Introduction to Solid State Physics

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Lecture - 74
Electrical conductivity and Hall coefficient in semiconductors

In the lecture so far I have given you how the charge carriers, their number, their density changes with temperature for intrinsic and doped semiconductors. We want to now use this to understand the temperature dependence of the conductivity of semiconductors and we will also talk about Hall coefficient of semiconductors and why we do Hall measurements for semiconductors and how we can also use Hall measurements to make a good magnetic field meter using semiconductors.

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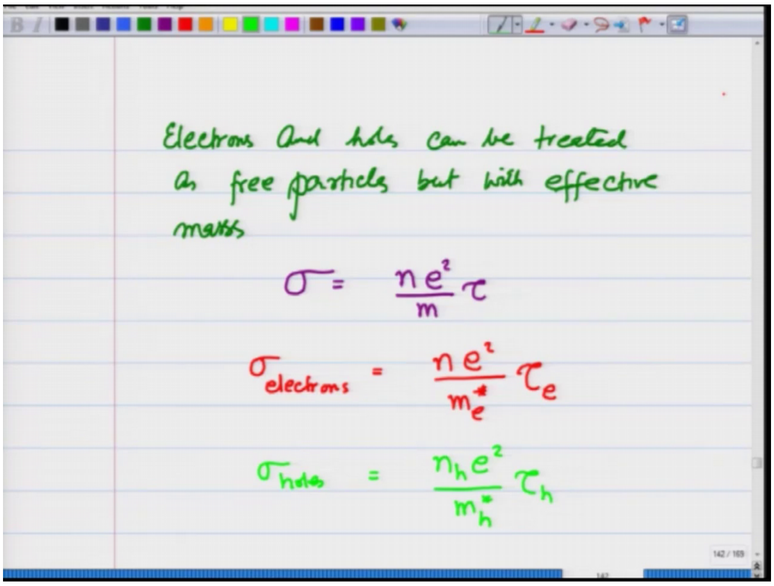

So, once we understand that the electrons and holes they are essentially at the bottom of the bands can be treated therefore, they can be treated as free particles, but with effective masses, then the formula for conductivities under the model of collisions and things like those is going to be exactly what we had obtained earlier n e square over m tau. This is the formula obtained earlier for the conductivity of free electrons. So, sigma due to electrons is going to be number of electrons times e square divided by m e star in the semiconductor times the collision time for the electrons.

And sigma for holes is going to be number of holes e square divided by m hole star tau holes, tau hole and tau electron could be different. So, we need not assume they are the same. Let us see first how the two contribute to the current.

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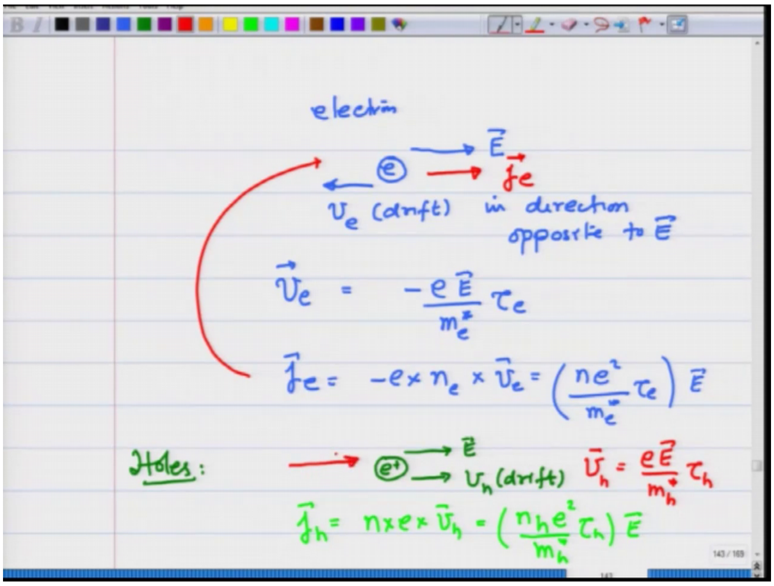

So, suppose I have an electron when an electric field is applied on the electron in this direction to the right it develops an acceleration in the opposite direction and therefore, V e drift is in the opposite direction and this V e comes out to be under the collision approximation minus e E over m. Now, I am going to use m e star tau e and the current density j due to e is going to be minus e times n e times the velocity V e and this comes out to be n e square over m e star tau e times E.

So, the current density is in the same direction as the electric field and let me show it here this is the current density due to electrons. How about the holes? Holes I can use exactly the same formula and so, here is the hole let me write it e plus, here is the electric field this would have a velocity drift velocity in the same direction as the electric field with the expression V hole is going to be e E over m hole star tau hole and the current j due to the hole is going to be n times e times V hole which is n hole e square over m hole star tau hole times E.

So, the current in the hole case is also in the direction of the field. So, both electrons and holes give the net current in the same direction as the electric field.

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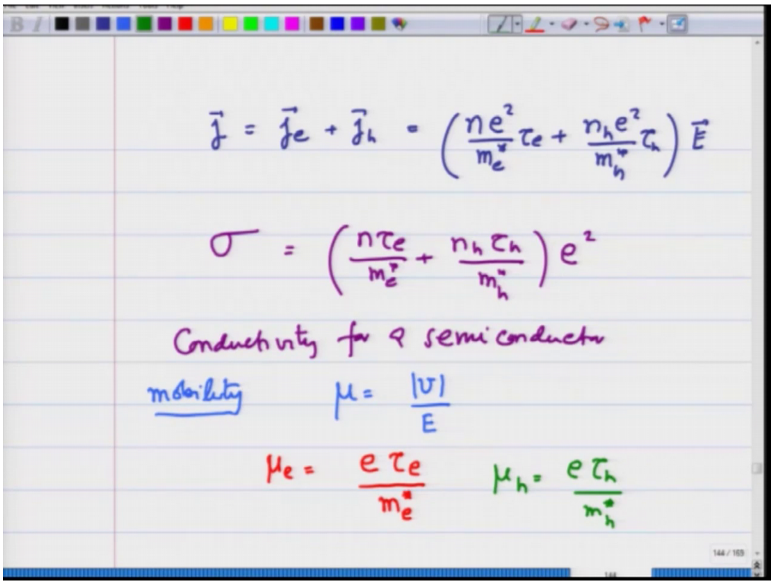

And therefore, the total current j is going to be added up which is going to be equal to n e square over m e star tau e plus n hole e square over m hole star tau hole times E. So, the conductivity for a semiconductor because of these two charge carriers is going to be n tau e over m e star plus n hole tau hole over m hole star e square.

Conductivity for a semiconductor; in the semiconductor, researchers or people who use semiconductors a slightly different terminology is used called the mobility and mobility mu is defined as the drift velocity obtain its magnitude divided by E and you can see that mu electron therefore, is going to be equal to e the charge times tau e divided by m e star and mu for the hole is going to be e tau hole divided by m h star.

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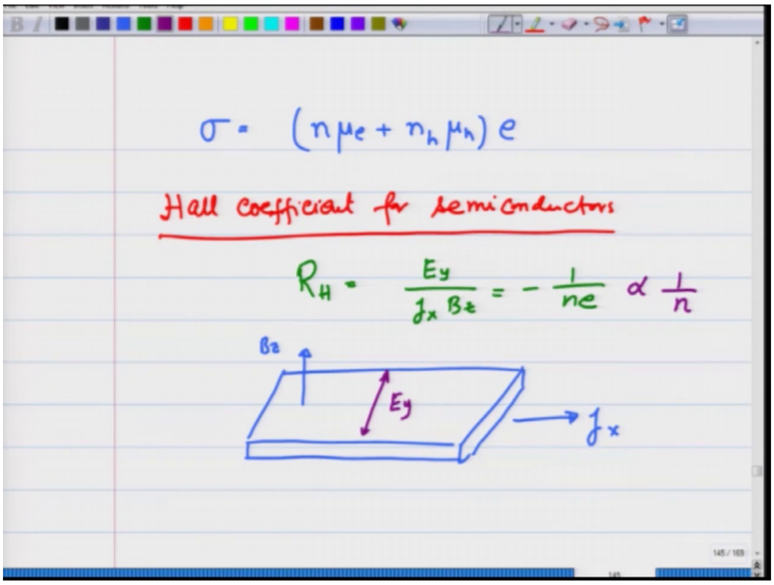

And therefore, the conductivity sigma can be written as n electrons mu e plus n holes mu holes times e. So, people talk in terms of mobilities. So, this is the expression for the conductivity. Next in the transfer of property I want to talk about Hall coefficient. This is important in semiconductors because number 1 it can give you the sign of the majority carrier. It also makes it possible to use semiconductors as hall probe that detect the magnetic field or measure the magnetic field because Hall coefficient for semiconductors comes out to be large.

Let us understand how? If you recall Hall coefficient was defined as E y over j x B z and came out to be minus 1 over n e. Let me explain these terms if I had a thin strip in which the current was flowing in x direction and we applied a magnetic field in the z direction, it developed a voltage in the y direction or developed an electric field in the y direction and this ratio was defined as the R H and now notice that this is 1 over proportional to 1 over n. Now n is very small for semiconductors compared to metals and therefore, R H, the hall coefficient for semiconductors this is going to be very large compared to metals.

The electric field that is produced across the y direction is going to be very large compared to that for a metal for the same j x and B z and therefore, these are very useful to find out the magnetic field, they are very sensitive to the magnetic field.

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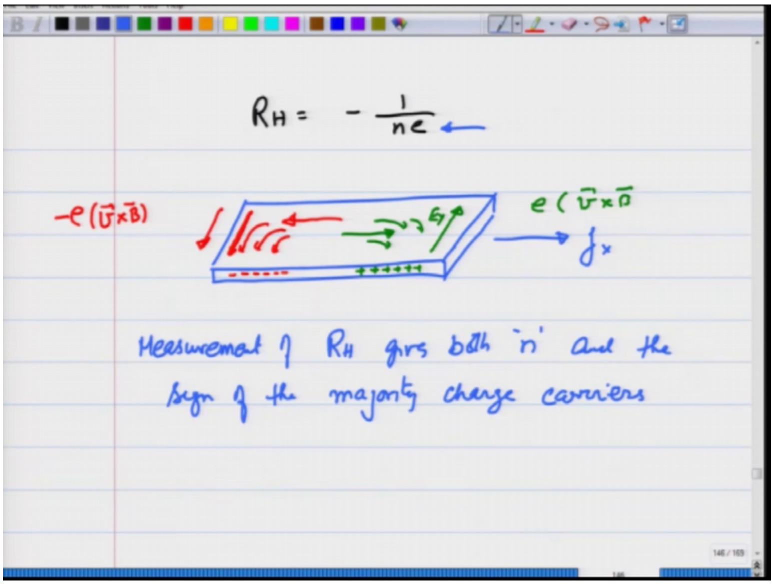

Now, since R H is given as minus 1 over n e depending on the charge e it is going to have different signs, let us understand that physically. So, again I will make this strip and this is a current j x in the strip. If the current is being carried by electrons, they will move in the opposite direction and they will experience a Lorentz force V cross B times minus e that will deflect them towards the lower side which I will show by arrows.

On the other hand, if I have current due to holes which I am showing by green then they will experience of force again in the same direction because their forces e V cross B. So, if the current is by electrons, the lower side is going to get negatively charged the electric field is going to be in the direction from upper edge to the lower edge like this.

On the other hand if, I have current flowing due to holes the lower edge is going to get positively charged and they produce electric field E y is going to be in the opposite direction. So, by measuring the sign of the field one can easily make out what kind of majority carriers effectively are there in the semiconductor and by measuring the R H, I can also make out what the number density is.

So, measurement of R H gives both n and the sign of the majority charge carriers. If we assume that the minority charge carriers are really number is very very small compared to majority charge carriers this n is very accurate otherwise it is really the difference in the n that comes out. So, this is the two transport properties that one usually measures in a semiconductor.

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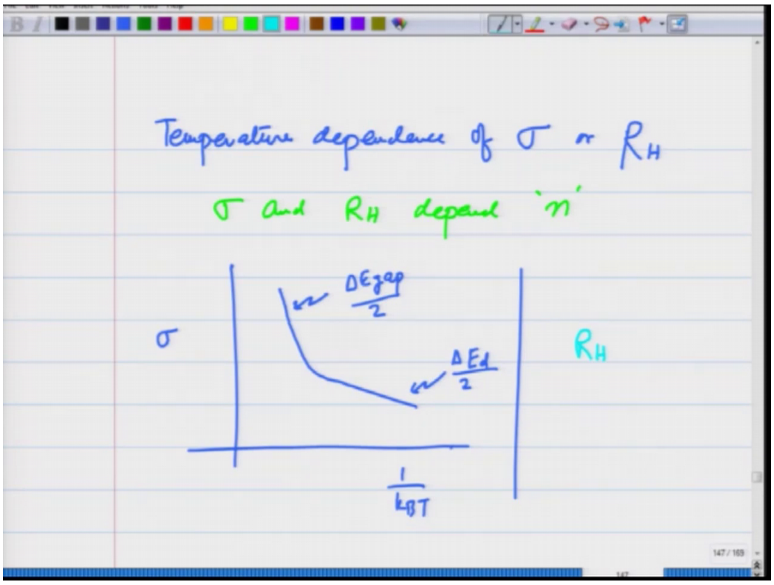

How about the Temperature dependence of sigma or R H? Since both depend on n sigma and R H depend on the carrier concentration they will also vary with temperature like the carrier concentration does. For example, if I were to plot the conductivity it will show two different slopes. If I plot it with respect to 1 over k B T, at low temperatures the slope is going to be proportional to E delta E d over 2 and at high temperature this is going to be of the proportional to delta E gap divided by 2 and similar thing you can expect for the R h also because it depends on 1 over n.

So, these are two properties that I have talked about because they are used by people who will work in semiconductors, the other thing is that you can now study and do learn about on your own.

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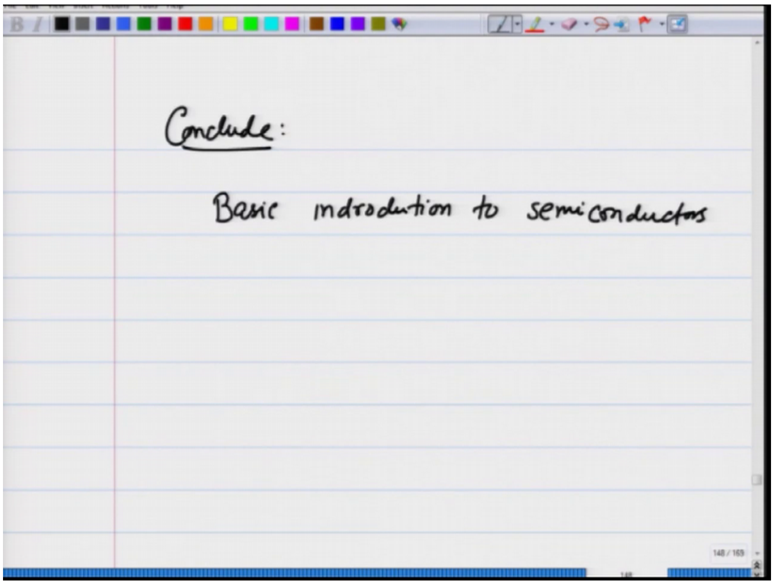

So, to conclude all these lectures of semiconductors what I have covered is some basic introduction to semiconductors. I have not covered certain aspects like where the band minima are, where the band maxima are, what are the some rules when the you know electrons go from one band to the other, what happens when they optically excited, I have not done that?

My main focus has been to show you the temperature dependence of these transport properties like the conductivity and the Hall coefficient, but with all this background you should be now able to read any book on the semiconductor devices because what we have done is essentially first or 1 or 2 chapters of any book on this topic. So, hopefully this is giving you a good start to study on your own.

Thank you.