Microfarbication by Micromachining and Deposition

FIB Applications I

- Principle of micromachining and deposition
- Mask repair
- IC chip modification
- Semiconductor failure analysis
- 3D microfabrication
- 2D nanofabriaction

Principle of micromachining and deposition

$$\text{Etch rate} = \frac{Y M m_p I}{A \rho e}$$

Y : yield rate of ion
M : atomic mass of solid surface
m_p : proton mass
A : area exposed to beam
ρ : density of solid surface
I : beam current
e : electron charge

Beam angle, scan rate

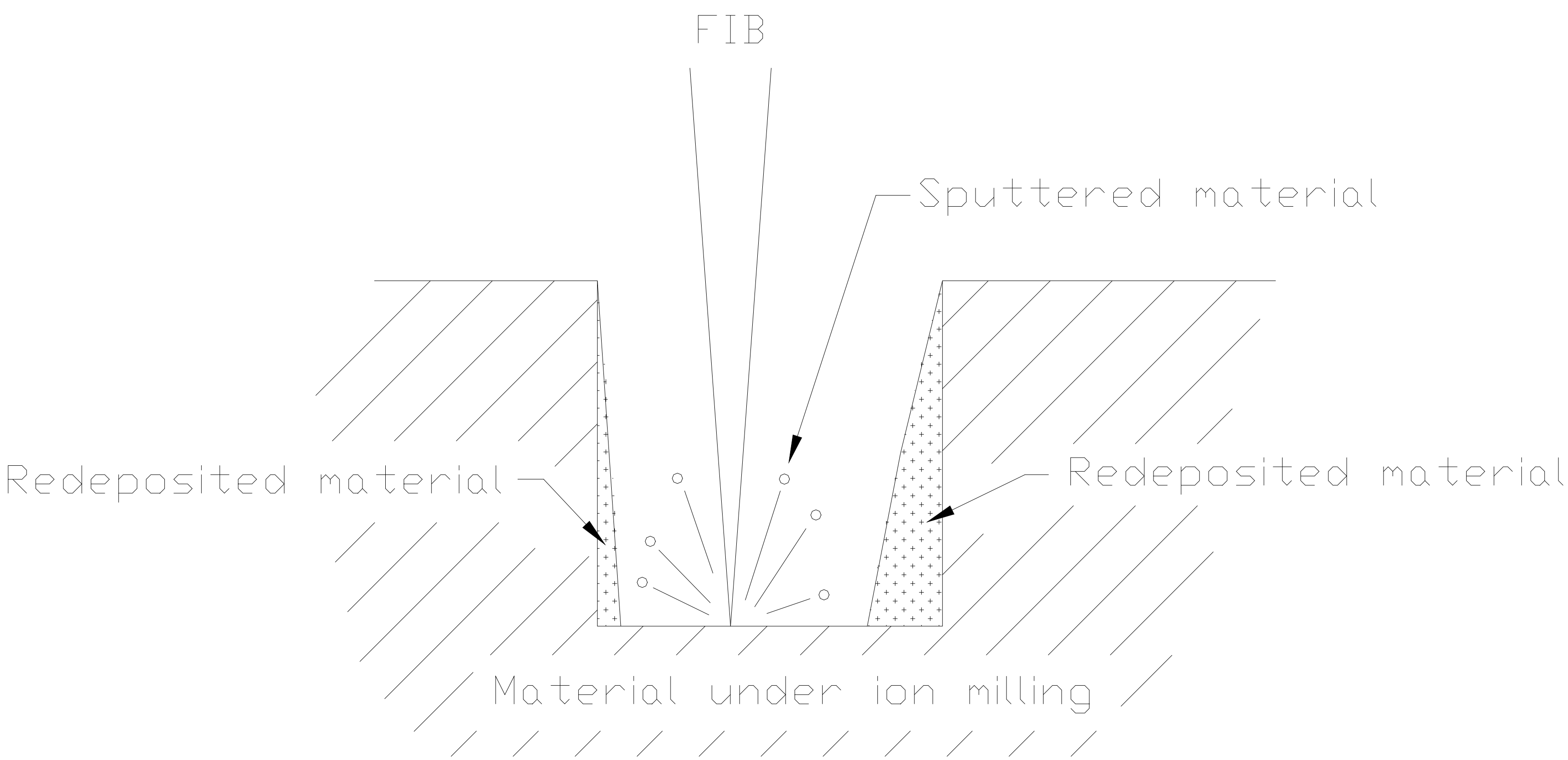
Imaging: Secondary electrons or ions produced by the incoming Ga^+ beam are collected to form an image of the sample.

Milling/Etching: FIB can locally etch the sample surface with submicron precision. Many variables and material properties affect the sputtering rate of a sample. These include beam current, sample density, sample atomic mass, and incoming ion mass. Ga^+ ion sources are the most widely used in commercially available FIBs.

Gas Assisted Etching: When a gas is introduced near the surface of the sample during milling, the sputtering yield can increase depending on the chemistry between the gas and the sample. This results in less redeposition and more efficient milling.

Deposition: Conductive or insulator material can also be deposited with the aid of a gas in close proximity to the sample surface. Metals often deposited are either Pt or W, while insulators are usually SiO_2 or TiO_2.

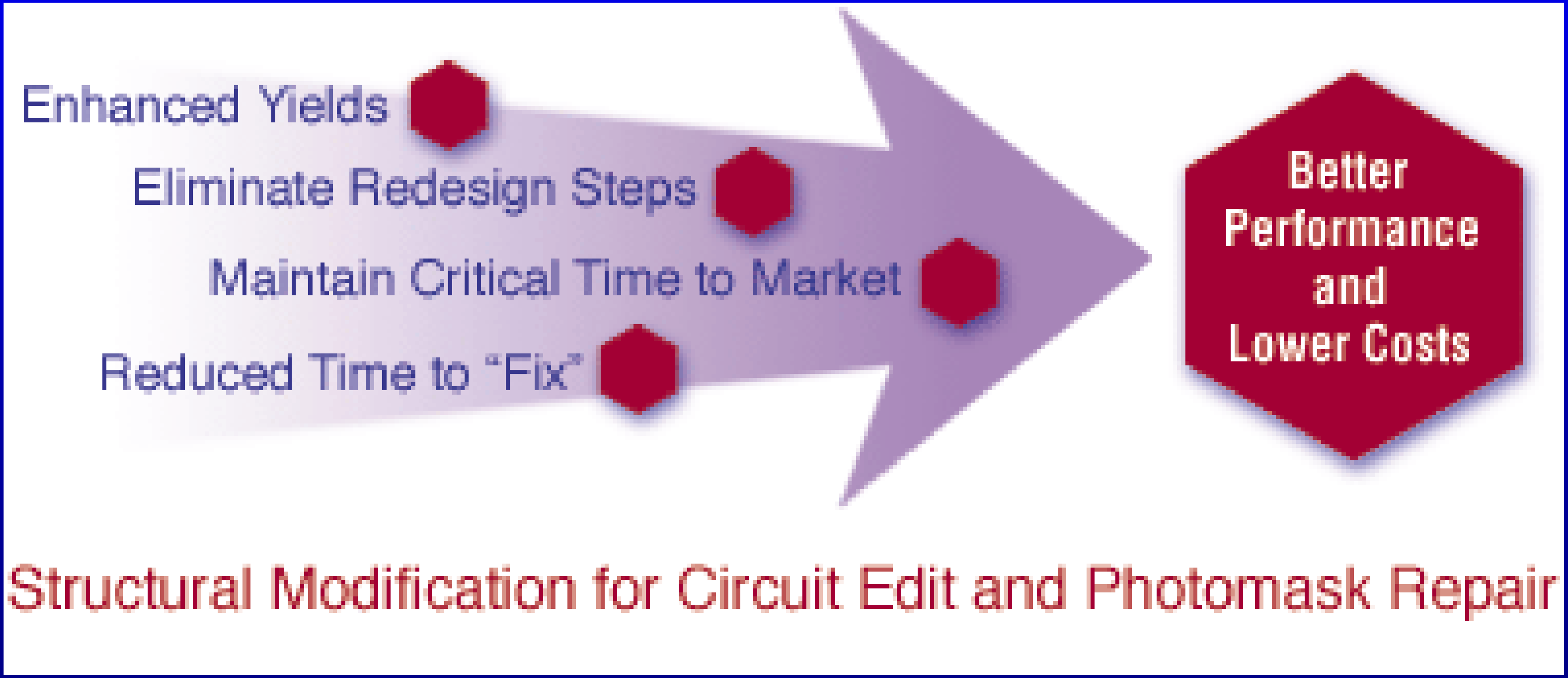
Redeposition effect: a negative issue



Redeposition effect of ion beam micromachining

Mask repair

Opaque and transparent repair



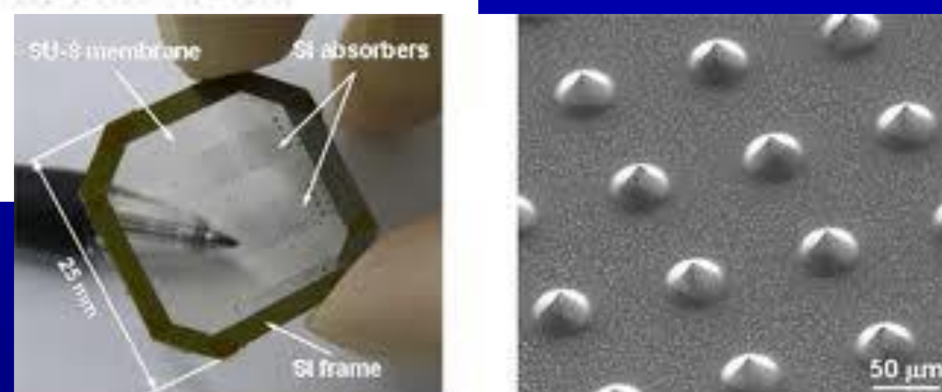
Method for mask repair

Deposition

Ion beam deposition principle

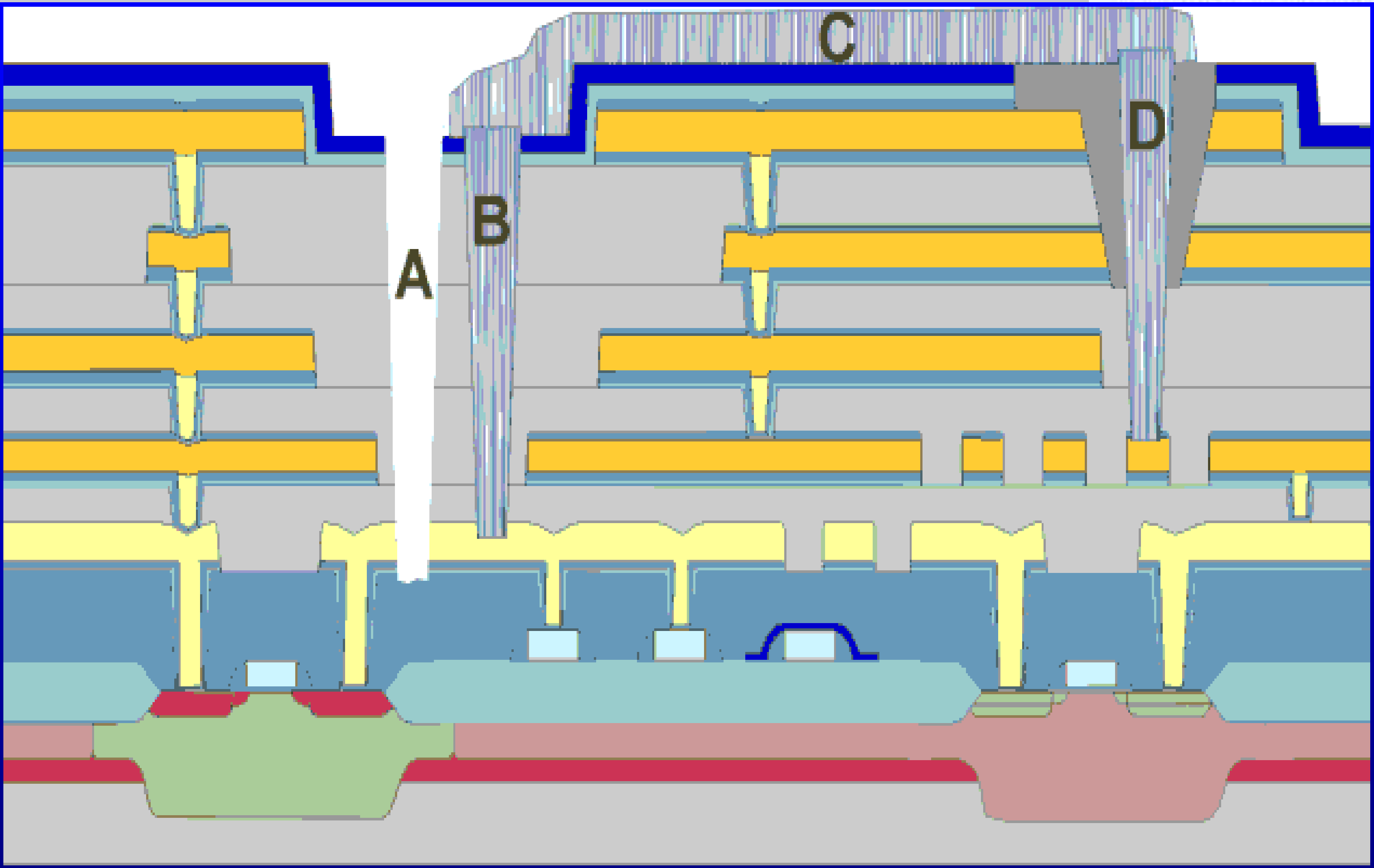
Chemical gas is decomposed under the ion beam sputtering process, and deposited on a defined area with certain defined shape.

X-ray Mask Repair



(a) (b)

IC Chip Modification by FIB

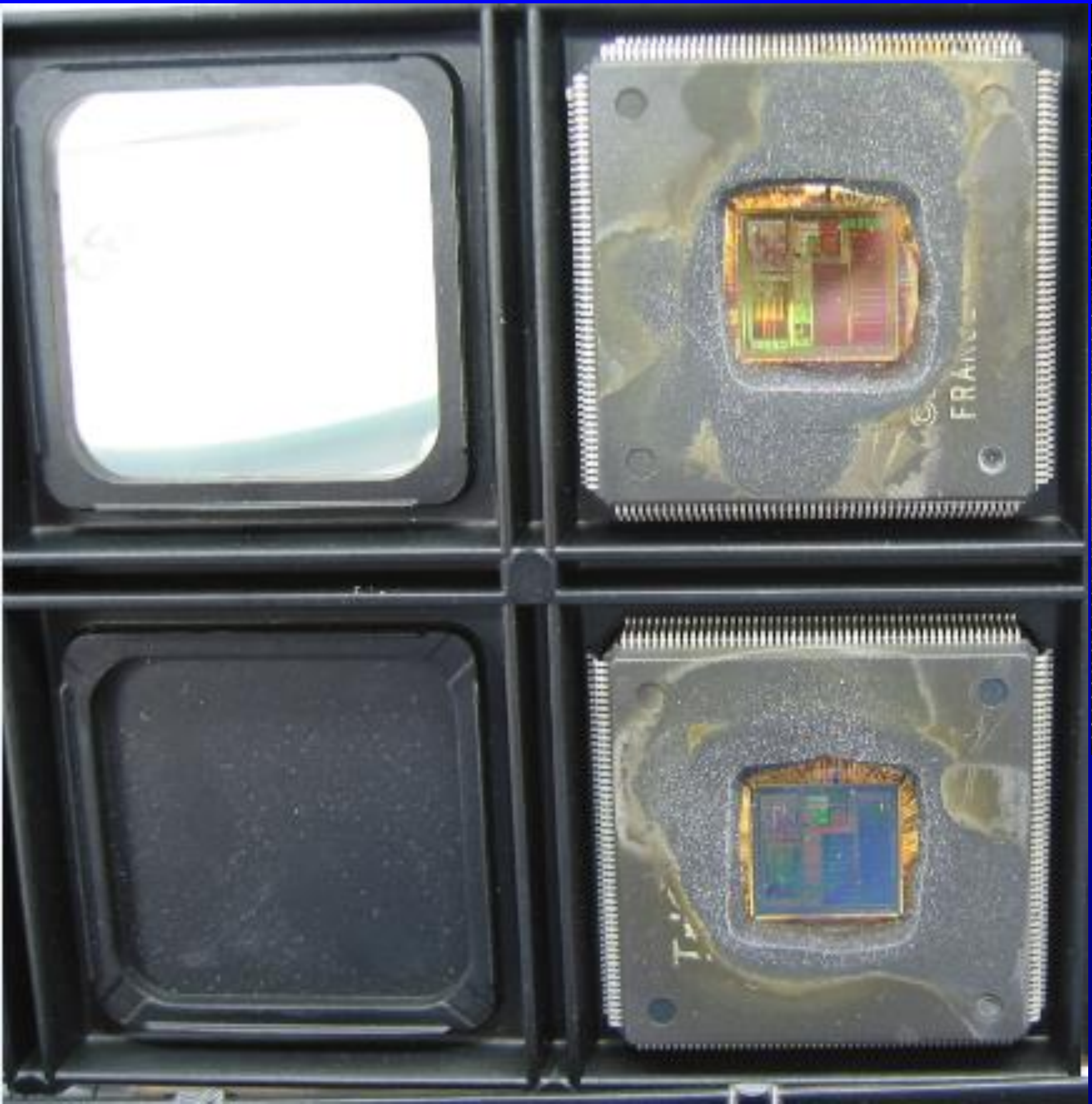


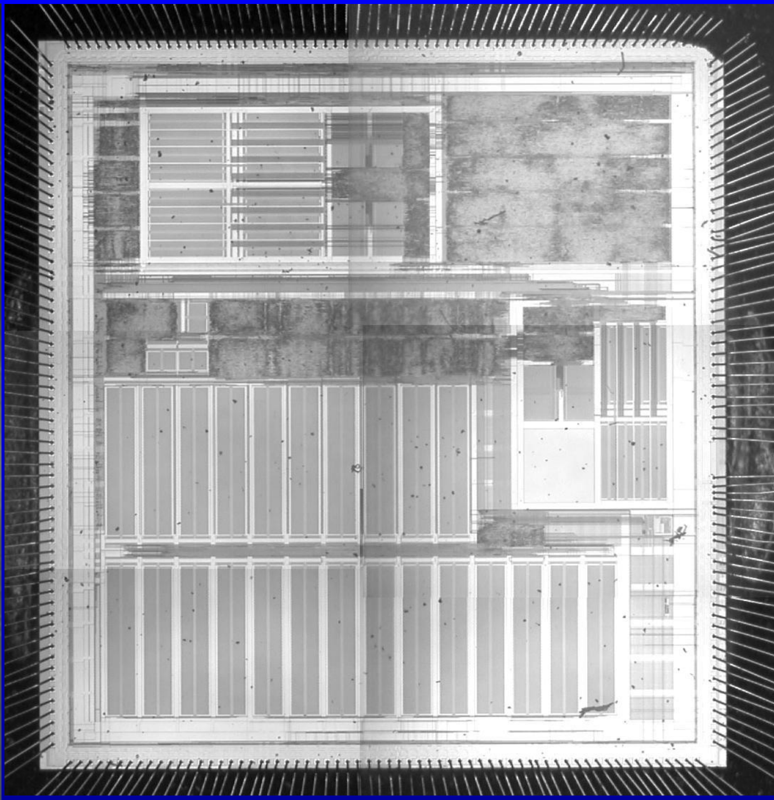
Schematic diagram of multi-layer IC chip modification

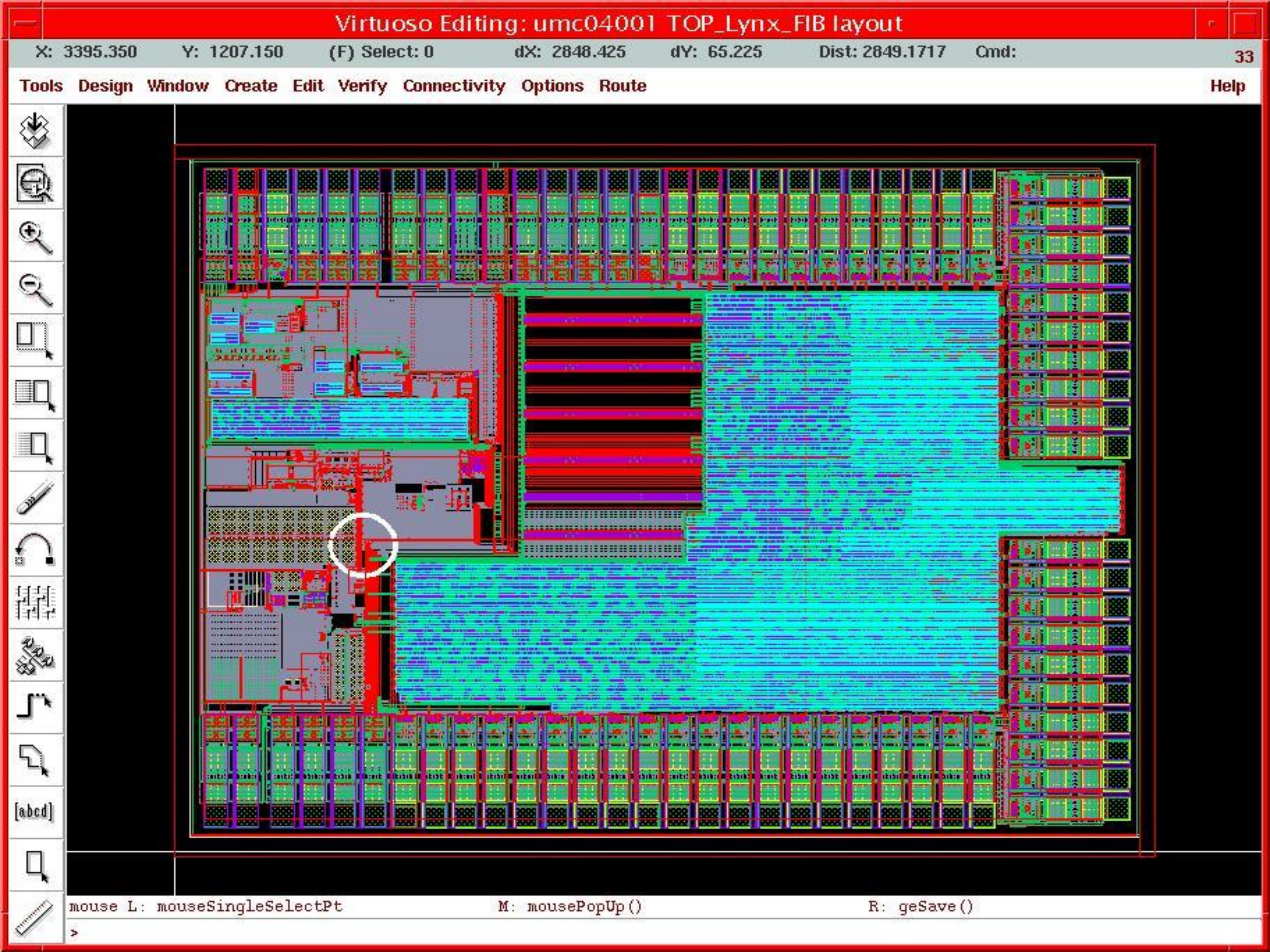
Two questions for the process:

1. How to accurately find the cutting or joining location?
2. How to know the end point from chip layout?

IC Chip Alignment in FIB



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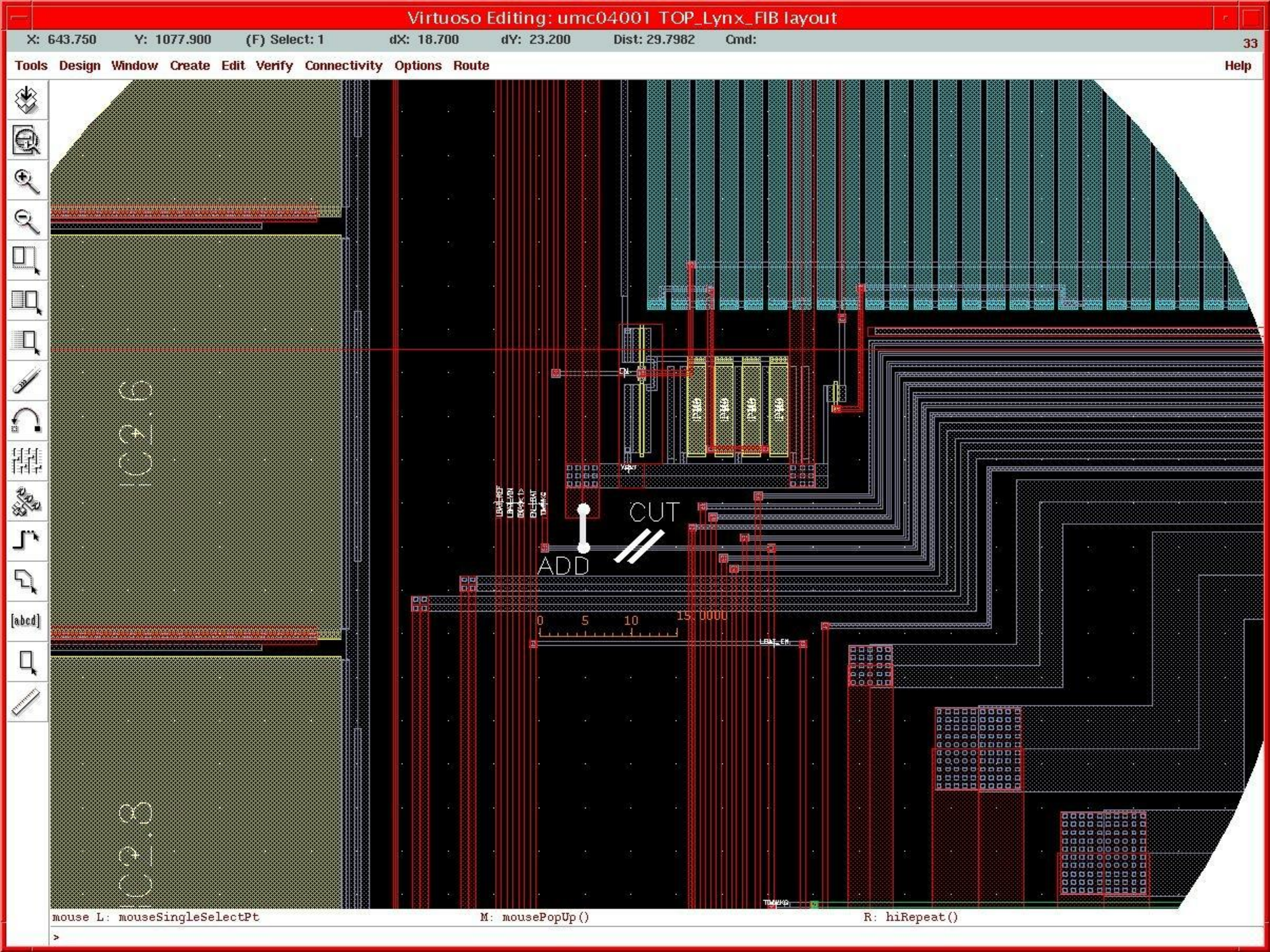
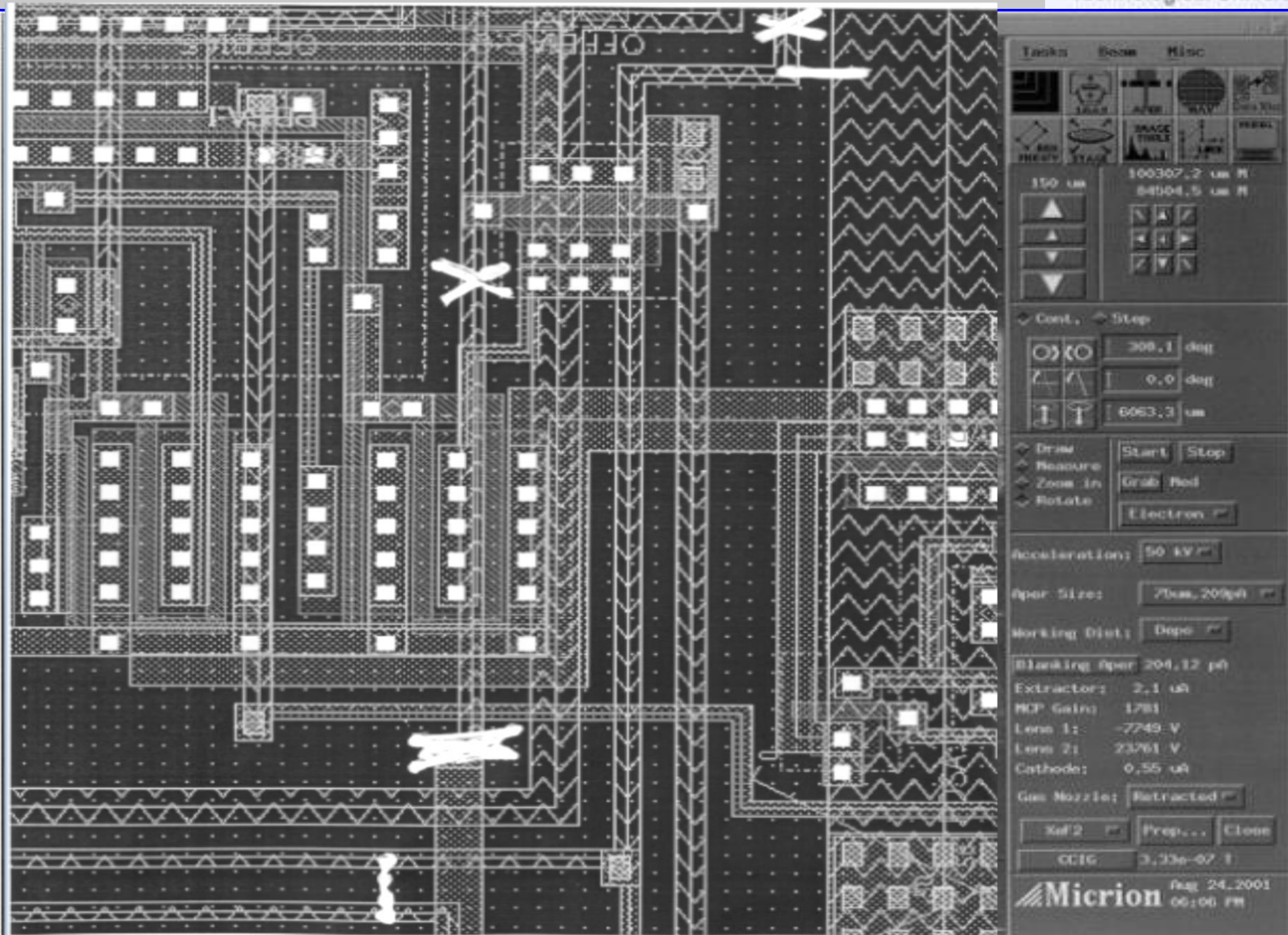
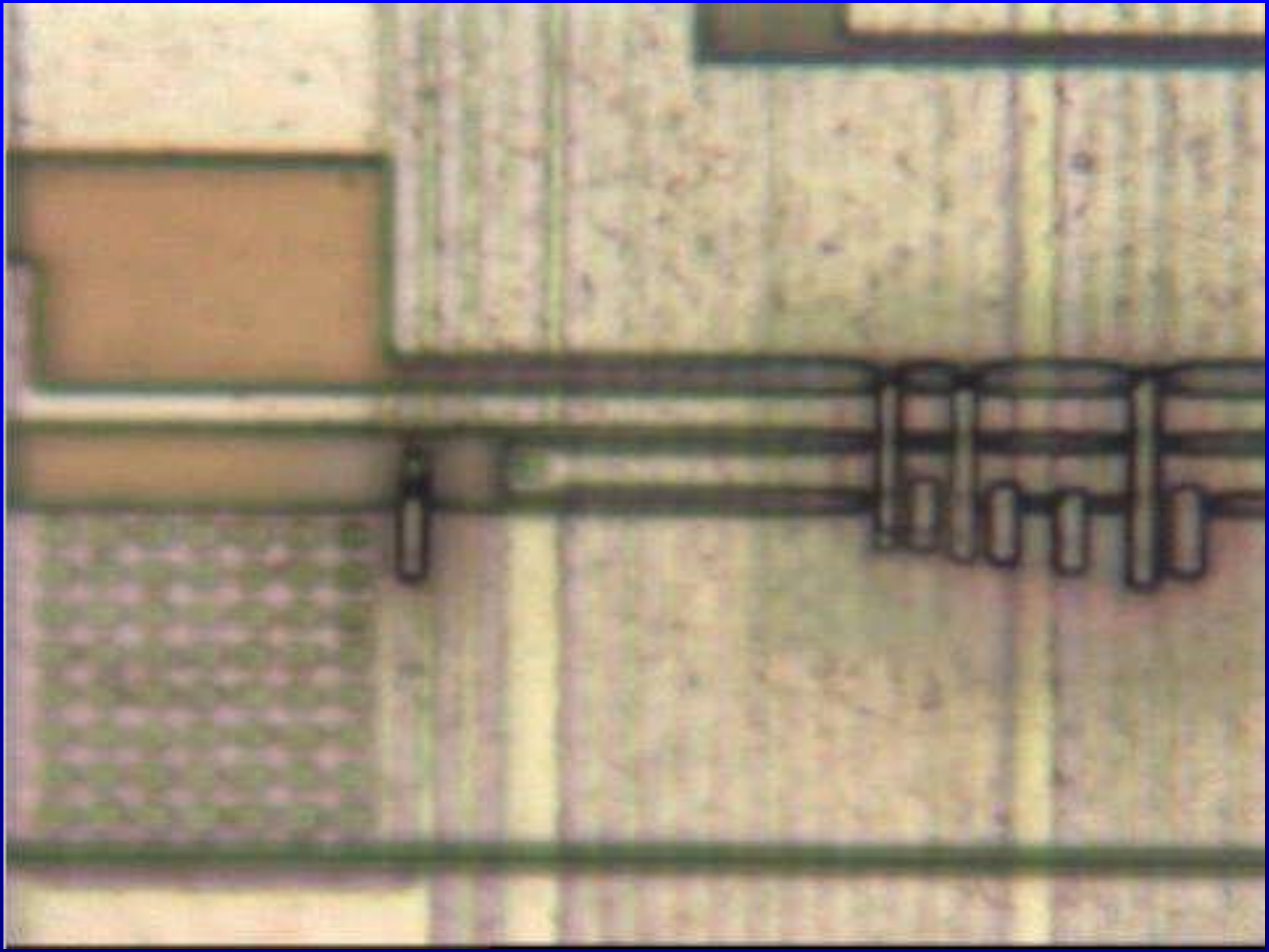
X: 3395.350 Y: 1207.150 (F) Select: 0 dX: 2848.425 dY: 65.225 Dist: 2849.1717 Cmd: 33
Tools Design Window Create Edit Verify Connectivity Options Route Help
mouse L: mouseSingleSelectPt M: mousePopUp() R: geSave()
>

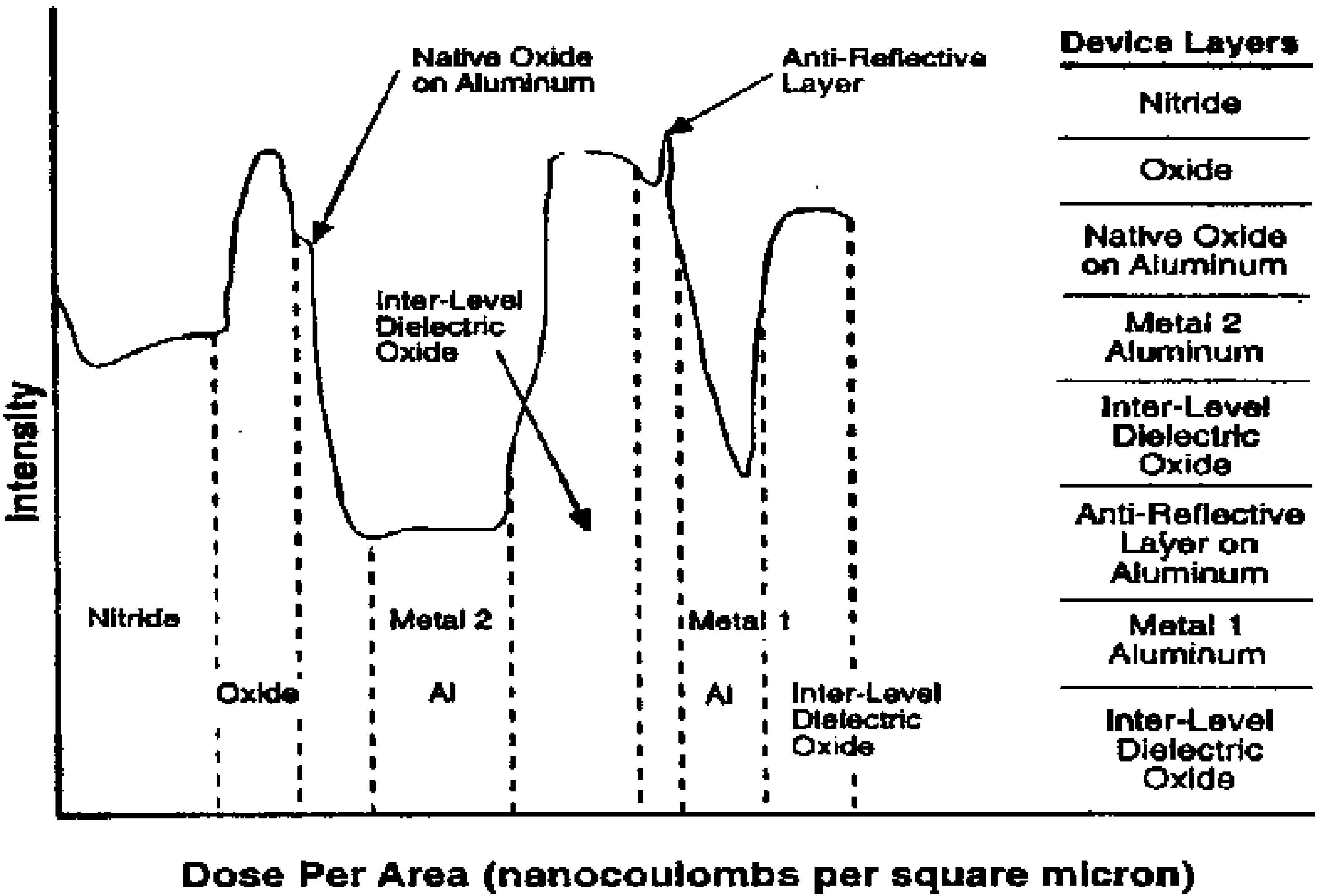

Virtuoso Editing: umc04001 TOP_Lynx_FIB layout
X: 643.750 Y: 1077.900 (F) Select: 1 dX: 18.700 dY: 23.200 Dist: 29.7982 Cmd:
33
Tools Design Window Create Edit Verify Connectivity Options Route
Help
CUT
ADD
0 5 10 15.0000
mouse L: mouseSingleSelectPt
M: mousePopUp()
R: hiRepeat()


Tasks Beam Misc
150 um
100307.2 um M
84504.5 um M
Cont. Step
308.1 deg
0.0 deg
6063.3 um
Draw
Measure
Zoom in
Rotate
Start Stop
Grab Med
Electron
Acceleration: 50 kV
Aper Size: 70um,209pA
Working Dist: Depo
Blanking Aper 204.12 pA
Extractor: 2.1 uA
MCP Gain: 1781
Lens 1: -7749 V
Lens 2: 23761 V
Cathode: 0.55 uA
Gas Nozzle: Retracted
XeF2 Prep... Close
CCIG 3.33e-07 T
Micrion Aug 24.2001 06:06 PM

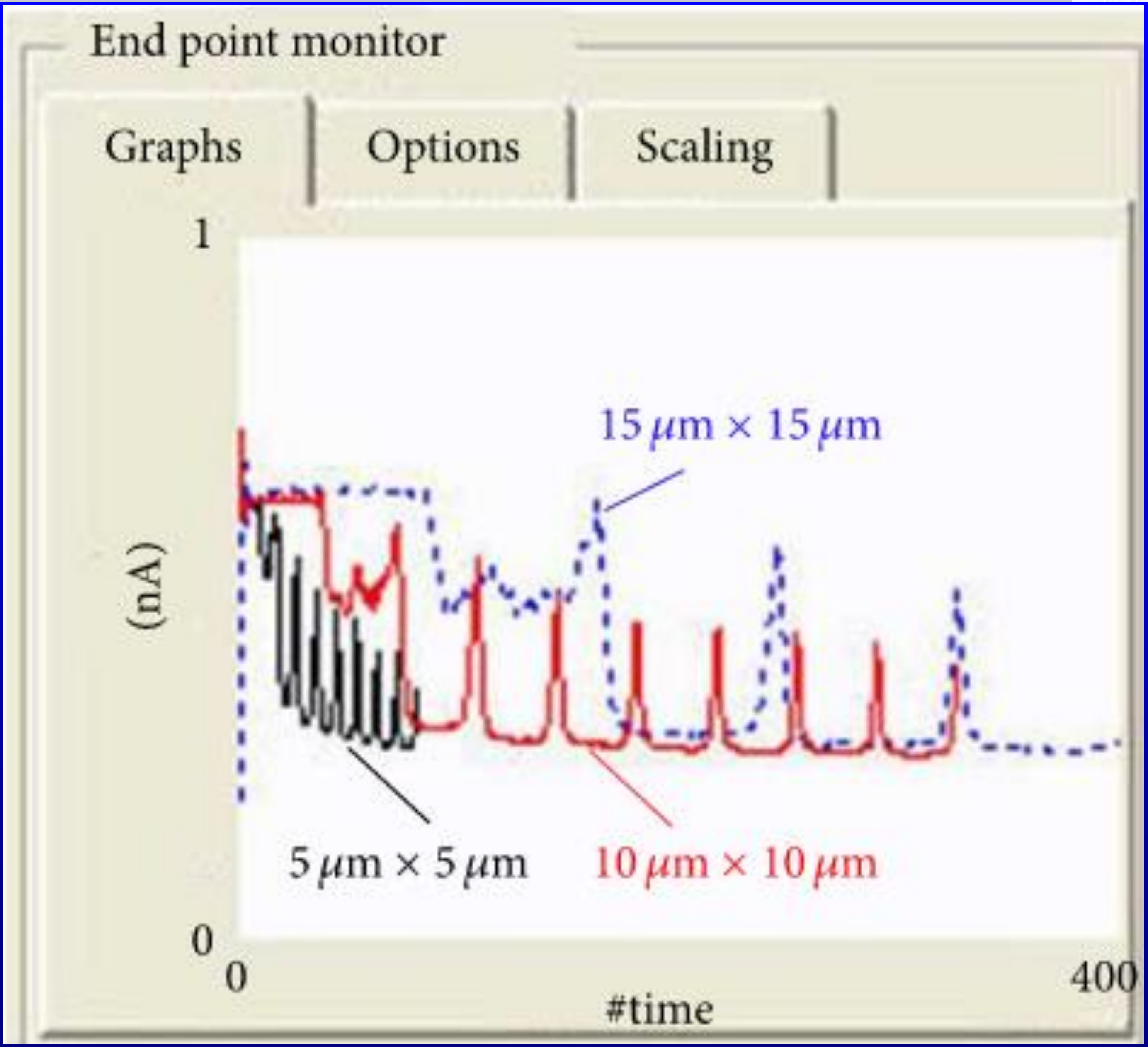
Completed IC FIB modification



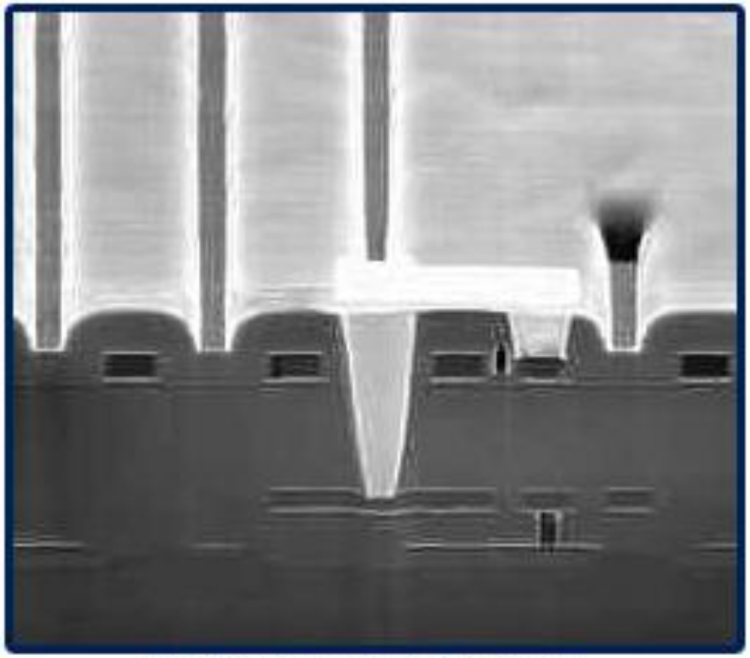
End Point Detection



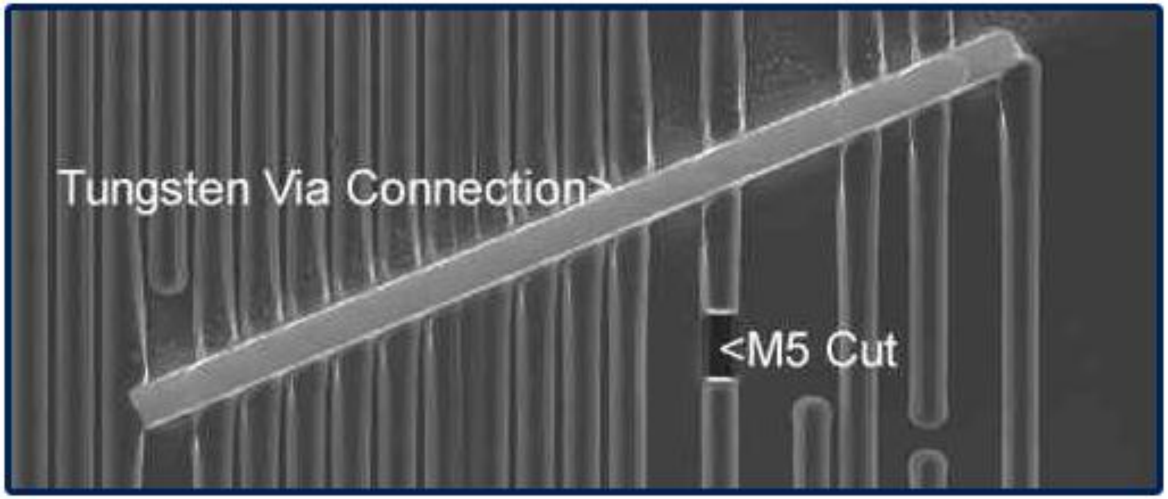
End Point Detection



IC chip modification



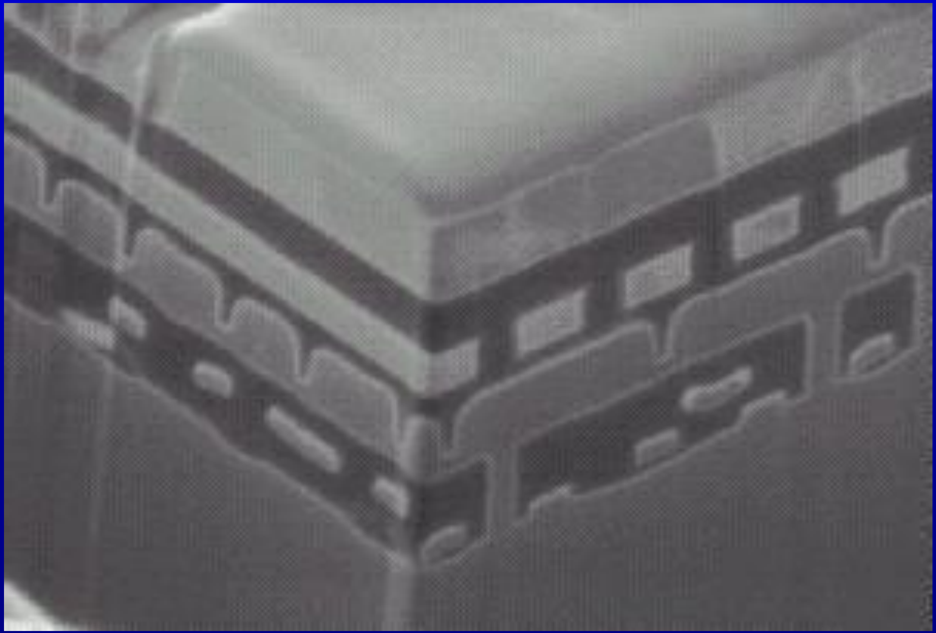
FIB Cross-section Showing
Device Modification



tungsten or silicon oxide

Rapid IC - Prototyping & Failure Analysis

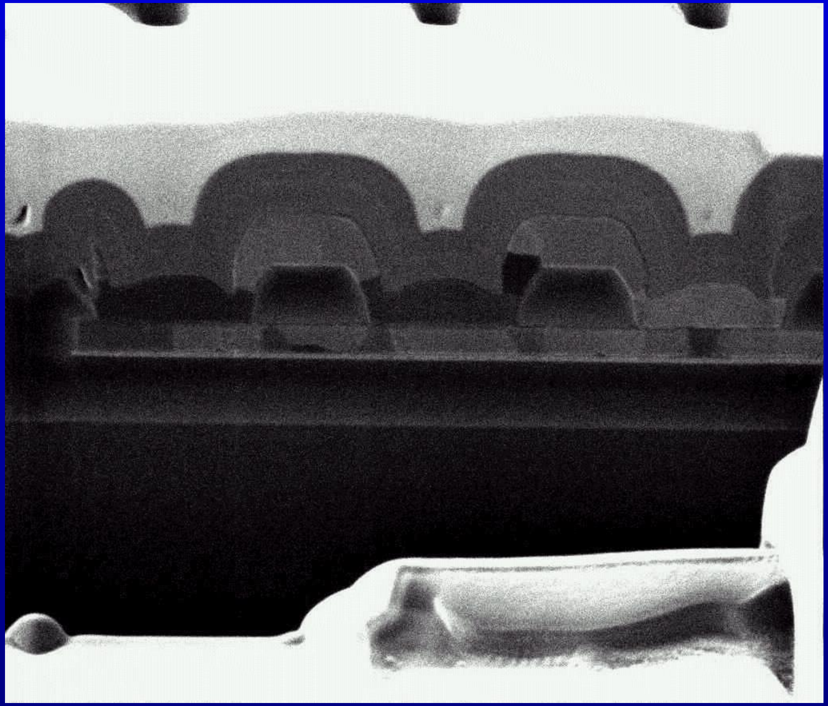
- FIB technology allows for fast failure analysis and circuit modification.
- FIB provides new access to prototyping of microsystems.
- Helps to shorten time-to-market for company ASICs.



Local cross sectioning of an integrated circuit

Advanced Focused Ion Beam Technology Provides:

- Local material removal on submicron scale
- Local deposition of conducting and insulating layers in direct writing mode
- In situ processing by high resolution secondary electron mapping

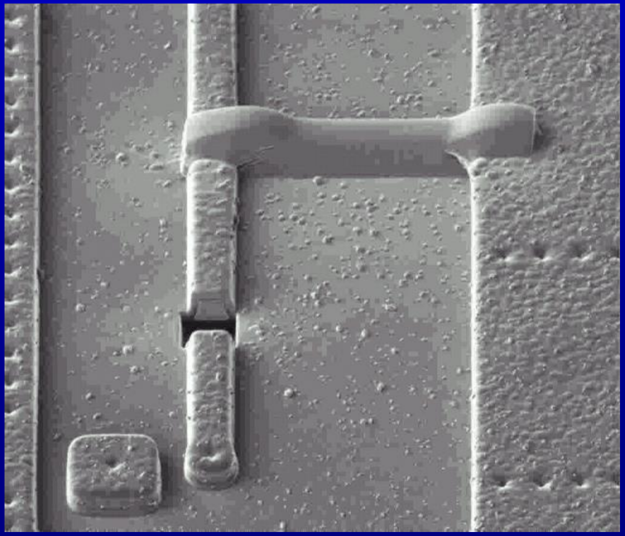


Local cross sectioning

Fast Verification of Design Changes: New device does not work properly. Rapid correction of the design and verify its function before starting a new process is required;

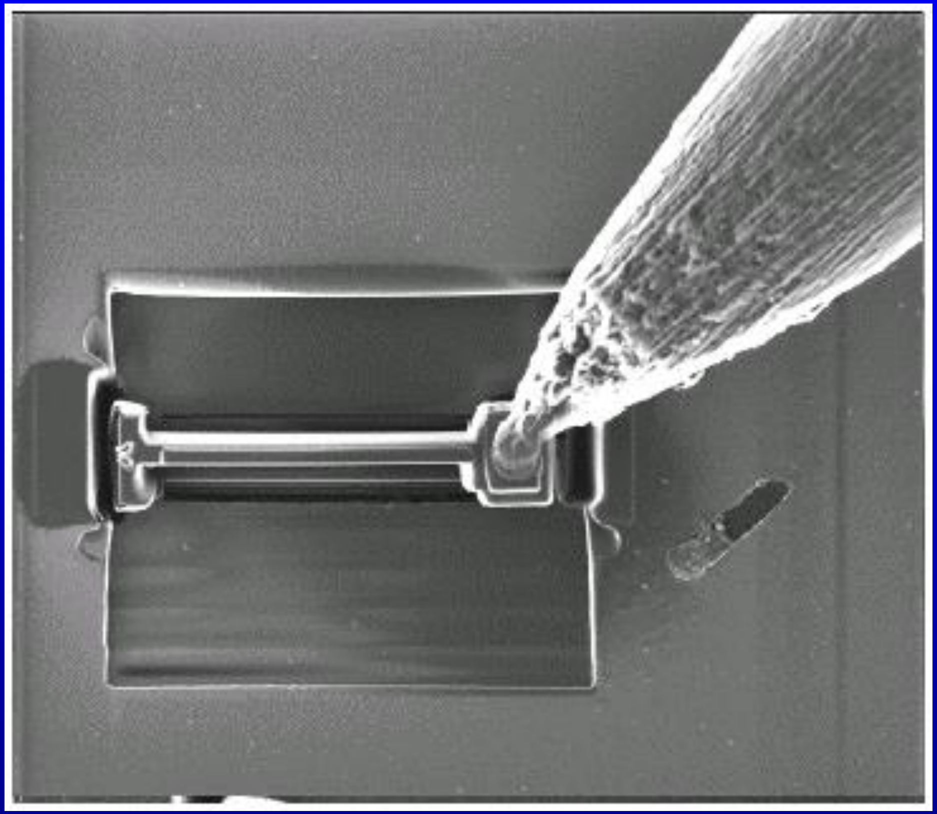
Using the redesign data, within a few hours, FIB modify the circuit by:

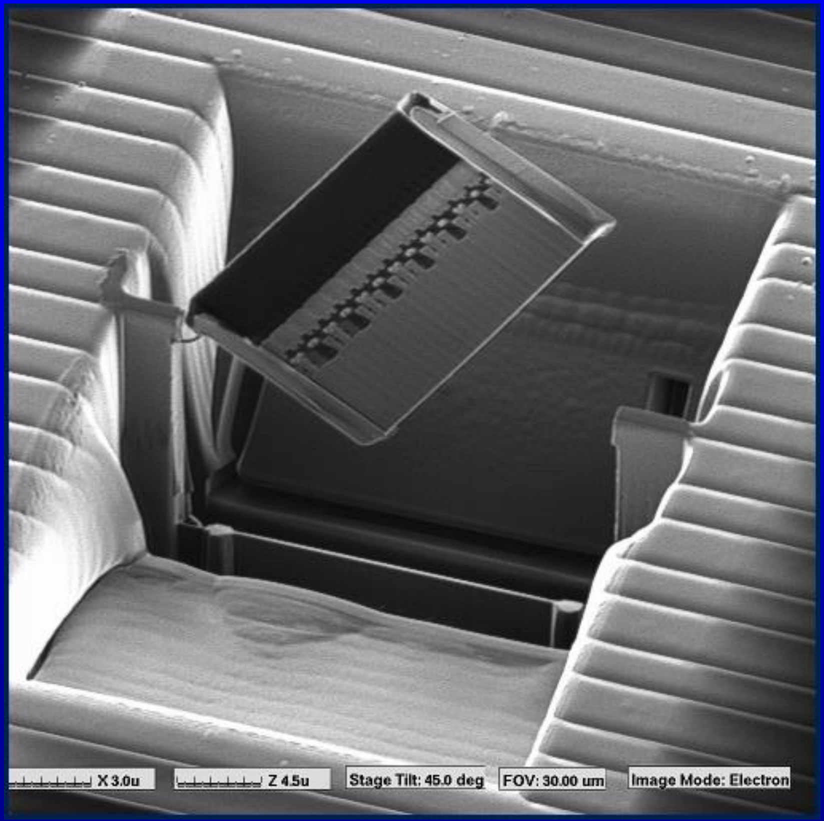
- Cutting metal lines by FIB - milling or gas enhancend etching
- Rewiring of the device by FIB - deposition of new metal interconnects



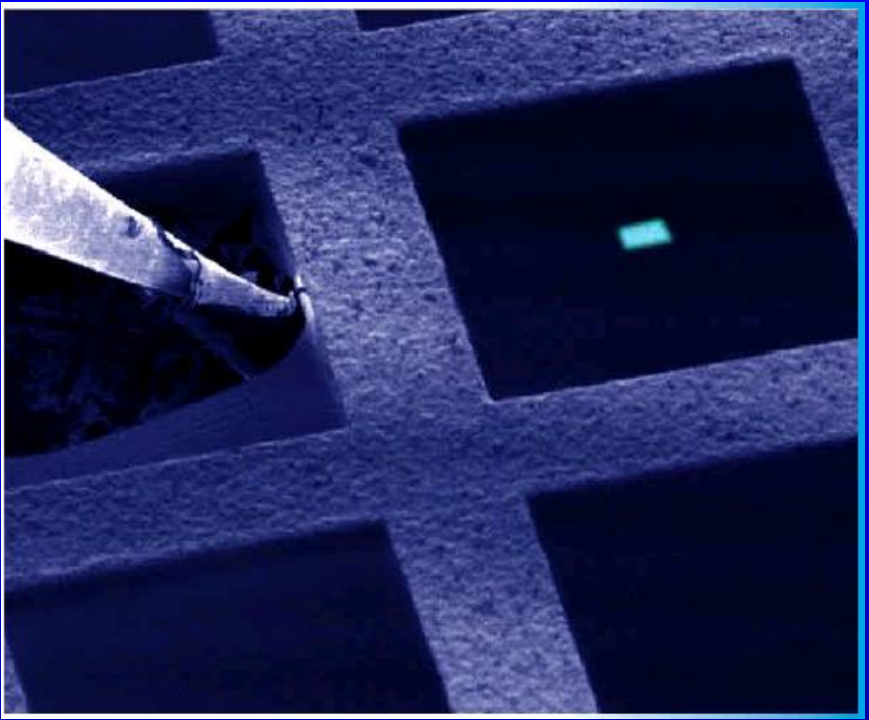
Circuit modification by FIB

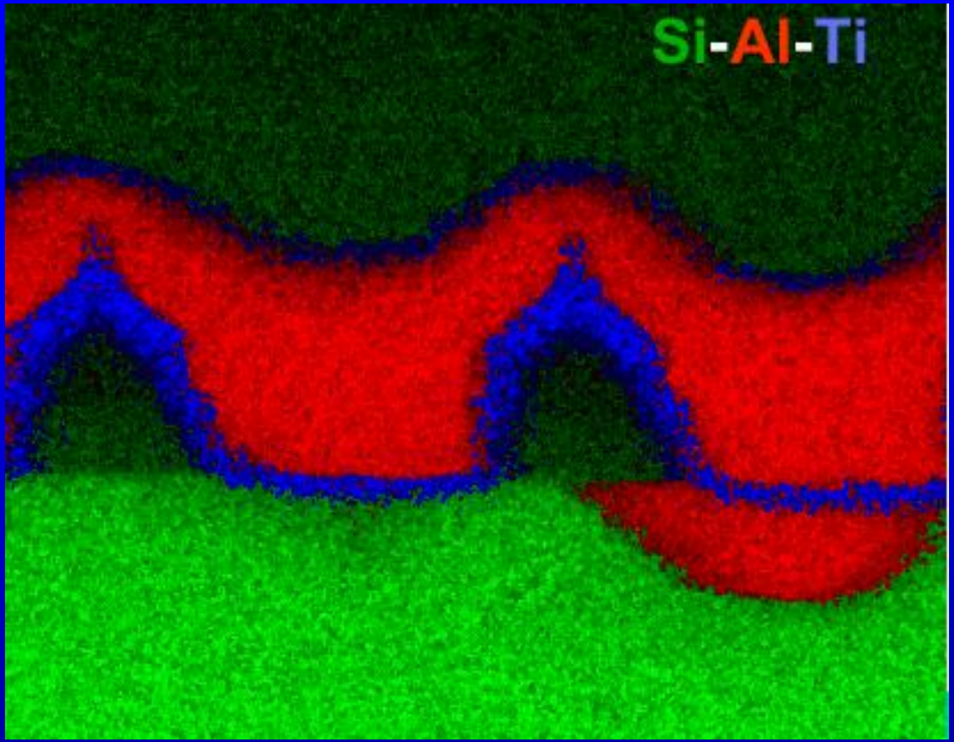
Semiconductor failure analysis





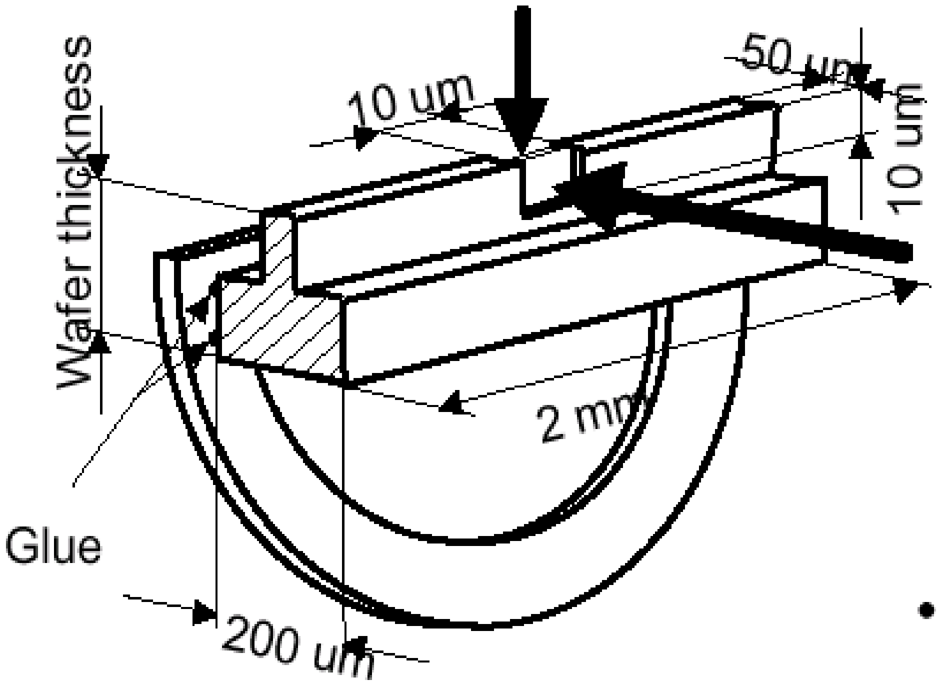
TEM sample preparation via FIBM

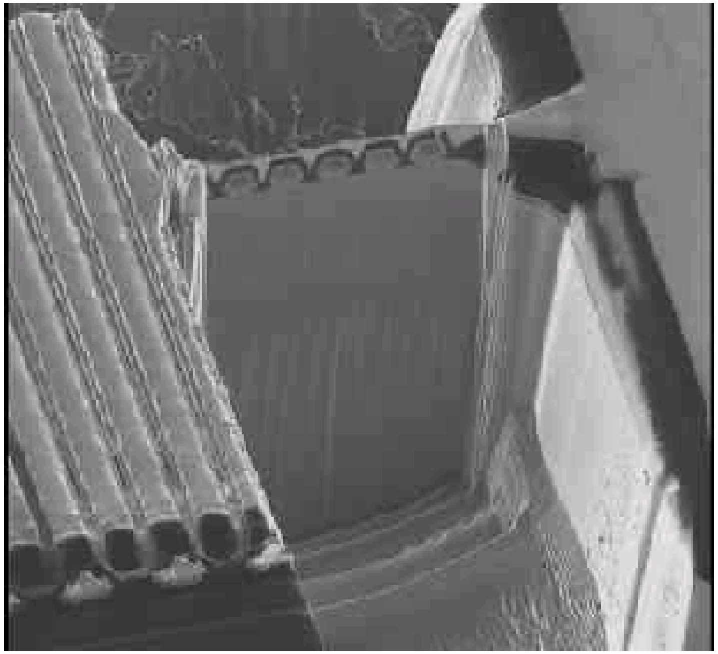




Transporting a lamella and dispose it onto the grid

FIB TEM sample preparation by bar sawing.

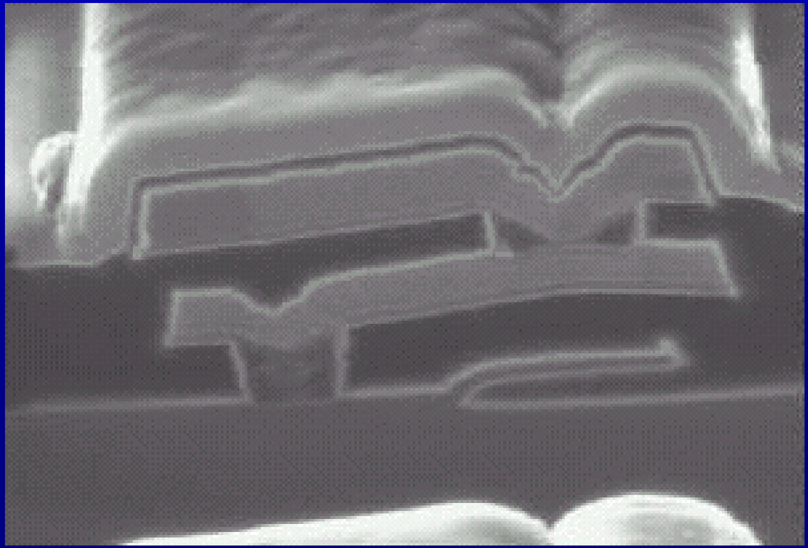




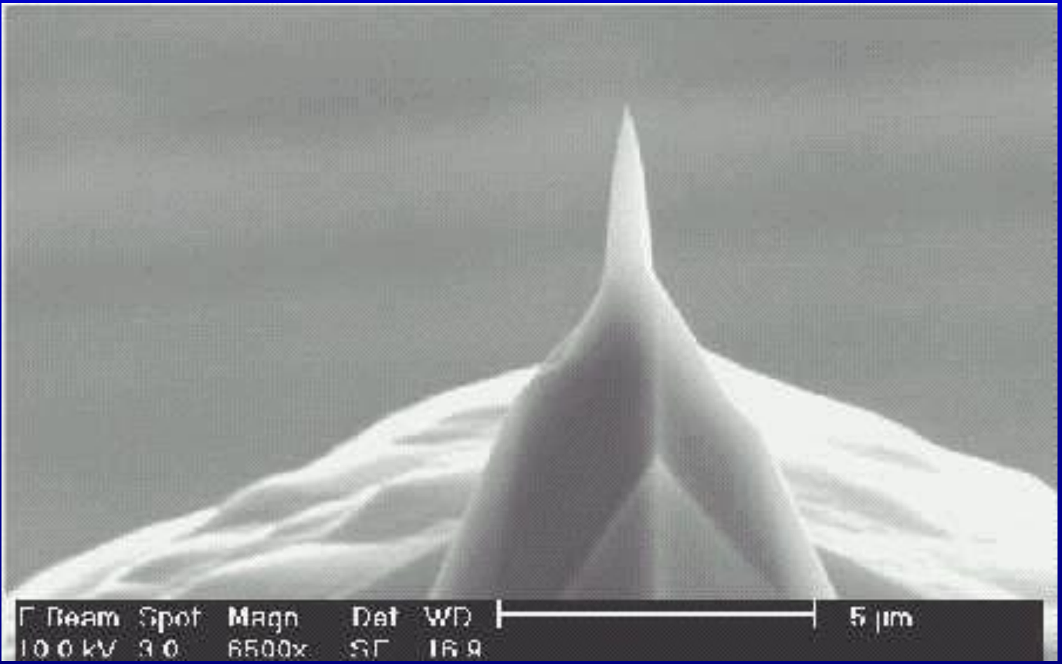
- Re-thinning possible
- High succes rate
- 2 mm bar needed
- Shadowing of X-ray detector

Failure Analysis in Multilayer Metallization:

- Your electrical tests indicate malfunction of your interconnects.
- Using local cross sectioning and in situ SE (Secondary Electon Imaging) - inspection exactly at the area of interest, the nature of the failure is identified, *e.g.*voids, cracks, particles, *etc*.
- Fabrication of thin lamella by FIB allows TEM (Transmission Electron Microscopy) and high resolution EDX (Electron Diffraction X-ray Spectroscopy) analysis at well defined areas.



- Access to buried metal lines for electrical testing.
- Create test pads by local removal of the passivation above metal lines or by deposition of new test pads.
- Integration of existing optional elements on the chip: Different device options already realized for circuit optimisation are activated/deactivated by FIB.



- Fine tuning of analog devices:

Passive device elements are trimmed by FIB.

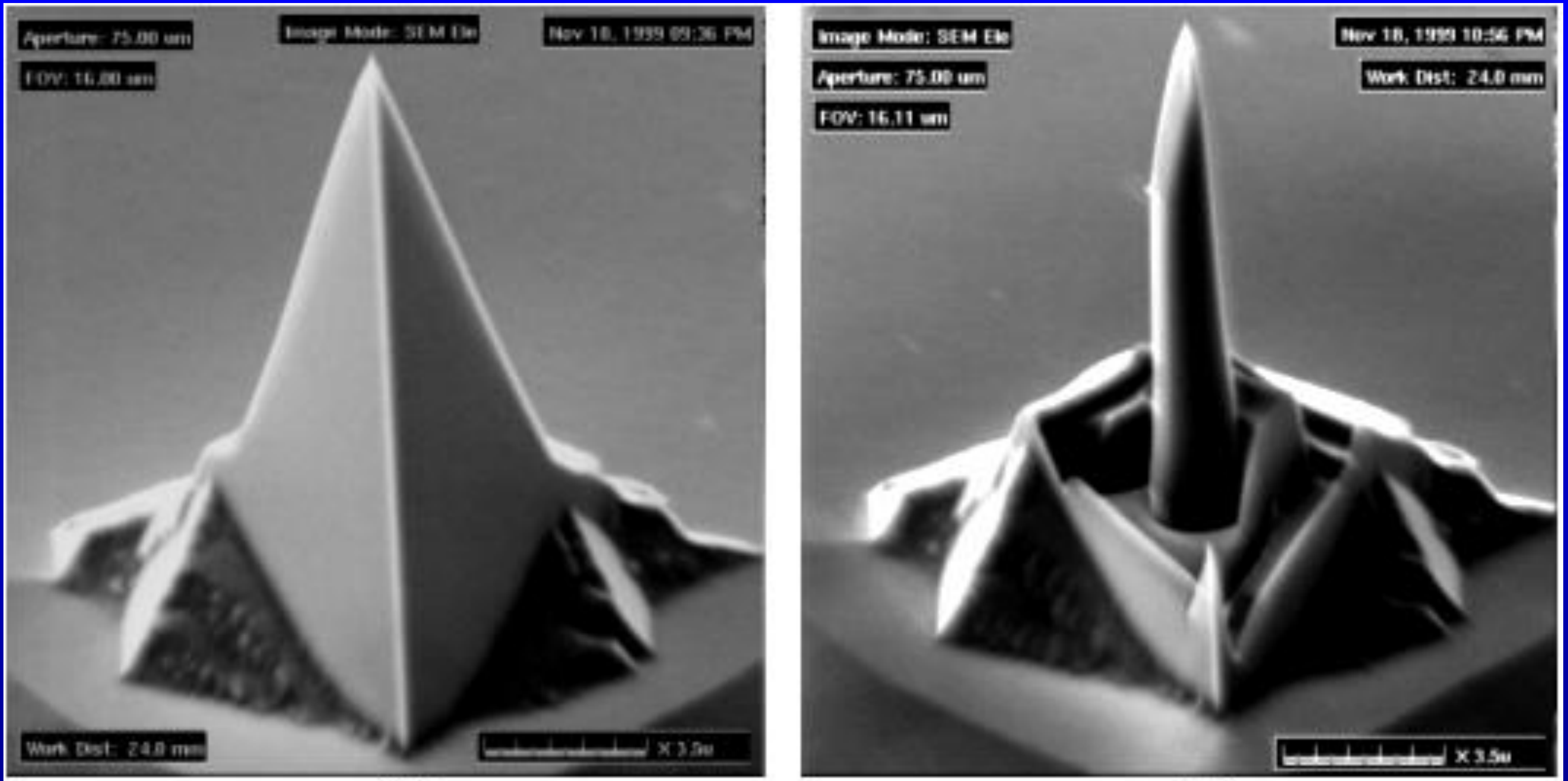
- Prototyping of microsystems:

Micromachining of actuators, sensors, and microoptics,

e.g. fabrication and polishing of optical elements,

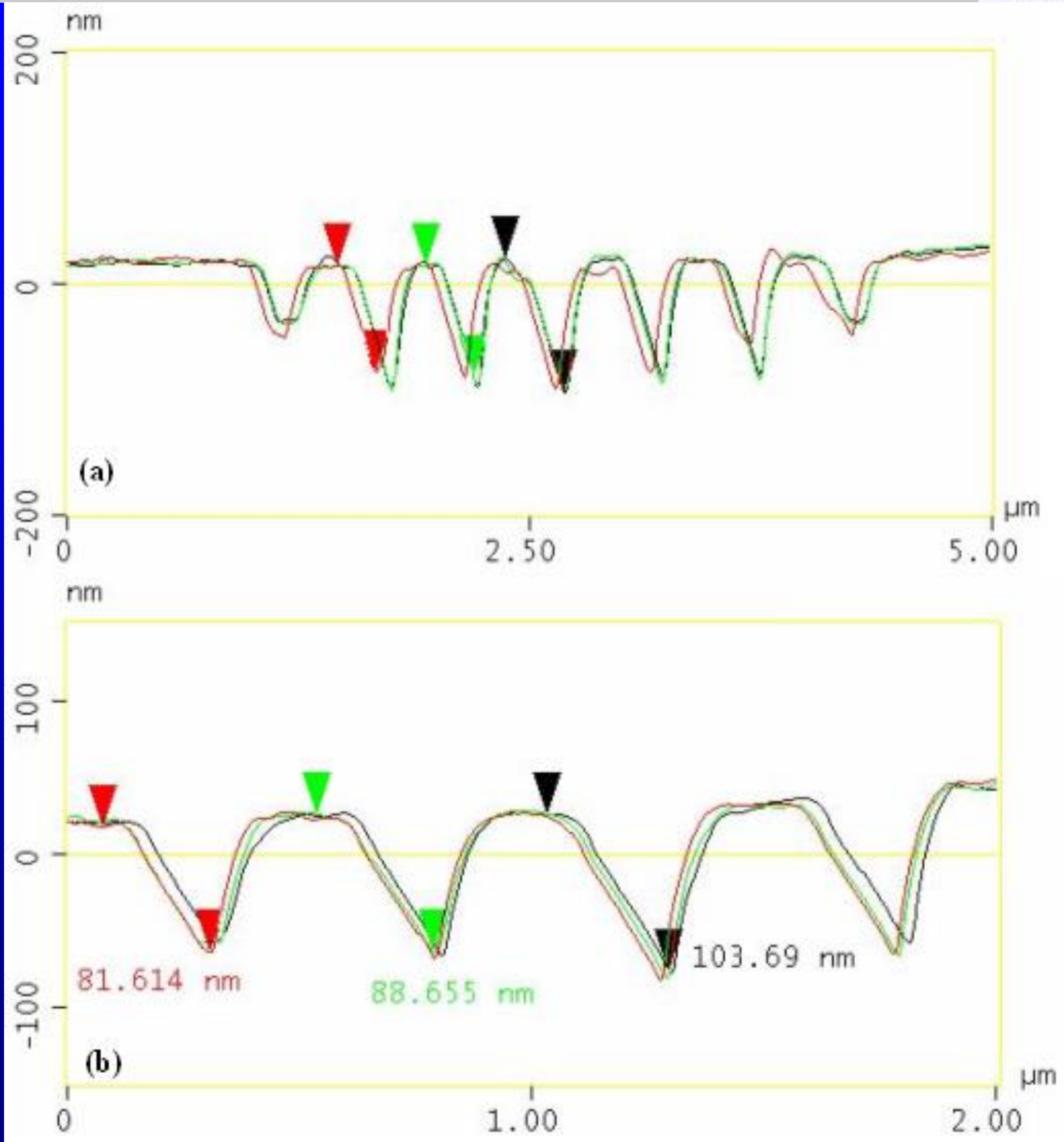
integration of sensors, fine tuning of cantilevers and tips.

Micro-part trimming



(a) (b)

AFM tip trimming by FIB fine milling



nm
200
0
-200
(a)
0
2.50
5.00
µm
nm
100
0
-100
(b)
81.614 nm
88.655 nm
103.69 nm
0
1.00
2.00
µm

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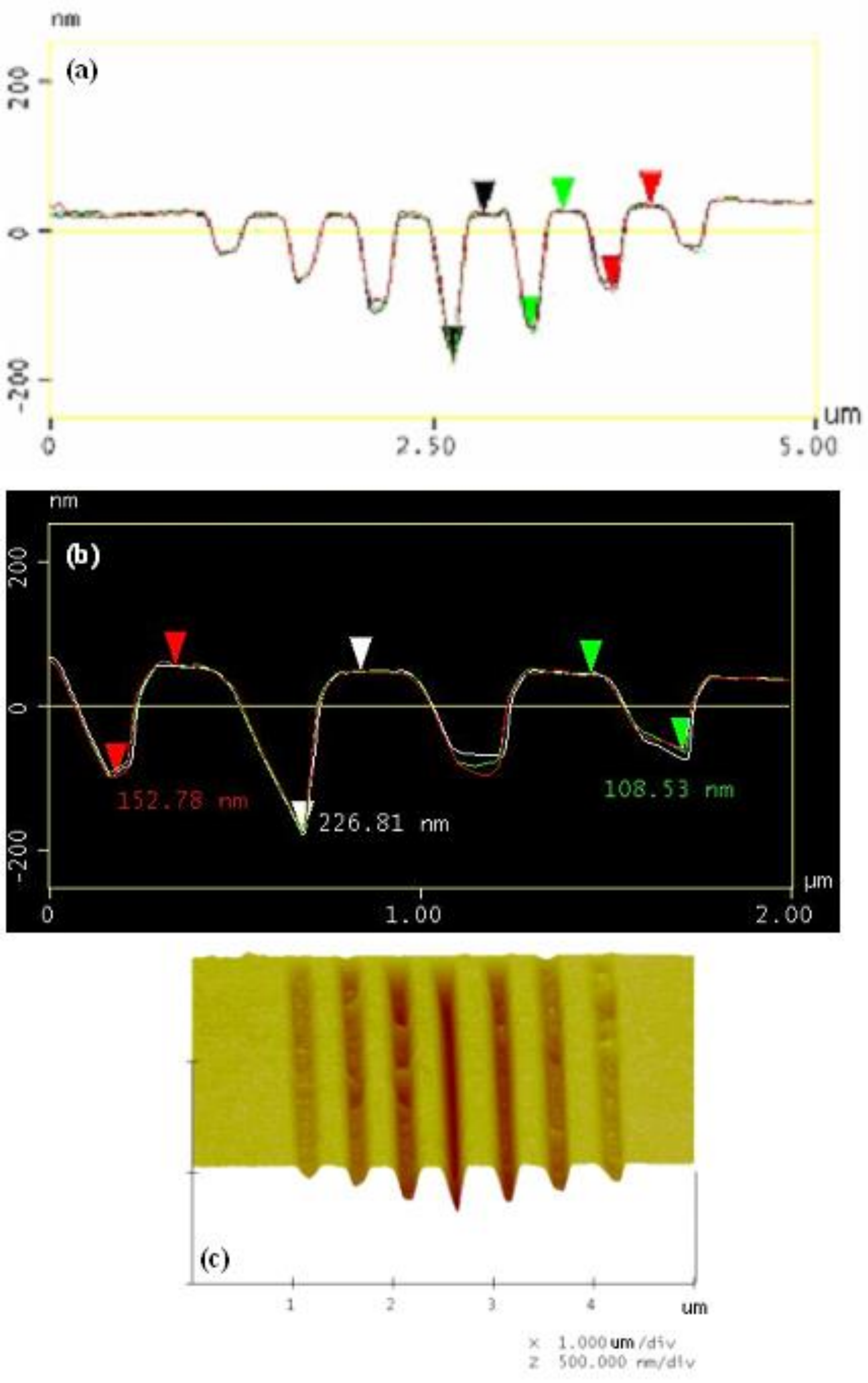
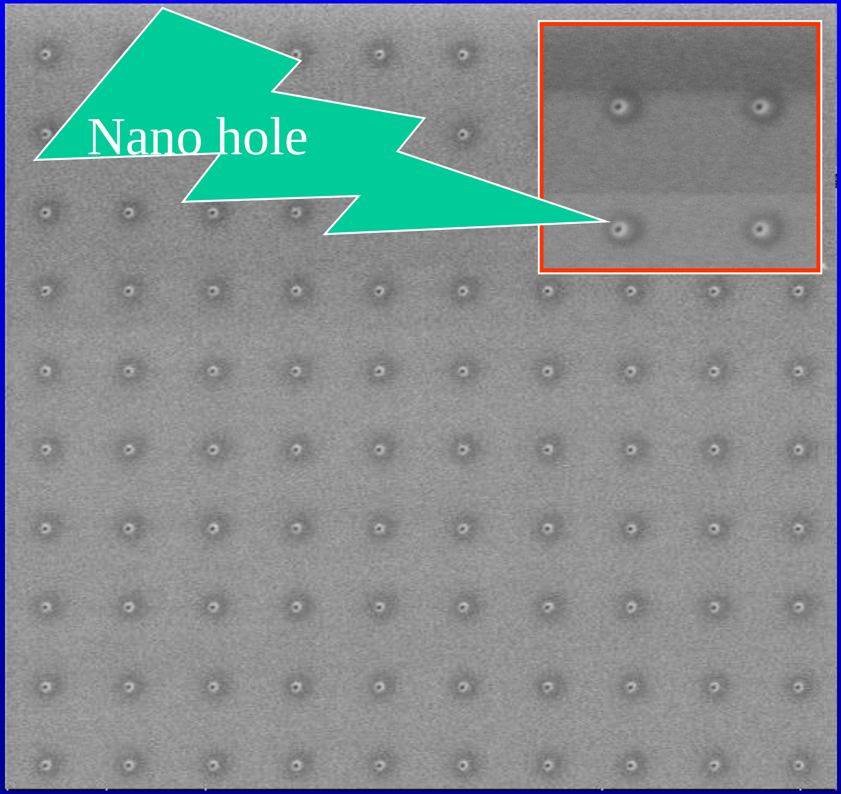
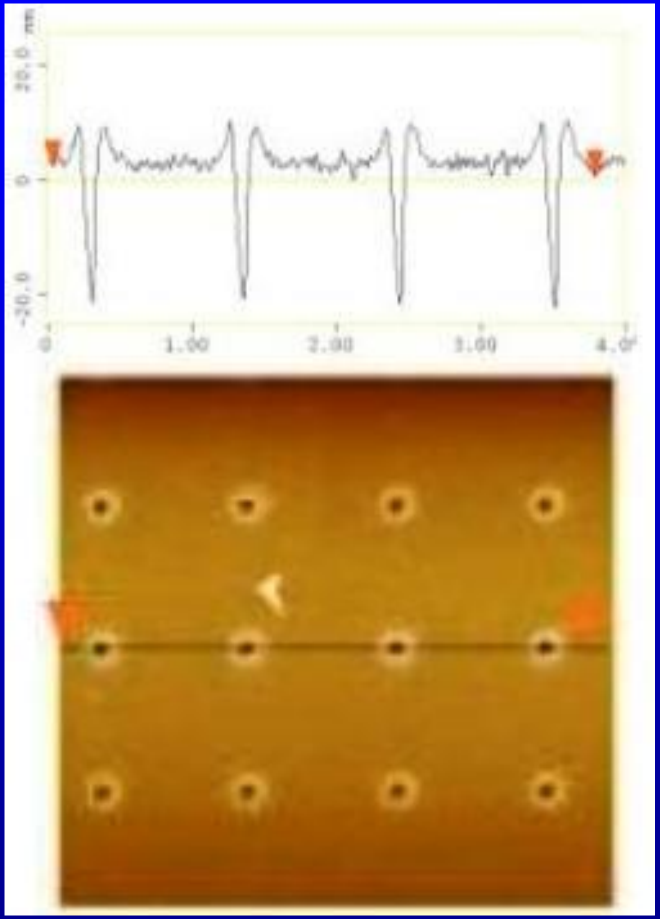


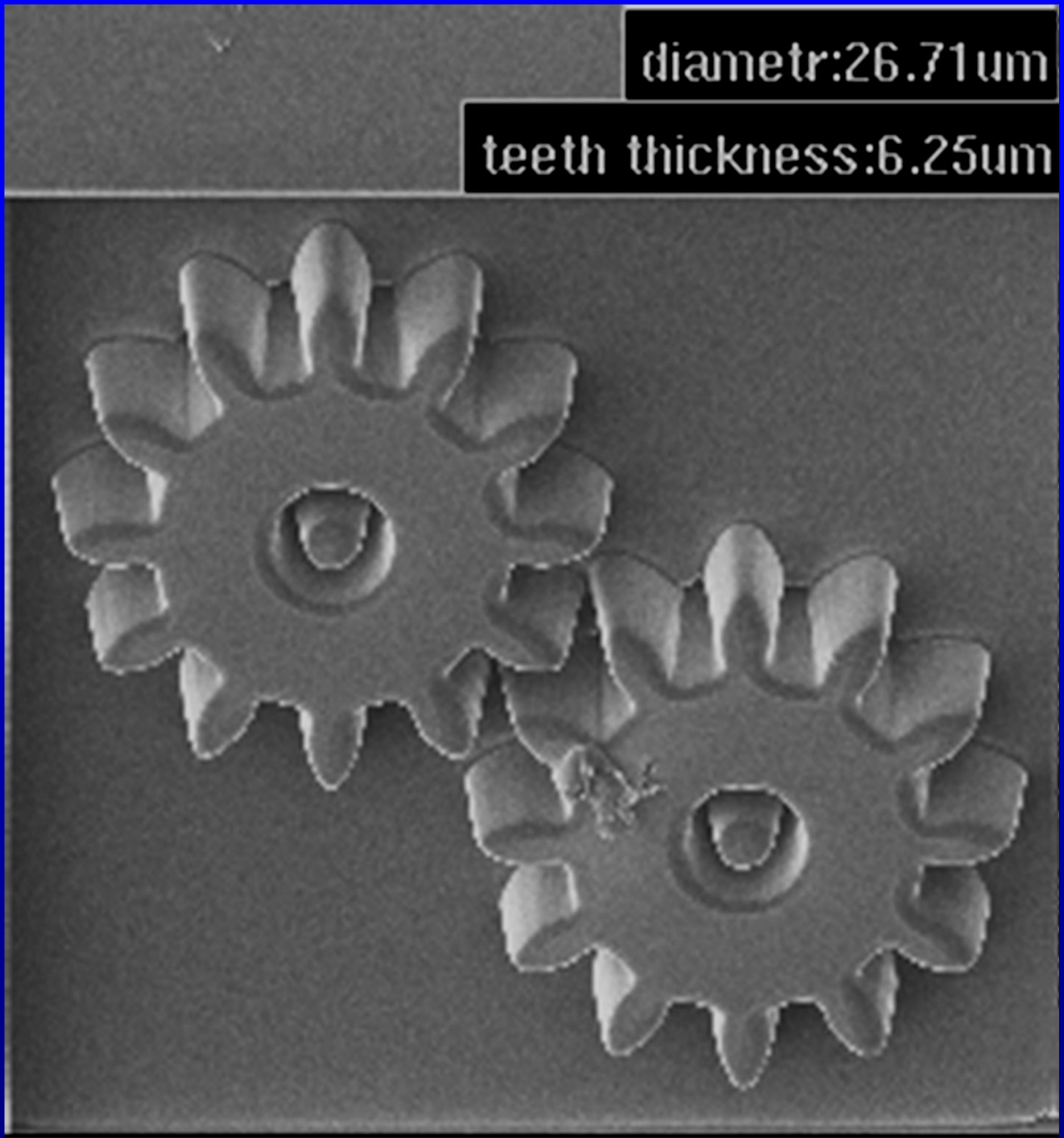
Nano-dots writing for data storage



Nano hole array



hole diameter ≈ 50nm



Gear with **26.71μm** pitch diameter

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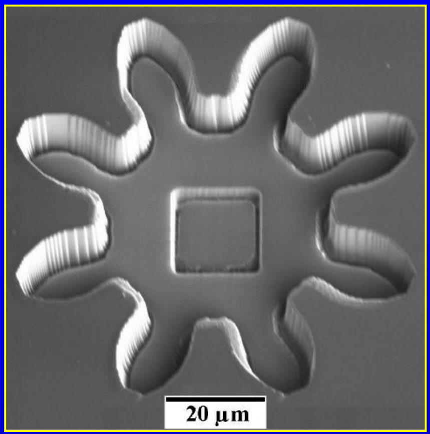
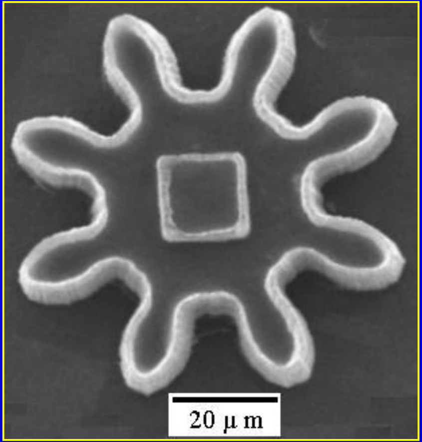
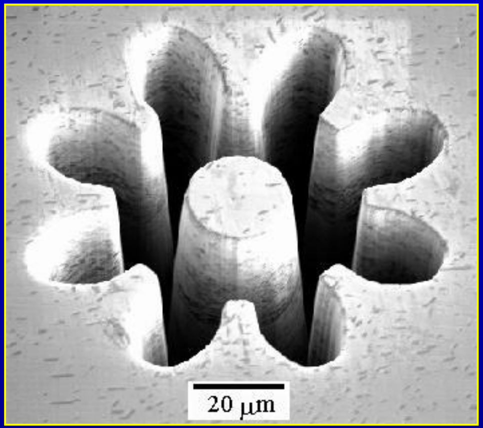
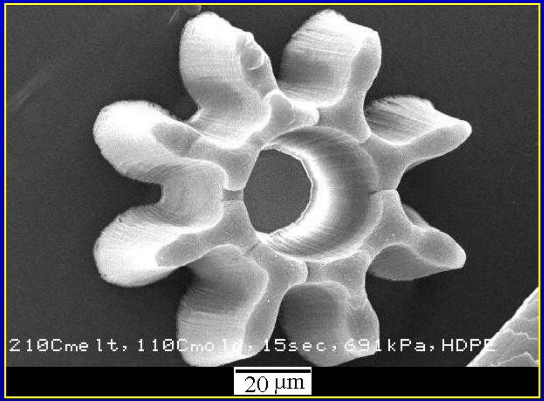




Microcavity on Silicon

Molded HDPE Microgear

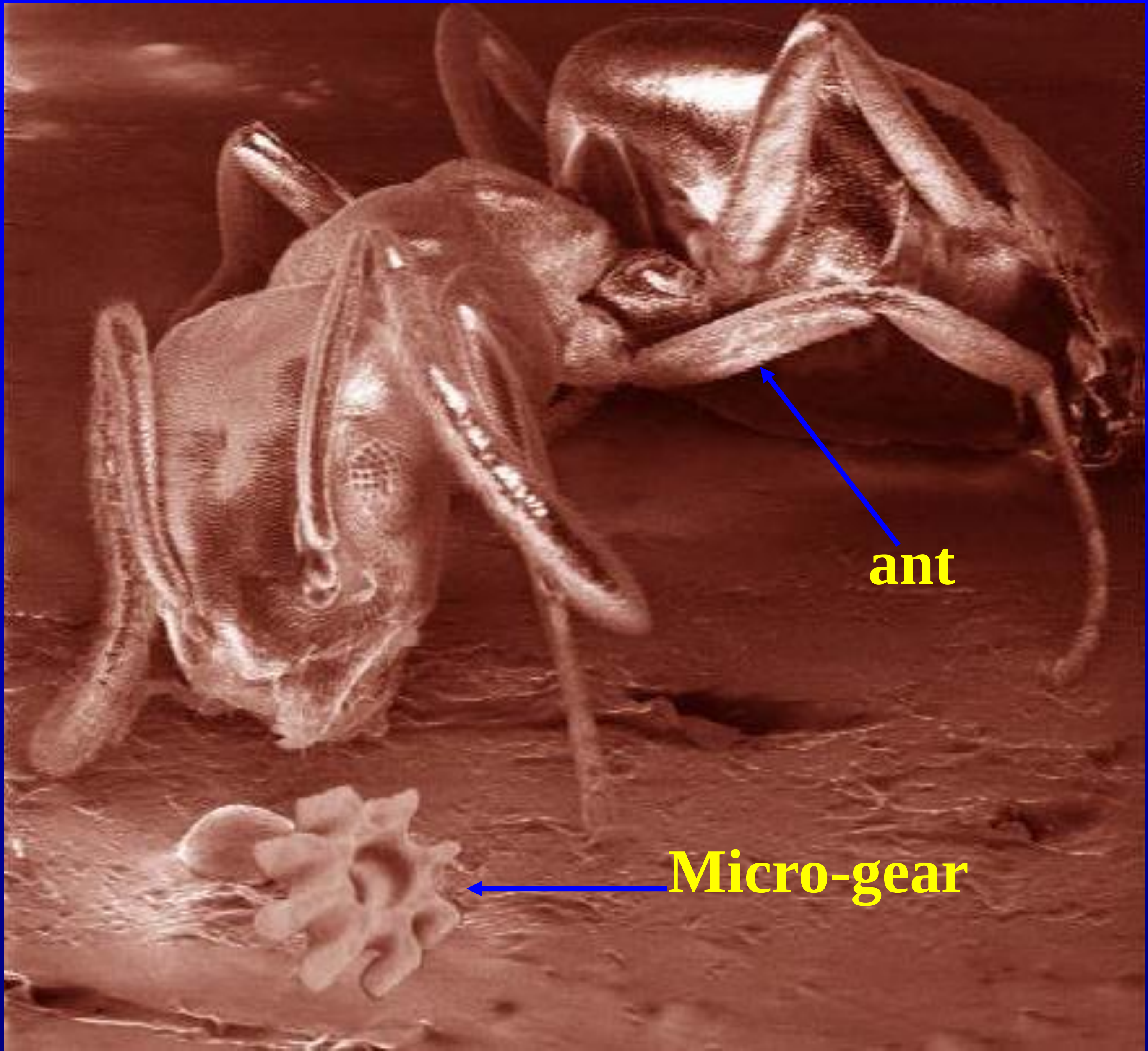


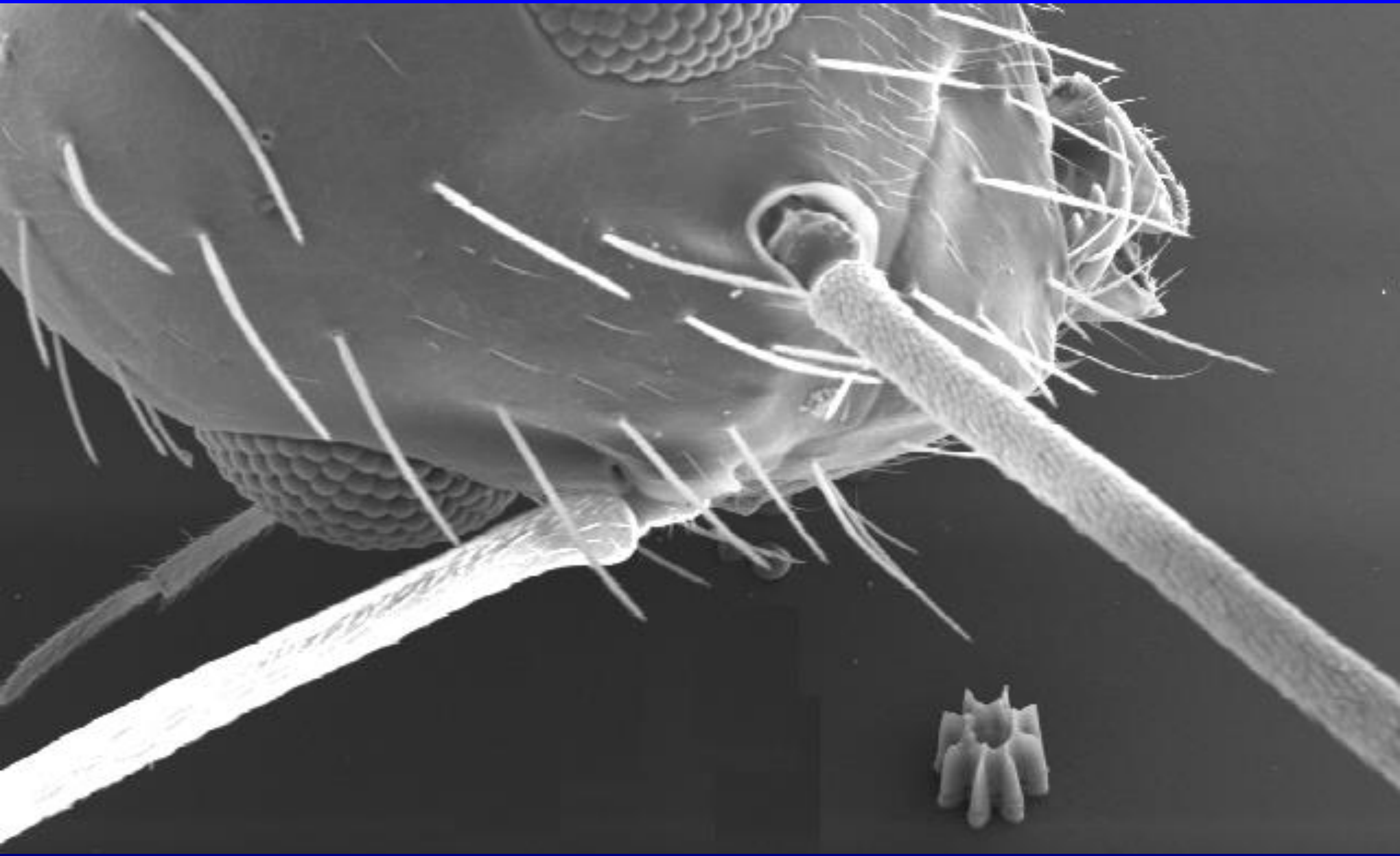


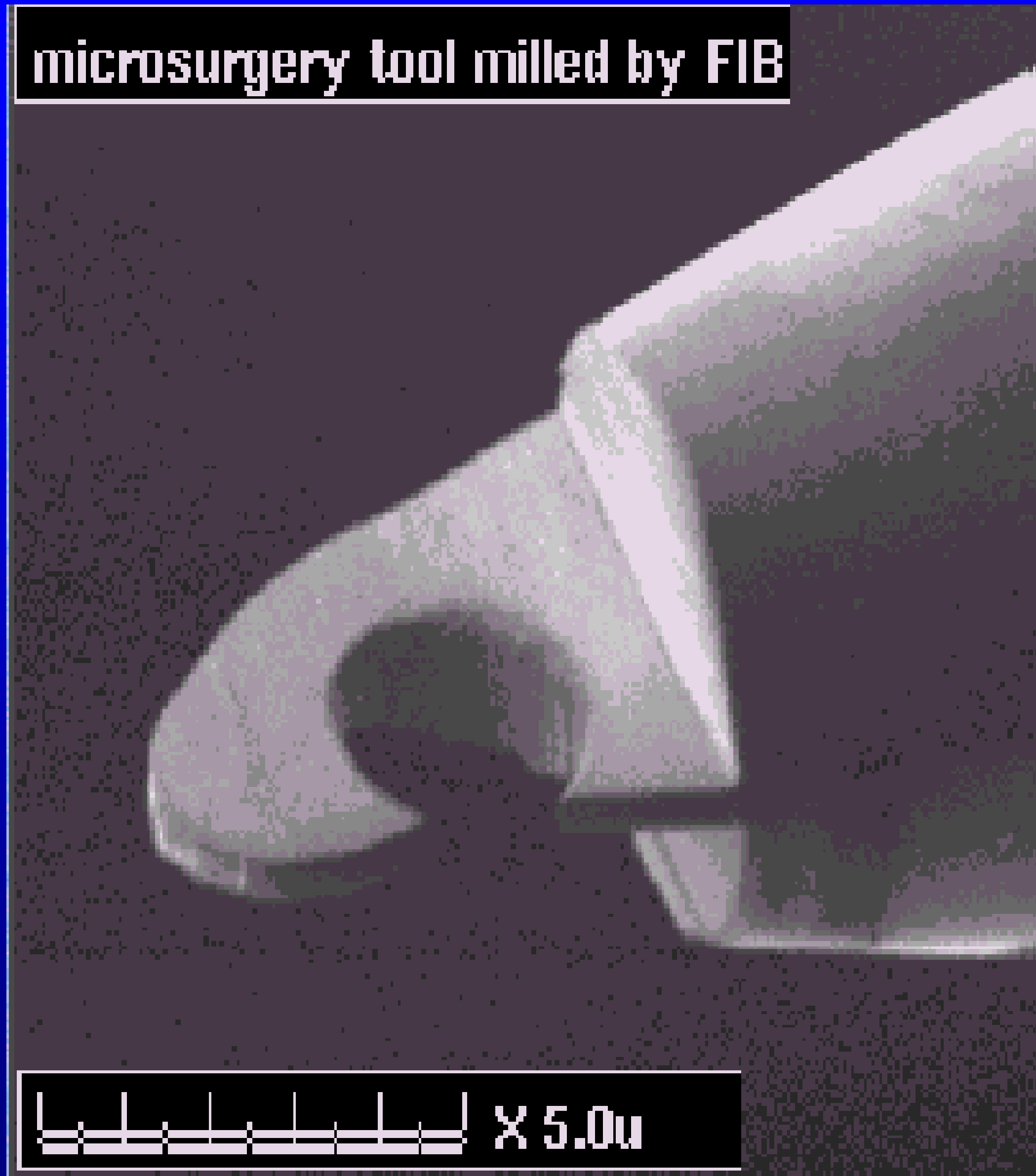
Microcavity on Ni-Be

Molded HDPE Microgear

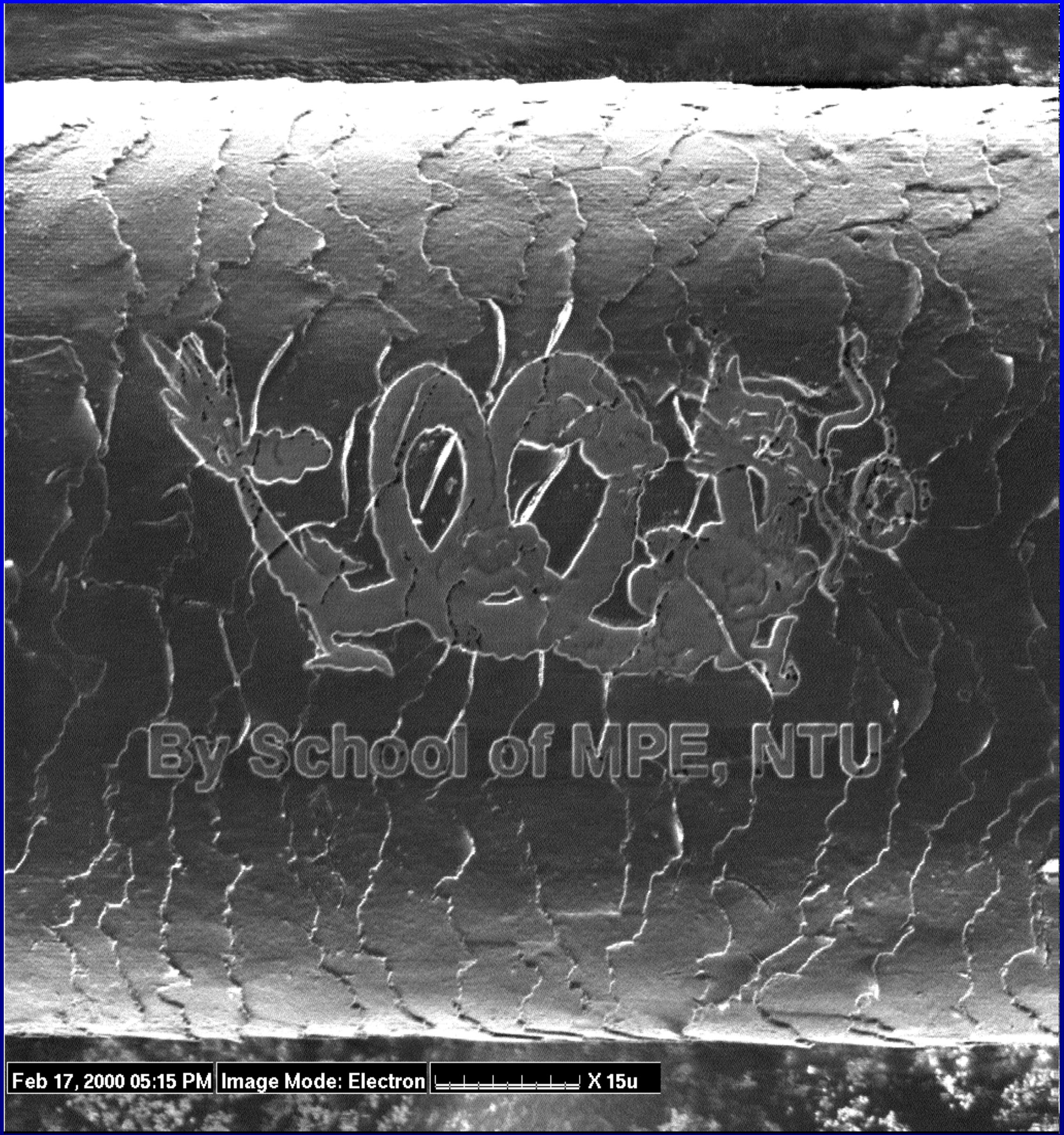
3D micro-cavity milling for master replication use


ant
Micro-gear

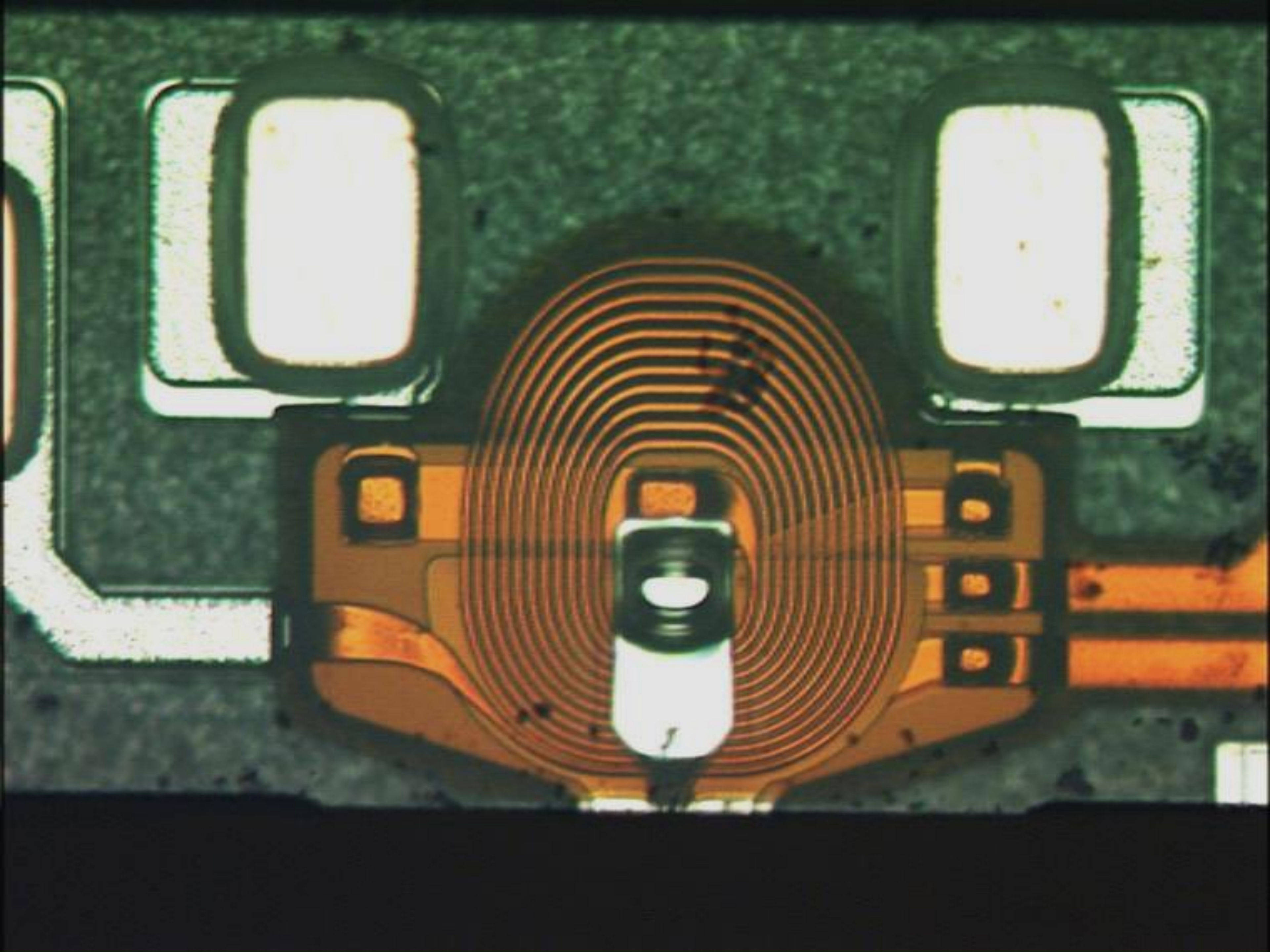




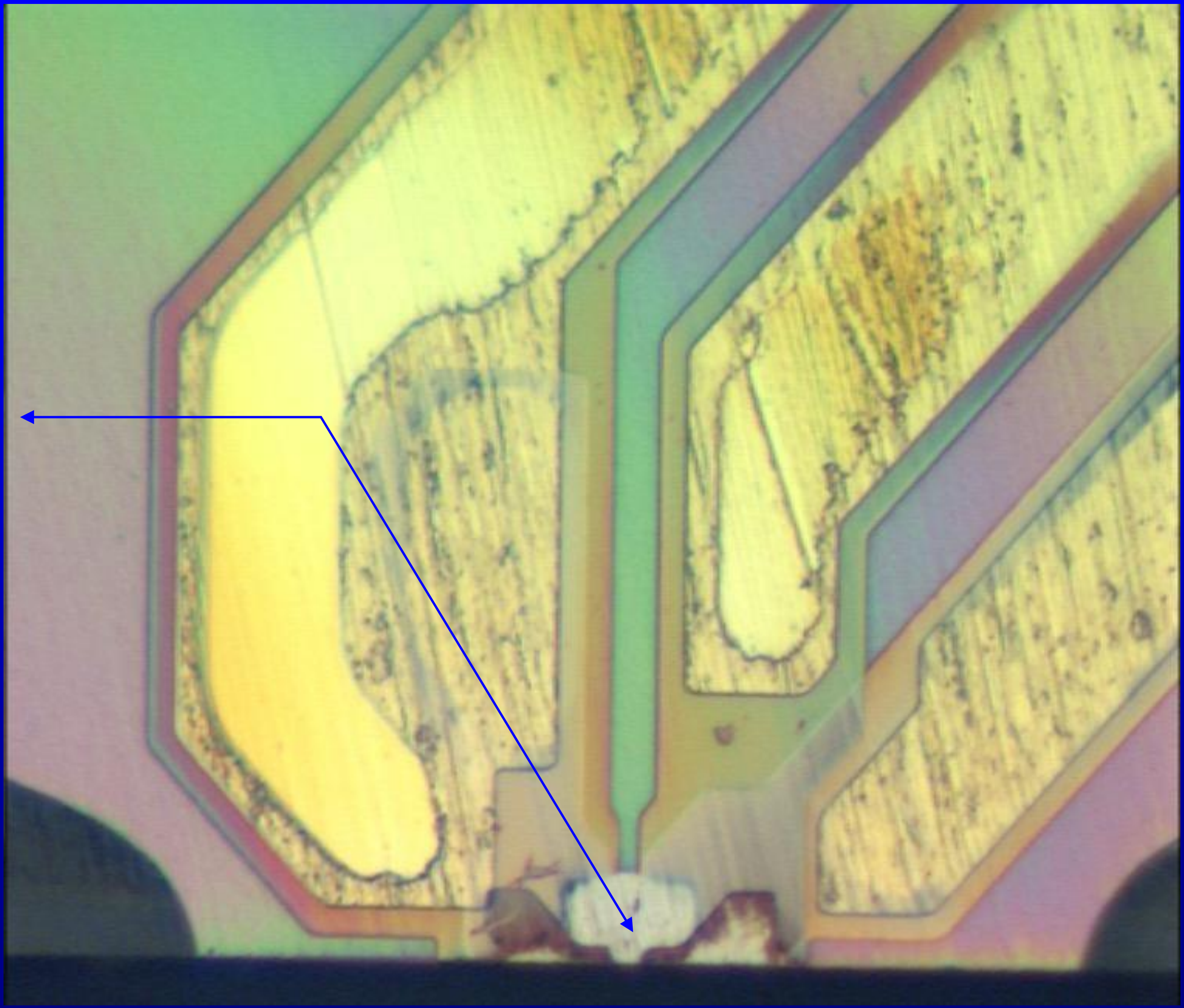
Sample8: microsurgery tool



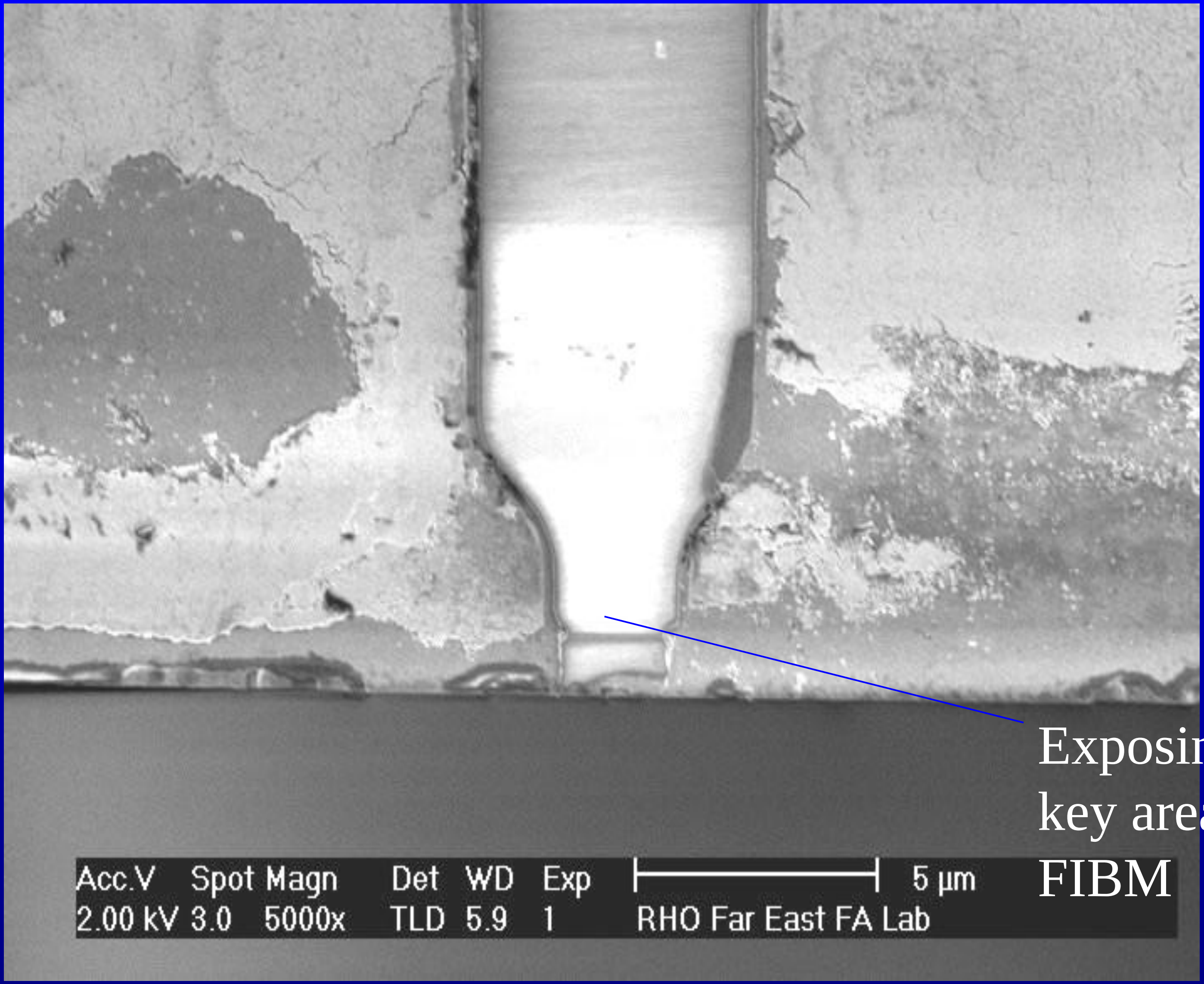
Dragon pattern milled on human hair with diameter of **60 μm** by FIB technology



Key area covered by polymer



MR head failure analysis before FIB process



MR head failure analysis after FIB fine milling

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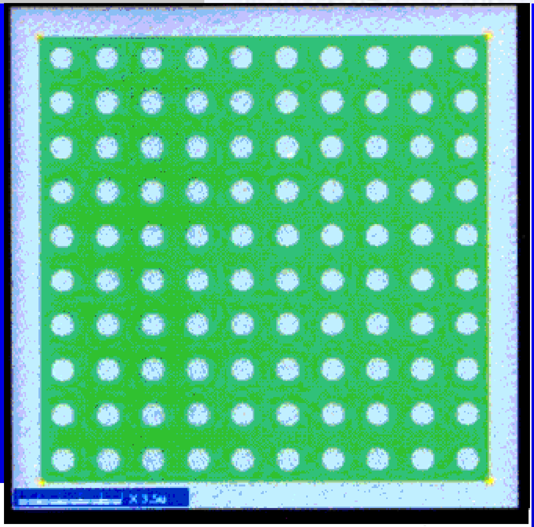
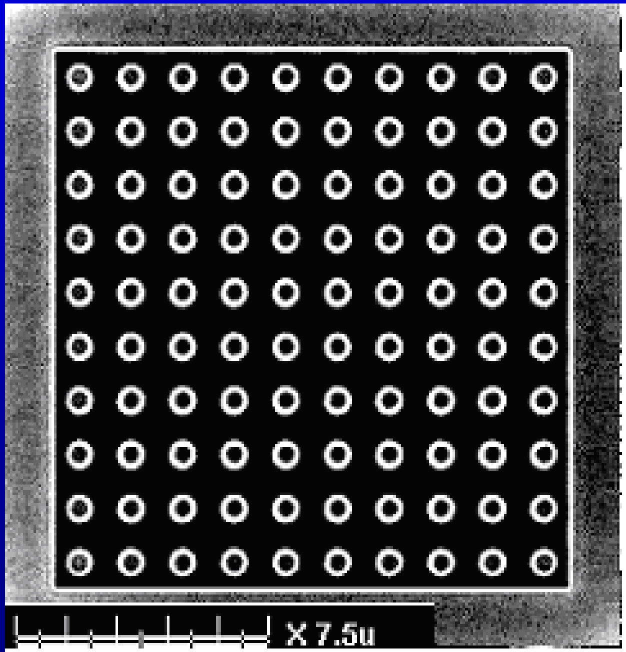
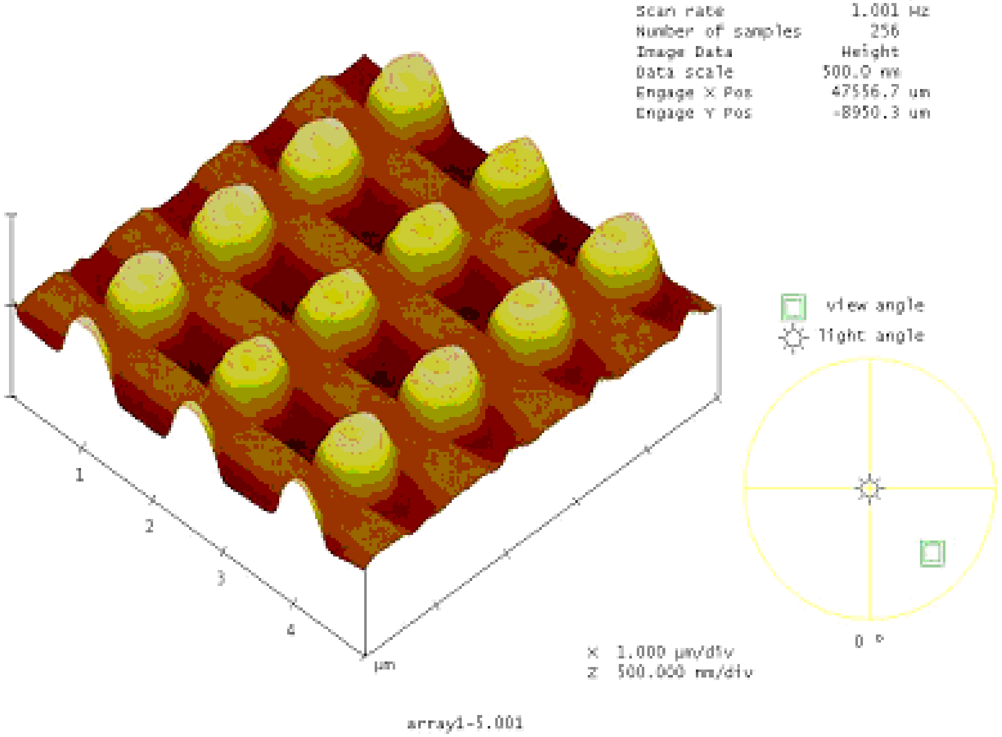
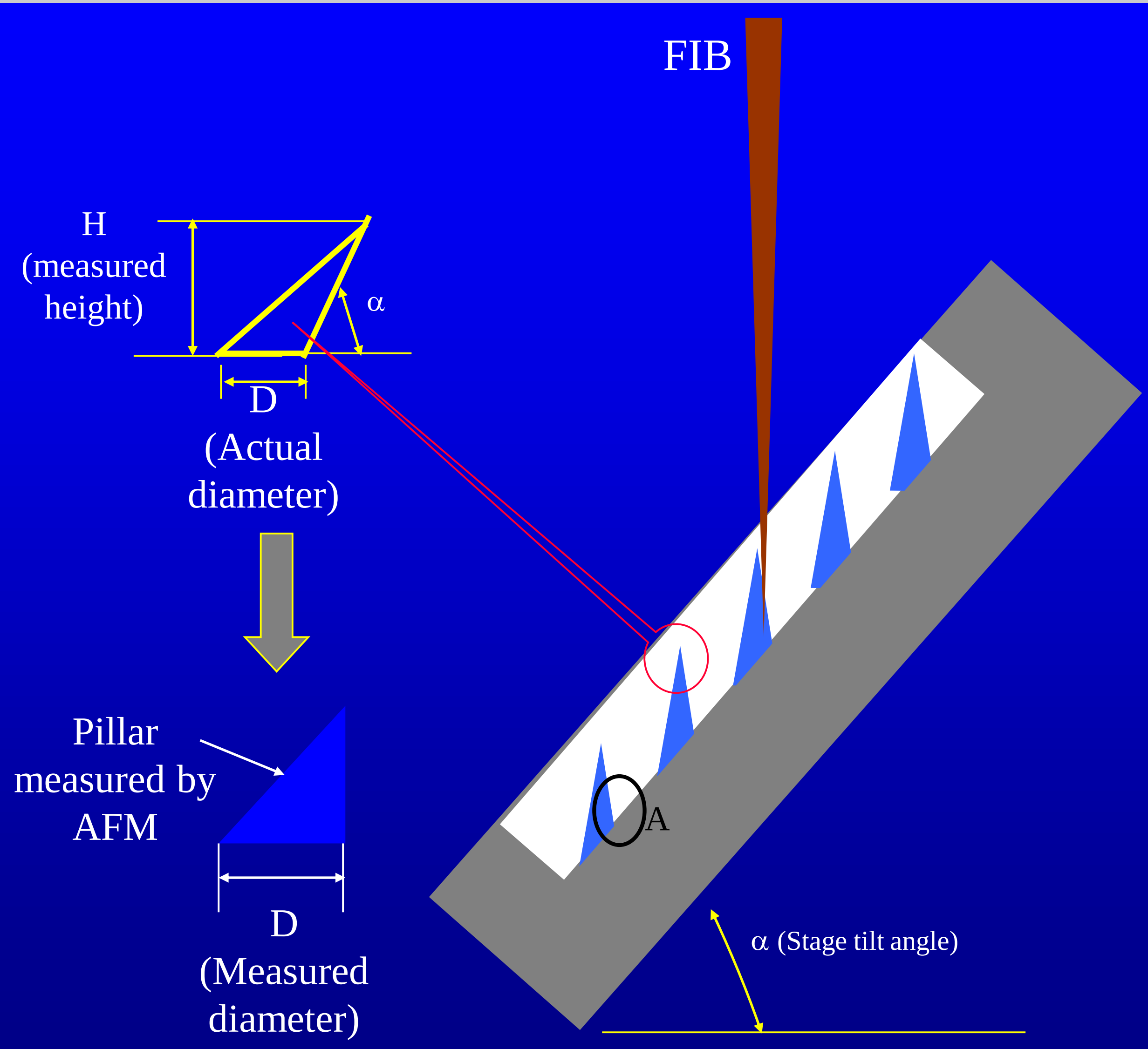
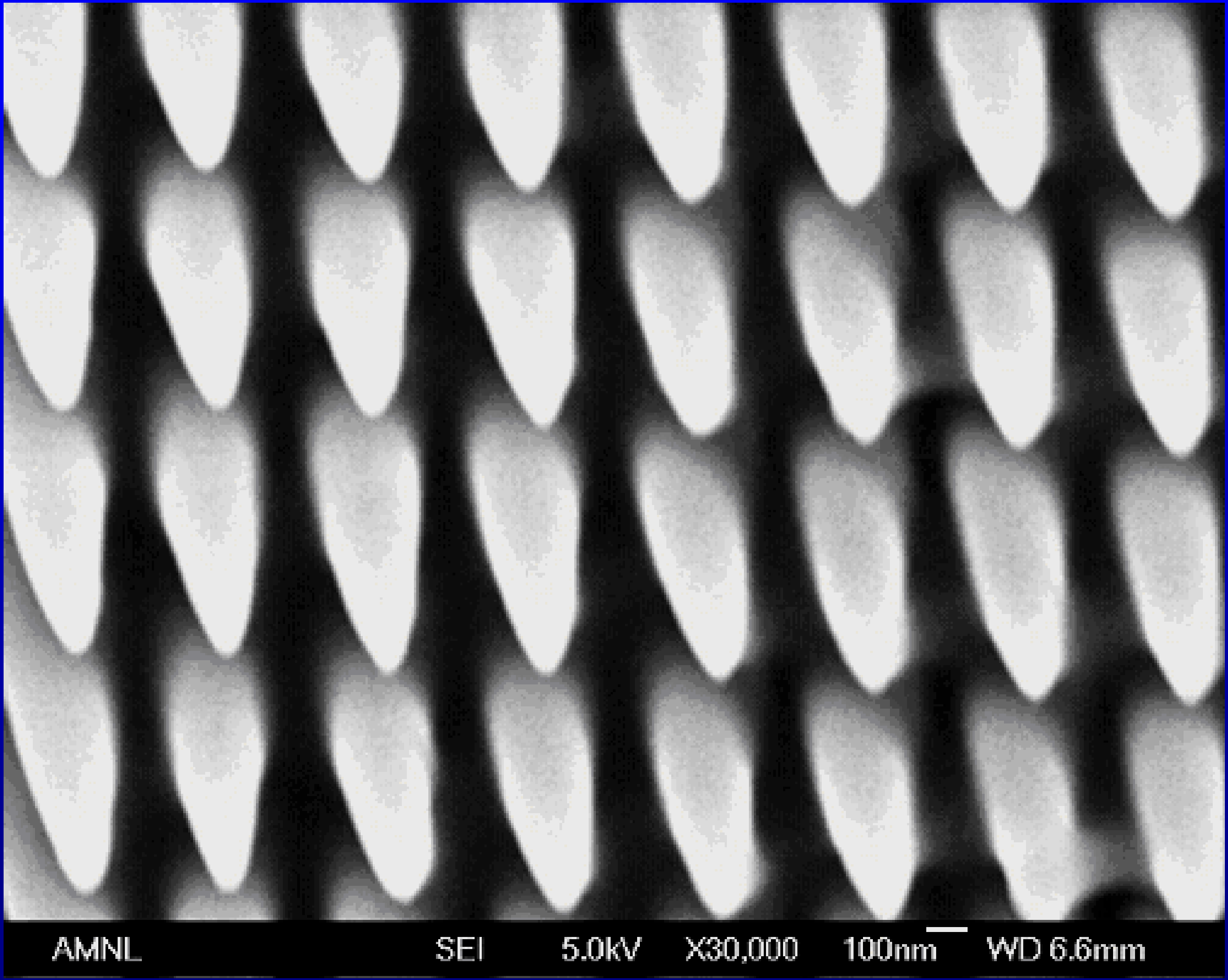
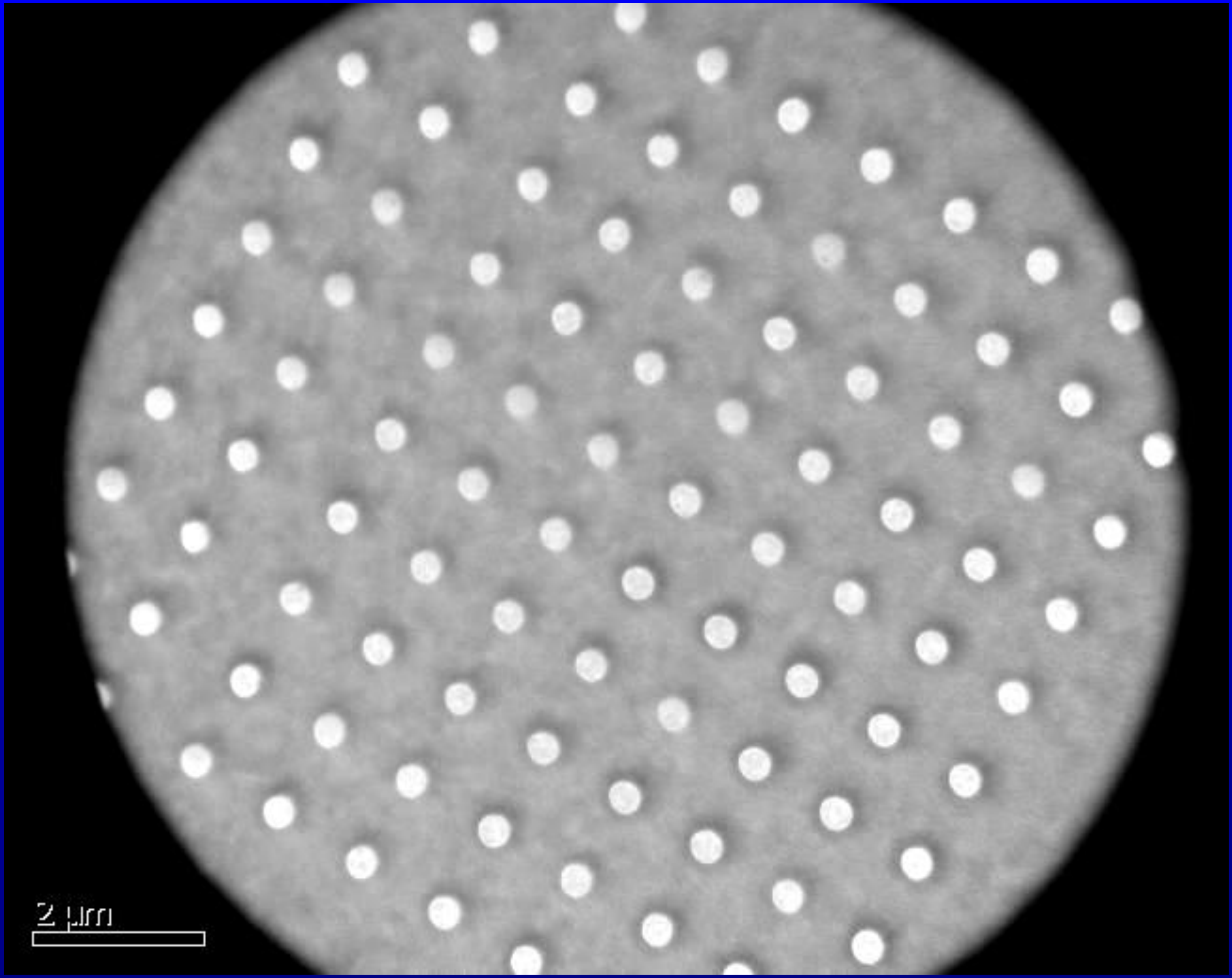


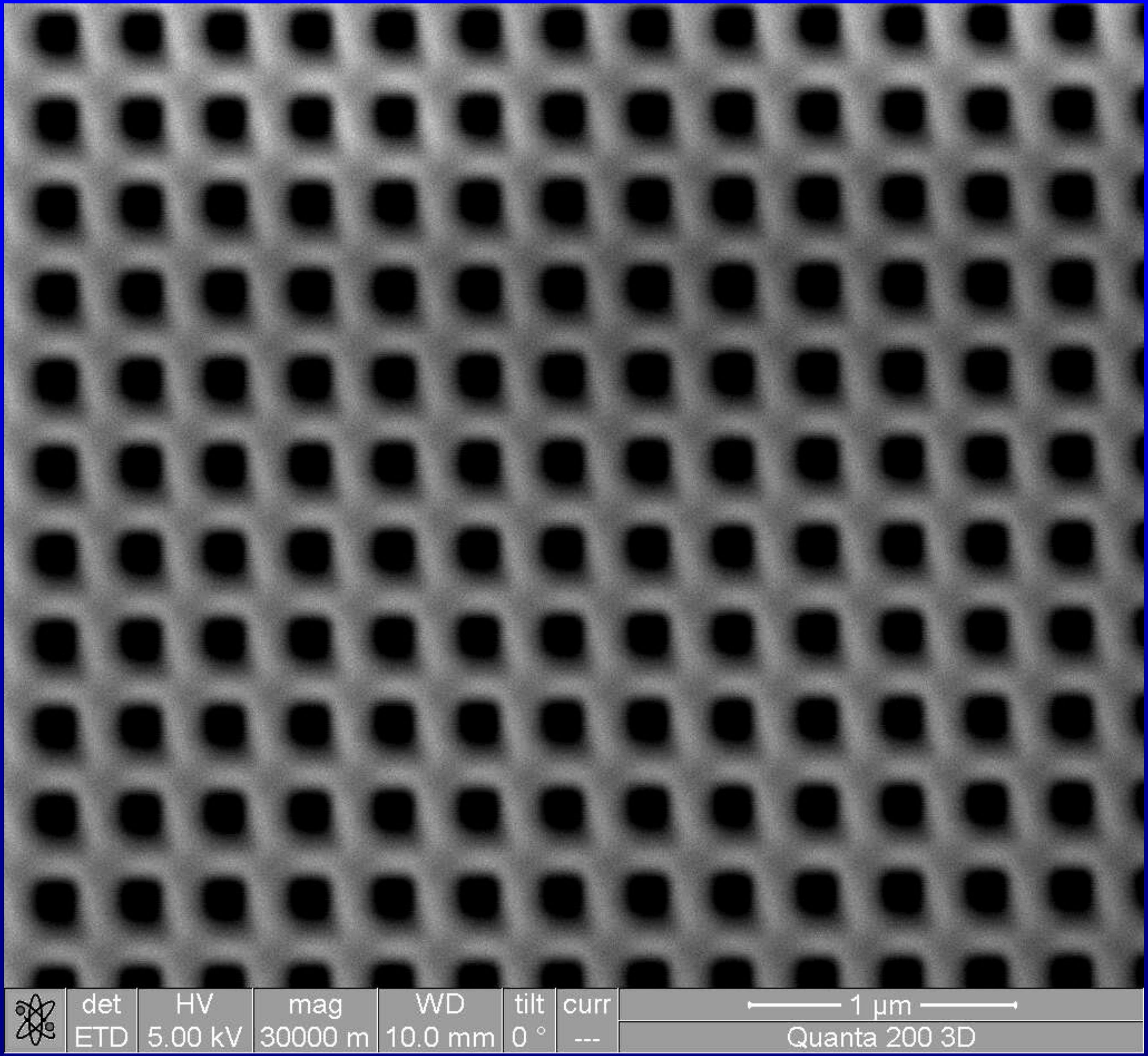





FIB
H
(measured
height)
α
D
(Actual
diameter)
Pillar
measured by
AFM
D
(Measured
diameter)
A
α (Stage tilt angle)


AMNL
SEI
5.0kV
X30,000
100nm
WD 6.6mm


2 μm


det
ETD
HV
5.00 kV
mag
30000 m
WD
10.0 mm
tilt
0 °
curr
---
1 µm
Quanta 200 3D

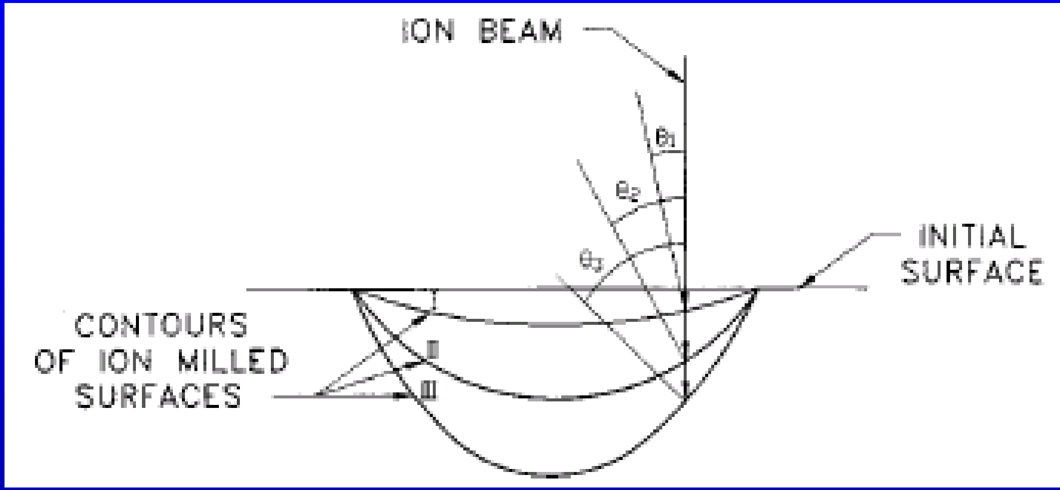
Theoretical issues

$$\text{Etch rate} = \frac{YM m_p I}{A\rho e}$$

Mathematical models of sputter yield

1. Sigmund model

$$Y(E,\theta) = \frac{Y(E)}{\cos^{f_s}\theta},$$



2. Yamamura model

$$Y(E,\theta) = Y(E)t^{f}\exp[-\Sigma(t-1)],$$

Michael J. Vasile, Jushan Xie, and Raji Nassar, JVSTB 17(6), 3085 (1999).

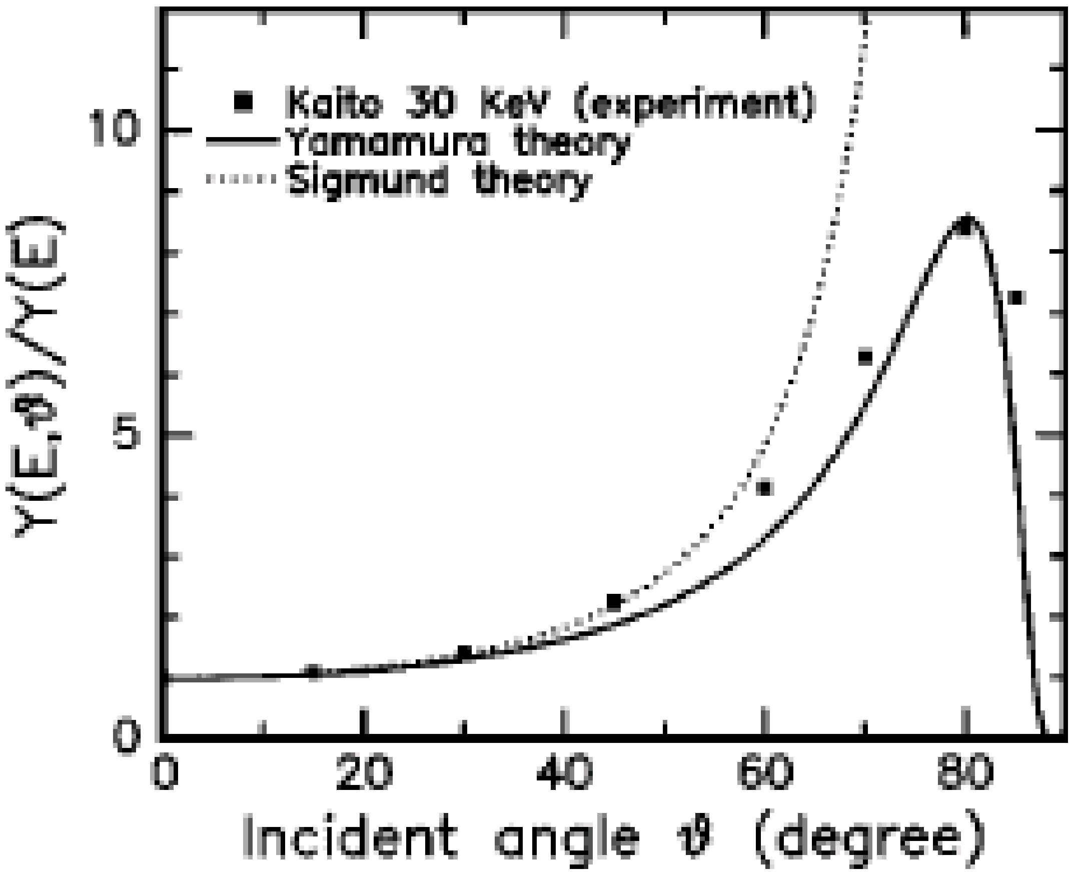


FIG. 2. Normalized sputtering yield of Ga^+/Si at 30 keV. The points are experimental data measured by Kaito (Ref. 18). The dotted line is calculated from the Sigmund's theory and the solid line from the Yamamura theory. All data are normalized to the sputter yield at $\theta=0°$.

3. Orloff model (normal incidence)

$$Y = 96.4\,\frac{\rho Y_r}{m}$$

where

m is the mass in the sputtered volume and ρ is the density in g/cm^3 , Y_r is sputter rates,

Table: Sputter rates and sputter yields for selected elements

Element	Symbol	Density (g/cm^3)	Sputter rates (μm^3 /nC)	Sputter yields (atoms/ion)
Carbon	C (diamond)	3.57	0.18	2.73
Aluminium	Al	2.7	0.3	2.89
Silicon	Si	2.33	0.27	2.08
Titanium	Ti	4.5	0.37	3.35
Chromium	Cr	7.19	0.09	1.20
Zinc	Zn	7.13	0.34	3.57
Germanium	Ge	5.32	0.22	1.55
Selenium	Se	4.81	0.43	2.52
Molybdenum	Mo	10.2	0.12	1.32
Silver	Ag	10.5	0.42	3.94
Tin	Sn	5.76	0.25	1.17
Tungsten	W	19.25	0.12	1.22
Platinum	Pt	21.47	0.23	2.44

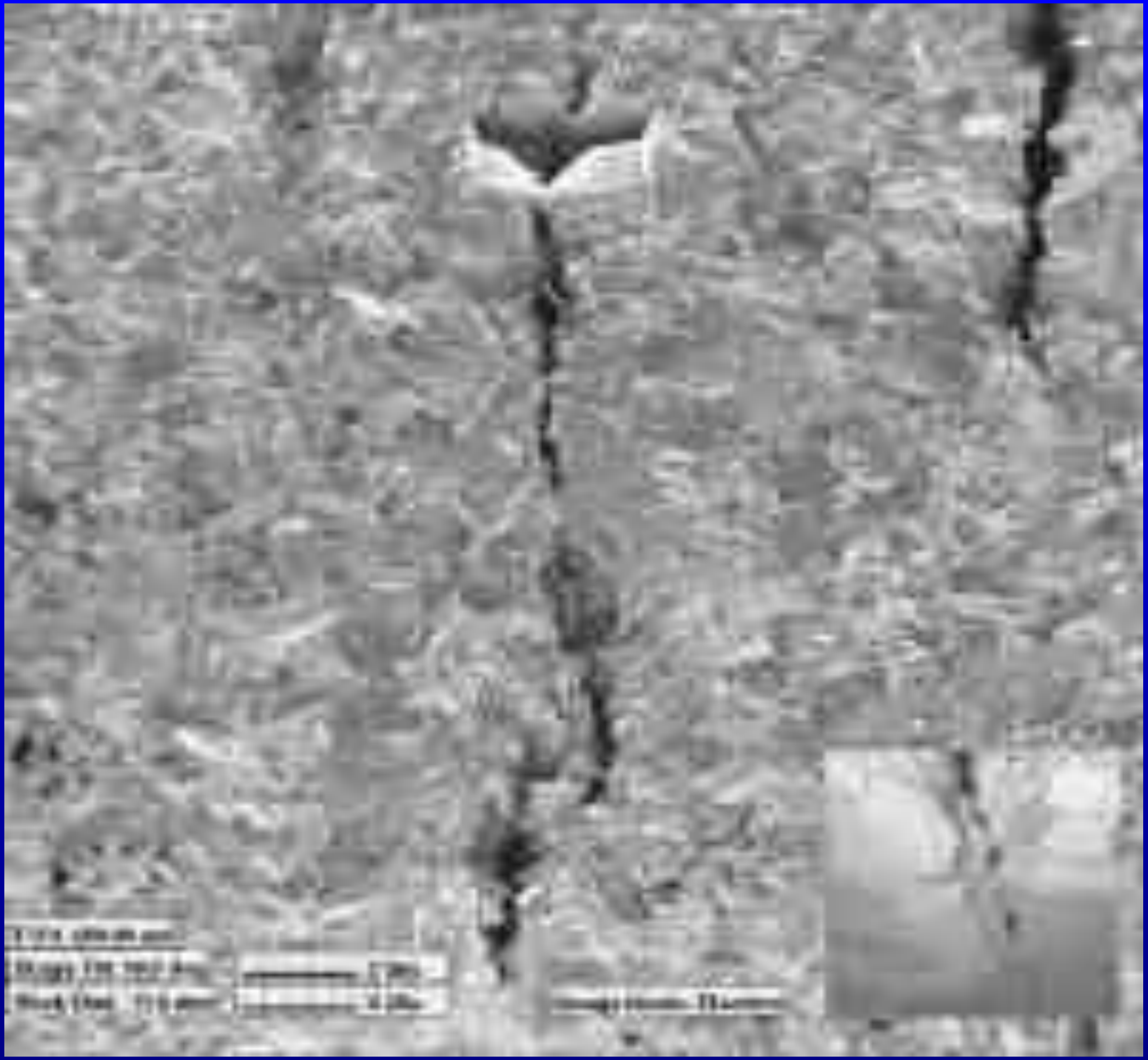
J. Orloff (Ed.), Handbook of Charged Particle Optics, Boca Raton, Fla: CRC Press, 1997.

Estimate the ion dose require

$$d = n\frac{I_b t_d}{e(\delta_d)^2}$$

where

I_b is the ion beam current, t_d is the beam dwell time, δ_d is the beam step size and n is the number of scans.



Study of Stress Corrosion Cracking in a Pipeline Steel