Nanometer Scale Patterning and Processing

Spring 2016

Lecture 26

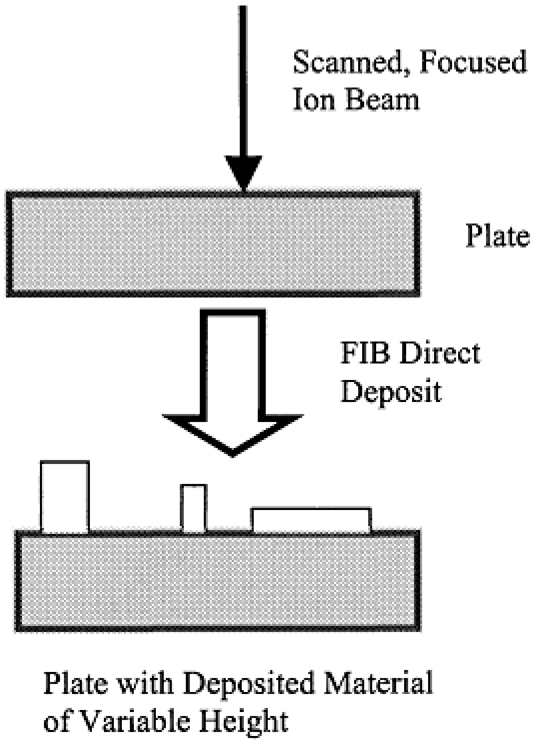
Non-Lithographic Applications of FIB

PURDUE UNIVERSITY

Non-Lithographic Applications of FIB

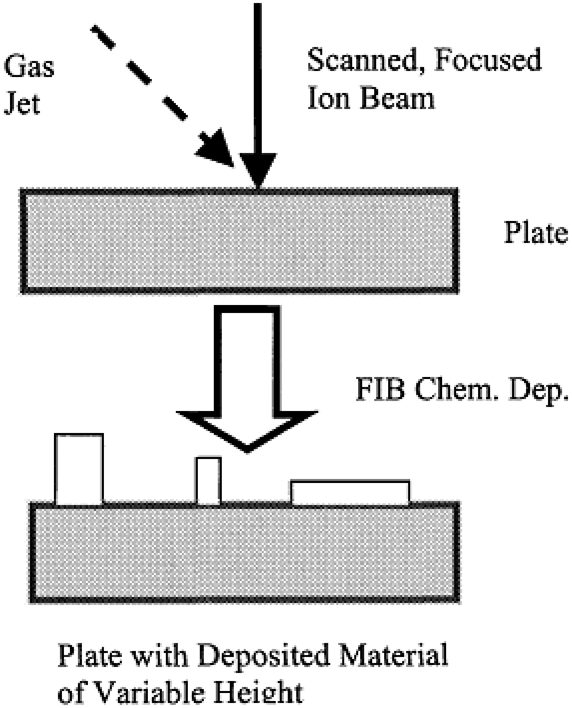
1. Overview
2. FIB milling, sputtering yield.
3. Redeposition.
4. Single line milling.
5. Other types of FIB lithography (implantation, intermixing…).
6. Gas-assisted FIB patterning.

FIB Deposition



FIB direct Deposition

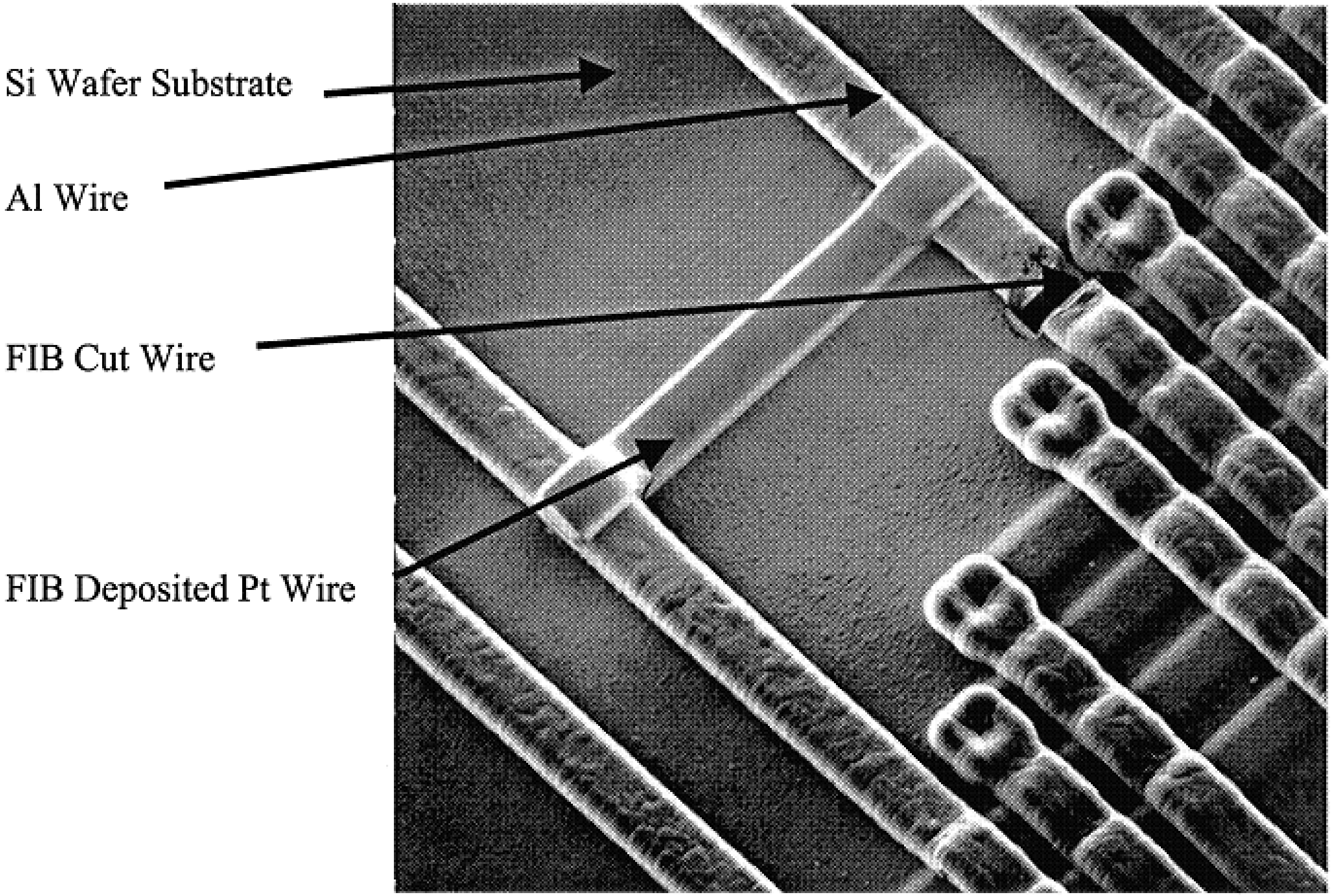
(a slow process, low voltage is required)



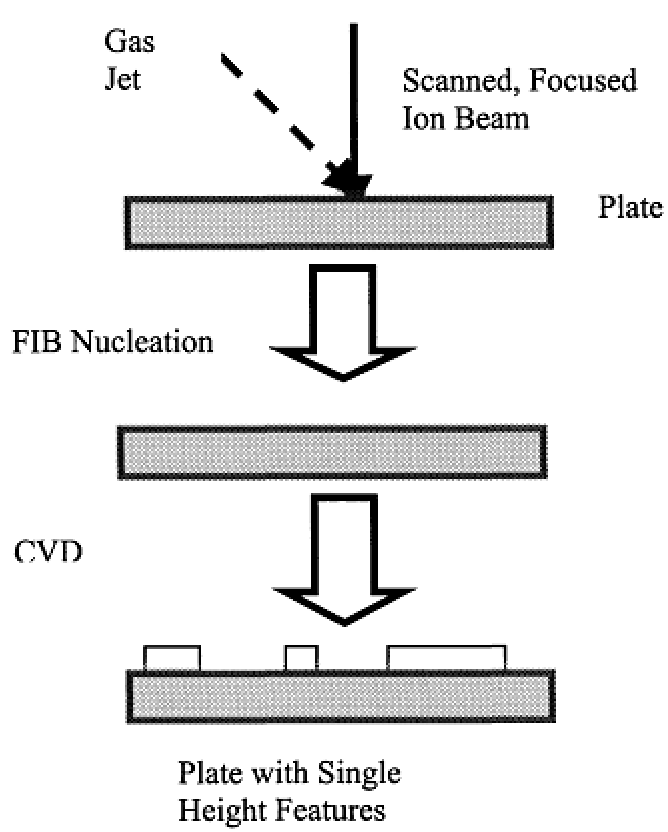
FIB assisted Chemical Deposition

Gas flow must be sufficient to avoid milling

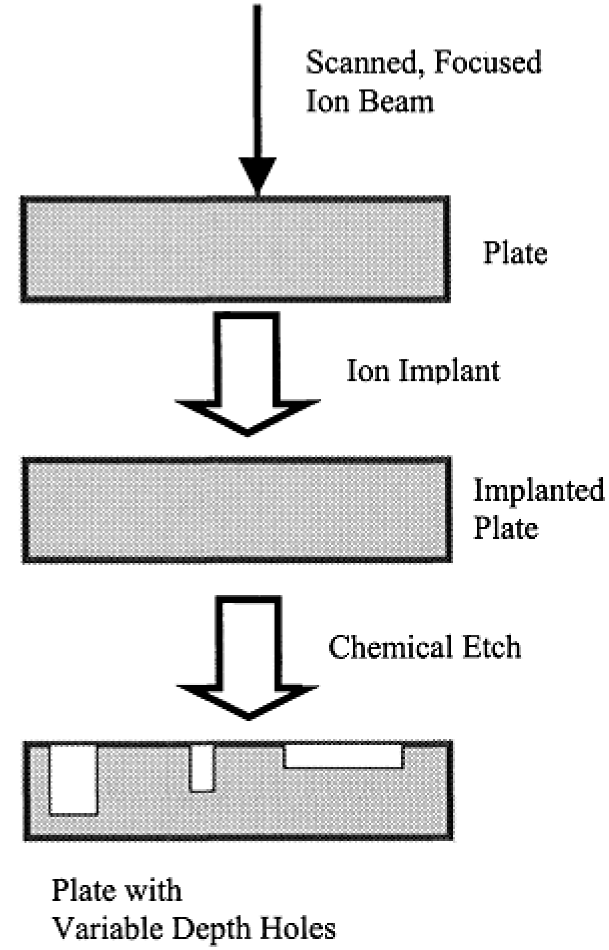
Semiconductor Mask or Device Modification



Other FIB processes

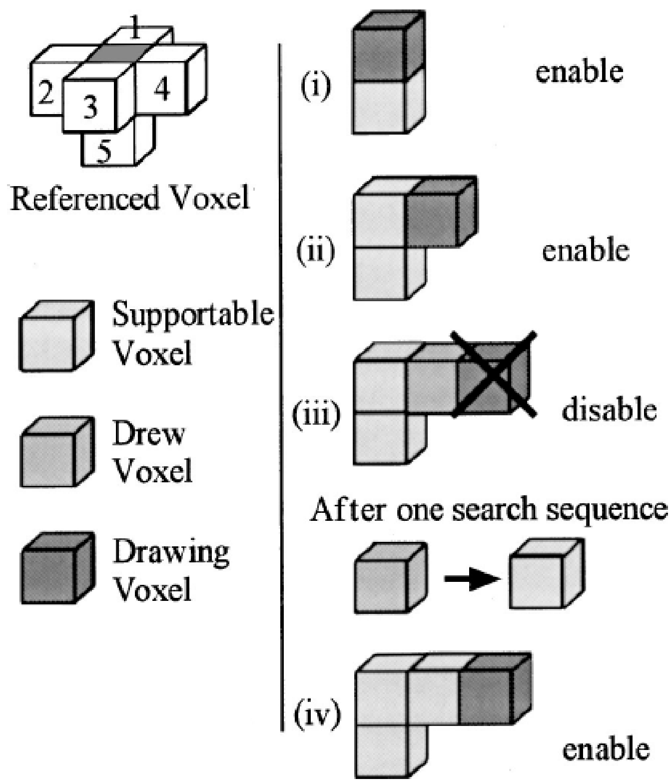


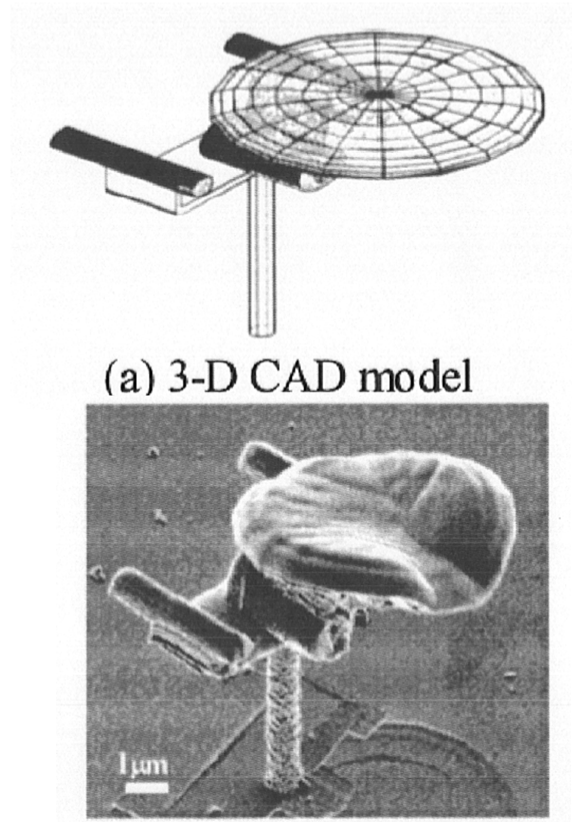
FIB induced Nucleation and Chemical Vapor Deposition. 3D structures are hard to form, but can be done (See next slide)



FIB implantation (cannot beat the parallel implantation process)

FIB Chemical Vapor Deposition



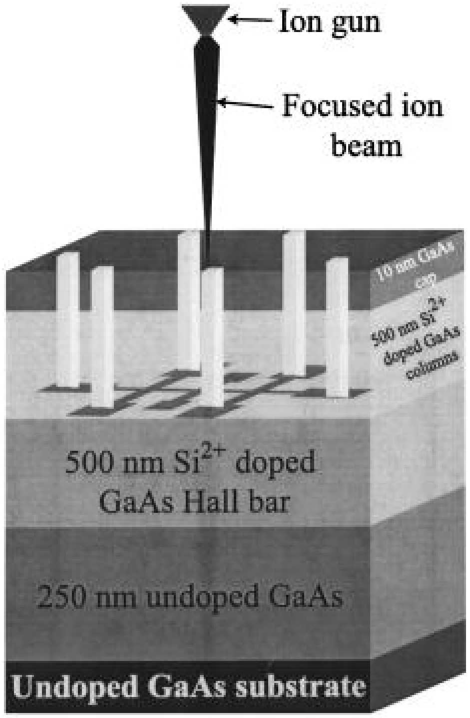


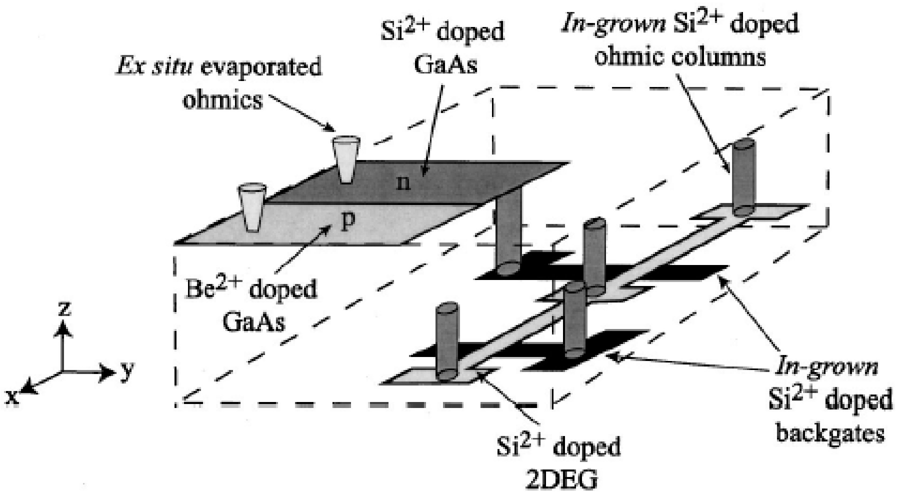
(a) 3-D CAD model
(b) SIM image (tilt 45deg)

Star Trek Enterprise, 8.8 µm long

T. Hoshino, et al, J. of Vac. Sci & Technol. B, Vol 21, p 2732, (2003).

FIB Doping for Device Prototyping





S. Vijendran, et al, J. Vac. Sci. and Technol., Vol 19, p2761, (2001)

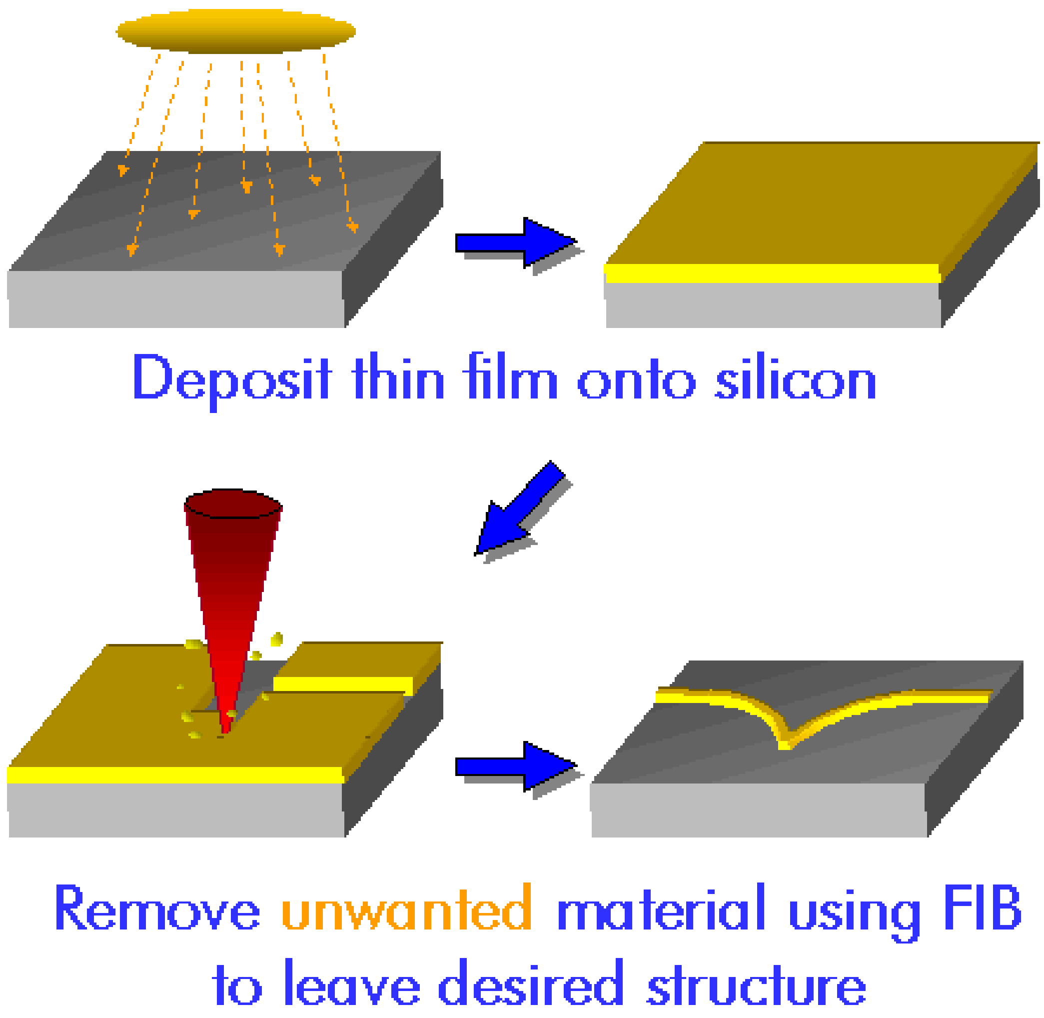
Efficiencies of Physical Processes

Method	Materials	Ref.	3D	Dose (ions/cm^2)	Depth (μm)	S (μm^3/nC)	Rate (μm^3/sec)
Direct Deposit	Au	10	Y				slow
Direct Mill	Most C, PMMA, Si, Al, Ni, W, Au		Y			 .1, .4, .2, .5, .1, .1, 1.5	1 to 15 1, 4, 2, 5, 1, 1, 15
FIB Chemistry							
Etch	Many C, PMMA, Si, Al, Ni, W, Au	3	Y			 1, 8, 2, 10, .8, 1, 1.5	1 to >100 10, 80, 20, 100, 8, 10, 15
Deposit	C, W, Pt	11-13	Y			.3, .1, .3-1.5	3, 1, 3-15
FIB Implant & Chem.							
Etch Enhance	Si, GaAs	7	Y	10^{14}	.05		3000
Etch Stop	Si, Ti	8,9	N	10^{13}, $4x10^{16}$	0.1		$6x10^4$; 15
FIB Nucleate & CVD	C, Al, Fe	15,16	N	10^{12}, 10^{17}, 10^{15}	1		$6x10^6$; 60; 6000
FIB Resist Litho.	many		Y?	10^{13}	0.1		$6x10^4$

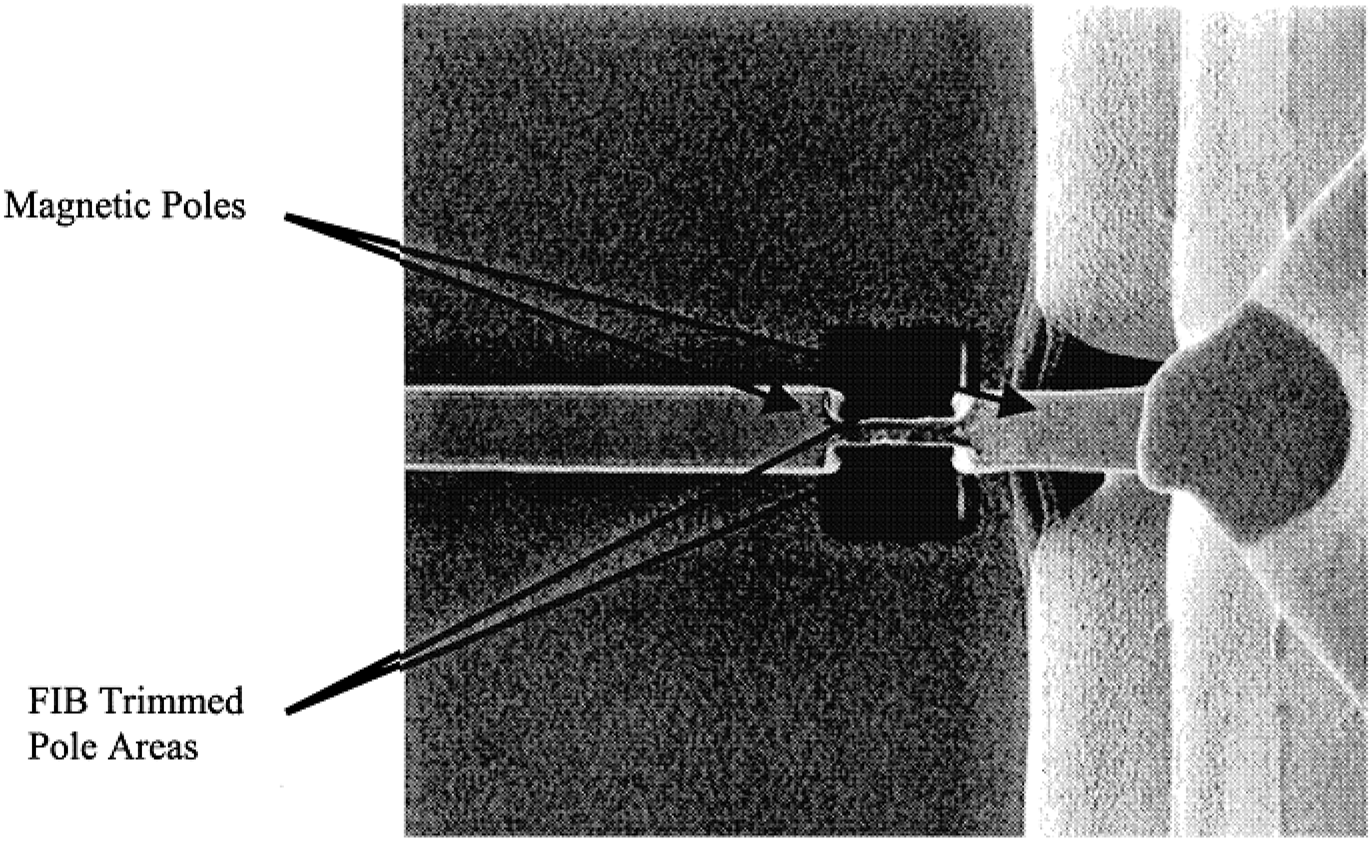
Applications of FIB

1. Overview
2. FIB milling, sputtering yield.
3. Redeposition.
4. Single line milling.
5. Other types of FIB lithographies (implantation, intermixing…).
6. Gas-assisted FIB patterning.

Based on Momentum Transfer



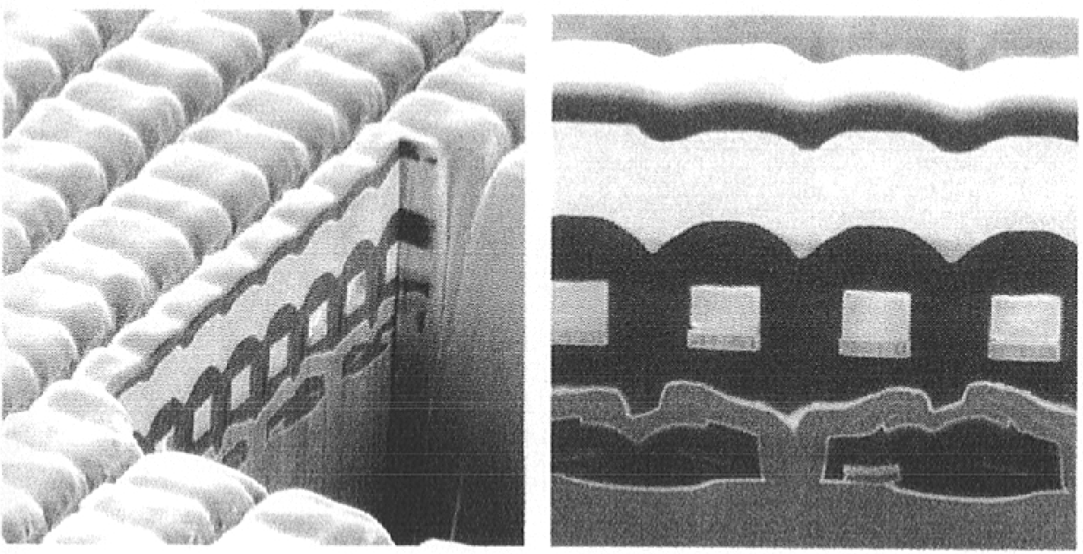
Magnetic Thin Film Head Trimming



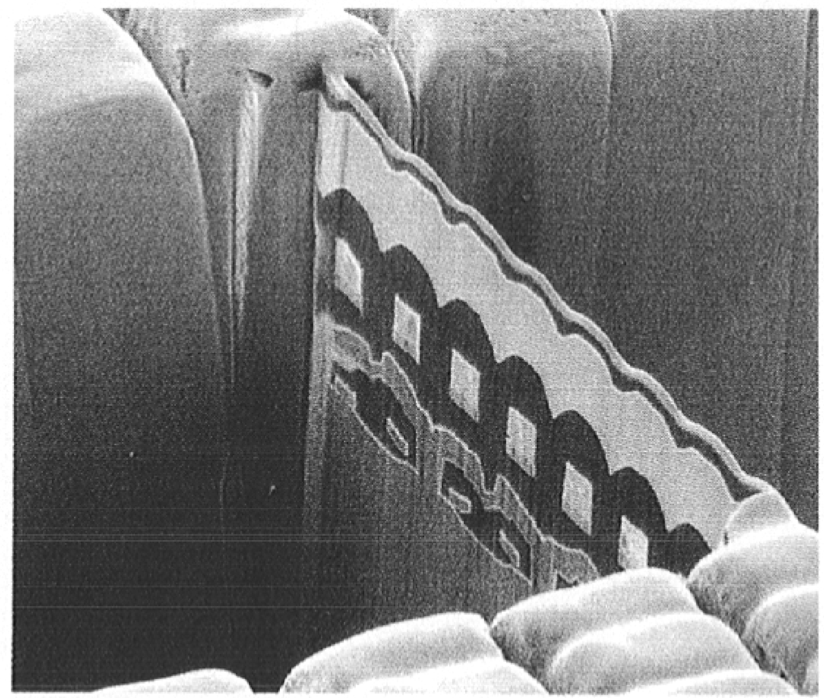
Cross-section preparation

● **Automatic cross sectioning**

Simply enter the processing depth and length and the computer system will automatically process cross sectioning tasks such as rough etching and final milling.



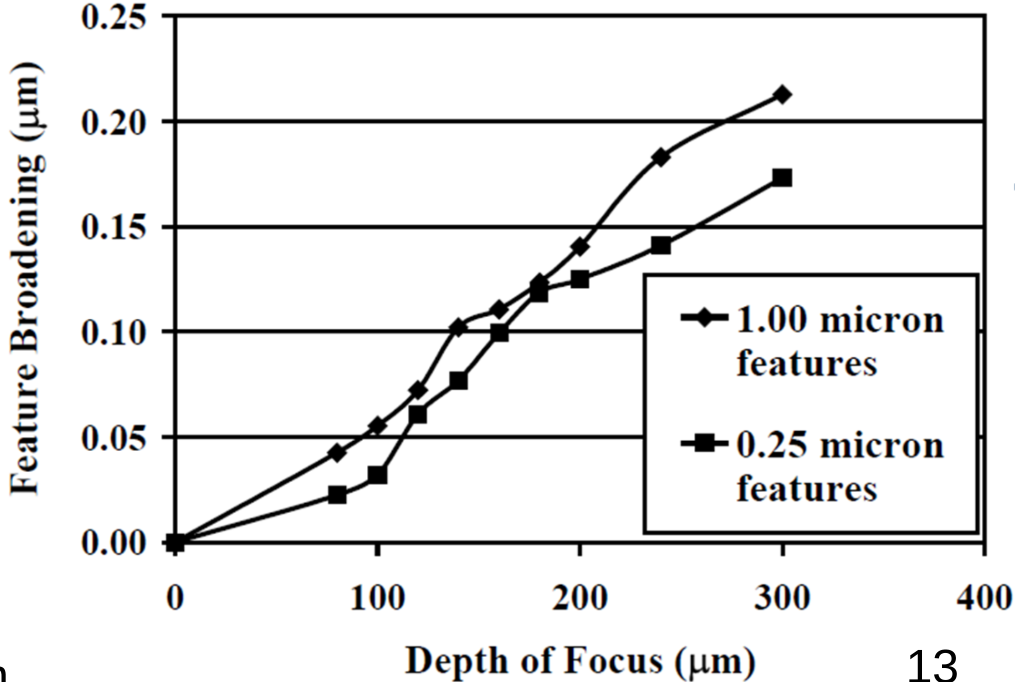
(DRAM cross section images)



(TEM sample preparation)

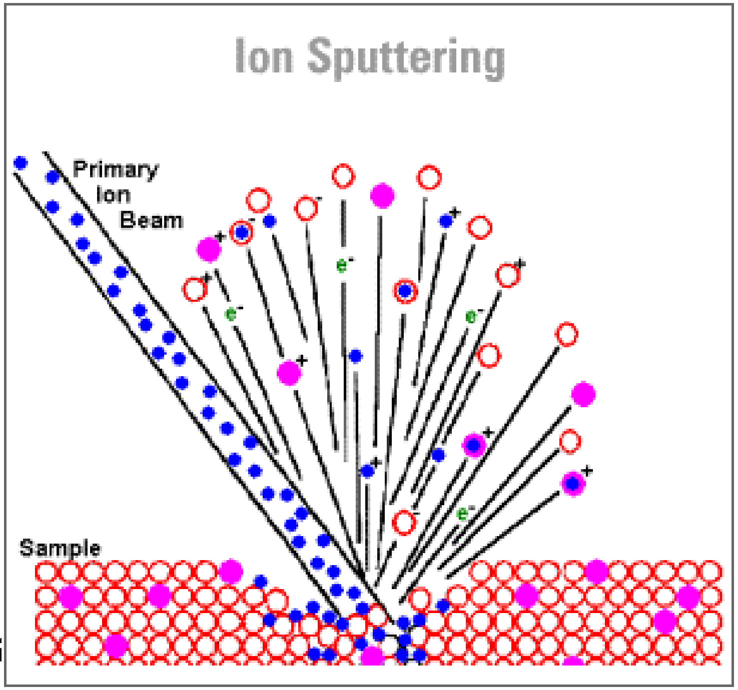
FIB milling

- Sputter process.
- Less damage at cutting surface for small currents.
- Resolution better for small current but high currents mill faster - use series of decreasing currents.
- Significant redeposition - milling strategy is important.
- High depth of focus (ion shorter wavelength than electron) – mill features with high aspect ratio, rough surface OK.
- Coupling with SIMS gives in-situ information on chemical content.



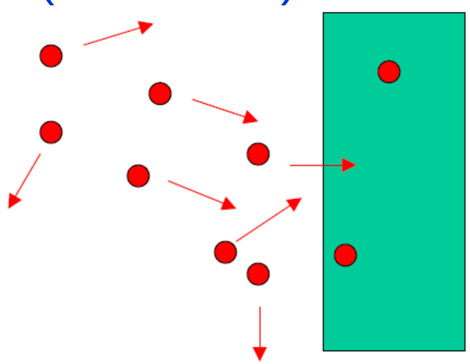
Sputtering by ion beam

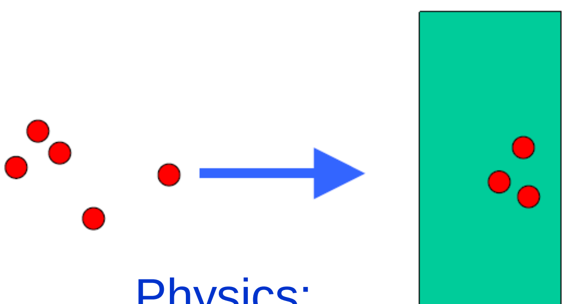
- Sputtering rate depends on ion energy, mass, crystal orientation, substrate nature.
  - One Ga ion of energy 30 keV sputters a few atoms from Si surface.
- Sputtered feature is broader than beam size: 10nm beam causes 20 to 30 nm sputtered recess.
- With a 1nA ion beam current, sputtering ~1μm^3/sec.
- Optimal ion energy 10-100keV.
- Higher energy leads to more implantation.
- For energy >1MeV, backscattering and nuclear reaction become dominant.



Materials modification with ion beams

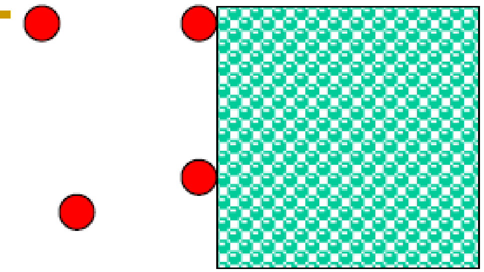
Chemistry:
(several eV)



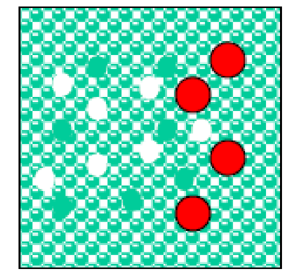


Physics:
(10^1-10^7eV)

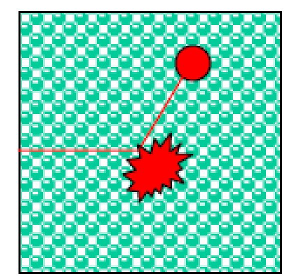
0-1 eV:
adsorption
Rp ≈ 0



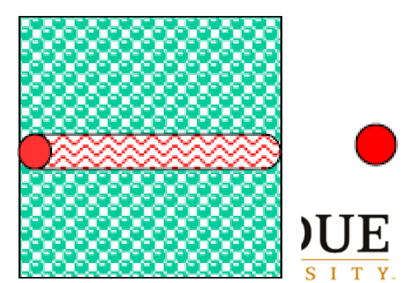
15-10^2 eV:
atomic
displacements
Rp ≈ 1-10 nm



10^3-10^5 eV:
dense cascades, local
melting
Rp ≈ 10-1000 nm

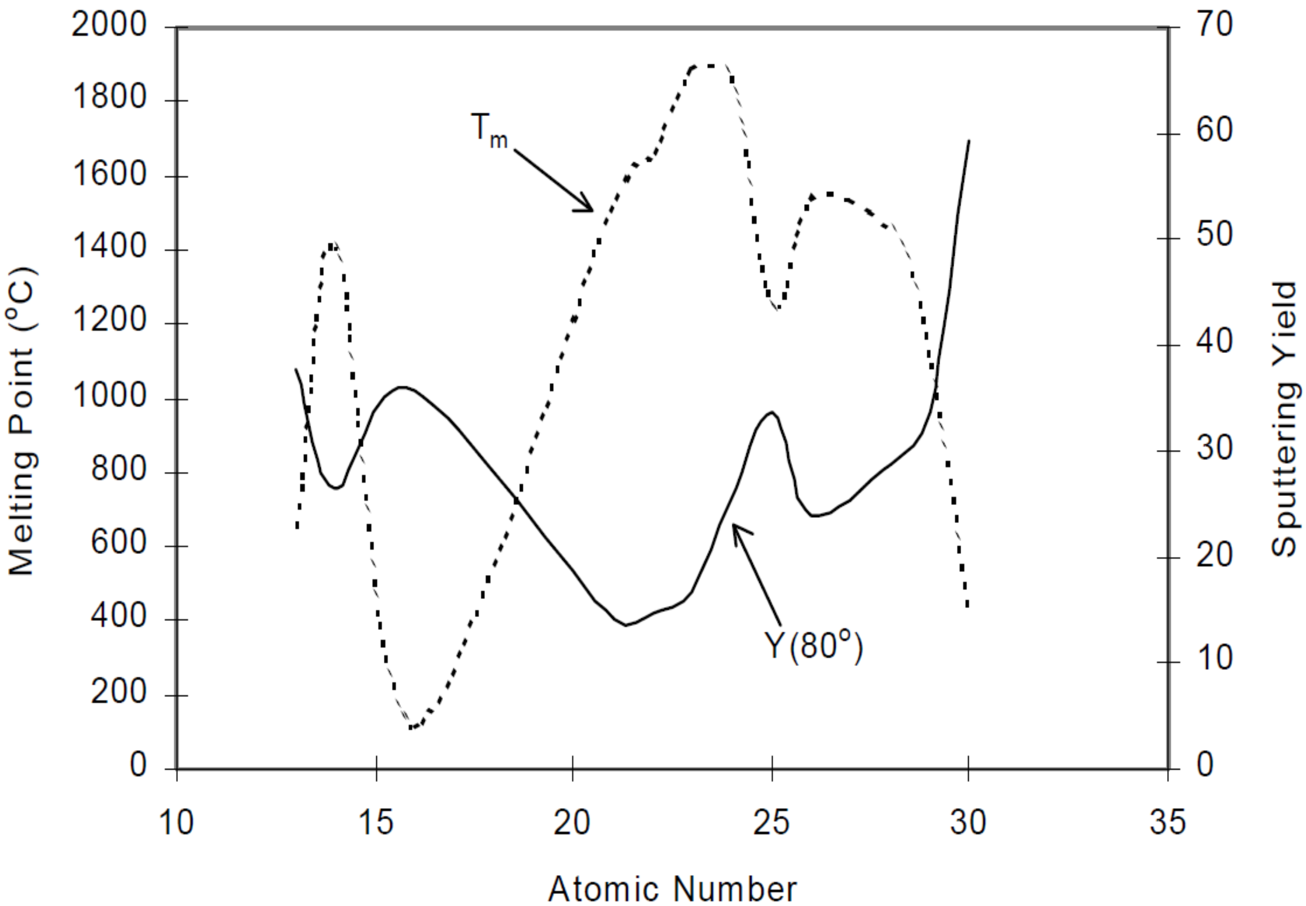


10^6-10^9 eV:
no-collisions, electronic
excitation
Rp ≈ 1-100 μm



Sputtering yield

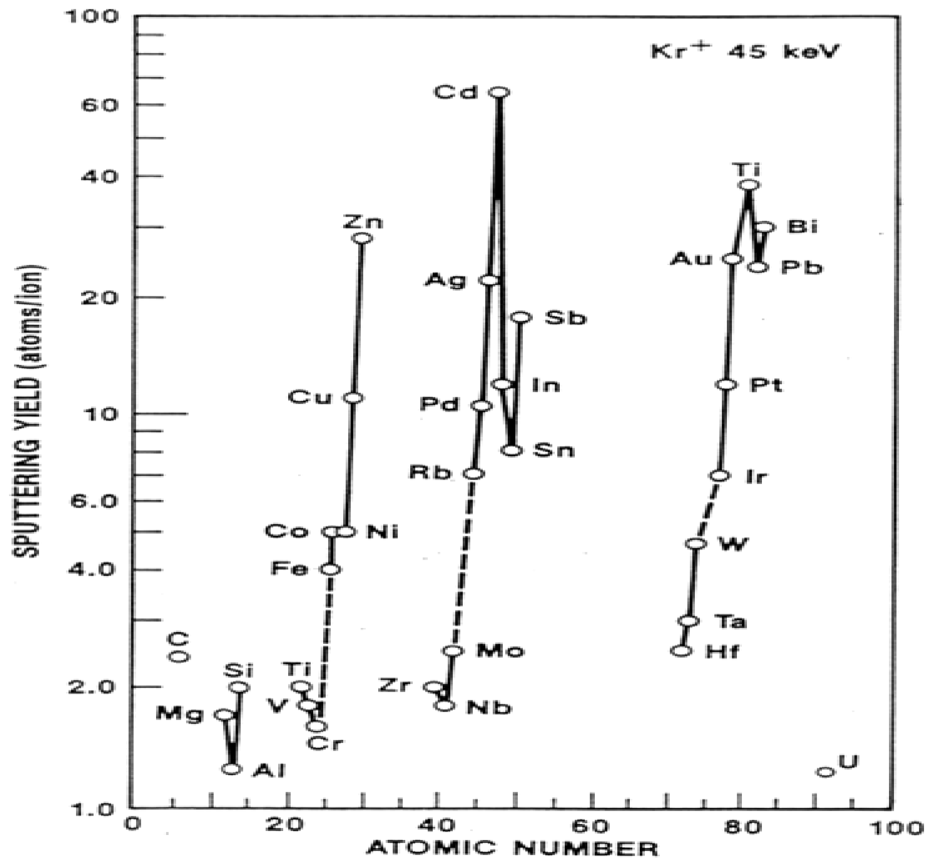
Y = number of recoiling atoms out of the target surface per incident ion = 1-50



Sputtering yield is correlated with melting point.

Sputtering yield of different material

Material	Sputterrate [μm³/nC]
Si	0.27
Thermal Oxide	0.24
TEOS	0.24
Al	0.3
Al2O3	0.08
GaAs	0.61
InP	1.2
Au	1.5
TiN	0.15
Si3N4	0.2
C	0.18
Ti	0.37
Cr	0.1
Fe	0.29
Ni	0.14
Cu	0.25
Mo	0.12
Ta	0.32
W	0.12
MgO	0.15
TiO	0.15
Fe2O3	0.25
Pt	0.23
PMMA	0.4



- Sputtering yield varies with material, orders of magnitude difference across periodic table.
- Sputter rate (μm³/sec) = yield(atoms/ion) × flux(# of ions/sec)/number density(atoms/μm³).
- Actual rate much lower due to re-deposition of sputtered material.

Energy dependence of sputtering yield

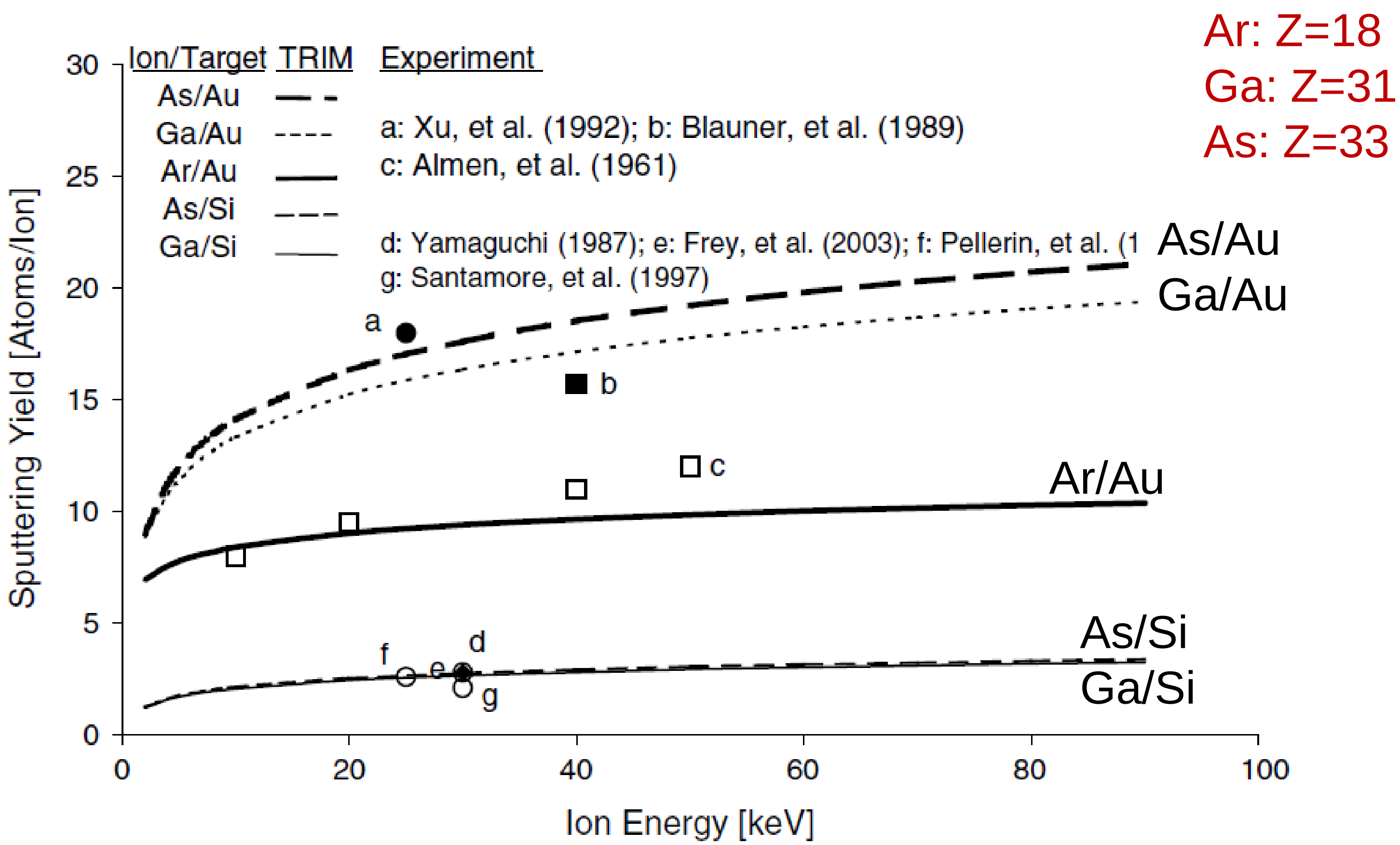


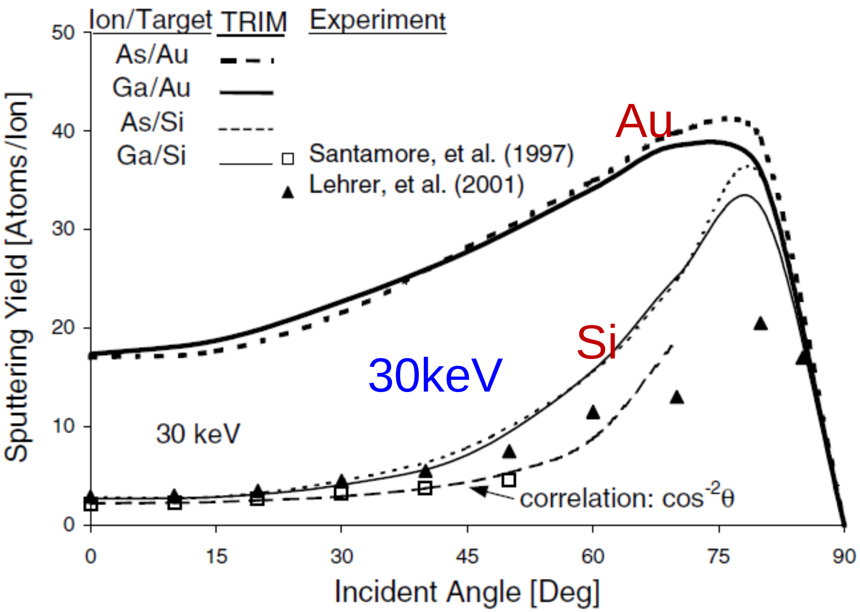
Figure 5. Energy dependence of sputtering yield of Au and Si target substrates by three types of ions at normal incidence.

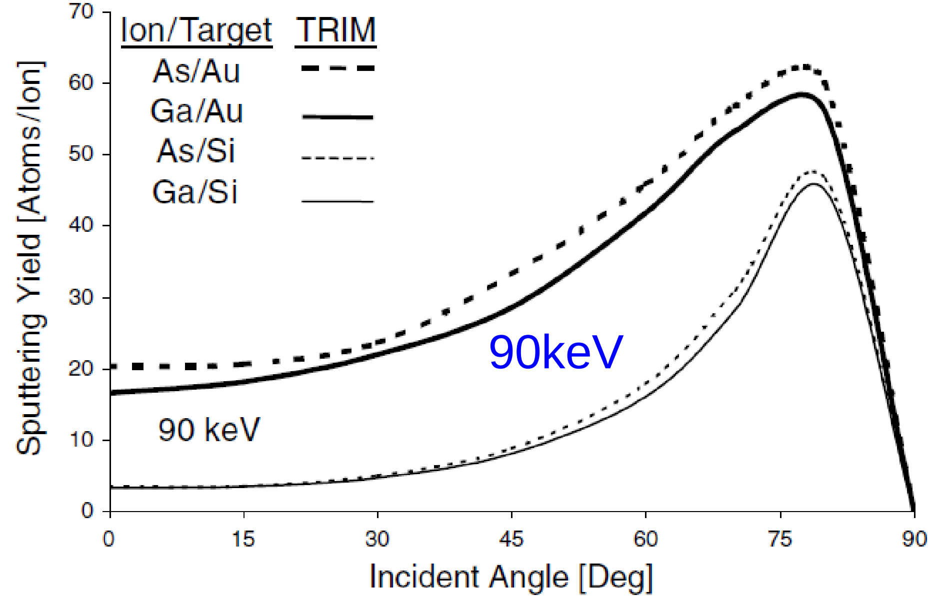
Sputter yield "saturates" at ~100keV, higher energy leads to significant implantation

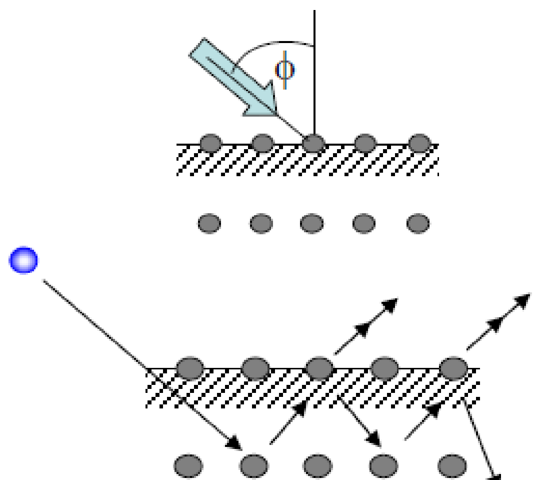
"Recent developments in micromilling using focused ion beam technology", Tseng, 2004

Angular dependence of sputtering yield

Au sputtering rate is less angle-dependent than Si.







- Maximum sputter yield at 75-80º.
- However, FIB milling is usually done at normal incidence for vertical trench profile.
- Actually no longer “normal” once milling started – inclined incidence on tapered sidewall.