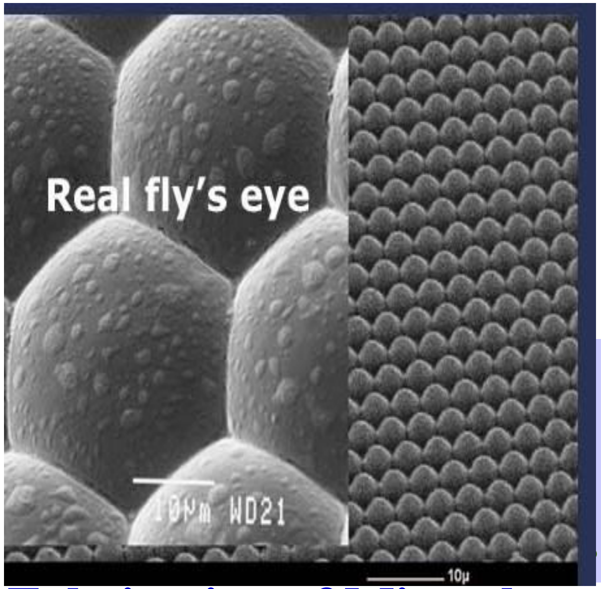
Nontraditional Manufacturing Processes,

MF30604

Ion Beam Machining

Feature size & Resolution: Demand of Modern Industries

In Semiconductor Industry: Electronics IC, MEMS
Features size: Submicron ($<10^{-6}$m)
Resolution : 100Å (0.01µm)
Surface roughness:10Å (~1nm)



Fabrication of Micro-lens

Material removal or addition in these feature sizes & resolution is a challenge

Feature size limited by Wavelength of the Exposure Source

		Wavelength	Energy
Light	UV	400 nm	3.1 eV
	Deep UV	250 nm	4.96 eV
	X-Ray	0.5 nm	2480 eV
Particles	Electrons	0.62 Å	20 keV
	Ions	0.12 Å	100 keV

Excimer Lasers

KrF*, λ = 248nm
ArF*, λ = 193nm
F_2*, λ = 157nm

$\Rightarrow$ Structure Size ~ λ
Resolution~50nm

Electron Beam Lithography

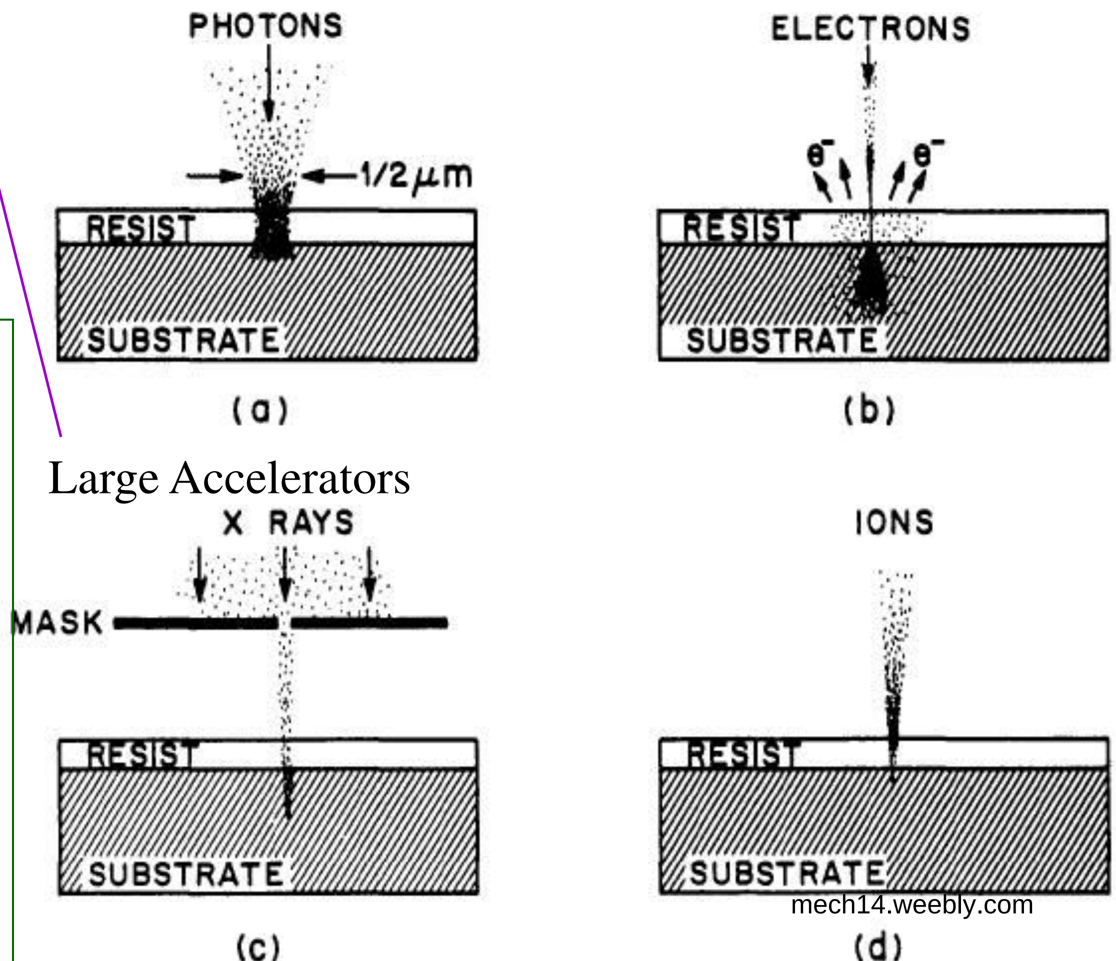
Direct writing on radiation sensitive polymer

Can be focused down to 5nm

Min Feature size =10nm

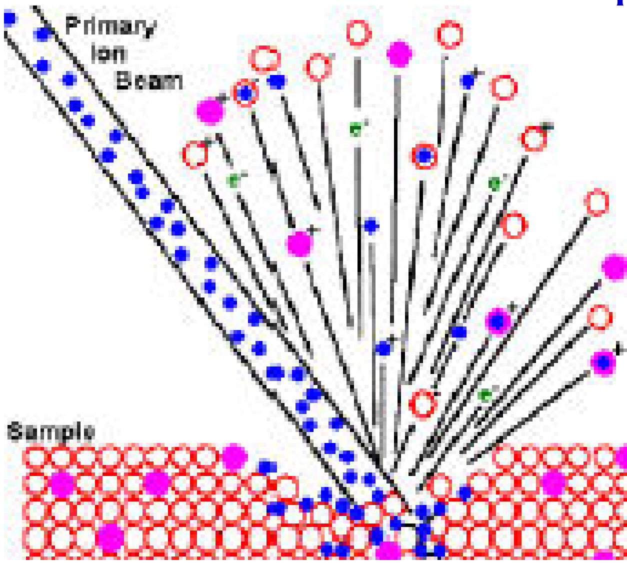
$$\lambda = \frac{h}{\{2mV_e e(1+eV_e/2mc^2)\}^{1/2}}$$

At acceleration voltage V_e=120kV, λ=0.0336Å



Ion Beam Machining (IBM)

Ion beam: A particle beam consisting of ionized atoms i.e. ions



Ion Sputtering

A stream of ions of an inert gas, such as argon
l such as gallium is accelerated in a
n by high energies and directed toward a
orkpiece.

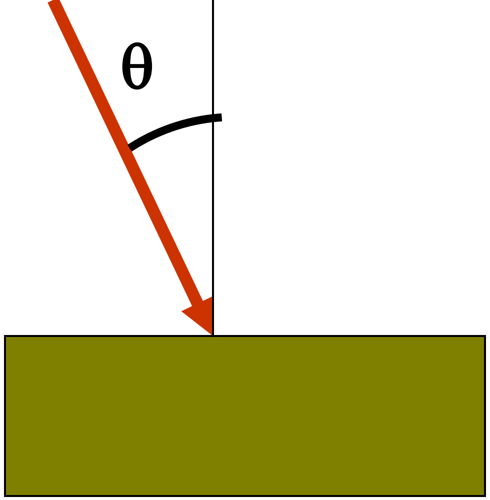
Ion beam knocks off atoms from workpiece by transferring kinetic energy and momentum to atoms on the surface of the object.
(E-beam: Heating, melting & vaporization)

When an ion strikes a cluster of atoms on the workpiece, it dislodges between 0.1 and 10 atoms from the workpiece. This process is called **Sputtering process**. Secondary electrons & ions are also ejected out.

Sputter Yield, S = No. atoms removed / No. of striking Ions

Sputter yield depends on the energy of the incident ions, angle of incidence on the surface of work-piece, masses of ions and target atoms, and the binding energy.

Sputtering rate as the depth of surface layer sputtered in the unit of time:



$$V(nm/s) = 0.1S(M/d)\ J.\cos\theta$$

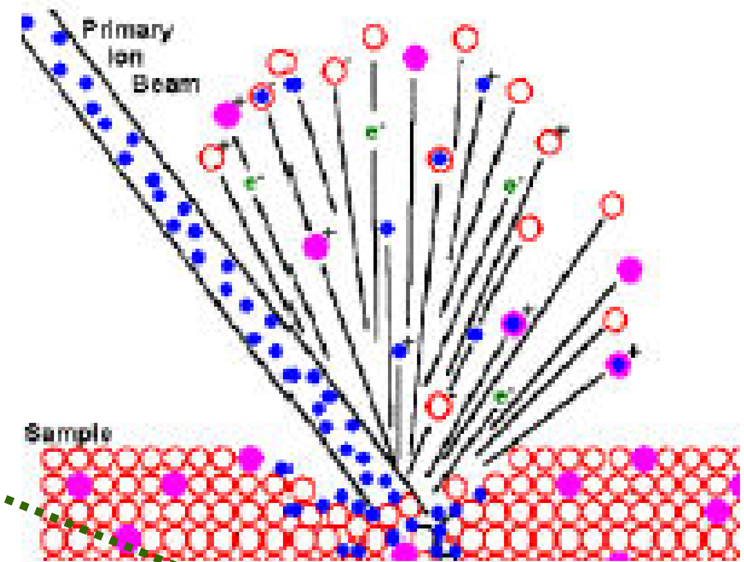
where S - sputtering yield (atoms/ion),
M - atomic (molecular) weight (g) of target,
d - target density (g/cm^3),
J - ion current density (mA/cm^2) and
θ - angle of incidence

Example: Ar+ ions,
J= $3mA/cm^2$ and E=200 eV
Sputtering rates of optical glasses V= 0.3 - 1.0 nm/s
Rate good enough for most engineering applications.

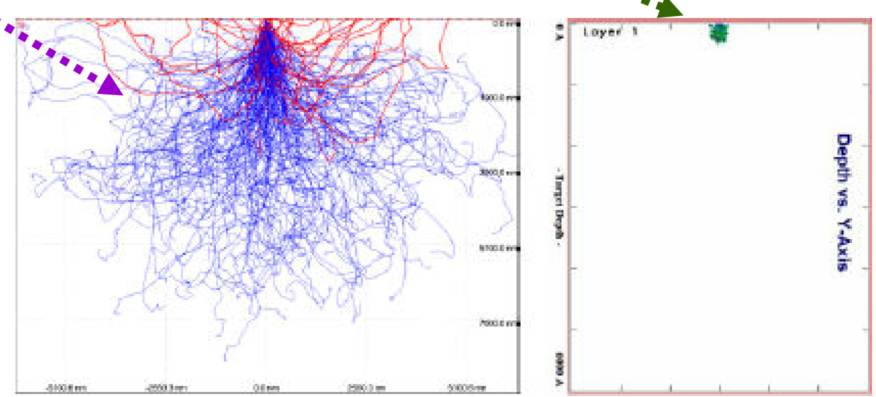
Only ~5% of ion energy spent for sputtering, 95% is scattering in other processes, mainly heating the target.
However, the power density on the surface of target = $0.6W/cm^2$, so the target will be heated only a little (usually up to 50^o - 90^oC).
One of the main advantages of ion beam treatment - we can work with a lot of temperature sensitive materials!

Difference and advantages of using Ion Beam instead of E-Beam

E-Beam	**I-Beam**
Light & Small	**Heavy & Big**
Velocity: High	Low
Low Momentum $\propto m_e^{1/2}$	High Momentum $\propto m_i^{1/2}$
Interaction length: **Large**	**Sallow (nm)**
Processing rate: Slower than Ion-Beam	Faster Than Electron Beam
Feature Size & Resolution: Similar order	Similar order, Better control
Mode of Processing: Thermal	Sputtering: Direct knocking of atoms
Process capability: All types of Materials	All types of Materials



30kV Electrons vs Ga Ions



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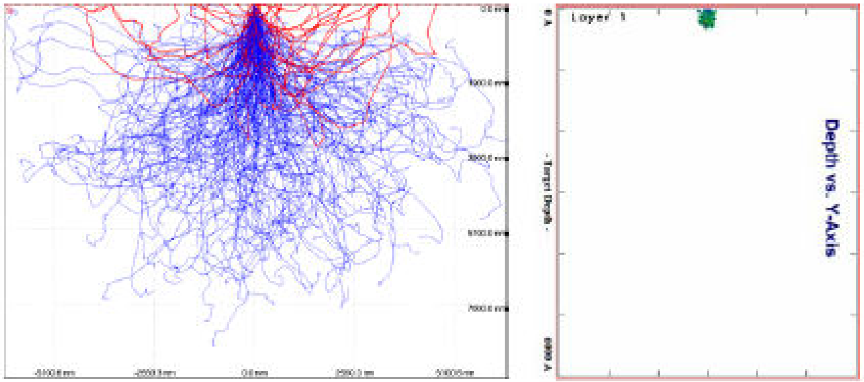
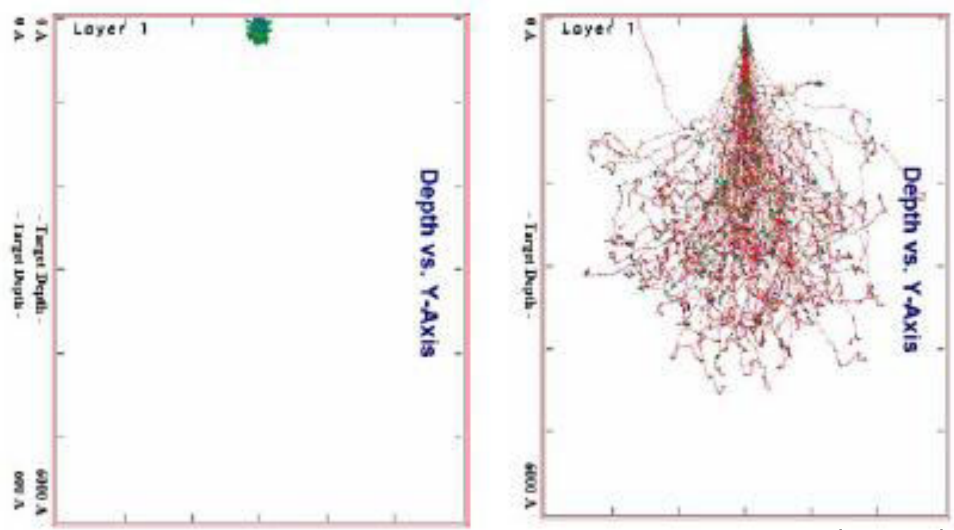
30kV Electrons vs Ga Ions

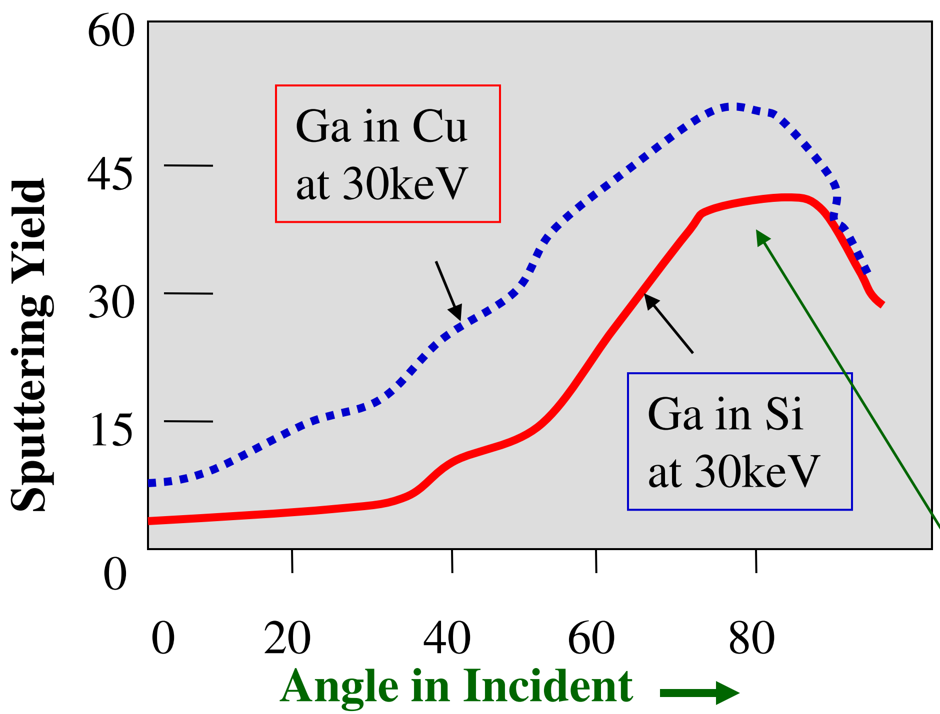


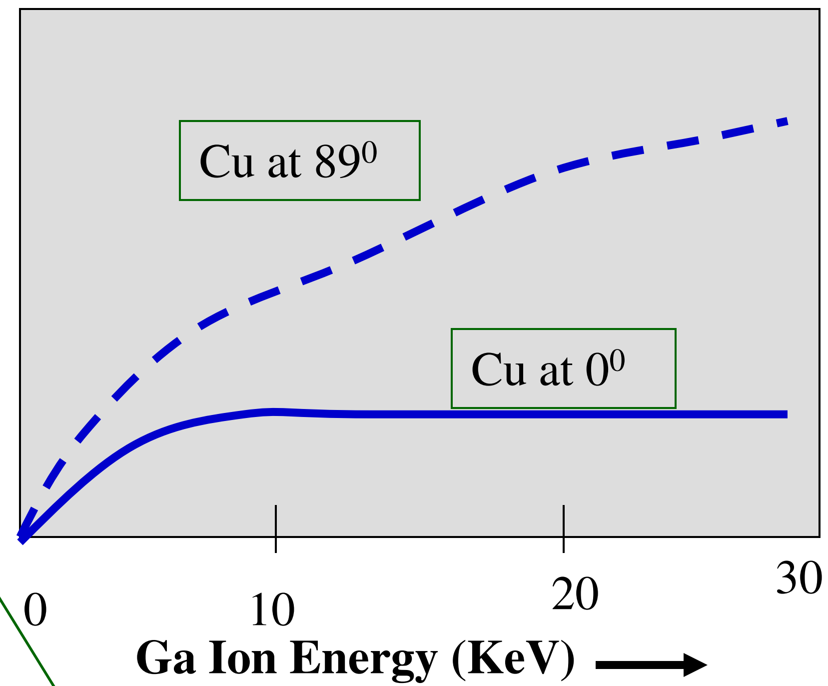
30kV Ga vs He

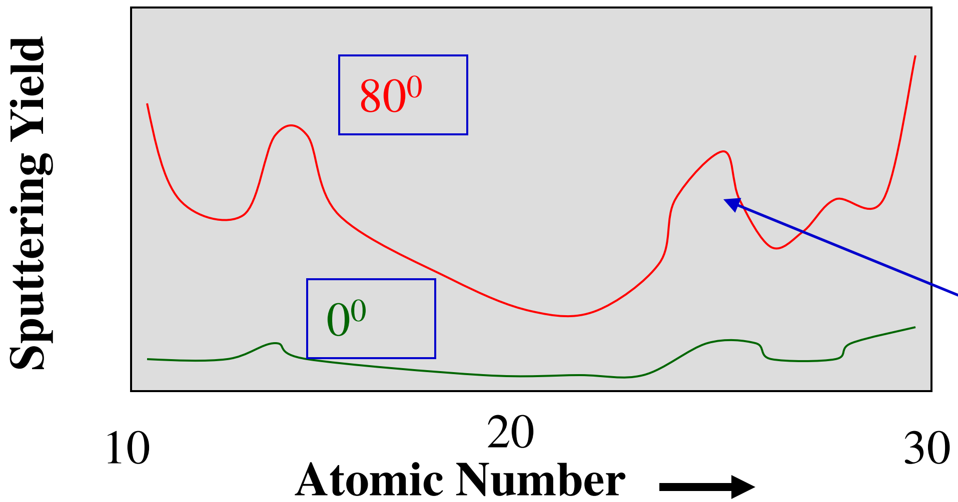


Heavier Ion beam:
* Very localized action
* Each striking ion can eject a few atoms from the surface

Dependence of Sputtering Yield on Target Material and Incident Angle







Higher Yield near Grazing Angle

Trend follows the Melting Temperature variation with Atomic No.

Applications:

Etching / Milling of all kinds of material,

Reactive etching,

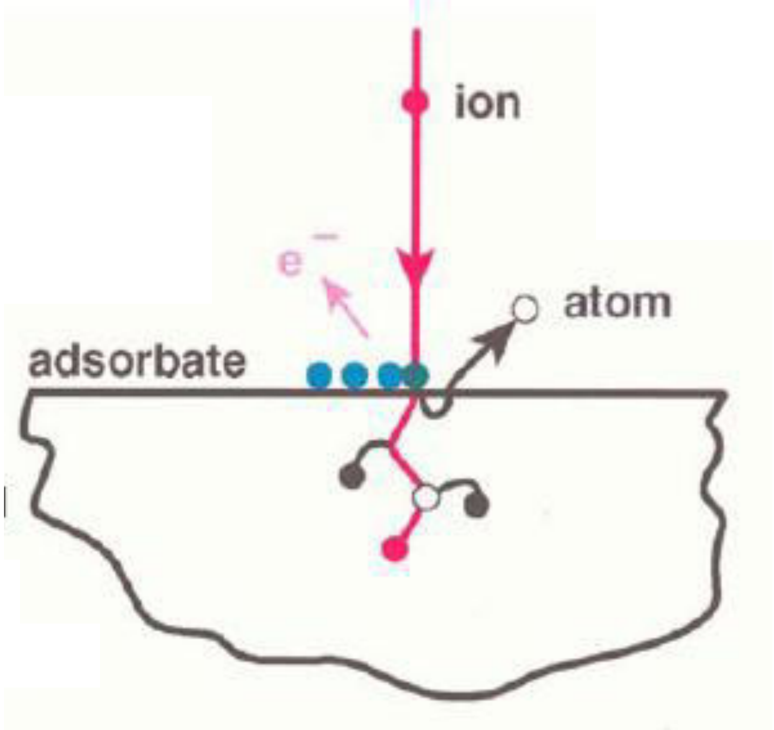
Substrate cleaning,

Deposition:

Sputter deposition,

Ion-beam assisted depostion,

Diamond-like coating and



Ion- beam Lithography

Ion-beam implantation

Types of Ion Beam Source:

Mainly two types-

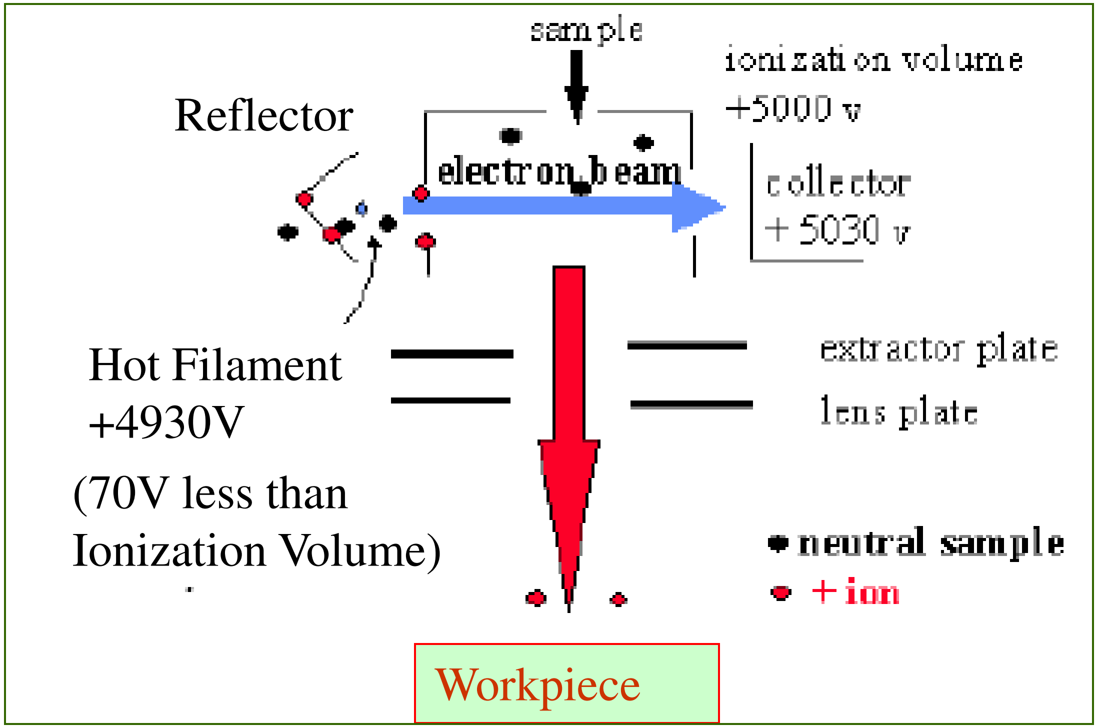
1. Broad Ion Beam supplied by a **plasma**
2. Focused Ion Beam using an **ion accelerator**.

The Electron Bombardment Ion Source:

Production of Ions: By ionizing i.e. removing an electron from an atom by electron bombardment.

Electron production:

A. Thermionic Emission from hot filament

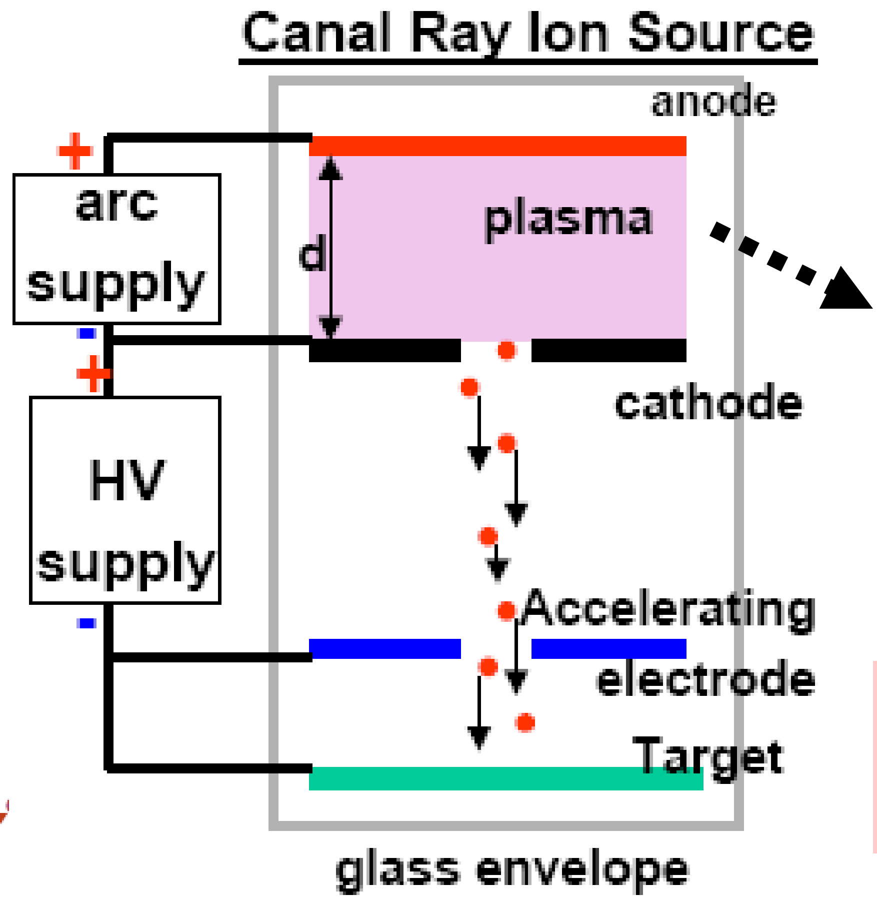


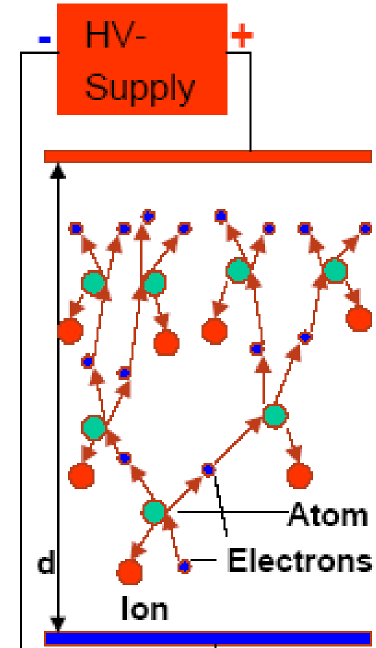
B. Broad Ion Beam supplied by a **plasma**

Energy for removing an electron from atom – Ionization Potential – a few eV to tens of eV.

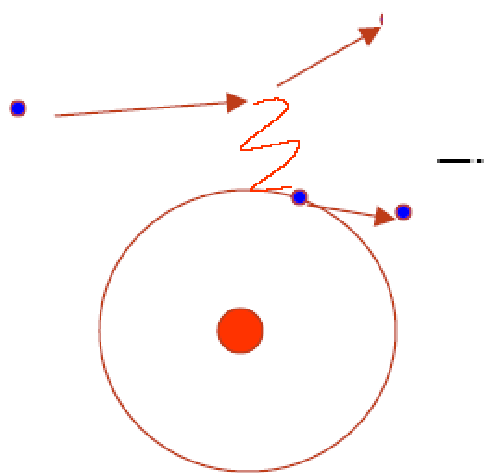
Ar- 15.6eV, O_2- 12.1eV, He-24.6eV, H_2-15.4eV, H- 13.6eV, **Ga – 6eV**

Ionization by electron bombardment





Electron Multiplication in High Electric Field



Invented in the mid-19th century, the canal ray ion source is not suited for producing intense ion beams

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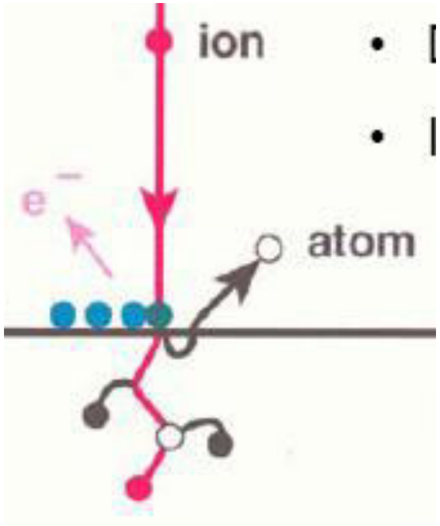
Ion Beam Etching / Milling - (IBM): Physical Etching Process.



Ion beam etching/milling ⇒ Similar to an atomic sand blaster
Submicron ion particles accelerated to bombard the work surface

Processed inside a vacuum chamber.

The work ⇒ Wafer or substrate that requires material removal by atomic sandblasting or dry etching.

Ions literally knock off atoms out of the target surface.
The etching mechanism is momentum transfer.

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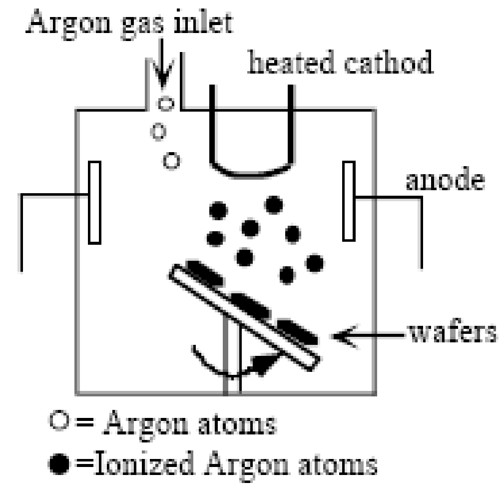
Ion Beam Etching for Patter Generation:



Basic procedures ⇒ similar to optical lithography.
First, desired pattern developed on the photoresist layer,
Etched by an ion beam instead of wet chemicals
⇒ dry etching process.

Noble gas e.g. argon ion produced by energetic electrons

Ion energy= 100-1500eV

Ar^+ ions attracted by Wafers at (-) potential
Ar^+ traveling toward wafers, are accelerated & gain energy.
Ar^+ impinging on the exposed wafer surface, knock out the atoms on the surface.
No chemical reaction takes place between Ar^+ & wafer material.

Material removal is **highly directional**
⇒ Good definition and high spatial resolution
⇒ ~ **10nm** and **sub-micron** range structures.

Poor selectivity on material.
Etching rate of wafer 3-10 times higher than properly chosen resin.

Typical etching rate up to 2500 Å/min
Current density of target is a few mA/cm^2.

Reactive-Ion Etching (RIE):

* Reactive gas introduced along with inert gas

* Reactive ions generated in the plasma are extracted and accelerated towards wafers.

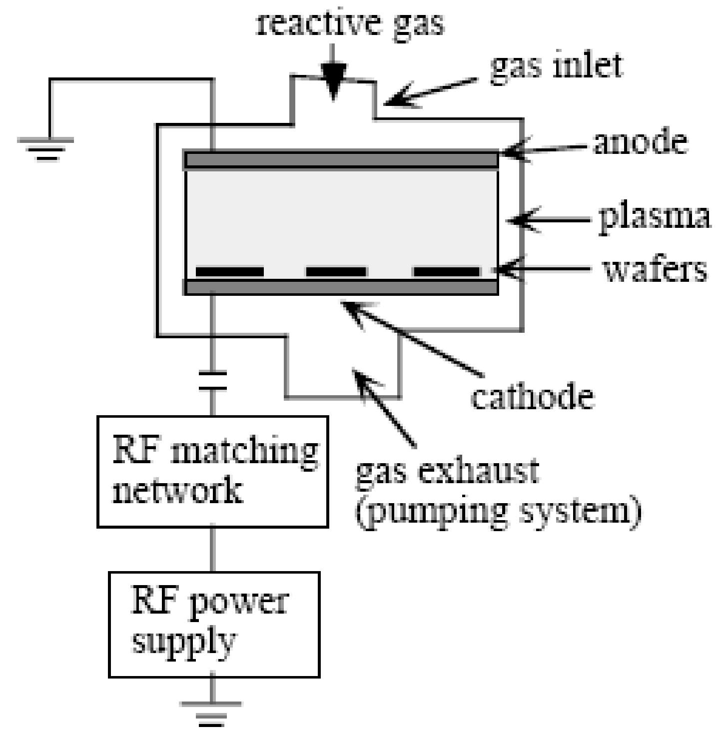
*Combination of physical and chemical etching processes.

* Etching occurs when chemical reaction between reactive ions and surface material produces volatile compounds.

* Volatile products are removed by vacuum pump.

* Ion bombardment produce directional etching

* RIE is a highly selective process.



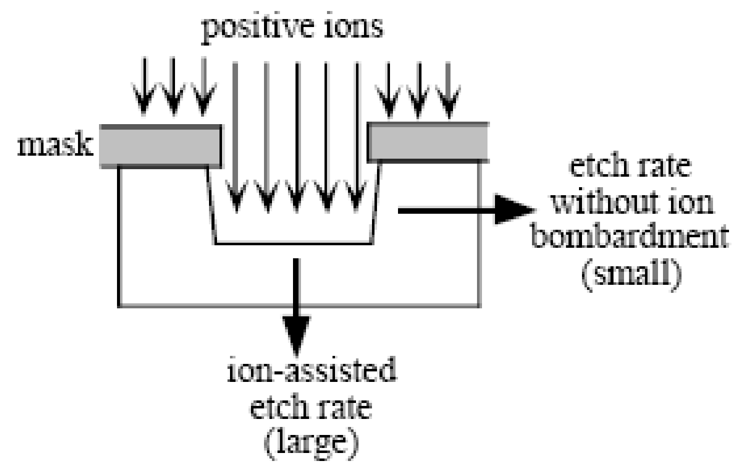
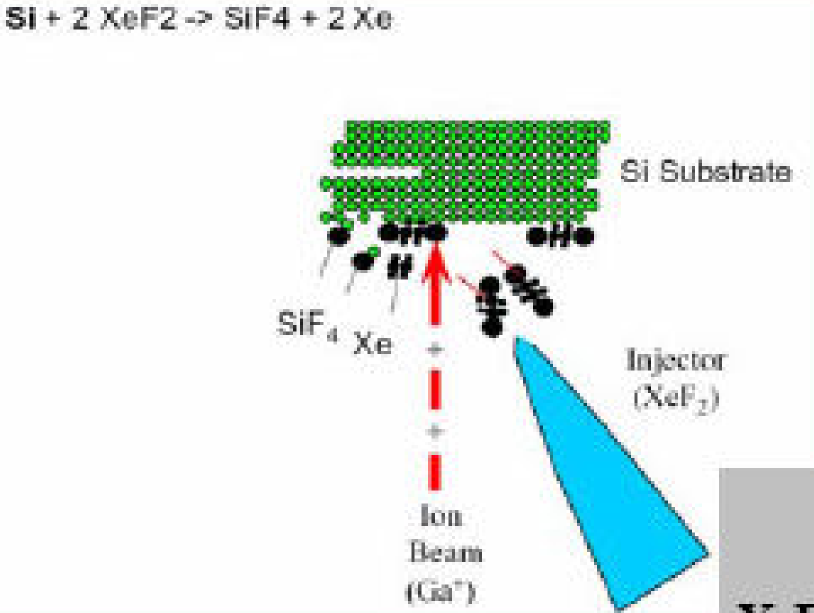


Fig. 25: The ion-assisted etching process.

Principles of Ion Beam Interactions



Source: FIB Folder TU Berlin, Institut für Hochfrequenz und Halbleitertechnologien

Gas Enhancement Factors:

The enhancement factor indicate the removal efficiency of the FIB process with etchant gas relative to ion sputtering without etchant

	SiO_2	Si_3N_4	Al	W	Si
XeF_2	10	8	-	6	>100
Cl_2	-	-	15	-	7
Br_2			15		6
H_2O	-	-	-	-	-

During the gas-assisted process, gas is adsorbed onto the surface, where it reacts with the ion beam and the surface material, producing volatile compounds that are pumped away.

Halogen gases such as iodine, chlorine, and bromine are used to enhance aluminum etching.

Xenon fluoride is used for the etching of insulators, and

Water vapour for the milling of carbon-based materials.

Process Capability:

- Suitable for **sub-micron range** milling, slotting, drilling with high aspect ratio in all most all types of materials, metal, semiconductors, diamond, Diamond like Carbon (DLC) coatings, quartz, other oxides and ceramics.

  Silicon wafer of thickness up to 300 μm can be etched

- Reactive ion beam etching (RIBE) processes: MEMS structures on quartz & Si; CMT (CdHgTe); diamond and DLC; SiO_2; InP/InGaAsP; GaAs.

- Material Removal Rate : 2.5n/min. - 0.25 μm/min depending upon ion energy, angle of incidence, material and gas (reactive) assist.

- Features: Sub-micron

- Resolution : 100Å (0.01μm)

- Surface roughness:10Å (~1nm)

Advantages:

Process is almost universal & well controlled

Processing with or without chemical reagent etchants

Minimum undercutting

Disadvantages: Relatively Expensive, Slow etching process

Applications -
Electronic & mechanical elements for a wide variety of commercial, industrial, military and satellite applications including circuits for RF and Microwave applications.

Material Addition Process: Ion Beam Deposition

Several Configurations : Direct Deposition- Ion Beam Sputter Deposition (IBSD)

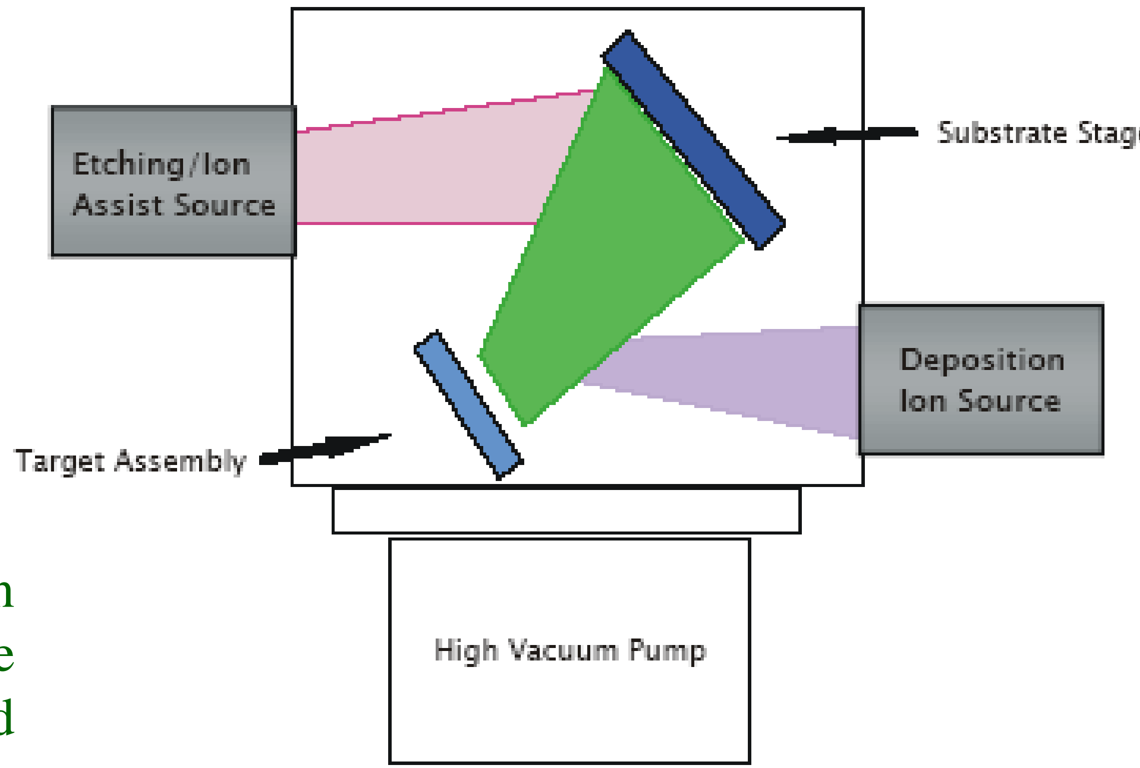
Two Independent Ion Beams in a Vacuum chamber :

First IB aimed at the target, produces sputtered material, which gets deposited on substrate.

Second IB aimed on substrate to provide ion-assist in the growth of good quality film with outstanding properties.

Independent control of Ion beam parameters facilitate depositing films of desired properties

Typical Dual Beam Deposition Configuration

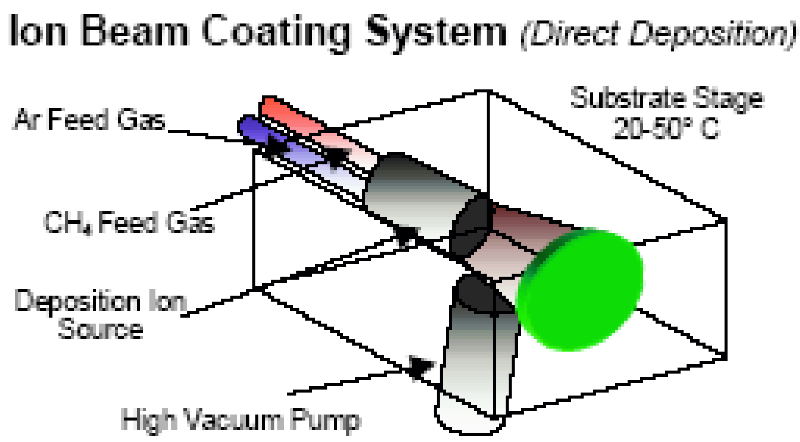


Typical Pressure $=10^{-4}$Torr

Diamond Like Carbon Coating (DLC) Deposition

- * Gas precursor directly injected into the ion source.
- * Methane (CH_4)usual precursor gas
- * A beam of carbon atoms/ions is accelerated toward the substrate.

⇒A combination of chemical vapor deposition (CVD) technique and physical technique.



Film composition can be engineered with suitable precursors ⇒ great flexibility

Films of high hardness, excellent wear-resistance properties, high corrosion resistance and having extremely low static and dynamic friction

Also, high optically transparent films

Most widely used diamond- like carbon applications are for : Magnetic heads; Ophthalmic coatings; hard , wear - resistant coatings; medical devices; flat panel displays; tribological coatings; electronic and semiconductor devices; and corrosion-barrier coatings.

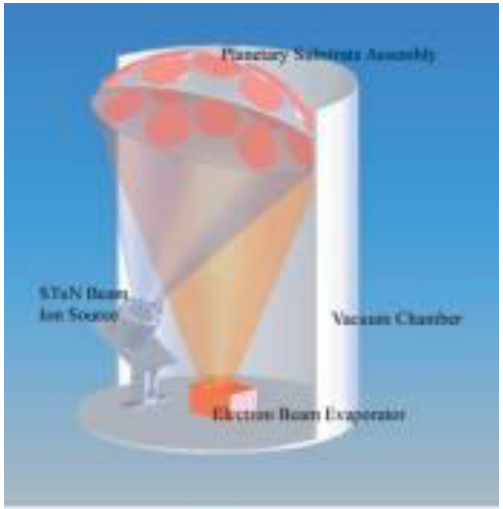
Ion Beam Assisted Deposition (IBAD)

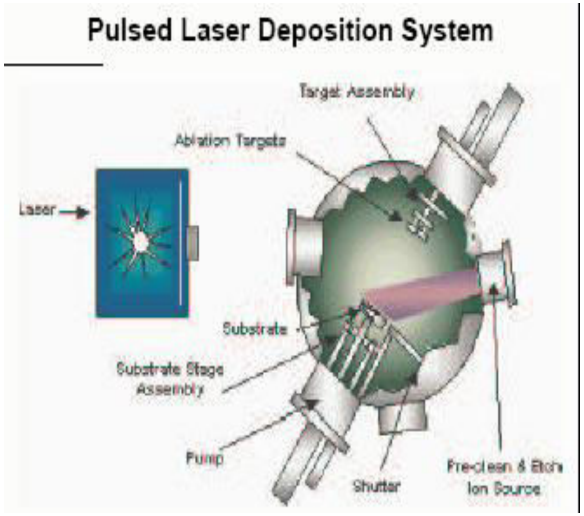
Generally used in conjunction with other source of film deposition e.g. e-beam evaporation, pulsed laser deposition, molecular beam epitaxy to enhance the properties of film:

Film densification,

Reduction of stress without any need of substrate heating,

Control of microstructure & stoichiometry.



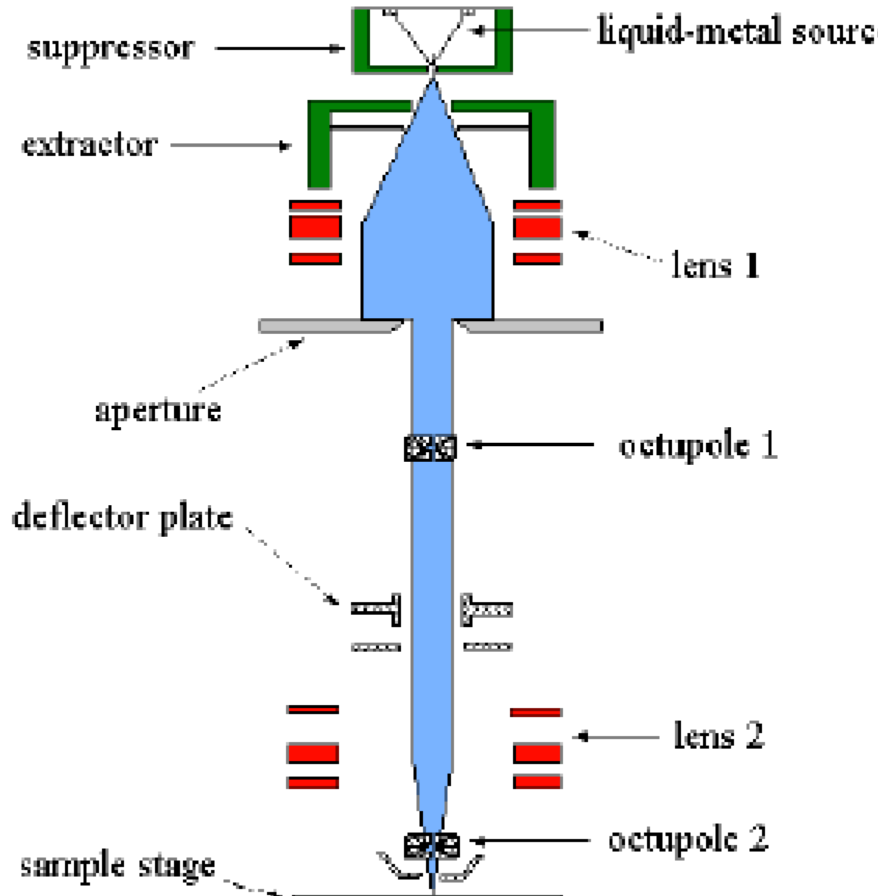


Ion Beam Sputter Deposition (IBSD) Applications

DEVICE / PROCESS	MATERIALS
Advanced Magnetic Heads	NiFe, Ta, Cu, Co, FeMn
Anti-reflection Coatings	MgF_2, SiO_2, Ta_2O_5, TiO_2
Dielectric Films	SiO_2, TiO_2, AlN, etc.
Encapsulation Films	Si_3N_4, Al_2O_3
High Reflectance Mirrors	SiO_2, Ta_2O_5, TiO_2, Si
Interconnect Films	W, Au, Cu
Laser Facets	Si_3N_4, SiO_2, Al_2O_3, Si, Ta_2O_5
Narrowband Pass Filters	SiO_2, Ta_2O_5, TiO_2, HfO_2, Nb_2O_5
Optical Thin Films	Al_2O_3, Ta_2O_5, TiO_2, SiO_2
Ring Laser Gyro Mirrors	Multilayer SiO_2/TiO_2
Semiconductor	Si_3N_4, DLC
Sensors	Composites or Alloys
Superconductors	$YBaCuO_x$, $LaSrTiO_x$
Thin Film Heads	NiFe, CrCo
X-ray Optics	W, Cu, Mo, Si, B_4C, Ni, C

Focused ion beam (FIB): Similar to a scanning electron microscope (SEM) in operation

Difference: FIB uses a finely focused beam of gallium ions in stead of a beam of electrons



FIB System:

Ga $^+$ion beam generated in a liquid-metal ion source (LMIS)

A liquid gallium cone is formed on the tip of a tungsten rod

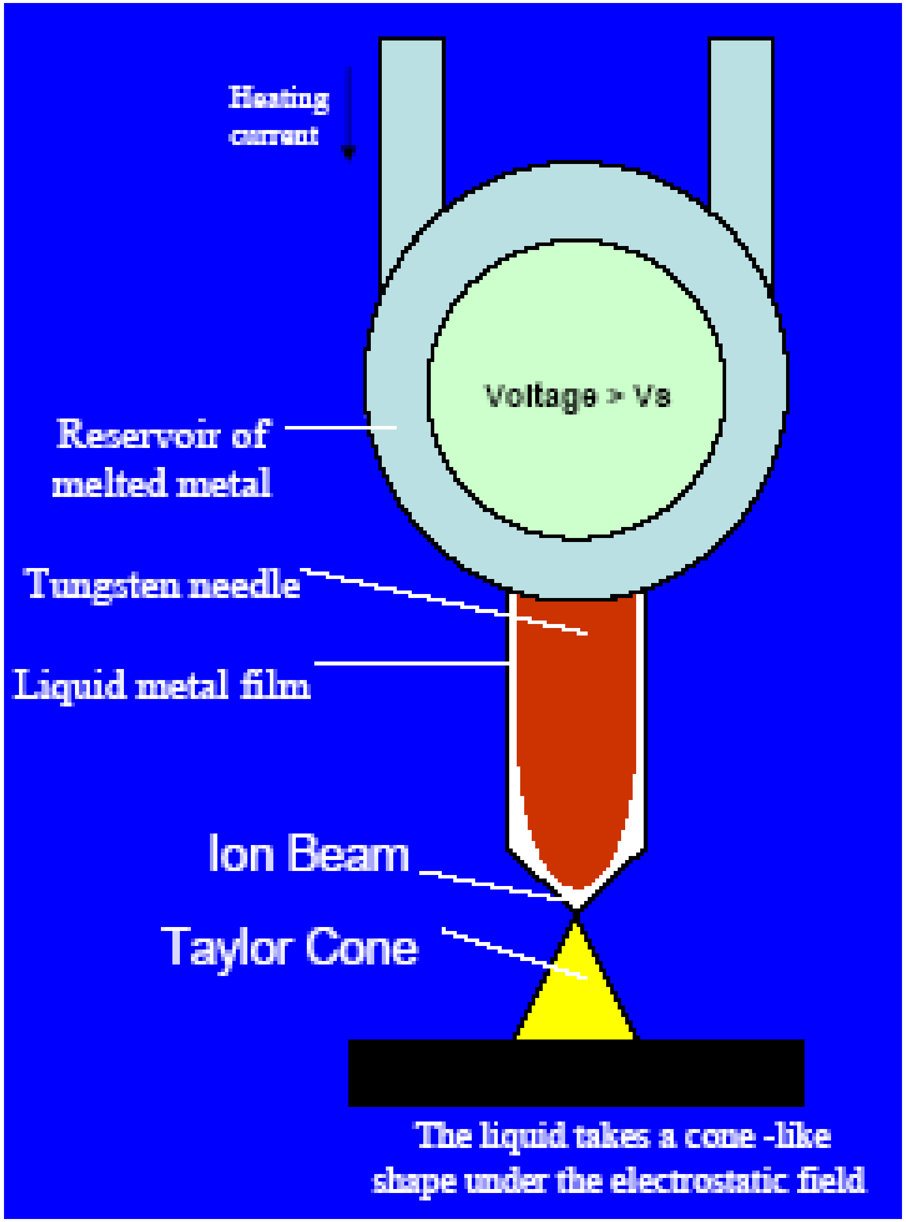
A strong electric field applied on the rod causes emission of positively charged ions from a liquid gallium cone.

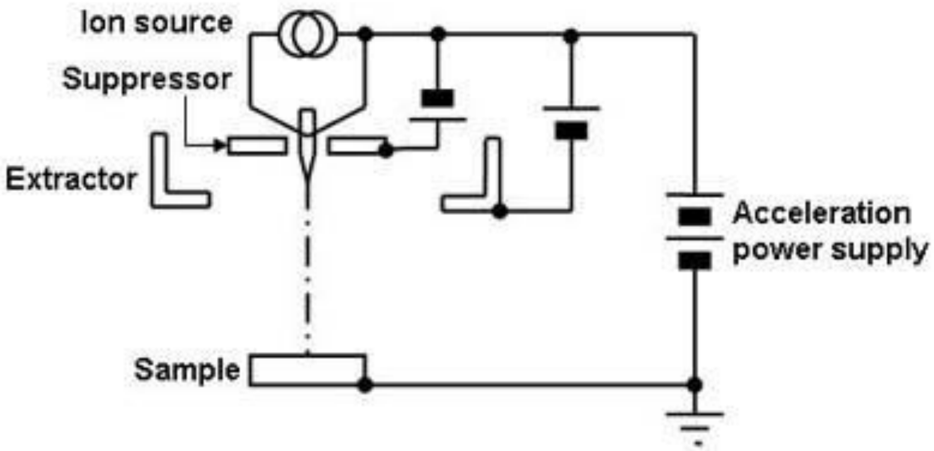
Ion beam passes through a set of lenses and aperture. Aperture is used to select the beam current and hence the beam size and image resolution.

Beam energy ~ 30 or 50 keV
Beam current ~1 to 20 nA, and
Best image resolution ~5 - 7 nm.
Vacuum Chamber pressure ~ 10^{-7}mbar

Operated at low beam currents for **imaging** or high beam currents for site specific **sputtering or milling**

The beam is raster-scanned over the sample mounted in a vacuum chamber.





Ion Source Conceptual Diagram

Why Gallium?

Most commonly used in Liquid Metal Ion Source because of the following characteristics:

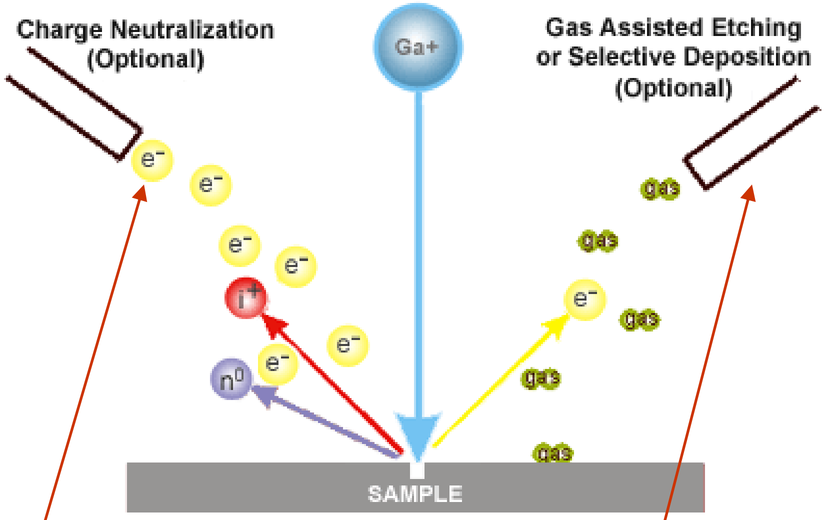
1. Low Ionization Potential of Ga = 6eV
2. Low melting ($T_m = 29.8^0C$) minimizes any reaction or inter-diffusion between liquid and tungsten needle substrate.
3. Low volatility at melting point conserves the supply of metal and yields a long source life
4. Good viscous property; no drop off
5. Excellent mechanical, electrical and vacuum properties &
6. Emission characteristics enable high angular intensity with a small energy spread.

Focused Ion Beam Processing & Imaging:

* FIB striking on the surface produce emission of secondary electrons, secondary ions & neutral atoms ⇒ Dry etching

* Monitoring Secondary Electron or ion-Surface Imaging

* Secondary electrons more than ions and provide images of better quality and resolution; secondary electrons used for most imaging applications.



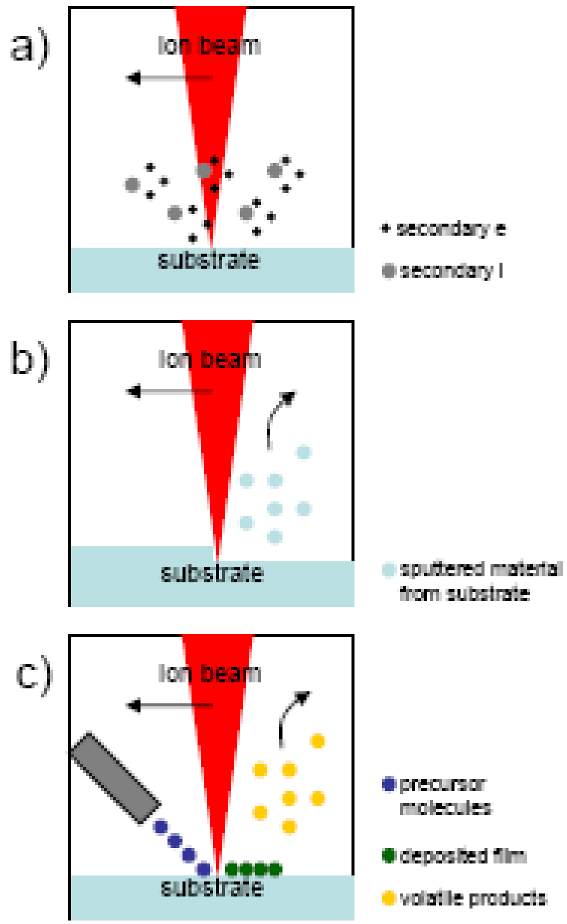
* For non-conductive samples, a low energy electron flood gun used to provide charge neutralization. Thus, insulating samples can be milled and imaged without a conducting surface coating, as required in a SEM.

* Local "flooding" of specimen with a variety of gases: These gases can either interact with the primary Ga^+ beam to provide selective gas assisted chemical etching or selective deposition of either conductive or insulating material by decomposition of the deposition gas by the primary ion beam.

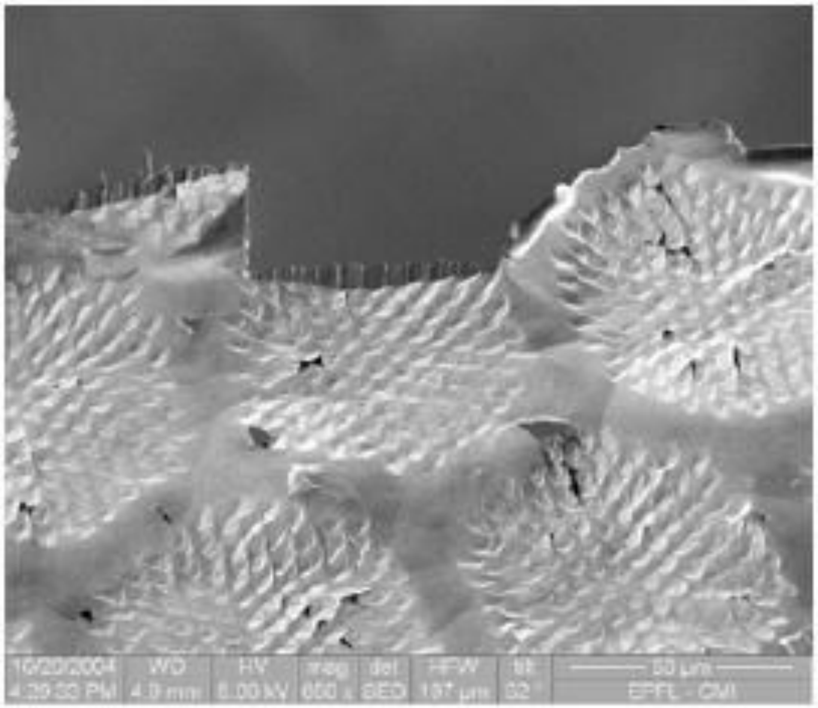
3 basic “operating modes”

- Emission of secondary ions and electrons
  - FIB **imaging** ← a)
    low ion current
- Sputtering of substrate atoms
  - FIB **milling** ← b)
    high ion current
- Chemical interactions (gas assisted)
  - FIB **deposition**
  - Enhanced (preferrential) etching ← c)

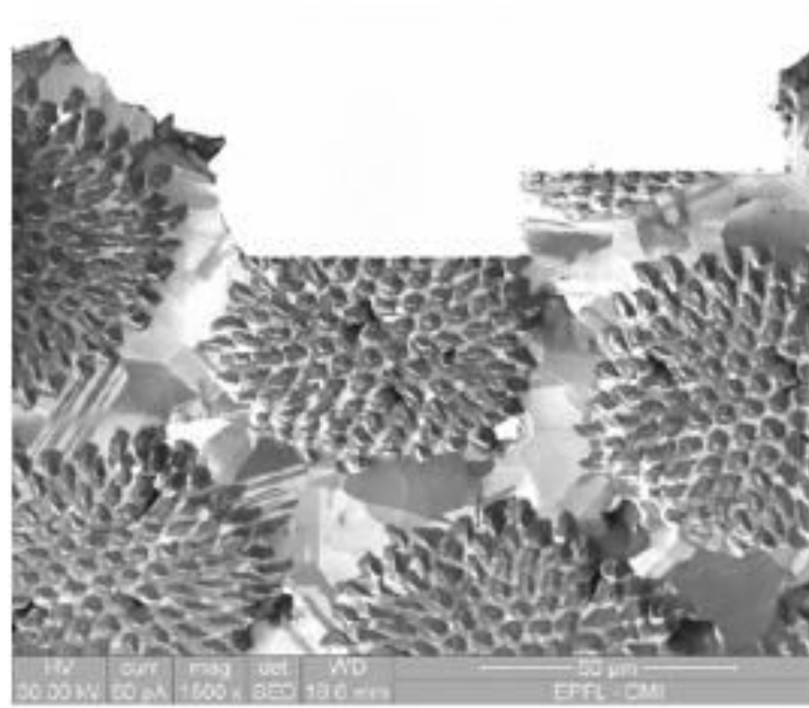
- Other effects:
- Ion implantation
- Displacement of atoms in the solid
  - Induced damage
- Emission of phonons
  - Heating



SE image contrast

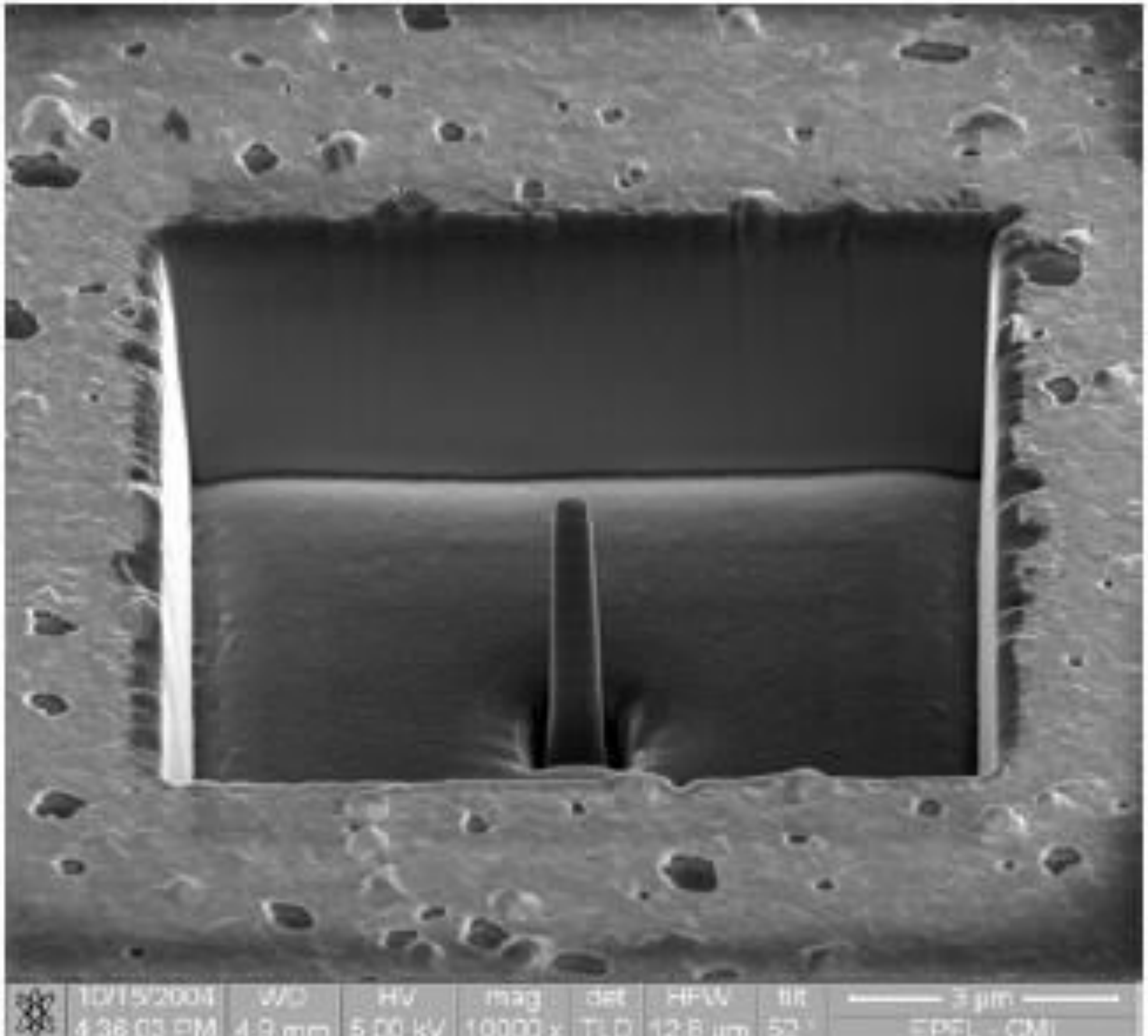


e-beam 5kV



ion-beam 30kV 50pA

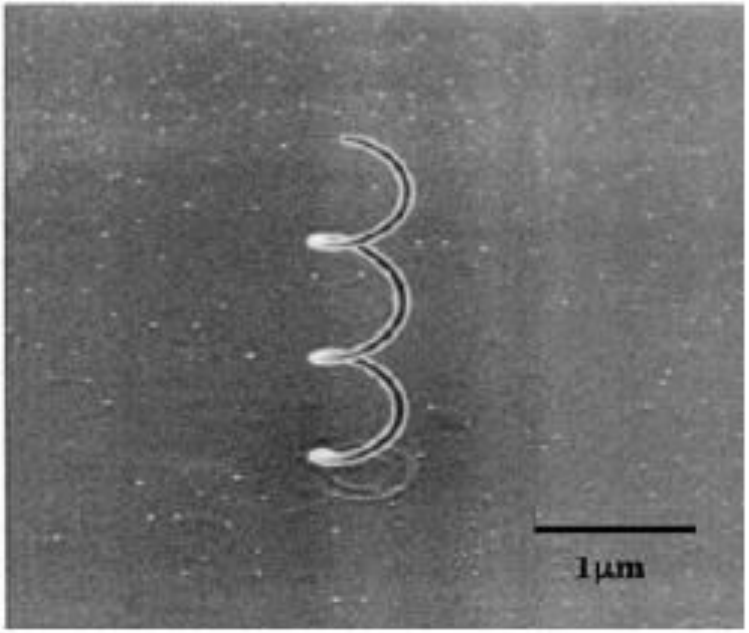
Milling



PZT-high aspect ratio „capacitor“, W. Adachi (EPFL-LC)

Nanofabricated structures

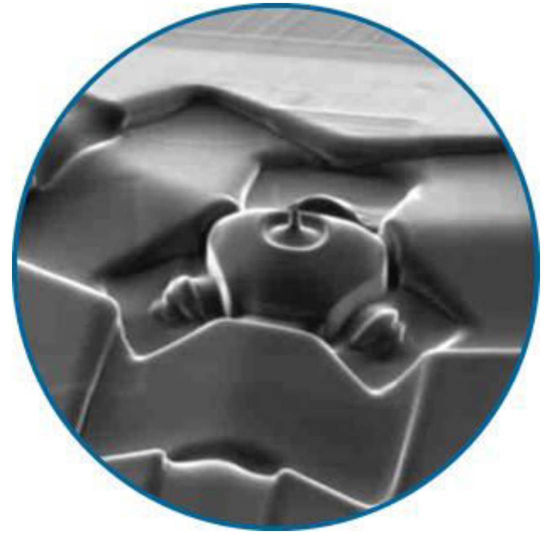
Coil 700nm pitch, 80nm line width, diamond-like amorphous carbon, FIB induced CVD



FIB Micromachining

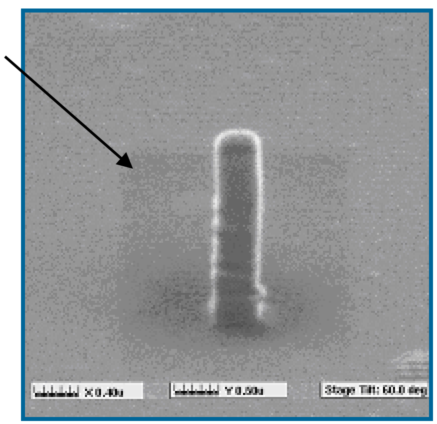
* Precise sectioning capability
* Complex pattern generation
* Imaging capabilities
* Machining variety of materials

-FIB: An ideal tool for micromachining

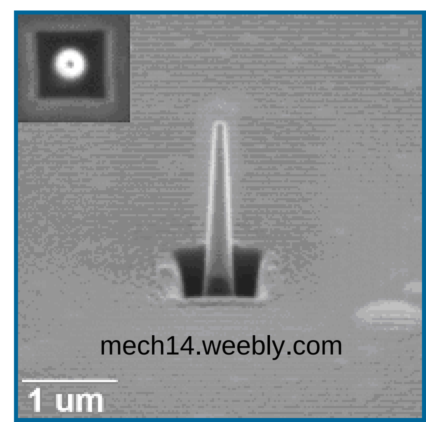


100-nm diameter parabolic tip for sub-micron indentation into hard materials micromachined by FIB

200 nm or thinner columns of tungsten or silicon oxide with aspect ratios exceeding 50:1deposted by FIB



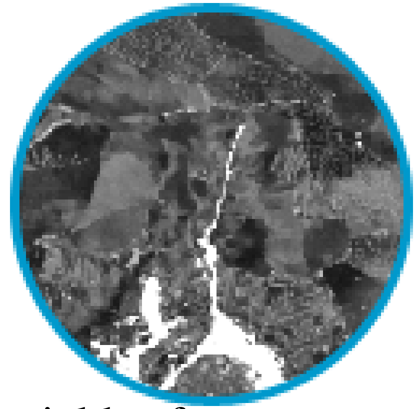
Subsequently, machined by FIB to a point with a radius of curvature less than 40 nm (inset at 0° tilt).

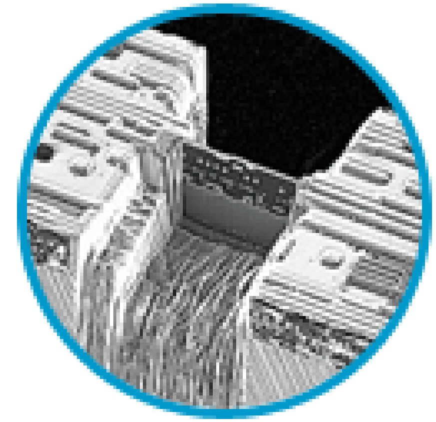


Typical applications:

- Imaging

  FIB secondary ion images reveal chemical differences, useful in corrosion studies, as secondary ion yields of metals can increase by 1000 times in the presence of oxygen.





Sectioning and imaging can be readily used to examine fragile and/or challenging materials science specimens that would otherwise be extremely difficult to investigate.

- TEM specimen preparations

- In situ cross-sectioning / analysis of device

  Repair / Modification electrical connections

- Mask repair

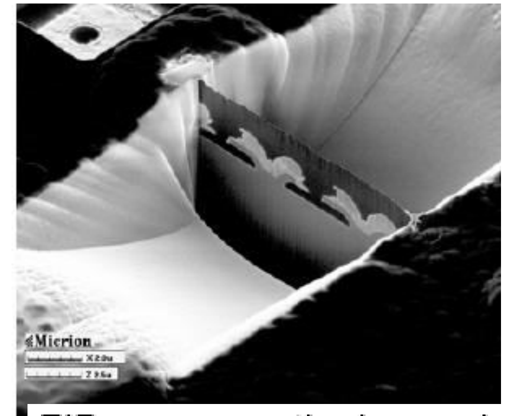
- Micro-machining

- Lithography

Applications

"Industrial" applications (semicondutor industry)

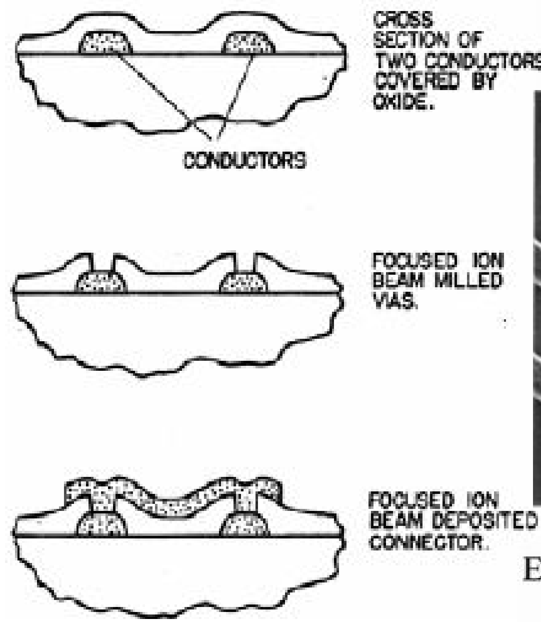
- sectioning for failure analysis
- Prototype circuit rewiring
- TEM sample preparation

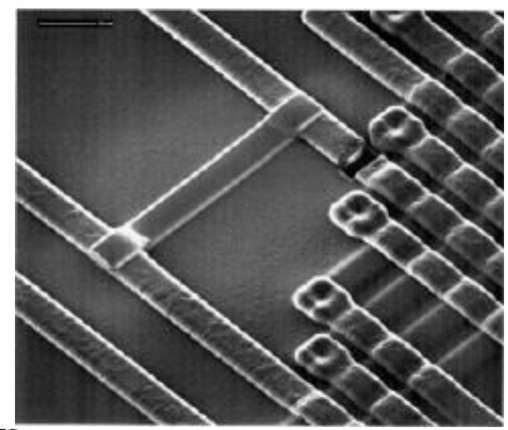


FIB cross-sectioning and SEM imaging

Research

- Micromachining
- Nanofabricated structures
- TEM sample preparation





Example of FIB Circuit Rewiring
Cut and Jumper

Comparison with Thermal Process:

Evaporative deposition

Ion Beam is highly energetic:100 eV Ion energy

$\Rightarrow$ 10^6 K

Compared to Plasma Processes-

Ion source permits independent control of ion energy, ion density, direction & background pressure.