Metrology for 3D Devices: Plasma-FIB for High Throughput Sectioning of Large Dimensions

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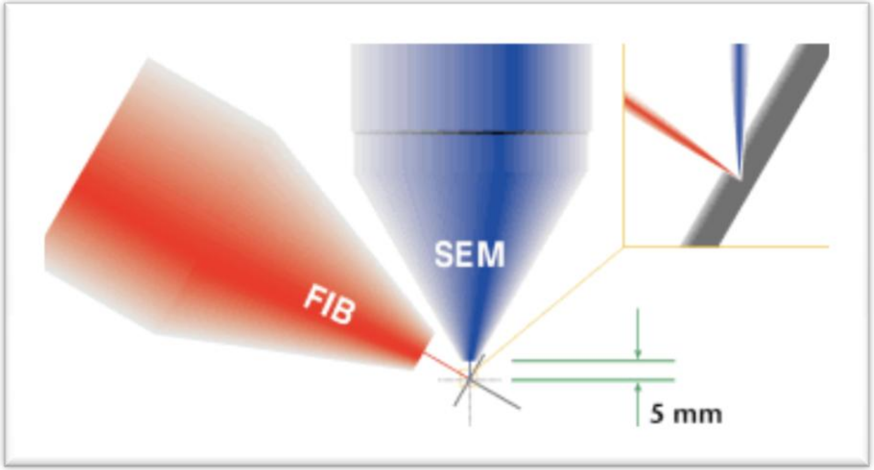
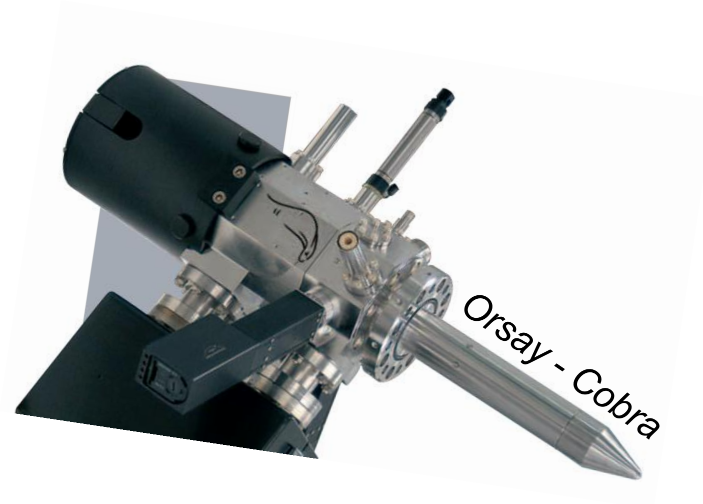
Overview

- State-of-the-Art FIB
- Limitations for Large Volume/High Current FIB Milling
- Inductively Coupled Plasma Ion Source Technology
- Plasma-FIB Performance
- Plasma-FIB for Large Volume Cross-Sectioning and other Milling Applications
- Conclusions and the Possible Future for Plasma FIB’s

Conventional Ga$^+$FIB/SEM





Ga$^+$ LMIS-FIB

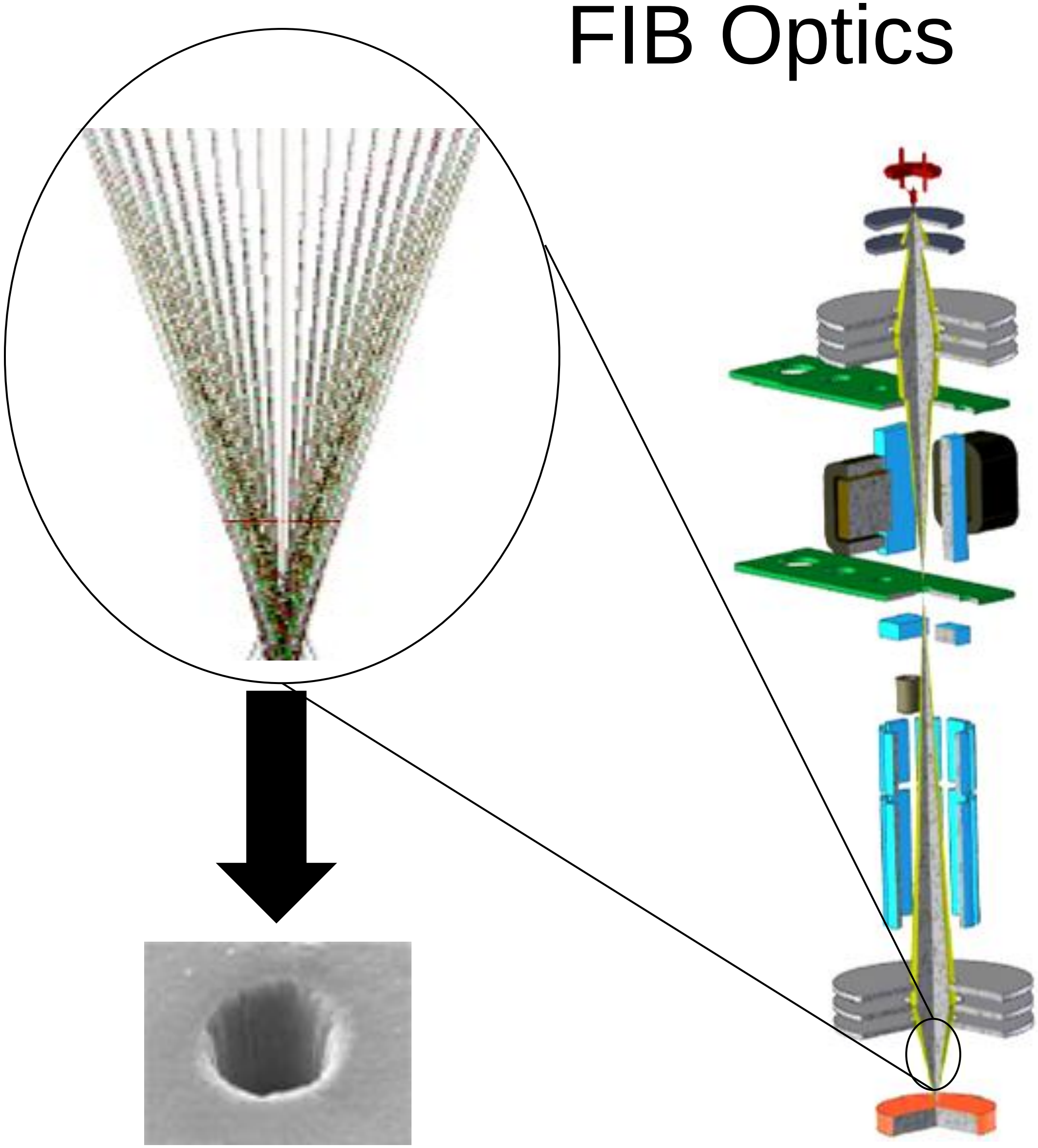
- Imaging resolution - 2.5nm at 1pA (30keV)

- 1pA-100nA at 10nm-10um, 30keV Ga$^+$
  - *IC failure analysis*
  - *Circuit edit*
  - *TEM lamella preparation*
  - *Lithographic Mask Repair*
  - *Small volume micromachining*

State-of-the-Art LMIS-FIB Columns

FEI	**Tomahawk**
Orsay/Zeiss	**Cobra**

FIB Optics



Ion Source

Extraction Electrode

Condenser Lens

Variable Beam Defining Aperture

Mass Filter

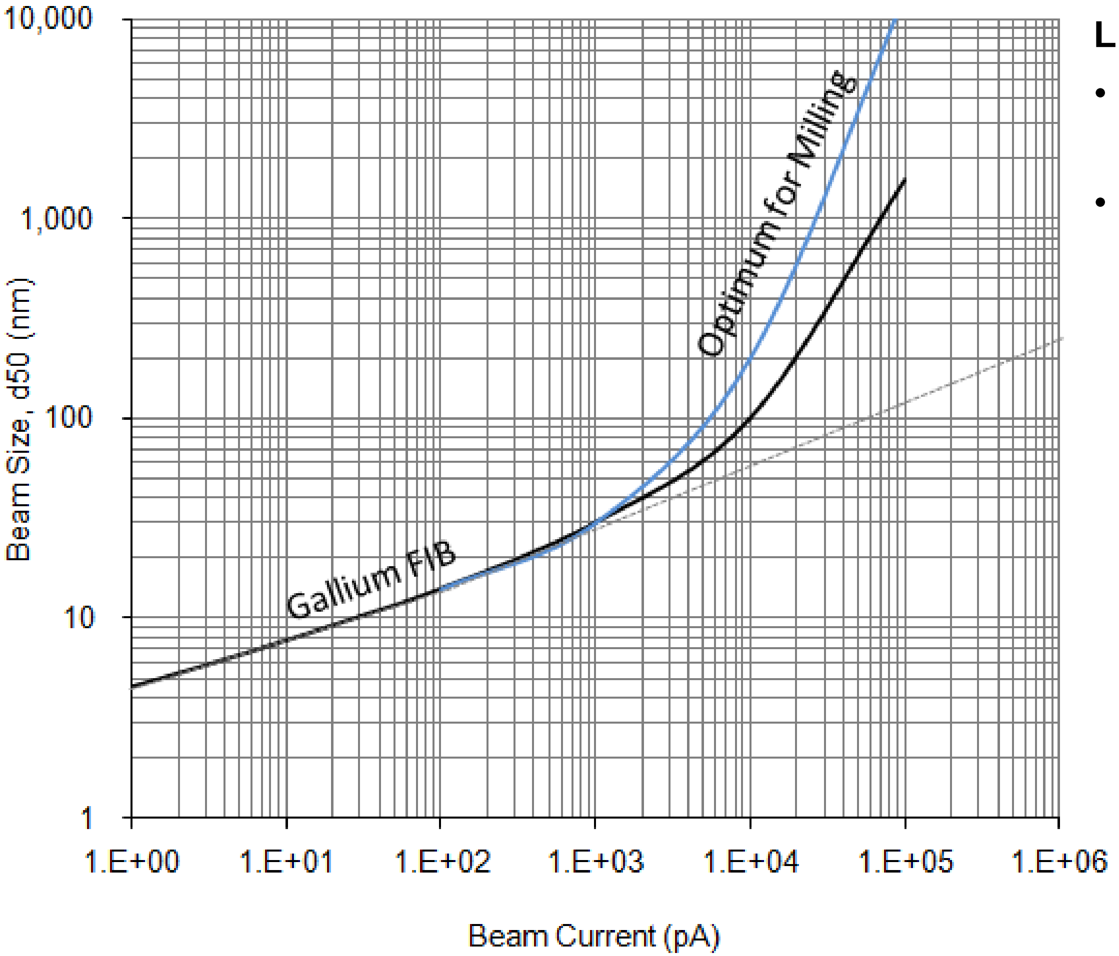
Mass Selection Aperture
Beam Blanking
Faraday Cup

Beam Scanning and Stigmation
(Octupole)

Objective Lens

Sample

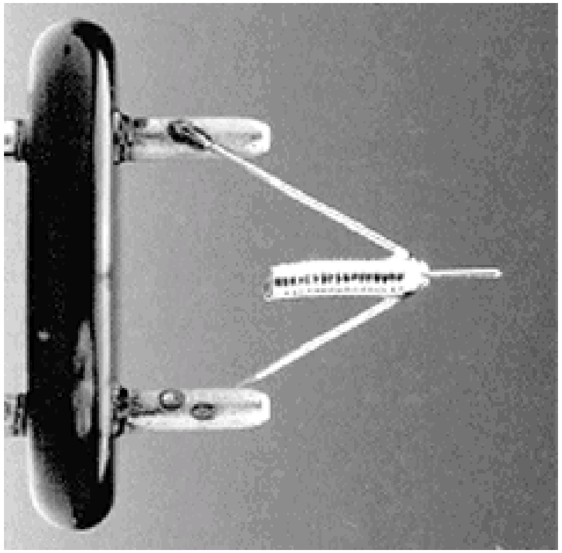
State-of-the-Art *(for the last 40 years)*



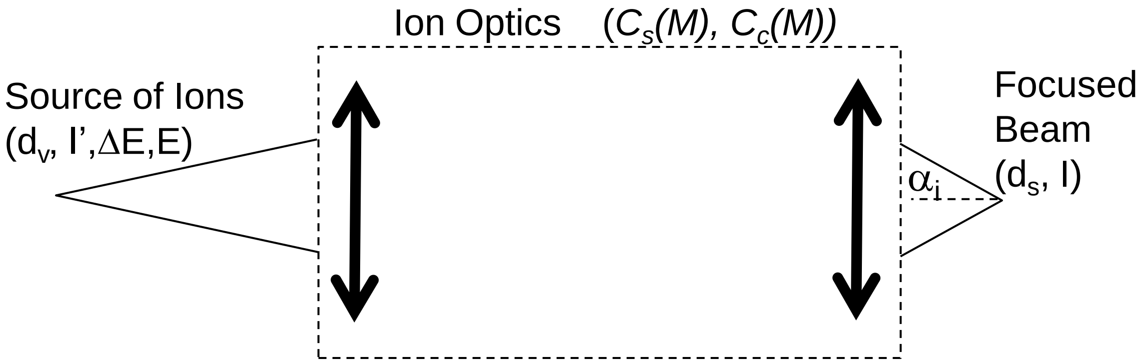
Liquid-Metal Ion Source (LMIS)

- Brightest ion source that's suitable for sputtering (*$1x10^6$ $Am^{-2}sr^{-1}V^{-1}$*).
- Low Angular Intensity *(15 uA/sr)*

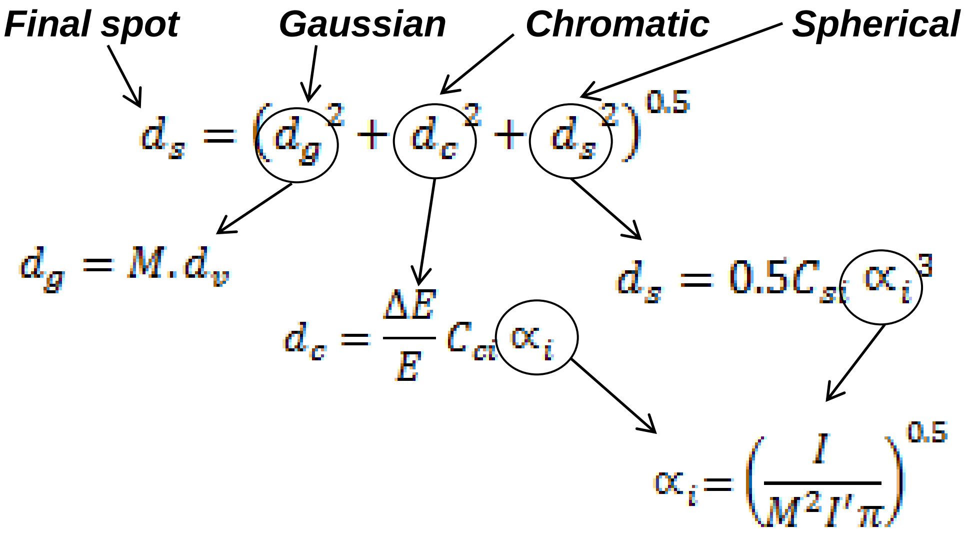
(ie only good for low beam currents)



Balancing Source Image and Aberrations for Best Spot Size



- Limit divergence angle to select required current.
- Set source image magnification (M) for optimum spot size, d_s.
- C_c and C_s are approximately constant for M<1.



$$d_s = \left(d_g^2 + d_c^2 + d_s^2\right)^{0.5}$$

$$d_g = M.d_v$$

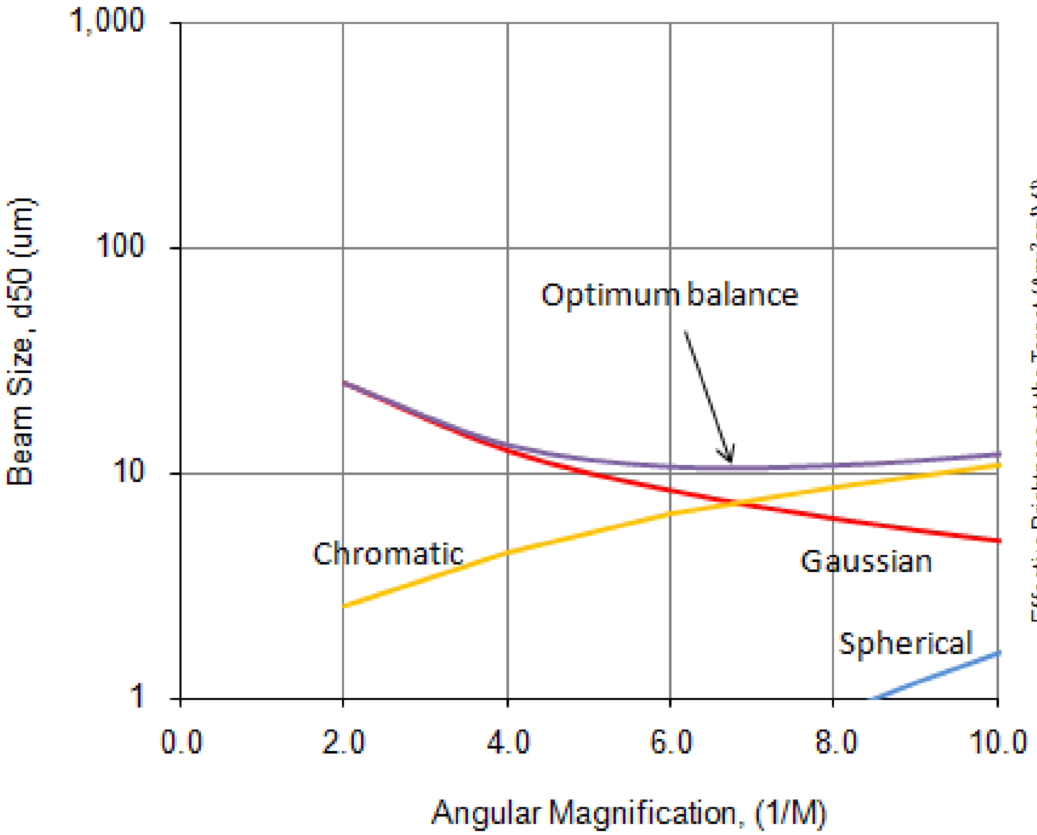
$$d_c = \frac{\Delta E}{E} C_{ci} \alpha_i$$

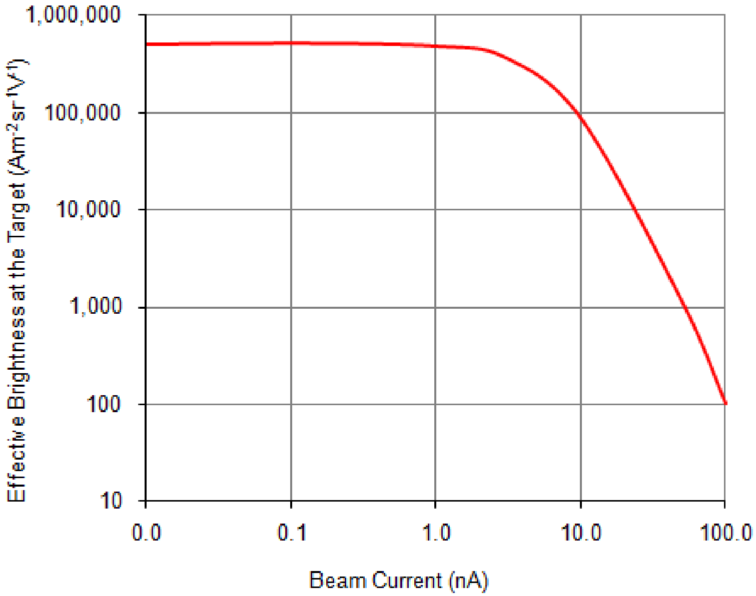
$$d_s = 0.5 C_{si} \alpha_i^3$$

$$\alpha_i = \left(\frac{I}{M^2 I' \pi}\right)^{0.5}$$

Assuming ions enter optics at the same energy as they exit

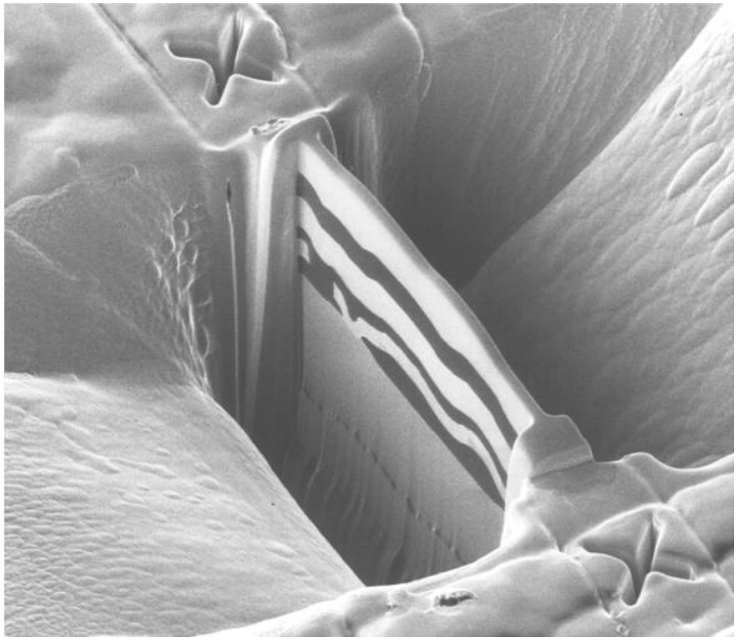
Gallium FIB Spot Size

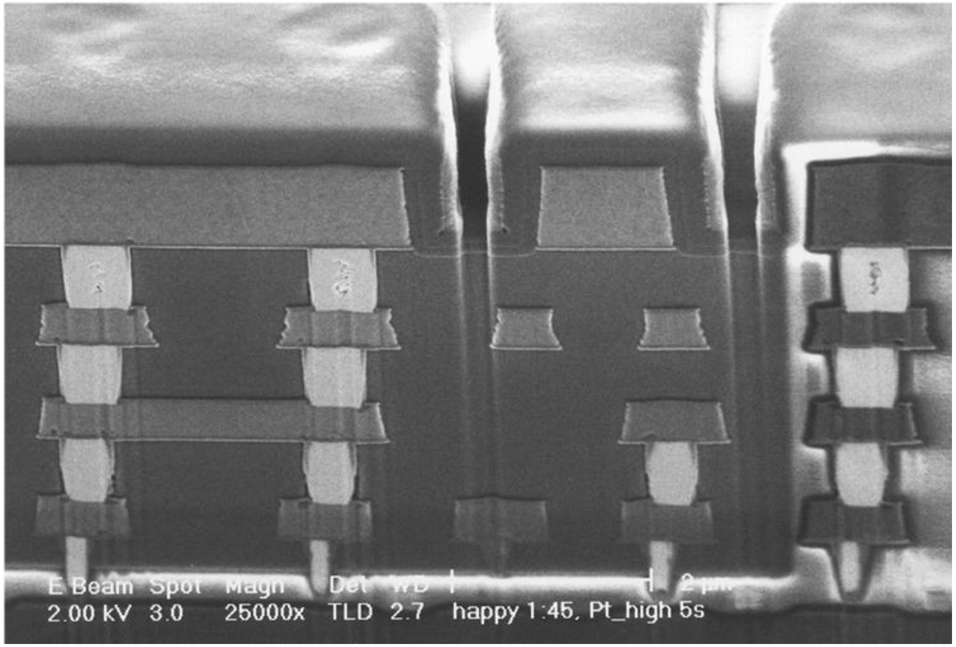




Beam Current: 100nA

Small Volume Sample Prep. for Sub-surface Analysis and Metrology





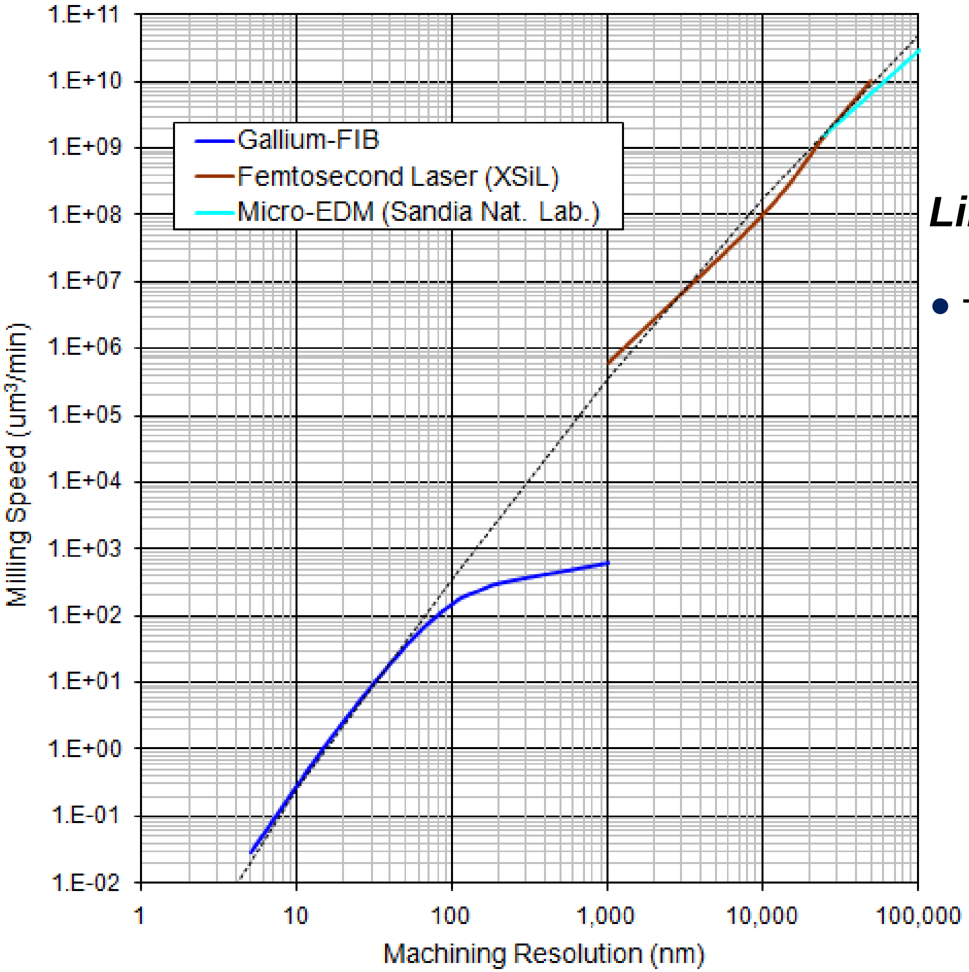
~10 um wide TEM lamella
1000um^3 of material milled
30-60minute preparation time

~10um cross-section of IC.
500um^3 removed (stairstep crater)
10-15 minutes preparation time

High Resolution Focused Ion Beams: FIB and Its Applications
J. Orloff, M. Utlaut and L. Swanson

Kluwer Academic/Plenum Publishers
ISBN 0-306-47350-X

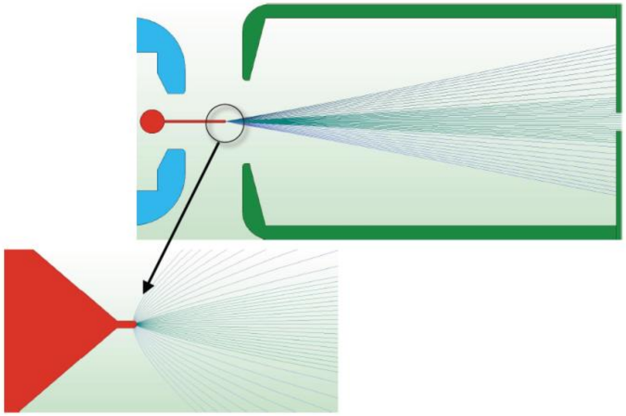
Non-Lithographic Milling Techniques



Limitations of Ga⁺ LMIS-FIB milling

- Too slow (<500μm^3/s) for large volume milling
    - *length scales of 25-500um (ie10^4-10^8 um^3)*
        - *IC packaging structures*
        - *3D-IC's/Interconnects*
        - *Delayering IC's*
        - *Micromachining.*

Alternative Ion Source

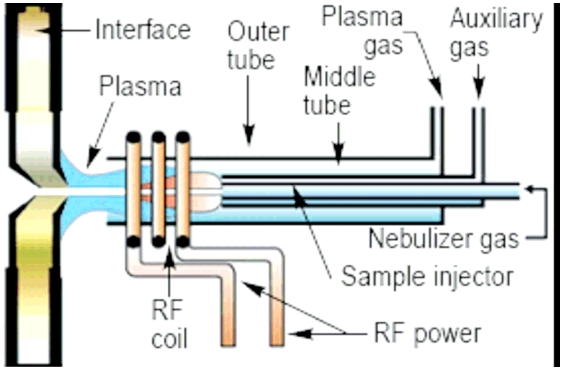


Liquid Metal Ion Source (Gallium)
Point source (50nm diameter)
Low angular intensity (15uA/sr)

Plasma Ion Source
Broad Area Source (10-100um diameter)
High Angular Intensity (5-10mA/sr)

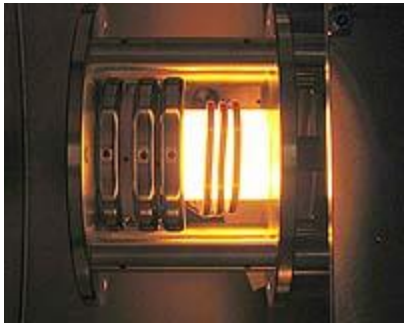
- ***DC Plasma sources have dominated for the last 50 years*** *(SIMS, ISS, High energy particle accelerators)*
  - *Limited brightness, stability and lifetime due to cathode erosion.*
  - *Broad Energy spread.*

Inductively Coupled Plasmas



ICP-OES (also ICP-MS)

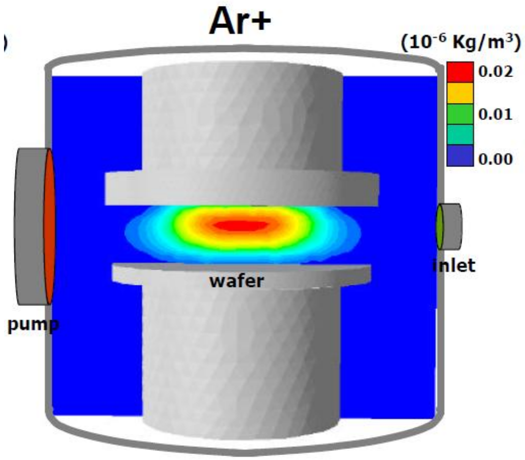
- No cathode – no source electrodes being sputtered
- High power density possible



DS4G Ion Thruster (ANU / ESA)

Lifetimes of >10^4 hours required

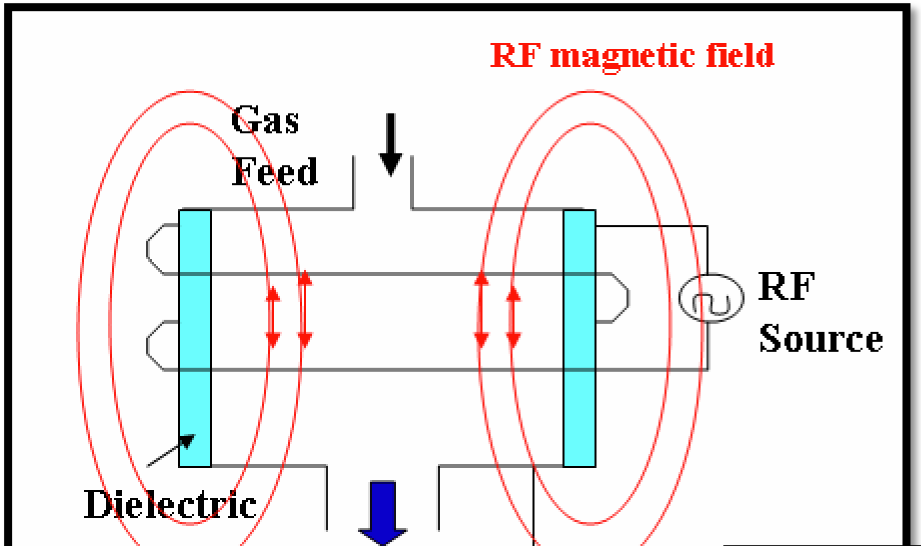
10x more fuel efficient than SMART-1 plasma thruster



ICP reactor –wafer etch/dep.

GEC ICP Reference Cell

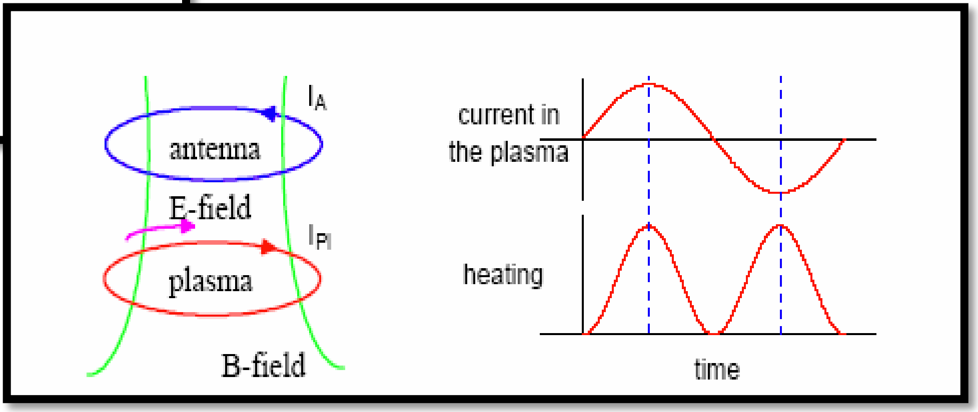
Inductive Power Transfer



Time varying current in an external coil creates a time varying B field, which induces an azimuthal E field.

$$\nabla \times \underline{E} = -\partial \underline{B}/\partial t$$

Induction E field accelerates electrons to ionize resident gas.



the electron plasma frequency

$$\omega_{pe} \triangleq \left(\frac{n_0 e^2}{\varepsilon_0 m_e}\right)^{1/2}$$ ~9GHz

the ion plasma frequency

$$\omega_{pi} \triangleq \left(\frac{n_0 e^2}{\varepsilon_0 m_i}\right)^{1/2}$$ ~18MHz ($n_o = 1 \times 10^{12} \mathrm{cm}^{-3}$)

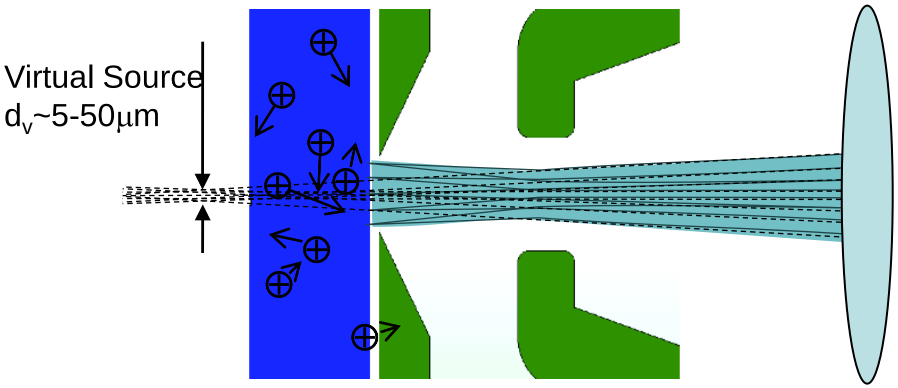
Ion Extraction

A drive frequency is chosen to accelerate electrons but not ions

– *low thermal ion energy*, (E_i)

No cathode – no sputtering and *high power densities* are possible without compromising life span

– *high plasma density*, (n_i)



	Brightness ($Am^{-2}sr^{-1}V^{-1}$)
Xenon	$1x10^4$
Oxygen	$4.5x10^3$
Helium	$6.5x10^3$
Hydrogen	$3x10^3$

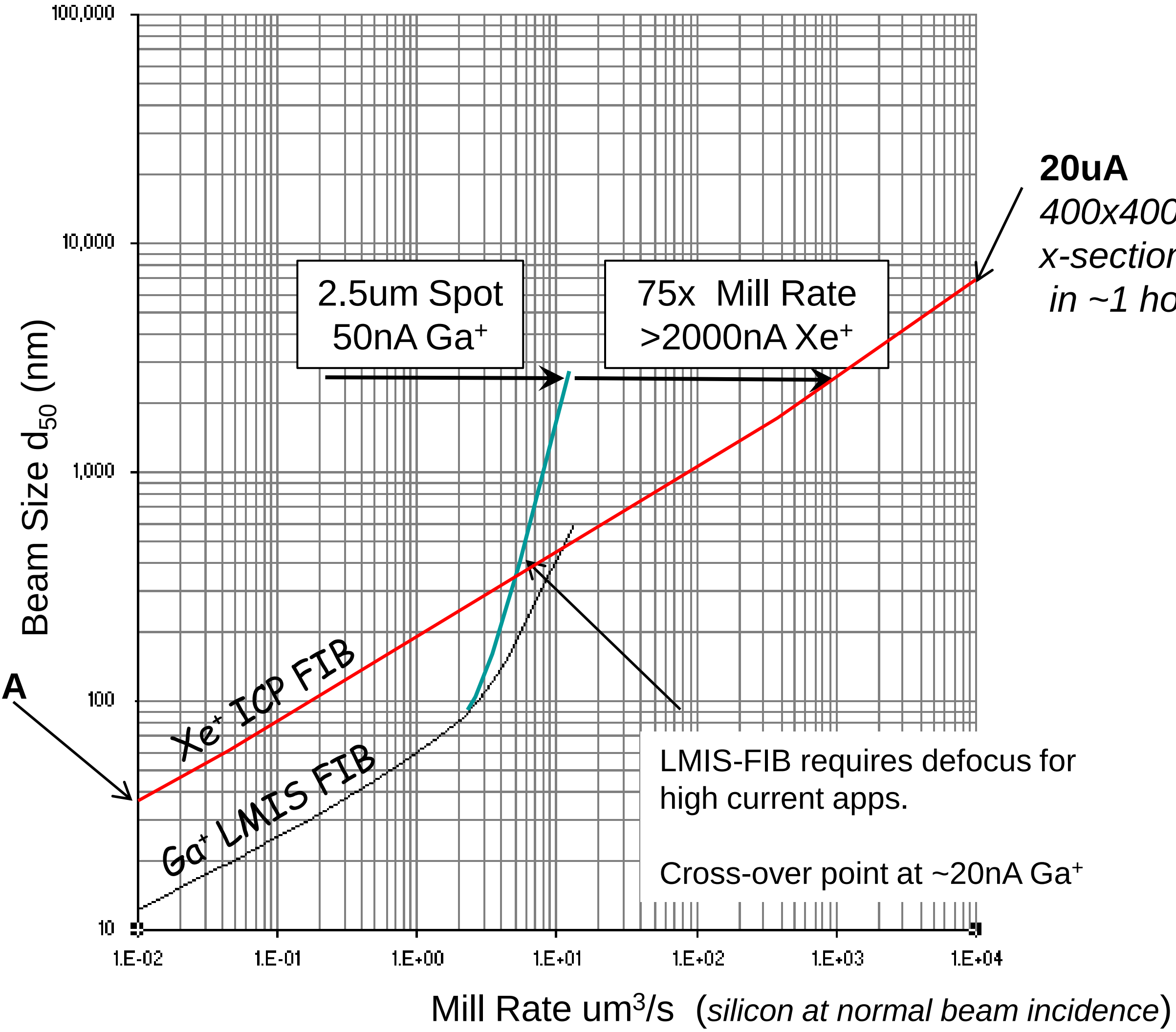
Angular Intensities 5-10mA/sr

$$\beta_{max} = 0.6qn_i\sqrt{\frac{k_BT_e}{M_i}}\left(\frac{E_0}{\pi E_i}\right)$$

$>1x10^{13}cm^{-3}$

$<0.045eV$

Xe$^+$ FIB for Large Volume Micromachining



2.5um Spot
50nA Ga$^+$

75x Mill Rate
>2000nA Xe$^+$

20uA
400x400um
x-sectioned faces
in ~1 hour

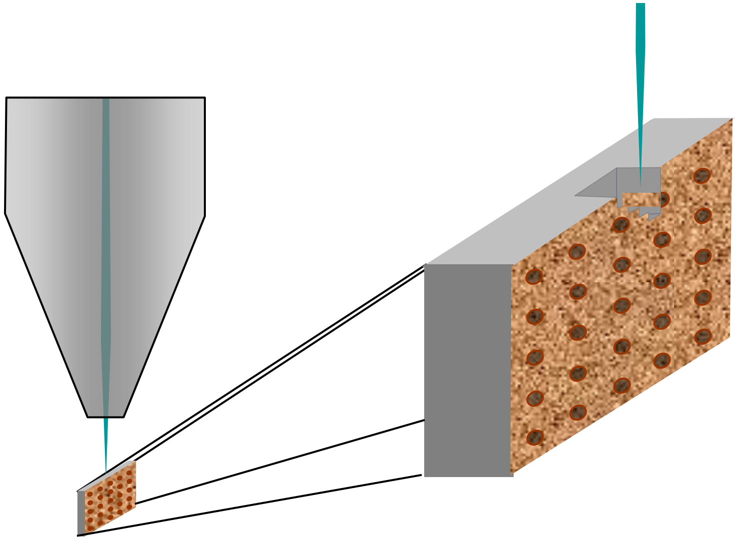
20pA

LMIS-FIB requires defocus for high current apps.

Cross-over point at ~20nA Ga$^+$

Rapid Plasma-FIB Milling

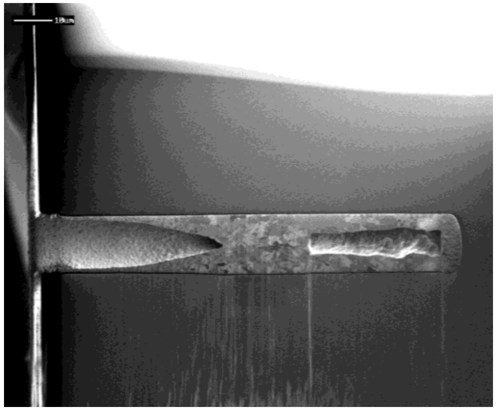
Through Silicon Vias (TSV's)

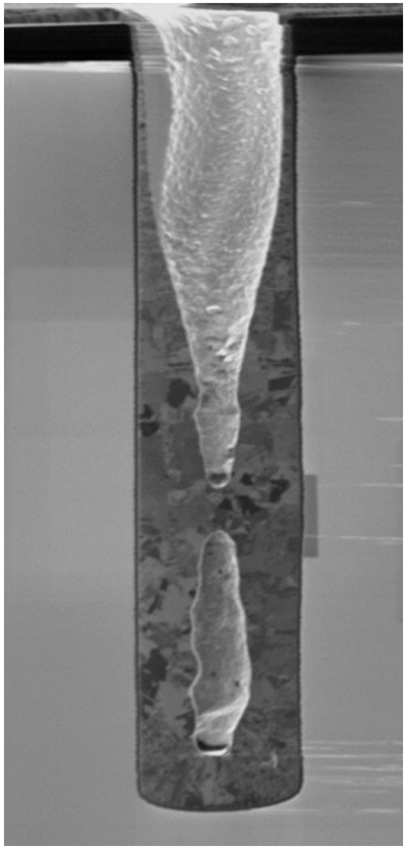


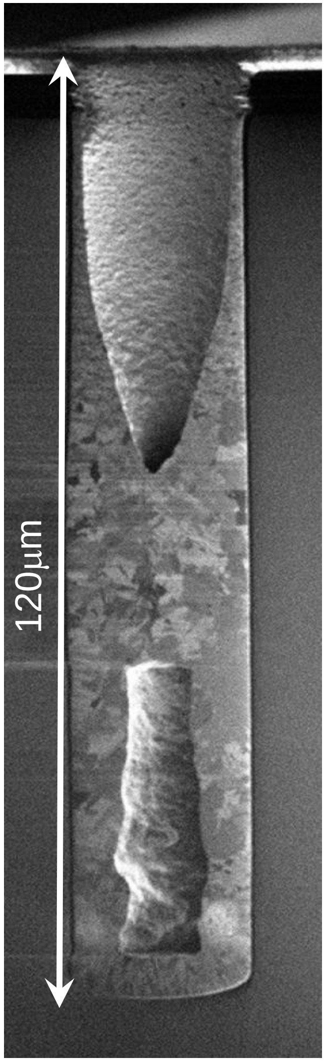
150x100x100um stair-step

1000 nA – 25 mins.
100 nA polish – 10 mins.
50 pA image ~50 nm

(v's 15hrs for 50nA Ga)



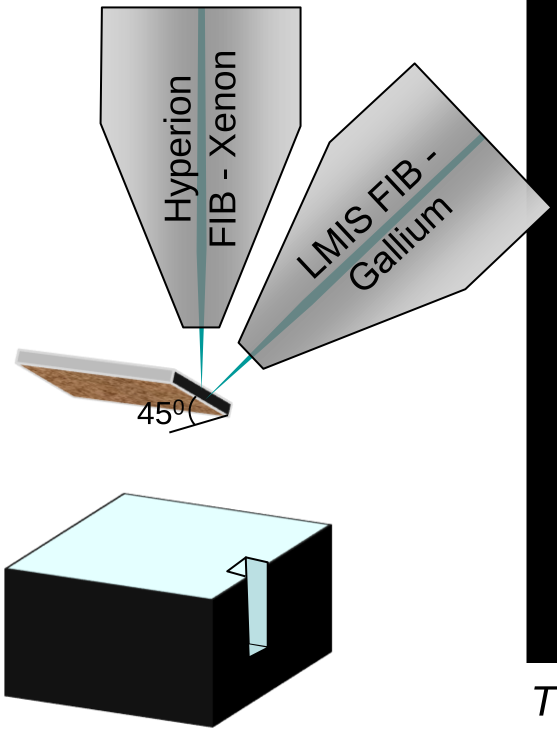


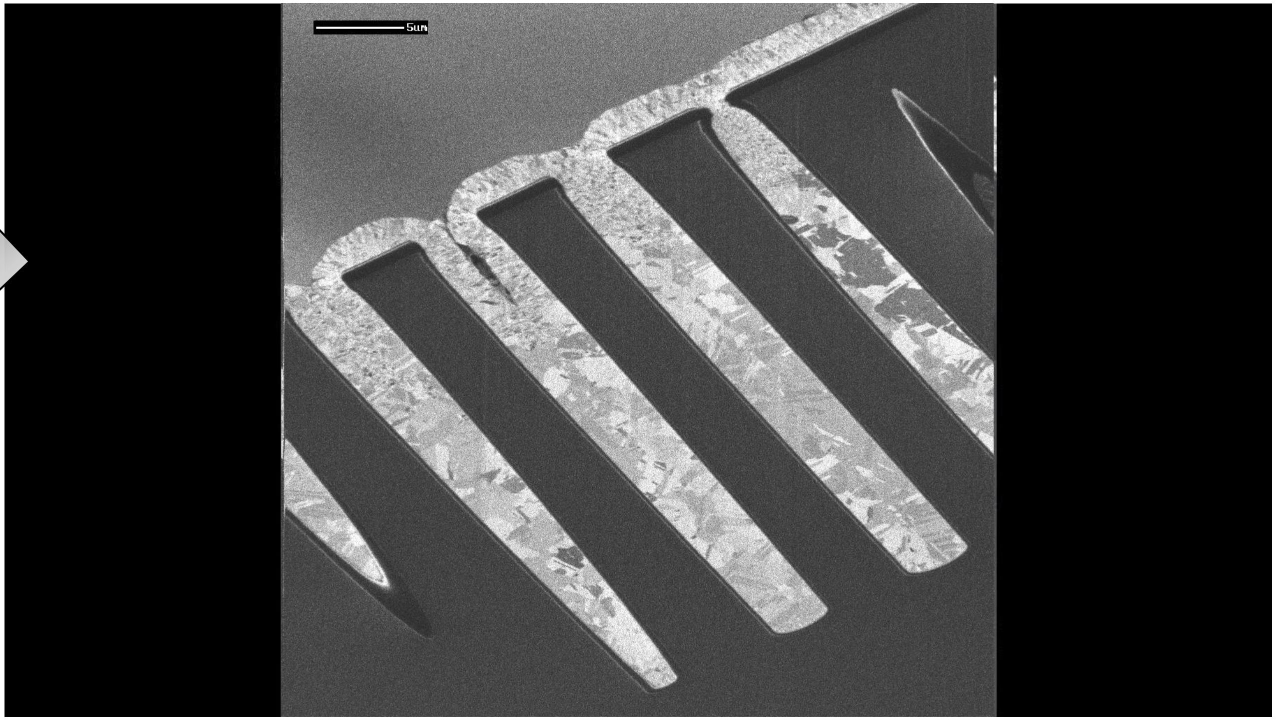


3D Tomography

FIB-FIB (Plasma-Gallium) built to study large area tomographic analysis.

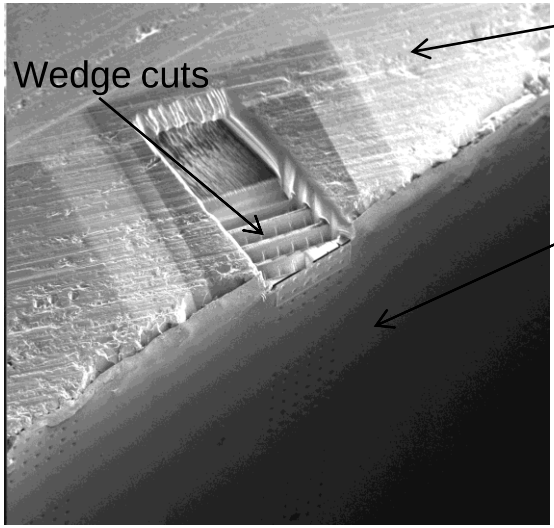
100 x 100um x 0.1um thick slices (500nA)
10 seconds/slice

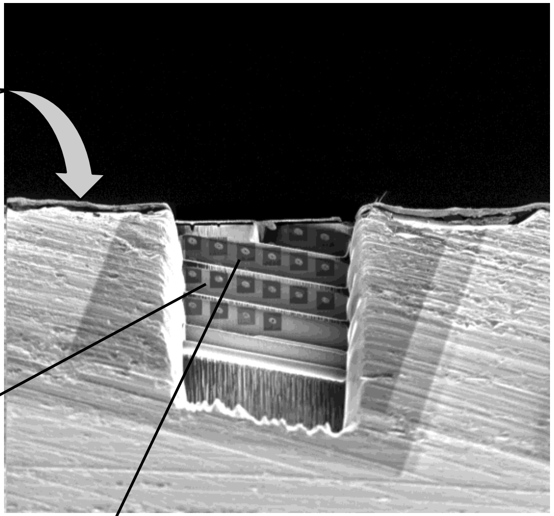




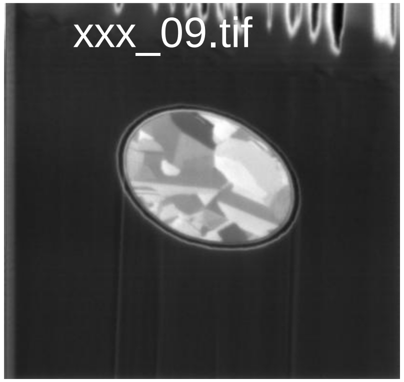
TSV structure, courtesy of Dr. Bender (vias developed at IMEC, while developing their fabrication process)

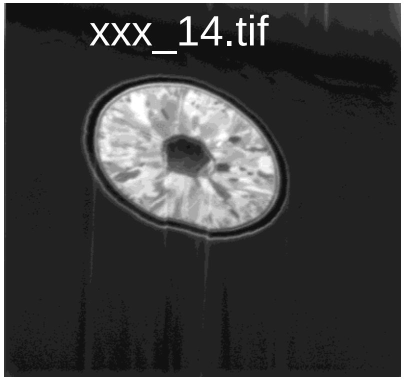
Wedge Cut





Useful for Catching Very Fine Axial Voids





Cut Parallel to vias:
80x200x30um
1000nA Xe^+ 8 minutes

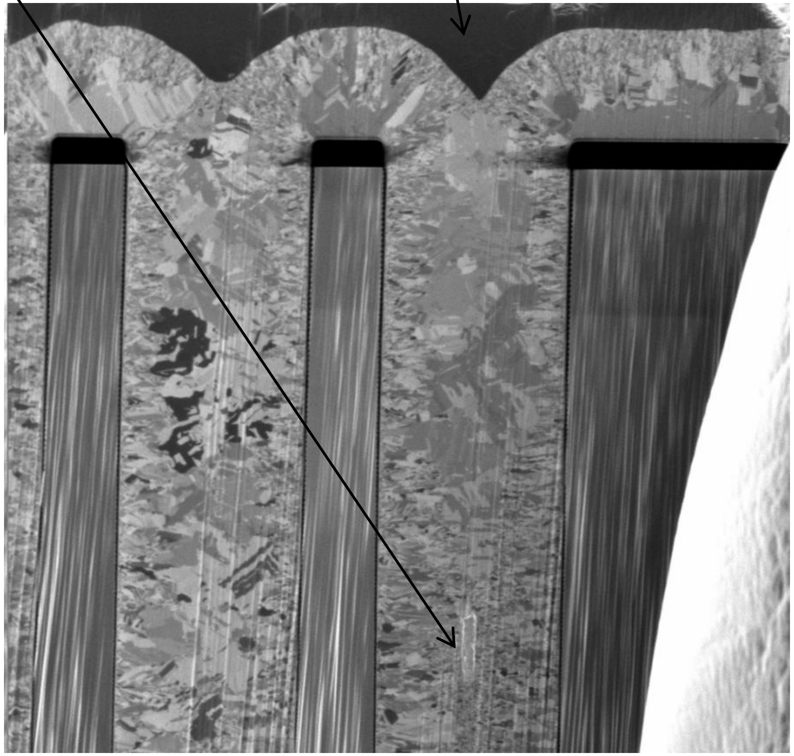
Wedge Cuts:
120x15x15um rows
100nA Xe^+ 20 minutes

Top Down Bias Cut

- Sample imaged with Gallium FIB (normal incidence)

Molybdenum deposited on surface, but more susceptible to curtaining

Axial Void



- In this example, 5 vias are in a row.
- The final via in the row, caught the axial void

Coarse Mill:150x150umx40um - 1uA Xe^+ (18 mins)
Polish Mill: 150x150x10um – 200nA Xe^+ (22mins)

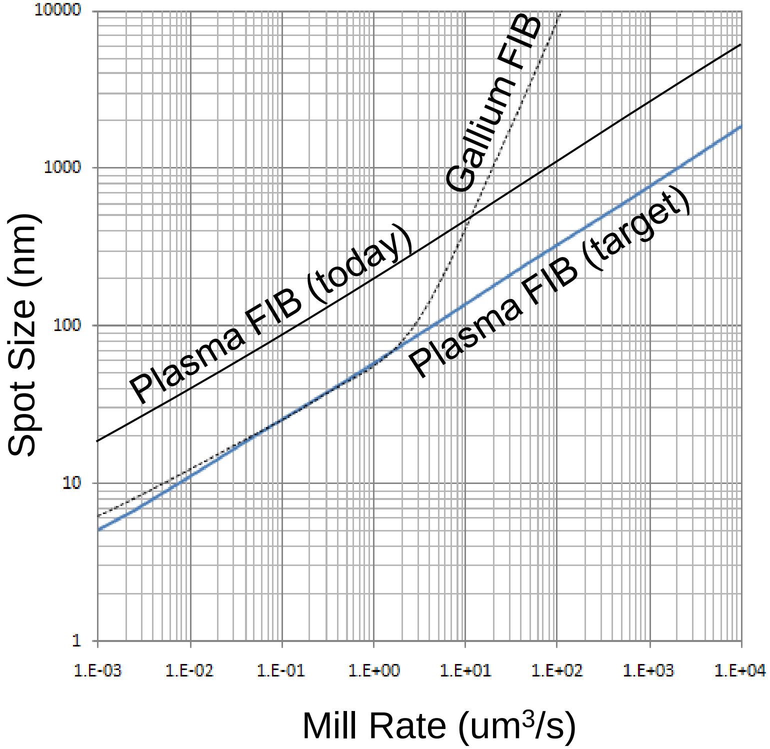
Conclusions

- **Application space for ICP ion source.**

  FIB
  - Large area FIB cross-sectioning.
  - Micromachining (custom apertures, machining steps for micro-mechanical devices)
  - Low Energy amorphous layer removal

  SIMS
  - Faster low energy depth profiling.
  - Higher resolution imaging.

- **ICP performance has not reached it limits.**
  - 50nm imaging resolution to date, but sub-20nm resolution 30keV/1pA Xe$^+$ beams are possible with today's source technology.
  - R&D over the next couple of years will certainly result in gains in source brightness and possibly energy spread. 8-10x gain in plasma density and 2.5x reduction in energy spread is the present target.



(normal incidence in silicon)