1) Implant Profile depends only on incident ion momentum, NOT on charge state

\[ \text{Same momentum} \quad \rightarrow \quad \text{Same implant profile} \]

Note: Kinetic Energy = \( \frac{(\text{momentum})^2}{2M} \)

2) Charge carried by ions will be neutralized by charges in the substrate after implantation.

3) n, p, Nd+, Na- charges in semiconductors are caused by the chemistry of the implanted dopants, and are NOT related to charges carried by the ions.
Kinetic Energy of Multiple Charged Ions

accelerating voltage = $x \text{ kV}$

- Singly charged: $B^+$, $P^+$, $As^+$
  - Kinetic Energy = $x \cdot \text{keV}$
- Doubly charged: $B^{++}$
  - Kinetic Energy = $2x \cdot \text{keV}$
- Triply charged: $B^{+++}$
  - Kinetic Energy = $3x \cdot \text{keV}$
Molecular Ion Implantation

Kinetic Energy = x keV

\[ \text{B} \text{F}_2^+ \rightarrow \text{B} \text{F} \text{F} \]

- accelerating voltage = x kV

B has 11 amu
F has 19 amu

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

Velocity \( v_B = v_F = v_F \)

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

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

\[ \frac{\text{K.E. of } B}{\text{K.E. of } \text{B} \text{F}_2^+} \approx \frac{11}{11+19+19} = 20\% \]
All Atomic Components have same Velocity…

Binding energy of molecule (~ several eV) is **negligible** compared with implantation energy (many keV).

\[
\frac{1}{2}m_B v_B^2 + 2\left(\frac{1}{2}m_F v_F^2\right) = \frac{1}{2}m_B v'_B^2 + 2\left(\frac{1}{2}m_F v'_F^2\right) \quad [1]
\]

\[
(m_B + 2m_F)v_B = m_B v'_B + 2m_F v'_F \quad [2]
\]

The only way to satisfy both [1] and [2] is:

\[v'_B = v'_F = v_B = v_F.\]
Molecular Implantation for Shallow Junctions

For conventional beamline implanters
Beam current $I \downarrow$ as accelerator voltage $\downarrow$

$B^+ \quad I (B^+) \downarrow$ as voltage $< 5\text{kV}$

$BF_2^+ \quad I (BF_2^+) \text{ can still be high with } 25\text{kV}$
accelerating voltage but the effective B implantation energy is $\sim 5\text{ keV}$

*For ultra-shallow junction which needs $\sim 1\text{keV} \text{ B}^+ \text{ energy, } B_{10}H_{14}(+) \text{ at } \sim 10\text{keV is proposed}
After implantation, we need an annealing step. A typical ~900°C, 30min will:

1. Restore Si crystallinity.

2. Put dopants into Si substitutional sites for electrical activation.
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

Diagram showing the relationship between disorder (relative units) and ions per cm². The x-axis represents ions per cm², ranging from $10^{13}$ to $10^{16}$, and the y-axis represents disorder in relative units, ranging from 1 to 100. The graph shows a clear transition from crystalline to amorphous states at high ion doses.
Solid Epitaxial “Growth” through the Implant Damaged Region

$tr = \text{regrown layer thickness}$
Solid Epitaxial “Growth” through the Implant Damaged Region – cont.

1. Regrow the amorphous region at $T = 500-600^\circ\text{C}$ into single crystal. The substrate acts as a seed. If higher temperatures are used then nucleation within the amorphous layer takes place making it polycrystalline and crystal structure can never be regained. This temperature range also recovers most of the electrical activity.

2. A further anneal at $T>900^\circ\text{C}$ restores the crystal structure and electrical activity 100%.
Dopant Activation Versus Annealing Temp

**Figure 5.15** Fraction of implanted boron activated in silicon for several isochronal anneals (after Seidel and MacRae, reprinted by permission, Elsevier Science).
Dopant Activation

* Sheet Resistance is limited by dopant solid solubility
* Shallower junctions will have higher $R_S$

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**Data from "As Rs Limits"**

**Data from "B Rs Limits"**

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Professor N Cheung, U.C. Berkeley
To minimize channeling, we tilt wafer by 7° with respect to ion beam.
"Lucky Ions"

Some scattered ions fall into other channeling directions, causing deeper penetration.

No Channeling

With channeling tail

$C(x)$

$x_j$

$x_j'$
Prevention of Channeling by Pre-amorphization

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

Si+ 1 E15/cm²

Step 2
Implantation of desired dopant into amorphous surface layer

B⁺

Disadvantage: Needs an additional high-dose implantation step
Transverse (or Lateral) Straggle ($\Delta R_t$ or $\Delta R_\perp$)

\[
\frac{\Delta R_t}{\Delta R_p} > 1
\]

Lateral standard deviation of boron, phosphorus, arsenic and antimony in silicon
Lateral Scattering Causes Feature Enlargement

\( y \)

\( x = R_p \)

Higher concentration

Lower concentration

Implanted specie has lateral distribution, larger than mask opening

\( C(y) \) at \( x = R_p \)
A 2-D formulation of Implantation Profile

\[ C(x, y) = K \cdot C(x) \cdot \int_{-a}^{+a} e^{\frac{-(y-y')^2}{2(\Delta R_t)^2}} \, dy \]

\[ = K \cdot C(x) \left[ \text{erfc} \left( \frac{y - a}{\sqrt{2}\Delta R_t} \right) - \text{erfc} \left( \frac{y + a}{\sqrt{2}\Delta R_t} \right) \right] \]
A 2-D formulation of Implantation Profile – cont.

For \( a \to \infty \) (i.e. no mask)

\[ C(x, y) = C(x) \]

\[ \therefore C(x, y) = C(x) \cdot K \cdot [\text{erfc}(-\infty) - \text{erfc}(+\infty)] \]

\[ C(x) = C(x) \cdot K \cdot 2 \]

\[ \therefore K = \frac{1}{2} \]
Semi-log Plots of Gaussian and erfc functions

(details of erfc function also covered in Diffusion section of EE143 Reader)

\[ \chi = \frac{x}{2\sqrt{Dr}} \]

Normalized distance from surface, \( \chi \)

[Curves also given in Jaeger]
Transmission Factor of Implantation Mask

What fraction of dose gets into Si substrate?

Mask material (e.g. photoresist) vs. Si substrate

Mask material with \( d = \infty \)
Transmitted Fraction

\[ T = \int_0^\infty C(x) \, dx - \int_0^d C(x) \, dx \]

\[ = \frac{1}{2} \text{erfc} \left( \frac{d - R_p}{\sqrt{2\Delta R_p}} \right) \]

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

Rule of thumb: Good masking thickness

\[ d = R_p + 4.3\Delta R_p \]

\[ \frac{C(x = d)}{C(x = R_p)} \sim 10^{-4} \]

\( R_p, \Delta R_p \) are values of for ions into the masking material.