Nanometer Scale Patterning and Processing

Spring 2016

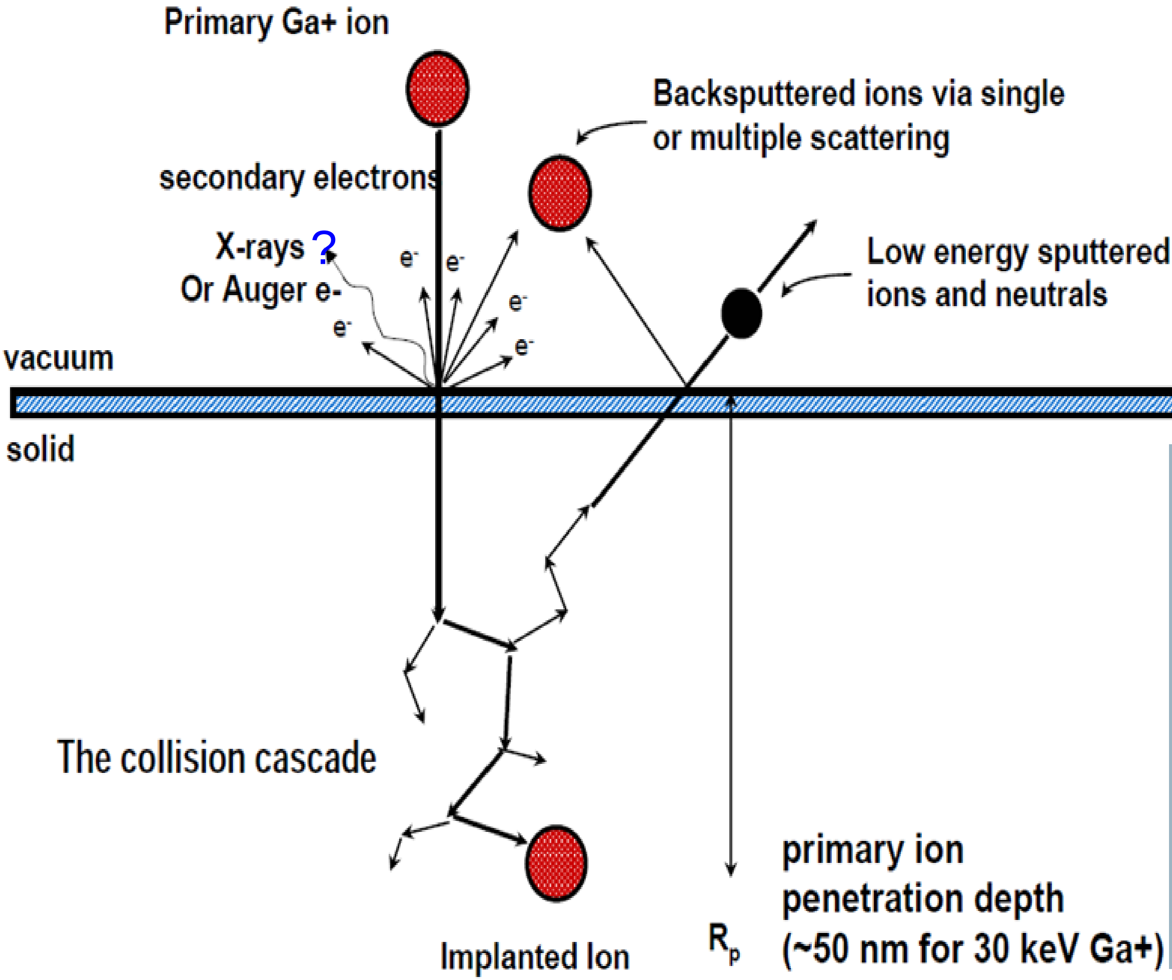
Lecture 24

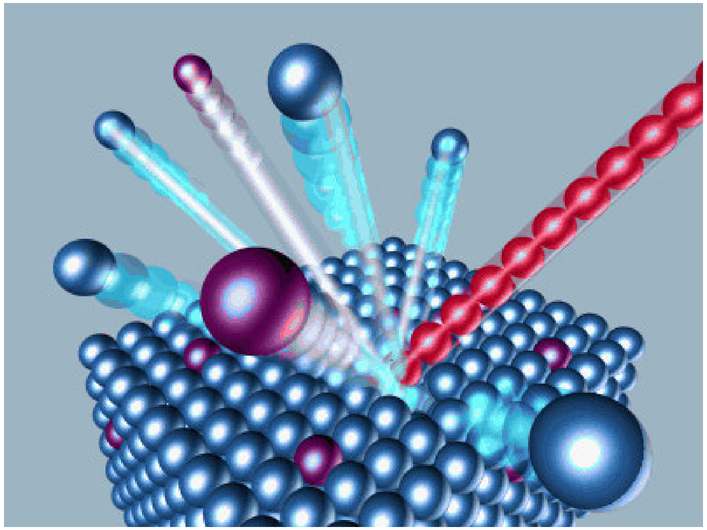
Nanofabrication with Focused Ion Beams – Ion-Solid Interaction, Damage

Focused ion beam (FIB)

1. Overview.
2. Ion source and optics.
3. Ion-solid interaction, damage.
4. Scanning ion beam imaging.

Ion-Solid Interactions





- Imaging (secondary electron image, 2-3 SE per ion), milling and deposition simultaneously.
- Leads to lattice defects (vacancies, interstitials, dislocations).
- Leads to damages, amorphization, re-crystallization.

Ion-ion and ion-electron scattering: the equations

Nuclear differential scattering cross-section, used to calculate scattering angle distribution.

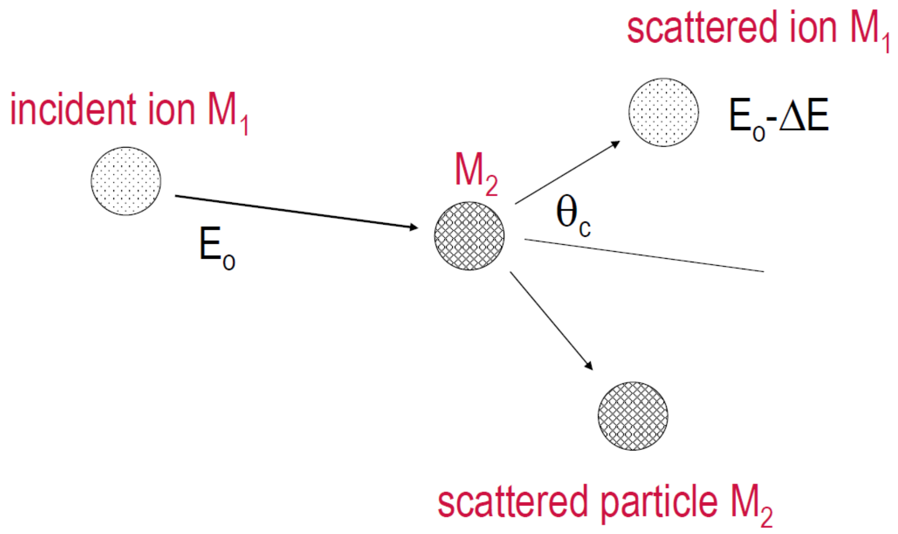
$$d\sigma = \frac{\pi a^2}{2} t^{-\frac{3}{2}} f(t^{\frac{1}{2}})\,dt$$

$$t^{\frac{1}{2}} = \varepsilon \sin\left(\frac{\theta}{2}\right);\ \varepsilon = \frac{aM_2}{e^2 Z_1 Z_2 (M_1 + M_2)} E_0$$

$$a = \frac{0.8853 a_0}{(Z_1^{\frac{2}{3}} + Z_2^{\frac{2}{3}})^{\frac{3}{2}}};\ a_0 = 0.529\,\mathring{A}$$

$$f(t^{\frac{1}{2}}) = \lambda t^{\frac{1}{2}-m}\left[1 + (2\lambda t^{1-m})^q\right]^{-\frac{1}{q}}$$

$$\lambda = 1.307,\ m = 0.333,\ q = 0.667$$



ΔE_n: energy loss to solid atom (nucleus), lead to sputtering, dislocation, recoiling…

ΔE_e: energy loss to electrons, leads to secondary electron emission, ionization…

$$\Delta E_n = \frac{4M_1M_2}{(M_1 + M_2)} E_0 \sin\left(\frac{\theta}{2}\right)$$

$$S_e = K_L\sqrt{E_0} = 1.211\frac{Z_1^{\frac{7}{6}} Z_2 \sqrt{E_0}}{\left(Z_1^{\frac{2}{3}} + Z_2^{\frac{2}{3}}\right)^{\frac{3}{2}}\sqrt{M_1}}$$

$$\Delta E_e = LNS_e(E_0)$$

L: mean free path between two collisions.

N: atomic density of solid material.

Ion-solid interactions

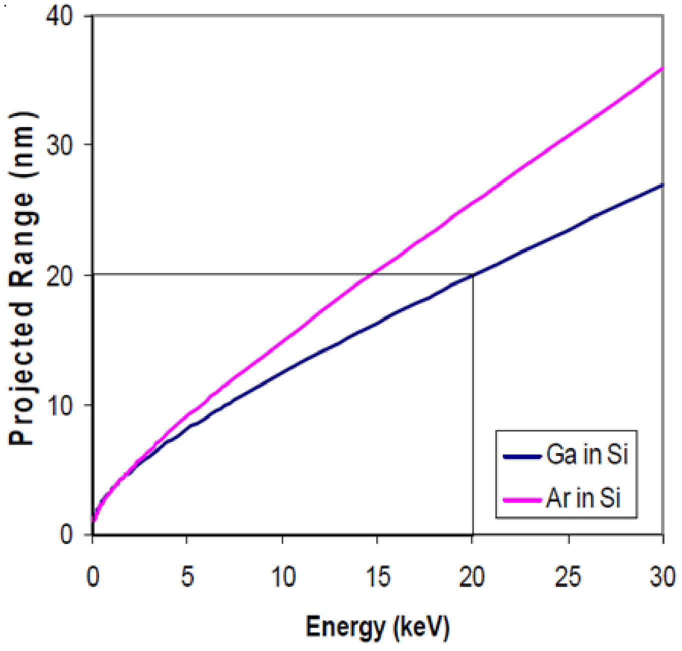
Three regimes of ion-solid interactions

Regime I (knock-on regime)
$M_1 << M_2$ or E_0 is low, minimum sputtering

Regime II (linear cascade regime), where FIB operates.
$M_1 \sim M_2$, E_0 is moderate, governed by nuclear effects

Regime III (spike-on regime)
$M_1 > M_2$ and/or E_0 is high, majority of atoms move in collision cascade

Ion range (penetration/attenuation depth)



(From SRIM simulations)

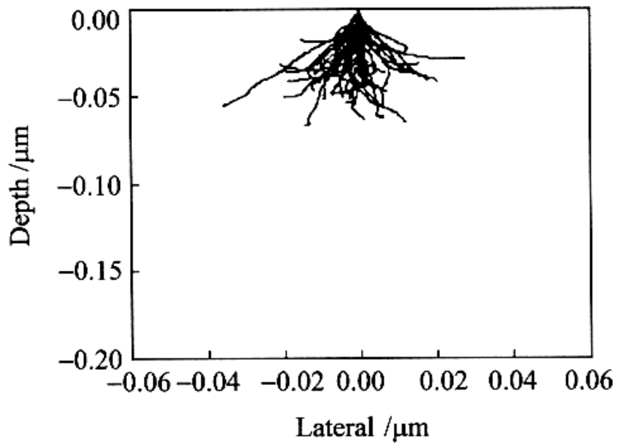
For typical FIB usage: $R = \frac{6E(keV)}{\rho(g/cm^3)} \frac{M_2}{Z_2} \frac{M_1 + M_2}{M_1} \frac{(Z_1^{2/3} + Z_2^{2/3})}{Z_1}$

Ion range varies with ion energy and substrate material, order 1nm/keV

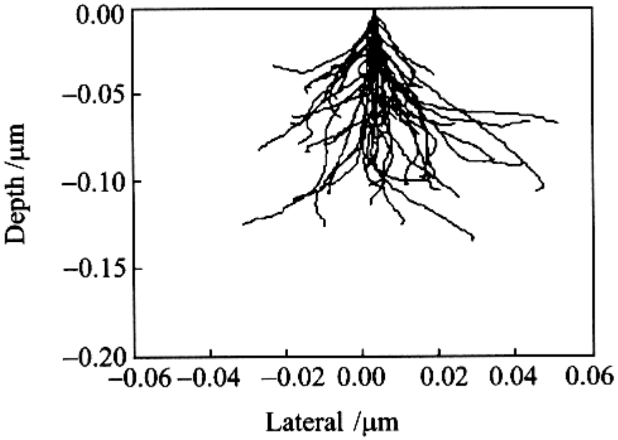
(for electron, a few μm at 30keV)

Trajectories for Ga$^+$ bombardment

30 keV Ga$^+$ on Si sample

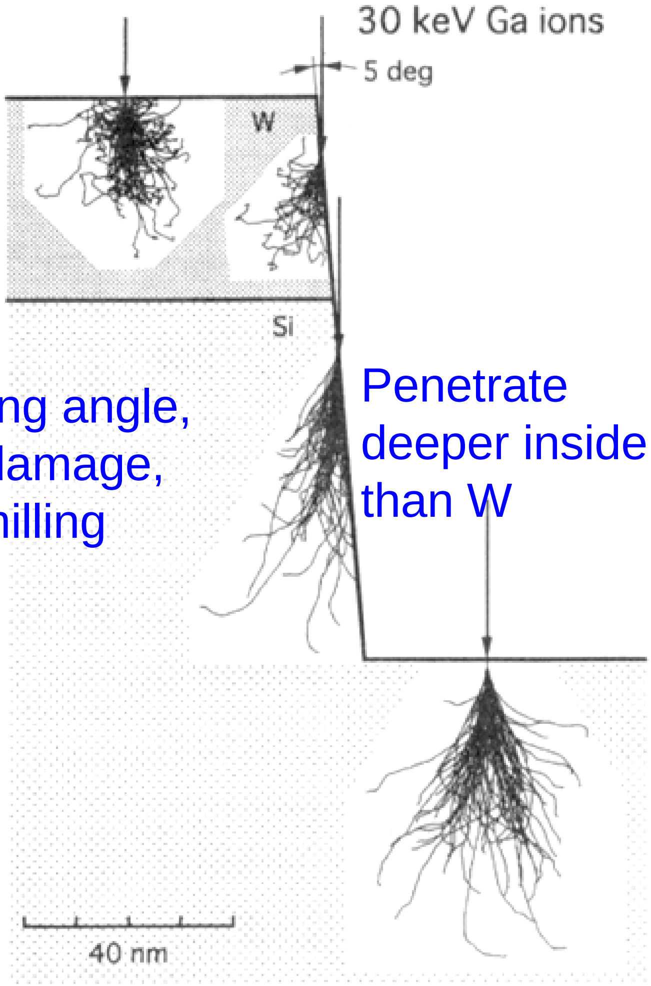


(a) Gallium ion energy = 50 keV



(b) Gallium ion energy = 100 keV

30 keV Ga$^+$ on W/Si sample

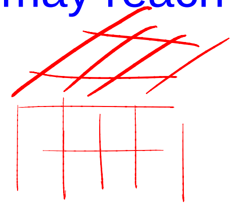


Grazing angle, less damage, fast milling rate

Penetrate deeper inside Si than W

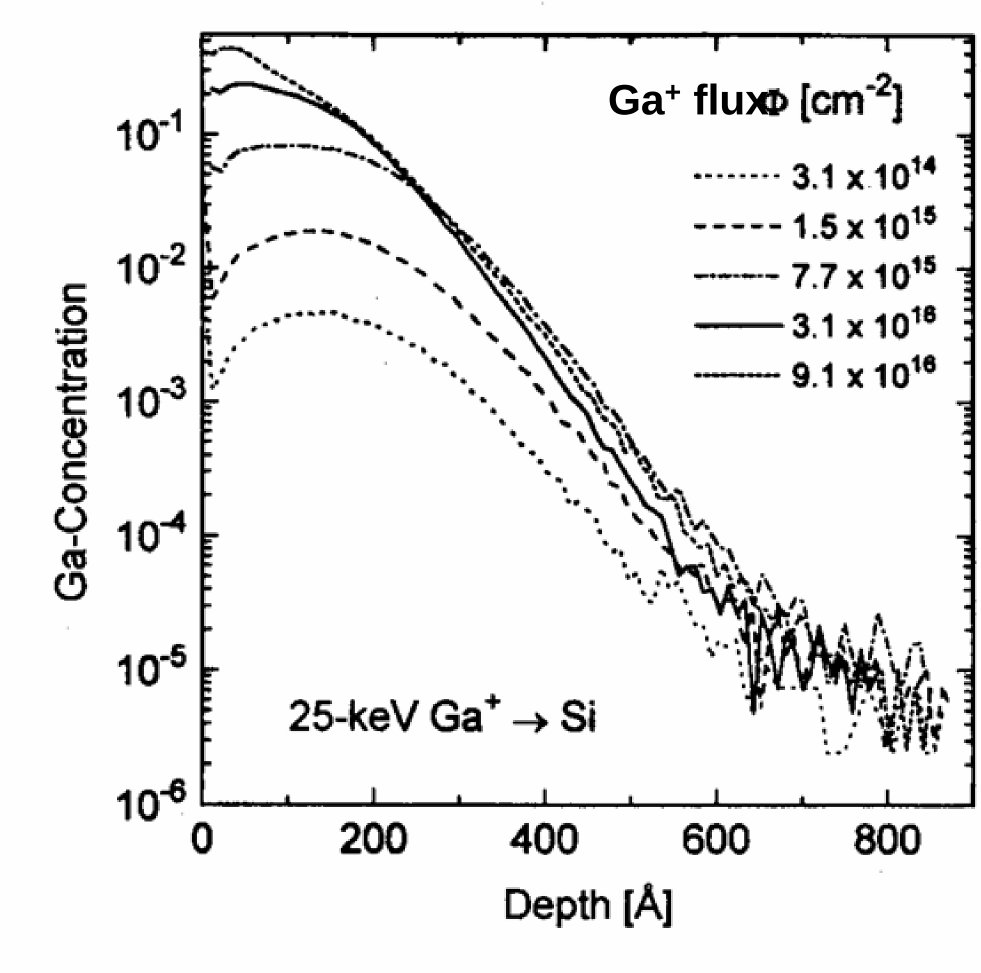
Ishitani, et al., J. Vac. Sci. Technol. B16, 1907 (1998)

Damage by Ga^+ bombardment



- Ion Implantation - Ga atoms remain in the sample target and may reach critical composition for second phase formation.
- Amorphization of surface – loss of crystallinity
- Lattice defects
  - Vacancies – displaced or “missing” atoms from their equilibrium lattice positions
  - Interstitials – atoms which are positioned in between equilibrium lattice positions
  - Dislocations – a missing “half-plane” of atoms
- Local heating due to large displacement of atoms that may occur within the collision cascade (10’s of nanometers from surface)
- Concentration of primary radiation defects (knock-outs from lattice sites) can be evaluated by Kinchin-Pease formula: $n_D = kE/2E_d$, where $k \approx 0.8$ is a coefficient, E is ion energy, E_d is displacement energy. Average 1000 defects per ion.
- Ga in most semiconductors is acceptor, affecting electronic, optical, magnetic and thermal properties. Concentration of Ga in the irradiated zone can be given by: $C_{Ga} = 1/(1+\gamma)$, where γ is sputter yield.

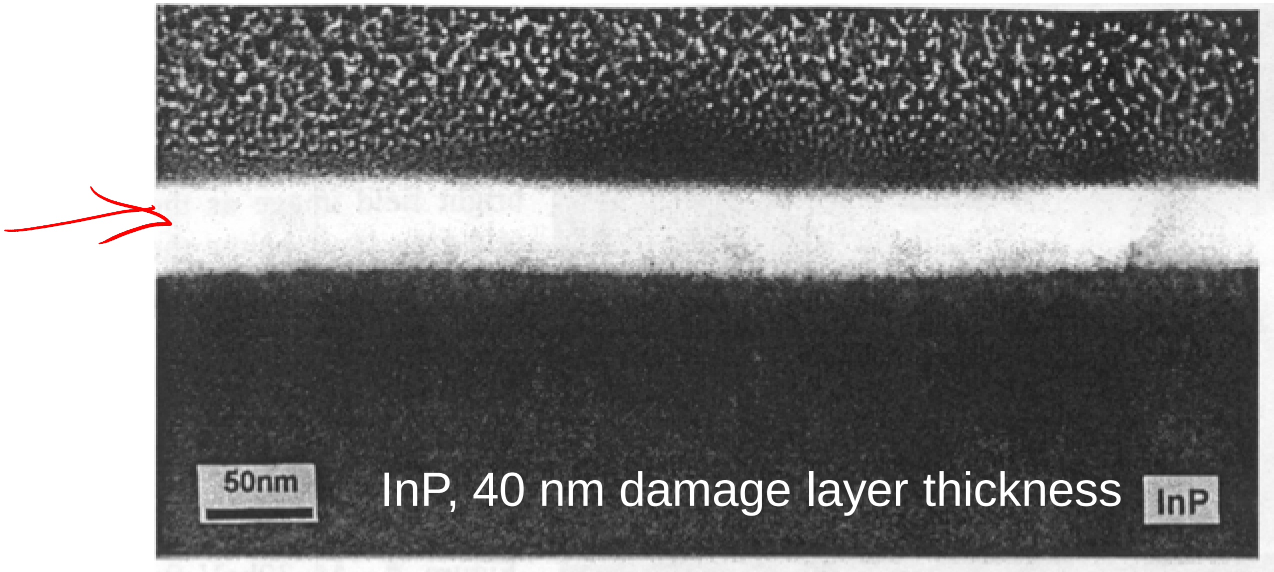
25keV Ga$^+$ depth distribution for silicon (implantation)



SIMS data, concentration is relative fraction of Ga

H. Gnaser et al., J. Vac. Sci. Technol. B13, 19 (1995)

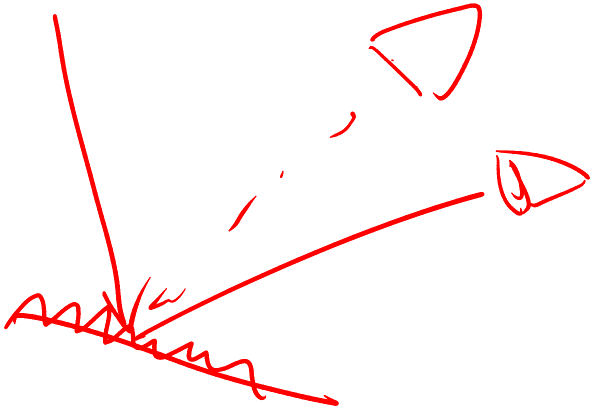
Damage by Ga$^+$ bombardment



InP, 40 nm damage layer thickness

Amorphization depth

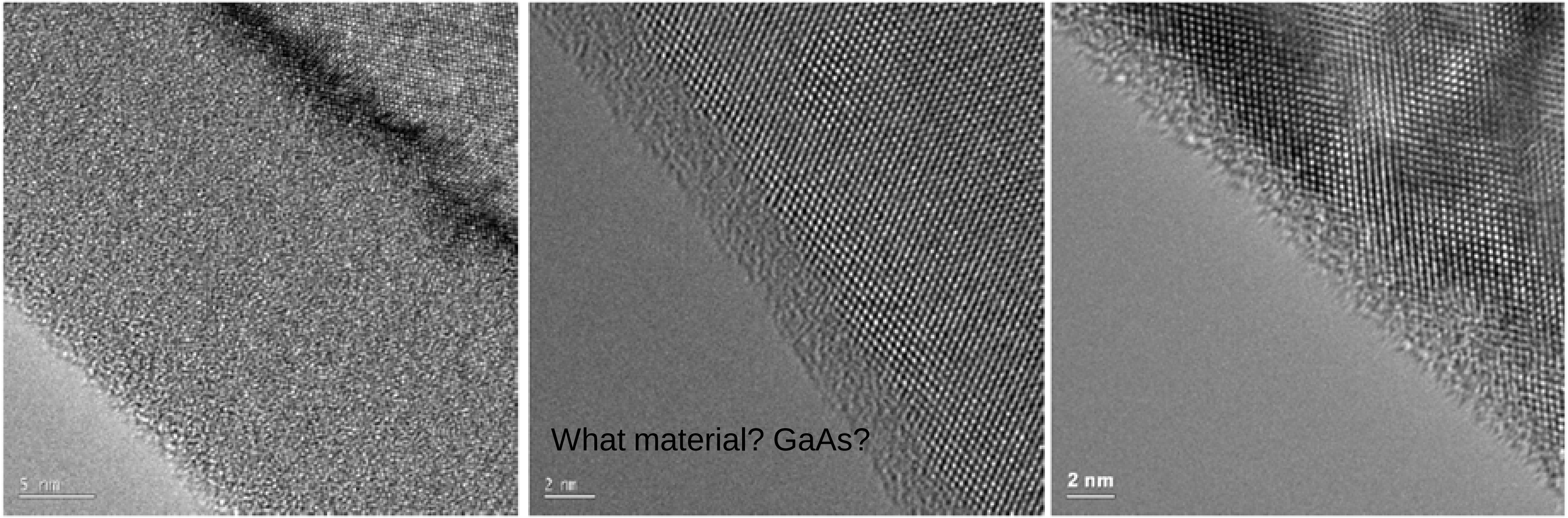
	10 keV	30 keV
Si	6 nm	28 nm
GaAs	4 nm	24 nm
InP	15 nm	40 nm



J. F. Walker and R. F. Broom, Inst. Phys. Conf. Ser. 157, 473 (1996)

Use low keV FIB milling to reduce ion damage

Reduced amorphous layer with reduced FIB energy



What material? GaAs?

30keV
~21nm

5keV
~2nm

2keV
0.5-1.5nm~

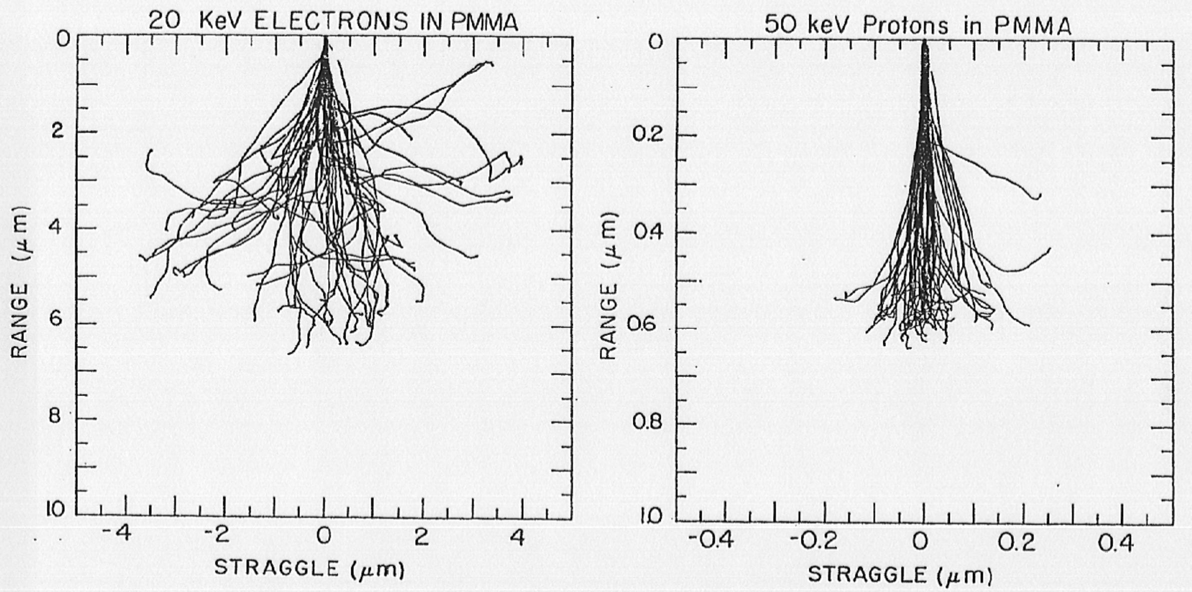
Focused ion beam (FIB) lithography overview

FIB lithography resembles e-beam lithography, but with more capabilities:

- Write pattern in a resist, like EBL.
- Etch atoms away locally by sputtering, with sub-10nm resolution (subtractive), most popular application of FIB.
- Deposit a material locally, with sub-10nm resolution (additive).
- Ion implantation to create an etching mask for subsequent pattern transfer.
- Material modification (ion-induced mixing, defect pattern…).
- Simultaneous observation of what is happening for resist-less lithography (i.e. local etch and deposit).

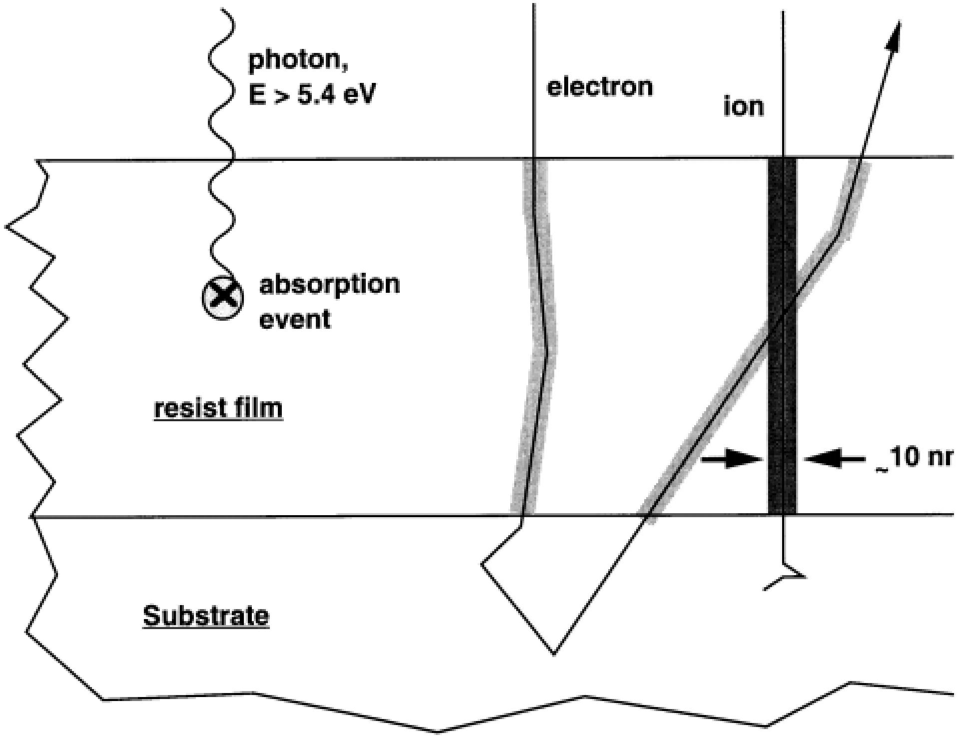
Advantages of heavy Ions in Lithography

- Less forward scattering

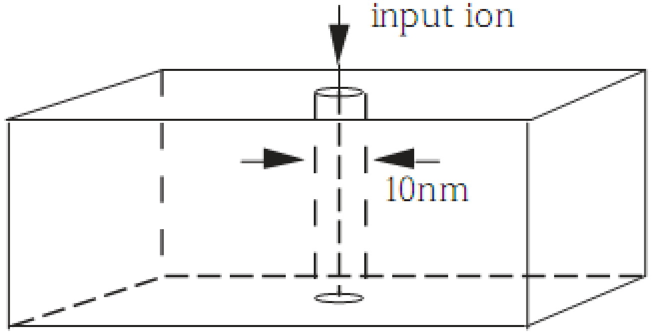


Monte Carlo Calculation of The Paths of Electrons and Protons in PMMA
(J.N. Randall, Texas Instruments)

Near absence of Backscattering



Photon, electron and ions interacting with PMMA



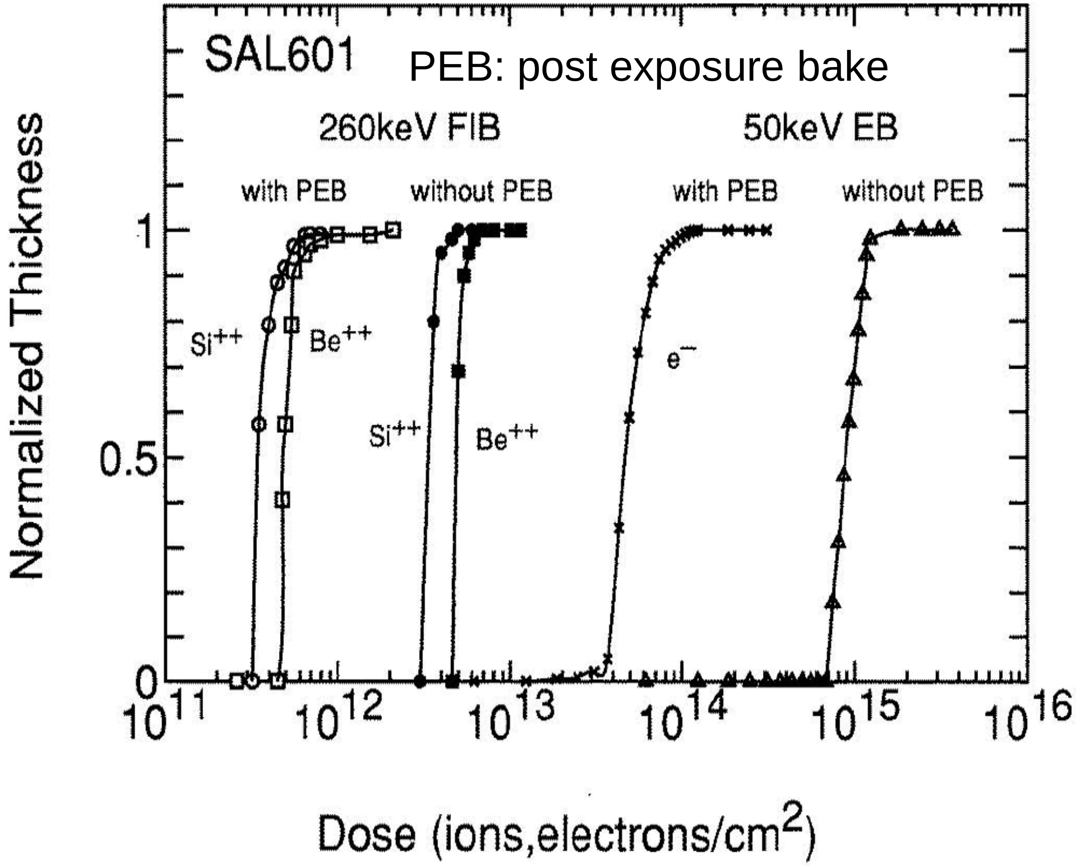
Swiss cheese model of ion lithography

Energy dissipates 2 orders of magnitude faster than electrons → higher sensitivity

Light ions are required to reduce resist removal

H^+, He^+, L^+, and Be^{++} are attractive but field ion sources are not readily available.

Comparison to EBL: resist sensitivity



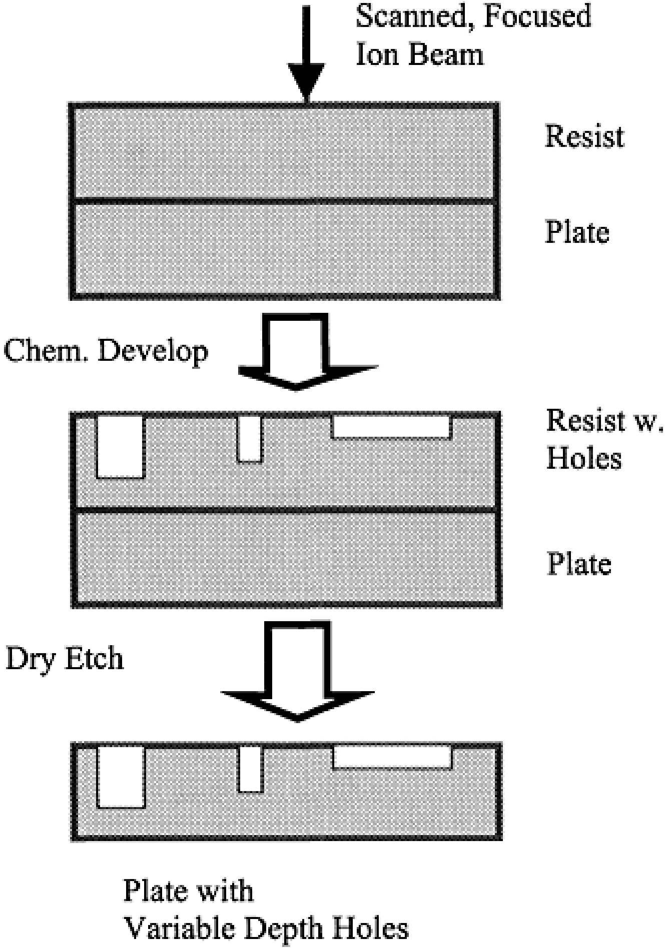
SAL-601:

High sensitivity (~10μC/cm^2) chemically amplified negative resist, with good resolution (sub-100nm), high contrast, and moderate dry etch selectivity. But not very stable with short shelf lifetime.

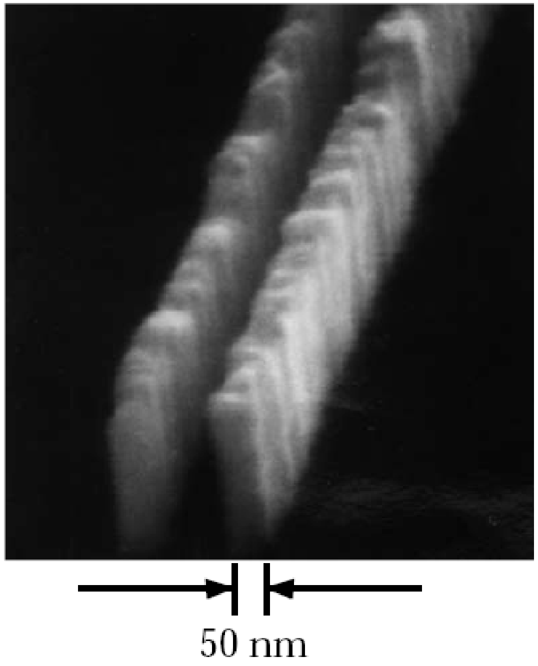
http://snf.stanford.edu/Process/Lithography/ebeamres.html

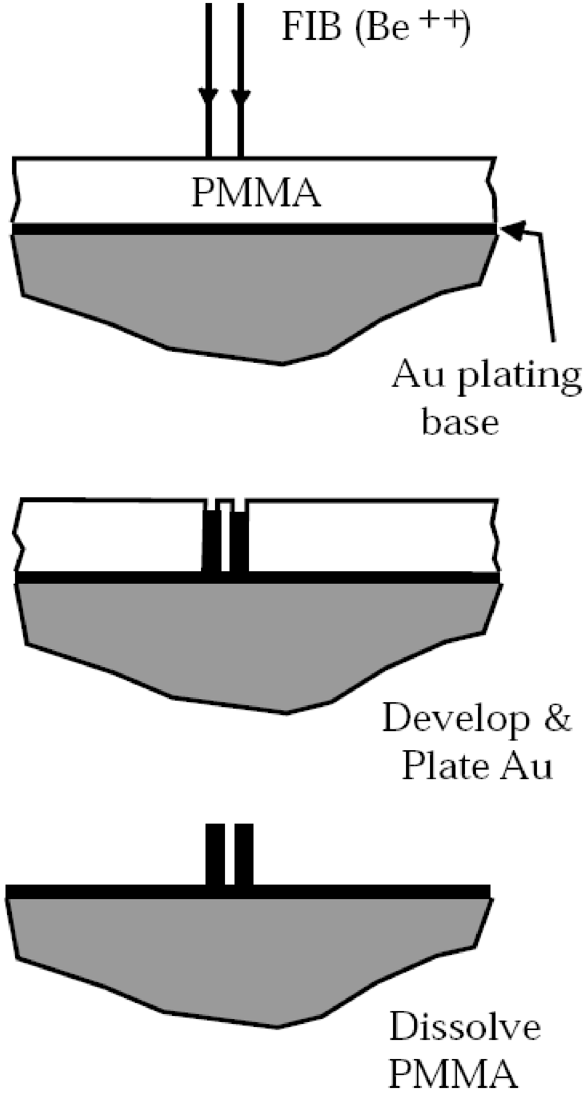
- Very high ion beam energy (260kV), so this comparison of sensitivity may not be typical.
- Here the resist sensitivity is about 2 orders higher than that of EBL.

FIB Lithography



FIB resist lithography
(variable exposure depth)





Unique Properties of Focused Ions

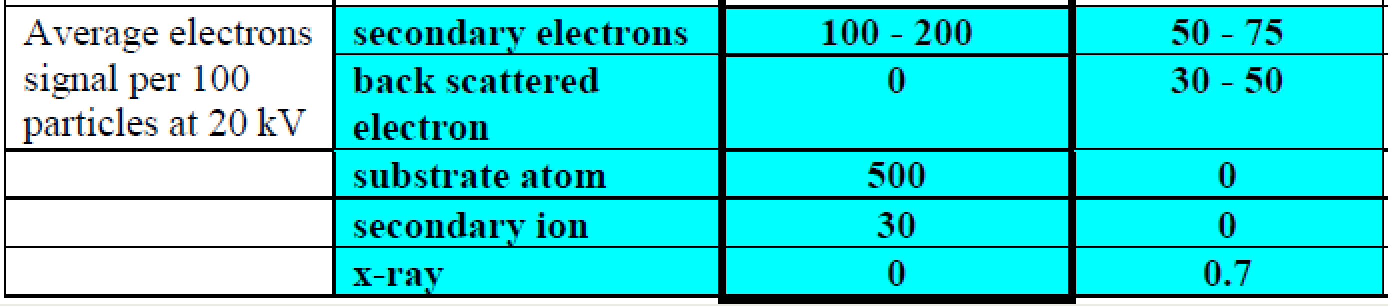
- Variety of source materials
  - Ga, Pt, Si, W, Ga alloys (GaMn, etc.)
  - Not all sources give stable current (1%/hour variation)
- Much higher momentum than electrons
  - More efficient energy exchange
  - Physical sputtering can etch almost any material
- Capability of 3D sculpturing
- Serial process, throughput is limited
  - Chemical assistance to improve the throughput

Advantages of FIB over EBL lithography (with resist)

Like EBL, ion-matter interaction can also generate low-energy secondary electrons, which can expose the resist for lithography.

Naturally, in principle all EBL resists can also be used as FIB lithography resist.

- Proximity effect of FIB lithography is negligible, no electron backscattering.
- Forward scattering is also weaker.
- This means writing pixel size ~ beam spot size, beam blanker may not follow. (For EBL, pixel size >> beam spot size, exposure by proximity effect.)
- For the same beam spot size, higher resolution than EBL, due to shorter ion range, smaller lateral straggling, weaker secondary electron generation, lower energy of secondary electrons.
- Greater resist sensitivity than EBL that increases throughput.



		Ion-beam	electron-beam
Average electrons signal per 100 particles at 20 kV	**secondary electrons**	**100 - 200**	**50 - 75**
	back scattered electron	**0**	**30 - 50**
	substrate atom	**500**	**0**
	secondary ion	**30**	**0**
	x-ray	**0**	**0.7**

Disadvantages of FIB lithography vs EBL

- However, it is more difficult to focus ion beam (chromatic aberration, no magnetic lens…).
- So one must use low beam current for the same resolution, which offset its high sensitivity and reduces writing speed.
- Impurity of source ions within resist is an issue.
- The biggest disadvantage of FIB lithography: limited exposure depth in resist (<100nm for 100keV); thin resist makes following liftoff or etching process difficult.

Spot size of a FEI FIB system. (Spot size for EBL can be <10nm at current several nA)

Beam current (pA)	1	10	30	50	100	300	500	1000	3000	5000	7000	20000
Spot size (nm)	7	12	16	19	23	33	39	50	81	110	141	427