Chapter 5
Ion Implantation

- A process that utilizes accelerated ions to penetrate through a solid surface to alter the properties of semiconductor materials in the form of surface composition, structure, electrical, or over all property of the solid material
- Modification depends on the ion species, energy, and flux of the "ions"
- The implanted ions serve as dopants (or impurities)
- Ions can change the conductivity by more than a factor of 10E8 in some cases

Differences between Diffusion and Ion Implantation

- The penetration depth is controlled by adjusting the ion energy and the type of ions used – more controllable, compared to diffusion process
- Allows for the precise placement of ions at low temperatures – differs from diffusion
- The total number of ions incorporated into the solid is determined by the ion flux and the duration of implantation – more controllable number densities
- Applications – modifying the electrical properties of semiconductors and improving the mechanical or chemical properties of alloys, metals, and dielectrics
Some of the most commonly implanted species highlighted on the periodic table, along with typical concentration-vs-depth traces for various implant energies.

Wide Ranges of Ion Energy and Dose Are Applied

- Ion energy ranging from 1 keV to 10 MeV
- Ion penetration depth varies from 10 nm to 50 µm. Doses ranging from 10E10 to 10E18 ions/cm² are typically applied
- Difficult to get deeper penetration - requires extremely high energy ions
- Not suitable for changing the entire bulk property of a solid
- For high-dose applications, high ion currents are needed (for reasonable implantation time)
- IC fabrication requires many steps of ion implantation with different ion species and energies, so it is a time-consuming process
Dose and energy requirements of major implantation applications (species shown roughly in order of decreasing usage).

Ion Implantation Systems
Ion Implantation Technology: High Energy Accelerator

- Wafer is Target in High Energy Accelerator and Impurities are "shot" into the 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 and operates in Vacuum

(1) Ion Source (high voltage - plasma)
(2) Mass Spectrometer
(3) High-Voltage Accelerator (Up to 5 MeV)
(4) Scanning System
(5) Target Chamber
Ion Implantation: Motion of Charges

- Charged particles from the ion beam source move to the analyzer magnet with a velocity, and the beam is bent.
- The selected impurities (based on the velocity, mass, and energy, travel and reach the neutral beam trap, only allowing the ions to propagate to the target (wafer)
- Wafer is attached to the target holder where electrons can neutralize the implanted ions
- Current is measured, then the dose is determined

\[
\begin{align*}
\text{Force on charged particle} & \quad \vec{F} = q(\vec{v} \times \vec{B}) \\
\text{Magnetic Field} & \quad |\vec{B}| = \sqrt{\frac{2mV}{qr^2}} \\
\text{Implanted Dose} & \quad Q = \frac{1}{mqA} \int_{0}^{T} I(t) dt
\end{align*}
\]

- \(m\) = degree of ionization
- \(\vec{v}\) = velocity
- \(V\) = acceleration potential
- \(A\) = wafer area

Example

- If the wafer is biased so that the current flows to the wafer is 1 \(\mu A\), (a) what is the dose, if the implantation time is 20 minutes? (b) what is the energy capability of the machine, if it is operated at 1MV. Assume the wafer area is 0.2x0.2 cm\(^2\).
Gaussian (Normal) Distribution

- The variables of the distribution is as follows:

\[ f(x, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{- \frac{(x-\mu)^2}{2\sigma^2}} \]

- \(\mu\) is the “mean” or “expectation”
- \(\sigma\) is the “standard deviation”
- \(\sigma^2\) is the “variance”
Mathematical Model

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

Surface density ~ \(10^{15}/\text{cm}^2\)

3-D view of Gaussian function

Mathematical Model (2)

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 (standard deviation)

Dose

\[ Q = \int_0^\infty N(x) dx = \sqrt{2\pi} N_p \Delta R_p \]

Typical \(Q\) ~ \(10^{10}\) to \(10^{18}\) \(\text{cm}^3\)

Can be used as pre-deposition for a two-step diffusion
Projected Range & Straggle

Function of Energy & Mass of ions and target material

Projected range and straggle calculations Based on Lindhard-Scharff-Schiott (LSS) Theory (in amorphous silicon – assumes atoms in the base material are randomly positioned – assumed the results are the same for crystal-silicon)

Example 5.1

- Please work example at home.
Two Dimensional Ion Implantation

- Cross sectional view of the ion implantation in silicon
- As seen implantation creates a region of high density impurities in the base material (wafer).
- Contours represent the % of the impurities
- How do we calculate the range and struggle

3-D View of Distribution

ELEC 6730  Fall 2013  15
ELEC 6730  Fall 2013  16
Selective Implantation

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

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

\( \Delta R = \) transverse range

\( N(x) \) is a one-dimensional solution

\( a \) is the half-width of the window opening of the mask

Figure 5.4
Contours of equal ion concentration for an implantation into silicon through a 1-μm window. The profiles are symmetrical about the x-axis and were calculated using the equation above taken from Ref. [3].

Implantation into the Barrier Layer

How do we prevent altering the background concentration?

Desired Implanted Impurity Level to be Much Less Than Wafer Doping

\[ N(X_0) << N_B \]

or

\[ N(X_0) < N_B/10 \]

- Barrier materials: Silicon nitride, silicon dioxide, photosresist, metals
- Silicon nitride is the better barrier than silicon dioxide
- Metals cannot be used for diffusion as barrier, but for ions they mask better
- Photoresist is the worst barrier for ions
Implantation into the Barrier Layer

\[ N(x) = N_p \exp \left( -\frac{(x - R_p)^2}{2A_R^2} \right) \text{ at } x = \xi \]

\[ N_p \exp \left( -\frac{(X_o - R_p)^2}{2A_R^2} \right) < \left( \frac{N_B}{10} \right) \]

\[ X_o \geq R_p + \Delta R_p \sqrt{2 \ln \left( \frac{10N_p}{N_B} \right)} = R_p + m\Delta R_p \]

| TABLE 5.1 Values of \( m \) for Various Values of \( N_p/N_B \) |
|------------------|-------------|
| \( N_p/N_B \)    | \( m \)     |
| \( 10^{-2} \)    | 3.0         |
| \( 10^{-3} \)    | 3.7         |
| \( 10^{-4} \)    | 4.3         |
| \( 10^{-5} \)    | 4.8         |
| \( 10^{-6} \)    | 5.3         |
| \( 10^{-7} \)    | 5.7         |

Junction Depth & Sheet Resistance

- Used for shallow \( pn \) junction
- Profile approximates to a Gaussian profile – if surface is
- Depth can be found as:

\[ N(x_j) = N_B \]

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

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

Use Irvin’s curves to find sheet resistance

FIGURE 5.6
Junction formation by impurity implantation in silicon. Two \( pn \) junctions are formed at \( x_1 \) and \( x_2 \).
Junction Depth & Sheet Resistance

- Used for shallow $pn$ junction
- Profile approximates to a Gaussian profile – if surface is
- Depth can be found as:

$$N(x_j) = N_B$$

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

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

Use Irvin’s curves to find sheet resistance.

FIGURE 5.6

Junction formation by impurity implantation in silicon. Two $pn$ junctions are formed at $x_{i1}$ and $x_{i2}$.

Substrate surface can either be anywhere (either above the implantation or at the peak of implantation)
Example 5.2
• Please work example at home.

Example 5.3
• Please work example at home.

Example 5.1:
Phosphorus with an energy of 100 keV is implanted into a silicon wafer. (a) what are the range and straggle associated with this implantation? (b) what should be the implanted dose if a peak concentration of $1 \times 10^{17}$ cm$^{-2}$ is desired? (c) what length of time is required to implant this dose into a 200 mm wafer using a 2 μA beam current with singly ionized phosphorus?
Example 5.2:
A boron implantation is to be performed through a 50 nm gate-oxide so that the peak of the distribution is at the Si-SiO₂ interface. The dose of the implantation in silicon is to be 1x10¹³ cm⁻².
(a) What are the energy of the implant and the peak concentration at the interface?
(b) How thick should the SiO₂ layer be in areas that are not to be implanted, if the background concentration is 1x10¹⁶ cm⁻²?
(c) Suppose the oxide is 50 nm thick everywhere, how much photoresist is required on top of the oxide to completely mask the ion implantations?

Example 5.3:
Boron is implanted into an n-type silicon wafer to a depth of 300 nm. Find the location of the junction if the peak concentration is 1x10¹⁶ cm⁻³ and the doping of the wafer is 3x10¹⁶ cm⁻³.
Summary of Mathematical Model

- Projected range is a function of the
  - ion energy
  - ion mass and atomic number,
  - target material (mass and atomic number)
- Theory of range and straggle (LSS theory: developed by Linland, Scharff and Schiott) assumes the implantation goes into an amorphous material
- The projected range and straggle are about the same for Si and SiO₂.
- The peak of the implantation usually is not positioned at the surface

Channeling

The silicon lattice viewed along the [110] axis. From THE ARCHITECTURE OF MOLECULES by Linus Pauling and Roger Haywood, © copyright © 1964 W. H. Freeman and Company. Reprinted with permission from Refs. [4a] and [4b].

Figure 5.7

Phosphorus impurity profiles for 40-keV implantations at various angles from the axis. Copyright 1968 by national Research Council of Canada. Reprinted with permission from Ref. [5].

FIGURE 5.8

Channelled case
Lattice Damage and Annealing

- Implantation Causes Damage to Surface — at high enough dose, amorphous layer is formed!
- Removed by annealing cycle at 800-1000°C for 30 min.
- But cause spreading of implants by diffusion.
- Rapid Thermal Annealing (RTA) Now Used for Lower Dt Product

![Graph showing Dose required to form amorphous layer vs Substrate Temperature](image)

**FIGURE 5.9**
A plot of the dose required to form an amorphous layer on silicon versus reciprocal target temperature. Arsenic falls between phosphorus and antimony. Copyright 1976 by Pernoum Publishing Corporation. Reprinted with permission from Ref. [6].

---

Deviation from Gaussian Theory

- Forward (heavier) and backward (lighter) scattering of impurities alter the tail end of distribution
- Curves Deviate from Gaussian for Deeper Implantations (> 200 keV)
- Curves Fit Four-Moment (Pearson Type-IV) Distribution Functions

![Graph showing Deviation from Gaussian Theory](image)

**FIGURE 5.10**
Measured boron impurity distributions compared with four-moment (Pearson IV) distribution functions. The boron was implanted into amorphous silicon without annealing. Reprinted with permission from Philips Journal of Research [8].
Shallow Implantation

Heavily doped source-drain regions with ~20 nm – low energy (0.25 to 5 keV) implantation and rapid thermal annealing (RTA)

FIGURE 5.11
Examples of transient enhanced diffusion. SIMS data comparing as-implanted and annealed depth profiles from (a) $3 \times 10^{15}$ cm$^{-2}$, 2 keV As, and (b) $3 \times 10^{15}$ cm$^{-2}$, 1 keV P. Annealing conditions were 950°C for 10 sec. SIMS depth profiles of $1 \times 10^{15}$ cm$^{-2}$ B implanted at 0.5, 1, 2, and 5 keV (c) as-implanted, and (d) after annealing at 1000°C for 10 sec.

Copyright 1997 IEEE. Reprinted with permission from Ref. [13].

Shallow Implantation (cont.)

FIGURE 5.11
Examples of transient enhanced diffusion. SIMS data comparing as-implanted and annealed depth profiles from (a) $3 \times 10^{15}$ cm$^{-2}$, 2 keV As, and (b) $3 \times 10^{15}$ cm$^{-2}$, 1 keV P. Annealing conditions were 950°C for 10 sec. SIMS depth profiles of $1 \times 10^{15}$ cm$^{-2}$ B implanted at 0.5, 1, 2, and 5 keV (c) as-implanted, and (d) after annealing at 1000°C for 10 sec.

Copyright 1997 IEEE. Reprinted with permission from Ref. [13].
Rapid Thermal Annealing

In addition to removing damage caused by implantations, annealing is needed to electrically activate the implanted impurities. To minimize the diffusion, $Dt$ associated by annealing must be as small as possible.

- Rapid Heating
- $950-1050^\circ C$
- $50^\circ C/sec$
- Very Low $Dt$

Figure 5.12
(a) Concept for a rapid thermal annealing (RTA) system. (b) Applied Materials 300 mm RTP System (Courtesy Applied Materials)

End of Chapter 5

See the website for the HW assignment for Chapter-5