# Fundamentals of Semiconductor Devices

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## Lecture - 04
## Band structure (contd.) And Fermi-Dirac distribution

So if you recall in the last class we had discussed about E-K diagram and I told you that in a real semiconductor crystal the electrons will face this periodic potential of the atoms, that is why the E-K diagram becomes distorted and thus E-K diagram has a huge impact on how we understand devices; because the effective mass of electrons as it moves inside a crystal is dictated by the curvature of the E-K diagram. So, it is very important hope you have you know recalled all those things. I told you in the last class while ending that I have introduced the concept of holes because that is as important as electrons ok. So, today we shall introduce the concept of holes and also the statistics that dictate how electrons and holes are populating in this energy bands ok. And it is a very crucial concept you will see electrons and holes are equally important in semiconductor research.

So, let us come back to the whiteboard here.

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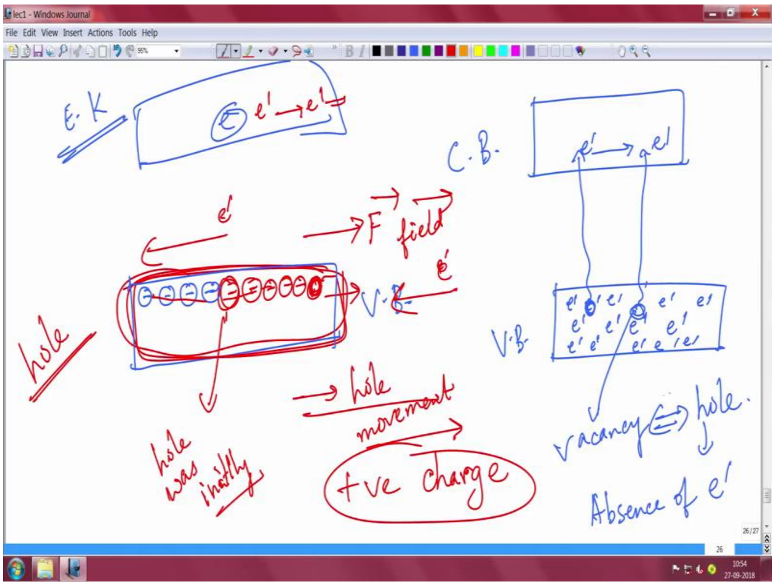


I told you that the conduction band here I will call C B conduction band and then there is a valence band here V B this is completely filled with electrons this is completely filled with electrons ok. And because it is completely filled with electrons, electrons do not have any empty states to move. So, it cannot carry current, but this is nearly empty. So, you can actually excite an electron somewhere here somehow you excite either by giving heat or by light or something excite some electron there, then this electron is actually free to move and that is how they carry current. And you can tune how many electrons you can excite or how many electrons you can have here and that is the beauty of semiconductor I keep telling you because in metals or in insulators it is very difficult or you cannot do that ok.

So, now we will keep in mind there is something called E K diagram we will not forget that because that is very important. Now when I take an electron from valence band to conduction band, it leaves behind a vacancy here you know. If I take one electron away from here to there, it leaves behind a vacancy here, that vacancy is called a hole. Actually, hole is a absence of electron right hole is an absence of electron you agree right. An electron thus move there it left behind an empty space it is a sort of a vacancy. So, that vacancy is called hole and hole is the absence of electron. But in semiconductor devices it’s much more convenient and its it makes sense, if you define the hole sort of a particle only. Although it is the absence of electron you can treat it as a particle and what will happen now? Suppose this is the valance band this is your valance band it is filled with electrons right I will give electrons like this its filled with electrons and also (Refer Time: 03:20), but I will only take.

So, one of this for example this, has gone to conduction band, it has gone to conduction band it has gone to conduction band lets it has come here that is fine. Now there is a vacancy here, there is a vacancy here. So, if you apply a field electric field in this direction; if you apply electric field in this direction which means electrons will try to move in this direction right? If a field is in this direction electrons will try to move in this direction what will happen now? See if this if this was field know if this was field initially, then the electrons cannot move because there is no empty state where will they move? They cannot move. So, there is no current. But now I told you that one electron has gone from here and it has left behind an empty space it is like a vacancy it is a hole what will happen now? If I apply a field in this direction x direction, electrons will move in negative x direction. So, this electron will be able to come here now right and then here it will be a empty space ok. Because electron has the near by electron has come here its an empty space. Now this electron can come here of course, so, because it is an empty space no its a vacancy so, it can come here and this will be blank. Of course, the other one can come so, on and so, forth so, essentially what will happen is that, you will have electrons like that and the hole empty it will keep moving.

The hole was initially here, the hole was initially there right. But the hole is moving in this direction, the hole is actually moving in this direction in a way the vacancy is moving in this direction because the electrons are jumping jumping right. So, coming here right. So, the hole is moving in this direction. So, I can say that the hole is moving in the direction which is in the same direction as electric field, which means it has a positive charge you agree? Electrons are moving to the left electrons are moving to the left because they will move opposite to the field. But because they moving to the left the hole is seems like moving to the right agree? Because the hole is moving to the right it looks like the hole is moving to the right initially the hole is over here. So, the hole has a positive charge because only then it is moving in the direction of field ok.

So, hole essentially is an absence of electron which can be modeled as a particle as a positive charge, that moves in the same direction as the electric field ok. That moves in the same direction of electric field and initially if everything was packed here no hole you know; then all the electrons are there they cannot be movement the total momentum is 0. But now the total momentum is not zero because there is an empty particle sort of it, you know its absence is moving. So, now, this is not a total momentum is 0.

So, that negative of the total momentum you know that is the hole momentum you can call the hole actually is a is the negative you know is the opposite of electron, but its mass is not the same by the way, its mass is not the same because this hole can now we model as also a particle its called a quasi particle, because it is not realistically a particle, but you can model it a particle and that makes life easier. Instead of explaining and understanding how electrons are moving here in this way, it is much easier to talk about a vacancy moving to the right a hole moving to the right that makes its simpler. Of course, in conduction when you talk about electron moving because there is all empty you know talk about electron, but here you talk about holes.

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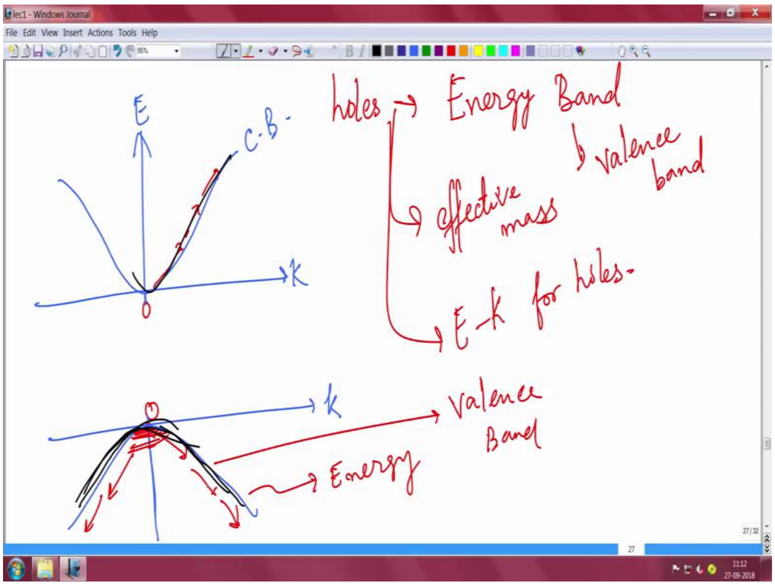


So, the beautiful thing is that holes also have their own energy band first of all they have their own energy band. And their energy band will correspond to the valence band right because they are moving in the valence band electrons are moving in the conduction band; holes are moving in the valance band. So, holes will correspond to valance band holes also have their own effective masses, because you can draw the E-K diagram for holes also and that will be valance band right.

For example, this is E this is K and I told you the electrons have a E-K diagram like that. Same way holes also can be drawn this is conduction band by the way hole because the hole energy is opposite of electron you know the hole will look like this, this is the hole, this is the hole E-K diagram energy. This is the hole energy and this is K equal to 0. An electron energy you know this is E-K diagram of electron as you go up the electron energy increases right here as you go down hole energy increases [FL] as you keep going down the hole energy increases. So, at this point at K equal to 0 point the hole energy is the lowest as go down it increases. So, this is the, this actually is the valance band and their holes are here we can say holes are here and this is the conduction band.

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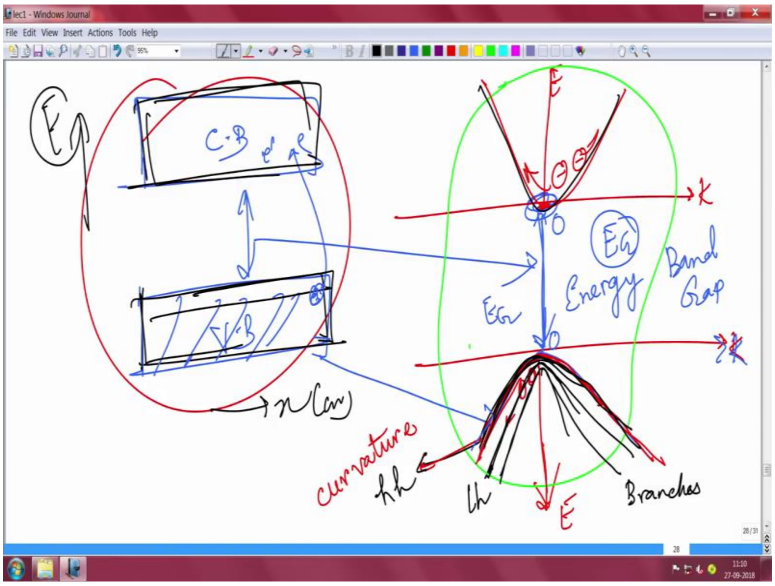


So, essentially we are talking about E K diagram for both electrons and holes, we are talking about E K diagram for both electrons and holes.

So, essentially you have this E, K, K, this is the hole energy here. So, this is electron this is hole this gap sorry this gap is the energy band gap again. Because this energy band gap is called Eg I told you. This energy band gap is the same as this conduction band, empty conduction band and the fully field valence band this is fully filled some electrons will go here leaving behind holes here and thus electrons will be here right. So, this valence band corresponds to this, this conduction band corresponds to this, this band gap of Eg corresponds to this (Refer Time: 09:29) this is called this whole thing this whole thing thing whole thing is called sorry. this whole thing is called band structure because it is E-K diagram this is called band structure E-K diagram and this is called band diagram just the band diagram because it is in real space ok, but this is the one to one correspondence between the same. So, valence band essentially you talk about hole transport in valence band it's filled with the electrons by the way, but holes are moving in the valence band and electrons are moving in the conduction band right that is what is happening ok. Holes are moving in valance band electrons are moving in conduction band, holes are essentially quasi particles they are absence of electrons, that you model as quasi particles they have the own effective mass, because this E-K diagram that you are drawing for a hole, same thing that comes for electrons. It also has a curvature know it also has a curvature. So, that will also give the effective mass of hole the inverse of this curvature

H square H bar square inverse of this curvature, will also give you the effective mass of hole and so, holes have their own effective mass electrons have their own effective mass and this point ok this point is called the lowest energy point of the conduction band and this is the top most point of the valence band, the distance between them this energy gap between them is energy band gap Eg this is K remember this is K, so, this is K equal to 0 this is K equal to 0.

There many important things here, number one thing is that unlike in electrons holes are more complicated because they are not technically particle right because they are quasi particle they are model the vacancies are model. So, there is a there is a little thing here a hole might not only has this one branch this is one band it might actually have 2-3 sort of it might have 2-3 sort of a we can call them branches of E-K diagram. Electrons that are technically do not have them, but they may typically holes will definitely have this you know mostly have this separate branches ok.

You might see that the curvature of the top most is the lowest the curvature of the topmost is the lowest then curvature increases. If the curvature becomes higher then effective mass becomes lower. So, this is called light hole branch the top one is called heavy hole branch why is it called heavy hole? Because the curvature is small let me draw it again may be freshly right.

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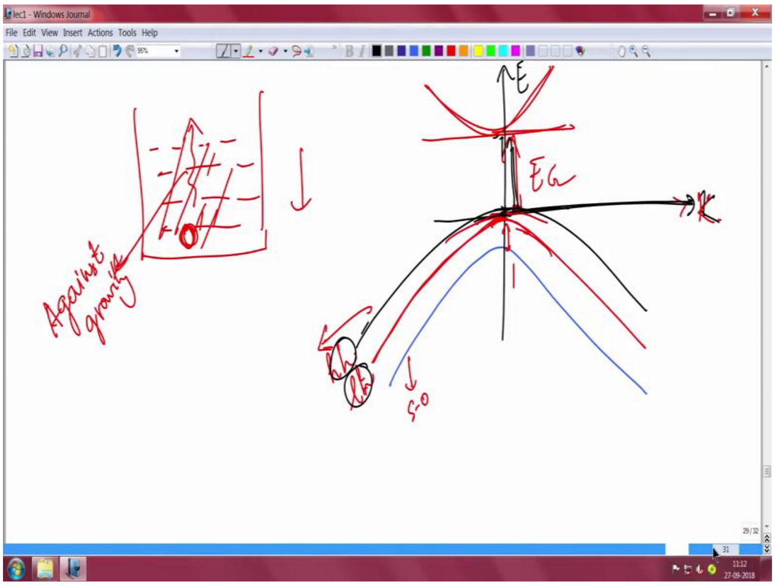

I am only talking about the E-K diagram for holes. So, this is E sorry this is K, this is there are three branches typically one is this, one is the red one, then one is the blue one for example ok.

This red one actually goes to almost K equal to 0 like this and touches and come where here, but the blue one has an offset here there is an offset here the blue and the red is an offset ok. So, the black one has the lowest curvature you see. So, it has got the highest effective mass. So, it is called the heavy hole branch, the middle one has a higher curvature, so, lower effective mass is called light hole branch. So, they are different branches of hole actually, and the last one is actually of spin orbit coupling we do not have to worry about it this basically some coupling between spin of the holes and other things.

So, it has three branches, but that is fine we can talk about the top branch here and this is how holes actually the energy split looks like and of course, the electron will have only one branch typically. So, electron is fine there, and this gives the energy gap that is what we need to know and this is K right this is K. You know it is almost like talking about water bubble, you know air bubble in a water. So, here water fill and gravity is pulling you this side right gravity is pulling you this side right, but there is a bubble of air. The bubble will move upward against gravity the bubble will move upward against gravity right.

So, how do you explain that? It is easier to explain if you say that the bubble has a negative mass. So, that it is acting against gravity is moving up. So, in a filled water you are talking about an empty bubble. Same thing you can talk about a hole a very crude analogy, you can talk about a hole in a valance band that is moving against the you know the its actually moving in the direction of the field against in the opposite of the direction of the electrons that is how you can talk about it. So, that is one thing and because I am in the E-K diagram I am talking about the holes and electrons already, I told you that electrons and holes have their effective masses, they have their own E-K diagram and the separation between them is the energy band gap, there is a one to one correspondence between the E-K diagram and the energy diagram here.

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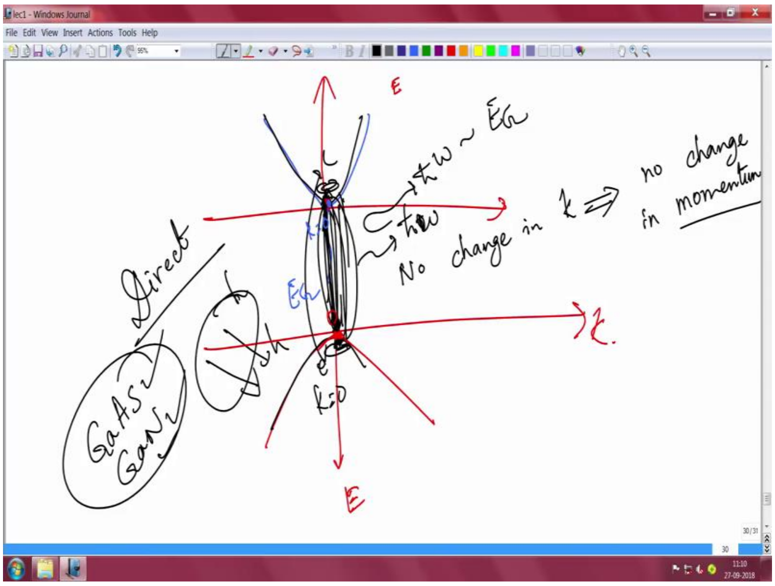


What is more important here to understand is that, when I have a E-K diagram like this right; and energy the lowest point is that K equal to 0, it is not necessary that it is not necessary that one second I will just put it here put here, K this is e this is K I told you that you know the hole has the energy like that. Typically will talk about that K equal to 0 point at K equal to 0 point, the hole will have this you know the topmost point of the E K diagram in hole will correspond to here, the bottom most point of E-K diagram in electron will correspond to here, but it is not necessary that all semiconductors will follow this rule. In some semiconductors in some semiconductors you know that in some semiconductors your bottom most point of conduction band need not be at K equal to 0, this is K equal to 0 point right.

It need not be K equal to 0 like this in this case it is fine; this point the bottommost point of conduction band, the topmost point of valence band they are the same K point, the energy difference is band gap, but it need not be same that is why I am saying what do I mean?

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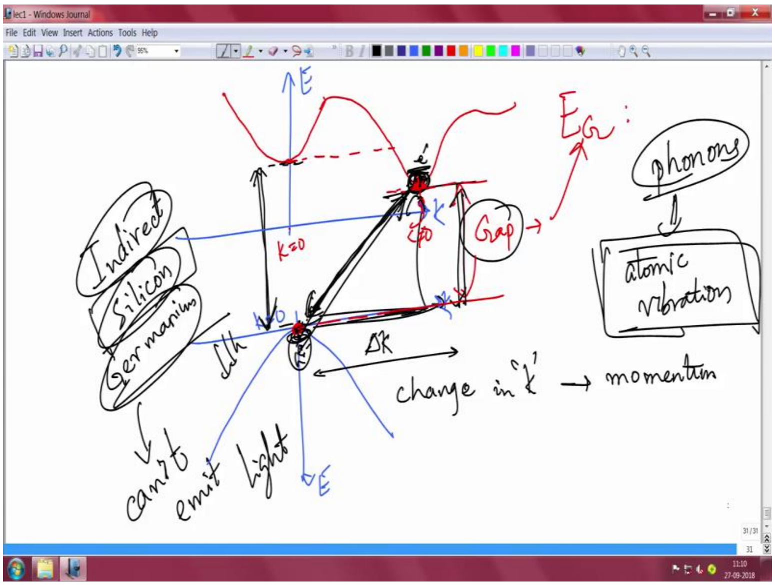

I mean that there can be semiconductors where you have E you have K, K, E. You will always take the hole for hole the valence band will always have the topmost point at K equal to 0 ok, but for electrons you know the conduction band may have a point here, but this is not here exactly and then there is somewhere here comes very low and goes at some other K at some other K. So, you see this is the lowest point. This point, this point is lower than this point agree this point is a much higher point no right. This point is at lower point then this, but this is K equal to 0 and this is K not equal to 0 this is some finite K we do not know what K is this right. But energy band gap Eg; energy band gap is defined between the highest point in the valence band here and the lowest point in the conduction band, which means this and this is the gap you are talking about and this is your energy band gap ok. this is energy band gap; you cannot call this as the energy band gap because this is much larger gap than this no this gap is much larger than this, we have to take the smallest gap.

The topmost point in the valence band and the bottommost point in the conduction band their separation in energy is the energy band gap; not this one and this one. What happens here is that the bottommost point of the conduction band is at not K equals to 0. Because it is not K equals to 0 so, an electron and a hole if they have to do a transition or recombine they have to go this way know it is very difficult not probable why because this change is a change in K and K is momentum. So, essentially for electron and hole to basically make a transition some way to excite or you know absorb light or emit light or so on.

Electron and a hole has to essentially make this transition across this gap this is a momentum change you know delta K and this change in momentum is pretty huge, you cannot electrons and holes do not have that kind of you know a light particle for example, a photon cannot give that kind of change of momentum to cross from here to there. So, transition of electron and hole this way is you know it is a process which needs the assistance of some other things like atomic vibrations. Because atoms when they vibrate they can give energy and change the momentum, that is how they come go from here to there. There is a very inefficient process. So, this kind of semiconductor, where the bottom of the conduction band and the top of the valence band are not exactly at the same K. These are called indirect band semiconductors indirect band semiconductors like silicon for example, or germanium for example, and those materials where top of the valence band like I had showed you in the previous slide here, where the top of the top the bottom of the conduction band and the top of the valence band and the same K. So, if you want to excite an electron from here to there, you do not have to change K.

No change in K which means no change in momentum right no change in momentum. So, essentially if you want to excite an electron from here to there or get a electron hole combine here, the K is only zero here right. So, electrons and holes essentially do not have to change their momentum. So, very efficient process these are called direct band gap semiconductors, and examples are like gallium arsenide right, gallium nitride and so on ok. These are direct band gap semiconductor and the semiconductors where E K diagrams are such that, bottom of the conduction band top of the valence band are not in the same K they are indirect semiconductor like silicon. So, transitioning from one point to another point becomes very difficult inefficient, you need to take the help of phonons or which are phonons are actually you do not have to use the word phonons these are actually atoms vibrations.

Atoms keep vibrating know about their mean position, you can quantify them or you can call them as phonons ok. And those atomic vibrations essentially give energy to the electrons or holes to change their momentum and inefficient process. So, things like indirect band gap semiconductor like silicon or germanium, they cannot emit light they cannot they cannot emit light why? Because for emitting light you will see the electrons that are here, have to come down and recombine whose holes are here and the energy that is there actually releases photon will see that in light optical processes.

Electrons that are here and the holes that are here will recombine directly, and the energy that is lost this energy know that is emitted as photon that is emitted as photon. And that energy that is emitted will be roughly equal to the band gap of course, whatever the band gap is there that is how you emit the light because they will recombine. It needs no change of momentum so, it is a efficient process that is how materials like gallium arsenide, gallium nitrite can be used to make led because they can emit light, but material like silicon for example, it cannot emit light because an electron that is here and the hole that is here for them to recombine you need the help of atomic vibration to change the momentum. So, that energy lost actually is energy that is given to the atomic vibration and hence you cannot emit light it's a very inefficient process.

Similarly, absorption of light in materials like gallium nitride, gallium arsenide is very high ok. The absorption is very high here you know, a photon comes here for example, an electron in the conduction valence band can be excited to the conduction band, and that energy is used of the photon energy is the used of which are very efficient process so, it is also a very high absorption coefficient. Now silicon and indirect material like silicon or germanium also can absorb light, although the absorption coefficient is much lower, but it can be still be absorbed light that is why they have used some silicon solar cells for example when the light comes that light energy the photon energy will be used to excite the electrons from here to there, its a not a very efficient process because part of the energy has to also be given up to the you know the photons will not have enough change energy to change the momentum. So, you have to take help from the atomic vibration anyways right.

So, you can excite the electrons of course, with taking the help of atomic vibration it is an inefficient process. So, the absorption is not very absorption coefficient is not very high unlike in direct bandgap material like gallium nitride or gallium arsenide where the E K diagram is such that, the conduction band, valance band and the same case absorption is very efficient there right.

But this material like silicon cannot emit light that is one thing. These are called indirect band material and this is a very important concept that you should know. But both indirect and direct band material their energy diagram in the real space will look like this only you know you have a conduction band here, valence band here whether it is a direct or indirect you do not know here because it is a x axis; it is a x axis in centimeter and this is energy this is called energy band diagram and from energy band diagram conduction band, valence band you actually cannot tell if it is a direct or indirect band semiconductor, but from these diagram you can tell if it is a direct or indirect band semiconductor from E K diagram. And that E K diagram actually tells you that is why it is very important, whether a material can emit light or not can be told very easily very nicely from the E K diagram ok.

So, that is the concept about indirect and direct band gap material ok. So, now, what are things that you have learnt? Tells take a recap and we go as we go to the next concept. So, one thing that you have learnt is so, let us see from where we have started this lecture, I told you the concept of holes we have introduced the ok so, we have introduced the concept of hole right. So, I told you that electrons can go from the conduction, valence band to conduction band they can leave behind hole, a vacancy and you see if there is a vacancy here then when you apply an electric field electrons move in the opposite direction to the electric field and it seems like the holes are moving to the right because electrons keep moving to the left.

So, we can treat the hole as a quasi particle which have positive charge that moves in the direction of electric field. Hole also has its own E-K diagram I told you holes also have their own E-K diagram and that E-K diagram of holes actually represents the valence band of the semiconductor valence band of semiconductor and the movement of holes is always associated with the movements of holes in the valence band, movements of electrons is associated with movement of electrons in the conduction band, and the curvature of this also give you the effective mass of holes.

So, holes also have their own effective mass. I told you that holes might actually have three different branches of E-K diagram the light hole, heavy hole, and spin orbit curve and the separate bandage here band hole here, but we typically consider only light hole or sometimes may be sorry heavy hole and sometimes may be light hole. They have different curvature this band this separation between the highest point of the valence band and lowest band of the conduction band it is basically defined as the band gap. If happen to be the same K and K equal to 0 it is called the direct band gets semiconductor and if they do not happen to be in the same position K then they are called indirect band semiconductor like silicon for example, that is an indirect band semiconductor.

So, it is a very poor you know it cannot emit light, also it is not a very good absorber of light although you can still make solar cells by making thick silicon layers. And to make a transition of electron hole if in these kind of material you need the help of atomic vibrations call on phonons, that is how you basically make a the transition between electron and hole its an inefficient process and that is why it cannot emit light. And the next immediate concept that we will learnt here in today's class that is very important is actually how this is we have learned it. How electrons and holes are occupying the energy you know.

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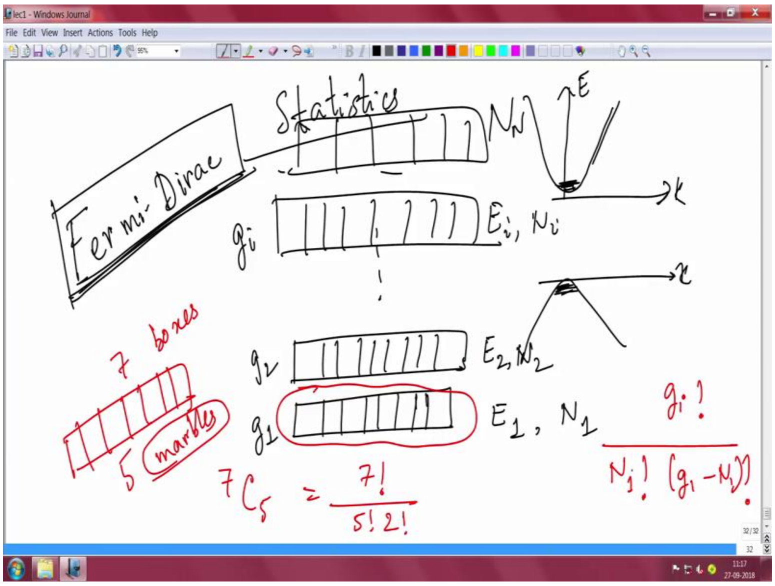


This is the conduction band for example, and this is the valence band for example, I am talking about the direct band semiconductor here this is E K diagram right, this is E K diagram. How are electrons populating the conduction band? How are holes populating in the valence band all this concepts we need to understand by using statistics.

Why? Because electrons and holes are very large in number you cannot individually pick up an electron and hole to do that, you have to talk about an ensemble like a collection and that is why a statistics comes handy and we have to use Fermi -Dirac statistics here Fermi-Dirac statistics. The Fermi-Dirac statistics nothing very fancy I mean there is two people Dirac and then Fermi of course, they both got noble prizes when they were very young and this Fermi Dirac statistics will tell you how electrons or holes will basically you know populate the energy bands and when we study Fermi Dirac statistics, we do not have to think of only electrons it can be applied to any particle which has certain properties, you know like in distinguishability and other things.

So, when we study Fermi Dirac statistics, it is not exclusively with respect to semiconductor, but its respect to many type of particles you know it can be applied to many kind of particles which satisfy this you call fermions, you do not have to worry about that so, much now. But how do we actually come up with this Fermi Dirac statistics to define the statistics of electrons and holes that are occupying this? You know that for we will take a very simple case into account let me do one thing. So, suppose I have many energy states. These are all at energy level E 1, these are all at energy level E 1 and there are g 1 states ok. There are g 1 states they are all at energy E 1 and the number of electrons that will occupy this is N 1.

N 1 electrons will suppose occupy g 1 energy states that had an energy E 1 ok. Then similarly there are g 2 energy states at energy E 2, and N 2 electrons have to occupy them. So, similarly there many right this is suppose g i energy states, at energy E i and N i has to be there and eventually you have a large number of thing, eventually it has N N you know N N for example, total number here ok. So, first let us look about this in how many ways can you; in how many ways I repeat in how many ways can you fill this g 1 states by N 1 electrons? It is like saying I have for example, 7 boxes I have 7 boxes and 5 say marbles. I need to fill up 7 boxes with 5 marbles in how many ways can I do that? I can do that by

$$ {}^{7}C_{5} = \frac{7!}{5!\,2!} $$

if you remember from high school physics high school sorry maths right.

So, the number of ways in which you can fill up g 1 energy states with N 1 electrons is actually

$$ {}^{g1}C_{N1} = \frac{g1!}{N1!(g1-N1)!} $$

that is the number of ways in which you can fill up the this states. Now of course, for the second level you can do g 2 N 2 and so on, for i th level it will be

$$^{gi}C_{Ni} = \frac{gi!}{Ni!(gi-Ni)!}$$

right it will be like that. So, the total number of ways in which you can fill up all these things will not be the sum, but will be the product.

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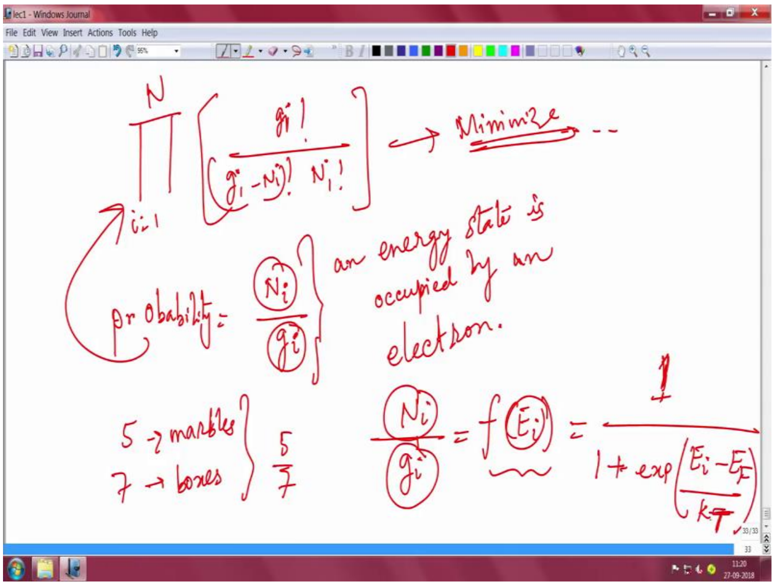


It will be the

$$\frac{g1!}{(g1-N1)!N1!} \text{ x } \frac{g2!}{(g2-N2)!N2!} \text{ x } ..........$$

This like the summation is given by sigma, the product is given by pi the product is given by pi.

$$\prod_{i=0}^{N}\left[\frac{gi!}{(gi-Ni)!\,Ni!}\right]$$

So, if I give sigma it is summation right if you remember. So, instead of summation I have to use product, product is given by big pi like that. So, this is basically i for example, and i goes from 1 to large number of N ok. So, the way is to minimize this and so, there are certain derivatives and some approximations that have to be used, called stirling approximation because it is a factorial and then you have to minimize this you know probability eventually. So, what you get essentially is something like, you have to get something like say N i by g i, the number of electrons that you are filling in the number of available states that you have it basically gives you the probability it basically gives you the probability that a state is occupied. It is like you have 5 marbles, and 7 empty boxes.

The probability that a box is occupied is 5 by 7 you agree? So, essentially you get this probability, this is the probability that an energy state this is the probability that energy state is occupied by electron is occupied by an electron it is occupied by an electron that is the probability ok. And this probability can be obtained by basically minimizing this function doing some approximation and simple maths. We will skip that but eventually this expression this N i by g i it is actually call and this is at E i level by the way. So, this is the probability that electron is occupying that and it is corresponding to i. So, it is called f the probability is called f, and this f of E i because this the corresponding to an energy state of E i that these are the number of states these are the number of electrons, but this is the energy by the way. And this is actually given

$$\frac{Ni}{gi} = f(E_i) = \frac{1}{1 + \exp(\frac{E_i - E_F}{kT})}$$

$E_F$ is the Fermi level, this K is not the reciprocal space momentum this K is Boltzmann constant K and T is temperature.

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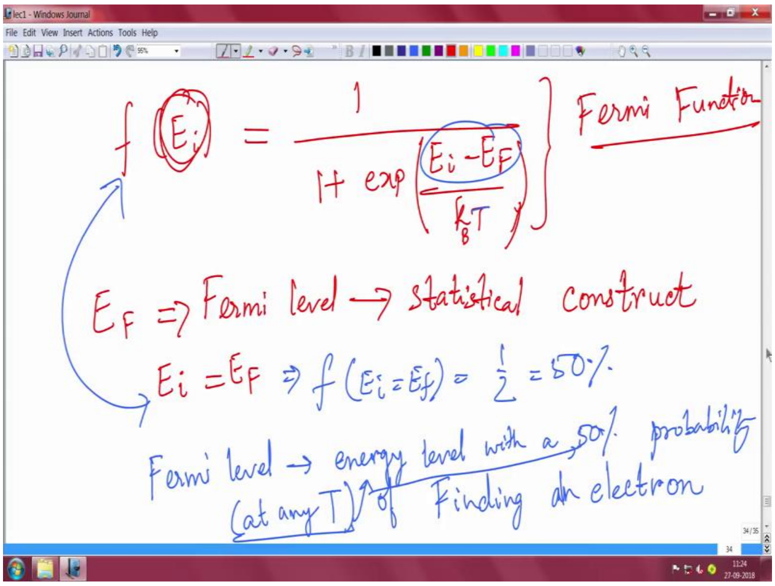


So, let us write down it again real its write it down again f(Ei) the probability that this energy state is occupied is

$$f(E_i) = \frac{1}{1 + \exp(\frac{E_i - E_F}{k_B T})}$$

$E_F$ is the Fermi level, $k_B$ is Boltzmann constant and T is temperature.

This is the probability that an energy state is occupied at E i write by an electron and E F here is called actually the Fermi level. You call it Fermi energy when it is temperature T equal to 0 otherwise you call it Fermi level and it is somewhere it is also called chemical potential by many people same thing actually ok. Is the Fermi level and what does this Fermi level mean? It is actually a statistical construct it does not exists in reality, but the difference of Fermi level can be actually a realistic quantity wherever a little different it is a statistical construct it is a statistical construct a statistical concept that helps in understanding many things.

For example, if your E i the energy that you are talking about is E F, then if you look here what will happen? f of E i equal to E f you put here E i equal to E f that will become

0. So, E to the power 0 is 1, 1 by 1 plus 1 is 1 by 2 and this is independent of temperature, does not matter what t you have this is 50 percent.

$$E_i = E_F, f(E_i = E_F) = \frac{1}{2} = 50\%$$

So, you can say the Fermi level is a statistical concept of course, it is the energy level it is the energy level where you have a probability of 50 percent the finding the electron of finding the electron right of finding the electron an electron ok. The probability, the energy level at which there is a 50 percent chance that there you will be an electron that energy level is called Fermi level and it is independent of temperature like this probability of 50 percent is independent of temperature any temperature ok.

This is at any temperature at any temperature the probability of finding the electron is 50 percent at Fermi level. That is your statistical construct or a concept of Fermi level. It helps in understanding so, many things ok. And a Fermi level as you will see will become the most important thing that will go along with you in that semiconductor device analysis none of the device that we will talk about in this course can be understood without Fermi level everything will be related to Fermi level. So, Fermi level is the statistical construct that tells you the probability of finding the electron, it is the level at which the probability of finding the electron is exactly 50 percent right.

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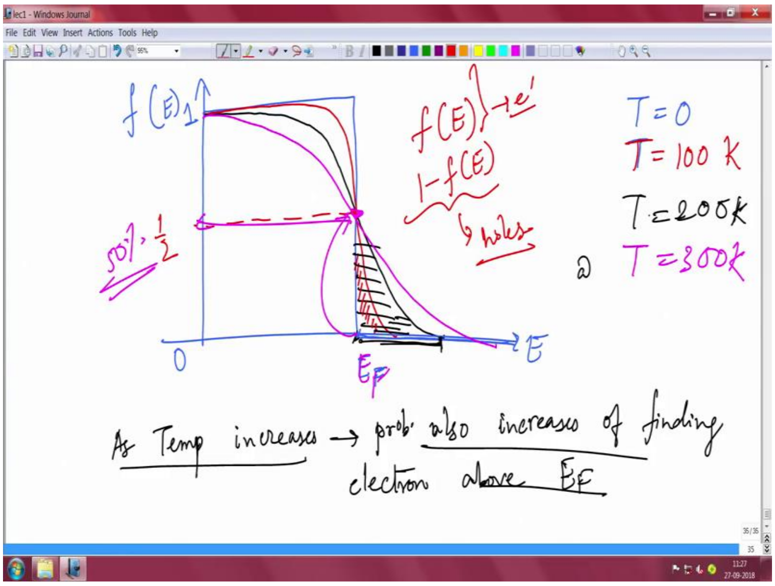

So, what I can do here is that I can plot the probability this f of E right versus E at say T equal to 0 Kelvin. So, at T equal to 0 Kelvin if you plot that function I just had drawn know, it will look like this it will look like this ok. This is E F till the Fermi level all the electrons in a it is 100 percent probability this is 1 this is 0; above Fermi level there is zero percent probability that electrons are there and below Fermi level there is 100 percent probability that electrons are there at 0 Kelvin. If I increase the temperature say know if I increase the temperature say. if I increase the temperature say 100 Kelvin, then this Fermi Dirac distribution this Fermi function by the way that in case I had not told you this actually this is a Fermi function it is a Fermi function and its its you can call this is a Fermi Dirac probability also its also called Fermi Dirac probability that probability distribution electrons in a way, you can find out the probability in any energy level E i told you that at E f at Fermi level it is 50 percent, but at any energy level E i you can find out because you know E i minus e f, that E i quantity you have to know and temperature of course, you have to know.

So, what do I do? So, this is at 100 Kelvin this will become how much how do you know this will become slightly this and this is slightly become this, it is point of course, is half this 50 percent. So, at Fermi level you have always 50 percent probability of finding the electron, but now there is a slight probability of finding the electron above the Fermi level also right because in and overall area has remain same, but this has become slightly deviated and then you have say T equal 200 Kelvin I am raising the temperature what will happen then? Then to you will have even more like this like this.

So, now, you have even more probability that there is a electron above Fermi level to much farer far away energy level you know this is also this has increase so, you have a finite probability of finding the electron above Fermi level also what it means as temperature you know? As your temperature increases as your temperature increases probability also increases that you probability also increases that you will of finding electron above Fermi level of finding electron above Fermi level.

So, finding the electron above Fermi level also increases, the probability of finding the electron above Fermi level also increases when your temperature increases that is what it means right. With higher temperature if you take for example, T equal to 300 Kelvin then of course, it will be even like that even more, but this at any temperature at Fermi level this is E F. At E F you will always have 50 percent probability of finding the electron that is what it means. So, basically Fermi Dirac statistics will tell you the distribution of electrons and it also you know if I want to tell you again if f of E gives you the probability of finding the electron at energy level E, then one minus f of actually E is the probability of not finding the electron so this is the probability of finding holes by the way and this is the probability of finding electrons by the way right.

So, the electrons and holes and how they are distributed and how we study them the devices and everything depends on the probability distribution ok. This probability, it is very important that is why introduced the concept of Fermi function. Now the another important concept that we probably will introduce in the next class of course, and that will be very important to understand the many of the things I will just briefly mention, what that is here and that is called actually density of states.

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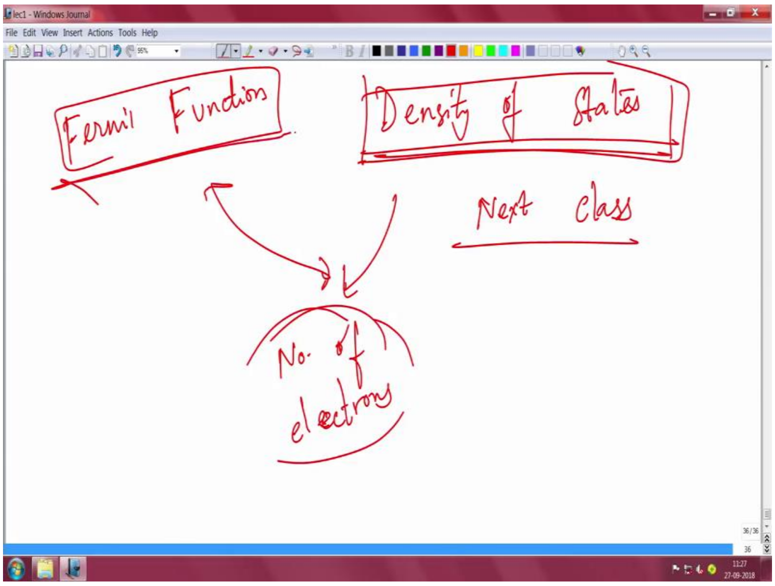


I will not introduce it in this class, in the next class I will come here density of states this is something we will discuss in the next class ok. And together with Fermi function, I told you the Fermi function and the Fermi probability here right. So, witht Fermi function and density of states that I will introduce in the next class within combining these two concept, you can find out the actual number of electrons or holes, actual number of electrons or holes can be found out by doing this two things.

Already I told you Fermi function is the probability function and density of states is something that will take up in the next class. Density of states essentially tells you how many energy states are available per unit energy per unit volume, per unit energy per unit volume how many empty states are there? How many energy states are there? Once you know that density of states and once you know the probability that you can occupy those empty states, the product of these two in a way will give you the actual number of electrons or holes that are there in the semiconductor.

So, all the devices will depend on how many electrons and how many holes you have in the device and for that you need density of states and then you need the probability. So, today we learnt about probability, the probability that an energy is occupied by an electron that comes from Fermi Dirac probability, and Fermi Dirac probability says that at exactly Fermi level which is a statistical concept you have 50 percent probability of finding the electron. But as you increase the temperature there is also a probability that above the Fermi level you will find some electron, at 0 Kelvin you have absolutely no chance that you will find electron above the Fermi level ok.

So, next class will introduce the concept of density of states from there will take it forward ok. So, thank you and will meet again in the next class with density of states ok.

Thank you.