

6.3 Chemical Vapor Deposition

6.3.1 Silicon Epitaxy

We have encountered the need for [epitaxial layers](#) before, and we also have seen a [Si CVD process](#) for making polycrystalline material good enough for growing crystals. All we have to do now is to put both things together.

We can use essentially the same **CVD** process as before, but instead of thin rods of poly-Si which we want to grow in diameter as fast as possible, we now want to make a thin, but absolutely perfect **Si** layer on top of a wafer.

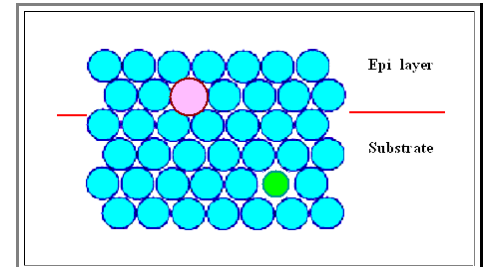
We now must have tremendous process control. We require:

A **precise continuation** of the substrate lattice. There should be no way whatsoever to identify the interface after the epitaxial layer has been deposited. This means that **no lattice defects whatsoever** should be generated.

Doping of the epitaxial layer with high precision (e.g. $5 \Omega\text{cm} \pm 5\%$), and the doping is usually very different from that of the substrate. The picture on the right symbolizes that by the two differently colored doping atoms.

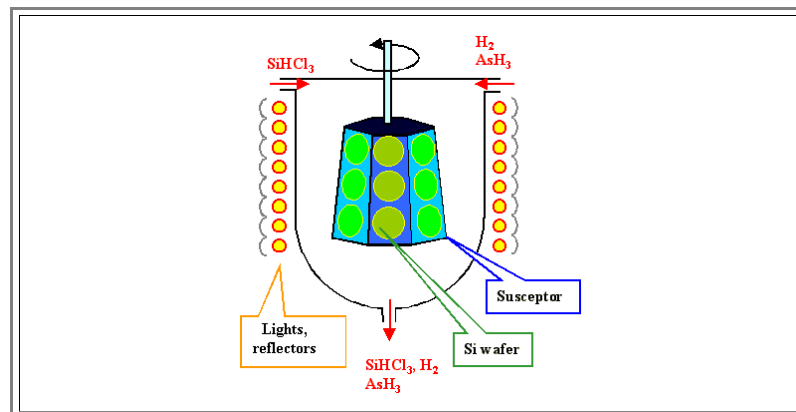
Precise thickness control, e.g. $d = 1.2 \mu\text{m} \pm 10\%$ over the entire wafer, from wafer to wafer and from day to day. Now there is a challenge: If you met the first point and thus can't tell where the interface is - how do you measure the thickness? (The answer: Only electronically, e.g. by finding the position of the **pn-junction** produced).

Cleanliness: No contaminants diffusing into the substrate and the epitaxial layer are allowed.

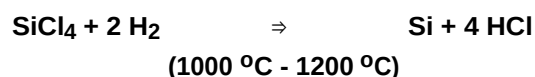


This looks tough and it is indeed fairly difficult to make good epitaxial layers. It is also quite expensive and is therefore avoided whenever possible (e.g. in mainstream **CMOS** technology). It is, however, a must in bipolar and some other technologies and also a good example for a very demanding process with technical solutions that are far from obvious.

Lets look at a typical epitaxial reactor from around **1990** (newer ones tend to be single wafer systems). It can process several wafers simultaneously and meets the above conditions. Here is a muchly simplified drawing:



The chemical reaction that produces the **Si** is fairly simple:

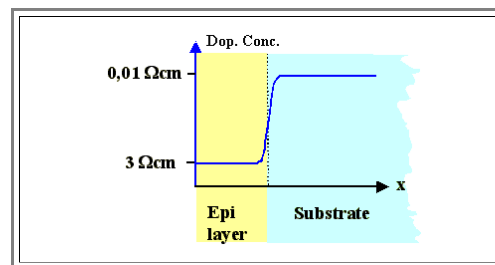


The dopant gases just decompose or react in similar ways. However, instead of **SiCl₄** you may want to use **SiH_xCl_{4-x}**.

The essential point is that the process needs high temperatures and the **Si** wafer will be at high temperature! In an Epi reactor as shown above, the **Si** wafer surfaces (and whatever shows of the susceptor) are the only hot surfaces of the system!

How is the process actually run? You need to meet some tight criteria for the layer specifications, as [outlined above](#), and that transfers to tight criteria for process control.

- 1. **Perfectly clean Si** surface before you start. This is not possible by just putting clean **Si** wafers inside the Epi-reactor (they always would be covered with **SiO₂**), but requires an in-situ cleaning step. This is done by first admitting only **H₂** and **Cl₂** into the chamber, at a very high temperature of about **1150 °C**. **Si** is etched by the gas mixture - every trace of **SiO₂** and especially foreign atoms at the surface will be removed.
 - 2. Temperature gradients of at most **(1 - 2) °C**. This is (better: was) achieved by **heating with light** as shown in the drawing. The high intensity light bulbs (actually rods) consume about **150 kW** electrical power (which necessitates a **30 kW** motor running the fan for air-cooling the machinery).
 - 3. Extremely tightly controlled gas flows within a range of about **200 l/min H₂**, **5 l/min SiCl₄** (or **Si HCl₃**), and fractions of **ml/min** of the doping gases.
- Not to forget: Epi-reactors are potentially very dangerous machines with a lot of "dirty" output that needs to be cleaned. All things taken together make Epi-reactors very expensive - you should be prepared to spend several million \$ if you want to enter this technology.
- Si** epitaxy thus is a process that is avoided if possible - it costs roughly **\$5** per wafer, which is quite a lot. So when do we use epitaxy?
- Epitaxy is definitely needed if a **doping profile** is required where the **resistivity in surface near regions is larger than in the bulk**. In other words, a profile like this:



- By diffusion, you can always lower the resistivity and even change the doping type, but **increasing the resistivity by diffusion** is not realistically possible.
 - Consider a substrate doping of 10^{16} cm^{-3} . Whatever resistivity it has (around **5 - 10 Ωcm**), if you diffuse $2 \cdot 10^{16} \text{ cm}^{-3}$ of a dopant into the substrate, you **lowered** the resistivity of the doped layer by a factor of 2.
 - To **increase** the resistivity you have to compensate half of the substrate doping by diffusing a dopant for the reverse doping type with a concentration of $5 \cdot 10^{15} \text{ cm}^{-3}$. Not only does that call for much better precision in controlling diffusion, but you will only get that value at a particular distance from the surface because you always have a **diffusion profile**. So all you can do by diffusion is to increase the resistivity somewhat near the surface regions; but you cannot make a sizeable layer this way.
- You also may use epitaxial layers if you simply need a **degree of freedom in doping** that is not achievable otherwise.
- While **DRAMs** were made without epitaxy up to the **16 Mbit** generation (often to the amazement of everybody, because in the beginning of the development work epitaxy seemed to be definitely necessary), epitaxial **Si** layers are now included from the **64 Mbit DRAM** upwards.