# Solar Photovoltaics: Principles, Technologies and Materials

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## Lecture – 11
## Carrier Transport

So welcome to lecture 11 of for a Solar Photovoltaics course.

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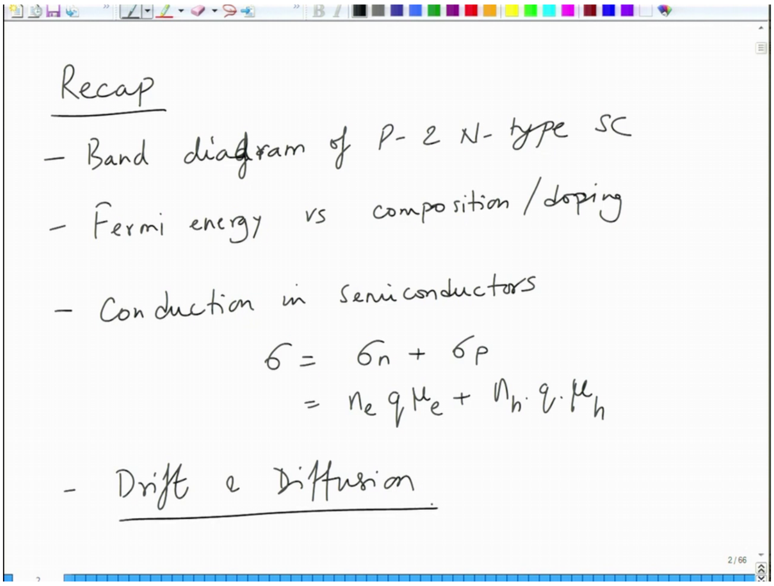

Recap

- Band diagram of P- & N- type SC
- Fermi energy vs composition / doping
- Conduction in semiconductors

$$\sigma = \sigma_n + \sigma_p$$
$$= n_e q \mu_e + n_h \cdot q \cdot \mu_h$$

- Drift & Diffusion

So, we will just first do a bit of recap of last lecture. So, in the last lecture we started talking about; we talked about the band diagram of a semiconductor of P and N type semiconductors. We looked at the variation or so we looked at the how Fermi level are aligned and P and N type semiconductors how do they vary as a function of dopant concentration. And so we saw that in a P type semiconductor the Fermi level is closer to the valence band edge below the intrinsic Fermi level.

And in the N type semiconductor Fermi level is above the Fermi level of intrinsic semiconductor that is slightly above the closer to the conduction band edge. And as it gets closer to conduction band edge upon doping or valence band edge upon doping it tends to become like a metal. So, when the difference between the Fermi level of P or N type and the conduction of valence band edge valence of conduction band edge becomes less than 3 kt then the semiconductor becomes a degenerate semiconductor it becomes like a metal behave such behaving like a metal then we also looked.

So, we looked at Fermi energy versus composition or let us say doping and then we started a bit of discussion on conduction in semiconductors. So, an conduction in semiconductor the conductivity of a semiconductor is given as so, sigma n plus sigma p so, it is for both N and P type carriers. So, sigma n would be due to electrons which is because of ne you can say q mu e and this would be n h q into mu h so, this would be the overall conductivity.

So, for a so we will take this discussion forward in this lecture and what we also did was we did a bit of discussion on what are the different types of currents that you can have so, you can have current due to drift and diffusion ok. So, we will again revisit some of these topics and further discuss these.

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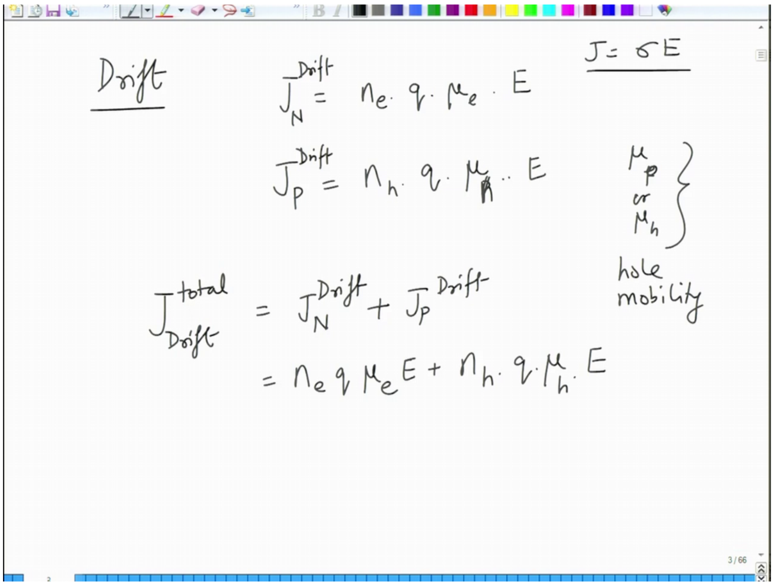

Drift

$J = \sigma E$

$$J_N^{Drift} = n_e \cdot q \cdot \mu_e \cdot E$$

$$J_P^{Drift} = n_h \cdot q \cdot \mu_h \cdot E$$

$\mu_p$ or $\mu_h$ } hole mobility

$$J_{Drift}^{total} = J_N^{Drift} + J_P^{Drift}$$

$$= n_e q \mu_e E + n_h \cdot q \cdot \mu_h \cdot E$$

So, as we saw that drift current is equal to J. So, you can say J N is equal to n e q mu e into E. Because J we know is equal to sigma E according to Ohm’s law ok. So, this is drift electron current and the drift peak whole current is n h q into mu p mu h into E.

So, you can write it as mu p or mu h these terms sometimes get interchanged ok. So, this is basically hole mobility. And we also looked at in the last classes the variation of mobility with respect to doping and variation of mobility with respect to temperature. So, as you dope it further a mole to keep dropping and has you increase the temperature again because of phonon scattering the mobility tops.

So, J drift current total drift current is so, J drift total will be equal to J N drift plus J P drift so this is drift. So, this will be equal to n e q mu e E plus n h q mu p mu h into E. So, that will the total drift current that we will have for a semiconductor.

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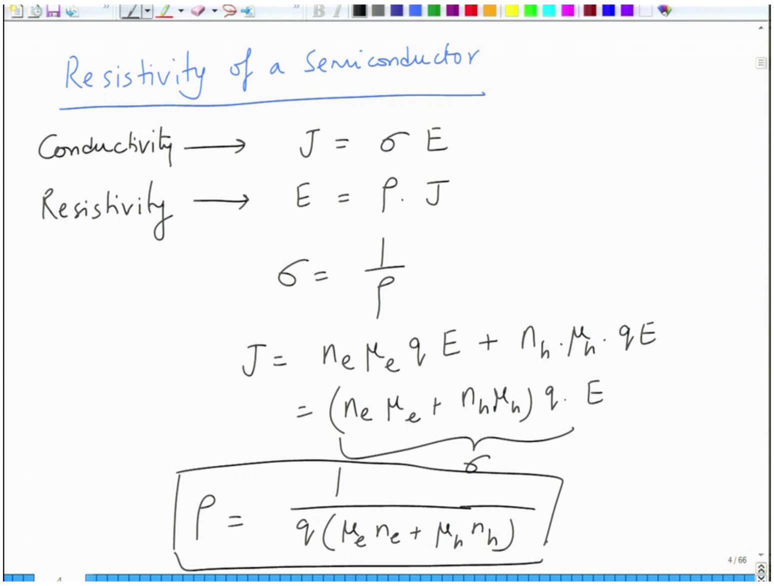

Resistivity of a Semiconductor

Conductivity $\longrightarrow$ $J = \sigma E$

Resistivity $\longrightarrow$ $E = \rho \cdot J$

$$\sigma = \frac{1}{\rho}$$

$$J = n_e \mu_e q E + n_h \cdot \mu_h \cdot qE$$

$$= \underbrace{(n_e \mu_e + n_h \mu_h)}_{\sigma} q \cdot E$$

$$\boxed{\rho = \frac{1}{q(\mu_e n_e + \mu_h n_h)}}$$

So, based on this we can define now the resistivity so resistivity basically. So, we write for conductivity we write J is equal to sigma E so, this is in terms of conductivity. And in terms of resistivity we write E is equal to rho J. So, which means sigma is equal to 1 over rho. So, basically resistivity is reciprocal of electrical conductivity. So, you can say that if J was equal to n e mu e q E plus n h mu h q E. If we take it out then this becomes n e mu e plus n h mu h into q into E.

So, this is a term which is sigma so, reciprocal of this will be the resistivity. So, resistivity is 1 over q into mu e n e plus mu h n h or ne mu e plus n h mu h. So, this is the electrical resistivity of semiconductors.

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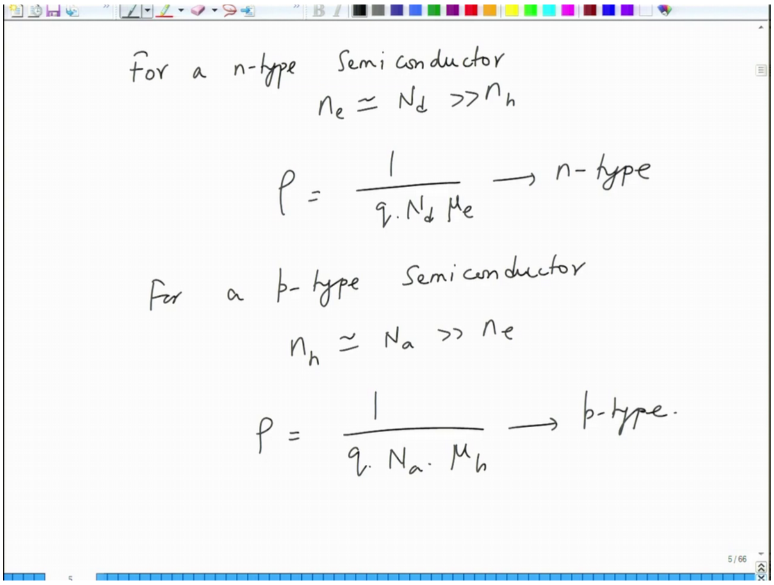

For a n-type Semiconductor

$$n_e \simeq N_d >> n_h$$

$$\rho = \frac{1}{q \cdot N_d \mu_e} \longrightarrow \text{n-type}$$

For a p-type Semiconductor

$$n_h \simeq N_a >> n_e$$

$$\rho = \frac{1}{q \cdot N_a \cdot \mu_h} \longrightarrow \text{p-type.}$$

Now, you can obviously, see from this if you have for n type semiconductor you know that n e is equal to N d which is a lot greater than n h right. So, as a result the resistivity of an n type material will be equal to 1 over q you can say N d into mu e for a n type right. Similarly for a p type semiconductor since n h is equal to N a which is a lot greater than n e you can define rho as 1 over q N a into mu h this is for p type semiconductor.

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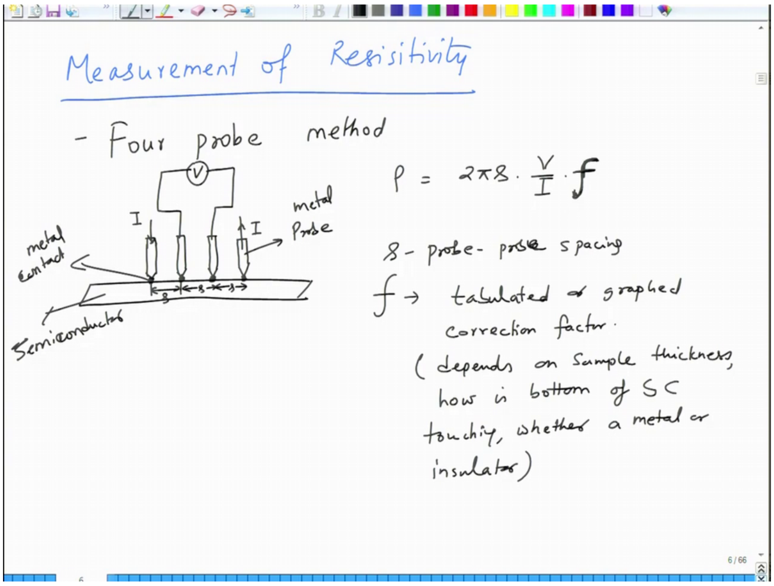

Measurement of Resisitivity

- Four probe method

$$\rho = 2\pi s \cdot \frac{V}{I} \cdot f$$

s - probe- probe spacing

f → tabulated or graphed correction factor.
( depends on Sample thickness, how is bottom of SC touching, whether a metal or insulator)

Now, the way I mean of course, so resistivity measurement in this case measurement of resistivity is basically done using what we call as four probe method four probe method.

So, essentially four probe method is the one which because metal and semiconductor often have contact resistance and for measurement of conductivity you would require metal contacts to be deposited.

So, to discount the effect of contact resistance in calculation of resistivity generally we use this four probe method instead of two probe method which is generally used for metals what we have here is we have. So, if this is your; if this is your wafer and on the surface of wafer you make four contacts equally spaced contacts. So, what we have here is? so, we have four probes here.

So, this is the first probe, this is the second probe and from these you flow the current in. So, this is for I so current is flown in this fashion and these are the other two probes which are connected to a voltage measuring device. So, you measure the voltage across these. So, the spacing between these is s let us say ok. So, do you are using two probes for flowing the current in and out at inert.

So, outer two probes for current to flow and the inner two probes to measure the voltage. And this prevents you to this the contact resistance which is between and that the tip and the semi conductor. Because if you will have to deposit a metal contact pad at this point and often there is a contact resistance to discount the contribution of voltage drop at that contact resistance you use this for probe method. So, essentially the resistivity is computed as rho is equal to 2 pi s V divided by I into a factor f ok.

I can write it differently this is the factor f and this factor f is basically calculated by doing the by the plotting. So, you can say that s is here probe to probe spacing and f is you can say at a tabulated or graphed correction factor. So, if you do the measurements at various voltages and currents you can get this and this depends upon sample thickness and whether the bottom of semiconducting.

So, this is semiconductor here this is the metal contact and this is the probe metal probe. So, it depends upon whether how is the, but. So, whether this so, on what surface is the semiconductor kept basically that is what. So, it is a easy method generally very useful method for measuring the photo resistive so.

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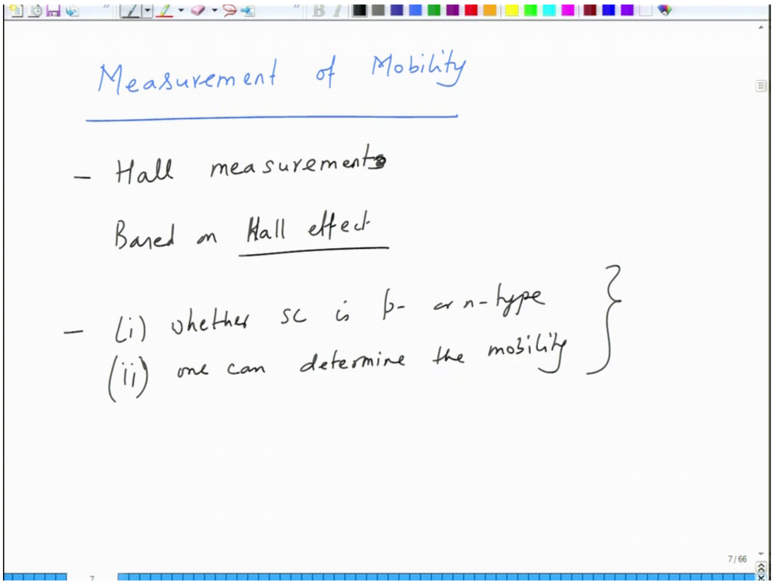

Measurement of Mobility

- Hall measurements

Based on Hall effect

- (i) whether SC is p- or n-type
(ii) one can determine the mobility

And the measurement of mobility is done through hall measurement. Hall measurement which is basically you have a current carrying conductor and you apply the magnetic field. So, you basically measure the hall voltage or so, basically based on Hall effect capital a Hall effect.

And this will tell you whether one it tells you whether semiconductor is p or n type. So, by the sign of the Hall voltage you can find out whether it is a pure n type semiconductor. And secondly you can one can determine the mobility carrier mobility can be determined. So, Hall effects you can find any book on Hall effect and this can do these measurements.

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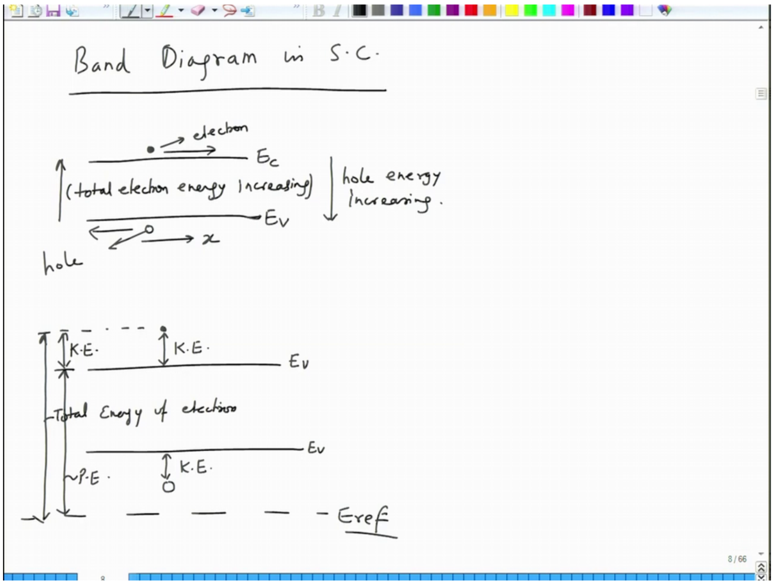

Now then we next we move to in semiconductors before we go to diffusion you need to know about the same energy a few things about energy band diagram. So, in semiconductors so semiconductors band diagram and there are some terminal there are some terminologies that you have to know. So, for example, if you have a semiconductor band diagram like this is your EC this is your EV conduction band edge in the valence band edge and this is basically the distance x ok. So, as you go away up from is EV to EC the electron energy is basically increasing.

So, this is total electron energy increasing right. And if you have the representation of carriers is basically generally electron is depicted as a dot and our fields circle and hole is depicted as a empty circle. And the carrier motion is opposite so, if electron if hole moves this way electrons move in this way the motion is opposite and hole energy will decrease in this fashion. So, this is hole energy sorry increasing this is hole energy increasing this is increase in whole energy. And if you have a carrier so if I draw another picture here so, if you have a carrier for example, little bit above the valence band then this much amount of energy which is available to the electron is basically the kinetic energy of electron. And if you have a hole sitting somewhere here then with respect to EV this much around energy is the kinetic energy of hole.

So, if you want to now measure for example, with respect to electron. So, this is the energy level at which electron is and let us say you have certain reference energy level E ref. Then the potential energy of electron will be equal to. So, this is the total energy right of electron out of which this is the potential energy contribution. And this is the kinetic energy contribution for electron. Another thing which is important in semiconductors is the band bending ok. Band bending generally happens because if you have differences for example, in electric field or if you have differences in any other thing.

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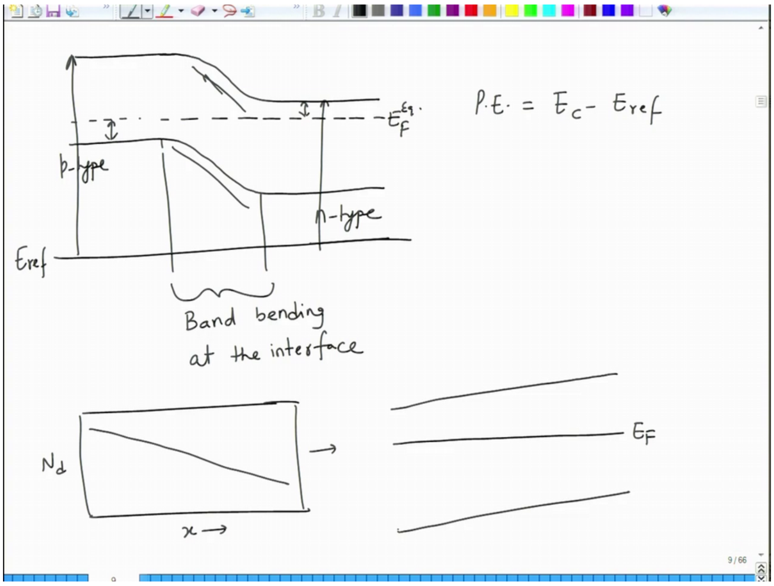

So, essentially let us say you have a if you have a so band bending can be represented by something like this. For example, if your semiconductor is non uniformly doped. If it is non uniformly doped which means it is Fermi level will be different at different places. If it is Fermi level is different at different places which means since Fermi level is different at different places. But chemically the material has thermodynamically material has to stay in equilibrium which means your material will have so you can have a situation like this in which Fermi level is equilibriated like this.

So, this is the E F equilibrium I am right other way round. So, you can see that in this side you have valence band being closer to Fermi level and this side you have conduction band being formal. Now to equate the Fermi level on the two sides because you have two compositions on two sides they has to be a band bending. So, this is where you see that there is a what we call as band bending at the interface. And this is because of differences in composition of two sides.

Fermi level is different on one side Fermi levels is other on other side, but since they are connected to each other chemically electrochemical speaking material has to be at equilibrium thermodynamically. So, to ensure that material is a thermodynamic equilibrium the Fermi level is at the same level throughout the material. But what it requires is that shifting off the conduction and valence band will be in shifted in different parts of material in such a manner so, that you have band bending at the interface.

So, this is the region at which so, this is you can say in this region you can say it is p type in this region you can say this is n type. So, if you have these composition differences you can have another picture like this let us say you have minute you have a semi conductor piece of semiconductor in which the composition varies like this as a function of distance let us say this is Nd, as a function of x all right. If you want to plot for this how will you plot for this? So, what this will have is since this is varying Nd is varying, but material will remain is thermodynamically equilibrium which means Fermi level will stay here.

On this side the Nd is higher on this side the N d is lower all right which means the valence band will be farther on this side a conduction band will be farther on this side and closer on this side. So, your this would be your energy band diagram sort of it is exaggerated. But this is the way you will have band bending taking place in the material of course, it is I do not know if it is NOP I mean here it looks like as if you know you have gone from very n type to very p type, but this is how it will probably vary in a material ok.

It may not be to this extent if it is purely n type the slope may be something like this. Let us say the slope may be something like that ok. So, you can see again you have a band bending; band bending means you have some electric field here so, basically you have a electric field here in this region ok, I will come to that. So, essentially in such a situation if you have band bending. Then if you have a reference energy level is this E ref then your potential energy is changing as a function of distance. The potential energy is something here and potential energy is something here right. So, basically so you can say that PE in this case is equal to EC minus E ref all right.

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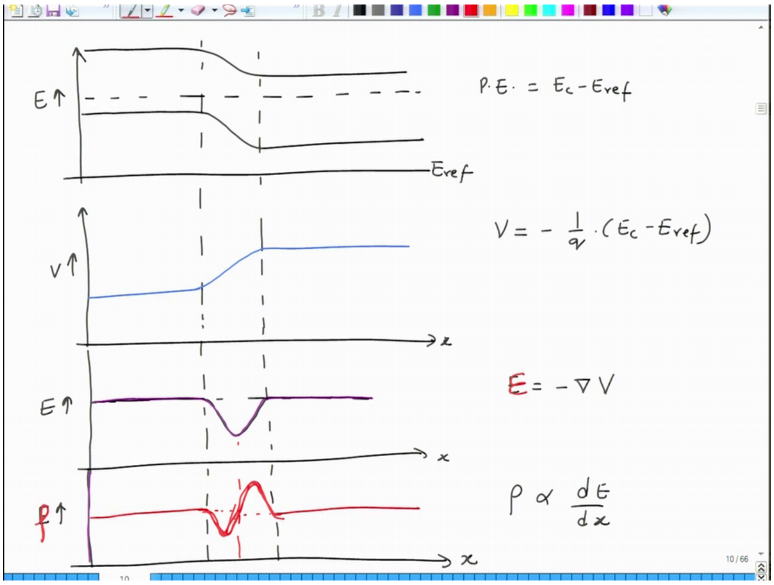

Now if potential energy is changing what it means is that. So, if I now draw the similar picture in such a fashion. And if I say PE is equal to EC minus E ref. Now if I want to draw this is the E ref and this is what is PE is measured as ok. If I now want to determine what is the potential V as a function of distance x? The potential goes as according to laws of electro statistics minus 1 over q into EC minus E ref ok. This is the definition of potential on the relating the electron energy with the voltage or potential. So, this goes as because potential is nothing, but E divided by q, but q it if it goes as negative of energy.

So, this goes as basically you can see since this goes in this fashion the potential will go in other fashion so, it will go something like this fashion ok. Now let us plot the electric field this will be useful when you learn the pn junction electric field is minus of del V right. So, electric field by definition is minus of del V. If you now plot the electric field this is so, in this part it is 0, in this part at 0. So, it is 0 here; it is 0 here, but it goes as something like this in this region right somewhere here you will have change of slope right. So, this is how electric field will plot itself.

Now, if you want to plot another thing which is called as charge density. Now we have plotting charge density which is proportional to dE over dx. So, if you now want to plot charge density and if you again take this as a so, this will be essentially something like that the charge density essentially you can see the negative charge density is equal to positive charge density within the band bending region.

So, essentially electric field is symmetric here so, total amount of negative charge is equal to total solid has to be at the end electrically neutral which means total or positive and total negative charge should balance each other. So, that is what will happen here. Now let us move to so this is an important exercise how to draw the energy band diagram. And from the energy band diagram how to determine the potential, how to determine the electric field, how to determine the charge density sorry this should be rho ok. And remember potential energy is with respect to a reference and for electron it goes increasing in the opposite in the up direction and for the hole it goes up and increase in the other direction ah

Potential is minus of let us say delta E divided by q minus of E divided by q electric field is you have to you have to watch out between the E for energy and E for electric field. So, maybe you can write this as in this fashion. So, the electric field is nothing, but minus of del of V by definition and then charge density is proportional to electric field gradient dE by dx. So, these are the four definitions that you have to remember. And this tells you how to draw the potential versus distance, energy electric field versus distance and charge density versus distance for a semiconductor and it is bend.

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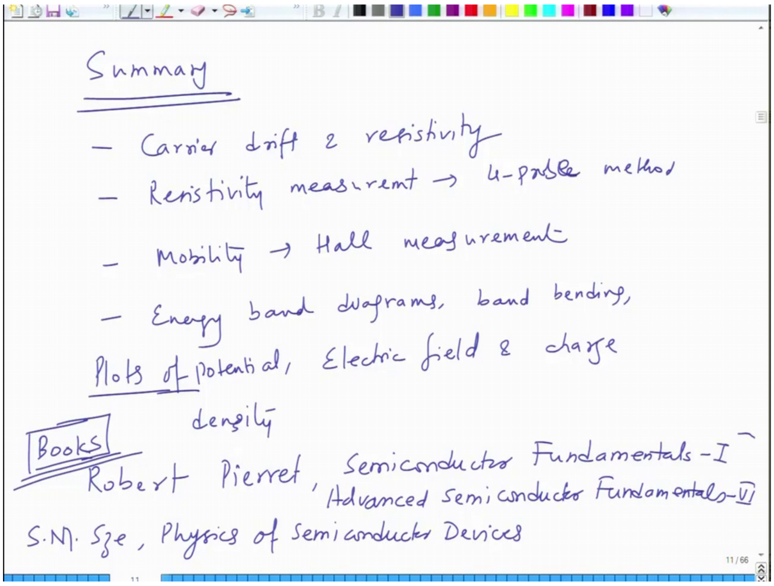
Summary

- Carrier drift & resistivity
- Resistivity measuremt → 4-probe method
- Mobility → Hall measurement
- Energy band diagrams, band bending,

Plots of potential, Electric field & charge density

Books

Robert Pierret, Semiconductor Fundamentals - I
Advanced Semiconductor Fundamentals - VI

S.M. Sze, Physics of Semiconductor Devices

Now, let us move to the next topic called as carrier diffusion. So, what we will do is that we will do I carry a diffusion in the next class. So, let me just summarize what we have done in this class. So, in this class essentially we have looked at a carrier drift and resistivity which is inversely proportional to the conductivity. Then we looked at resistivity measurements which is made by 4 probe method.

Then we briefly talked about mobility measurement which is done using Hall measurement. And then we looked at the energy band diagrams band bending, plotting of potential, electric field and charge density. So, these are important exercises you will have to do at some other systems considering other situations at home.

I would recommend you to go through this book by Robert Pierret Semiconductor Fundamentals volume I and Advanced Semiconductor Fundamentals volume VI. You can also go through S. M. Sze Physics of Semiconductor Devices this is again a very good book to give you idea about the semiconductors.

So, these are a few books which may be useful for you to improve upon your understanding of semiconductors in general. Specially these two volumes by Pierret Semiconductor Fundamentals volume I and semi Advanced Semiconductor Fundamental volume VI these are really good books for improving your understanding of semiconductors ok. So, we will stop here we will do the next lecture in which we learn about the diffusion.

Thank you.