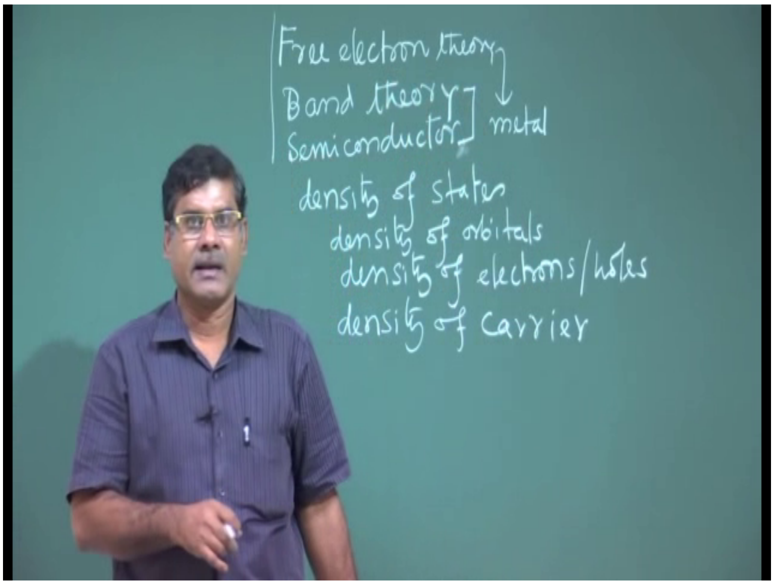
Solid State Physics
Prof. Amal Kumar Das
Department of Physics
Indian Institute of Technology, Kharagpur

Lecture - 50
Electrical Conduction

(Refer Slide Time: 00:27)

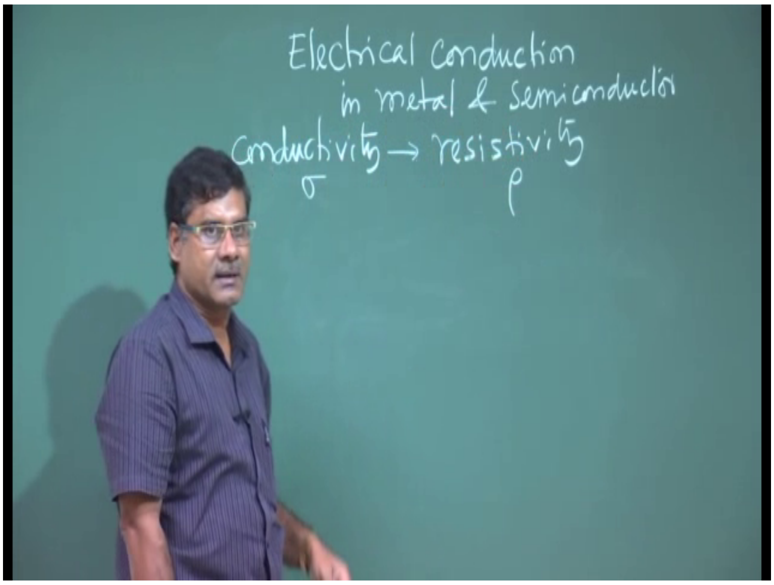


So far we have discussed about the free electron theory, then band theory, right. And using band theory we have we have studied the semiconductor. So, basically what we have done? In case of metal, so using band theory this one can explain semiconductor right. And using free electron theory one can explain metal right.

So, actually so far what we try to find out that is the density of states, density of states which is nothing but the density of orbital's, where each orbital contain one electrons are carrier. So, that is why that is also equivalent to density of electrons or holes right. So, actually in the system there are many electrons, there are many states also. So, here whatever density of states or density of electrons or holes, whatever we try to find out that is not all electrons. That is basically the electrons or holes which participate in transport, which act as a carrier of something either carrier of electricity or carrier of thermal energy etcetera. So, that is why it is better to tell that is density of carrier.

So, carrier can be either electron or holes because they participate in conduction either thermal conduction or electric electrical conduction. But, mainly we are interested for electrical conduction right; so electrical conductivity or conduction. So, basically today I will discuss about the electrical conduction in metal and semiconductor.

(Refer Slide Time: 03:49)



So, metal so there are we consider the electrons are free right, electrons are free and all electrons participate in conduction, as for classical theory, but as per quantum theory all electron does not participate all the electrons which are close to the Fermi level which are close to the Fermi level they participate in conduction.

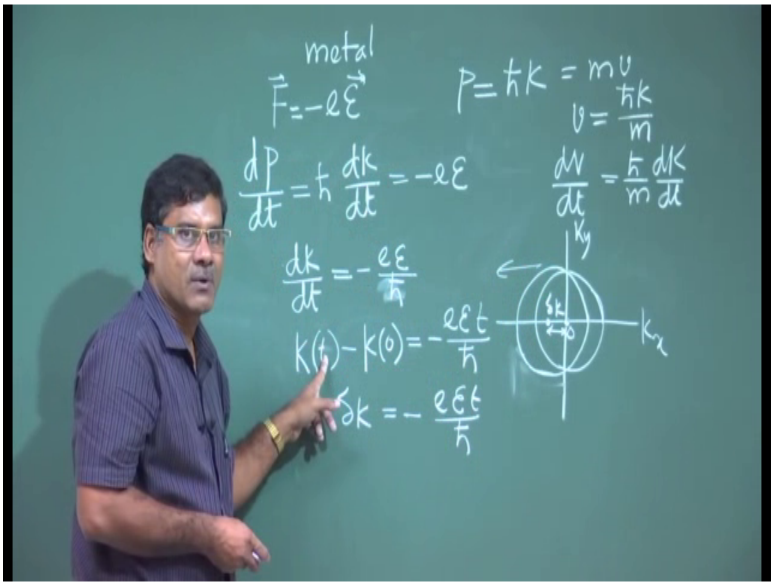
So, what is the density of states, or density of carriers at the Fermi level? That is what or near the Fermi level that is what we are interested and we found also right. Similarly, in semiconductor, so this carrier in conduction band they are similar to free electron, and holes in a valence band they are equivalent they are also this free carrier, because this conduct electronic conduction band and holes in valence band. So, both are near the Fermi level, because Fermi level in between this conduction band and a valence band. So, these carriers will participate in conduction in transport ok.

So, what is the density of this of these of that carrier? That also we have found for n type p type semiconductor. It may happen these both are there in case of intrinsic semiconductor. So, in that case these both carrier and holes they will participate in conduction right. So, conduction so we use the parameter conductivity to express the degree of degree of what I should tell degree of conduction of carriers in the in the metal or in the semiconductor. And this just opposite is resistivity. So, already earlier I had defined this. This conductivity and resistivity, but just that I did after this free electron theory. But now as a whole I want to this electrical conduction in metal and semiconductor.

So, this conduction generally we write sigma and we resistivity write is rho right. So, electrons in a metal or in a semiconductor they are all the time they are moving randomly. So, their resultant velocity net velocity along a particular direction is 0. So, to get the conduction of electron in a sample in a metal or semiconductor we need to apply force. So, basically we apply electrical force. So, electric field we apply.

So, electric field we apply on a on a sample it may be metal or semiconductor, but let us consider metal first and then we will extend it to the semiconductor.

(Refer Slide Time: 08:19)



So, in case of metal; so what if I apply electric field e, right; so, metal only electrons are there. So, this force will be act on this is minus charge minus e, e. So, that is the force that is the force will act on this, on this on the carrier right, on the electrons. Now due to this force what will happen? So, so this force is applied on a on a particle. Now this particle will move it is velocity will increase there will be acceleration right. So, that is the classical concept of motion of a particle under a force.

So, in this case if we so this force can be written as dP by d t change of momentum in case of net free electron you can write p equal to basically h cross k h cross k right. So, dP by dt equal to I can write h cross dk by dt equal to minus e means electrical energy electrical field. So, so this one can take as a equation of motion of an electron in a metal is minus e by h cross. Now what happens if this electric field is applied, if electric field is applied then because of this force this electron will be in motion, electron will be in motion and this dk by dt is basically. So, p equal to mv p equal to mv. So, this v this velocity is basically equivalent to h cross k by m right.

So, basically dv by dt equal to h cross m dk by dt right. So, change this basically dk by dt it is telling this it is basically acceleration, it is equivalent to acceleration right, dv by dt is acceleration anyway. So, if I look at this equation. So, it is just like dx by dt equal to, if I apply constant electric field, so it is like it is constant. So, it is like constant. So, what does it mean? This it is moving with constant velocity is moving this particle is moving with constant velocity. Or this particle is changing it is position. Tt is changing with position say some constant c as it is like this. So, with time it is change it is position uniformly ok.

So, without any acceleration just uniform velocity; so, in k space if I see this in k space; so as if this is the velocity in k space this is the velocity, and carrier is moving with uniform velocity. So, it is it is it is in k space. So, if it is kx this is ky and this is kz. So, one can draw a, one can draw a sphere. Now this from here so I can tell that k equal to see if I integrate. So, k at time t minus k at time 0 k at time 0 equal to minus e epsilon t by h cross see we will we will get this kind of things ok; if I at t equal to 0 just before applying electric field.

So, this as if this is the center of the sphere this is k 0, at time t equal to 0. Now after time t so it will change it will change this from k 0 to it will come at another position k at t. So, as if this sphere is moving, as if this sphere is this sphere is moving with time. So, here it was 0, now new center is here, this is this is this kt position. So, this at time t this sphere moved from this position to this position. So, it is new center of the sphere. So, I can tell this change is say delta k. So, for this time delta k time t it will move delta k equal to, so how much about this? It is a minus e epsilon t by h cross right.

So, due to electric field as if here this sphere in k space it is moving and this. So, this movement is basically given to the motion of the conduction of the electrons. So, because these electrons near the Fermi sphere or including the Fermi sphere. So, they participate they response in the electric field they participate in conduction, without changing the volume of this of this sphere, because this volume of the sphere as you remember there is a total volume of the sphere is the volume of the all states volume of the all orbital's ok.

So, due to electric field this volume of the orbital's is cannot be changed only what can be change? There is the electrons carriers can go from one states to another, one orbital's to another orbital's. Or it can move in from in each in same orbital, but from 1 place to another place. So now, we think that this so for time t. So, this sphere is moved by this amount right. Now for if I increase the time. So, it will continue to move it will continue to move right, it will continue to move. Because time is one second after one second what will happen after 2 second after 3 second after 4 seconds. So, it will it will move and move and move; so under uniform electric field.

But this, but this does not happen; what if we think this this way that just I have applied electric field for short time. So, time that time is t equal to tau. For this time, I have applied this applied this electric field e; so during this for this during this time. So, this it is moved from it is moved from this place to that place. Now electric field is not there. So, it is displacement will be delta k equal to this so t if I replace by delta.

So now for this electric field; so it will just shifted these things, shifted by this delta k. Now what will happen? Electric field is not there. So, what will happen? So, it will go back to it is original position, but why it will go back to original position. So, it will happen it will go back to it is original position, because due to the collision. So, collision with hurt or due to the friction it will it will go back due to the friction due to the collision. So, I will discuss about the source of collision due to the collision so this if electric field is there. In that case what will happen? So, this it is it is moving and electric this collision this friction because of that collision or friction so because of this, so basically scattering a scattering of the conduction electron.

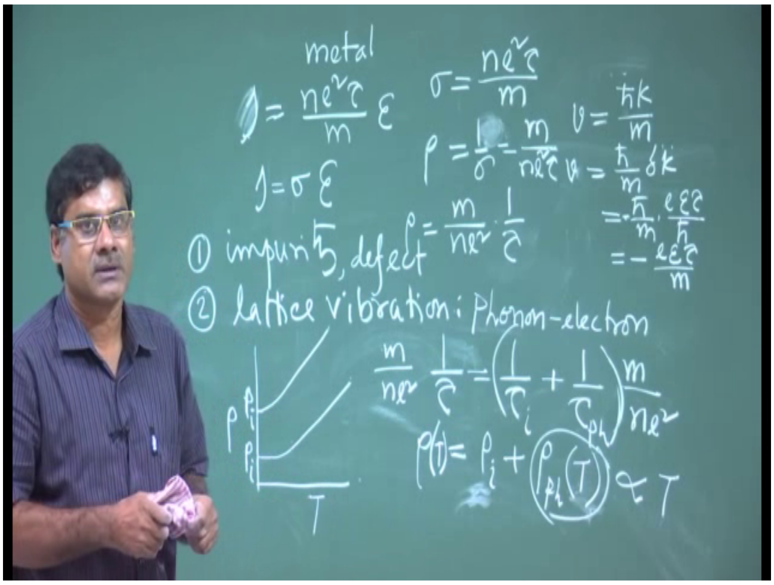
So, it will try to take it other side. So, between these 2 force one is collision because of that it will get friction opposite to the motion. So, and another electric field will apply force in this direction. So, they will balance then steady state will arrive, and in that steady state in that steady state. So, this sphere will move, means conduction electron will move and because of that we will get current, we will get current right. So, what is current? Current is basically this we express in terms of density; current density j means per unit volume so far per carrier are passing through a per unit cross section per unit time ok.

So, total amount of charge are passing through a unit cross section per unit time. So, that is the charge density. So, if I know the if I know the velocity. So, v velocity v, and these charge density is ne right n is the density of stairs density of carrier. So, multiply with charge so minus charge. So, I put minus here. So, minus j equal to minus nev that will be the this charge density. And this so here so v is important. So, this v is called generally drift velocity. And this drift velocity will get from because of the applying electric field. Before applying electric field, this net velocity is 0, after applying electric field. So, this carrier will move in one direction, overcoming the friction collision right; in steady state ok.

So, we can get this v from here, because here this collision is considered. So, so this we can consider that when a p equal to 0, we applied electric field. And then this sphere is moving, and if collision time this t whatever I have considered. So, this t is if we tell this is the relaxation time or collision time or relaxation time. So, what is that what does it mean? So, it since the time, this is the time between 2 successive collisions, ok.

So, when it is moving after this time tau, it will have collision it will scattered. So, this is during that time it will move delta k, it will move by delta k. So, these delta k from here this velocity, velocity from here one can get. So, this velocity is called this drift velocity that will be that will be h cross m and this k. So, this you can take delta k, for this you can take delta k.

(Refer Slide Time: 24:05)



So, why you are taking delta k? Because this is the motion starting from 0, up to the time for this deviation before getting collision. So, it was moving this ok.

So, during that time whatever that is velocity in the system that is taken as a drift velocity. So, this we have to put here delta k. So, v is basically then you are getting h cross by m and delta k is minus I will put here, e epsilon tau by h cross right. So, h cross h cross will go, and this velocity I will get minus e this electric field tau by m right. So, that will be the velocity. So, here I can write that so this minus minus will be plus, minus minus will be plus. So, here ne here e is there. So, ne square tau by m tau by m.

So, ne square tau by m. So, that will be the conduction, current density right; so I so with this. So, basically current density j equal to ne square tau by m. And electric field is there, electric field is there. So, I have to write electric field. And by definition we know that this j is basically current density is current density is proportional to electric field, and this proportionality constant equal to it is a sigma and sigma is called conductivity. So, from here comparing these 2, we can get this, we can get this sigma equal to ne square tau by m.

So, resistivity rho equal to n 1 by 1 by sigma, equal to m n e square tau. So, here one thing clear that resistivity, resistivity depends on m ne square into 1 by tau. So, collision time relaxation time is also very important. And of course, n is there this density of states. One has to know the density of states. So, this has all the time it has importance.

So, mainly depends on the density of states of the metal or semiconductor this conductivity, also depends on this collision a time or relaxation time right.

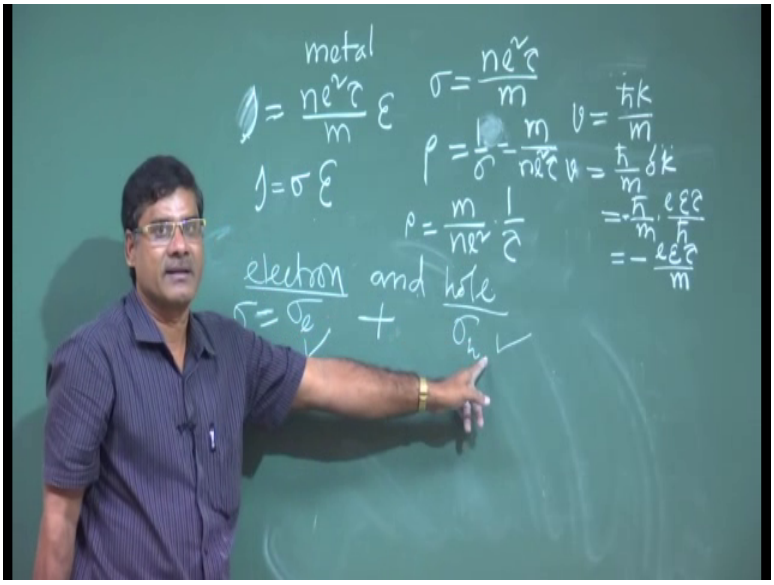
So, here what I want to do is that. So, I want to tell you the source of this scattering collision. So, one is impurity in metal or semiconductor, or this defect mechanical defect in in metal. Because here we have considered the lattice structure sometime this some sometimes atoms are missing. So, there is the defect. So, that are the that act as a scattering center, and when conduction electrons are moving going they gets scattered from this source. And another is the lattice vibration, lattice vibration, vibration.

So, lattice vibration due to lattice vibration. This is the quantize storm is equivalent to follow photon. So, here basically we tell this due to lattice vibration it is, it is, it is gives it gives phonon we can describe in terms of phonon. So, that is phonon carrier electron scattering. So, this is another source for this scattering. So, that is why these tau is basically have 2 parts. One is this 1 by tau, one can write 1 by tau i for impurity, plus 1 by tau a phonon that is vibration. So, this is the source of these 2.

So, your resistivity this 1 by tau is here. So, if I multiply with m ne square; so this one also m by ne square. So, it is give basically rho whatever resistance you get resistivity you get there is have 2 contribution one is rho I and rho phonon; this resistivity due to the phonon, and this resistivity due to the electron. Generally this impurity this one is independent of temperature, but this one is depends on temperature. So, so that is why we write that is this it is the function of temperatures. So, it is a function of temperature, but that temperature contribution mainly comes from here.

So, if we draw this resistivity with temperature, with temperatures resistivity with temperature. So, you get this type of curve. So, this is the basically rho i this is the rho i here we will get. Because it is independent of temperature and at t equal to 0 this part goes then whatever. So, this generally this we tell this part is it is relation is basically proportional to temperature. So, this impurity resistivity it is called also residual resistivity, because it is all the time it is there and depending on that impurity for same metal one can get 2 part.

(Refer Slide Time: 32:01)



So, these parts are just shifting because of this residual resistivity, because same metal, but impurity are higher. So, scattering is higher resistivity is higher ok.

So, this is the conduction of electrons in a metal. So, this resistivity or conductivity is expressly. Say, now in case of semiconductor, what will happen? In case of semiconductor in case of semiconductor, we have we have 2 types of charge carrier right. So, electron and hole electron and hole electron and hole right hole. So, we will get the conductivity for both. So, this sigma for e electron and sigma for hole right. And now this formula we can use for this also, because this electrons this carriers is basically in conduction band they are like free this hole in valence band who are participating in conduction, they are also like free only one has to consider the effective mass. So, lattice so band from band theory we have seen that, this it is one has to take effective vector and effective mass ok.

So, effective mass so that is what one has to do. So, we have to take for this semiconductor we have to take effective mass and same formula can be used. And then for both this it will be additive. So, total sigma will be equal to sigma e plus sigma h right. So, so this way one can get the conductivity of the of the metal and semiconductor, and the source of resistivity that we have discuss how it comes it is because of mainly this collision, with lattice collision with the impurities in the system. So, for p type so this is for intrinsic case for p type, it is this is dominate these are negligible. So, it will be just sigma will be equal to sigma h and vice versa, if for n types. So, sigma will be equal to only this one can neglect this contribution of this one ok.

So, I will stop here. Then I will discuss about the effect of magnetic field on the conduction in next class.

Thank you.