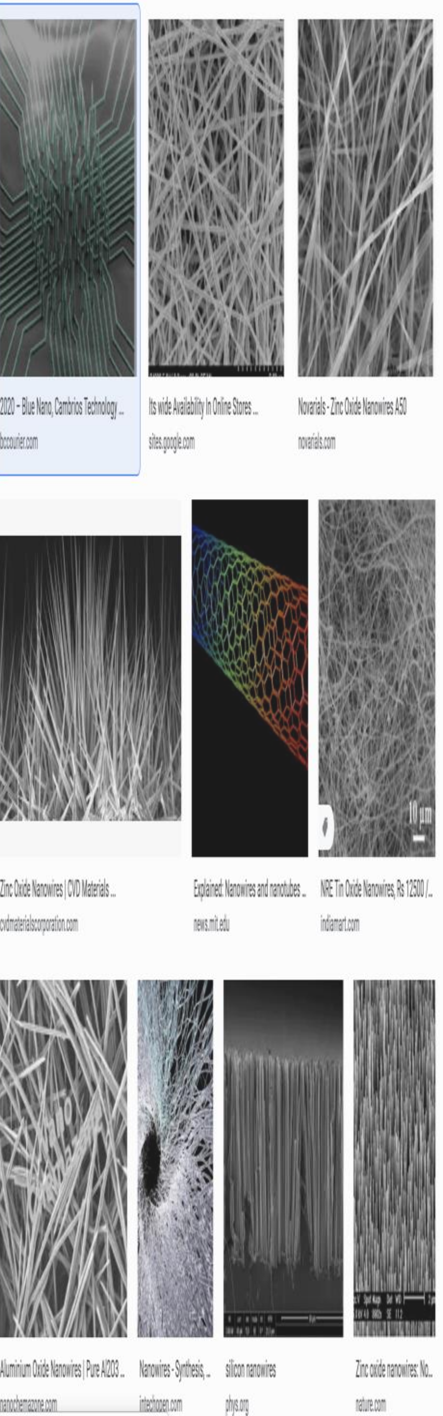


Epitaxial Growth

Nanowires—From Basic Materials Research to Real-World Applications

https://www.youtube.com/watch?v=2NUG957W72Q

Epitaxial Growth

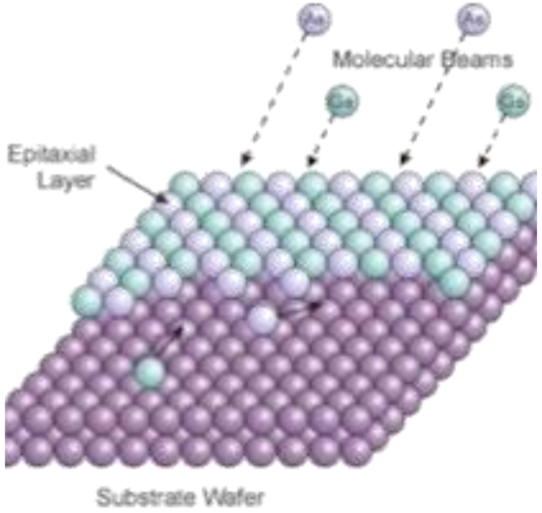
Outline

- Introduction
  - What is Epitaxy?
  - Types of Epitaxial films or layers
  - Selection of proper Epitaxial growth technique
  - General Epitaxial deposition requirements
  - Application of Epitaxial Growth
- Liquid Phase Epitaxy (LPE)
- Molecular Beam Epitaxy (MBE)
- Comparison

Epitaxial Growth

What is Epitaxy?

Epitaxy refers to the method of depositing a mono-crystalline film on a mono-crystalline substrate. The deposited film is denoted as epitaxial film or epitaxial layer.



- *Epi* means **above**
- *Taxis* means **deposition in ordered manner**

Epitaxial films may be grown from gaseous or liquid precursors.

The substrate acts as a **seed crystal**, the deposited film takes on a lattice structure and orientation identical to the surface.

Types of Epitaxial films or layers

Epitaxial films can be classified in two broad categories:

1) **Homoepitaxy** (homoepi)
   - The film and substrate are the same material (Si/Si, GaAs/GaAs)
   - Epitaxially grown layers are purer tan the substrate and can be doped independently of it.
   - **Pseudo homoepitaxy –** Epi film and substrate are of the same material but doping in epi layer can be different from that of the substrate (doped Si/undoped Si)

2) **Heteroepitaxy**
   - Film and substrate are of different materials (AlAs on GaAs)
   - **Pseudo heteroepitaxy –** Chemical commonality between film and substrate (GaP and GaSb or GaAs)

Epitaxial Growth

Selection of proper Epitaxial Growth technique

- Basic principles of thermodynamics and kinetics
- Surface energies
- Practical issues
  - Reproducibility
  - Scalability
  - Process control and safety
  - Instrumentation
  - Capital equipment cost

Epitaxial Growth

General Epitaxial Deposition Requirements

Surface preparation

- Clean surface needed
- Defects of surface duplicated in epitaxial layer
- Hydrogen passivation of surface with water or hydrofluoric acid (HF)

Surface mobility

- High temperature required -> heated substrate
- Epitaxial temperature exists, above which deposition is ordered
- Species need to be able to move into correct crystallographic location
- Relatively slow growth rates result in low thickness of layer
  - Ex. ~0.4 to 4 nm/min, SiGe on Si

Epitaxial Growth

Applications of Epitaxial growth

- Nanotechnology
- Semiconductor fabrication
- High quality crystal growth (Si-Ge, GaN, GaAs, InP, graphene)
- Growing layers of pre-doped silicon (pacemakers, vending machine controllers, automobiles, computers, etc.)
- To deposit organic molecules onto a crystalline substrate

Liquid Phase Epitaxy (LPE)

Epitaxial Growth

Definitions

- *Nelson* – developed the first LPE system – produced multilayer compound semiconducting structure
- LPE is basically a high-temperature solution growth technique in which a thin layer of the required material is deposited onto a suitable substrate.
- LPE technique is widely used for preparation of epitaxial layers on compound semiconductors and for magnetic bubble memory films on garnet substrate.
- LPE is characterized as a **near-equilibrium growth process**, when compared to the various vapor-phase epitaxy techniques.
- The basic requirement is to bring the substrate and growth solution into contact while the epitaxal layer growth, and then to separate them cleanly at the end of the growth cycle.

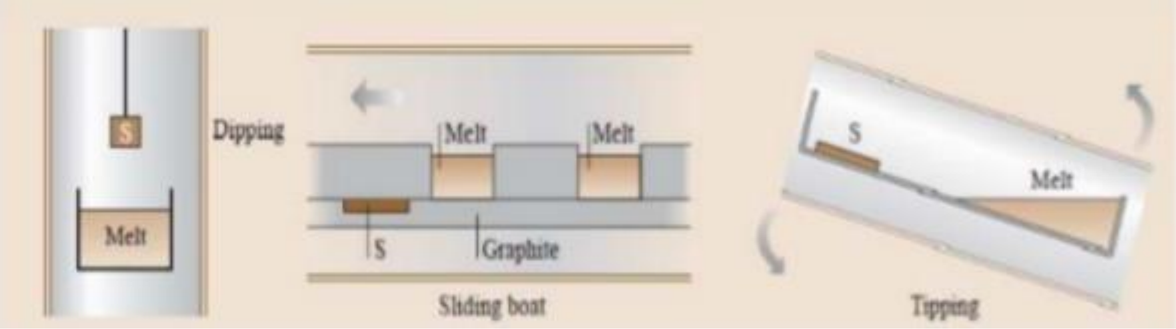
Epitaxial Growth

Apparatus and Techniques

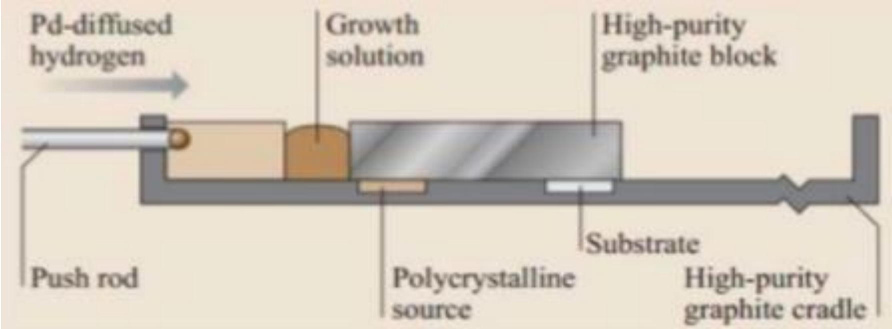
Three main embodiments – tipping, dipping and sliding boat

A graphite sliding boat system is the most popular and versatile

Drawback of melt retention – Multilayer growth possible in single run (three-layer GaAlAs structures run)

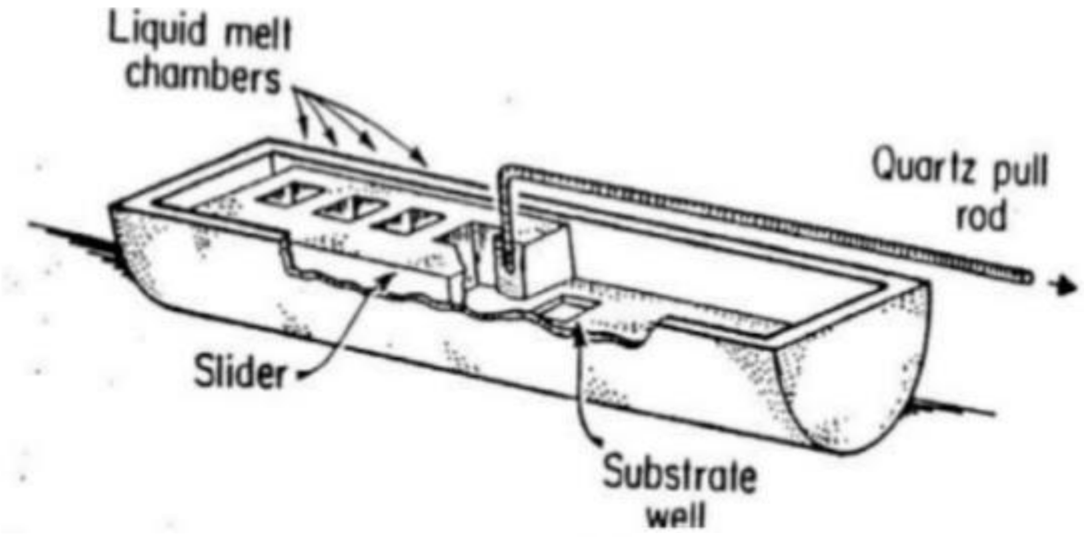


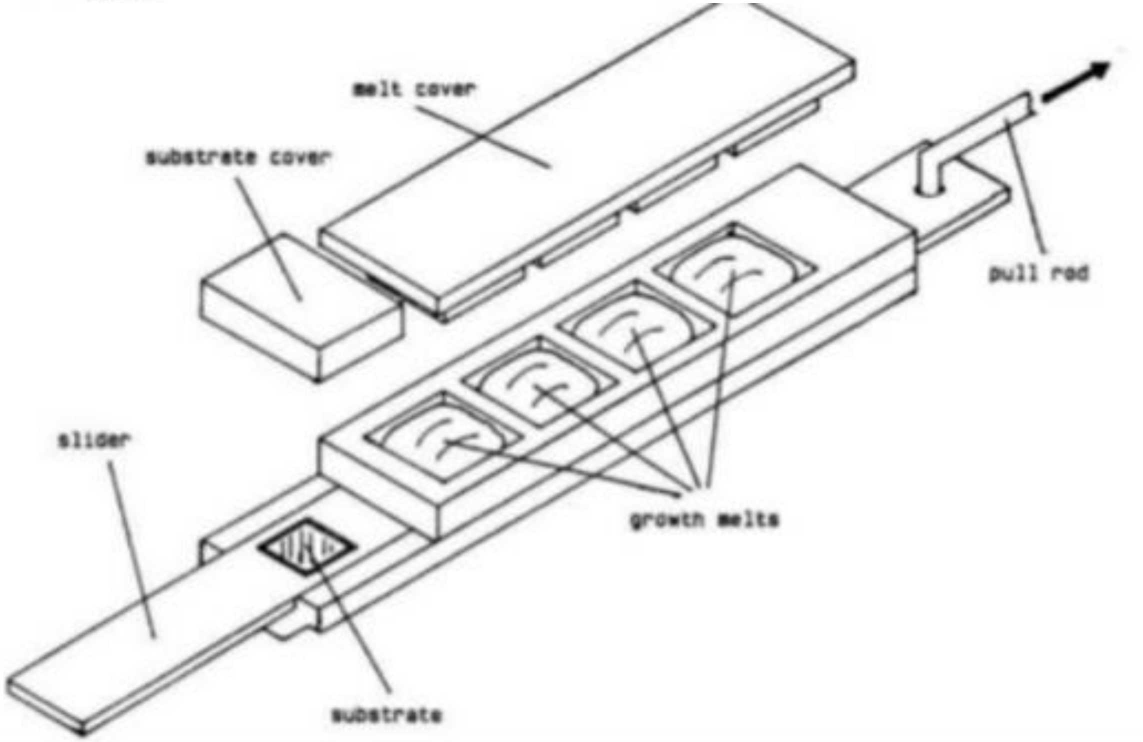
Dipping, sliding boat and tipping LPE arrangement.



Basic structure of graphite horizontal sliding boat LPE.

Epitaxial Growth





Epitaxial Growth

Liquid Phase Epitaxy (LPE)

Advantages

- High growth rates typically at 0.1 – 10 μm/h, faster than in MOVPE or MBE
- Favorable segregation of impurities into the liquid phase
- Able to produce very flat surfaces and excellent structural perfection
- Wide selection of dopants
- Growth can be made to occur at a wide range of temperatures
- Absence of highly toxic precursors or byproducts

Limitations

- To control layer thickness, alloy compositions, doping, interface smoothness
- Difficultiy in growing certain combinations of interest for heterostructure devices
- Poor reproducibility, problems scaling size upward or throughput
- Difficulty achieving abrupt interfaces between successive layers within structures

Epitaxial Growth

Applications

- III – V compound semiconductor layers
- LEDs, photodiodes and solar cells
- Growth of Si, Ge, SiGe alloys, SiC, GaAs, InP, GaP, GaSb, InAs, InSb (and their ternary and quaternary alloys), GaN, ZnSe, CdHgTe, HgZnTe and HgMnTe
- High-temperature superconductors
- Garnets, para and ferroelectrics
- For various other crystals for optics and magnetics

Molecular Beam Epitaxy (MBE)

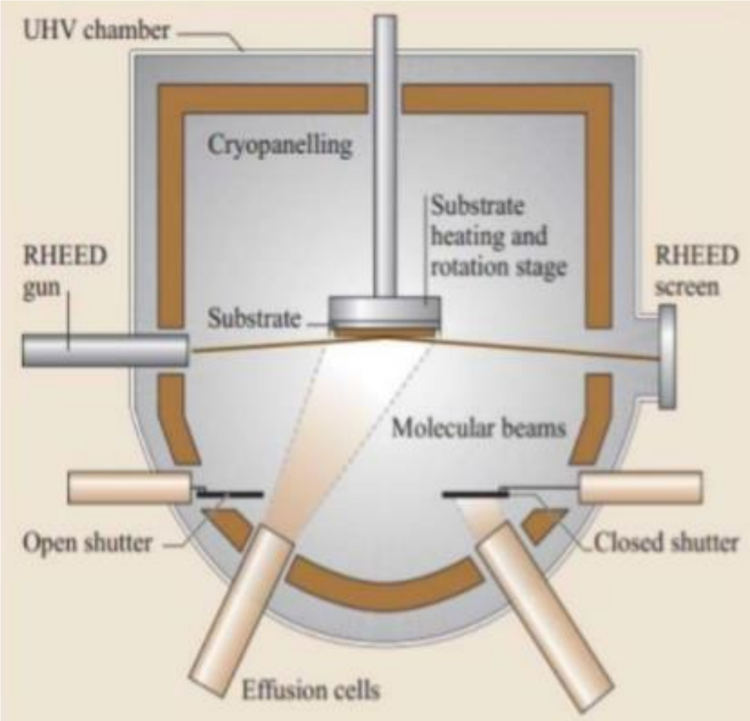
Epitaxial Growth

MBE: System and Working Principle

- **Epitaxial growth:** Due to the interaction of molecular or atomic beams on a surface of a heated crystalline substrate in UHV.

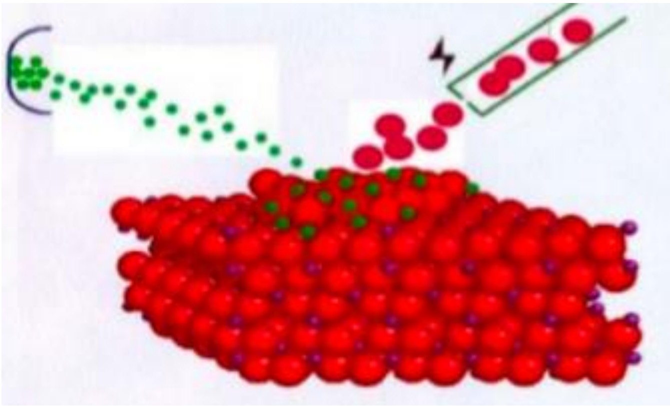
Basic elements of MBE system

1. Heated substrate
2. Effusion cells and shutter
3. Reflection High Energy Electron Diffraction (RHEED system – RHEED gun and screen)
4. Ultra high vacuum (UHV)
5. Liquid Nitrogen cryopanelling



Epitaxial Growth

Process



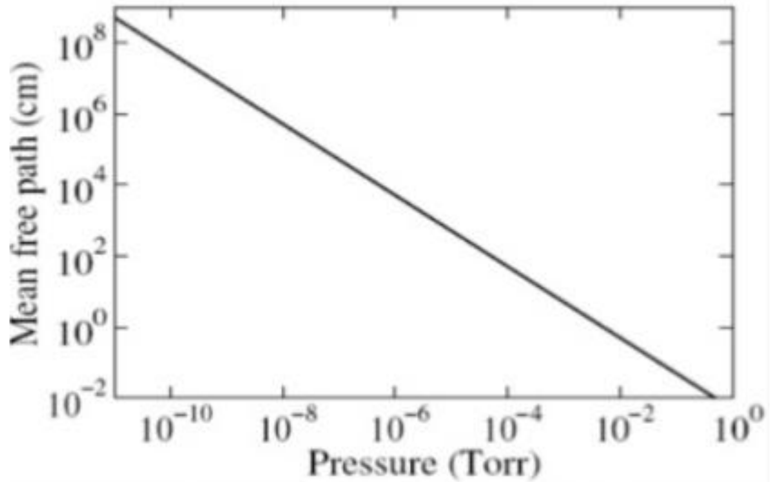
1. The solid source material sublimates.
2. They provide angular distribution of atoms or molecules in beam.
3. The sustrate is heated to the necessary temperature.
4. The gaseous elements then deposit on the wafer where they may react with each other to form a layer.
5. Atoms on a clean surface are free to move until they find the correct position in the crystal lattice to bond.

Epitaxial Growth

MBE: Working Conditions

➢ The mean free path (λ) of the particles > geometrical size of the chamber (10^{-5} Torr is sufficient)

- Ultra high vacuum (10^{-11} Torr) to obtain a sufficiently clean epilayer.
- Gas evolution from materials has to be as low as possible. Pyrolytic boron nitride (PBN) is chosen for crucibles (stable up to 1400 °C).
- Molybdenum and tantalum are widely employed for shutters.
- Ultrapure materials are used as a source.



Mean free path for Nitrogen molecules at 300 K.

Epitaxial Growth

Molecular Beam Epitaxy (MBE)

Advantages

- Clean surfaces, free of an oxide layer
- In-situ deposition of metal seeds, semiconductor materials and dopants
- Low growth rate (1 μm/h)
- Precisely controllable thermal evaporation
- Separate evaporation of each component
- Substrate temperature is not high
- Ultrasharp profiles

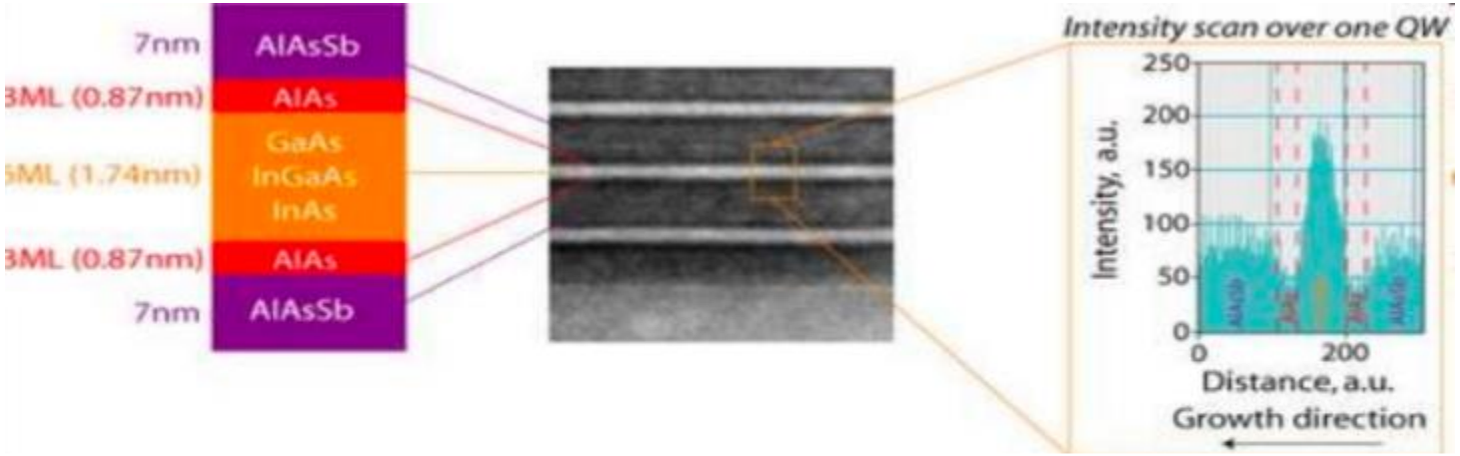
Limitations

- Expensive (\$$10^6$ per MBE chamber)
- ATG instability
- Very complicated system
- Epitaxial growth under ultra-high vacuum conditions

Epitaxial Growth

Applications

- Novel structures as quantum devices
- Silicon/Insulator/Metal sandwiches
- Superlattices
- Microelectronic devices



TEM image of MBE-grown ultra-thin InGaAs/AlAsSb Quantum Wells

Epitaxial Growth

Comparison of GaAs epitaxial processes

	Liquid Phase Epitaxy (LPE)	Vapor Phase Epitaxy		Molecular Beam Epitaxy (MBE)
		Chemical Vapor Deposition (CVD)	Metal Organic CVD	
Growth rate (μm/min)	~ 1	~ 0.1	~ 0.1	~ 0.01
Growth temperature (°C)	850	750	750	550
Thickness control (Å)	500	250	25	5
Interface width (Å)	≥ 50	~ 65	< 10	< 5
Dopant range (cm^{-3})	$10^{13} – 10^{19}$	$10^{13} – 10^{19}$	$10^{14} – 10^{19}$	$10^{14} – 10^{19}$
Mobility at 77K (cm^2/Vs) (n-type GaAs)	150,000 – 200,000	150,000 – 200,000	140,000	160,000