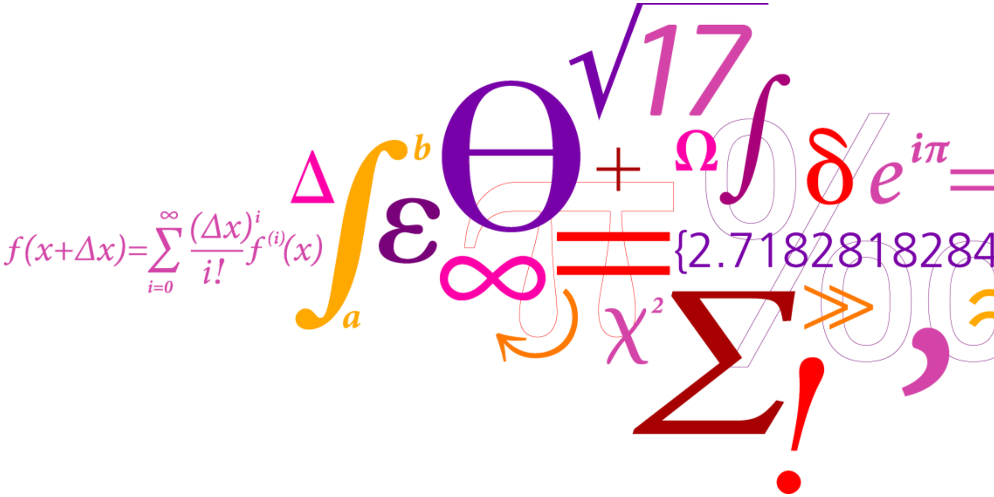
Focused Ion Beam

Alice B. S. Fanta



DTU Cen

Center for Electron Nanoscopy

Outline

- Principle of Focused Ion Beam
    - Comparison between SEM and FIB
    - Physical effects of incident ions
- FIB at CEN
- Basic Applications
- TEM sample preparation
    - Lift out / H-Bar/ Ex-Situ lift out
    - tricks and tips (others)
- FIB for 3D microstructure characterization
    - 3D slice and View
    - 3D EBSD
- Damage
- Other Ions sources

Principle of Focused Ion Beam

Focused Ion Beam (FIB) was developed in the late 1970s and the early 1980s

Ion column structure similar to that of SEM

Major difference :

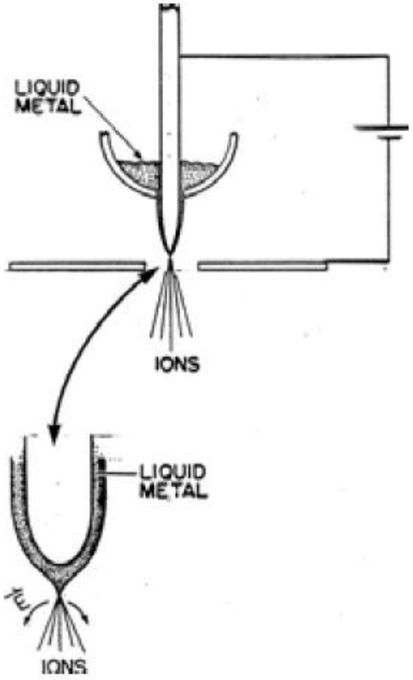
Source: Liquid Metal Ion Source (LMIS)

Electromagnetic lenses are not of sufficient strength to focus the heavy ion beam and so electrostatic lenses are used.

Principle:

A strong electromagnetic field causes the emission of positively charged ions from the liquid metal cone which is formed on the tip of a tungsten needle.

Liquid metal is usually Ga



Ref.: John Melngailis and Marco Cantoni

Principle of Focused Ion Beam

Upper octopole
Stigmator

Beam is focused to a fine spot (best resolution ~ sub 10 nm range)

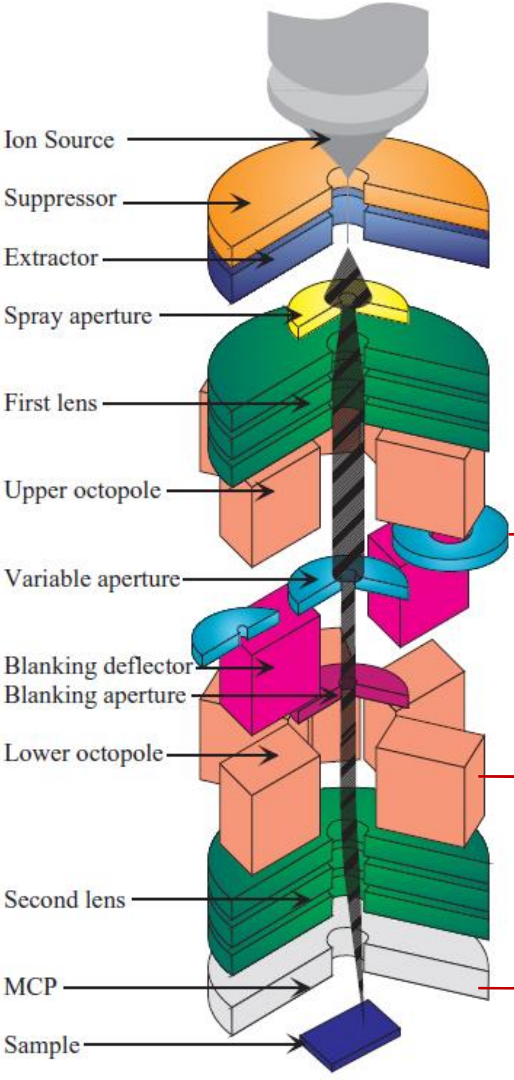


Figure 2. Schematic diagram of a FIB ion column.

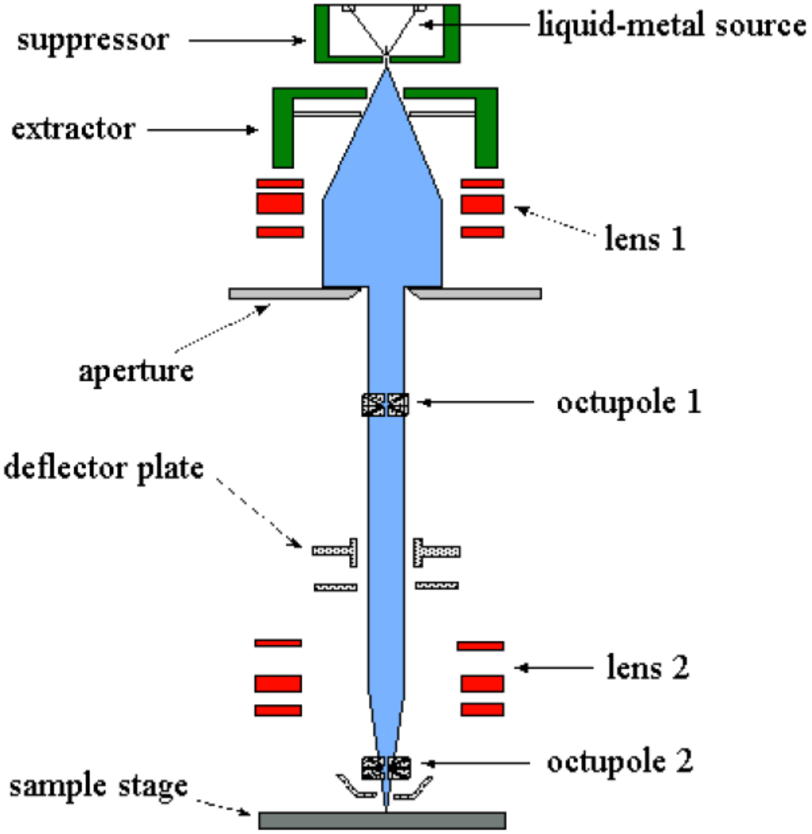
The variable aperture mechanism allows the beam current to be varied (1pA to 22nA)

Lower octopole is used for raster scanning the beam over the sample in a user-defined pattern

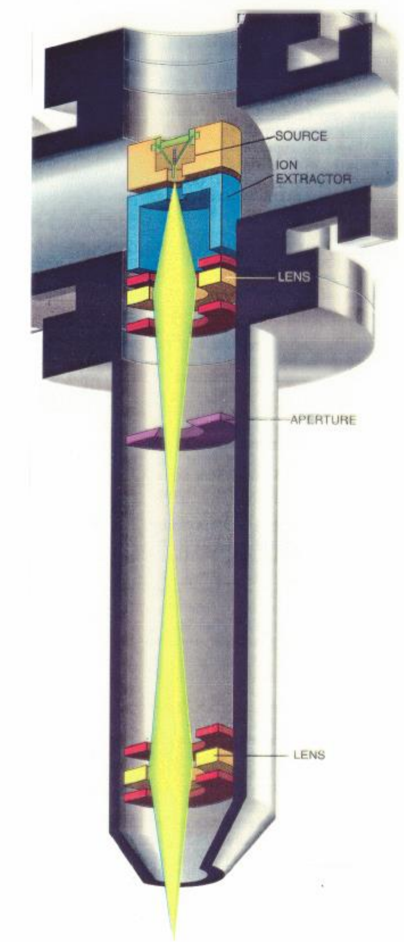
Multichannel plate (MCP) is used to collect secondary particles for imaging

Ref.: S. Reyntjens and R. Puers 2001 J. Micromech. Microeng. ***11*** *287*

Principle of Focused Ion Beam



Schematic diagram of a FIB ion column
Source: IBM Almaden Research Center



Ref.: J. Orloff, Scientific American, Oct. 1991

Outline

- Principle of Focused Ion Beam
  - Comparison between SEM and FIB
  - Physical effects of incident ions
- FIB at CEN
- Basic Applications
- TEM sample preparation
  - Lift out / H-Bar/ Ex-Situ lift out
  - tricks and tips (others)
- FIB for 3D microstructure characterization
  - 3D slice and View
  - 3D EBSD
- Damage
- Other Ions sources

Comparison between SEM and FIB

Electrons	**Ions**
are very small	Big
Inner shell reactions	-> Outer shell reactions (no x-rays)
High penetration depth	Less penetration depth
Low mass -> higher speed for given energy	High mass -> slow speed but high Momentum milling !!!
Electrons are negative	Ions are positive
Magnetic lens (Lorentz force)	Electrostatic lenses

=> One Gallium-Ion ist approx. 127.000x heavier than an electron!

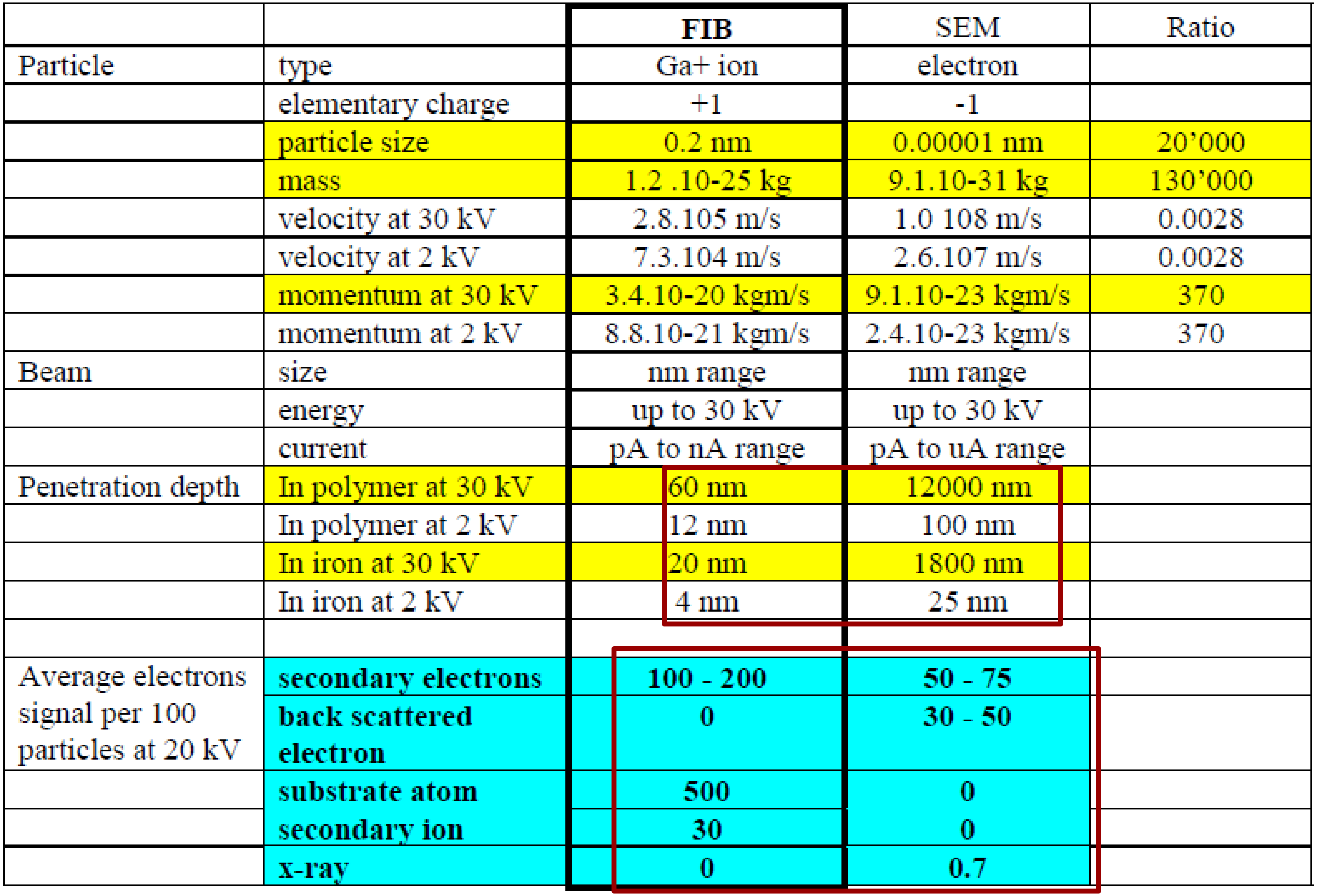
Ref.: Tim Armbruster

Why Gallium ?

Ga is metallic, low melting point, in the middle of the periodic table, no overlap with other elements in EDX

Ref.: Marco Cantoni

Comparison between SEM and FIB



		FIB	SEM	Ratio
Particle	type	Ga+ ion	electron	
	elementary charge	+1	-1	
	particle size	0.2 nm	0.00001 nm	20’000
	mass	1.2 .10-25 kg	9.1.10-31 kg	130’000
	velocity at 30 kV	2.8.105 m/s	1.0 108 m/s	0.0028
	velocity at 2 kV	7.3.104 m/s	2.6.107 m/s	0.0028
	momentum at 30 kV	3.4.10-20 kgm/s	9.1.10-23 kgm/s	370
	momentum at 2 kV	8.8.10-21 kgm/s	2.4.10-23 kgm/s	370
Beam	size	nm range	nm range	
	energy	up to 30 kV	up to 30 kV	
	current	pA to nA range	pA to uA range	
Penetration depth	In polymer at 30 kV	60 nm	12000 nm	
	In polymer at 2 kV	12 nm	100 nm	
	In iron at 30 kV	20 nm	1800 nm	
	In iron at 2 kV	4 nm	25 nm	
Average electrons signal per 100 particles at 20 kV	**secondary electrons**	**100 - 200**	**50 - 75**	
	back scattered electron	**0**	**30 - 50**	
	substrate atom	**500**	**0**	
	secondary ion	**30**	**0**	
	x-ray	**0**	**0.7**	

Ref.: Marco Cantoni

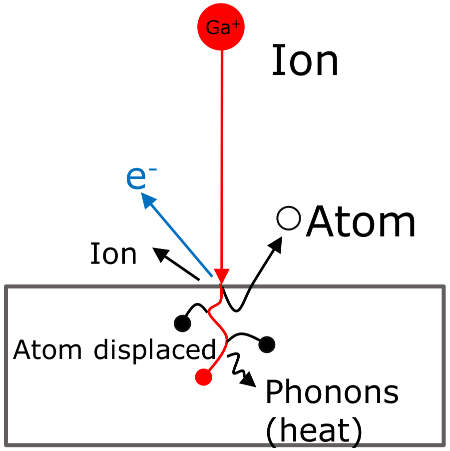
Outline

- Principle of Focused Ion Beam
  - Comparison between SEM and FIB
  - Physical effects of incident ions
    - Basic operation modes
- FIB at CEN
- Basic Applications
- TEM sample preparation
  - Lift out / H-Bar/ Ex-Situ lift out
  - tricks and tips (others)
- FIB for 3D microstructure characterization
  - 3D slice and View
  - 3D EBSD
- Damage
- Other Ions sources

Physical effects of incident ions

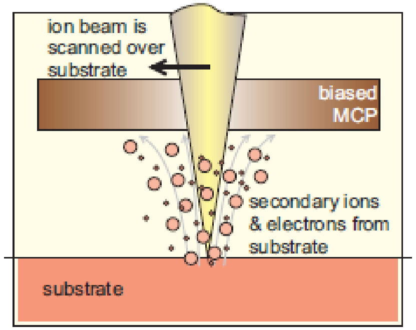
The most important physical effects of incident ions on the substrate are:

- ✓ Sputtering of neutral and ionized substrate atoms → Enables surface milling
- ✓ Secondary electron emission → Enables imaging
  May also cause charging
- ✓ Displacement of atoms in the solid → Induced damage
- ✓ Emission of phonons → Heating
- ✓ Chemical interaction including the breaking of chemical bonds → During deposition

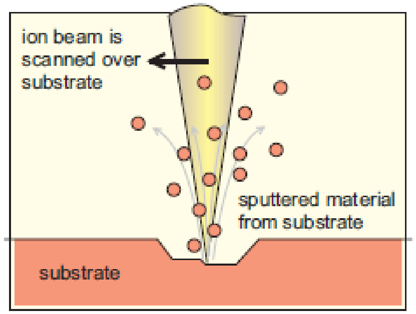


Basic operating modes

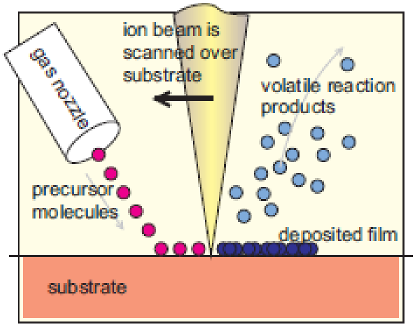
1. Image mode



2. Milling mode



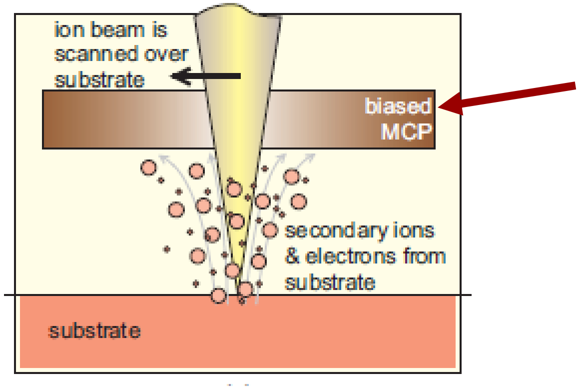
3. Deposition mode



Ref.: S. Reyntjens and R. Puers 2001 J. Micromech. Microeng. ***11*** *287*

Basic operating modes - Image

During FIB imaging the finely focused ion beam is raster scanned over the substrate and secondary particles are generated in the sample (Emission of atoms, secondary ions and electrons)



The detector bias

- at positive voltage to collect secondary electrons
- at negative voltage to collect secondary ions

Can be used for secondary ion mass spectroscopy (SIMS)

Best resolution <10nm

Imaging with FIB induces some damage:

- Ga^+ Ions implantation (depth is related to ion energy, and angle of incidence)
- Some milling always occurs

Use of low ion current

Ref.: S. Reyntjens and R. Puers 2001 J. Micromech. Microeng. ***11*** *287*

FIB imaging

A. Crystallographic orientation (channeling) contrast

B. Material contrast

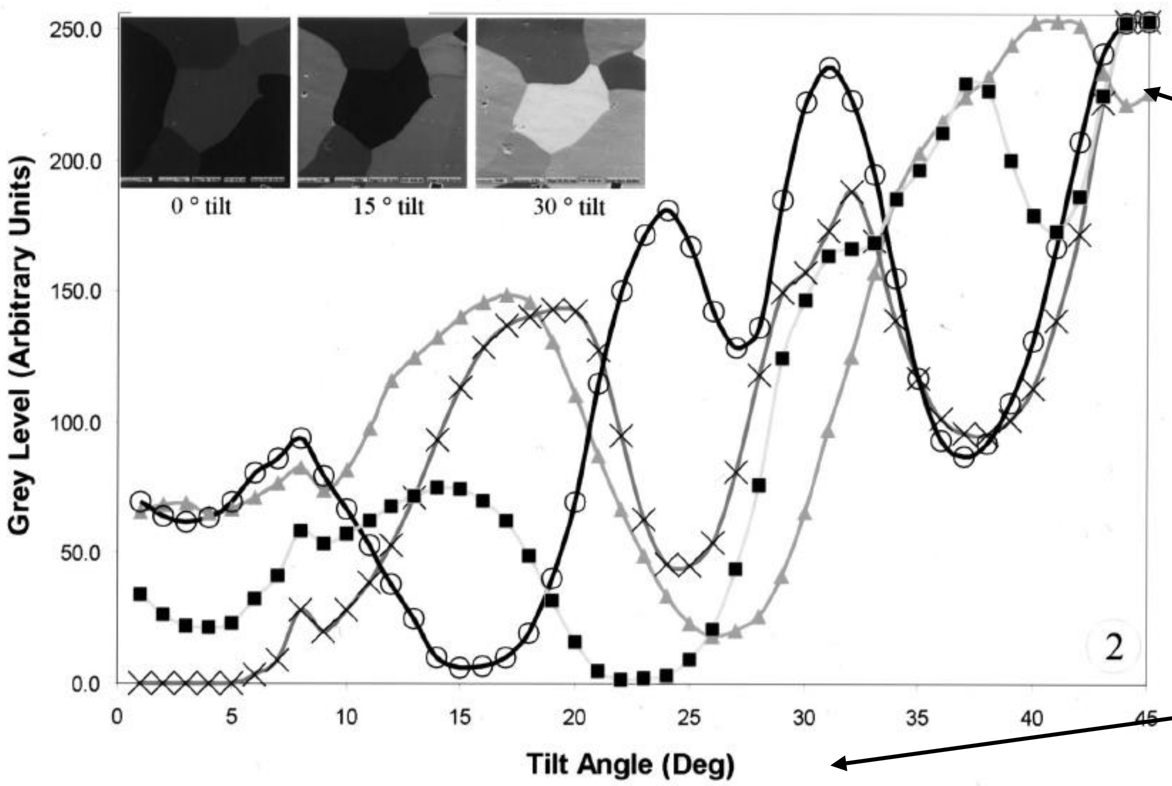
C. Topographic contrast

A. Orientation contrast arises from channeling of the incident ions between lattice planes of the specimen. Depth varies with the angle between the ion beam and the lattice plane and the interlunar spacing of the lattice.

Secondary electron yield is greater than that of secondary ions and less sensitive to changes in chemistry

FIB imaging – Crystallographic orientation

Pure Aluminium



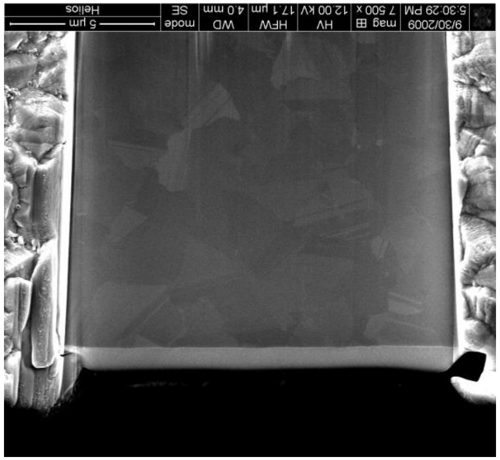
Each line represent the change in intensity of a discrete grain

Deviation from the normal incidence as the speciment is tilted relative to the ion beam

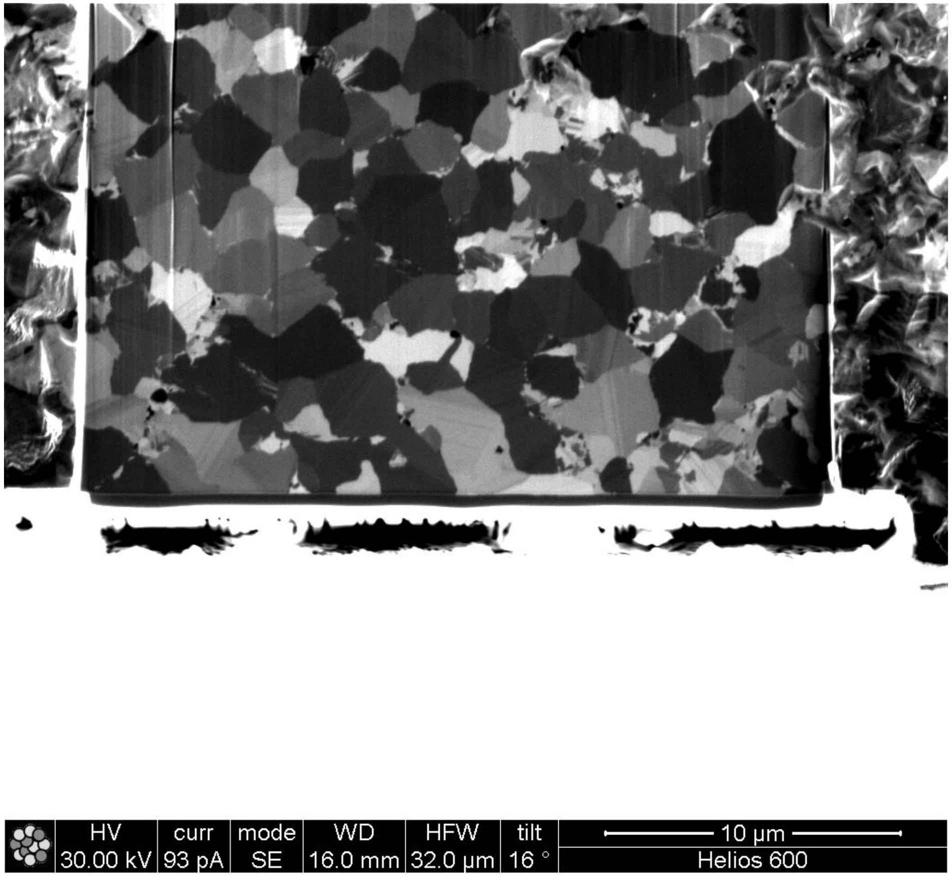
Fig. 2. FIB secondary electron mode orientation contrast of a fully annealed, nominally pure polycrystalline aluminum specimen changes the intensity (grey level) of each grain as a function of deviation from normal incidence as the specimen is tilted with respect to the gallium beam. The same region is imaged (inset) at angles of 0, 15, and 30° tilt (foreshortening due to tilt angle is evident). The change in intensity (in arbitrary 'grey level' units) is plotted as a function of tilt angle in 1° increments. Dark grains (low intensity) represent significant channeling of the primary ions. The angular width of channeling 'troughs' and the angular distance between troughs can be used to calculate the relative orientation of different grains.

Ref.:M.W. Phaneuf / Micron 30 (1999) 277–288

FIB imaging – Crystallographic orientation



SEM image

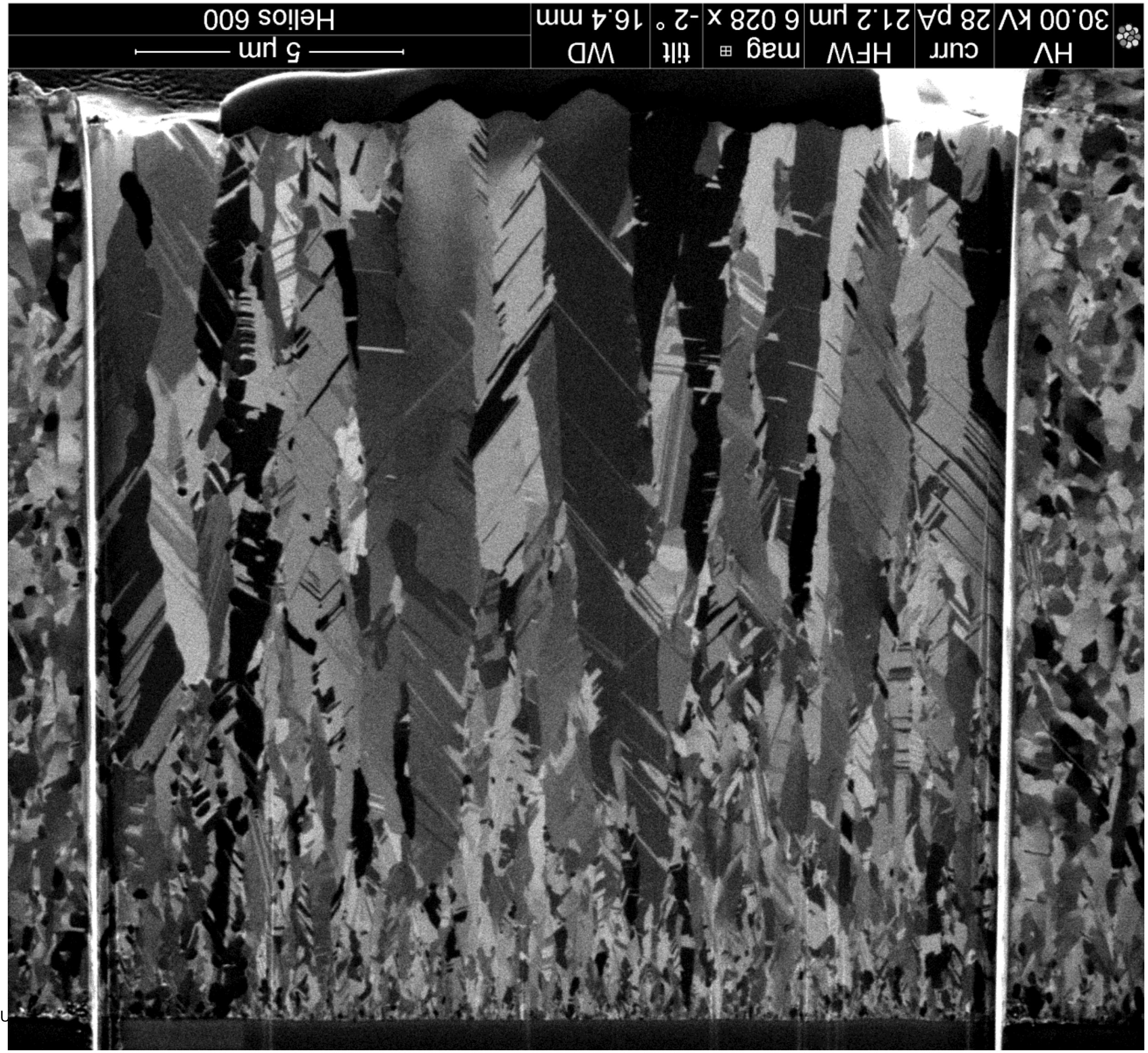


FIB image : Ion induced secondary electron image

Ref.:Ni electrodeposit
(Hossein Alimadadi)

FIB imaging – Crystallographic orientation

FIB image : Ion induced secondary electron image



Ref.:Ni electrodeposit (Hossein Alimadadi)

FIB imaging – Material contrast

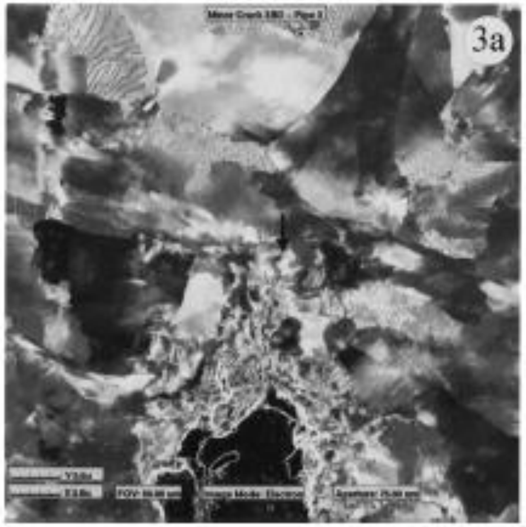
B. Material contrast arises from difference in the yield of secondary particles as a function of specimen chemistry

→ This effect is most readily observed in FIB secondary ion images

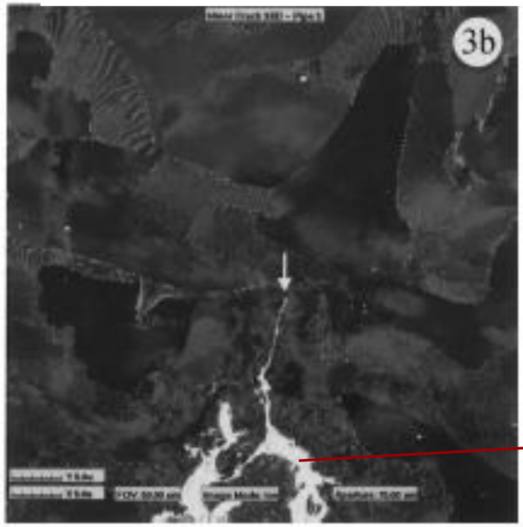
Secondary ion yields from galium beam can be increased by up to 3 orders of magnitude for metalic species in the presence of oxygen.

The presence of electronegative oxygen increases the probability that the sputtered atom or molecule can release an electron, thus becoming a positive secondary ion which can be observed.

Secondary electron



Secondary ion



Corroded crack in a steel pressure vessel

Ref.:M.W. Phaneuf / Micron 30 (1999) 277–288

FIB imaging - Topographic contrast

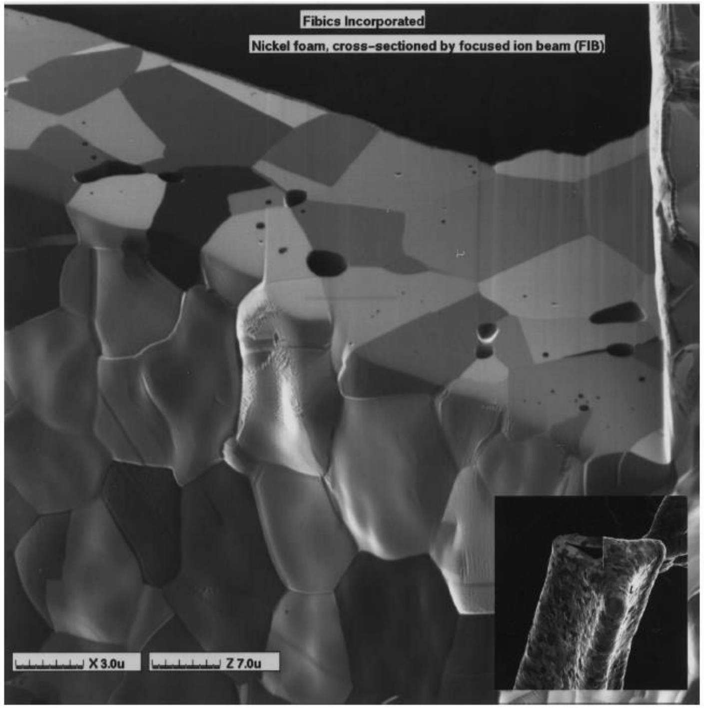


Fig. 1. FIB secondary electron mode image of a nickel foam 'strut' which forms a component of nickel-hydroxide-based batteries intended for automotive applications. One third of the tip of the strut has been sectioned in the FIB (inset) to expose internal detail. Both the sectioned and original surfaces have been imaged so as to illustrate the grain orientation contrast achievable in FIB secondary electron images, and the ability to reveal sub-micron voids and other fragile specimen features without the stress and potential damage involved in mechanical sectioning.

Topographic contrast is frequently overwhelmed by channeling contrast in certain material systems and geometries.

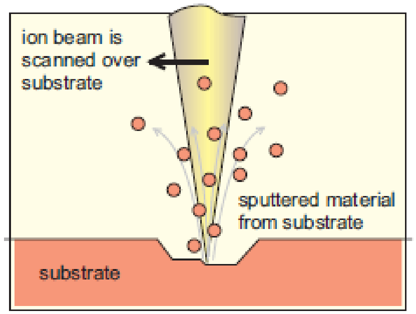
In general, topographic contrast in FIB has been explained in a similar manner to topographic contrast in SEM.

→Differences in signal as a function of the angle of incidence of the primary beam relative to specimen surface normal as the local inclination of the specimen surface varies.

Further study of topographic contrast is required to resolve differences in topographic contrast between secondary-ion and secondary-electron imaging in the FIB, and differences between secondary electron imaging in the FIB and in the SEM.

Ref.:M.W. Phaneuf / Micron 30 (1999) 277–288

Basic operating modes - Milling



Use of high ion current

By scanning the beam over the substrate, an arbitrary shape can be etched.

Etch rate depend on:

- Material
- Scanning type
- Redeposition
- Angle of incidence

Cleaning cs

Rectangle ...

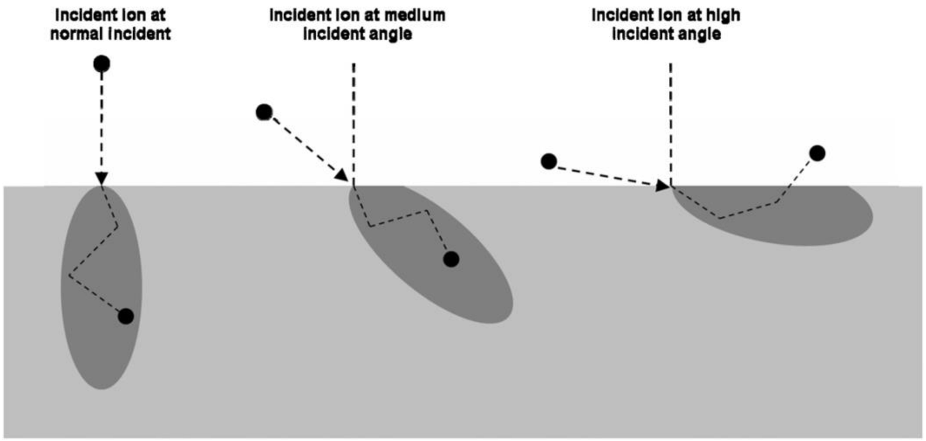
Material	Sputterrate $[\mu m^3/nC]$
Si	0.27
Thermal Oxide	0.24
TEOS	0.24
Al	0.3
Al2O3	0.08
GaAs	0.61
InP	1.2
Au	1.5
TiN	0.15
Si3N4	0.2
C	0.18
Ti	0.37
Cr	0.1
Fe	0.29
Ni	0.14
Cu	0.25
Mo	0.12
Ta	0.32
W	0.12
MgO	0.15
TiO	0.15
Fe2O3	0.25
Pt	0.23
PMMA	0.4

Ref.: S. Reyntjens and R. Puers 2001 J. Micromech. Microeng. ***11*** *287*

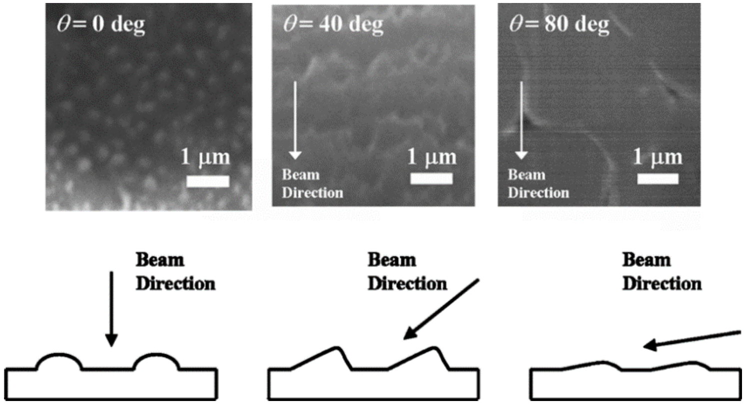
Ref.: Marco Cantoni

Basic operating modes - Milling

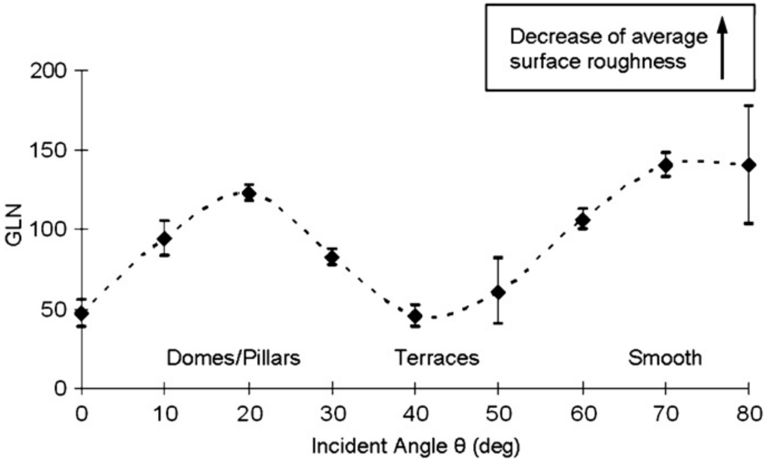
- Ion sputtering yield (*Y*) depende on *incidence angle* (*θ*)
- *A* larger *Y is achieved by increasing the θ from* normal incidence.
- The maximum sputtering yield is typically achieved at *θ* ≈ *80◦, and Y dramatically approaches zero* from 80◦ to 90◦



Schematic diagram of the effective region of ion track at different incident angles

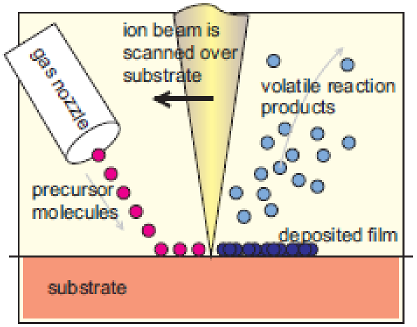


Experiment in ice



Ref.: Jing Fu in J. Micromech. Microeng. 18 (2008)

Basic operating modes -Deposition



Chemical interaction:

- Deposition
  - Principal is of CVD (chemical vapour deposition) with better resolution and lower deposition rate.
  - Commercially available:
    - Pt, W, SiO_2 , TMCTS (tetramethyl-cyclotetrasiloxane), O_2 or H_2O

- The precursor gases are sprayed on the surface by a fine needle, where they absorb →the incending ion beam decomposes the adsorbed precursor gases than the volatile reaction products desorb from the surface while the desired reaction products remain fixed on the surfaces as a thin film.

- The smallest feature that can be deposited are of the order of 100nm (lateral) and the minimal thinckness is about 10nm. Aspect ration between 5 and 10 are obtained.

Ref.: S. Reyntjens and R. Puers 2001 J. Micromech. Microeng. ***11*** *287*

Ref.: Marco Cantoni

Basic operating modes -Deposition

E-beam deposition: ↑Deposition by lower KV and higher beam current

The ion beam deposition is much faster than deposition with the electron beam. This is primarily due to the ion beam producing many more secondary electrons near the surface of the sample compared to the electron beam.

for standard accelerating voltages (30 kV for the ion beam and 5 kV for the electron beam) at a given beam current, the electron beam deposition is ~10 times slower than the ion beam when depositing platinum for example.

W deposition is in general able to fulfill the same use cases at Pt deposition, but for electrical applications where a deposit with good conductivity is required, W deposition is preferred over Pt deposition. However, the W deposition rate is slower . The W deposition is harder than Pt so it is useful for making mechanical structures such as probing tips and for using as the protective layer on very heterogeneous materials before cross sectioning to reduce the curtaining effect. W deposition also has a lower proportion of carbon in the final deposit when compared with Pt deposition.

Basic operating modes -Deposition

The deposition rate of a material depends on a range of parameters.

- Distance to the GIS needle
- Sample orientation

fixed

- Ion beam current,
- Pattern area,
- Pattern speed (dwell time and overlap)
- Refresh time (time allowed for each point to replenish with adsorbed gas)

varied by the operator

1 µm thickness in 300 seconds

Figure 1 Deposition Efficiency for Platinum

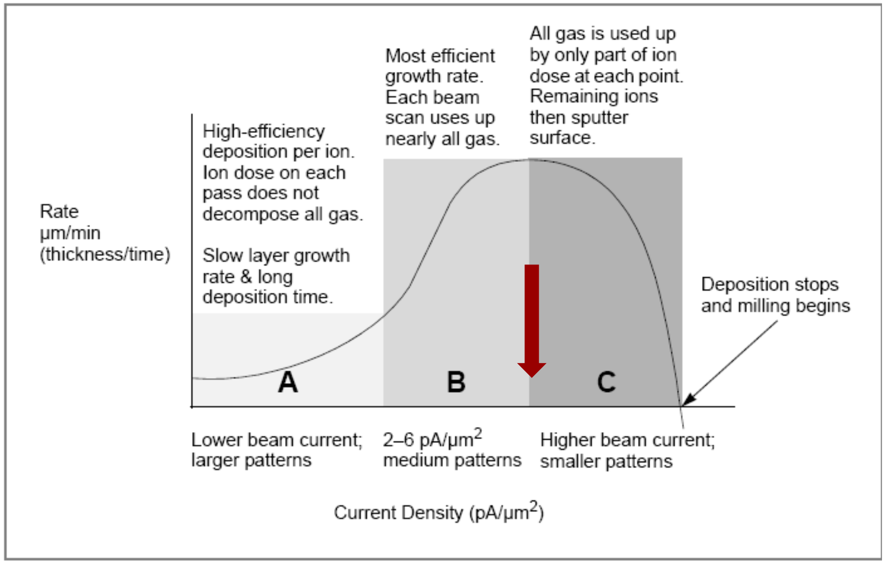
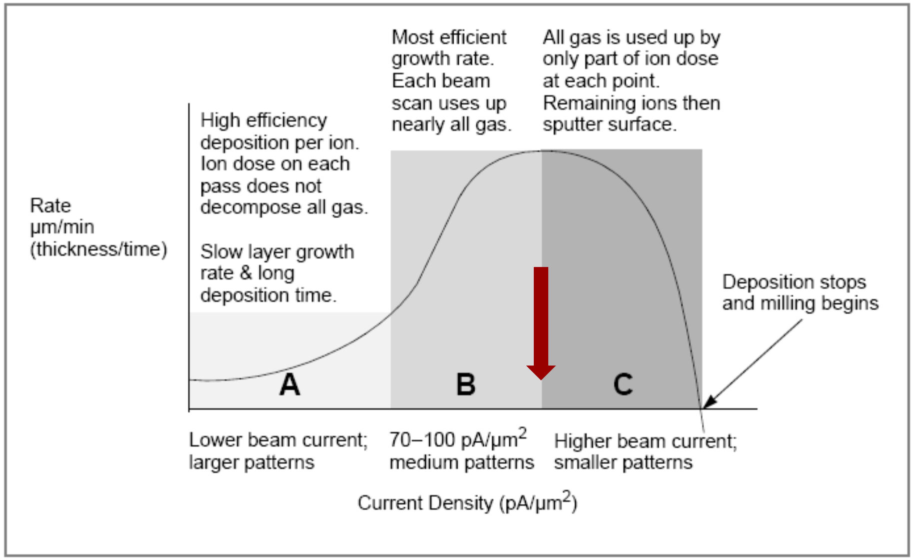
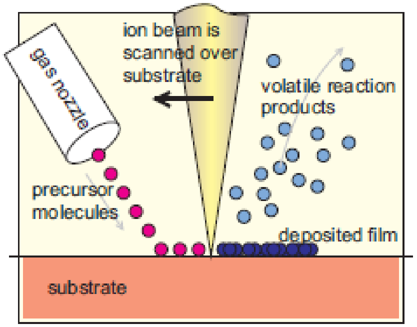


Figure 1 Deposition Efficiency for Tungsten



Ref.: http://www.fei.com/uploadedFiles/Documents/Content/AN-GIS_Beam_Chemistries-AN-web-2010.pdf

Basic operating modes – Enhanced Etching



Chemical interaction:

- Enhanced etching is used
  - To speed up milling
  - to increase selectivity toward different materials
- Etching gas is introduced to chemically facilitate the removal of reaction products.

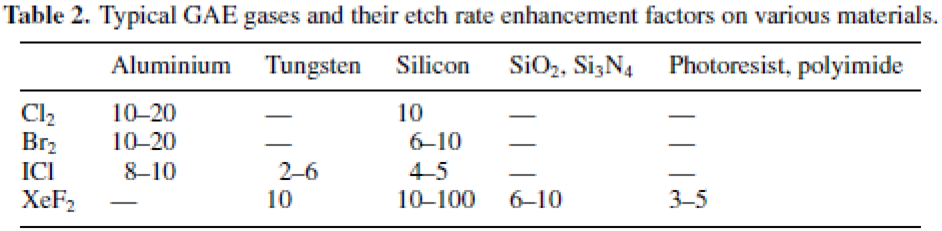


Table 2. Typical GAE gases and their etch rate enhancement factors on various materials.

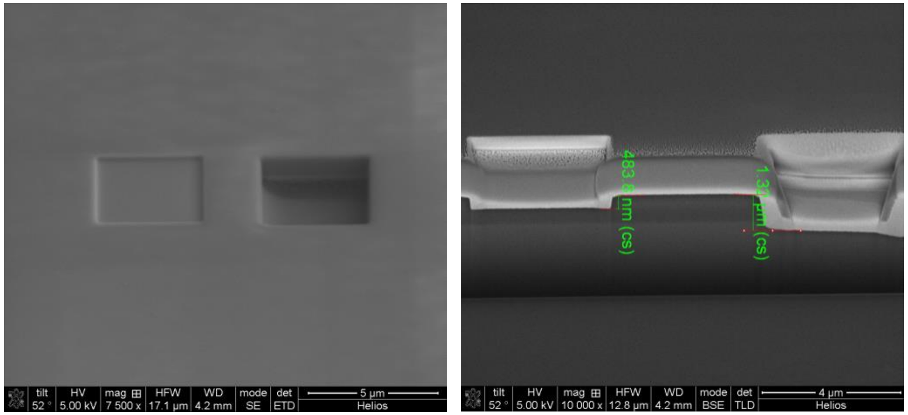
	Aluminium	Tungsten	Silicon	SiO_2, Si_3N_4	Photoresist, polyimide
Cl_2	10–20	—	10	—	—
Br_2	10–20	—	6–10	—	—
ICl	8–10	2–6	4–5	—	—
XeF_2	—	10	10–100	6–10	3–5

Ref.: S. Reyntjens and R. Puers 2001 J. Micromech. Microeng. ***11*** *287*

Ref.: Marco Cantoni

Enhanced etching

- Delineation Etch is used for the etching of integrated circuit (IC) cross sections →Good for Oxide layers, Insulators and Nitrides
- Insulator Enhanced Etch (IEE) is used to rapidly etch films of many types of insulating material with the assistance of xenon difluoride (XeF2), a halogen compound. IEE removes insulating materials preferentially and leaves the conductor.(speeds up maching of glass, nitrides and other isulators.)
- Selective Carbon Mill (SCM) uses water vapor to increase the removal rate of carbon-containing materials such as polyimide, PMMA (polymethyl methacrylate), and diamond. In addition, SCM decreases the removal rate of other materials (e.g., Si and Al). This effectively increases the etch selectivity of polymers over these other materials.



Use of IEE in SiO_2

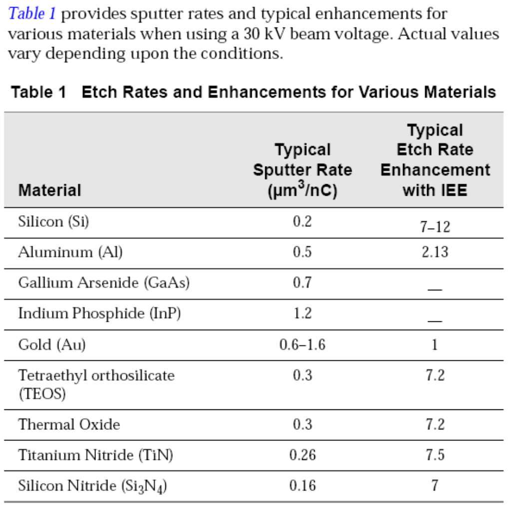


Table 1 provides sputter rates and typical enhancements for various materials when using a 30 kV beam voltage. Actual values vary depending upon the conditions.

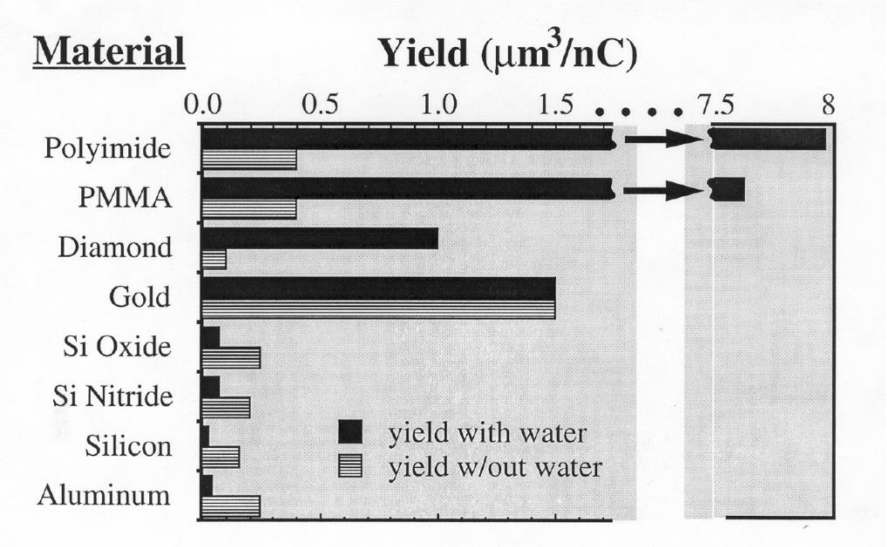
Table 1 Etch Rates and Enhancements for Various Materials

Material	Typical Sputter Rate ($\mu m^3/nC$)	Typical Etch Rate Enhancement with IEE
Silicon (Si)	0.2	7–12
Aluminum (Al)	0.5	2.13
Gallium Arsenide (GaAs)	0.7	—
Indium Phosphide (InP)	1.2	—
Gold (Au)	0.6–1.6	1
Tetraethyl orthosilicate (TEOS)	0.3	7.2
Thermal Oxide	0.3	7.2
Titanium Nitride (TiN)	0.26	7.5
Silicon Nitride (Si_3N_4)	0.16	7

Others available GISes

- Enhanced Etch etches metals and to some extent silicon and some nitrides faster. Helps to prevent re-deposition and enables higher aspect ration holes. Uses halogens.
- Insulator deposition used to produce insulating coating
- Carbon deposition
- Gold deposition

FIB Ion Milling Yield of Various Material with and without Water Vapor



T.J. Stark, et. al. J. Vac. Sci. Technol. **B13**, 2565 (1995)

Hardware configuration CEN – Quanta 3D

Scanning electron microscope (W- filament SEM)

- observation microstructure

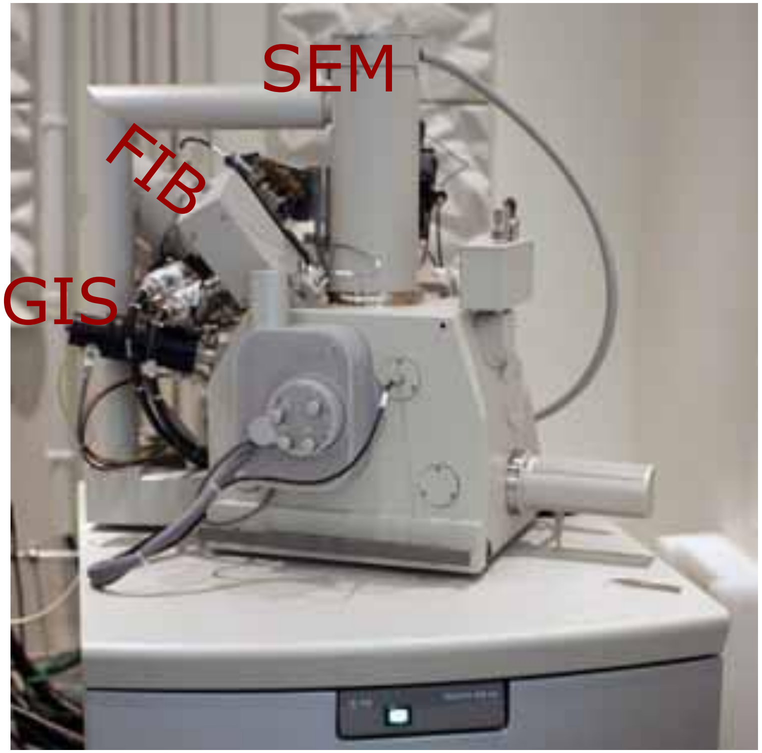
FIB = focused ion beam

- 30KV, 15KV, 5KV beam energies
- Second electron detector and backscattered electron detector
- STEM detector
- High and low vacuum mode
- CDEM- Charge neutralizer

2 Gas Injection System:

- deposition of W and Pt films from organic precursor gasses

In-situ manipulation of specimens using Omniprobe manipulator



Hardware configuration CEN – Helios 600

Scanning electron microscope (FEGSEM)

- observation microstructure (high resolution)

FIB = focused ion beam

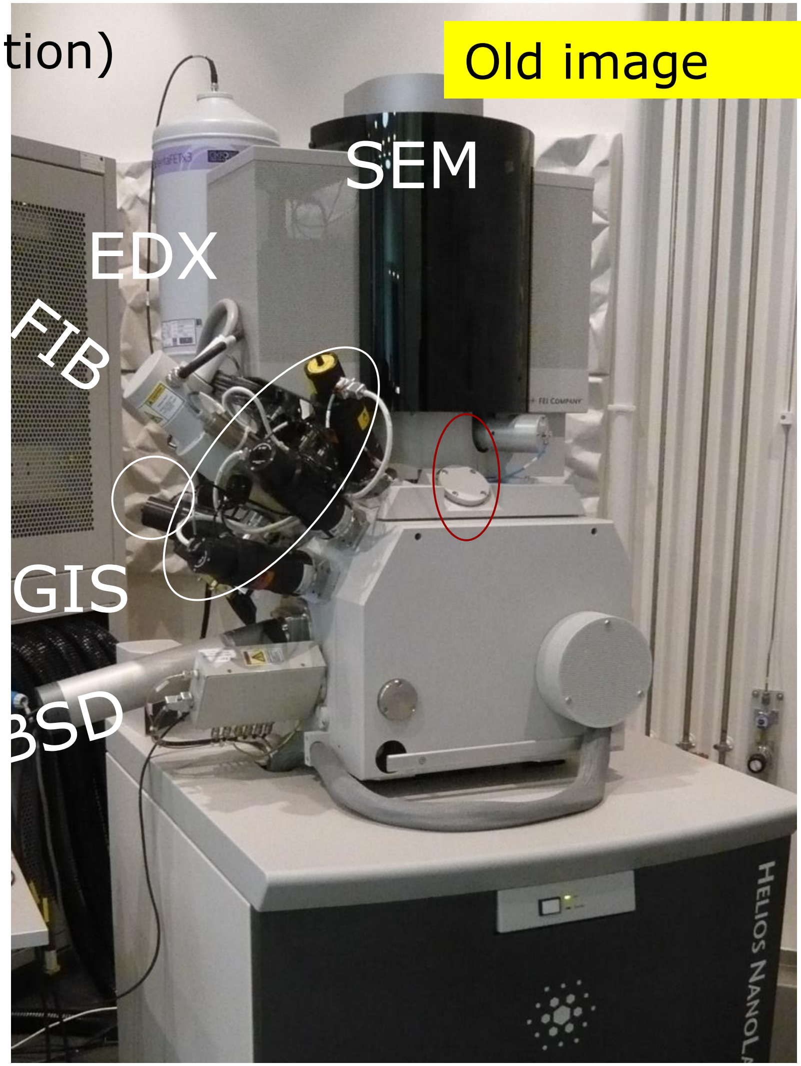
- 30KV -500V beam energies
- Second electron detector and backscattered electron detector
- Thru-the-Lens detector
- CDEM- Charge neutralizer

5 Gas Injection System:

- deposition of W and Pt films from organic precursor gasses
- use reactive gases XeF2, water vapor and TFA

Quantitative images with EBSD and EDX

- quantitative characterisation of microstructure



Old image

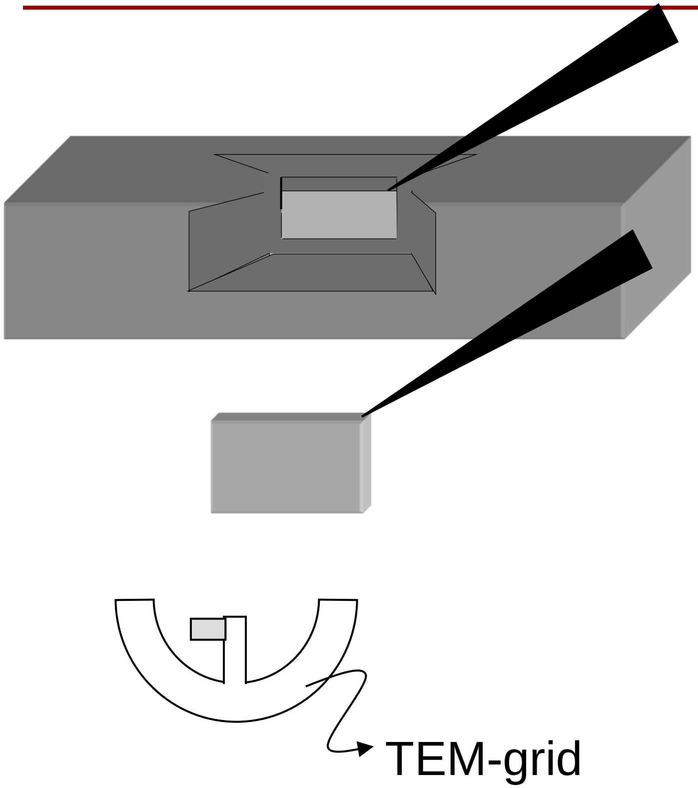
In-situ manipulation of specimens using Omniprobe manipulator

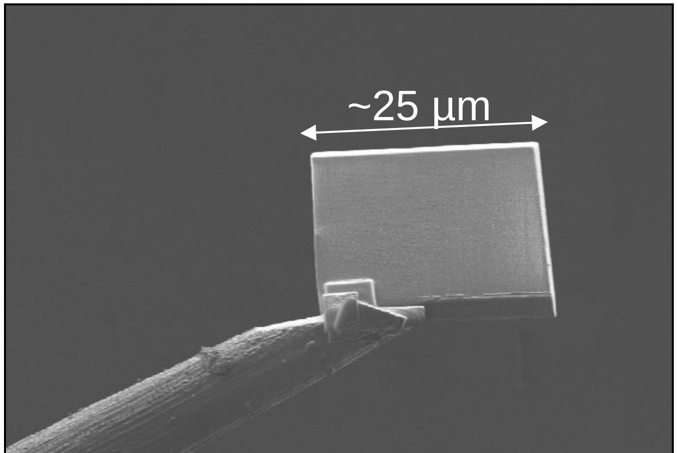
- Principle of Focused Ion Beam
  - How does it works
  - FIB at CEN
- Basic Applications
- TEM sample preparation
  - Lift out / no lift out
  - single beam
  - tricks and tips (others)
- FIB for 3D microstructure characterization
  - 3D slice and View
  - 3D EDS
  - 3D EBSD
- Damage
- Other Ions sources

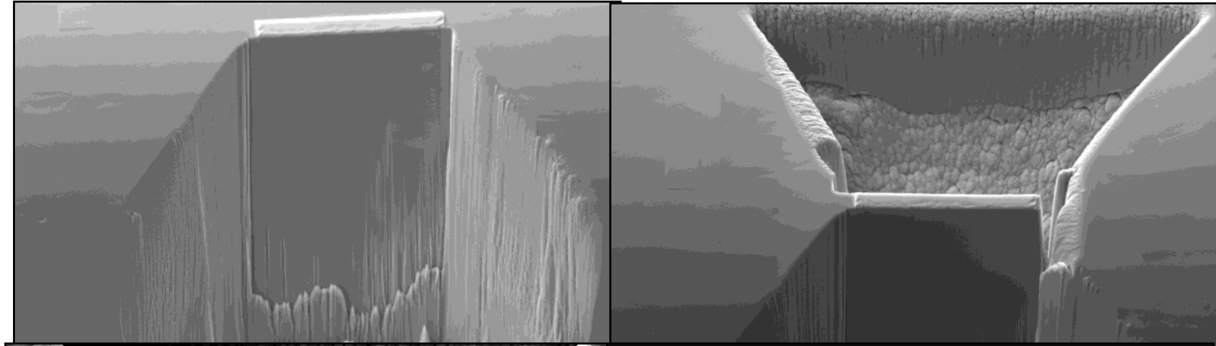
Basic applications

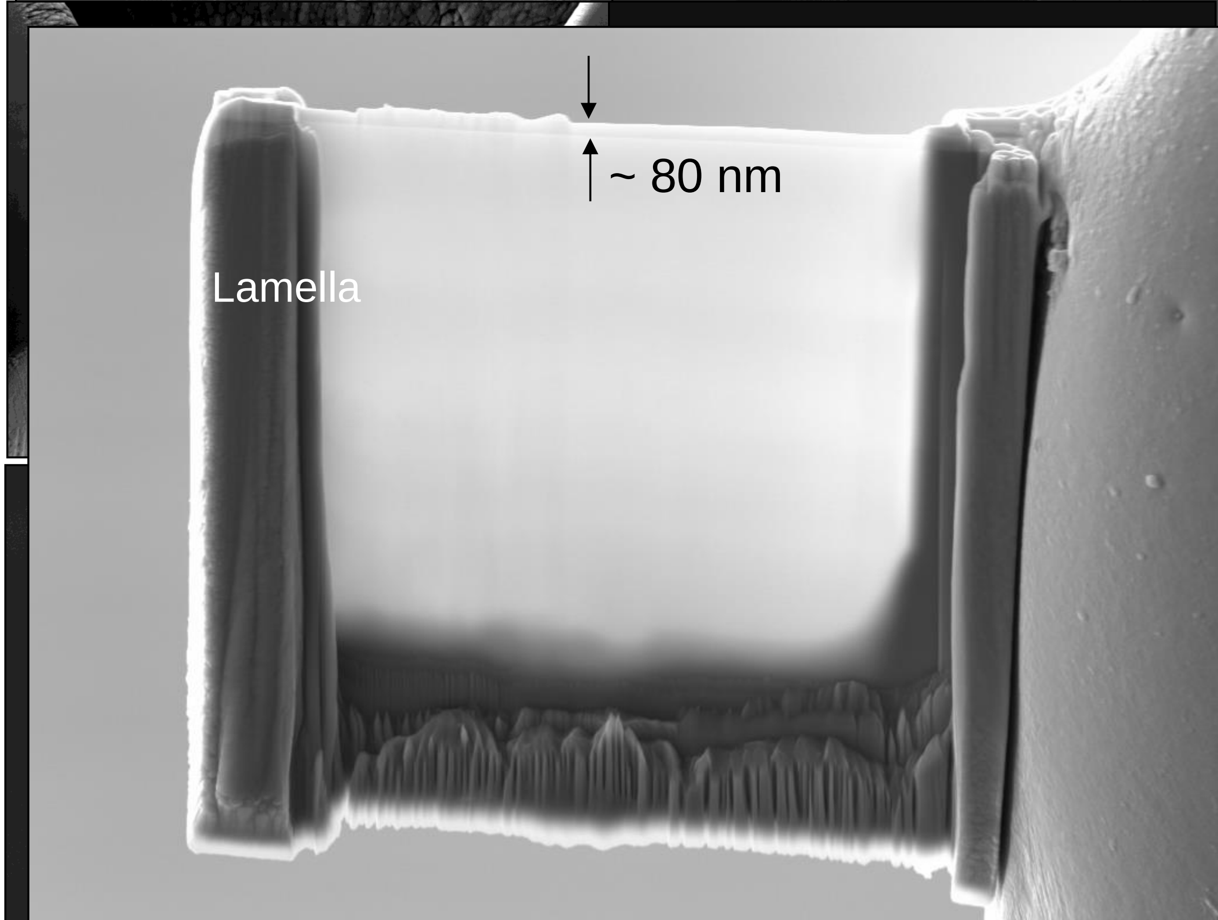
- Direct device fabrication or lithography instruments
- Sectioning for failure analysis
- Mask repair
- Micromachining
- Nanofabricated structures
- TEM sample preparation
- Atom Probe sample preparation
- Manufacture of AFM tips
- 3D microstructure characterization

TEM sample preparation – Lift out

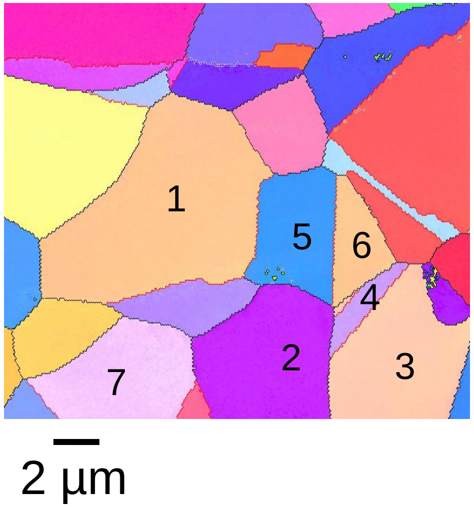


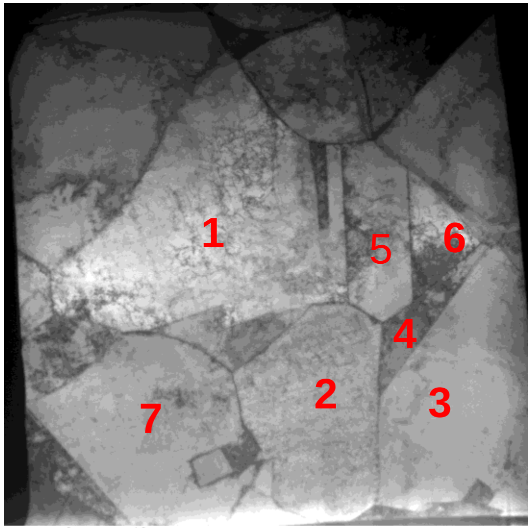






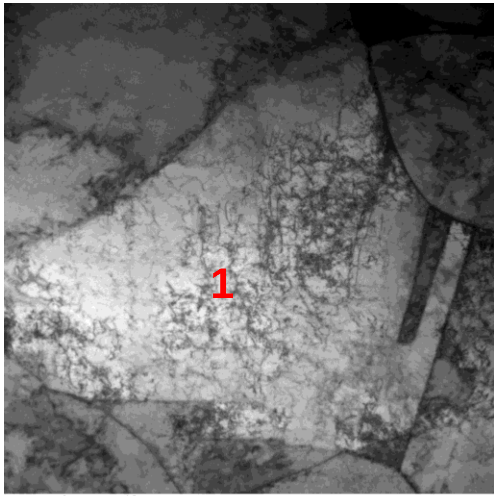
TEM sample preparation – Lift out





TWIPUnverformt.001.tif
Overview thin foil from FIB
14:29 06/01/07
TEM Mode: Imaging

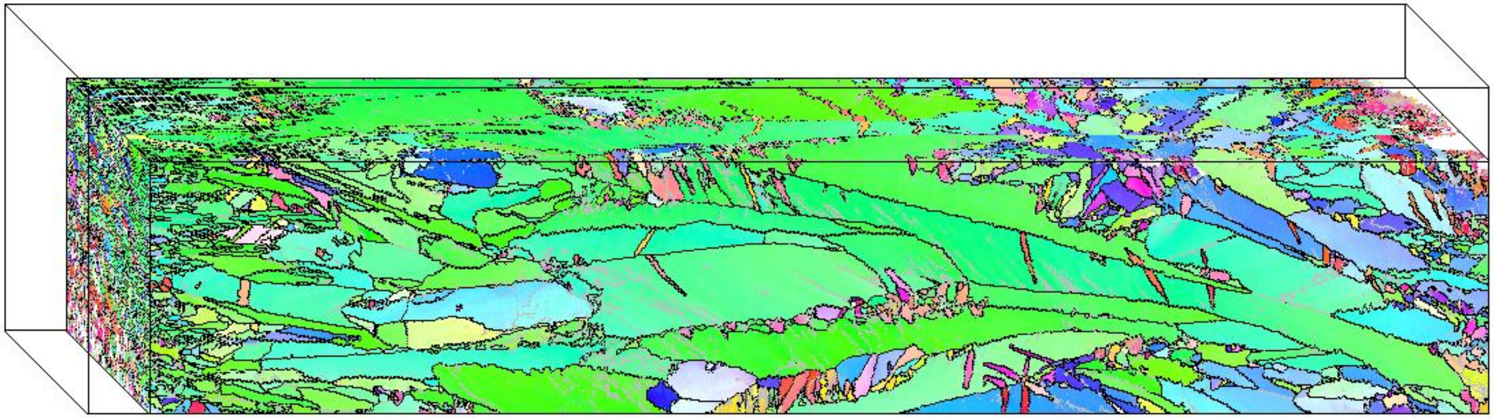
2 microns
HV=200kV
Direct Mag: 4400x
X: 141.102 Y: -1.007 T:0

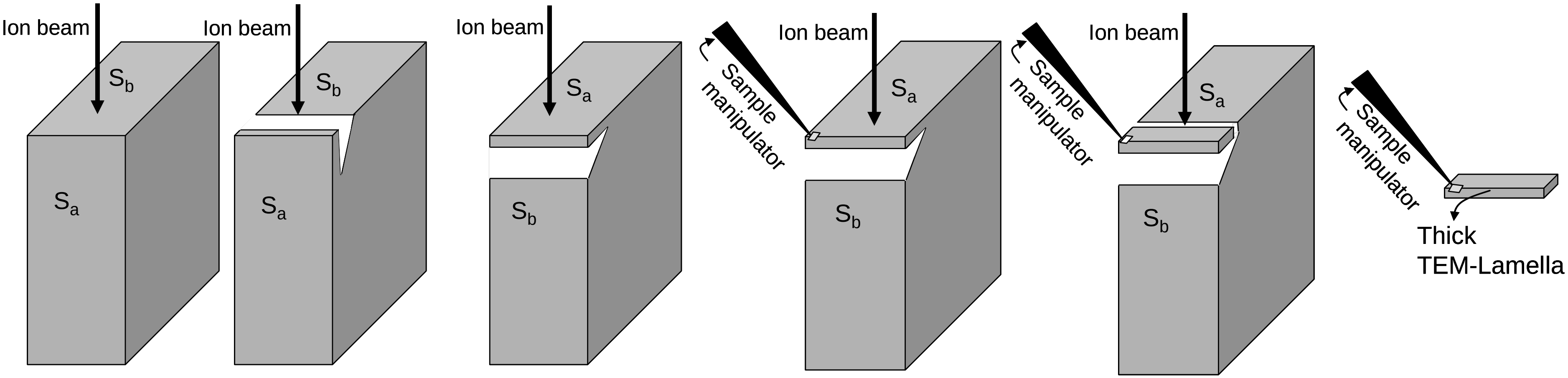


TWIPUnverformt.002.tif
one grain with individual
dislocations and a twin
14:37 06/01/07
TEM Mode: Imaging

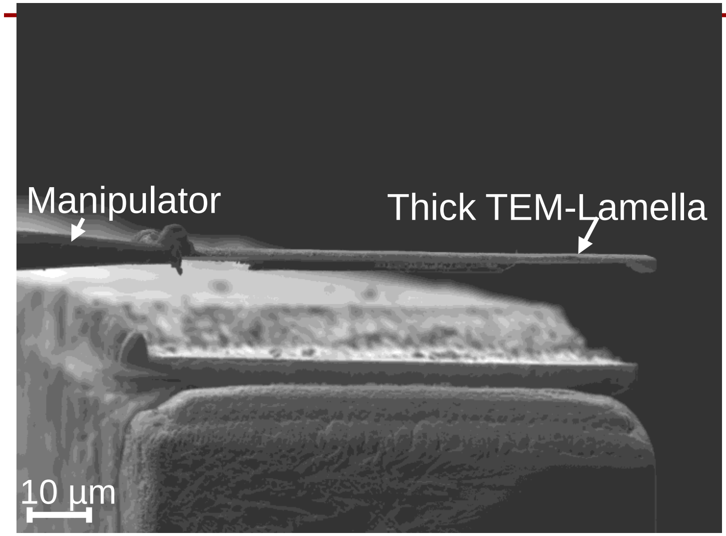
2 microns
HV=200kV
Direct Mag: 7800x
X: 139.214 Y: -.5 T:0

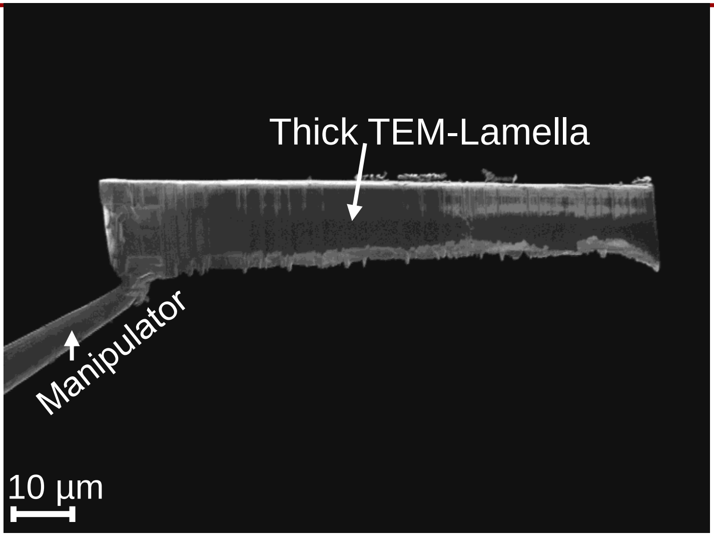
TEM sample preparation – Lift out

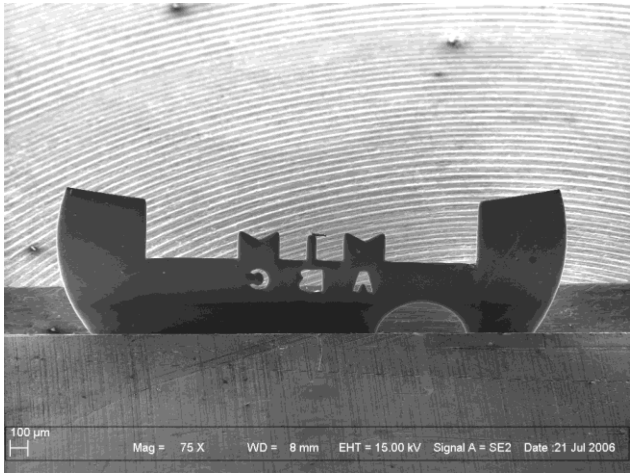


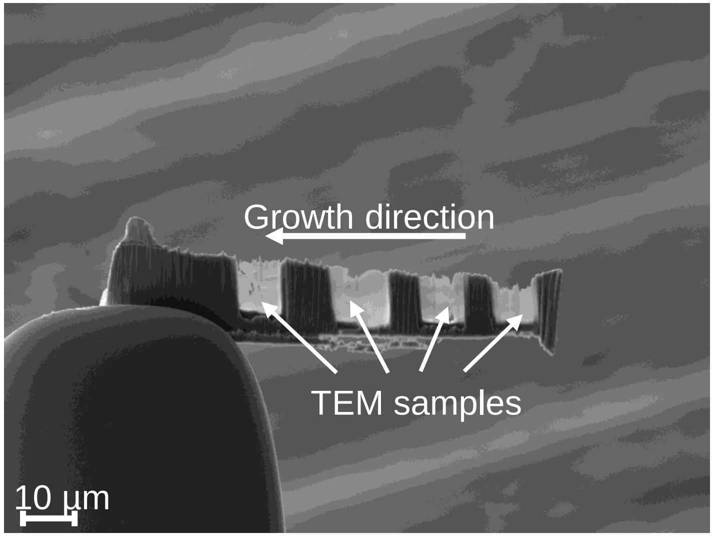


TEM sample preparation – Lift out









TEM sample preparation – H-bar

✓specimen must first be mechanically polished as thin as possible before the sample is placed in the FIB for milling.

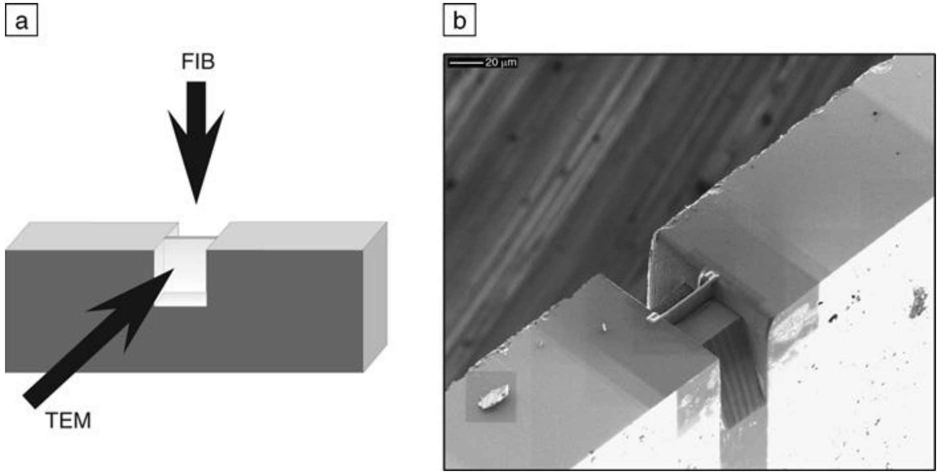
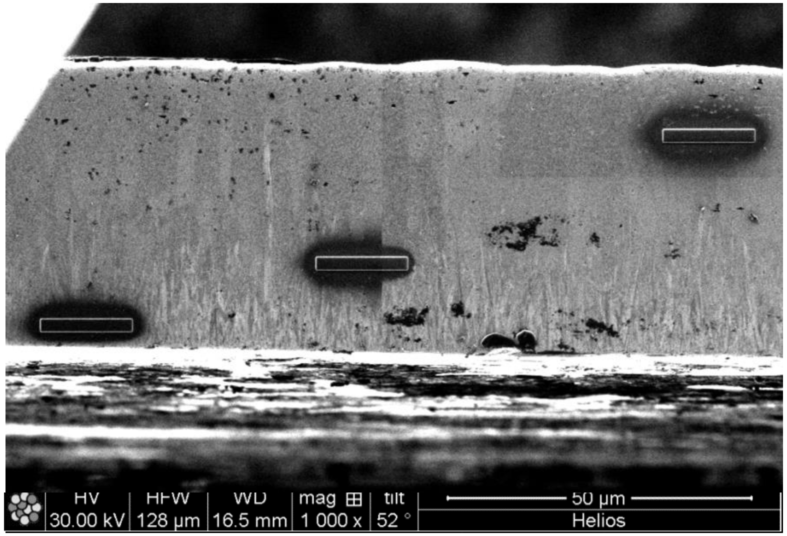


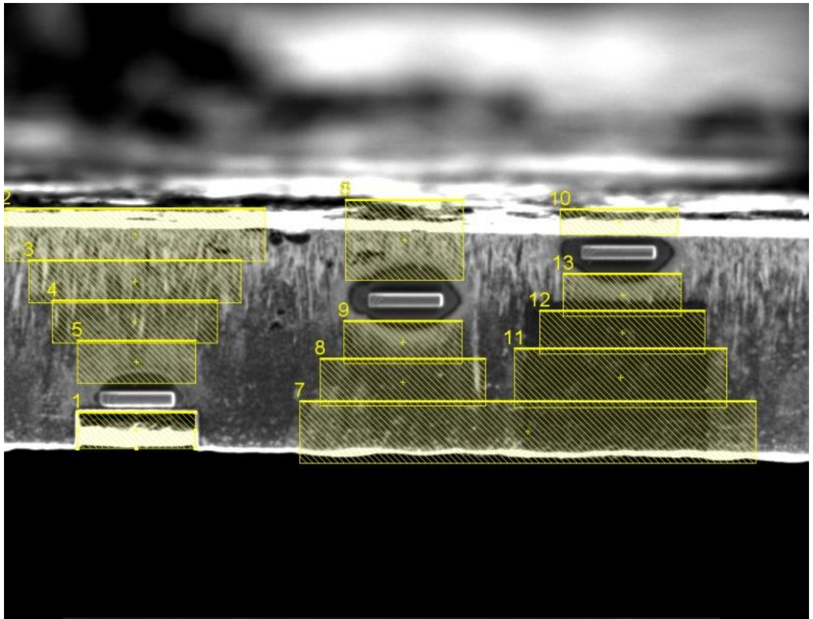
Figure 1. (a) Schematic illustration of the H-bar focused ion beam (FIB) technique. Material on opposite sides of a region of interest is FIB-milled until it is electron-transparent.

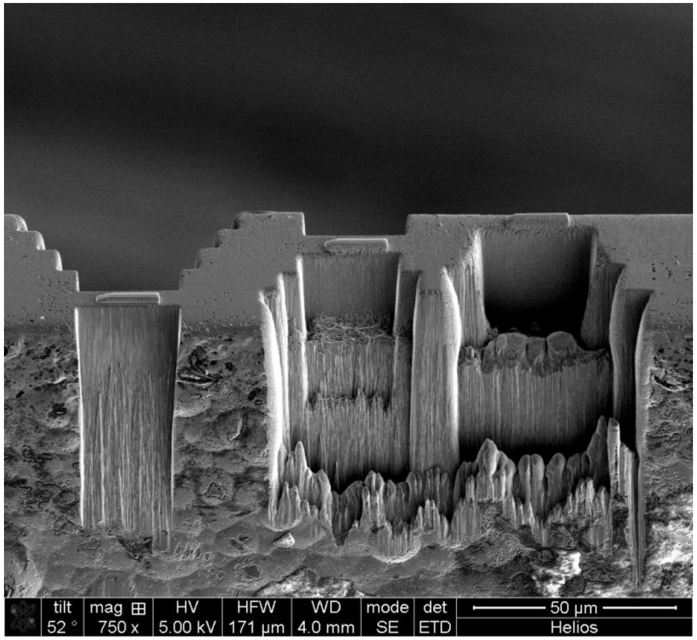
(b) Scanning electron microscopy (SEM) image showing the top-down view of an H-bar FIB specimen in progress. The metal sample was mechanically thinned to ~40 mm and glued to a transmission electron microscope (TEM) half-grid. (Figure courtesy of Richard Young, FEI Co.

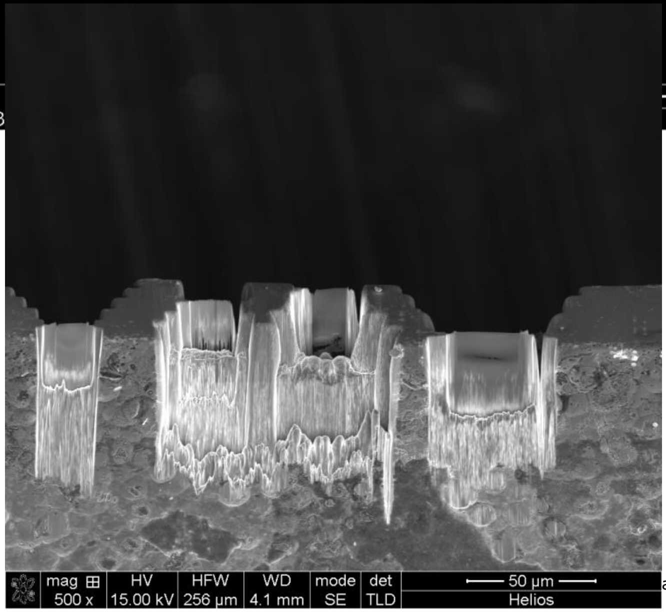
Ref.: Meyer MRS BULLETIN • VOLUME 32 • MAY 2007 •www/mrs.org/bulletin

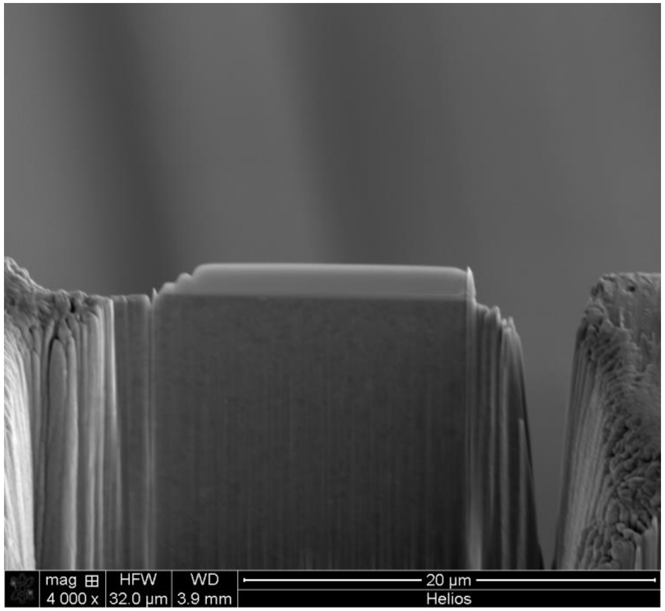
TEM sample preparation – no lift out

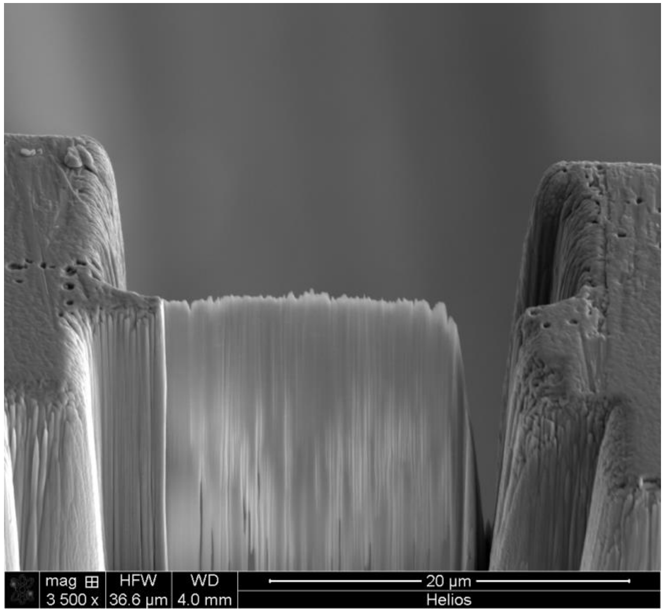


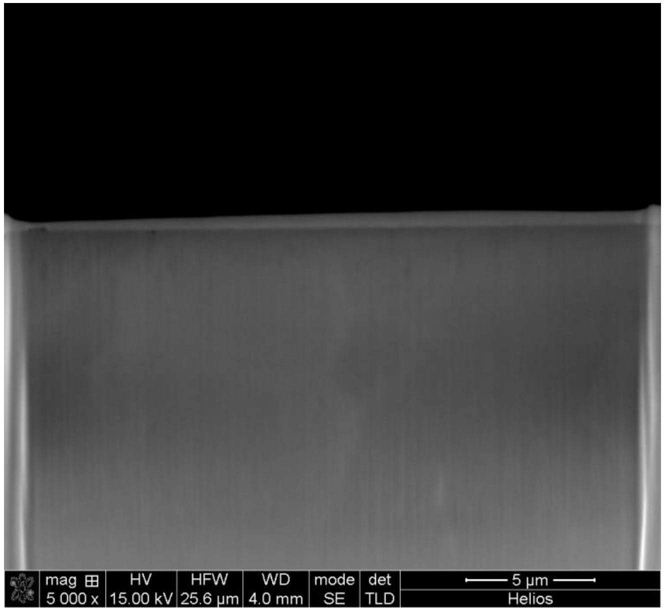


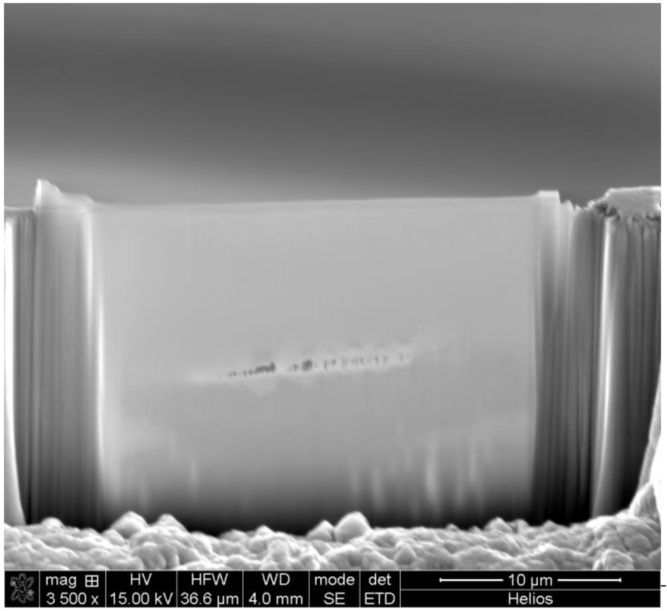





mag ⊞ 4 000 x
HFW 32.0 µm
WD 3.9 mm
20 µm
Helios

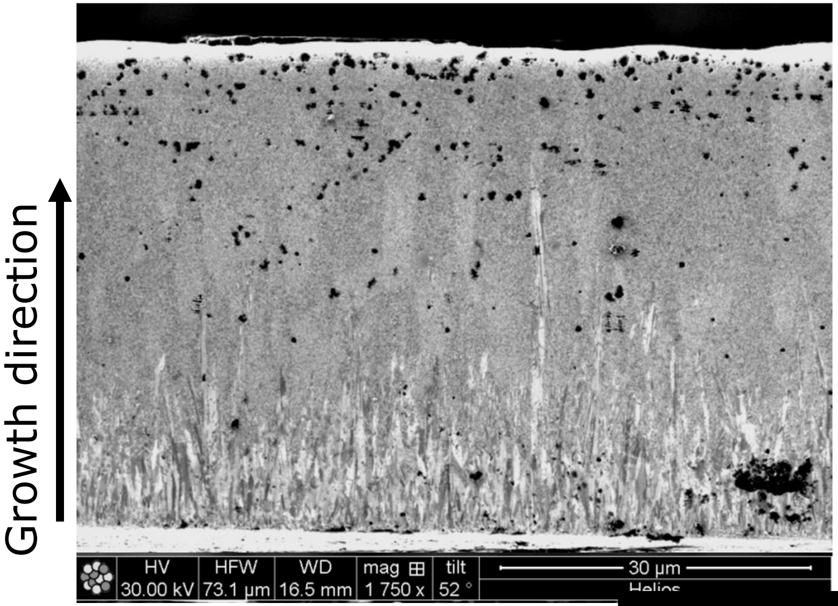

mag ⊞ 3 500 x
HFW 36.6 µm
WD 4.0 mm
20 µm
Helios

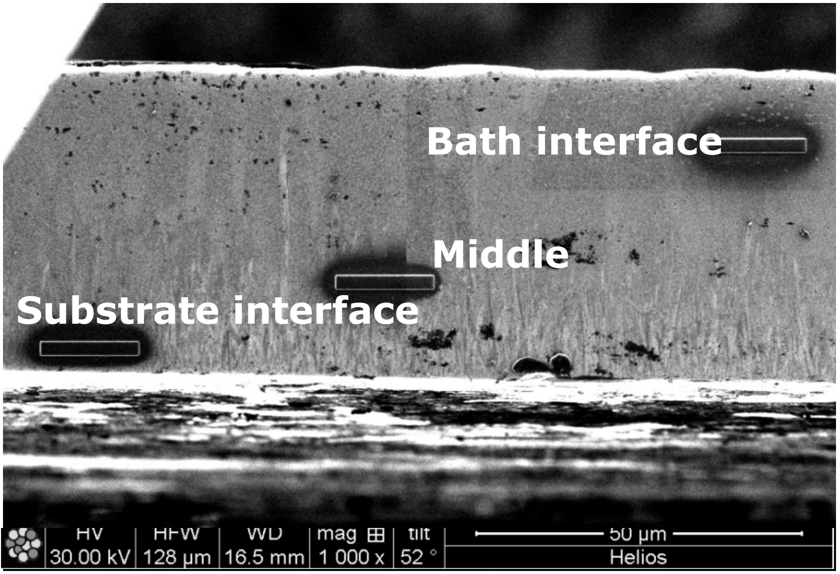

mag ⊞ 5 000 x
HV 15.00 kV
HFW 25.6 µm
WD 4.0 mm
mode SE
det TLD
5 µm
Helios

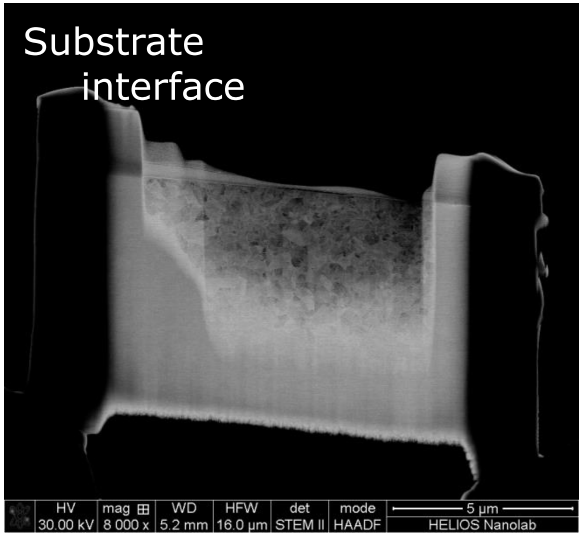

mag ⊞ 3 500 x
HV 15.00 kV
HFW 36.6 µm
WD 4.0 mm
mode SE
det ETD
10 µm
Helios

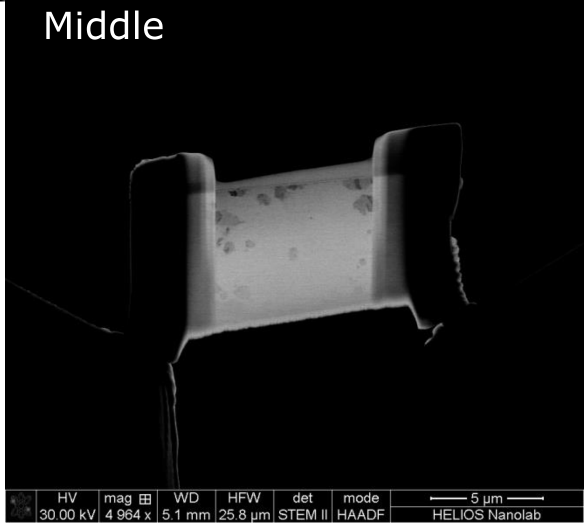
TEM sample preparation – Lift out

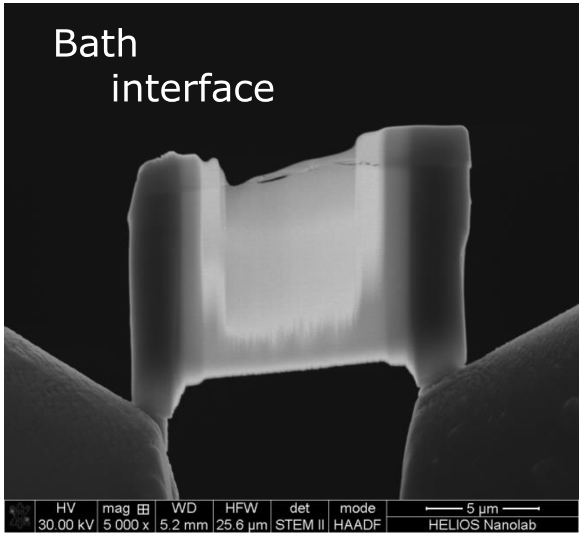
Bath containing 0.04g/l of saccharin











Samples preparation: Steve Reyntjens

TEM sample preparation – Ex-situ lift out

- Freestanding site-specific region is FIB milled to electron transparency,
- The thin lamella is removed from its trench with a micromanipulator under an optical microscope.
- The specimen attaches to the micromanipulator tip via electrostatic forces and can be removed easily from its trench.
- Specimens can be transferred to carbon-coated TEM grids, form var-coated grids, holey carbon grids, or directly to the surface of small mesh grids.

TEM sample preparation – plan-view specimen

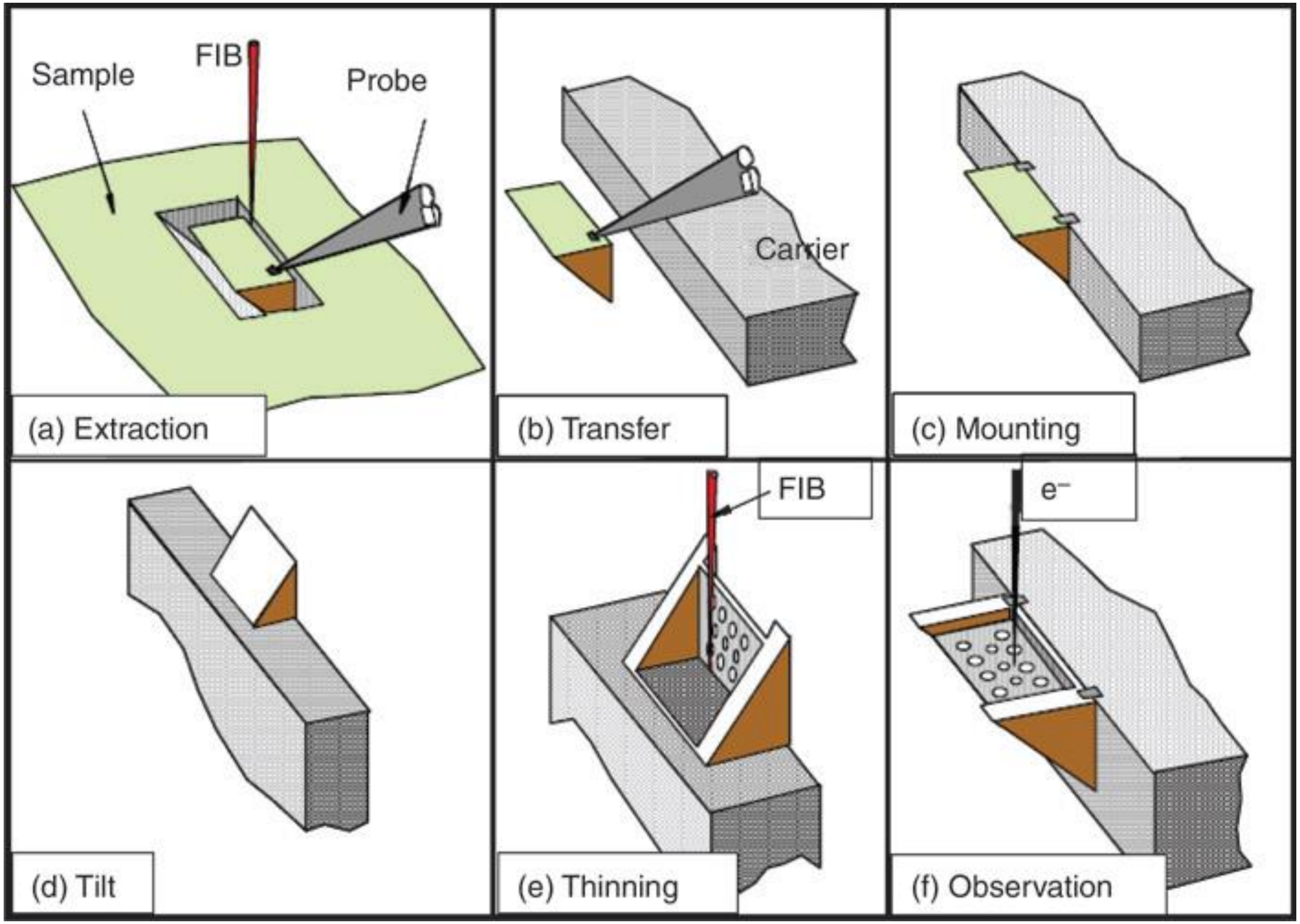
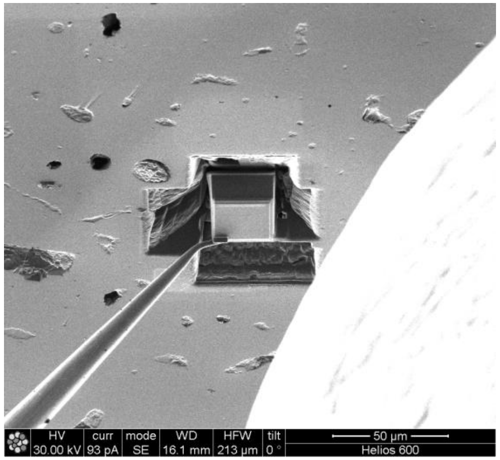
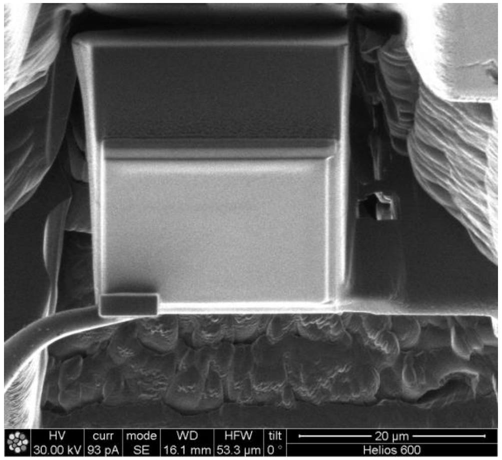


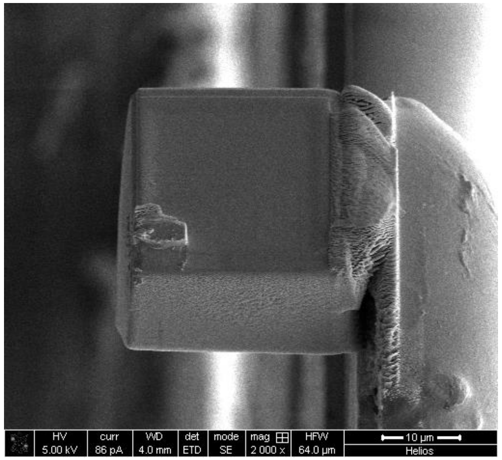
Figure 3. Method to prepare a plan-view specimen from a specific site based on the microsampling technique (see text for details).

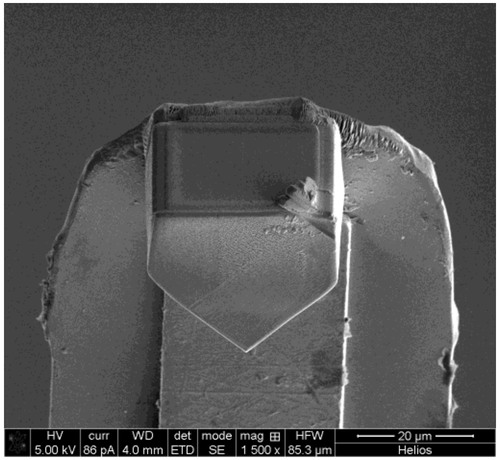
Ref.: Meyer MRS BULLETIN • VOLUME 32 • MAY 2007 •www/mrs.org/bulletin

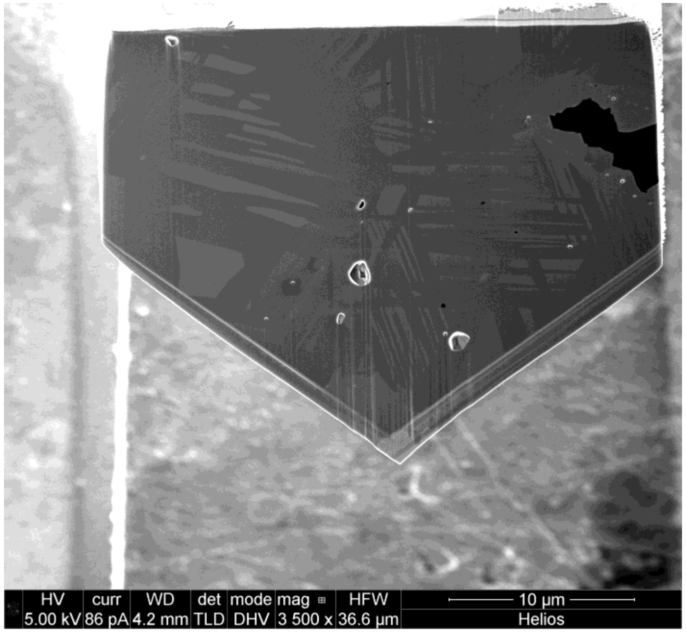
Block– Lift out











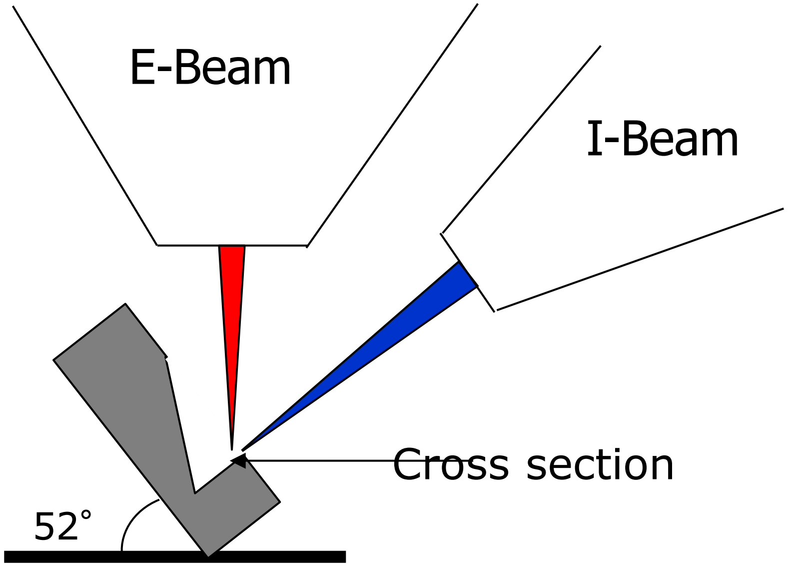
Samples preparation: A. Nicole MacDonald

FIB-SEM: Slice and view

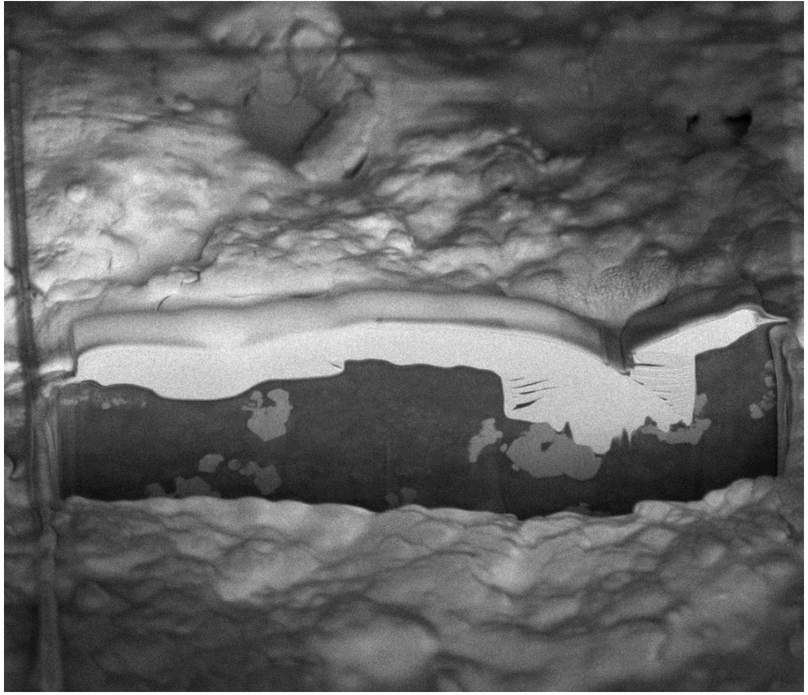
Cutting the material — FIB (Ion milling)

↓

Recording the structure — BSE images

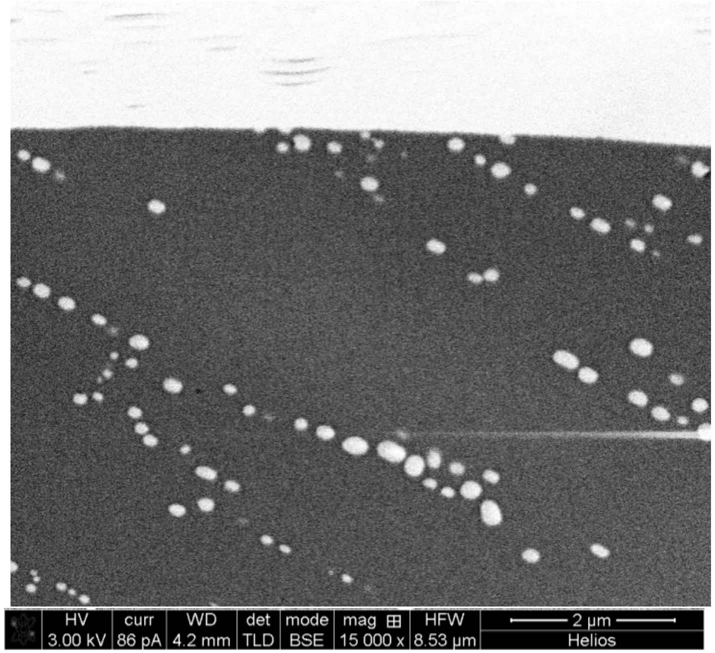


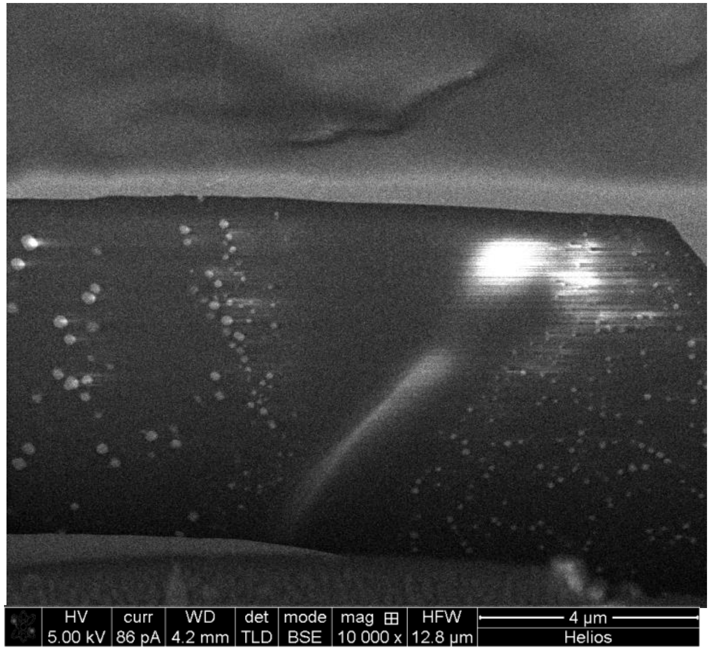
Slice and view in polymer at RT

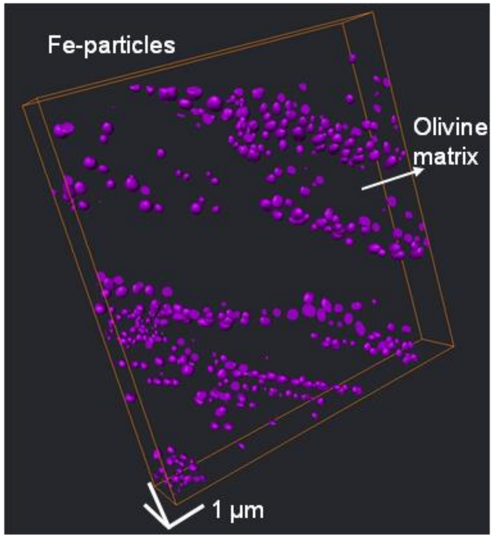


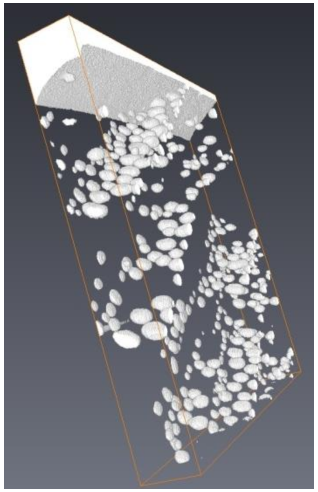
- No stage movement
- no charge neutralization
- Use of gas to increase milling rate: <u>Selective Carbon Mill</u> (water vapor) to increase the removal rate of carbon-containing materials

FIB-SEM: Slice and view

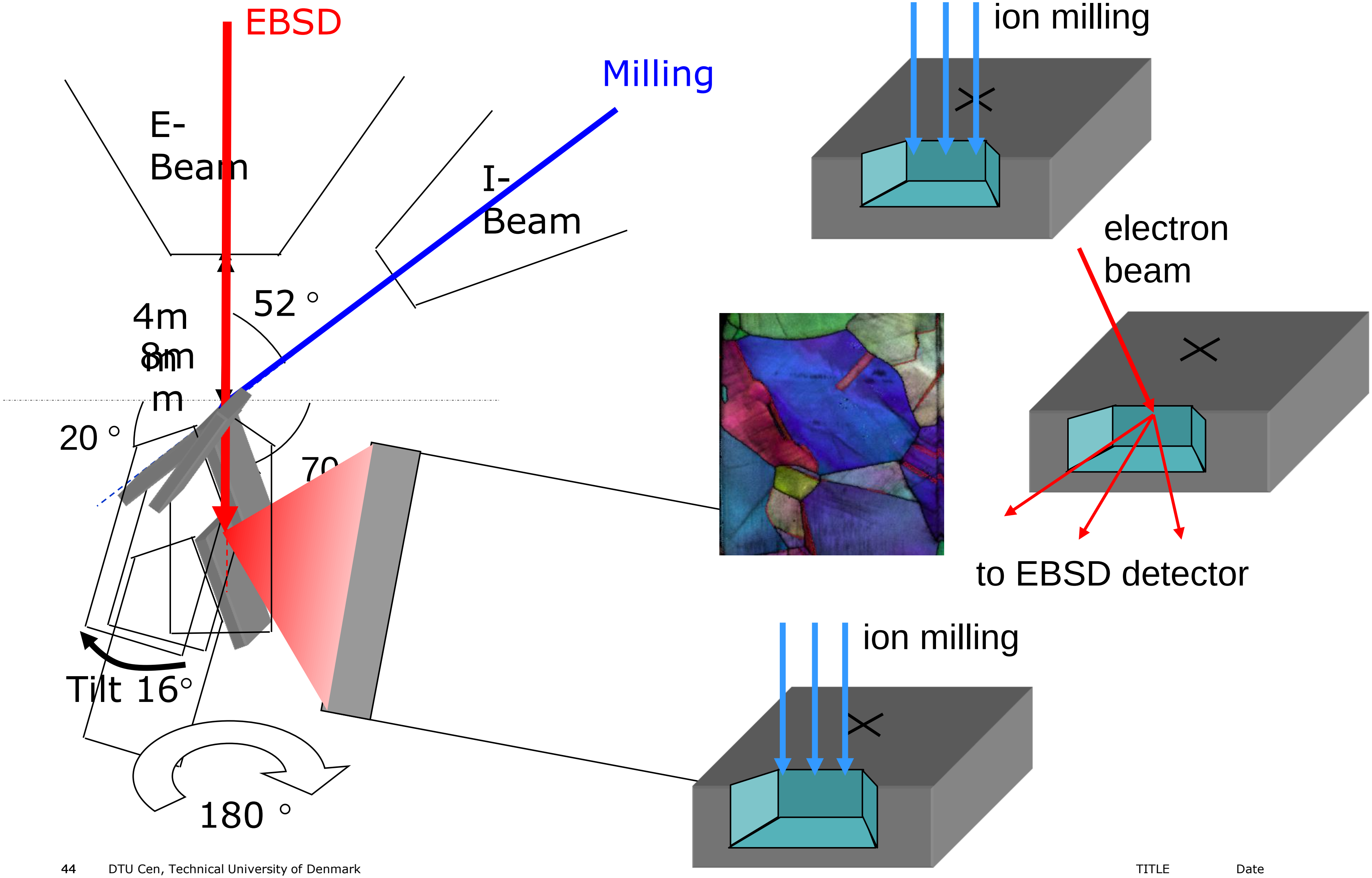




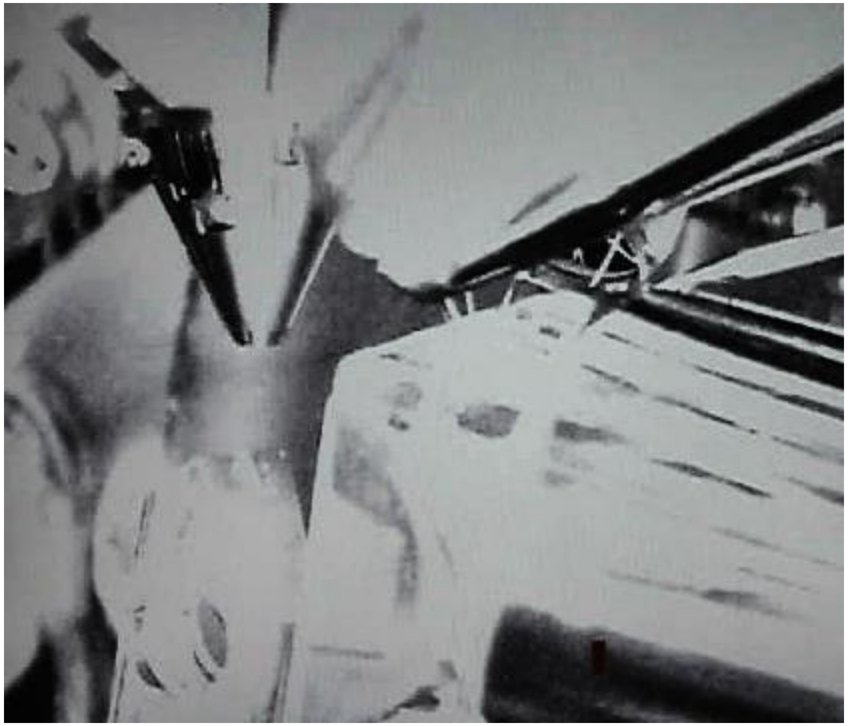




“Rotation” set-up: Helios



“Rotation” set-up: Helios

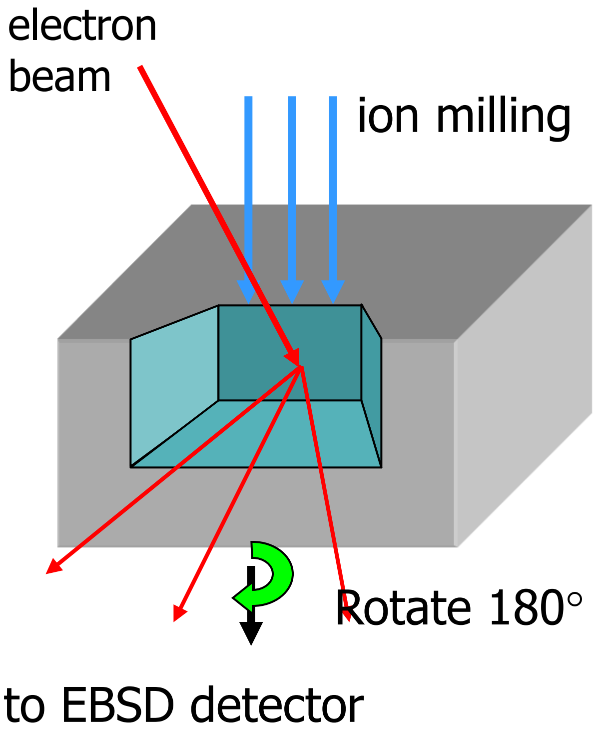


Movements:

- rotation 180°
- x and y movements
- z movement 4 to 8 mm WD
- tilt (in case the sample is not perfect align with sample holder)

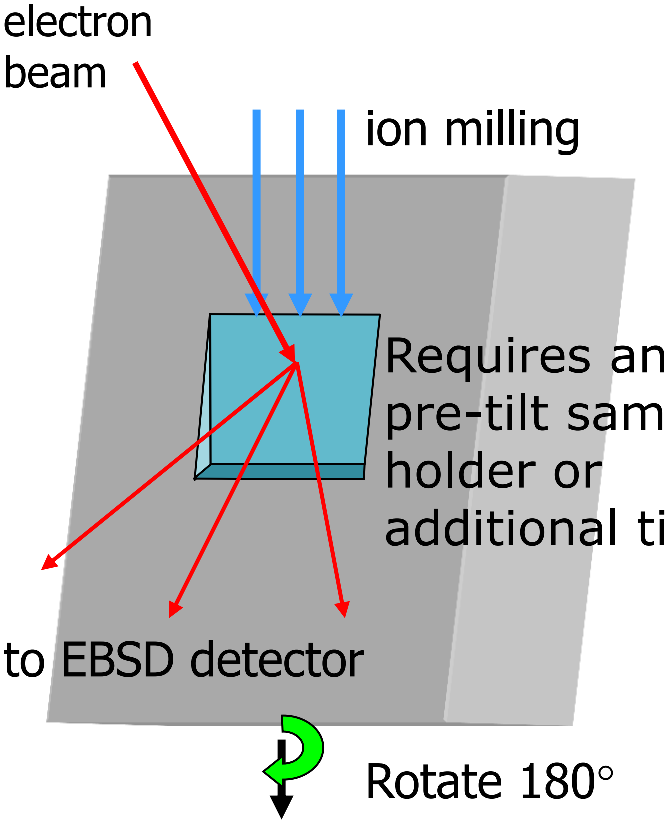
Milling strategy (rotation set-up)

milling strategy:
grazing-incidence edge-milling



feature has to be at edge

milling strategy:
low-incidence surface-milling



Requires another pre-tilt sample holder or additional tilt

large milling areas required to avoid shadowing of EBSD

Damage

In semiconductor materials, the thickness of the amorphous layer formed on the FIB-prepared sample surfaces is nearly proportional to:

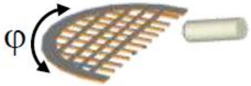
- the range of Ga ion implantation,which in turn is roughly proportional to the primary energy of the Ga ions.
- The reduction of amorphous layer formation in a sidewall of Si as a function of Ga energy
- For ion energies of 30 keV, 5 keV, and 2 keV, the observed sidewall damage is ~22 nm, 2.5 nm, and 0.5–1.5 nm, respectively.

Alternatively, low-energy ion milling with a broad Ar ion beam can be used to remove damage layers created by the FIB during lamellae formation and also to further reduce the specimen thickness. Special ion polishers are in development that will enable milling to a controlled final specimen thickness.

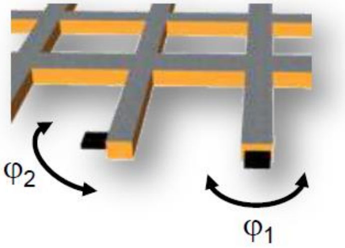
Parameters to be Optimized

- **Ion energy** ↓ - sputtering rate ↓ and bombardment induced damage ↓.
- **Milling time**.
- **Angle of incident ion beam (θ)** ↑ - sputtering rate ↑, bombardment induced damage ↑ and shadowing ↓.

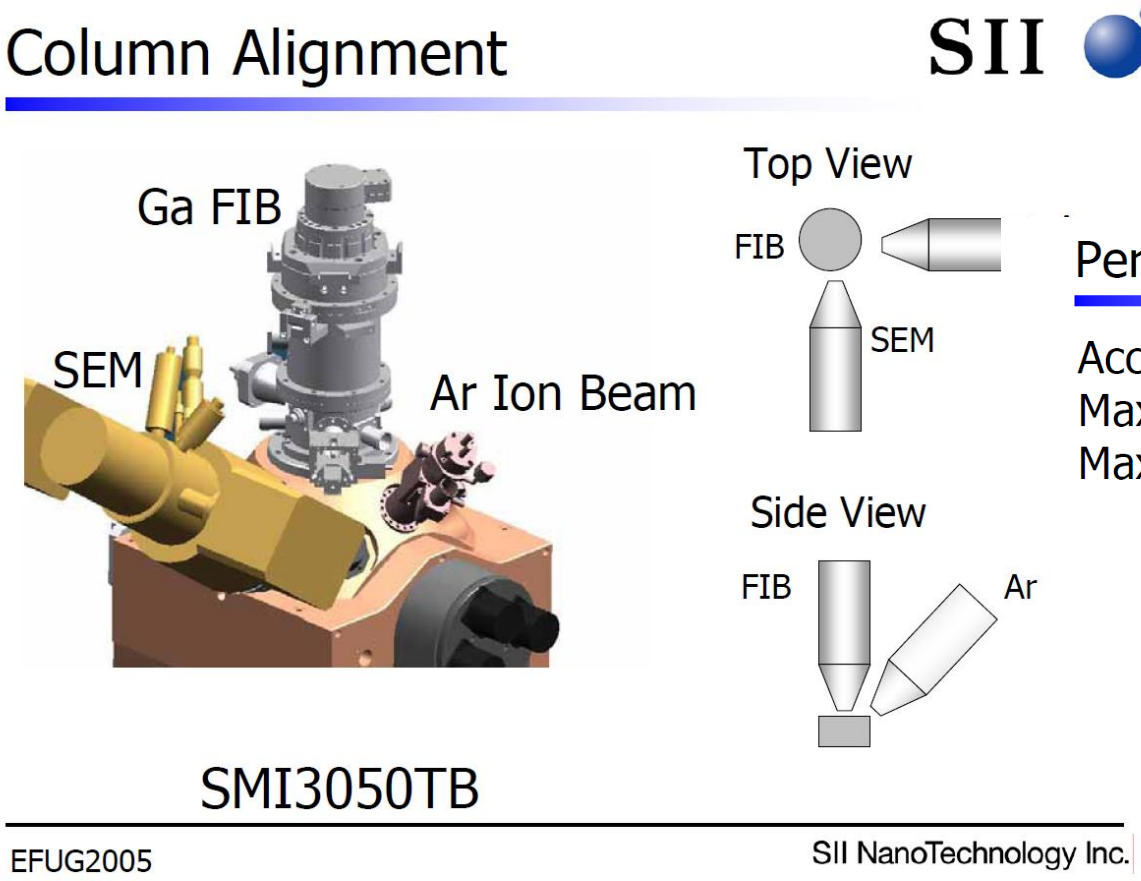
- **Oscillation angle (φ)** ↑ - curtaining effects ↓.



- **Type of protection layers**: Pt/C/SiO_2 - protect the area of interest / shadowing / conducting or non conducting.
- **Type of supporting grid** - minimize redeposition.
- **Position of the FIB lamella on the supporting grid** - minimize redeposition.



Ref.:EFUG2010: Tzipi Cohen-Hyams



Column Alignment

SII

SMI3050TB

Performance of Ar Ion Beam

Acceleration Voltage:	1.0kV
Max Beam Current:	10nA
Max Etching rate:	>5nm/min

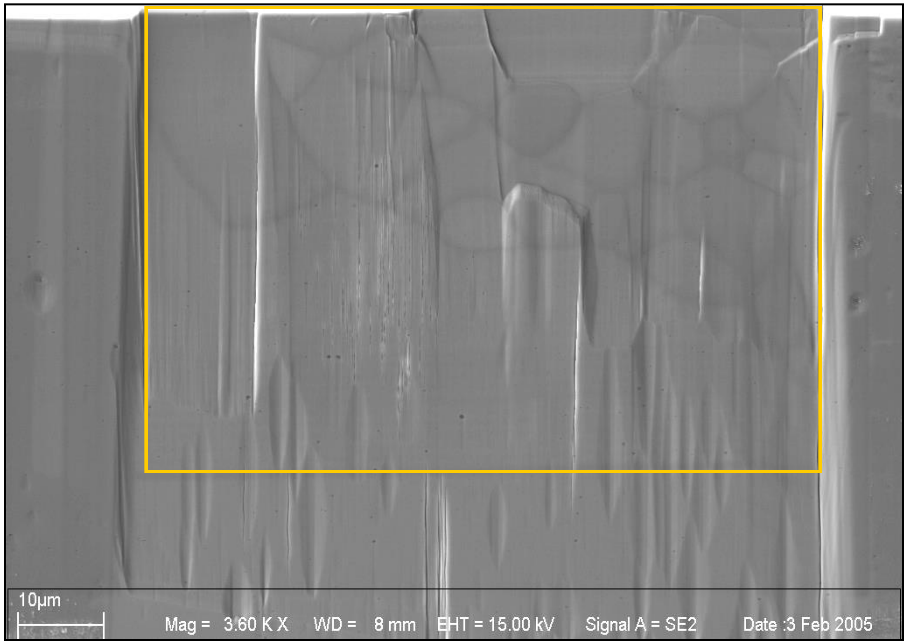
EFUG2005

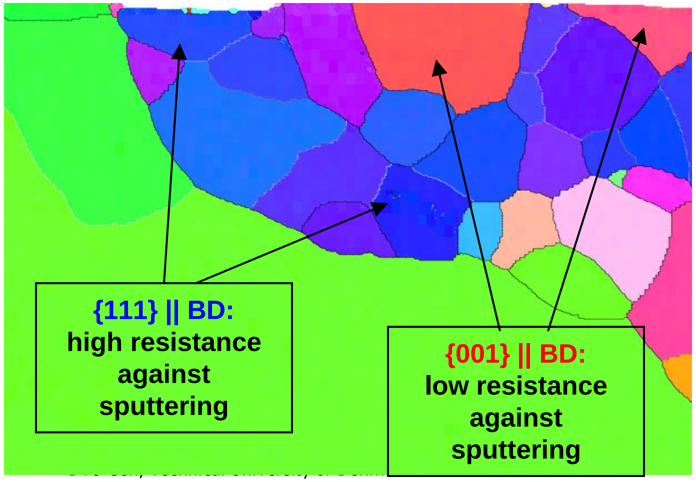
SII NanoTechnology Inc.

Ref.:EFUG 2005: Haruo Takahashi

Anisotropic sputtering & curtaining

Anisotropic sputtering on Fe 3% Si





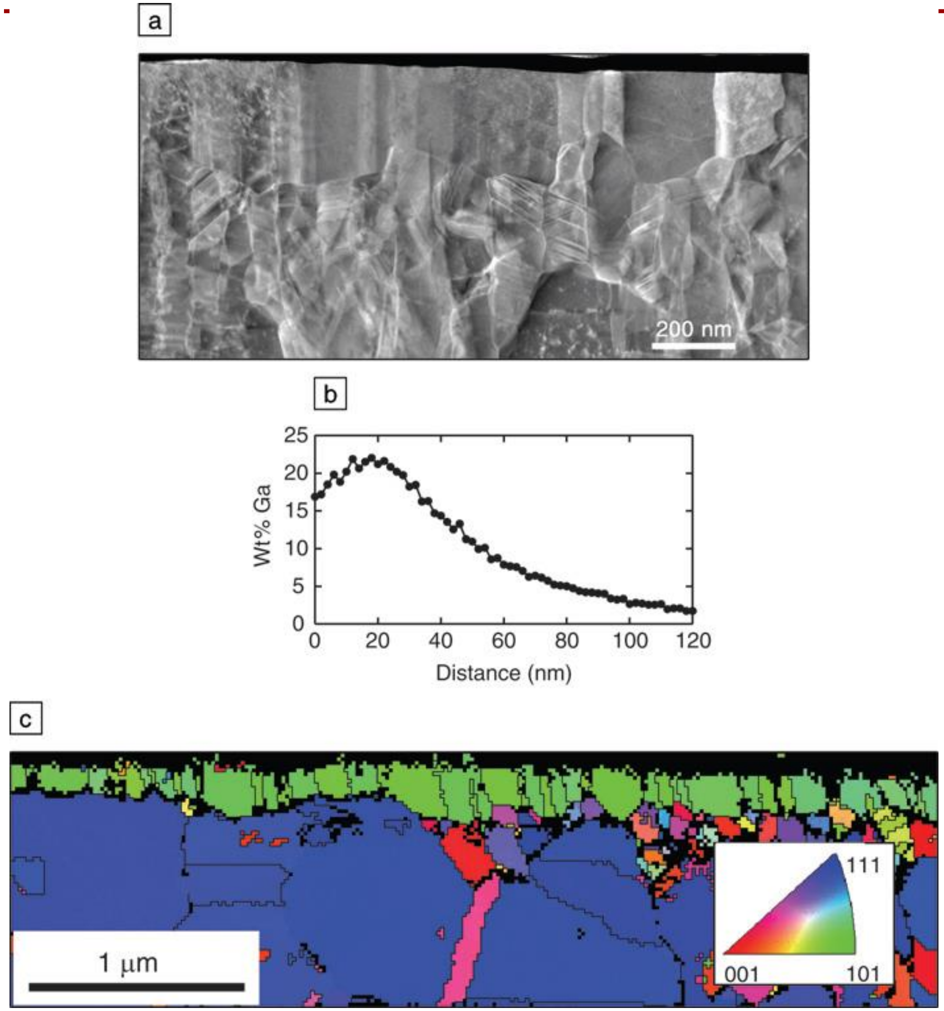
{111} || BD:
high resistance against sputtering

{001} || BD:
low resistance against sputtering

Experiments and calculations on anisotropic sputtering of Cu

B.W. Kempshall et al.,
J.Vac.Sci.Tech. B19 (2001), 749

- Additional to surface amorphization here have been several reports in the literature that FIB milling of fine-grained fcc metals can change the orientatio and size of the surface grains and form Ga intermetallic compounds.2
- The extensive use of FIB milling for sample preparation and the use of ion channeling contrast to characterize and measure grain sizes require that these ion beam–induced modifications be properly understood.



Cu grain structure modification to a depth of 200 nm by an ion dose of 2.5 \ 1017 Ga/cm2, despite the fact that calculated ranges for 30 kV Ga ions are close to 50 nm (Figure 5b).

EBSD orientation mapping of the sample shows that the surface grains are reoriented so that the <110> direction, the strong channeling direction in fcc crystal structures, is oriented parallel to the incident ion beam

Similar effects were observed in other fcc metals (Au, Ni), and bcc metals were observed to reorient at the surface with a <111> crystallographic direction normal to the exposed surface

- 30 kV Ga+ ion exposure can cause extensive microstructural modification of metal samples, even to depths beyond the expected, nonchanneling-orientation, ion range.

- Until these effects are understood and/or catalogued, caution should be used when FIB is employed to prepare samples for microstructural investigation, as even short exposures can result in unwanted changes to the sample.

- One must also be careful that the implantation of Ga into the sample does not result in changes induced by the formation of new Ga-containing phases.

- The addition of Ga to many metals can result in low-melting temperature phases.

- Cu_3Ga has been observed at the bottom of FIB-milled trenches in Cu.

- Thin TEM samples prepared from Al may show Ga enrichment at the grain boundaries.

- In extreme cases, because of its low melting point, Ga can form phases with other metals that have melting points at or below room temperature.

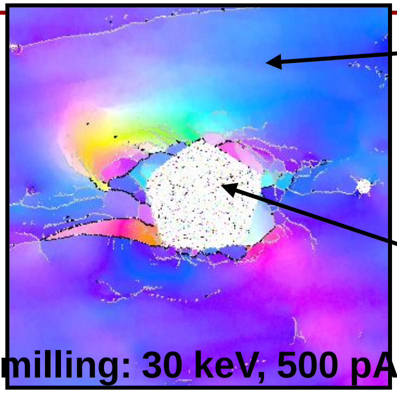
- For example, Ga addition during ion milling to In results in eutectic formation, with a melting temperature of 15.3∞C. Thus, the potential exists to have a liquid phase present in Ga FIB milled samples of In.

- The addition of 2.5 at.% Ga to Ge will also result in liquidphase formation. Other metals, like Al, Zn, and Pb, have similar problems.
- It is highly recommended the phase diagram be reviewed before FIB-milling new materials with Ga to avoid problem materials or prepare them in a different manner.

FIB-beam-induced material changes

Amorphisation

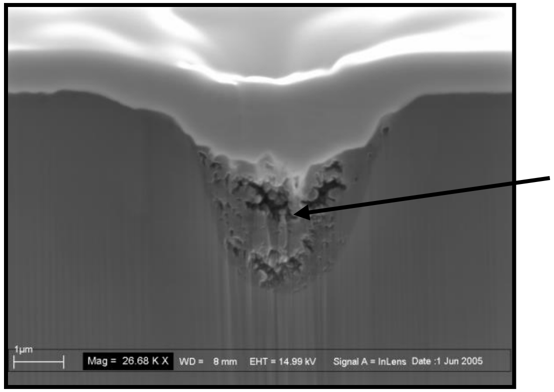
(see e.g. *Kato et al., J.Vac.Sci.Tech. A17(1999), 1201)*



Fe_3Al matrix: excellent diffraction patterns

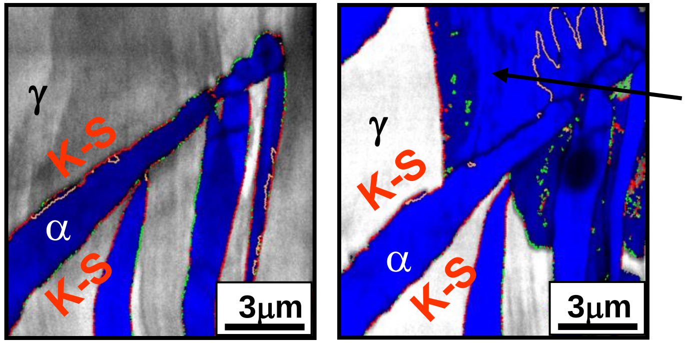
Laves phase inclusion: complete amorphisation

Reaction of Ga and Al



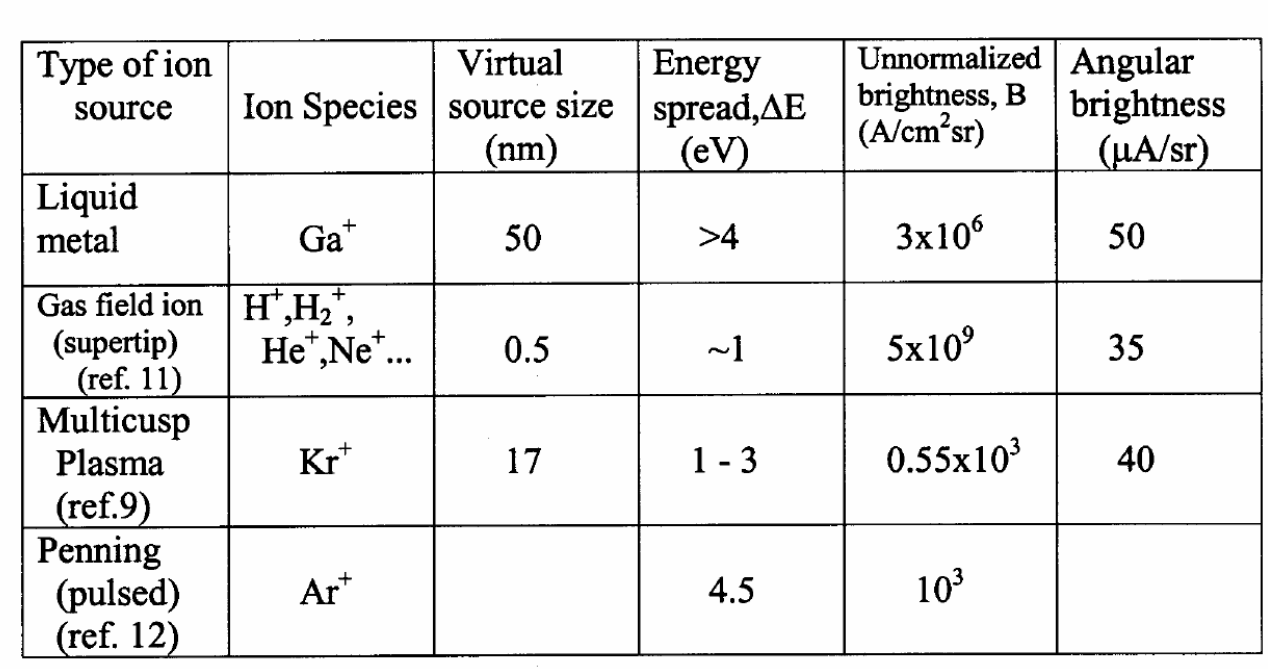
damage due to Ga-Al interaction at grain boundaries under a nano-indentation in Al

Beam-induced α-γ phase transformation in Fe-Ni



transformation of metastable austenite into martensite during milling

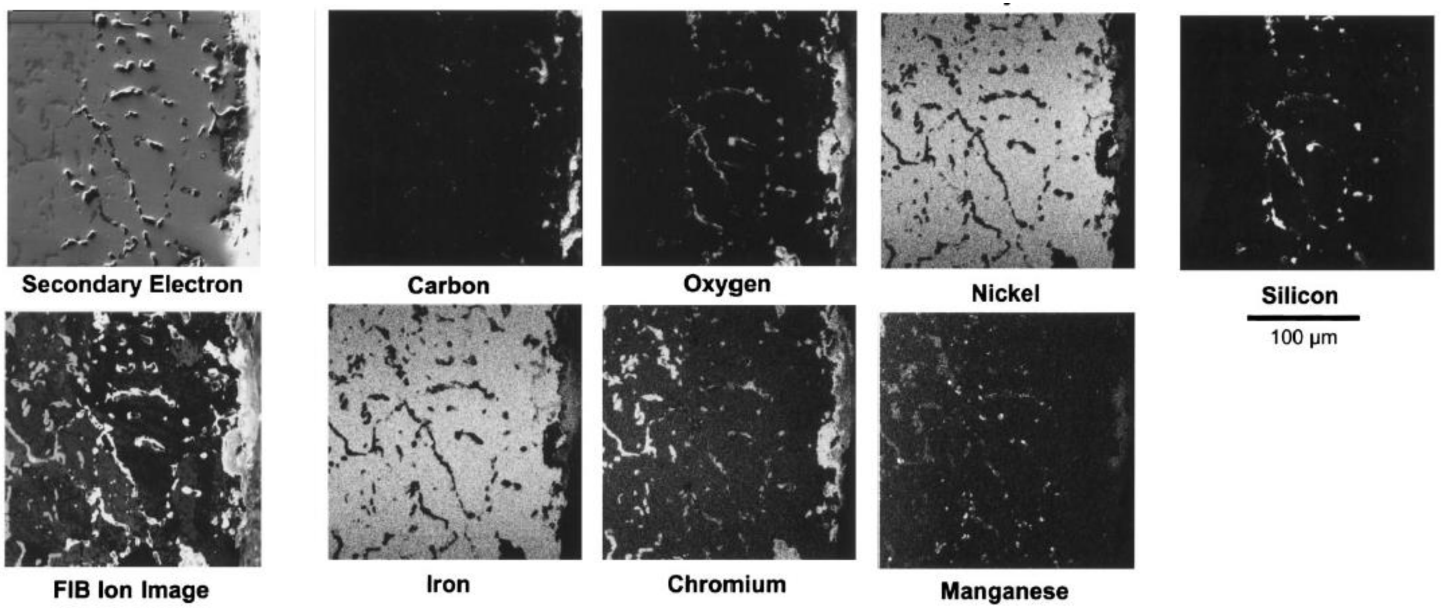
Comparison of Ion Sources for FIB



Type of ion source	Ion Species	Virtual source size (nm)	Energy spread, ΔE (eV)	Unnormalized brightness, B ($A/cm^2 sr$)	Angular brightness ($\mu A/sr$)
Liquid metal	Ga^+	50	>4	$3x10^6$	50
Gas field ion (supertip) (ref. 11)	H^+, H_2^+, He^+, Ne^+...	0.5	~1	$5x10^9$	35
Multicusp Plasma (ref.9)	Kr^+	17	1 - 3	$0.55x10^3$	40
Penning (pulsed) (ref. 12)	Ar^+		4.5	10^3	

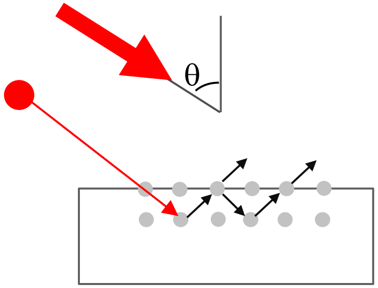
Ref.: John Melngailis

FIB imaging – Material contrast

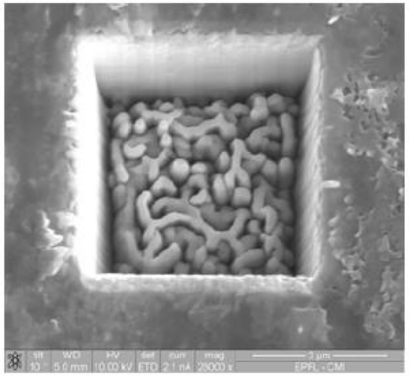


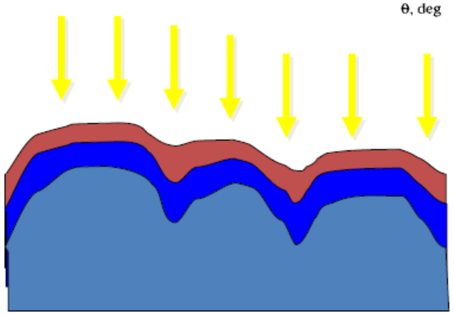
*Ref.:M.W. Phaneuf /
Micron 30 (1999)
277–288*

Basic operating modes - Milling

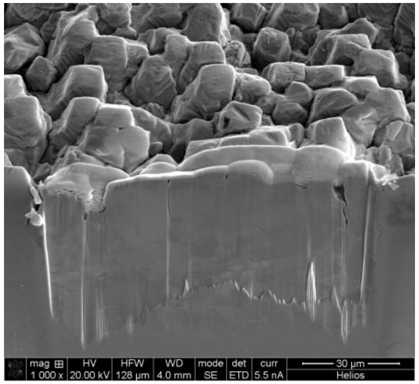


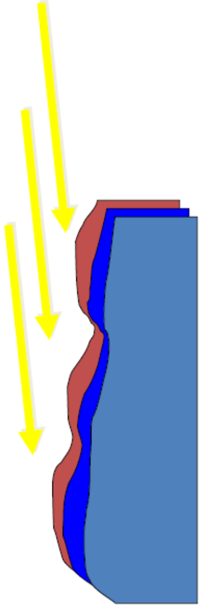
Higher probability of collision cascades near the surface at higher θ

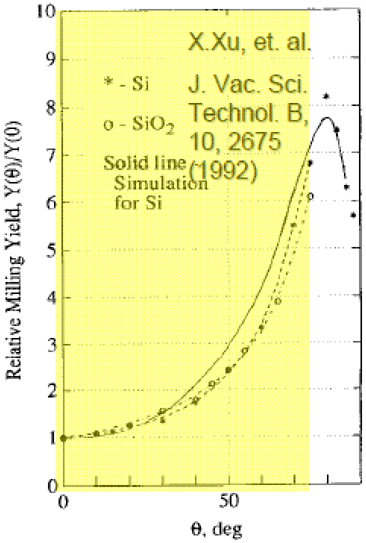




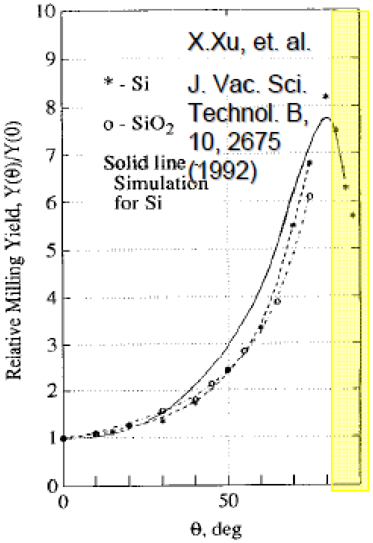
Polishing at shallow angle







X.Xu, et. al.
J. Vac. Sci. Technol. B, 10, 2675 (1992)



X.Xu, et. al.
J. Vac. Sci. Technol. B, 10, 2675 (1992)

Ref.: Marco Cantoni