Optoelectronic Material and Devices
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Lecture - 01
Conductivity of Materials, Drude's theory and its failures

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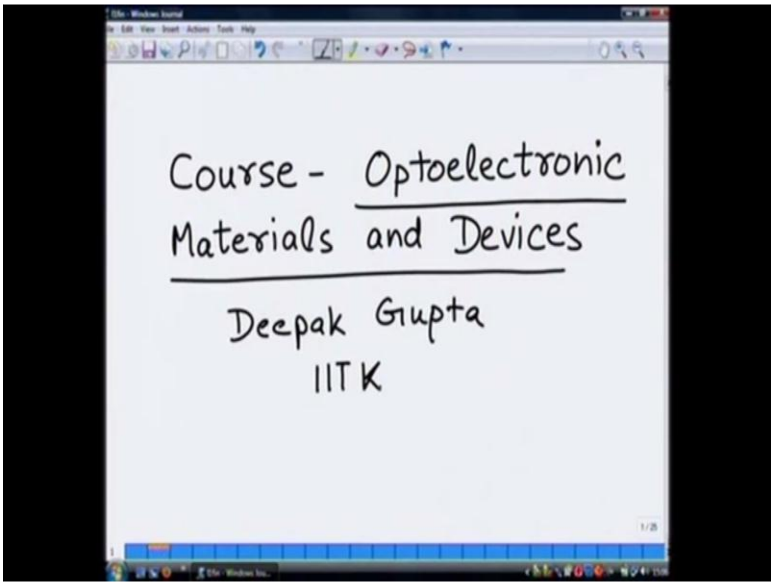

Welcome to this course on optoelectronic materials and devices. This course we are going to start in now.

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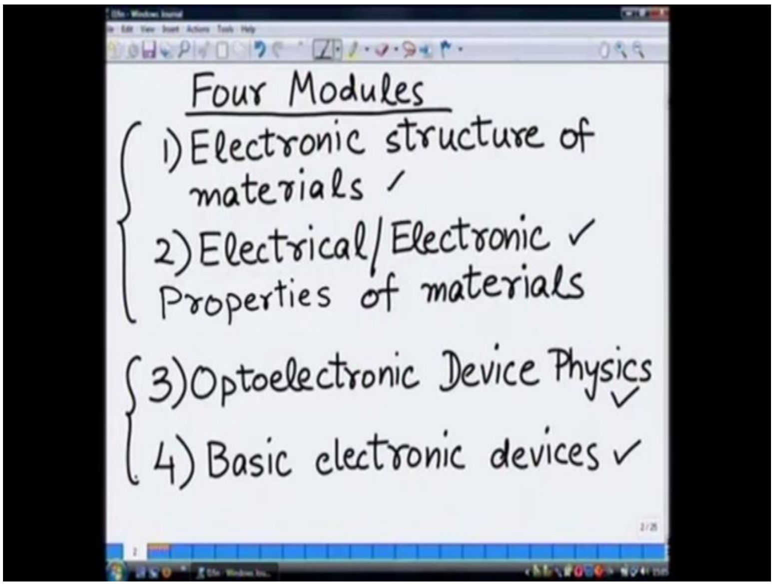

The course will be in 4 modules and these modules are electronic structure of materials which is what we will start with today about 10 lectures on this total. And then after doing electronic structure of materials, we will go on to this electrical and electronic properties of materials about 10 lectures again, then optoelectronic device physics and basic electronic devices.

I will be covering these two topics. These two modules about 20 lectures, and Dr Monica Katiyar will be taking care of other two modules which means who am I? My name is Deepak Gupta. And I am at IIT Kanpur in Department of Material Science and Engineering. So, let us see the flow of these four modules how this works? So, essentially this course is an optoelectronic materials and devices which means we have to tell you about optoelectronic device physics and basic electronic devices. These are the two things basic essentially we need to tell you about. In order to do so what we need to know upfront is electronic properties of materials. Hence it comes before this and in order to understand electronic properties of materials, we need electronic structure of materials from which we derive electronic properties of materials. So, this is how the whole thing will be arranged.

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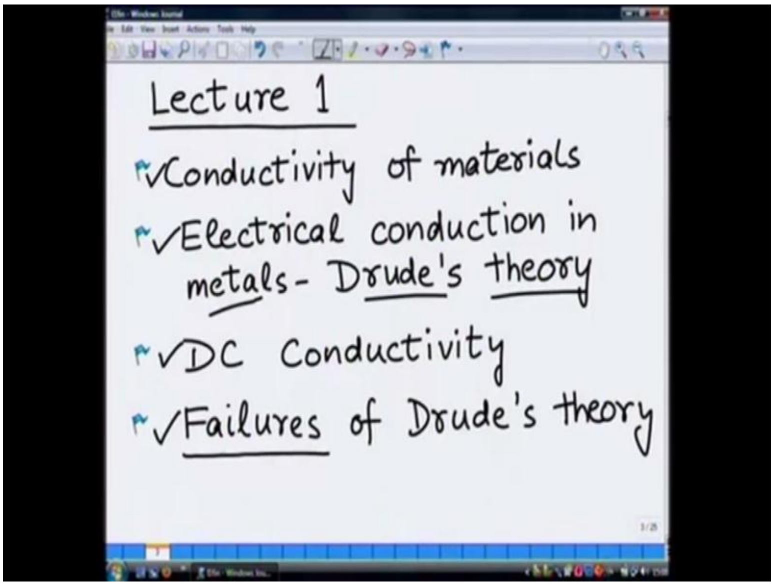

With this background let us start with lecture number 1, this lecture number 1 I have written down here. In this lecture, we hope to cover we will finish this four topics. One is we will talk about conductivity of material as in macroscopic property material. You know conductivity; we say conductivity metals are more conducting insulators are less conducting. What is that conductivity mean? What are those numbers? Is what we will start with following that, we will start taking a view of electrical conduction in metals. How electricity is conducted in metals? And what we will do is, we will take a historical perspective. We will go back more than 100 years back or all most hundred years back. And talk about Drude's theory which really we will see is a wrong theory that is, what we are going to prove a classical theory it is a wrong theory. Again none the less its normally a starting point to understand conduction conduction of metals and start looking at, why this is wrong and what else we need to do?

Following Drude's theory in context of Drude's theory, then I will talk about DC conductivity of material. And I will show you why Drude's theory became celebrated theory in its time and finally, what I will start doing is 4 topic we will talk about is which I said is a wrong theory. So, I will start talking about failures of Drude's theory so that, is the last topic in this lecture which we will cover and then of course, following that what can we do to make the theory better is how this particular lecture will flow. So, let us move on with that background. Let us start looking at conductivity.

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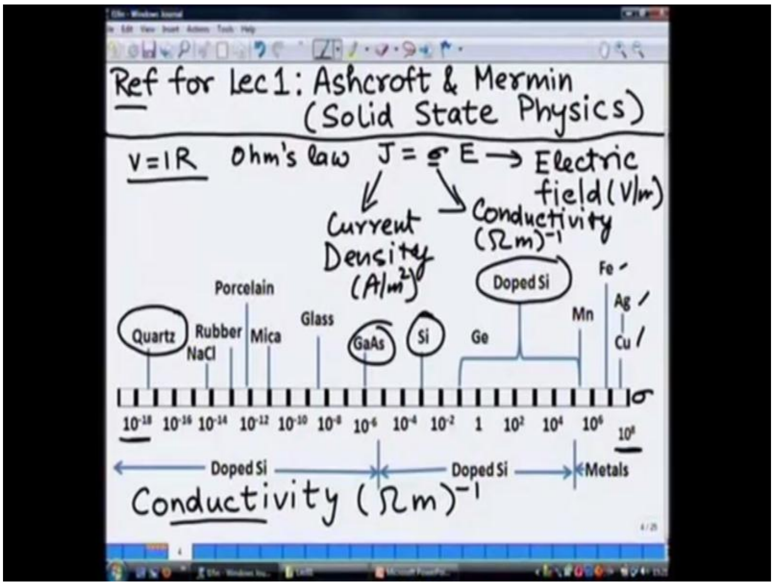

So, for this lecture 1 and also subsequently 2 lectures I would ask you to, in case you need more information you could use this reference which is given in the course content itself. The Ashcroft and Mermin solid state physics, this is a somewhat advance book.

So, those of you are curious would go through this also. First I would point to you that, let us write down Ohm's law. What is Ohm's law? If I have, you are quite familiar with a term which is like this, which is the Ohm's law which you have seen in your basic physics. The same thing we can write in form of current density. In which case, I will write this whole thing as J equal to sigma E, E being the electric field in volts per meter per second. Let us say this is the current density. Let us say in amperes per meters square in that case, this becomes a material quantity as the post to raise tens or inverse of raise ten which also depends on the dimension of the material. Then this Ohm's law is written in a form where dimension of E material does not matter and then this becomes the conductivity electrical conductivity which is in units. In this case of inverse of Ohm's meter, Ohm's meter being the units of then resistivity.

Anyway if you start looking at some of these numbers so I have written down conductivity numbers in inverse of Ohm's meter for several materials. Now, notice its among the most fantastic quantities which we know of notice. Have you seen any quantity which varies in order of magnitude from 10 to the power minus 18 to the 10 power 8, hardly any? It varies over huge range order of magnitude going from 8 to 18 which is 18 plus 8 about 26 orders of magnitude which we have seen in this scale on. Among the most insulating materials we see are is like quartz with a conductivity of 10 to the power minus 18 and among the most conducting are these metals copper silver even gold from where from here, in between are semiconductors which lies somewhere between here silicon and gallium arsenide, we see a semiconductors.

But, you also know the conductivity of semiconductors can be changed by doping that means you can increase and hence that doped semiconductors shift towards right. So, that is the semiconductor, thus the materials range of connectivity which you see in materials. Notice this is a bulk property, in other words it is a measure quantity you measure you apply electric field, you measure current density and whatever the ratio is you start calling the conductivity.

What our job is now to understand the origin of conductivity where does this come from, where does this conduction electrical conduction come from, what at microscopic level is happening. Thus the intent of this first lecture and Drude's theory begins to try to explain all that stuff. So, let us start with that. So, before we do that let us write this like this.

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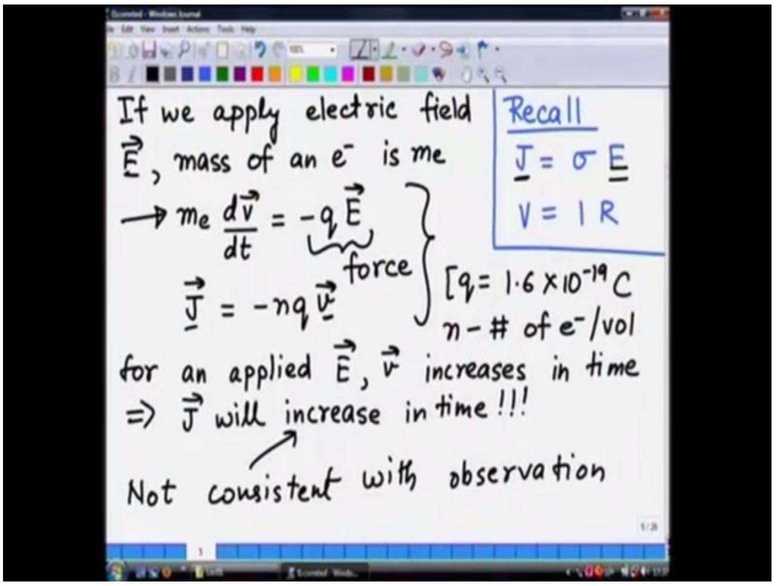

Suppose I apply electric field E, if we apply electric field E in that case what happens. If a mass of an electron is m e then I could think first order as, mass of electron times the velocity of this electron this acceleration should be equal to minus I am putting charged negative charge and the quantity of charge is q where I am writing q as equal to 1.6 into 10 to power minus 19 coulomb's then q times E.

I would think of this is the force on the electron and this force of electron is equal to mass times acceleration, is would what I would like to think of. Now, let us look at the current density. If I look at current density then this current density J which is amperes meter square should be written as minus n q v. You know this n is number of electrons in a transfer to volume and q of course, is charge so that is the current density numbered with all volume multiplied by charge and multiplied by velocity is the current density.

What do you notice? If I want to look at conductivity then I need relationship between this quantity J and this quantity E. But, if you notice this if I apply electric field which is a force, this equation tells me the velocity will increase as a function of time. So, velocity will continue to increase in time the velocity increases then current density must also increase. That is contrary to our observation, you know that if you apply electric field then at a electric field you get a unique value of double x cube being nearby if you apply a certain voltage we get a fixed number for current.

Now, what this question is saying? These two equations are saying, that is if you apply electric field then velocity will increase in time because velocity will increase in time therefore, j will increase in time that is current density will increase in time that means continuity will increase in time. That is contrary to our observation that is something is wrong, not consistent with observation. So, what is going wrong? So, let us start looking at why this happened? What is wrong? With the wrong, with…

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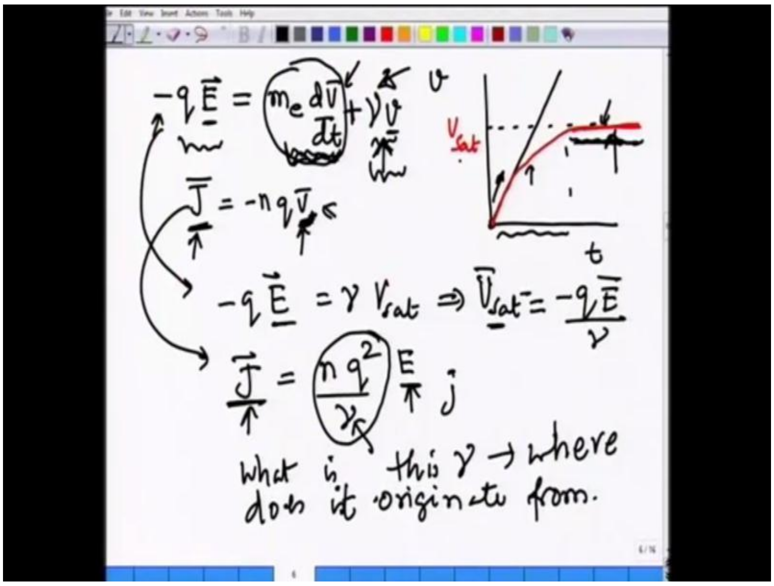

So, I will suggest that you can recon file with our problem if we introduce some kind of damping. So, let me explain that will for that what was our problem? Our problem was that if we apply a force which was on electron which was like this, then we said that this would become equal to mass of electron dv dt. Now, if I plot this velocity of field that we say actually the minus sign says direction of v and E are different. This E and this v direction of these are opposite that is all this minus sign indicates. Otherwise, we are only looking at the magnitude.

So, if I look in time and I plot this velocity or speed v, then this expression says that because you have applied the force here. Hence velocity will linearly increase in time initially if it was 0. Here at t equal to 0 and in time continue to increase something like this and that was our problem and our problem was that then of course, the current would have become minus n v and there would have applied that the current density would continuously increase as v increases in time but what is our physical observation that given this electric field because quantity of electric field there is a specific current. This is what is our observation and therefore, there must be a specific value single value of this velocity which should come in this expression. What that means is that velocity should become a constant in time and something should be like this.

So, that would happen if our velocity instead of following this path had followed something like this that at t equal to 0. It is zero then increases but then slowly it become like this and acquires a constant velocity something like this. This should have been out nature of the velocity if it was so then you would have been fine. Let us call this as v sat if you wish for better choice or let me call erase this one. Let us call this as v sat for the moment that we want this velocity to be saturated to some value.

Now, we can do that if we include other term which is what I am saying like a damping term. Let us call this damping as follows what that means is that initial t is equal to 0 when velocity was 0 then this term of course, was 0 this was not contributing anything. So, whatever the total force was totally balanced by this term and hence we had a linear increase near to equal to 0 of velocity but as this velocity begin to increase. Now, this term is non zero and starts acquiring from greater and greater value and therefore, since it acquires greater value and this total left hand side must remain the same. So, the value of this term keeps decreasing therefore, this which means the velocity acceleration of electron will decrease.

And that is what I am showing you, so this red line that will start decreasing until it so happens that this velocity becomes the saturation velocity V sat. That means, this term alone becomes equal to this term here and in that case this whole term should go down to 0 which means dv dt should go to 0 and then we have the saturation portion and we will acquire that. And hence it will be better if we include that means what our physical observation is that there must be some sort of damping term also coming in which we have included.

Now, notice that if we had this damping term then. When we have reached the saturated velocity and in sometime, this time interval will view the saturation velocity but after that this expression should have become minus q E equal to gamma V sat because in this case dv dt will be in this region, dv dt will be 0 and that means I have value of E implies that E is equal to or rather I should say. Sorry, let me do v. So, this v saturation what we are writing as should be equal to minus q E by what is there gamma the factor. This damping factor which I have included, which means if I substitute back into this expression then J would become equal to n q, another q coming from q square I am substituting this v into this because this is a saturation velocity, velocity when this current corresponds to this velocity.

This velocity is corresponding to which I have calculated this current, this current density. So, then I am substituting this V sat in this v here to see what happens in q and q square E divided by I would get a gamma in there. So right here… So, this now notice you will see this is now, for like corresponding for e field I get apply a field e then I get a current density called J and they have related through this term.

So, essentially now, you can see but if I had some form of damping factor here then I would have gotten a my physical observation. I would have matched my physical observation. So, essentially now next question would be what is this damping factor? What is this gamma or where does it originate from? Does it originate from… So, this is the question we therefore, if we answer this then microscopic level will be able to tell when and what is the origin of this conductivity in a material. Could it be, let us say lattice atoms with which electrons collide or impurities or grain boundaries or anything that gives imperfection in a lattice.

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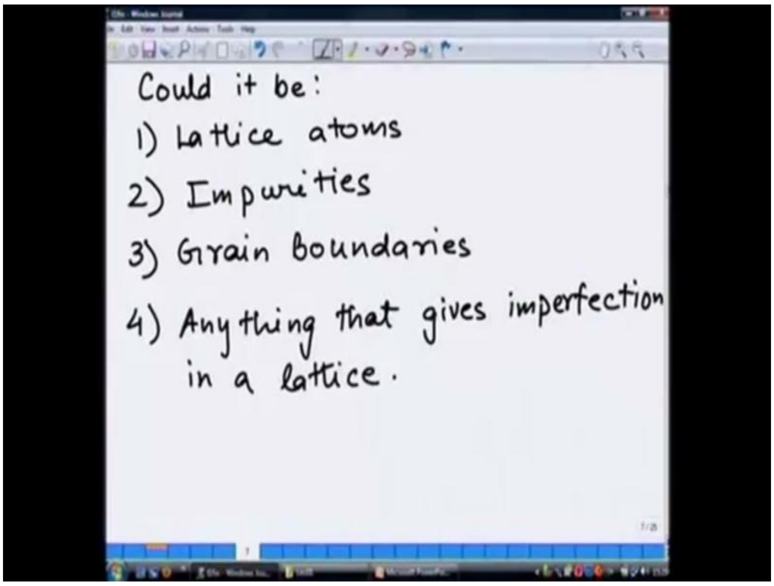

So, essentially I am hinting towards where we are heading. Essentially, what I need is damping, the damping must come from somewhere. An electron going around could collide with atoms could collide with impurities grain boundaries is anything which can break the periodicity of lattice would therefore, call scattering and therefore, essentially understanding gamma means understanding this processes with this, then now let us move on to what is a classical view of conduction?

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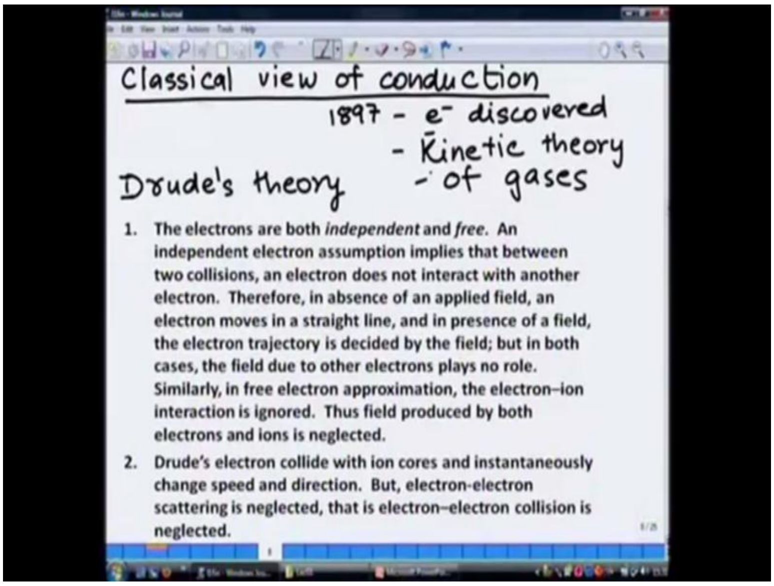

Now, imagine a turn of twentieth century 1897's J J Thompson had discovered electron already which was know already. Second thing what was this electron also, we knew at this point of time was kinetic theory of gases that is what Drude's theory? So, Drude's was aware of electron, was aware of kinetic theory of gases but what was known at that point of time was the structure of atom was not known. So, this is what is beautiful about this theory that would, who did not know the theory structure of atom at the time went on to apply make assumptions or about that structure of material and he proposed certain, he made certain assumptions based on that started explaining the conduction in metal. So, we got to go through that. Before doing that, let me start it here again.

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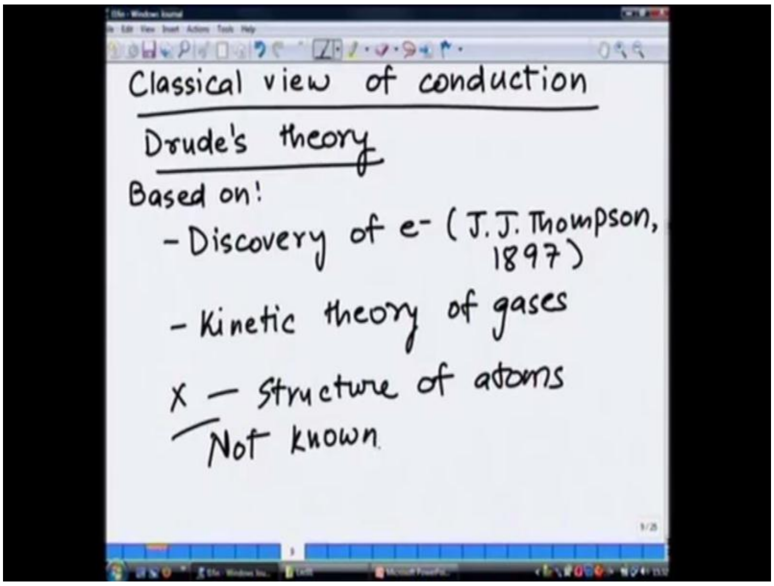

Drude’s theory: What we are going to do based on of electron this was not known at the time.

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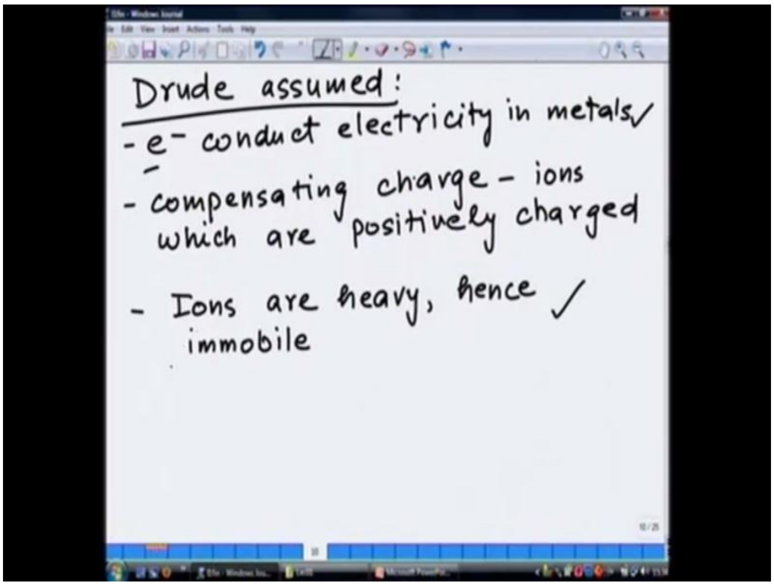

So, Drude went on to hyper size what is going on Drude assumed electron which are charged carriers conduct eletricity in metals. Since now, this is important statement he makes that since there is a electron a negative charged then there must be a compensating charge. So, he makes assumption for compensating charge in form of ions which is positive charged.

Now, remember this is in the time when there is no structure of atoms is not known. He is making this assumption because he used to compensating charge. Another thing which he does is that, he says ions are heavy and hence immobile. This another assumption he makes this assumption you see in connection with the first one. This assumption let electrons conduct electricity in metals if you have that is connected that in the sense ions do not conduct these electrons and there is a compensating charge that compensating charge is a positive charge and is being called as ions and then it says that since electrons conduct, which means ions are not conducting that means, the ions are immobile had they been moving then they would have also been conducting. Therefore, here the basic things he assumed.

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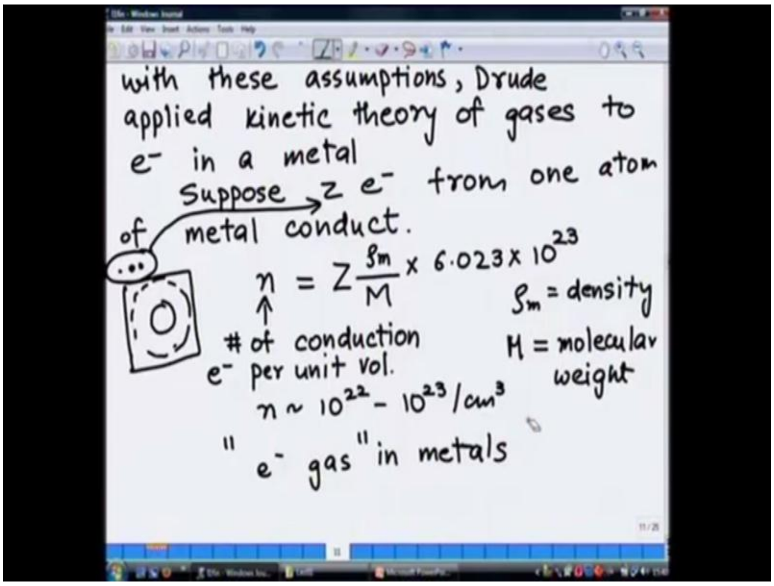

And beyond that what he did was with these assumptions Drude applied kinetic theory of gases to electrons in a metal. Now, remember kinetic theory gases deal is valid for dilute gases, that means distances between electron between gaseous atoms is large. The electrons can we think of them as electron can think of that is a gas or the too close to each other that we need to see. So, let us see how many electrons are there that are conducting?

So let make a Let us look at this suppose z atoms z electrons form 1 atom of metal conduct what does that mean if we think of, if we think that there is a valance. The valance electrons the tightly bound electron and the outer most shell whatever the number of electrons are those are conducting per atom. That means, for the lithium example there is only 1 electron in the outer shell rest is the part of ion. We think like this all this nucleus all this inner shells of electrons these are the ion and this is the valance electron, these are the ones which are conducting and this is number is z. So, outing this is shown as three.

So, if these are the electrons which are conducting suppose that we have rho m is the density of metal that is a k g per meter cube. This is a number of… this is the density of metal, if we divide it by the molecular weight of the metal then I have things in moles per meter cube, moles per unit volume. This many moles, if you multiply that by avogadro's numbers 6.023 into 10 to the power 23. Then, I have this many number of atoms per unit volume in a metal. And if I multiply this by z which a number of electrons per atom which are conducting then I have number of electrons per unit volume, per meter cube of electron which are conducting and that number is n.

Therefore, N is number of conduction electrons per unit volume in a metal and these of course, rho 1 is density and m is molecular weight. So, this is the number of electrons that are going to conduct in case of Drude's theory. These numbers in the plug in values I will show 1 case eventually. So, n typically will vary between 10 to the power 22 to 10 power 23 per centimeter cube of metal therefore, this is number of electrons that are there for conduction. So, if this is the number of electrons then what it will told to do.

After this of course, now given this persisting to cube these many number of electrons then you can what you can do is inverse of n 1 over n that means 1 electron volume associated with per electron you can calculate. And from that you can get an estimate of what is the distance between electrons? You would find of course, that these the electrons gases we will be dense from and remember kinetic theory gases can be applied only to dilute gases but none the less Drude went ahead and applied this to electron gas in metals though now, given that the 10 to the power 22 to 10 to the power 23 electrons percent cube. So, nearly dense and still he went ahead and applied kinetic theory of gases. So, assumptions are similar to kinetic theory of gases and those are like this.

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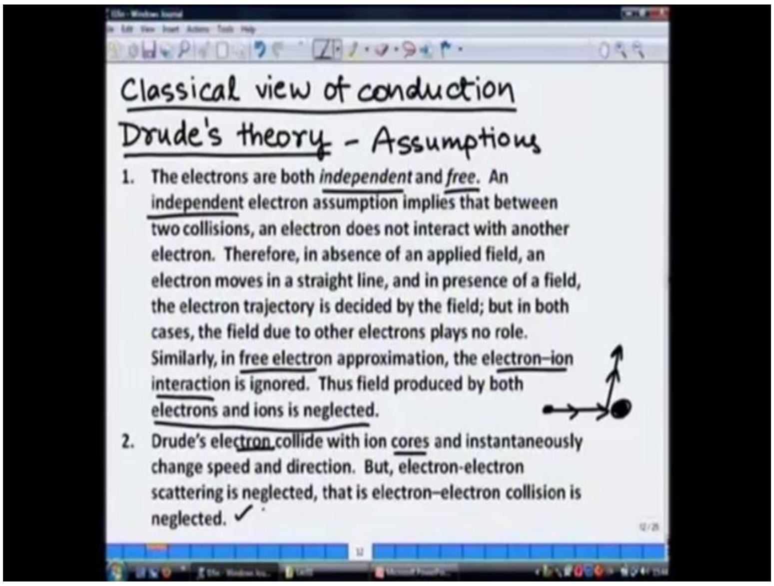

The electrons are both so let us start looking at the assumptions of Drude's theory. In next assumptions that the electrons are both independent and free, what does that mean? He says that this electrons which you have an electron is a independent (( )) assumption that applies that between two collisions. So, he is assuming what he did was so what he assumed is that these electrons are moving around in metal then they collide with ion cores. These ion cores which are immobile compensative positively charged and then they move away.

And this is picture of how electrons are conducting. So, this collision and then evolving of electron out of these collision provides it is a damping, that gamma factor in Drude's theory so that, the velocity does not continuously increase. What it does is an independent electron assumption electron implies that between two collision, that means electrons forms and collides 1 ion emerges out of it and then collides another ion between these two collision. An electron does not interact with another electron, independent electron is there. There is no electron interaction this is what it repeats therefore, in the absence of the applied field is an electron moves in a straight line and in presence of the field electrons penetrate try to decided by the field but in both cases the field due to other electrons based (( )).

So, understand this that electron comes out of this collision and is going to collide again with another ion. Since it does not see other electron it does not interact with other electron, does not see other electron feel. Therefore, it just continues to move in a straight line if you apply another external field then of course, follows external field but if you not apply the external field similarly, we think of free electrons.

So, there is independent electron I have just explained similarly, you can think of free electrons approximation where we also neglected. Remember this electron and ion would have a columbic interaction between them, but he says that these are the valence electrons which are very loosely bound. That means whatever the positive charge is shielded by so many inner shell electrons. So, the inner shell electrons screen the positive charge in the nucleus and therefore, this electron is the very weakly interacting with them he makes assumptions that this interaction is nearly 0. That means between the electron and ion interaction is ignored. Thus the field produced by both electrons and ions are also neglected and that is called free electrons approximation so that, the two major approximation he makes independent and free electrons approximation.

Then these Drude's electrons about which he has made assumption of independent free they collide with ion cores and when they collide what happens? Instantly, the moment they collide ion core is electron that comes and collide with it and then what happens then they change its it comes out with some speed. It changes its speed and the direction this electron and of course, this ion core is immobile this sitting heavy and it is sitting there.

Therefore, scattering is happening because of the ion core that means electron comes hits it and then it changes directional speed so that, is what happens in case of Drude's model but electron scattering is neglected that means a electron does not interact with another electron and gets scattered and does not change the direction of speed in since that we are not assuming any electron interaction so that, it is not possible for or another electron does not change the direction or the speed of this electron which is going where. So, that is second assumption which he makes out of the total four assumptions which are inherent Drude's assumptions. So, these are the two major assumptions. Then let us look at the third assumption.

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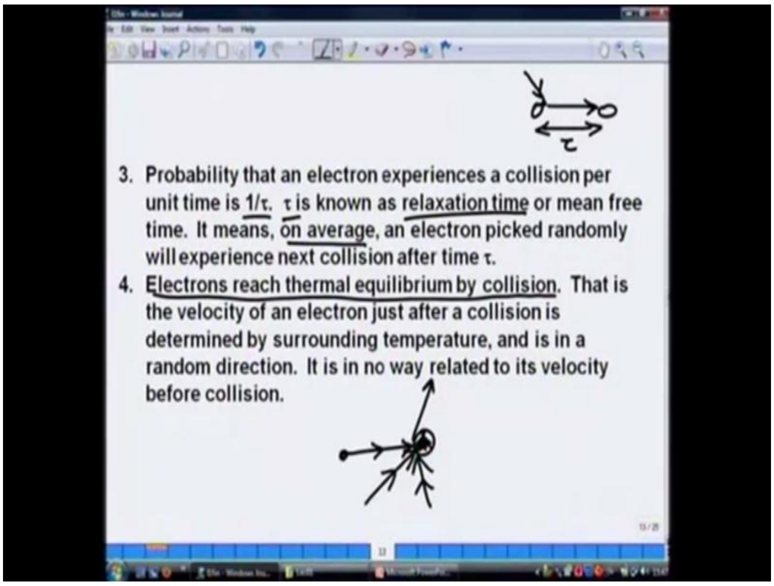

Now, he says that there is an ion here, this electron collided with this and then started evolved in this direction and started this way towards this direction. Probability that an electron experiences a collision per unit time is 1 by tau, which means if you think that average time taken between collisions. An average whatever is the time spent is tau between collisions, then you can think of probability of electron experiencing collision in a unit time is then 1 over tau that is what he is assuming here. So, this tau is known as the relaxation time or mean free time time between it is on an average this is the time electron so on. An average if you pick an electron pick randomly you will experience next collision after time tau.

So, that is the time on average time which is spent between collision by an electron so that, is the definition of relaxation time in Drude's model. And finally, a very important one now, I have an ion and an electron comes and collides with it is coming in this direction and it has some speed question is, when it is scattered which direction will it go? Second what will be its speed? Third will it have a history will the speed be dependent on what the speed earlier was? So, this is the third assumption Drude makes that electrons reach thermal equilibrium by collisions. That means when it comes and hits it, then it reaches thermal equilibrium is attained by this process itself.

What does that mean, that the velocity of an electron just after collision. That immediately after collision is dependent only on surrounding temperature and therefore, it evolves in a random direction, if you go in any random direction it does not matter electron was coming from here or electron was coming from like this or electron was coming like this. The incoming electron came like this or like this it does not matter. From what direction it came and collided it. It evolves in a direction which is random and its speed is entirely dependent on what the local temperature is because that is how this is the thermal equilibrium.

Which means that after collision the evolution of speed is made based on thermal equilibrium in random directions, it has no history that electron does not remember what speed and what direction it came from. These are the four major assumptions based on this therefore, the Drude's theory evolves. So, these are four essentially the Drude's theory. Now, when you apply this Drude's theory and start looking at DC conductivity in metals and see what it means to us, that is what we are going to do now next.

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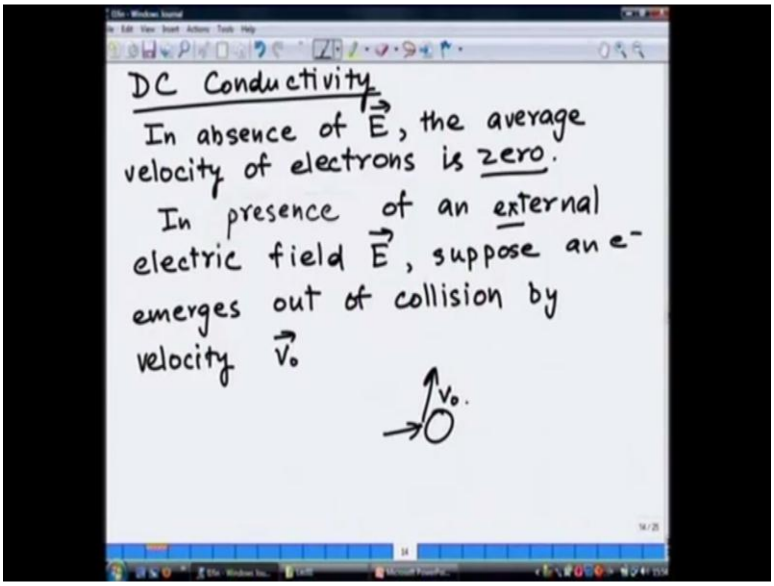

What do I mean? Question is when you apply a electric field what happens? Absence of electric field what happens, the average velocity of electrons is exactly 0. Why remember electrons collide and then they emerge out of this collision in random directions. In random directions and velocity is which are corresponding to the local temperature. If you think of Maxwell Boltzmann's distribution then evolve for the with a random set of velocities also. Therefore, in random velocities in random directions net effect is that in absence of the electric field the average velocity of electrons is 0.

What happens in presence of electric field? In presence an external electric E will start having an impact. Suppose an electron emerges out of collision by velocity V 0. Let us say this is the velocity that means here is a ion electron collided with it, when it came out it came out with this velocity V naught and this V naught is a random velocity, random direction, random speed not determined by any external field but now once it emerges out of these V 0 field then after this what happens. How this velocity evolves of this electron depends on what the electric field is. So, according to and what the electric field is…

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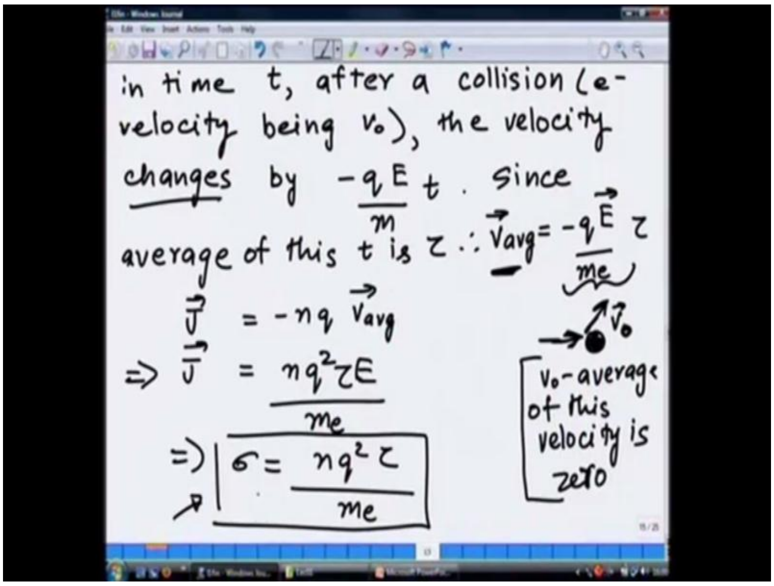

Therefore, in time t this velocity after a collision being this v 0 velocity. The velocity changes in time t, the velocity changes from v 0 changes by an amount which is equal to what, this change in is equal to if I think of minus q and E as the force divided by mass of electron is the acceleration into time t is the quantity by which this quantity, then the velocity changes.

Since average of this t, the time between collisions, the time it emerges out of 1 collision and then let us say in t time it increases the velocity changes by this amount which is written out here. And then it collides with the next the electron, next ion then electron collides with the next ion. So, this is a change of velocity during that time. So, on average since this time t is tau, tau is the average time between collisions. Therefore, V average is equal to minus q E by m e tau. Remember V 0 is the random velocity from which this is the ion and here is the electron which came out with velocity V 0.

So, this is the velocity by which came out and this random velocity so therefore, average for and it came out of an random direction. So, average of this velocity is of course, 0 so only part in presence of electric field only average contribution to average field to average velocity due to electric field. Is therefore, this is the change in average velocity due to electric field. Once I have this now, I see this V average depends on electric field. Given electric field there is a average component velocity that is now, no more does not increase in time because this is the average time in their and there is fixed number.

So, no more you have a fixed velocity in here. in which what that means now, current density is equal to minus n q V average. As we wrote earlier which now, I can write as equal to that implies that J I can substitute. Now, in this case this velocity therefore, we can write n q square e by e tau by m of e implies that conductivity now, is n q square tau by m e. Now, we have derived in Drude's theory. According to Drude's theory what the conductivity of a material therefore, will be... Ok now, what we have done. Now, this is a consequence of Drude's theory. Based on the assumptions we made about this relaxation time what definition of relaxation time. Now, what happened was that because electron comes and hits and forgets about its past. And emerges out of it by according to the whatever the velocity is according to thermal equilibrium. What that means is that average of that velocity is 0 and that essentially means damping.

Again and again the electrons getting damped but if I apply electric field then only contribution which comes is, due to electric field and since tau is the time between average time between two collision. That is correspondingly there is a average velocity which electron gains between two collisions. What this is a average velocity of all the electrons. Now, if I have average velocity so I have a current. Accordingly, once I have current and relation proportionality between J and electric field gives me the conductivity. Hence I have a conductivity or the material. Now, what have we gained?

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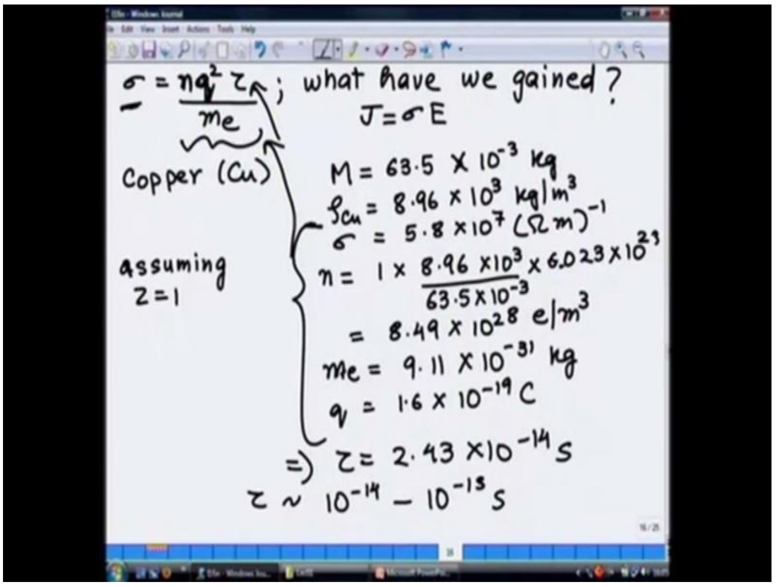

Let us do start looking at sigma, we wrote as n q square tau by m e. What have we gained? Essentially, what has happened is now, earlier we had a major quantity called sigma which was relationship between proportionality constant between J and E. It is a measured microscopic quantity. Now, we have gone 1 level down and established a mechanism by which conduction happens and accordingly obtained this relationship. So, in that sense now but then I know what n is? I know what q is? I know what mass of electron is but again I am stuck with this quantity t tau which I do not know.

Essentially, I still have not figure out what the conductivity of the material is I have merely changed my problem from knowing sigma to knowing tau, which is the relaxation time but now instead of microscopic level we are talking about at microscopic level so that, is what we have gained. We have gained a microscopic picture but but my problem in knowing what the conductivity still remains were it is. Because I will still have to measure the tau, I have no means of knowing what tau just get yes at least.

So, what does that mean let us start looking at so is this theory good or not. So, let us say first I start looking at this quantity. Now, let us look at this let us make an estimate what the value of tau is here. We put down some numbers say copper. Its molecular weight is equal to 63.5 grams so I am going to put this as minus 3 k g. its density of copper is equal to 8.96 grams per centimeter cube all 10 to the power 3 k g per meter cube.

Therefore, and its conductivity we know is equal to 5.8 into 10 to power 7 Ohms meter inverse. That is what the conductivity is.

So, now let us estimate what assuming z is equal to 1. Let us assume z in copper equal to 1 that means 1 electron per copper atom is conducting. This you could argue it is not 1, it is d and s shell electrons within 11 electrons but we will see that also that for time being let us assume. So, only s shell electrons 1 s electrons which is conducting in copper. In that case we calculate now, the based on the formula we have derived n calculated is equal to. In fact you can calculate this 1 into the density is 8.96 into 10 to power 3 k g per meter cube divided by molecular weight 63.5 into 10 to power minus 3 moles per meter cube into 6.023 into 10 to power 23 number of atoms per meter cube and since there is 1 electron per atom. So, these many electrons which is equal to I have calculated as 8.49 into 10 to power 28 electrons per meter cube or 10 to power 22 electrons per centimeter cube.

And mass of electron is 9.11 into 10 to power 31 k g. Charge of electron 1.6 into 10 to power minus 90 columb's, therefore based on that if you plug in all these numbers into our formula right here. Then what do we get tau as, implies tau is equal to all these numbers input also in their conductivity. So, tau is calculated as 2.43 into 10 to power minus 14 seconds that is value of tau is.

So, depending if you have chosen therefore, z as equal to order of magnitude higher in that case we all. So, let us say tau therefore, we will say varies between 10 to power 14 to 10 to power minus 15 seconds is tau Now, if you look at the velocities involved in these materials if you think since Drude's this kinetic theory gases of gases being applied, this thermal equilibrium being assumed. Then it is reasonable to also from the ideal inherent in kinetic theory of gases.

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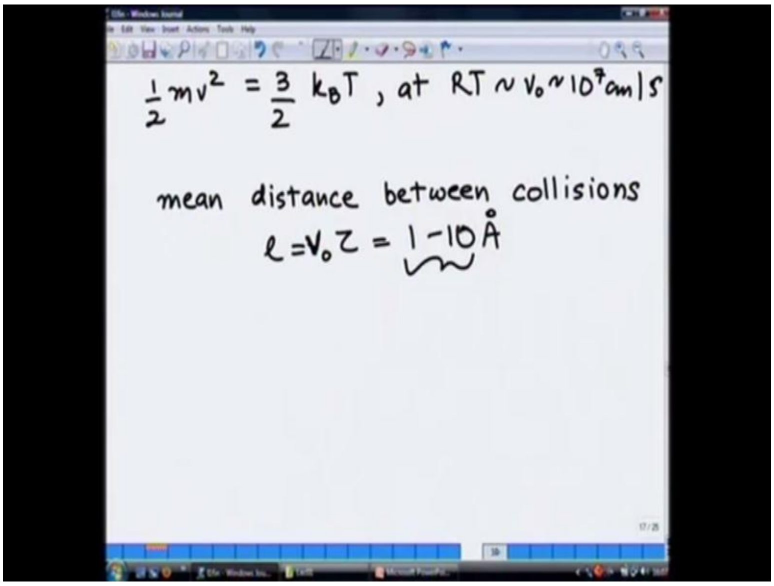

That velocity could be estimated as half m v square as equal to three-second by equi-partition of energy as Boltzmann constant time temperature, that local (( )) temperature. So, this at room temperature this velocity v is approximately equal to 10 to power 7 centimeters per second. That is what the velocity is therefore, if you look at mean distance between collisions. Then this would be the velocity which are involved or diameter of velocities of course, this is the velocity by which electron will emerge out of collision whose average component is 0 but that is the order of magnitude of velocity and multiplied by tau that the average time between collisions.

Then this distance therefore, will become equal to about 1 to 10 Armstrong's based on the value of tau and V 0. Now, this became the proof of Drude's theory that this is good theory because into atomic distances are on the order 1 to 10 Armstrong and since he assumed that the conductivity is arising out of electron colliding with these ions. Therefore, and since this theory starts predicting l which is equal to on same model as 1 to 10 Armstrong's mean distance between collisions therefore, then when it is matching in atomic distance then it appears therefore, that this is a good theory. So, now let us start so this is why the basic idea of Drude's theory, but what I will start telling you about is now, failure of Drude's theory.

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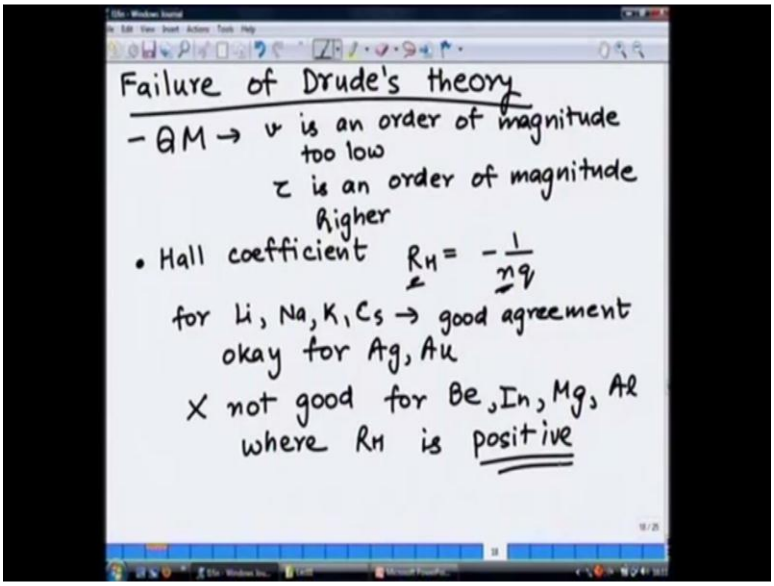

From modern we will see modern quantum mechanics, when the electron is a fermions which means it follows fermi direct statics and so if I take as a quantum mechanical theories. Then these velocities are are in order of magnitude too low, in what we have taken the classical theory and tau is in fact whereas, tau is an order of magnitude higher and what we have so far. We have taken from reality the two errors cancelled out and l came out to be very decent. That is while it appears on the Drude's theory is good but there is a problem. Second thing is, it does not say anything about for example, in copper if you make a realistic really pure copper and go down to very low temperatures. Then this mean free path, mean distance between collisions may be as high as an order of centimeters.

So, here is another problem which we will see but let us look at some more points which I have not derived but I would merely point out to you where the Drude's theory is begins to fail. For example, take Hall's coefficient in the context of Drude's theory if I look at the hall measurement, hall coefficient with which I will assume that you guys are familiar. If you not maybe read up a text book on hall effect which is taught to you in school also. By assume that this you know this there is a hall coefficient which is equal to, which is derived as minus 1 over n times q. Now, this remember when we start looking at the mean free, mean distance between collision they was v velocity term the tau term and these two can the errors cancel out and the Drude's theory appear.

So, what we are doing. Now, we are trying to apply Drude's theory to essentially those places where only 1 property occurs. That means this case, here it is independent of tau now, let us see what happens to hall coefficient. What we find is n, we can calculate. What we find is for lithium, sodium, potassium, cesium good agreement with measurement. That means you calculate R h based on n. We can calculate as shown the calculation for n and to calculate n for lithium, sodium, potassium, cesium etcetera substitute in there. Calculate what R h is also measure R h and if you measure R h through Hall measurement of course, the then you will find that the very good observation between theory and measurement which says that Drude's theory works.

But then it works for noble metals like silver gold it does not work and not good for beryllium, indium, magnesium, indium, aluminum where R h is positive. It turns out that R h is changes its signs, sign itself is wrong. Meaning thereby that it appears if you do a measurement so if you take a aluminum and you think 3 electrons are conducting and you calculate R h for with aluminum here. And if you and it will of course, be a negative value and if you measure it then you find that R h is a positive quantity. It appears therefore, in aluminum and measurement it will appear as if not electron conducting but it is like a positive charge is conducting and it turns out if you do it properly you find that it appears as if 1 positive charge is conducting rather than 3 negative charge is conducting. So, what is going on? Drude's theory cannot explain this. So, that is 1 failure which I would like to point you attention to...

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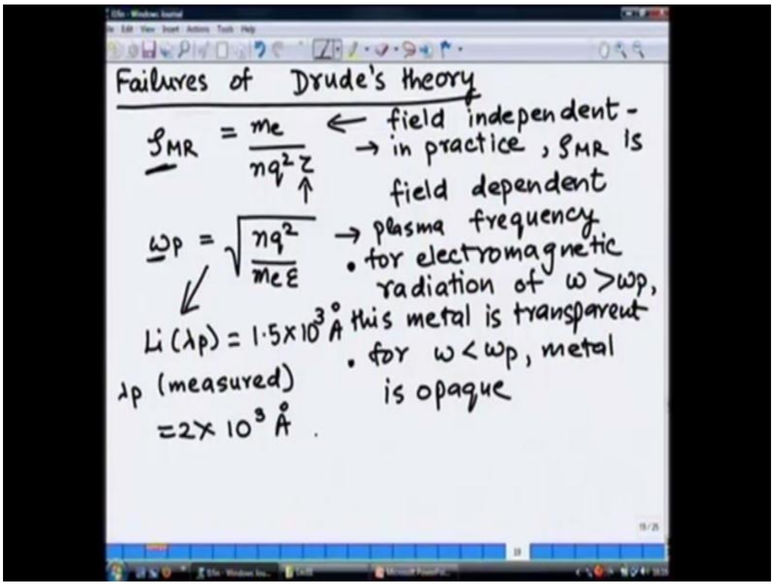

Similarly, if you look to magnitude resistance that means resistance in presence of magnetic field if you look at magnetic resistance then this quantity is m e divided by n q square for this part either you can read the reference you are well interested you can read the reference which I have given you in (( )) moment or you can just follow the steps assume in (( )) it is derived those are something which you can take a look at if you're interested in where these formulas are coming from but in context of this class is now what I am going to do is that just give you these formulas what point I am trying to point out of there is now this is a quantity which is tau dependent.

This tau dependent if there is l in tau then this rho m r if there is an error in tau how we estimate tau from conductivity measurements then independently if you try to match with rho m r you should be able to see if the Drude's theory is right should match if Drude's theory is not right they will not match what we find is that this quantity is field independent independent magnetic field you apply but in practice it is not, so so if you take measurement then it turns out to be field dependent according to Drude's theory derive this you calculate (( )) it becomes a independent of a field

Similarly we will take you one more plasma frequency a plasma frequency is quantity derived as n q square divided by m e into dielectric constant (( )) of material what is this? This is plasma frequency for if you take electrolyte for electromagnetic radiation of omega greater than omega p this metal is transparent for omega less than omega p metal is opaque meaning that if you have electromagnetic radiation I have metal electromagnetic radiation there is something defined called plasma frequency

This electromagnetic radiation will get absorbed in this metal and would not go through if the frequency is less than this plasma frequency if this frequency of the electromagnetic radiation was greater than this quantity plasma frequency then this electromagnetic radiation will go through that means the metal will look transparent to that frequency that also can be now seen in context of those theory and what we find is that that for lithium it works very well for lithium we find that lambda plasma frequency the wavelength of plasma frequency corresponding to this is equal to i have number of it theoretically is one point five into ten to power three Armstrong's and lambda p measured is equal to two and the to the power three Armstrong very decent match in terms of plasma frequency called lithium but for most of the metal may on the next page for most.

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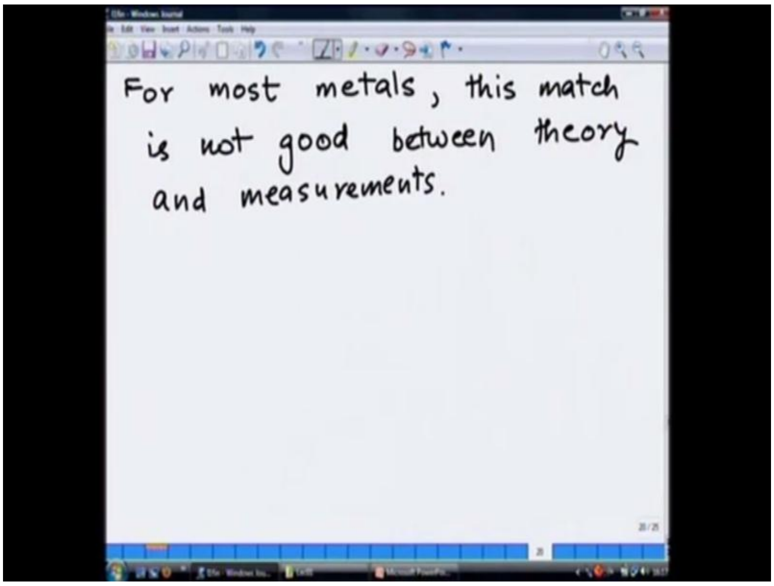

For most metals this match is not good not good between theory and observation measurement so these are few examples of failures of Drude's theory at this point of time I will stop and in next lecture, I will to show that where these errors maybe where the problems will come from and then start developing a theory which is much better than Drude's theory and for more modern theory based on quantum mechanics as you will see.

Thank you.