Fundamentals of Semiconductor Devices

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Lecture - 07
Equilibrium carrier concentration

Welcome back. So, we shall continue with our discussions today. If, you recall in the last lecture what are the things that we studied? We have covered already Fermi Dirac statistics, the probability of finding electron in a semiconductor; we also discussed density of states that is how many states are available for electrons to occupy? I told you that you know the product of this density of states and Fermi function, there actually product represents, how many electrons or holes will actually be there? We also introduce the concept of holes by the way right.

So, the last lecture was ended with thus discussion on intrinsic and extrinsic semiconductor. And, I told you, I gave you the expression for intrinsic semiconductor we derived that expression actually for a semiconductor, what is the intrinsic carrier concentration in a semiconductor which we can express in terms of band gap. It has a lot of actually implications for devices we will come to see that, but we also told that today we shall also do some numericals and try to get simplification of the ideas of the p and n type doping that we have studied ok.

How to apply in the numericals, how to actually understand real world problems? So, those are the things we will cover today. And, if time permits will also go to things like carrier mobility for example, which is very important later on ok.

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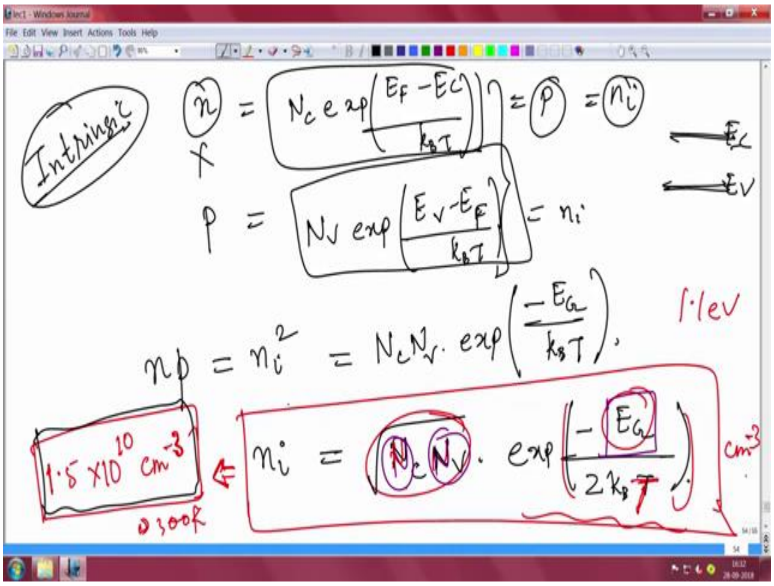

So, let us come back to the last slide of where we had ended. If you recall this was the slide that we ended right. In the last, you know, I told you that there is an expression for intrinsic carrier concentration, which can be expressed in terms of band gap, right, exponentially in terms of band gap and also depends on N_C and N_V.

If you recall N_C and N_V. are the conduction and valence band effective density of states ok. Those numbers are very much temperature dependent, there is an expression for N_C, there is an expression for N_V. We know those expressions, they depend on temperature and effective mass if you recall. And, this expression of n_i was derived very nicely. I told you, that an intrinsic semiconductor is a semiconductor where there are no impurities, it is pristine and pure.

So, in that case there will always be some electrons and some holes in equal number in the semiconductor, because of thermal energy. For example, in silicon, the intrinsic carrier concentration turns out to be 1.5 X $10^{10}/cm^3$ of both electrons and holes at room temperature ok.

I told you that intrinsic semiconductor, n = p right, that electrons and holes are equal in number and that is equal to ni. So, I multiplied n and p and I got this n_i^2 and n and p can be expressed in terms of this right, this particular terms. And so, we got this expression of n_i.

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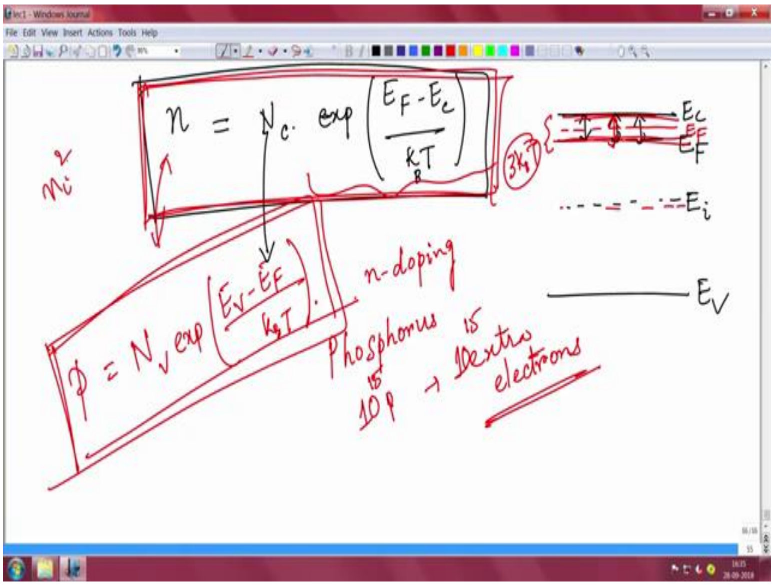

So, if you recall now I will come to the next page now, we will start from here. To make sure that we are not losing track of things, I will again repeat it, that the number of electrons in a semiconductor for which, is not very highly doped, is given by

$n = N_C\, exp^{\frac{Ef-EC}{kT}}$.

This is going to be a very fundamental equation that we will always keep using and using, ok.

So, I draw a conduction band and I draw sorry, I draw a valence band. I told you that if you take a middle of line here that is the intrinsic level E_i that is always there. If, your Fermi level is in the top half, say for example, if Fermi level is here E_F. It means the semiconductor is n type doped or there are more electrons than holes, and if your Fermi level is in the bottom half, then there are more holes than electrons ok, it is p type doped that we know right.

So, I told you if a semiconductor is not very highly doped, then this equation holds true ok. This equation holds true and this is very easy to actually see N_C is a constant right, it depends on temperature and it depends on effective mass, it can be calculated, it will be provide in the question. And, it depends exponentially on the difference between E_C and E_F you see, this gap, negative of this gap, $(E_F - E_C)$ is the negative of this gap.

So, if this gap becomes smaller and smaller, which means the Fermi level keeps coming closer and closer; if, the Fermi level comes up like that I am giving in red color, then you will have more electrons. Because, this gap reduces and if the gap reduces, then this minus of this gap know. So, this quantity will increase basically. So, your doping becomes higher. One way to raise the Fermi level closer to the conduction band is to have more electrons, which means you dope it high.

I told you right, there is n-doping, which means you are adding an pentavalent impurities of things, you have more electrons than what you need, you know each atom will give 1 electron. So, if I for example, phosphorous is a dopant. So, if you add phosphorous atoms, then 1 phosphorous atom will give you 1 extra electron ok.

So, if I 10^{10}, 10^{15} phosphorous atoms, I will get 10^{15} extra electrons. So, that is how I modulate the conductivity because I can change the number of carriers available in the semiconductor for carrying current, that is how we do it ok. This equation is going to be very fundamental through out now. So, let us not lose track of this equation. Similarly, for holes we have another equation.

$p = N_V exp^{\frac{EV-Ef}{kT}}$ i.e. exponential of the negative of the gap here, you know. ok.

So, these 2 equations are going to be very fundamental. One very important thing to notice here is that these equations are valid when the doping is not very high. And, I told you doping not very high means that this spacing should be at least 3kT or should be more than that ok. So, this spacing should be 3kT or more than that. If, it is not 3kT or less than 3kT, then the Fermi level is too close to conduction band, and this equation will not hold true then you have to use the actual Fermi integral ok.

Most of the equations and situations in our life will revolve around moderate doping ok. And, that is why this equation will definitely hold true ok, this equation will definitely hold true. If, it is a high doping effect we will see that this gap becomes very small and this equation is not holding true. Actually for an intrinsic semiconductor the Fermi level lies close to middle of the band gap, and we multiply the product we got that is equal to ni^2 and that is how we got the expression for n_i.

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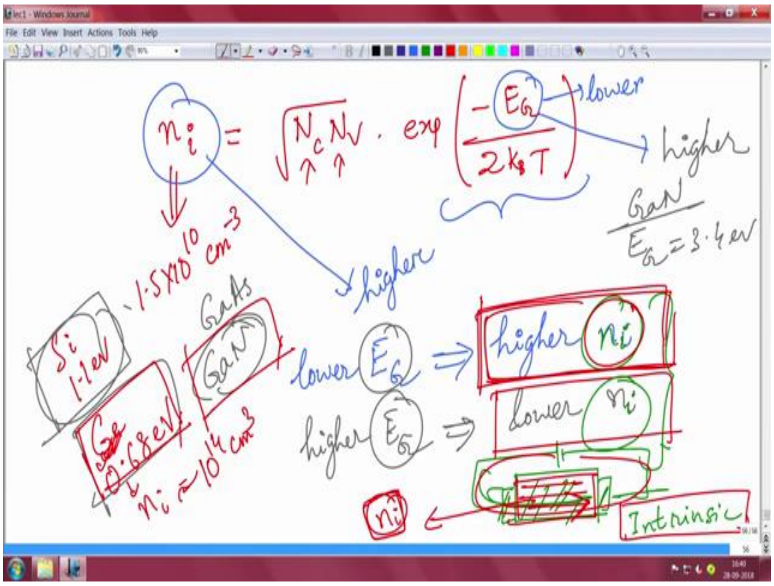

So, let us come to that expression for ni now. I told you intrinsic carrier concentration in a semiconductor depends as

$\sqrt{N_C N_V}\ exp^{\frac{-EG}{2kT}}$ i.e. N_C N_V square root exponential of minus band gap by 2kT. So, you see it depends on band gap, right, it depends also on this quantity and that quantity which is fine. Now, for silicon it comes out to be around 1.5 X 10^{10}/cm^3, it is always normalized volume. So, silicon has a band gap of 1.1 e v. What if I take a material whose band gap is lower, say material germanium. Germanium has a band gap of 0.68 e v which is lower than silicon.

If your band gap becomes lower, which means if this quantity becomes lower, ok. Negative of the exponent know, if it becomes lower, then this quantity becomes higher right, the whole thing becomes higher. So, basically what it means? It means that lower band gap material, if your band gap is lower gives you higher intrinsic carrier concentration, ok and, if this band gap is higher, for example, if this band gap is higher right. Say for example, I take gallium nitrite, it is a semiconductor also. There are many semiconductors it is band gap is 3.4 eV, which is much larger than silicon right.

In that case your if your band gap is much higher then your n i will be much lower. So, what implications does it have? See there are different kinds of semiconductors, silicon is one of the most widely used, but there is germanium, there is gallium arsenide, all your white light LEDs that you see in the market and you in your house those are made of gallium nitrite. So, there many semiconductors actually, different semiconductors have different band gap. And, because of that different semiconductors also will have different intrinsic carrier concentration right.

So, now this intrinsic carrier concentration is the minimum concentration that you will always have in a material. And, under any circumstance you cannot bring it down lower than this because this is thermally generated. So, if you take a semiconductor. If, you take a semiconductor for example, this is a semiconductor. And, I take 1 metal contact here, I take another metal contact here and I apply voltage, right. The current that I will get and imagine this is undoped, this is intrinsic ok, which means this is the purest form of semiconductor that you can get ok.

This is the purest form of semiconductor you can get; then, the lowest current you can get you cannot get lower than that ok. The lowest current you can get depends on how many carriers are there in the intrinsic condition which is n i which means, that the lowest current you will get in the semiconductor under any circumstance will be limited by how many free carriers are there at any temperature; say room temperature any other temperature, without adding any impurity, without doping it.

So, if your back this is the background carrier concentration, this is the background carrier concentration, this is default carrier concentration intrinsic carrier concentration you cannot decrease below that. So, if your carrier intrinsic carrier concentration is higher, then this current that you will get is also higher. And, if your intrinsic carrier concentration is low, then the current that you get also is low, which means you know a wider band gap semiconductor like gallium nitrite with much higher wide band gap, the large band gap, which has much lower intrinsic area concentration will give you a much lower background current, then compare to silicon or germanium; germanium will give even more.

Whose band gap is smaller and that is why your n_i is higher that is why the background current also will be high. Is it a good thing or bad thing? It depends on the application. For example; this will manifest as the leakage current in a device like a photo detector or a transistor, you know this, there is something called a leakage current you know it is not a good current actually it is a leakage it is leads to noise. So, that if you have a smaller band gap material like germanium, then your leakage will be higher. For example, germanium for germanium, n_i is much higher.

I forgot the number exactly, but for germanium I think the ni was almost because it has lower band gap know. It almost like $10^{14}/cm^3$ close to that, ok so, that is a very large number. So, what it means is that your lower band gap material like germanium for example, will lead to inherently higher leakage current in devices. So, that is a very important technological you know statement actually because we design the devices based on the band gap. So, is very important to have that. So, this is one thing that we learn from there, ok.

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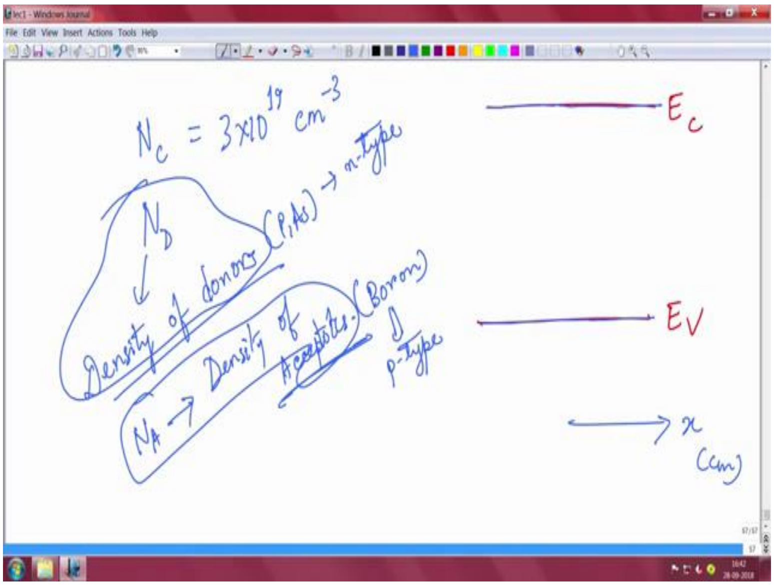

Now, let us take things 1 by 1 slowly, will not rush things ok. So, let us get the concepts again much better here. So, for example, I take a condition here. So, remember what I what are this E_C and E_V, if you remember I will be keep drawing I will keep drawing this E_C and E_V very repeatedly now. Remember that 1 to 1 equivalence E_C and E_V this is actually comes from E-k diagram only this is except this is x in centimeter ok.

So, this is this line basically represents the bottom of the conduction band in that E-k diagram over position it is flat ok, over position it is flat basically it is a constant band gap material like that, that is what we mean ok. This is the actually this is the valence band which is filled up right and this is the conduction band which is nearly empty. So, that thing actually comes, but I do not represent this all I just give it a straight line that is it that is how we device engineers do that ok.

Now, if I suppose tell you that I have N_C of say 3 X 10^{19}, that is the number that is given ok. N_C is the conduction band effective density of states. And, I told you that I have doped the material you know I can add doping, and I can increase or decrease, I can increase the conductivity, where I can tune the conductivity. So, external dopants are added know in a silicon for example, phosphorous is a donor that will give you electron I told you. So, the donor density is always represented by N_D. It means the density of it means the density of dopants that you are adding right or density of donors that you are adding ok. How many donors you are adding? Ok.

And, N_A represents to how many acceptors you are adding for p type doping ok, density of acceptors. I told you already, if you recall that atoms like phosphorous which can give electrons like phosphorous or arsenic they give electrons to silicon, they donate electrons that is why they are called donors and these are basically n-type doping, they lead to increase in electrons and acceptors like boron for example, they are able to accept one electron and give a hole out. So, they actually are p type doping because they lead to higher holes ok. So, N_A is the density of acceptor and N_D is the density of donor. So, now, I tell you for example, if I take you a case I will just read out this case again.

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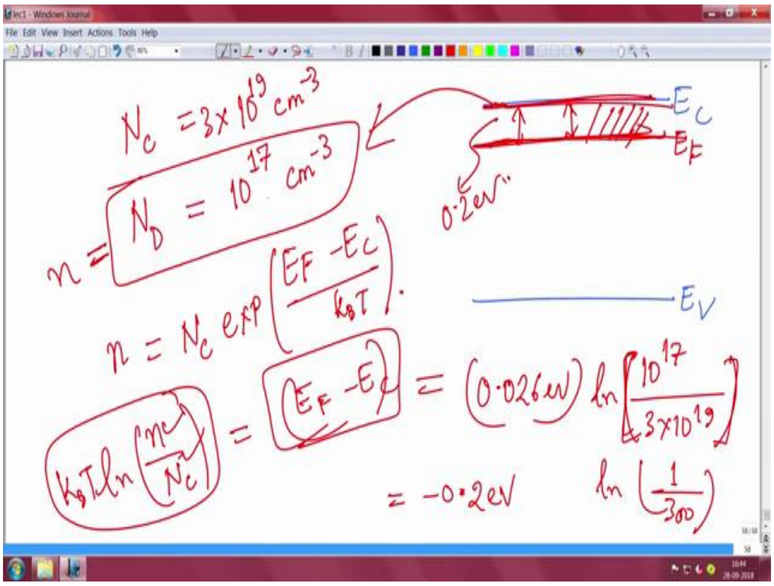

So, for example, I have conduction band here, I have valence band here ok. And, I tell you that you see N_C is given to be 3 X 10^{19}, this is a at room temperature, it changes, with temperature by the way ok, this is fixed number per cm^3. And, then I tell you that I have doped the material with phosphorous N type, N_D is equal to for example, say $10^{17}/cm^3$ ok, $10^{17}/cm^3$, that is the number of phosphorous atoms I have added. So, that is the number of electrons basically that I am getting extra.

So, what is the position of the Fermi level within the band gap. The question is inside the band gap what is the position of the Fermi level? Now, because this is N-type dope you immediately know that Fermi level will be in the top half, in this half region it will be there know. What is the exact position of the Fermi level? In other words, what is the difference between the position of the Fermi level will be somewhere here. What is this (E_C - E_F), can you do that, that is an equation we have know, I told you n = $N_C\ exp^{\frac{Ef-EC}{kT}}$.

So, here you see if I take this n by N_C then I can take a log, natural log here and that will become $(E_F – E_C)/kT$. I can bring the kT here actually. So, $E_F – E_C$, $E_F – E_C$, the negative of this gap is given by actually this quantity which is kT is 0.026 e V ok. 0.026. that is the room temperature into log of n by N_C. I told you n is equal to N_D only right. Because, that is the number of doping you added and that is the number of electrons you are going to get. So, that will be 10^{17} by 3 X 10^{19}.

So, you can take a log of this number know what will be. I do not have a calculator here, but you can do log of 10^{17} by 3 X 10^{19}. So, this is like log of 1 by 300 only. So, some negative quantity will come, of course, will be negative know this is (E_F - E_C). (E_F - E_C) will be negative because this is the gap. So, you can do that and you will find out some number. So, it might come out I do not know you have to do a calculator, but may be it comes out to be say 0 point say around 2 eV (0.2eV) may be I do not know it may be wrong it may be 0.3 also I am just telling you.

So, this will be 0.2 eV right, because they have negative of that right. That is how you solve a problem, what is the position? And, if your position is given then you can back calculate and calculate this term N_D right. Similar thing can be done for holes. So, that is an important thing.

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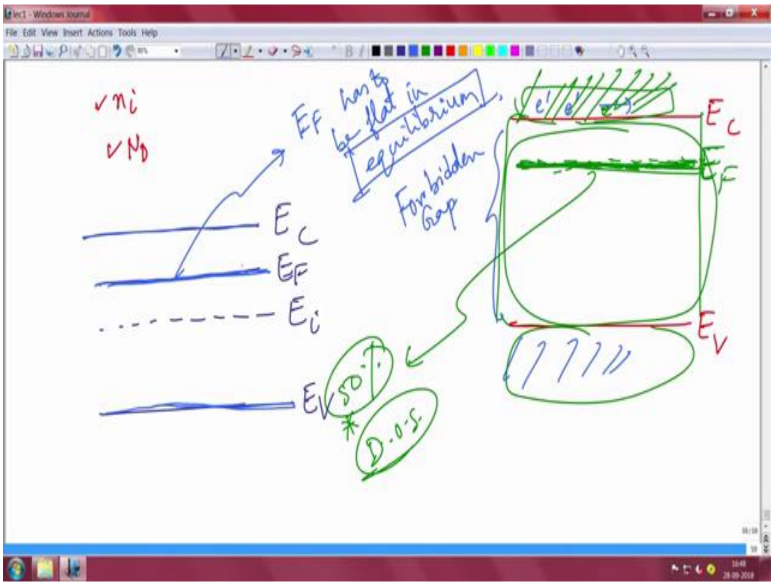

Now, for example, now the important thing is that I told you about n i, I already told you about intrinsic carrier concentration, I told you about this doping and how you know we can do this simple numerical, there are some conceptual questions that the textbooks do not talk about. So, while I am in the topic I will tell you also those, there are some conceptual questions ok. You see this band gap that is there this within this band gap.

Actually, this is a forbidden gap ok. Because, see this is a forbidden gap, why do you know it is a forbidden gap, because I told you this is actually filled with electrons and this is nearly empty, but you can get extra electrons here which can move, this is a forbidden gap. So, carriers cannot exist within this band gap, within this band gap, you cannot have carriers because, this is forbidden gap.

Suppose you have a Fermi level here ok. Suppose, you have a Fermi level here, the Fermi level tells you that there is a 50 percent chance of finding electron here, at the Fermi level, if you recall Fermi Dirac. The question is, if electrons and holes cannot exist within this band gap, it is a forbidden gap ok. Then, how come there is a 50 percent chance of finding the electron here, does it mean there is a 50 percent chance of actually finding a electron here right. The solution to the paradox is that Fermi level is only a statistical construct, it makes lives easier to understand many of these things ok, it is not a real level here.

What it means is that of course, electrons cannot exists within the band gap. Within the band gap electrons will not exist, but, here it means that there is a higher probability of finding electron here, you know than finding a hole here for example, ok. So, it means that there is a 50 percent chance of finding here. it is the statistical construct that tells you how close you are to finding the electron in the conduction band, it is what is the probability here? So, there is higher probability you will find lower probability will find hole or stuff like that.

So, it basically gives you a number as to what is the probability? And, this probability itself will not tell you electrons will be there or not. I told you there is density of states also, you remember density of states. So, only density of states times the probability both has to be multiplied, both has to be multiplied only then you will get the number just because there 50 percent probability here does not mean you will find a electron here. Because, the density of states is 0 here. 0 multiplied by probability 0, you need to have some density of states and density of states are only here.

So, basically you have to multiply both together. So, one of them alone cannot tell you/ fifty percent probability does not mean there is an electron ok. It is a probability times the density of states that will give you the exact number of electron, same with holes. So, this is one thing they may not many may not tell you so much. Another thing the people often do not tell you is that you see I we typically draw a conduction band and then valence band. Of course, there is an intrinsic level at the middle at the middle of the gap, this is half way through. And, suppose this is N-type dope material or even p type. So, n type will be say Fermi level is here right.

See these are straight these lines are very straight right if you recall these lines are very straight right, whenever there is a straight line what does it mean? It mean actually it means there is no field. I will come to that very quickly now. You see the Fermi level here it is straight, the Fermi level has to be flat, Fermi level has to be flat in equilibrium. What does it mean? It means that there cannot be a slope in the Fermi level. Your Fermi level cannot have a slope.

The moment you have a slope in Fermi level it means current is flowing. So, in equilibrium when I say equilibrium there is no current flowing, your Fermi level has to be same because the probability the electrons has to be same everywhere. If the Fermi level is tilting, for example, I go back here I will go to new page may be you know.

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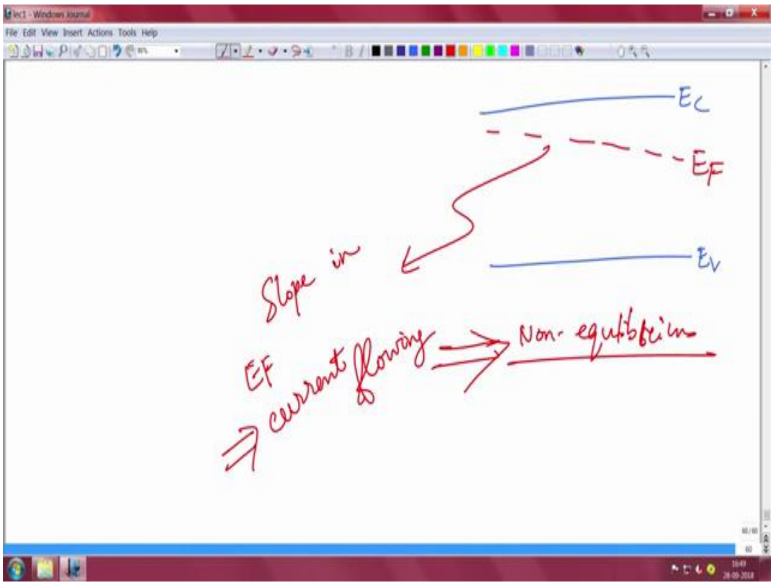

Suppose, I have a conduction band here, valence band here, and then I say that Fermi level is like this. This is not possible in equilibrium. This will mean it is non-equilibrium, why, because, you know a slope in the Fermi level this is the slope know. A slope in the Fermi level implies that there is a current that is flowing. And, if current is flowing then it means there is non-equilibrium.

So, your Fermi level cannot have a slope ok. The Fermi level has to be straight that is 1 very important thing, in equilibrium. Of course, if it is non-equilibrium, then Fermi level can have slope ok. So, please keep it in mind, many of the textbook do not tell you that ok.

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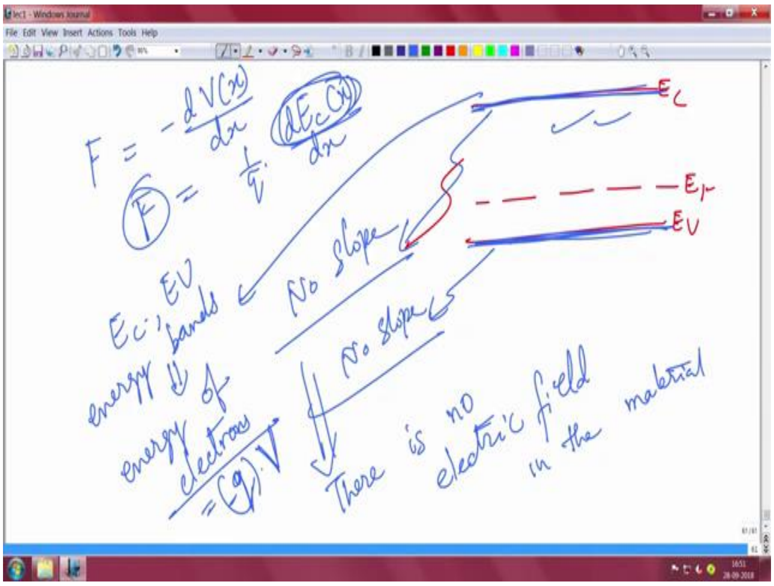

Another thing that textbook do not tell you is that, if you have a conduction band and valence band that are flat; Fermi level may be here, p-type dope material may be, if these are flat there is no slope right, no slope, this has also no slope right. Of course, they are same band gap there is no slope. It means that what does it mean it means that there is no electric field in the material, there is no electric field in the material ok, there is no electric field in the material. Because, if there is a slope; that means, that the potential is changing basically. And, if the potential is changing then the field also will come, right, because this energy are actually reflecting their potential only.

So, a flat profile means that there is no field ok. They have sense of field that is what it means. Because, if you recall from high school, field is nothing, but the negative of the slope of potential, you remember that, it is a gradient of the potential. And, this energy band diagram that I keep drawing, this one know, this energy is actually energy of the electron. This E_C E_V whatever we draw know, energy bands. This energy bands actually represent the energy of electron ok. These represent the energy of electrons. And energy of electrons is given by you know what negative of the charge is there of course, times V, V is the potential. So, potential time the negative of charge electron will give you the energy of the electron.

So, essentially this will become

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

So, if the bands are flat, then the derivative of that is 0 know. So, the field is 0. So, whenever there is a slope in the electric field, slope in the energy band sorry then you know the electric field.

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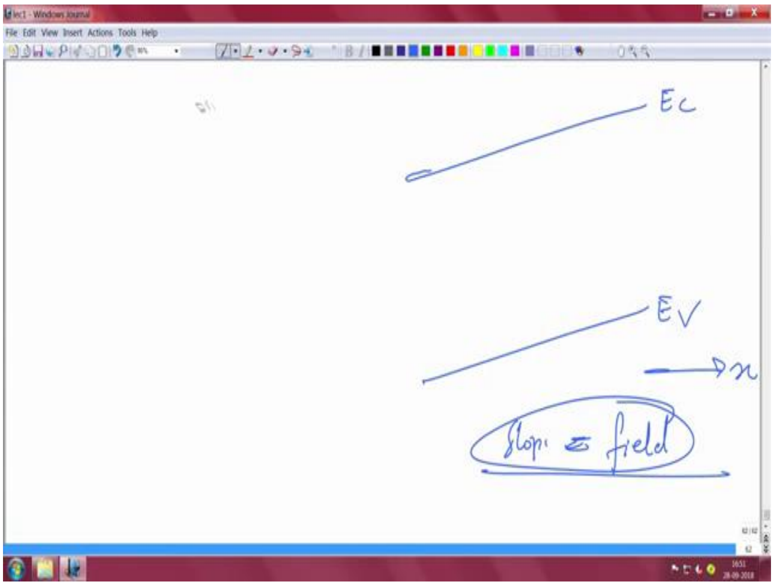

For example, if I have E_C like that, E_V like that then; that means, there is a slope; that means, there is a field here ok. This can be or cannot be in equilibrium, because I have not drawn the Fermi level here. I have not drawn the Fermi level here this is x here by the way ok, but this is slope means that there is a field, whether equilibrium or nor equilibrium is not a concern right now here ok.

So, now let us take I am trying to solve some simple questions. So, that know things become more and more clear. So, that is one important thing.

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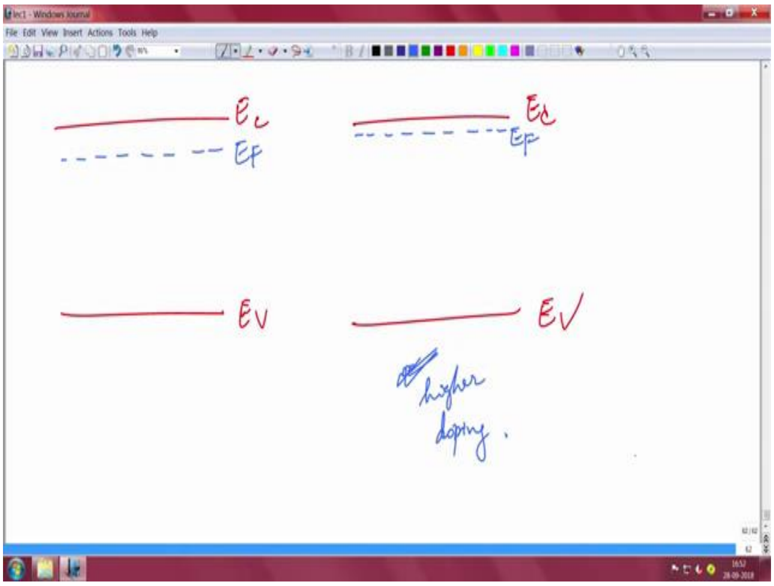

Now, suppose I have, let us suppose I have silicon 2 pieces of silicon, there is 1 piece here; E_C E_V exactly there is one here, another piece of silicon E_C E_V. In one, the Fermi level is here, in one the Fermi level is here, which has higher electron. Of course, this is higher electron. Because, the Fermi level is closer to the conduction band this also means this higher electron, it may also means that this is higher doping.

Now suppose, now suppose, what I will do is that, this is x the x axis is distance you know that right, this x axis is distance you know that right.

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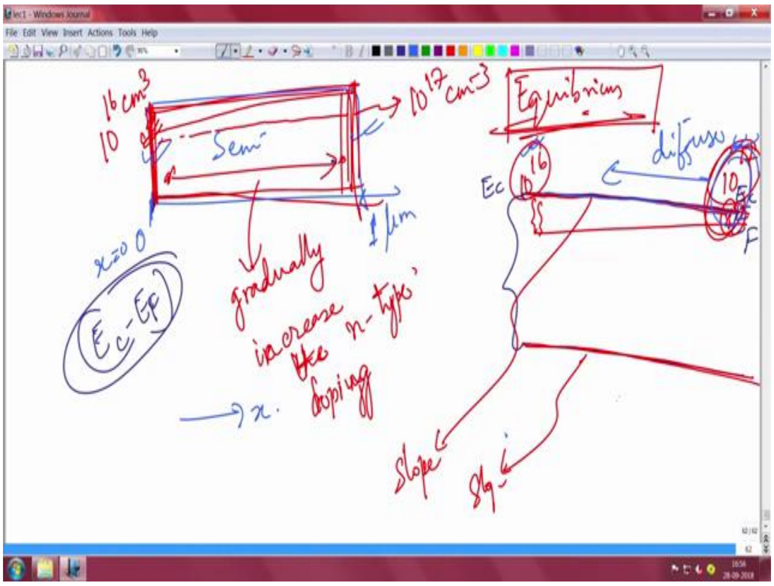

Now, suppose I take a piece of semiconductor, I take a piece of semiconductor, this is the piece of semiconductor, from this point say x = 0 this point, and say that length of the semiconductor is say 1 micron, 1 micron ok, this is this. From this side to that side ok, from this side to that side, I gradually, I gradually increase the doping; I gradually increase the doping n-type doping, what is happening second, doping the increasing the n-type doping, which means, from this side, I am increasing the doping n-type doping gradually to this side, I am doping it more and more.

For example, at this side, I have a doping of $10^{16}/cm^3$. I slowly keep increasing 2 into 10 to the power, gradually I keep and here I become $10^{17}/cm^3$ for example. So, that doping is gradually increasing from left to right. So, this part becomes more doping, this side becomes less doping and gradually it is changing. It is in equilibrium which means there is no current flowing, how will it look like now how will the energy band diagram look like. These are the concepts that textbooks often do not tell you, how will the concept look like.

So, for example, the band gap is remain same, doping will not change the band gap right. At least the moderate doping you are talking about. If, it is in equilibrium, one thing that you know is that what, your Fermi level will stay constant you agree, if your Fermi level will stays constant; that means, I will first draw the Fermi level here. So, this is your Fermi level which has state constant ok. sorry. This is your Fermi level which is constant.

Now, on the left side the doping is lower and the right side the doping is higher. If you recall, the (E_C - E_F) this spacing, (E_C - E_F) this becomes smaller for higher doping and larger for smaller doping. So, on this side this is the left side right, x = 0, this is x = 1 micron. At this side the doping is lower right. So, your (E_C - E_F) will be at some positions. So, here 10^{16} scale this is here, this is E_C. But now other side, the doping has increased. So, your E_C will be closer here than here right ,you agree, the you know the E_C will be closer there than here.

So, what will happen is that your conduction band will bend like this. And, your valence band of course also will bend like that, because the band gap has to remain constant. If one bends the other has to bend otherwise the band gap will not remain constant know this spacing the gap will not remain constant. So, what it means? It means the Fermi level is here sorry, Fermi level is here, it is a constant 1 line, I am very bad at drawing this is Fermi level E_F. And, your conduction band has been drifting like this changing like that, why because this position is far. So, less doping this is low. So, higher doping ok, conduction band valence band will go like that.

Now, you see there is a slope there, is a slope in the conduction band, slope in the valence band, it means that there is a field. A slope in the conduction band means that there is a field for field experienced by electrons, slope in the valence band means there is a field experienced by the holes. So, of course, both electrons and holes now they have a same band gap of course. So, electrons and holes will experience a field, which way will the field be do you know.

See, if there is a concentration gradient of see there is 10^{16} electrons here, there is 10^{17} electrons here, then there is a concentration gradient, you agree. So, there are more things associated with this, will come to that, it is called diffusion. If there is a concentration gradient of species, then you will always the it always tries to go from the higher concentration area to the lower concentration area right. If you spray deodorant in one corner of the room, the particles of the deodorant are highly concentrated in that corner.

So, it will diffuse through the corners where it is low. So, the whole room will start after some smelling that deodorant after some time right. So, electrons also try to diffuse from the higher region, from here it will try to diffuse from here right, it will try to diffuse from here to this side it will try to diffuse. Because, electrons are higher concentration here lower concentration here, but that will lead to a flow of current know, if electrons move. So, that current is balanced by this electric field that is there, electric field will not allow that to happen ok. So, I will tell a little it more about electric field here before we go to the next concept.

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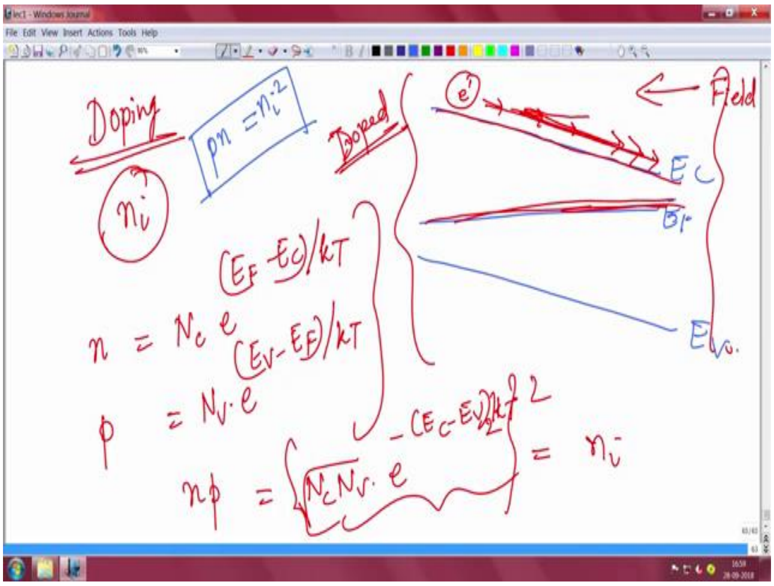

So, if your conduction band looks like that, this is your Fermi level ok. And, then your valence band looks like this, there is a slope here that I agree, which direction is the electric field do you know, a very easy way to find out which direction the electric field is, I told you if there is a slope there is electric field. A very easy way to find out which direction the electric field is, is think of this of this as a concrete floor a slope like that right. And, you think of an electron here as like a cosco ball or tennis ball, it will try to roll this side know, which means electrons will try to move in this direction. Because, it will rolling in this direction not diffusion ok.

This is the drift this is rolling down, which means the field will be in this direction because electrons will move opposite to field. So, that is how we quickly find out which direction is the electric field ok. Now, this is a separate case I will come to this very quickly in sometime, but you know this is a case the people do not talk about mostly in textbooks, as to the field existence of field can be inferred from a slope in the band diagram. Fermi level has to be flat, if this Fermi level has the slope; that means, there is a current is flowing ok.

Now, these are with doping by the way. And, doping is very essential to increase or decrease the number of electrons or holes and that is how I, you know, we change the conductivity of the material by tuning the electron or hole density. If, it is of course, undoped then n_i is that n_i that we talked about and n_i expression has been there. So, n_i depends exponentially on band gap, it also depends exponentially on temperature right.

Now, the question is there is something called mass section law, balance section you know in a way. So, what happens is that, for example, I told you that for moderate doping,

$n = N_C \, exp^{\frac{Ef-EC}{kT}}$. And, then you have $p = N_V \, exp^{\frac{EV-Ef}{kT}}$. And, this is not intrinsic, ok, this is not intrinsic, I am talking about doped, I am talking about doped material for example, not intrinsic not intrinsic.

So, if I multiply n and p, I get $N_C N_V \, exp^{\frac{EC-EV}{kT}}$, right, which is nothing, but if I take a square root here take a 2 here then I can take a square here this quantity is n_i. So, the product of p and n will always be equal to n_i^2 at equilibrium, this is a very fundamental rule ok. The product of p and n will always be equal to n_i^2 it is a rule ok, it is a fundamental rule under equilibrium it will always be true.

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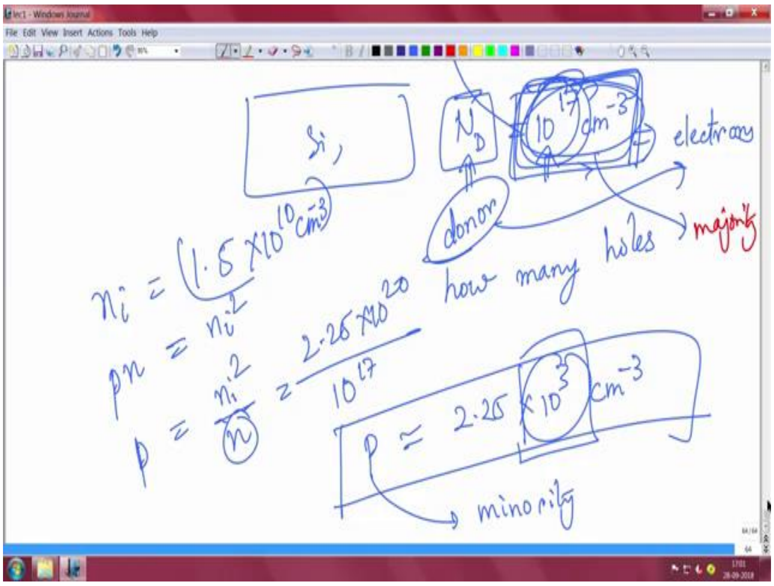

So, what does it mean? It means that suppose I have a material, I have a semiconductor silicon which is say n-type doped, with say $10^{17}/cm^3$ of doping, this is a donor atom right. So, this is donor doping which means so many phosphorous atoms have been put or arsenic atoms have been put. So, so many electrons also will get. So, the number of electrons is equal to this right.

So, how many holes will be there? How many holes will be there? In this material, how many holes will be there, naturally holes will be lower in number know, because I have added more electrons here, donor will give you electrons. So, these many number of electrons are there. Whatever number of dopants you have added, that many number of electrons will be there that is what we are you know assuming till now that is ok.

How many holes will be there? You know n i for silicon is 1.5 X $10^{10}/cm^3$ and I told you this p into n will always be equal to n_i^2, which means p = $\frac{ni^2}{n}$, which means that will be 1.5 will be how much, this square will be how much 2.25 X 10^{20}. And, n_i, n is n n is given to be this 10^{17}. So, p will be equal to 2.25 X $10^3/cm^3$, you see the number of hole is 10^3, number of electrons is 10^{17}, huge difference you know.

So, that is why it is called, you know, n type dope semiconductor there are more electrons than holes but see the number 10^{17} electrons and 10^3 holes. Because, there so, many so, few holes this is called minority ok. And, this is called majority, this is called majority electron doping. So, if you dope n type the electrons become majority and the holes become minority, you agree becomes minority and becomes majority. And, similarly if you dope p type if I instead of this if I put a p-type doping then the holes become majority and electrons become minority ok.

So, let us wrap up the lecture here today let us wrap up the lecture here today. We have discussed about doping we solved very fundamental simple problems of doping, I told you, few things that the textbooks generally do not tell you, one is that your slope in the Fermi level means that the current is flowing it is not on equilibrium. So, if a device or material is in equilibrium, Fermi level cannot have a slope which has to be straight. It is all with respect to the position by the way and conduction band and valence band, a slope in their profile means there is a field I told you how that field comes right.

So, if and there can be equilibrium or may not be equilibrium we do not know, but a slope in conduction and valence band means there are fields there ok. So, I told you about intrinsic carrier concentration, how it depends on band gap, how it also has a role in or devices, because leakage current will be high, or noise will be higher. For a photo detector for example, made of lower band gap material, then compared to higher band gap material. Because, the intrinsic carrier concentration is the base line, the minimum carrier concentration that you will have you cannot go lower than that ok.

And, I told you that you know just now I told you here that x, your electrons and holes how you calculate the number. If your doping n type, then electrons are majority holes are minority and vice versa. p into n will be always is equal to n_i^2. So, if you know the n_i you can always calculate p or n if the other value is given. I also told you that, you know if you dope it n-type the dopant is called donor because it is donating electron and p-type dopant is called acceptor because it is accepting electron and giving you holes basically right. And, I told you that if you had 1 phosphorus atom, you get 1 electron that always need not be true in need not hold true.

So, those things we will come in the next class, incomplete ionization incomplete ionization and little bit more advance on this before we go to mobility and scattering, which I already introduced in a briefly, the diffusion thing I told you all those things will depend on mobility also the drift and diffusion ok. So, will come to that before that we will cover a few of the slightly more advanced things, but with examples and numerical; so, that we will take up in the next class.

Thank you.