Semiconductor Technology from A to Z

Wafer Fabrication

Doping techniques

Doping

Doping means introducing a foreign substance into the semiconductor crystal in order to deliberately alter its conductivity through an excess or a deficiency of electrons. In contrast to doping during wafer fabrication itself, where the entire wafer is doped, the doping techniques described on this page allow silicon wafers to be doped partially. The introduction of the foreign substance can be achieved using various methods: diffusion, implantation (and alloying).

Diffusion

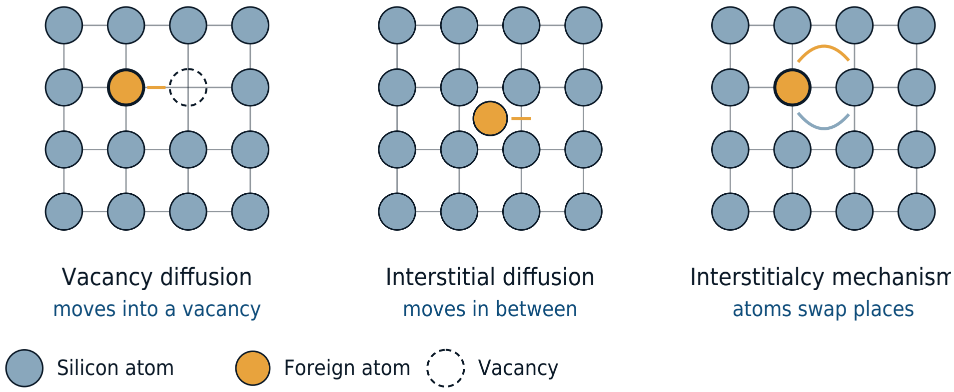
Diffusion is barely used anymore for targeted doping today; it has been superseded by ion implantation. Nevertheless, understanding it remains essential, because it never stops acting: every subsequent high-temperature step causes dopants that have already been introduced to keep migrating. This limits how much heat a wafer may still be subjected to after doping, and is the reason why furnace processes have increasingly been replaced by rapid, second-scale heating.

Diffusion means the spontaneous spreading of a substance within another substance due to a difference in concentration; for example, a drop of ink in a glass of water becomes evenly distributed after a certain amount of time. In a silicon crystal, one finds a solid lattice of atoms through which the dopant must move. This can happen in three ways:

- Vacancy diffusion: the foreign atoms occupy empty sites in the crystal lattice, which can always occur. Similar to hole conduction, an interplay arises between occupied lattice sites and vacancies.
- Interstitial diffusion: the foreign atoms move between the silicon atoms within the crystal lattice.
- Site exchange: foreign atoms located in the crystal lattice swap lattice sites with silicon atoms.

Diffusion in the crystal lattice

Three paths by which the dopant migrates through the lattice



All three paths occur side by side. Which one dominates depends on the dopant and on the temperature – boron and phosphorus mainly migrate via vacancies, smaller atoms more often between lattice sites.

The dopant can continue to move within the semiconductor crystal until either a concentration gradient has been equalized, or the temperature has been lowered far enough that the atoms can no longer move.
The speed of the diffusion process depends on several factors:

- dopant
- concentration difference
- temperature
- substrate
- crystal orientation of the substrate (see fabrication of single crystals)

Diffusion with an Exhaustible Source

Diffusion with an exhaustible source means that only a limited amount of dopant is available. The longer the diffusion process continues, the lower the concentration at the surface becomes; in return, the penetration depth into the substrate increases. The diffusion coefficient of a substance indicates how quickly it moves within the crystal. Arsenic, with a low diffusion coefficient, penetrates the substrate more slowly than, for example, phosphorus or boron.

Diffusion with an Inexhaustible Source

Here, the dopant is available in unlimited quantity. The concentration at the surface therefore remains constant throughout the process, since particles that have penetrated into the substrate are continuously replenished.

Diffusion Methods

In the following processes, the wafers are placed inside a quartz tube that is heated to a specific temperature along its entire length.

Diffusion from the Gas Phase

A carrier gas (nitrogen, argon) is enriched with the desired dopant (likewise in gaseous form, e.g. phosphine (PH_3) or diborane (B_2H_6)) and passed over the silicon wafers, where concentration equalization can take place.

Solid-Source Diffusion

Discs onto which the dopant has been applied are placed between the wafers. As the temperature in the quartz tube rises, the dopant diffuses out of the source discs into the atmosphere. A carrier gas then distributes the dopant evenly throughout the quartz tube, allowing it to reach the surface of the wafers.

Diffusion with a Liquid Source

Boron tribromide (BBr_3) or phosphorus oxychloride ($POCl_3$) serve as liquid sources. A carrier gas is passed through the liquid and thereby transports the dopant to the wafers, where it then reaches the surface of the silicon discs.

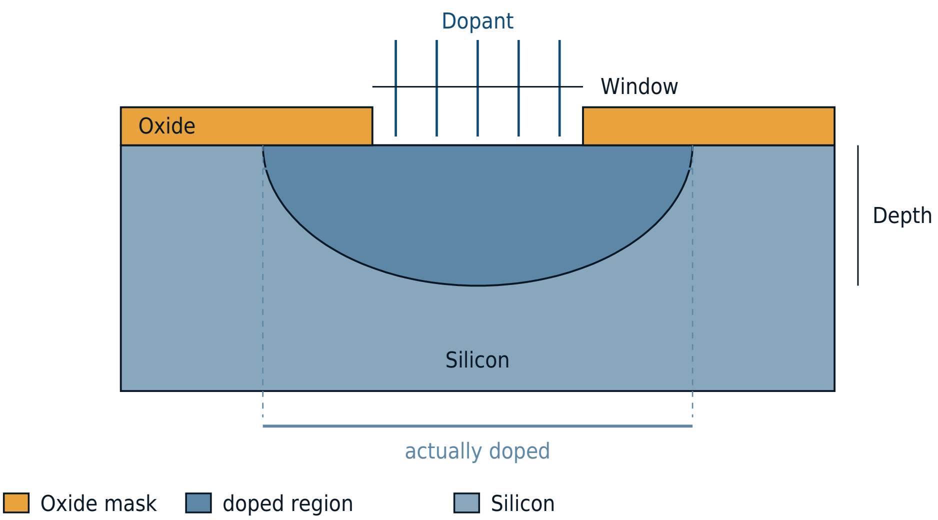
Since the entire wafer is not meant to be doped, certain regions are masked with silicon dioxide. Dopants cannot penetrate this oxide, so no doping takes place at these locations. To avoid stress or even breakage of the wafers, the tube is heated in steps (10 °C per minute) up to approximately 900 °C, at which point the dopant is introduced to the wafers. To initiate the diffusion process, the temperature is then raised to approximately 1200 °C.

Characteristics:

- Since many wafers can be processed simultaneously, this method is quite cost-effective
- If foreign substances from earlier doping steps are already present in the crystal, renewed exposure to heat can cause them to diffuse out again
- Over time, dopants accumulate inside the quartz tube and are additionally transported to the wafers by the carrier gas during subsequent doping steps
- Dopants spread within the crystal not only vertically but also laterally, so the doping windows always end up doped over a larger area than intended

Diffusion through a window in the mask

The dopant also migrates sideways and undercuts the oxide



The lateral spread is roughly eight tenths of the penetration depth.
As a result, the doped region always ends up wider than the window –
this has to be accounted for when designing the masks.

Ion implantation

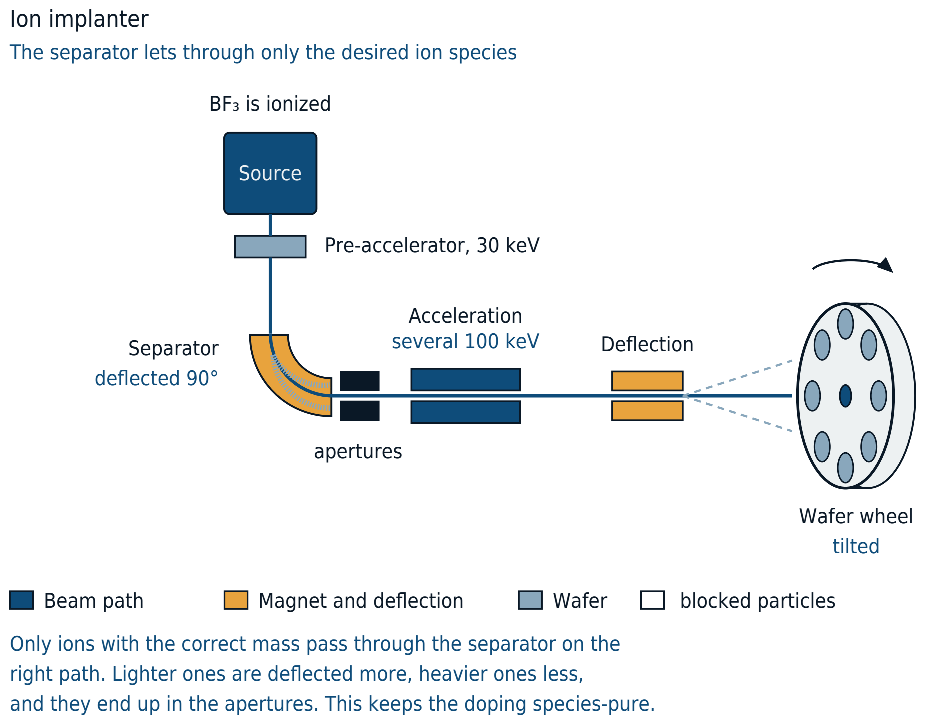
In the ion implantation charged dopants (ions) are accelerated in an electric field and irradiated onto the wafer. The penetration depth can be set very precisely by reducing or increasing the voltage needed to accelerate the ions. Since the process takes place at room temperature, previously added dopants 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

Illustration of an ion implanter



Penetration depth of ions in the wafer

In contrast to diffusion processes the particles do not penetrate into the crystal due 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 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 produced 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 1017 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, however, brings disadvantages with it such as cracks in the substrate, it is not used in today's semiconductor technology any more.