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]
Monte Carlo Simulation of 50keV Boron implanted into Si

You can download this program from http://www.srim.org/index.htm
(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

\[ C(x) \text{ in } \#/\text{cm}^3 \]

\[ \text{dose } \phi = \int_0^{\infty} C(x) dx \]

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

photoresist  
\[ \text{SiO}_2, \quad \text{Si}_3\text{N}_4, \quad \text{or others} \]

Complete blocking  
No blocking  
Incomplete Blocking

SUBSTRATE
Ion Implanter

e.g. AsH$_3$
As$^+$, AsH$^+$, H$^+$, AsH$_2^+$

Magnetic Mass separation

Ion source

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

$3-4$M/implanter
~60 wafers/hour

Translational wafer holder motion.

ion beam (stationary)

spinning wafer holder

~60 wafers/hour
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$^+$)

\[
\Phi = \frac{\text{Ion Beam Current inamps}}{q} \times \frac{\text{Implant time}}{\text{[Ion Beam Scanning Area]}}
\]

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

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
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
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.
\( S_n \equiv \frac{dE}{dx}|_n \)
\( S_e \equiv \frac{dE}{dx}|_e \)

More crystalline damage at end of range \( S_n > S_e \)

Less crystalline damage \( S_e > S_n \)

\( E \sim 0 \)
\( E = E_0 \)

Depth \( x \) → Surface

\( x \sim R_p \)

\( E_0 = \) incident kinetic energy

Substrate

\( A^+ \)
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

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

\( R_p = \) projected range

\( \Delta R_p = \) longitudinal straggle

Note: This is for no masking
Projected Range and Straggle

Rp and \( \Delta R_p \) values are given in tables or charts
e.g. see pp. 113 of Jaeger

Note: this means 0.02 \( \mu \text{m} \).
Rp and ∆Rp values from Monte Carlo simulation

[see 143 Reader for other ions]

\[ \text{Rp} = 51.051 + 32.60883 \times 10^{-6} E^2 + 3.758 \times 10^{-5} E^3 - 1.433 \times 10^{-8} E^4 \]

\[ \text{ΔRp} = 185.34201 + 6.5308 \times 10^{-2} E^2 + 2.098 \times 10^{-5} E^3 - 8.884 \times 10^{-9} E^4 \]

(both theoretical & expt values are well known for Si substrate)
Using Gaussian Approximation:

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

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

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

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

- **Shallow Implant**
  - $C(x)$
  - $x_j$
  - $C_B$

- **Deep Implant**
  - $C(x)$
  - $x_{j1}$
  - $x_{j2}$
  - $C_B$

\[
C \left( x = x_j \right) = C_B = \text{Bulk Concentration}
\]

*If Gaussian approx for $C(x)$ is used:*

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

we can solve for $x_j$. 

Sheet Resistance $R_S$ of Implanted Layers

**Example:**

n-type dopants implanted into p-type substrate

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

- $n$-type doping
- $p$-type substrate ($C_B$)

- Needs numerical integration to get $R_S$ value

C(x) log scale

Total doping conc

Professor N Cheung, U.C. Berkeley
Approximate Value for $R_S$

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

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

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

$[R_s] = \text{ohm/square}$

This expression assumes ALL implanted dopants are 100% electrically activated

use the $\mu$ for the highest doping region which carries most of the current

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

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

(b) Find junction depths

\(C_p \exp\left[-\frac{(x_j - 0.254)^2}{2 \Delta R_p^2}\right] = C_B\) 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.

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

\[ \exp \left( -\frac{b_1}{b_2} + 2 \cdot a \cdot \frac{1}{\sqrt{4 \cdot b_2 \cdot b_0 - b_1^2}} \cdot \arctan \left( \frac{2 \cdot b_2 \cdot (x - R_p) + b_1}{\sqrt{4 \cdot b_2 \cdot b_0 - b_1^2}} \right) \right). \]

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**: \( R_p \equiv \frac{1}{\phi} \int_{0}^{\infty} x \cdot C(x) dx \)

(3) **Longitudinal Straggle**: \( (\Delta R_p)^2 \equiv \frac{1}{\phi} \int_{0}^{\infty} (x - R_p)^2 \cdot C(x) dx \)

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

- describes asymmetry between left side and right side

(5) **Kurtosis**: \( \sim \int_{0}^{\infty} (x - R_p)^4 C(x) dx \)

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