Solar Photovoltaics: Principles, Technologies and Materials
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Lecture - 10
Electrical Properties of Semiconductors

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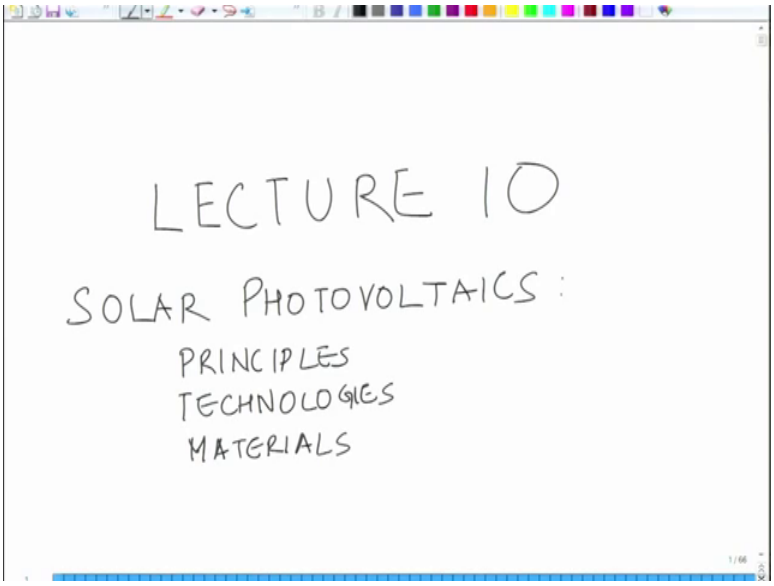

LECTURE 10

SOLAR PHOTOVOLTAICS :
PRINCIPLES
TECHNOLOGIES
MATERIALS

So, welcome again to lecture number 10 of this course on Solar Photovoltaics.

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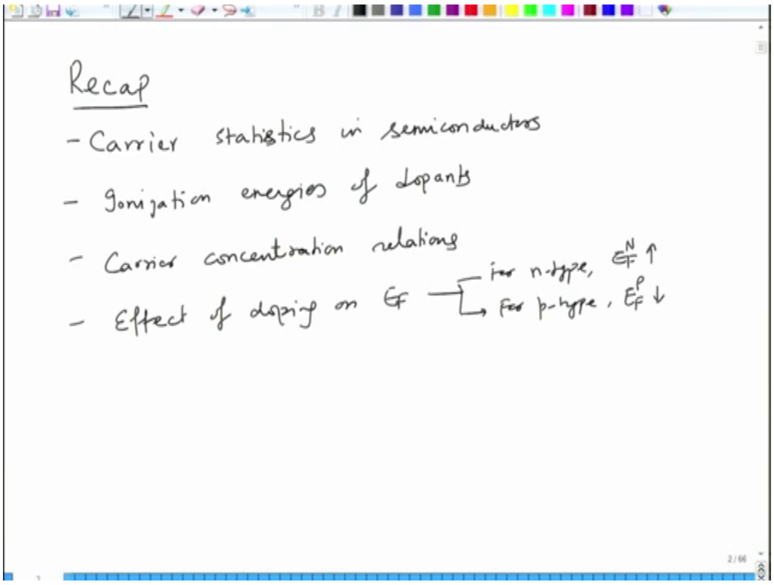

Recap

- Carrier statistics in semiconductors
- Ionization energies of dopants
- Carrier concentration relations
- Effect of doping on E_F → for n-type, $E_F^N \uparrow$; for p-type, $E_F^P \downarrow$

So, in the last lecture, we were talking about carrier statistics and semiconductors. So, we talked about the carrier statistics in semiconductors. We also looked at the ionization energies of dopants. And then we looked at carrier concentration relations, and finally, we have direct effect of composition on effect of doping on E F. So, basically we said that for n-type E F is E F increases as compared to E F i. And for p-type E F, so you can say E F n and this could be E F p this goes down with respect to E F i in the intrinsic Fermi level ok.

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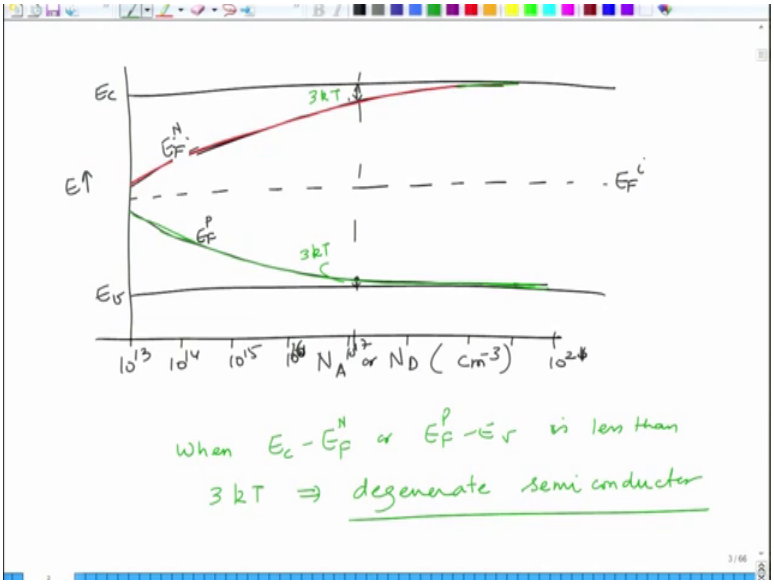

When $E_c - E_F^N$ or $E_F^P - E_v$ is less than $3kT \Rightarrow$ degenerate semiconductor

And if you if you plot, it is going to look like this. So, this is your energy scale, this is let us say N A or N D typically given in in to centimeter cube. So, let us say if this is the value of E F i then they tend to and if this is let us say your E c, and this is let us say your E v ok. Then Fermi level tends to so let us say you are plotting from 10 to power 13 to I do not know 20 and about 20 ok. So, we want to have 14, 15, 16, 17, 18, 19 and 20, 21 ok; 14, 15, 16 and so on and so forth. So, this tends to it about somewhere in this range. The semiconductors tend to become it is almost sort of a straight line. And it gets very close to and from this side also it tends to sort of.

So, when this gap is so you can see that at very high doping level the Fermi level, so this is E F n, and this is E F p, let we put it different this color. And this would be for the p-type ok. So, you can see that as it approaches high doping levels, it tends to touch the conduction band, which means it becomes like a metal. So, since the E F n and E F p get closer to E F n, and E F p, E F n gets closer to E c and E F p gets closer to E v as you keep doping the material. They comes a limit when this gap is smaller than 3 k T. So, this is the limit you have of 3 k T ok; so, when the gap is smaller than 3 k T, then what the semiconductor converts into what we call as a.

So, when E c minus E F n or E F p minus E v is less than 3 k T, then what we make a semiconductor is called in this case as degenerate semiconductor. It becomes like a basically it tends to become like a metal. So, essentially Fermi level is almost merged into the valence or conduction band right. So, this is the effect of concentration on Fermi level.

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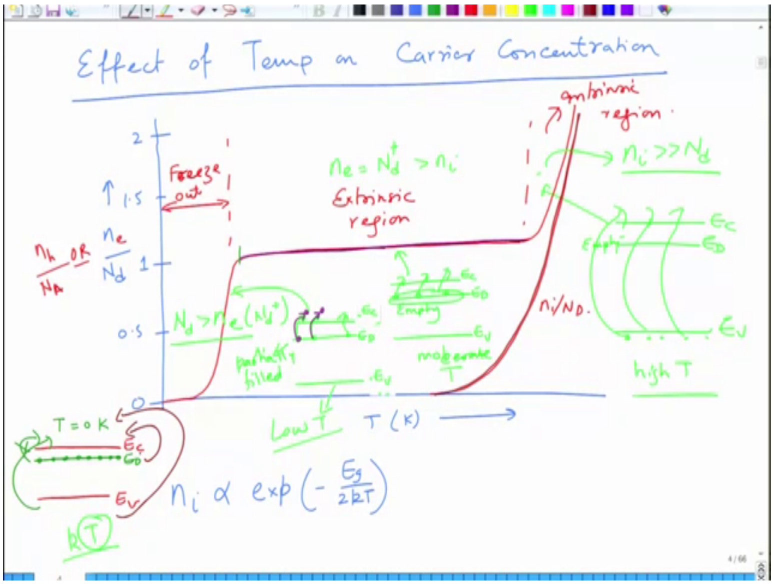

Effect of Temp on Carrier Concentration

Now, let us look at the effect of carrier concentration, effect of temperature on the carrier concentration. So, let us see temperature on carrier. Now, in case of so when you plot let us say for a n-type semiconductor, n divided by let us say N d as a function of temperature in Kelvin ok. So, n divided by n N d will be equal to 1 at certain place, then it will be 0 at certain place, it will be half, and then it keeps increasing as you go to high temperatures so 1.5, 2 and so on and so forth.

Now, what happens in semiconductors is for a you can see that for n-type semiconductor for an intrinsic semiconductor n i is proportional to exponential of minus E g by 2 k T. So, there is a exponential dependence upon temperature for the carrier concentration. And carrier concentration at finite temperature keeps increasing exponentially as a function of. So, if you plot n i, n i would follow a behavior like this ok, exponential kind of behavior and i divided by N d. So, this is n i by N d ok.

Now, for the same thing if you plot for extrinsic semiconductor and initially the carrier conductivity, the carrier concentration is very low or almost equal to 0, then it keeps increasing. And then it flattens out at some temperature, and then it starts following this intrinsic behavior. So, there are three regions in which carrier concentration in a semiconductor changes.

The first region is called as freeze out region, and this is called as extrinsic region, and this is called as intrinsic region ok. So, initially what happens is that initially so why, what is the meaning of this extrinsic region. So, when you look at this at the 0 Kelvin, at 0 Kelvin let us say this is the situation, this is your E v this is your E c and somewhere here we have E D ok. Now, when at when the material is at 0 Kelvin, all the electrons which are sitting at E D.

So, when T is equal to 0 k, they do not get excited to E c, which means there is no carrier concentration. And since these carriers cannot reach here, there is nothing which can reach here also. So, as a result the carrier concentration is very close very is 0 at 0 Kelvin. And as you slowly increase the temperature, because there is a because there is a certain energy has to be crossed, the carrier concentration starts increasing only at a certain temperature. And it keeps increasing until your temperature is high enough, so that all the carriers from donor levels are able to excite to the conduction band.

So, this is when you reach the boundary of extrinsic region, when n becomes equal to N d, which means all the electrons, which you have in conduction band are because of donor impurities or in acceptor in the p-type semiconductor, it will be equal to the acceptor carrier, acceptor impurity concentration. So, you can write this you know it should it could be equal to. So, this is n e this could be n h divided by N A OR or for, for p-type. And for p-type instead of E D you will have E A.

So, it continues to remain in extrinsic region until you reach significantly high enough temperature, so that you are able to excite now the electrons from the variance to the conduction band in significant numbers. So, when that starts happening, your intrinsic carrier concentration takes over the extrinsic carrier concentration. So, you can say that in this region n i outweighs N d. In this region n e is equal to N d larger than n i ok. In this region your N d is larger than n e, because you are not able to ionize N d ok. We can say that this is equal to N d plus here you can write n.

So, donor impurity atoms are not ionized as a result you electron concentration is lower in the lower temperature region. When you reach sufficient and high enough temperature all the donor atoms gets ionized, as a result all the electrons, which are in the conduction band are due to donor atoms. And hence their concentration is equal to concentration of donor atoms, but it is far bigger than the intrinsic carrier concentration, because you are still in the low temperature regime. When you reach high temperatures, then intrinsic carrier starts building up in number and soon they take over the extrinsic character. So, as a result semi conductor always shows three regimes - freeze out, extrinsic and intrinsic.

What happens at low temperature? For example, so we looked at 0 Kelvin. At low temperature what will happen is that you will have, so this is the valence. So, this is E C, E V, E D. So, you had some electrons hopping over here ok. And so this will perhaps correspond to this state let us say, somewhere here E C, E V, E D, all the electrons from here have hopped over.

So, this is empty, you can say this is empty, and this is you can say partially filled, so all the electrons have hopped over right. And here somewhere here at that, so this is let us say at moderate temperature this is at moderate temperature, this is at low temperature. And at very high temperature what you will have is basically this is E D, this is E C, this is E V, this is empty, all the electrons have crossed, but even from here the electrons cross. So, they start jumping here ok, this is at high temperature all right. This response to this region. So, this is how temperature carrier concentration varies in semiconductor as a function of temperature.

Student: Low Temperature (Refer Time: 12:10).

Sorry.

Student: Low temperature (Refer Time: 12:14).

No, low temperature; what low temperature means is that, see E V, E C are fixed, this is the donor energy level. So, when the atoms, when the electrons the impurities, which are to which this donor level corresponds to they do not get ionized, they certain amount of ionization energy, which is thermally provided. When the temperature is very low, then thermal energy is k T right. When T is very low, this k T is very low. And k T is very low you not able to excite the electrons from here to here. So, which means there are no electrons for conduction, the electrons were supposed to come from the donor level, but they cannot move to conduction band, because the thermal energy is very low.

So, as you keep increasing the temperature to higher temperatures, you get enough thermal energy to overcome the ionization energy of donor, donor atoms, as a result the electrons from this stage, they go there, and at slightly higher temperature. So, they start going, but they do not all of them go it is a probabilistic process right. So, at slightly higher temperature, all of them leave at lower temperature only some of them leave, and it is within this range all of them have left. So, within this range, since once all the donor atoms lose their electrons, there is nothing more to come. As a result the electron concentration stays flat. And you are not able to increase the n i substantially only until you reach a substantial temperature beyond which n i increases fast enough.

So, these two curves in some sense, if you look at the lower curve, this curve, this is the intrinsic part. So, these two curves the top and the bottom, they are competing with each other ok. So, why, what is this competition? You have to move electrons from here to here, and you have to move electrons from here to here. So, obviously, from for electrons to move from valence to conduction band, you will require larger energy. And hence it happens only at high temperature. At low temperature, you were only able to excite electron from the donor to conduction band, and that is why the extrinsic behavior dominates at lower temperature ok, and same will happen in case of p-type semiconductor.

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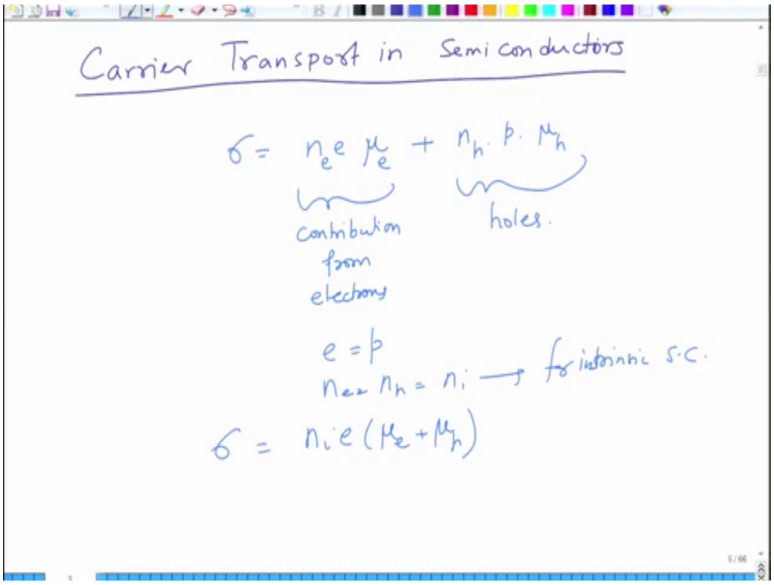

Carrier Transport in Semiconductors

$$\sigma = \underbrace{n_e e \mu_e}_{\text{contribution from electrons}} + \underbrace{n_h \cdot p \cdot \mu_h}_{\text{holes.}}$$

$$e = p$$

$$n_e = n_h = n_i \rightarrow \text{for intrinsic s.c.}$$

$$\sigma = n_i e (\mu_e + \mu_h)$$

Now, let us see having seen the effect of, having seen in some detail the carrier statistics, now let us see what is the effect, what is the carrier action or carrier transport. So, just like we write for metals, for metals, we write sigma is equal to n e mu right, where n is the electron concentration, e is the electronic charge mu is the mobility. Now, this is for metals, because we are in metals we only consider one carrier as a moving especially, which is the electron.

In case of semiconductor, we add another term here, so this is n e e mu e we also consider on the carrier which is n h p mu e and mu h. So, this is the contribution from electrons, and this is the contribution from holes. Now, if you say that e is equal to p, and n for a for intrinsic semiconductor, n e is equal to n h is equal to n i for intrinsic semiconductor, then you can write sigma to be equal to n i e mu e plus mu h ok. So, depending upon the relative magnitude of mu e and mu h, one of them will dominate.

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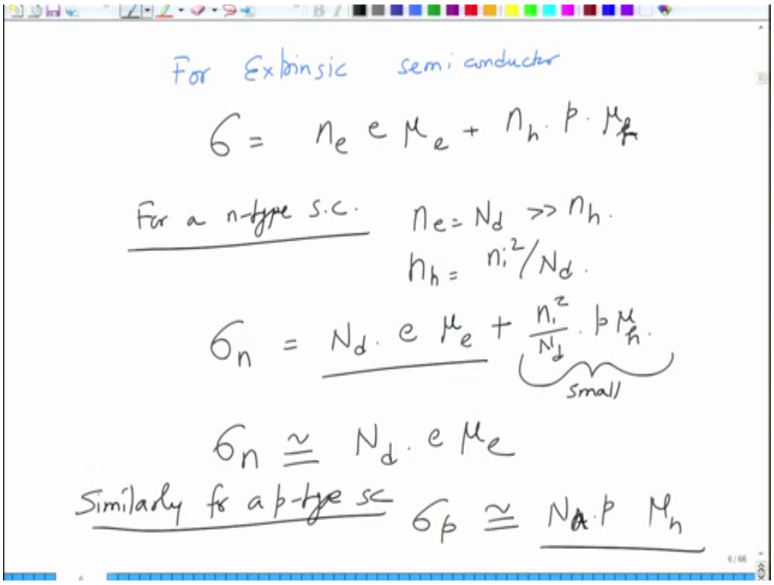

For Extrinsic semiconductor

$$\sigma = n_e e \mu_e + n_h \cdot p \cdot \mu_h$$

For a n-type s.c. $n_e = N_d >> n_h$.

$n_h = n_i^2 / N_d$.

$$\sigma_n = \underline{N_d \cdot e \mu_e} + \underbrace{\frac{n_i^2}{N_d} \cdot p \mu_h}_{small}$$

$$\sigma_n \simeq N_d \cdot e \mu_e$$

Similarly for a p-type sc $\sigma_p \simeq \underline{N_A \cdot p \mu_h}$

However, for extrinsic semiconductor, the expression changes a bit. So, we are saying that sigma is equal to n e e mu e plus n h p mu e ok. So, p is the hole charge, and e is the electronic charge which are plus and minus 1 in both cases. Now, let us say for n-type semiconductor, we are saying that n e is equal to N d, which is a lot higher than n h; and n h is equal to n i square divided by N d. So, sigma n becomes in this case N d e mu e plus n i square divided by N d into p sorry this should be n a p mu h ok.

Now, since this component is very small this, so this is small this tends to dominate. So, as a result sigma for n semiconductor is almost equal to N d e mu e. Similarly, for a p-type semiconductor, the sigma p tends to be equal to N A p mu h ok, this is what the carrier concentration and the conductivity of these two semiconductors will be.

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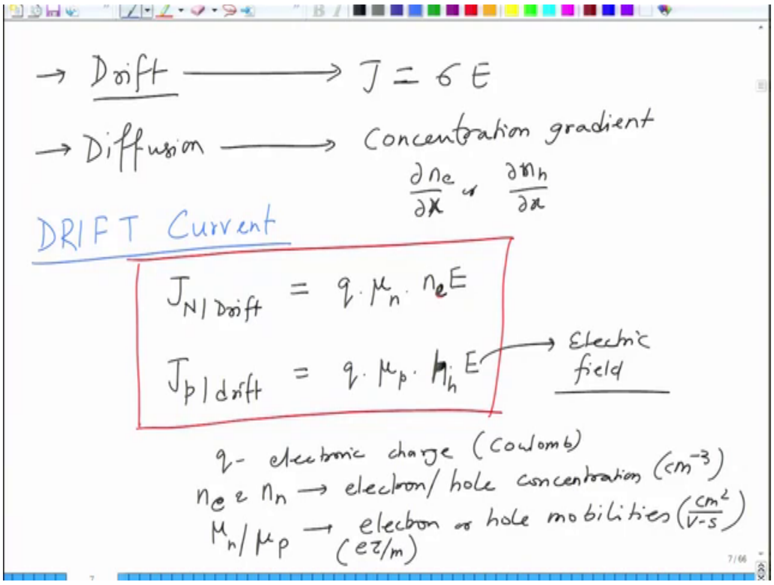

→ Drift ——→ $J = \sigma E$

→ Diffusion ——→ Concentration gradient

$\frac{\partial n_e}{\partial x}$ or $\frac{\partial n_h}{\partial x}$

DRIFT Current

$$\boxed{\begin{aligned} J_{N|Drift} &= q \cdot \mu_n \cdot n_e E \\ J_{p|drift} &= q \cdot \mu_p \cdot n_h E \end{aligned}}$$

→ Electric field

q - electronic charge (Coulomb)

n_e & n_h → electron/ hole concentration (cm^{-3})

μ_n/μ_p → electron or hole mobilities ($\frac{cm^2}{V\text{-}s}$)
($e\tau/m$)

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Now, in general there are two methods of conduction in semiconducting materials. The first one is called as drift; and second one is called as diffusion. These are two mechanisms under which carriers move in semiconductors. Now, this, so this is the conductivity. The current that you obtain is equal to J is equal to sigma E ok. This is pertaining to drift part, where carriers move under the influence of electric field, but you may also have a current because of, see current is because the motion of charges.

The charges do not necessarily move only because of electric field, they can also move because if you have a concentration gradient. So, a concentration gradient may drive the diffusion of carriers leading to another type of current, which is the basically diffusion current. So, you have a current which is driven by a phenomena called as drift, which takes place because of electric field. And then you have so you can say d n by d x or d p n e by d x or d n h by d x ok. If you take one-dimensional model of these, you can also take three dimensional-model that is not a problem.

So, these are the two phenomena. First is drift electric field driven; second is diffusion that is the concentration gradient driven. So, in case of drift, we would not be able to get into details of it. In case of electrons, J N drift is basically q mu n into n E. Whereas J p drift it comes basically from the derivation of Ohms law. And you can find that in any q into mu p into p E. These are the two expressions, which one can follow for drift current essentially it is nothing but J is equal to sigma E ok. Let me just this is n E, let me just sorry we are changing the terminologies this is n h ok; q is the electronic charge ok, which we took as e and p earlier. And e is the electron concentration; n h is the whole concentration; mu n is the electron mobility; mu p is the hole mobility and E is the electric field.

So, q is electronic charge; n e and n h are electron slash hole concentration, and by the way this is an coulomb, this is typically in per centimeter cube or per meter cube. Mu n and mu p are electron or hole mobilities, which is basically e tau divided by m ok. And this is in centimeter square or meter square. So, if this is in centimeter, you can see centimeter square per volt second. And then E is the electric field; this is electric field. So, the drift current we can say this is drift current is basically anything but Ohm's law.

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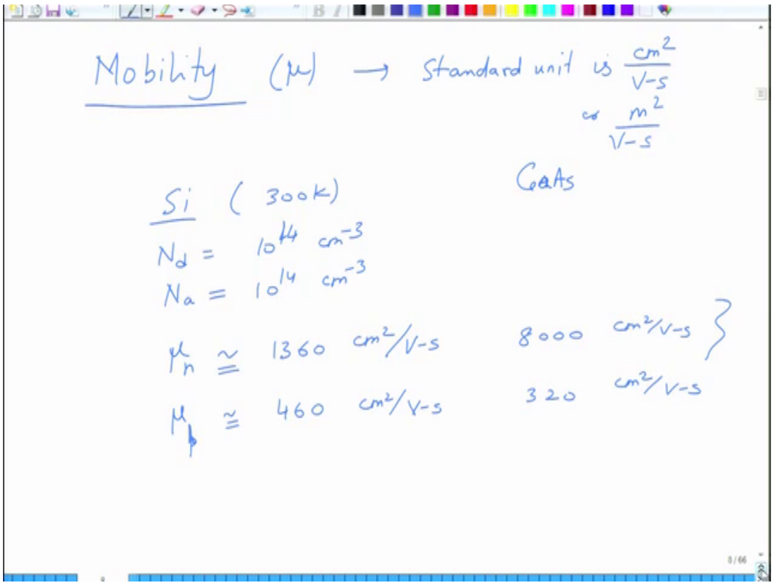

Mobility $(\mu) \rightarrow$ Standard unit is $\frac{cm^2}{V-s}$ or $\frac{m^2}{V-s}$

Si (300k)

GaAs

$N_d = 10^{14}\ cm^{-3}$

$N_a = 10^{14}\ cm^{-3}$

$\mu_n \cong 1360\ cm^2/V\text{-}s$ $\quad 8000\ cm^2/V\text{-}s$ }

$\mu_p \cong 460\ cm^2/V\text{-}s$ $\quad 320\ cm^2/V\text{-}s$

Now, a important parameter in semiconductor is mobility. Mobility the standard unit it is called as mu, and the standard unit is the standard unit is centimeter square per volt second or some people also write it as meter square per volt second ok. The new typical values let us say for silicon at you know 300 k. So, if you have N d is equal to 10 to power 14 per centimeter cube, N a as 10 to power 14 per centimeter cube, then mu n is approximately equal to 1360 centimeter square per volt second. And mu mu h what are we writing it as mu n mu p mu p let us say mu p is equal to approximately 460 centimeter square per volt second.

So, generally for semiconductors like silicon the electron mobility is a lot greater than the hole mobility, whereas these mobility are significantly higher as compared to as in materials like gallium arsenide. So, gallium arsenide on the other hand will have mobility electron mobility of 8000 centimeter square per volt second, and hole mobility of 320 per centimeter square volts again. So, let me gallium arsenide is a very good semiconductor n-type semiconductor as compared to and mobility also varies as a function of temperature. So, let me just show you the plot of that. So, since the carriers undergo scattering, the scattering takes scattering is because of.

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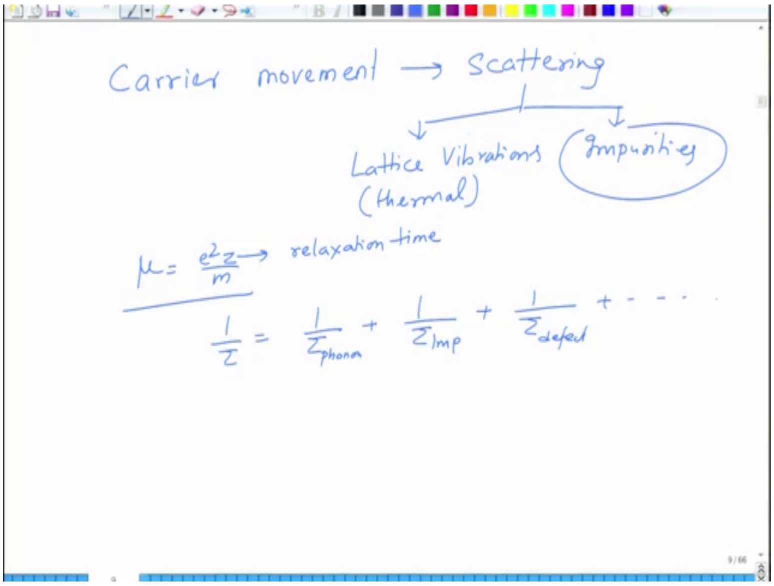

Carrier movement → Scattering

Lattice Vibrations (thermal)

Impurities

$\mu = \frac{e^2 \tau}{m} \rightarrow$ relaxation time

$$\frac{1}{\tau} = \frac{1}{\tau_{phonon}} + \frac{1}{\tau_{Imp}} + \frac{1}{\tau_{defect}} + \cdots$$

The carrier movement undergoes the scattering. And the scattering could be because of lattice vibrations which is called as a thermal scattering, and then you have impurities right, because you have dopants. So, they also cause the carriers to scatter. So, when you have this scattering taking place, then one can write and generally since mobility depends upon the relaxation time, we are saying that it is mu is equal to e square tau divided by m, this tau is the relaxation time.

Relaxation time means the time which is spent for a carrier between two successive collisions. So, it undergoes collision with the lattice a turn undergoes collision with the impurities. And higher the tau higher the mobility will be. So, this tau is expressed as 1 over tau phonon plus 1 over tau impurities, you might also have defects like dislocations vacancies etcetera and so on and so forth. There are various contributions to it.

Generally, so this tau decreases when you increase the impurity concentration or you increase the temperature, because when you when the temperature increases the lattice atoms tend to vibrate mode, as a result there are there is more scattering of carriers. And when you increase the impurity concentration, then again the carriers tend to get scattered more.

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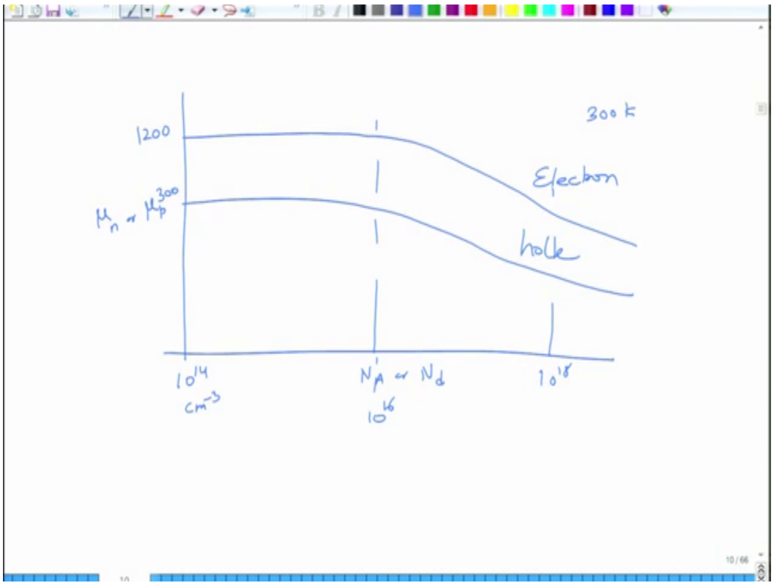

So, generally the at so if you look at the first impurity dependence, so if you write mu n or mu p as a function of N A or N d at lower concentration its relatively flat, but at higher concentration tends to go down. So, this is would be let us say at about in 14 per centimeter cube, and the crossover will come at about was 16 or so, and then this would be at about it were 18 or so, this is at 300 k. And the values would be this would be about I do not know 1200, this would be about 300 or 400 something like that ok. So, this is for electron, and this is for hole. So, both electron and hole mobility decrease as the impurity concentration increases, but they also tend to change with the temperature.

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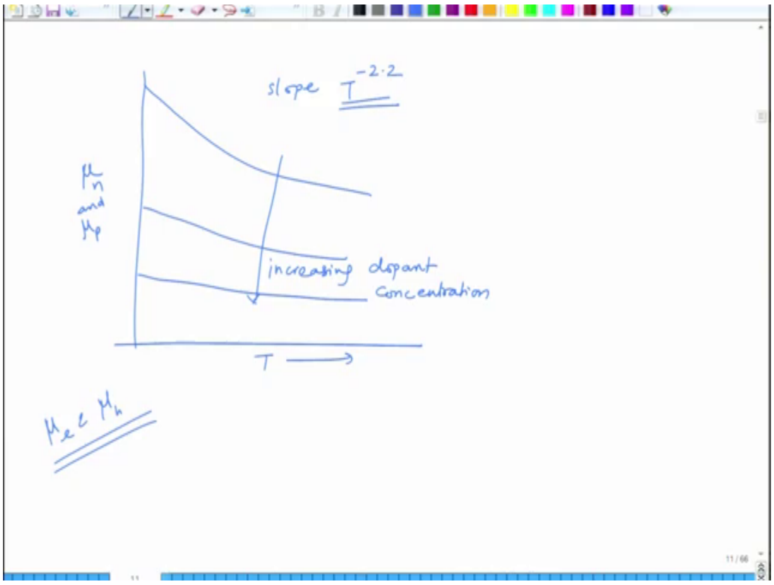

The mobility as you plot with respect to temperature, so let us say mu versus temperature and at certain. At lower doping concentration they tend to change a little faster. And if you look at the variation, if you look at the slope of this plot, the slope of this plot is approximately 2. So, it goes as T to power minus 2.2 or so if you plot it approximately the slope yeah. And so they tend to vary little faster as lower doping levels; at higher doping levels, they tend to be relatively in this fashion.

So, so you can say this is increasing dopant concentration. So, dopant concentration leads to reduction in mobility; and temperature also tends to lower the mobility. So, this is temperate. So, this is true for both mu n and mu p so or you can have mu e and mu h. I think, we will interchange some of these terms sometimes, but mu is nothing but mu n and mu h is nothing but mu p. So, this is how mobility varies as a function of impurity concentration and temperature.

So, this is the drift part. And the diffusion part would be we will discuss in the next class I think we have run out of time today. So, we will discuss the diffusion part and other aspects of carrier concentration and their change, the current generation and the combination generation etcetera in the next few lectures ok.

Thank you.