Non-Traditional Manufacturing Processes (NTMP)

Lecture 8: Ion Beam Machining

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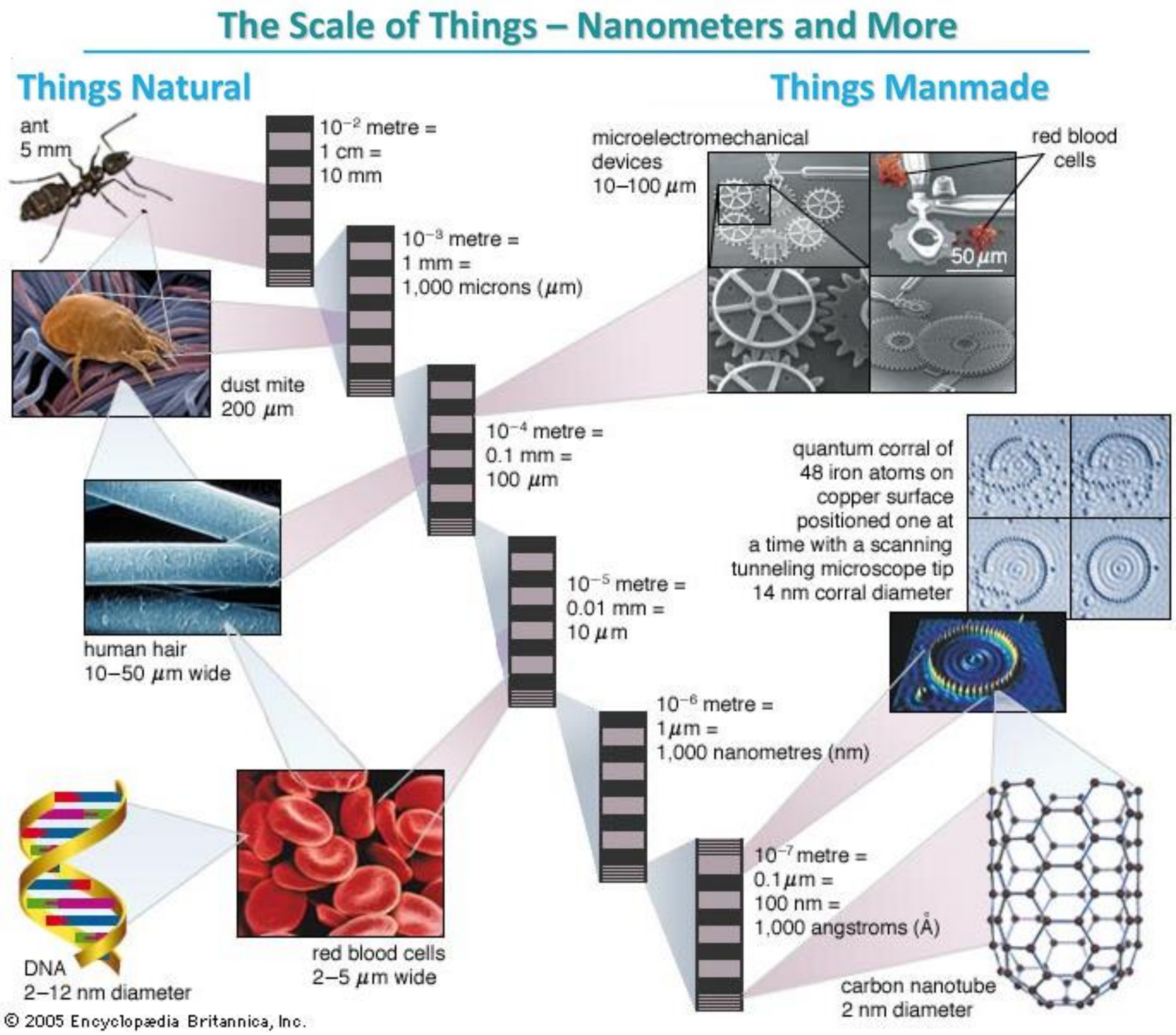
Demand of Modern Industries : Nanomanufacturing



In Semiconductor Industry: Electronics

IC, MEMS

Features size: Submicron ($<10^{-6}$ m)

Resolution : 100Å (0.01 µm)

Surface roughness:10Å (~1nm)

Material removal or addition in these feature sizes & resolution is a challenge using traditional methods.

Ion Beam Machining : Nanomanufacturing method

- Material removal takes place in the form of removal of atom (size 0.1 to 0.5 nm) from the surface of the work-piece.

- A stream of energetic ions ranging in energy from few Electron Volt (eV) to several mega electron volts created by “particle accelerators”.

- The first accelerator was developed in 1932 for Nuclear physics experiments. Subsequently the accelerator and ion beams found way in device technology (and revolutionized this area in microchip fabrication), materials science and more recently in micro and nanofabrication.

- Focused ion beams has become finest possible drill machine ever possible, and it can create the smallest structural element.

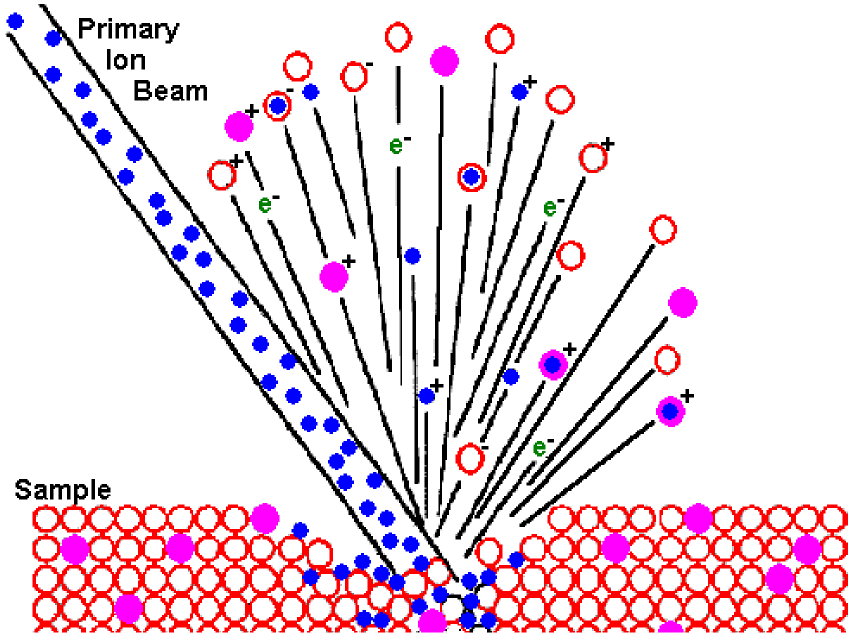


Fig. Schematic of sputtering process

Ion Beam Machining : Nanomanufacturing method

- Ion beam: A type of particle beam consisting of ionized atoms i.e. Ions

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Sputtering:

- A stream of ions of an inert gas, such as argon or metal such as gallium is accelerated in a vacuum by high energies and directed toward a solid workpiece.

- Ion beam knocks off atoms from workpiece by transferring kinetic energy and momentum from incident ion to the to atoms to the targeted atoms.
- 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**.

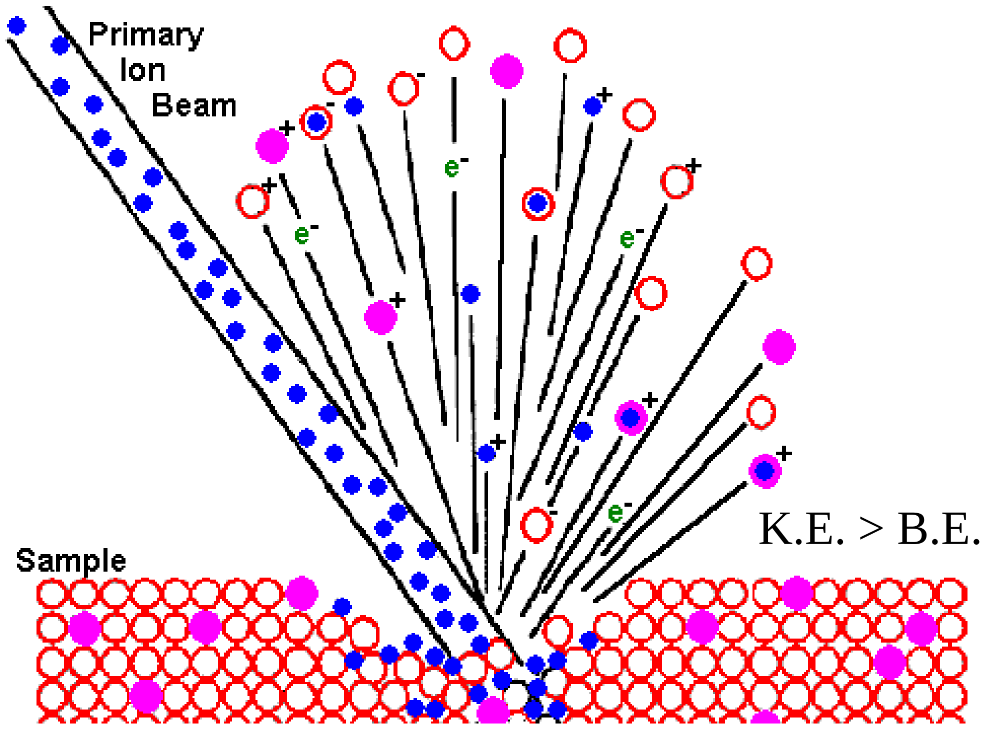


Fig. Schematic of ion sputtering process

- This process can be applied to the manufacturing of ultrafine precision parts of electronic and mechanical devices.

Sputtering Yield in IBM

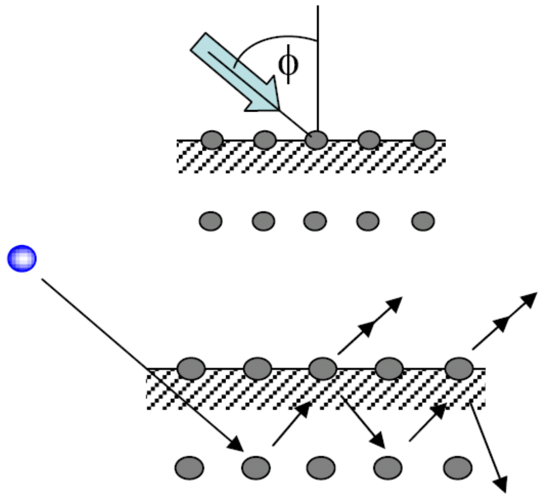
- Sputter yield depends on the **energy of the incident ions, angle of incidence on the surface of work-piece, masses of ions and target atoms, and the binding energy**.

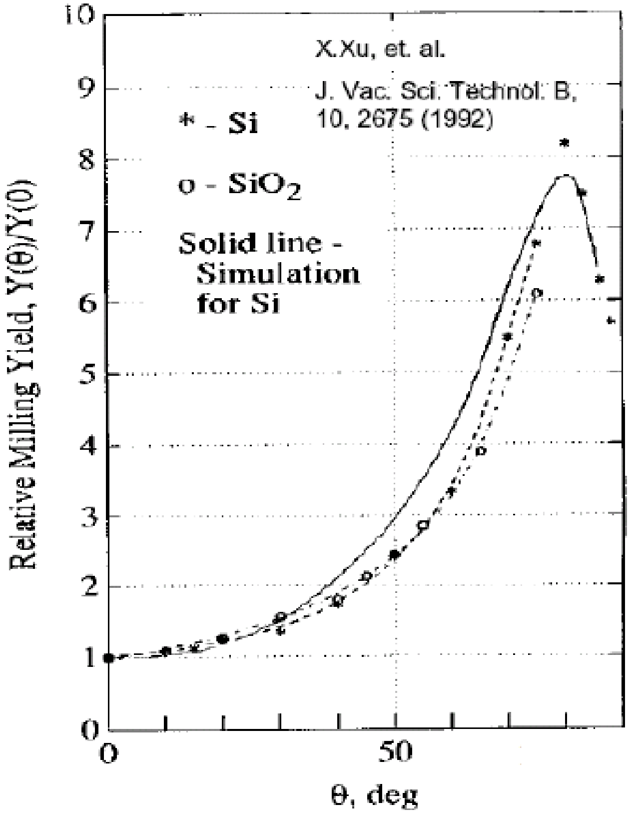
Sputter Yield, S = No. atoms removed / No. of striking Ions

- Generally increasing the incidence angle increases the sputter yield – Max around 80 degrees.

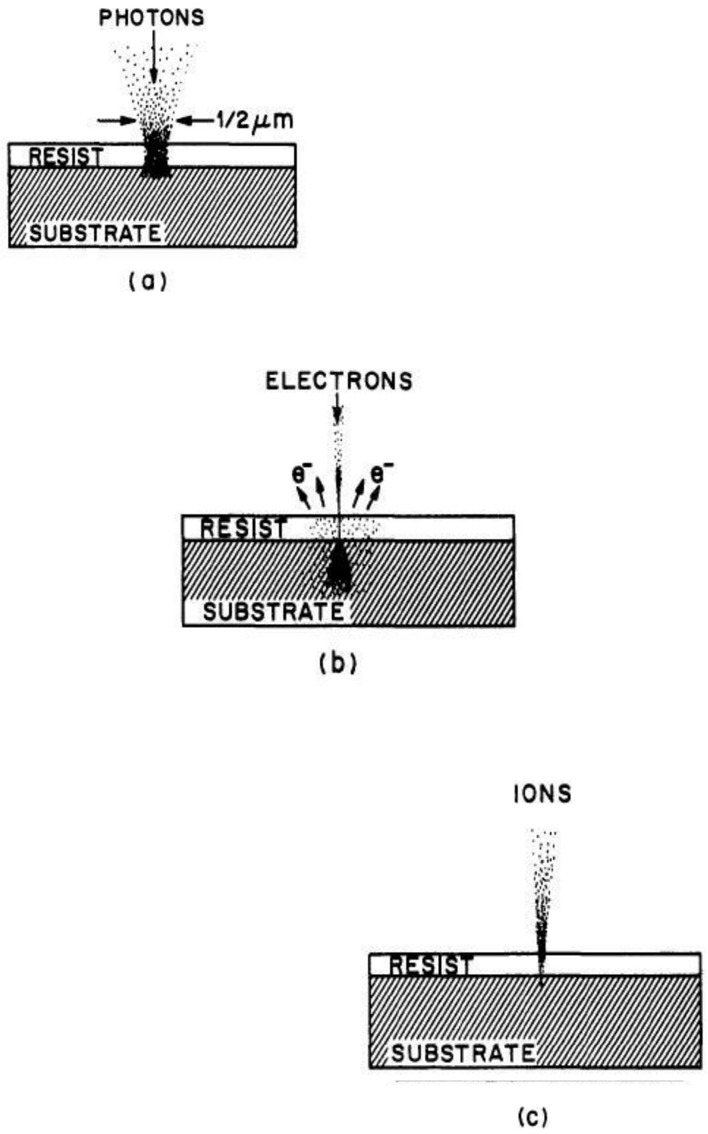
- As the angle of incidence increases from normal incidence, the possibility of the target atoms escaping from the surface during collision cascades, increases and eventually leads to increased sputter.

- After reaching a maximum, the sputter yield decreases again as the ion approaches glancing incidence.

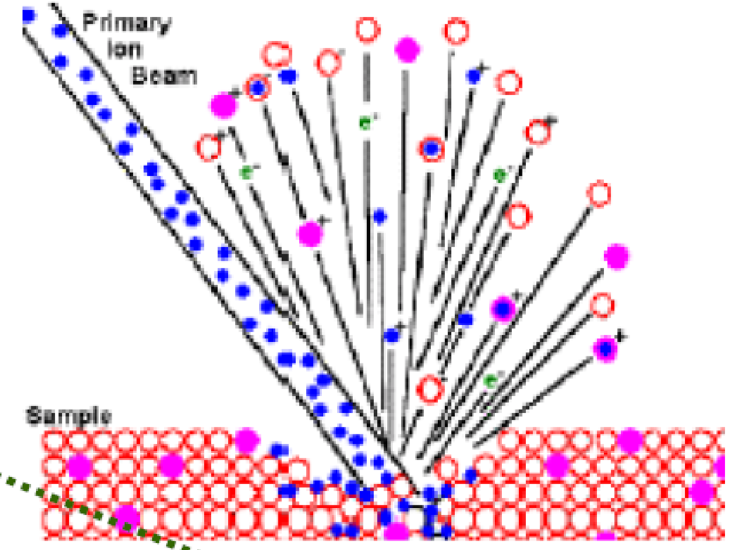




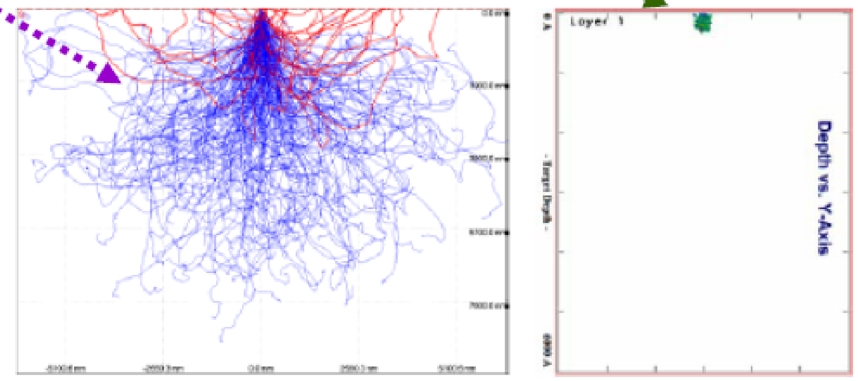
Why IBM is better for Nanomanufacturing



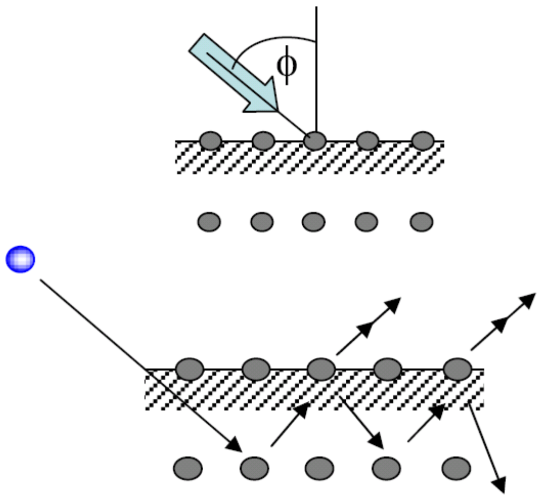
E-Beam	I-Beam
Light & Small	**Heavy & Big**
Velocity: High	Low
Low Momentum	High Momentum
Interaction length: **Large**	**Sallow (nm)**
Processing rate: Slower than Ion-Beam	Faster Than Electron Beam
Feature Size & Resolution: Similar order	Similar order, Better control
Mode of Processing: Thermal	Sputtering: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



30kV Electrons vs Ga Ions



Sputtering Rate in IBM



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

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

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

- 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 = 0.6 W/cm^2, so the target will be heated only a little (usually up to 50-90 ºC).
- One of the main advantages of ion beam treatment -we can work with a lot of temperature sensitive materials!

Example: Ar^+ ions, J= 3 mA/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.

Process Parameters

- Workpiece material
- Angle of incidence
- Ion energy
- Current density

$$\text{MRR} = \frac{SMI}{A\rho e}$$

where, S = sputtering yield

M = atomic mass of workpiece material

I = current

A = machined area

e = charge

ρ = density of target material

Applications of Ion Beam Machining

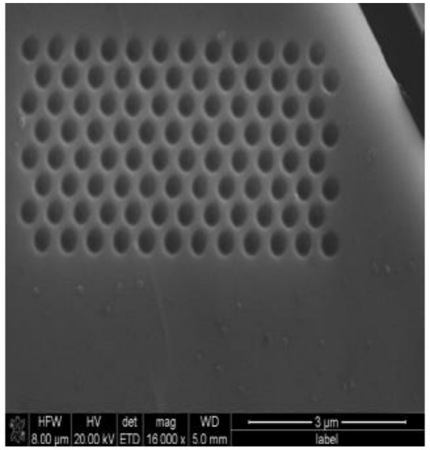
- **Etching / Milling** of all material,

  Reactive etching, Substrate cleaning.

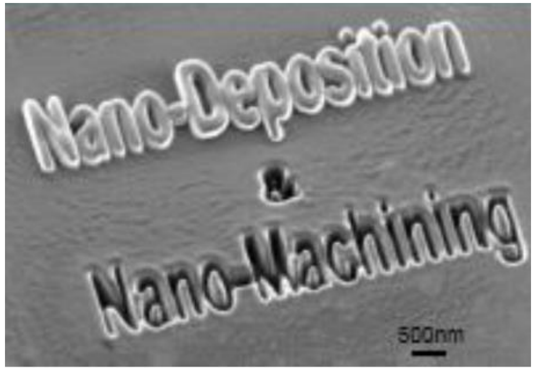
- **Deposition:** Sputter deposition,

- **Ion- beam Lithography**

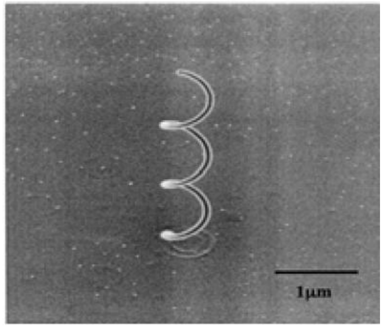
- **Ion-beam implantation**



50 nm size holes patterned on a thin film using IBM

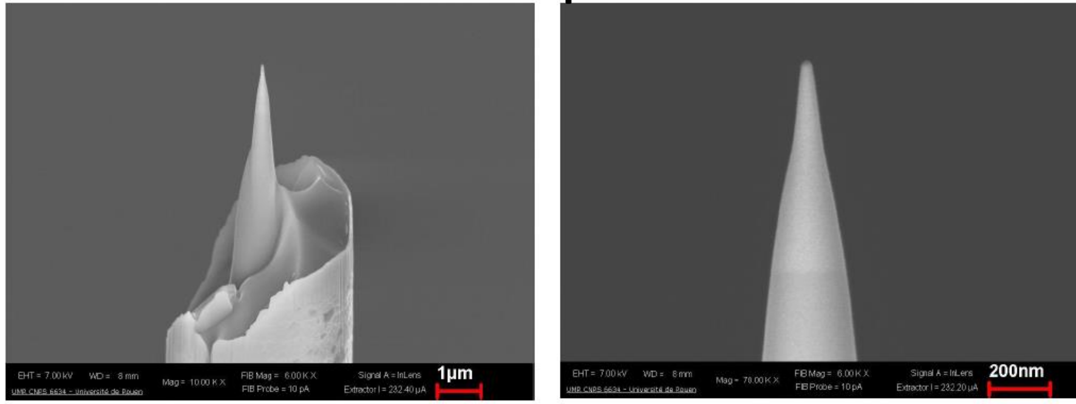


Deposition and machining using FIB



Helical Coil- diamond like amorphous carbon, Fabricated by FIB induced deposition

STM Tips



SAMPLE COURTESY UNIVERSITY ROUEN

Basic Operating Modes in IBM

- **Emission of secondary ions and electrons**

FIB Imaging (Low ion current)

✓**Sputtering of substrate atoms**

- **FIB Milling (High ion current)**

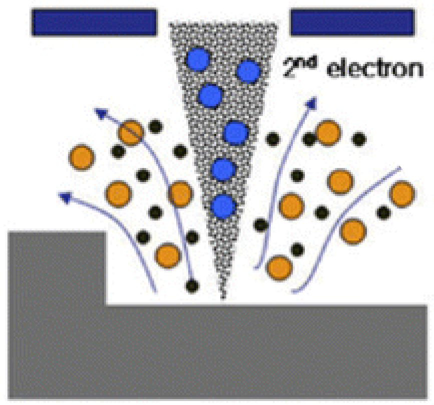
✓**Chemical interactions (Gas assisted)**

- **FIB Deposition**

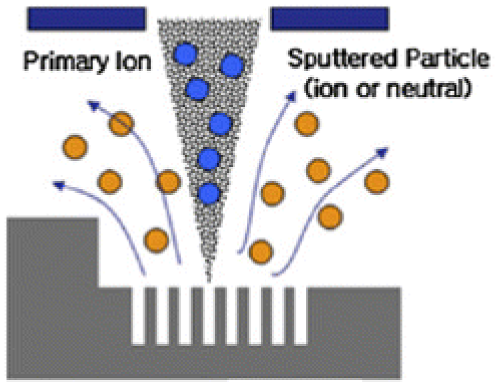
- **Implantation**

- **Enhanced Etching**

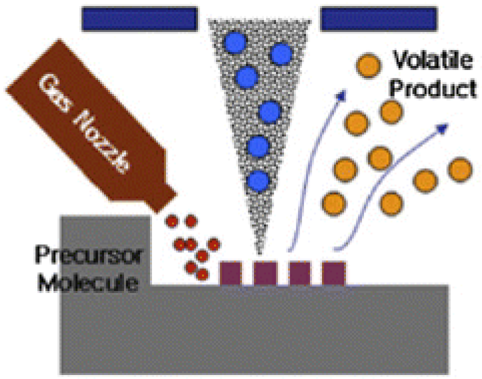
Imaging



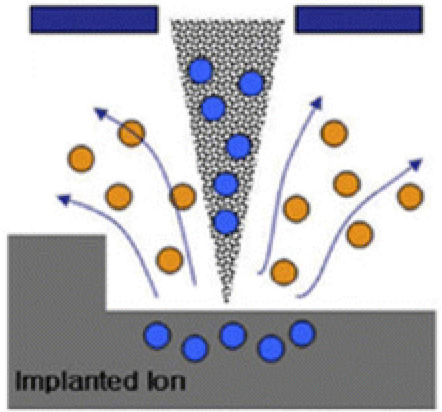
Milling



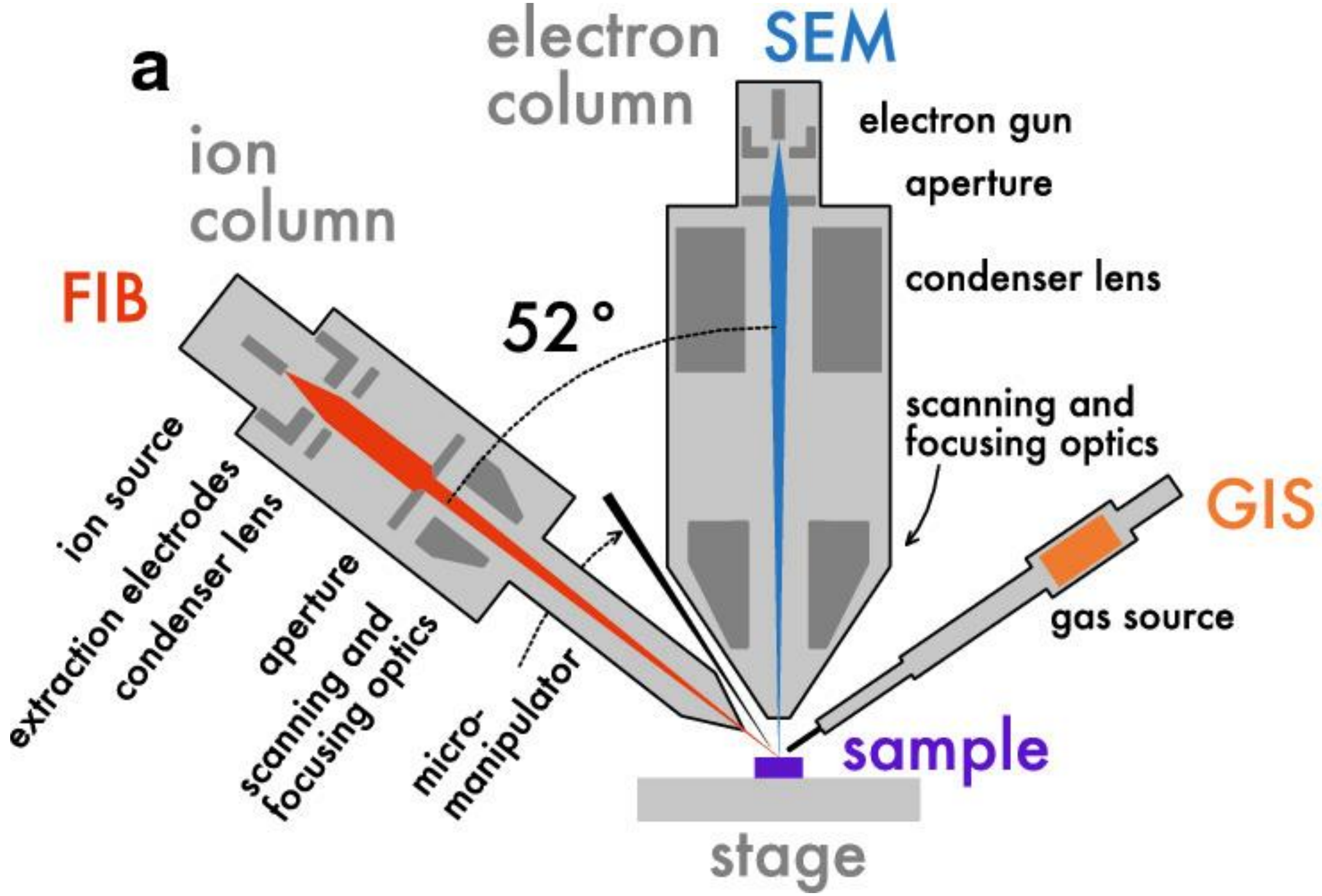
Deposition

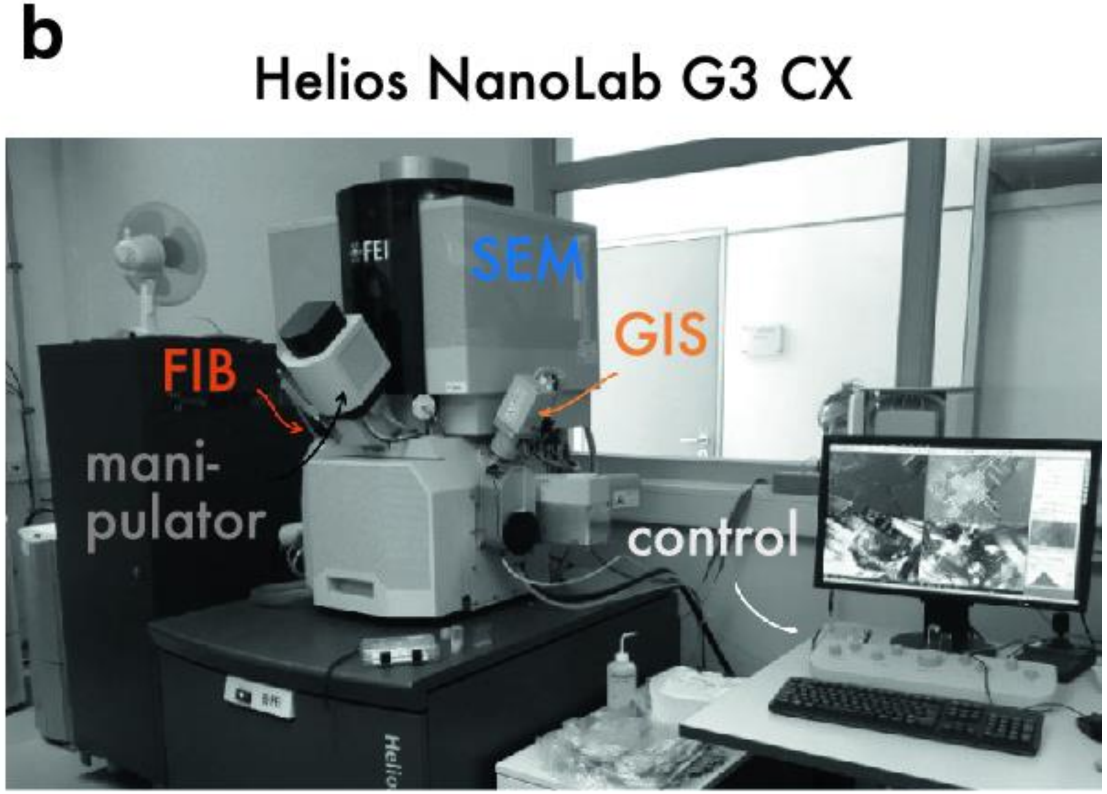


Implantation



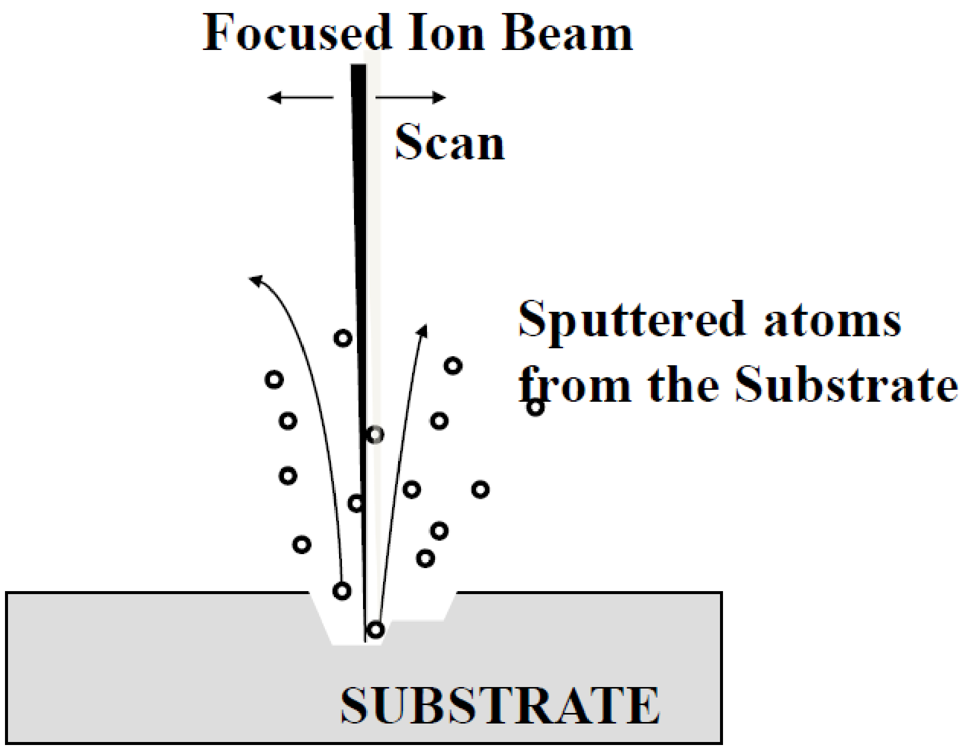
Focused Ion Beam (FIB) Setup





FIB Milling

- In FIB milling, typically a gallium (Ga) primary ion beam hits the sample surface and sputters away a small amount of material.
- If the ion energy is adequate the collision can transfer sufficient energy to the surface atom to overcome its surface binding energy (3.8 eV for Au and 4.7 eV for Si).
- At high primary currents, material can be efficiently removed from the sample surface, allowing precision milling of the sample with achievable feature sizes of well below 1 µm.
- At the same time, the sample can be imaged with very high precision.



Nanoscale Milling by FIB

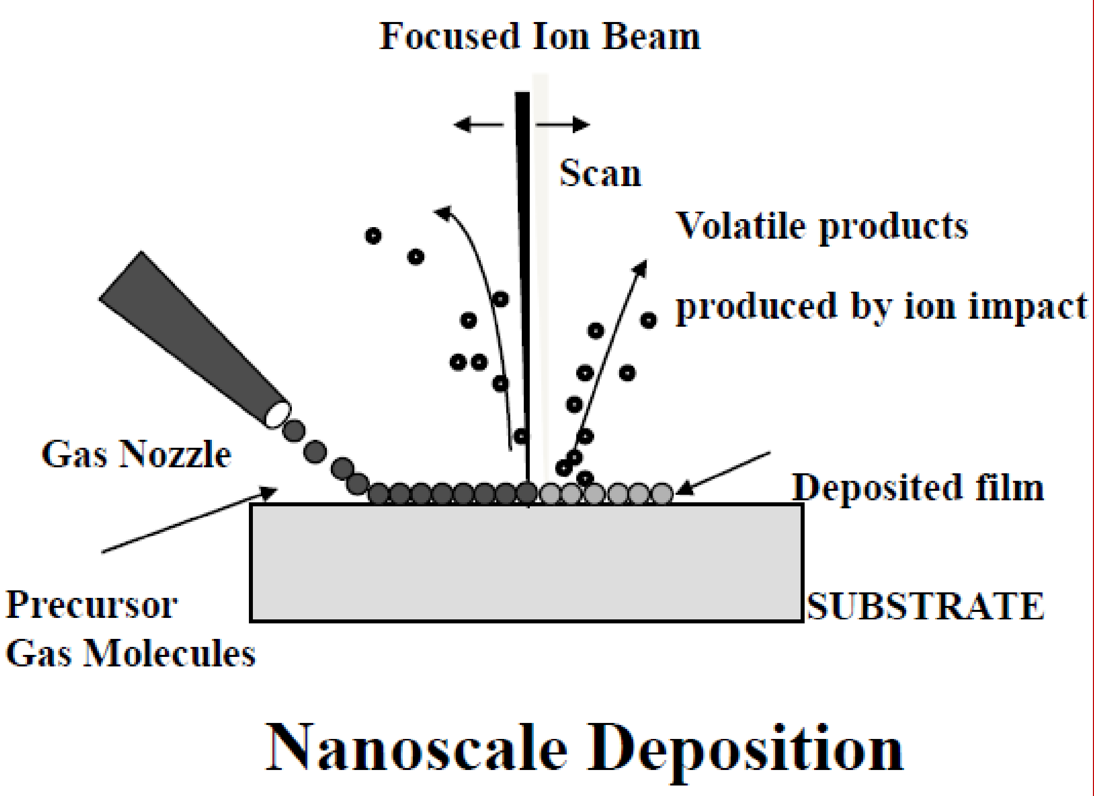
Typical material removal rate is about 1 µm^3 per second.

Note: There are other variants of the process like Reactive Ion Etching (RIE) where chemical species are incorporated, and the process proceeds chemically.

FIB Deposition

For FIB induced deposition, the necessary processes are:

- Adsorption of the chemical precursor gas onto the sample surface.
- Decomposition of gas molecules into volatile and non-volatile products by focused ion beam.



3 dimensional nanostructures can be fabricated using layer by layer deposition.

Precursor must have two properties, namely :

- **Sufficient sticking probability to stick to a surface of interest in sufficient quantity.**
- **Decompose more rapidly than it is sputtered away by the ion beam.**

Components of FIB system

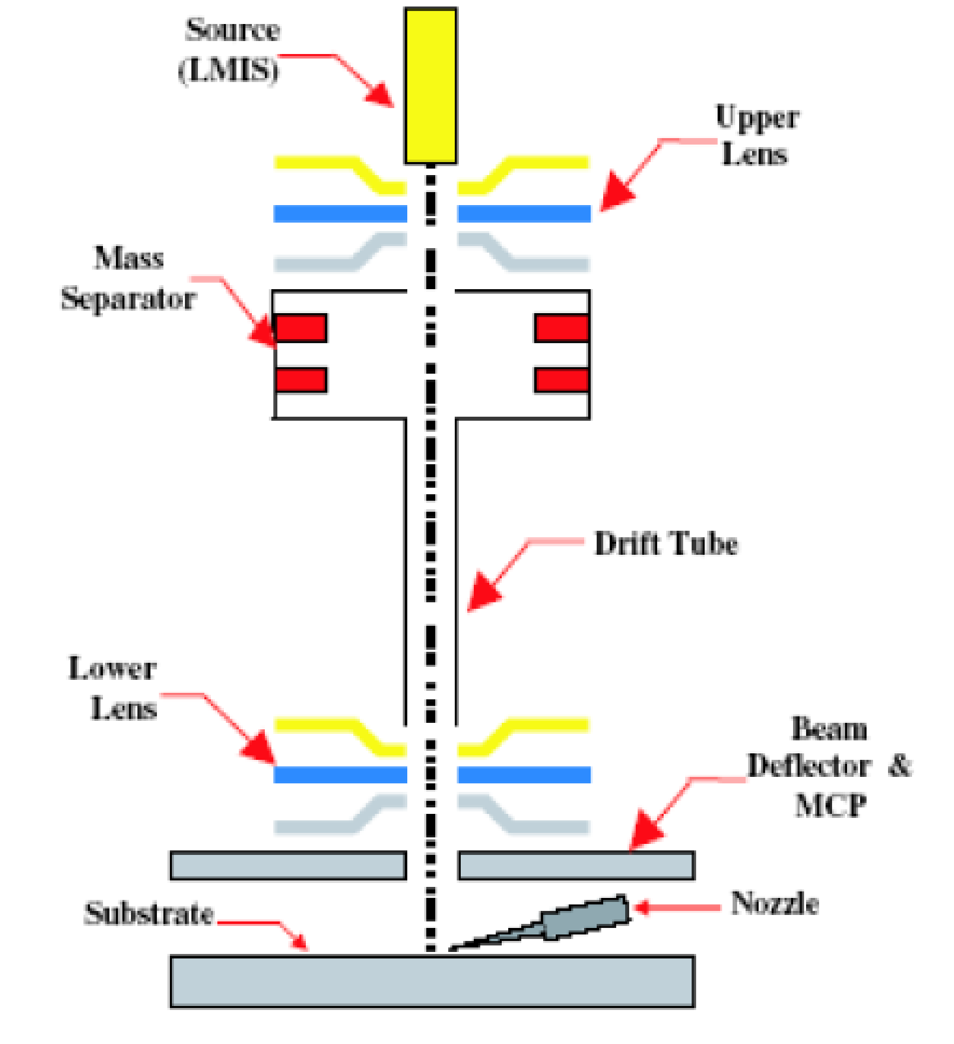


Figure 1. Schematic diagram of a two-lens FIB system.

- A Vacuum system and chamber
- A liquid metal ion source (LMIS)
- An ion column for milling and deposition
- A precision Goniometer stage for sample mounting and manipulation
- Imaging detectors
- A gas injection system to spray a precursor gas on the sample surface
- An electron column for imaging
- Scan generators for ions and electrons
- Computer control

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

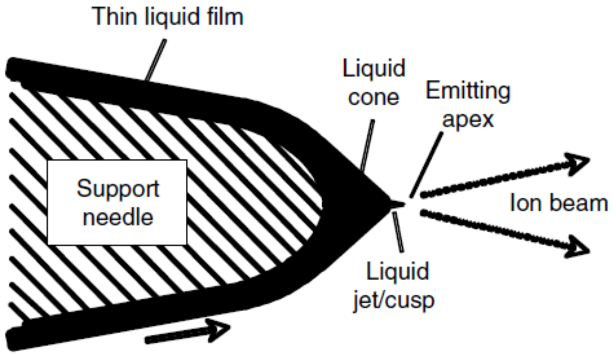
Liquid Metal Ion Source (LMIS)

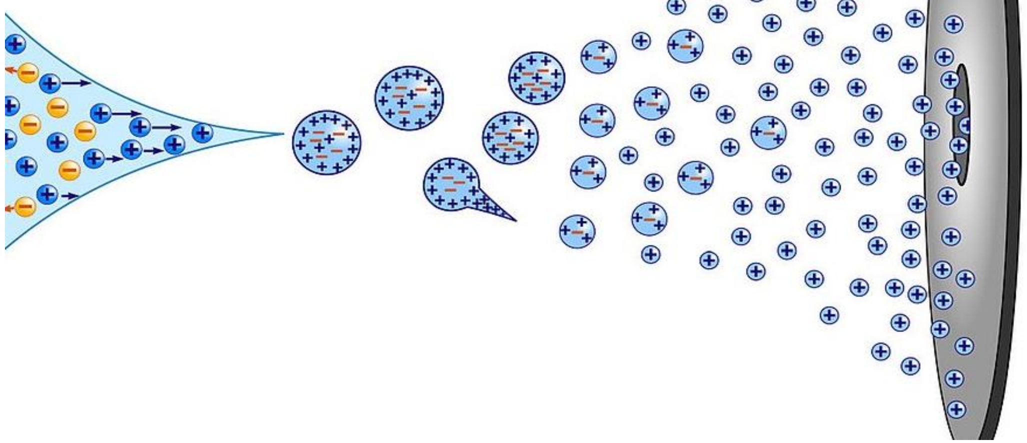
- In a Liquid metal ion source (LMIS), a metal (typically gallium) heated to the liquid state and provided at the end of a capillary or needle. (T_m= 29.8 $^{\circ}$C)

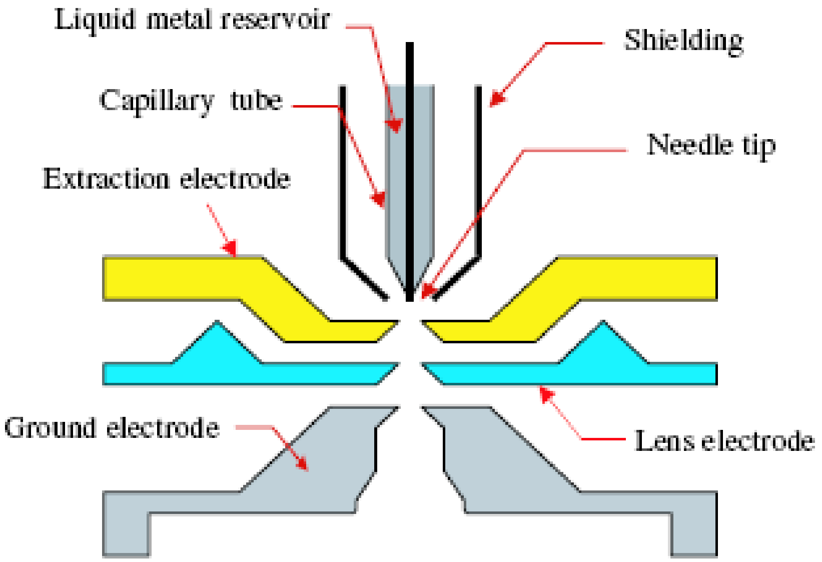
- An electric field (10^8 V/cm) is applied to the end of the wetted tip that causes the liquid Ga to form a point source (2-5 nm tip) in the shape of "Taylor cone".

- Conical shape forms because of electrostatic and surface tension force balance.

- An extraction voltage (negative) pulls Ga from the tip and efficiently ionizes it by field evaporation of the metal at the end of the Taylor cone.







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 ^{o}C) 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

Ion Column

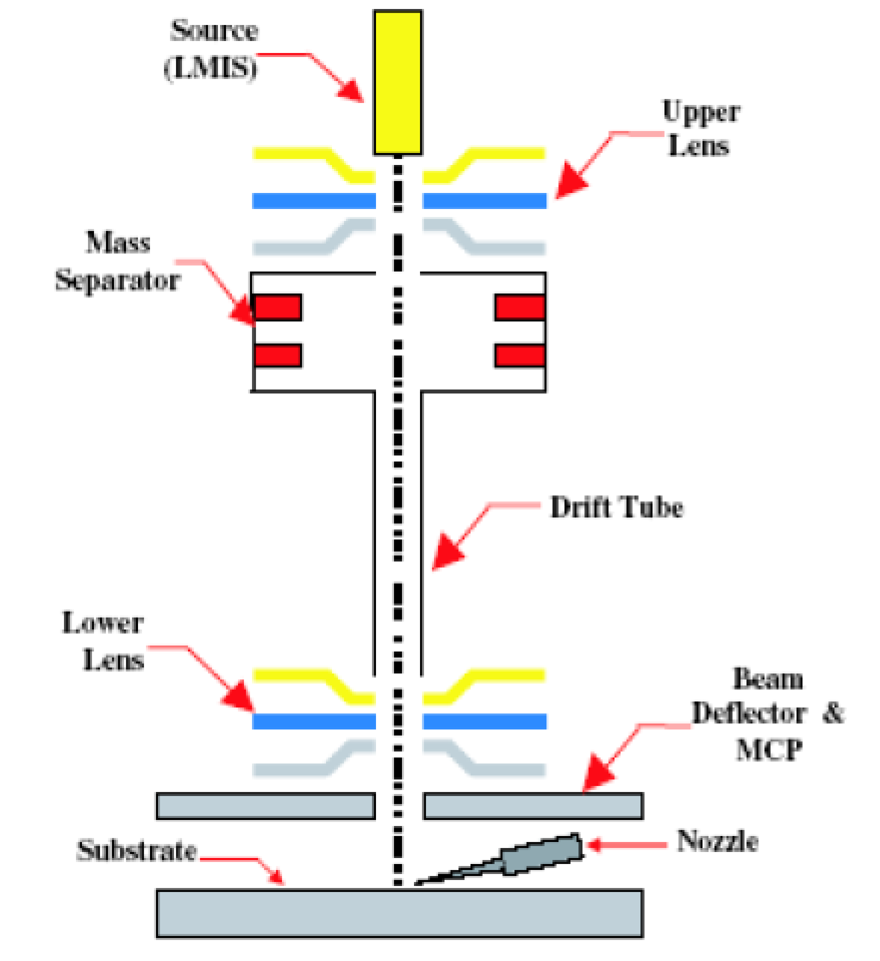


Figure 1. Schematic diagram of a two-lens FIB system.

- **Mass separator is a setup that allows only the required amount of ions with a fixed mass-charge ratio to pass through.**
- **Below the mass separator there is a long and thin drift tube, which eliminates the ions that are not directed vertically.**
- **The lower objective lens helps in reducing the spot size of the beam and in improving focus.**
- **Finally, there is the electrostatic beam deflector which controls the final landing location of the ions.**

Process Capability

- Suitable for **sub-micron range** milling, slotting, drilling with high aspect ratio in almost 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
- Material Removal Rate : 2.5 nm/min. to 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

Limitations

- 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

Thank You!