Solid State Physics
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Lecture - 51
Electrical Conduction (Contd.)

So, we will continue our discussion about the conduction of carriers in metal and semiconductor.

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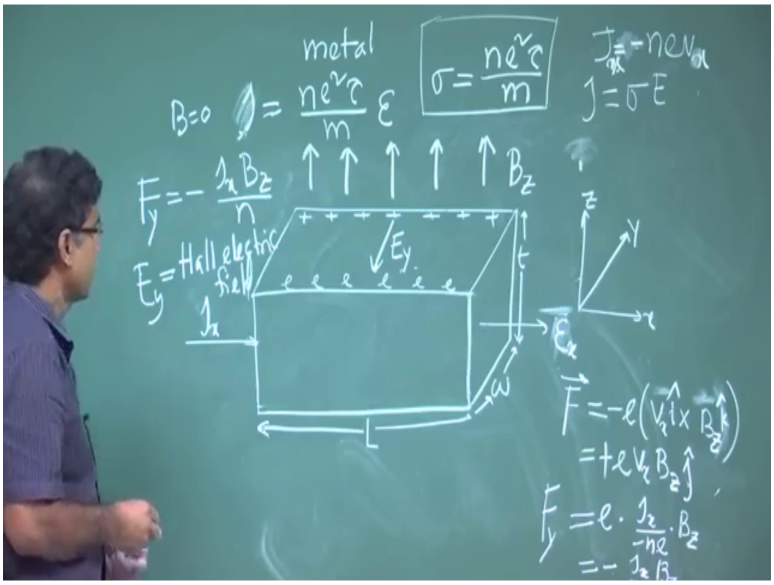

So, here you see this if we apply electric field on a sample, whether it is metal or semiconductor, then what is the current density? Now, I want to apply electric magnetic field along with this electric field, means electric field is there, and because of that this current is flowing through the sample. Now if I apply electric field magnetic field on it. So, what will happen that we want to study?

So, let us take as simplified model means just one-dimensional conduction. So, means if I take a sample, rod type of sample or of this just sample. I think I have to is slightly or I can take fine. So, these sample dimension or geometry of the sample. So, these the x direction, say this is the x direction, this is the y direction, this is the z direction, this y, this is z.

So, length is along the x axis length is say L and this this is width of the sample width of the sample. So, this is say w, and these the thickness of the sample. We say it is t, this is a t, thickness of the sample this t right. So, it is it is t thickness of the sample is t, width of the sample is w and length of the sample z right. So, we have applied electric field along the x direction. So, due to this electric field current will flow through this along the x direction.

So, j x so I can now give this j x, j x is may be current density j x, because of the electric. So, I was even electric field this because of this electric field along this. So, this let us say x right electric field is given along x direction. So, current is flowing in this direction. So, without so before apply any magnetic B equal to 0 right. So, this will be the current density J equal to Nev. So, I will put one negative sign that we have seen earlier right. And yes, so this so now, if I apply magnetic field; so what will happen? So, if I choose the direction of magnetic field is along the along the z direction, so I have drawn like this means it is this sample is under uniform magnetic field. So, field direction is in in the so all the whole the sample are getting are getting expressed with this magnetic field that magnitude of this field is B z. So, z we are giving this direction is along the z direction.

So now before applying magnetic field is charge carrier was moving charge carrier was moving right. So, whether it is, so just let us consider the metal then we can generalize to the semiconductor. So that means, electron are moving electron are moving in which direction. So, if it is electric field in in this direction. So, field are having this this is having negative electrons are negative charge. So, it will move in this direction (Refer Time: 06:26) this negative x direction, but conventionally current is taken that this is along opposite to the electron flow, ok.

So, current is so this is the case, now if I consider the effect of this magnetic field on this on this on this charge. So now, charge is moving charge has velocity right. Now that moving charge will experience force, because of this Lorentz force. What is Lorentz force? Due to magnetic field Lorentz force F equal to minus e. So, for electric field it is there. So, these V cross B V cross B. So, what will be the force direction? That will depend on the direction of V and direction of B right. So, direction of B is along the k direction. I can write this is a k direction unit vector k with z direction right. So, I think I can tell here. So, this F of I can write here F that for Lorentz force will act on this moving charge carrier. So, that is minus e right then V cross B right.

Now, in order geometric B is along x direction. So, I can write V x along this unit vector I, and this B I can write this it is along z direction. So, B z along k direction unit vector k right. So now, here basically you are getting minus e V x B z into here I cross k. So, I cross k is basically minus j, because k cross I equal to j. So, I cross k will be minus j. So, this is j and minus minus plus.

So, here some force is Lorentz force will act on the moving charge carrier because if V 0. So, there is this Lorentz force will not act on this on the charge carrier all the magnetic field is there. So, in presence of magnetic field moving carrier only get affected field force. So, that force is along the z direction, that force is along the along the z direction right, means along the y direction. So, this is the y direction. So, force will act on this in this direction.

So, it looks like this, but problem is that I cannot say, because I have to this. So, what is the direction of v. So, I have to take kth rid of this V from this expression. So, V from here, I can get J equal to minus nev right, nev so j x and this is V x right. So, j x this is V x. So, V x so V x is j x by any minus sign is there. So, this is coming as a V x if I want to replace. So, V x I have to replace by so this is e and then j x by minus ne, then B z. So, these the unit vector along the y direction, it is telling this force along the y direction.

So, I can I can move to move this one and I can write here F y. So, it means Lorentz force acting on the along the y direction. So, that is why this j we should not be confused with the d j with this current density. So, so here we can see that this basically you are getting minus sign and then ad is there. So, I will get minus sign g x B z, and I am missing any electric field. So, this minus sign divided by n. So, that is the force I got. So, due to this magnetic field along the y direction, along the y direction I am getting Lorentz force acting on the moving carriers; so minus j x B z by n.

So, here what is this this is the carrier density? The j x it is set constant value some particular value current density we have shaped in this sample now particular magnetic field we have applied for that in that case. So, this amount of force will act on the moving charge carrier. So, this now here it is negative sign; that means, it this force along the negative y direction. So, earlier it was difficult to say, because this V x we do not know this V x it is whether it is because it was of course this V x one can take negative, because it was moving along this direction right velocity. So, that way if you consider the negative sign of this V x. So, same theory will come, but it is better to just replace in terms of our known direction, this is positive direction, this is positive direction z direction this is of course, density is positive. So, minus sign is telling. So, this force is acting alone just opposite to this negative direction of the along the y axis.

So, electron are moving electron are moving electron are moving now these electrons are experienced force in this direction, negative direction. So, electrons will accumulate will move in this direction, and come to this to this phase come to this tortoise phase. And when these electrons are moving towards this phase of density of electrons will be moved here on this space. And divisions of electron will be there this other phase opposite phase right. So, here one can say this it is there will be positive charge accumulated in this side and this negative charge. So, here there is no hole. So, these electrons are in this side. So, it is a more negative the other side equivalent be is more positive ok.

So, what will happen? Because of this, what will happen? So, due to this Lorentz force here this charge separation as if here. So, this it will give electric field. So, this direction of the electric field will be positive to negative in this direction. So, this electric field along the y direction, but it is towards negative y direction, and we can write e y. So, we have applied electric field along the x direction because of that we are getting current, now because of magnetic field along the z direction there is a voltage there is electric field generated in the in our sample. And that is just along the y direction.

So, this electric field is called a hall electric field. This electric field e y is called hall electric field, E y is basically called hall electric field. Hall electric field right, electric field and corresponding voltage is called hall voltage.

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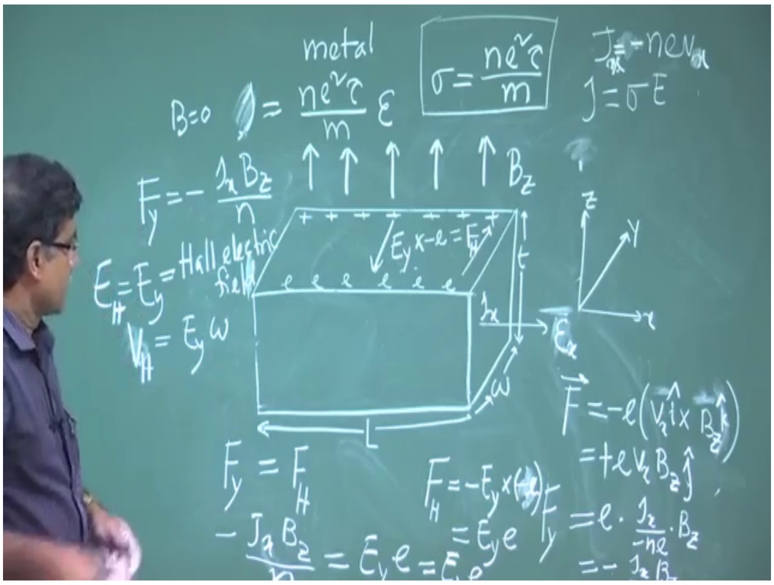

So, V we write V H, but it is along this y direction. So, V H equal to basically ey, and this separation right. So, this is w this is w. So, ew will be the voltage corresponding to this hall electric field. So, this is called hall voltage right.

So, this from here I can. So, this electric field because of this electric field, if this electric field this electric field does not form what will happen; because of this magnetic field magnetic field. So, all charge will try to move in this direction negative y direction, but all the hall all the time it does not happen. So, there should be some steady state and for this steady state we need some opposite force on this on this on this charge.

So, that opposite force basically will come when these voltage this this voltage what is called hall voltage or hall electric field is formed here or generated here. So, due to this electric field what will happen? So, it will act on this carrier my carrier is minus e negative charge right. So, this field was in this direction, and now because of this field electron charge. So, they is it will to get force. So, that is that is the that is n again Lorentz force right, because of electric field; so e minus e into y right.

So, these force due to hall voltage. So, it will act in this direction this force will act in this direction right. So, this force is basically it will be in this direction, positive x direction. So, so it will try to get back the electrons again pair towards positive direction; when this force was trying to get the electrons in this direction. So, these 2 has to be balanced, then only equilibrium condition steady state will arrive. So, this if y it is it is the minus j x. So, basically one has to analyst. So, F y along the negative direction this has to be equal to this.

So now note that here this is the electric field direction this e y is basically itself is negative right. So, just since electric field is in this direction. So, on negative charge this force will act other direction. So, it is positive direction right. So, if I consider the direction then basically this force is positive y direction. So, how we are getting positive or y direction? So, that force that force this is because of these force, because of hall electric field hall electric field if I right F H. So, F H F force due to this hall electric field. So, this F H will be, this F H has to be this F H has to be F H equal to my E y in this direction. So, I have to write if I consider the direction minus ey, and it is acting on this acting on this on this negative charge right. On this negative charge minus you have to write minus e right minus e. So, this is basically E y e.

So, that is now it is positive direction, along the y direction positive direction. This is negative direction, negative y direction. So, they are magnitude there. So, they with they are in opposite direction, and they will balance each other. So, I will I can write this. This is minus j x B z by n equal to here E y e. So, here also now we can use this, now I do not need direction either positive or negative. So, but this then I can replace this y by h. So, then this y I can replace by h so E H. So, this I can write E H hall electric field (Refer Time: 23:10).

So, ultimately what I am getting? So, from here I am getting E H equal to so I want to find out hall electric field. So, I am getting hall electric field e E H is hall electric field, because of this force is I do not need.

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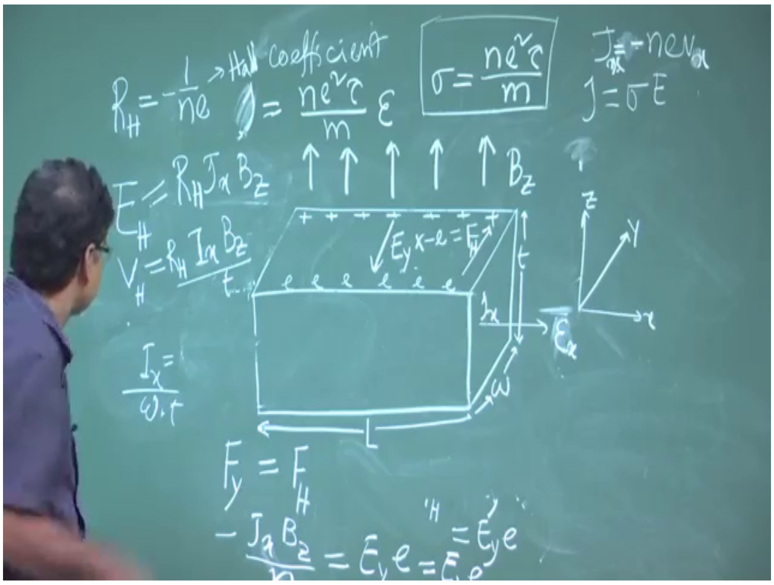

So, hall electric field equal to hall electric field equal to please just divide by n. So, I am getting minus gx B z by ne right. So, if I define R H equal to minus 1 by ne 1 by ne if I define. So, then this I can write E H equal to R H j x B z, there is the hall. So, R H it is called hall coefficient. It is called hall coefficient, it is called the hall coefficient right. Hall coefficient it is called hall coefficient, this it is will see what is this.

So, it is minus 1 by ne. And if we look at this; yes. So, then hall voltage, I can write hall voltage equal to now this y is basically I have replaced by h is w right. So, hall voltage this here let me write V h hall voltage equal to R H, and then I have to multiply it with just w; so here j x B z w right. So, that will be the hall voltage.

Now again we are not much familiar with j x right, we have familiar with current I x I. So, I have to multiply with the I x equal to I x equal to a area cross sectional area into j x right. What is the cross sectional area? This is the w into t that is the area w into d that the cross section; so w into t right. So, j x I can replace by I x w into t right. So, here you replace it here you replace it j x by I x divided by w into t right. Now this w you can remove this w, then you are getting R H I x B z by t right.

Now, this is very important formula, you know this very important formula. So, if I if current I x is flowing through these along the exact axis; so constant current if I set right applying some voltage. So, this constant current is flowing through this sample along the x axis. Now if I place the sample in a magnetic field of constant magnetic field of B. So, along the z direction; so it is B z.

So, what will happen here? So, there will be voltage along the y direction. So, I can measure this voltage I can measure this voltage. So, I have to just measure the voltage along this y direction. So, I can get directly this V H I can get directly, I x I can get directly, B z I can get directly right. Because this I applied these I have applied. So, I have applied constant magnetic field, I know the what is the magnitude of this magnetic field. I have apply constant current I x what is the magnitude of this from a meter I can know, on this what is the current is flowing through this and from this from gauss meter right you know the gauss meter is used for measuring the magnetic field from gauss meter reading I can get the magnetic field. And then then this how voltage the voltage another voltmeter I have to put across this. So, I can get I can measure this voltage V H right.

So, t is of course, from geometry one can find out the t a thickness of the sample from geometry one can find out.

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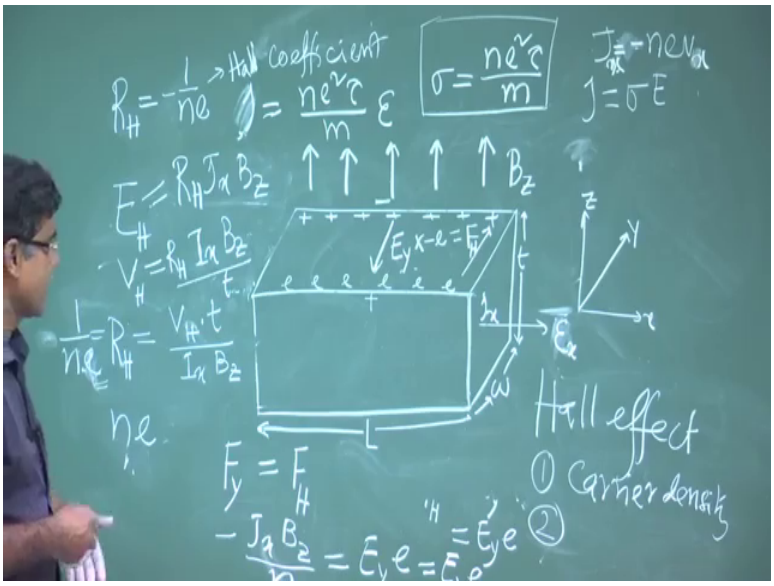

So, these also known one can measure or either. So, you can what you can get then you can get R H equal to V H into t divided by I x B z right. So, you can get the R H value. So, R H value is nothing but 1 by any right. So, any equal to you will get any equal to so from here you will get value of any you will get from here. So, this is the so I can replace this 1 by 1 by ne. So, negative sign is there negative sign is there negative sign is there right. So, from here I know the arrangement. So, from here I can find out ne value. So, this negative sign is basically taken care by this V H, ok.

So, when you will just, I think if this side is positive terminal of this your volt meter and this negative terminal of the voltmeter. So, along the so we have chosen in such a way these it is along the positive x direction positive this negative. So, all voltage you will get here, you will get here negative voltage. You will get here negative voltage. So, it is negative voltage or positive voltage that we have to set reference right. So, in this direction when I will set this reference; so when I will get whatever voltage that I will take as a negative, because I know this the for electron negative charge.

So, keeping this staple is fixed if I get this voltage just opposite sign, then it is positive voltage I will tell. And then this value this value automatically this value automatically whatever this R H value, because depending on the sign of this V H will get R H either positive or negative because of sign of V H. And then that will tell me that whether it is 1 by minus ne or 1 by plus ne. So, plus ne then I will tell this carrier is whole plus ne charge easy, but sine is positive. So, it is whole. So, this conduction is because of hole or if I get this value r is very negative. So, this then I will tell it is a charge negative charge eclectic. So, this conduction is for electron right, this conduction is for electron.

So, this hole this this over whatever I have discussed here this called Hall Effect, very famous discovery is called Hall Effect. And it is so important. It is so important that you can you can find out, what you can find out? You can find out the carrier density. Carrier density you can find, out carrier density. It can be n it can be p also in case of semiconductor p type semiconductor that will be pe, please positive charge. And the sign will tell you about the type of carrier whether it is hole or electrons.

So, this for in specially for semiconductor, it is very important to very important this effect is very important. And based on this effect we can we can tell which type of carrier is there in semiconductor. Either it is hole type or electron; that means, whether it is n type semiconductor or it is p type semiconductor. And what is the density of these of this carrier that also one can tell in p type it is; what is the density of there. So, this is important.

So, for whatever we have studied everything we try to fire in case of electrical property to understand the electrical properties. So, this fee electron theory band theory then in case of semiconductor in case of metal, just all theoretical calculation is to get the density of states to get the density of carriers. And how to measure this density of carrier, that one should know, one should be able to measure. And that can be measured using this fantastic effect hall effect. And it is so simple experimentally also one can measure easily.

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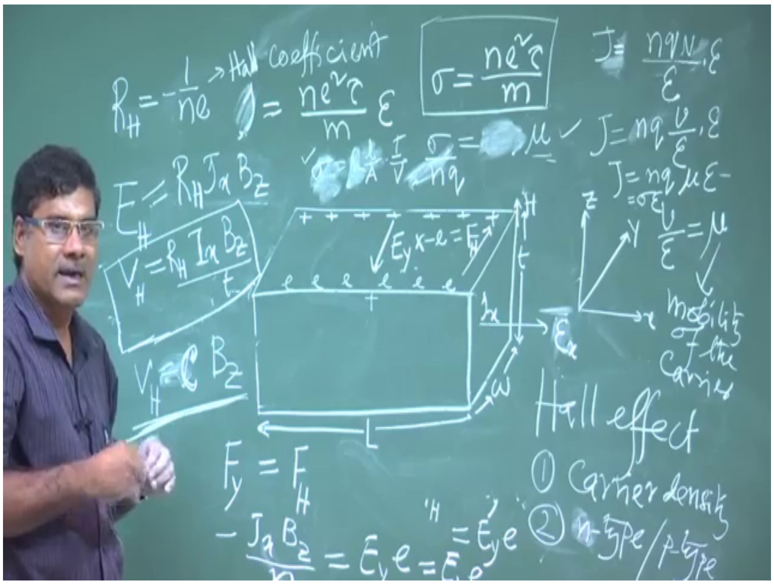

So, that is basically your, this measurement will tell you the area density. It will tell you the sign of it will tell you the whether it is n type semiconductor or p types in conductor right.

So, yes, so basically this form and another important fact is there that J equal to yes, another important fact I should tell you. So, in general I can tell that j, in general I can tell that je equal to nev without specifying the direction nev. And now if I define if I define if I define that this just divided by electric field, and then multiplied with electric field multiplied with electric field I think it is not clear. So, I am dividing this expression and multiplying this this electric field. So, this I can write J equal to minus n and again you forget this sign, you forget the sign the sign we are we using this whether it is electron or whether it is hole.

So now it just I am writing, but in general. In general, this I can write this e is as a q you can be whole or you can be electron. So, accordingly we can choose sign. So, in general if I write this way. So, I will not bother about the sign one can put sign whenever necessary. So, I can write nq this V by electric field into electric field. So, if I define this V by e this deep voltage, deep velocity per unit electric field if it is defined as a as a mu it is defined as a mu. Mu is called the mobility of the carrier, that is important mobility of the carrier of the carrier right mobility of the carrier. That is very important concept or parameter for studying the conductivity.

So, here what I can write? J equal to n q mu and then you see right. So now so J equal to sigma e J equal to sigma e. So now, sigma another form of sigma you are getting, another form of sigma you are getting. So, that is sigma another form of sigma you are getting that sigma. So, J equal to so this one can write get is sigma e. So, sigma equal to n q mu right nq mu. So, this see this is important because this conductivity it does the depend only on the on the carrier density. It depends on depends on the carrier mobility also. So, it is just like resistance resistivity no, because the velocity depends on the amount of electric field right. Now if I divided by this electric field now it is independent of electric field. So, it is like a constant right, ok.

So, mobility is more independent parameters like resistivity likes conductivity is different from the from the conductance difference from the resistance. So, that way this these the parameter mu is have significance. So, this conductivity is very important in that sense that it depends not only on the carrier density n, it depends on the mobility of the carrier also. Now mobility is for electron it varies in which band it is mobility of the hole it varies, in which band it is sometimes it becomes negative, sometimes like mass you know mass. Sometimes become negative some sometimes become positive whether it is in upper band or it is the bottom of the band etcetera.

So, that effective mass you have seen. So, this so we want to measure the mobility also, we want to measure the mobility also right; so to measure the mobility if I want to get mobility. So, from here I cannot get mobility, from here I cannot get mobility. So, for that what I need so I so here I have measured the hall voltage. And I got the got the got the things right. And what things I got? I got the carrier density, I got the whether it is n type or p type, but I cannot get mobility. So, to get mobility I have to measure the conductivity. That can be measured conductive what is conductivity? Conductivity is basically you know this I equal to yes. So, V equal to I R, V equal to I R right. V equal to I R so this if I so V by I equal to r V r and r equal to rho L by a I think yes V equal to rho L by a. So, this basically I can write yes sigma 1 by sigma right.

So, I can find sigma. So, sigma I can give this side sigma, and V by I means here I by I by v. So, I can do experiment, where I will apply voltage and measure the current say in this sample I will apply voltage and measure the current. Then I know the dimension of the of the of my sample what is the length what is the idea cross section area, then I will get I will get the c right. So, if I measure the conductivity, then I will get the I will get the sigma. Now if sigma is known if sigma is not conductivity is known, then if n is known yes n is known now because from here I get the current density. From hall measurement I can get the current density. So, come here n is known then you can find out is mu. So, mu you will get in terms of sigma by n q ok.

So, n from hall measurement one can get; sigma you can one can get from resistivity measurement, and then one can get the mobility. So, if you measure the resistivity or conductivity of your sample. And if you measure the hall voltage of your sample, then you can get all information on the all information about the conduct or about the parameter which participate in conduction. So, there is the carrier or carrier density there is the mobility of the carrier. So, there is these 2 are very important and of course, type of carrier and this that also one can know.

So, and one can tell which type of similar this p type or n type or both at the earth. So, that one can tell. So, that is what yes, yes, yes, I think another important fact is there if we looked at this expression I just you see. So, so whether I can use this formula for, whether I can use this formula for measuring for measuring the magnetic field. So, whether I can, I can make device using the Hall Effect what device I want to make? I want to make a device which will act as a sensor, which can sense the magnetic field and can tell me the magnitude of the magnetic field, or reading of the of the of the magnetic field. If I want to get that type of sensors using the hall effect. So, whether it is possible or not. So, for any sensor with the temperature sensor magnetic field sensor or gas sensor or whatever; so it has to so we get the signal we should get the signal from that sensor that electrical signal if I get electrical signal which will be proportional to that parameter, whether it is temperature or this magnetic field right or the density of gas.

So, that that I should get in terms of electrical signal, and this some relation with them, then I can use that property for device purpose. So, here you can see if I take a very small piece of sample. And set the current set the current I x current, if I said it is easy to set I will set the current. And then then the magnetic field whatever magnetic field I want to measure if I put this sensor to that in that magnetic field, in that magnetic field that value I do not know, but I want to know, I want to know.

So, what will happen? What will happen? This R H is constant of course, it is it is it is the property of the sample nothing to do it is this constant and this t constant. So, what I will get? I will only measure this this hall voltage. Now this hall voltage is hall voltage is proportional to mediate magnetic field right. And these if I keep them constant. So, this will be some proportionality constant say c some proportionality constant.

So now when B is increased we are increasing B. So, voltage is increasing. So, I can measure the voltage and after some calibration I can tell what is the magnetic field. So, this can so this this sample using this Hall Effect, this can be used for measuring the magnetic field. So, that is that is what it is there we use this sensor in or may elaborative measure the magnetic field. So, this is called hall sensor hall flow hall sensor, or hall flow, I have a proof arrangement with this current and if I put in magnetic field, then I will get the get the voltage. So, it sometimes one has to calibrate it then using that calibration all the time, because this calibration if I keep this is constant. So, the calibration factor is all the time it will work. So, I can use anywhere. So, I will get I will get magnetic field.

Now, important is sensor for sensor it is important that this how we are it is very important that the sensitivity of the sensor or regulation of the sensor, what does it mean? This sensitivity of the sensor means it very small. So, magnetic field is there. Now I have put my sensor now I am changing the magnetic field, but this voltage change is not much. So, it will not be sensitive to the small change of the magnetic field. So, our proof our device will be more sensitive if for small change of magnetic field, the change of hall voltage will be more, for small change of magnetic field this change of hall voltage will be more. So, that is so a one has to design the sensor. So, here we have scope you know. Here you see these things I kept constant right. So, R H I cannot control because this is the density I ne or pe whatever, so nothing to do with that. So, I have only I x and t in my hand. So, I x I cannot also put very high value, then this sample will be hot. So, I cannot put a higher current in the system; so kept it also current a particular suitable value ok.

After that this t is there, you see this is in denominator. Means, when t will be smaller t will be smaller. So, this factor this constant will be higher this factor will be higher. If t is higher so this factor will be. So, this constant will be higher or smaller it will depend on we can control with this. So, if c is higher then what does it mean? C is higher so small change of magnetic field since this constant is higher. So, this V H will be higher, because this is the multiplication factor right.

So does this, if you see any time in your lab or in higher education, this we are using this some proof for measuring the magnetic field. That is hall flow and in that hall flow there is a small sample and that sample is taken is a very thin. So, because that will 4 same magnetic field for this geometry I will get higher hall voltage. So, my sensor will be sensitive. So, whenever you see whenever we get some formula, always we should look at the parameter and try to find out whether we can use this effect for some any device purpose. So, for device purpose where when we are going to use then I have to think, how I can make it more sensitive. So, that is one has to look at it.

Thank you for your kind attention. I will stop here.