

Molecular Beam Epitaxy

09/26/2008

MSE 576: Thin Films

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- Epitaxy
- Molecular Beam Epitaxy
- Molecular Beam
- Problems and Diagnostics

Epitaxy

- Method of depositing a monocrystalline film.
- Greek root: *epi* means “above” and *taxis* means “ordered”.
- Grown from: *gaseous* or *liquid* precursors.
- Substrate acts as a seed crystal: film follows that !
- Two kinds: **Homoepitaxy** (same composition) and **Heteroepitaxy** (different composition).

Epitaxy

- Homoepitaxy:

- # To grow more purified films than the substrate.

- # To fabricate layers with different doping levels

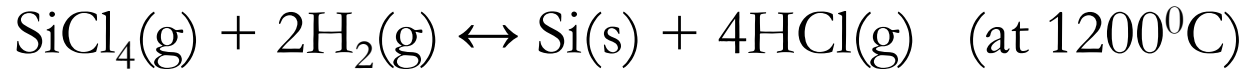
- Heteroepitaxy:

- # To grow films of materials of which single crystals cannot be grown.

- # To fabricate integrated crystalline layers of different materials

Epitaxy

- Vapor Phase Epitaxy (VPE)



VPE growth rate: proportion of the two source gases

- Liquid Phase Epitaxy (LPE)

Czochralski method (Si, Ge, GaAs)

Growing crystals from melt on solid substrates

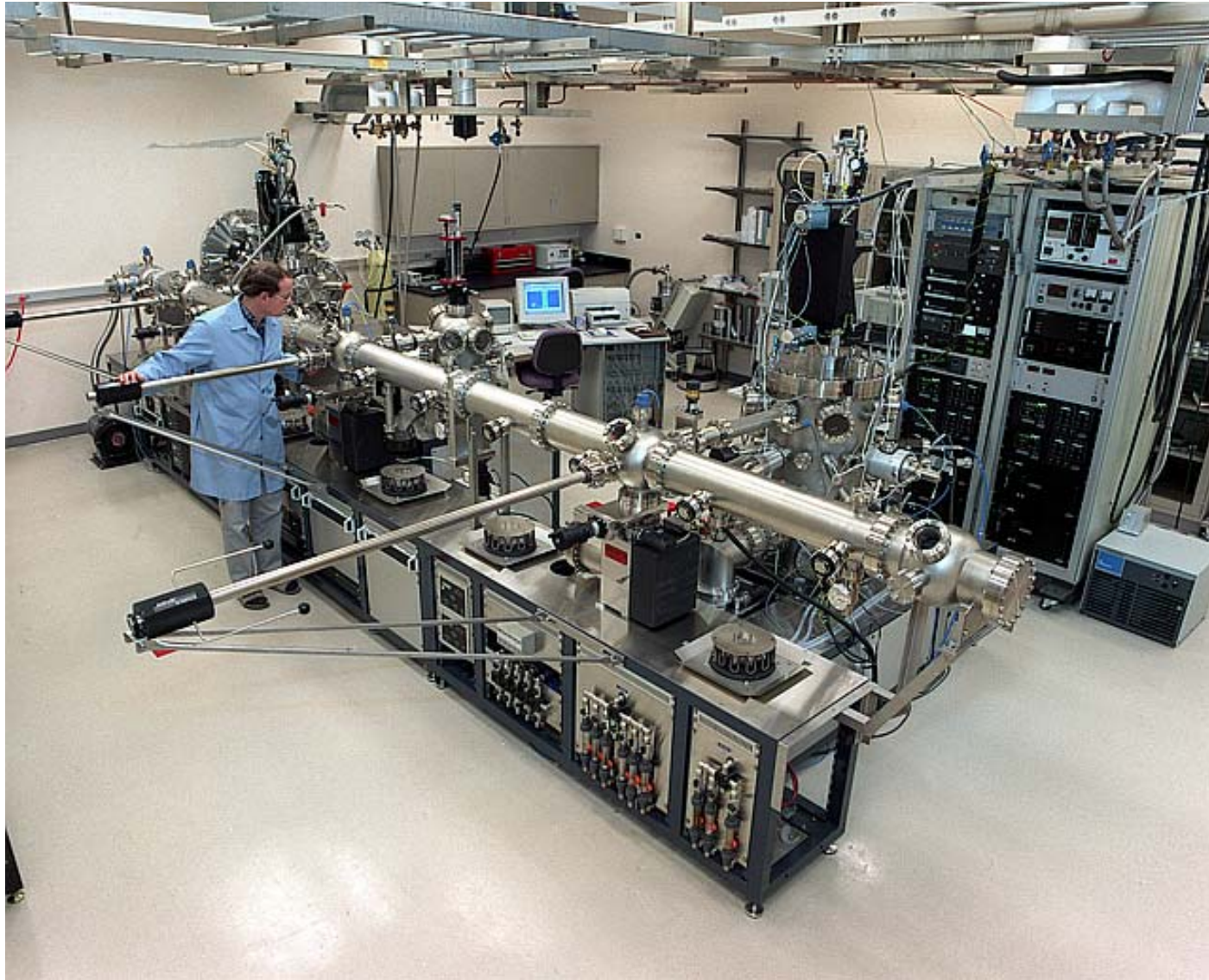
Compound semiconductors (ternary and quaternary III-V compounds on GaAs substrates)

- Molecular Beam Epitaxy (MBE)

Evaporated beam of particles

Very high vacuum (10^{-8} Pa); condense on the substrate

Molecular Beam Epitaxy



Molecular Beam Epitaxy: Idea !

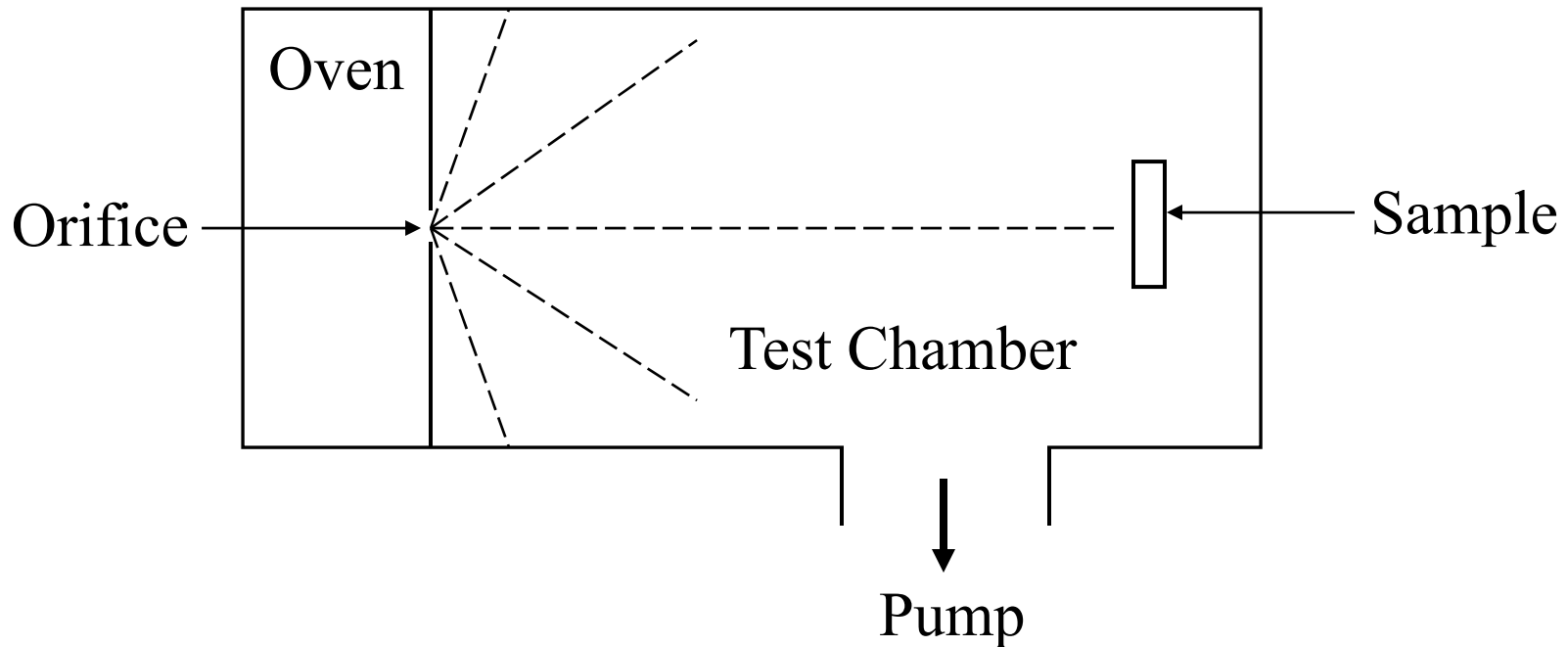
- Objective: To deposit single crystal thin films !
- Inventors: J.R. Arthur and Alfred Y. Chuo (Bell Labs, 1960)
- Very/Ultra high vacuum (10^{-8} Pa)
- Important aspect: slow deposition rate (1 micron/hour)
- Slow deposition rates require proportionally better vacuum.

Molecular Beam Epitaxy: Process

- Ultra-pure elements are heated in separate quasi-knudson effusion cells (e.g., Ga and As) until they begin to slowly sublime.
- Gaseous elements then condense on the wafer, where they may react with each other (e.g., GaAs).
- The term “beam” means the evaporated atoms do not interact with each other or with other vacuum chamber gases until they reach the wafer.

Molecular Beam

- A collection of gas molecules moving in the same direction.
- Simplest way to generate: Effusion cell or Knudsen cell



Knudson cell effusion beam system

Molecular beam

- Oven contains the material to make the beam.
- Oven is connected to a vacuum system through a hole.
- The substrate is located with a line-of-sight to the oven aperture.
- From kinetic theory, the flow through the aperture is simply the molecular impingement rate on the area of the orifice.

Molecular Beam

- Impingement rate is:

$$I = \frac{1}{4} n \bar{v} = \frac{1}{4} \left(\frac{p}{kT} \right) \sqrt{\left(\frac{8kT}{\pi m} \right)}$$

- The total flux through the hole will thus be:

$$Q = IA = \frac{p \pi r^2}{\sqrt{2\pi m kT}}$$

- The spatial distribution of molecules from the orifice of a knudsen cell is normally a cosine distribution:

$$I' = \frac{1}{4} n \bar{v} \left(\frac{\cos \theta}{\pi} \right)$$

Molecular Beam

- The intensity drops off as the square of the distance from the orifice.

$$I_{sub} = IA \left(\frac{\cos \vartheta}{\pi} \right) \left(\frac{1}{L^2} \right)$$

or,

$$I_{sub} = \left[\frac{p}{\sqrt{2\pi mkT}} \right] \left(\frac{r}{L} \right)^2 \cos \vartheta$$

- High velocity, greater probability; the appropriate distribution:

$$\frac{dn_v}{n} = 2 \left(\frac{v^3}{\alpha^4} \right) \exp \left(\frac{-v^2}{\alpha^2} \right) dv$$

where $\alpha = \sqrt{2kT / m}$

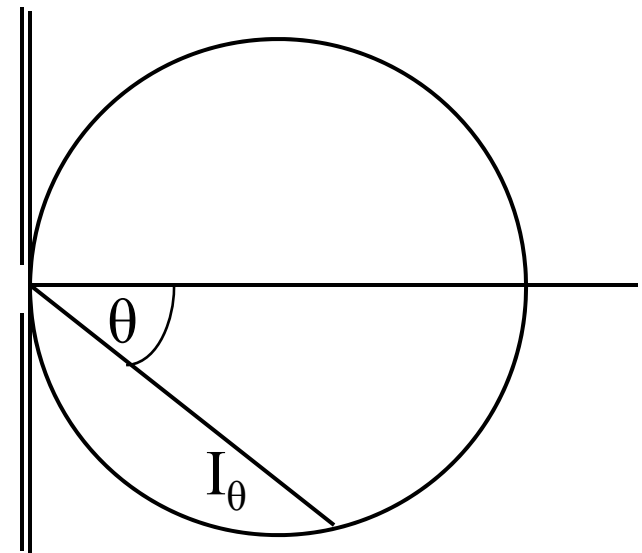
Molecular Beam

- Integrating the equation gives:

$$E_{tr} = 2kT$$

as the mean translational energy of the molecules

Intensity is maximum in the direction normal to the orifice and decreases with increasing θ , which causes problems.



Use collimator, a barrier with a small hole; it intercepts all of the flow except for that traveling towards the sample.

MBE: In-situ process diagnostics

- RHEED (Reflection High Energy Electron Diffraction) is used to monitor the growth of the crystal layers.
- Computer controlled shutters of each furnace allows precise control of the thickness of each layer, down to a single layer of atoms.
- Intricate structures of layers of different materials can be fabricated this way e.g., semiconductor lasers, LEDs.
- Systems requiring substrates to be cooled: Cryopumps and Cryopanel are used using liquid nitrogen.

ATG Instability

- Ataro-Tiller-Grinfeld (ATG) Instability: Often encountered during MBE.
- If there is a lattice mismatch between the substrate and the growing film, elastic energy is accumulated in the growing film.
- At some critical film thickness, the film may break/crack to lower the free energy of the film.
- The critical film thickness depends on the Young's moduli, mismatch size, and surface tensions.

Assignment

- Solve the equation to find the mean translational energy (E_{tr}) of the molecules:

$$\frac{dn_v}{n} = 2 \left(\frac{v^3}{\alpha^4} \right) \exp \left(\frac{-v^2}{\alpha^2} \right) dv$$

where $\alpha = \sqrt{2kT / m}$

- What fraction of the molecules in a molecular beam of N_2 formed by effusion of N_2 gas initially at 300 K from an orifice at a large Knudsen number will have kinetic energies greater than 8kcal/mol?