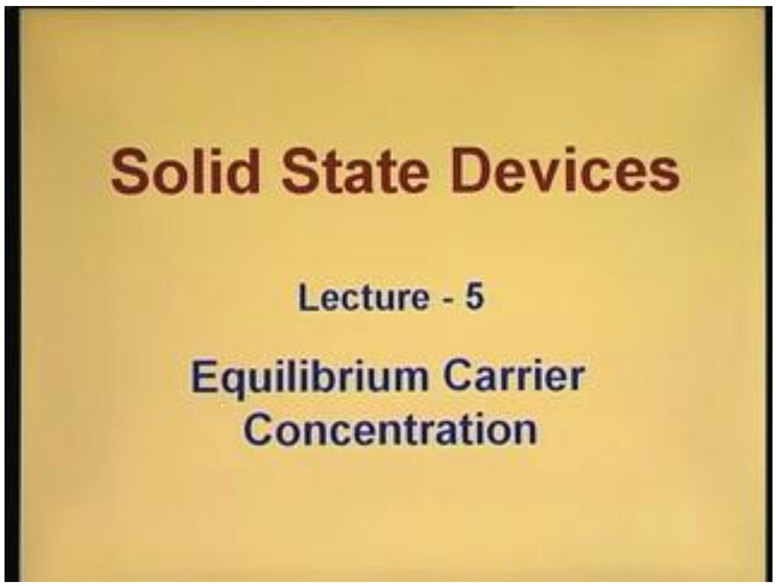
Solid State Devices
Dr. S. Karmalkar
Department of Electronics and Communication Engineering
Indian Institute of Technology, Madras
Lecture - 5
Equilibrium and Carrier Concentration

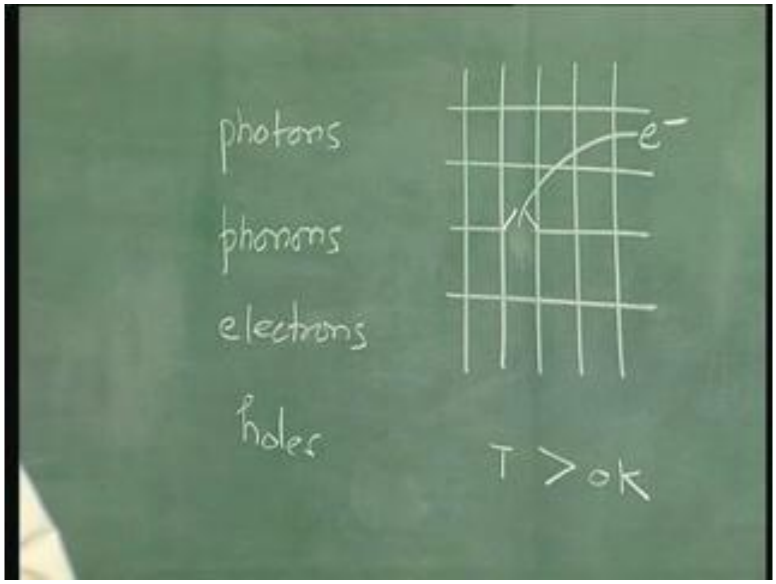
This is the 5th lecture of this course and the 3rd lecture on the topic Equilibrium Carrier Concentration.

(Refer Slide Time: 01:09)



In the last class we have seen the meaning of the wave-particle duality, why this concept has been introduced, and how it simplifies the analysis of various physical situations. Then, we have started constructing a qualitative model of the intrinsic semiconductor, wherein we have shown how the four types of particles named electrons, holes, photons and phonons arise in the semiconductor for T greater than 0k.

(Refer Slide Time: 01:48)



What we said is that using the two dimensional of the silicon crystal, at T is equal to 0 you have each atom being bonded to the four nearest neighbors and there are no particles at T is equal to 0 and that is because there are no thermal vibrations. For T greater than 0k the atoms are set into vibration because of thermal energy. So, if you visualize each of these bonds between two atoms as some kind of a spring, then this whole matrix looks like small balls representing the atoms connected by springs to the neighboring steel balls.

Let us say they are steel balls. So, T greater than 0k is analogous to situation where this particular matrix is being tapped with a hammer at different points. And every time you tap a steel ball in this matrix it sends out a traveling wave just as if you flex the rope at one end, and the rope is connected or fixed to the other end and if you flex the rope at the one end holding a rope part, then you know a traveling wave is sent out.

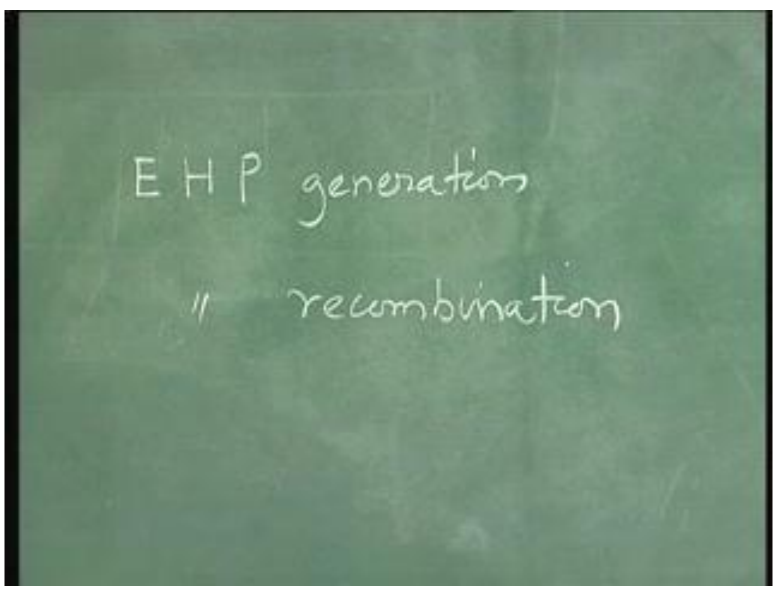
Similarly, a traveling wave is sent out from each of these points where tapping is being done and all these different waves interfere at some point. So, wherever a large amount of such waves interfere, there you are suddenly going to have high amplitude of oscillation. This is also analogous to the situation in a pond, where if waves are created at different points by rain drops or by dropping of stones then, at some points in the pond you find the water splashing up. This is because the waves from different points, the ripples which are being emanating from different points converge at some points and suddenly there is large amount of energy and therefore the water splashes up. So, these points where water splashes up is analogous to the points here where an atom may break its bond from its neighbor and electron can become free. That is how at some points in this matrix, the bonds can break and a free electron can be created. So whenever a free electron is created, it leaves behind a hole. This vacancy is the hole. That is how the electrons, holes and phonons are created.

We explained how photons are also created by the fact that a vibrating atom is equivalent to an oscillating dipole because an atom has a positively charged core and a negative electron cloud, and when it is vibrating, the center of the negative electron cloud and the center of the core are not at the same place, they are displaced with respect to each other. We have seen this using an animation and so it creates an oscillating dipole, and any such oscillating electric dipole is a source of an electromagnetic wave. So that is how an electromagnetic wave or photons are created. That is how we said that there are four types of particles: photons, phonons, electrons, and holes.

Now, it is to be understood that when I write in this fashion, the word electrons means "free electrons". Anywhere in the crystal electrons are present; the question only is whether they are free or not. So when I am writing electrons here, you must understand that free electrons are created. We already defined what free electrons are.

Free electrons are those which are not attached to any single atom, they can move about anywhere within the crystal but they cannot move out of the crystal. So, when you talk of electrons as carriers, normally the word "free" is dropped. It is to be understood that they are all free electrons that we are talking about. Now let us proceed further in this class from this model. What we see here is that for every free electron created you have a vacancy or a hole which means electrons and holes are generated in pairs. That is why one talks of an electron hole pair generation, EHP generation.

(Refer Slide Time: 06:50)



So in an intrinsic semiconductor electrons and holes are generated in pairs. For every free electron there is a hole. Now, how is the concentration of photons, phonons, electrons and holes are maintained constant? This is important. Now here we have explained how all these particles are created. But it is important to note since it is an equilibrium condition their concentration should be maintained constant.

Obviously, for every process there should be an inverse process going on at the same rate otherwise this balance cannot be maintained. Now, if there is a process for example of generation of an electron hole pair then there must be an inverse process where an electron and hole combine. That process is called Electron Hole Pair Recombination.

Now, when will a recombination occur? The free electron, after it is set free, it has a energy because of thermal energy. This energy makes it move about in a crystal. What may happen is it may encounter a vacancy somewhere, maybe somewhere else, not the same vacancy. It may encounter a frequency somewhere here. So this has created a free electron, which is moving about somewhere here. This electron when moving about encounters a vacancy and then it can happen that it will fall into the vacancy. And this process is the recombination process.

The process of generation and the process of recombination go on simultaneously. It is important to note that an electron is set free and then it moves about for a certain amount of time and only after that it recombines. So, when we say that generation and recombination are in balance it means that when at one point in a crystal electron is created, at some other point in the crystal an electron is recombined. Only then can electrons stay for sometime before it recombines. So when we are talking about the balance, it does not mean that the same electron immediately after it is set free then it recombines, that is not correct and if that happens then you will not have any free electrons at any point of time. It is exactly like the human population.

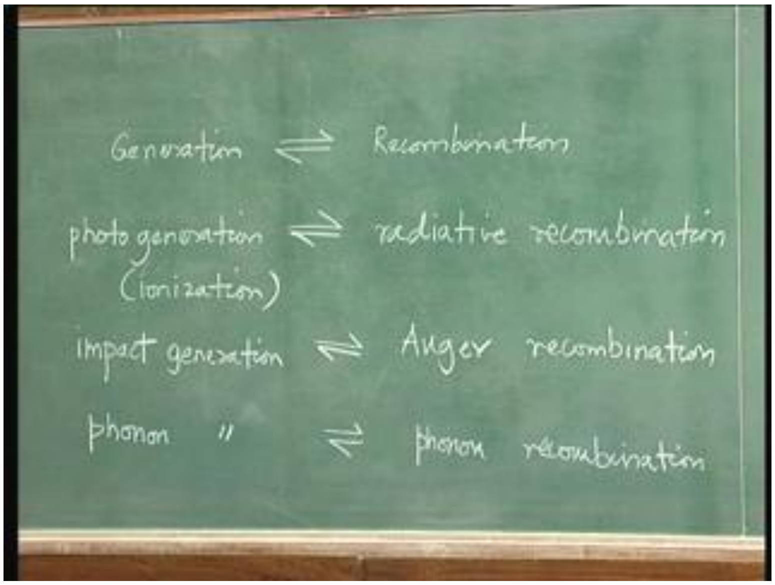
Imagine the human population, constantly people are born and also there are deaths. Now, if the number of people born is equal to the number of people who are dying, then within any given unit time interval, you will have the population remaining constant. So what is important is that the person who is born does not die immediately; he has a life time.

Exactly the same situation is present here. You must understand the meaning of balance between various processes. Now, we have seen how generation takes place. Some photons and phonons are converging and providing the energy. In fact, once you known that you also have electrons and holes, it is not necessary that only photons and phonons have to provide the energy for generation. It is possible for a free electron which has a high amount of energy also to participate in this generation of another electron hole pair. In principle any of these particles can participate.

When I use the word “any”, it means “any” or “every”. So it can be only photons, or it can be photons and phonons, or it could be phonons and electrons, or it could be photons, phonons and electrons because all these are moving about in the crystal and all these are available. Any collection of these can together provide the energy required for generation. Together their energy will exceed the energy required to break the silicon-to-silicon bond.

Exactly similarly, in a recombination, when an electron is recombining with a hole, the energy and momentum has to be given away to a particle. So the energy and the momentum can be given away either to a photon, or as a photon. It could be given away as a phonon, or it could be given away to an electron or a hole which is already free. It can be given away to electron in a hole which is already free. That means it is gaining some more energy in addition to what it has. That is the meaning of a detailed balance of the various processes. So if I were to write down the detailed balance, this is how it would look.

(Refer Slide Time: 12:09)



Firstly, generation is exactly balanced by recombination. The process of generation is balanced by recombination. Is analogous to saying, the birth rate in a human population is equal to the death rate.

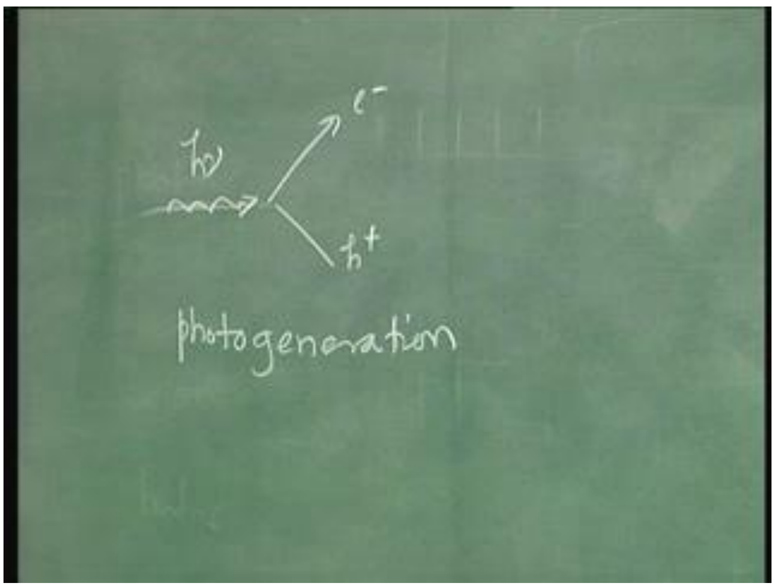
When we talk about the detailed balance, you now consider the various ways in which the generation can take place. So, if the generation happens because of photons, then you call the process as photo generation. That means photons alone are participating in the process. Then the thermal equilibrium implies that it should be exactly balanced by a process in which photons are being produced as a result of recombination. That is called radiative recombination. So, photo generation is balanced by radiative recombination. What if an electron or a hole which is having lot of energy collides with an atom and then results in electron and whole pair generation? This electron which is colliding remains a free electron, but it gives its energy to an electron hole pair. Such a process is called Impact Ionization.

In fact the word generation can also replaced by ionization. So you can call it photo generation or photo ionization. These words can be used interchangeably. So it is impact generation or impact ionization. What is the reverse process of this? It is a process in which an electron combines with a hole, the energy given away either to a free electron or to a free hole which is nearby. That process is called Auger Recombination. And then you have the third process where phonons may be involved. There is no specific name for that. You can call it Generation through Phonons. Here I will write this process as Phonon Generation or Phonon Ionization and Recombination involved in phonons.

Now, many times this recombination phenomenon is divided into two types: radiative recombination and non-radiative recombination because radiative recombination is very useful in practice and you can generate light from electricity, it is this radiative recombination mechanism.

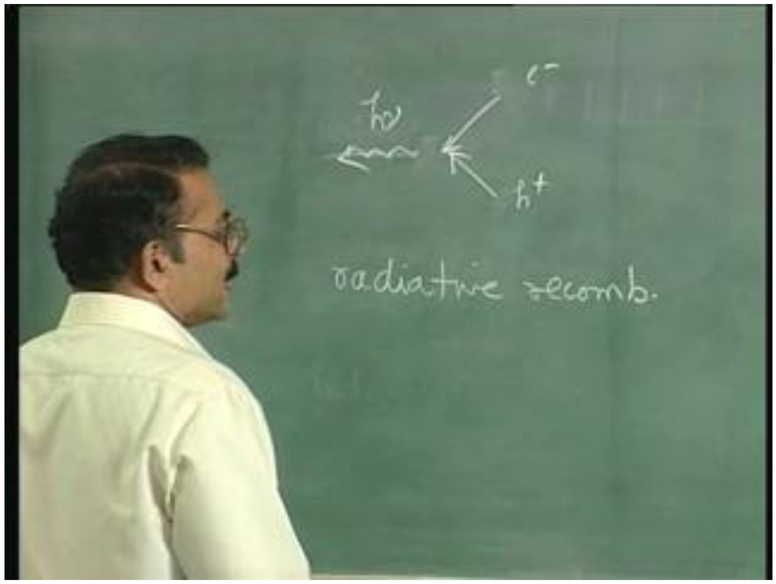
As we will see later, not every semiconductor will have large amounts of radiative recombination. That is why one way of dividing the recombination process is into radiative recombination process and non-radiative process. Non-radiative will include Auger recombination or recombination wherein phonons are created. So both these are non-radiative recombination process. If I have to show this pictorially it would look something like this.

(Refer Slide Time: 16:25)



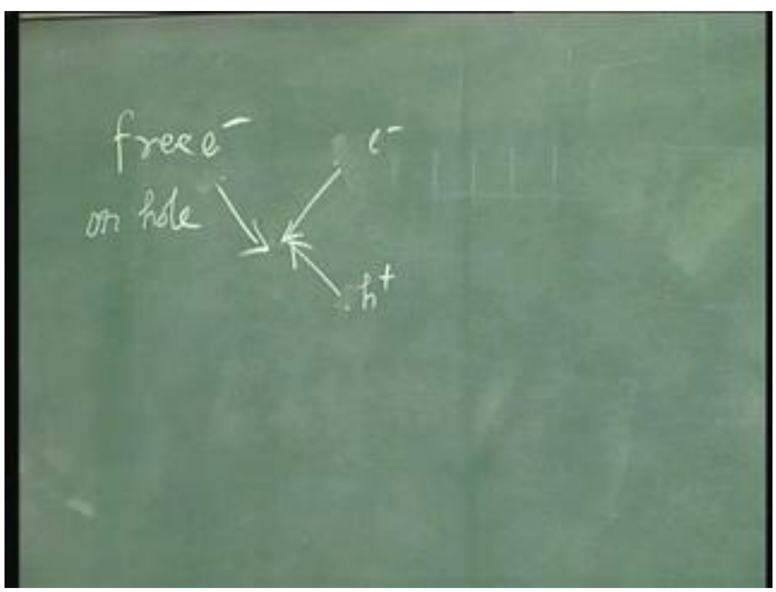
The process of photo generation is photon falling on an atom giving rise to electron hole pair. This is photo generation. Now how do I get its inverse? By simply reversing the direction of arrows you get the reverse process. So if I want to make it radiative recombination, all that I do is reverse the arrows.

(Refer Slide Time: 17:02)



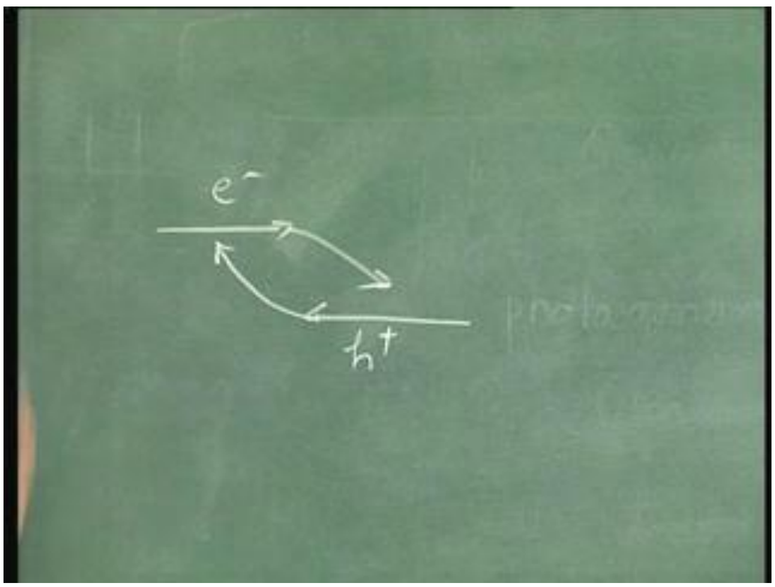
So an electron hole pair recombines giving out a light. You can use exactly a similar concept and simply replace these photons by free electrons or holes then it becomes impact ionization and Auger recombination. And similarly you can do it for phonons. So for impact ionization and Auger recombination I will leave it as an exercise for you to do the last type of generation recombination using phonons. For Auger recombination, it is electron and hole recombining and an energetic free electron comes out which means that these two electrons and holes recombine but there is another free electron which was nearby that gains the energy. The energy is given to a free electron or it could be a hole.

(Refer Slide Time: 18:13)



The reverse process is free electron or a hole hitting an atom and giving rise to electron hole pair. This is impact ionization. Let us also understand the difference between recombination and scattering, both are collisions. The scattering event is also a collision and a recombination is also a kind of collision. In the recombination, an electron collides with a hole and both of them are annihilated. That is the free electron collides with a hole, and both of them are annihilated, that is recombination. However, if an electron comes near a hole but it does not recombine but only its direction changes. The direction of motion of electrons and holes changes because of the force of attraction between them. So this action at a distance is a kind of phenomenon. They are coming near but they are not exactly meeting each other. Then what can happen is the direction of an electron and the hole can change as something like this.

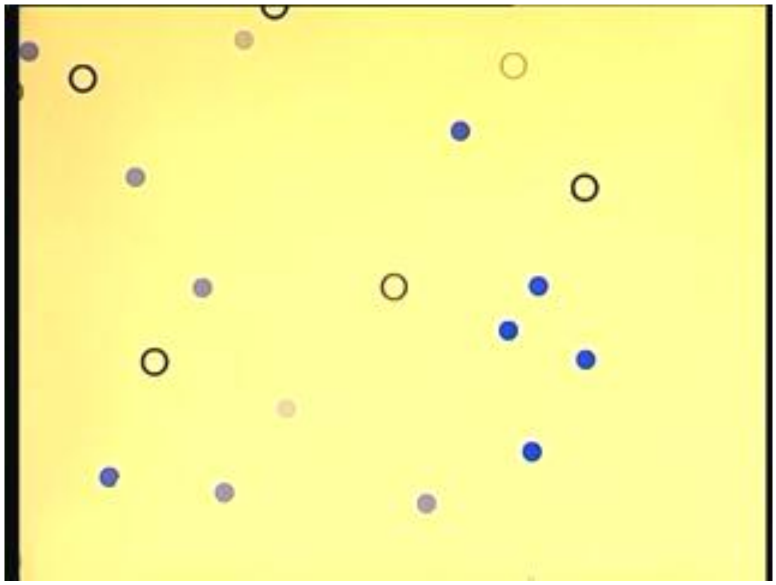
(Refer Slide Time: 19:54)



Supposing this is an electron moving in this direction and it meets a hole which is coming like this; now there is a tendency for an electron and hole to attract each other. What is going to happen is, as they come near, their path will change and this may go like this and the other one may go like that. What has happened is because of the other hole coming near the electron, the path of the electron has changed as well as that of the hole has changed. This event is called scattering where the direction of the motion of the particle has changed. It will not result in annihilation of the particle; it will only result in change in directions of that particle. The scattering is not necessarily present only between electron and hole. Therefore after a free electron is generated and before it recombines, during the time when it is alive, it is moving about and it can always collide with a vibrating atom that is equivalent to saying it is colliding with phonons. So what happens if an electron collides with a phonon?

Obviously, there is going to be energy and momentum exchange and the direction of motion of an electron is going to change. Similarly a hole can collide with a phonon; no recombination can take place in this case. So such events are called scattering because when all these particles are moving about they can collide with each other. These events are called scattering. We shall discuss more on scattering when we consider carrier transport.

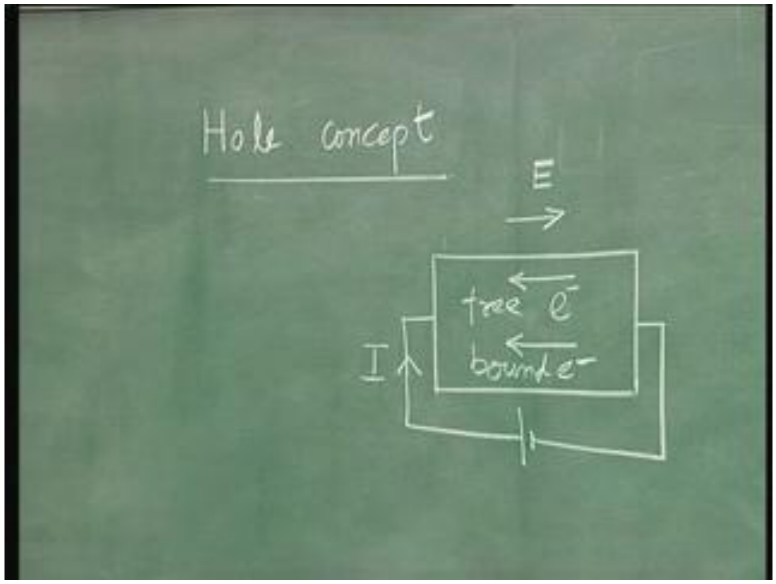
(Refer Slide Time: 21:30)



I will show you an animation of what is the net result of this. This is an animation showing generation and recombination of electrons. However this is a partial picture. Between the generation process and the recombination process no movement is shown. So the movement aspect has not been included in this animation. It shows how the picture would look like if you did not bother about the movement.

At some point there is a generation and at the other point is recombination. But at any instant of time if you freeze the picture you will always have the same number of electrons or holes and that is important. If you include the movement, then how does the picture look like? This is the picture of electrons and holes; they are generated, they move about and at some point they recombine. Let us discuss in detail the concept of the hole.

(Refer Slide Time: 23:24)



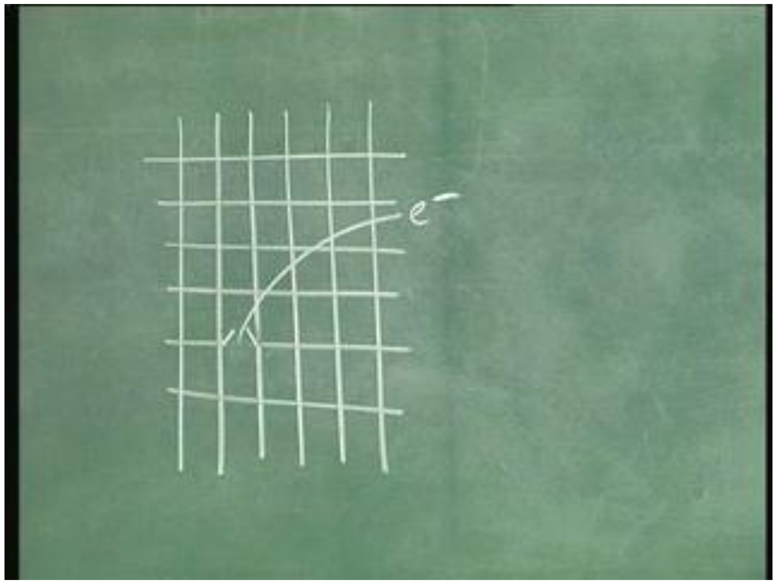
So far what we have said is that the hole is absence of an electron in a bond between silicon and silicon atoms. Now the question is, why should such a vacancy participate in a conduction process? Only then, this hole can change the conductivity of the sample.

Why should a vacancy participate in conduction and give rise to current? It is okay for us to understand that with the electron in the bond the situation is charged neutral around the atom, but with the electron out of the bond, near the atom there is a positive charge. So this tells us that the vacancy should behave like a positively charged particle. But it does not explain to us why the vacancy should participate in conduction process so that is what we want to see.

Supposing I take a semiconductor and apply an electric field, let us say, this is the direction of electric field. Now what is going to happen? There are electrons in this semiconductor which will move in this direction and they will contribute to current. It turns out that if you were to estimate the current in the semiconductor from the concentration of electrons, and the knowledge of what is called mobility you will find here, that estimated current falls short off the current that is measured.

Conventional current is a direction of positive charged flow, the electrons are moving from right to left but conventional current is into the sample because it is always from the positive point. If you were to measure this “I”, you will find that this “I” cannot be accounted for simply by the free electrons. This obviously means there is an additional current and that current is because of bound electrons. So these are free electrons and now you have what are called bound electrons, so ultimately the current is carried by the electrons; but the point is there is a current because of bound electrons.

(Refer Slide Time: 26:22)



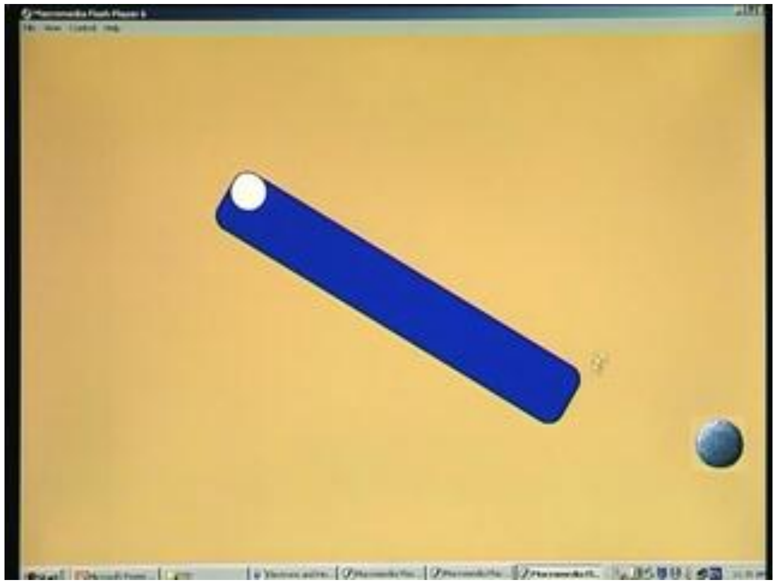
What are the bound electrons?

If you take this picture of two dimensional representation of the silicon, the valance electrons which are taking part in bounding process are the bound electrons that we are talking about here. As we have said there are 5(10 to the power 22) atoms cm cube of silicon. Each of these atoms has 4 valance electrons in its outermost orbit. Out of these 4 electrons, some have become free because bonds are broken.

There is a current because of bound electrons which means that the electrons which are already participating in the bounding process can also contribute to the current because of the presence of the vacancy. This is the current we are talking of, that we attribute to holes. Now let us understand this in detail.

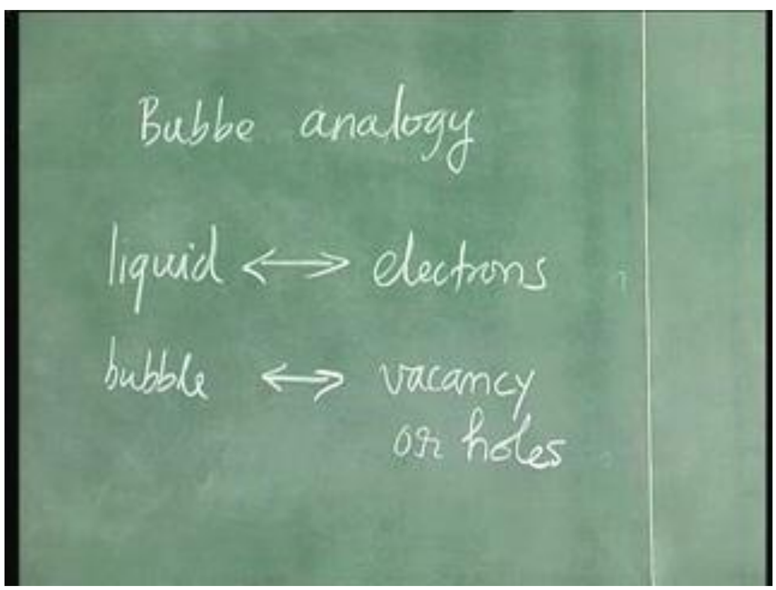
How is it that the vacancies which are present can help the bound electrons to move which otherwise cannot participate in conduction? This can be understood with the help of an analogy.

(Refer Slide Time: 27:42)



Here is an example of water in tube analogy. Here what you find is bubble in a tube. A bubble represents absence of a liquid, so there is a small amount of liquid that has been removed. In this analogy that is the bubble analogy the liquid is analogous to electrons, and the bubble is analogous to vacancies or holes.

(Refer Slide Time: 28:05)



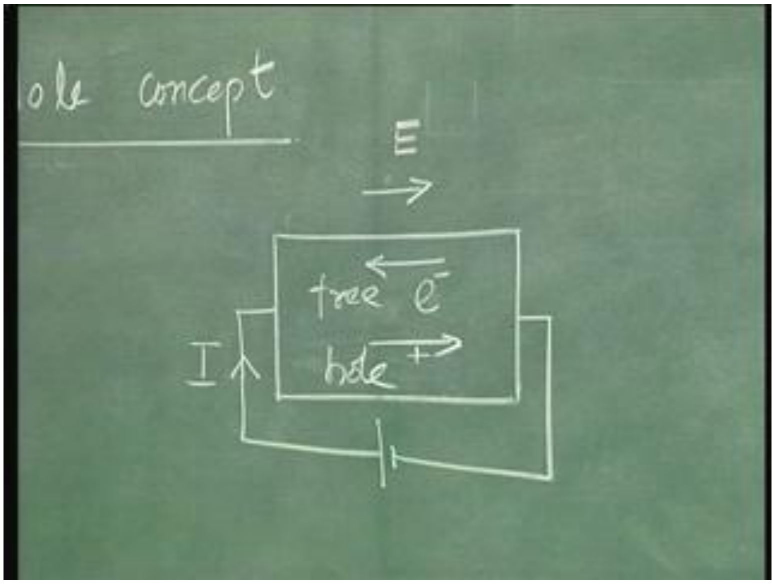
Supposing, I start from a horizontal position and tilt the tube you will that find the bubble moves up. Actually it is not the bubble that is moving, but it is the liquid that is moving and because of gravity the liquid tends to move down. So what happens is, there is a vacancy and the liquid tends to move into a vacancy. If there was no vacancy and even though there is a presence of gravity the bubble will not move. If the entire tube was full of liquid and then you were to tilt the tube there would not be any movement of liquid even though the gravity is there; but the moment you have a vacancy or a bubble created, what happens is, the liquid on left hand side of the bubble tends to move in because of the presence of gravity. The gravity is actually downwards, but there is a component in that direction of that force. And as the liquid tries to get into the bubble, in effect, what happens is that the bubble has shifted to the left.

Again coming back to this slide, to the animation, the liquid moving down, this motion of the liquid is captured in the movement of the bubble in the opposite direction. So the liquid moves down, but the bubble moves up. Exactly similarly the bound electrons which are present in the silicon crystal tend to move via the vacancies in response to the electric field.

If the vacancies were not there then there is no way they can move but for the bounded electrons to jump into the vacancy it requires negligible energy, this is when the vacancies are present. It takes lot of energy for it to become free, but it does not take much of the energy for the bound electron to jump into a neighboring vacancy. That is how the bound electrons will tend to move via the vacancies and contribute to current. It is a current because of bound electrons can be very easily captured by the movement of vacancies. There are large number of bound electrons and small number of vacancies. Instead of trying to see how such a large number of bound electrons are moving about, all that you are interested is, at what rate all the electrons moving.

Like in the bubble in the tube analogy you are interested in knowing at what rate is the fluid moving down. So you can simply concentrate on the bubble, and you can see at what rate it is moving up and you can find out the volume of the bubble, and then you can put this information together, and find out at what rate the liquid is moving. The bubble helps you to simplify the analysis of the movement of the liquid. Similarly, here, the concept of the hole helps you to simplify the analysis of the movement of the bound electrons.

(Refer Slide Time: 32:02)

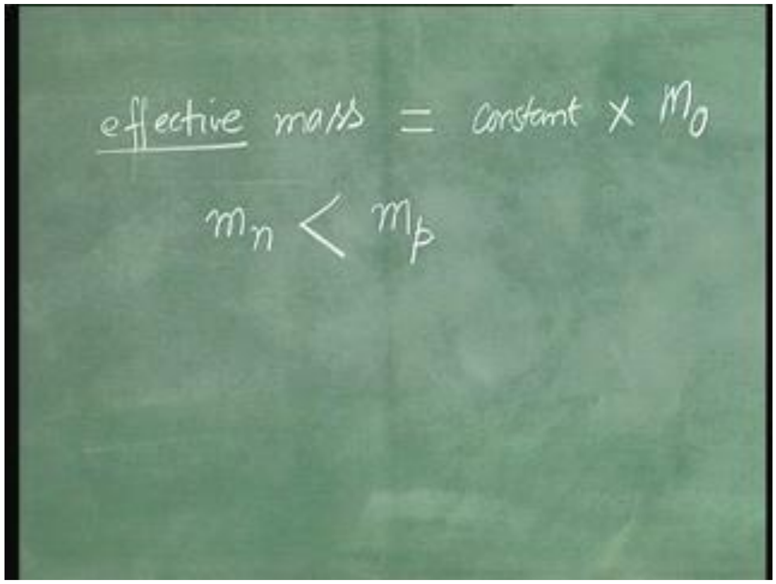


Therefore in the analogy if I want to show you the movement of bound electrons in terms of movement of the holes, I replace this arrow by an arrow in the opposite direction because the vacancy moves in the direction opposite to that of the electrons, and I assign a positive charge in that case because if any entity is moving in the direction of the electric field, obviously its charge is positive.

Therefore I assign a positive charge and then I give it a name and call it the hole. The hole is a fictitious concept. Actually it is only the electrons which are moving, but it is also real in sense it helps to really analyze the situations and when you use the concept again and again it acquires reality. It is as simple as that.

The movement of bound electrons in response to the electric field will definitely be different than the movement of free electrons. That is, the free electron will tend to move faster as compared to the bound electrons. Now how do you capture this information in our concept of free electrons and holes? What you do is, you assign the particular moving particle also a mass. The force is same on both the particles because the force is QE, but the rate of movement is different. This difference can be captured by assigning the particle an effective mass.

(Refer Slide Time: 33:33)

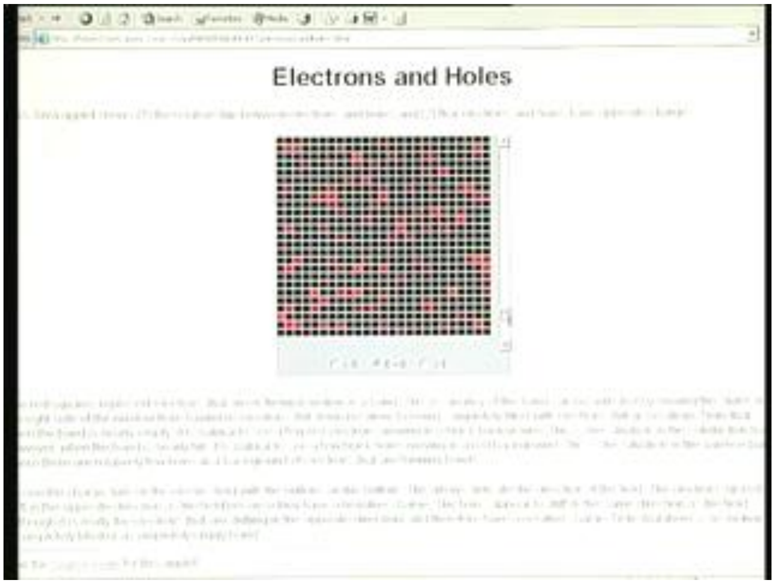


We call it an effective mass because it is an effective idea. The vacancy cannot have a mass. We are assigning this parameter so that we can again estimate the movement very easily. The effective mass of an electron is different from effective mass of the hole. And further even for the free electron the effective mass in the crystal is not as same as the mass of the electron in vacuum. This is because the movement of the free electron is restricted by the presence of other particles.

We will consider this aspect in more detail when we take Carrier Transport. But intuitively it is obvious that the movement of the electron is going to be restricted and therefore in response to the electric field it will not move at the same rate as in the vacuum. Generally the effective mass is expressed in terms of the mass of electron in vacuum that is, m_0. So effective mass is equal to constant into m_0, where m_0 is mass of electron in vacuum. So effective mass of hole also is expressed in terms of mass of electron in vacuum, and effective mass of free electron is also expressed in terms of mass of electron in vacuum.

We will use the symbol m_n to represent effective mass of electron in the crystal and m_p to represent effective mass of hole in the crystal. From the simple understanding that we have, we understand that if we were to use this effective mass to calculate the current or the conductivity then we know that effective mass of the electron is less than the effective mass of hole because in response to the same force the movement of free electron should be faster. The hole is heavier than the electron in conductivity situation where you are talking of the current. We will see the exact values of m_n and m_p in terms of m_0. We will do this sometime later when we are talking of Carrier Transport.

(Refer Slide Time: 36:14)

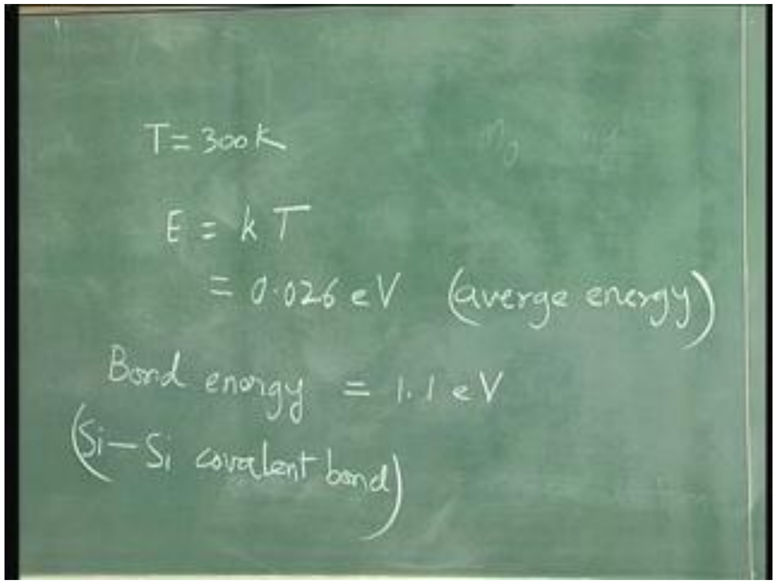


I will show you another animation or analogy to understand the concept of hole. Look at this slide. It has small red particles moving in a black background. The red particles are electrons. Now I go on increasing the number of electrons, you can see in this extreme, rather than looking at the movement of electrons it is easier to look at the movement of the black squares.

It is evident, in fact what you see there is the black squares which seem to be moving. Actually it is the red squares that are moving. The only thing is the number is so large and the number of the black squares has become small, then it becomes prudent to look at the movement of the black squares. In the movement of the black squares, the movement of red squares is captured.

This illustrates the concept of the hole, the black squares can be regarded as holes. You can see if I make the electrons more, it is clear that the movement of the black squares is what is evident to us. So when I go to the other extreme of small number of electrons then it is the movement of the electrons which we can very easily see or perceive. Now let us come back to our discussion of the concentration of electrons and holes. We can write based on our discussion in an intrinsic semiconductor n_i is equal to p_i where p is the concentration of holes and n is the concentration of electrons.

(Refer Slide Time: 38:24)



This equation is a reflection of the fact that electrons and holes are generated in pairs, also the recombining pairs. Now, the question is what is the concentration of these electrons and holes? Given this particular parameter we can get a feel for it from our simple model. We find that unless a large number of particles converge on to an atom the electron hole pair cannot be created. Why? Let us take example of room temperature, let us say T is equal to 300k. At T is equal to 300k the average energy of these particles under thermal equilibrium is k into T where k stands for Boltzmann constant. The average energy is of this order k into T.

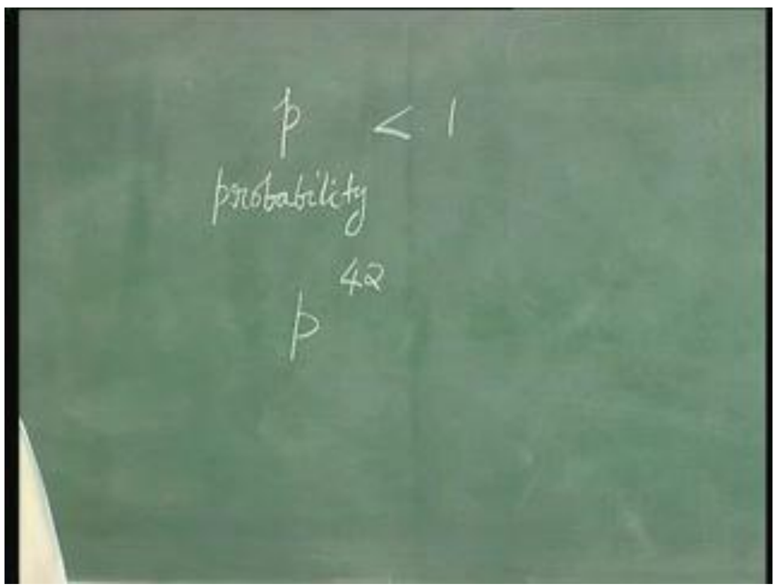
You know this is is equal to 0.026 electron volts. This is average energy of particles. You take average energy of photons, phonons all this average energy will be same. This is because it is in thermal equilibrium condition; average energy of free electrons will also be same. Now, if you have difficulty understanding why average energy should be exactly k into T, well we will not discuss that point in detail, you will take it as a fact.

It is easy for you to understand that since this energy is because of the temperature, it should be related to temperature. It is like energy of gas molecules at any temperature; you just take all these particles as gas molecules: 0.026 electron volts. If you want to break silicon to silicon bond we have said that the bond energy is 1.1 electron volt eV. Here we are talking of silicon to silicon covalent bond. That bond energy is 1.1 electron volt, take it as a fact.

Now, it is obvious one particle at room temperature cannot give rise to electron hole pair. It is important to note that we are not saying all particles have the same energy, this is average energy of particles in the population. If we are talking about photons, you will photons of very small energy and photons of very high energy because it is a distribution all particles do not have the same energy. But if you take the average then it is this, let us talk in terms of the average picture because it is a simple situation in that case. So we will assume for simplicity that as though all particles have the same energy. Although this is not true, it is just for the purpose of simple understanding, this is a qualitative model. We can now find out how many particles are required to converge on to the silicon bond in order to break it. Number of particles will be given by 1.1 by .026 and this will be about 42, so numerator is also electron volt and the denominator is also electron volt. So, 42 particles must converge at a bond.

Obviously this cannot happen at every silicon atom. In fact more the number of particles that should converge smaller is the probability of that event. One can readily see that this probability will be very small. How? Supposing the probability that a particle collides with an atom and if that is p, here we are using p for the probability not for the hole; this kind of a problem will arise when you use the symbols for which various quantities. For example; the symbol E here is not electric field but it is energy. So I hope depending on the context you will understand whether it is energy or electric field.

(Refer Slide Time: 43:51)

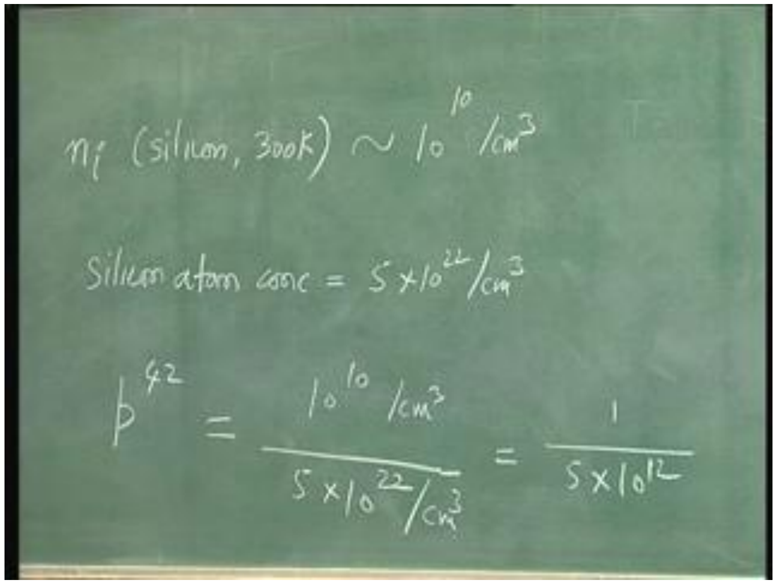


Here p is a probability. If p is the probability that a particle collides, then obviously this is p less than 1. Now, if collision by different particles is independent events, then if 42 particles should collide the probability of such an event will be p power 42, for 42 times you must take p and then multiply if all these are independent events and they must happen simultaneously.

This you will understand from probability and statistics if you have done this course. If you have not done, well intuitively you understand that if some event can only take place if 40 people work in Unison then the probability of that event is very small. If only one man is required to do that activity, achieve something, then it has some probability. But if 40 people have to work in Unison, think in the same way, and then achieve something, the probability of that event is less. This we know by experience.

Now, if you take p is equal to 0.9, and you rise 0.9 to the power 42, you will find that you will end up getting extremely small number of this probability. You do it as an exercise, if p is equal to 0.9, what is 0.9 p power 42? Now that explains why only a very small fraction of the silicon atoms actually contribute to electron hole pairs at room temperature. The fraction is very small.

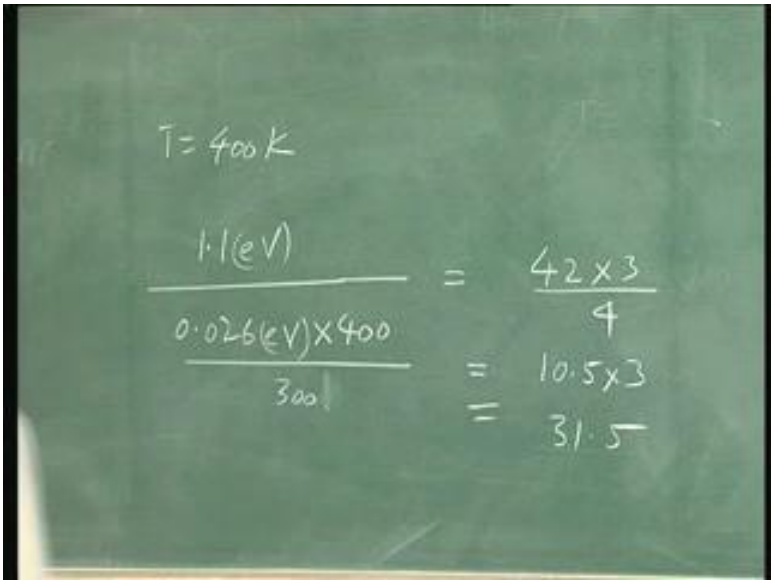
(Refer Slide Time: 45:52)



It turns out that n_i at room temperature in silicon is of the order of 10 to the power 10 by cm cube. We will calculate the exact value from a formula when we take up the quantitative model. I am giving the order here: 10 to the power 10 by cm cube. The number of atoms is silicon atom concentration 5 into 10 to the power 22 by cm cube. This means that 10 to the power 10 by 5 into 10 to the power 22, one atom into 5 into 10 to the power 12 contributes to an electron hole pair. So, in other words, that p power 42 is equal to 10 to the power 10 by 5 into 10 to the power 22 by cm cube as both are in cm cube so they get canceled, 1 by 5 into 10 to the power 12.

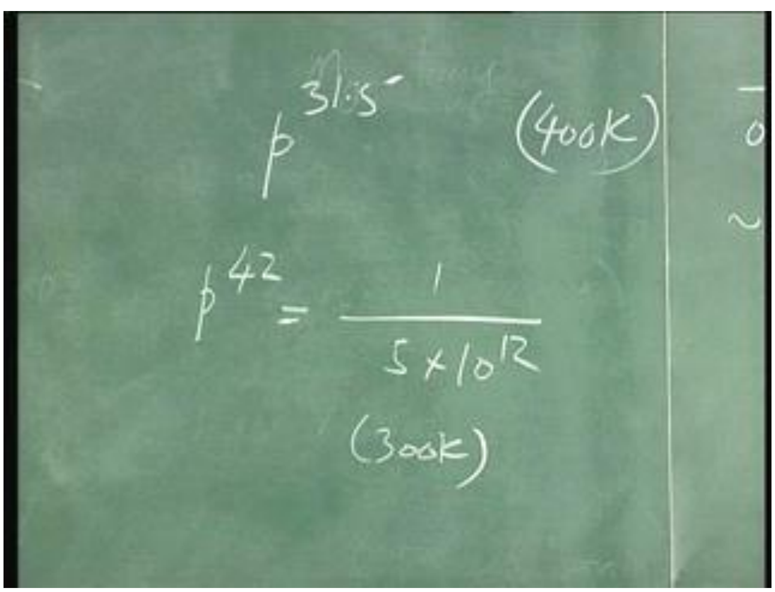
In fact, you can do reverse exercise and find out what is that p. It is p power 42 is equal to 1 by 5 into 10 to the power 12, what is the p and then does it sound reasonable. You can do this exercise. Now, based on the qualitative model we have also explained why, very small fraction of silicon atoms will contribute to free electrons and therefore free holes because electrons and holes pairs are generated in pairs so n_i is equal to p_i. Next is, using the same qualitative model we can also explain why as a function of temperature the concentration will change rapidly, it will increase rapidly.

(Refer Slide Time: 49:00)



Supposing I go to a different temperature T is equal to 400k, I want to find out what will be my concentration at that temperature in terms of the concentration at T is equal to 300k? I can do a simple exercise. The number of particles that must converge on to an atom at 400k will be given by 1.1 eV by 0.026 eV which is the energy corresponding to 300k into 400 by 300 because 0.026 into 400 by 300 is the average energy at 400k. Earlier we have seen 1.1 by .026 is equal to 4 2. 42 into 3 by 4 is equal to 10.5 into 3 is equal to 31.5. Now if you want to find out what fraction of silicon atoms are going to contribute to electron hole pairs, it is going to be p to the power 31.5 .

(Refer Slide Time: 49:55)

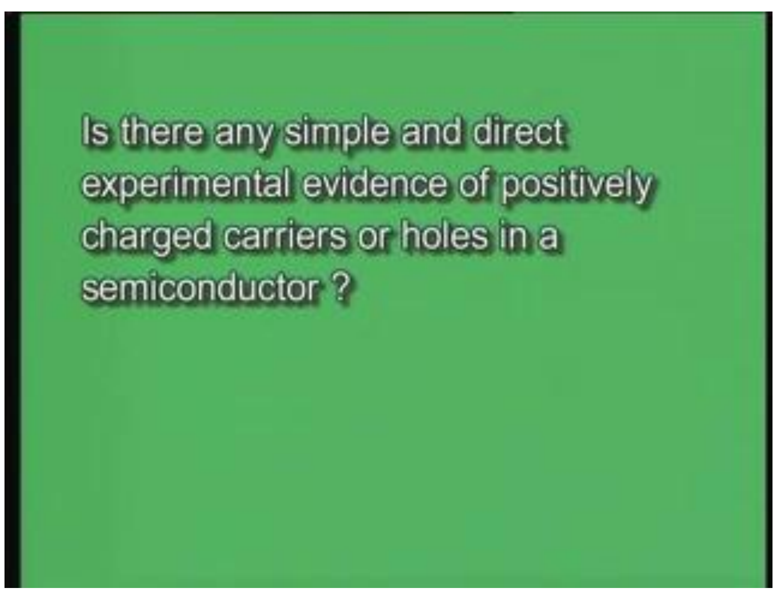


Now, given that p power 42 is equal to 1 by 5 into 10 to the power 12 at 300k, this is true at 300k. The new fraction is p to the power 31.5 at 400k. Again I leave it as an exercise to you to find out what is this p to the power 31.5 and you will find that the order of magnitude will be more than this concentration.

Make a calculation and see. If p power 42 is equal to 1 by 5 into 10 to the power 12 what is p to the power 31.5? That fraction also is small. But the question is, what p to the power 31.5 by p power 42 p is lesser than 1 is, and this is what is important. This explains why the concentration changes rapidly. When temperature raises smaller and smaller particles, the number of particles needs to be involved in this process, and the probability of the event starts increasing rapidly. When smaller and smaller numbers of particles are required for electron hole pair generation it starts increasing rapidly. Here we have come to the end of the Bond model. It has told us that electrons and holes both are present, it has also told us electron concentration is equal to hole concentration where we always mean free electrons when we are talking of electrons. Free electron concentration is equal to hole concentration.

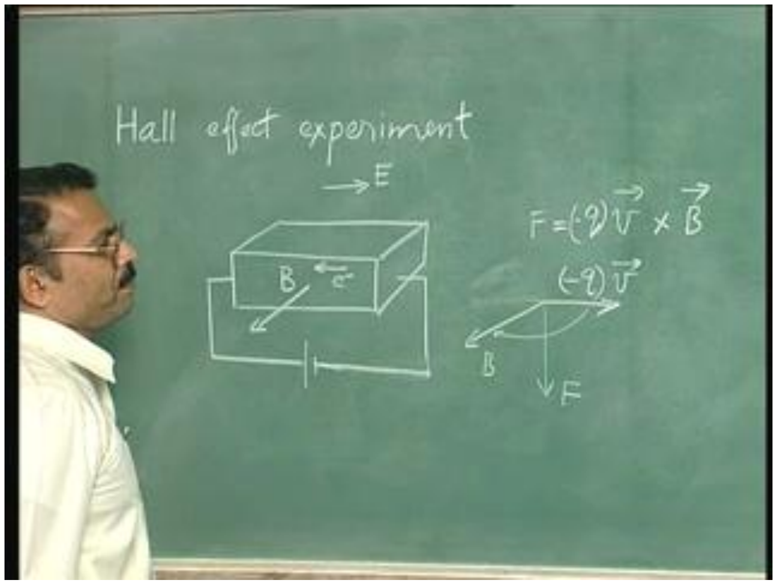
The free electron concentration or the hole concentration at room temperature is a very small fraction of the concentration of silicon atoms. So this is very much unlike in a metal. In a metal every atom contributes to a current carrier, you can see the difference in conductivity. So we can explain, what is the reason that conductivity of semiconductor at room temperature is very small compared to conductivity of a metal? Why it is so?
Thirdly, we have also explained using our model why the concentration of electrons and holes should change rapidly as a function of temperature. They are the three important things that we have explained. Next, if you want to find out the concentration of electrons accurately then you must move to a quantitative model and that model is called the Energy band or Band model. So that will be the next model that we are going to discuss. Now we can have some questions.

(Refer Slide Time: 52:58)



Is there any simple and direct experimental evidence of positively charged carriers and holes in a semiconductor?

(Refer Slide Time: 53:13)



Yes, in fact this evidence is in the form of what is called the Hall effect experiment. If you take a semiconductor and apply an electric field and in addition you also apply a magnetic field, let us say the magnetic field is in this direction perpendicular to the electric field that is outward from this particular phase. Let us see what will be the effect of these two fields. We know that when an electric field and magnetic field both are acting on a charge carrier then there is force acting on the charge carrier given by (q)v into B. Now in this case, if the charge carriers are negative then in response to the electric field they will move in this direction.

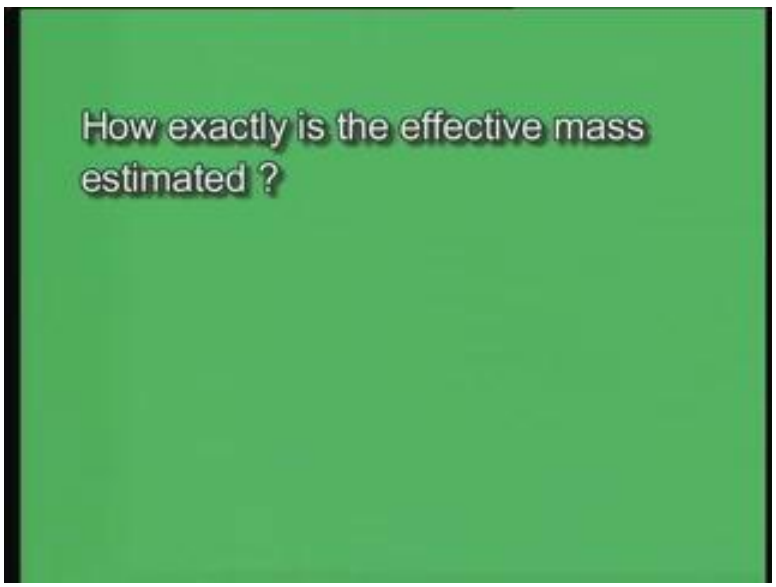
Now, what will be the direction of movement of these electrons because of the presence of magnetic field it can be easily obtained by this formula. So v is in this direction, b is in this direction, but q is negative so q into v for electrons is in this direction. So this is because the charge is actually negative, so charge is minus q and when you multiply minus q into v that would be in this direction, so minus (q)v into B. You know you are moving clockwise. It is a vector product which means the force will be in downward direction, so this is a direction of force.

On electrons the charge is minus q which means the electrons flowing in this direction will tend to move downward. As a result what will happen is that you will find this phase, lower phase becoming negative and the upper phase becoming positive. So if you were to measure the voltage between the top phase and bottom phase you will find the top phase of positive polarity with respect to the bottom phase.

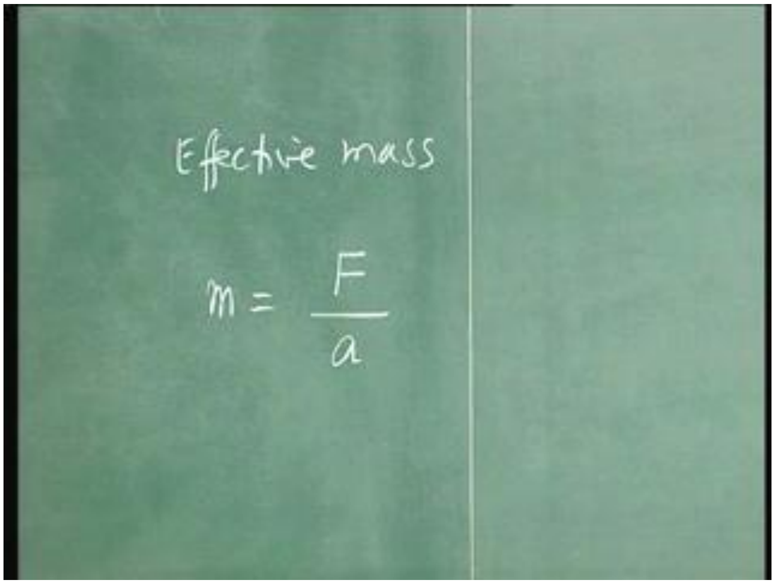
Now, instead of electrons if the semiconductor has positively charged carriers then what would be the picture? If positively charged carriers or holes were there they could move in this direction in the direction of electric field and the force on this holes can be written as where charge is plus (q)v into b, the velocity from left to right, the charge is positive so (q)v is also in the same direction so (q)v into b again the force is in the downward direction on the holes. So even on the holes the force is in the downward direction which means this phase now becomes positive and the upper phase becomes negative, so the top phase is negative if the charge carriers are positive.

In fact when this experiment was done for some semiconductors the top phase was positive while for other semiconductors the top phase was found to be negative. This is what conclusively proves that in those semiconductors in which top phase was negative, the charged carriers or holes are positively charge carriers. So these are direct and simple evidence of the presence of positively charged carriers.

(Refer Slide Time: 57:23)



(Refer Slide Time: 57:29)



How exactly is the effective mass estimated?
The effective mass is estimated using a simple formula m is equal to F by a mass equal to force by acceleration. You apply a force, you see the acceleration that a particle gains, take the ratio of force to acceleration and you will get the mass. This mass is called the effective mass.