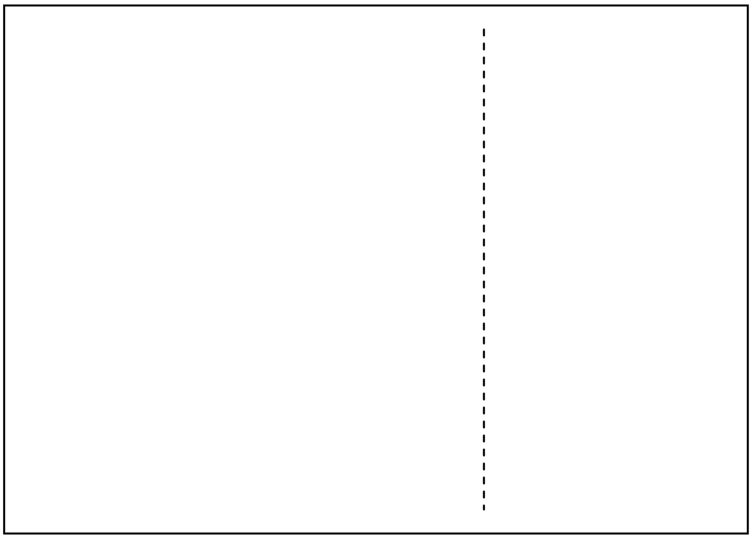
EEE105 - Electronic Devices
Lecture 10

Introduction to Band Structure

(CAL: semic(i))

In atoms electrons are in well defined energy levels, which are given by quantum mechanical considerations. In a solid the energy levels spread into energy bands, due to the interaction of each atom's outer electron energy levels with the neighbouring atoms.



Let us consider an isolated atom. In the case of Si for example it has 14 electrons. These electrons each occupy a different energy level, and these occupied levels can be broadly grouped into three.

The lowest two groups of energy levels give what are called ***core*** electrons. These electrons spend most of their time very close to the atom core. Electrons in the highest group of energy levels spend more of their time further away from the atom core. In a very (very) simplistic model we can show the electrons as being in orbits around the Si atom core. Another way to represent the states is as a series of energy states.

Note that not all the energy states will contain electrons. There will be excited states which will normally be empty, unless we apply energy (e.g. heat, light) to excite the electrons into a higher energy state.

The above representation is the situation for an isolated Si atom. However, Si normally forms as a solid. This makes no difference to the electrons that are close to the atom core, as they are so tightly bound that they only experience the effect of the atom itself, not the environment in which the atom finds itself. For the purposes of this course these electrons are not important and from now on we will ignore them.

The key issue is what happens to the energy states associated with the outer electrons (and any further out excited states with no electrons in them). These states will overlap with the same energy states for the outer electrons in the neighbouring atoms, and the interactions between them spread the energy levels into e**nergy bands**. These energy bands are in effect the energy states for the Si atom bonds.

We are only interested the energy band where the outer electrons sit and also the next highest band, where the electrons can be excited to if energy is applied to them.

The band where the outer electrons normally sit is the energy state of the Si-Si atom bond.

This state is called the ***VALENCE BAND.***

The next highest energy state is where electrons sit if they have enough energy to jump out of the bond. Another way to look at this next highest state is to say that it is an excited state of the Si-Si atom bond.

This state is called the ***CONDUCTION BAND.***

We can show these bands against energy as in the diagram here. There is a gap between the two bands which represents the energy required to break and electron away from the bond into the excited bonding state. The energy of this gap is the ionisation energy.

This is called the ***FORBIDDEN GAP*** or the ***BANDGAP*** of the semiconductor

We can use this band model also to describe generation and recombination:

At very low temperatures clearly virtually all the electrons will be in the bonds, or in the valence band (VB). When the material is heated up some electrons can escape from the bonds and move into the higher energy state called the conduction band (CB) where they are free to move around the material. When the electron jumps up to the CB it leaves a hole in the VB. This hole is also free to move around the material.

Thus: Free electrons move around in the conduction band

Holes are free to mover around in the valence band.

Note from this process the electron must gain energy to move from the valence band to conduction band. (This is the same as saying it must gain energy to jump out of the bond.

For recombination a free electron in the conduction band will fall into a hole (i.e. an empty space) in the valence band. When it does this the electron will lose energy and this energy. The energy lost will be equivalent to the energy difference between the top of the valence band (where the hole was) and the bottom of the conduction band (where the free electron was).

This energy is simply the energy of the forbidden gap (bandgap).

i.e. *Energy Emitted* $= W_g = E_{CB}\text{-}E_{VB}$

The energy can be released as heat, or light (Thus if we can inject lots of free electrons into p-type material then the electrons will recombine, potentially emitting light with photons of energy equal to W_g. – This is what is happening in a light emitting diode!)

Doping

We can also use this approach to describe the situation when we dope the material.

Let us consider the n-type situation first. For Si let us dope the material with arsenic.

When we do this we create an extra state (called a *donor level*) for the fifth electron to sit in. This state is just below the bottom of the conduction band, within the forbidden gap. At very low temperature the electron will sit in this state. This is the same as saying it sits next to the donor impurity atom.

However, it only takes a very small amount of thermal energy to excite this electron out of this state into the conduction band where it can move freely.

For p-type material we will dope the material with boron.

In this case we form an extra state (called an *acceptor level*) for the hole to sit in. This state is just above the top of the valence band within the forbidden gap. At very low temperature the state will be empty (i.e. the hole will sit in this state.) This is the same as saying that the hole sits next to the acceptor impurity atom.

However when we raise the temperature, an electron can very easily jump up from the valence band to this acceptor level. This releases the hole into the valence band where it is free to move.

You should also note that we can also represent undesirable impurities on such a diagram. These impurities often lead to energy states in the middle of the forbidden gap. Clearly it is much, much harder for electrons, or holes, to escape from such an impurity state and these defects are not electrically useful. In fact they are likely to be detrimental to the conductivity of the material as:

The p-n junction diode

(CAL: pn(a))

The junction diode is a p-n region created in a single semiconductor.

It has a number of practical applications:

Furthermore it is also fundamental to the understanding of other semiconductor devices, such as bipolar junction transistors (BJTs) and junction field effect transistors (JFETs).

In order to examine this device let us consider the situation where we bring a p-type and n-type piece of the same semiconductor together instantaneously. (This is not physically the way we create junctions and would be nearly impossible to do in practice, but it will help us to understand what happens.

We can plot the density of acceptors and donors in the material.

Note that these two densities do not need to be the same (and this is often aimed for in the design for reasons that we will discuss later).

Now we said that this junction was created instantaneously, at say some time, t=0.

The question is what will happen to the holes in the p-type material and electrons in the n-type material with time. At t=0 the profile of the hole and electron concentrations will be the same as for the acceptor and donor concentrations. However a t increases:

Next lecture we will discuss the effect that this process has on the p-n junction and ultimately what sort of equilibrium situation we can reach.

Key Points to Remember:

1. The electrons in atoms form into well defined states called energy levels.
2. In a solid the outer energy states overlap and form bands.
3. The bonding state forms a band that is full of electrons called the VALENCE band
4. The first excited state forms a band that is empty of electrons (at very low temperature) called the CONDUCTION band.
5. Electrons cannot exist in an energy state between the bands. This region is called the FORBIDDEN GAP.
6. Free electrons move in the conduction band and holes move in the valence band.
7. Electron-hole recombination can be characterised as an electron in the conduction band falling into a hole in the valence band emitting energy equal to the energy of the forbidden gap.
8. Doping introduces levels near the edges of the bands from which electrons or holes can easily be released into the conduction or valence band, respectively.
9. In a p-n junction there is a sharp change in the electron and hole densities in the material at the junction.