EE143 – Fall 2016
Microfabrication Technologies

Lecture 7: Ion Implantation
Reading: Jaeger Chapter 5

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Ion Implantation - Overview

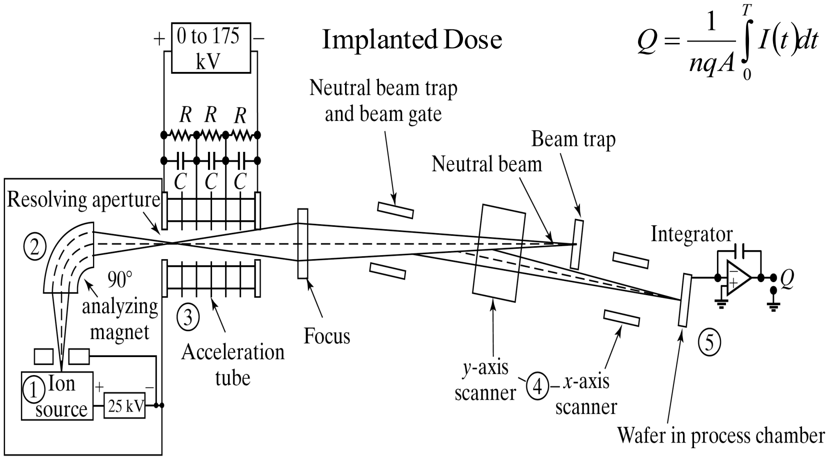
- **Wafer is target in high energy accelerator**
- **Impurities “shot” into wafer**
- **Preferred method of adding impurities to wafers**
  - **Wide range of impurity species (almost anything)**
  - **Tight dose control (A few % vs. 20-30% for high temperature pre-deposition processes)**
  - **Low temperature process**
- **Expensive systems**
- **Vacuum system**

Equipment

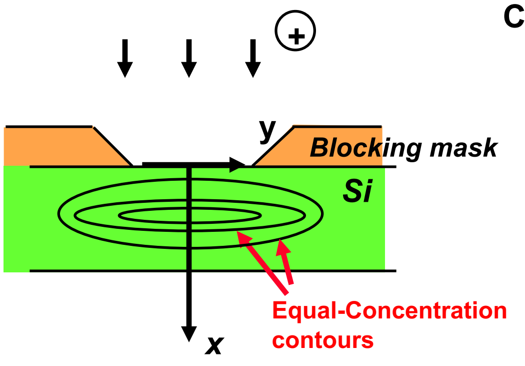
Force on charged particle $\vec{\mathbf{F}} = \mathrm{q}\left(\vec{\mathbf{v}} \text{ x } \vec{\mathbf{B}}\right)$

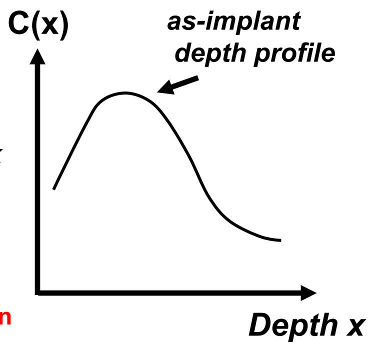
Magnetic Field $\left|\vec{\mathbf{B}}\right| = \sqrt{\frac{2mV}{qr^2}}$

Implanted Dose $Q = \frac{1}{nqA}\int_0^T I(t)dt$



Ion Implantation



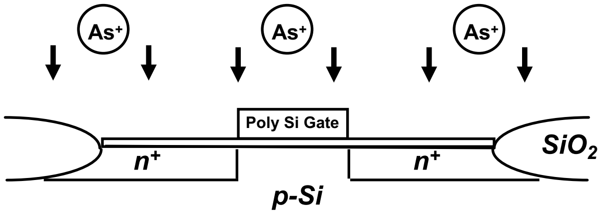


During implantation, temperature is ambient.
Post-implant annealing step (> 900°C) is required to anneal out defects.

Advantages of Ion Implantation

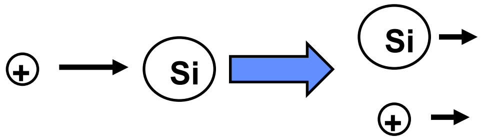
- **Precise control of dose and depth profile**
- **Low-temperature process (can use photoresist as mask)**
- **Wide selection of masking materials**
- **e.g. photoresist, oxide, poly-Si, metal**
- **Less sensitive to surface cleaning procedures**
- **Excellent lateral uniformity (< 1% variation across 12" wafer)**

Application example: self-aligned MOSFET source/drain regions



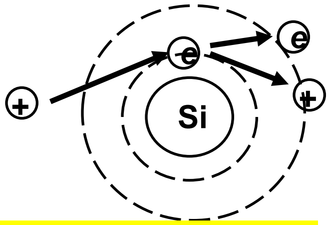
Ion Implantation Energy Loss Mechanisms

Nuclear stopping



Crystalline Si substrate damaged by collision

Electronic stopping



Electronic excitation creates heat

Ion Energy Loss Characteristics

Light ions/at higher energy → more electronic stopping

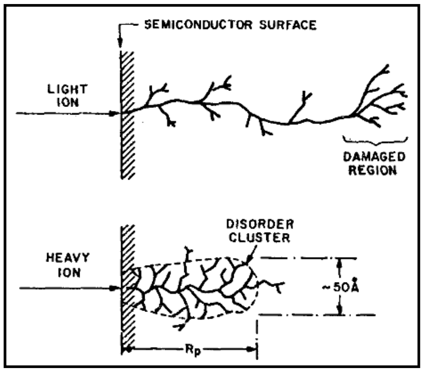
Heavier ions/at lower energy → more nuclear stopping

EXAMPLES
Implanting into Si:

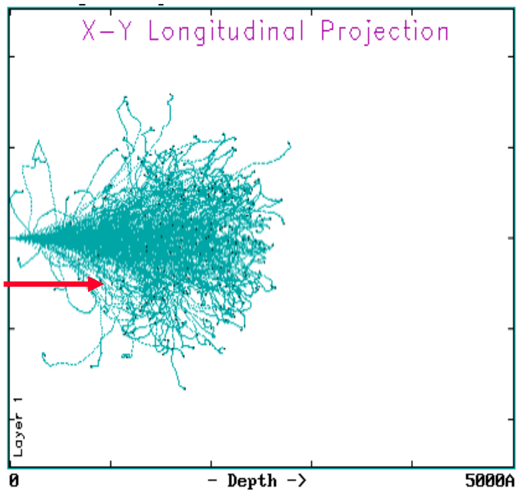
H^+ ⇨ Electronic stopping dominates

B^+ ⇨ Electronic stopping dominates

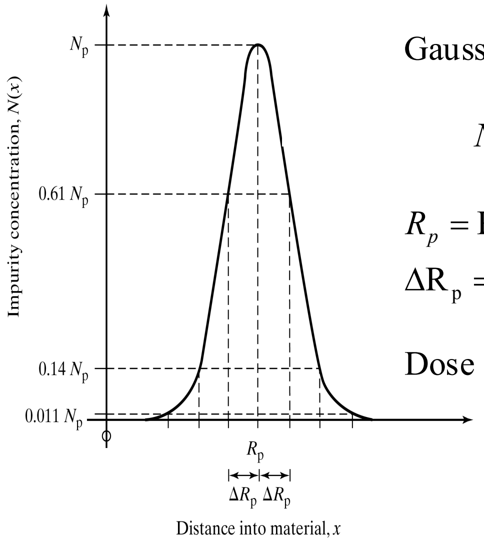
As^+ ⇨ Nuclear stopping dominates



Simulation of 50 keV Boron implanted into Si



Model for blanket implantation



Gaussian Profile

$$N(x) = N_p \exp\left[-\frac{(x - R_p)^2}{2\Delta R_p^2} \right]$$

R_p = Projected Range

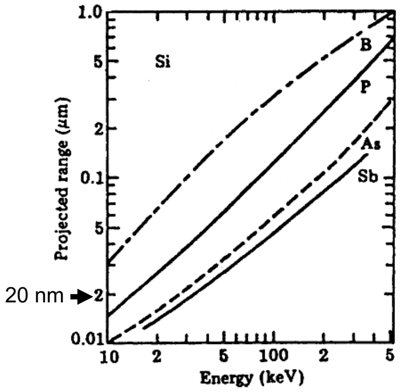
ΔR_p = Straggle

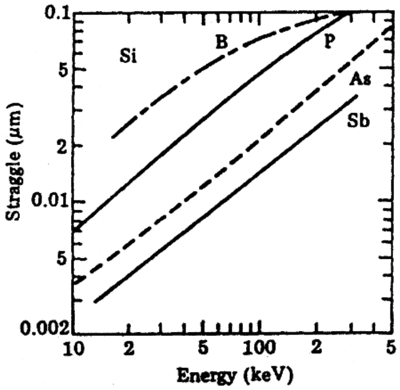
Dose $\quad Q = \int_0^\infty N(x)dx = \sqrt{2\pi} N_p \Delta R_p$

Projected Range and Straggle

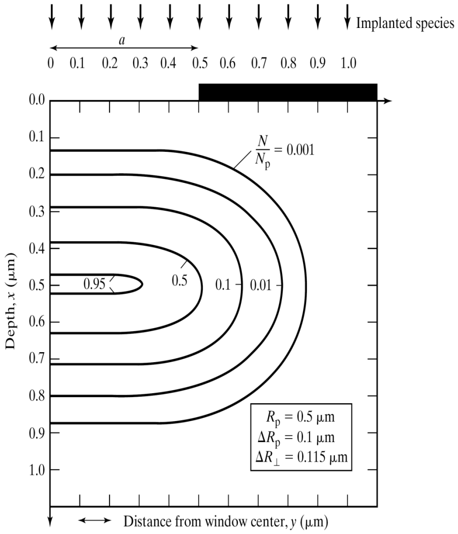
R_p and ΔR_p values are given in tables or charts

e.g. see pp. 113 of Jaeger





Selective Implantation



$$N(x,y) = N(x)F(y)$$

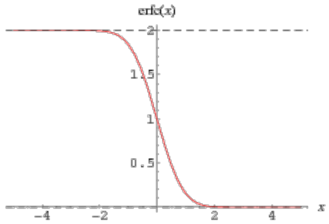
$$F(y) = \frac{1}{2}\left[erfc\left(\frac{y-a}{\sqrt{2}\Delta R_\perp} \right) - erfc\left(\frac{y+a}{\sqrt{2}\Delta R_\perp} \right) \right]$$

$\Delta R_\perp$ = transverse straggle

N(x) is one-dimensional solution

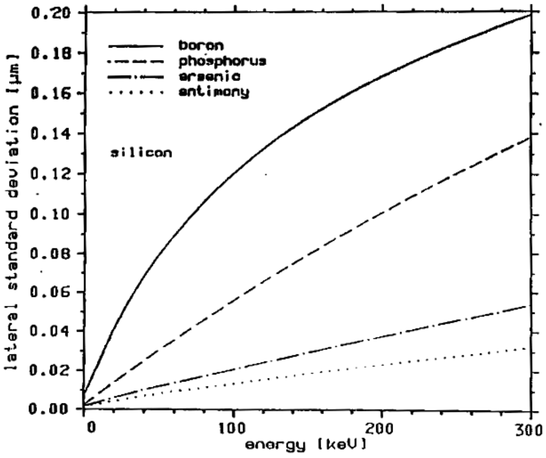
Complementary error function:

$$erfc(x) = 1 - erf(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$$



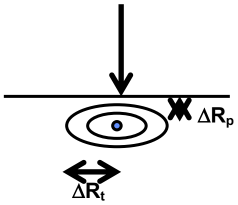
Transverse (or Lateral) Straggle
(ΔR_t or $\Delta R_\perp$)

ΔR_t

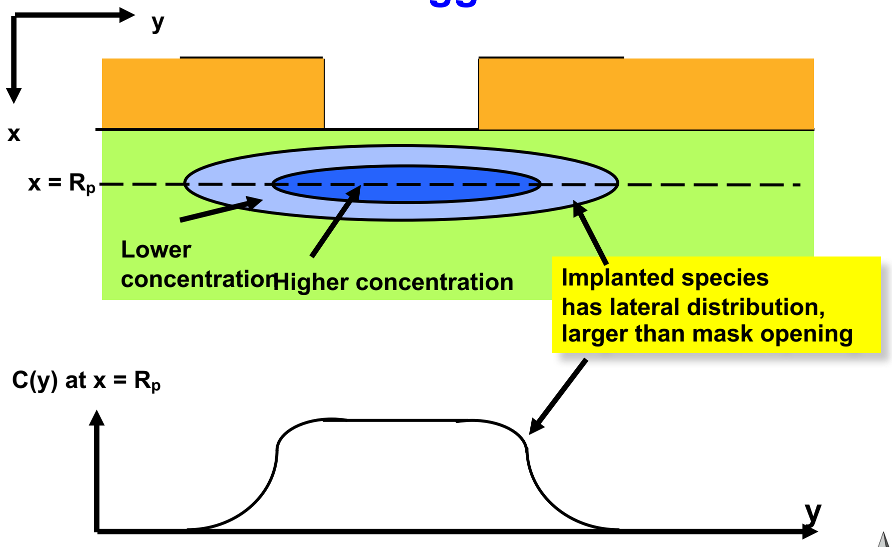


Lateral standard deviation of boron, phosphorus, arsenic and antimony in silicon

$$\frac{\Delta R_t}{\Delta R_\perp} > 1$$



Feature Enlargement due to Lateral Straggle



Implanted species has lateral distribution, larger than mask opening

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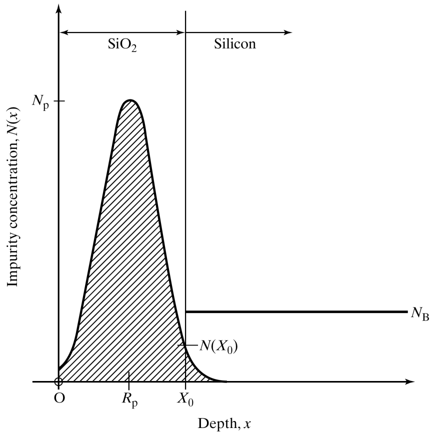
Selective Implantation – Mask Thickness



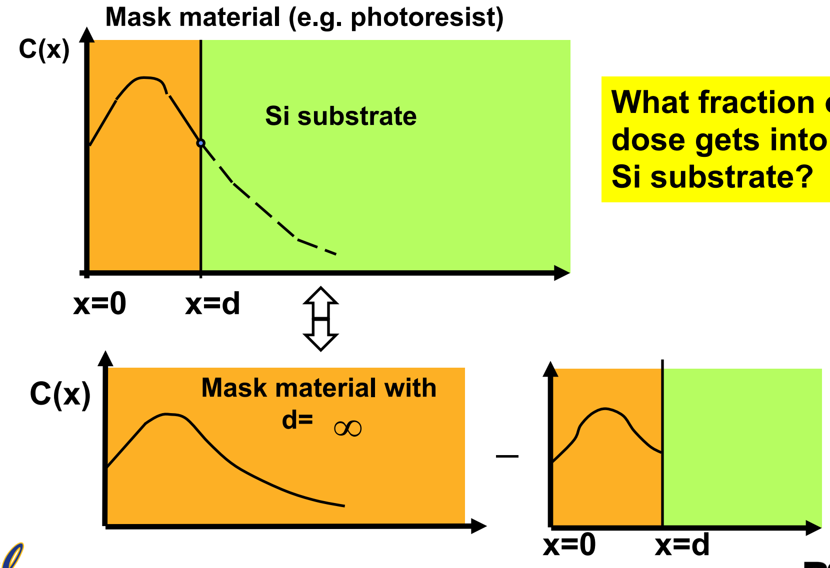
- Desire implanted impurity level under the mask should be much less than background doping

$$N(x_0) \ll N_B$$

or

$$N(x_0) < \frac{N_B}{10}$$

Transmission Factor of Implantation Mask



What fraction of dose gets into Si substrate?

Transmitted Fraction

$$T = \int_0^\infty C(x)dx - \int_0^d C(x)dx$$

$$= \frac{1}{2}\, erfc\left\{\frac{d - R_p}{\sqrt{2}\Delta R_p}\right\}$$

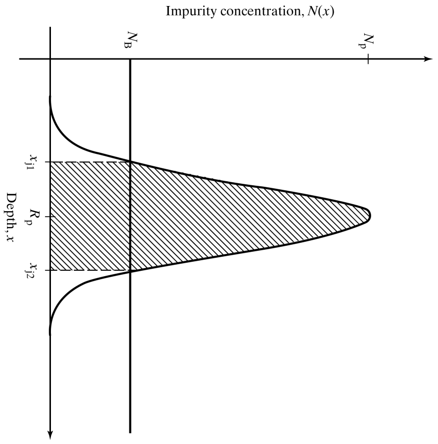
$$erfc(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-y^2}dy$$

R_p, ΔR_p
are values of
for ions into
the masking material

Rule of thumb: Good masking thickness

$$d = R_p + 4.3\Delta R_p \qquad \frac{C(x=d)}{C(x=R_p)} \sim 10^{-4}$$

Junction Depth



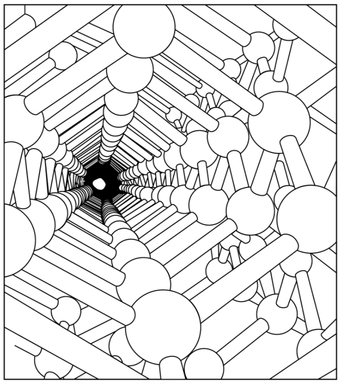
- The junction depth is calculated from the point at which the implant profile concentration = bulk concentration:

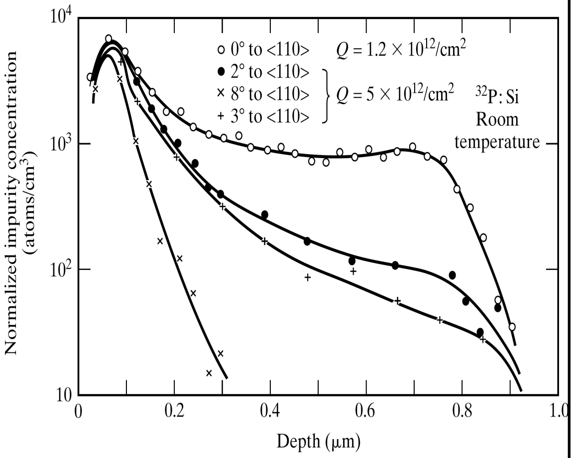
$$N(x_j) = N_B$$

$$N_p \exp\left[-\frac{(x_j - R_p)^2}{2\Delta R_p^2}\right] = N_B$$

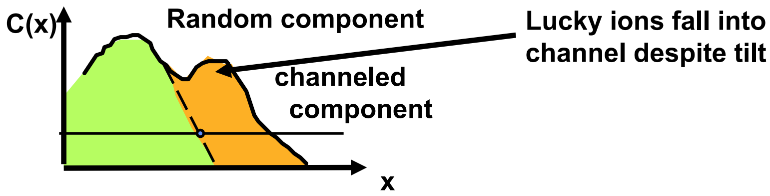
$$x_j = R_p \pm \Delta R_p \sqrt{2\ln\left(\frac{N_p}{N_B}\right)}$$

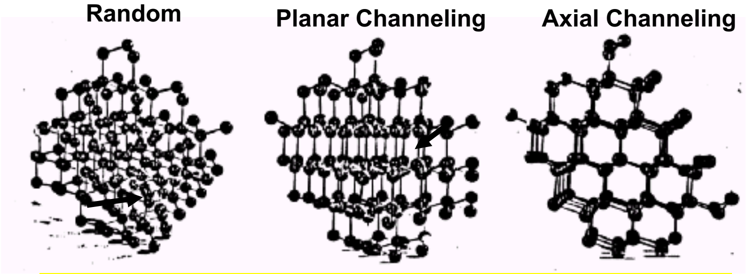
Channeling





Use of tilt to reduce channeling



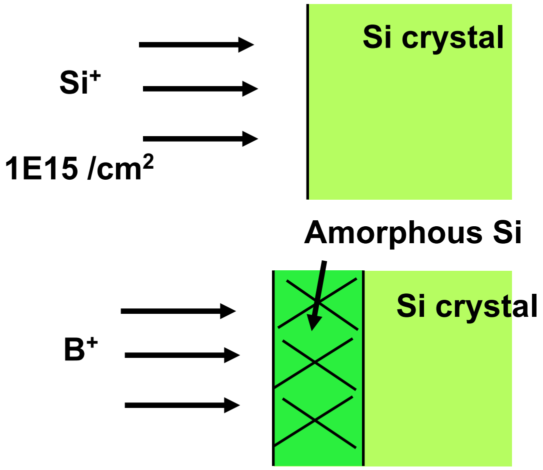


To minimize channeling, we tilt wafer by 7° with respect to ion beam.

Prevention of Channeling by Pre-amorphization

Step 1
High dose Si+ implantation to covert surface layer into amorphous Si

Step 2
Implantation of desired dopant into amorphous surface layer



Disadvantage:
Needs an additional high-dose implantation step

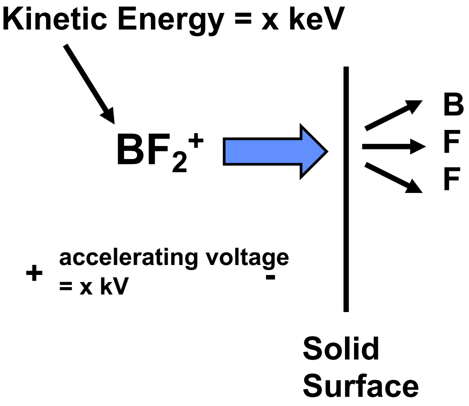
Kinetic Energy of Multiply Charged Ions

With Accelerating Voltage = x kV

Singly charged	B^+ P^+ As^+	Kinetic Energy = x · keV
Doubly charged	B^{++}	Kinetic Energy = 2x · keV
Triply charged	B^{+++}	Kinetic Energy = 3x · keV

Note:
Kinetic energy is expressed in eV. An electronic charge q experiencing a voltage drop of 1 Volt will gain a kinetic energy of 1 eV

Molecular Ion Implantation



Molecular ion will dissociate immediately into atomic components after entering a solid. *All atomic components will have same velocity after dissociation*.

B has 11 amu
F has 19 amu

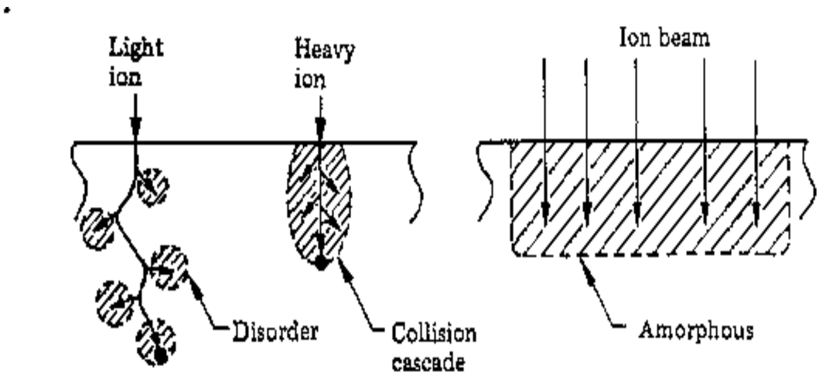
$$\text{Velocity} \quad v_B = v_F = v_F$$

$$\text{K.E. of B} = \frac{1}{2} m_B \cdot v_B{}^2$$

$$\text{K.E. of F} = \frac{1}{2} m_F \cdot v_B{}^2$$

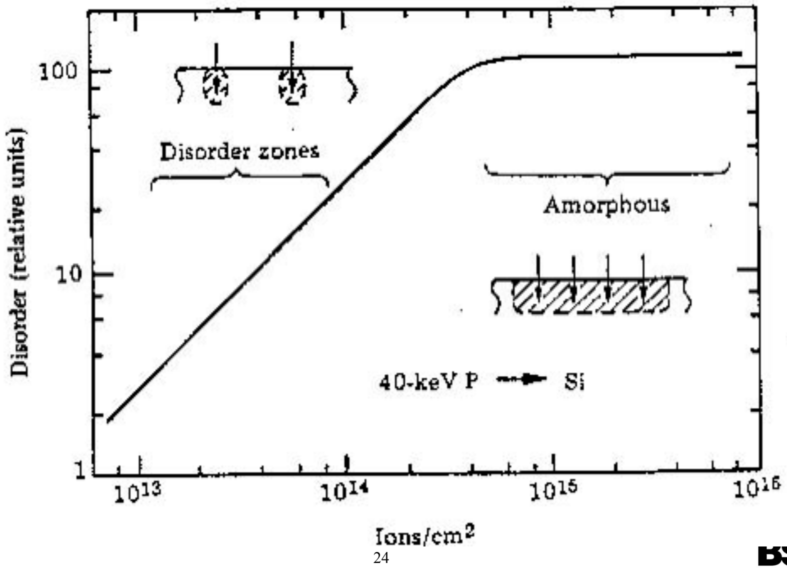
$$\frac{\text{K.E. of B}}{\text{K.E. of BF}_2{}^+} \approx \frac{11}{11+19+19} = 20\%$$

Implantation Damage



Schematic of the disorder produced along the individual paths of light and heavy ions and the formation of an amorphous region.

Amount and Type of Crystalline Damage



Post-Implantation Annealing Summary

- After implantation, we need an annealing step
- A typical anneal will:
  1. Restore Si crystallinity.
  2. Place dopants into Si substitutional sites for electrical activation

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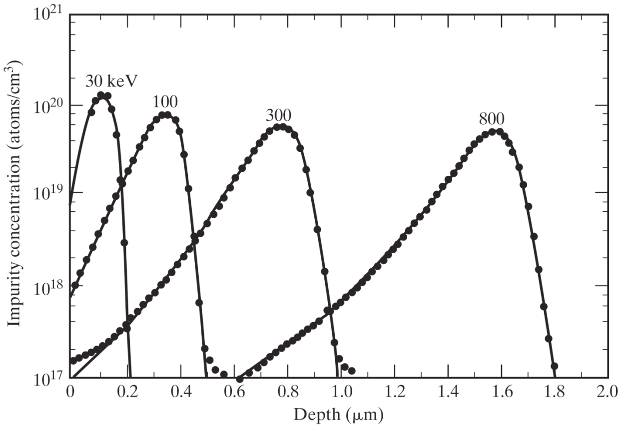
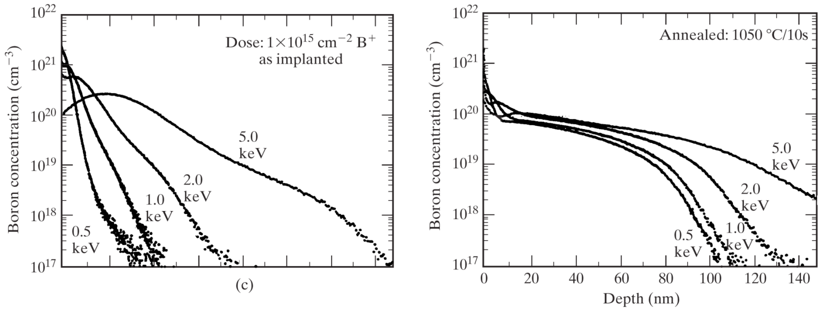
Deviation from Gaussian Theory



- Curves deviate from Gaussian for deeper implants (> 200 keV)

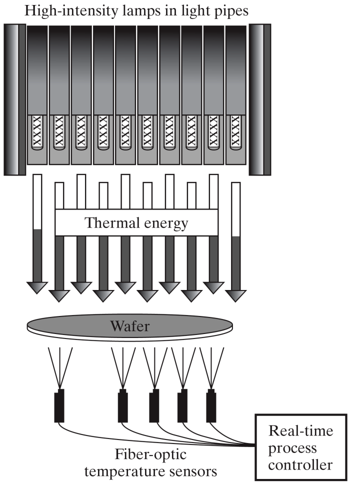
Shallow Implantation



(c)

(d)

Rapid Thermal Annealing



(a)

- **Rapid Heating**
- **950-1050° C**
- **>50° C/sec**
- **Very low dopant diffusion**

(b)

Dose-Energy Application Space