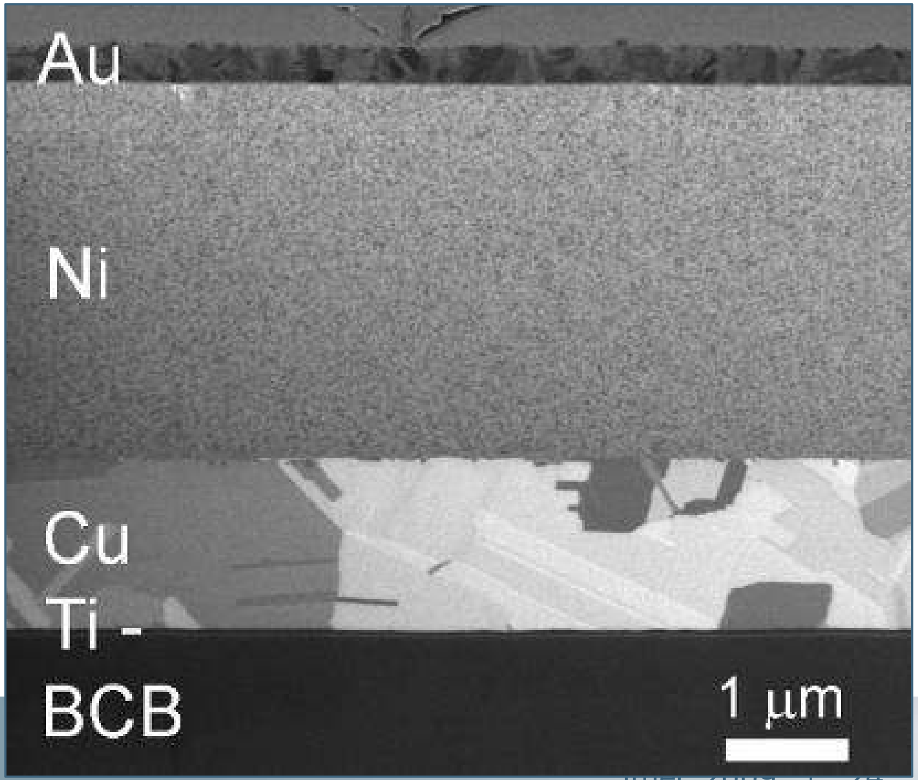
reduction by 5 keV Ga 15º



# Ion beam interactions : metals

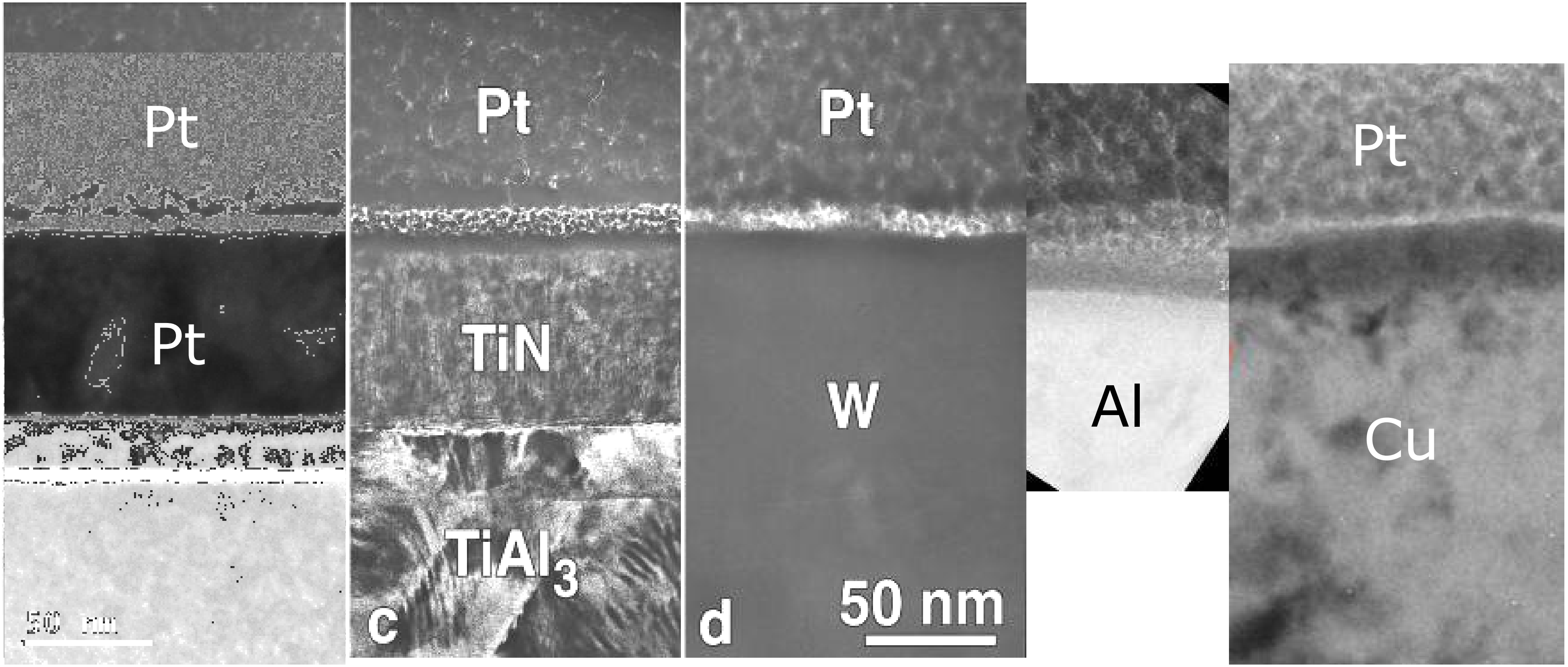
- channeling contrast occurs in all freshly milled metal, e.g. Al, Cu, Ni, W, Au, TiN, … indicating that full amorphisation does not occur
- no channeling in $TiAl_3$





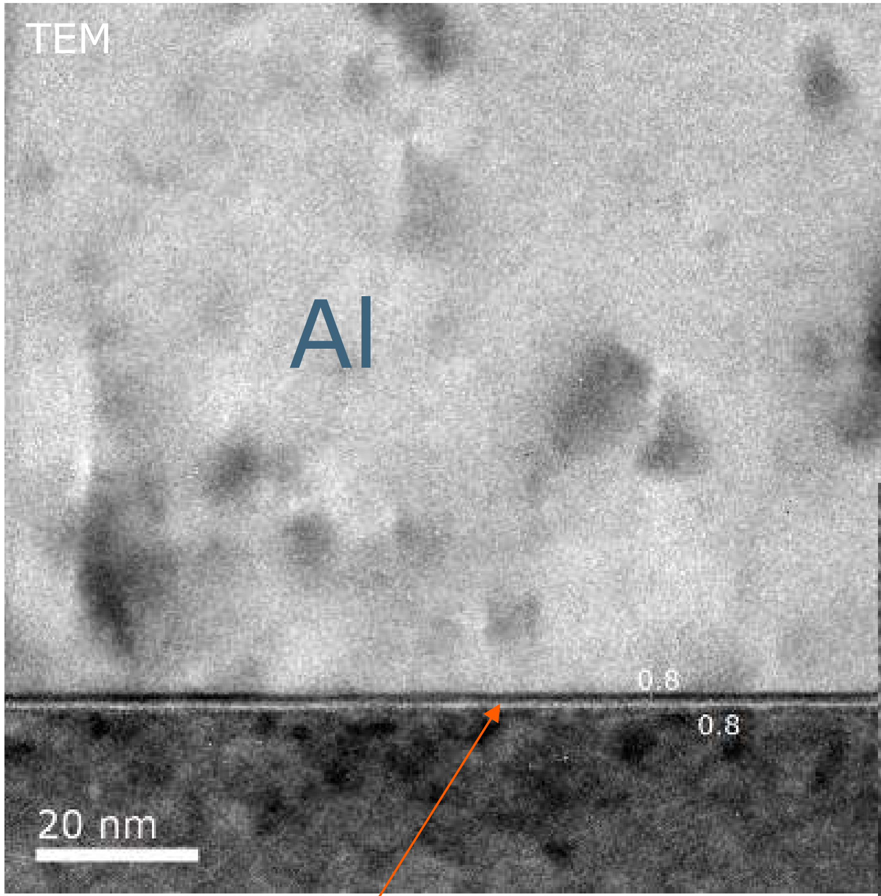
# Ion beam interactions : metals

30 keV ion-Pt deposition



C-rich interfacial layer / Pt and Ga in top of the metal
no amorphous layer

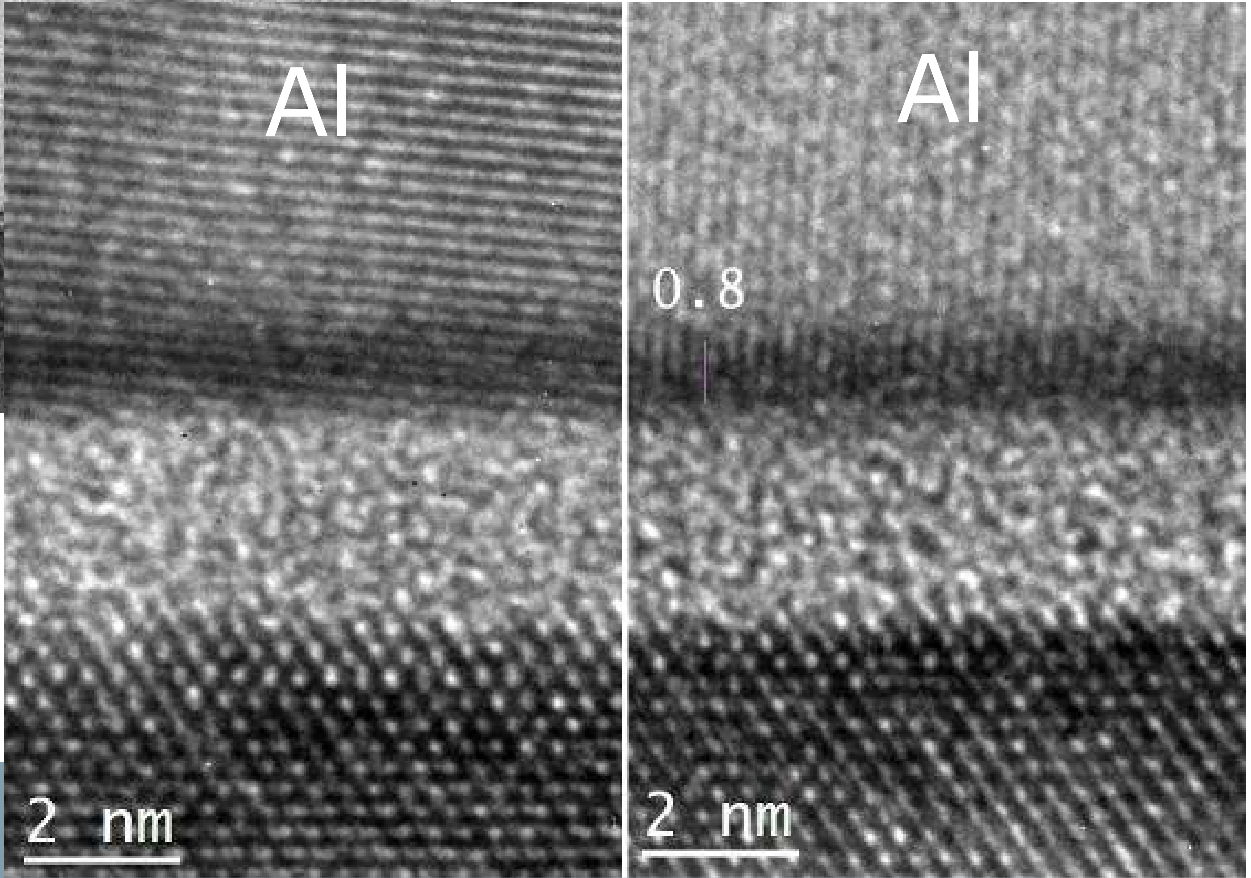
# Al / thin oxide / Si : TEM - HREM



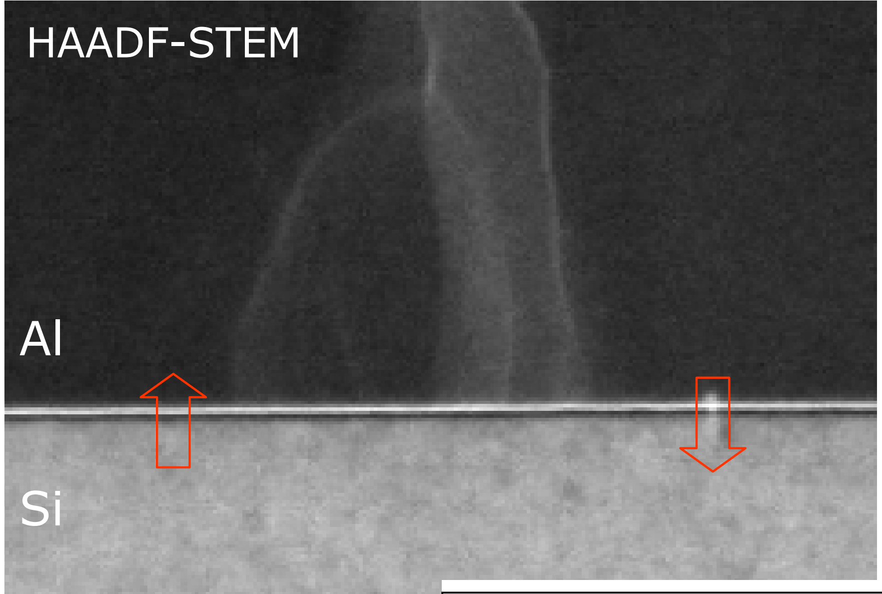
30 keV Ga

Al lattice is continuous in the dark layer

dark contrast layer in the Al near Al/$SiO_2$/Si interface



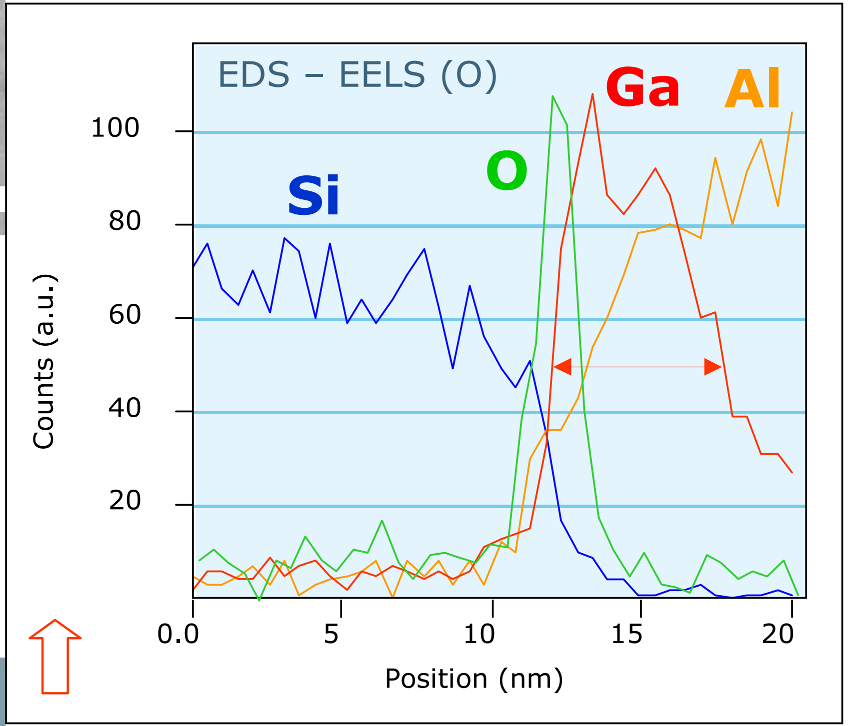
# Al / thin oxide / Si : HAADF-STEM – EDS/EELS

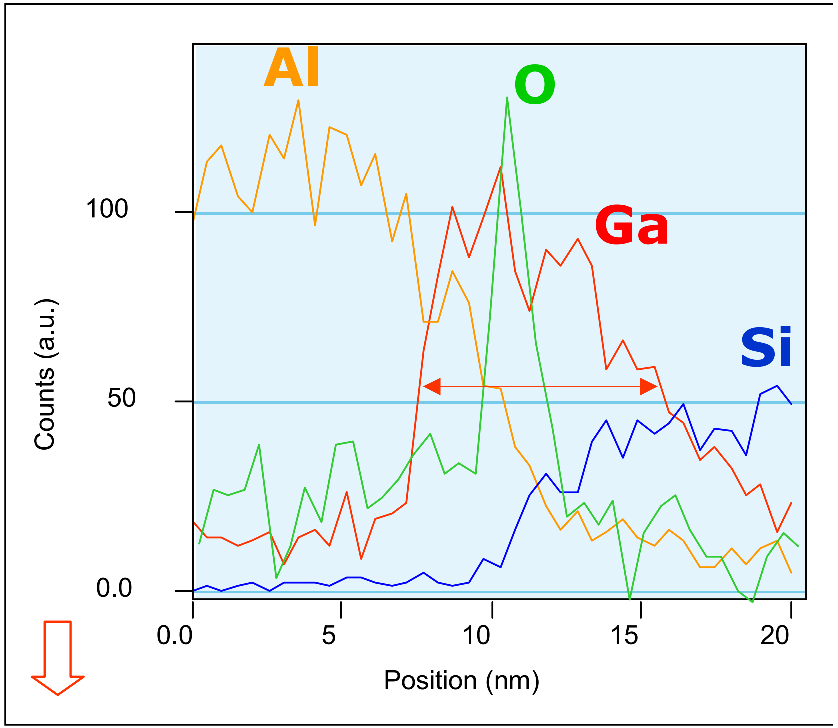


30 keV Ga

EDS/EELS :

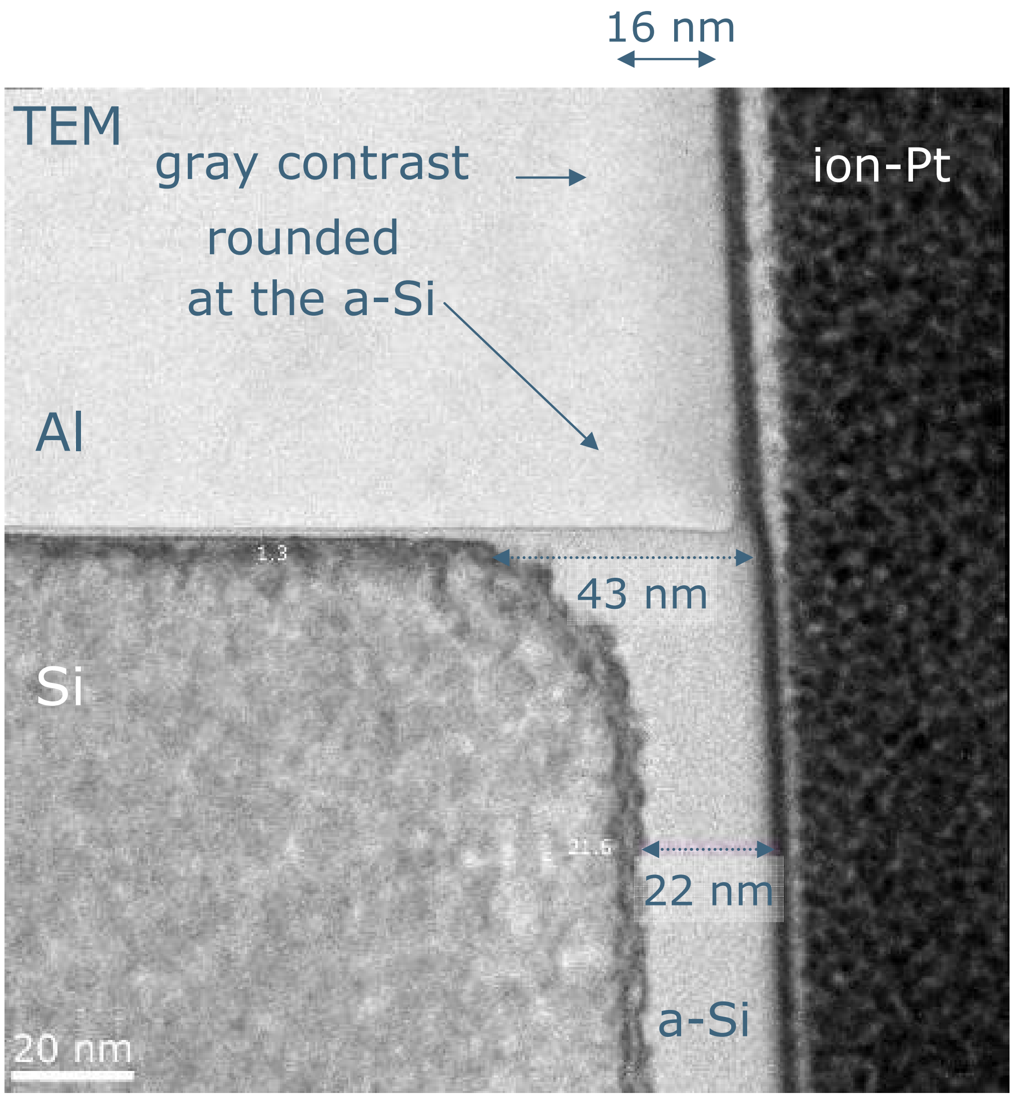
- **accumulation of Ga** in Al near the interface
- width of the Ga profile is much larger than on the images and depends on the sense of the linescan

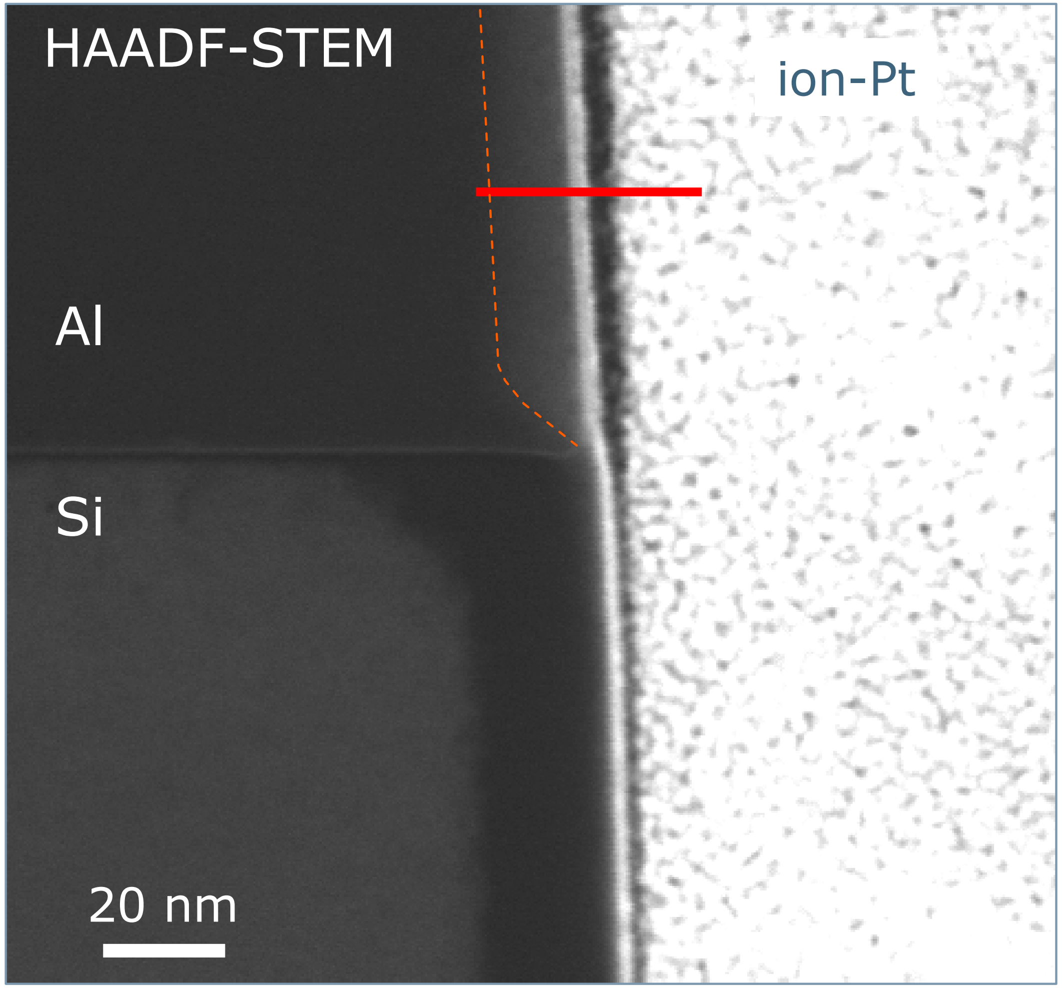




# Al / ion-Pt – trench sidewall : TEM / HAADF-STEM

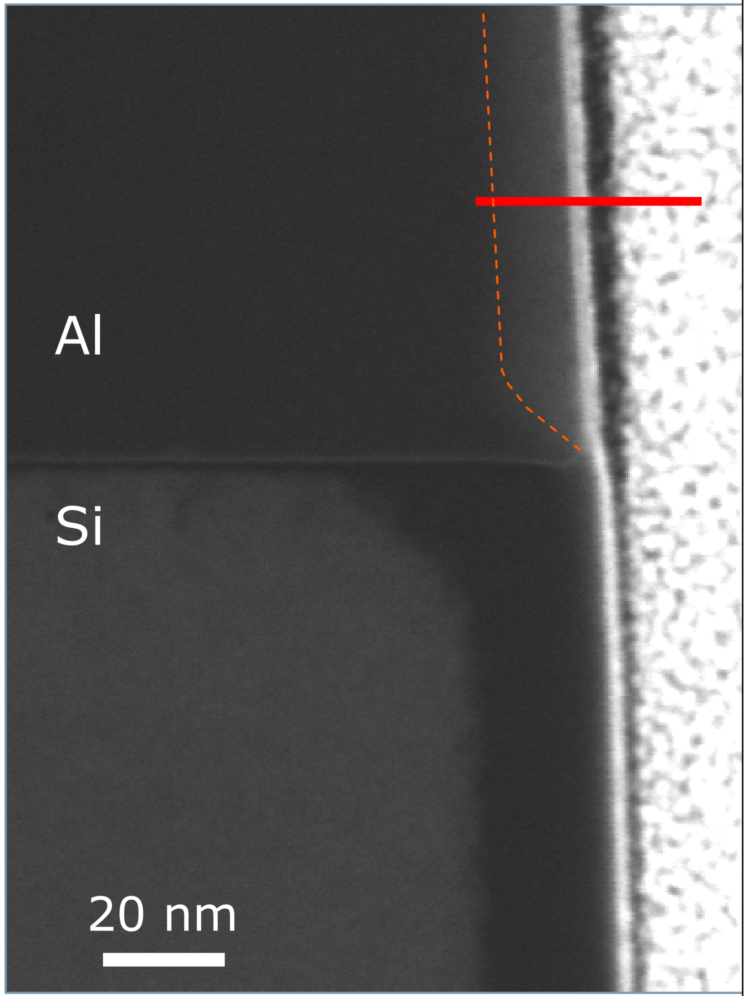
30 keV Ga

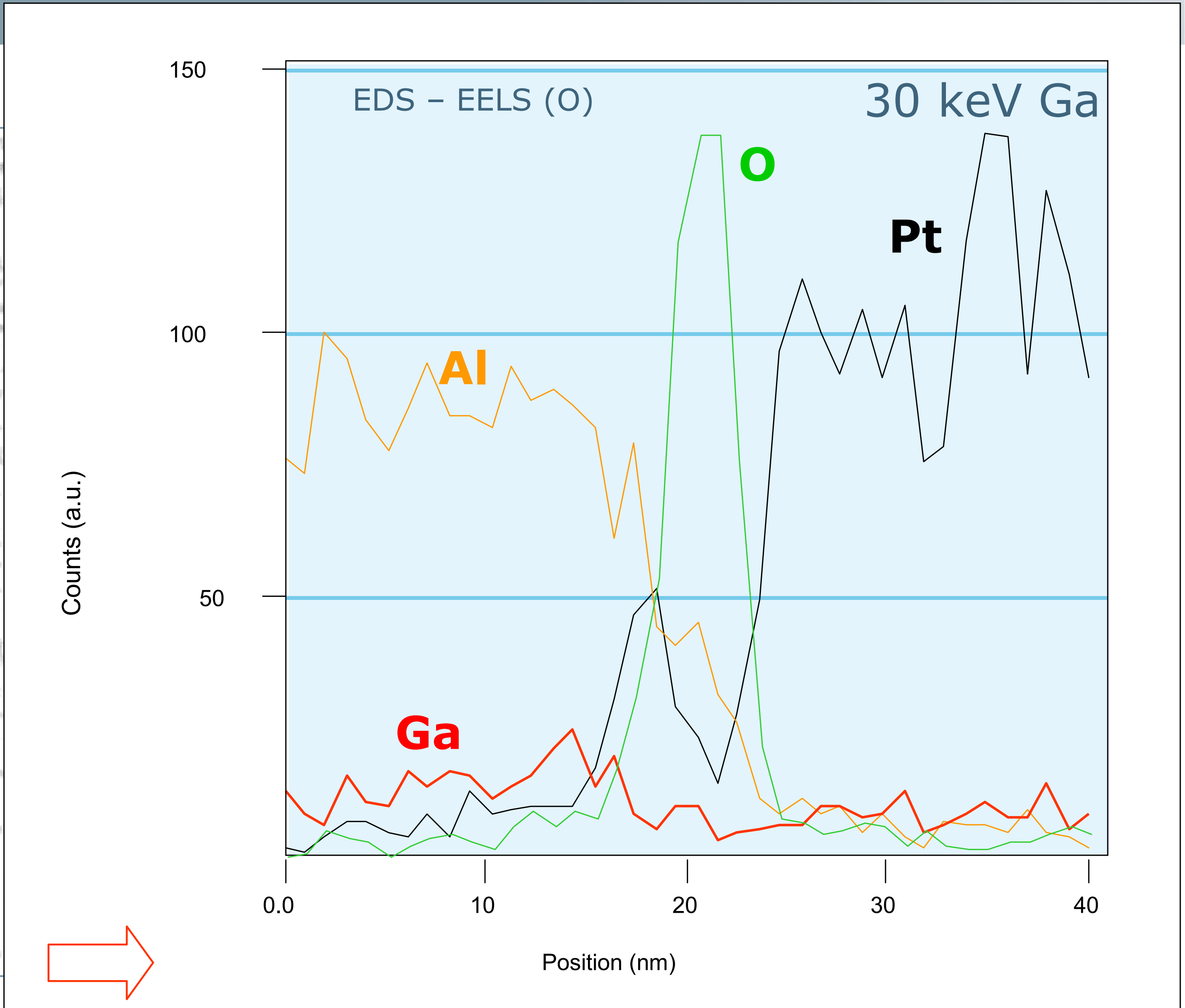




(no tilt during clean : ~ 2º slope

# Al / ion-Pt – trench sidewall : EDS/EELS





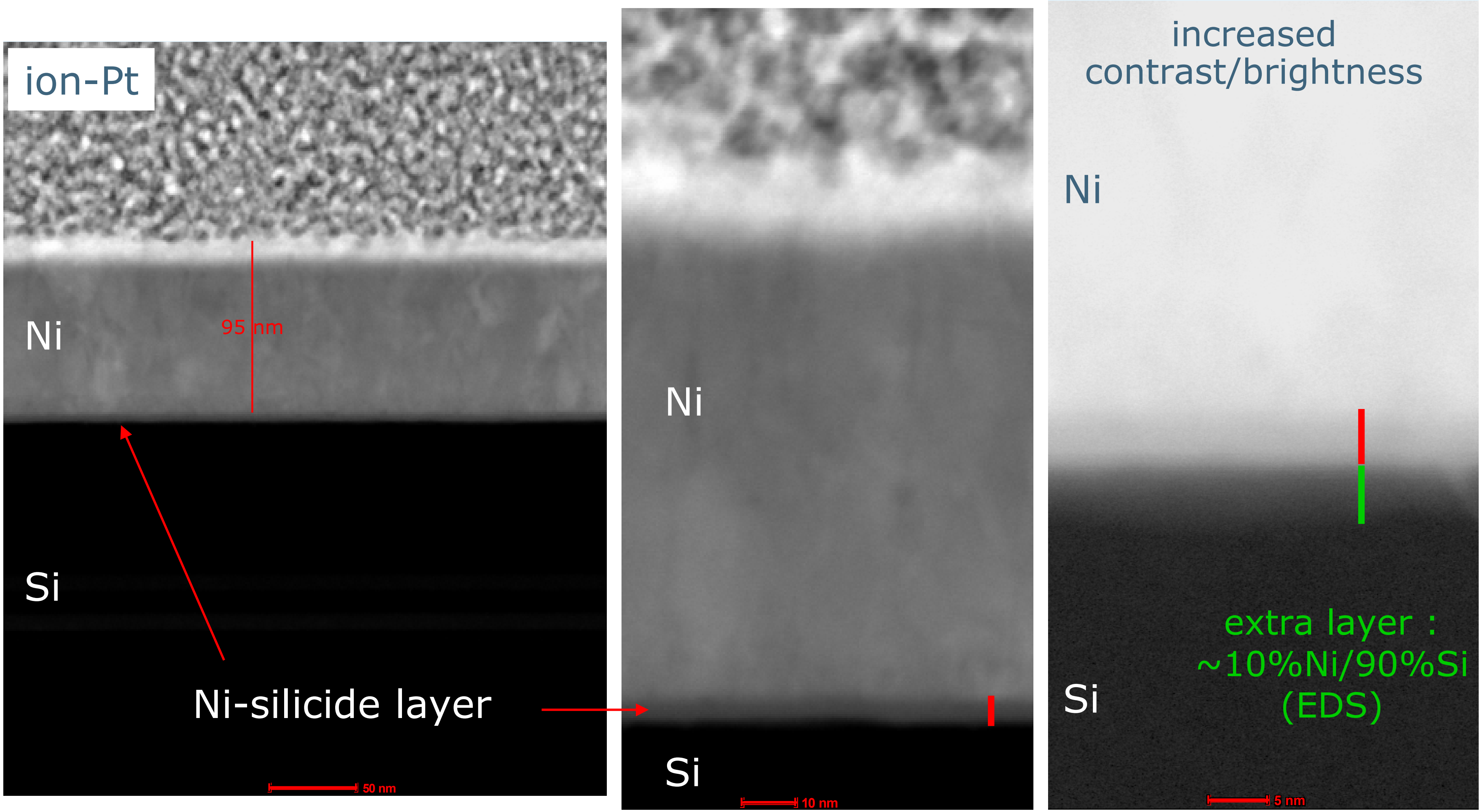
Al / Pt-Al / Al-O / Pt
Ga profile in the bright region

# Ion beam interactions : Ni on Si

- evaporated Ni on Si
- silicide formed at the interface during the deposition

- specimens
  - chunk / plan parallel specimen : finished with 30 keV Ga and tilted to compensate the slope
  - chunk / needle specimen as for atom probe : finished with 2 keV Ga, no tilt possible

# Ni on Si – 30 keV FIB lift-out - HAADF-STEM

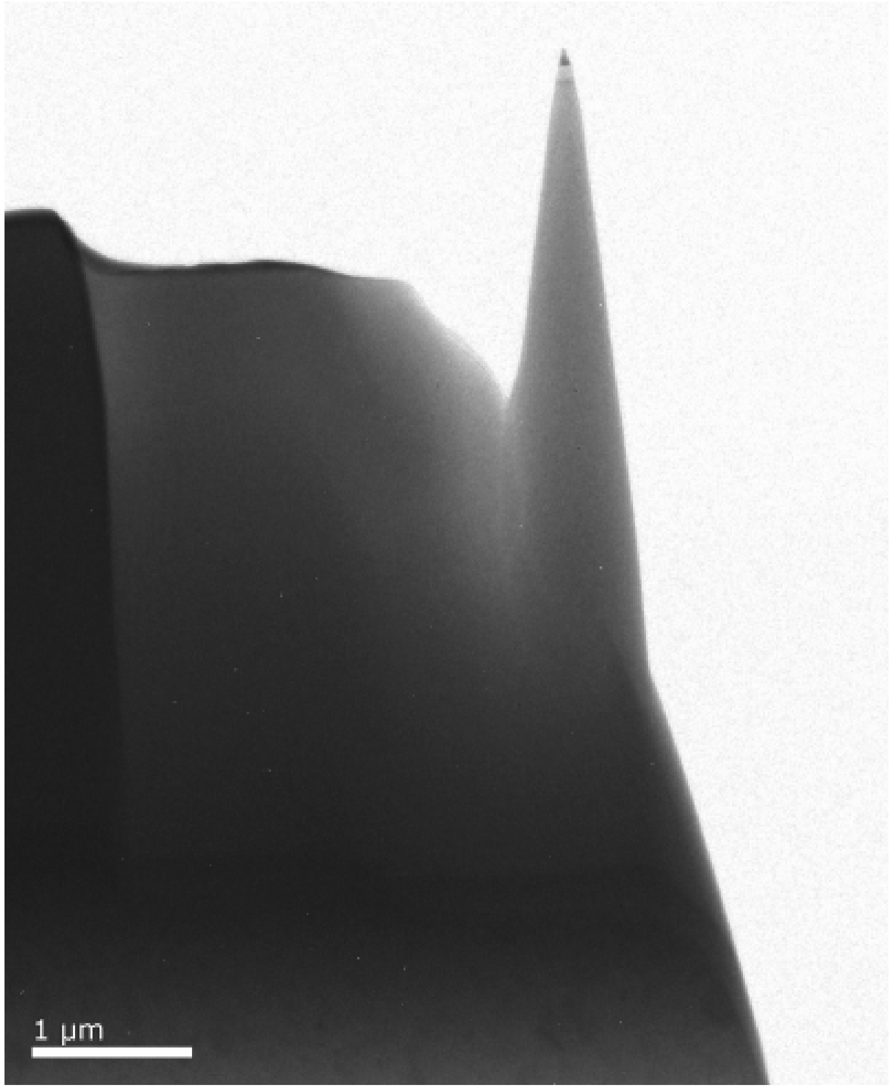


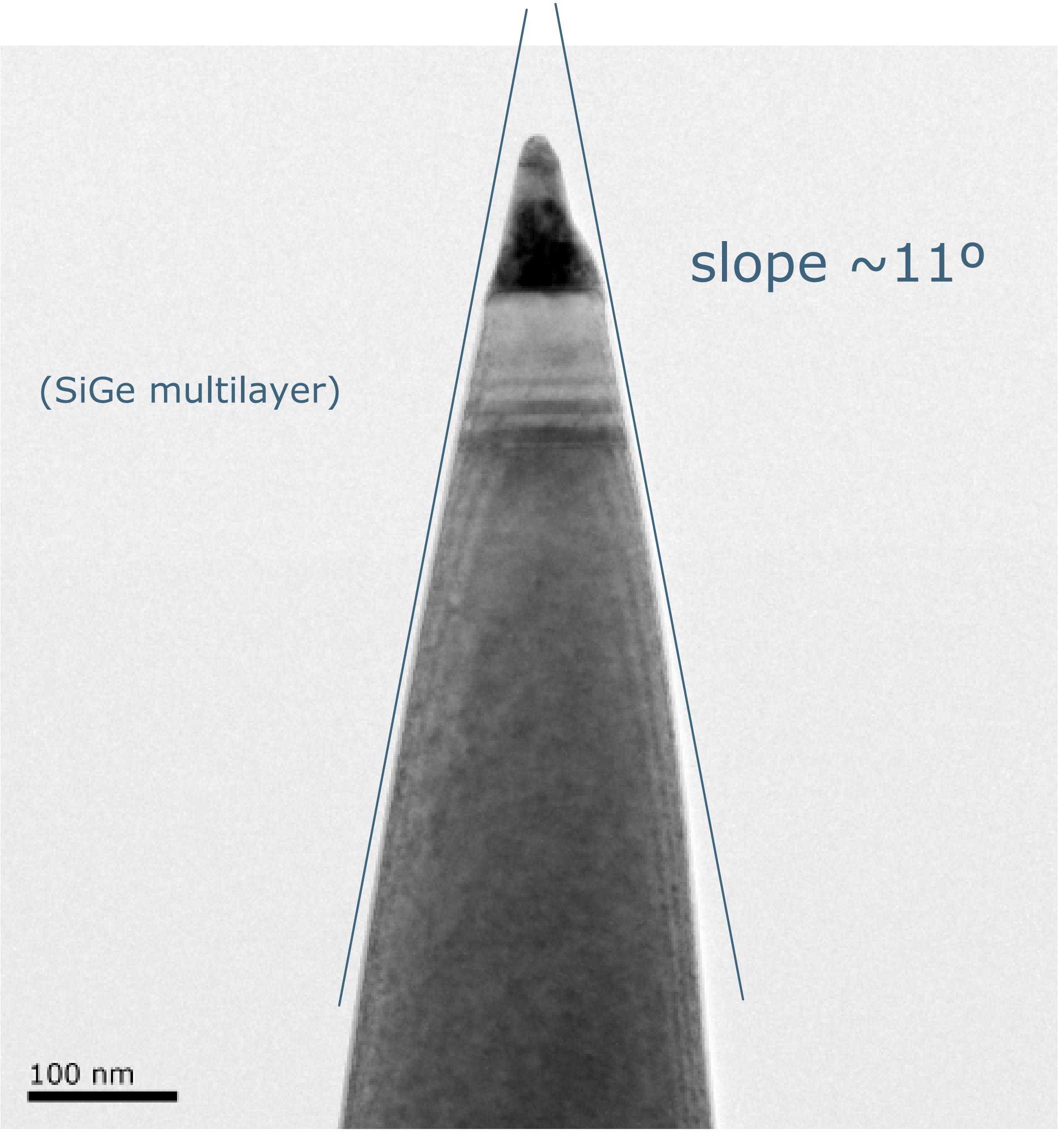
Ni-silicide layer

increased contrast/brightness

extra layer : ~10%Ni/90%Si (EDS)

# Ni on Si – needle finished 2 keV - TEM

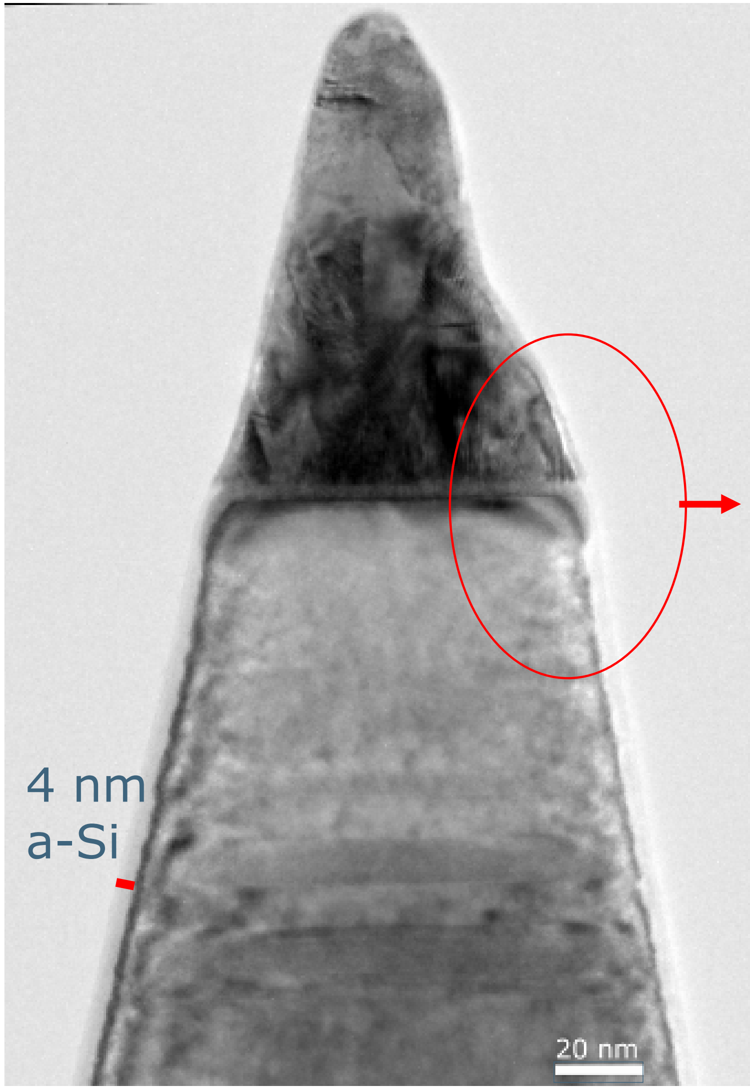


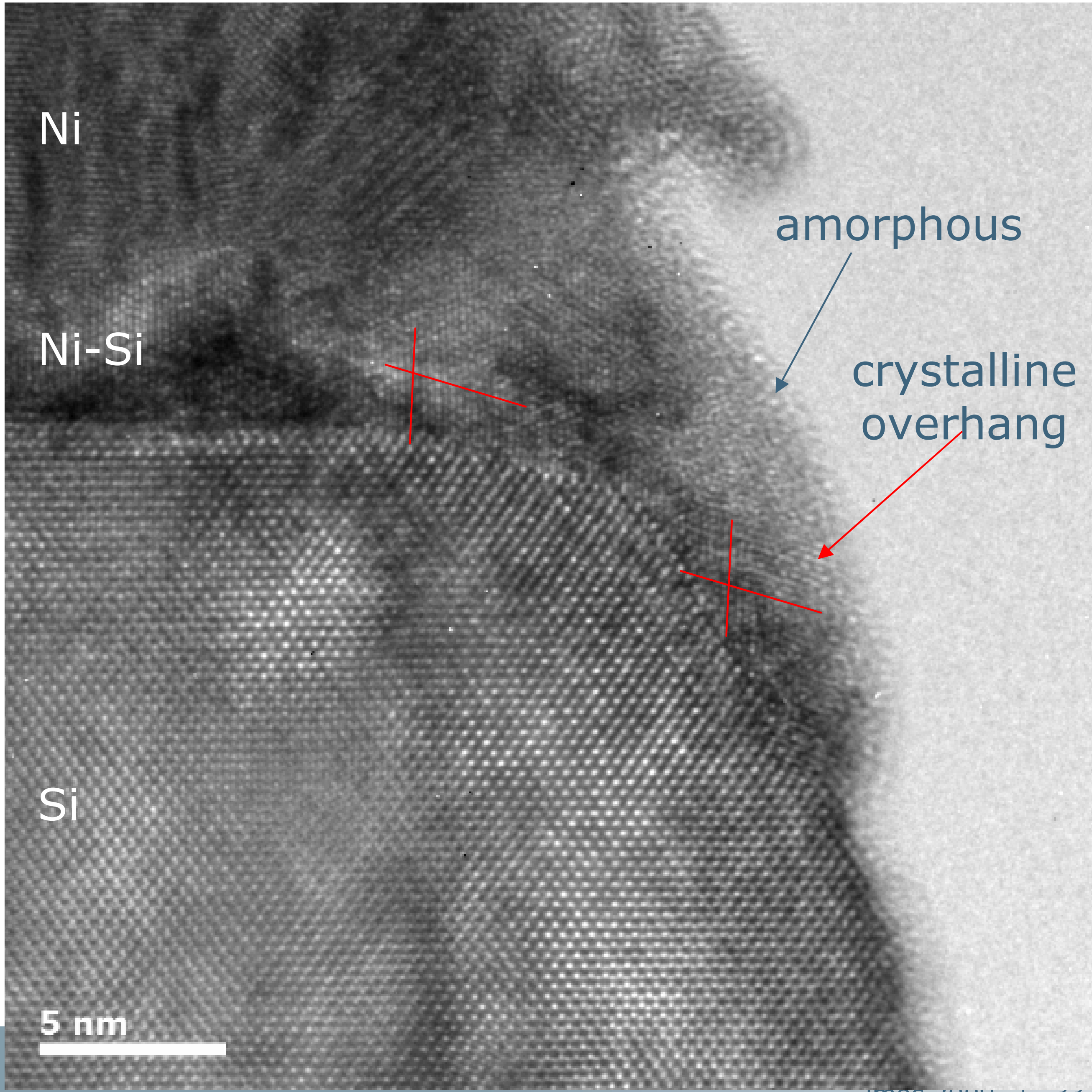


(SiGe multilayer)

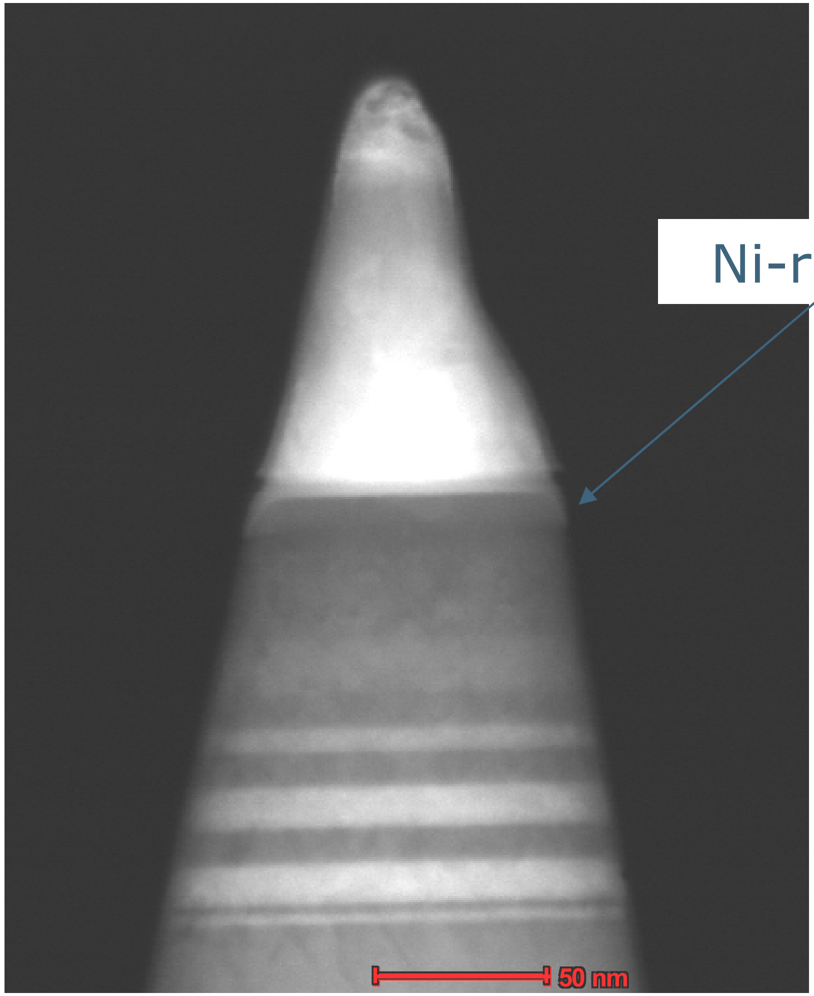
slope ~11º

# Ni on Si – needle finished 2 keV - TEM

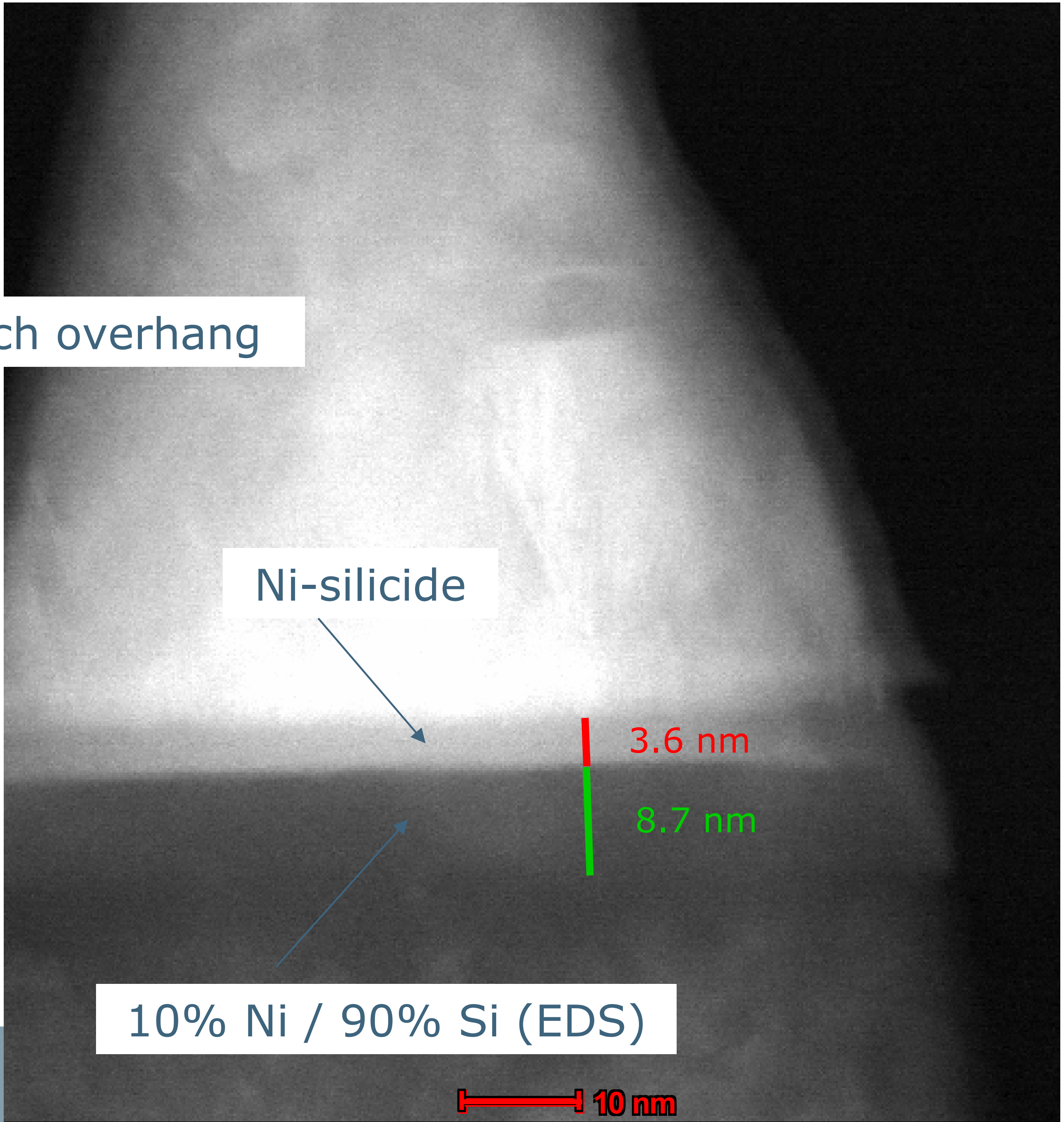




# Ni on Si – needle finished 2 keV – HAADF-STEM



Ni-rich overhang



Ni-silicide

10% Ni / 90% Si (EDS)

# Ni reaction

- Ni reacts with the amorphized Si, forming a Ni-silicide layer on the outsides of the TEM specimen (a ring in case of needle sample)
- the “10% Ni” layer thickness :
  - 30 kV 3.5 nm
  - 2 kV 8.7 nm

  thickness difference likely related to different slope : “0º” for the chunk vs “11º” for the needle

# Conclusions

- semicondutors : amorphise under the Ga beam
- metals :
  - Ga implanted
  - Al : Ga diffuses to interfaces and grain boundaries
  - Ni : silicide formation

- outlook : needs for the future
  - better low keV image quality
  - faster milling systems
    (plasma-FIB, higher energy, higher currents)

Years of Making
Technology Fly