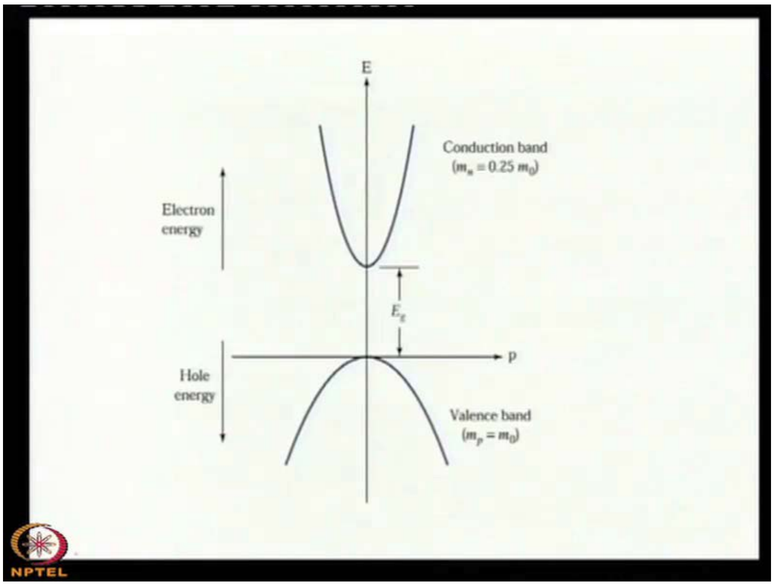
Processing of Semiconducting Materials
Prof. Pallab Banerji
Department of Metallurgy and Material Science
Indian Institute of Technology, Kharagpur

Lecture - 3
Direct and Indirect Band Semiconductors

Good morning everybody. Today, we shall discuss about the direct and indirect band semi conductors; because most of the electronic materials are basically semi conducting in nature. And today, we shall give some inside story, inside of the direct and indirect band of semi conductor. First thing is that how band is formed in a material. Do you know how band is formed in a material? Because we are talking about the valence band and the conduction band.

(Refer Slide Time 00:53)

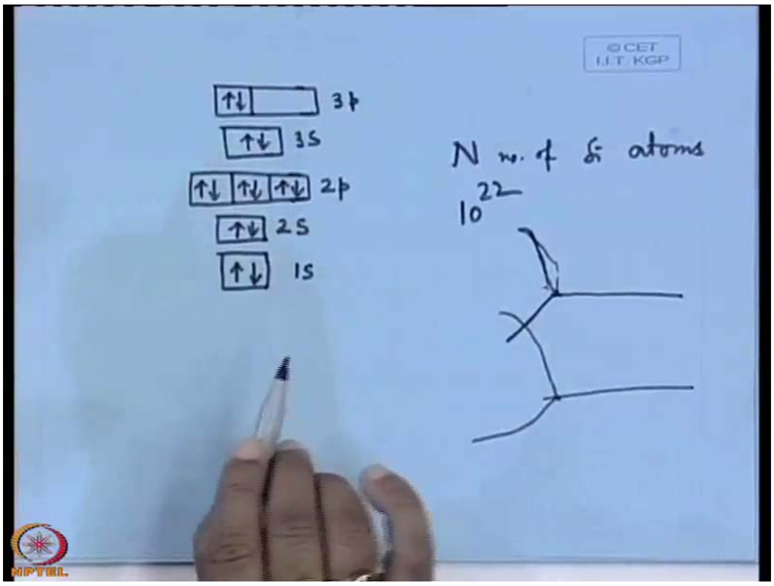


And, if you look at this power point slide, you will see that there are two bands; we have discussed it in my last class also. The upper one is known as the conduction band and the lower, the upper one is known as the conduction band and the lower one is the valence band. And they are separated by a gap, which is known as band gap of the material. But how these band forms? How these band forms? The band is formed, because of the interaction and over lapping of a large number of electronic levels in a material. Suppose, let us talk about the silicon. How many electrons are there in silicon? 14. How many electrons are there?

Student: 14, sir.

14 number of electrons are there, right. Now, out of this 14 electrons, if I can divide it into 1 s 2 2 s 2 3 s 2 etcetera; then what you will find?

(Refer Slide Time 02:01)



You will find that in 1 s level, there are two electrons, right. Then, in 2 s level there are 2 electrons. Then, in 2 P level; how much?

Student: 6.

6. Then the 3 s level and finally, 3 P level. So, you see that the lower levels or that means, when N equals 1 or 2, 1 s or 2 s or 2 P; those levels are full basically and they are also very close to the nucleus. But 3 s and 3 P levels are farther away from the nucleus. So, now, if you take N number of silicon atoms, N number of silicon atoms. If they come closer, then what will happen? These electron levels will split into a large number of energy levels. So, that means, because of the splitting of the energy levels, because of the splitting of the energy levels the bands are formed basically. One electron level split into many electron levels; why this splitting takes place? Why this splitting takes place?

Student: (( ))

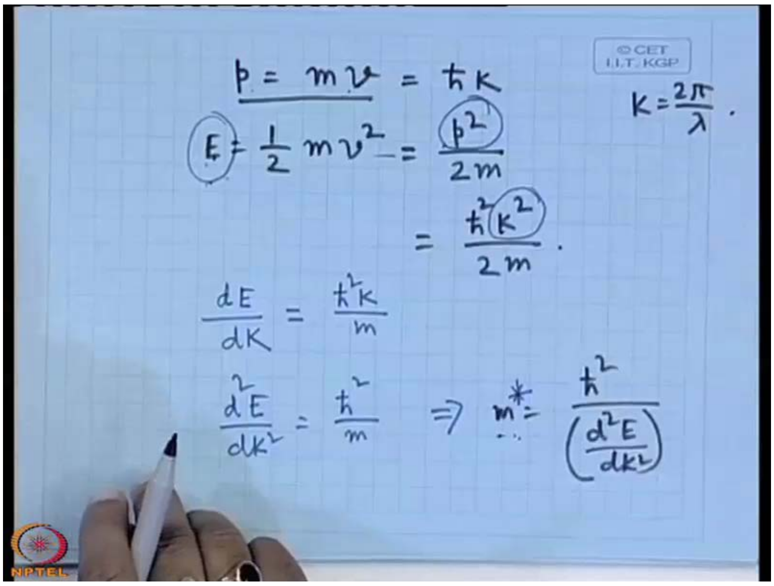
Yes. Basically, if many electrons, many atoms come together; if you force many atoms to come together, then what will happen? They will overlap, the electron levels are basically will overlap they will interact among themselves and there is Pauli Exclusion Principle, because in all the levels, only 2 electrons; in any level basically 2 electrons of opposite spin can be accommodated. So, when they interact, so because of the Pauli's exclusion principle they will align themselves, basically they will split themselves into a large number of levels.

So, for N number of silicon atoms, what will happen? Each electron energy level will split into N number of levels, what is the value of N? Basically, 10 to the power 22; silicon has 14 electrons and N is 10 to the power of 22 atoms, say N is 10 to the power 22 atoms are there. So, innumerable, huge number of electron levels will be created. Basically, all the levels will split; each level will split into 10 to the power 22 levels. So, suppose this is a level. So, that will split into a large number of levels. This is the lower limit of the splitting and this is the upper limit of the splitting. Similarly, there is another level it will split into a large number of levels.

Then, these levels will form the band; conduction band and valence band. And the and if you go more deep inside in this story, then you have to take resort of the quantum mechanical treatment. Schrodinger wave equation we have to solve, then you can fully understand how it splits and other conditions are there like the wave nature of electron, then your Pauli exclusion principle. So, those things are there, so now for our semi conducting material class, only 2 bands are required; the conduction band and the valence band. And, the bands are formed because of the splitting of the energy levels in a material. Mostly, we are concerned about silicon; so, I have given the example of silicon.

You can take example of other thing also. In textbook, you will find that the example is given for the carbon; where the diamond like structure is there. So, now if you see that this conduction band and valence band are there in this picture and they are separated by a band gap, the band is basically parabolic in nature; we have discussed earlier also. And, I also informed you that in the Y axis there is a, there is the energy axis; it is the energy axis and in the Y X axis, it is basically the wave vector or momentum axis. Now, I shall show you how they are inter related, how they are inter related.

(Refer Slide Time 07:09)



You know that P equals to m into v. I am avoiding the vector notation. Here, you know that the momentum is a vector, velocity is a vector; I am avoiding the vector notation that is not required in our case. So, P equals to m v. Now, this is equals to h bar k, right. What is h bar? h bar is the plank’s constant and what is k? k is the wave vector and k equals to twice pi by lambda. Lambda is the wave length. Now, E equals to half m v square; that you know, that is the kinetic energy. In our case it is the electron kinetic energy; that is equals to P square by twice m, because if you put v equals to P by m, from this equation here; then, it will be P square by twice m. That means, that is equals to h bar square k square by twice m, right. h bar square k square by twice m because P equals to h bar k. So, that means, E k diagram, here you see that E k diagram; this is E, this is k, is nothing but the E P diagram.

So, if you plot E as a function of P or if you plot P as a function of k, the nature will be same; it is parabolic in nature. But what is the implication of parabolic in nature of a band gap? What is the implication? The implication is huge. Because if you take this equation. E equals to h bar square k square by twice m; then, one thing is that the curvature of these bands, the curvature of these bands is different you see. The curvature of these band is basically different. Now, how the curvature is determined mathematically? How the curvature mathematically is determined?

Student: (( ))

By?

Student: (( ))

But suppose you have a equation; E equals to h bar square k square by twice m. From this equation, how you can determine the curvature?

Student: (( ))

Basically the second derivative will give you the curvature. Basically the second derivative will give you the curvature. So, E equals to, you write down E equals to h bar square k square by twice m and sees what is the curvature? First you do d E d k. First you simplify u into d E d k; that is equals to how much?

Student: h bar square k by m.

h bar square k by m, right. Then d 2 E by d k square.

Student: h bar square by m.

h bar square by m. Now, if you write down the value of m, then what is m? m equals to h bar square by d 2 E by d k square. Now, what is d 2 E by d k square? It is the curvature; d 2 E by d k square is the curvature. So, if the curvature is very high; for large curvature the value of m will be low. If the curvature is small, it will be high; it will be high because it is inversely proportional to the curvature. This m is known as the effective mass of carriers; it may be electron, it may be hole. Because I we discussed in my last class, that in semi conductor both the electrons and holes take part in the conduction mechanism. Both the electrons and holes take part in the conduction mechanism; Unlike in metal where only the electrons take part in the conduction mechanism.

So, it may be electrons it may be holes; in broad sense you can tell it has the carrier mass. But this mass has a name which is known as the effective mass of the carriers; effective mass of carriers. And that is denoted by m star; to differentiate between the effective mass and the rest mass, say a for electron. What is the rest mass of electron? What is the rest mass of electron?

Student: (( ))

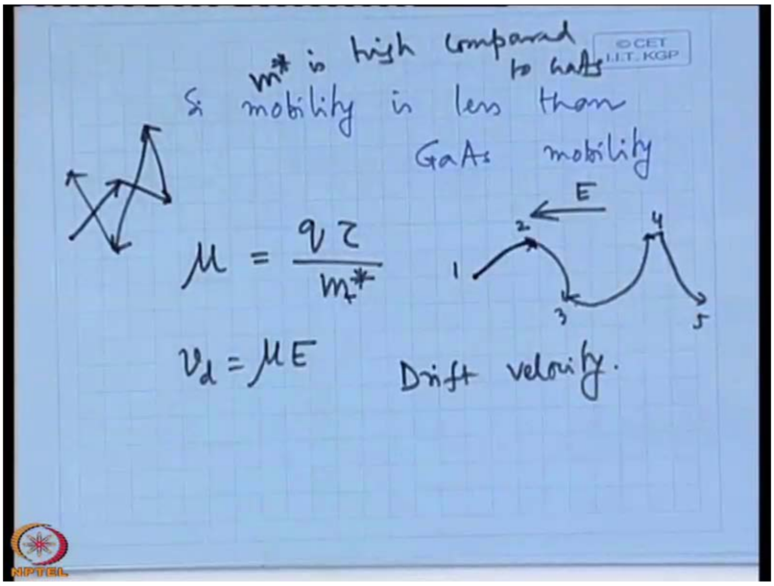
Yes, 10 to the power minus 31 k g. So, that is not this mass to differentiate between that mass; 9 into 10 to the power minus 31 k g and this thing; a star is given at the top of m. So, basically this is the effective mass and this effective mass is directly related to the curvature; that is also unique thing for semi conductor. Here the mass is not constant. Let us come to this picture; you see that the curvature here is very large. So, the effective mass will be less. Here the curvature is not so high.

So, the effective mass will be high compared to the previous one and electron can stay anywhere in the curvature; so because the curvature is different at different points in the band. So, the mass will be different at different points of the mass of the curve of the curve. So, basically the mass can be negative even. Why? Because in the valence band the curvature will be negative the valence band the curvature will be negative. So, the mass can be negative as well.

So, that is the unique feature of the semi conducting carriers. Remember, for electrons and holes this is the unique property that because of the band the carriers can have different electron effective mass or hole effective mass. And, in valence band since the curvature is negative at top of the valence band. So, the mass can even be negative.

Now, this mass has a direct implication on the mobility of the semi conductor. What are the main parameters for a semi conductor? Suppose, you have grown a semi conductor, you have synthesis 1 semiconductor may anything say silicon, germanium, gallium, arsenide, indium, phosphide, the silicon carbide gallium nitride anything. What are the main parameters that you need to see that you need to evaluate? One thing is the mobility of the carriers because for electronic application the mobility is very much important. The mobility of silicon is less compared to gallium arsenide.

(Refer Slide Time 15:06)



The mobility of silicon, silicon mobility is less than gallium arsenide mobility. That means, explicitly precisely the electron mobility in silicon is less than the electron mobility in gallium arsenide. Why, why such a difference in mobility? It is because of your band structure yes effective mass is different. Since, effective mass is different so the mobility is different. How the effective mass and mobility is related? You see that mobility mu is given by q tau by m star mobility q mu is given by q tau by m star.

Now, what is q? q is the charge and it is its value is 1.6 into 10 to the power minus 19 coulomb, m star is the effective mass that we have defined right now. And, what is tau? tau is the actually the collision time, time between two successive collisions or the average time between collisions. Now, from where the collision comes. Why we are introducing the term collision in this class? Who can tell? How the collisions come into picture? Why we are more interested in tau?

Student: (( ))

Basically, you see that normally in a material the electrons move at random manner. Without any electric field applied the motion is random in nature it is like Brownian motion. Say from this point to that point from this point to that point from here to there from here to then there and. so on and. so forth from here to there. They does not move in a particular direction in the absence of any electric field, but if you put an electric field. Then what will happen? They will move in a particular motion in a particular direction. They will move in a particular direction. How? Suppose the electric field is in this direction because electric field has a direction. So, this point if it starts from this point.

So, first say from 1 point to 2 point then from 2 point to 3 point then from 3 point to 4 point then 4 point to then again a 5 point etcetera. So, they move in the reverse direction of the electric field. If electric field is in the negative x direction they move in the positive x direction. You see does the direction is towards the reverse field direction.

So, this is possible because of the application of the electric field. Without electric field they do not have any net displacement. But in presence of electric field they have a velocity, which is known as the drift velocity, which is known as the drift velocity? And, this drift velocity v d is equals to mu into E; E is the electric field, mu is the mobility and v d is the drift velocity. Now, between these 2 movement suppose it is from 1 to 2 point look at the board it is 1 to 2 and then from 2 to 3. Why it bends? Why not that it is moving straight?

Student: It is because of the collision.

Yes. It is because of the collision. Something is there at point 2. something is there at point 2. You are moving from material science to say aerospace engineering department; and suddenly there is a collision. Then, what will happen? You will change your direction. Then, again there is a collision you will change your direction. So, because of that collision the movement sometimes bends from 1 point to another point. And, between two successive collisions the distance travelled is known as the mean free path and that time required is known as the time that is the tau.

If you take the average then that is the tau. Suppose from point a to point b there are many tau from 1 to 2 the mean free path is say x 1 time is t 1. Then, from 2 to 3 the main free path is say so you will take a large number of values and you can average. So, tau is basically the average of all such collision time between 2 collisions the average time. If you concept the drift velocity without any electric field without any field. When you talk about field the field can be electric field it can be magnetic field. When we shall discuss about the Hall Effect we shall introduce the concept of magnetic field, but in other normal discussions it is basically field means the electric field. So, without any electric field the electrons move in a random manner like the Brownian motion. And, the average distance travelled is basically 0 because it is random in nature.

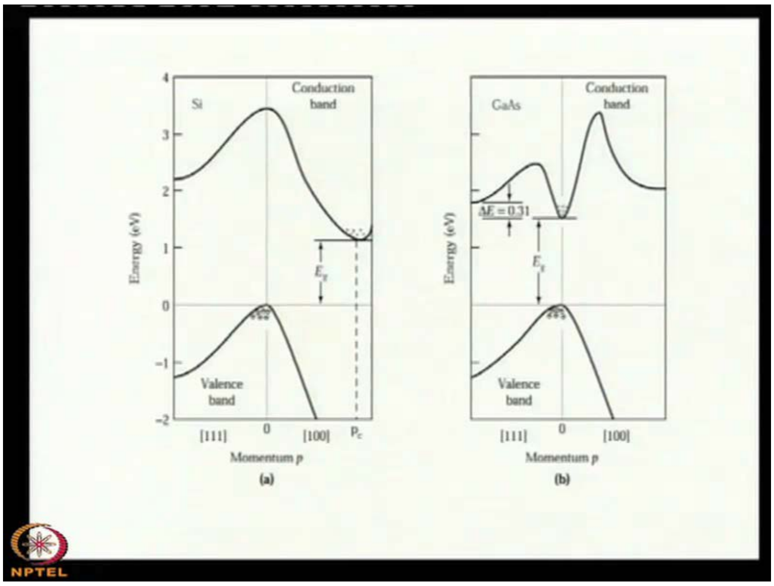
But if you apply an electric field they will move in the direction opposite to the direction of the applied field. Here I have shown you that an electron moves from point 1 to 2 and at 0.2 there is a collision. So, it moves from 2 to 3, again there is a collision it moves from 3 to 4 and from 4 to 5 etcetera. You can tell me sir the direction is taking place very slowly; obviously, from 3, again 4, then again 5. But you see that the result and direction is opposite to the field applied because of the field it happens. If there is no field then we will take the Brownian motion type of movement.

Student: (( ))

In a displacement 0, but since there is a field it will super impose on it. And, it will try to move to in the direction opposite to that of the field. And, between 2 successive collisions it will travel a distance which is known as the mean free path. And, the time between 2 successive collision is known as the collision time or relaxation time. So, now this tau which is there in the mu expression is basically that time of the basically it is a relaxation time or the time average time during collisions. So, m star is in the denominator you see in the mobility expression m star in is in the denominator.

So, that means, if m star is less mobility is high and vice versa. For silicon m star is for silicon m star is high compared to compared to gallium arsenide. It is compared to gallium arsenide it is because of the curvature of its band. So, the origin of the mobility is also related to the curvature of the band.

(Refer Slide Time 24:05)



Let me you show you that this diagram; you see that here this is silicon this is silicon. So, this is the curvature, and in gallium arsenide this is the curvature. This is silicon band, this is gallium arsenide conduction band, the dotteds are basically the electron here this dots. How many dots are there? 6 dots are there. You find very small dots they those are electrons, and that these are the holes, the small circles are the holes in the valence band; here you see the same number of electrons are there and this is the holes. Now, the curvature of gallium arsenide is very high if you see this if you compare these 2 Picture.

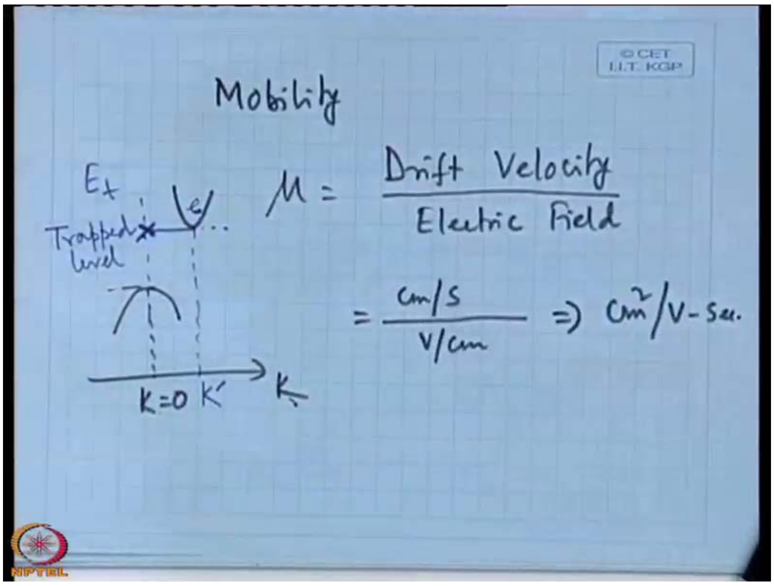
Then, you will see that this is the curvature is high for gallium arsenide. Since, the curvature is high the electron mobility will be higher for gallium arsenide than in silicon. The normal value of gallium arsenide mobility is almost 9200, but what is the unit of mobility? What is the, what is the unit of mobility?

Student: (( ))

What is the definition of mobility?

Drift mobility is nothing, but the drift velocity per unit electric field.

(Refer Slide Time 25:29)



What is the unit of velocity?

Student: Centimetre per second.

Centimetre per second or meter per second. Let us take centimetre per second. And, what is the unit of electric field electric field?

Student: Volt per meter.

Yes. Volt per metre here it is centimetre we have taken because field is nothing, but the applied voltage divided by the length. Volt per unit length is the electric field. So, it is centimetre square per volt second.

This is the unit of mobility. And, in m case it is beta square per volt second. For silicon the mobility is around say 1300 1400 or even less centimetre square per volt second. For gallium arsenide it is almost 9000 9200 8500. So, it is almost 6 times larger 6 7 times higher it is because of the band which is more curve in nature the curvature is very large here compared to the silicon band. So, this picture shows you 2 types of bands. Let us come here; there are 2 types of band. 1 is you see that the bottom of the conduction band or conduction band minimum; and it is the valence band maximum. And, they are not on the same k value or momentum value because on the x axis the P is plotted momentum is plotted and we know that the momentum and wave vector are all the same thing conceptually.

So, in silicon what we find? That this is the valence conduction band minima and that is the valence band maxima. And, these 2 bands if you plot against k or P whatever be the value you see that at k equals to 0 the top of the valence band or the valence band maximum is there but not the conduction band minimum. If this is the situation then this structure is known as the indirect band structure this structure is known as the indirect in nature. That means the valence band maximum and the conduction band minimum are not on the same k value this k or momentum value.

So, if this is the situation then that is material is known as the indirect band gap material and silicon is the indirect band gap material, Germanium is the indirect band gap material, and if the material is indirect in nature so far as the band is concerned. Then that material is not used for optical sources for fabrication of optical sources. But you see for gallium arsenide you see that the top of the valence band and bottom of the conduction band are on the same k value at k equals to 0. This type of band is known as the direct band gap semi conductor gallium arsenide, indium phosphate so those are the examples of direct band gap semi conductor.

Now, what is the problem with the indirect band and that the silicon is not used for the fabrication of 2 electronic sources. What is the problem? Because of this band gap what is the associated problem? The associated problem is that you see the associated problem that you see the associated problem is this point; that means, this point and that point because the k value are different. So, when one carrier says electron is now at this point electron is now at this point here electron is there. So, its momentum is different its momentum is different. So, if it come backs or jumps down the valence band.

So, momentum conservation is required momentum momentum conservation is required because there is a change of momentum associated. Here it is k 0? And, what is the momentum here? It is say k dash it is say k dash. So, momentum conservation is required. Then, only it will able to recombine with a hole in the valence band because emission of light is associated with the recombination of the electrons and holes. First the electrons are exited from this point to that point. Then the exited electron comes back or jumps down the valence band where they recombine with the hole. So, during recombination the energy it releases in the form of electromagnetic radiation.

Whether it will be photon or not that will depend on whether the recombination will be radiative or non-radiative. If the recombination is radiative in nature, then the light will be emitted; that means photon will be emitted. Otherwise if the recombination is non radiative in nature no light will be emitted only heat will be generated. For in case of silicon since the momentum conservation is required since the momentum conservation is required because they are on the different momentum space. So, first this electron here will come to this point.

They first come to this point. But how they will come to that point? What is the mechanism? The mechanism is that some electron states must be there. Because in my last class we have discussed that electrons are very choosy. They will occupy only those places if there is at all a position for it because the Pauli Exclusion Principle is there. So, suppose in a level already if there are 2 electrons of opposite spins are there; can a 3 rd electron be accommodate?

Student: No.

No. So, that means, electron must have the space, levels; this is known as the states. The number of states available, which is also there is a scientific term for that it is known as the density of states. That means, the number of states available for the accommodation of the electrons or holes in the conduction band or the valence band respectively. It is like; suppose you have gone for an educational excursion. How many of you are here? 16 you are here right now. In m tech you have 16 students; you are 16. Then, you went for to some place and there is a hotel where there are 200 rooms; so, that means, the density of states is 200, the density of states is 200.

You are 16. So; that means, 100 divided by 16 is the probability of occupation of a particular room. That means, you can take more rooms; that is different. For electron it is not possible. For electron, suppose there are 16 electrons and there are 16 states, 16 rooms. Then, first 1 room it will be accommodated by 2 electrons. If suppose there are 16 electrons and there are 4 rooms, what will happen? Only 8 electrons can be accommodated. But if there are 5 rooms and you have 16 students, what will happen?

Student: (( )).

Yes.

Student: (( )).

Yes. You can share. 3 4 students can share among themselves. For electrons it is not possible; because of the Pauli exclusion principle. So, that means, number of states must be there, number of electrons will occupy; a large number of electrons will occupy those large number of states depending on the Pauli exclusion principle. So, this electron when come to this place, it depends on whether a state is available to accommodate; the electron whether the state can be occupied by the electron. If it can occupy it will come here, at this point what will happen? Its momentum will be.

Student: (( ))

Yes, k equal to 0; it is coming to that momentum. Now, there is no problem in getting down to valence band for recombination. But for this case, for gallium arsenide the electrons are there in k equals to 0 already. So, directly they can come down to jump down to valance band; where they will recombine with the holes and they will give away the extra energy in the form of electromagnetic radiation on light. Here, since suppose there is a state and it is coming here, for silicon. Now, the momentum become same, but the problem is elsewhere. What is the problem? That these electrons can be trapped here. This is this is known as the trapped level or trapped states.

That means, that is an electronic state; where the electron can be accommodated. But it is due to some impurity or it is due to some vacancy or defect in it. So, the electron can come; without that state electron cannot come. If at k equals to 0 if some states are there only the electrons can come to that place. But in this time, what will happen; time is required, it is in not instantaneous.

The electrons has to search for a particular E t or the trapped level; E suffix t, trapped level. By that process it will be too late and the heat will be generated, the recombination with the holes will not be possible. So, the because of this band structure; the band structure is very much important in two ways. One is that it is directly related to the mobility. As the mobility is inversely proportional to the effective mass and that effective mass is basically a function of the curvature of the band.

So, one point is that the band structure will determine the mobility and another thing is that the band structure will give rise to either direct or indirect type of recombination.

That means, the recombination can be radiative or non radiative type of thing. So, the material can be used as optoelectronic sources or cannot be. So, upto that point if you have any question please feel free to ask me. Yes.

Student: (( )).

Yes.

Student: (( )).

No, no. You cannot change. For indirect band gap semi conductor, it is non radiative in nature. For direct band gap semi conductor, it is radiative in nature. Whether it will be radiative or non radiative, there are some conditions, there are some special selection rules, those will be discussed in the next semester optoelectronic materials and applications classes. During our class 1 optoelectronic materials and device, those selection rules or the conditions will be elaborately discussed.

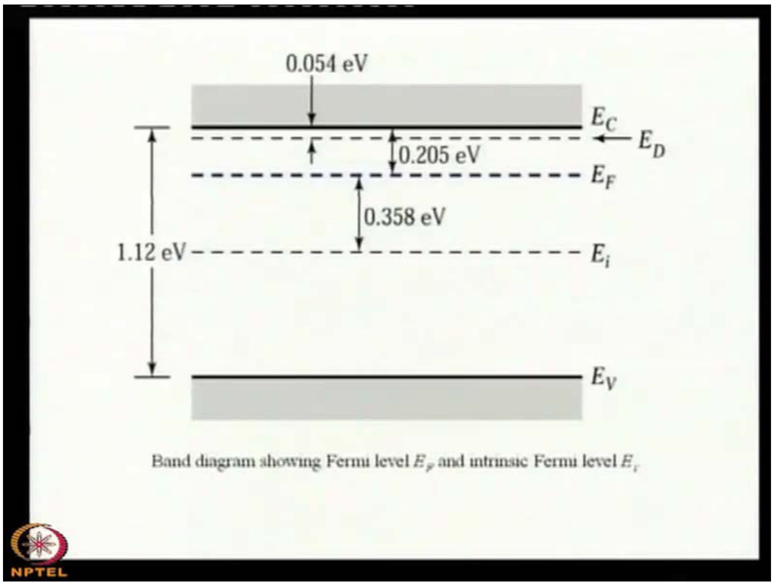
Student: (( )).

Right.

Student: (( )).

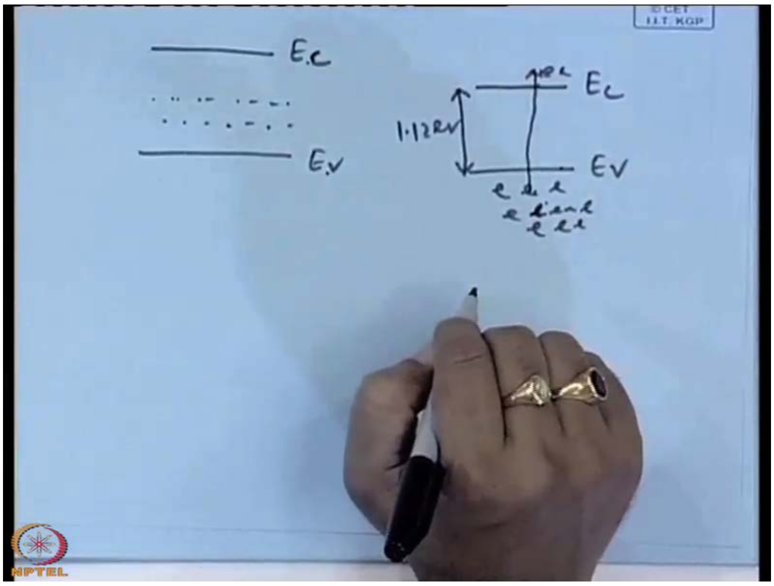
Sure, sure. You know that in the band gap, in the band gap there is a large number of impurity levels. Normally, in my last class we have discussed; normally what happens? The gap is forbidden, because between these two points; between this E g, there should not be any level. Level means, where the electron or whole can be accommodated. Level means that, level or states the same thing; that means a room for electron or hole where it can be accommodated.

(Refer Slide Time 40:33)



But you see here. This is a diagram where you see that E D is shown; this E D dotted line and what is this E D? E D you see that 0.054 electron volt, below the bottom of the conduction band; E C is the bottom of the conduction band or the conduction band minimum. 0.054 electron volt is the value just below the conduction band, there is a donor level or defect level.

(Refer Slide Time: 41:19)



So, though ideally there should not be any electronic or hole levels in the forbidden gap. There may be some levels due to impurity or vacancy or defect and this thing was discussed; that it can be intentionally or unintentionally, intentional levels are basically due to the doping in semi conductors. In my next class we shall start, doping of semi conductors. How doping can be done, what are the process and the result and effects etcetera. So, you can introduce or you cannot; intentionally. But during growth of the material, during preparation of the material; some impurity can be unintentionally stay inside the material.

And, they give rise to some levels which are known as the trap levels which can trap the electrons of holes and it must have a polarity also. If there is a neutral level it can trap either electrons or holes. If the trap level is positive in nature, it can trap electrons only. If the trap level is negative, holes only will be trapped. So, basically this is a level which is due to the impurity or defect in a material.

Student: Sir?

Yes.

Student: (( ))

No, no. They have to, if they come to k equals to 0 from k dash; so, basically they have to change the momentum. But momentum change associated with the finding of that trap level. If there is a trap level, then only that is possible. The extra momentum it will transferred to the that level.

Student: (( ))

Obviously.

Student: (( ))

Then the trap level momentum will be higher, but problem is that what is trapped level? Trapped level is not like an electron and hole, that gaining of momentum it will start moving.

Student: It is a static level.

Yes, it is a static level.

Student: (( ))

It can gain or it can lose also.

Student: (( ))

No, no. The electron is moving, it is not at rest. So, it will search for a particular place where it can move depending on its momentum, right. We do not know whether the momentum it will loss or it will gain. It depends; where it is in the frame. Absolute value we cannot say. The physical implication is that, it will try to get one a momentum conservation by coming down to E T level. That E T level; obviously, at is that level where that momentum conservation is possible. And the extra energy it will lose in the form of heat basically; the extra energy it will lose in the form of heat only.

Student: (( ))

No, no. Electron at k dash means, what is there? Electron is in an excited state. Is it the proper state for the electron? It is in the exited state. So, it will try to come down; it will try to come down, because it is already in the excited state. What will happen here? Here also the electrons are at k 0, the holes are also at k 0. But the electrons original residence was where? In the valence band. So, when you lift the electrons, excite the electrons by some means of energy from the valence band to the conduction band, basically the electrons are energized.

So, they have electron energy; they are already energized. So, they will come down to the valence band. But if they come down to valence band, problem is that; the momentum conservation is also required. Here they can jump down. But here cannot; with the help of a trap level they can come. And now where the momentum will go? Obviously, the momentum will be conserved with the help of E t. So, that means, then E t and the electron will form a system, where the conservation will take place; where, but that is not related to your valence band holes.

Student: (( )) So, the energy will come down (( )).

Energy cannot come down, energy it is heat. It will be desipated through the crystal lattice vibration.

Student: So, the energy losses, sir?

May be. Energy may be loss or energy may be gain; energy is loss means, what energy is lost?

Student: (( ))

No, no. what energy is lost? No, no. Let me clear the point. First you have energized the electrons. So, basically you have supplied energy to the electrons from electricity or from battery. Then they went from valence band to conduction band. So, already they are in the higher energy compared to the system energy. So, that energy will be lost. Yes?

(( )) How does the electron go from the valence band to the conduction band? In that case, why does the trap level coming into the picture?

Yes. That is all. There also the trap level can comes into the picture; there also the trap level comes into the picture here you. So, let me conclude basically because we are running out of time. And we have started our discussion on conduction band and valence band. And, there are to say two types of energy states here; one is E c and another is E v and there may be traps level also. The origin of the traps level and the pros and con of the trap level, we shall discuss in some other classes. Let us take the example of silicon, here we have taken 1.1 electron volt as the band gap. And, this the valence bands are full of electrons. Then, if you supply some energy at least 1.12 electron volt; the electron will move from valence band to the conduction band.

Here, the trap levels are not important; because you are supplying the energy, you are supplying the energy. So, there is no concept or there is no necessary for the change of momentum. But when it is in an energized state, in particular state say in the conduction band; so, if it jumps down to the valence band, conservation of energy must be there. For direct band gap semi conductor, it is not a problem. But for indirect band gap semiconductor, this state must be there to conserve the system momentum.

So, thank you.

We shall, in the next class, we shall discuss about the doping in semiconductors.