Section 6: Ion Implantation

Jaeger Chapter 5
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**

**Magnetic Field**

\[ \vec{F} = q(\vec{v} \times \vec{B}) \]

\[ |\vec{B}| = \sqrt{\frac{2mV}{qr^2}} \]

\[ Q = \frac{1}{nqA} \int_0^T I(t) dt \]

**Implanted Dose**

Neutral beam trap and beam gate

Neutral beam

Beam trap

Focus

y-axis scanner

x-axis scanner

Integrator

\[ Q \]

Resolving aperture

90° analyzing magnet

Ion source

+ 25 kV

+ 0 to 175 kV

Acceleration tube

Focus

y-axis scanner

x-axis scanner

Integrator

\[ Q \]

Wafer in process chamber
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 uniformity  (< 1% variation across 12” wafer)

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

![Diagram of self-aligned MOSFET source/drain regions](image-url)
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:

- $\text{H}^+$ → Electronic stopping dominates
- $\text{B}^+$ → Electronic stopping dominates
- $\text{As}^+$ → 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>
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<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>
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</tbody>
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Simulation of 50keV 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
- \( \Delta R_p = \) Straggle

Dose

\[ Q = \int_0^{\infty} N(x) dx = \sqrt{2\pi N_p \Delta R_p} \]
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 $0.02 \ \mu m$. 
Selective Implantation

\[ \frac{N}{N_p} = 0.001 \]

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

\[ \Delta R_{\perp} = \text{transverse straggle} \]

\[ N(x, y) = N(x)F(y) \]

\[ R_p = 0.5 \, \mu m \]
\[ \Delta R_p = 0.1 \, \mu m \]
\[ \Delta R_{\perp} = 0.115 \, \mu m \]
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.
Feature Enlargement due to lateral straggle

- Implanted species has lateral distribution, larger than mask opening
- Lower concentration
- Higher concentration

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

5. **Kurtosis**: \( K \equiv \int_0^\infty (x - R_p)^4 C(x)dx \)

*Kurtosis characterizes the contributions of the “tail” regions*
Selective Implantation – Mask thickness

- Desire Implanted Impurity Level to be Much Less Than Wafer Doping
  \[ N(X_0) \ll N_B \]
  or
  \[ N(X_0) < \frac{N_B}{10} \]
What fraction of dose gets into Si substrate?

Transmission Factor of Implantation Mask

Mask material (e.g. photoresist)

C(x)

Si substrate

x=0  x=d

Mask material with d=∞

x=0  x=d

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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

\[ d = R_p + 4.3\Delta R_p \quad \frac{C(x = d)}{C(x = R_p)} \sim 10^{-4} \]

\[ \text{erfc} dR \]

\[ R_p, \Delta R_p \]

are values of for ions into the \textbf{masking material}

\[ \Delta \pi \]

\[ R_p \]

\[ \Delta R_p \]
The junction depth is calculated from the point at which the implant profile concentration = bulk concentration:

\[ N(x_j) = N_B \]

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

\[ x_j = R_p \pm \Delta R_p \sqrt{2 \ln\left(\frac{N_p}{N_B}\right)} \]
Sheet Resistance $R_S$ of Implanted Layers

Example:

n-type dopants implanted into p-type substrate.

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

$x = 0$

$p$-sub ($C_B$)

$x = x_j$

$x$

$C_B$

$10^{17}$

$10^{19}$

$\mu_p$

$\mu_n$

Total doping conc
Approximate Value for $R_S$

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

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

This expression assumes ALL implanted dopants are 100% electrically activated

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

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

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

or ohm/square
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

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

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

or\[x_j = 0.254 \pm 0.22 \, \mu\text{m} \quad ; \quad x_{j1} = 0.032 \, \mu\text{m} \quad \text{and} \quad x_{j2} = 0.474 \, \mu\text{m}\]

(c) Find sheet resistance

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

\[R_s = \frac{1}{q\mu_n\phi} = \frac{1}{1.6 \times 10^{-19} \times 350 \times 10^{13}} \approx 1780 \, \Omega/\text{square}.\]
Use of tilt to reduce channeling

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

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

Random component

Lucky ions fall into channel despite tilt

C(x)

x

Random Channeling

Planar Channeling

Axial Channeling

Random

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 convert surface layer into amorphous Si

Si$^+$

1 E15/cm$^2$

Step 2
Implantation of desired dopant into amorphous surface layer

B$^+$

Disadvantage: Needs an additional high-dose implantation step
**Kinetic Energy of Multiply Charged Ions**

With 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 \(= 3x \cdot \text{keV}\)

**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

Kinetic Energy = x keV

$\text{BF}_2^+$

accelerating voltage = x kV

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

Velocity $v_B = v_F = v_F$

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

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

Disorder zones

Amorphous

40-keV P → Si

Disorder (relative units)

Ions/cm²

10^13

10^14

10^15

10^16

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(1) Restore Si crystallinity.

(2) Place dopants into Si substitutional sites for electrical activation.
Deviation from Gaussian Theory

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

Dose: $1 \times 10^{15} \text{ cm}^{-2} \text{ B}^+$ as implanted

Annealed: $1050 \, ^\circ\text{C}/10\text{s}$
Rapid Thermal Annealing

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