Semiconductor Technology from A to Z

Deposition

Physical deposition methods

MBE: Molecular beam epitaxy

The growth behavior in molecular beam epitaxy (MBE) corresponds to that of silicon vapor phase epitaxy. However, in this case the silicon is deposited onto the wafer in a different way.

The process takes place under ultra-high vacuum (UHV, 10^{-8} Pa); the wafer to be processed is held upside down at the top of the process chamber and heated to about 600–800 °C so that the native oxide volatilizes.

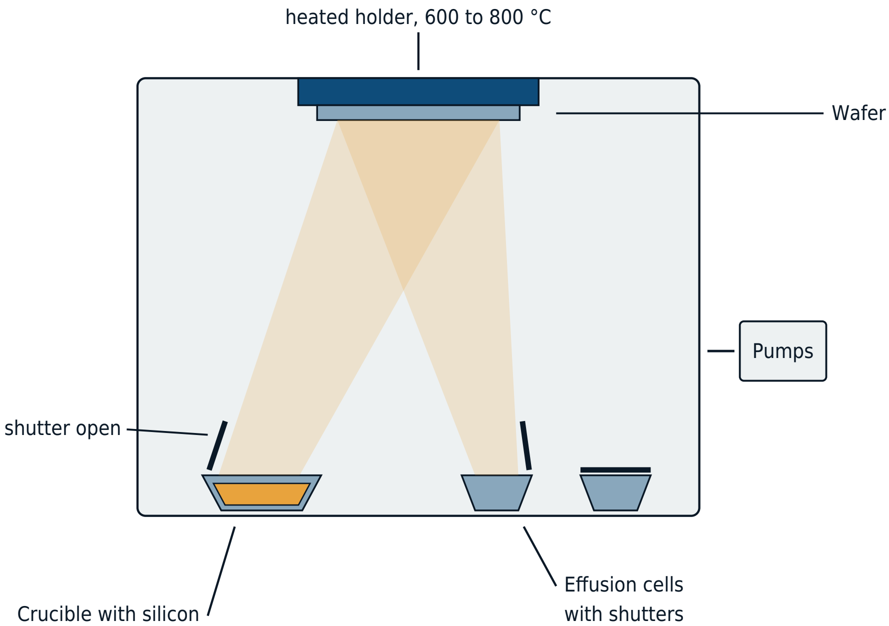
Silicon is evaporated using an electron beam in a crucible and then deposits onto the wafer. Dopants can be evaporated in an effusion source and thus reach the wafer together with the silicon vapor. Through targeted temperature control and the use of shutters, the particle beam can be precisely dosed. This process also makes it possible to grow layers of different materials on top of one another that would otherwise not be possible due to differing atomic sizes. This allows a layer of silicon and germanium to be produced, which is needed for high-frequency applications in bipolar technology.

This is precisely where the strength of the process lies: because the atoms arrive individually and without a chemical reaction, the composition can be changed from one atomic layer to the next. For layer sequences made of compound semiconductors, as needed in laser diodes and high-frequency devices, this is indispensable. In silicon manufacturing, on the other hand, MBE plays no role – there it is too slow.

However, the effort required to generate the UHV in this epitaxy process is very high. To reach this pressure, which is less than one-trillionth of normal atmospheric pressure, several pumps must be combined and the process chamber pumped down for a long time. Only one wafer can be processed at a time, and growth amounts to only about 1 µm per hour.

MBE System

The atoms fly individually through the ultra-high vacuum onto the wafer



Each source can be switched on individually; growth is about one micrometer per hour. This is the only way to change the composition from one atomic layer to the next. The pressure is around 10^{-8} Pa.

Evaporating

In evaporation, metallic layers, such as aluminum, can be produced on the wafers. The material is placed in a crucible made of a high-melting-point metal such as tantalum and heated there until it transitions into the gaseous state. The metal vapor strikes the wafer perpendicularly, so that edges are not covered well; the resulting layer is polycrystalline. As an alternative to melting in a crucible, the metal can also be evaporated using an electron beam. Compared to thermal evaporation, this electron beam method makes it possible to achieve a very precise deposition rate. Since edge coverage is not very good, these two processes are mostly used for full-area backside coating for later electrical contacting.

In the manufacturing of integrated circuits, evaporation has largely been displaced by sputtering, which provides denser layers and better edge coverage. It has been retained where poor edge coverage is precisely what is desired: in the lift-off process, a resist mask is first patterned, then the metal is evaporated, and afterward the resist together with the metal lying on top of it is removed. Because the sidewalls of the resist mask are barely covered, the film breaks cleanly at the edge. This makes it possible to pattern metals that are difficult to etch.

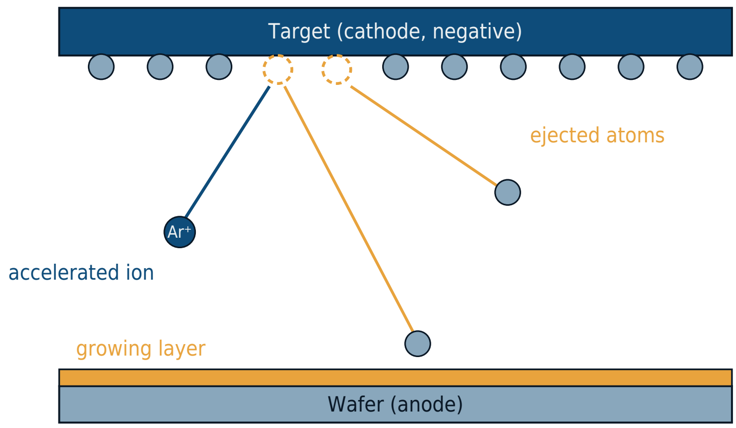
Schematic illustration of an evaporation system

Sputtering

In sputtering, ions (usually argon) are accelerated onto a target and strike out atoms or molecules there; the target consists of the material of the layer to be deposited. The mean free path of these particles is a few millimeters long, i.e. they collide frequently, which means that vertical surfaces on the wafer are also covered well. The deposited particles form a porous layer, which can be densified by annealing. Sputtering can be divided into passive (inert) and reactive sputtering.

Sputtering

Argon ions knock atoms out of the target, which deposit on the wafer



The atoms fly off in all directions and collide with gas particles along the way. That's why even vertical surfaces are well covered – the layer stays porous at first and is later densified by annealing.

In passive sputtering, only the material of the target is deposited on the wafers; depending on the target material, highly pure layers can be produced, since a precise mixing ratio of the substances in the target is possible. In reactive sputtering, a reactive gas (e.g. oxygen O_2) is added to the gas in the process chamber, which combines with the sputtered material from the target and then deposits on the wafer. This makes it possible to produce insulating layers from a metal target (e.g. aluminum Al):

$4\ Al + 3\ O_2 \rightarrow 2\ Al_2O_3$

To produce metallic layers, DC sputtering is used. Here, the ions are accelerated onto the target with up to 3 kilovolts (kV) and discharge there. Since these charges always have to be dissipated, only a conductive material can serve as the target here. For insulating layers, reactive sputtering must be used. If an insulating layer is to be produced directly from the target, radio-frequency sputtering (RF sputtering) is used.

In RF sputtering, the voltage is applied to one electrode each behind the target (cathode) and the wafer (anode). Due to the high-frequency voltage, electrons are attracted to the target during the positive half-wave, causing the target to charge negatively. This negatively charged target attracts ions, which knock particles out of it. In magnetron sputtering, magnets are additionally placed behind the target so that electrons are deflected into circular paths and can thus ionize argon atoms more frequently, causing a considerable increase in the deposition rate. Since the anode is connected to the process chamber, its potential difference relative to the plasma, averaged over time and referenced to the surface, is substantially smaller than that of the cathode, which is why the ions migrate only toward the target and not toward the wafer.

To increase edge coverage, BIAS sputtering is used, in which a negative voltage is applied to the substrate. As a result, particles of the deposited layer are removed here as well, just as at the target, and the surface is planarized. However, care must be taken that no removal of the substrate itself occurs. This so-called back-etching is also the principle behind most plasma etching systems.

Sputtering into narrow structures

The particles knocked out are uncharged and fly off in all directions. Over a narrow, deep contact hole, this means: most of them strike the edge of the opening, and only a little reaches the bottom. The opening closes up before the bottom is covered.

A remedy is to ionize the sputtered particles themselves. In a dense plasma between the target and the wafer, they lose an electron and can then be accelerated straight down by a voltage applied to the wafer. This directs the material flow and allows it to reach the bottom of deep holes as well. In this way, the tantalum barrier and the copper seed layer are deposited in the damascene process – the seed layer must be present without gaps, on the sidewalls just as much as on the bottom, otherwise the copper will not grow continuously during the subsequent electroplating.

Sputtering is therefore well suited for producing metallic layers with good conformity and very good reproducibility. The effort involved is low, and the reduced pressure of about 5 Pa is fairly easy to generate.