Introduction to Semiconductor Devices
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Lecture – 3.1
Semiconductor Bands in a Electric Field

Hello, everyone, welcome back to Introduction to Semiconductor Devices. We are starting the third week of the course.

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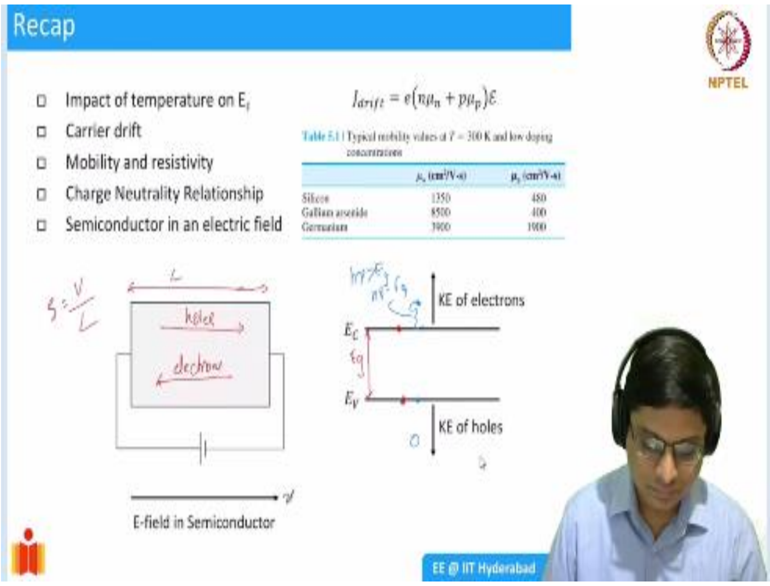

So, in the last lecture, we were talking about the impact of temperature on Fermi energy. And we have introduced the concept of carrier drift; how do the electrons move when there is an applied electric field or how do the holes move? We introduce the concept of drift current, which is given by this expression here

$$J_{drift} = e(n\mu_e + p\mu_p)E$$

essentially the drift current is proportional to the electric field and then you have a coefficient of proportionality mobility in the expression and then the concentration and the charge.

And then we went on to talk a little bit about mobility and resistivity, which are important parameters in a semiconductor and we showed how by introducing dopants, we are able to reduce the resistivity. So, for n type and p type carriers, we have showed how this happens. And then we also estimated. We asked you to estimate how the resistivity can be calculated.

And then we went on to talk about compensated semiconductors, which are essentially semiconductors where you have both electrons and holes present or the acceptor and donor dopants present. So, you have to take the net difference and that we can derive by actually what is known as charge neutrality relationship. We showed you an expression for this and then we derived the carrier concentration for electrons.

And we said that that could be applied for holes as well by a small modification. And towards the end of the lecture, we were talking about what happens to carriers, the physical picture or sort of the band diagram picture or the physical picture how what happens, you know, when you are playing electric field and we said that if you have an electric field applied, let us say, a positive terminal to the side and the negative terminal to the right side as shown here, there will be an electric field in this positive x direction if we call this x, the electric field is in the positive x direction.

So now, because of that the holes in the semiconductor would move in the positive x direction and electrons would move in the opposite direction. This is what happens when you apply an electric field to the carriers. So, what is the magnitude of the electric field? Well, it will simply be the distance, you know, the length of the semiconductor, let us say this is L.

$$E = \frac{V}{L}$$

So, electric field will be simply the voltage applied by the length, voltage per centimetre in our case. So, what happens? We showed that the electrons acquire kinetic energy as they travel across the semiconductor even a holes acquire the kinetic energy as they travel across semiconductor and we wanted to represent it in form of a band diagram. And to do that we have argued based on the photo excitation, you know, let us say if you have a band like this E_C and E_V shown here and have an electron at the edge of the valence band, it is basically you know, bonded to the silicon atoms.

So, you have an electron that that lots of electrons in the valence band. Now, if you shine a photon of energy E_g, this is my band gap E_g, if I shine a photon of E_g energy, then the electron will essentially be, you know, the bonds will be broken and electron will move into the conduction band, exactly into the conduction band. But it does not have any more energy, all energy has been consumed for breaking the bonds. So, it does not have any more energy.

So, it will be at the E_C. Now, if you use another photon with a higher energy greater than E_g, like if I use $h\vartheta$, I will put it in blue, let us say $h\vartheta > E_g$ then the electron from the edge of the band would be excited to the conduction band, but it would actually acquire additional energy. So, this additional energy is essentially $(h\vartheta - E_g)$. So, then the E_g amount of energy is consumed to break the bond and the additional energy is transferred as kinetic energy.

So, electron starts moving. So, whenever an electron moves in a band, we show that you know, the kinetic energy is essentially proportional the distance from the E_C. So, we are actually writing here that as you go away from the E_C, the kinetic energy of electrons increases. And similarly, you could talk of holes and the same picture actually, I mean you just have to reverse arguments, you know, you take an electron from deep within the valence band.

And then excite it up to the conduction band edge, you could repeat the same arguments and you will see that the kinetic energy of holes essentially becomes proportional to the distance from the conduction band, valence band edge in this case. So, in this case if you have a higher energy hole, it will be something like this. So, it will be deeper in it. So, this is what we introduced. Now, we would like to understand how do we represent that in a band diagram.

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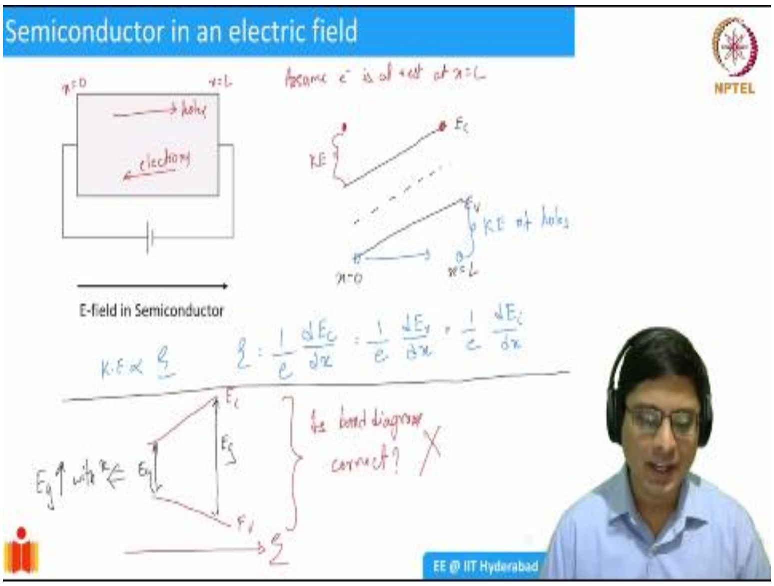

So now, let us you know, just for the sake of continuity, I put this diagram again. So, let us say, we have holes going in this direction and then electrons going in this direction. This, I will call it as x = 0 and this, I will call it as x = L, the distance, the total length is L. So, now I am interested in drawing the bands. How do I represent? We understand that as electron, let us say electron initially was a rest at x = L.

Let us assume, electron is at rest at x = L. So, I know and then as it moves towards x = 0, it is acquiring kinetic energy. To show that what I can do is, I will represent the bands in this fashion. So, I will say E_C, E_V. So, if this was my x = L, let me know this is equal to x = L, and this is going to be x = 0. As it travels, so initially, my electron was at rest. So, it will be somewhere here.

As it travels, it gains kinetic energy that can easily be represented by this line, it just acquires the energy. So, by the time, it comes to the left edge, electron might be somewhere here. So, this is the amount of kinetic energy. This is a KE of electron. Similar analysis works even for holes. Holes move in the positive x direction. So, let us say initially, the hole was you know, let us say there was a hole here, which is at rest. So, It is at E_V.

And as it travels in the positive x direction to its across kinetic energy, so eventually, it might end up somewhere here. So, this will show as kinetic energy of holes. So, what are we doing here? The electric field in a semiconductor is essentially being represented by the gradient in the bands. So, let me see, what this kinetic energy is essentially going to be proportional to the electric field; is it? greater the electric field, greater the velocity and greater the kinetic energy. So, how is it related?

To do that we could essentially write out you know, we know that q times electric field, the charge times electric field is essentially the force and force times the distance is the energy. So, you could easily verify this that electric field is going to be.

$$E = \frac{1}{e}\frac{dE_C}{dx}$$

It could easily verify this, you know E times, the electric field times the charge is going to be the force times; the distance is going to be work energy.

So, well, you could also, you know, you do not have to write it only as E_C. Now, we can also write it as .

$$E = \frac{1}{e}\frac{dE_V}{dx}$$

Or you could also use it in terms of the intrinsic energy

$$E = \frac{1}{e}\frac{dE_i}{dx}$$

$$i.e, E = \frac{1}{e}\frac{dE_C}{dx} = \frac{1}{e}\frac{dE_V}{dx} = \frac{1}{e}\frac{dE_i}{dx}$$

So, essentially, your intrinsic energy level is going to be in the between. So, what we are saying is; the electric field applied is going to be represented with the slope of the bands.

Now, let us say, you are new; you are drawing band diagrams because band diagrams are very, very helpful in understanding the physics of the semiconductor device. So, you are new and you are confused. And at some point, we asked you to draw a band diagram. And you draw something like this E_C and E_V. Would it be; I will say that there is an applied electric field here, which is this.

So, if I draw bands like this, would it be correct? So, is this band diagram correct? Think a moment it. I will say you. Is band diagram correct? If you think, it is correct, why it is correct? If you think it is wrong, why is it wrong? You can pause the video a moment and then think about it. It turns out that this is incorrect. The reason for that is, we are essentially saying that as the field is applied remember always $E_C – E_V$ is going to be band gap. This is E_g right and you are showing that the band gap is increasing.

So, this implies you know, if this was correct, implies E_g is increasing with x and that is not possible. We saw you know, if you think about the physical origin of the band gap, we saw that it is because of the lattice structure and then we have the energy levels interacting forming bands and so on, just by applying electric field, I am not going to change it.

The only way to change that would be to modify the lattice spacing that anyway, we are not doing. Just by applying an electric field, we are not really going to modify the lattice spacing. So, E_g is not going to change and because of that, your band diagram like this is wrong. And even from the energy argument, you could say that you know, because as the electron is travelling here, if I apply this sort of E_C, kinetic energy of electron is like this increasing; whereas, what happens to hole?

The kinetic energy is actually not increasing. So, that is again the wrong argument. So, essentially this sort of you know, picture if you come across, this is one way to verify your, one way of sanity checking. So, always the E_C and E_V are going to be parallel. Unless, we introduced what are known as hetero-junctions and that is another story. For a simpler if you take a simple piece of silicon, it is going to be always parallel to each other, E_g is going to fixed.

If you use silicon plus gallium arsenide, something you know different materials silicon, germanium, something, add different material, then I could modify the bands a little bit anyway. So, this is how a semiconductor behaves in electric field. Let us try a simple problem.

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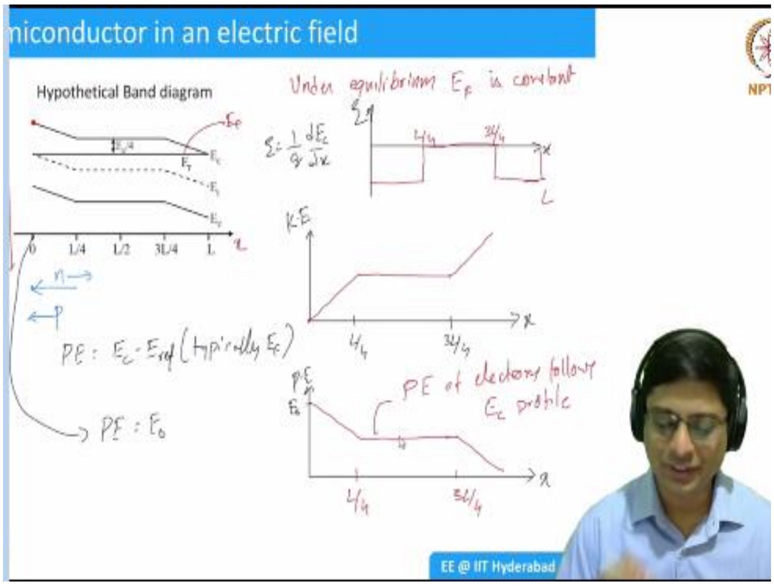

This is a hypothetical band diagram that you are seeing on the screen. And always remember that on the y axis, whatever, whenever you are talking of energy band diagrams, on the y axis here, this essentially means energy of electrons is increasing as you go higher on the band diagram. And conversely, if you go lower energy of holes increases. Remember, we said as the hole was deeper into the valence band, it has a higher kinetic energy.

So, basically, the energy of the holes increases as you go lower; energy of the electrons increases as you go higher. So, you have a band diagram like this. The first question will ask you, let us try to analyse and this is the hypothetical scenario. It is going to be more realistically there. But let us analyse. Let us say at x = 0; this be x. So, what is the electric field across the semiconductor, some semiconductor? And you have the bands.

One important feature that you should note here is the Fermi level. This is Fermi level here this is E_F and E_F is shown to be constant in a semiconductor. That is, you know, under equilibrium whenever you have equilibrium conditions , E_F is constant. It cannot change with x. There is no gradient in E_F. The reason for that is, suppose it is not true, what happens?

When E_F is not uniform, then electrons from the higher energy, higher E_F regions can travel into the lower E_F regions and then equilibrate. Sort of like, you know, if you have a tank of water, the top of the water, if you take the E_F as, you know, the level at which the water is at the top of a water level that is never going to be different in a particular tank, it is always going to equilibrate.

So, when if by chance, you start pouring water from one side of the tank, even then it will simply equilibrate and then we will sort of have a constant uniform level of water. Similarly, in a semiconductor, this is, we will again go back and explain it a little bit more later on. But essentially under equilibrium always, you will see that the Fermi energy is going to be constant. So, okay, fine.

Now, what is the electric field across this structure? How do we analyse that? We said that electric field is going to be

$$E = \frac{1}{q}\frac{dE_C}{dx}$$

Well, sometimes I am using E and sometimes q, charge of electron you know, because when I write E, it can be confusing with electric field when I talk about it. So, q might be better in some occasions. So, it is, you understand anyway.

Electrical is the gradient of the conduction band. So, if I want to draw the bands, electric field, so it is going to be this way, this is going to be my x and this is going to be my E. So, at x = 0 and x = (L/4), you have certain, you know, negative slope. So, the field is going to be negative and it is a constant slope. So, it is going to be a constant number. And then from (L/4), to (3L/2), there is like no gradient, so it is going to be 0.

There is no field and then this is (L/4),and till up to (3L/4), there is no gradient and then again, there is a negative gradient. So, it is going to be this way, this will be L. So, this is how your electric field is going to be in a semiconductor. Remember always because we will be showing the band diagrams of p-n junctions, MOS caps , MOSFETs must always whenever you see, if you see a gradient, along the gradient holes will travel.

Electrons will travel opposite to the gradient. This is how you should think about it. So, this is your electric field. How about the kinetic energy of the electrons? What happens as they travel? So, to analyse that let us try it one more time. So, axis, along x and along a kinetic energy on the y axis. So, let us start from L = 0. Let us say that you know the electron, you know this picture that red dot here is representing an electron.

So, electron has 0 kinetic energy at x = 0. So, I will put a 0 kinetic energy here and then as it travels, it across a certain kinetic energy, because how is electron going to go. Because electric field is negative that means (dE_C/dx). So, this is like this, electric field is pointing in this direction. Electric field always points in the gradient in the, positive gradient in the E_C.

So, if the electric field is pointing like this, holes are going to move like this. Let me say p is going to move in this direction, electron is going to move in the opposite direction. So, electron will acquire energy. And that can be displayed by this. And then of course, there is, you know, if I sort of move this electron across the you know, middle region, it is not when the bands are constant, there is no extra electric field there.

So, you will see that the kinetic energy is going to remain constant here. So, I am going to change but then, when you reach the (3L/4), this is going to be (3L/4), as you reach the (3L/4), you have gain a field, which is going to positive accelerate and then you are going to have a higher amount of kinetic energy. So, this is how kinetic energy changes. It is possible to actually avoid some of these things.

But you know, when we talk of barriers, you know, potential barrier in a p-n junction, it will be useful to revisit this concepts. So, essentially, what we are trying to do is build up a toolbox. So, by the end of this week, our toolbox will be done. We will have all the basic tools necessary to understand semiconductor devices. And then next week, we will talk of p-n junctions and so on.

So, when we talk about this potential barriers and all that, these concepts will be useful, that is why I am discovering it right away. So, that you have some time to review and then when we talk about devices, we can understand it easily. So, this is how kinetic energy changes. Well, you know, we also have something called as potential energy, kinetic energy and potential energy.

In this case, essentially, we are not taking any other external effects into account. So, whatever potential energy change is going to happen, that is going to happen only because of the electric field in which the carriers are changing. So, you know, we know that potential energy can be defined as basically with respect to our reference level. So, in this case, what we do is we define the potential energy of a carrier let us say, electron, we are going to define as PE is going to be

$$PE = E_C - E_{ref}$$

Why? Reference level is a constant level. It could be you know, typically, in our case, we can take it as typical E_F. E_F is an easy reference for us. Because E_F is going to be constant everywhere across the device equilibrium, so, you can take it. And why E_C? Well, we are saying that the potential energy is simply going to correspond to the changes in E_C. So, whenever you apply a electric field, the bands are going to bend.

And that is also going to be a measure of your potential energy because no other forces are involved. So, with this, we could draw a potential energy also, same as similar to whatever we have done in the case here. So, here, it is going to be x, this is going to be a potential energy. So, initially, let us say there is some potential energy x at x = 0. At this point, let us say PE is equal to some number, let us call it E_0.

We started of E_0 here, because essentially at that point, your kinetic energy is 0. So, whatever energy you know E_0 is going to be a potential energy. And as it traverses, what is happening? Essentially this is your potential energy definition, basically, the distance from the E_F. So, as you are travelling, the bands are bending, because of which potential energy is going to reduce. It is going to reduce.

It is going to reduce and then the bands are constant. So, it is going to be like this. Again, it is going to reduce further. So, essentially, this is (L/4) and this is (3L/4). So, what you see is in band diagrams, the potential energy is going to, of electrons, potential energy of electrons follows E_C profile. So, whatever the shape of a E_C that similarly follows the electrons.

And I mean, once you have potential energy, you can define potential, simply is going to be q times the potential sorry, charge times a potential is going to be potential energy. You can think about it. We will revisit this later. So, this is how you know, this is about how semiconductors became an electric field.