# Semiconductors and Low-dimensional structures: fabrication methods.

# Semiconductor Doping.

We have considered in some details the properties of semiconductors and identified the ability to control carrier concentration and type as one of the major advantages for the point of view of applications. We also know that doping of semiconductors is one of the main methods to control carrier type and concentration. Doping refers to the process of introducing impurity atoms into a semiconductor region in a controllable manner in order to define the electrical properties of this region. The doping with donors and acceptors allows to modify the electron and hole concentration in silicon in a very large range from  $10^{13}$  cm<sup>-3</sup> up to  $10^{21}$  cm<sup>-3</sup>. The carrier concentration can also be varied spatially quite accurately which is essential to produce pn-junctions and built-in electric fields. All electronic and optical semiconductor devices incorporate dopants as a crucial ingredient of their device structure.

We can appreciate that current device sizes dictate the accuracy of the doping method both spatially and in terms of concentration of dopands. Ion implantation is the primary technology to introduce doping atoms into a semiconductors to form various devices. This low-temperature process uses ionized atoms which are accelerated by electric fields to high energies and are injected into the wafer. The chief reason this technique is used is the precision with which the amount and position of the doping can be controlled. After the low-temperature implantation process the crystal structure of the semiconductor is damaged by the implanted particles and the dopants are electrically inactive as at large they are not part of the crystal lattice. Therefore, the procedure is followed by the thermal annealing process to activate the dopants and to eliminate damage to the crystal lattice.

Schematic diagram of the ion implantation process can be found in figure below.





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Ion implantation equipment typically consists of an ion source, where ions of the desired element are produced, an accelerator, where the ions are electrostatically accelerated to a high energy, and a target chamber, where the ions impinge on a target, which is the material to be implanted. The currents supplied by implanters are typically small (microamperes), and thus the dose which can be implanted in a reasonable amount of time is small just as required for doping. Typical ion energies are in the range of 10 to 500 keV. Energies in the range 1 to 10 keV can be used, but result in a penetration of only a few nanometers or less. The energy of the ions, as well as the ion species and the composition of the target determine the depth of penetration of the ions in the solid: A monoenergetic ion beam will generally have a broad depth distribution. The average penetration depth is called the range of the ions. Under typical circumstances ion ranges will be between 10 nanometers and 1 micrometer. Ions are charged particles and interact strongly with the target and other substances (e.g. air, gasses), hence ion deposition requires high vacuum. Ion implantation was developed as a method of producing the p-n junction of photovoltaic devices in the late 1970s and early 1980s.

### Semiconductor device fabrication

Molecular beam epitaxy (MBE) takes place in high vacuum or ultra-high vacuum (10<sup>-8</sup> Pa). The most important aspect of MBE is the slow deposition rate (typically less than 1000 nm per hour), which allows the films to grow epitaxially (from Greek epi, meaning "above", and taxis, meaning "in ordered manner"). The slow deposition rates require proportionally better vacuum to achieve the same impurity levels as other deposition techniques. Molecular beam epitaxy is essentially a sophisticated form of vacuum evaporation. Molecular beams of the constituent elements are generated from sources and travel without scattering to a substrate where they combine to form an epitaxial film. In solid source MBE, material is evaporated from solid ingots by heating or with an electron beam. The rate of growth depends on the flux of material in the molecular beams which can be controlled by the evaporation rate and, most importantly, switched on and off with shutters in a fraction of the time required to grow one monolayer. Typical growth rates are 1 mono-layer per second or 1 mkm per hour. Great care is taken to ensure that minimal possible quantities of impurity atoms are introduced into the material: substrates are carefully prepared and cleaned; only ultra pure sources are used; the reaction chamber is evacuated to <10<sup>-11</sup>mbar and the walls of the chamber cooled with liquid nitrogen. Even so the highest mobility layers are only grown after an extended run when inside of the chamber has been completely degassed.



Figure 2. MBE growth

The basic principle of epitaxial growth is that atoms on a clean surface are free to move around until they find a correct position in the crystal lattice to bond. Growth occurs at the step edges formed since

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at an edge an atom experiences more binding forces than on the free surface. In practice there will be more than one nucleation site on a surface and so growth is by the spreading of islands. In high quality material these islands will be large with height differences of less than a ML. The mobility of an atom on the surface will be greater at higher substrate temperature resulting in smoother interfaces, but higher temperatures also lead to a lower "sticking coefficient" and more migration of atoms within the layers already grown. So, temperature must be optimized for specific type of atoms.

In solid-source MBE, elements such as gallium and arsenic, in ultra-pure form, are heated in separate effusion cells until they begin to slowly sublimate. The gaseous elements then condense on the wafer, where they may react with each other. In the example of gallium and arsenic, single-crystal gallium arsenide is formed. The term "beam" means that evaporated atoms do not interact with each other or vacuum chamber gases until they reach the wafer, due to the long mean free paths of the atoms.

During operation, reflection high energy electron diffraction (RHEED) is often used for monitoring the growth of the crystal layers. A computer controls shutters in front of each furnace, allowing precise control of the thickness of each layer, down to a single layer of atoms. Intricate structures of layers of different materials may be fabricated this way. Such control has allowed the development of structures where the electrons can be confined in space, giving quantum wells or even quantum dots. Such layers are now a critical part of many modern semiconductor devices, including semiconductor lasers and light-emitting diodes.

In systems where the substrate needs to be cooled, the ultra-high vacuum environment within the growth chamber is maintained by a system of cryopumps, and cryopanels, chilled using liquid nitrogen or cold nitrogen gas to a temperature close to 77 Kelvin (–196 degrees Celsius). Cryogenic temperatures act as a sink for impurities in the vacuum, so vacuum levels need to be several orders of magnitude better to deposit films under these conditions. In other systems, the wafers on which the crystals are grown may be mounted on a rotating platter which can be heated to several hundred degrees Celsius during operation.

Molecular beam epitaxy is also used for the deposition of some types of organic semiconductors. In this case, molecules, rather than atoms, are evaporated and deposited onto the wafer. Other variations include gas-source MBE, which resembles chemical vapor deposition.

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Figure 3. Molecular Beam Epitaxy growth chamber. Author: Vegar Ottesen. Source: Wikipedia