Ion Implantation for Fabrication of Semiconductor Materials & Devices

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1. Overview of ion implantation for semiconductors
2. Radiation issues:
   Plasma Immersion (x-rays)
   8 to 12 MeV Boron (neutrons)
3. Toxic materials: molecular ions
4. Summary

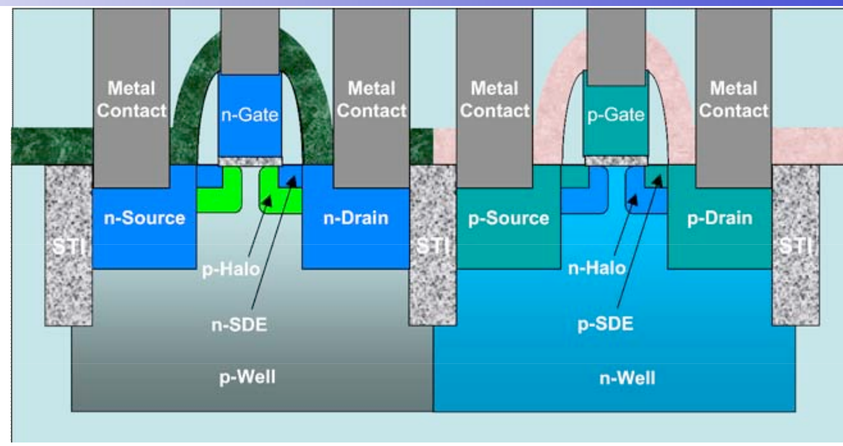
Applications for Semiconductors

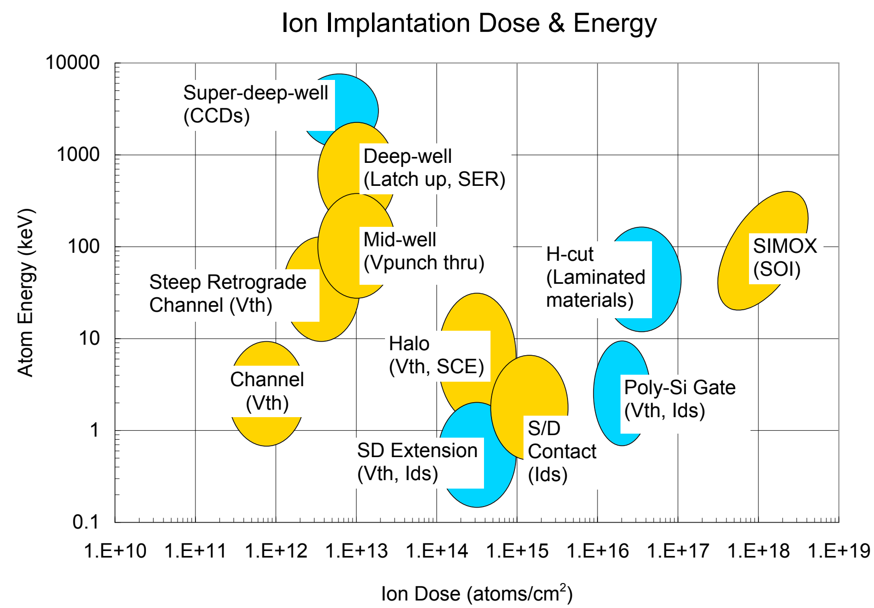
Doping of transistors:
Ions:
B, BF_2, $B_{10}H_{14}$, $B_{18}H_{22}$
As, P, Sb, In, (Si, Ge, He, F, C)

Energy Range:
0.2 keV to 3 MeV (8 MeV)

Dose Range:
1e11 ions//cm^2 (threshold)
5e16 ions/cm^2 (poly-gate)

Lamination and SOI:
H-cut: 5e16 H/cm^2
SIMOX: 2e17 to 5e18 O/cm^2





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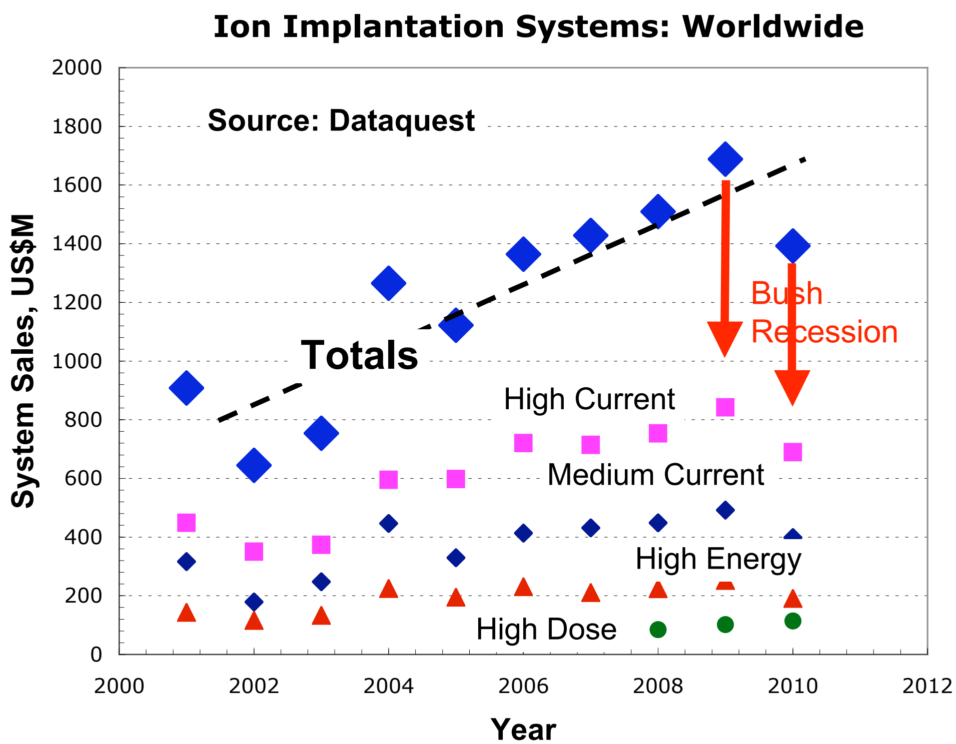
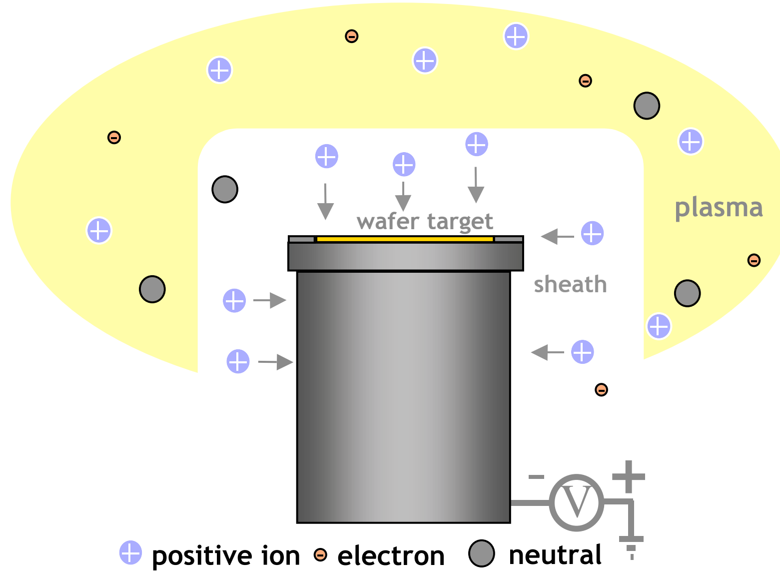
Overview of Ion Implantation: System Sales

- Implantation system sales is a robust, global business now at ~$1.5 B/year.
- Average selling price is $3 to 5 M/tool with hundreds of machines shipped per year.
- Since 1970, >7,000 commercial implanters have been shipped for semiconductor fabrication.
- Most of them are still in use.

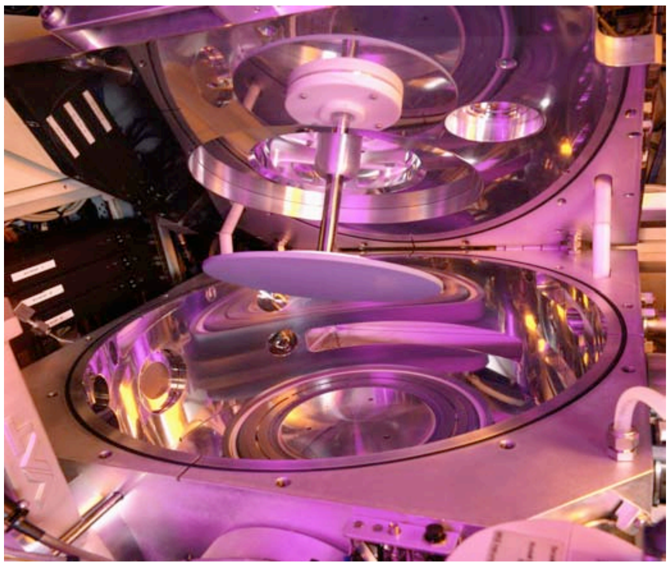


Plasma Immersion Ion Implantation

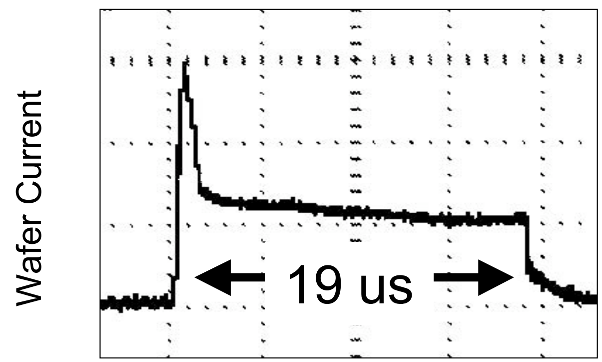
- "Simple" plasma-wafer system
- Excellent for high-dose, low-energy
- Doping (poly-Si gates); H-cut



H_2 plasma, 19 μs, 300 A(peak)



Varian PLAD



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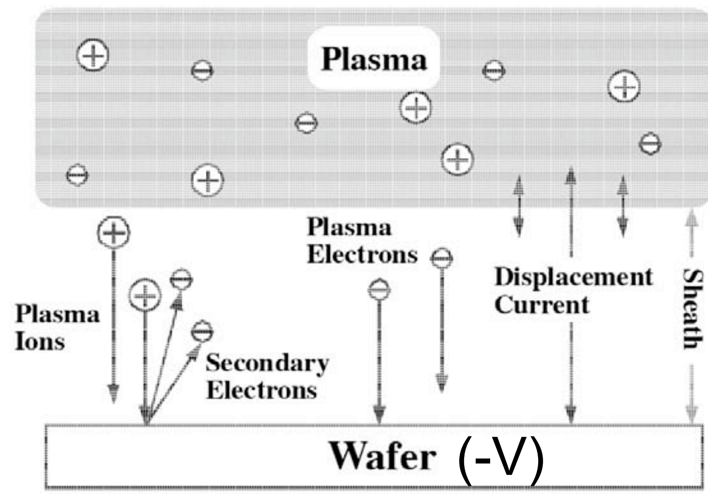
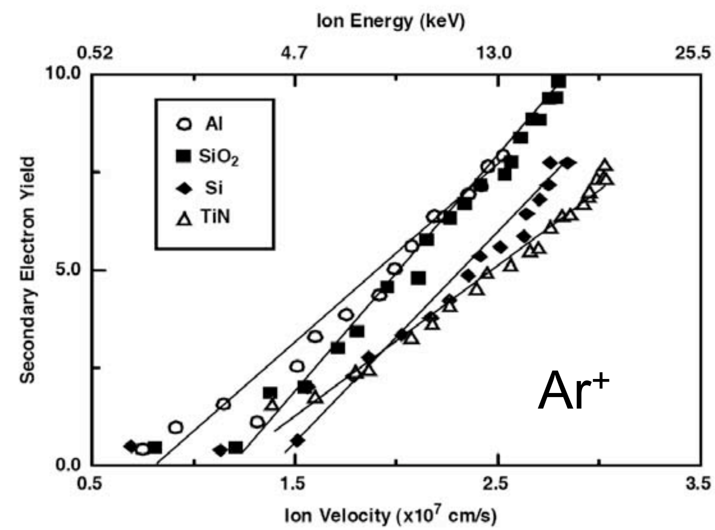
Secondary Electrons

- Copious ion current (100's A) yields lots of secondary electrons from the wafer and platen.
- Secondary yield increases with wafer bias.
- Secondary electrons are accelerated by the wafer bias.
- Fast secondaries generate x-rays slowing down in grounded chamber walls.





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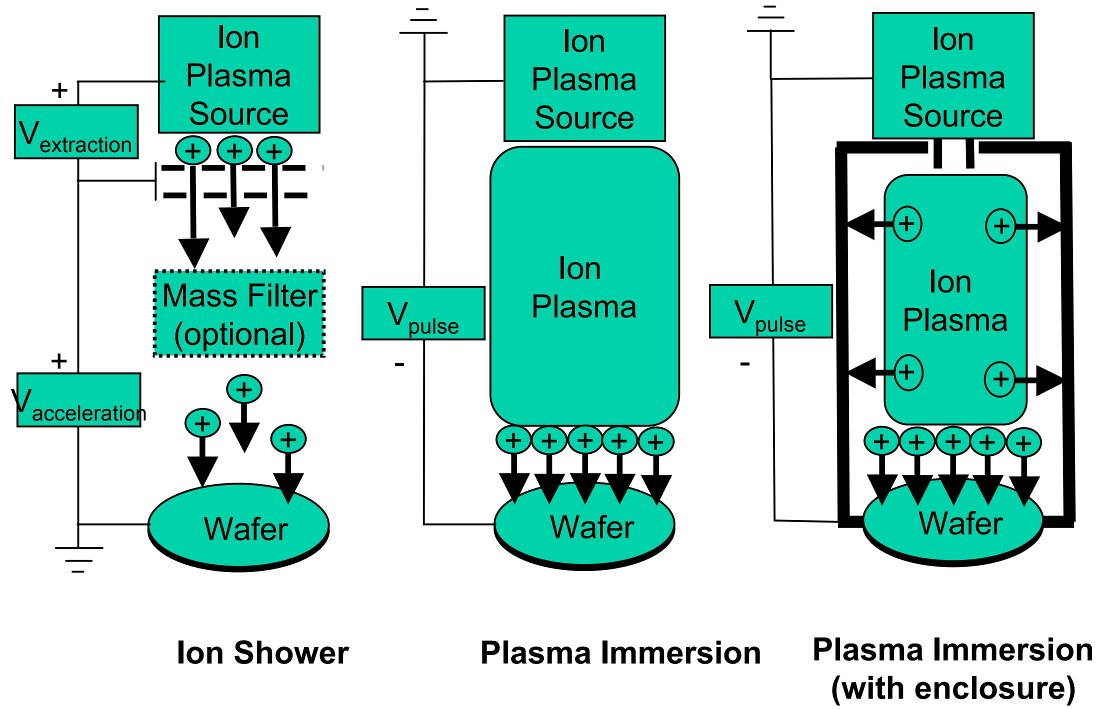
Plasma Immersion: X-ray Suppression

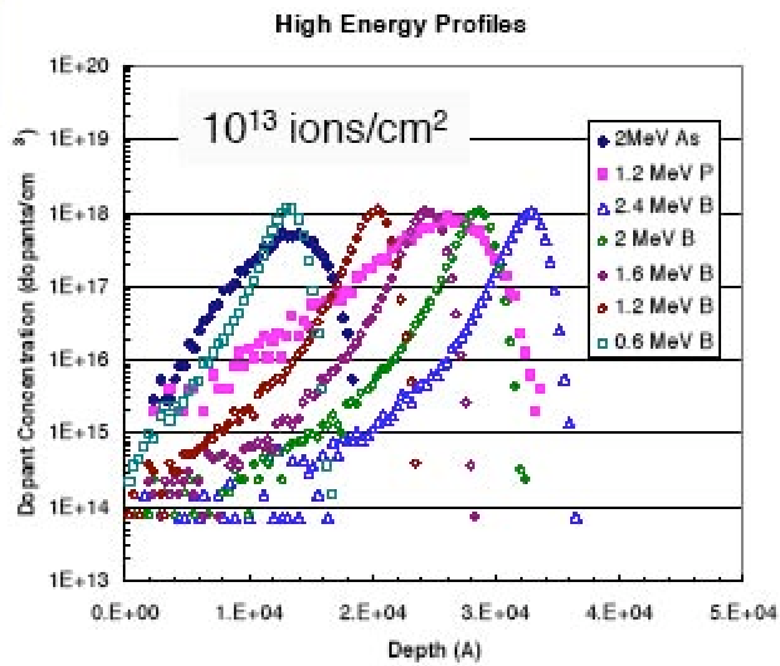
- Mass filters in ion showers (left) and floating enclosures in PIII (right) suppress x-ray generation at high bias (~100 kV) operation.

- Many commercial PIII systems operate at <5 kV with modest shielding (center).



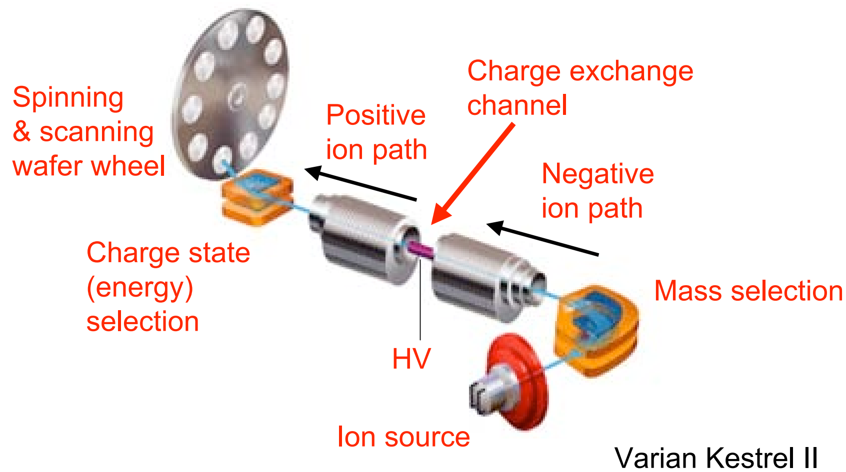
Very-High Energy Doping: Cameras

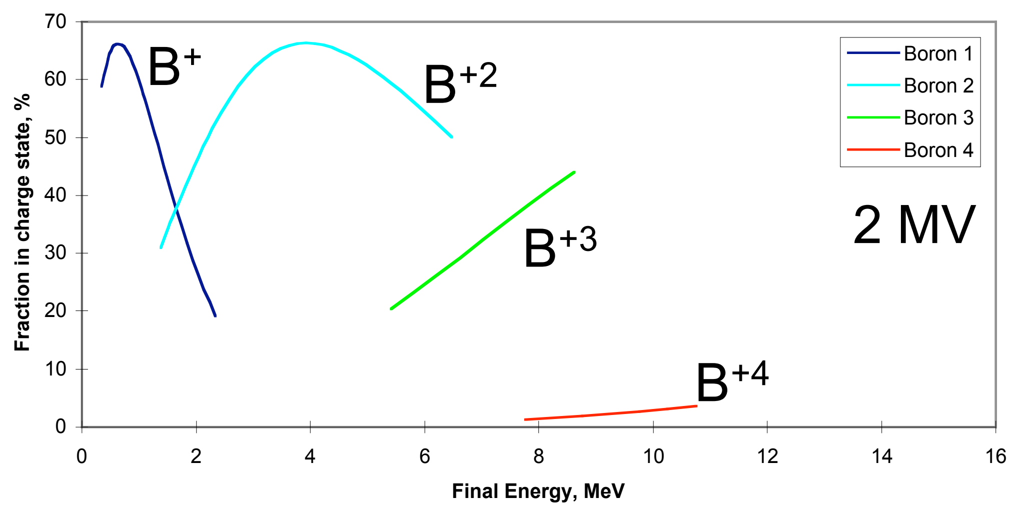
- "Routine" CMOS wells for logic, DRAM & FLASH use ion energies from 0.5 to ~3 MeV.
- Deep wells for high-performance CCD & CMOS imagers would like profile depths of ~10 um or more.
- Range of 8 MeV B is ~10 um.



Tandem Accelerators

- Tandem accelerators "multiply" the terminal voltage by charge exchanges at the HV.
- >8 MeV ions are produced with B^{+3} ions and a 2 MV terminal.
- >10 MeV B^{+4} are also produced.





The Wrong Kind of Tandem

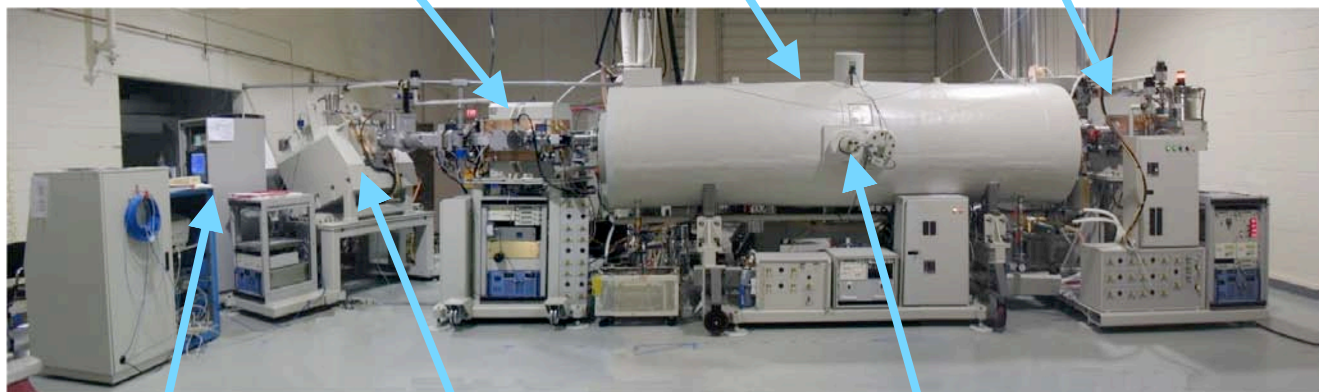
2 MV Tandem Implanter

Clean room interface

Final ion selection

SF_6 enclosure

Negative ion source & injection



Wafer chamber

Beam scanning

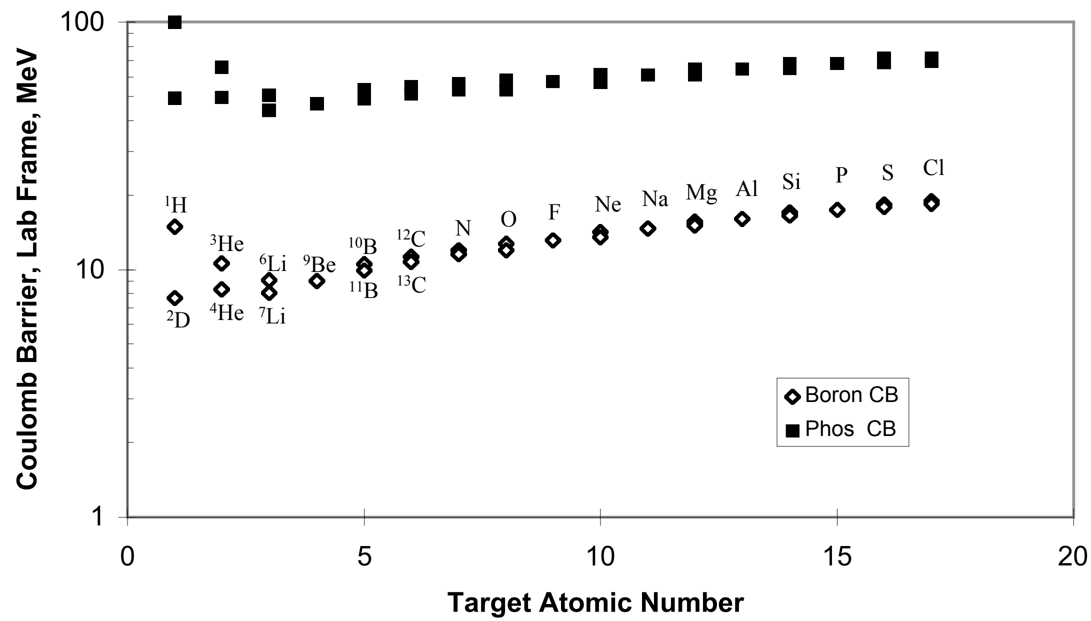
2 MV terminal (inside enclosure)

Coulomb Barrier

$$CB = \frac{e^2 Z_p Z_t}{4\pi\varepsilon_0 R_0 \left[A_p^{\frac{1}{3}} + A_t^{\frac{1}{3}}\right]} \frac{A_p + A_t}{A_t}$$

- Coulomb repulsion is 1st order threshold for nuclear reactions, generating neutrons, gammas, etc.
- ^{31}P CB's are >40 MeV.
- ^{11}B CB's are <10 MeV for light (AMU <15) targets.

Coulomb Barriers for Boron-11 and Phosphorus-31



Neutron Generation

Model Target (IC wafer)

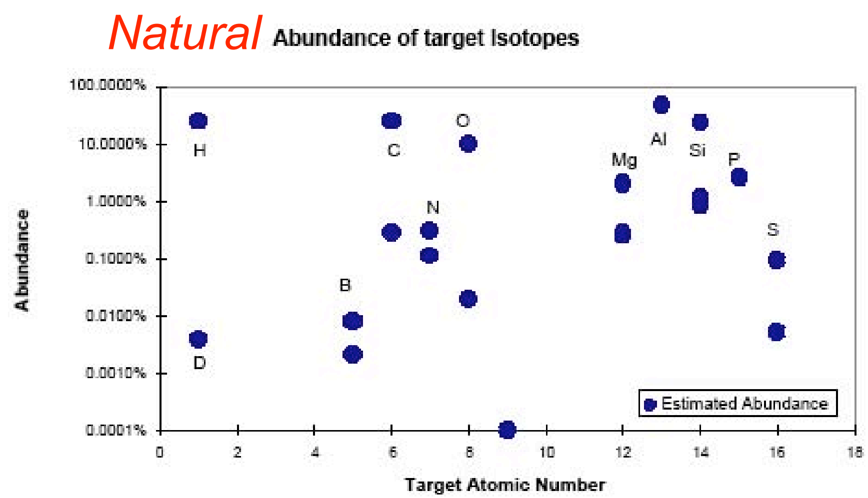
Si wafer with 50% resist (C) coverage.

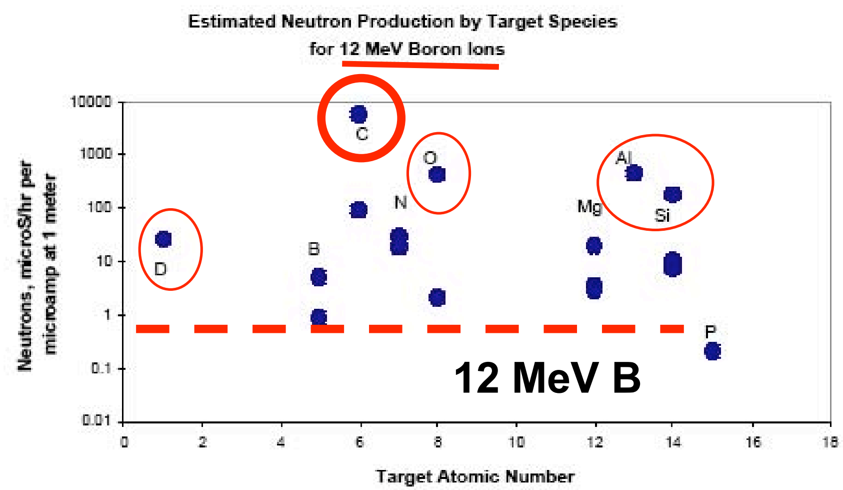
Operation Mode

50% beam on wafer.

*** C target material is the primary neutron generation concern.**

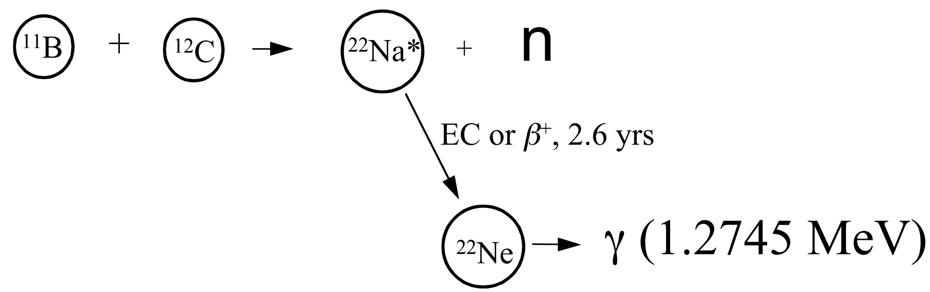
- **12 MeV B with 1 particle-uA at 1 m from the wafer produces neutrons at >1,000 uSv/hr.**
- **Safe limit is 0.6 uSv/hr.**

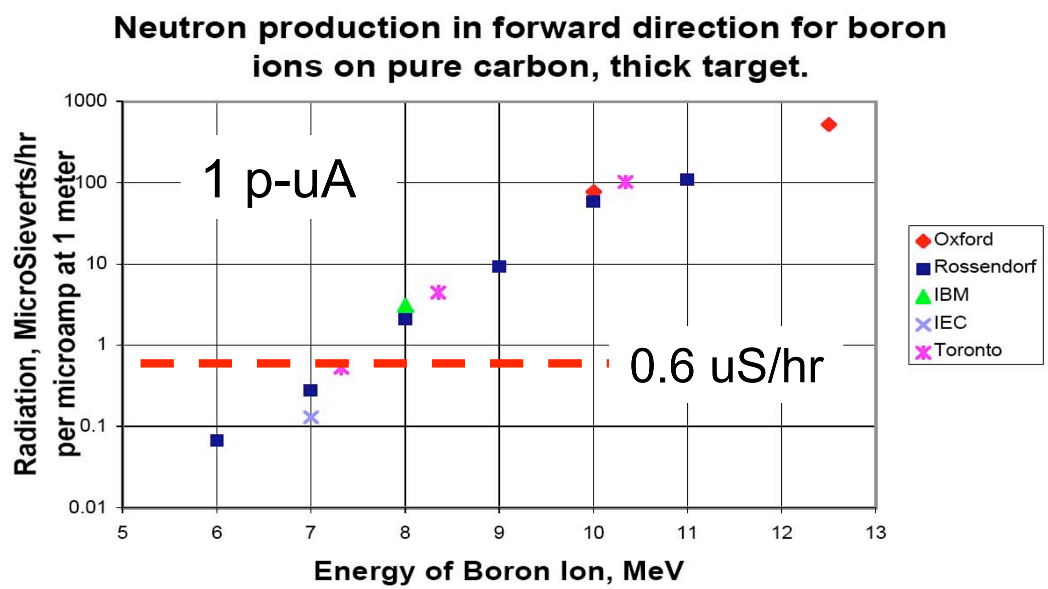




Neutrons: Boron on Carbon (Photoresist)

- Neutron generation measured in forward direction.
- Some data collected ^{12}C ions into solid B targets.
- Gy to Sv conversion = 10.
- Neutron generation rate drops ~1 decade per MeV below 12 MeV.



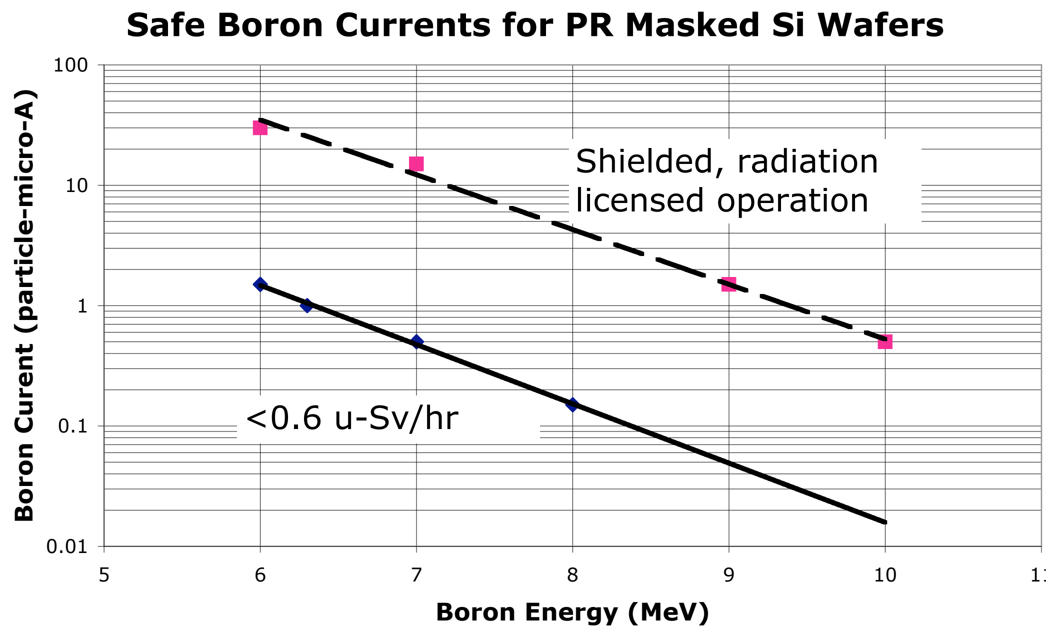


Operating Conditions

- Safe (<0.6 uSv/hr) operational beam currents drop ~1 decade/MeV at ~8 MeV B into 50% PR covered IC wafers.

- 0.1 p-uA of B is sufficient for ~20 300 mm wafers/hour at 1e11 B/cm^2.

- Higher currents (and throughputs) are possible with shielded, licensed operations.



2 MV Terminal Tandem Implanter

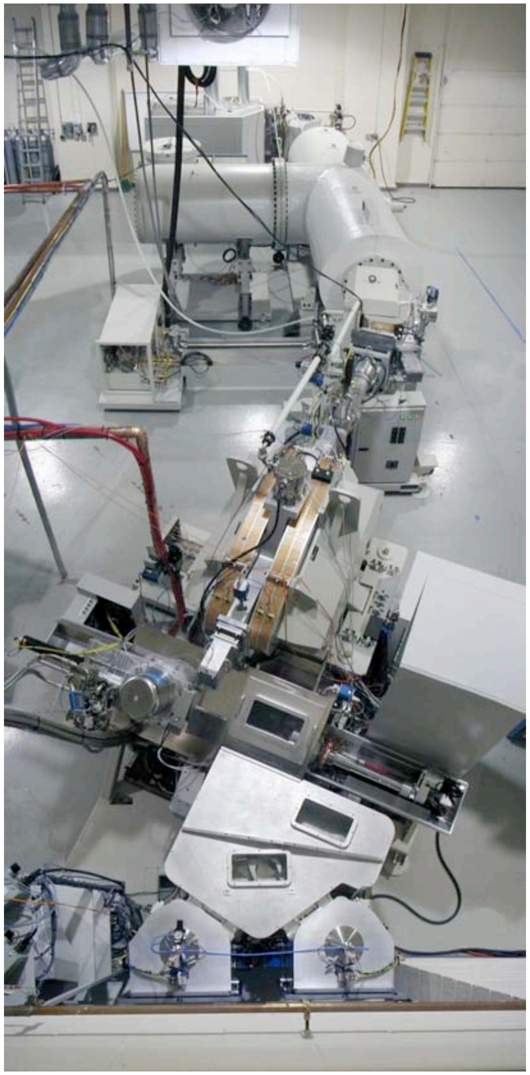
Safety Features for 8 MeV Operation:

- **Heavy metal beamstop target for 10 MeV B^{+4} ions.**

- **Ludlam neutron monitor linked to alert and shutdown systems. Sampling times adjusted to avoid false warnings at ~0.6 uS/hr.**

- **Interlocked wall enclosure at >1 m from wafers and beamstops.**

- **Injection magnet field monitored to prevent deuterium beam injection.**



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Large Molecular and Cluster Ions

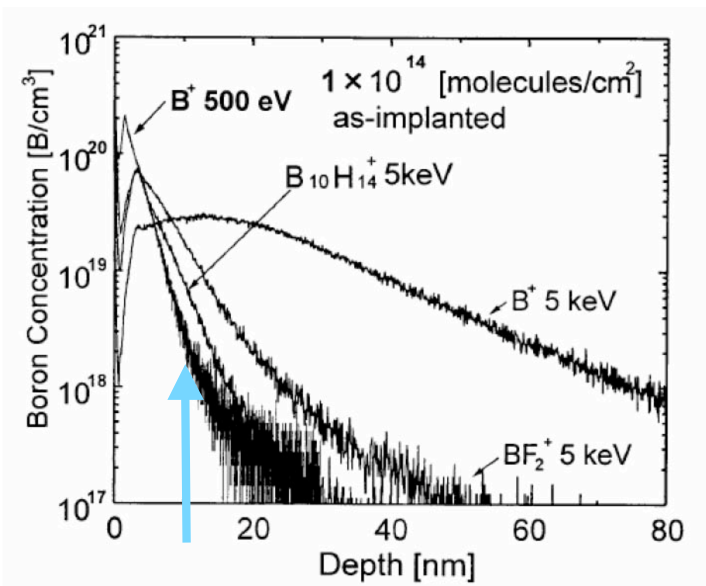
- 30 nm Lgate requires 15 to 10 nm SD Extension junction depth.
- Sub-keV B doping favors the use of large molecular or cluster ions.
- New ions are: $B_{10}H_{14}$, $C_2B_{10}H_{12}$, $B_{18}H_{22}$ and "massive" (~10k) clusters.

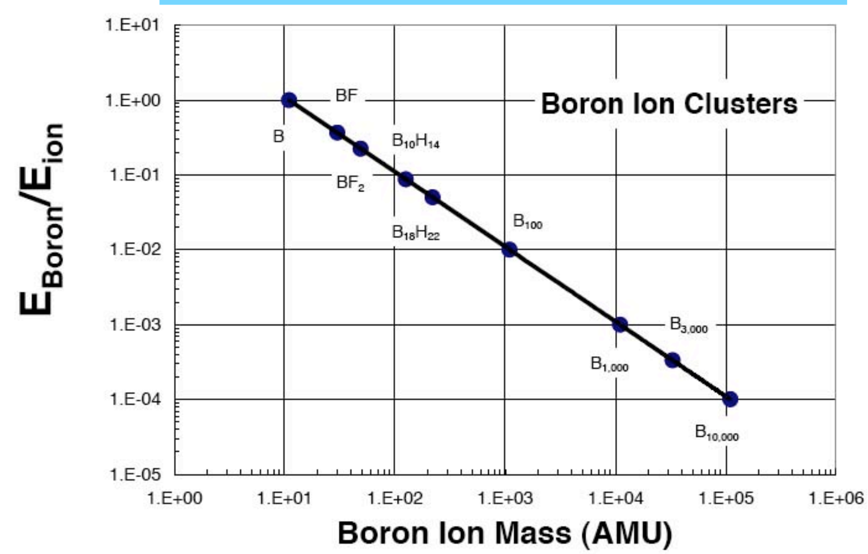
Energy per atom

$E_{atom} = (M_{atom}/M_{ion})*E_{ion}$

Charge = $(Q_{ion}/e)*(N_{ion}/N = 1)$

When N = 10^4 atoms,
***new stopping physics** applies.*





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Toxic Source Materials

- New molecular ions (→) are as toxic as the "old" materials.
- Handling and abatement procedures are not relaxed.
- Even Carborane breaks up into toxic components (Diborane, etc.) in the beamline and pumps.

Name	Chemistry	Room Temperature Form	PEL or TLV	Notes
			(ppm) or (mg/m^3)	PEL: Permissible Exposue Limit TLV: Threshold Limit Value
Arsenic	As	soild	0.2	possible carcinogenic
Arsine	AsH_3	gas	0.05	pyrophoric
Arsenictriflouride	AsF_3	gas	2.5	carcinogenic
Borontriflouride	BF_3	gas	1 and 3	reacts with moist air
→ **Diborane**	B_2H_6	gas	0.1	pyrophoric
→ **Decaborane**	$B_{10}H_{14}$	solid	0.05	explosive above 80 C in air
→ **Octadecaborane**	$B_{18}H_{22}$	solid	0.25	highly flamable
→ **Carborane**	$C_2B_{10}H_{12}$	solid	not listed	
Phosphorus	P	solid	not listed	
Phosphine	PH_3	gas	0.3	pyrophoric
Antimony	Sb	solid	0.5	carcinogenic
Silane	SiH_4	gas	0.5	pyrophoric
Germane	GeH_3	gas	0.2 and 0.6	pyrophoric

Safety for Ion Implantation

- Ion implantation for fabrication of materials (SOI wafers) & IC devices is a robust, global business.
- Ion implantation equipment operates with significant risks for high-voltages & currents, toxic materials, high-vacuum, high mechanical energy, & ionizing radiation.
- Safe operations is a key factor in the design, fabrication, installation, operation, maintenance & shut-down of implanters.
- New source materials, new system designs & new operating regimes continually challenge the safety needs of the industry.
- Safety training of engineers, operators and maintenance in new environments (China, India, etc.) is particularly challenging.

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