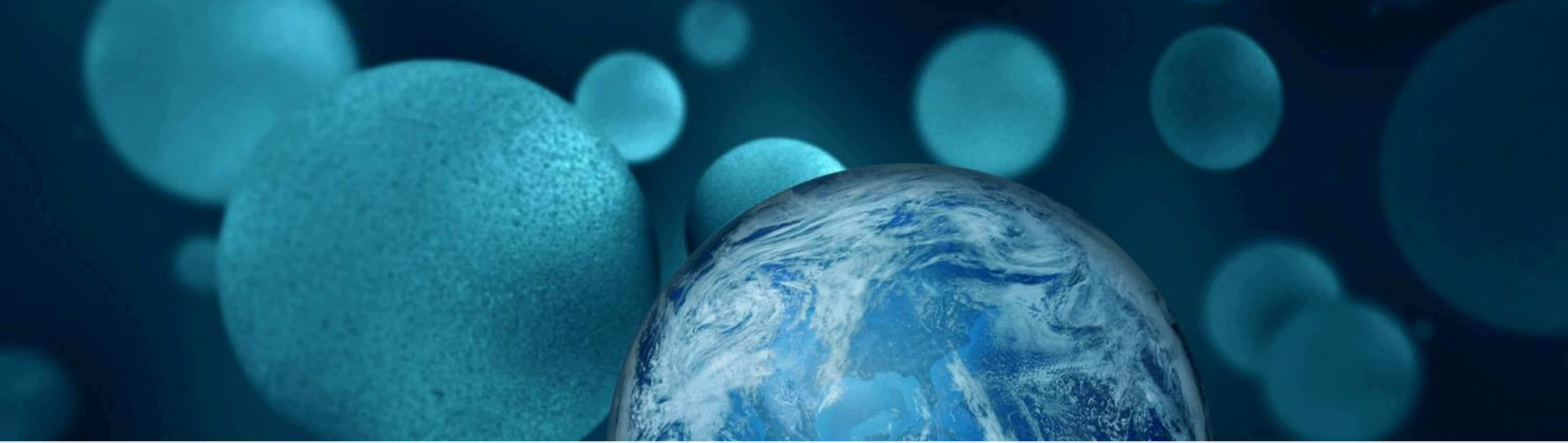


Scios 2
HT Sidewinder

Module 4

Ion Beam Operation

- THE FIB SYSTEM
  - FIB Compared to SEM
  - FIB system
  - The source, LMIS
  - Ion Column
  - Detectors

What’s a FIB and what can it do?

- **F**ocused 6 nm spot size at 1pA
- **I**on 500V-30 kV Ga^{+}
- **B**eam 1pA to 65 nA

• **FIB is a scanning ion microscope.** As the primary beam rasters on the sample surface, the signal from the sputtered ions or secondary electrons is collected by detector to form a secondary ion image or secondary electron image.

• **FIB is a milling machine.** The milling is site specific. The Gallium (Ga+) primary ion beam strikes the sample surface removing material through the physical sputtering of sample material.

• **FIB can deposit metals and chemical enhanced etching**. By injecting special gases, an ion beam is able to deposit materials with submicron precision. Gases can interacts with the primary Gallium beam to provide assisted chemical etching or for selective milling

Ions vs electrons

- Ions are positively charged atoms with one or more electrons missing from their valence electron shell. The mass of the ionized atom, along with its high energy and momentum (360 times electron), provide unique capabilities for milling, imaging and micro-depositions

- For the same Beam Energy there are big differences in other critical parameters:

- Mass: Ga^+ Ion = 128,000 times heavier than Electron
- Velocity: Ga^+ Ion = 1/360 of Electron
- Momentum: Ga^+ Ion = 360 times Electron

Comparing Electrons and (Ga+) Ions

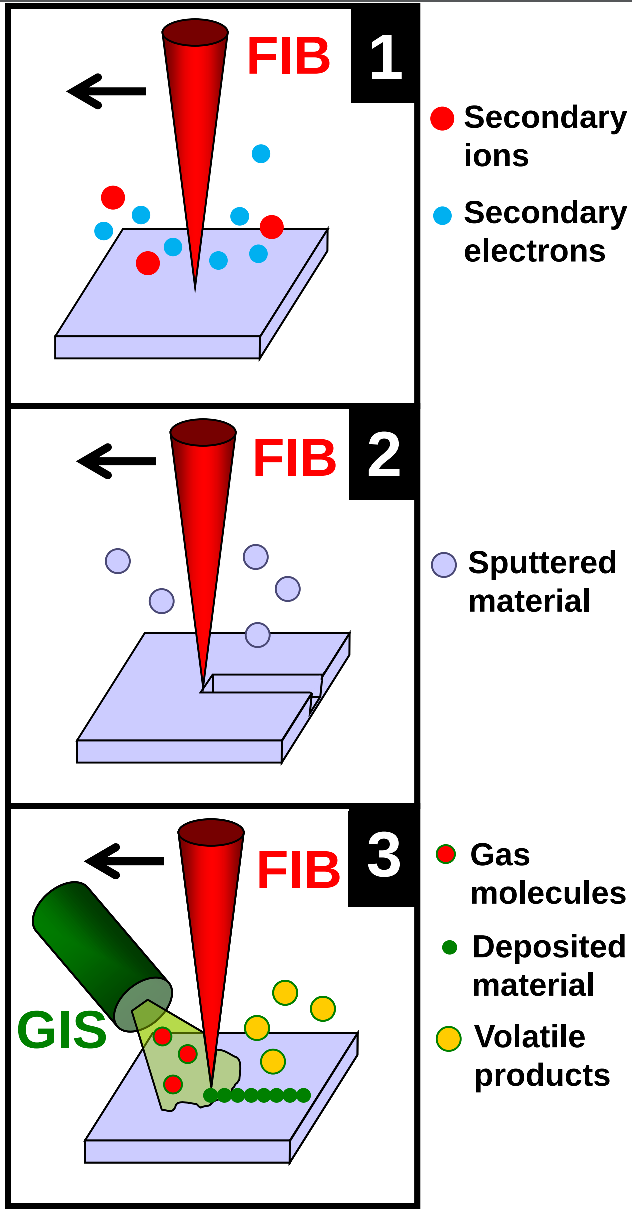
		FIB	SEM	Ratio
Particle	type	Ga+ ion	electron	
	elementary charge	+1	-1	
	particle size	0.2 nm	0.00001 nm	20.000
	mass	$1.2\ .10^{-25}$ kg	$9.1.10^{-31}$ kg	130.000
	velocity at 30 kV	$2.8.10^{5}$ m/s	$1.0\ 10^{8}$ m/s	0.0028
	velocity at 2 kV	$7.3.10^{4}$ m/s	$2.6.10^{7}$ m/s	0.0028
	momentum at 30 kV	$3.4.10^{-20}$ 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	secondary electrons	100 - 200	50 - 75	
signal per 100				
particles at 20 kV	back scattered electron	0	30 - 50	
	substrate atom	500	0	
	secondary ion	30	0	
	x-ray	0	0.7	

3 basic FIB operations

1. Emission of secondary electrons and ions
   - **FIB imaging**
2. Sputtering of substrate atoms
   - **FIB milling**
3. Chemical interactions
   - **FIB deposition / enhanced etch**

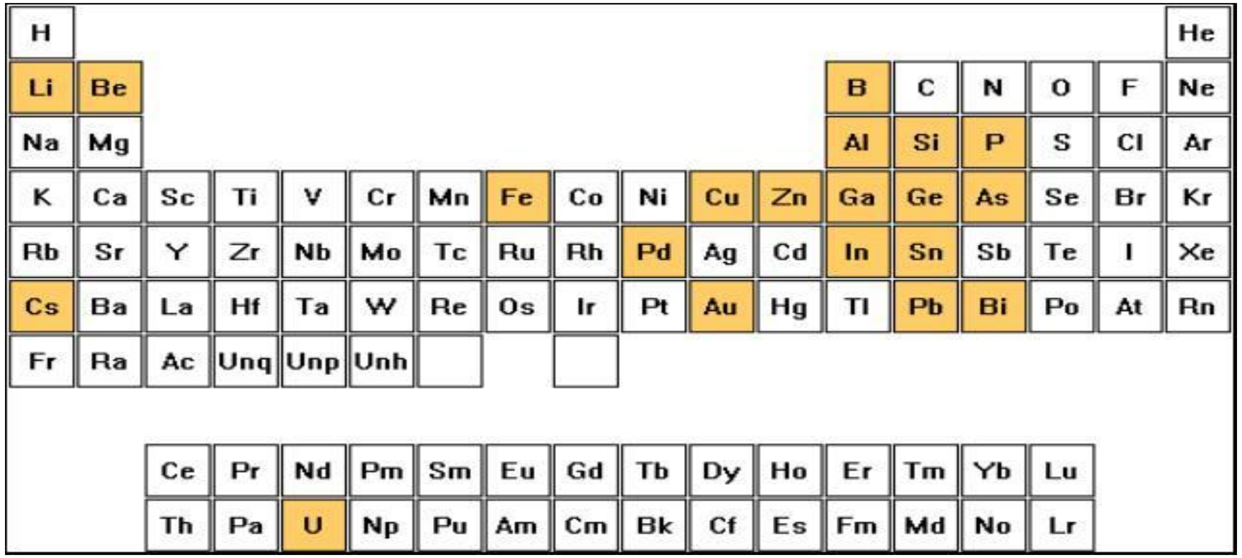
Other effects :

- Ion implantation
- Displacements of atoms in the solid (induced damages)
- Heating



- **A FIB System:**
  - Ion Source - LMIS
  - Ion Column - electrostatic lenses
  - Detector
  - Vacuum System
  - Gas Delivery
  - Stage
  - Computer with Integrated Image Processing

LMIS: Liquid metal field ionisation sources



Physical and chemical properties of Gallium
(Form: Solid; Colour: Silver-colour; Odour: Odourless)

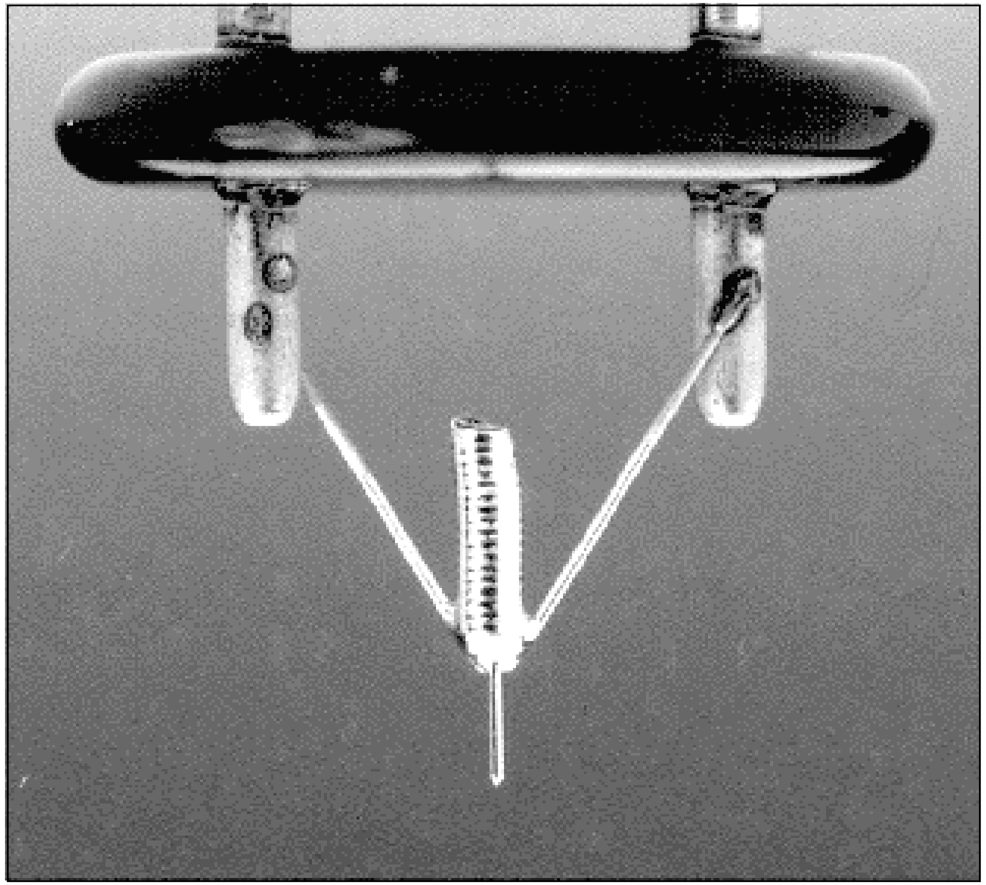
Melting Point, °C	Boiling Point, °C	Density, g/cm^3
29.78	2403	5.907

Until now, the following LMIS have been produced and studied: Ga, Sn, In, Au, AuSi, AuGe, AuCo, CoGe, CoY, CuGe,CuMg, AlGe, GaIn, AuCoGe, AuCoY, AuSiPr, AuSiBe, AuCoPr, AuCoSi, AuErSi.

The most commonly used ion is Gallium since it has the longest liquid range of any metal (from 29.8°C to 2175°C) providing room temperature operation and yields a long lifetime source. Gallium can be focused to a very fine probe size (< 10 nm in diameter). Liquid metal Gallium is high vacuum compatible and Gallium is large ions for physical sputtering. Below the melting point Gallium is a soft, silver white metal that is stable in both air and water.

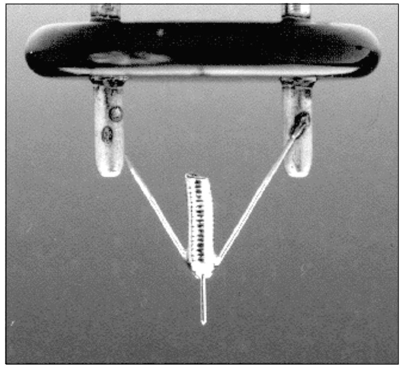
LMIS: Gallium is the most popular

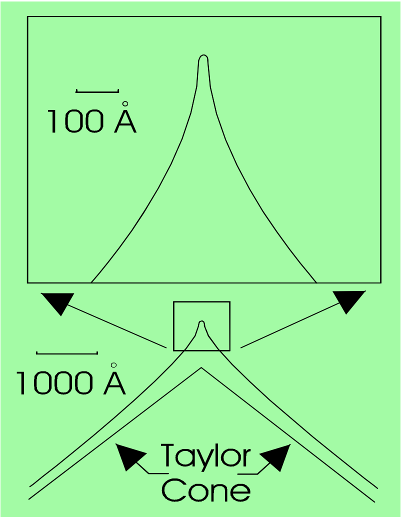
- A liquid metal
- Room temperature operation
- Long life (500-1500 hr sources)
- High vacuum compatible
- Large ion for sputtering –
  optimum momentum transfer capability
- High brightness source
  (sharp tip / Taylor cone)
- Can be focused

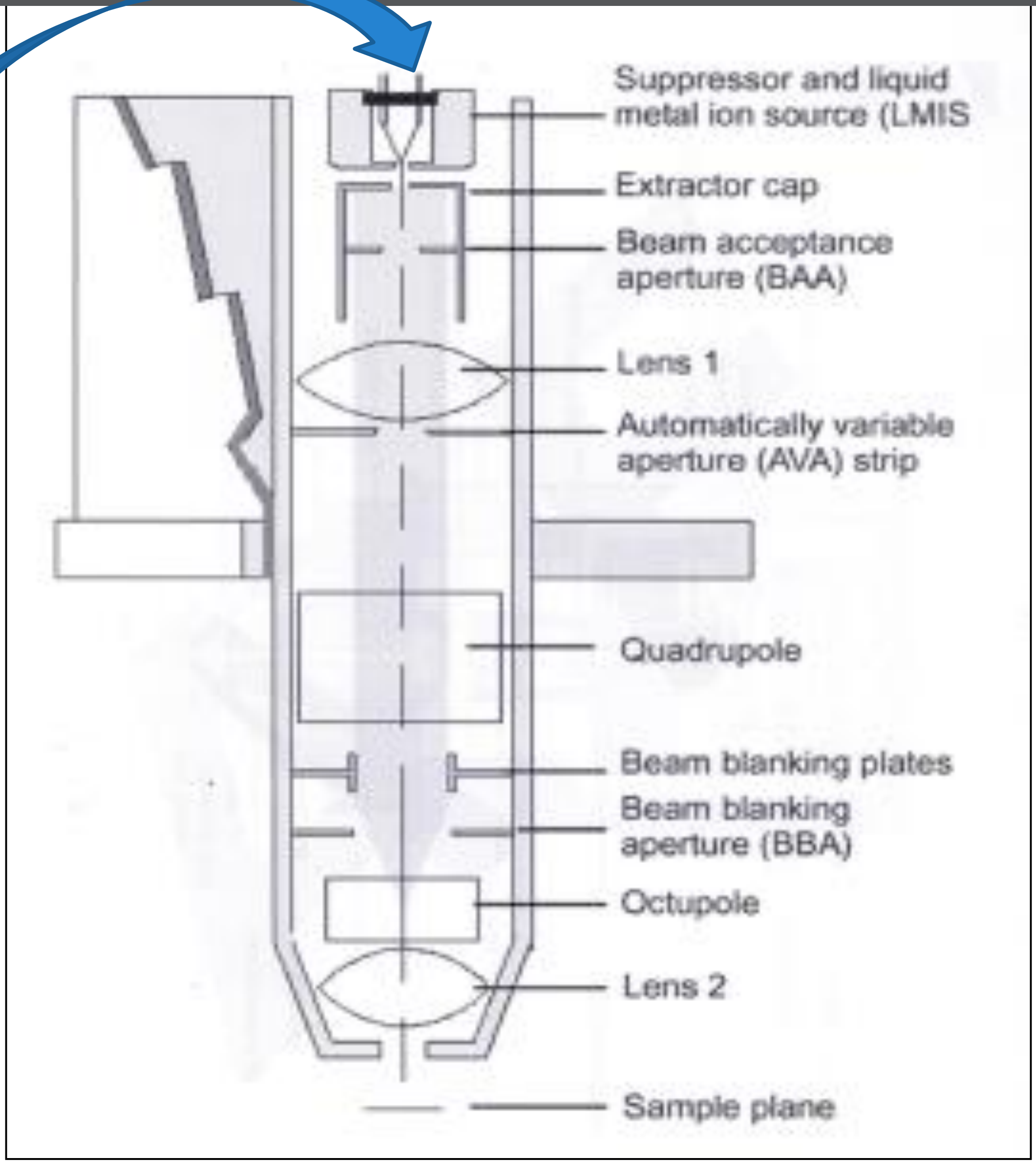


Liquid metal ion source

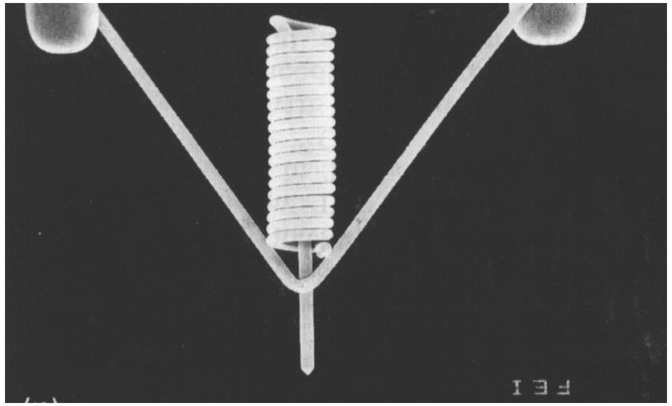
- Liquid gallium forms a Taylor Cone
- Material ionizes.
- Charged particles are extracted.

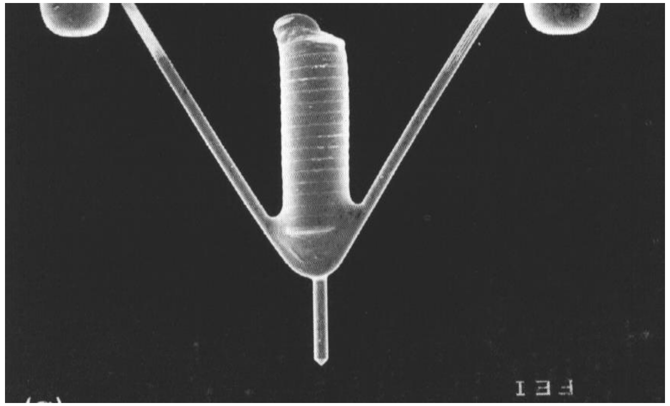




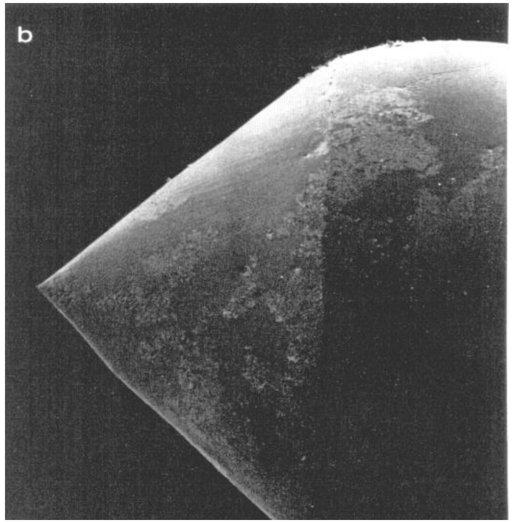


LMIS: Liquid Metal Ion Source





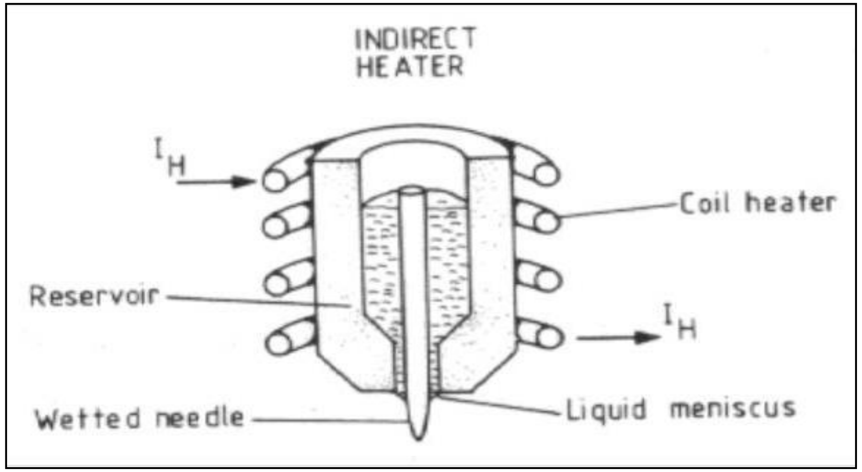
The Tungsten is wetted with Gallium which is held in the spiral by surface tension. The vapour pressure is about 10^{-7} mbar.

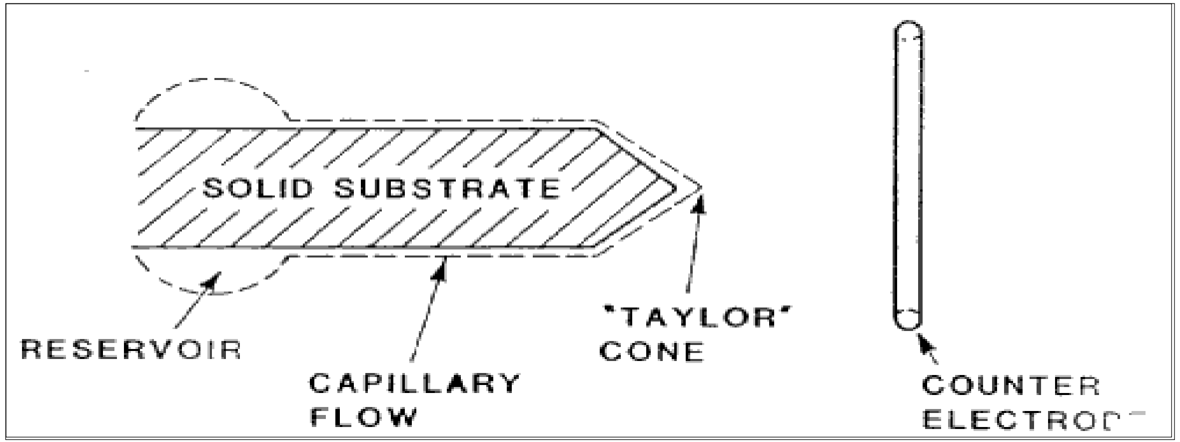


Frozen-in-shape LMIS
showing 49^{o} half angle. The field emission area is a 2-5nm across giving current densities $>10^{8}$ Acm^{-2}.

Gallium LMIS **liquid metal ion source:**

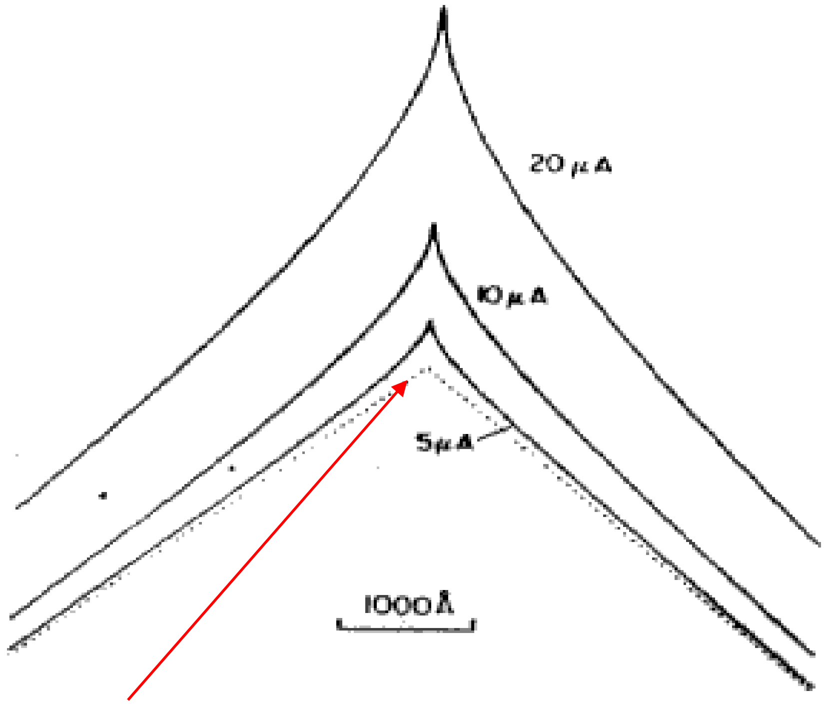
- Ga (liquid) metal is heated to a thin liquid state
- The Ga wets the tungsten and flows to the tip of the needle
- By applying a strong electric field a (electrospray) Taylor cone is formed ; the tip radius of this cone is ~2 nm
- The electric field at this small tip is typically >1 x 10^8 V/cm and causes ionization and field emission of the gallium atoms.





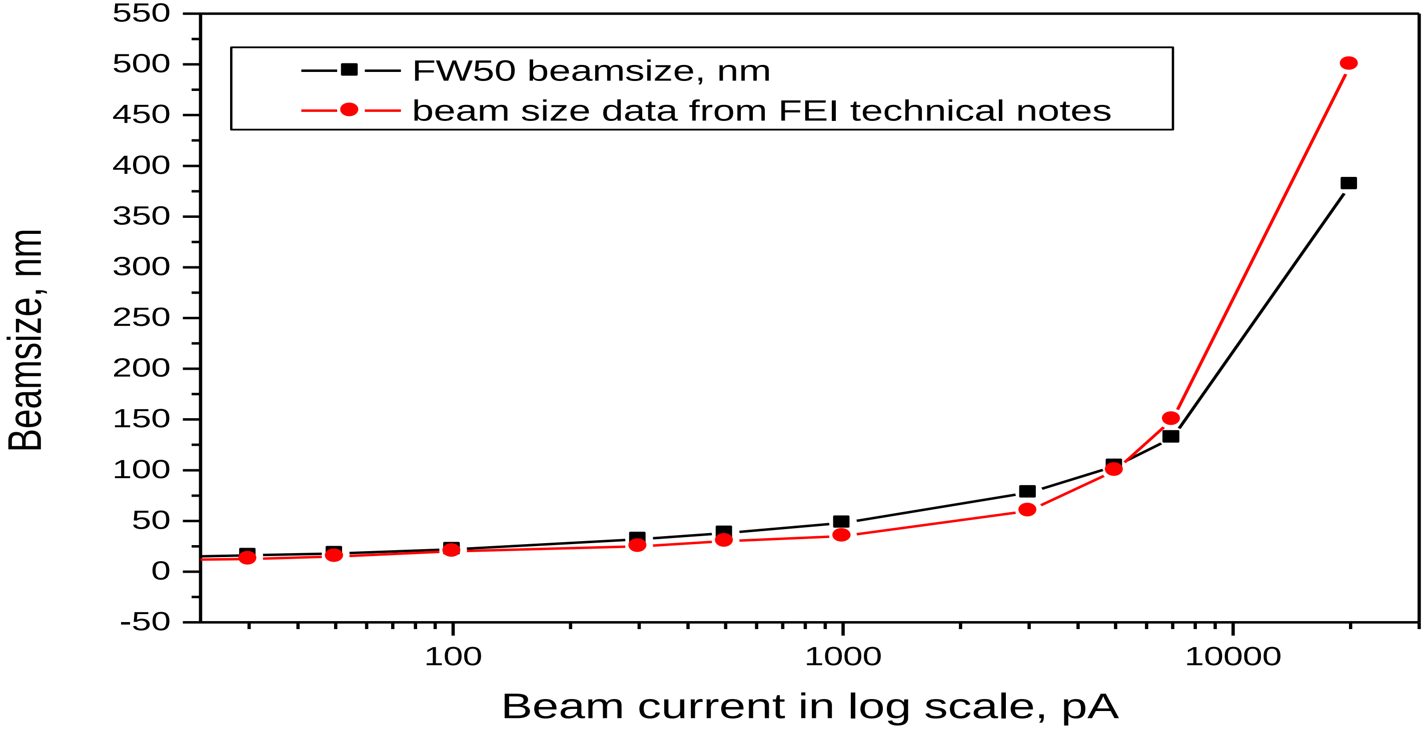
Extractor field

- Jet-like protrusion for Ga LMIS at various currents
- The tip is sharper and sharper, and the volume of liquid increases
- Dashed line is Scios Taylor Cone shape



For Scios the (optimal) emission current = 2μA

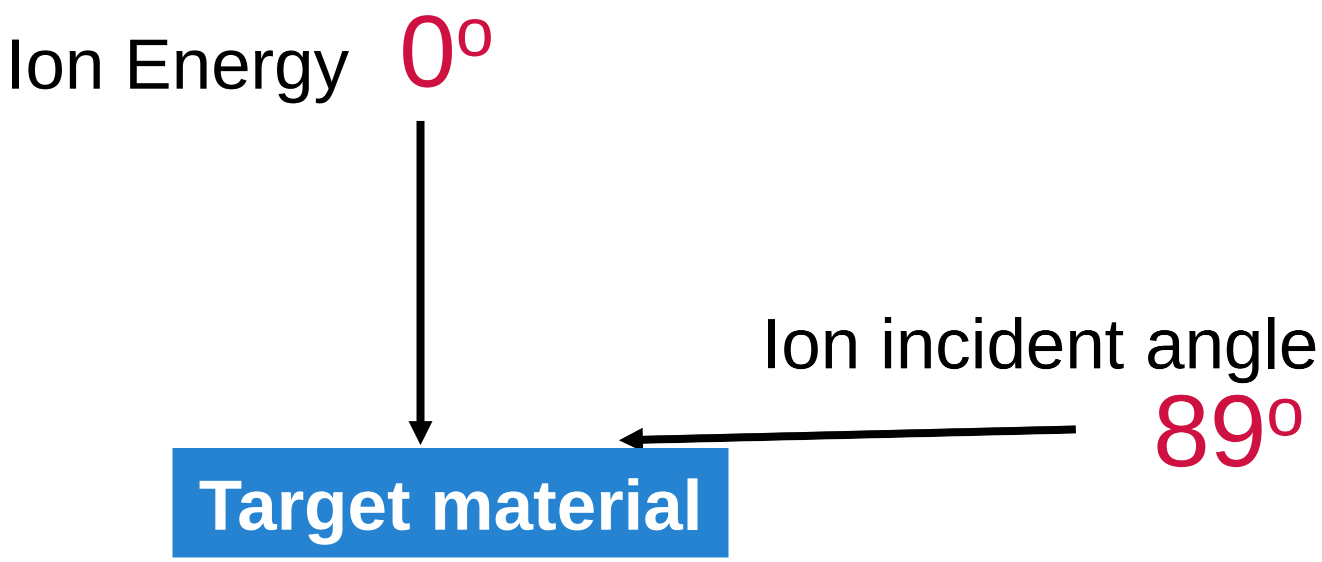
Ion beam currents and spot sizes



HC Sidewinder

Index	Beam current	Aperture diameter (um)	Beam diameter
0	1.5	0.008	7.0
1	10	0.016	13.0
2	30	0.025	17.0
3	50	0.032	19.0
4	**100**	0.042	24.0
5	300	0.068	31.0
6	500	0.087	35.0
7	**1000**	0.118	44.0
8	3000	0.198	66.0
9	5000	0.250	85.0
10	7000	0.294	102.0
11	15000	0.420	182.0
12	30000	0.600	210.0
13	50000	0.750	300.0
14	maxmium	1000.000	400.0

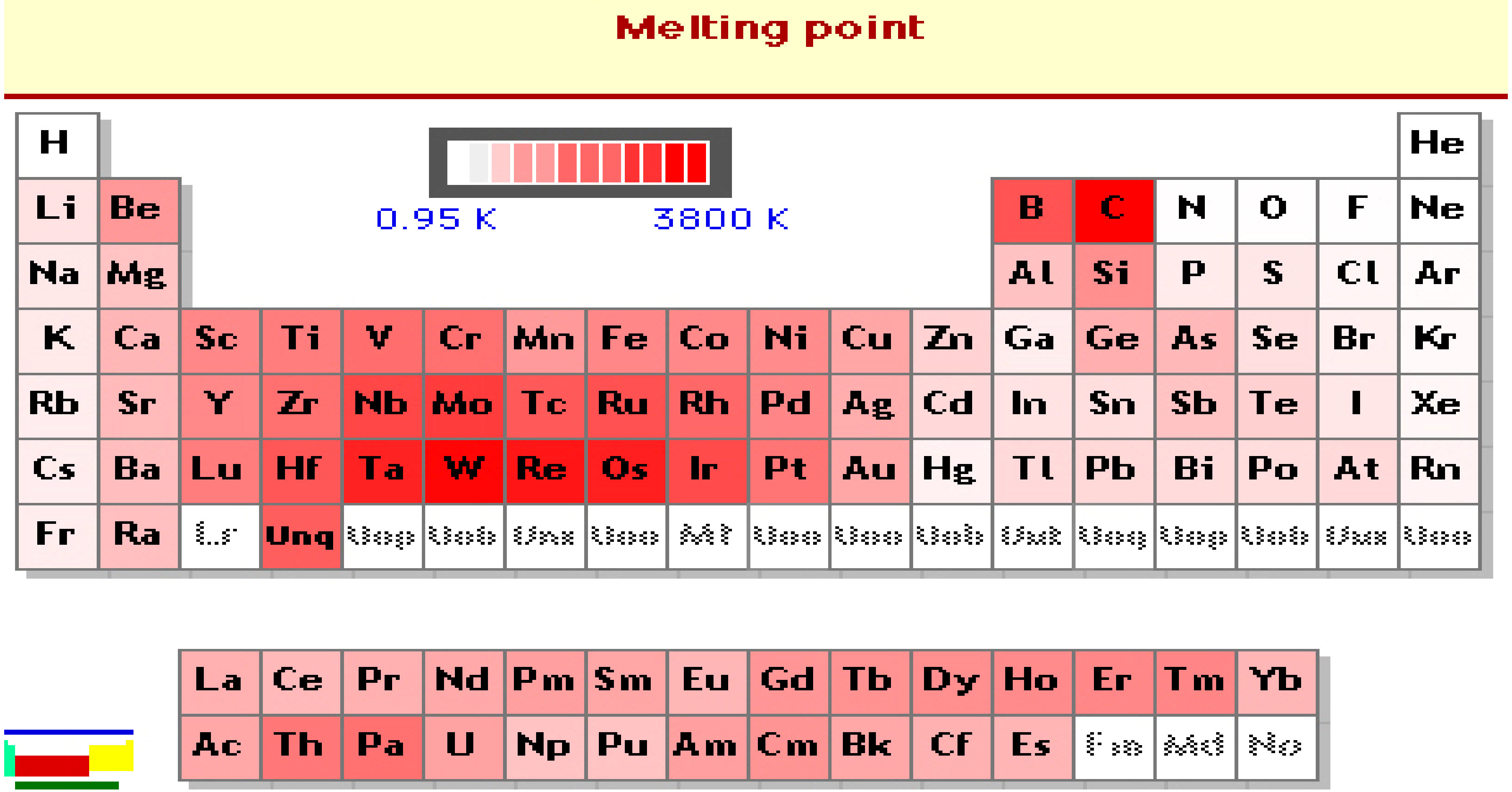
Sputter Yield



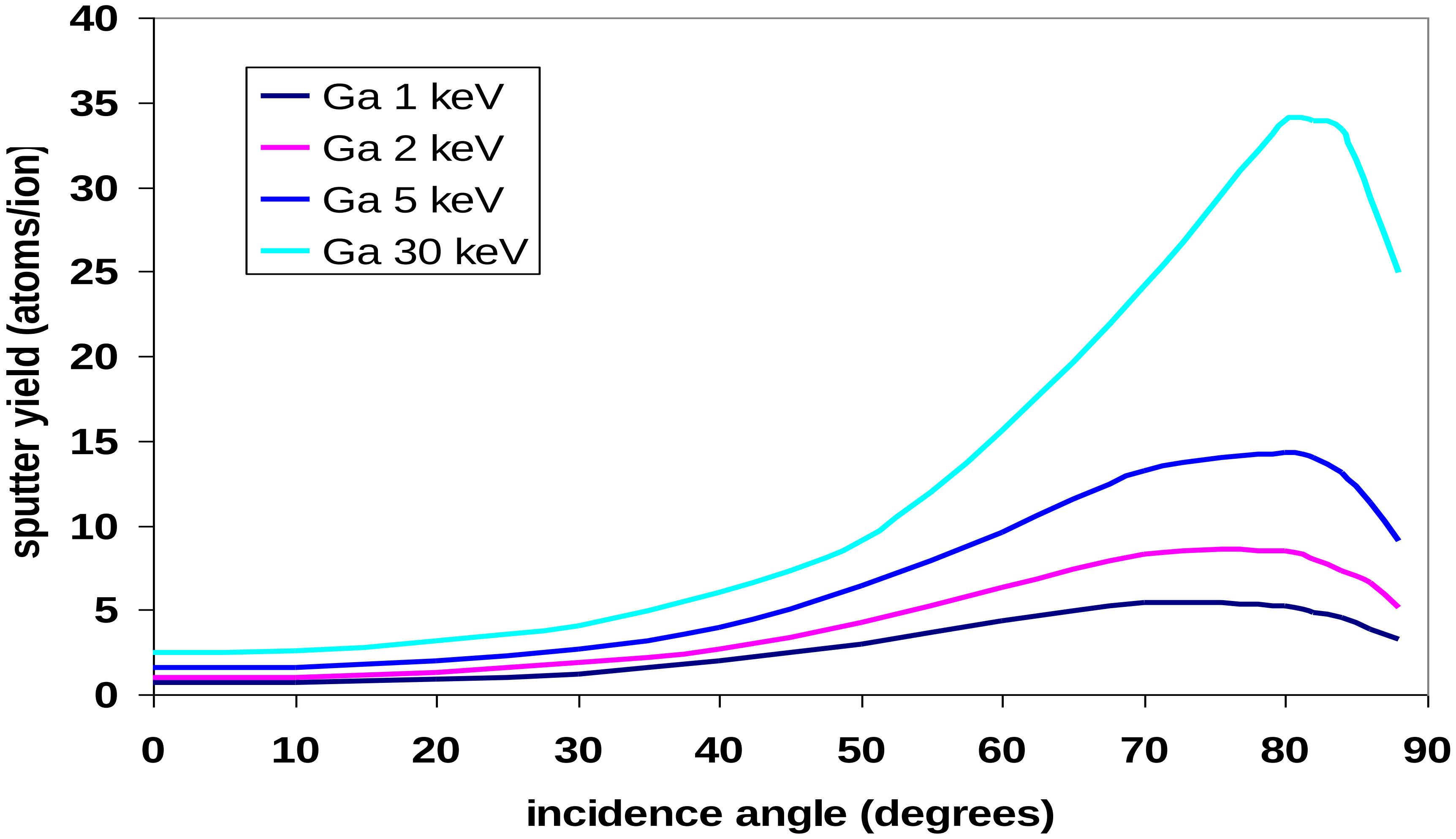
The sputter yield depends on:

- ion energy
- incident angle
- target material
- crystallographic orientation

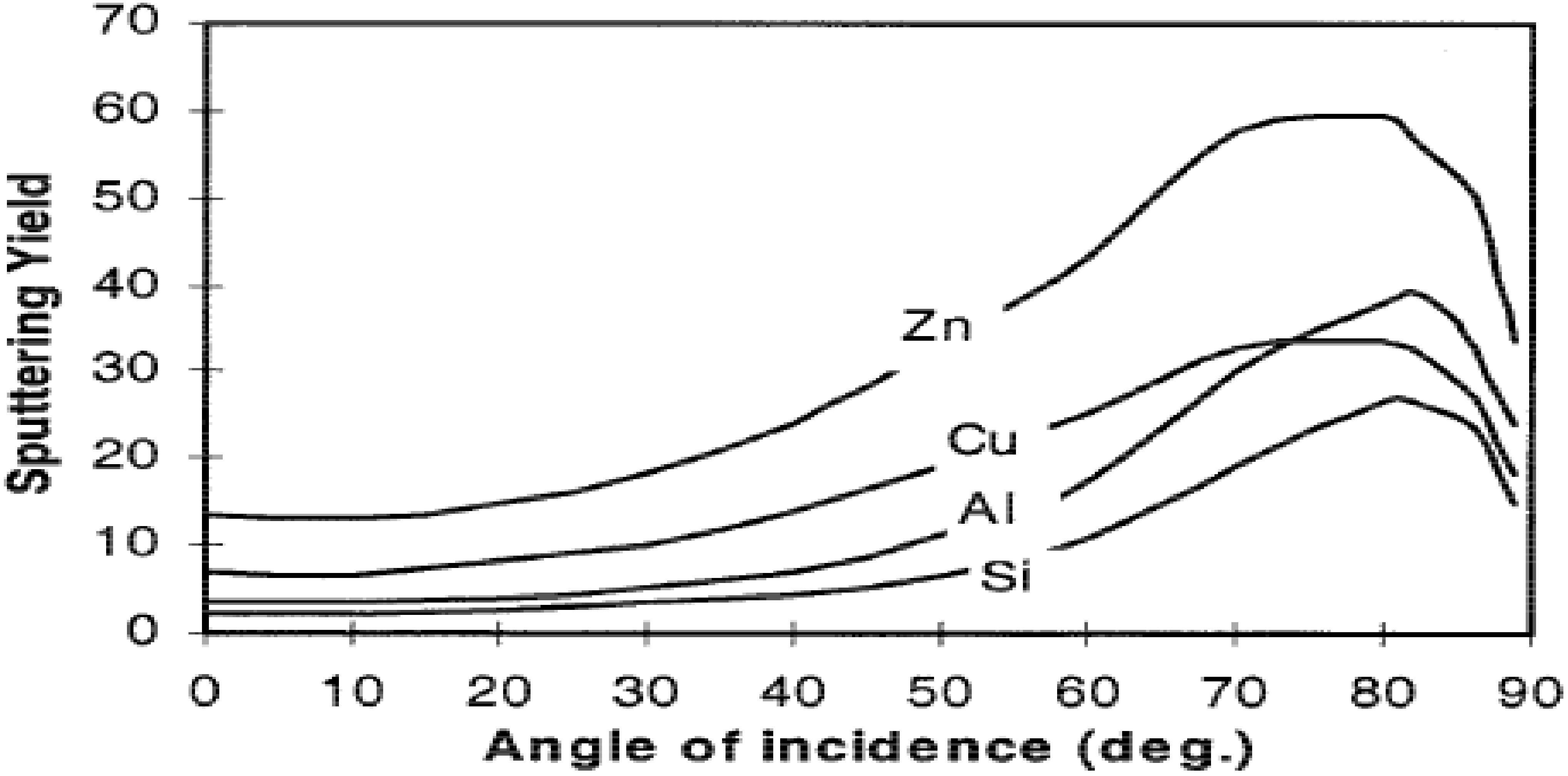
Relation of Sputter Yield and Melting points; *(related to surface binding energy)*



Sputter Yield: depends on angle and E

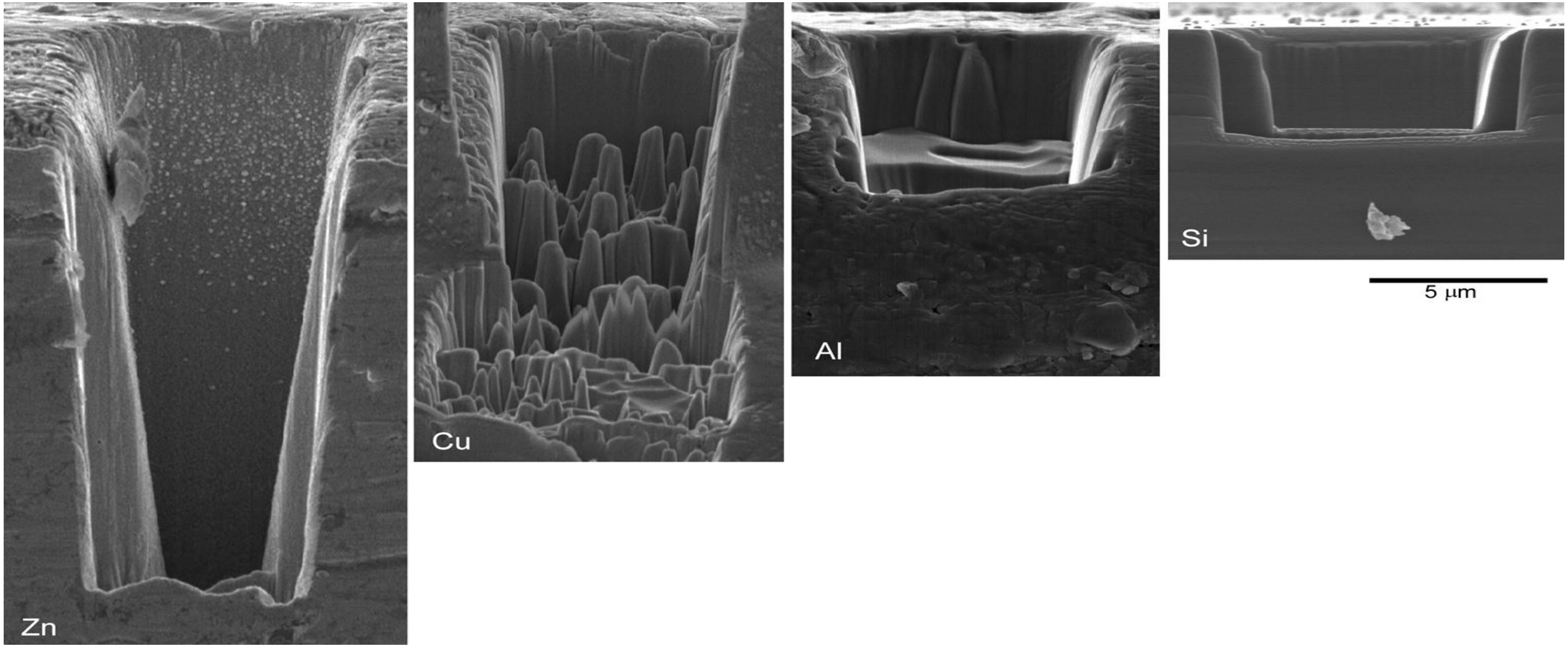


Sputter Yield: depends on target material



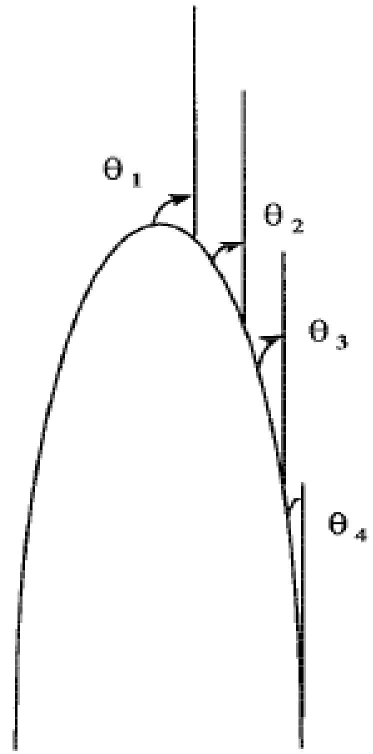
Prenitzer et al., M&M 2003

Sputter Yield: depends on target material



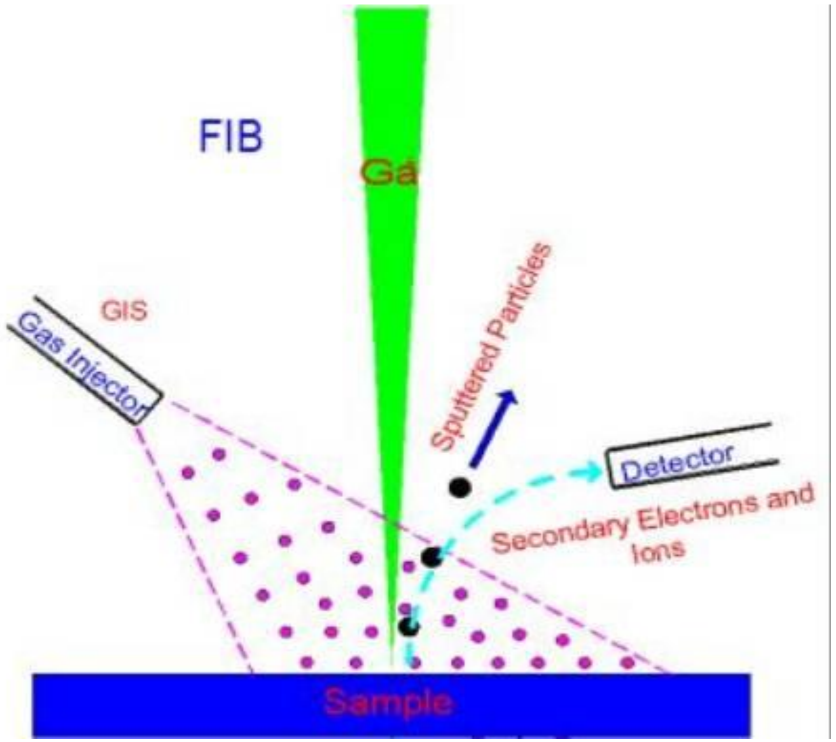
Sputter Yield: Beam profiles and Incidence Angle

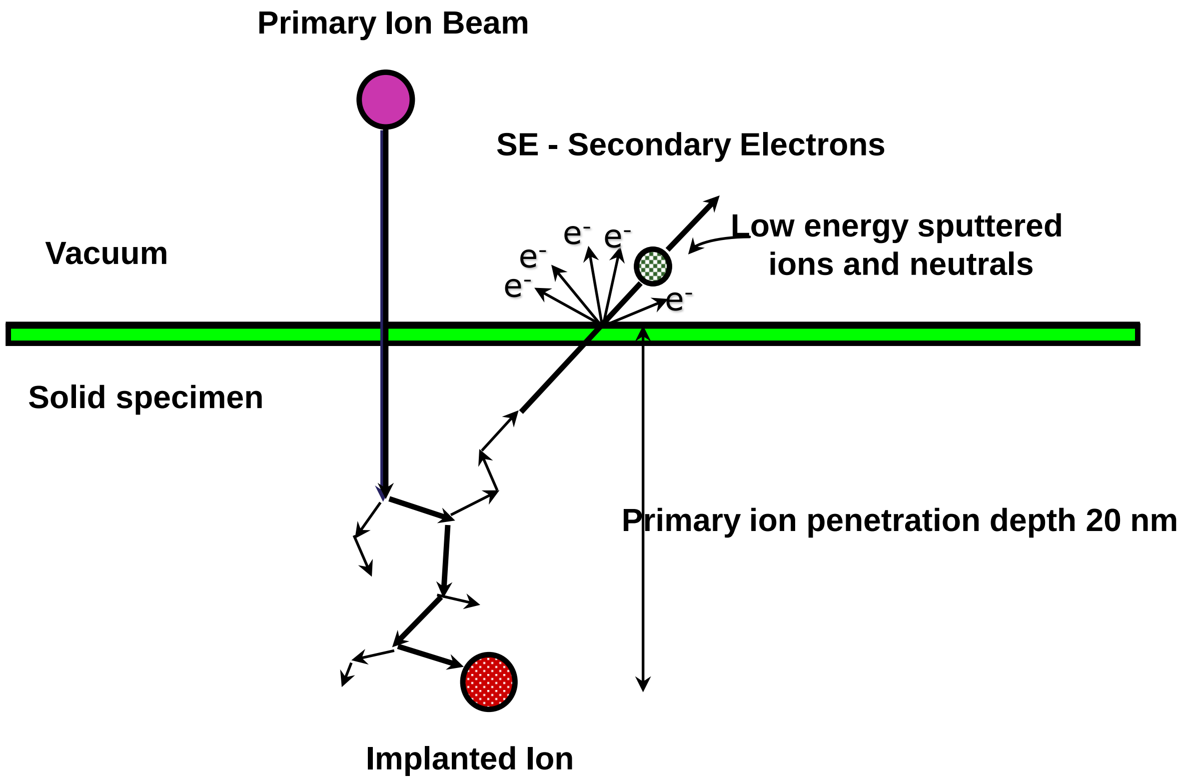
- Asperities on a surface will be FIB milled at different rates due to topographic effects on milling
- The topographic effects will grow and exacerbate as FIB milling continues
- This is why surfaces are “never” FIB milled from top-down, but rather, are created by FIB milling at high incident angles.



$$\theta_1 \neq \theta_2 \neq \theta_2 \neq \theta_4$$

Ion Beam - Sample Interactions





- Reflection: sputtering, SIMS
- Emission: Electron emission, ion emission,
- Absorption: Ion implantation

Using FIB for imaging

- **Image Modes**
  - Secondary Electron
  - Secondary Ion
- **Contrast Mechanisms**
  - Topography
  - Voltage Contrast
  - SE/SI Yield
  - Channeling

Detectors – possibilities

- **Standard ETD**: Everhart Thornley Detector (Scintillator):

  collects secondary electrons induced by the i-beam

  (collects secondary electrons induced by the e-beam)

- **Optional ICE detector**: Ion Conversion and Electron detector:

  collects secondary ions or secondary electrons induced by the i-beam

  (collects secondary electrons induced by the e-beam; better at low kV)

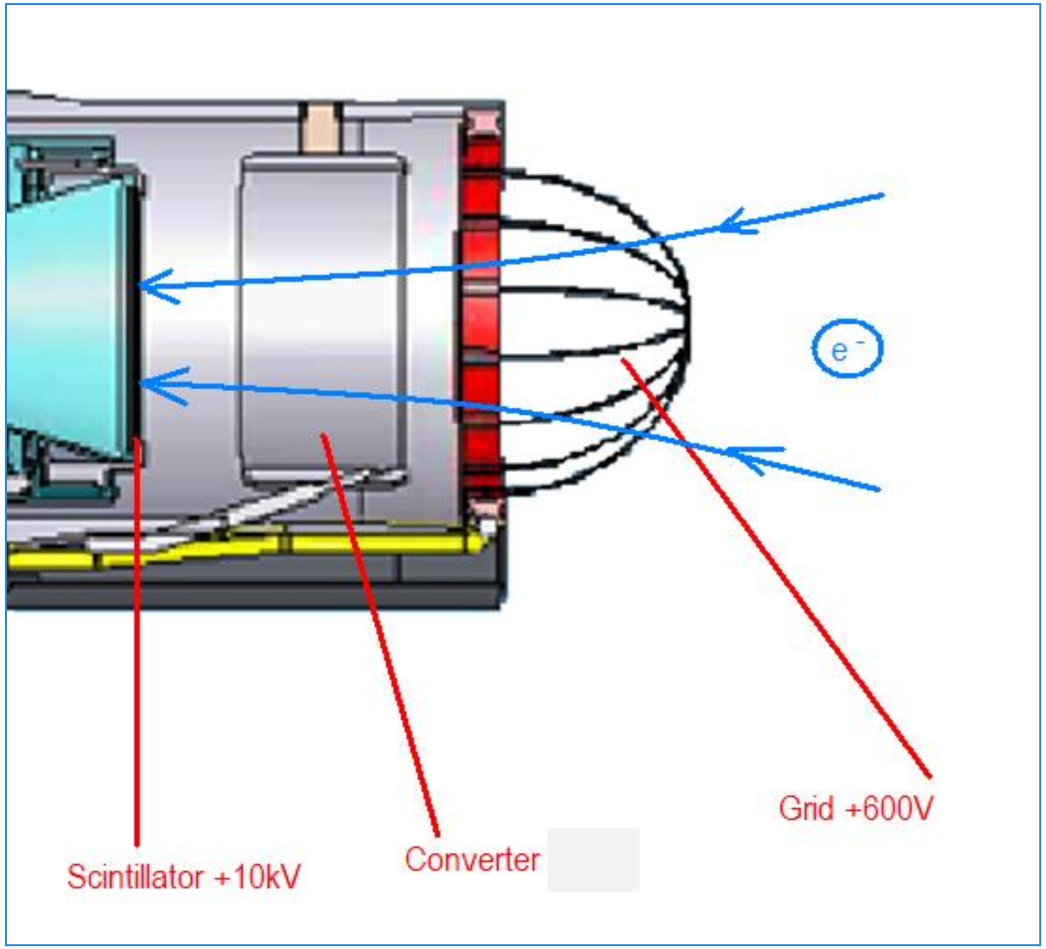
ICE: Imaging Detector Modes

- Secondary Electron
  - Detector biased positive
  - Images generated from e-
  - Emitted from top 5-10 nm
  - Only charging up a few volts to go dark
  - Grounded metals very bright, oxides dark

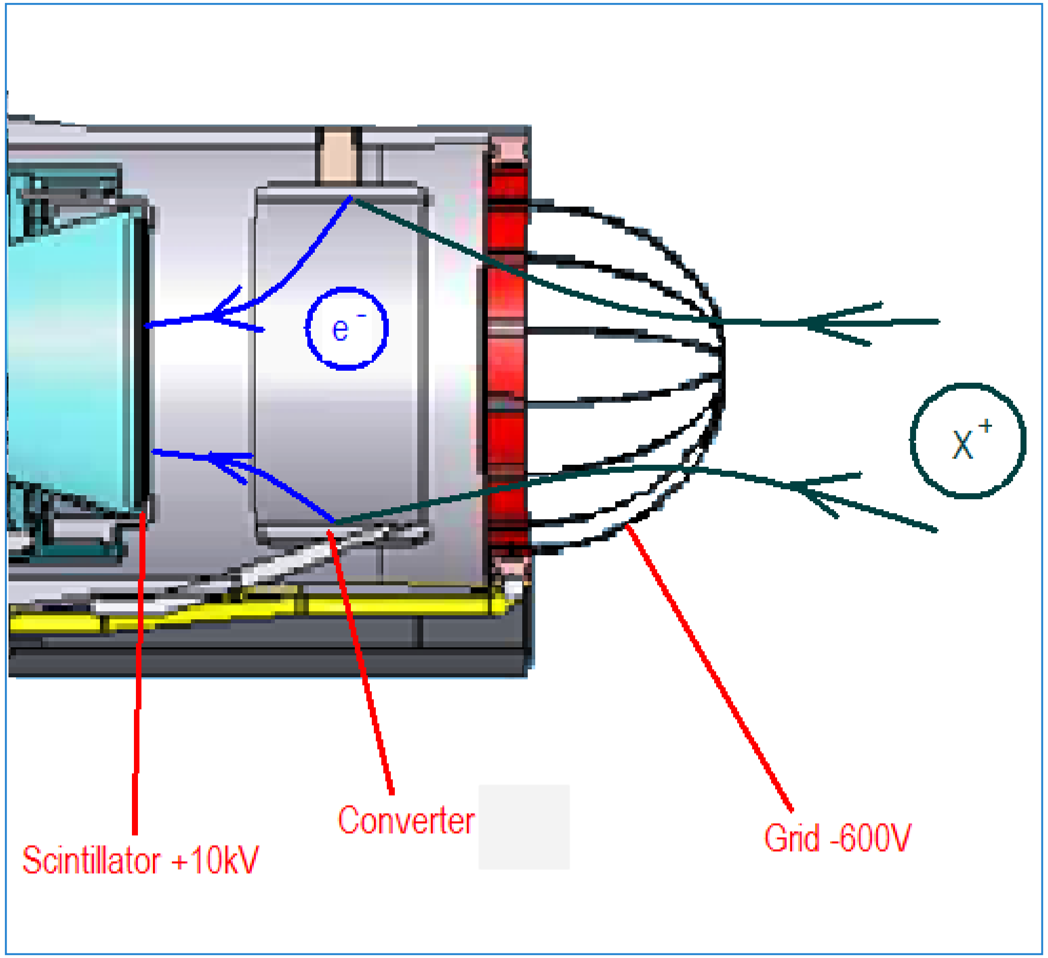
- Secondary Ion Mode
  - Detector biased negative
  - Images generated with I+
  - Emitted from top 0.5-1 nm
  - Very surface sensitive
  - No voltage-contrast
  - Oxides brighter
  - Less yield, so images noisier

ICE detector – working principle

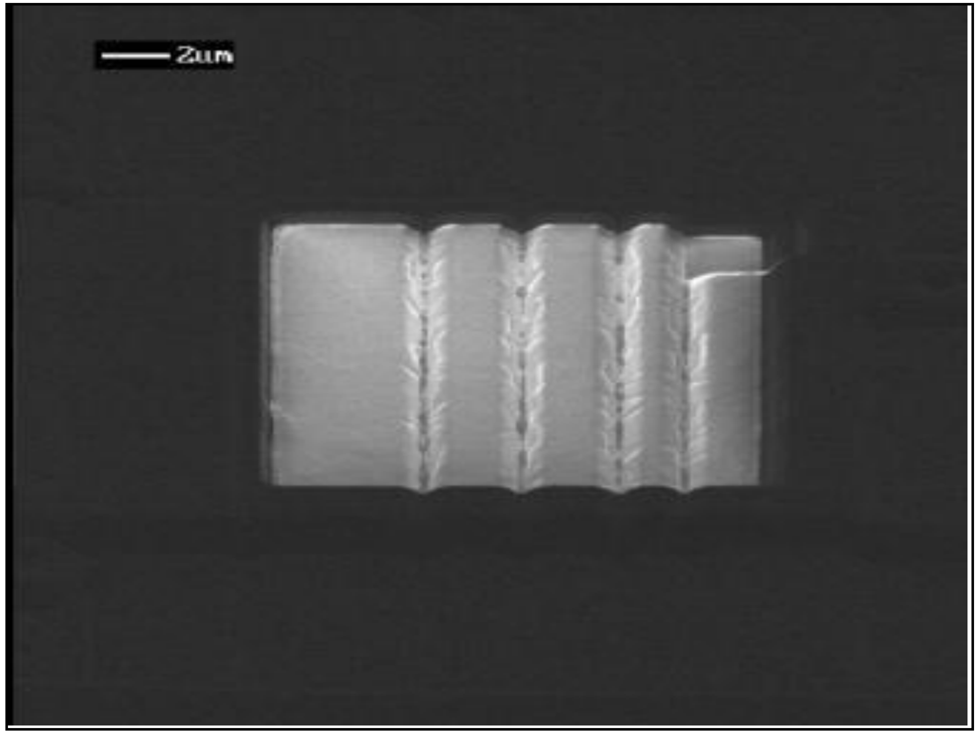
SE mode



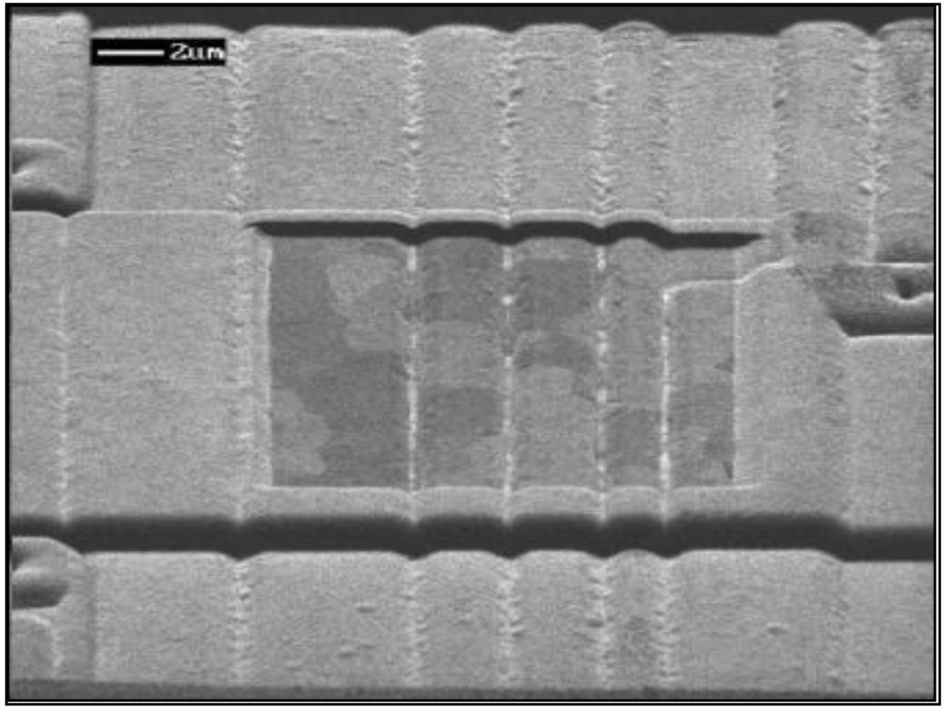
SI mode



SE v. SI Detector Modes

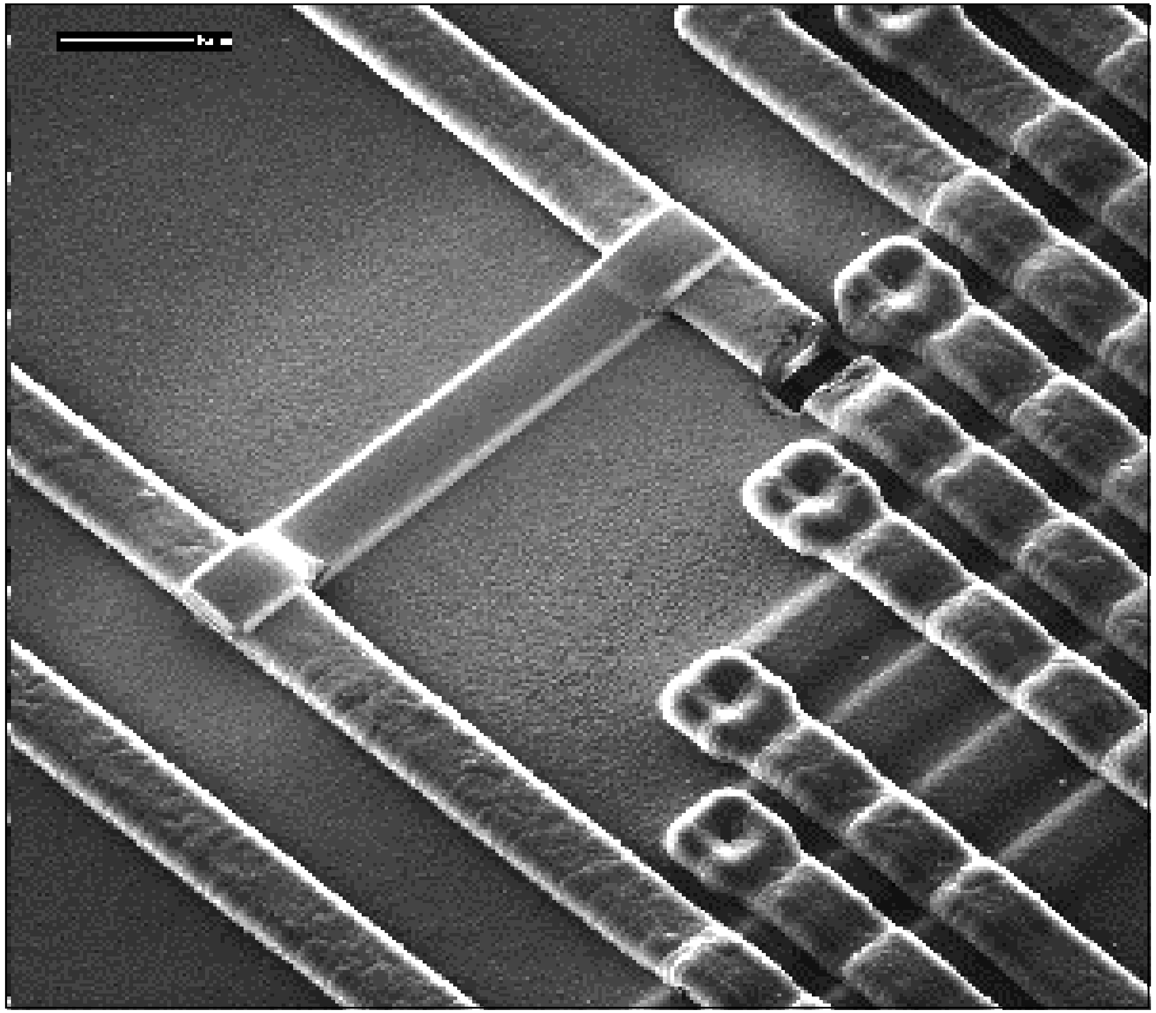


Secondary Electron

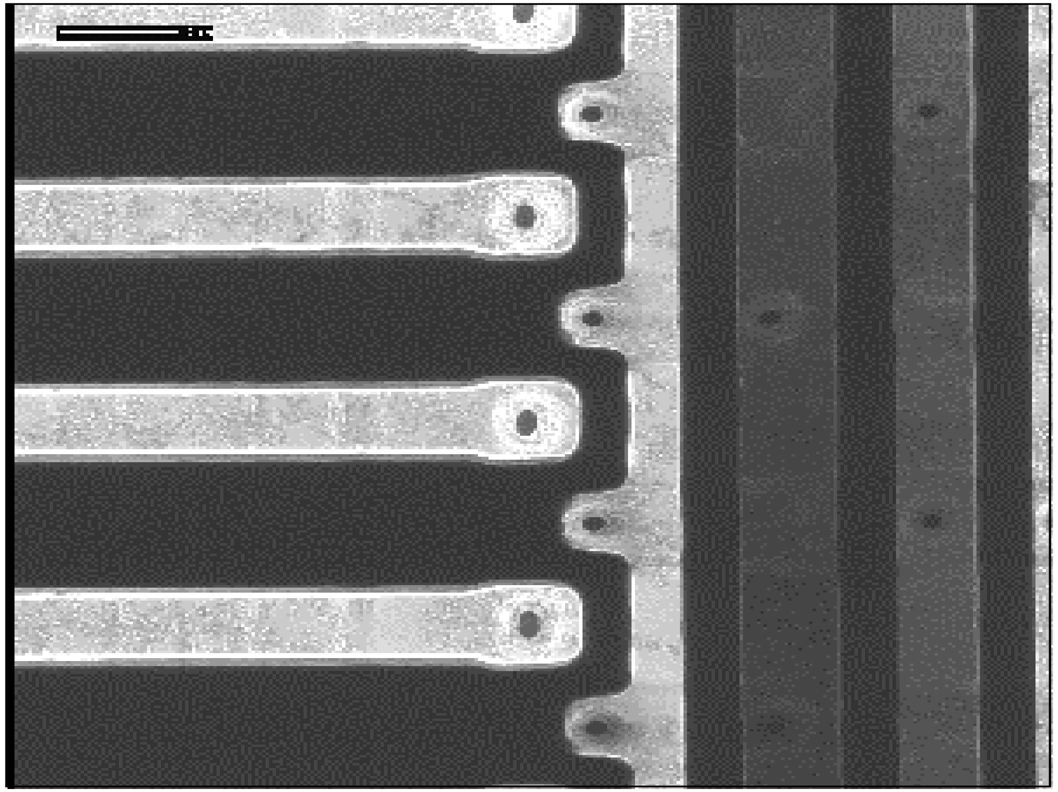


Secondary Ion

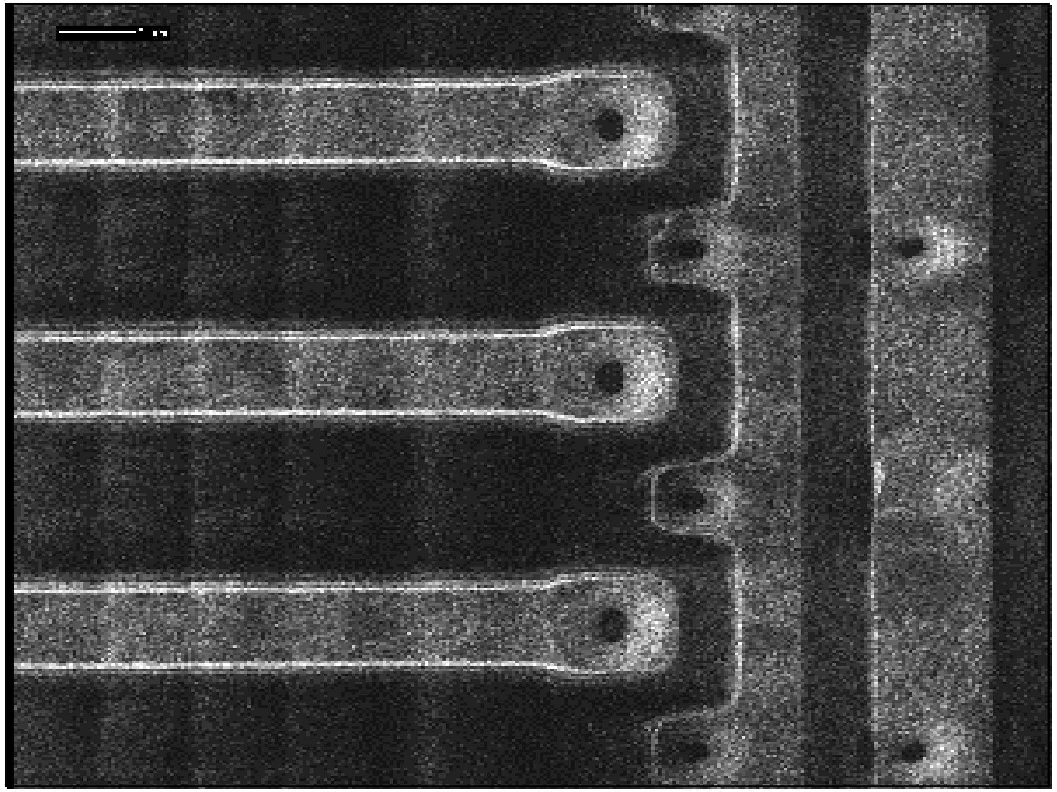
Topography



Contrast Mechanism 2: Voltage/Contrast

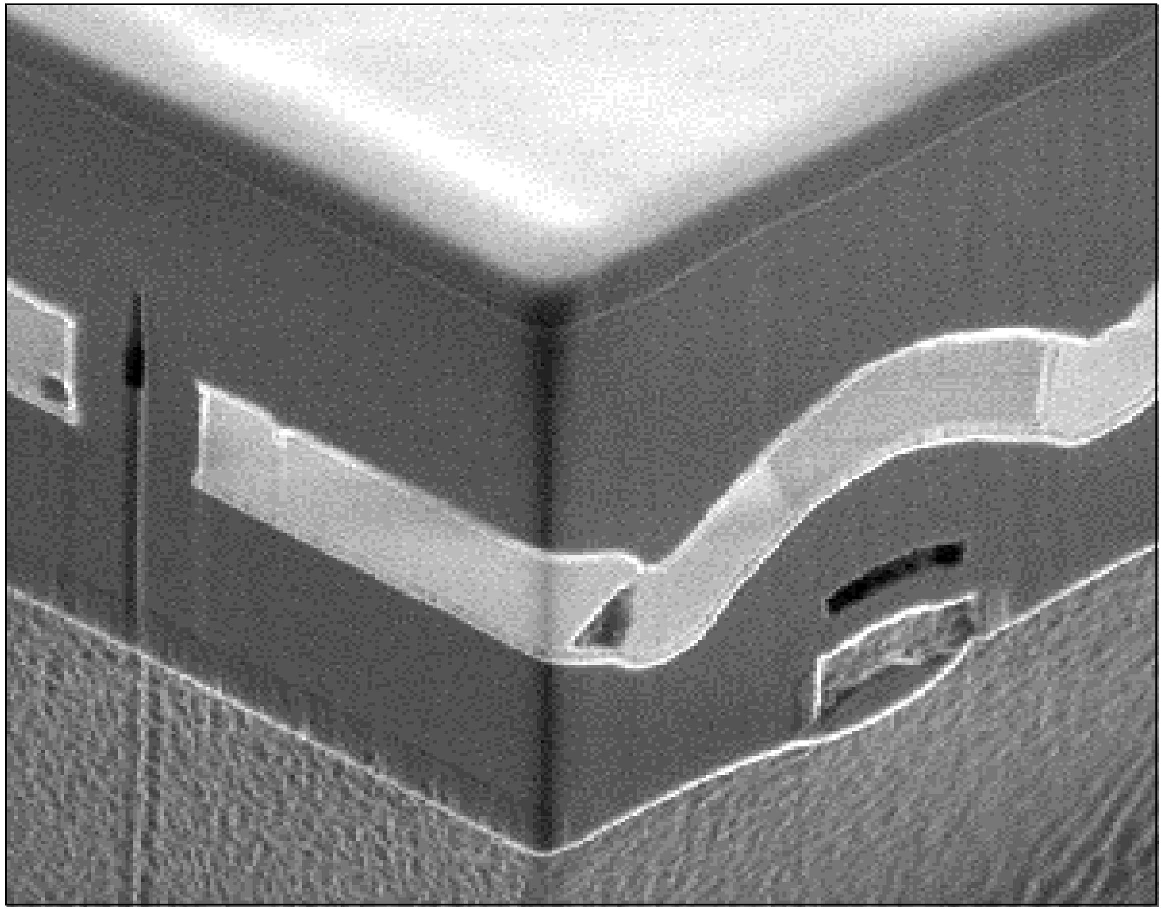


Secondary electron



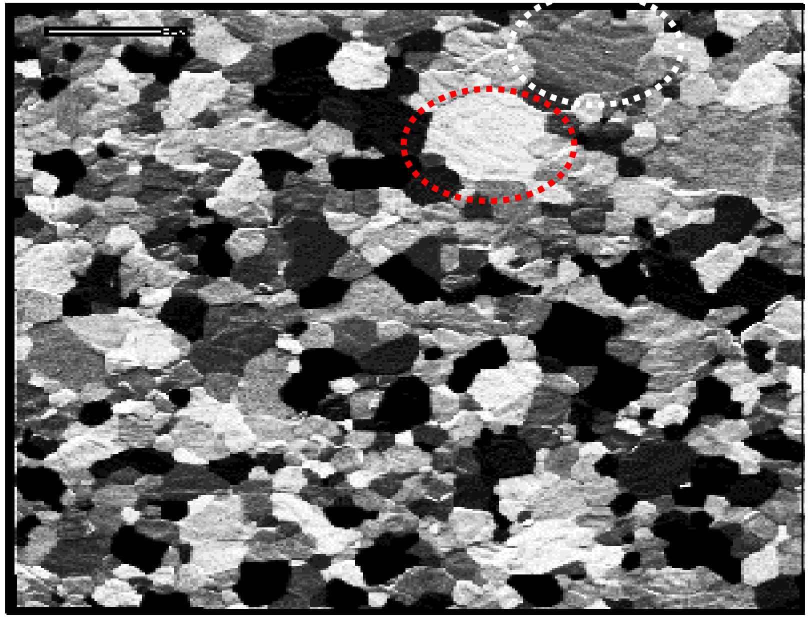
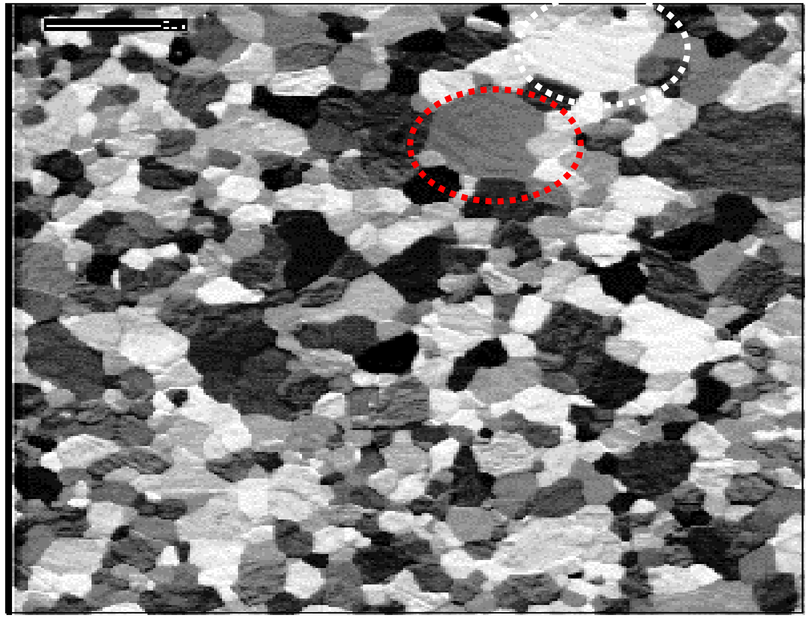
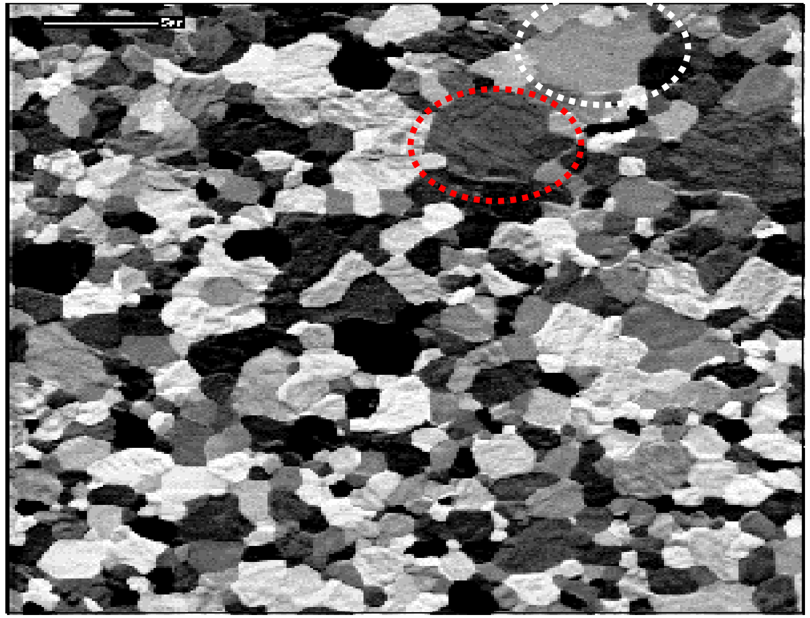
Secondary ion

Contrast Mechanism 3: SE/SI Yield

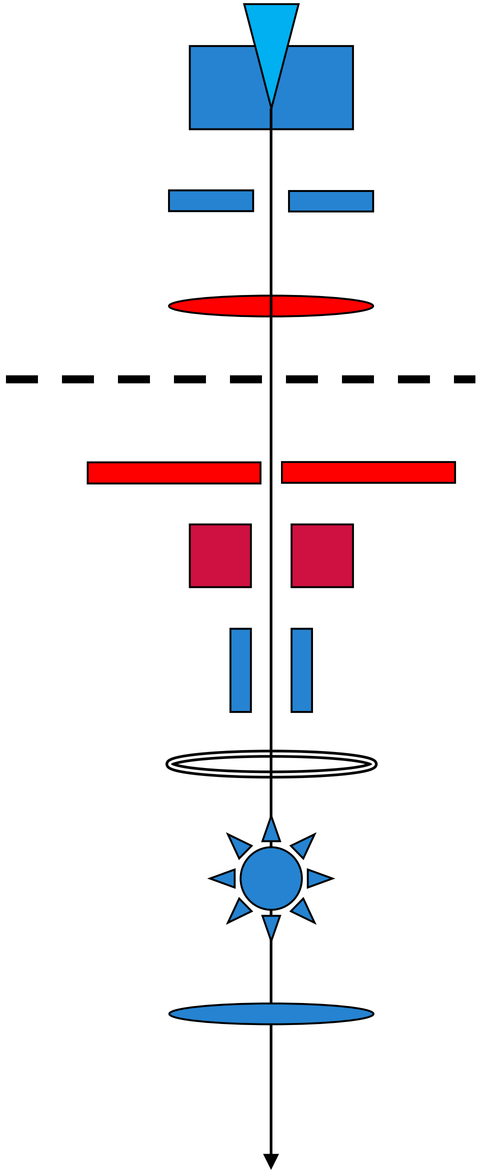


Contrast Mechanism 4: Channeling

- Tilt series

HC/HT Sidewinder



HT sidewinder:

maximum ion beam current of 65nA. HT sidewinder differs from the standard sidewinder in BAA size and beam limiting aperture strip.

Ion Beam alignments – Why?

- Ion column user alignment is VERY important for the successful performance of *automatic* scripts, e.g. AutoTEM and AutoFIB/ iFAST

- The ion beam alignment also affects the beam profile what is important for patterning.

- Using aligned ion beam will minimize the ion beam damage

When all alignments are done properly,

- the image will *stay in focus* while changing ion beam currents and beam energy (when sample is at the eucentric height), and

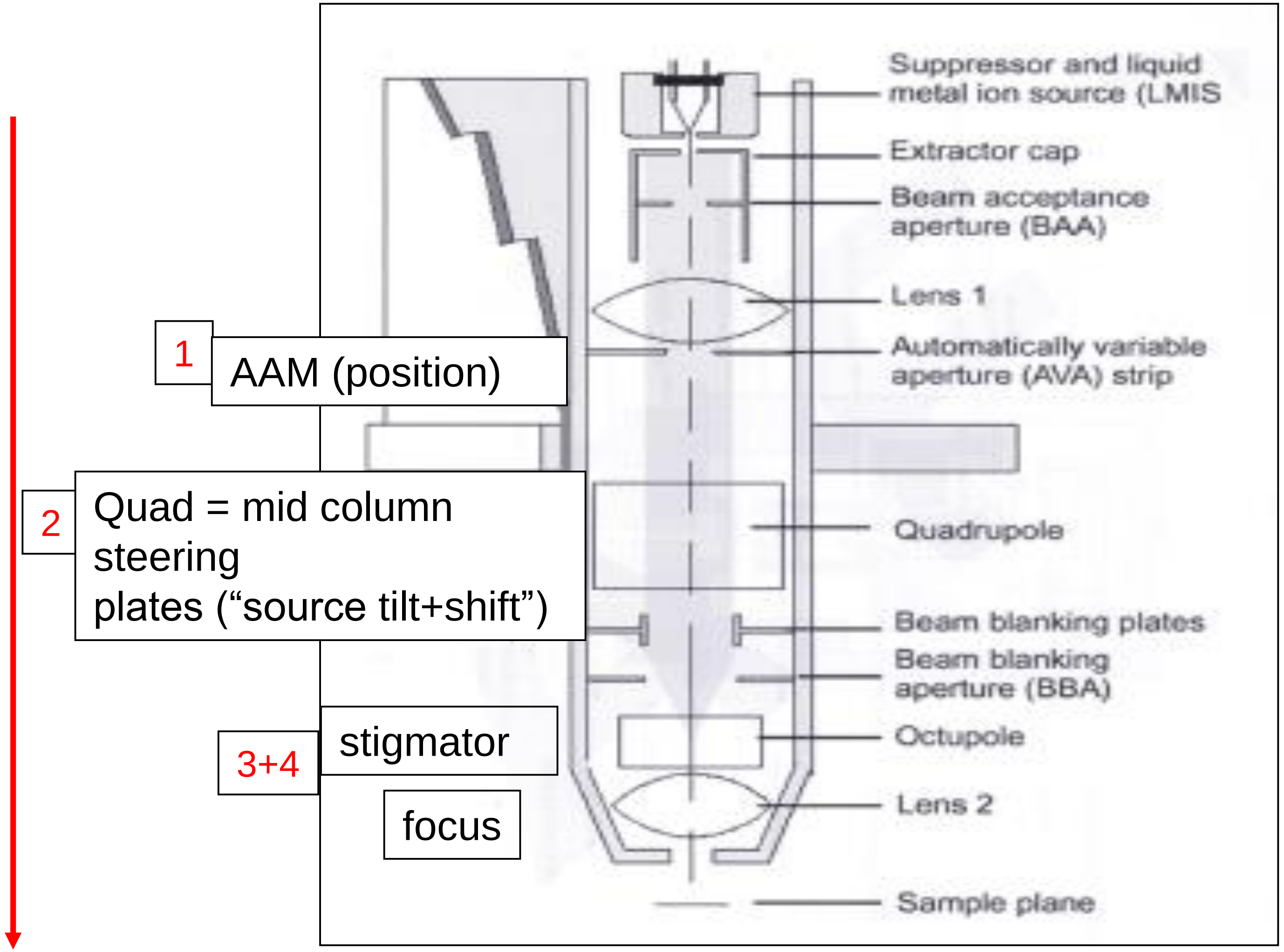
- the feature should stay exactly under the central cross while changing beam current and beam energy
- If it not, alignments need to be done

Ion Beam alignments – How?

During ION beam alignments, for each of the ion beam apertures and ion beam energies:

- image motion is minimized
- beam stigmation and focus are adjusted
- image shift is corrected

1. Alignments from top to bottom
2. Start at 30kV 100pA, than first to lower currents
3. Back to 100pA, than the higher currents



ThermoFisher SCIENTIFIC

Set-up Alignments (HC) Sidewinder

- (Make User data backup before the alignments)
- Use the Silicon sample with the crosses
- Reference points: e-beam=20kV+200pA/400pA, i-beam=30kV+100pA/300pA
- Set coincidence point using e-beam + Z (height) adjustment

note: zero e-beam shift + uncheck compu tilt (navigation control page) before setting beam coinc. point

- Go to quad 2 for i-beam alignments (full frame)
- Ion beam alignments in quad 2 @ 52° tilt
- Zero Beam Shift and Stigmator for ion beam
- Centre feature (stage) and press Ctrl+F WD ion=19mm

Ready for alignments!

Go to alignment 210 - ION: Beam Alignment

1. Start alignment with focus+stig (save)
2. Check aperture position. Correct any movement using

   2D-box (carefully) or wheels of AAS. When no movement;
3. Go to Quad and correct any movement
4. Go to StigSin and StigCos adjust if needed

   Go to stigmator and correct stigmator and focus (save)
5. When all beam currents are aligned,

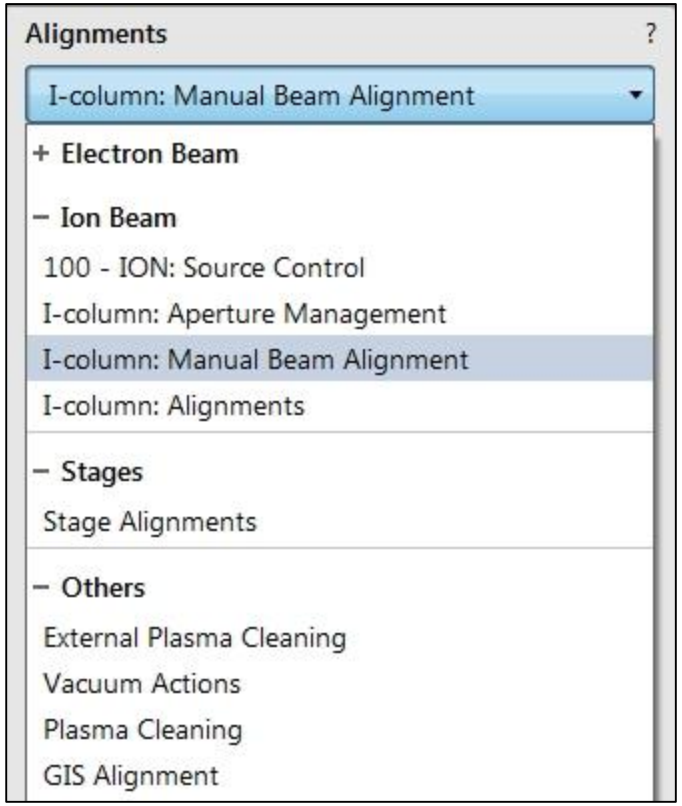
   than beam shift is corrected for the entire range

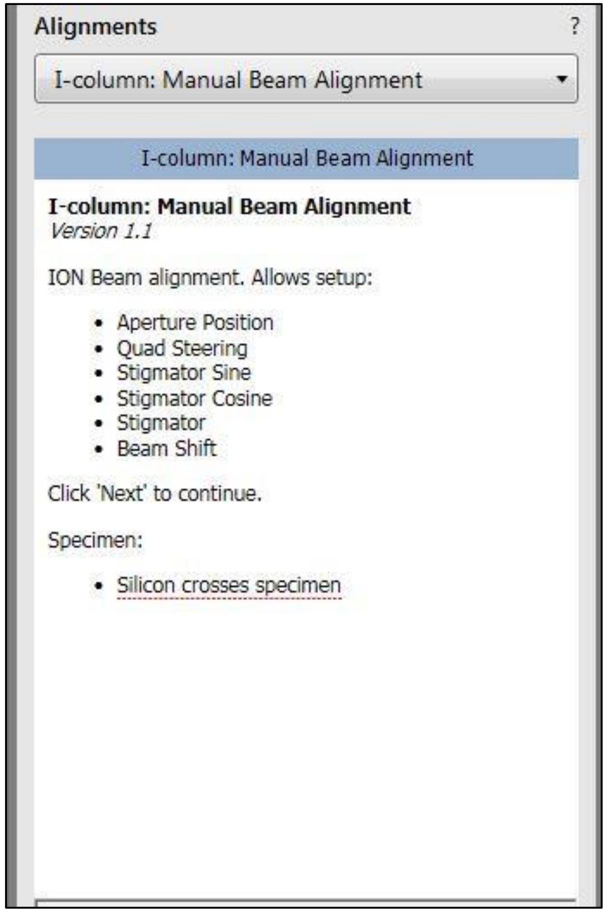
Alignments (HT) Sidewinder

NOTE: no interpolation between kV’s

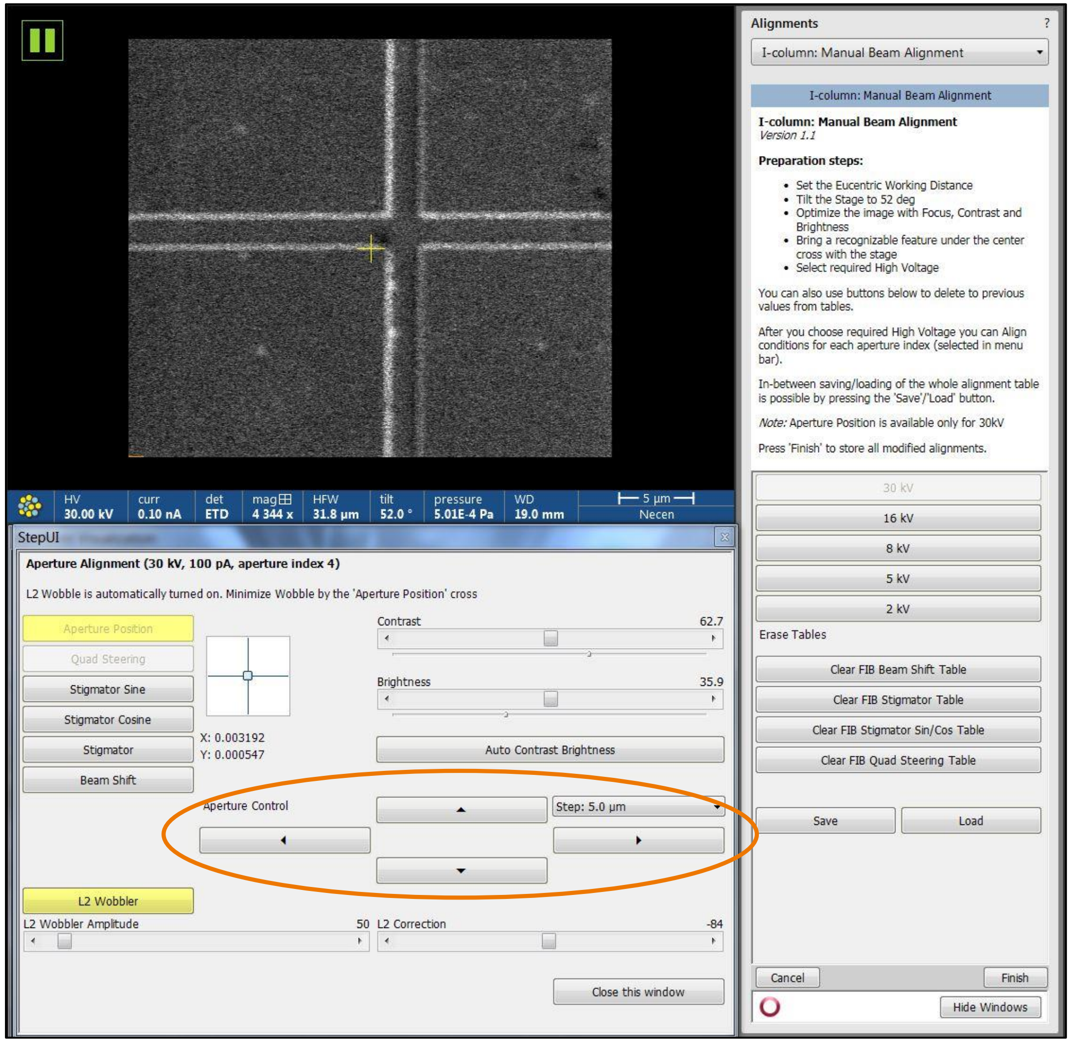
- 30kV alignment completely
- For TEM prep:
  - 30kV – 300pA
  - 5kV - 48pA
  - 2kV - 27pA

Scios manual FIB alignments

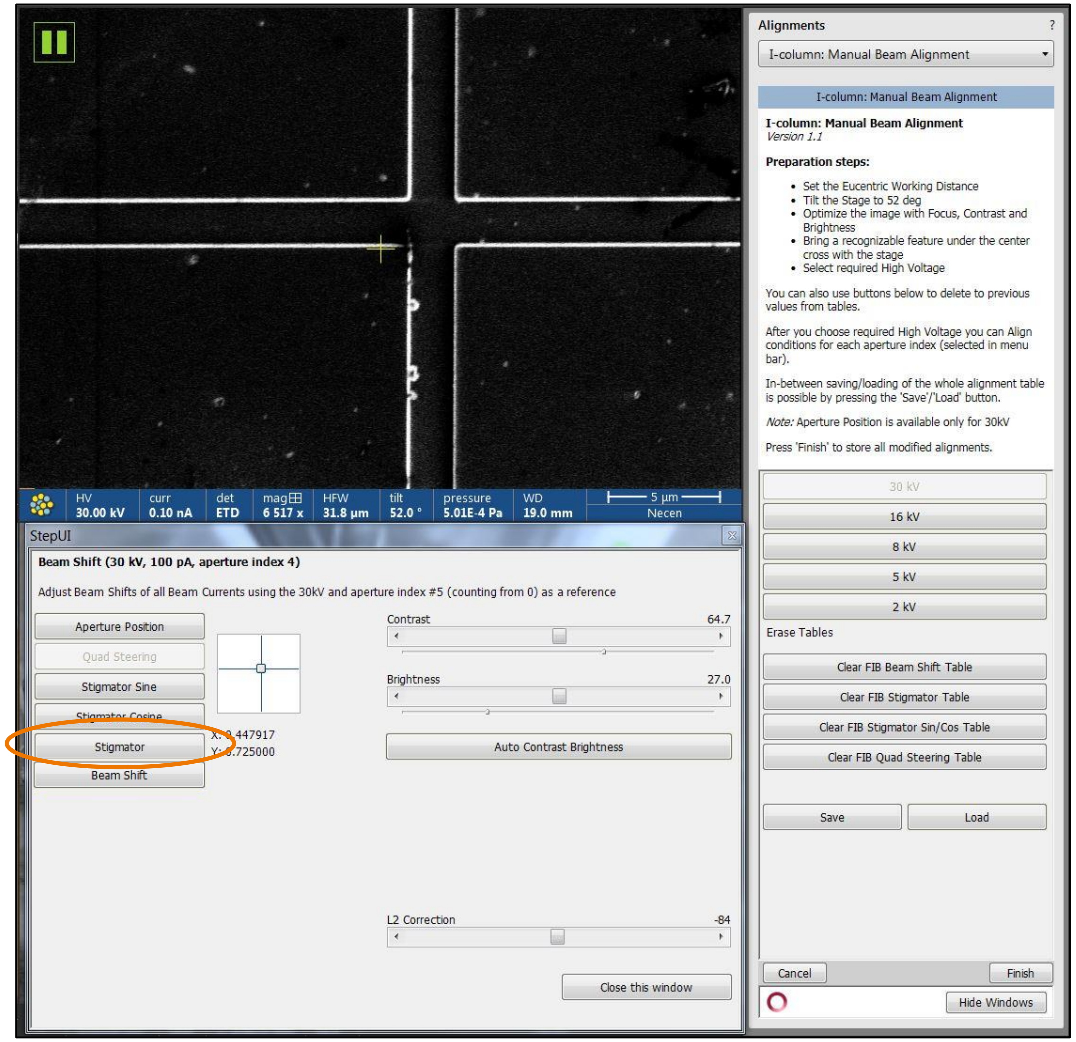




Scios manual FIB alignments

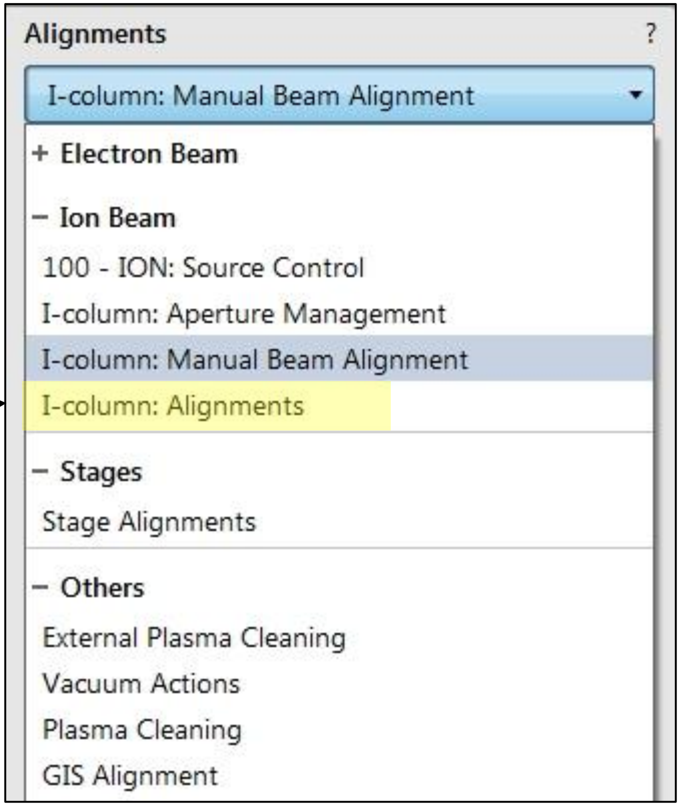


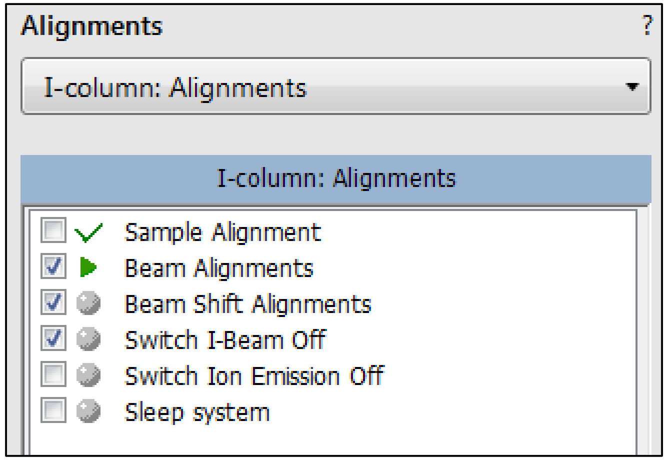
Aperture position is corrected by arrow keys



Stigmator is corrected by using 2D box

Scios automatic FIB alignments





Graphite pencil sample of DB test sample
Can be used to run the auto alignments.