ION IMPLANTATION

We saw how dopants were introduced into a wafer by using diffusion (‘predeposition’ and ‘drive-in’).

This process is limited:

- cannot exceed solid solubility of dopant
- difficult to achieve light doping

Ion implantation is preferred because:

- controlled, low or high dose can be introduced ($10^{11} - 10^{18}$ cm$^{-2}$)
- depth of implant can be controlled.

Used since 1980, despite substrate damage;
  
  low throughput, and cost.

Plummer Ch. 8, Campbell Ch. 5
Solution for a limitless source of dopant (constant surface concentration):

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2}
\]

\[C(z, t) = C_{\text{surf}} \text{erfc} \left[ \frac{z}{2\sqrt{Dt}} \right], \quad t > 0\]

where \(\text{erfc}(x) = 1 - \text{erf}(x)\) and \(t_p = \text{predep time}\)

**Dose** \(Q = \frac{2}{\sqrt{\pi}} C_{\text{surf}} \sqrt{Dt_p}\)

Dose in sample increases as \(t^{1/2}\)

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Diffusion of a thin surface layer into a solid

When a thin surface layer diffuses into a solid, what is $C(z, t)$?

$Q = \text{initial amount of dopant (‘dose’), assumed to be a delta-function}$

Integral:

$$\int_{-\infty}^{\infty} C(z, t) dz = Q = \text{const. (# /area)}$$

Boundary conditions:

$$dC(0, t) = 0$$

$$C(\infty, t) = 0$$

Solution is a Gaussian:

$$C(z, t) = \frac{Q}{\sqrt{\pi Dt}} \exp \left[ -\frac{z^2}{4Dt} \right]$$

Diffusion length:

$$a = 2\sqrt{Dt}$$

Dose in sample constant in time
Example:

wafer originally has a uniform dopant level, e.g. donor.

Predep plus drive-in introduces a second dopant, an acceptor.

At a certain depth, a p-n junction is formed.

A third pre-dep of donor can then be done to make an npn transistor.

**Problem:**
can only make profiles consisting of superposed Gaussians centered at the substrate surface.
Since the maximum amount of a dopant that can dissolve in the Si is given by the solid solubility, you may be limited in the amount of dopant that can be incorporated.
Ion Implantation

Beam of energetic dopant ions is fired into surface of wafer. Energies are 5 - 200 keV.

This leads to implantation (burial) of the ions into the substrate.

What happens at the substrate?

Ions can: bounce off
absorb
sputter atoms (10 eV - 10 keV)
implant into surface (5 keV - 200 keV)...
and do tremendous damage

Ion Implantation Equipment

Ions generated in a source (from feed gas, e.g. BF$_3$, AsH$_3$, PH$_3$ ... or heated solid source, then ionized in arc chamber by electrons from hot filament) select desired species by $q/m$, using a magnet, accelerated by an $E$-field and focused using electrostatic lenses and impact substrate (a bend removes neutrals) in raster pattern.
What happens to ions inside the material?

Ions lose energy, $dE/dx$, interacting elastically with nuclei and inelastically with electrons

$$\frac{dE}{dx} = -N\left[ S_n(E) + S_e(E) \right]$$

$S_i(E)$ is Stopping power (eVcm$^2$)

Ion range in target:

$$R = \int_0^R dx = \frac{1}{N} \int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)}$$

What can we say about nuclear and electronic stopping...
**Nuclear stopping power**: Coulomb scattering (assumed *elastic*)

Incident ion interacts with nucleus of stationary ion

\[ b = \text{impact parameter} \]

\[ E_1, M_1 \]

\[ M_2 \]

Energy lost by incoming ion (microscopic)

\[ \Delta E = E_1 \left\{ 1 - \frac{\sin^2 \phi}{\cos \theta \sin \phi + \cos \phi \sin \theta} \right\} \]

The angles depend on masses and on \( b \).

Max. energy loss is when \( b = 0, \phi = 0 \):

\[ \Delta E = E_1 \frac{4 M_1 M_2}{(M_1 + M_2)^2} \]
**Nuclear stopping power**: Coulomb scattering (assumed *elastic*)

At 100 keV an ion of 15 amu has velocity $v_{\text{ion}} \approx 10^6$ m/s!

This is 1000 times faster than speed of sound in solids…

So ion is far past nucleus before nucleus can displace in response to Coulomb force.

So nuclear scattering is not strong at high ion velocity; only significant when ion slows down.

There are also *inelastic* collisions that transfer energy…
Electronic stopping power: also Coulomb interactions, but *inelastic*)

**Non-local:** ion experiences drag due to “free” or polarizable electrons:
incident ion
attracts electron polarization, Ion velocity=> charge separation, drag

**Local:** passing ion causes internal electronic transitions
=> energy and moment transfer

Because electrons can follow fields up to optical frequencies,
(velocities of $10^5$ m/s - 100 times faster than phonons)
electronic losses dominate at higher ion velocities.

$$S_e(E) = c v_{ion} = k E \nu^2$$
Stopping power in Ion Implantation

At each impact, the ion loses some energy. It travels through a vertical projected range $R_p$ before stopping. It transfers energy to target via both electronic and nuclear interactions.

- **Viscosity, non-local electrons**
- **Transitions, local electrons**
- **Nuclear Coulomb collisions**

More effective at larger $v_{ion}$

More effective at smaller $v_{ion}$

\[ R_p = \int_0^R dx = \frac{1}{N} \int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)} \]

**Stopping power in Ion Implantation**

Most damage is done by nuclear interactions

About 15 eV needed to displace Si from lattice site, create vacancy/interstitial pair (Frankel defect)

Viscosity, non-local electrons

Transitions, local electrons

Nuclear Coulomb collisions

More effective at larger \( v_{\text{ion}} \)

More effective at smaller \( v_{\text{ion}} \)

Most damage occurs near limit of \( R_p \).
From $S_e$ and $S_n$, $R_p$ and $\Delta R_p$ can be calculated:

in Si

\[ R_p \] (Å)

\[ \Delta R_p \] (Å)

in Si

in GaAs

\[ R_p \] (Å)

\[ \Delta R_p \] (Å)
Composition profile for ion implantation

If the depth is $x$, the impurity concentration $C(x)$ is approximated by a gaussian

$$C(x) = C_p \exp \left( -\frac{(x - R_p)^2}{2\Delta R_p^2} \right)$$

where $C_p$ is the peak concentration, $R_p$ the projected range and $\Delta R_p$ the standard deviation of the projected range (vertical straggle).

The implanted dose is given by $Q$ (Number/area)

$$Q = \int_{-\infty}^{\infty} C(x) \, dx = \sqrt{2\pi} \Delta R_p C_p$$

So a given dose will determine the peak concentration.
Why do light atoms have greater vertical projected range $R_p$ and standard deviation $\Delta R_p$?
The composition profiles are not always perfect Gaussians: there can be a skew or distortion (kurtosis) making the profile asymmetric.
Channeling

If the ions are incident parallel to a major crystal direction, they can pass through the structure with less scattering, so the range is much larger than expected.
Nuclear Stopping

Need to sum the effects of all the scattering events, e.g. using Monte Carlo modeling. Nuclear stopping, $S_n$, can be modeled by Coulomb scattering (so it depends on impact parameter, relative masses, and $E$).
Modeling
Distributions of ions after implant can be modeled using a Monte Carlo calculation to give projected range. Can include both nuclear and electronic stopping.
Ion implantation can be modeled using SUPREM, which calculates dopant profiles vs. implant conditions and annealing.
Ion implantation through a mask

Range, $R_p^*$ and standard deviation, $\Delta R_p^*$ are for ions in mask

For an efficient mask:

$C^*(x_m) = C_p^* \exp\left(-\frac{(x_m - R_p^*)^2}{2\Delta R_p^*}\right) \leq C_B$

Mask thickness:

$x_m = R_p^* + \Delta R_p^* \sqrt{2 \ln \left( \frac{C_p^*}{C_B} \right)} = R_p^* + m\Delta R_p^*$

$x_m = \text{range} + \text{some multiple, } m, \text{ of std dev’n}$

Dose penetrating mask:

$Q_p = \frac{Q}{\sqrt{2\pi\Delta R_p^*}} \int_{x_m}^{\infty} \exp\left[-\frac{(x - R_p^*)^2}{2\Delta R_p^*}\right] dx$

$Q_p = \frac{Q}{2} \text{erfc}\left(\frac{x_m - R_p^*}{\sqrt{2}\Delta R_p^*}\right)$
**Damage in Ion Implantation**

Most damage is done by nuclear interactions.

- About 15 eV needed to displace Si from lattice site, create vacancy/interstitial pair.

**Viscosity, non-local electrons**

**Transitions, local electrons**

**Nuclear Coulomb collisions**

- More effective at larger \( v_{\text{ion}} \).
- More effective at smaller \( v_{\text{ion}} \).

Most damage occurs near limit of \( R_p \).
Implantation damage

The ions damage the crystal structure, and might cause amorphization.

Dose needed to amorphize a silicon substrate

Need solid-phase epitaxy to recrystallize the amorphous regions

How many Si atoms does an implant displace?
Implantation damage

A post-implant anneal (e.g. >850°C) must be done to restore atoms to lattice sites and ‘activate’ the dopant. This causes diffusion of the dopant profile, and formation of defect clusters. Transient effect on diffusion are very important!

Effective transient diffusion distance for B in Si after implantation with Si ions.

As the damage anneals out, diffusion const, $D$, decreases
**Example:**
A 30 kV implant of B is done into bare Si. The dose is $10^{12}$ cm$^{-2}$.

-what is the as-implanted profile?

From chart: in Si
Rp = 110 nm, ΔRp = 38 nm
also from $Q = c_o \sqrt{2\pi\Delta R_p}$ you can get $c_o$

-what thickness of silica mask would you need to keep the B content below the background level of $10^{14}$ cm$^{-3}$ of P?

From chart: in silica
Rp = 100 nm, ΔRp = 36 nm
also from $Q$ you can get $c_o$
Now find the depth at which $N(x)$ reaches the background depth.
How can we make shallow implants (e.g. 50 nm)?

e.g. Boron has a large projected range, and channeling is a problem. How can we reduce this?

- lower energy?

- implant other species?

- preamorphize?

- transient high diffusion due to kickout?

- use predep/drivein using solid source?

- plasma implant?
Some other applications

1) Implant only certain parts of wafer: use a mask such that $R_p$ lies within the mask material. Use to form self-aligned source and drain regions, for example, in a MOSFET.

how thick should the mask be??

what really happens at the edges of the implanted region??
2) Buried dielectrics, e.g. SOI (Silicon on insulator)
Form $\text{Si}_3\text{N}_4$ using N+ implant, or $\text{SiO}_2$ using O+ implant

Useful to isolate devices: why is this important?
Discussion

When do you prefer to use predep/drive in vs. ion implantation?

Can you think of cases where you could save some process steps using ion implantation?

What could the ion implant do to the background dopant?

Are there any particular problems in ion implantation for substrates such as GaAs?