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.
Step 12

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
**Some advantages of ion implantation.**

Ion species can be implanted with high accuracy over many orders of magnitude of doping level. Depth profiles can be defined by control of ion energy. Dopants can be implanted in selected regions at low temperatures. Both p and n type dopants with variety of diffusion characteristics can be implanted. Damage can be removed with thermal annealing. Lateral displacement of dopants less than with thermal diffusion. Distribution can be modeled and predicted to high degree of accuracy. Implantation can take place through a thin protective surface layer (such as SiO$_2$). Implantation takes place at low temperature. Exotic doping profiles can be created.
Some disadvantages or limitations of ion implantation.

Ion implantation imparts some damage to crystal structure. Maximum depth of implantation is relatively shallow (on order of 1 micron). Throughput is typically lower than for conventional diffusion.

Ion implanters are complex and expensive. Ion implanters contain many potential safety hazards including high voltage, radiation, and toxic gases.
Ion basics: energy, acceleration, and dynamics.

Positive ion in electric field experiences force: $ZeE$
Where $Z$ is number of positive charges, $e$ is the electronic charge unit, and $E$ is the electric field (in appropriate units....).

Ion acquires an energy corresponding to $(V-V_o)$ where $V$ is the applied potential and $V_o$ is the reference potential.

If initial velocity is zero at $V_o$ and if the ion has mass $m$, then $mv^2/2 = ZeV$.
Thus ion is accelerated in response to field.
Often energy is simply given in electron volts – that is the energy achieved with $Z=1$ and potential of 1V.

Note that 1 eV is a large amount of energy relative for example to thermal energy.
Fundamentals

High voltage $V=25\text{kV}$ at the Ion Source:

Leads to impurities with a velocity $v$ leaving it: $qV = \frac{1}{2} mv^2$

The impurities (charged) enters into a magnet (Mass spectrometer):

$$F = q(v \times B)$$

With $B$ perpendicular to $v$, the force tends to move the particle in a circle and is balanced by the centrifugal force:

$$qvB = m \frac{v^2}{r}$$

Therefore: $B$ can be adjusted to select an desired ion species with a given mass:

$$B = \sqrt{\frac{2mV}{qr^2}}$$

Total dose $Q$: Integrate the electron current over time (The wafer is grounded, so electrons flow to neutralize the implanted ions)

$$Q = \frac{1}{nqA} \int_0^T Idt$$

$n$: =1 single ionized; =2 doubly ionized
Ion basics: behavior in magnetic field.

Force on a moving charged particle:
\[ F = (Ze) \, v \times B \] where \( v \) and \( B \) are velocity and magnetic field vectors.

For ion moving in a circular path, centripetal force is \( mv^2/R \) where \( R \) is radius of path.

Thus where \( B \) is perpendicular to \( v \), \( mv^2/R = ZeBv \) from which we may deduce that
\[ R = \frac{\sqrt{2m(V_0 - V)/eZ}}{B} \]

Working through the magnetic field units, this gives:
\[ R = \frac{\sqrt{m(V_0 - V)/Z}}{B} \times 4.55 \]

Where \( B \) is in kgauss, \( V \) in kilovolts, mass in amu and \( R \) is in cm.

For example, boron\(^+\) (11 amu mass) ions at 100KV through \( B=15 \) kilogauss moves through a radius of 10 cm.
Ion basics … continued.

Some notes:

- Isotope is important: boron consists of isotopes with both mass 10 (19%) and 11 (81%) for example and each will be deflected differently in the magnetic field.

- Dynamics generally depend upon ratio m/Z – thus where velocity selection or mass selection is involved, doubly charged ions of twice the mass will behave the same as singly charged ions of a given mass.

- Beam intensity becomes limited because of mutual repulsion of like-charged particles. This phenomenon also causes defocusing of particles.
Ion implantation apparatus.

- Ion source
- Ion mass selection
- Ion acceleration
- Ion deflection
- Substrate rotation
- Vacuum system
- Faraday cup: dose measurement
- Wafer loading etc.
Ion optics: control of ion beam characteristics.
**Ion implantation: Characteristics.**

Apparatus characterized by:
- Current (dose per unit time).
- Beam energy.

Net dose = current (ions/sec) × time (sec) / beam area (cm$^2$).

Interaction of ion beam with matter (and in particular a silicon wafer):
- Realm of high energy physics.
- Theoretical models for interaction of high energy particles with matter abound.
Meaning of dose and concentration

Dose [#/area]: looking downward, how many fish per unit area for ALL depths?

Concentration [#/volume]: Looking at a particular location, how many fish per unit volume?
Interaction of ion beam with matter.

Beam has high energy, small wavelength. The ion is scattered repeatedly by lattice atoms until it is ultimately stopped. Process is statistical and can be described by a Gaussian distribution.

$R_p$ is “projected range” or average distance traveled before ion stops.

$N_p$ is maximum concentration.

$\Delta R_p$ is “straggle” and describes standard deviation of distance traveled.

Note: the dispersion horizontally can be described by an additional $\Delta R_\perp$.
Typical range parameters for ion implantation.
Theoretical models for implantation profiles.
http://home3.netcarrier.com/~chan/IMPLANT/
Example calculational results:

Model output: phosphorus doping of silicon.
Interaction of ion beam with matter...continued.

Total dose per unit area: \[ Q = \sqrt{2\pi N_p \Delta R_p} \]

Comparison of ion implant distribution to diffusion distribution:
Parameters approximate for B doping of Si at 150KeV.
Channeling phenomena in ion implantation.

Wavelength of ionic particles is very small. Lattice structure has channels within structure.
Channeling in ion implantation....continued.

Solution is to angle ion beam slightly to normal of substrate. For silicon the angle is typically 7-10 degrees.
Dopant depth with ion energy

- Higher ion energy (implanter acceleration voltage), greater depth
- Deviation from Gaussian: light boron ions easily backscattered by Si
**Typical parameters for ion implantation equipment.**

Medium current implanters.

- Beam currents from 10 μamps to 1 mA.
- Ion energies from 20-200 KeV.
- Basically these are the work horse machines for the industry.

High current implanters.

- Beam currents from to 30 mA.
- Ion energies from 80-200 KeV.
- Used for doping levels greater than $10^{15}$ ions/cm².

Low energy (and ultra-low energy) implanters.

- Beam currents above 20 mA.
- Ion energies from 0.2-80 KeV.

High energy implanters.

- Ion energies from 200-3,000 KeV.
Eaton implanter process chamber with beam.

HE3 process chamber with beam.
30 cm wafer system.
Varian EH2 and related systems.

Varian EHPi:
The World's Leading Medium Current Ion Implanter
EHPi-220  5 - 200 keV
EHPi-500  5 - 260 keV (X+)

When it comes to medium current implanters, the E-series is the undisputed world leader. Over 550 are in production around the world.....all in the most reliable medium current system available for features sizes down to 0.18 micron and wafer sizes up to 200mm.
Example: Estimation of doping process conditions.

Imagine that we have a substrate which is n-type (phosphorus doped for example) with impurity concentration of $3 \times 10^{16} \text{ cm}^{-3}$. We wish to dope with boron to create a p-n junction at distance $d_2=2.77$ microns ($2.77 \times 10^{-4} \text{ cm}$) with overall doping level given by $Q_2=1.42 \times 10^{14} \text{ cm}^{-2}$.

How can we accomplish that through a two-step diffusion process and how can we define the predeposition and drive-in process parameters?

Let us consider a two step process. In step 1 we will deposit the appropriate amount of dopant within a short distance at the surface of the wafer (from a constant concentration) and in step 2 we will drive that fixed level of dopant to the desired junction depth.
First let us note that the junction will occur where the p-type dopant (boron) concentration equals the base n-type concentration. Thus we seek to provide concentration of $3\times 10^{16}$ cm$^{-3}$. The total dopant provided needs to correspond to $Q_2 = 1.42\times 10^{14}$ cm$^{-2}$. Since:

$$C_A(x,t) = \left(\frac{Q_0}{\sqrt{\pi D_{AB}t}}\right)\exp\left(-\frac{x^2}{4D_{AB}t}\right)$$

It must be that

$$C(2.77\times10^{-4}, t_2) = 3\times10^{16} = \left(\frac{1.42\times10^{14}}{\sqrt{\pi D_2 t_2}}\right)\exp\left(-\frac{(2.77\times10^{-4})^2}{4D_2 t_2}\right)$$

Where $D_2$ is the diffusion coefficient for boron (at drive in temperature $T_2$) and $t_2$ is the drive-in diffusion time.
Example …continued.

This determines the desired value of diffusion coefficient – diffusion time product for the drive in process.

Plot of concentration vs $D_2t_2$ product:

Solution is clearly near $D_2t_2=6 \times 10^{-9}$.

Numerical analysis gives $D_2t_2=5.33 \times 10^{-9}$
Example ….continued.

For this solution, we may map the boron profile needed after drive in.

This can be achieved with any combination of $D_2 t_2 = 5.33 \times 10^{-9}$ cm$^2$.

If we chose to carry out drive in at 1100°C, then $D_2$ is about $2.96 \times 10^{-13}$ cm$^2$/sec giving $t_2 = 1.8 \times 10^4$ sec, or 5 hours.
Example ….continued.

We now need only to determine the predeposition conditions. We desire to identify a source and diffusion conditions \((D_1, T_1, t_1)\) that will provide for \(Q_2\) loading within a distance short compared to \(d_2\) (2.7 microns).

If we work from a source that saturates Boron at 900\(^\circ\)C, then the saturation concentration is \(1.1 \times 10^{20}\) cm\(^{-3}\). From such a source, we may obtain the correct dopant dose:

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

\[
Q_A(t_1) = 1.42 \times 10^{14} = \left(\frac{2}{\sqrt{\pi}}\right) \times 1.1 \times 10^{20} \sqrt{D_1t_1}
\]

From which we may deduce that \(D_1t_1 = 1.31 \times 10^{-12}\) cm\(^2\).
**Example ....continued.**

If we take 900°C, the diffusion coefficient for B is about $1.45 \times 10^{-15}$ cm$^2$/sec and thus the predeposition drive-in time would be 903 sec or about 15 minutes.

We can thus calculate the profiles after step 1 and after step 2 and make sure that this all makes sense.
Example ….continued.

Slightly expanded timescale.

![Graph](image-url)

- $C(x_k, \text{answer}) \times 10^{19}$
- $C1(x_k, U1) \times 10^{18}$

Final profile