
Course Title: Processing &
Fabrication Technology
Course No.: EEE 707

Class lecture -3



Introduction to Epitaxy



Introduction

To fabricate discrete devices and integrated circuits, we use many different kinds of thin films. We can classify thin films into five groups:

1. Thermal oxides
2. Dielectric layers
 - Used for insulation between conducting layers, for diffusion and ion implementation masks, for passivation.
3. **Epitaxial layers**
4. Polycrystalline silicon and
 - Used as a gate electrode material in MOS devices
5. Metal films
 - Used to form low resistance interconnections, ohmic contacts



Epitaxy and Epitaxial Growth

- ▶ Epitaxy is the ordered growth of a mono crystalline layer that bears a definite relation to the underlying mono crystalline substrate.
- ▶ A process of depositing a thin layer (0.5 to 20pm) of single crystal material over a single crystal substrate, usually through chemical vapor deposition (CVD).
- ▶ The technique of growing an oriented single crystal layer on a substrate wafer is called epitaxial growth or Epitaxy. Epitaxy is performed at temperature considerably below the melting of the substrate crystal.



Starting Substrate



Substrate plus epitaxial growth

Epitaxy and Epitaxial Growth...

Epitaxial growth systems can be divided into two broad categories:

- ▶ **Homoepitaxy:** the grown layer is chemically similar to the substrate (p-Si on p-sub Si)
- ▶ **Heteroepitaxy:** the grown layer differs in terms of chemistry, crystal structure, symmetry and/ or lattice parameter from the substrate (AlGaAs on GaAs; GaN on SiC).

Why all the interest in Epitaxy?

Advantages:

- ▶ Epitaxial growth is a **standard processing technology** in silicon device fabrication.
- ▶ Advanced epitaxial growth methods **permit the fabrication of extraordinarily advanced electronic and photonic device structures.**
- ▶ Epitaxy permits the **fabrication of thin-film single crystal materials** that would be difficult or impossible to grow as bulk single crystals.
- ▶ The extreme thickness control of modern epitaxial growth methods **allow unusual and unique physical and chemical phenomenon to be studied.**

Why all the interest in Epitaxy?...

Advantages:

- ▶ Silicon Epitaxy is done to **improve the performance of bipolar devices.**
- ▶ By growing a lightly doped Epi-layer over a heavily-doped silicon substrate, a **higher breakdown voltage** across the collector-substrate junction is **achieved** while maintaining low collector resistance, which **allows a higher operating speed** with the same current.
- ▶ Epitaxy has also recently been **used in CMOS VLSI** circuits.
- ▶ Epitaxy also allows **better control of doping concentrations** of the devices. The layer can also be made oxygen-and carbon-free.

Why all the interest in Epitaxy?...

Disadvantages:

- ▶ The disadvantages of Epitaxy include **higher cost** of wafer fabrication, additional process **complexities** and problems associated with **defects** in the epi-layer.

Methods

Epitaxy methods include:

- Chemical Vapor Deposition (CVD) / Vapor Phase Epitaxy (VPE)
- Liquid Phase Epitaxy (LPE)
- Molecular Beam Epitaxy (MBE)

The common techniques for epitaxial growth are CVD and MBE.

Vapor Phase Epitaxy (VPE)

CVD is used for the deposition of layers that may be polycrystalline or amorphous and VPE is used for the deposition of single crystal epitaxial layer.

Crystalline layers can be grown onto a wafer/substrate from the chemical vapor of the semiconductor material or mixtures of chemical vapors containing the semiconductor. VPE is a particularly important source of semiconductor material for use in devices. VPE ensures the better purity and crystal perfection than other methods.

Vapor Phase Epitaxy (VPE)...

Epitaxial layers are generally grown on Si substrates by the controlled deposition of Si atoms onto the surface from a chemical vapor containing Si.

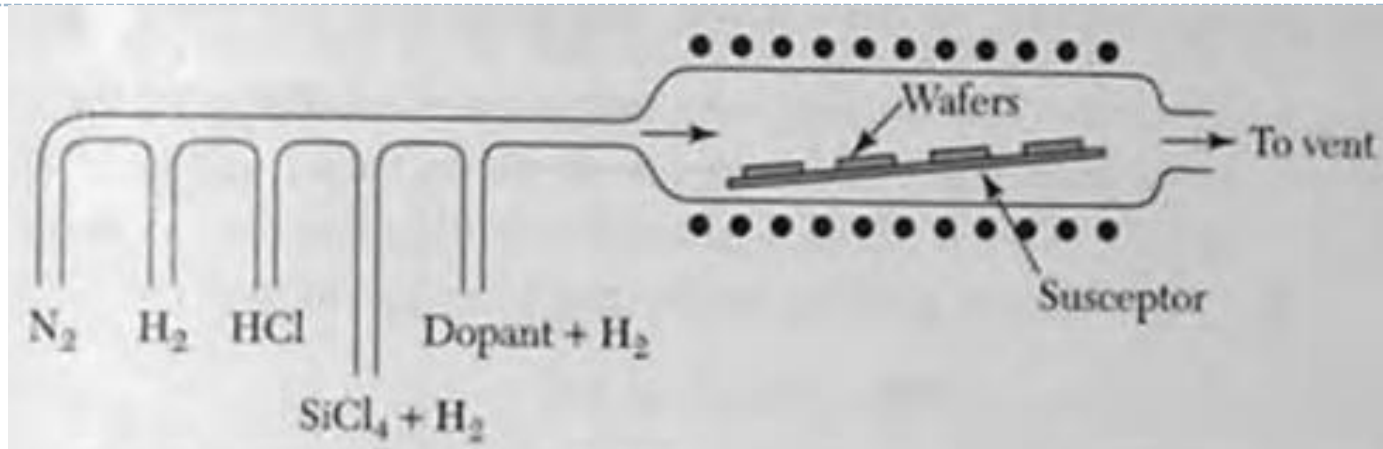
CVD for Silicon:

A gas of silicon tetrachloride (SiCl_4) reacts with hydrogen (H_2) to give Si and HCl.



If this reaction occurs at the surface of a heated crystal, the Si atoms released in the reaction can be deposited as an epitaxial layer. HCl remains gaseous at the reaction temperature and does not affect the growing crystal.

Vapor Phase Epitaxy (VPE)...



The VPE requires a chamber into which the gases can be introduced and a heating-method for heating the Si wafers. The chamber is called reaction chamber or simply reactor as chemical reactions take place in the chamber. H_2 gas is passed through a heated vessel in which SiCl_4 is evaporated; then the two gases are introduced into the reaction chamber over the substrate crystal, along with other gases containing the desired doping impurities.

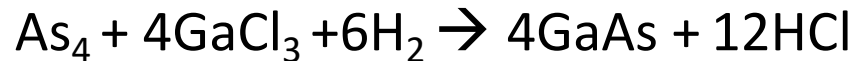
The Si Wafer is placed on a graphite susceptor that can be heated to the reaction temperature with an RF heating coil. In this method, a number of Si wafers may have epitaxial layers simultaneously with controlled impurity concentrations.

Vapor Phase Epitaxy (VPE)...

CVD for Gallium Arsenide:

Because gallium arsenide decomposes into gallium and arsenic upon evaporation, its direct transport in the vapor phase is not possible. One approach is the use of As_4 for the arsenic component and gallium chloride (GaCl_3) for the gallium component.

The overall reaction leading to epitaxial growth of gallium arsenide is



The As_4 is generated by thermal decomposition of arsine (AsH_3):



and the gallium chloride is generated by the reaction



Vapor Phase Epitaxy (VPE)...

The reactants are introduced into a reactor with a carrier gas (e.g. H_2). The gallium arsenide wafers are typically held within the 650C to 850C temperature range. There must be sufficient arsenic overpressure to prevent thermal decomposition of the substrate and the growing layer.

Advantage of Vapor Phase Epitaxy (VPE)

- Lower reaction temperature reduces the migration of impurities from the substrate to the growing epitaxial layer.
- Thin Si layer may be produced over an insulating layer.

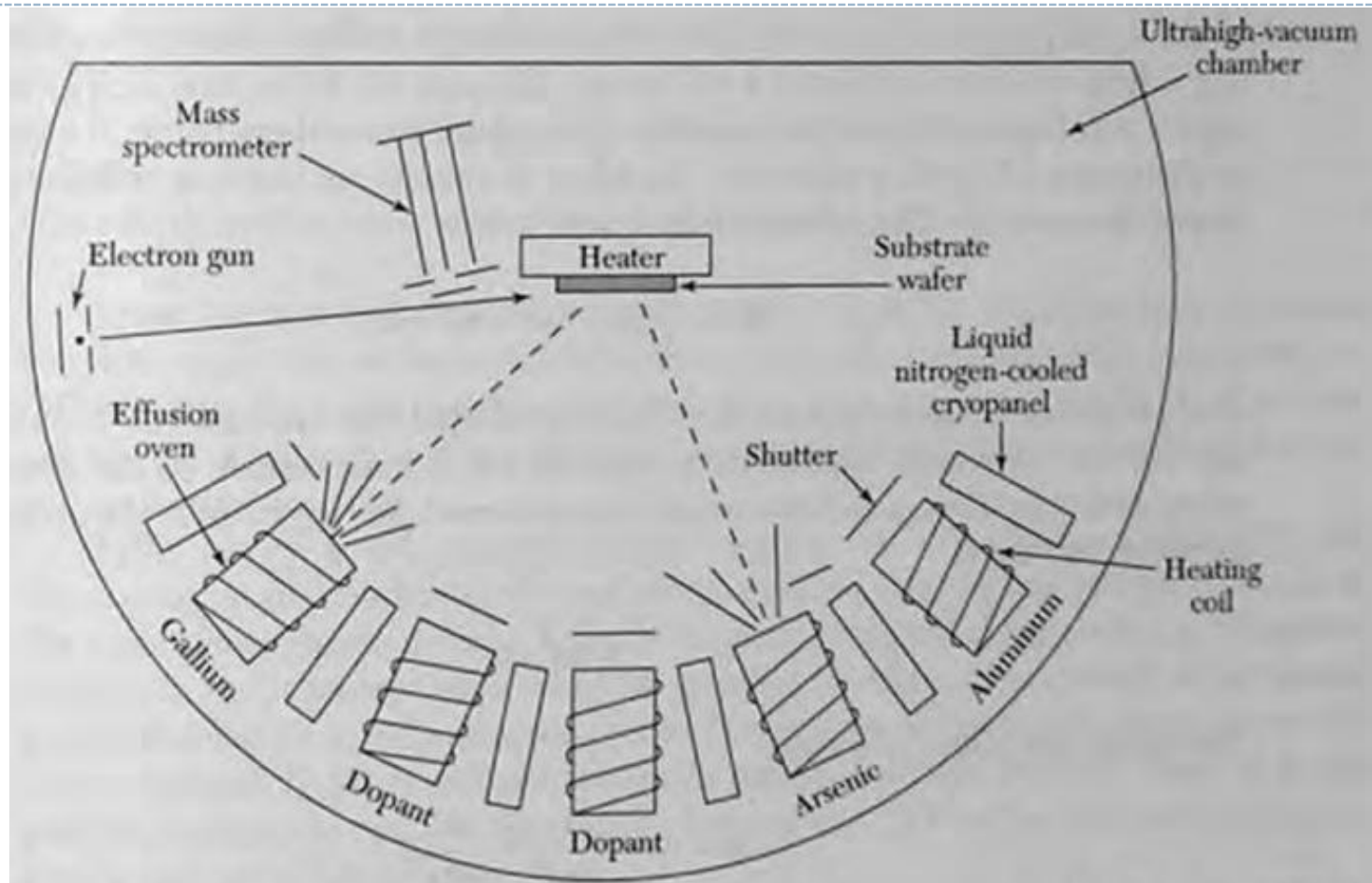
Liquid Phase Epitaxy (LPE)

It is possible to grow crystals of many semiconductors from a liquid solution at temperatures well below their melting point. Since a mixture of the semiconductor with a second element may melt at a lower temperature than the semiconductor itself. It is often an advantage to grow crystal from solution at the temperature of the mixture. In LPE the solution can be placed onto the wafer in a number of ways: one of the most direct methods involves **holding the wafer in a graphite slider and moving it into a pocket containing the melt**. After growth, the epitaxial surface is wiped clean as it is moved to the pocket for further growth (in case of multiple layers).

Molecular Beam Epitaxy (MBE)

One of the most versatile techniques for growing epitaxial layer is called MBE. In this method the substrate is placed in a high vacuum while molecular or atomic beams of the constituents impinge upon its surface. For example, in the growth of AlGaAs layer on GaAs substrate, Al, Ga and As components along with the dopants are heated in separate cylindrical cells. Collimated beams of this constituents escape into the vacuum and directed onto the surface of the substrate. An electron gun is used to evaporate the silicon. The rates at which the atomic beams strike the surface and be closely controlled and a high quality crystal is grown. Because of high vacuum and close control involved, MBE requires sophisticated setup. In general, MBE growth rates are quite low. For GaAs, a value of $1\mu\text{m/hr}$ is typical.

Molecular Beam Epitaxy (MBE)...



Arrangement of the sources and substrate in a conventional molecular beam Epitaxy

Types of CVD

- ▶ Atmospheric pressure CVD (APCVD)
- ▶ Low pressure CVD (LPCVD)
- ▶ Plasma Enhanced CVD (PECVD)

CVD is the process of formation of non-volatile solid film on substrate by reaction of vapor phase chemicals.

Comparison

Low temperature oxide formation by APCVD, LPCVD/ PECVD VS. Thermal oxidation of silicon:

Advantages:

- ▶ Low temperatures
- ▶ Fast deposition rates especially APCVD.
- ▶ Good Step Coverage especially PECVD.

Disadvantages:

- ▶ Contamination especially PECVD.
- ▶ Inferior electrical properties of PECVD films as compared with thermally grown ones.
- ▶ Less dense films are obtained.

Defects in Epitaxial Layers

Defects in epitaxial layers will degrade device properties. For example, defects can result in reduced mobility or increased leakage current.

1. **Defects from the substrates:** these defects may propagate from the substrate into the epitaxial layer. To avoid these defects, dislocation-free semiconductor substrates are required.
2. **Defects from the interface:** oxide precipitates or any contamination at the interface of the epitaxial layer and substrate may cause the formation of misoriented clusters or nuclei containing stacking faults. These clusters and stacking faults may coalesce with normal nuclei and grow into the film in the shape of an inverted pyramid. To avoid these defects, the surface of the substrate must be thoroughly cleaned.

Defects in Epitaxial Layers...

3. **Precipitates or dislocation loops:** their formation is due to super saturation of impurities or dopants. Epitaxial layers containing very high intentional or unintentional dopants or impurity concentrations are susceptible to such defects.
4. **Low-angle grain boundaries and twins:** any misoriented areas of an epitaxial film during growth may meet and coalesce to form these defects.
5. **Edge dislocation:** these are formed in the heteroepitaxy of two lattice-mismatched semiconductors. If both lattices are rigid, they will retain their fundamental lattice spacing's and the interface will contain rows of misbonded atoms described as misfit or edge dislocations. The edge dislocations can also form in a strained layer when the layer thickness becomes larger than critical layer thickness.

Thin-Film Deposition

- ▶ Physical Vapor Deposition (PVD)
 - ▶ Evaporation
 - ▶ Sputtering
- ▶ Chemical Vapor Deposition (CVD)
 - ▶ Oxidation
 - ▶ Low Pressure CVD (LPCVD)
 - ▶ Plasma Enhanced CVD (PECVD)

CVD Chemistries

▶ ***Silicon oxide:***

- ▶ Dry Oxidation: $\text{Si} + \text{O}_2 \rightarrow \text{SiO}_2$
- ▶ Wet oxidation: $\text{Si} + \text{H}_2\text{O} \rightarrow \text{SiO}_2 + \text{H}_2$
- ▶ $\text{SiH}_4 + \text{O}_2 \rightarrow \text{SiO}_2 + 2\text{H}_2$
- ▶ $\text{SiH}_4 + \text{N}_2\text{O} \rightarrow \text{SiO}_2 + \text{by-products}$
- ▶ $\text{SiCl}_2\text{H}_2 + \text{N}_2\text{O} \rightarrow \text{SiO}_2 + \text{by-products}$
- ▶ $\text{Si}(\text{OC}_2\text{H}_5)_4 \rightarrow \text{SiO}_2 + \text{by-products}$

▶ ***Silicon Nitride:***

- ▶ $3\text{SiH}_4 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 12\text{H}_2$
- ▶ $\text{SiCl}_2\text{H}_2 + \text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + \text{by-products}$
- ▶ $\text{SiH}_4 + 4\text{N}_2\text{O} \rightarrow \text{Si}_3\text{N}_4 + \text{by-products}$
- ▶ $\text{SiH}_4 + \text{N}_2 \rightarrow \text{Si}_3\text{N}_4 + \text{by-products}$