EE M150:
Introduction to Micromachining and MEMS

Lecture:
Thermal Processing:
Ion Implantation

Prof. Jack W. Judy

Lecture Outline

• Topics:
  – Mechanics of Implantation
  – Mathematics of Implantation
Limitations of Diffusion

• High-Temperature Thermal Processes
  – melts (Aluminum) or refloows (PSG) films
  – slow to regulate (heat up / cool down)
  – difficult to precisely control the dose of dopants
• Diffusion Barriers
  – thermal diffusion can be stopped by thin films
    (sometimes good, sometimes bad)
• Dopant Profile
  – diffused profiles always have the highest concentration at the surface
    • difficult to arbitrarily form a buried concentration

Ion Implantation

• Electrostatically accelerate ions to velocities and energies that can deposit or implant dopants below the surface
  – process performed at low temperatures
  – instant-on and instant-off control
  – precise control of implanting current and charge allow for better control of the implanted dose
  – increased implant energies can penetrate thin films of materials
  – the peak of implanted dopant profiles are always below the surface (buried)
Ion Implantation

• Advantages:
  – precise dose control
  – good depth and profile control
  – wide selection of masking materials
    • PR, SiO₂, polysilicon, Al, ...
    • can be a low temperature material

• Disadvantages:
  – expensive
    • (equipment cost is excessive)
  – channeling
    • (implanted dopants can sometimes be undesirably deep)
  – crystalline damage

Ion-Implantation System

\[
Q_{\text{dose}} = \int_{0}^{T} \frac{I \cdot dt}{\eta \cdot q \cdot A}
\]

\( q = 1.6 \times 10^{-19} \text{ coulombs}, \eta = \text{valence} \)

Fig. 5.1 Schematic drawing of a typical ion implanter showing (1) ion source, (2) mass spectrometer, (3) high-voltage accelerator column, (4) \( x \)- and \( y \)-axis deflection system, and (5) target chamber.

• system is very expensive
• easily available implantation service is cheap

Figure taken from Jaeger
Implanted Dopant Distribution

- Dopants follow a completely Gaussian distribution
  - Average depth (Projected Range) = \( R_p \)
  - Variance (Straggle) = \( \pm \Delta R_p \)
  - Asymmetry (Skewness)

\[
Q_{\text{dose}} = \int_0^T \frac{I \cdot dt}{\eta \cdot q \cdot A} = \int_0^\infty N(x) \cdot dx
\]

If profile is fully below surface:
\[
Q = \left( \sqrt{2 \cdot \pi} \right) \cdot N_p \cdot \Delta R_p
\]

Implantation Control Parameters

- Ion Energy
  - controls the depth and shape of implant
- Dose
  - control concentration
- Mask Shape
  - controls in-plane geometry of the implant
- Ion Species
  - controls the type (n or p)
  - Impacts profile depth and shape
Implantation Parameter vs. Implantation Energy

- Typical Implant Energy ~10 to 200 keV
- Typical Depth of Implant ~0.05 to 1.0 µm

Sheet Resistance of an Implant

- From discussion of $R_s$ during diffusion lecture:
  
  $$R_s = \frac{1}{\int_{x_h}^{x_j} q \cdot \mu(x) \left( N_{A,D}(x) - N_B \right) \, dx}$$

- numerical solution needed since $\mu(x)$ is concentration dependent
- Just as with diffusion, use Irvin’s Curves when
  - peak of implant is positioned at the surface or
  - implant is fully recessed (i.e., parallel Gaussian distributions require the $R_s$ to be reduced by 2X)
- In other cases use a gross approximation:
  - $N(x) >> N_B$
  - $\mu(x) = \mu(x = R_p)$
  
  $$R_s \approx \frac{1}{q \cdot \mu \int_{x}^{x_{dep}} N(x) \, dx} = \frac{1}{q \cdot \mu \cdot Q_{implanted}}$$
Implant Redistribution by Diffusion

Gaussian Diffusion Distribution:

\[ N_{\text{diff}}(x,t) = \frac{Q}{\sqrt{\pi} \cdot D \cdot t} \cdot e^{-\left(\frac{x-x_0}{2\sqrt{D \cdot t}}\right)^2} \]

Translate Implant Gaussian into Diffusion Gaussian (in terms of \(D \cdot t\))

\[ (D \cdot t)_{\text{implant}} = \Delta R_p \cdot \sqrt{2} \]

Implant Gaussian Distribution:

\[ N_{\text{implant}}(x) = N_p \cdot e^{-\left(\frac{x-R_p}{\Delta R_p \cdot \sqrt{2}}\right)^2} \cdot 2 \cdot \sqrt{(D \cdot t)_{\text{implant}}} = \Delta R_p \cdot \sqrt{2} \]

The \((D \cdot t)_{\text{implant}}\) of the implant must be added to the overall total \((D \cdot t)_{\text{total}}\) when calculating diffusion:

\[ (D \cdot t)_{\text{total}} = (D \cdot t)_{\text{implant}} + \sum D_i \cdot t_i \]

The dose of the implant \(Q_{\text{implant}}\) can be translated into the dose of the constant-dose diffusion

\[ Q = \left(\sqrt{\frac{2}{\pi}}\right) \cdot N_p \cdot \Delta R_p \]

\[ N_{\text{redirected implant}}(x,t) = \frac{N_p}{1 + \frac{1}{2} \cdot \Delta R_p^2} \cdot e^{-\left(\frac{x-R_p}{\Delta R_p \cdot \sqrt{2}}\right)^2} \]

Implanting Through a Mask

Portion “transmitted” into substrate

Fraction Transmitted

\[ \frac{\int_{t_{\text{mask}}}^{t} N(x) \cdot dx}{\int_{0}^{t} N(x) \cdot dx} \]

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

\[ \int_{z}^{\infty} e^{-x^2} \cdot dx = \frac{1}{2} \cdot \sqrt{\pi} \cdot \text{erfc}(z \cdot \sqrt{a}) \]

\[ \int_{z}^{\infty} N_p \cdot e^{-\left(\frac{x-R_p}{\Delta R_p \cdot \sqrt{2}}\right)^2} \cdot dx = N_p \cdot \Delta R_p \cdot \sqrt{\frac{\pi}{2}} \cdot \text{erfc}\left(\frac{x-R_p}{\Delta R_p \cdot \sqrt{2}}\right) \]

Resulting in:

\[ \text{Fraction Transmitted} = \frac{1}{2} \cdot \text{erfc}\left(\frac{t_{\text{mask}} - R_p}{\Delta R_p \cdot \sqrt{2}}\right) \]
3-D Implantation (Point Source)

- Gaussian distribution (lateral and vertical)
  - vertical spread determined by the straggle $\Delta R_p$
  - lateral spread determined by the lateral straggle $\Delta R_{p\perp}$

- For a single implant beam:

$$N_{\text{implant}}(x, y, z) = N_p \cdot e^{-\left(\frac{x-R_p}{\Delta R_p \sqrt{2}}\right)^2} \cdot e^{-\left(\frac{y}{\Delta R_{p\perp} \sqrt{2}}\right)^2} \cdot e^{-\left(\frac{z}{\Delta R_{p\perp} \sqrt{2}}\right)^2}$$

3-D Implantation (Plane Source)

- For a plane source one must take the convolution of a of the distribution from a point source of the region of interest:

$$N_{\text{implant}}(x, y) = K_{\text{normalization}} \cdot N_p \cdot e^{-\left(\frac{x-R_p}{\Delta R_p \sqrt{2}}\right)^2} \cdot \left[ e^{-\left(\frac{y-a}{\Delta R_{p\perp} \sqrt{2}}\right)^2} + e^{-\left(\frac{y-a}{\Delta R_{p\perp} \sqrt{2}}\right)^2} \right] dy'$$

$$= K_{\text{normalization}} \cdot N_p \cdot e^{-\left(\frac{x-R_p}{\Delta R_p \sqrt{2}}\right)^2} \cdot \left[ \text{erfc}\left(\frac{y-a}{\Delta R_{p\perp} \sqrt{2}}\right) - \text{erfc}\left(\frac{y+a}{\Delta R_{p\perp} \sqrt{2}}\right) \right]$$

- By letting $a \to \infty$, since $\text{erfc}(\infty) = 0$ and $\text{erfc}(\infty) = 2$, thus $K_{\text{normalization}} = 1/2$ to have the result simplify to the 1-D case
What is the \textit{erfc}?

- Normal Probability Function:
  \[ f(x) = \frac{1}{\sqrt{2 \cdot \pi}} e^{-\left(\frac{1}{2} x^2\right)} \]

- Integral:
  \[ \int_0^a \frac{1}{\sqrt{2 \cdot \pi}} e^{-\left(\frac{1}{2} x^2\right)} \, dx = \frac{1}{2} \cdot \text{erf}\left(\frac{a}{\sqrt{2}}\right)\]
  \[ \text{erf}(x) = -\text{erf}(-x) \]

- Complementary Error Functions:
  \[ \text{erfc}(x) = 1 - \text{erf}(x) \]

Channeling Ions Through Lattice

- Crystal structure can lead to “channeling”
- Results is \( \sim 2X \) increase in implant depth

Above figure taken from Jaeger
Above figures taken from Wolf and Tauber