Lecture 11

Degenerate and Non-Degenerate Semiconductors

Recap: Difference between Direct and Indirect Semiconductor was discussed. In a direct band gap semiconductor, the top of the valence band and the bottom of the conduction band occur at the same value of momentum. In an indirect band gap semiconductor, the maximum energy of the valence band occurs at a different value of momentum to the minimum in the conduction band energy.

Degenerate and non-degenerate Semiconductors

Typical dopant concentrations are in range of ppm (parts of gas per million) or ppb and form individual energy levels in the band gap. This is because N_D and N_A are much smaller than the effective density of states at the band edges (N_c and N_v). These are called non-degenerate semiconductors. Under such conditions, it is possible to consider the dopants as individual atoms in the Si lattice and ignore interactions between the dopant levels. This is why dopants are shown as individual energy levels, close to the valence or conduction band, and not as an energy band.

As the dopant concentration increases, the individual energy levels start to overlap so that there are no longer energy levels but energy bands. This happens at typical dopant concentrations of 10^{19} and 10^{20} cm^{-3}, comparable to N_c and N_v (10^{20} cm^{-3}). These are called degenerate semiconductors, and their energy band diagram is shown schematically in figure 1. The dopant energy levels can merge with the conduction or valence band, so that the Fermi energy lies within the band. Thus, degenerate semiconductors behave more like metals than semiconductors. Degenerate doped semiconductors are used for some opto-electronic devices like lasers due to the large carrier concentration.

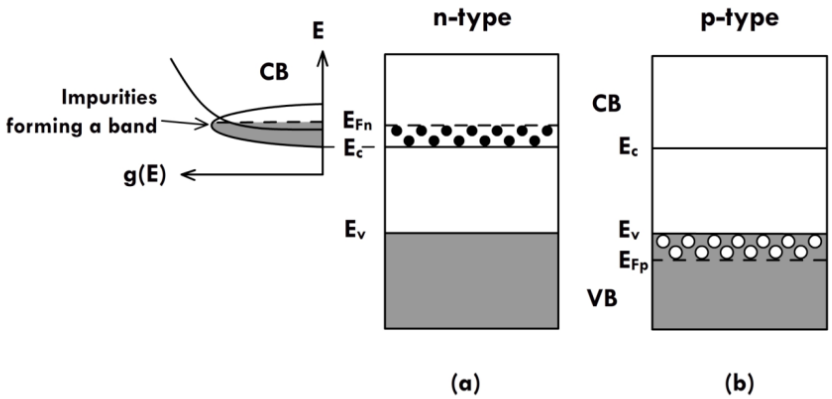
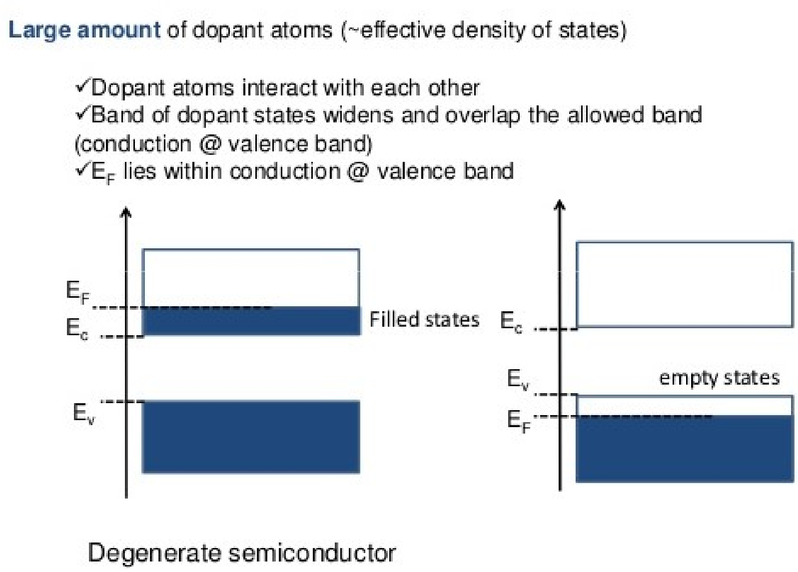


Figure 1 Degenerate (a) n and (b) p type semiconductors. The impurities form an energy band that can merge with either the valence or conduction band. The Fermi level lies within this band rather that in the band gap. Degenerate semiconductors hence have properties similar to metals.

A **degenerate semiconductor** is a semiconductor with such a high level of doping that the material starts to act more like a metal than as a semiconductor.

What happens if we add dopants at much higher concentrations? Dopant atoms come much closer to each other and it is no longer valid to assume the donor levels as atom like. If the inter-atomic distance is closer (typically < 10nm) then the atomic levels turn into bands. This leads to significant changes in the crystal structure as well as the physical properties. Another very important effect is, highly doped semiconductors come to freeze-out at much lower temperatures, meaning the



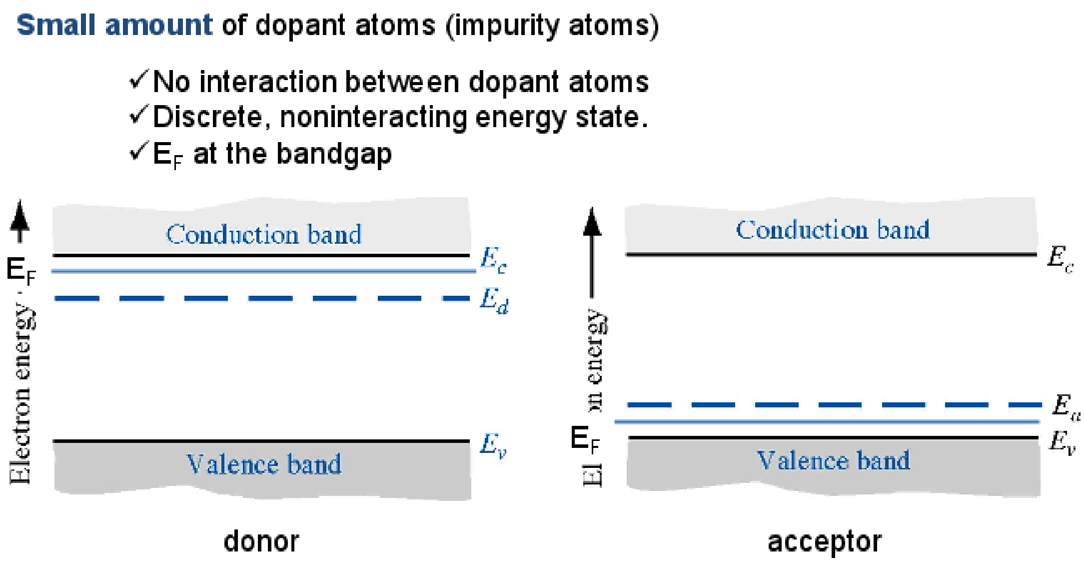
freeze-out region is almost eliminated!. Such highly doped semiconductors are called Degenerate semiconductors.

At moderate doping levels the dopant atoms create individual doping levels that can often be considered as localized states that can donate electrons or holes by thermal promotion (or an optical transition) to the conduction or valence bands respectively. At high enough impurity concentrations the individual impurity atoms may become close enough neighbors that their doping levels merge into an impurity band and the behavior of such a system ceases to show the typical traits of a semiconductor, e.g. its increase in conductivity with temperature. On the other hand a degenerate semiconductor still has far fewer charge carriers than a true metal so that its behavior is in many ways intermediary between semiconductor and metal.

Many copper chalcogenides are degenerate p-type semiconductors with relatively large numbers of holes in their valence band. An example is the system $LaCuOS_{1-x}Se_x$ with Mg doping. It is a wide gap p-type degenerate semiconductor. The hole concentration does not change with temperature, a typical trait of degenerate semiconductors.

It is also to be noted that the donors (or acceptors) energy levels are assumed as atom like. Such assumptions are limited up to a certain level of dopant concentration and such extrinsic semiconductors are called **non-degenerate** semiconductors.

Non-degenerate semiconductors are defined as semiconductors for which the Fermi energy is at least $3kT$ away from either band edge. The key to a semiconductor is that the Fermi level is somewhere between the conduction and valence bands, in the forbidden gap. There are no available states within a few kT of the Fermi level. This is a non-degenerate semiconductor.



Nondegenerate semiconductor

Summary

A **degenerate semiconductor** is a semiconductor with such a high level of doping that the material starts to act more like a metal than as a semiconductor. If we add dopants at much higher concentrations, dopant atoms come much closer to each other and it is no longer valid to assume the donor levels as atom like. If the inter-atomic distance is closer (typically < 10nm) then the atomic levels turn into bands. This leads to significant changes in the crystal structure as well as the physical properties. It is also to be noted that the donors (or acceptors) energy levels are assumed as atom like. Such assumptions are limited up to a certain level of dopant concentration and such extrinsic semiconductors are called **non-degenerate** semiconductors.