**Molecular Beam Epitaxy (MBE)**

**Introduction**

Molecular Beam Epitaxy (MBE) is a technology used for the deposition of thin film compound semiconductors, metals or insulators that allows a precise control of compositional profiles by using a process far from the thermodynamic equilibrium. The term epitaxy originates from the Greek roots “epi” and “taxis” which mean to arrange upon. In other words, the epitaxy is the arrangement of one or more thermal particles atop a heated and ordered crystalline substrate to form a thin layer whose crystallinity matches that of the substrate even though the composition of the materials may differ (e.g. SiGe/Si, GaAlAs/GaAs, CdTe/GaAs,…). Again, the term beam means that evaporated elements (atoms and/or molecules) do not interact with each other or with vacuum chamber gases until they impinge the substrate because of their long mean free paths which are involved in the deposition process.

This unique growth technique is widely used to produce superlattice structures consisting of many alternate thin layers with single thickness as low as 10 Å. Furthermore, impurities are evaporated onto the growing film through separate sources. In this way the doping profile, orthogonal to the surface, may be varied and controlled with a spatial resolution not easily achieved by more conventional techniques.

MBE was developed by Alfred Cho and John Arthur at Bell Telephone Labs in the early 1970s.

**Principle:** The principle underlying MBE growth is relatively simple: it consists essentially of atoms or clusters of atoms, which are produced by heating up a solid source. They then migrate in an UHV environment and impinge on a hot substrate surface, where they can diffuse and eventually incorporate into the growing film. Despite the conceptual simplicity, a great technological effort is required to produce systems that yield the desired quality in terms of material purity, uniformity and interface control.

**Growth apparatus**

A schematic drawing of a generic MBE system is presented in Fig. 1. Some basic components can be identified:

* The vacuum system consists in a stainless-steel growth chamber, UHV-connected to a preparation chamber, where substrates are degassed prior to growth, and a load-lock module for transfer to and from air (not shown). All the components of the growth chamber must be able to resist bake-out temperatures of up to 200ºC for extended periods of time, which are necessary to minimize outgassing from the internal walls.
* The pumping system must be able to efficiently reduce residual impurities to a minimum. Typical MBE growth rates for III-V type semiconductors are of the order of 1 m/h (˜ 1ML/sec), obtained for group III partial pressures of ~10-6 Torr. With atomic densities in the crystal of about 1022 cm-3, this means that to reduce the impurity concentrations below 1015 cm-3, the impurity partial pressures must be reduced below ~10-13 Torr, assuming a unity sticking coefficient [1]. In practice, base pressure is reduced to the 10-11-10-12 Torr range, with the residual gas being essentially H2. The pumping system usually consists of ion pumps, with auxiliary Ti-sublimation and cryogenic pumps, for the pumping of specific gas species.
* Liquid N2 cryopanels surround internally both the main chamber wall and the source flange. Since MBE is a cold wall technique, cryopanels prevent re-evaporation from parts other than the hot cells. Besides, they provide thermal isolation among the different cells, as well as additional pumping of the residual gas.
* Effusion cells are the key components of an MBE system, because they must provide excellent flux stability and uniformity, and material purity. Furthermore, being the parts that must withstand the highest temperatures (up to 1400ºC) for the longest periods, they are often responsible for machine downtime. Therefore a careful choice of elements, materials and geometry must be taken. The cells (usually six to ten) are placed on a source flange, and are co-focused on the substrate heater, to optimise flux uniformity. The flux stability must be better than 1% during a work day, with day-to-day variations less than 5% [1]. This means that the temperature control must be of the order of ±1ºC at 1000ºC [2]. Furthermore, the cell geometry must be chosen in a way that the material flux does not drift appreciably as the source is depleted. The first analytical studies on flux distribution were performed on the socalled Knudsen cells, with small orifices that ensure thermodynamic equilibrium between the melt and the vapour in the cell. As a matter of fact, however, Langmuir-type (i.e., nonequilibrium) effusion cells are used in MBE growth. Due to the large orifice in these real cells, a given flux to the substrate can be reached with a lower cell temperature, resulting in a lower power consumption and in a reduction of thermal generation of impurities [1].
* A schematic drawing of a typical effusion cell is shown in Fig. 2, and some of the main features are indicated. The crucible (1) is usually made of pyrolitic boron nitride, which can stand temperatures of up to ~1300ºC without appreciable degassing. Its shape can be cylindrical or conical with different tapering angles, depending on the material to be evaporated. Its size depends on the material to be evaporated as well, and has to be big enough to provide several months of operation before the depletion of the material. Heating is provided by a Ta filament (2), while multiple Ta foils provide heat shielding (3). A thermocouple (4) is located in an appropriate position in order to measure the material temperature; temperature regulation is provided by high-precision PID regulators. A mechanical or pneumatic shutter, usually made of Ta or Mo, is placed in front of the cell to trigger the flux (see Fig. 1). The shutters must be operated much faster than the growth rate (typically 0.1 s), and should be computer-controlled to provide reproducible growth cycles, especially for superlattices. Besides, they must be designed not to outgas when heated from the cells, and not to constitute an appreciable heat shield, giving rise to flux transients after opening.
* The substrate manipulator is capable of continuous azimuthal rotation (CAR) around its axis (see Fig. 1) to improve uniformity across the wafer and from wafer to wafer in multiwafer systems. The heater behind the sample is designed to maximize temperature uniformity and minimize power consumption and impurity outgassing. Opposite to the substrate holder, an ionisation gauge is used (by rotating 180° the CAR assembly) as a beam flux monitor (BFM), for day-to-day calibration of the molecular beam intensities. On the manipulator a Mo or Ta substrate holder is mounted, onto which the wafers are either glued with an In or Ga film, or clamped with a ring.
* Several analysis tools are available in MBE systems. The most valuable and peculiar one is Reflection High Energy Electron Diffraction (RHEED). This technique employs a high energy (up to 20 KeV) electron beam, directed on the sample surface at grazing incidence (a few degrees); the diffraction pattern is imaged on a symmetrically placed fluorescent screen.





