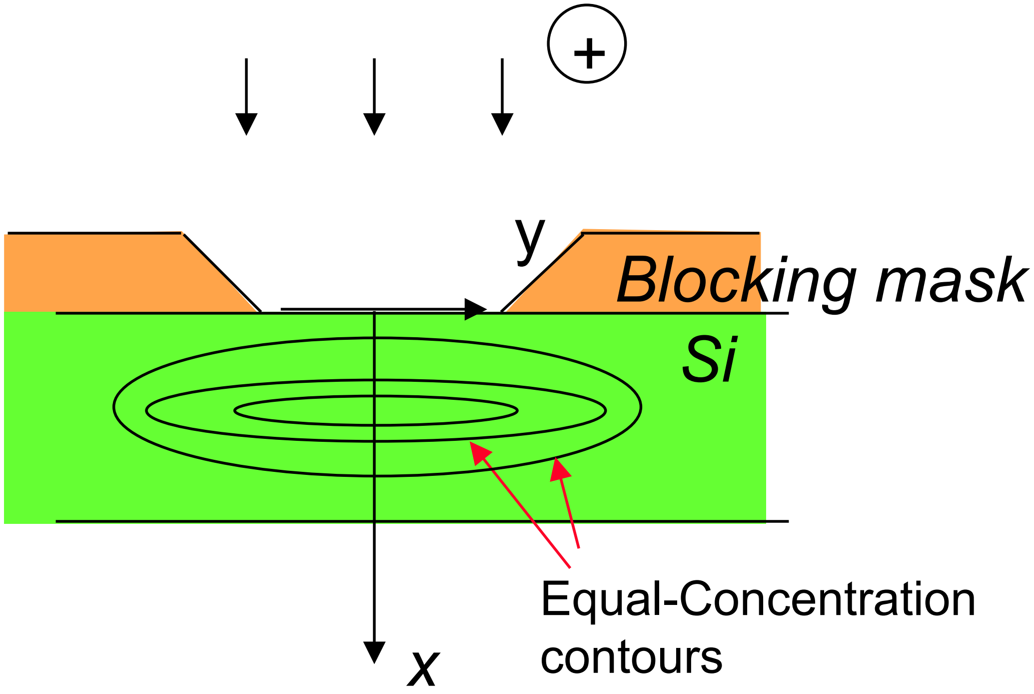
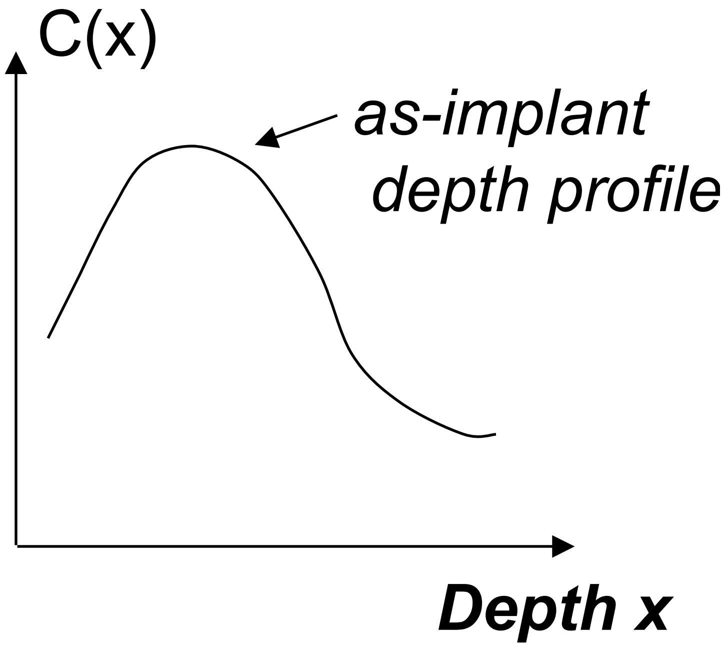
Ion Implantation





Concentration Profile versus Depth is a single-peak function

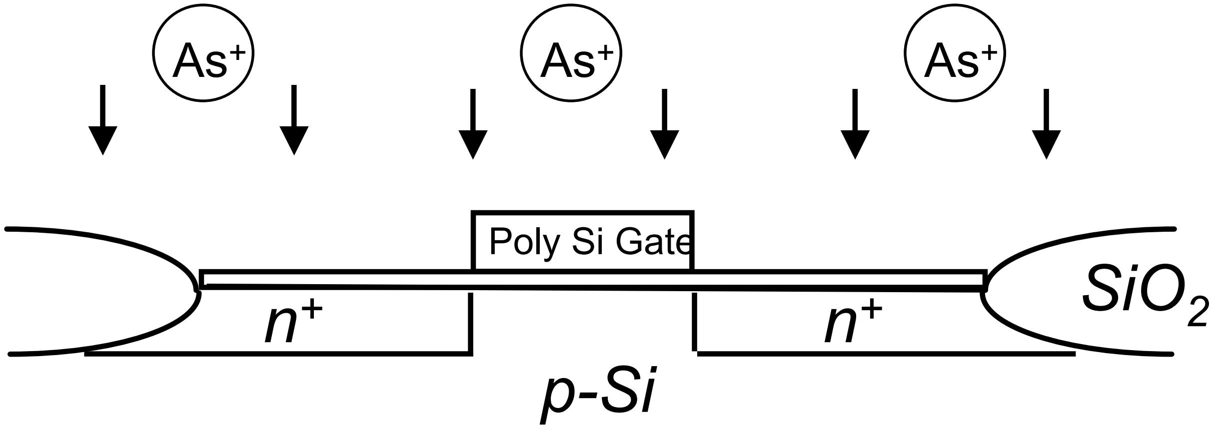
Reminder: During implantation, temperature is ambient. However, post-implant annealing step (>900^{o}C) is required to anneal out defects.

Advantages of Ion Implantation

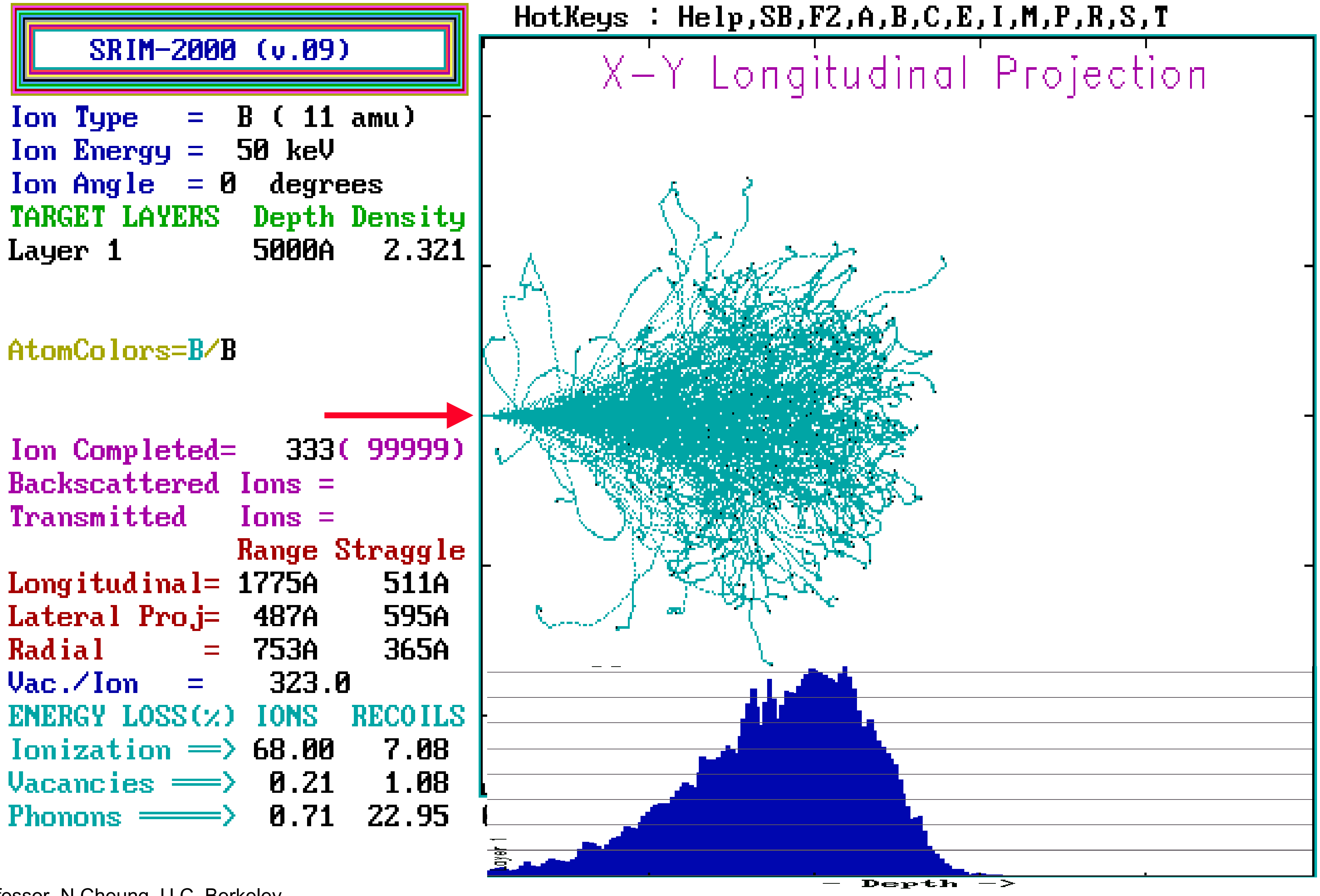
- Precise control of <u>dose</u> and <u>depth</u> profile
- Low-temp. process (can use photoresist as mask)
- Wide selection of masking materials

  e.g. photoresist, oxide, poly-Si, metal
- Less sensitive to surface cleaning procedures
- Excellent lateral dose uniformity (< 1% variation across 12" wafer)

<u>Application example</u>: self-aligned MOSFET source/drain regions



Monte Carlo Simulation of 50keV Boron implanted into Si

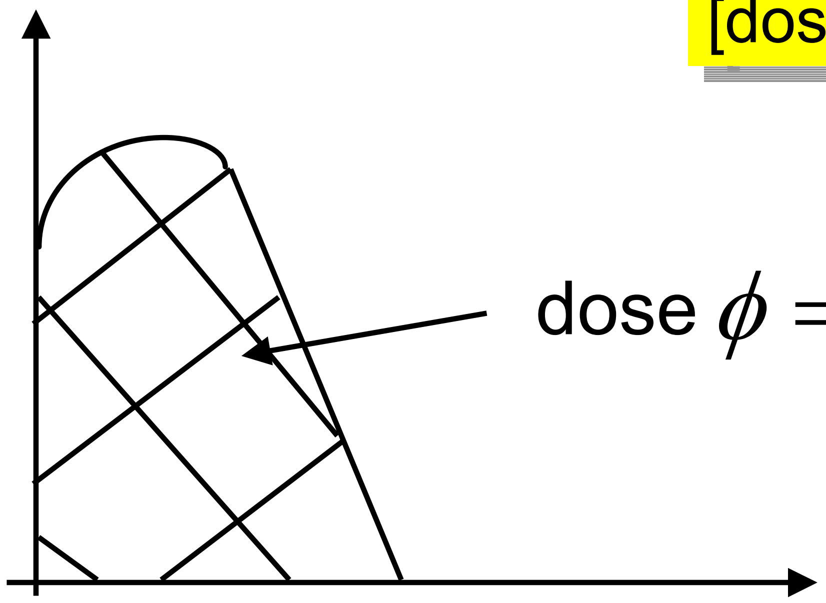


```
SRIM-2000 (v.09)
Ion Type     =   B ( 11 amu)
Ion Energy =   50 keV
Ion Angle   = 0   degrees
TARGET LAYERS   Depth Density
Layer 1           5000A    2.321


AtomColors=B/B


Ion Completed=     333( 99999)
Backscattered Ions =
Transmitted     Ions =
                    Range Straggle
Longitudinal= 1775A     511A
Lateral Proj=  487A     595A
Radial         =  753A     365A
Vac./Ion     =     323.0
ENERGY LOSS(%) IONS   RECOILS
Ionization ==> 68.00    7.08
Vacancies ===>  0.21    1.08
Phonons ====>  0.71   22.95
```

(1) Range and profile shape depends on the ion energy
(for a particular ion/substrate combination)

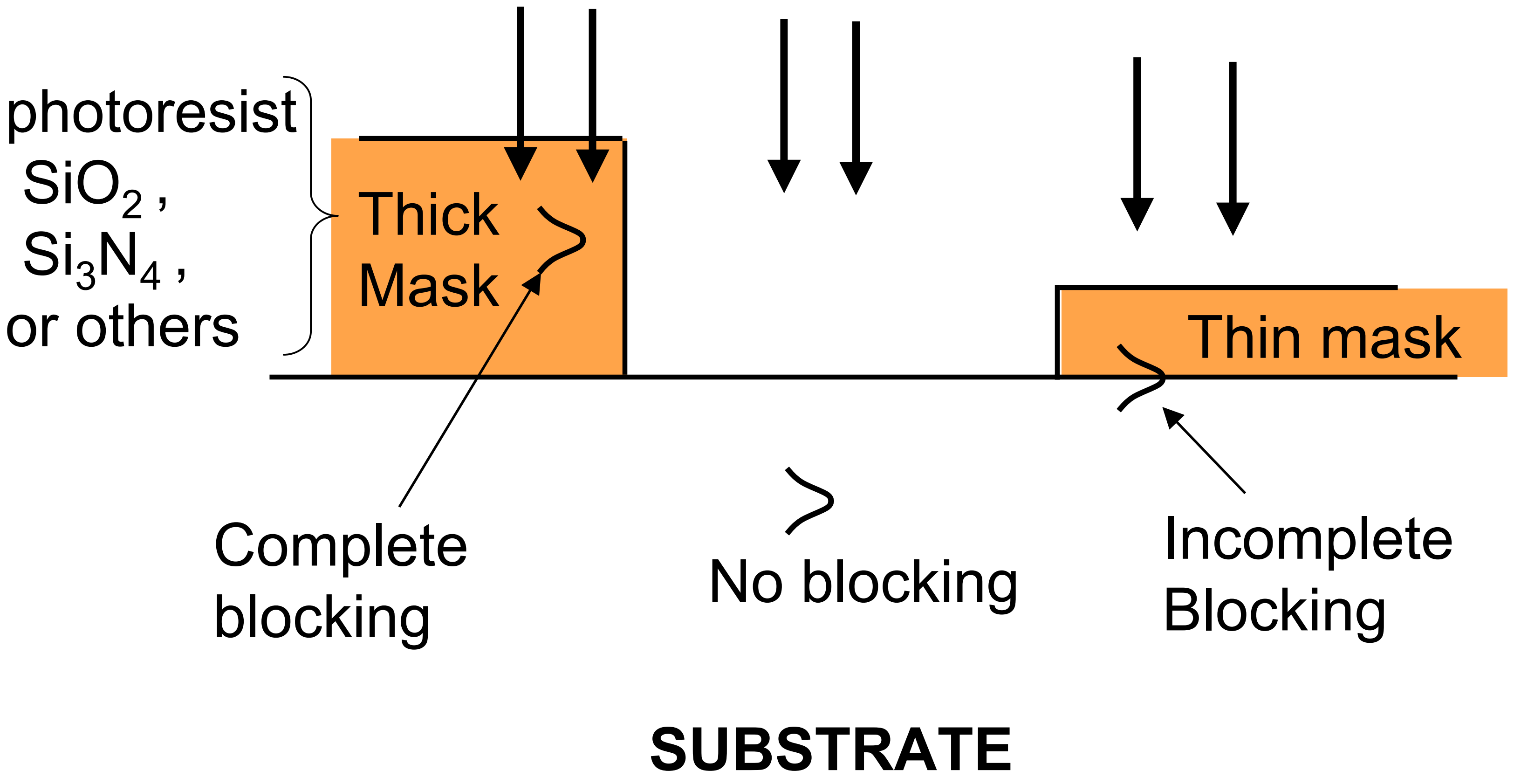
(2) Height (i.e. Concentration) of profile depends on the implantation dose

[Conc] = # of atoms/**cm^3**
[dose] = # of atoms/**cm^2**



dose $\phi = \int_0^\infty C(x)dx$

Mask layer thickness can block ion penetration



Ion Implanter

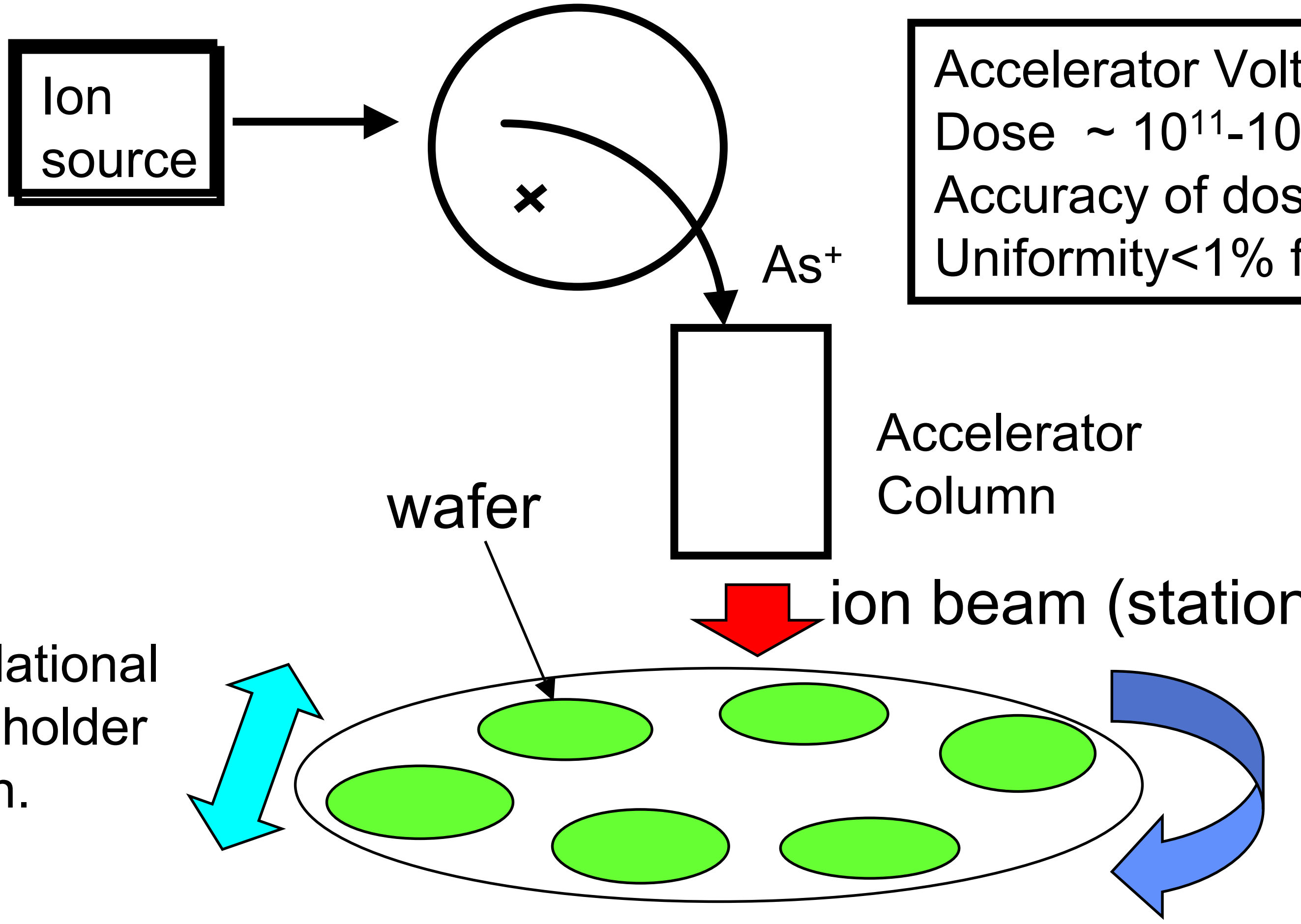
$3-4M/implanter

~60 wafers/hour

e.g. AsH_3

As^+, AsH^+, H^+, AsH_2^+

Magnetic Mass separation



Ion source

As^+

Accelerator Voltage: 1-200kV
Dose ~ 10^{11}-10^{16}/cm^2
Accuracy of dose: <0.5%
Uniformity<1% for 8” wafer

Accelerator Column

wafer

ion beam (stationary)

Translational wafer holder motion.

spinning wafer holder

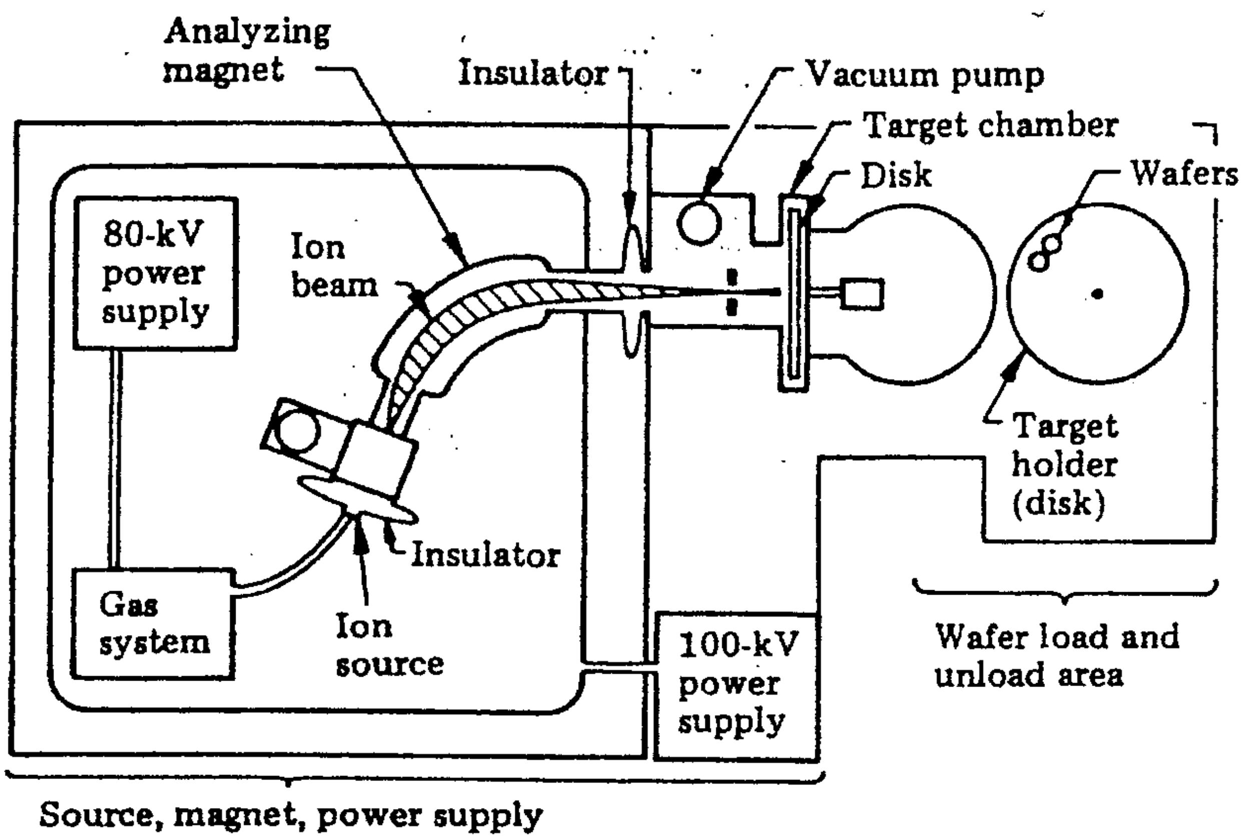
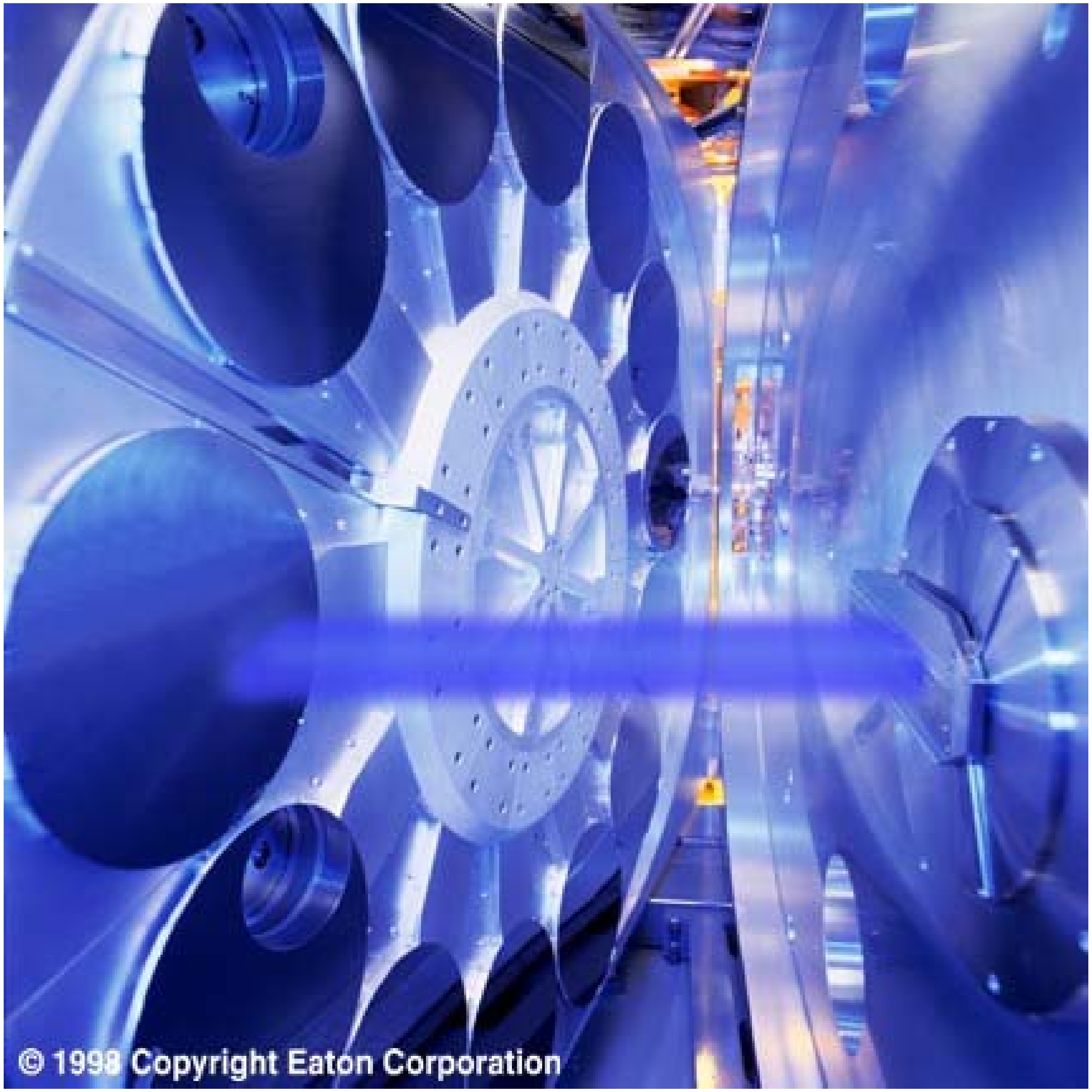


FIGURE 8.4 Schematic of a commercial ion-implantation system, the Nova-10-160, 10 mA at 160 keV.

Energetic ions penetrate the surface of the wafer and then undergo a series of collisions with the atoms and electrons in the target.

Eaton HE3 High Energy Implanter, showing the ion beam hitting the 300mm wafer end-station.



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Implantation Dose

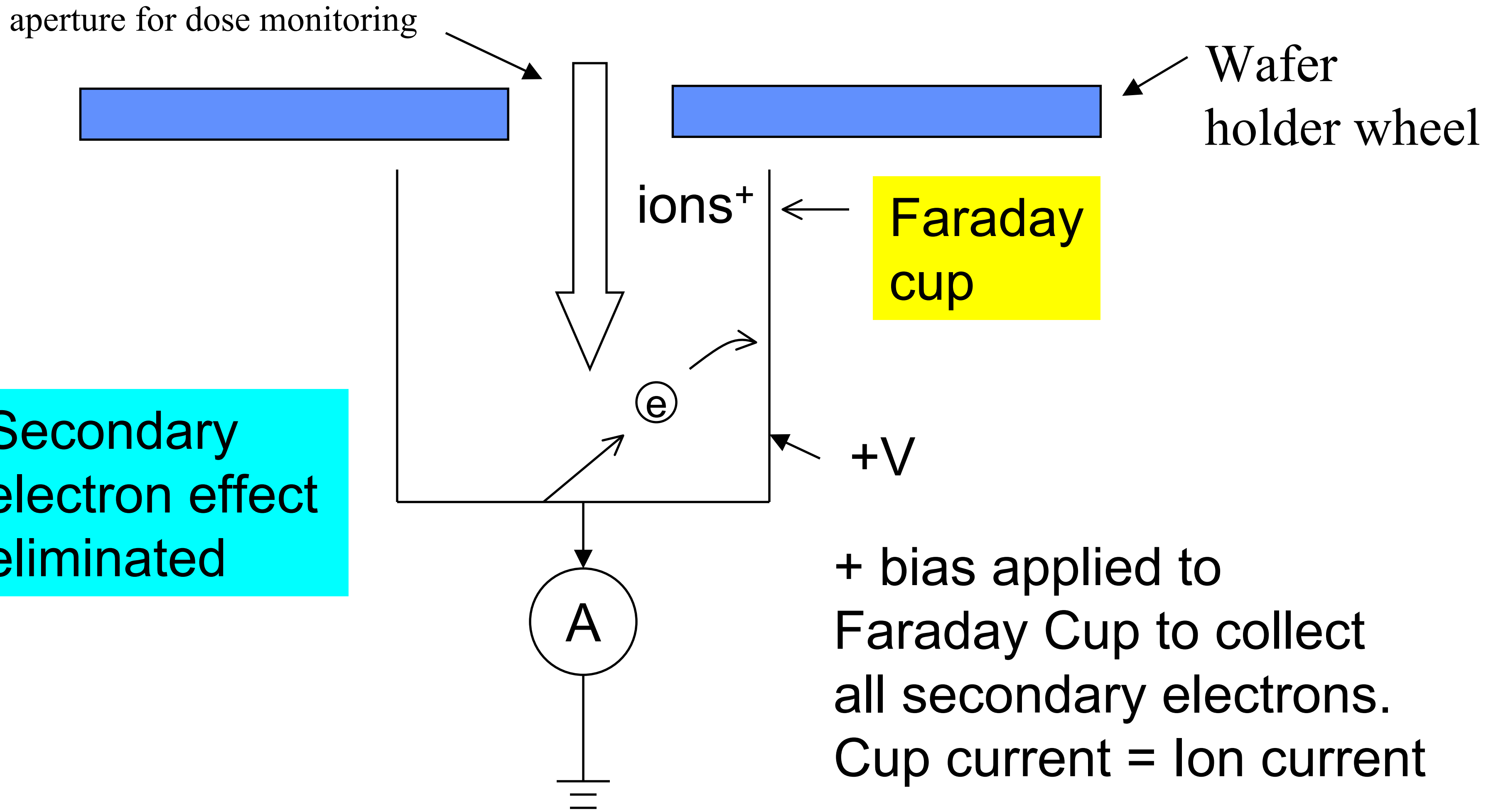
For *singly charged* ions (e.g. As$^+$)

$$\text{Dose}\quad \Phi = \frac{\left(\dfrac{\textbf{Ion Beam Current in amps}}{q}\right)\times\left(\begin{matrix}\textbf{Implant}\\ \textbf{time}\end{matrix}\right)}{\left[\textbf{Implant area}\right]}$$

$$= {}^{\#}\!/_{cm^2}$$

Over-scanning of beam across wafer is common.
In general , Implant area > Wafer area

Practical Implantation Dosimetry

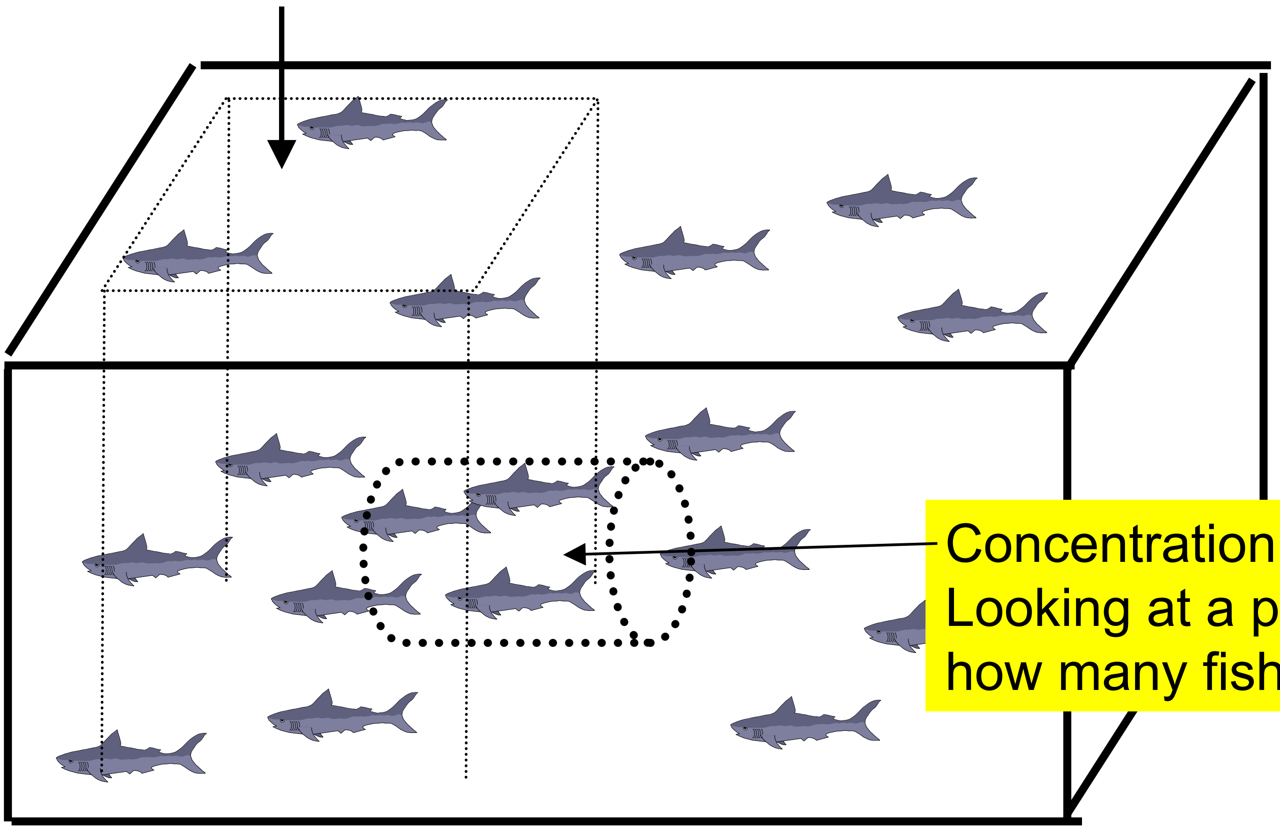


Secondary electron effect eliminated

+ bias applied to Faraday Cup to collect all secondary electrons.
Cup current = Ion current

* (Charge collected by integrating cup current) / (cup area) = dose

Meaning of Dose and Concentration

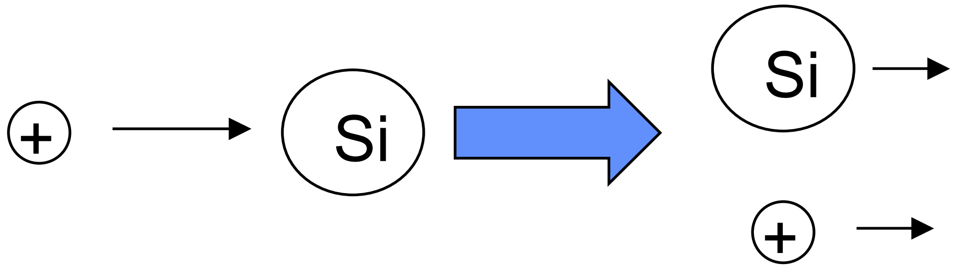


Dose [#/area] : looking downward, how many fish per unit area for ALL depths ?

Concentration [#/volume] : Looking at a particular location, how many fish per unit volume ?

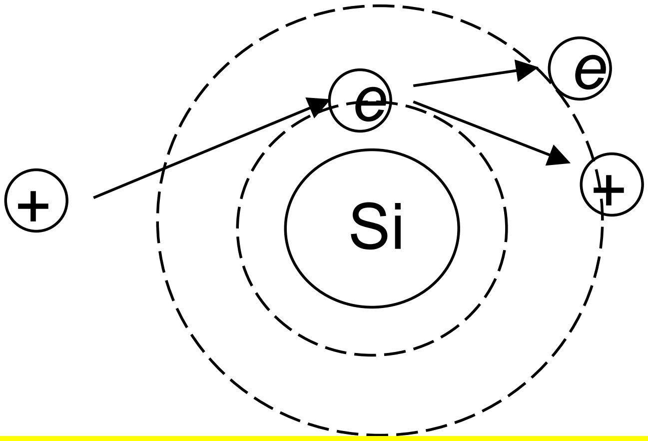
Ion Implantation Energy Loss Mechanisms

Nuclear stopping



Crystalline Si substrate damaged by collision

Electronic stopping



Electronic excitation creates heat

Energy Loss and Ion Properties

Light ions/at higher energy ⟶ more electronic stopping

Heavier ions/at lower energy ⟶ more nuclear stopping

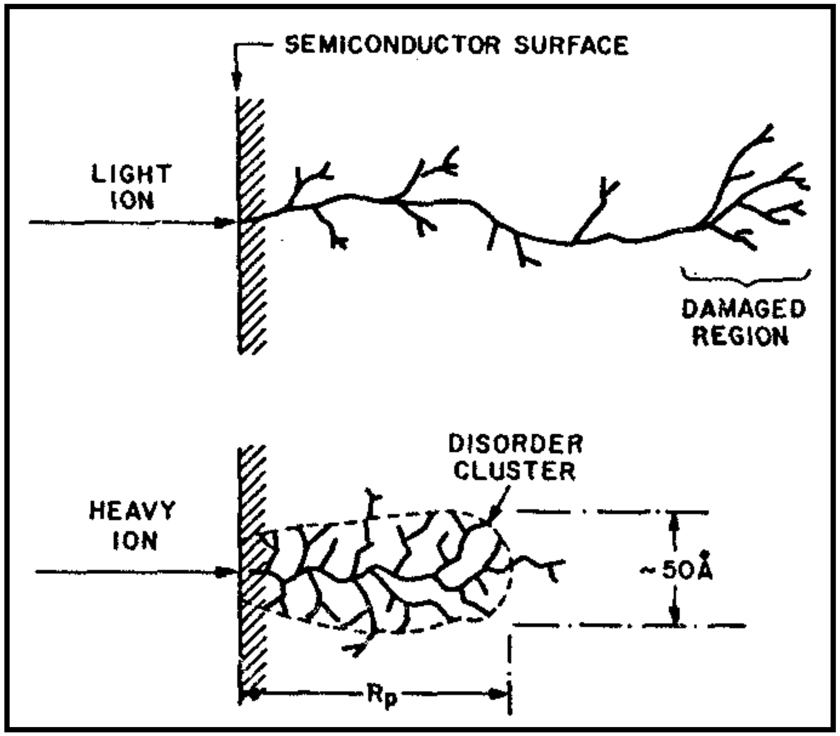
EXAMPLES

Implanting into Si:

H^+ ⇨ Electronic stopping dominates

B^+ ⇨ Electronic stopping dominates

As^+ ⇨ Nuclear stopping dominates



Stopping Mechanisms

- Electronic collisions dominate at high energies.
- Nuclear collisions dominate at low energies.

	E1(keV)	E2(keV)
B into Si	3	17
P into Si	17	140
As into Si	73	800

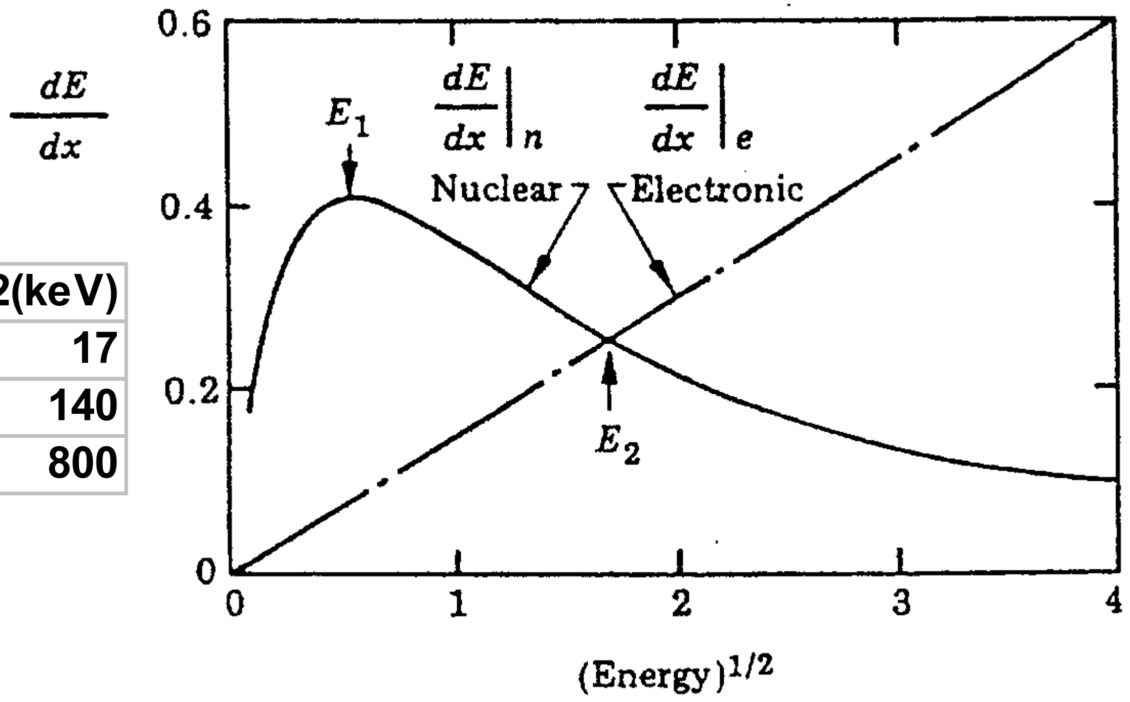
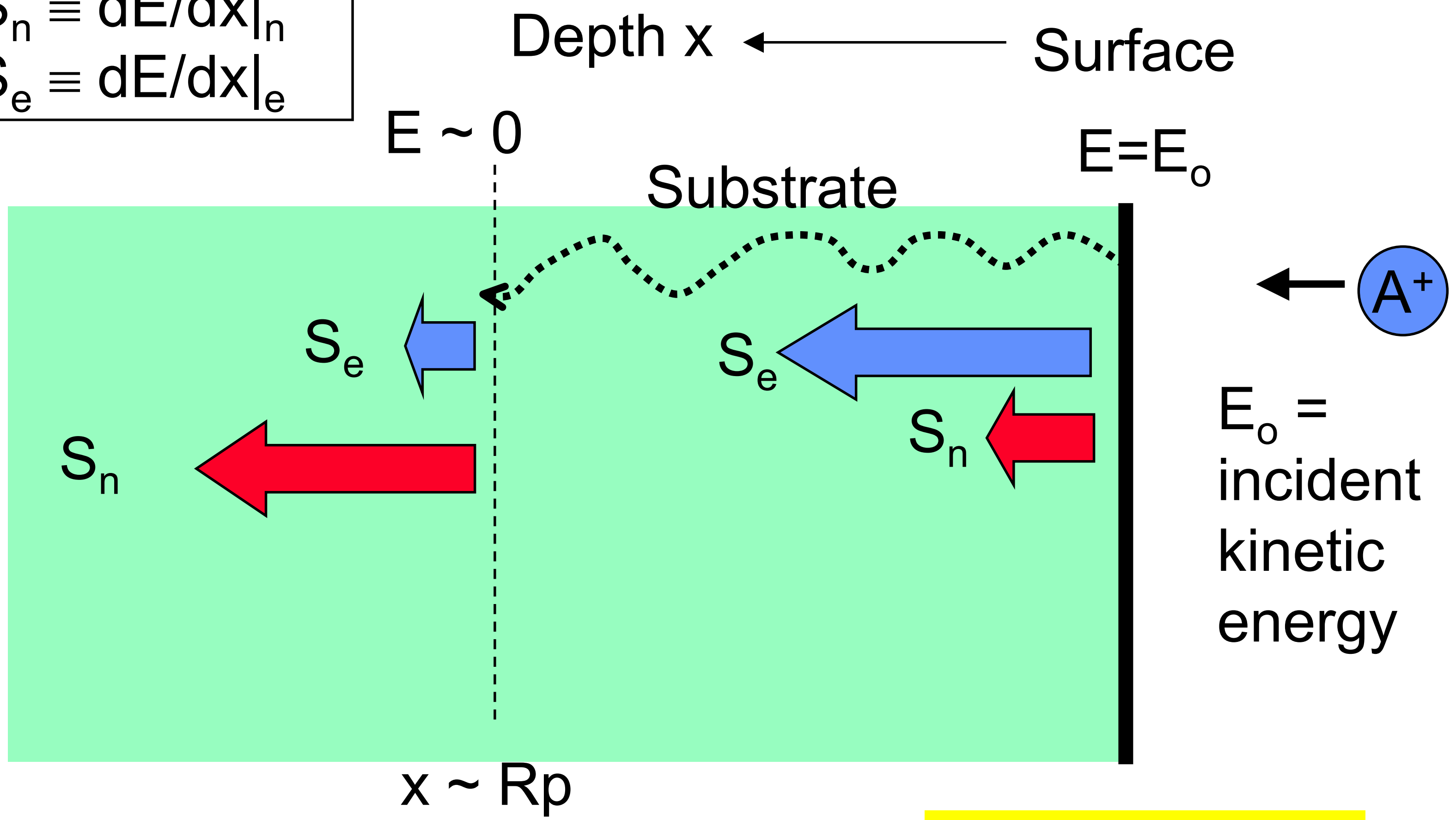


FIGURE 8.12 Rate of energy loss dE/dx versus $(\text{energy})^{1/2}$, showing nuclear and electronic loss contributions.

$S_n \equiv dE/dx|_n$
$S_e \equiv dE/dx|_e$



More crystalline damage at end of range $S_n > S_e$

Less crystalline damage $S_e > S_n$

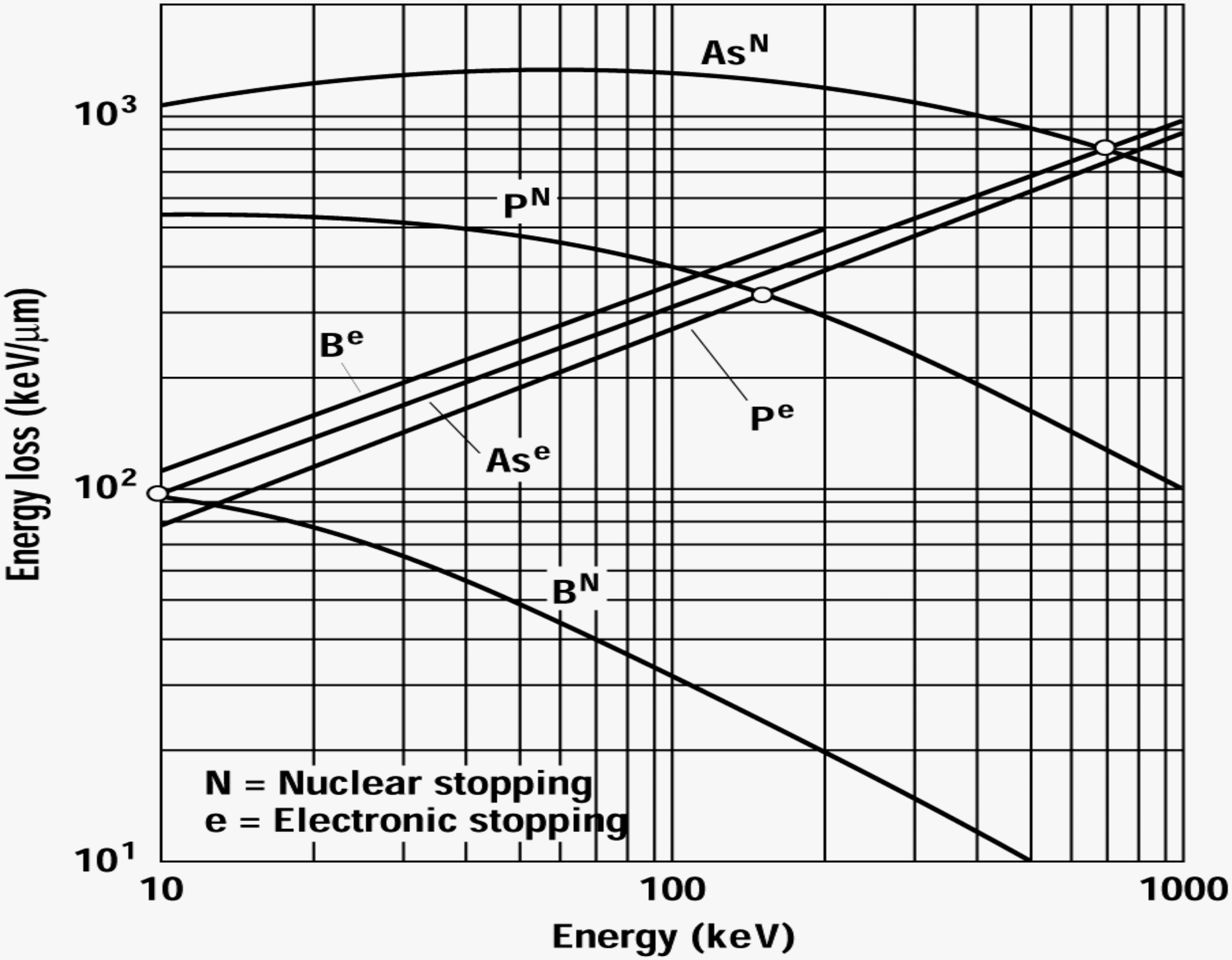
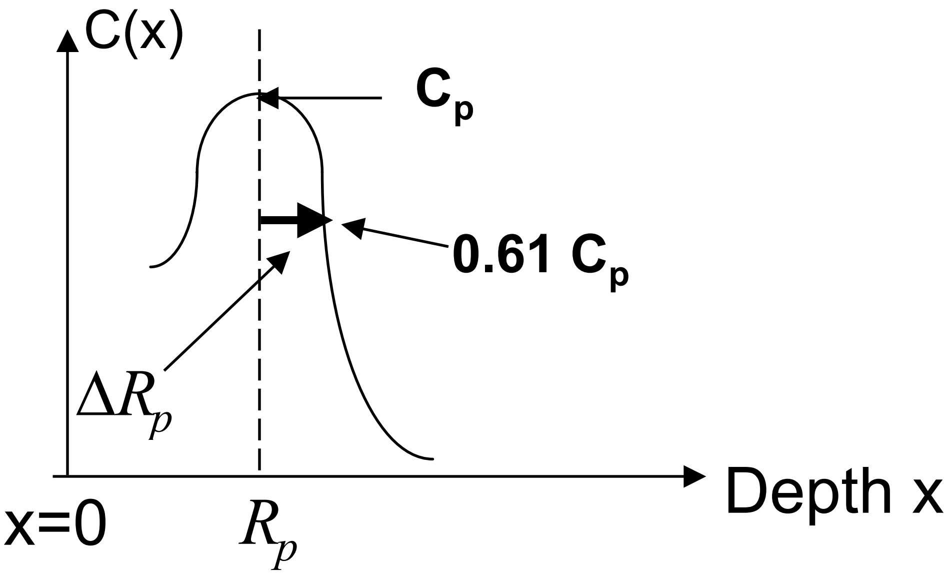
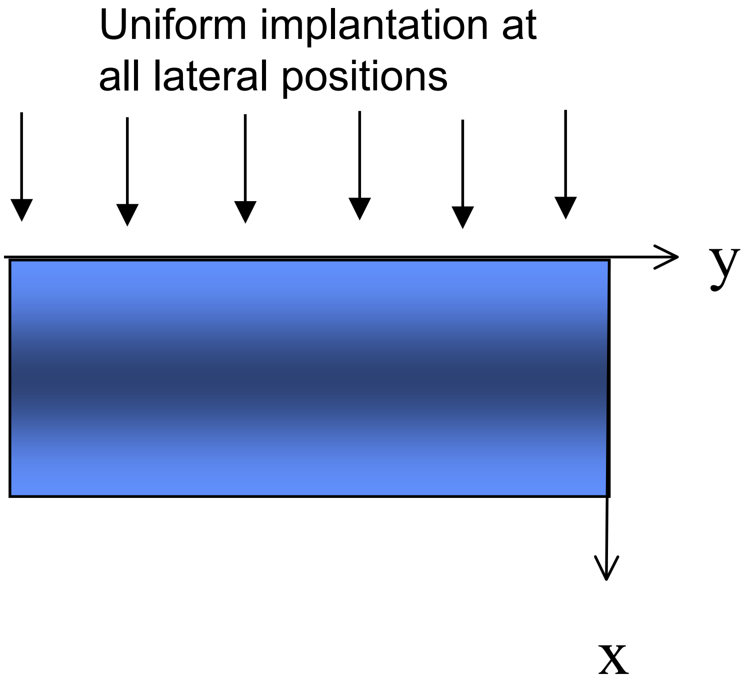


Figure 5.8 Nuclear and electronic components of $S(E)$ for several common silicon dopants as a function of energy *(after Smith as redrawn by Seidel, "Ion Implantation," reproduced by permission, McGraw-Hill, 1983).*

Gaussian Approximation of One-Dimensional Implant Depth Profile





$$C(x) = C_p \cdot e^{\frac{-(x-R_p)^2}{2(\Delta R_p)^2}}$$

R_p = **projected range**

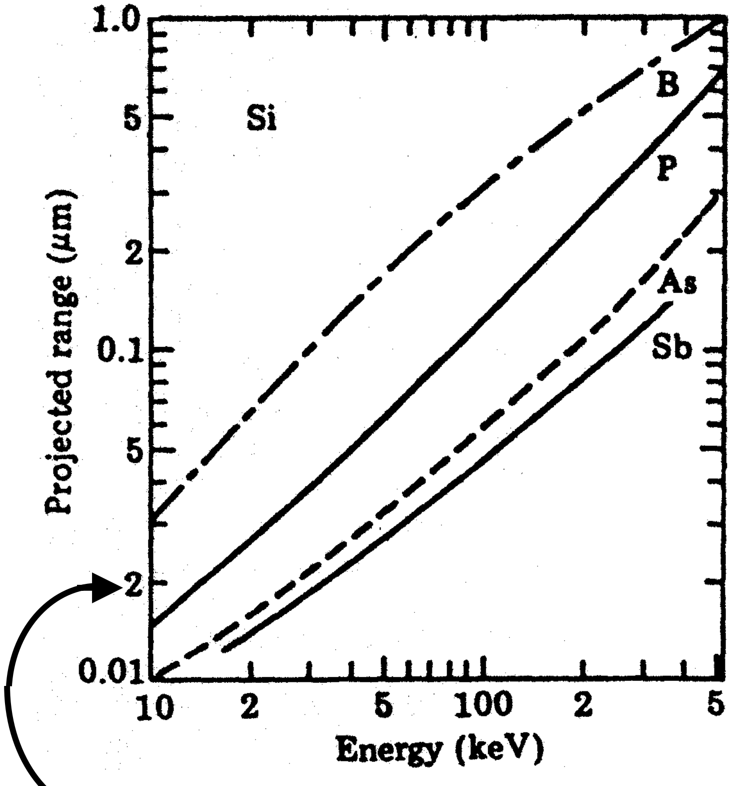
ΔR_p = **longitudinal straggle**

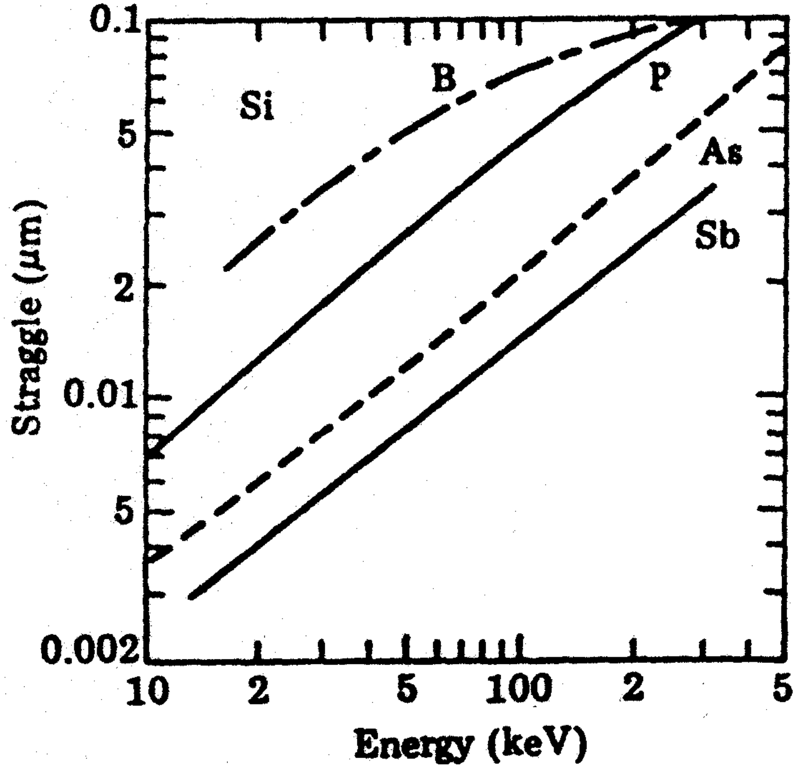
Note: For lateral positions far from masking boundaries, C(x) is independent of lateral position y

Projected Range and Straggle

Rp and ΔRp values are given in tables or charts

e.g. see pp. 113 of Jaeger





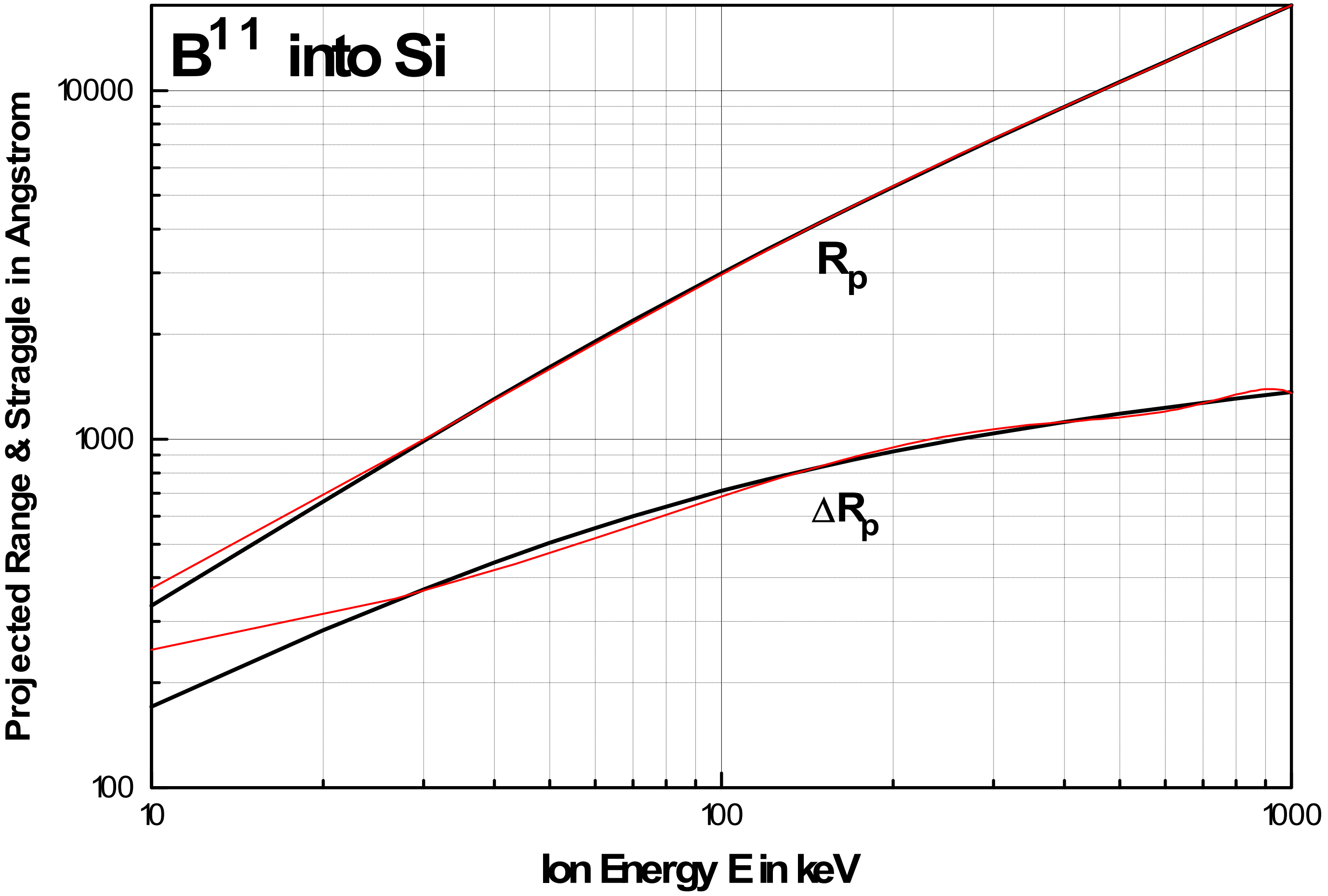
Note: this means 0.02 μm.

Rp and ΔRp values from Monte Carlo simulation

[see 143 Reader for other ions]

$$R_p = 51.051 + 32.60883\,E - 0.03837\,E^2 + 3.758\text{e-}5\,E^3 - 1.433\text{e-}8\,E^4$$

$$\Delta R_p = 185.34201 + 6.5308\,E - 0.01745\,E^2 + 2.098\text{e-}5\,E^3 - 8.884\text{e-}9\,E^4$$



(both theoretical & expt values are well known for Si substrate)

Dose-Concentration Relationship

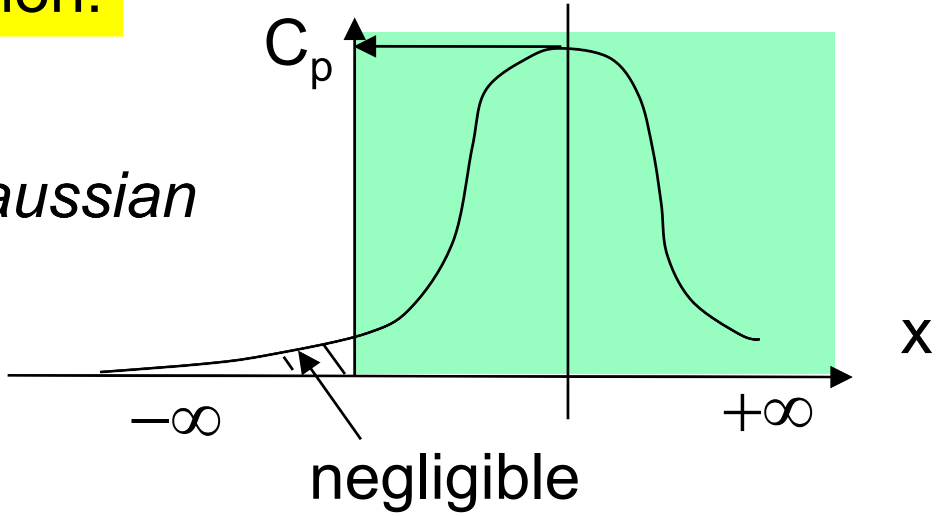
Using Gaussian Approximation:

$$\text{Dose} = \phi = \int_0^\infty C(x)\,dx$$

Gaussian

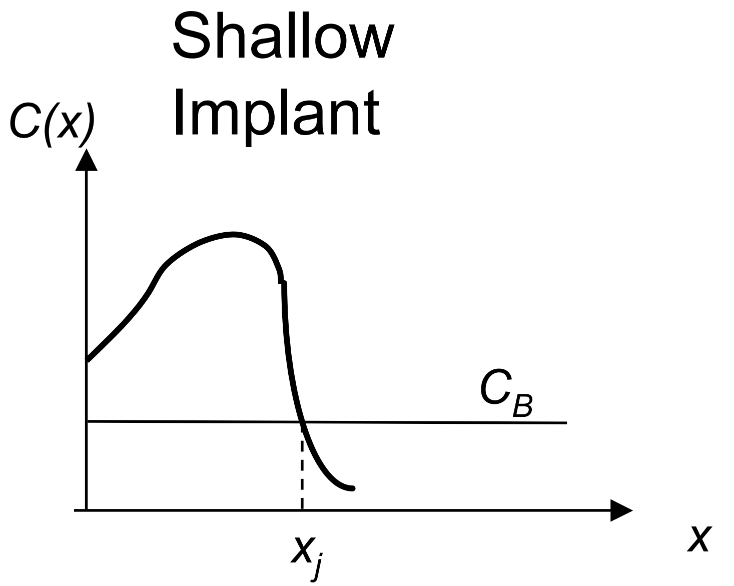
$$\approx \int_{-\infty}^{+\infty} C(x)\,dx$$

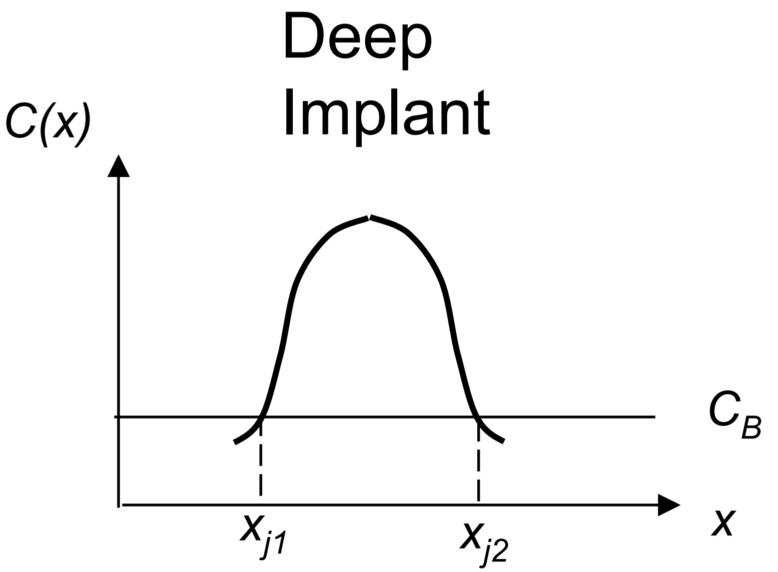
$$= C_p \cdot \left[\sqrt{2\pi} \cdot \Delta R_p\right]$$



$$\therefore C_p = \frac{\phi}{\sqrt{2\pi}\cdot\Delta R_p} \cong \frac{0.4\phi}{\Delta R_p}$$

Junction Depth, x_j





$C(x = x_j) = N_B$ = Bulk Conc. $\Rightarrow$ Solution for x_j

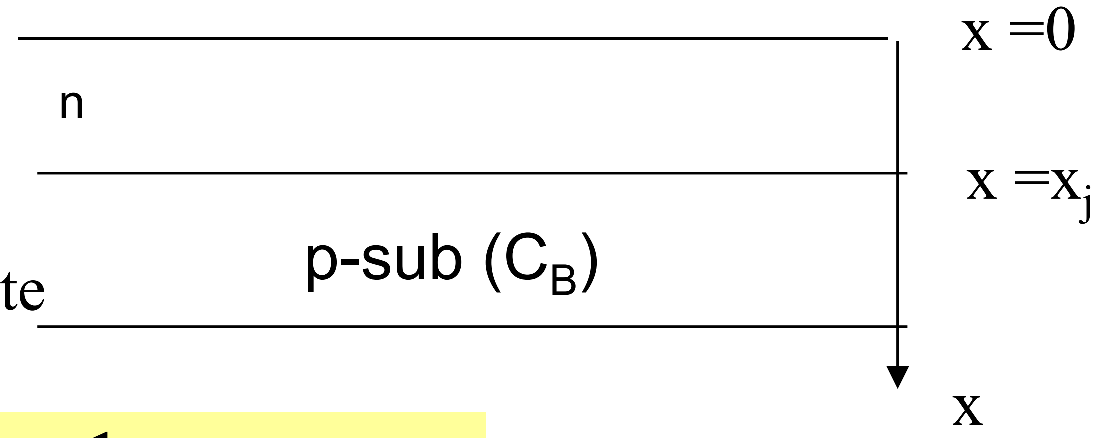
If Gaussian approx for C(x) is used , from

$$C_p \exp\left[- (x_j - R_p)^2 / 2(\Delta R_p)^2 \right] = C_B$$

we can solve for x_j .

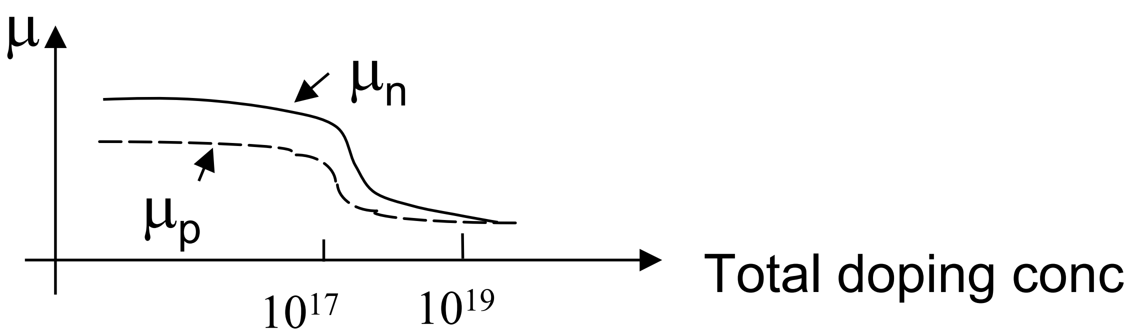
Sheet Resistance R_S of Implanted Layers

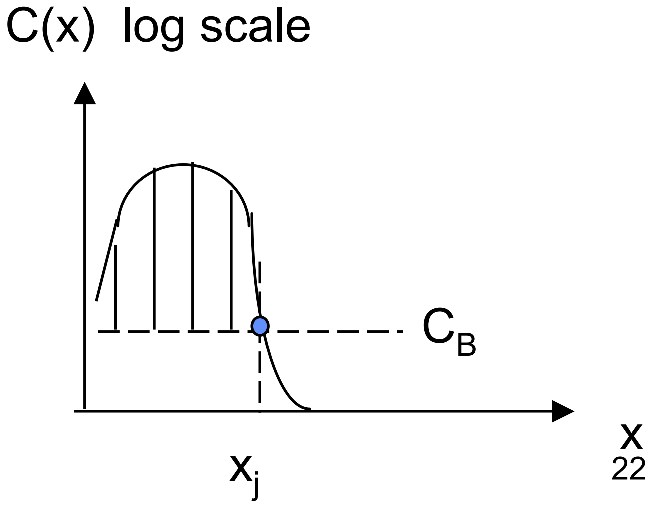
Example:
n-type dopants
implanted
into p-type substrate



$$\mathbf{R_S = \frac{1}{\int_0^{x_j} q \cdot \mu(x)\left[C(x) - C_B\right] dx}}$$

•Needs numerical integration to get Rs value





Approximate Value for R_S

If C(x) >>C_B for most depth x of interest
and use approximation: μ(x) ~ constant

$$\Rightarrow R_s \rightarrow \frac{1}{q\mu\int_0^{x_j} C(x)dx} \cong \frac{1}{q\mu\phi}$$

This expression assumes ALL implanted dopants are 100% electrically activated

$$R_s \cong \frac{1}{q\mu\phi}$$

use the μ for the highest doping region which carries most of the current

$$[R_s] = ohm/\square$$

or ohm/square

Example Calculations

200 keV Phosphorus is implanted into a p-Si ($C_B = 10^{16}/\text{cm}^3$) with a dose of $10^{13}/\text{cm}^2$.

From graphs or tables , $R_p = 0.254\ \mu\text{m}$, $\Delta R_p = 0.0775\mu\text{m}$

(a) Find peak concentration

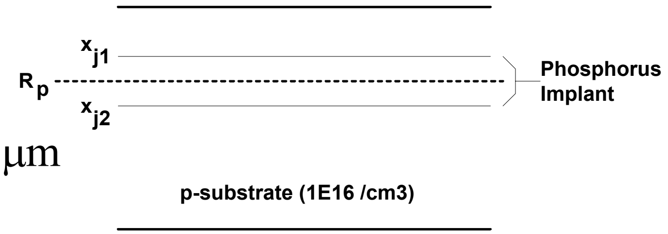
$$C_p = (0.4 \times 10^{13})/(0.0775 \times 10^{-4}) = 5.2 \times 10^{17}/\text{cm}^3$$

(b) Find junction depths

(b) $C_p \exp[-(x_j - 0.254)^2 / 2\,\Delta R_p^{\,2}] = C_B$ with x_j in µm

$\therefore\ (x_j - 0.254)^2 = 2 \times (0.0775)^2 \ln[5.2 \times 10^{17}/10^{16}]$

or $x_j = 0.254 \pm 0.22\ \mu\text{m}$; $x_{j1} = 0.032\ \mu\text{m}$ and $x_{j2} = 0.474\ \mu\text{m}$



(c) Find sheet resistance

From the mobility curve for electrons (using peak conc as impurity conc), $\mu_n = 350\ \text{cm}^2/\text{V-sec}$

$$R_s = \frac{1}{q\mu_n\phi} = \frac{1}{1.6 \times 10^{-19} \times 350 \times 10^{13}} \approx 1780\ \Omega/\text{square}.$$

Common Approximations used to describe implant profiles

For reference only

1. Gaussian Distribution – Simple algebra
   - Good fit only near peak concentration regions

2. Pearson IV Distribution - 4 shape-parameters, messy algebra
   - Better fit even down to low concentration regions.
   - Default model used in CAD tools.

$$f(x) = K\left(-\left(b_0 + b_1\cdot(x-R_p) + b_2\cdot(x-R_p)^2\right)\right)^{\left(\frac{1}{2\cdot b_2}\right)}\cdot$$

$$\cdot\exp\left(-\frac{b_1/b_2 + 2\cdot a}{\sqrt{4\cdot b_2\cdot b_0 - b_1^2}}\cdot\operatorname{atan}\left(\frac{2\cdot b_2\cdot(x-R_p)+b_1}{\sqrt{4\cdot b_2\cdot b_0 - b_1^2}}\right)\right)$$

In EE143, we use Gaussian approximations for convenience and simplicity.

Definitions of Profile Parameters

For reference only

(1) **Dose** $\phi = \int_0^\infty C(x)dx$

(2) **Projected Range**: $R_p \equiv \frac{1}{\phi}\int_0^\infty x \cdot C(x)dx$

(3) **Longitudinal Straggle**: $(\Delta R_p)^2 \equiv \frac{1}{\phi}\int_0^\infty (x - R_p)^2 \cdot C(x)dx$

(4) **Skewness**: $M_3 \equiv \frac{1}{\phi}\int_0^\infty (x - R_p)^3 C(x)dx$, $M_3 > 0$ or < 0

-describes asymmetry between left side and right side

(5) **Kurtosis**: $\propto \int_0^\infty (x - R_p)^4 C(x)dx$

Kurtosis characterizes the contributions of the "tail" regions