Ion Implantation

Concentration Profile versus Depth is a single-peak function

Reminder: During implantation, temperature is ambient. However, post-implant annealing step (>900°C) is required to anneal out defects.
Advantages of Ion Implantation

- Precise control of **dose** and **depth** 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)

**Application example**: self-aligned MOSFET source/drain regions

![Diagram of self-aligned MOSFET source/drain regions with As⁺ ions implanted into p-Si]
Monte Carlo Simulation of 50keV Boron implanted into Si

- Ion Type = B (11 amu)
- Ion Energy = 50 keV
- Ion Angle = 0 degrees

**TARGET LAYERS**

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5000A</td>
<td>2.321</td>
</tr>
</tbody>
</table>

**Atom Colors**

**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

C(x) in #/cm\(^3\)

\[ \phi = \int_{0}^{\infty} C(x)\,dx \]

[Conc] = # of atoms/cm\(^3\)
[dose] = # of atoms/cm\(^2\)
Mask layer thickness can block ion penetration

- Photoresist: SiO$_2$, Si$_3$N$_4$, or others
- Thick Mask
  - Complete blocking
- Thin Mask
  - No blocking
  - Incomplete Blocking

SUBSTRATE
Ion Implanter

e.g. \(\text{AsH}_3\), \(\text{As}^+, \text{AsH}^+, \text{H}^+, \text{AsH}_2^+\)

Translational wafer holder motion.

$3-4M$/implanter

$\sim$60 wafers/hour

Accuracy of dose: <0.5%

Uniformity <1% for 8” wafer

Accelerator Voltage: 1-200kV

Dose \(\sim 10^{11}-10^{16}/\text{cm}^2\)

Ion source

Magnetic Mass separation

Ion beam (stationary)

spinning wafer holder

Accelerator Column

wafer
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.
Implantation Dose

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

\[
\Phi = \left( \frac{\text{Ion Beam Current in amps}}{q} \right) \times \left( \frac{\text{Implant area}}{\text{Implant time}} \right)
\]

\[
= \frac{\#}{cm^2}
\]

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.

<table>
<thead>
<tr>
<th></th>
<th>E1(keV)</th>
<th>E2(keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B into Si</td>
<td>3</td>
<td>17</td>
</tr>
<tr>
<td>P into Si</td>
<td>17</td>
<td>140</td>
</tr>
<tr>
<td>As into Si</td>
<td>73</td>
<td>800</td>
</tr>
</tbody>
</table>

**FIGURE 8.12** Rate of energy loss $dE/dx$ versus $(\text{energy})^{1/2}$, showing nuclear and electronic loss contributions.
More crystalline damage at end of range $S_n > S_e$

Less crystalline damage $S_e > S_n$

$S_n \equiv dE/dx|_n$

$S_e \equiv dE/dx|_e$

$E_o = \text{incident kinetic energy}$

Substrate

Depth $x$ ---- Surface

$E \approx 0$

$x \sim R_p$

$A^+$
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

Uniform implantation at all lateral positions

Uniform implantation at all lateral positions

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

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

\( R_p = \text{projected range} \)

\( \Delta R_p = \text{longitudinal straggle} \)
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 $\Delta$Rp values from Monte Carlo simulation
[see 143 Reader for other ions]

$$R_p = 51.051 + 32.60883 \times 10^{-7} E^2 + 3.758 \times 10^{-5} E^3 - 1.433 \times 10^{-8} E^4$$

$$\Delta R_p = 185.34201 + 6.5308 \times 10^{-3} E^2 + 2.098 \times 10^{-5} E^3 - 8.884 \times 10^{-9} E^4$$

(both theoretical & expt values are well known for Si substrate)
Dose-Concentration Relationship

Using Gaussian Approximation:

\[
\text{Dose} = \phi = \int_{0}^{\infty} C(x) \, dx = \left[ \sqrt{2\pi \cdot \Delta R_p} \right] \cdot C_p
\]

\[
\approx \int_{-\infty}^{+\infty} \hat{C}(x) \, dx
\]

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

\[
\therefore C_p = \frac{\phi}{\sqrt{2\pi \cdot \Delta R_p}} \approx 0.4\phi \frac{1}{\Delta R_p}
\]
Junction Depth, $x_j$

**Shallow Implant**

$C(x)$

$x_j$

$C_B$

**Deep Implant**

$C(x)$

$x_{j1}$

$x_{j2}$

$C_B$

\[ C( x = x_j ) = N_B = \text{Bulk Conc.} \Rightarrow \text{Solution for } x_j \]

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

\[
C_p \exp \left[ - \frac{(x_j - R_p)^2}{2(\Delta R_p)^2} \right] = C_B
\]

we can solve for $x_j$. 
Sheet Resistance $R_S$ of Implanted Layers

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

$$R_S = \frac{1}{\int_{0}^{x_j} q \cdot \mu(x) [C(x) - C_B] \, dx}$$

- Needs numerical integration to get $R_S$ value
- $C(x)$ log scale

$n$-type dopants implanted into $p$-type substrate

$x = 0$

$x = x_j$

$\mu_p$, $\mu_n$

Total doping conc

$10^{17}$ $10^{19}$

$C_B$

$x_j$
Approximate Value for $R_S$

If $C(x) \gg C_B$ for most depth $x$ of interest and use approximation: $\mu(x) \sim \text{constant}$

$$\Rightarrow R_S \rightarrow \frac{1}{q\mu \int_0^x C(x) \, dx} \approx \frac{1}{q\mu \phi}$$

$R_S \approx \frac{1}{q\mu \phi}$

$[R_S] = \text{ohm}$

or ohm/square

**Note:** This expression assumes ALL implanted dopants are 100% electrically activated.

**Use the $\mu$ for the highest doping region which carries most of the current.**
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

\[C_p = \frac{0.4 \times 10^{13}}{0.0775 \times 10^{-4}} = 5.2 \times 10^{17}/\text{cm}^3\]

(b) Find junction depths

(b) \(C_p \exp\left[-\left(x_j - 0.254\right)^2/2 \Delta R_p^2\right] = C_B\) with \(x_j\) in \(\mu\text{m}\)

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

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

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.

\[
\int f(x) = K \left( \frac{1}{b_0 + b_1 \cdot (x - R_p) + b_2 \cdot (x - R_p)^2} \right)^{\frac{1}{2 \cdot b_2}} \cdot \exp \left( -\frac{b_1}{2} + 2 \cdot a \cdot \frac{1}{\sqrt{4 \cdot b_2 \cdot b_0 - b_1^2}} \cdot \tan \left( \frac{2 \cdot b_2 \cdot (x - R_p) + b_1}{\sqrt{4 \cdot b_2 \cdot b_0 - b_1^2}} \right) \right)
\]

In EE143, we use Gaussian approximations for convenience and simplicity.
Definitions of Profile Parameters

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

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

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

(4) **Skewness**:  \( M_3 = \frac{1}{\phi} \int_0^\infty (x - R_p)^3 C(x)dx \quad M_3 > 0 \text{ or } < 0 \)
- describes asymmetry between left side and right side

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

*Kurtosis* characterizes the contributions of the “tail” regions