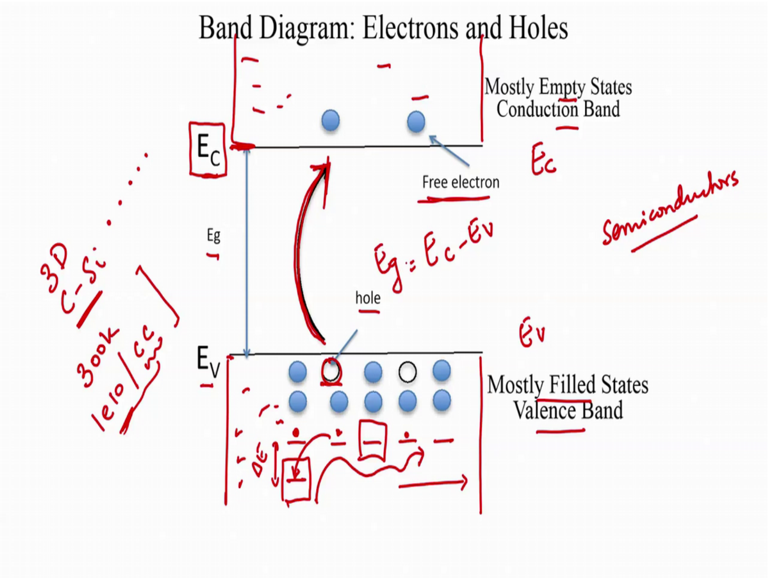
Semiconductor Devices and Circuits
Prof. Sanjiv Sambandan
Department of Instrumentation and Applied Physics
Indian Institute of Science, Bangalore

Lecture - 06
Solids: Electrons and Holes

(Refer Slide Time: 00:14)



Band Diagram: Electrons and Holes

So, now let us describe this picture in a semiconductor much more clearly. So, we say that we have a conduction, we have a valence band which is mostly filled states and we have a conduction band which is mostly empty states. And what do you mean by states? You have these potential solutions to Schrodinger's equation that in a valence band is definitely taken up by electrons; whereas, you have potential solutions to Schrodinger's equations that are not yet taken up by electrons in the case in the conduction band.

Now upon receiving some energy; so, these are electrons that are held in the outermost shell of your atoms. So, upon receiving some energies for example, say thermal energy; the electron can get excited and can jump across this forbidden gap and into the conduction band states and occupy a solution to Schrodinger's equation that defines it to have an energy level in the conduction band. Now this electron is free to move about in the crystal and it is something called as a free electron. It is of great interest to us to count the number of free electrons in the crystal because that is the; it provides a measure of the current through the crystal.

Now, the electron that has left the valence band and moved into the conduction band leaves behind a vacancy which is called a hole ok and the hole is basically a state that has now become empty ok. So, there was a state which is occupied by an electron, the electron left that state and moved into the conduction band and therefore, that state has now become empty and it is called a hole. So, therefore, there are plenty of holes in the conduction band or plenty of vacancies in the conduction band, but we are not interested in those. We are only interested in the vacancies in the valence band because once again it is these vacancies that can lead to that can add on to charge transport and we will see how in a minute.

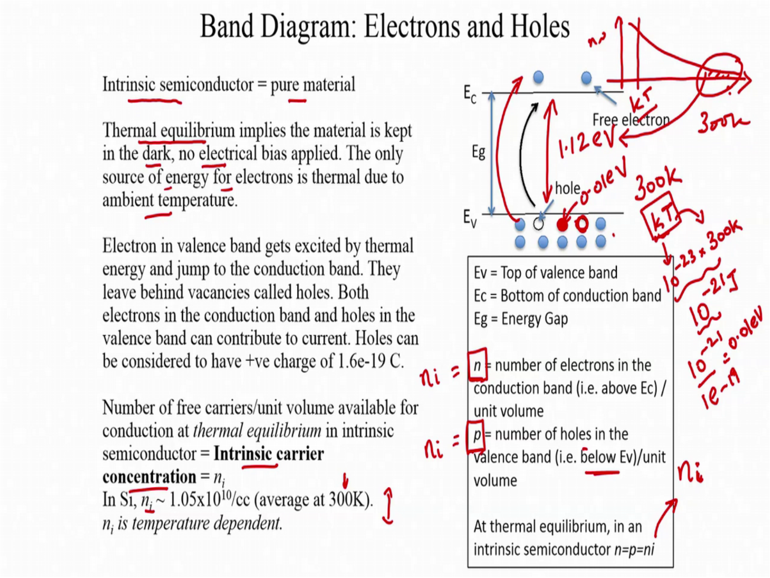
Now it is possible for the electron since these energy levels are all very fine very small. It is possible for the electrons in the valence band to jump into these vacancies and therefore, create a new vacancy. So, let us say that these electrons were to jump into these vacancies. And therefore, this vacancy which is located here would appear to move through the states in the valence band because, of electrons job occupying it ok.

So, it is possible for the hole to appear like as though it is moving in the valence band because of these electrons from other states are coming into occupied, thereby leaving the previous state vacant.

Now, in the case of crystalline silicon; in the case of crystalline silicon which will be in some sense is our role model of study. Let us say three dimensional crystalline silicon which is a basically a periodic arrangement of silicon atoms in 3 dimensions. We find that at room temperature, at 300 kelvin, we do have about 1 e 10 electrons per CC that is per centimetre cube being promoted from the valence band and into the conduction band states ok. So, this is when the silicon atom is pure and it is kept in the dark with no light no voltages or no currents through it. So, it is that something called as a thermal equilibrium condition. It is it is possible for electrons to move in and therefore, it leaves behind holes which have the same concentration.

Now here we also define these three energies the bottom of the conduction band ok. So, this is all the conduction band states the bottom of the conduction band is given this very special symbol that we will use throughout the course and it is called as E c. The top of the valence band is something called as E v and this gap which is the forbidden gap it is E C minus E V is given a symbol E g.

(Refer Slide Time: 04:54)



Band Diagram: Electrons and Holes

Intrinsic semiconductor = pure material

Thermal equilibrium implies the material is kept in the dark, no electrical bias applied. The only source of energy for electrons is thermal due to ambient temperature.

Electron in valence band gets excited by thermal energy and jump to the conduction band. They leave behind vacancies called holes. Both electrons in the conduction band and holes in the valence band can contribute to current. Holes can be considered to have +ve charge of 1.6e-19 C.

Number of free carriers/unit volume available for conduction at *thermal equilibrium* in intrinsic semiconductor = **Intrinsic carrier concentration** = n_i

In Si, $n_i \sim 1.05 \times 10^{10}$/cc (average at 300K).

n_i *is temperature dependent.*

Ev = Top of valence band

Ec = Bottom of conduction band

Eg = Energy Gap

n = number of electrons in the conduction band (i.e. above Ec) / unit volume

p = number of holes in the valence band (i.e. below Ev)/unit volume

At thermal equilibrium, in an intrinsic semiconductor *n=p=ni*

So, let us continue discussing this picture here. So, we saw that it is possible for the electron to take up energy and jump into the conduction band. Now we are going to have several definitions.

Now, the first definition is to do with something called as an intrinsic semiconductor. An intrinsic semiconductors essentially a pure semiconductor that is, it does not have any impurities such as dopants present in it. The second definition has got to do with something called as a thermal equilibrium condition which means that you have prepared the semiconductor and we keep the semiconductor in the dark; that is, interest it is not exposed to any photons. And we also do not apply any electrical bias say for example, voltages or currents across the semiconductor.

The semiconductors kept as is in the dark and the only source of energy for the electrons could be the thermal energy due to their ambient temperature. And this thermal energy is given by k T where k is the Boltzmann's coefficient. So, please do not confuse this term now with the wave vector. It is the Boltzmann's coefficient and T is the temperature. So, that is the order of the energy given to the electron due to due to the ambient temperature.

Now a material in thermal equilibrium is in no way silent ok. It is not a very quiet material. There are many processes happening in a material in thermal equilibrium.

So, for example, an electron in the valence band could acquire the thermal energy and could jump into the conduction band and you will find many such electrons doing it. But statistically speaking on an average nothing changes, which means that if there are n electrons that jump into the conduction band; you have n electrons that are coming back into the valence band. So, this process of creation is very finely balanced by the process of destruction. Destruction implies the loss of free carriers which is a more appropriate term as recombination which we will look at later in the course.

And also you could have electrons moving about in the crystal. So, an electron and the conduction band few electrons could be moving about in one direction, but this movement basically which basically constitutes a current is completely balanced by an equal number of electrons moving about in the opposite direction. So, there is a lot of randomness and a lot of events happening at thermal equilibrium, but statistically speaking these are all averaged doubt in time and you find that there are zero currents and zero shift from the so, called equilibrium position at thermal equilibrium. And this complete balance is something called as a detailed balance.

Now, if you were to take an intrinsic semiconductor, an intrinsic material. It needs a pure material and keep it at thermal equilibrium which means that you do not throw light on it etcetera. And the only source of energy for that is the ambient temperature ok. So, be it be give it some temperature T and therefore, some thermal energy T and we take an intrinsic material and keep it at equilibrium. Then we would find that there is a certain number of electrons that acquired this thermal energy and jumped into the conduction band states. And this concentration of electrons in the conduction band states which is basically the number of electrons above E c per unit volume of the material. So, this is the electron concentration in the conduction band states is given a symbol n. And the number of holes in the valence band per unit volume; that is a number of holes below E v per unit volume or the number of vacancies is given a symbol p.

Now in an intrinsic material at thermal equilibrium, this there is a certain value for n. And for an intrinsic material that value is given a special symbol and it is called as the intrinsic carrier concentration which is a technical term which you will use quite often and it is given a special symbol n i.

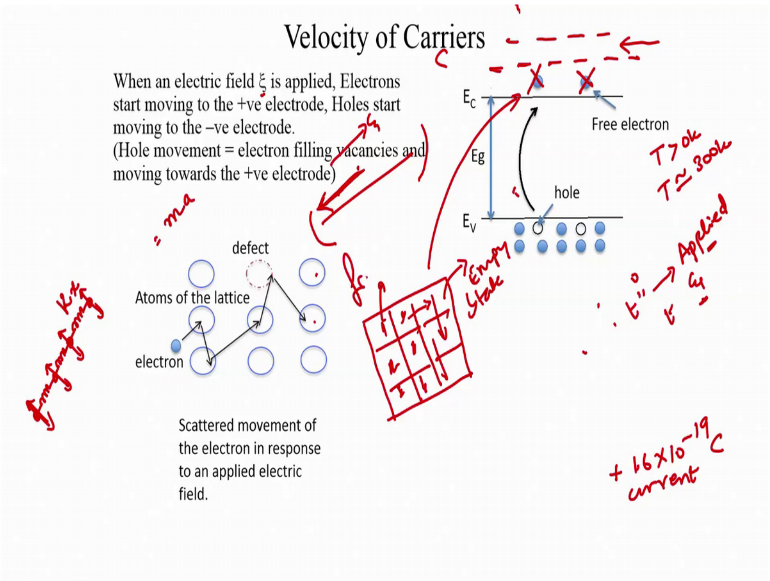
So, yes in a material in general you have n number of electrons per unit volume in the conduction band, p number of electrons per unit of, p number of holes per unit volume in the valence band, but for this special condition where you choose an intrinsic material that is without impurities and you keep it in thermal equilibrium. Then n would be equal to the special value which is n i and in that case, what would the value of p be equal to? It would also be n i and, why is that? It is because in such a case, it is only the electrons that jumped from the valence band to the conduction band that contributed to n i and these electrons would have left behind an equal number of holes in the valence band. Therefore, at in this condition your n and p would at thermal equilibrium, you will find that n is equal to p is equal to n i

Now, in silicon n i is about 1 e 10 per CC at 300 kelvin, but n i is clearly temperature dependent. It is very strongly temperature dependent and we will see this dependence dependency much more clearly later on. And n i is temperature dependent, why? It is temperature dependent because if I increase the temperature, more electrons could take up the ambient energy, the thermal energy and get into the conduction band.

So, just before we conclude this discussion one more final aspect. So, in the case of silicon for example, the energy gap is of the order of 1.12 electron volt ok. So, that is the energy gap in 2 dimensional crystalline silicon. Now at 300 kelvin, what does the order of the thermal energy provided to you know provided to the electron? The order is the order of k, it is of the order of k T where k is the Boltzmann's coefficient which is of the order of 10 power minus 23 joule per kelvin and T is the ambient temperature which is about 300 kelvin. And therefore, this product has got a value of about 10 power minus 21 joules which is of the order of 10 power minus 21 divided by 1 e minus 19 which is 0.01 electron volt. So, does that imply that since the electron has got 0.01 electron volt has thermal energy, does it imply that the electron that no electrons can climb across the gap and into the conduction band at 300 kelvin? The answer is no that is not the case.

Now, this value of energy which is k T is an average value and there is a large distribution. If you were to look at the number of electrons versus the energy they possess, because of thermal energy this distribution has got a very large tail. And the average energy possessed is about of the order of k T, but you do have enough electrons having an energy that is larger than your 1.12 electron volts and it is these electrons that can actually jump across and into the conduction band. And the number of such electrons per unit volume, in the case of intrinsic silicon at 300 kelvin is your 1.05 into 10 power 10 per cc per unit volume that is, particularly per centimetre cube at 300 Kelvin.

(Refer Slide Time: 13:26)



Velocity of Carriers

When an electric field ξ is applied, Electrons start moving to the +ve electrode, Holes start moving to the –ve electrode.
(Hole movement = electron filling vacancies and moving towards the +ve electrode)

Scattered movement of the electron in response to an applied electric field.

So, let us now start to look at the impact of applying an voltage and external voltage on the electrons in a crystalline semiconductor. So, let us say, we have a semiconductor crystal and we now attach a battery across this semiconductor crystal. We apply a voltage v a across the semiconductor crystal. So, let us say that is the positive terminal of the battery that is the negative terminal. And therefore, this establishes a low electric field inside the semiconductor crystal. So, we will denote the electric field by this symbol and we will say the electric field is it is a weak electric field inside the semiconductor crystal.

So, now in the semiconductor we have already seen that we have the conduction band states and we have the valence band states. And at some temperature given some temperature T; so, let us say the T is greater than 0 kelvin and let us say you know for some practical purposes the T is close to say 300 kelvin. And we see that the electrons would take in some thermal energy and some of these electrons will be able to jump from the valence band states into the conduction band states. And in the conduction band, these electrons are free to move about in the crystal. So, you therefore, have free electrons in your semiconductor crystal and these electrons are free to move about.

So, the moment these electrons which have basically got a negative charge so they have got a charge of minus 1.6 into 10 power minus 19 coulombs. So, the moment these electrons see this electric field they will respond to the electric field and they will start heading towards the positive terminal of the battery. So, all the electrons will start moving towards the positive terminal of the battery. And this movement of the electrons is something called as it drifts. So, drift is a very particular term used when the electron moves because often applied electric field ok. It is a very characteristic charge transport mechanism which is the response of electrons to an applied electric field and we will look at this idea in much more greater detail later on in the course.

Now, the movement of the electron in the semiconductor lattice is quite different as from the way it would move in say vacuum. So, if an electron were to be placed in vacuum and if an external electric field or if apply if a voltage were to be applied across these plates and vacuum, we would see that the electron would experience a force and therefore, it would start begin to accelerate. And we could write Newton's laws of motion to say that the mass and the acceleration of the electron is equal to the force that the electron fields.

Now this mass which we would take for an electron in vacuum is something called as the rest mass of the electron or you know the mass which is of about 9.1 into 10 power minus 31 kilograms. But in the semiconductor crystal the movement of the electron is a lot more complex. So, firstly, imagine the electron sitting in a lattice ok. So, these are all the lattice atoms. So, you have you have all the silicon atoms in the semiconductor lattice. And these silicon atoms have got a positively charged nuclei and it is got an electron cloud which is negatively charged. And now we have this one free electron that has that is migrating through this lattice. So, let us say that is our free electron that is responding to the applied electric field.

Now this free electron has got a negative charge. So, since this free electron has a negative charge, it will tend to polarize all the nearby atoms of silicon. So, all the nearby silicon lattice atoms will now get polarized in such a manner that the new positively charged nucleus is drawn towards the electron and the negatively charged cloud of electrons is pushed away. So, we will see all the silicon atoms surrounding in the vicinity of the free electron getting polarized.

So, now the movement of the electron is quite unique right. So, you have these positively charged nuclei closer to it and therefore, this polarization effectively creates a kind of a trap for these electrons. So, if you want to imagine in the movement of an electron in a semiconductor crystal in a more poetic fashion, let us say you are asked to run on a very hard surface ok. So, you have a person running on a very hard surface. So, on a very hard surface with each step of the foot, there is a good normal reaction and then the person could actually run very quickly.

But now, let us say a person is asked to run on a very slushy ground. So, you have a slushy ground when the soil or the surface is very soft. So, with each step of the foot the soil would actually sink inside and then you will have to pull the foot out and then take another step in the soil will sink in again. So, it would appear to be you do not appear to be much more difficult for the person to run on this very slushy ground. Because each time a person puts his foot down. His foot is stuck in a small gravitational potential well or you could also imagine a person running on a rubber sheet wherein with each step the rubber sheet is distorted and you know it is not it is not a very friendly surface to run on; although it could be a lot of fun.

So, the movement of the electron in the crystalline semiconductor could be imagined to be exactly that right. So, with each with this polarization, the electron sinks into a little well which is created by these positively charged nuclei and then, it continues to move about and then it polarizes another bunch of atoms and so, on and so, forth. And this entity which constitutes these polarized atoms and this electron is something called as a polar. And this is something that we will never use in this course, but it is just a definition that I am giving you or since we are discussing this. So, that is not the only complexity with regards to the movement of the electron in an in a crystalline lattice.

So, if there is an electric field, the electron almost never goes through the semi-conductor without interacting with the lattice ions in a much more stronger man. So, the electron; so, all these lattice atoms are also vibrating about because of thermal energy.

So, you can imagine the silicon atoms to be to be a bunch of you know hard spheres connected by springs. And there is a certain spring constant dependent depending on the kind of bonding etcetera. So, these atoms are all jiggling around because of the thermal energy that is available and this at this movement of the lattice the lattice points or the this movement of these silicon atoms results in a very strong interaction with the free electron and results in the free electron getting scattered. So, the electron the way it would move in response to an electric field in a semiconductors if you have an electric field in this direction the electron would move, it would scatter off from this atom. It would move away in another direction, it is scatter from through another atom, it would probably encounter a defect somewhere which could be a impurity or a dopant ion it could be a charge defect for example, and that would result in some other kind of scattering and so on, so forth.

So, it is a; so, the electron tries to accelerate due to the application of the field. It does in this little miniscule length scale, the electron does accelerate. So, you could say that the electron is trying to accelerate in that little length scale, but then it very quickly scatters and exchanges momentum and comes to a rest. And then it accelerates once more and then scatters again and so and so forth. Therefore, the effective movement of the electron in the crystal would appear to have this periodic bunch of velocity jumps.

So, you will see the velocity increase and then, there will be a scattering and then there will be a velocity increase and scattering and so on so, forth and therefore, unlike in vacuum the electron does not completely accelerate throughout it instead exhibits a constant velocity. And this is something called as the drift velocity of the electron and it is a technical term and it is a term that describes the velocity of an electron in response to an applied electric field which we have already defined as the drift transport mechanism.

So, if we want to continue modelling the electron using Newton's laws of physics. You know some you know some very simple relations, we need to consider all these complications with regard to the microscopic phenomena, which is the microscopic aspects of the electrons interaction with the lattice. So, that is the movement of the electron with regard with respect to the applied electric field.

But now, let us look at the hole or the vacancy here. So, you also have vacancies in the valence band. So, you had your you have the electrons in the conduction band that are moving through the lattice in this particular manner. But then you also have these pots or these empty states left behind by the electrons that got promoted to the conduction band and these vacancies were called as holes. And essentially these are solutions to Schrodinger's equations or these are energy levels that another electron could come in and occupy.

So, let us say that you have these states all being filled with the electrons. Now these electrons too would like to move in response to the electric field ok, but they do not have enough energy to jump across into the conduction band and then move through the crystal. But instead they could jump from one location in the valence band to another and because the energy required there is quite small. And therefore, in some sense respond to the applied electric field.

So, let us say that this electron were to jump into this vacancy which implies that it would leave behind a vacant, it would occupy the state and leave behind a vacancy here. And further let us say, this electron now jumps into this vacancy which implies that it would occupy this state and create a vacancy there. And if this process were to continue, you will find that the electrons all in the valence band also try to respond to the field and try to move towards one side. And it would appear like as though the vacancies they are moving towards the other side in the opposite direction.

So, therefore, in response to an applied electric field; it is not only the it is not only the electrons in the conduction band that responds to this field, but it also appear that the holes in the valence band are responding to this applied field and they are moving in the opposite direction as the as compared to the electrons in the conduction band. So, that would that that is the picture that is the effective picture, the holes would represent because as the electrons move here it would appear like as though the holes or these vacant states are moving in the opposite direction.

Therefore, we can in fact, treat the hole as a particle as a charged particle that can contribute to charge transport because it does participate in charge transport, but we can assign to it a positive charge of 1.6 into 10 power minus 13 coulombs. Therefore, we can say that the electrons ok; so, just to summarize in this discussion, we can say that the electrons in the conduction band have a charge of minus 1.6 into 10 power minus 19 coulombs and contribute to current. But the holes in the valence band have a charge of plus 1.6 into 10 power minus 19 coulombs and also contribute to current.

Therefore, in a crystal in a semiconductor crystal; if say this is the semiconductor crystal, we would have a in response to an applied voltage say let us say we have applied a voltage V a. So, that is the positive side and this is the minus negative side. It would appear like as though there are two kinds of particles in the semiconductor. You have the free electrons. So, these are the electrons in the conduction band and then you also have the holes which are the holes in the valence band and these electrons will have a negative charge and these holes will have a positive charge. Therefore, in response to the electric field since the electric field direction is in this as shown here, the electrons will all run towards the positive side and the holes will all run towards the negative side of the battery ok.

So, this is the effective response of the electrons and holes to an applied electric field. So, therefore, we could treat the holes as particles of positive charge that are running in the opposite direction to the electron and therefore, these two currents would add up. You will have if you look at the effective current, since you have negative charge due to the electrons moving in this manner, you have a current due to electrons moving from the positive side of the battery to the negative side of the battery.

And since you have the positively charged holes running from the running in there in this manner, you will have a current due to the holes also moving from the positive side of the battery to the negative side of the battery. And therefore, the hole current and electron current would add up to constitute the total current in response to the applied electric field. Therefore, we need to have a combination of empty states and carriers in order for charge transport. So, just to give you some analogies here ok.

So, let us let us play around with this. So, if you if you were as kids you might have played with this little game which would have which would appear like that. There would have seen a lot of tiles and these tiles would have had say a certain picture; say some picture on them that you need that he needed to complete by arranging these tiles by moving these tiles around and arranging them in proper order or in a proper sequence. And you might have always seen that there was one empty slot in this puzzle and therefore, we could move these tiles around and therefore, complete the picture.

Now if I were to ask you as to what would happen as to how quickly would the tiles moved, if there were no empty slots. So, let us say all the slots had a picture in them and if you were asked to solve this puzzle by moving these tiles around the, answer is probably is that you cannot solve the puzzle because the tiles cannot move around. And why cannot they move around? Because there are no empty states or empty places for the tiles to move about; two tiles cannot occupy the same spot that is exactly the case with electrons.

On the other hand, if I were to have no tiles at all no tiles at all and give you only empty spaces and asked you to tell me and asked you to move the tiles around or tell me or measure the flux of the tiles in this game. The answer is zero because you have only empty states or empty spots and there are no tiles for you to move around ok. So, that is equivalent to having only empty states and no cap free carriers. So, again the answer is zero, but on the other hand if I were to give you a few tiles and if I gave you a lot more empty slots instead of one, I gave you so, let us say three empty slots. Now, it should be much easier and you would probably solve the puzzle a lot quicker because, you can now very quickly move a lot of these tiles around. So, it is a combination of empty states and free carriers that leads to current.