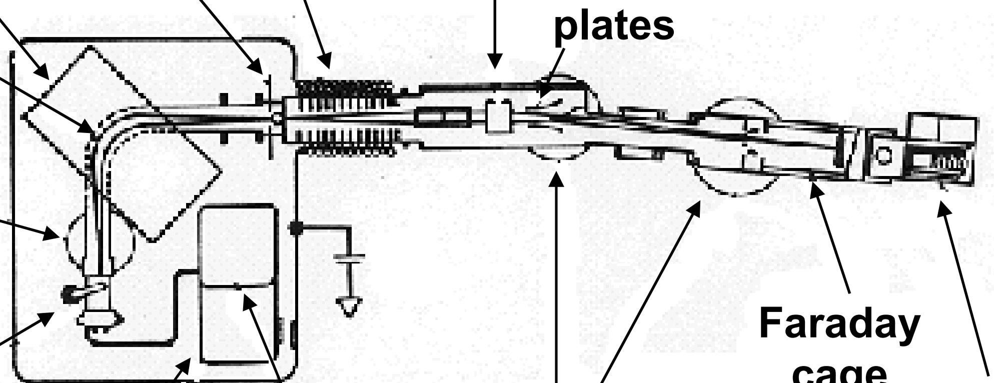
Ion Implantation

- alternative to diffusion for the introduction of dopants
- essentially a “physical” process, rather than “chemical”
- advantages:
  - mass separation allows wide varies of dopants
  - dose control:
    - diffusion 5 - 10%
    - implantation:
      - 10^{11} - 10^{17} ions / cm^2 ± 1 %
      - 10^{14} - 10^{21} ions / cm^3
  - low temperature
  - tailored doping profiles

Ion Implantation

- high voltage particle accelerator
  - electrostatic and mechanical scanning
    - dose uniformity critically dependent on scan uniformity
  - “dose” monitored by measuring current flowing through wafer

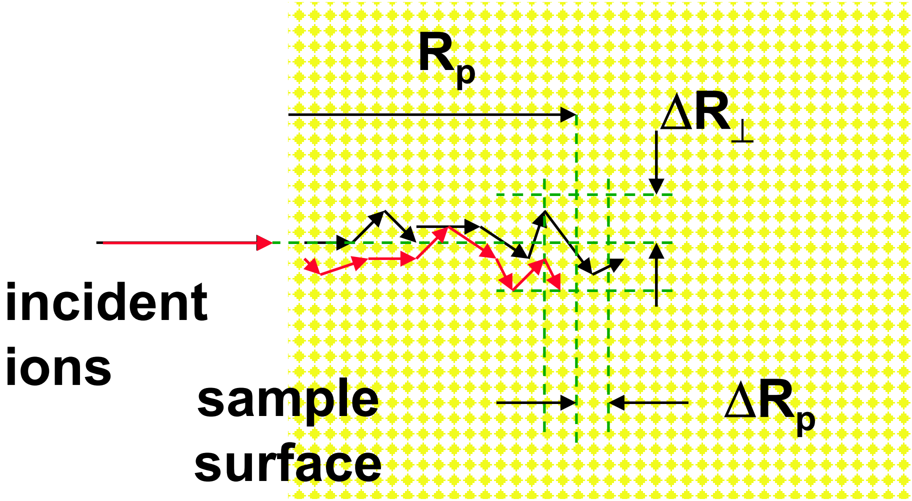


from: Sze, VLSI Technology, 2nd edition, p. 348.

Energy loss and ion stopping

- **Note that actual stopping is statistical in nature**

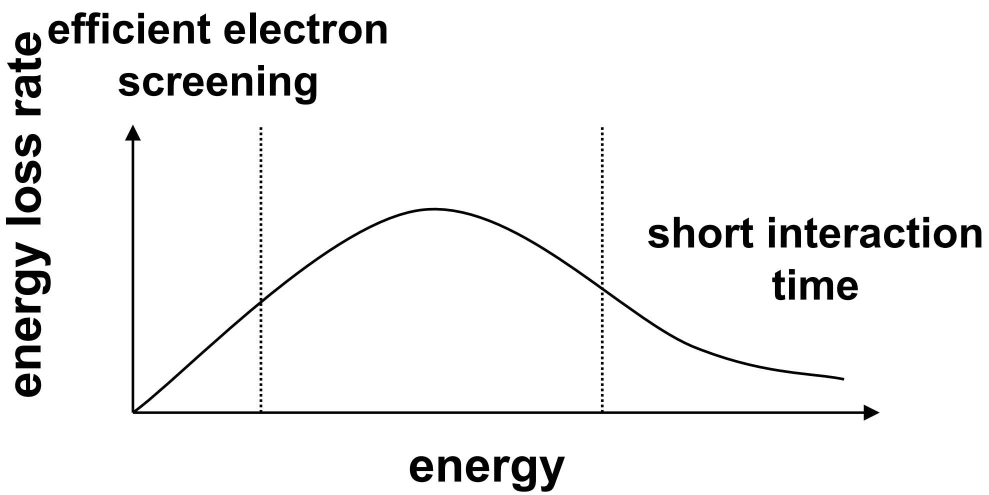
$$R = \int_0^E \frac{dE}{\left| dE/dx \right|}$$



- **where**
  - **dE/dx is the energy loss rate**
  - **R_p = projected range**
  - **ΔR_p = straggle**
  - **$\Delta R_\perp$ = lateral straggle**

Nuclear Stopping: $(dE/dx)_n$

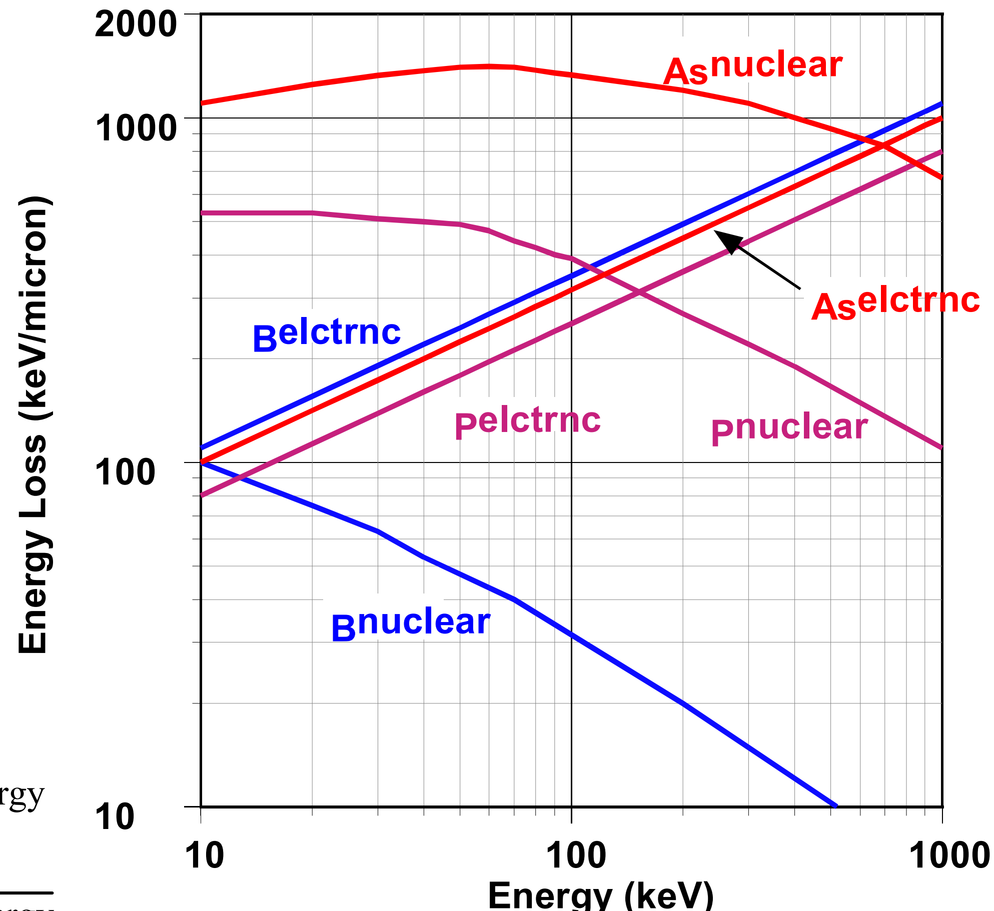
- "billiard ball" collisions
  - can use classical mechanics to describe energy exchange between incident ion and target particle
- must consider
  - Coulombic interaction between + charged ion and + nuclei in target
  - charge screening of target nuclei by their electron charge clouds
  - damage due to displaced target atoms



Electronic Stopping

- energy lost to electronic excitation of target atoms
  - similar to stopping in a viscous medium, is ∝ ion velocity (√E)
- total stopping power
  - very roughly CONSTANT vs energy if nuclear dominates
  - ∝ √E if electronic stopping dominates
- to "lowest order" the range is approximately

$$R = \int_0^E \frac{dE}{|dE/dx|} \approx \begin{cases} \text{nuclear}: \int_0^E \frac{dE}{\text{constant}} & \propto \text{energy} \\ \text{electronic}: \int_0^E \frac{dE}{\sqrt{E}} & \propto \sqrt{\text{energy}} \end{cases}$$



Implant profiles

- to lowest order implant profile is approximately gaussian

$$N(x) = \frac{Q_o}{\sqrt{2\pi}\,\Delta R_p} \mathbf{exp}\left(-\frac{1}{2}\left[\frac{x - R_p}{\Delta R_p}\right]^2 \right)$$

$$R = \int_0^E \frac{dE}{|dE/dx|} \approx \begin{cases} \text{nuclear}: \int_0^E \frac{dE}{\text{constant}} & \propto \text{energy} \\ \text{electronic}: \int_0^E \frac{dE}{\sqrt{E}} & \propto \sqrt{\text{energy}} \end{cases}$$

$$\Delta R_p \approx \frac{2}{3} \cdot R_p \cdot \left[\frac{\sqrt{M_{ion} \cdot M_{target}}}{M_{ion} + M_{target}}\right], \text{ M in amu}$$

  - works well for moderate energies near the peak
  - essentially uses only first two moments of the distribution

$$m_i = \frac{1}{Q_o}\int_{-\infty}^{\infty} \left(x - R_p\right)^i \cdot N(x)\, dx$$

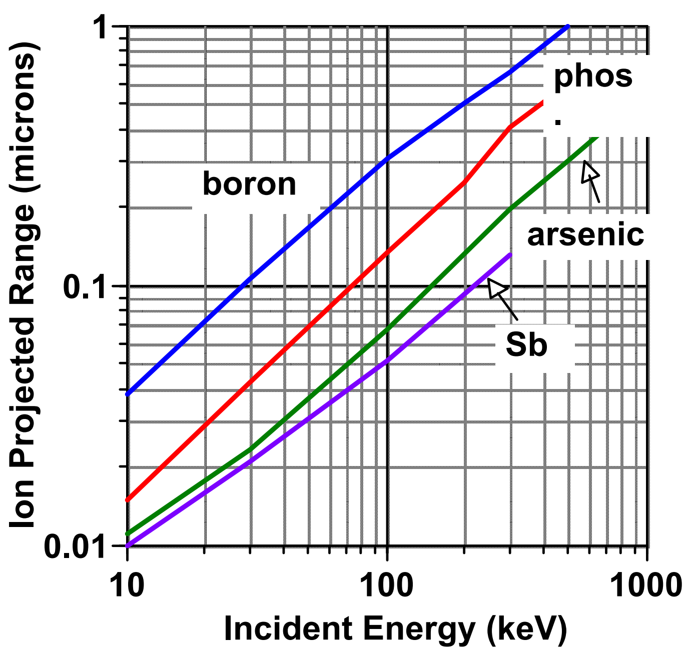
$$m_0 = \frac{1}{Q_o}\int_{-\infty}^{\infty} N(x)\, dx = 1$$

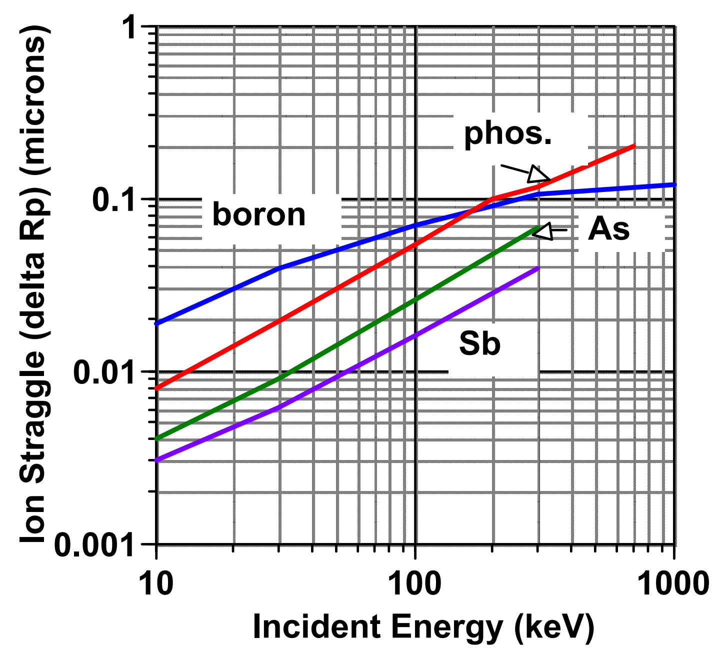
$$m_1 = \frac{1}{Q_o}\int_{-\infty}^{\infty} \left(x - R_p\right)^1 \cdot N(x)\, dx = R_p$$

$$m_2 = \frac{1}{Q_o}\int_{-\infty}^{\infty} \left(x - R_p\right)^2 \cdot N(x)\, dx = \left(\Delta R_p\right)^2$$

Summary of Projected Ranges in Silicon

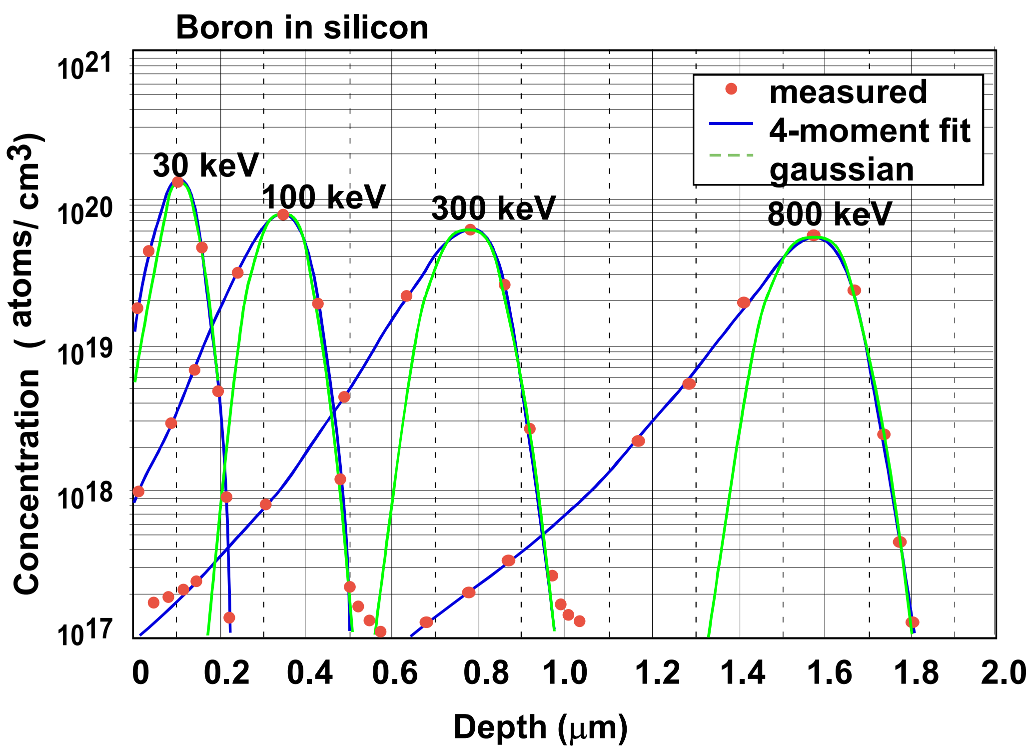
ion	Range (μm)				approx range/ MeV
	energy (keV)				
	10keV	30keV	100keV	300keV	
boron B^{11}	0.04	0.11	0.307	0.66	~3.1
phos. P^{31}	0.015	0.04	0.135	0.406	~1.1
arsenic As^{75}	0.011	0.023	0.068	0.19	~0.58





Pearson IV distribution

- four moments: R_p, ΔR_p, and
  - skewness of profile γ_1
    - $\gamma_1 < 0$ implant "heavy" to surface side of peak
      - light species
    - $\gamma_1 > 0$ implant "heavy" to deep side of peak
      - heavy species
  - kurtosis β
    - large kurtosis ⇨ flatter "top"



adapted from: Sze, VLSI Technology, 2nd edition, p. 335.

Ion stopping in other materials

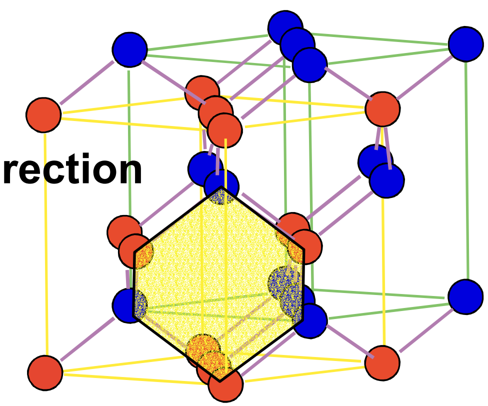
- for masking want “all” the ions to stop in the mask
  - oxide and photoresist

	thickness for 99.99% blocking		
energy:	50keV	100keV	500keV
ion / material			
B^{11} / photoresist	0.4μm	0.6μm	1.8μm
B^{11} / oxide	0.35μm	0.6μm	
P^{31} / photoresist	0.2μm	0.35μm	1.5μm
P^{31} / oxide	0.13μm	0.22μm	

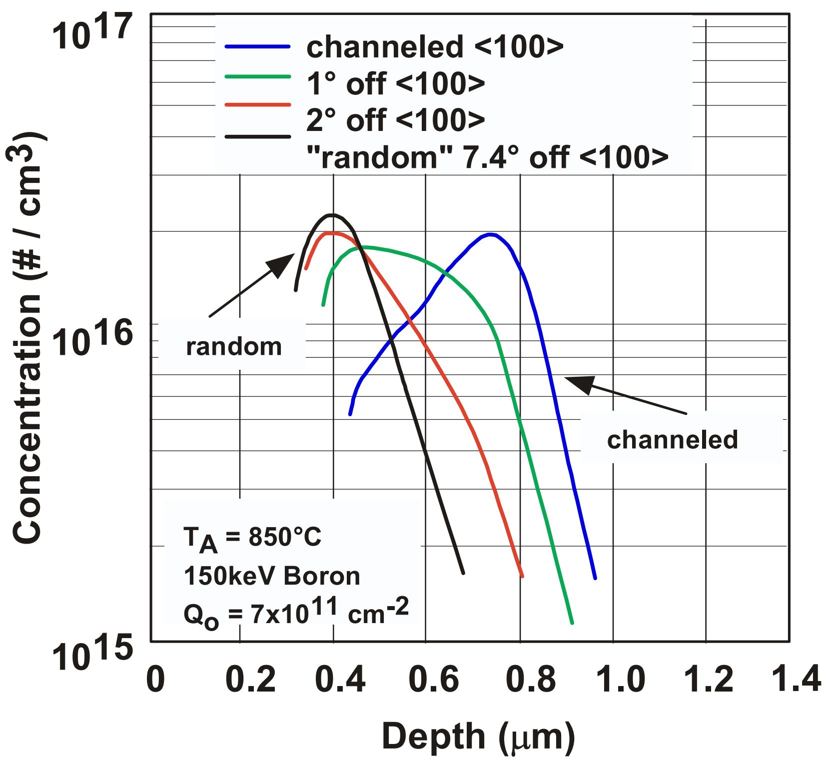
  - densities of oxide and resist are similar, so are stopping powers
  - do have to be careful about (unintentional) heating of mask material during implant

Ion channeling

- if ions align with a “channel” in a crystal the number of collisions drops dramatically



  – significant increase in penetration distance for channeled ions
  – very sensitive to direction
- many implants are done at an angle (~7˚)
  – shadowing at mask edges



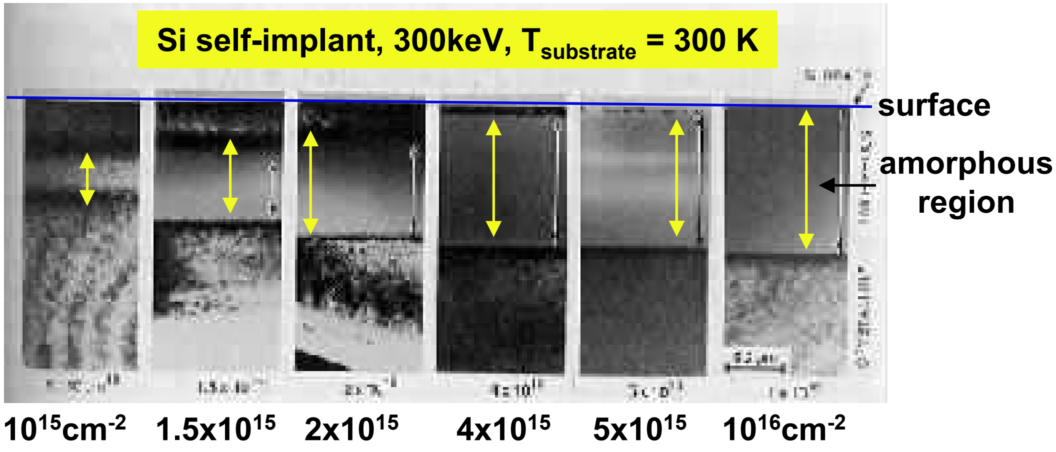
adapted from: Ghandhi, 1st edition, p. 237.

Disorder production during implantation

- first 10^{-13} sec:
  - ion comes to rest
- next 10^{-12} sec:
  - thermal equilibrium established
- next 10^{-9} sec:
  - non - stable crystal disorder relaxes via local diffusion
- very roughly, 10^3 - 10^4 lattice atoms displaced for <u>each</u> implanted ion.

Damage during ion implant

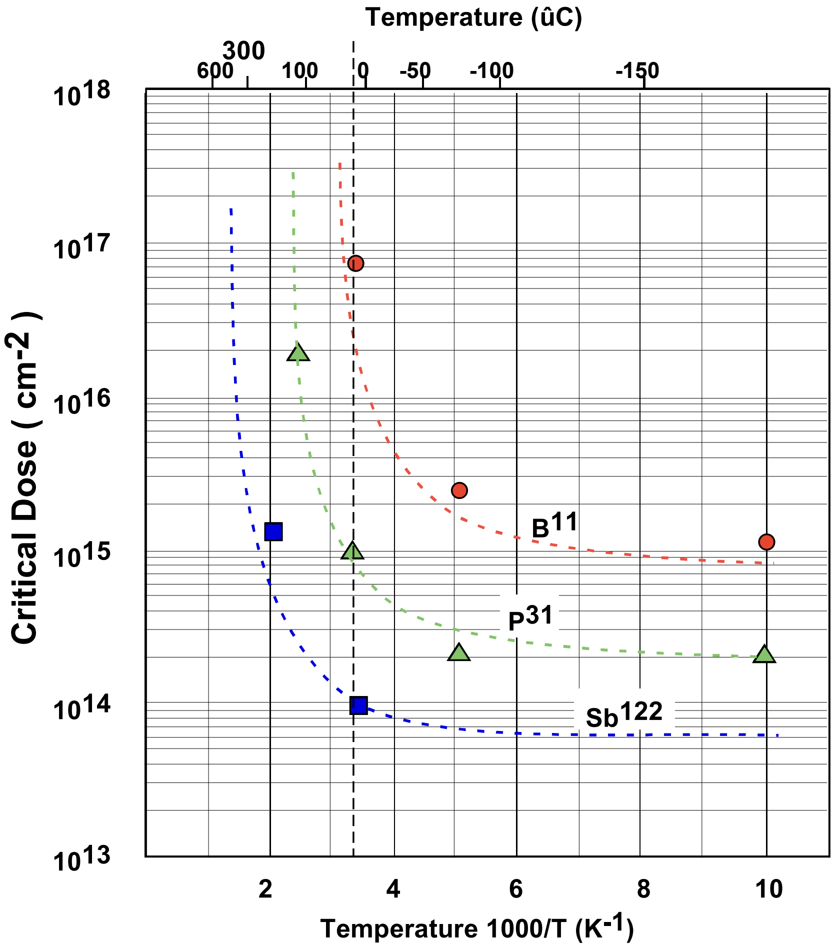
- light atom damage (B^{11})
  - initially mostly electronic stopping, followed by nuclear stopping, at low energies
    - generates buried damage peak
- heavy atoms (P^{31} or As^{75})
  - initially large amounts of nuclear stopping
    - generates broad peak with large surface damage
- typically damage peaks at about 0.75 R_p



adapted from: Sze, 2nd edition, p. 341.

Amorphization during implant

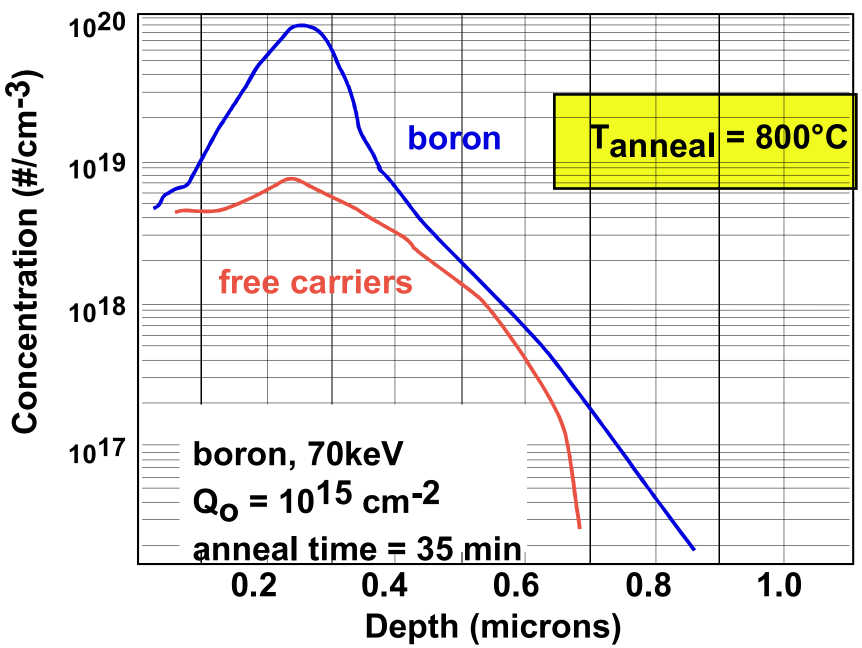
- damage can be so large that crystal order is completely destroyed in implanted layer
  - temperature, mass, & dose dependent
    - boron, ~30˚C: $Q_o \sim 10^{17}$ cm^{-2}
    - phosphorus, ~30˚C: $Q_o \sim 10^{15}$ cm^{-2}
    - antimony, ~30˚C: $Q_o \sim 10^{14}$ cm^{-2}

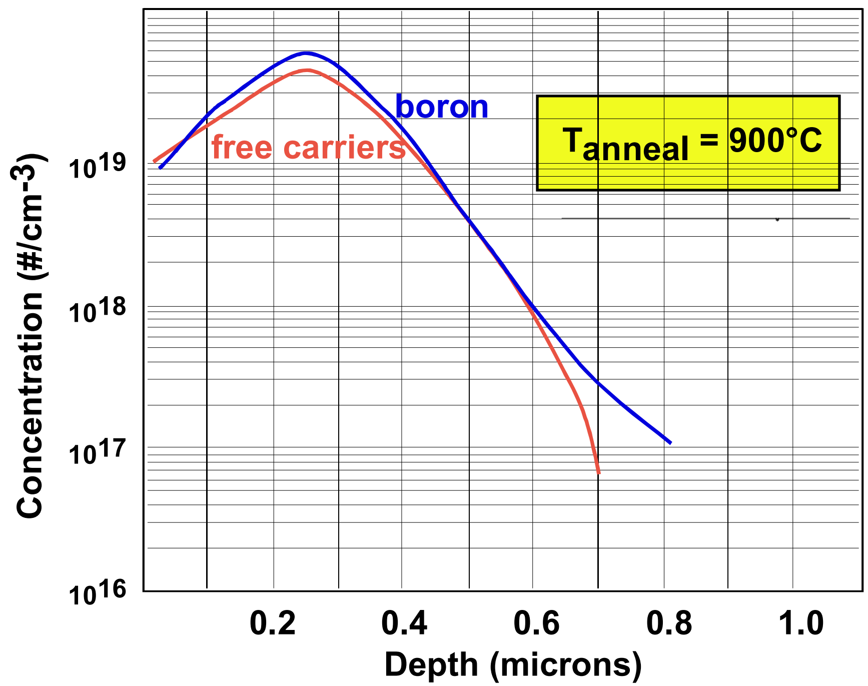


adapted from: Sze, 2nd edition, p. 343.

Implant activation: light atoms

- as-implanted samples have carrier concentration << implanted impurity concentration
- electrical activation requires annealing

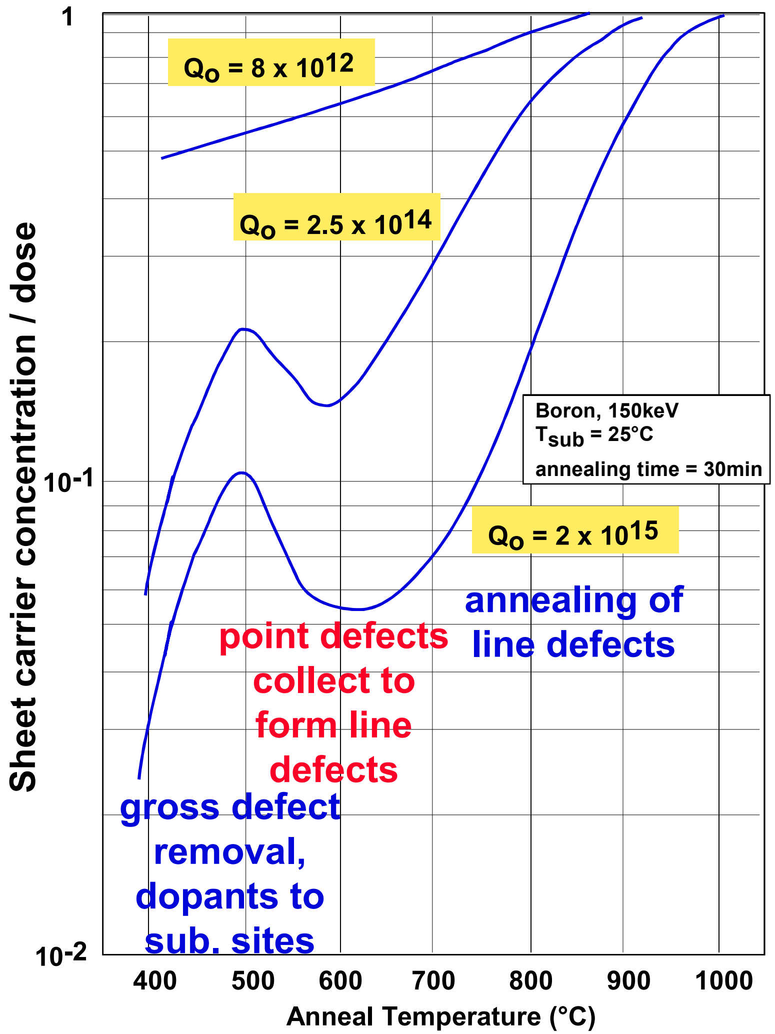




adapted from: Sze, 2nd edition, p. 357.

Annealing and defects: boron

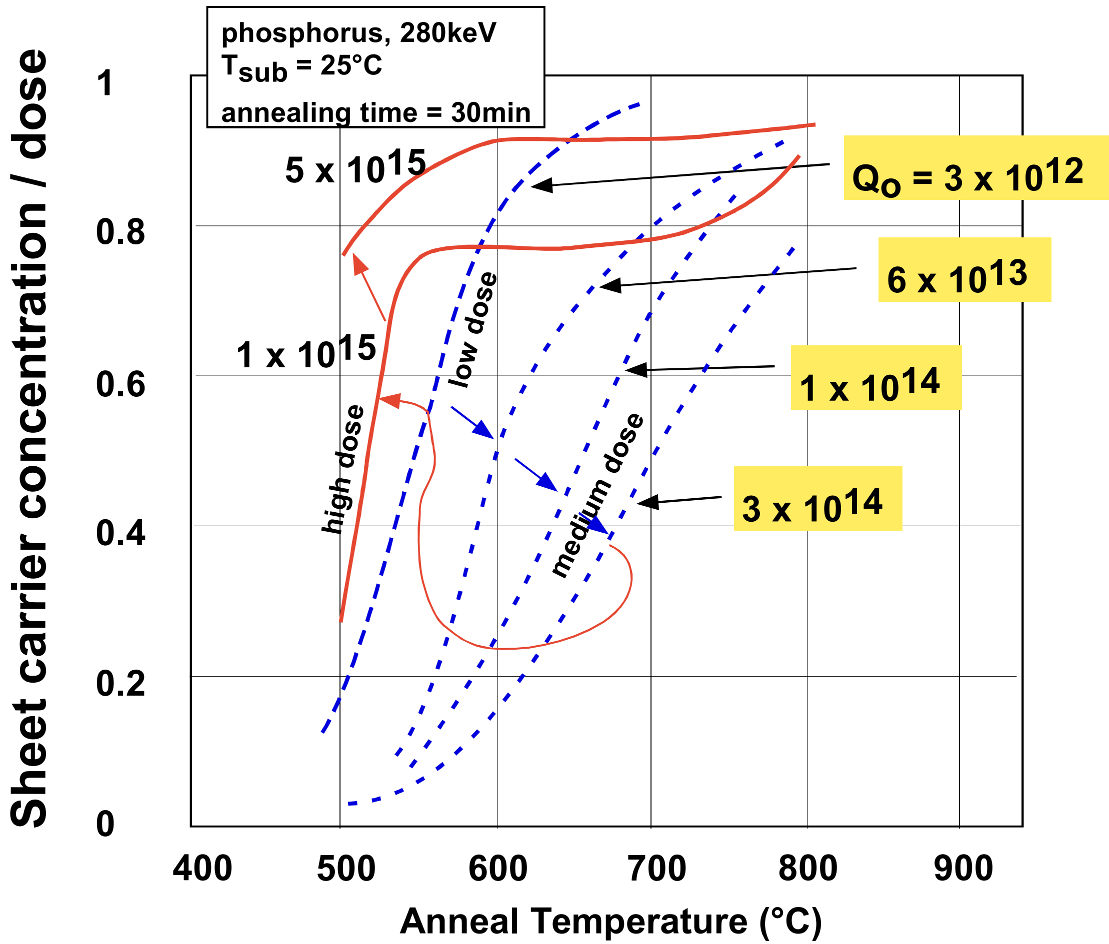
- initial effect: impurities onto substitutional sites
- mid-range temp, high dose: point defects “collect” into line defects
  - fairly stable, efficient carrier traps
- high temp, high dose: line defects annealing out
  - quite stable
  - need ~900-1000° C to remove completely



adapted from: Sze, 2nd edition, p. 358.

Implant activation: heavy atoms

- amorphization can strongly influence temperature dependence of activation / anneal
  - amorphous for phosphorus dose ~ 3×10^{14} cm^{-2}
  - solid phase epitaxial re-growth occurs at T ~ 600˚C



adapted from: Sze, 2nd edition, p. 359.

Diffusion of ion implants

- **implant profile:** $$N(x) = \frac{Q_o^{implant}}{\sqrt{2\pi}\Delta R_p} \exp\left(-\frac{1}{2}\left[\frac{x-R_p}{\Delta R_p}\right]^2\right)$$
- **recall limited source diffusion profile**

$$N(x,t) = \frac{Q_o^{(\text{half gaussian})}}{\sqrt{\pi D t}} \exp\left(-\left[\frac{x}{2\sqrt{Dt}}\right]^2\right)$$

$$= \frac{Q_o^{implant}/2}{\sqrt{\pi D t}} \exp\left(-\left[\frac{x}{2\sqrt{Dt}}\right]^2\right)$$

  - **so $\sqrt{Dt}$ is analogous to ΔR_p**
- **to include effects of diffusion add the two contributions:**

$$N(x) = \frac{Q_o}{\sqrt{2\pi}\sqrt{(\Delta R_p)^2 + 2Dt}} \exp\left(-\frac{1}{2}\left[\frac{(x-R_p)^2}{(\Delta R_p)^2 + 2Dt}\right]\right)$$

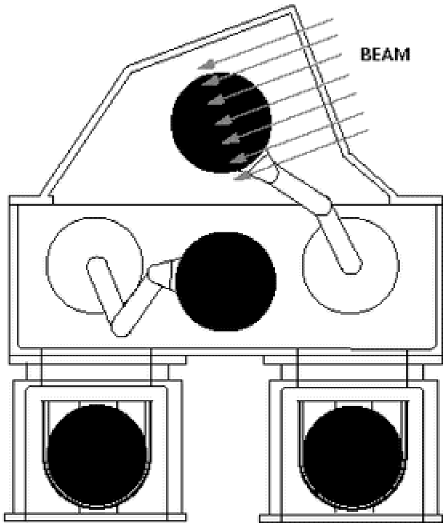
Diffusion of ion implants

- how big are the Dt products?
  - temps: 600˚ C ⇨ 1000˚ C
  - D's: 9×10^{-18} cm²/sec ⇨ 2.5×10^{-11} cm²/sec
  - t's : ~ 1000 sec (~17 min)
  - Diffusion lengths ~ 0.3 Å ⇨ ~ 500Å
- Rapid thermal annealing
  - to reduce diffusion, must reduce Dt products
    - critical parameter in anneal is temperature, not time
    - rapid heating requires high power density, "low" thermal mass

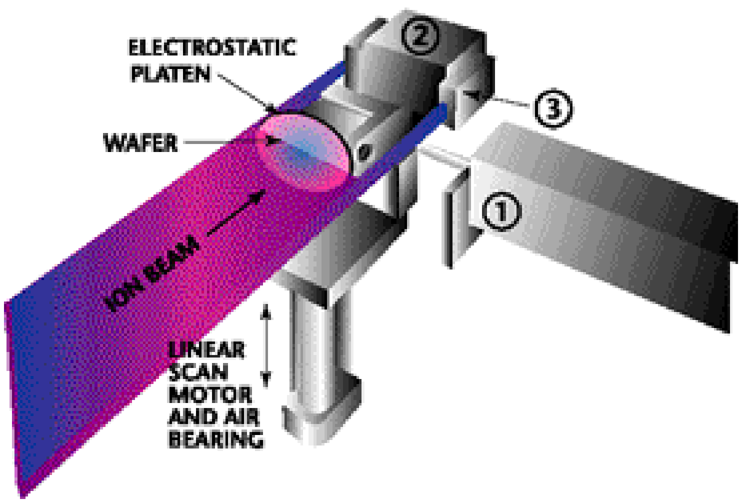
Ion implant systems

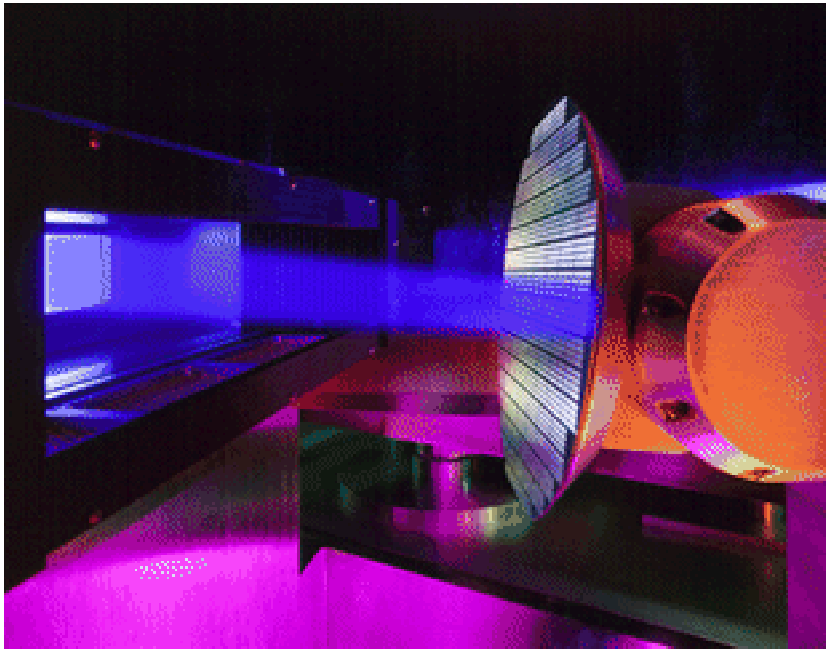
- sources
  - usually gas source: BF_3, BCl_3, PH_3, AsH_3, $SiCl_4$
    - to keep boron shallow ionize BF_3 without disassociation of molecule
  - ionization sources
    - arc discharge
    - oven, hot filament
- machine classifications
  - medium current machines (threshold adjusts, $Q_o < 10^{14}$ cm^{-2})
    - ~2 mA, ~200 kV
    - electrically scanned, ± 2° incident angle variation
    - ~10 sec to implant, few sec wafer handling time
  - high current machines (source/drains, $Q_o > 10^{14}$ cm^{-2})
    - > 5 mA
    - mechanically scanned
    - can produce 10^{15} dose over 150mm wafer in ~6 sec to implant
    - wafer heating potential problem

Ion Implanter



- high current implanter example: Varian SHC-80



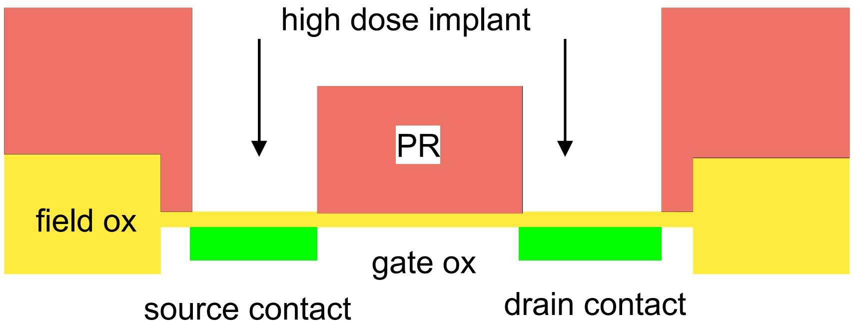


images from http://www.varian.com/seb/shc80/shc80-1.html

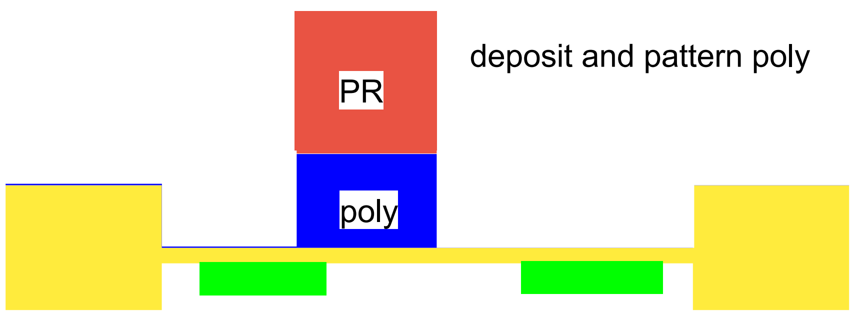
Applications of Ion Implantation

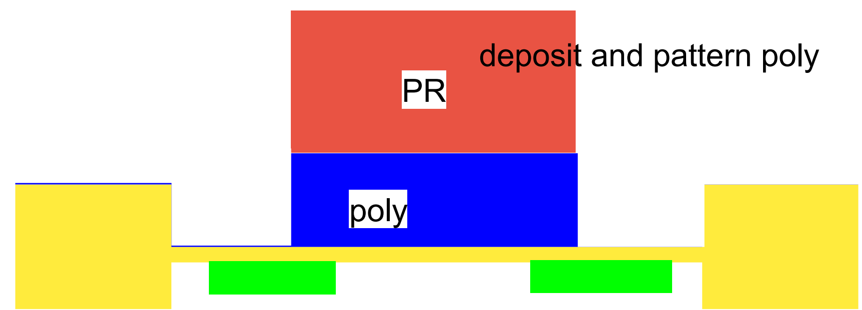
- high precision, high resistance resistor fabrication
  - diffusion ≤ 180 Ω /square ± 10%
  - implantation ≤ 4 kΩ / square ± 1%
- MOS applications
  - p-well formation in CMOS: precise,low dose control ~ 1- 5 x 10^{12} cm^{-2}
  - threshold voltage adjustment:
    - not possible to control threshold voltage with sufficient accuracy via oxidation process control
    - critical post-gate growth adjustment possible by controlled dose implant:
    - ΔV_t ~ q•dose / (oxide capacitance per unit area)
  - “self-aligned” MOSFET fabrication

Tailored MOSFET source/drain doping



- alignment between source/drain doping and gate is critical



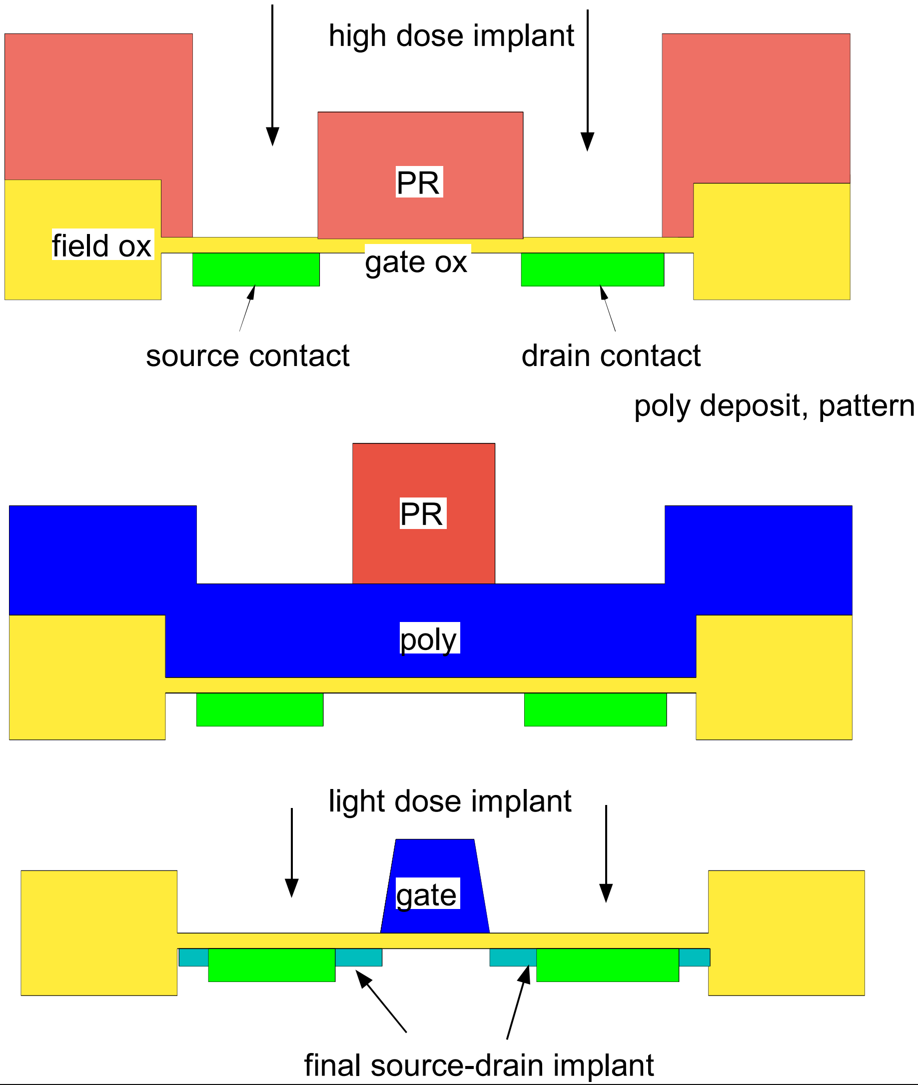


no overlap: can't "complete" channel

too much overlap, too much gate/source, gate/drain capacitance

- what about using the gate itself as mask?

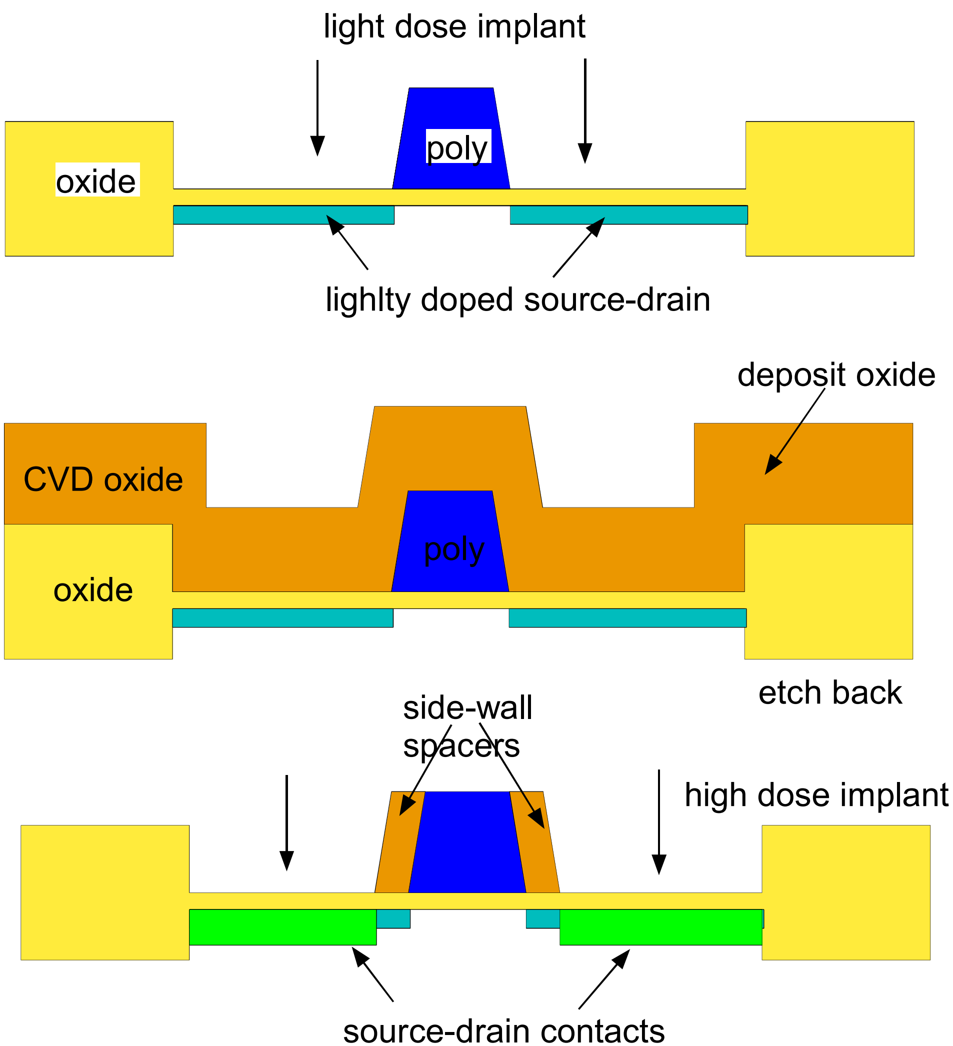
Tailored MOSFET source/drain doping



- alignment between source/drain doping and gate is critical
  - if no overlap, can't "complete" channel
  - if too much overlap, have too much gate/source, gate/drain capacitance
- use gate itself as mask!
- lightly-doped drain (LDD) device

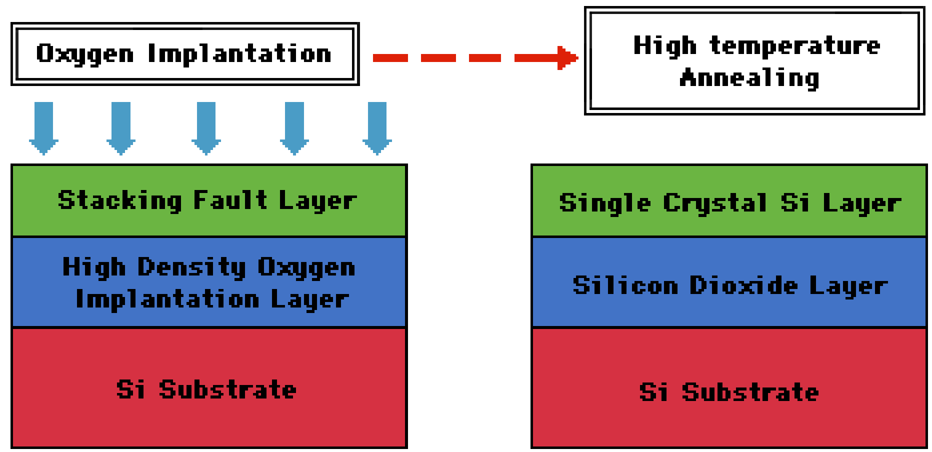
Self-aligned LDD process

- **"fully" self-aligned**
  - **"side-wall spacers" can be formed many ways**
    - **actual oxidation of poly gate**
    - **cvd deposition / etch back**



Silicon “on insulator”: Separation by IMplanted OXygen (SIMOX)

- high dose / energy oxygen implant
  - dose ~ mid 10^{17} to 10^{18} cm^{-2}
  - energy ~ several hundred keV
  - after anneal forms buried layer of SiO_2



High Dose	Implantation Voltage	: ~200KeV	Annealing temperature	:	>1300 ℃
	Dose	: ~2×10^{18}/cm^2	Annealing time	:	~8hours
	Substrate Temperature	: ~650℃	Annealing atmosphere	:	Ar+O_2
Law Dose	Implantation Voltage	: ~200KeV			
	Dose	: ~4×10^{17}/cm^2			

http://www.egg.or.jp/MSIL/english/semicon/simox-e.html

Layer characterization

- need to characterize the layers produced thus far
  - oxides
    - thickness
    - dielectric constant / index of refraction
  - doped layers
    - junction depth
    - dopant concentrations
    - electrical resistance / carrier concentration