Changing the Dopant Concentration

• Diffusion Doping
• Ion Implantation
Step 11

The photoresist is removed with solvent leaving a ridge of polysilicon (the transistor's gate), which rises above the silicon wells.
Chemical doping implants phosphorous (green) deep within the silicon wells surrounded by the silicon dioxide and polysilicon layers to produce negatively doped silicon.
Diffusion vs. Implantation
Changing the Dopant Concentration

- Diffusion Doping
- Ion Implantation
**Diffusion: general considerations.**

Fick’s first law:

Diffusion of A molecules in pure B.

\[ \vec{J}_A = -D_{AB} \vec{\nabla} C_A \]

Where

- \( J_A \) = net flux of A molecules at a point (cm\(^{-2}\) sec\(^{-1}\)).
- \( D_{AB} \) = diffusion coefficient of A in B (cm\(^2\) sec\(^{-1}\)).
- \( C_A \) = concentration of A (cm\(^{-3}\)).

Note: \( C_A = C_A(x,y,z,t) \)

Negative sign shows that movement is from higher concentration to lower concentration.

One dimensional form:

\[ J_x = -D_{AB} \times \partial C_A(x,t) / \partial x \]

Note: \( D \) is a phenomenological constant which can be calculated from appropriate physical models or determined from experiment.
**Diffusion model: infinite source.**

Initial condition:
\[ C_A(x,0) = 0, \ x > 0 \]

Boundary condition:
\[ C_A(0,t) = C_0 \]
\[ C_A(\infty,t) = 0 \]

Solution:
\[
C_A(x,t) = C_0 \text{erfc} \left( \frac{x}{2\sqrt{D_{AB}t}} \right)
\]

where
\[
\text{erfc}(u) = 1 - \frac{2}{\sqrt{\pi}} \int_0^u e^{-a^2} \, da
\]
Diffusion model: infinite source….continued.

Concept of diffusion length.

Can define “diffusion length”:

\[ L_D = 2\sqrt{Dt} \]

\[ C_A(x, t) = C_0 \text{erfc} \left( \frac{x}{L_D} \right) \]

For large \( u \),

\[ \text{erfc}(u) \approx \frac{1}{\sqrt{\pi}} \left( \frac{e^{-u^2}}{u} \right) \]

Note also:

\[ \int_0^\infty \text{erfc}(u) du = \frac{1}{\sqrt{\pi}} \]
Concentration as a function of time according to infinite source model.

\[ B(x, t) := \text{erfc} \left( \frac{x}{2 \cdot \sqrt{t}} \right) \]
**Net dopant deposition and junction depth.**

Total dopant per square area:

\[ Q_A(t) = \int_0^\infty C_A(x,t)dx = \left( \frac{2}{\sqrt{\pi}} \right) C_0 \sqrt{D_{AB}t} \]

or

\[ Q_A(t) = \left( \frac{1}{\sqrt{\pi}} \right) C_0 L_D \]

*Increases with time as dopant supplied from infinite source.*

Junction depth:

Junction forms at depth where dopant concentration equals background carrier concentration.

\[ C_{\text{sub}} \equiv \text{concentration of substrate “background”}. \]

Then junction depth, \( d_j \) is given by

\[ d = (2\sqrt{Dt}) \text{erfc}^{-1} \left( \frac{C_{\text{sub}}}{C_0} \right) \]
Diffusion model: Finite source.

Initial condition:
\[ C_A(x,0)=0, \ x>\delta \ (\text{in limit at } \delta \text{ goes to zero}) \]

Boundary condition:
\[ C_A(\infty,t) = 0 \]

\[ Q_0 = \int_{0}^{\infty} C_A(x,t) dx \quad \text{(Fixed dopant per area)} \]

Solution:
\[
C_A(x,t) = \left( \frac{Q_0}{\sqrt{\pi D_{AB} t}} \right) \exp \left( \frac{-x^2}{4D_{AB} t} \right)
\]
**Additional characteristics: finite source.**

Surface concentration \((t>0)\)

\[
C_A(0, t) = \left( \frac{Q_0}{\sqrt{\pi Dt}} \right)
\]

Junction depth:

\[
d_j = 2\sqrt{Dt} \ln\left( \frac{Q_0}{C_{\text{sub}} \sqrt{\pi Dt}} \right)
\]
Dopant distributions from finite source.

Concentrations as function of depth and doping time.

\[ C(x, t) := \frac{\exp\left(-\frac{x^2}{(4\cdot\sqrt{t})}\right)}{\sqrt{\pi \cdot t}} \]

Linear

Logarithmic
**Diffusion activation model.**

Thermal activation model:

\[ D_{AB} = D_0 \exp (-E_A / kT) \]

\( D_0 \) relates to frequency of vibrations. For simple model, \( D_0 \sim \nu_0 d^2 \) where \( d \) is lattice constant and \( \nu_0 \) is vibrational frequency -- approximately \( 3 \times 10^{14} \) sec\(^{-1}\).

Activation energy varies enormously depending on specific mechanism for diffusion.

**Substitutional vacancy diffusion.**

**Interstitial displacement diffusion.**

**Interstitial diffusion.**
Diffusion coefficients in Silicon – Substitutional diffusers.

<table>
<thead>
<tr>
<th>Dopant</th>
<th>$E_A$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>3.5-3.7</td>
</tr>
<tr>
<td>As</td>
<td>4.0-4.3</td>
</tr>
<tr>
<td>Sb</td>
<td>3.8-4.1</td>
</tr>
<tr>
<td>B</td>
<td>3.3-3.9</td>
</tr>
<tr>
<td>Al</td>
<td>3.4</td>
</tr>
<tr>
<td>Ga</td>
<td>3.8</td>
</tr>
<tr>
<td>In</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Diffusion coefficients in Silicon – Interstitial diffusers.

![Graph showing diffusion coefficients in Silicon for different elements like Fe, Li, Cu, and Au. The graph plots temperature against diffusion coefficient, with temperature in degrees Celsius and diffusion coefficient in cm²/sec.]
### "Fast Diffusers" in Silicon.

**Diffusion Coefficients of Fast Diffusants in Silicon at 900 °C**

<table>
<thead>
<tr>
<th>Element</th>
<th>D (cm²/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni</td>
<td>1.00E-01</td>
</tr>
<tr>
<td>O₂</td>
<td>7.00E-02</td>
</tr>
<tr>
<td>Cu</td>
<td>4.70E-02</td>
</tr>
<tr>
<td>Pt</td>
<td>1.60E-02</td>
</tr>
<tr>
<td>H₂</td>
<td>9.40E-03</td>
</tr>
<tr>
<td>Fe</td>
<td>6.20E-03</td>
</tr>
<tr>
<td>Au(s)</td>
<td>2.80E-03</td>
</tr>
<tr>
<td>Ag</td>
<td>2.00E-03</td>
</tr>
<tr>
<td>Na</td>
<td>1.60E-03</td>
</tr>
<tr>
<td>K</td>
<td>1.10E-03</td>
</tr>
<tr>
<td>Au</td>
<td>1.10E-03</td>
</tr>
<tr>
<td>Au(i)</td>
<td>2.40E-04</td>
</tr>
</tbody>
</table>

*source: Wolf and Tauber, Silicon Processing. page 337.*

Activation energies in range of 0.2-2 eV (relatively low).
Solubility limits for dopants in Silicon.

Impurity concentration (cm$^{-3}$).
Practical methodology for silicon doping.

A common strategy for defining dopant profile and concentration.

Deposit known amount of dopant with narrow spatial profile (often at solubility limit) to determine net dopant quantity. This is often termed “pre-deposition”.

Diffuse for known time at known temperature to determine profile. This is often termed “drive-in”.

Can work backward:
First: what is desired junction depth and dopant load?
Second: what final profile will yield desired properties?
Third: what initial conditions will give dose and profile based on a given dopant source?
**Diffusion masking and three dimensional diffusion.**

*Thermal oxide as diffusion barrier.*
Some practical materials for thermal doping.

Boron (p-type dopant).
Normally the active dopant is $B_2O_3$ deposited in situ via a number of techniques:
  Oxidation of boron nitride (wafer) followed by evaporation to silicon wafer.
  Oxidation of diborane or $BCl_3$ or other gaseous source.
Spin-on glass materials containing boron (eg borosilicate glass chemistries).

Arsenic and Antimony (n-type dopant).
  Gaseous sources such as arsine ($AsH_3$) or stybnine ($SbH_3$) are used (in spite of the high degree of toxicity of both).
  The active dopant can be $As_2O_3$ or $Sb_2O_3$ deposited in situ via direct evaporation in furnace (sometimes under sealed conditions).
Spin-on glass materials containing arsenic or antimony can also be used.

Phosphorus (n-type dopant).
  Phosphine ($PH_3$) can be used as gaseous source.
  Oxidation of gaseous $POCl_3$ to $P_2O_5$ in situ.
  Transfer of $P_2O_5$ from wafer sources.
Spin-on glasses containing phosphorus can also be used.
Note: at high temperatures metals and alkalai metals diffuse rapidly through silicon. Thus fused quartz (polycrystalline SiO₂) is the preferred material for diffusion furnaces. Also used are silicon and silicon carbide.
**Rapid Thermal Processing**

Usually single wafer

Fast radiative heating of surface/bulk is not brought to max temp. Less dislocations.

**Tube Furnace**

![Diagram of Rapid Thermal Processing system](image)

Figure 7.26 RTP design (Source: Semiconductor International, May 1993).

![Graph of RTP Cycle](image)

Figure 7.18 Temperature levels during oxidation.