电子与电气工程系
Department of Electrical and Electronic Engineering

Ion Implantation

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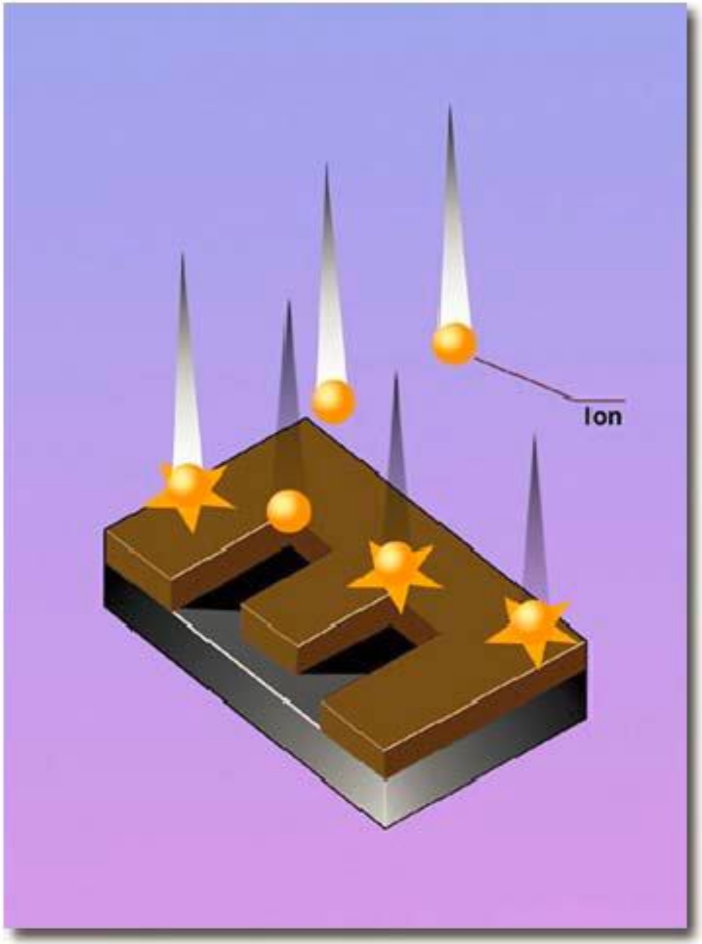
Outline

- Introduction
- Energy Loss
- Ion Distribution Profiles
- Channelling
- Damage
- Annealing

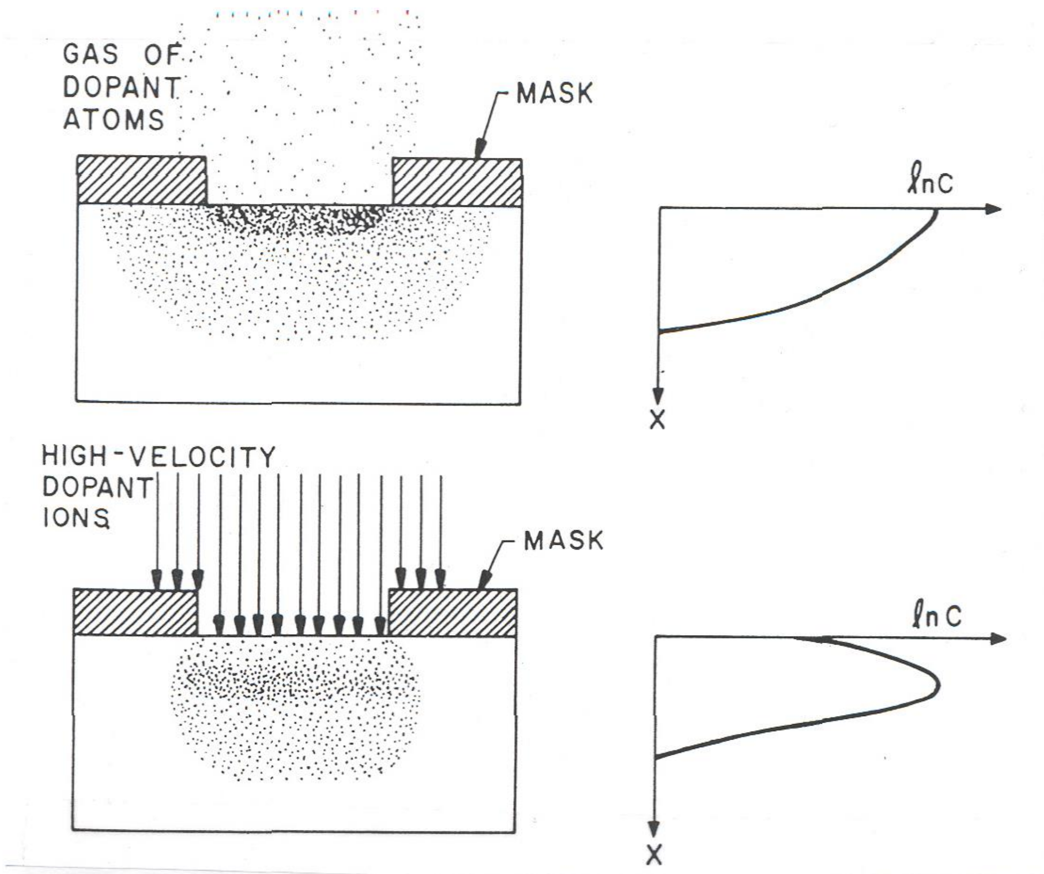


Ion Implantation

Dopants in Semiconductors

Diffusion

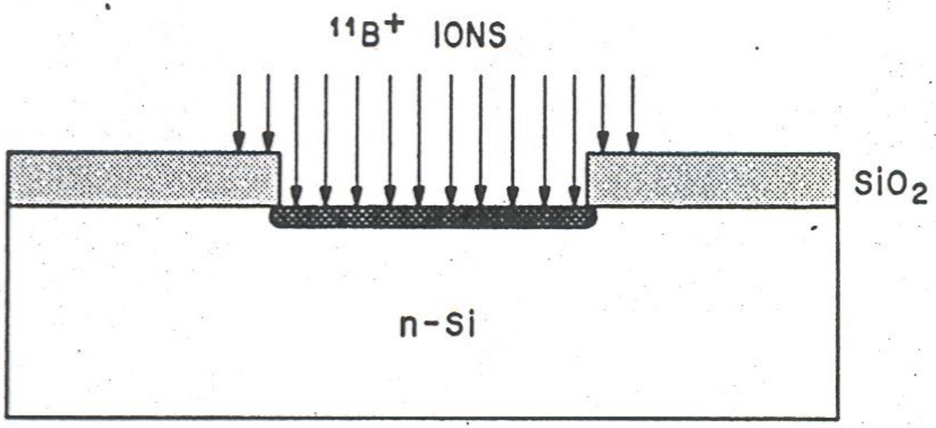
Implantation



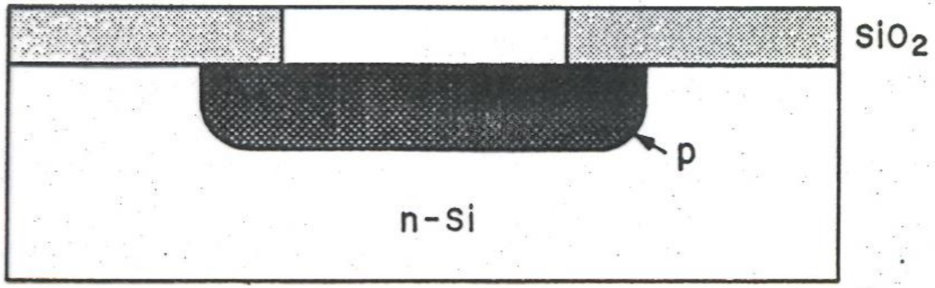
- Alternative to thermal diffusion
- Small penetration depth
- Maximum concentration peak beneath surface
- # injected ions – proportional to current and time

Example of Pre-Deposition

Pre-Dep



After Drive-In



"Things of Interest"

- Which atoms? (Selection of ions)
- How many? (Beam current, implant time)
- How deep? (Acc. voltage → energy)
- Which precision? (Depth spread – Straggle)
- Lattice position? (Substitutional/Interstitial)
- Implant induced defects (Restoring lattice - annealing)

Terminology of Ion Implantation

Applications

1. Dopant source – replace pre-deposition

2. Creation of getter damage

3. Change composition
   - e.g. Ge in Si to form $Si_{1-x}Ge_x$

4. Introduce <u>known</u> amounts of some atom for physical studies (e.g. standards for SIMS)
   - e.g. Au in Si

5. Introduce buried defect layer
   - e.g. "Smart-Cut" technique for SOI fabrication: formation of microcavities by H-implant

Ion Implantation - Advantages

- Low temperature process
- Excellent dose control
- Even very small doses are controllable
- Buried profile – e.g. through-oxide implants
- Extremely shallow profiles possible
- Any material usable as a mask
- Any ion in any substrate
- Ion concentrations > C_{sol} possible
- Purity of source materials less important

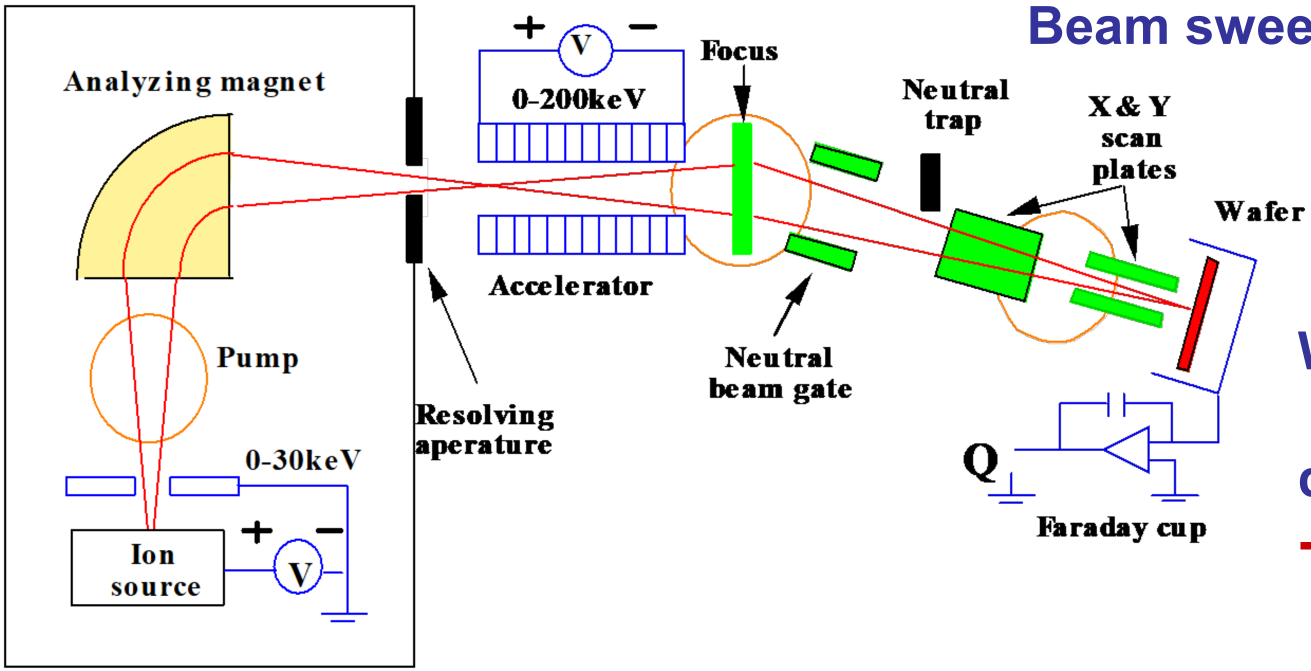
Equipment

Pre-acceleration & mass separation

$$B = \frac{1}{r}\sqrt{\frac{2mU}{q}}$$

Acceleration & beam transport
- typical 30 – 300 keV

Beam sweep & focus



Wafer handling
&
dose monitoring
- dose / temp. control

$$Q = \frac{1}{A}\int \frac{I}{q}\,dt$$

Ion source: Convert molecules into ions

Energy Loss

Energetic ions incident on a target lose energy by collisions with target particles:

1. **Inelastic collisions with bound electrons**
   Ionization, Excitation
2. **Elastic collisions with bound or free electrons**
3. **Elastic collisions with nuclei**
   Partial transfer of kinetic energy
4. **Inelastic collisions with nuclei**
   Bremsstrahlung, nuclear excitation or reaction

Ion Stopping

Elastic collisions with nuclei:

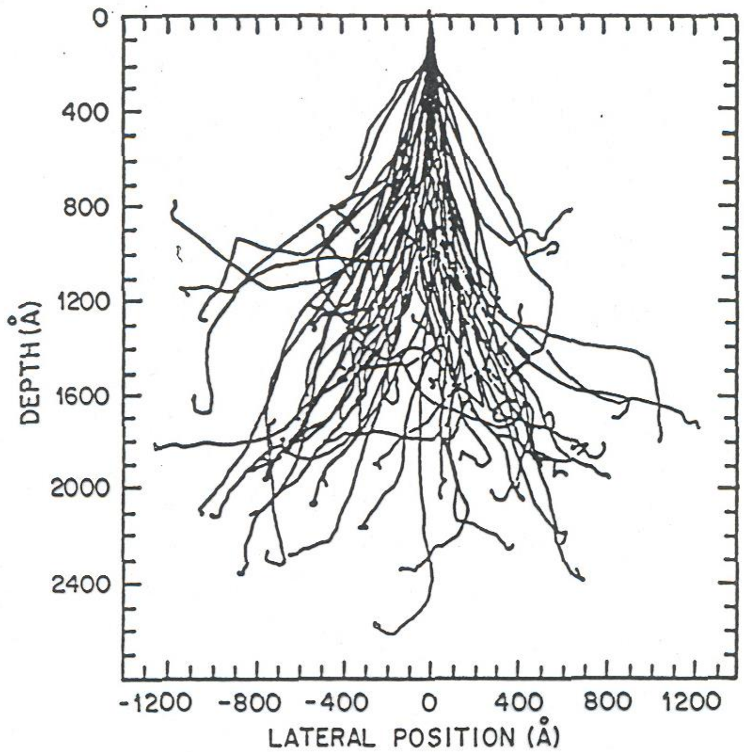
$$S_n(E) = \left(\frac{dE}{dx}\right)_n$$

Inelastic collisions with electrons:

$$S_e(E) = \left(\frac{dE}{dx}\right)_e$$

Energy loss: $$\frac{dE}{dx} = S_n(E) + S_e(E)$$

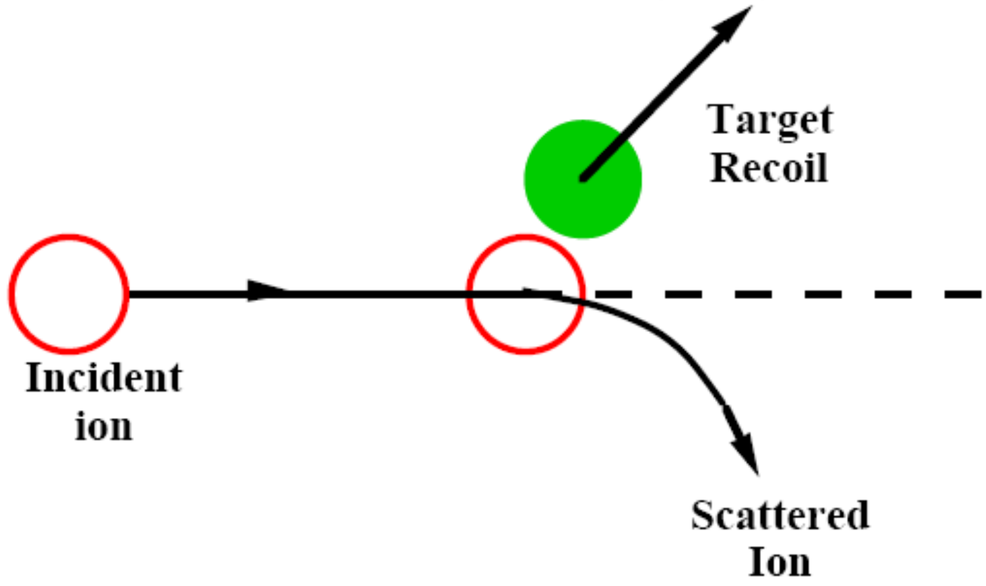
Range (before rest): $$R = \int_0^R dx = \int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)}$$



Nuclear Stopping Process

Screened Coulomb scattering potential

$$V(r) = \frac{q^2 Z_1 Z_2}{4\pi\varepsilon r}\exp\left(-\frac{r}{a}\right)$$



Energy transfer and scattering angle calculated by integrating potential along ion-trajectory (function of impact parameter)

Nuclear Stopping Process

Visualization: Hard spheres

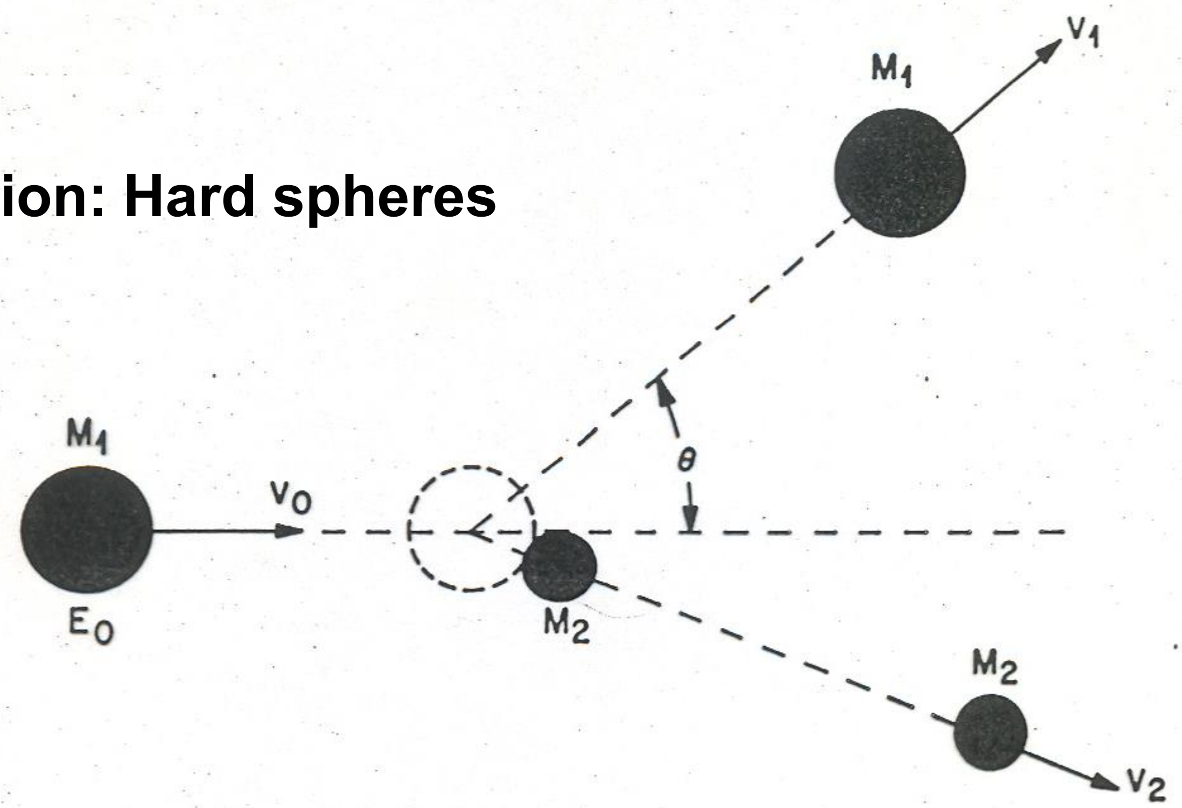


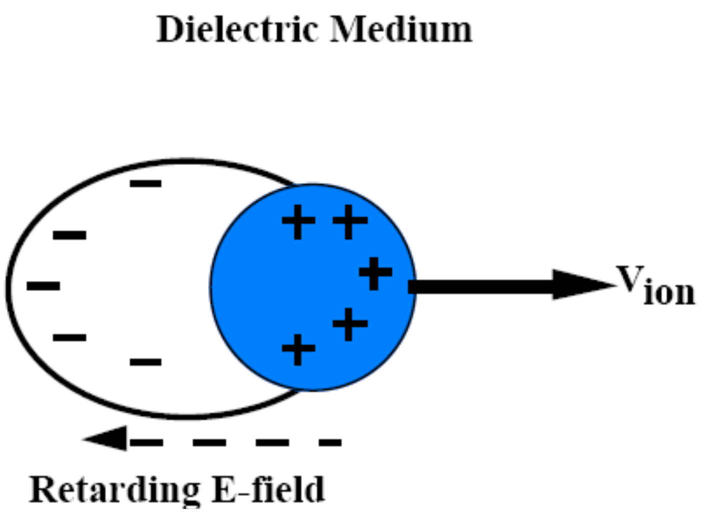
Fig. 20 Collision of hard spheres.

$$E_{2\max} = \frac{1}{2} M_2 v_2^2 = \frac{4 M_1 M_2}{(M_1 + M_2)^2} E_0$$

Electronic Stopping

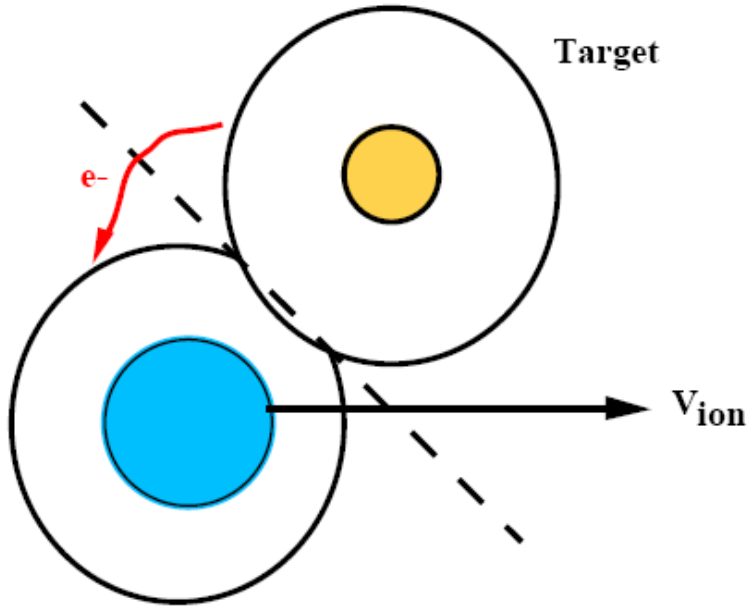
Non-local:

Drag force caused by charged ion in "sea" of electrons
- resembles transport in viscous medium



Local:

Momentum transfer by collisions with electrons around atoms



Both contributions scale with ion velocity

Energy Losses - Summarized

Total energy loss per unit distance:

$$\frac{dE}{dx} = S_n(E) + S_e(E)$$

Comprises of:

Electronic Stopping Power:

$$S_e(E) = \left(\frac{dE}{dx}\right)_e$$

Depend on target and energy

$$S_e(E) \propto K\sqrt{E}$$

Nuclear Stopping Power:

$$S_n(E) = \left(\frac{dE}{dx}\right)_n$$

Depend on target, projectile, and energy

Range:

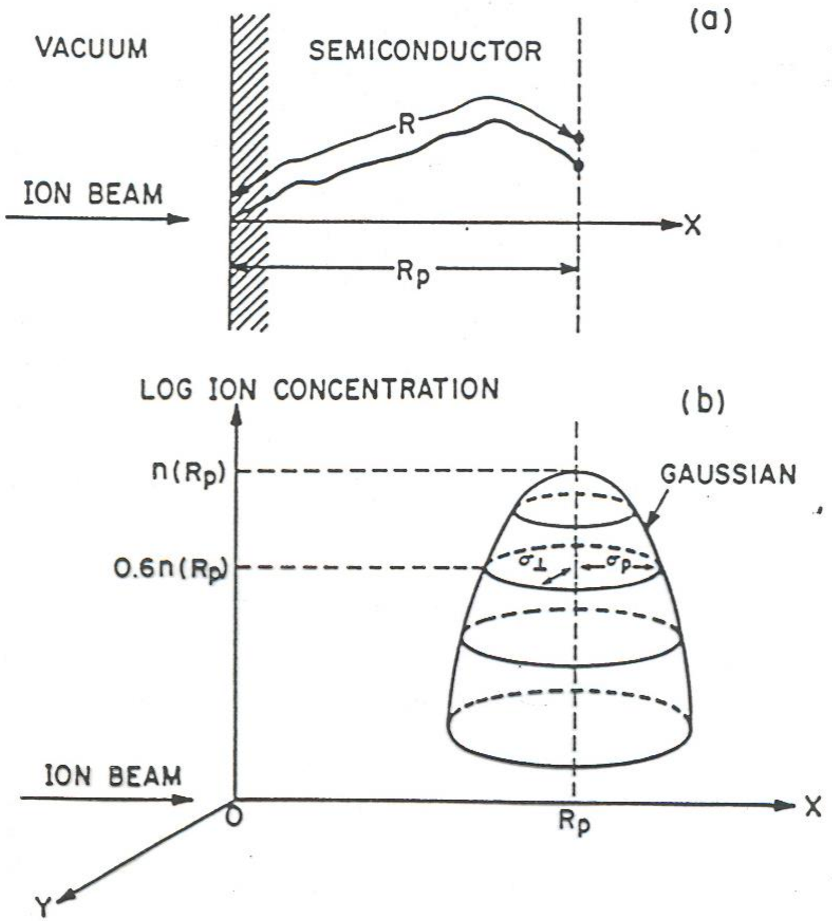
$$R = \int_0^R dx = \int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)}$$

High energy
Light projectiles } **Electronic stopping**

Low energy
Heavy projectiles } **Nuclear stopping**

$\longrightarrow$ ***Damage***

Ion Distribution - Profiles



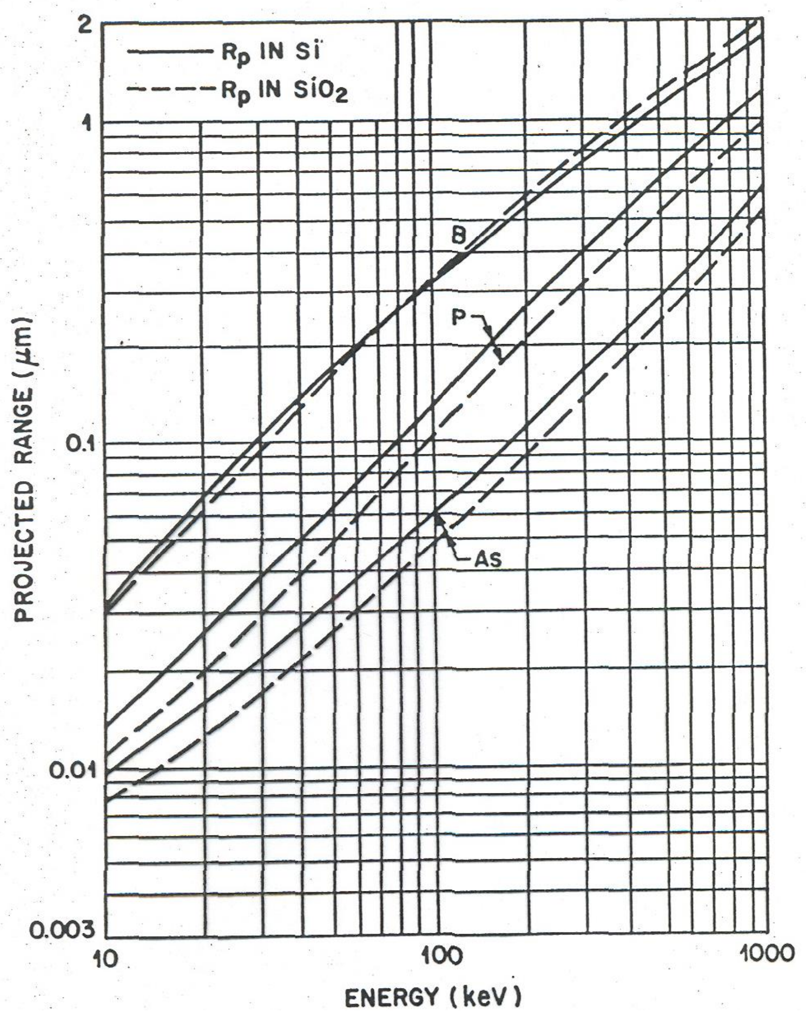
Gaussian Distribution Function

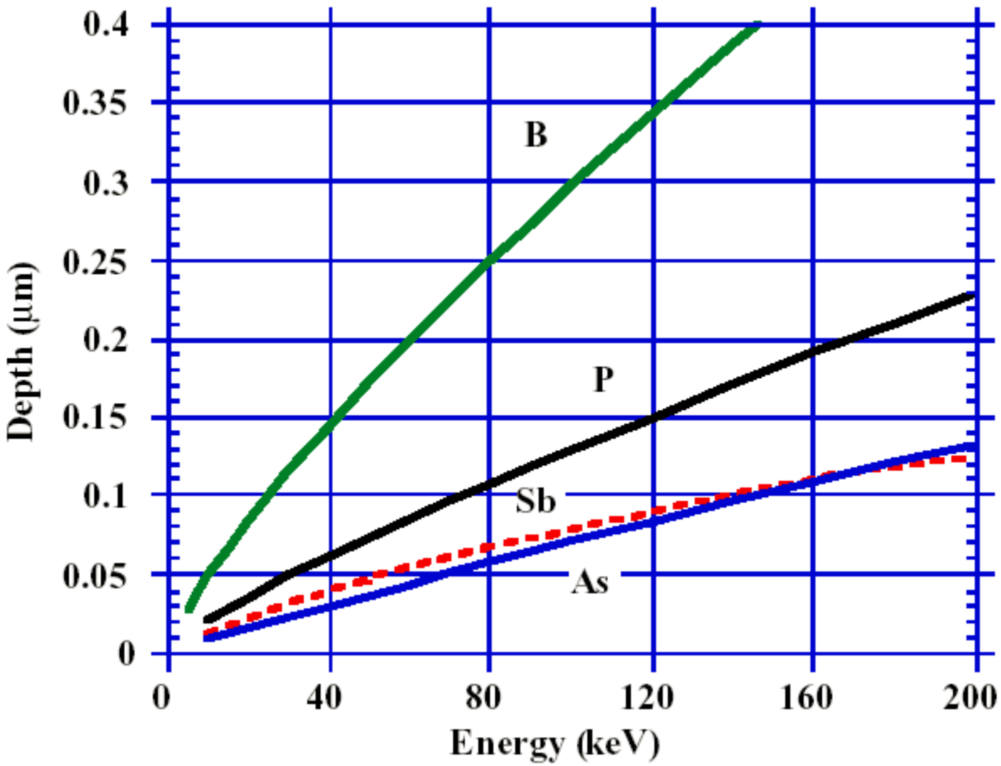
$$C(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p} \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^{\ 2}} \right]$$

Peak concentration:

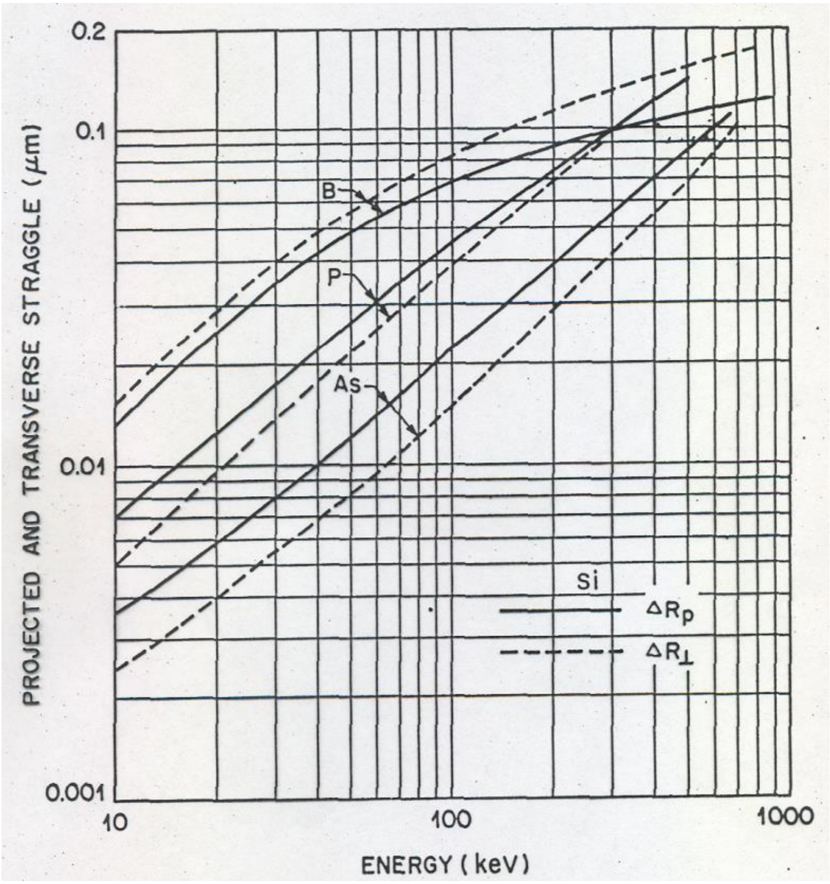
$$C_p = \frac{Q}{\sqrt{2\pi}\Delta R_p}$$

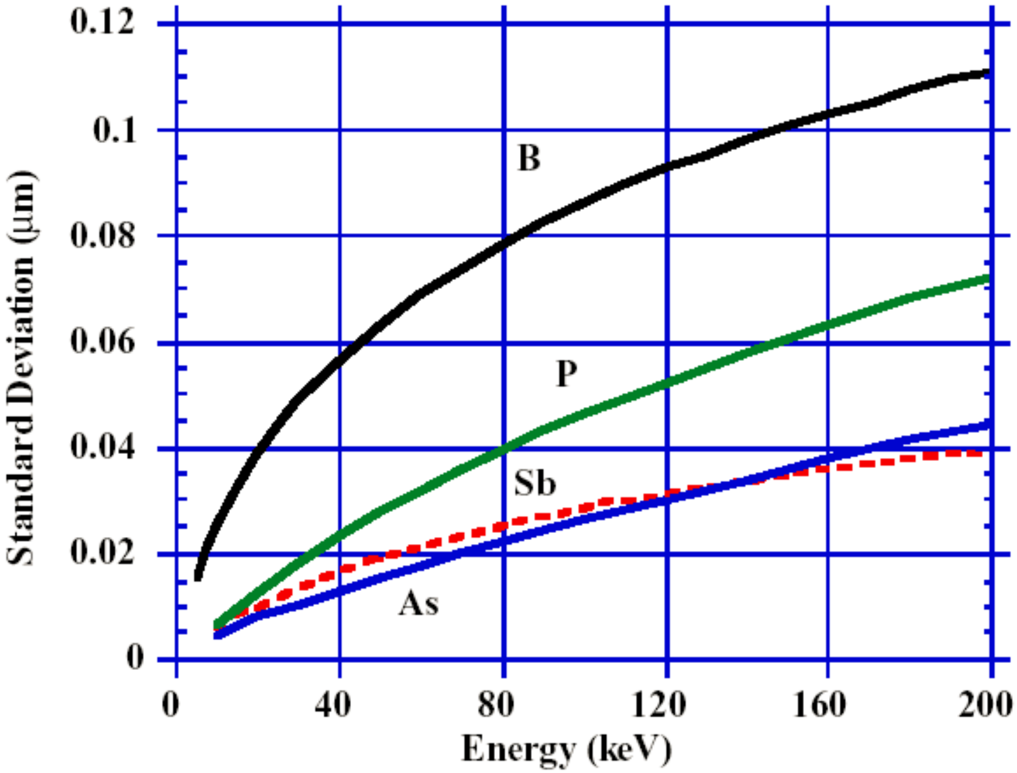
Projected Range





Straggle (Range Dispersion)





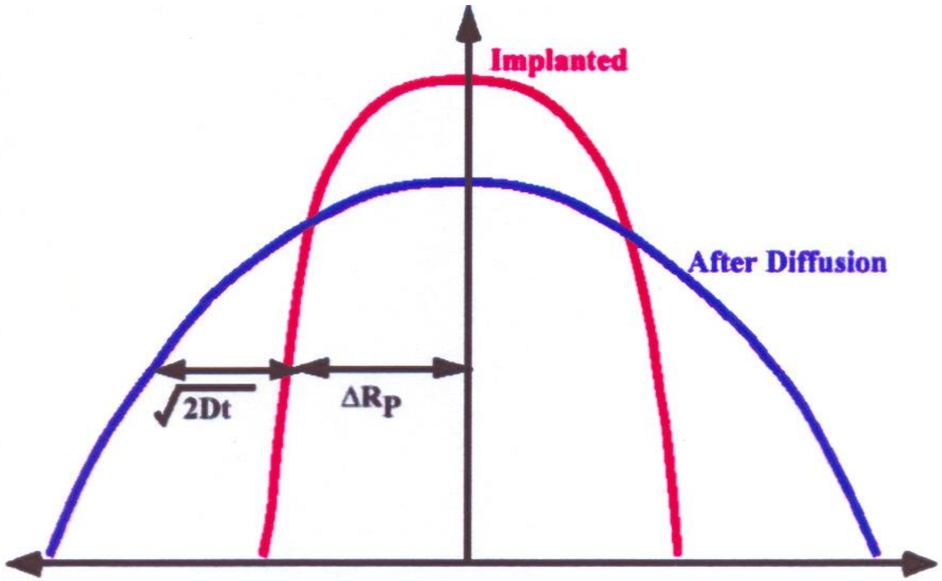
Implanted Diffused Profile

Implanted profile:

$$C(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p} \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^{\ 2}} \right]$$

Diffused profile:

$$C(x) = \frac{Q}{2\sqrt{\pi}\sqrt{Dt}} \exp\left[-\frac{x^2}{4Dt} \right]$$



$$\boxed{\Delta R_p^{\ 2} \Leftrightarrow 2Dt}$$

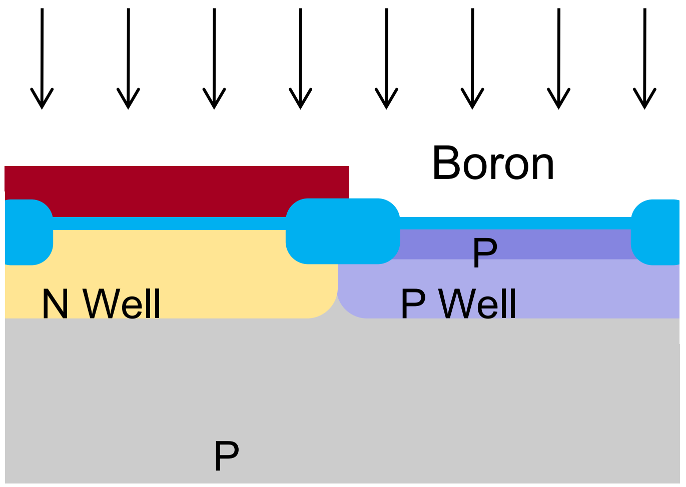
Implanted & diffused profile:

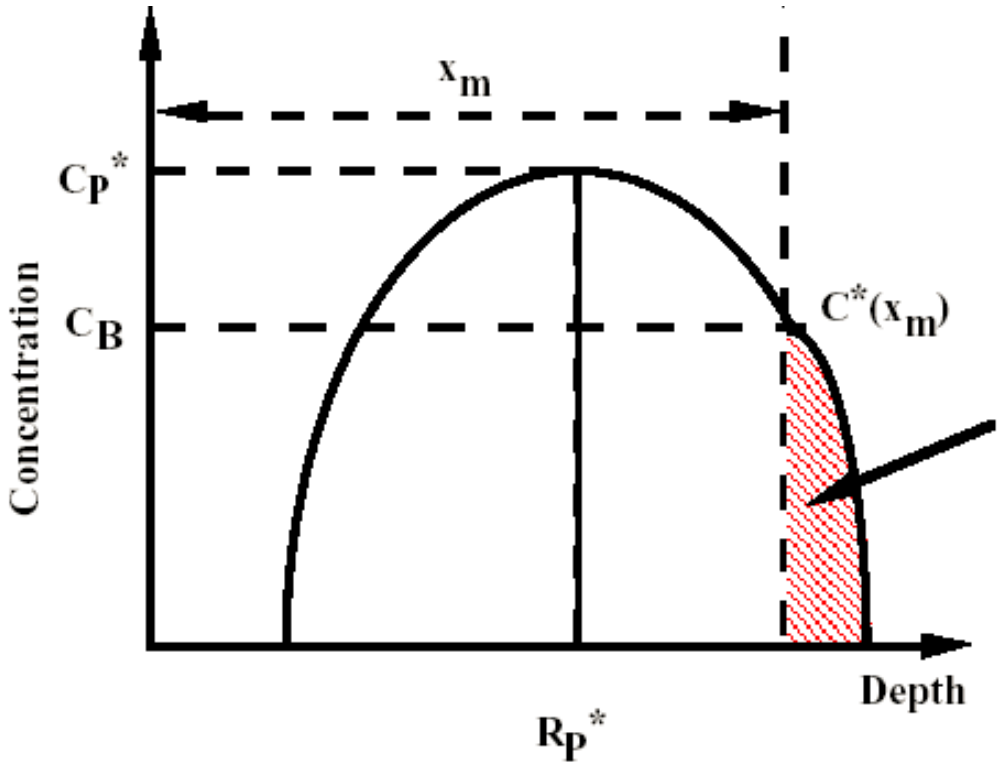
$$C(x) = \frac{Q}{\sqrt{2\pi(\Delta R_p^{\ 2} + 2Dt)}} \exp\left[-\frac{(x - R_p)^2}{2(\Delta R_p^{\ 2} + 2Dt)} \right]$$

Implantation with mask

To shield the implantation ions:

$$C^*(x_m) = C_P^*\left[\exp-\frac{(x_m - R_P^*)^2}{2\Delta R_P^{*2}}\right] \le C_B$$





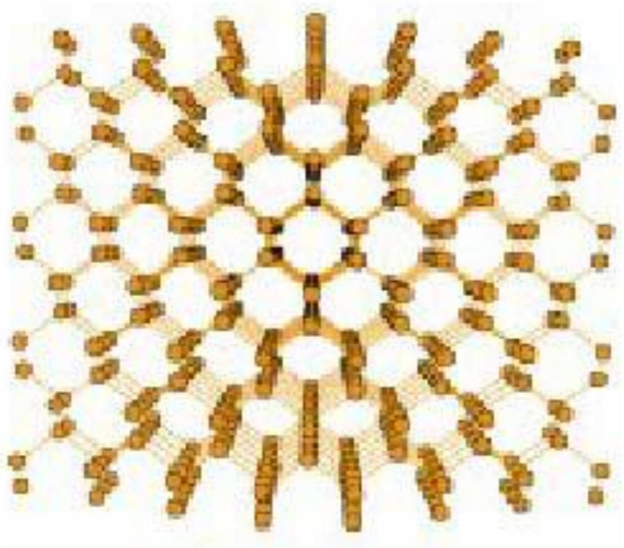
Mask thickness:

$$x_m = R_P^* + \Delta R_P^*\sqrt{2\ln\left(\frac{C_P^*}{C_B}\right)} = R_P^* + m\Delta R_P^*$$

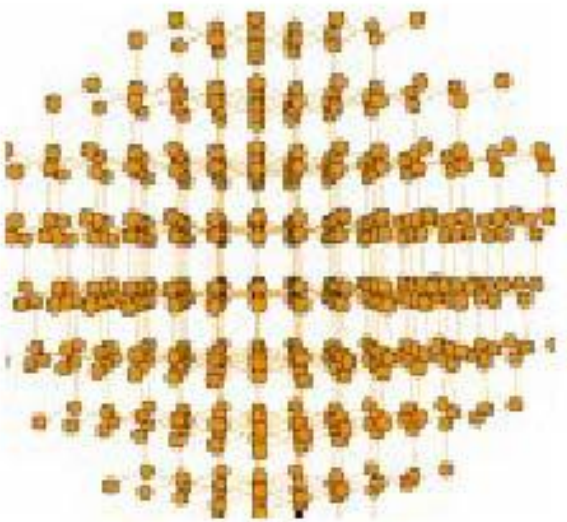
Penetrated dose:

$$Q_P = \frac{Q}{2}\operatorname{erfc}\left(\frac{x_m - R_P^*}{\sqrt{2}\Delta R_p^*}\right)$$

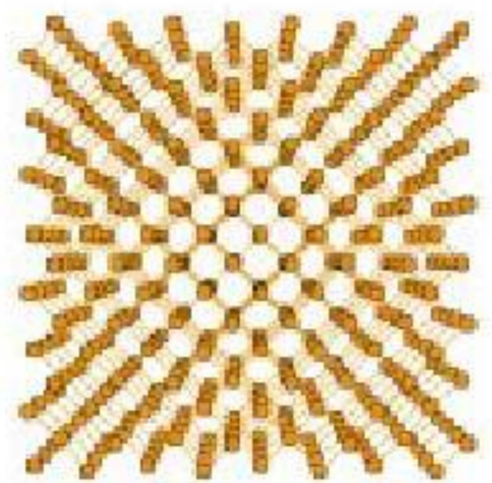
Channelling – Silicon crystalline



110



111



100

random

Channelling

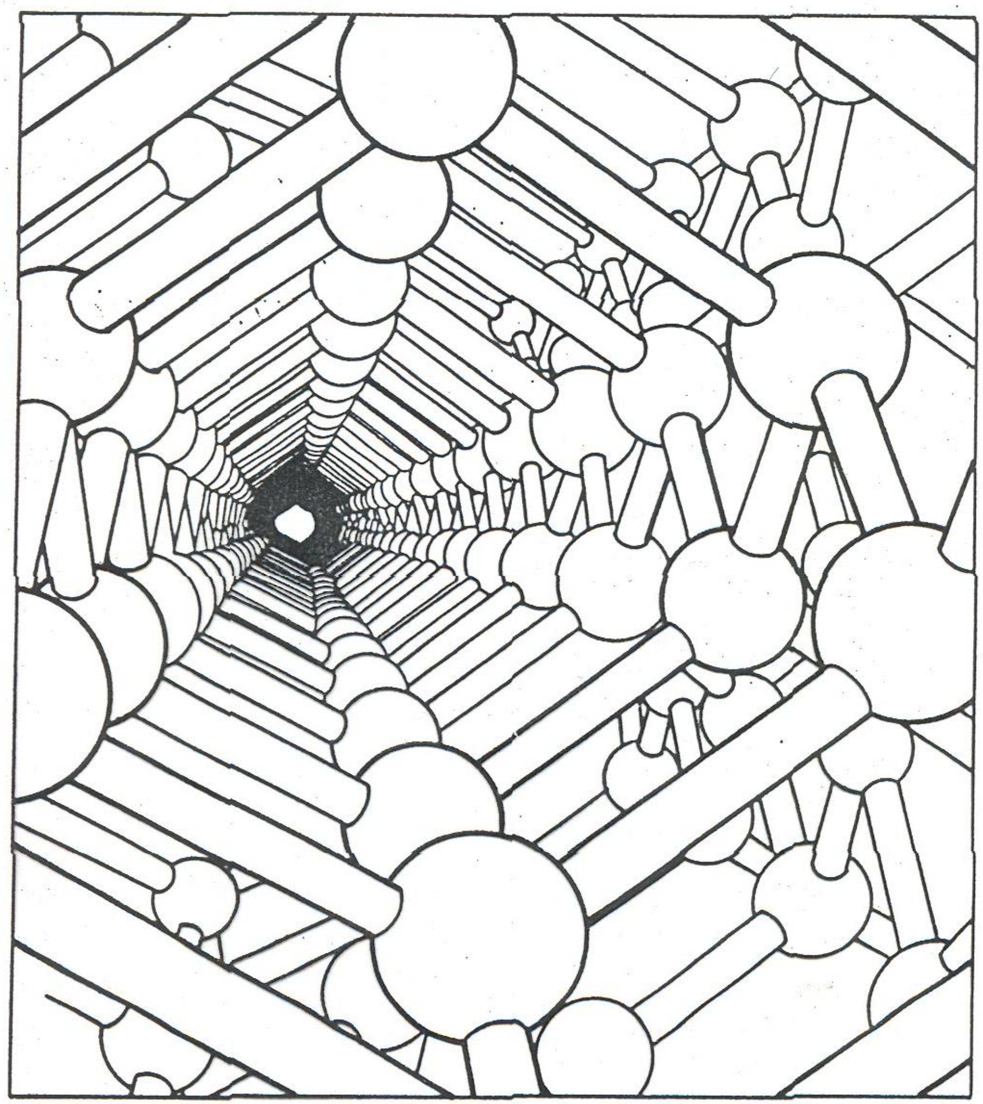


Fig. 27 Model for a diamond structure, viewed along a <110>-axis.[20]

- Low-loss crystal directions

Critical angle:

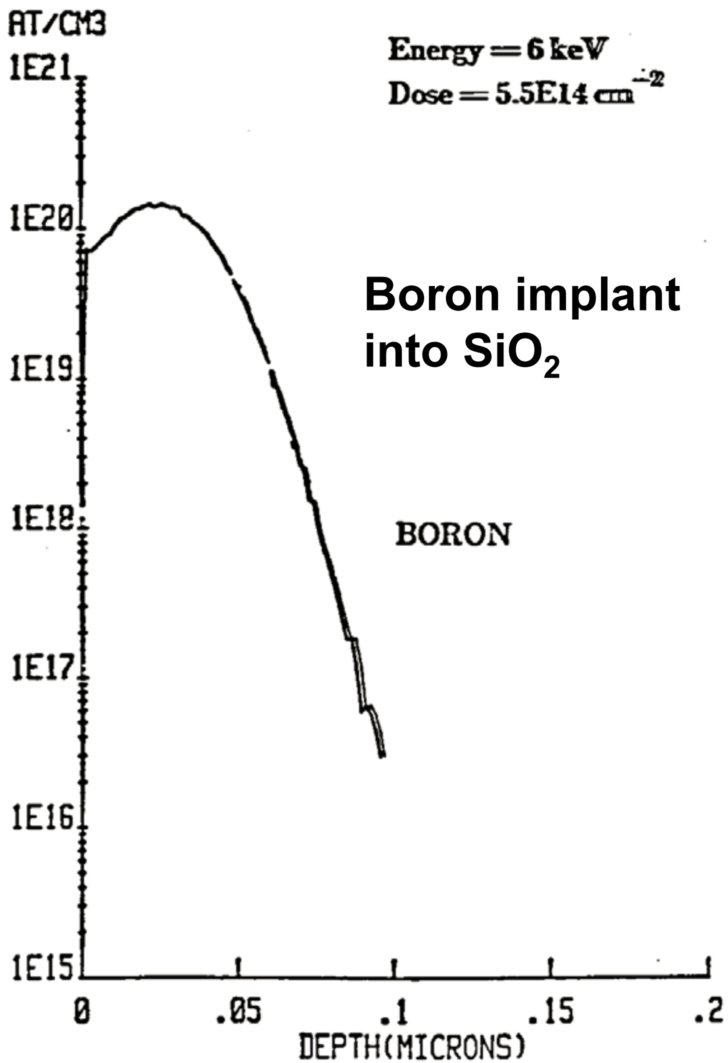
$$\psi \propto \frac{1}{\sqrt{E}}$$

Typical values:

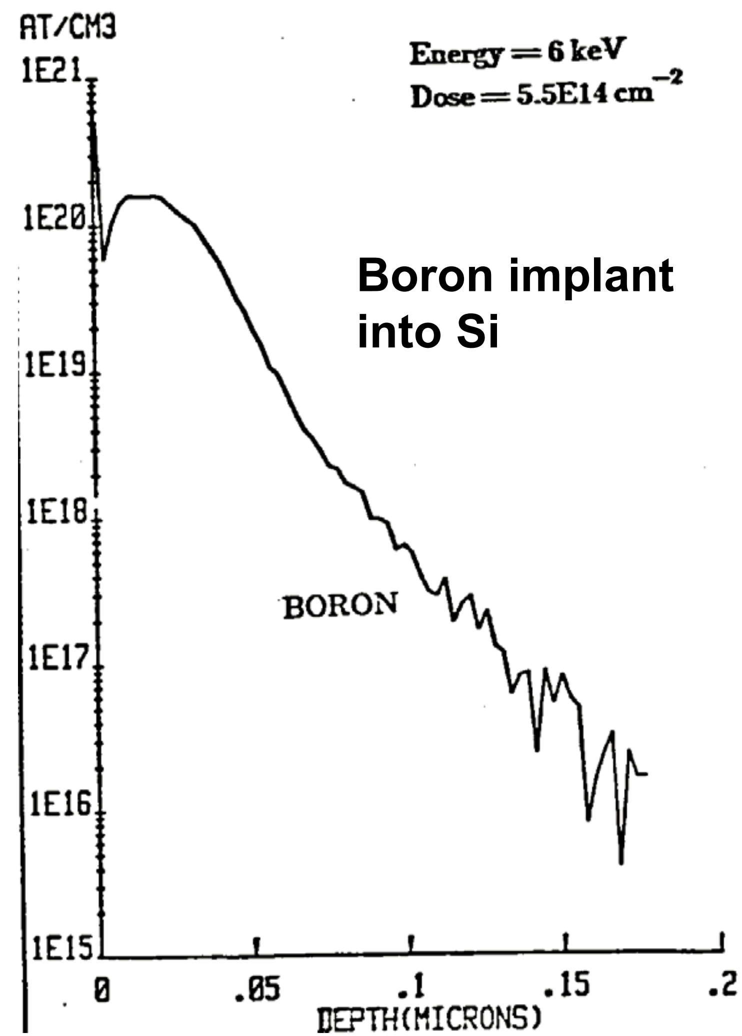
ψ ~ 2° - 7°

E ~ 300 - 30 keV

Implantation into amorphous layer

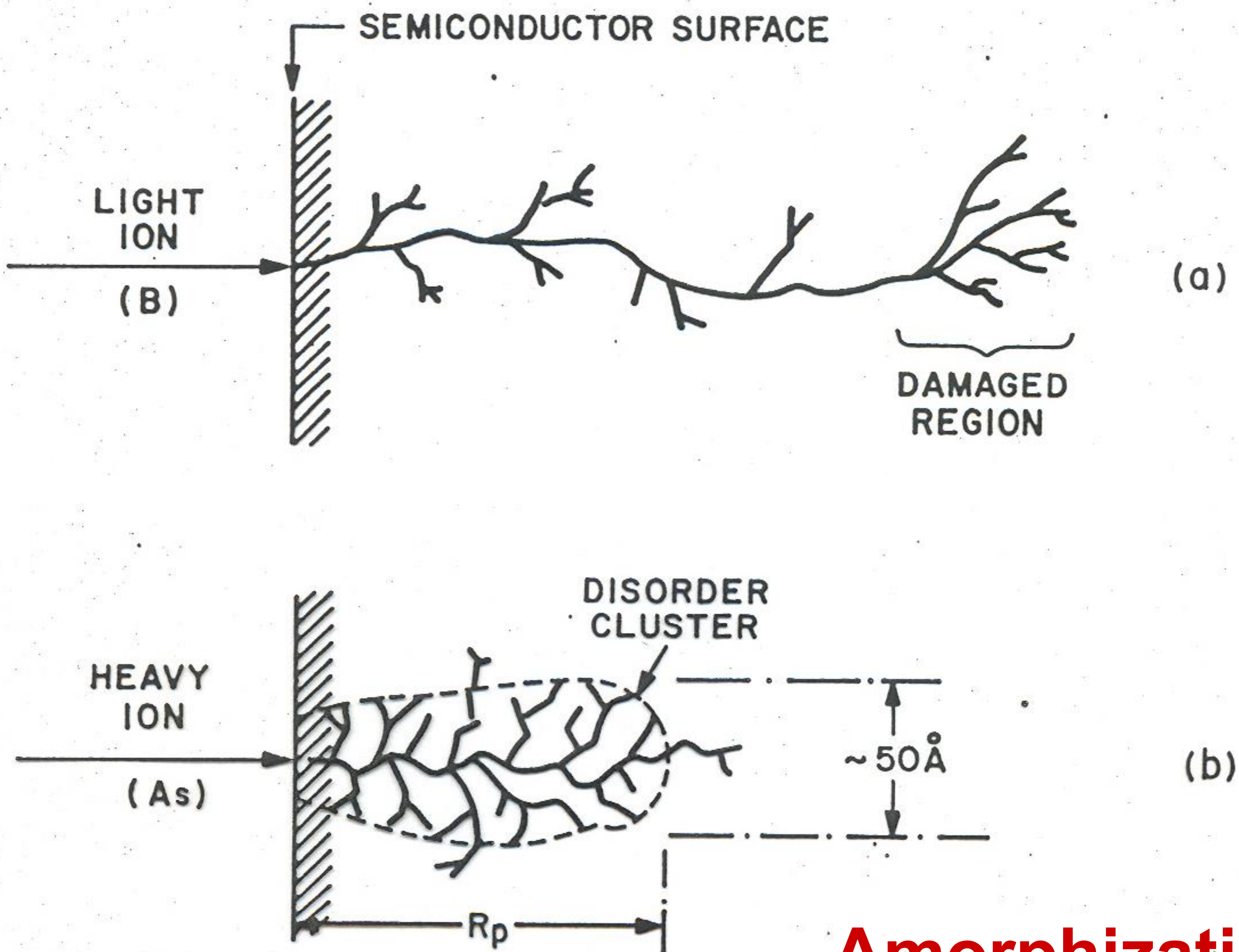


Boron implant into SiO_2



Boron implant into Si

Damage Generation



- Amorphization

Amorphization

Damage by the implanted ions may cause the amorphization of the crystalline structure.

More severe with higher dose;

Critical dose for amorphization;

Critical dose is related to the ion mass;

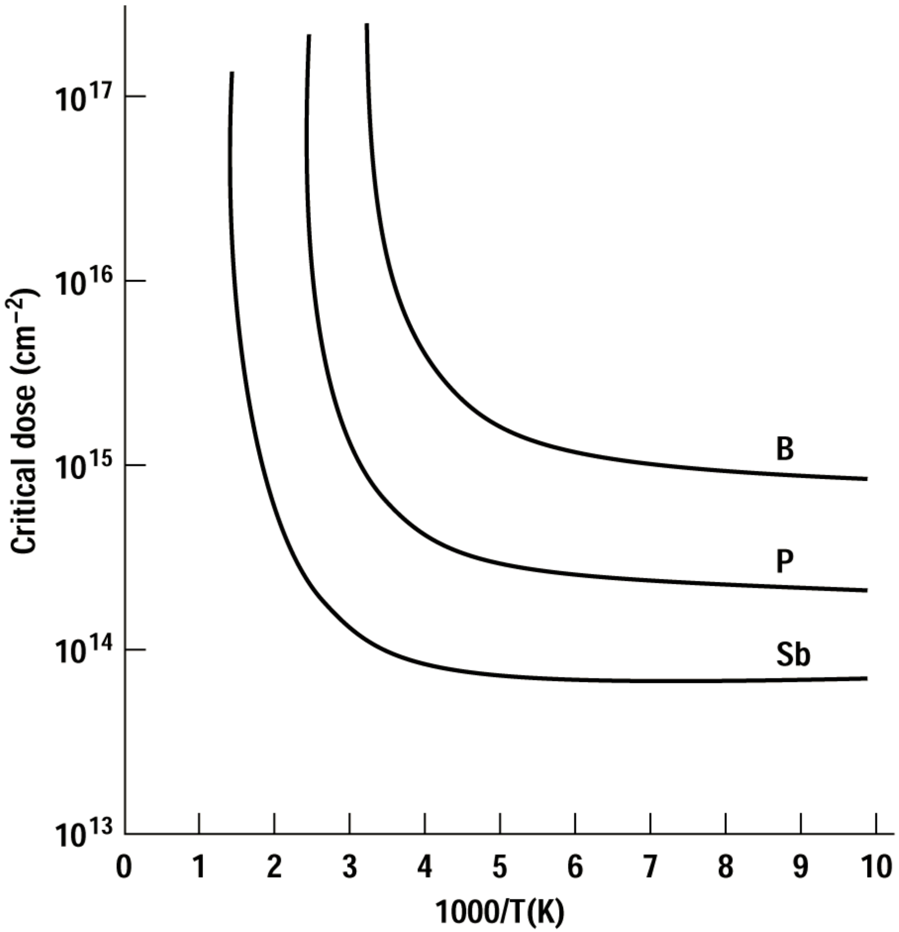


Figure 5.13 Critical implant dose required to amorphize a silicon substrate as a function of substrate temperature for several common silicon dopants *(after Morehead and Crowder)*.

Annealing of Ion Implants

Purpose: - Activation of dopants
- Removal of damage

<u>Low-dose implants</u>

High temperature needed for full activation

Temperature increasing with the dose

<u>High-dose implants</u>

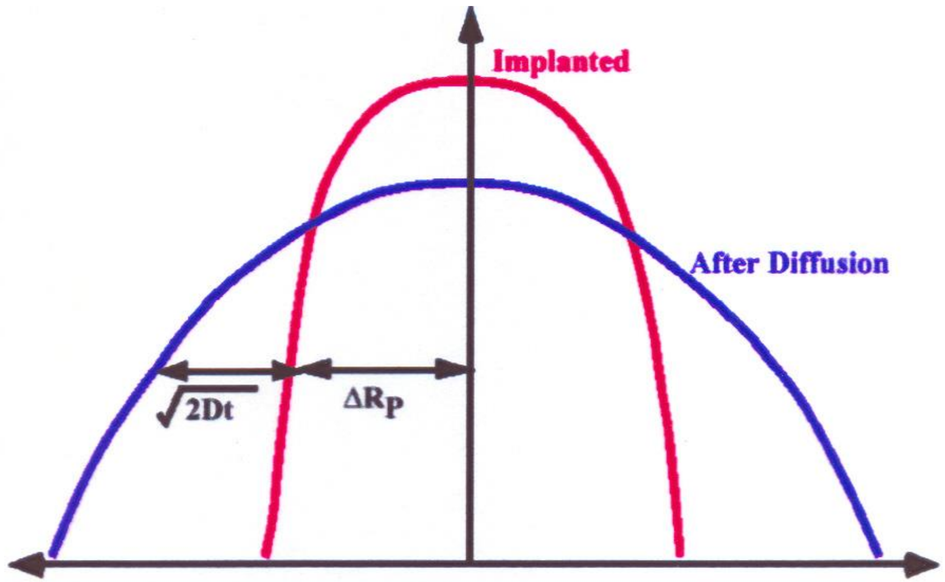
Solid phase epitaxial regrowth (low temperature) - SPE

Substantial activation even at low temperature

<u>Rapid thermal annealing - RTA</u>

Activation and damage removal almost without diffusion

Annealing of Ion Implants



$$C(x,t)=\frac{Q}{\sqrt{2\pi(\Delta R_p{}^2+2Dt)}}\exp\left[-\frac{(x-R_p)^2}{2(\Delta R_p{}^2+2Dt)}\right]$$

- Restore lattice (>600° C, ~hours)
- Activation of dopants (650~900 ° C, 10~30 min)
- Diffusion-broadened profile

Short-Time Annealing Techniques