1 Wafer fabrication

1.1 Doping techniques

1.1.1 Definition

Doping means the introduction of impurities into the semiconductor crystal to deliberately change its conductivity due to deficiency or excess of electrons. In contrast to the doping during the wafer fabrication, where the entire wafer is doped, this article describes the partial doping of silicon. The introduction of foreign substances can be achieved by diffusion, ion implantation (or alloy).

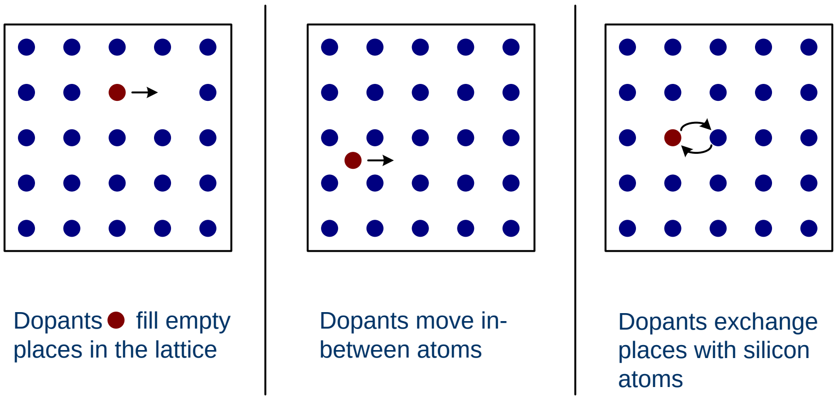
1.1.2 Diffusion

Molecular diffusion, often called simply diffusion, is a net transport of molecules from a region of higher concentration to one of lower concentration by random molecular motion. The result of diffusion is a gradual mixing of materials. To illustrate: a drop of ink in a glass of water is evenly distributed after a certain amount of time. In a silicon crystal, one finds a solid lattice of atoms through which the dopant has to move. This can be done in different ways:

- **Empty space diffusion:** the impurity atoms can fill empty places in the crystal lattice which are always present, even in perfect single crystals.
- **Inter lattice diffusion:** the impurity atoms move in-between the silicon atoms in the crystal lattice.
- **Changing of places:** the impurity atoms are located in the crystal lattice and are exchanged with the silicon atoms.

The dopant can diffuse as long as either a concentration gradient is balanced, or the temperature was lowered, so that the atoms can no longer move. The speed of the diffusion process depends on several factors:

- Dopant
- Concentration gradient
- Temperature
- Substrate
- crystallographic orientation of the substrate



Dopants ● fill empty places in the lattice

Dopants move in-between atoms

Dopants exchange places with silicon atoms

Fig. 1.1: Diffusion process

Diffusion with an exhaustible source:
Diffusion with an exhaustible source means that the dopant is available in a limited amount only. The longer the diffusion process continues, the lower the concentration at the surface, and therefore the depth of penetration into the substrate increases. The diffusion coefficient of a substance indicates how fast it moves in the crystal. Arsenic with a low diffusion coefficient penetrates slower into the substrate, as for example phosphorus or boron.

Diffusion with an inexhaustible source:
In diffusion processes with an inexhaustible source the dopants are available in unlimited amount, and therefore the concentration at the surface remains constant during the process. Particles that have penetrated into the substrate are continually replenished.

1.1.3 Diffusion methods

In the subsequent processes the wafers are placed in a quartz tube that is heated to a certain temperature.

Diffusion from the gas phase:
A carrier gas (nitrogen, argon, ...) is enriched with the desired dopant (also in gaseous form, e.g. phosphine PH_3 or diborane B_2H_6) and led to the silicon wafers, on which the concentration balance can take place.

Diffusion with solid source:
Slices which contain the dopants are placed in-between the wafers. If the temperature in the quartz tube is increased, the dopant from the source discs diffuses into the atmosphere. With a carrier gas, the dopant will be distributed uniformly, and thus reaches the surface of the wafers.

Diffusion with liquid source:
As liquid sources boron bromide BBr_3 or phosphoryl chloride $POCl_3$ can be used. A carrier gas is led through the liquids and thus transporting the dopant in gaseous state. Since not the entire wafers should be doped, certain areas can be masked with silicon dioxide. The dopants can not penetrate through the oxide, and therefore no doping takes place at these locations. To avoid tensions or even fractions of the discs, the quartz tube is gradually heated (e.g. +10 °C per minute) till 900 C. Subsequent the dopant is led to the wafers. To set the diffusion process in motion, the temperature is then increased up to 1200 C.

Characteristic:

- since many wafers can be processed simultaneously, this method is quite favorable
- if there already are dopants in the silicon crystal, they can diffuse out in later processes due to high process temperatures
- dopants can deposit in the quartz tube, and be transported to the wafers in later processes
- dopants in the crystal are spreading not only in perpendicular orientation but also laterally, so that the doped area is enlarged in a unwanted manner

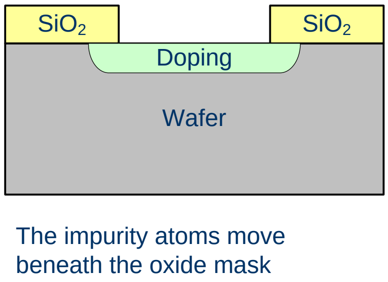


Fig. 1.2: Diffusion with an oxide mask

1.1.4 Ion implantation

In the ion implantation charged dopants (ions) are accelerated in an electric field and irradiated onto the wafer. The penetration depth can be set very precisely by reducing or increasing the voltage needed to accelerate the ions. Since the process takes place at room temperature, previously added dopants can not diffuse out. Regions that should not be doped, can be covered with a masking photoresist layer.

An implanter consists of the following components:

- **ion source:** the dopants in gaseous state (e.g. boron trifluoride BF_3) are ionized
- **accelerator:** the ions are drawn with approximately 30 kiloelectron volts out of the ion source
- **mass separation:** the charged particles are deflected by a magnetic field by 90 degrees. Too light/heavy particles are deflected more/less than the desired ions and trapped with screens behind the separator
- **acceleration lane:** several 100 keV accelerate the particles to their final velocity (200 keV accelerate bor ions up to 2.000.000 m/s)
- **Lenses:** lenses are distributed inside the entire system to focus the ion beam
- **distraction:** the ions are deflected with electrical fields to irradiate the desired location
- **wafer station:** the wafers are placed on large rotating wheels and held into the ion beam

Penetration depth of ions in the wafer:
In contrast to diffusion processes the particles do not penetrate into the crystal due

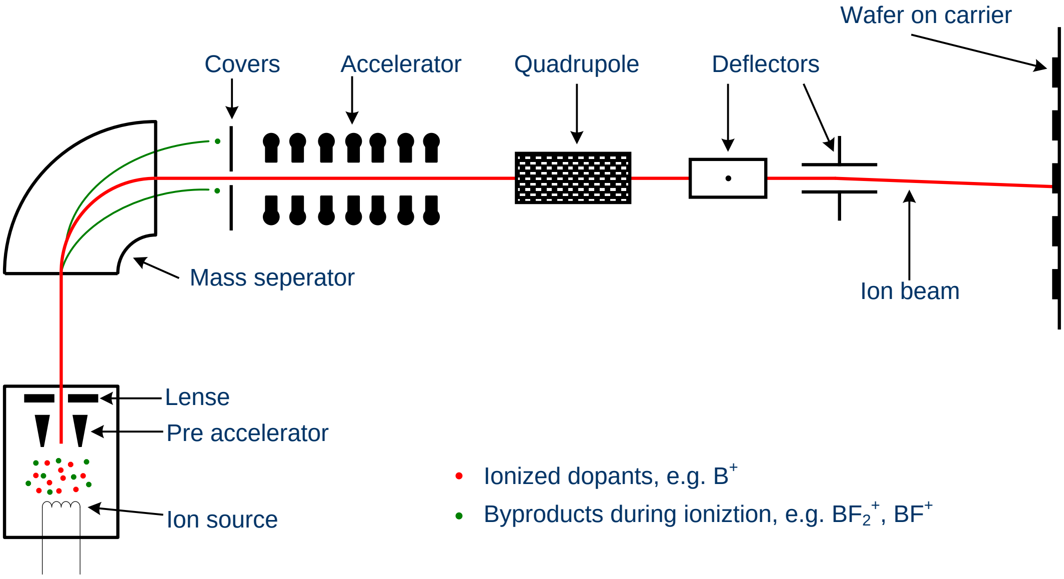


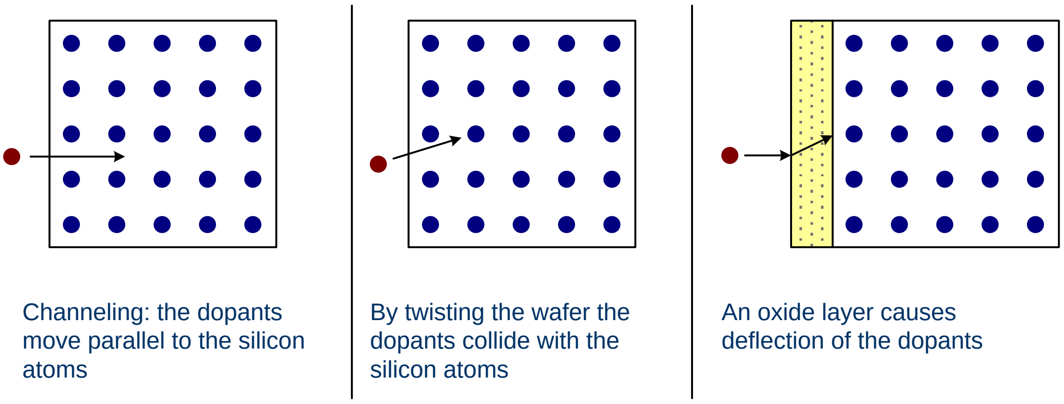
Fig. 1.3: Illustration of an ion implanter

to their own movement, but because of their high velocity. Inside the crystal they are slowed down by collisions with silicon atoms. The impact causes damage to the lattice since silicon atoms are knocked from their sites, the dopants themselves are mostly placed interstitial. There, they are not electrically active, because there are no bonds with other atoms which may give rise to free charge carriers. The displaced silicon atoms must be re-installed into the crystal lattice, and the electrically inactive dopants must be activated.

Recovery the crystal lattice and activation of dopants:
Right after the implantation process, only about 5 % of the dopants are bond in the lattice. In a high temperature process at about 1000 °C, the dopants move on lattice sites. The lattice damage caused by the collisions have already been cured at about 500 °C. Since the dopants move inside the crystal during high temperature processes, these steps are carried out only for a very short time.

Channeling:
The substrate is present as a single crystal, and thus the silicon atoms are regularly arranged and form “channels”. The dopant atoms injected via ion implantation can move parallel to these channels and are slowed only slightly, and therefore penetrate very deeply into the substrate. To prevent this, there are several possibilities:

- **Wafer alignment:** the wafers are deflected by about 7° with respect to the ion



Channeling: the dopants move parallel to the silicon atoms

By twisting the wafer the dopants collide with the silicon atoms

An oxide layer causes deflection of the dopants

Fig. 1.4: Channeling effect in the ingot

beam. Thus the radiation is not in parallel direction to the channels and the ions are decelerated by collisions immediately.

- **Scattering:** on top of the wafer surface a thin oxide is applied, which deflects the ions, and therefore prevents a parallel arival

Characteristic:

- the reproducibility of ion implantation is very high
- the process at room temperature prevents the outward diffusion of other dopants
- spin coated photoresist as a mask is sufficient, an oxide layer, as it is used in diffusion processes, is not necessary
- ion implanters are very expensive, the costs per wafer are relatively high
- the dopants do not spread laterally under the mask (only minimally due to collisions)
- nearly every element can be implanted in highest purity
- previous used dopants can deposit on walls or screens inside the implanter and later be carried to the wafer
- three-dimensional structures (e.g. trenches) can not be doped by ion implantation
- the implantation process takes place under high vacuum, which must be pro-

duced with several vacuum pumps

There are several types of implanters for small to medium doses of ions (10^{11} to 10^{15} $ions/cm^2$) or for even higher doses of 10^{15} to 10^{17} $ions/cm^2$.

The ion implantation has replaced the diffusion mostly due to its advantages.

Doping using alloy
For completeness it should be mentioned that besides ion implanation and diffusion there is an alternative process: doping using alloy. Since this procedure has disadvantages such as cracks in the substrate, it is not used in today's semiconductor technology any more.