Fiber - Optic Communication Systems and Techniques

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Lecture – 36
Basic properties of semiconductor lasers-II (Fermi level)

Welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques; in this module, we will continue our study of Basic properties of semiconductors. What we saw at the end of the previous module was that you could take a pure semiconductor, and then dope that pure semiconductor with either group 3 elements or group 5 elements.

Group 3 elements are called as acceptors because they accept 3 electrons and then they have one free hole left ok. Of course, that hole is still bound to the material it is not free to just wander away, but I mean at low temperatures; as a temperature rises then some of this holes will move up to the valence band ok.

If you have groups 5 elements doping the group 4 or pure semiconductor; then you create the extrinsic semiconductor, which consists mainly of the electrons free electrons ok. The others because they actually have 5 valence electrons and 4 of them will get paired whereas, the others electron will be loosely bound and at higher temperatures then they can just rise up from the conduction I mean valence band and then be located in the conduction band ok.

So, depending on whether you have doped the pure semiconductor with the majority of acceptor levels or with the donors; then you have a different type of material. So, the former is called as p type material and the other is called as the n type material.

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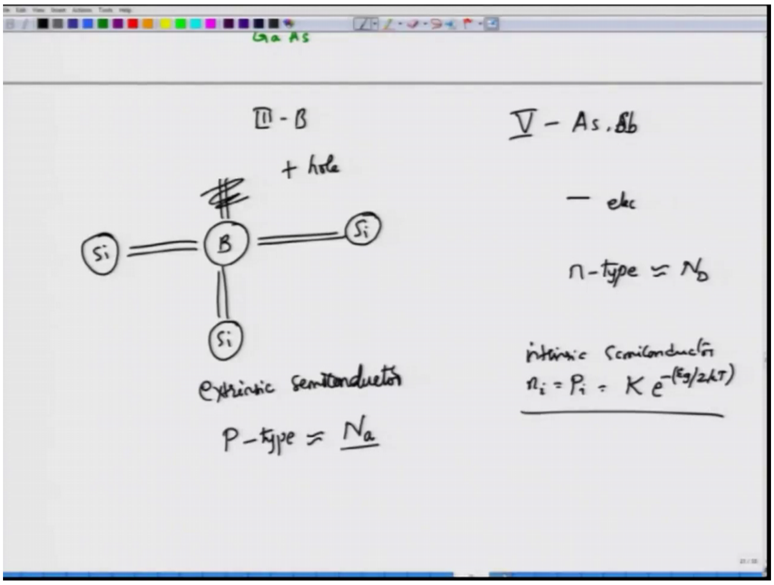

If the acceptor ions or acceptor density or the doping concentration is about N a atoms per centimeter cube ok; then the majority holes in this extrinsic p type semiconductor will be roughly equal to N a. And for the n type material they will be equal to N D, where N D is the donor atom density or the donor doping concentration.

Of course in a pure or intrinsic semiconductor ok. So, when there is no doping and this material is actually in the equilibrium condition; then the intrinsic concentration of n i will be exactly equal to the concentration of P i, where i stands for intrinsic in this case, n stands for electrons, P stands for holes. So, the concentration of n i and P i are equal under the equilibrium condition and this is equal to or this is proportional to the energy gap to the exponential function of energy gap to temperature.

So, what you see is that as for a fixed energy gap; as the temperature starts to increase or rather the temperature starts to decrease then n i and P i will be approximating this constant K ok. So, there is an exponential value out there and what is important is that this is just the property of the material itself. So, it does not depend on anything else; it simply depends on the temperature and the energy gap; so, this is for the intrinsic semiconductor.

Now, for the extrinsic semiconductor we have already said that the concentration would be mirroring N a or N D depending on whether you have doped the material with group 3 atoms or group 5 atoms.

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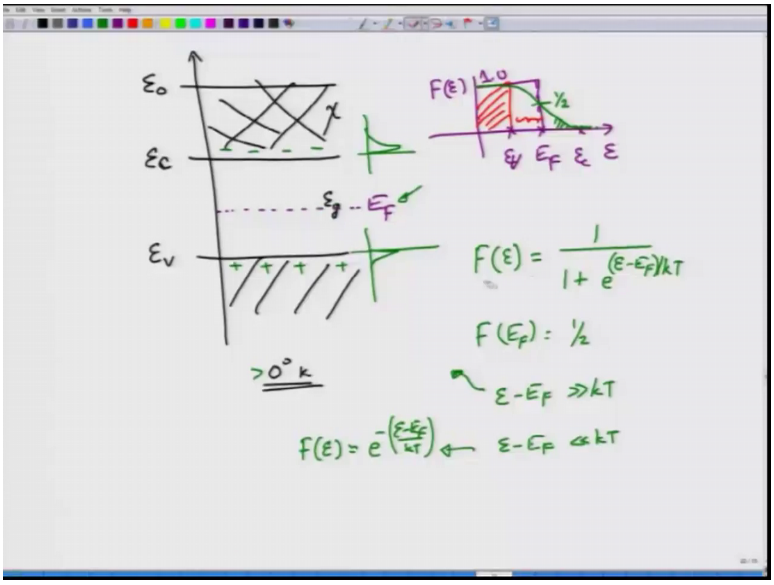

Now there is an important concept called as Fermi level, which I would like to discuss.

So, I will redraw this diagram of course, I have been kind of exaggerating the band gap here just to show the effect of all this. So, as before E 0 corresponds to our vacuum level and the difference between E 0 and E c corresponds to the electron affinity; E g would be the band gap between the conduction and the valence band. So, this is my valence band this is the conduction band.

If you look at a 0 degree Kelvin that is at 0 degree temperature; we do know that all the electrons are located in the valence band. So, there are no electrons in the higher energy states ok; then we define in this equilibrium a certain energy level called as the Fermi level and we denote this Fermi level by E F; F subscript on to the letter E.

This Fermi level tells you that if at all and this is a property of the material of course, for different materials they have different Fermi levels. And for this material which we are considering; what this Fermi level signifies is that, if at all this Fermi level were to be available for the electrons to occupy, that is a very important point here.

If the Fermi level were to be available for the electrons to occupy; then the probability of the electron being found with the Fermi level will be about half ok. Of course, for 0 degree Kelvin; it is kind of a very discontinuous way of the probability of electron being occupying in the sense that if you plot the energy as we vary the energy here. And then this is somewhere the Fermi level is located, this is E v and then this is E c; what you find at 0 degree Kelvin is that the probability of any electron being found with a certain energy E is exactly a step like function.

So, below E F all allowable energy levels are filled and please remember the allowed energy levels are these guys. So, these energy levels are not allowed. So, this Fermi level is the nice this you know kind of an abstract idea that although it is the property of the material, this actual Fermi level will not be accessible to the electrons to go and occupy. That is why I said if E F is available then the probability will be half.

You will not see that half probability coming up nicely in the step like function, but if you raise the temperature what you will find is that because some of the electrons can now get sufficient thermal energy to move from the valence to the conduction band, there will be some nonzero value of electrons once the conduction band or once the energy is greater than E F.

So, there is a finite probability that electrons can be found in the conduction band as the temperature is raised. And there is a finite probability that not all the energy levels below this Fermi level will be filled; of course, at Fermi level the probability is exactly equal to half, but again I want to tell you this is a very important concept; the Fermi level actually does not exist in a realistic sense. I mean because Fermi level exists at least for the intrinsic semiconductor cases; it would be right in the middle of the band gap and of course, no electron can be found in the forbidden gap.

And therefore, Fermi level is a nice abstraction its not a real quantity when you actually look at it. But of course, it the Fermi level helps you in dealing with many of the semiconductor properties of which of course, we are not going to look at that one. So, for our purposes just be this one that Fermi levels will be found at least for 0 degree Kelvin operation; right in the middle of the forbidden region and the existence of Fermi level is an important topic as the temperature raises some of the electrons can be found.

So, when the temperature is greater than 0 degree Kelvin, some electrons can be found leaving behind some of the holes. And this is exactly the reason why we had those plots of concentration looking something like this right. So, you had this edge having larger concentration and then as we move away about 2 k T or so, then the probability would actually drop out.

There is an expression for the probability of electron occupying an energy state with an energy value of E and it is given by 1 by 1 plus E to the power E minus E F divided by k T. So, clearly if k T is equal to 0; 1 by k T will be infinity this entire term of the exponential will be infinity and the F of E term will be equal to 0 right.

Of course that is that will give you the step like kind of a thing and when you substitute E equal to E F; you will see that the exponential term will have the argument of 0, which means that this will be 1 and F of E F will be exactly equal to half. Because most materials are not operated at 0 degree Kelvin; the relevant conditions that are interesting for this F of E function, if this is the probability distribution function. The interesting results are when E minus E F is much larger than k T or E minus E F is much smaller than k T ok.

So, I will leave for you to consider that when E minus E F is much larger than k T; then the approximate expression for F of E will be an exponential function with E minus E F divided k T minus of E minus E F by k T as the argument. I will leave the other case as an example for you, you can find out what would happen. So, what is the summary of all this is that.

When there is a Fermi level; the probability of occupying that particular state by an electron will be half. Of course, in most cases these Fermi levels are not available and therefore, that occupation part does not arise, but Fermi level becomes important when you start doing something else with semiconductors. And one of the things that we have done is to take an intrinsic semiconductor and then make it extrinsic by doping.

Let us consider this suppose my dopants are all of the n type. So, n type means you are allowing excess electrons and because now you have doped and that material is still in the equilibrium situation; what you find is that there are excess electrons. And when there is sufficient amount of thermal energy available, then these electrons should be easily crossing over to the conduction band and therefore, must correspond to the conduction band electrons right must contribute to the conduction band electrons.

So, which means that, when you dope the materials with n type dopants or the donor material the corresponding energy levels because of that doping would be just below the conduction band.

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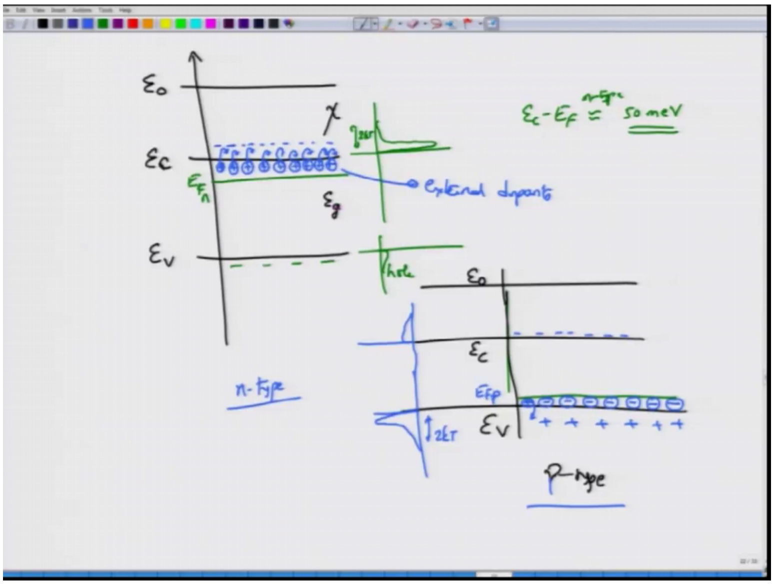

Of course, in this case the electrons are not free right, but when the energy is sufficiently higher; then these electrons will actually jump over and go to the conduction band. And when they do so they leave behind positive ions; which are bounded and they are bounded of course, because the electrons have left them and gone to the conduction region where they become free to move and contribute to the current.

So, this is what happens when you dope with the material with an n type and therefore, convert an intrinsic material or intrinsic semiconductor into an n type semiconductor; where the energy or the conduction electrons are actually contributed by the extensive. So, these are the external dopants right; so, external or dopants whose energy levels are just slightly below the conduction band and they contribute here ok.

So, now what happens the Fermi level? Remember Fermi level was something that would tell you how the electrons are occupying right. Now there is an excess electron density compared to the; you know the pure semiconductor, there is an excess electrons in the conduction band. So, which means that the Fermi level cannot be located in the middle of the band because above the Fermi level there are electrons; so, therefore, you need to move the Fermi level up.

And the Fermi level moves up and becomes very close to the conduction band; I am exaggerating this, but in practice this E F is so close to E c; it is just about the difference between E c and E F in the n type material, when you have doped sufficiently it is just about 50 milli electron volts. So, it is actually quite small amount of gap between the Fermi levels and then I will put an n as another subscript so that we are dealing with n type materials.

If you look at the concentration of the electrons well there is a huge concentration of the electrons which of course, falls off; again over the range of some 2 k T. And some of the electrons because you are not operating it at a level above the 0 degree Kelvin; there will be a few holes as well ok. In fact, you can find out what would be the hole concentration in a extrinsic semiconductor material by utilizing a certain equation which we do not need to worry about it at this point ok.

So, this is the hole concentration and the hole concentration will also will not be exactly located or localized to 2 k T; it will go slightly beyond that one. But compare this the electron concentration is quite high; the hole concentration is quite small ok. But please remember as a hole the material is still neutral because all those free electrons are paired up with the ions which have been given by the donors.

So, they are not coming in on their own and it does not mean that because there are electrons as the majority carriers; the material itself is somehow unstable. The material is still neutral the total charges are still conserved otherwise the material would simply explode. A very different condition would happen when you go to the p type material. So, I am going to go to the p type material and then show you what happens to the concentration.

Of course, now you might have guessed that one. So, this is the valence band, this is the conduction band and somewhere up will be the vacuum level and then when you dope the material so that it becomes a p type material; what you find is that the Fermi level has to be located very close to E v because the externally doped atoms right or the external dopants, which are the acceptors start to create holes ok.

So, they create holes which means that the hole has moved and you know contributes to the valence band here. So, there will be an excess holes there. Whereas in this band they will only be negative ions ok; so, all the acceptor ions have actually taken the. So, what is actually how they have obtained is that, there was an electron here; this electron went up and occupied the vacant slot in this one. So, therefore, it became negatively ionized and when it became you know when it just went up to this one right which we will call as the Fermi level EFP.

And when it just went up then it left behind the positively charged hole here. So, that is how actually the holes were produced, but we do not really need to worry about that. What we see here is that once you have the materials to be doped with P type, then the Fermi level moves very close to the valence band and the valence band will now have excess holes here ok.

So, if you look at the concentration; the concentration will be quite high here and then drops off having a width of roughly 2 k T. And because you are now operating this one material or the metal is kept at a temperature greater than 0 degree Kelvin; there will be some electrons also, but the concentration of electrons is quite small compared to the concentration of the holes.

So, this is a difference between n type material and a p type material and what we want to now do is to bring these 2 materials closer to each other. And when you bring the materials closer to each other and have it remain in the equilibrium then what happens is that the Fermi level must remain constant across the material ok. So, let us see what actually happens when you bring an n type material close to a p type material.

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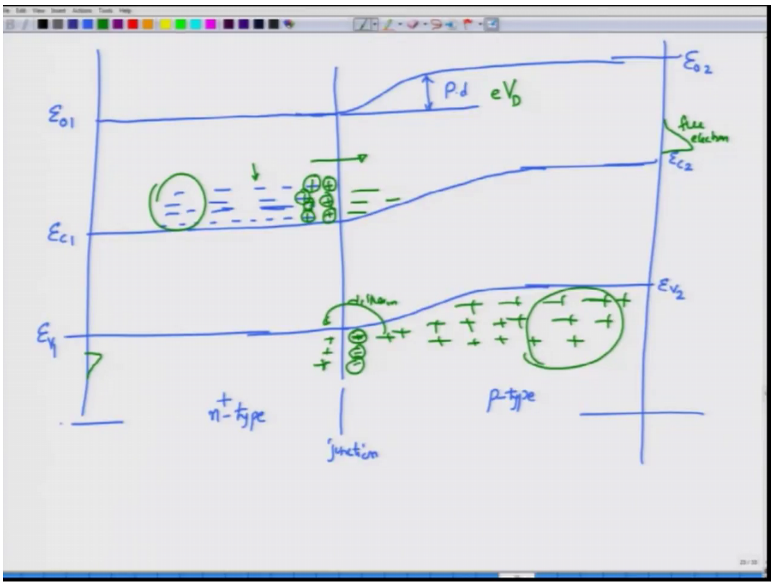

I have written down this or I have drawn this blue line to indicate that we are at a junction; left to the left of this junction we have n type material and to the right of this junction we have p type material and we are assuming that the material properties changes abruptly at this junction. So, this is the junction line that I have drawn and because the material properties are changing from n to p type abruptly; this is called as a abrupt or a step junction.

Now, what happens? What is actually going to happen? Well this is an n type material far away from the junction the material is going to be n type right. And what is the condition for the n type? Well in the n type material; there will be an excess of electrons in the conduction band right whereas, if you go to the p type material and be allowed to you know go far away from the junction; the p type material will have most of the holes located in the valence band ok.

And it turns out that the vacuum level will not remain the same for the n type material and the p type material, but actually will be different from n to p type material. I am also assuming that the n type material is heavily doped so, that I can use a plus superscript to indicate that the number of carriers; the majority carriers in the electrons far exceeds the majority carriers of the holes in the p type material. So, this is called as heavy doping and what the heavy doping does if you remember from your p-n junction theory is that; it pushes the depletion layer which will be created at the junction into deeper into deeper into the p type region.

What is the depletion layer? Well we know that when we are looking at n type regions far away of course, will be this one, but you have a valence band here right. So, we will call this valence band to be E v 1, having an energy E v 1 and then this is of course, E 0 one is the vacuum level; somewhere in between of course, you have the conduction band which is E c 1. The affinity of these two is still the same chi or now it will be chi 1 and the energy gap that you have we can call this as E g 1 ok.

On the right hand side you have a similar valence band; now the valence band is shifted up compared to E v 1 and the corresponding conduction band is also shifted up and the corresponding vacuum band is also shifted up. Now the vacuum band or the vacuum levels have shifted up means that you actually have a certain potential difference set up across the junction. And most of these potential differences exist right at the junction itself and this potential difference causes the electrons to respond to certain effects of this.

So the first thing that would happen is of course,, but there are lot of these electrons here right. So, this is completely an electron c if you will and their immediate tendency of these electrons would be to kind of cross over to the p type region because there is a excess concentration and then diffusion tells you that; when there is an excess concentration you will see that they will be crossing over to the junction. Of course, they do not really cross over because the potential difference that exists here will create; an electric field from this region the other region; why?

Because as the electrons some of the electrons move and then be located now here because of the diffusion; what they would leave behind at the junction or the positive immobile ions ok. These ions are not moving, but the region here have become positive and as the holes are present here. So, there are a lot of these holes correct; so, these holes are present. Some of those holes would diffuse onto the left hand side and therefore, you will have some holes here, but when they do so; they will leave behind negative ions.

So, because these are moving and then creating other type of ions; the electric field is created in this direction from n to p region; which further stops the electrons which are located here in moving out. Because electrons cannot move in the same direction of the electric field; they would always move in the opposite direction of the electric field.

What you would find is that the mere or the reason why the electrons once they diffuse initially they cannot diffuse anymore is simply because the set up electric field will oppose the motion of these electrons from n type to p type. And similarly the holes are also opposed by the; you know electric field that has been set up see; the electric field is from n to p region. Therefore, the holes also cannot diffuse as much as possible and therefore, their concentration remains quite high in the p region; far away from the junction.

Similarly the n region far away from the junction will have an excess number of electrons. So, this is what actually happens and you can go ahead and calculate various properties of this p-n junction or the n-p junction that we have written. If you look at what is the concentration of the holes you would find that in the p type region the hole concentration actually is non zero and this concentration of nonzero holes is because of the fact that there have been some holes which have moved into the p type region because of diffusion.

So, this initial diffusion has created some excess holes in the n type material and similarly; there will be some excess electrons here the free electrons here which are also created because of the initial movement in the form of diffusion. So, the difference between these two or the potential difference will be e V D; where V D is the junction potential and that would be the energy here. And this is the basic p-n junction ok; what we want to do is to tell you in this basic junction how can we have radiative combinations, recombinations and how these electrons and holes can move together or combine together to give off light ok. So, that is something we are going to talk about in the next module.

Thank you very much.