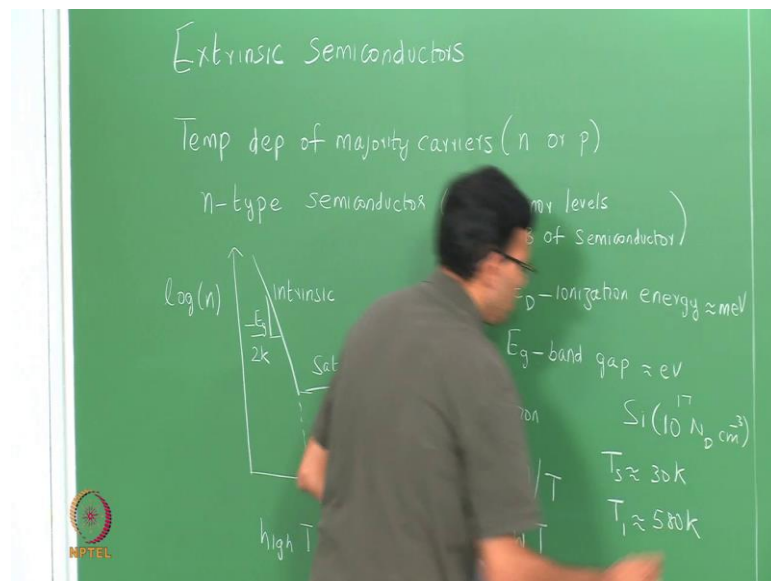


Electronic Materials, Devices and Fabrication
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Lecture - 08
Extrinsic Semiconductors - Conductivity

Let us start with a brief review of last class, in last class we continued discussing about extrinsic semiconductors.

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If you remember extrinsic semiconductors are those where we add a small amount with specific impurity in order to selectively increase concentration of either electron or holes. Towards the end of last class, we looked at the temperature dependents of the majority carriers concentrations. So, these would be electrons in the case of n type semiconductors and holes in the case of p type semiconductors. We use the example of a n type semiconductors, whatever discussion that we do using n type is same is valid for a p type.

So, in this case electrons are the majority charge carriers and the essentially two sources of electrons. One your electrons can come from donor levels, these levels are closed to the edge of conduction band at high temperatures, the electrons can also come from the valence band of the semiconductor. Putting these two information together, we did a plot of the log of the electron concentration versus 1 over T this is $\log n$ this is $1/T$.

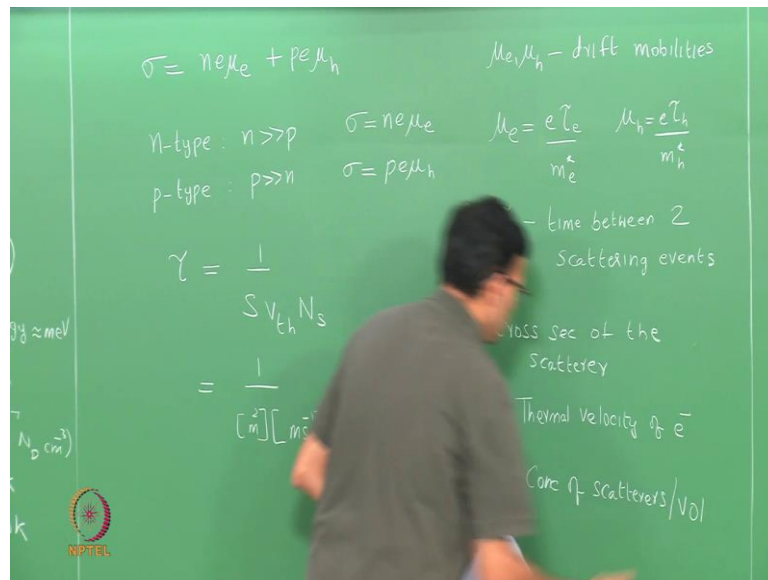
Since, this is lower, the temperature this represents the high temperature side, this represents the low temperature side. In this plot, we said that we could divide extrinsic semiconductor into essentially three regions at low temperature the concentration of electrons is dominated by those electrons that comes from the donor level.

So, we plot n this is $1/T$ we going to get straight line with a slope that was given by the ionization energy. So, E_d is the ionization energy of the donor, we also saw this is typically of the order of milli electron volts. Once, the entire donor atoms are ionized, we have a regime where the electron concentration is more or less constant. Then, at high temperature we find that we have an electron that come from the valence band. Your extrinsic semiconductor behaves like an intrinsic so this is the high temperature behavior and the source is $-E_g/2k$, where E_g is the band gap and this is usually of the order of electron volts.

So, we have three regime in the case of extrinsic semiconductors, the low temperature one is called the ionization regime because it is dominated by ionization of the donor atoms. Then, you have a saturation regime where the concentrations of electrons which are the majority charge carriers nearly a constant. Then, we have intrinsic regime where your extrinsic materials behaves like an intrinsic one. We also called the temperature corresponding to these as T_s , which is your saturation temperature and T_i , which is your intrinsic temperature.

We did some calculations for the value of T_s and T_i in the case of silicon with 10^{17} donor atoms. We got a value of T_s is approximately 30 Kelvin and T_i is approximately 580 Kelvin. This means there is a wide temperature range, where the concentration of the majority carriers is nearly a constant and it is equal to concentration of your donor or your acceptor. So, we have two advantages, if we dope semiconductors, the first is that the conductivity increases because the carrier concentration increases, but secondly we also have a regime, where the carrier concentration almost constant and it is independent of temperature.

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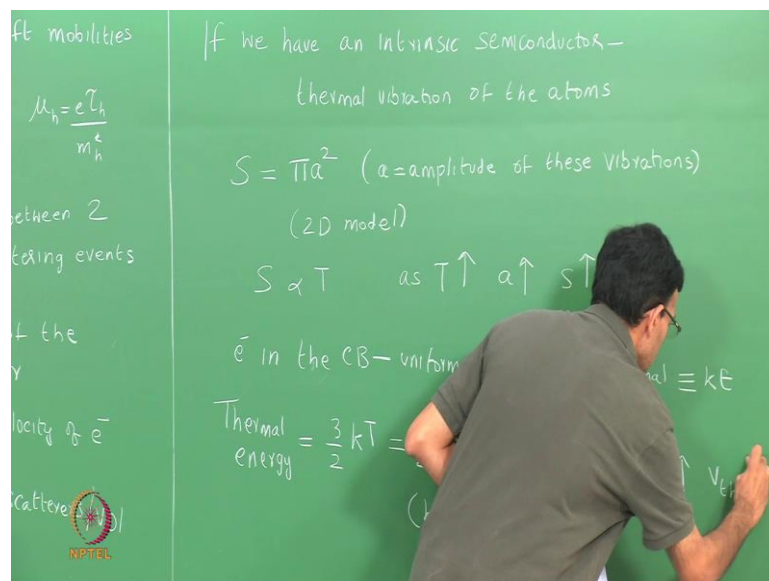
So, today we will go further and talk about conductivity in the case of extrinsic semiconductor and how they depend on temperature. So, we start with the equation of conductivity, we have written this earlier $\sigma = ne\mu_e + pe\mu_h$, this is your general equation for your conductivity. We have n type semiconductor n is typically much larger than p, we saw in the case of silicon that n could be more than seven or eight orders of magnitude higher depending upon the total concentration in which case σ just be $ne\mu_e$. In the other hand, we have p type semiconductor, p is much larger than n in which case σ just be $pe\mu_h$.

We have seen μ_e and μ_h earlier μ_e and μ_h are the drift mobility. So, μ_e is the mobility of the electron in the conduction band μ_h is the mobility of the hole in the valence band. Also, we saw earlier that $\mu_e = \frac{e\tau_e}{m_e^*}$ and $\mu_h = \frac{e\tau_h}{m_h^*}$, where τ_e and τ_h are the time between 2 scattering events. Now, if you want to look the temperature dependent conductivity, we need to look at the temperature dependents of the carrier concentration and also temperature dependent mobility. We have done looking when the temperature dependent, the carrier concentration, which is what we did in the last class, the beginning of today. Now, we look at how μ_e and μ_h depend on both temperature and in the case of extrinsic semiconductors how it depends upon the presence of these dopants.

Now, there is another way we can write tau which is the time between 2 scattering events tau can be written as $\frac{1}{S v_{th} n_s}$. So, what are these terms? S represents cross section of the scatterer, v_{th} is the thermal velocity of the electrons and n_s is the concentration of the scatterers. If we plug in the units S is a cross section area, which is in meter square v_{th} is a velocity, so it is meter per second, n_s is concentration of scatterers, it is usually given per unit volume, so this is in meter cube, so the final unit is in seconds.

So, to understand this if you have a larger cross section of the scatterer, then you are going to have a shorter scattering time if the electrons travel faster. Then, once again they can interact between two scattering events quickly. So, the time will be short and if we have a more number of scatterer, once again the time will be short. Now, the question is what are these scatterers? We talk about and how do these values depend on temperature, let us start first with intrinsic semiconductors.

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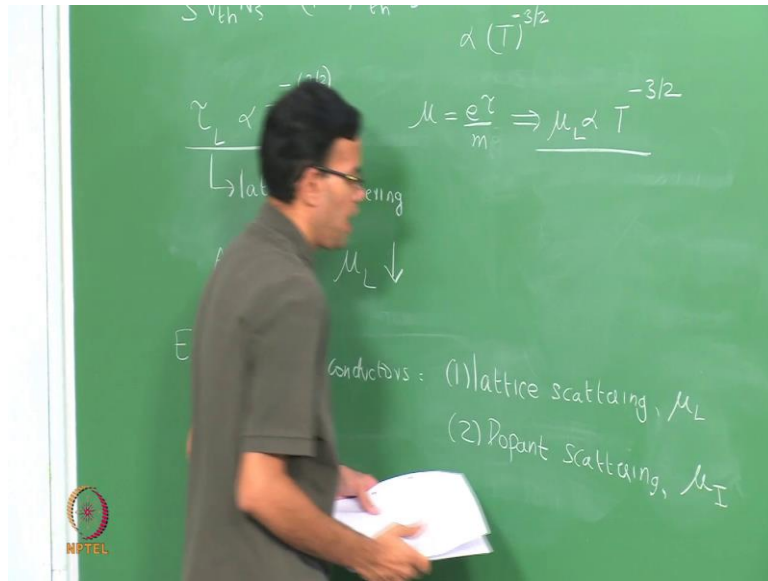
If we have an intrinsic semiconductor, then the electrons will scatter because of the thermal vibrations of the silicon atoms, so we have thermal vibration of the atoms. So, if S is the scattering cross section S can be written as πa^2 , where a is the amplitude of these vibrations. So, this is in the case of simple 2 D model, we can show that if your scatterers are your thermal vibration of the atoms, then S is proportional to the temperature.

This means as temperature increases the amplitude of the vibration increase. So, a increases and correspondingly s will also increase the next term in the equation for τ is v_{thermal} . If you have electrons moving in the conduction band, we can say they are moving through a uniform potential region and in this case we can say that the thermal energy of the electrons is approximately the same as the kinetic energy. Typically, the thermal energy is given as $\frac{3}{2} k T$ and the kinetic energy is nothing but one-half $m v^2$. So, this is the kinetic energy, so if you use this expression v_{thermal} is proportional to square root of temperature, which means once again as the temperature increases your thermal energy increases.

So, the kinetic energy will also increase, so v_{thermal} will increase, so let us put these two term together. So, we have the expression for τ which is nothing but $\frac{1}{S v_{\text{thermal}} n_s}$. In the case of intrinsic silicon atom we said that the scattering is only due to the lattice vibrations. So, we wrote this as $\frac{1}{\pi^2 a^2 v_{\text{thermal}} n_s}$ we found that $\pi^2 a^2$ is directly proportional to $\frac{1}{T}$ over the temperature v_{thermal} is proportional to square root of the temperature.

This means τ is proportional to $\frac{1}{T}$ times square root of T , n_s is the number of atoms and that is usually a constant, it is not going to change with temperature. So, if you take these two into count is proportional to $T^{-\frac{3}{2}}$ of the negative sign. So, τ due to the scattering of the lattice and this going to denote as τ_1 and this proportional to $T^{-\frac{3}{2}}$ and this. Now, μ is equal to $e \tau$ over m and since τ is proportional to temperature minus $\frac{3}{2}$, you can say that μ is proportional to temperature $\frac{3}{2}$.

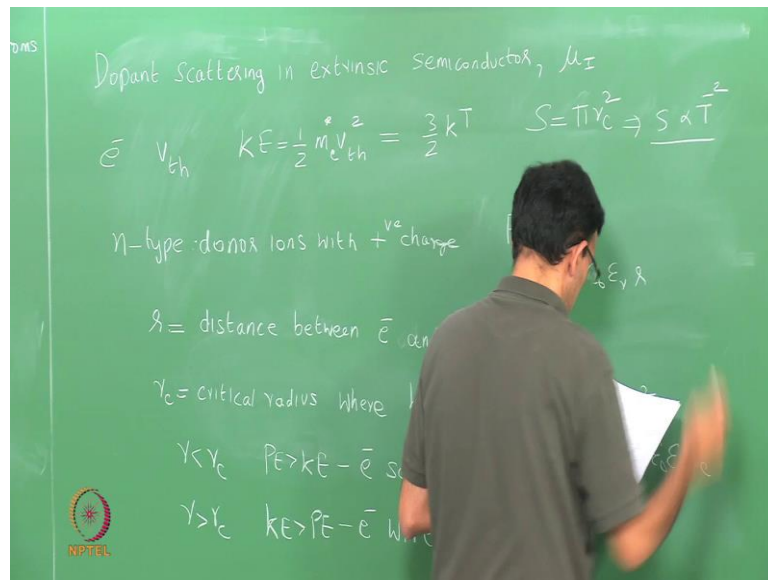
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So, we have an intrinsic material, where the conductivity is by the scattering is due to the vibration of the lattice atom as the temperature increases the vibration increases. So, there is small scattering and hence the mobility will go down, so I will write this as μ_L to denote that this is due to lattice scattering. So, as temperature increases μ_L will decrease. So, this makes sense because the temperature increases, we have greater lattice vibration and also you have electrons they are travelling faster. Now, in the case of extrinsic semiconductors, you also have this lattice scattering because you also have silicon lattice.

If your material is silicon, you also have a lattice scattering, this is given by a term μ_L , but you also have a scattering due to your dopants whether they been donors or accepters call that μ_i . So, i denotes the fact what these are? In the case of extrinsic semiconductors, we have scattering due to the lattice we also have the scattering due to the dopants. So, both of them play a role in determining the mobility of the electrons and holes.

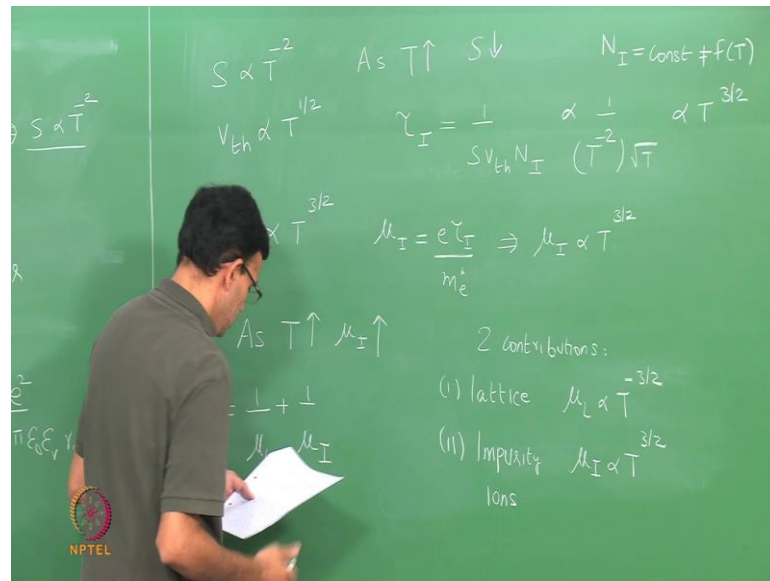
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The lattice scattering term is very similar to what we did for intrinsic semiconductors. So, once again μ_i is proportional to t to the minus 3 over 2, one thing we have to see is how the dopant scattering changes with temperature. So, we want to look at the dopant scattering in the extrinsic semiconductor, we call this μ_i , we want to find out the temperature dependents of the system. So, we look at an extrinsic semiconductor whether you have n type or p type. We are going to have donors or acceptors in these are ionized because you find that in the case of n type the donor atom has an extra electron that goes to the conduction band in the case of p type.

You have an acceptor atom that can accept an extra electron and create a hole. So, these are ionized impurities and these can then interact with a electron. So, we have an electron with a velocity $v_{thermal}$, then the kinetic energy is one half $m_e v_{thermal}^2$ or one half $m_e^* v_{thermal}^2$. We said that in the case of intrinsic semiconductor, where an electron is travelling in the conduction band, this kinetic energy is nothing but the thermal energy.

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So, this is three half kT , but now you have the electron having an electro static force of attraction with an ionized donor. So, we have a n type, we have donor atoms or donor ions with a positive charge and these can interact with the electrons. So, this electro static force, I will call it a potential energy is nothing but e^2 over $4\pi\epsilon_0 r$ times r . So, r here is a distance between the electron and the ionized impurity. Usually, in the case of extrinsic semiconductor, we define a critical radial r_c , where the kinetic energy and the potential energy are equal. If r is less than r_c here, then the potential energy is greater than the kinetic energy and your electron scatter. If r is greater than r_c it is the reverse the kinetic energy will be greater than the potential energy in the electron will not scatter or the electron will escape matching.

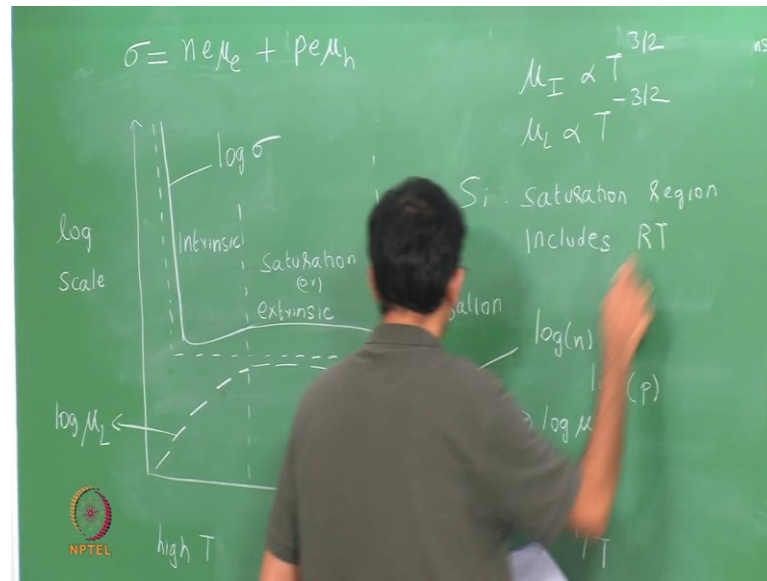
These two terms we define a critical radius when the kinetic and potential energies are equal if we do that you can say that $\frac{3}{2}kT$ is equal e^2 over $4\pi\epsilon_0 r_c$ sorry and r_c . It means r_c is proportional to t to the minus 1, now if you want to look at the cross section for scattering, s is nothing but πr_c^2 square knowing that r_c is proportional to $1/t$ s is proportional to t the minus 2. So, in the case of extrinsic semiconductor, where we are looking at the interaction of the electron with the ionized impurities, we find that the scattering cross section area s is proportional to t to the minus 2.

This, we got by looking at the balance between the kinetic energy of the electron and the potential energy of the attraction between the electron and the ionized impurities. As temperature increases, the electron can travel faster which means the kinetic energy becomes higher, so becomes easier for it to escape the influence of the ionized impurity, which means the scattering cross section s goes down. Earlier, we saw the v_{thermal} is proportional to T to the half this is the same argument that we use in the case of intrinsic semiconductor, putting these two together due to scattering from the impurities.

So, τ_i is equal to $1/s v_{\text{thermal}} n_i$ once again n_i is the concentration of impurities which is a constant is not a function of temperature. So, this is proportional $1/T$ to the minus 2 in the case of s square root of T proportional T to the 3/2. So, τ_i which is time due to scattering because of impurities is proportional to T to the 3/2 μ_i is nothing, but, $e \tau_i / m_e^*$. So, μ_i is proportional to T to the 2/2, which means the contribution of the impurities to mobility is such that as the temperature increases μ_i increases and this is because as the temperature increases our electron can move faster. So, they can easily escape the electro static force.

So, in the case of extrinsic semiconductor we have 2 contributions to the mobility μ is from the lattice and we saw earlier that this is proportional to T to the minus 3/2 the other is from the impurity for your dopant and these are ionized. So, I will write these as impurity ions when μ_i is proportional to T to the 3/2. So, we have two contributions, both of which have an opposite dependence on temperature. If you look at the total mobility, it will be dominated by whichever scattering process has a lower value. So, we can write $1/\mu_e = 1/\mu_l + 1/\mu_i$. So, this is in the case of extrinsic semiconductor, where we have contribution over both the impurity atom μ_i and the lattice μ_l .

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So, let us put this together and then do plots of the conductivity versus $1/T$ over temperature. Again, let me rewrite the equation for the conductivity $\sigma = ne\mu_e + pe\mu_h$. So, in this equation the first thing we will look at is the carrier concentration. So, on a log scale this is $1/T$ since this is $1/T$ this end is the high temperature end, this is your low temperature end if we plot log of the carrier concentration and this is similar to what we had before. So, at the high temperature you have a intrinsic contribution you have a saturation region where the concentration is nearly a constant then you have a low temperature here, where it is due to ionization of your donors or acceptors.

So, this is $\log n$ or $\log p$, if we then plot log of the mobility we know at low temperature mobility's are dominated by scattering due to the impurities because at low temperature the lattice vibrations are very small. So, mobility is dominated by impurity scattering and as temperature increases your mobility increases remember μ_i is proportional to $T^{3/2}$. To do that, this is the contribution due to scattering of the ionized impurity this is $\log \mu$ at low temperatures.

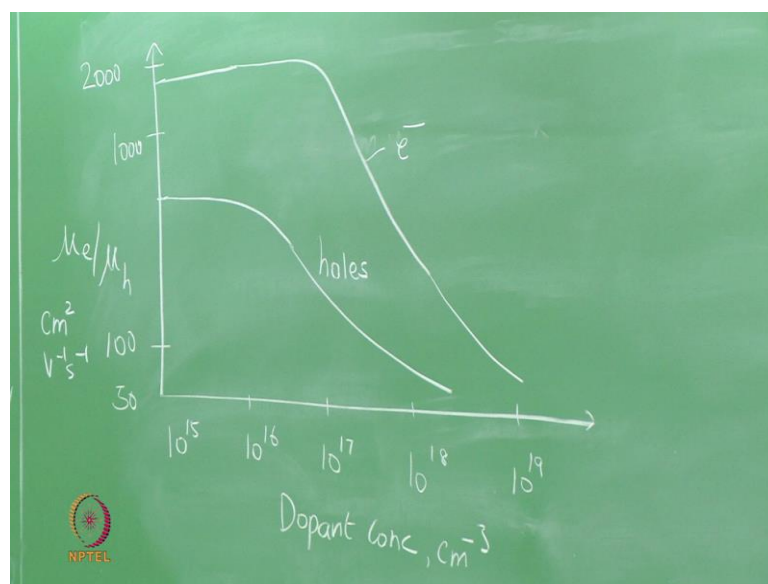
So, it is dominated by impurities at high temperature scattering is dominated by the silicon lattice which case μ_l is proportional to $T^{-3/2}$ so that as the temperature increases μ value goes down.

So, this is $\log \mu$ at intermediate temperature both the scattering from the lattice and the scattering from the impurities will be more or less equal. So, the first dotted line represents n and the second dotted line dash line represents \log of μ . If we put both these together, we will get the conductivity and if we plot the conductivity, which is the solid line, we get a curve like this. So, this is \log of σ versus $1/T$, we just erase this section and plotted slightly better, so this is \log of σ .

So, once again we have three regions at low temperature, we have an ionization region at high temperatures we have an intrinsic region. Then, there is a region in the middle where σ does not change much with temperature in that is saturation region another word for saturation region is your extrinsic region. So, doping gives two advantages one that increases the conductivity, but at the same time there is also a temperature region where both the carrier concentration.

Hence, the conductivity is almost a constant and is independent of temperature in the case of silicon this saturation region the extrinsic region is around room temperature or you should say includes room temperature. This means if you have doped silicon, then your conductivity is almost constant in an around room temperature, this is very important when we try and form devices later with these extrinsic semiconductors. So, this is the carrier concentration as a function of temperature. So, how does a carrier concentration in the case of extrinsic semiconductor change with dopant concentration?

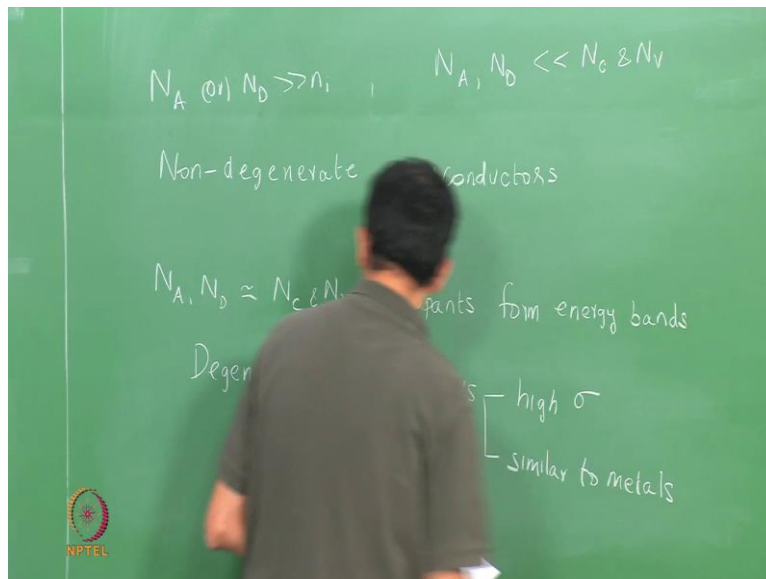
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So, let me just plot log of mu versus dopant concentration. So, I want to plot how mu e or mu h changes with concentration of the dopants this is mu e can be mu h. We use the example of silicon, this is again true for any other semiconductor this is dopant concentration square to increase the dopant concentration the overall mobility decreases because now you have more scattering from this ionized impurities. So, let me make the plot 100, this is your y axis concentration is 10 to the 15.

So, if we plot mu e start with a high value in the case of silicon room temperature mu e is for intrinsic silicon is 1350 centimeter square per volts per second. Let me just write down the unit here centimeter square per volts per 2nd. So, it is start of high initially your mobility is more or less or constant and then as your dopant concentration increases mobility starts to drop this for electron. We can do a similar plot for a holes, once again when you have intrinsic silicon the hole mobility is around 450 centimeter square per volts per second. So, if you do similar plot for holes, again it stays a constant and then it starts to drop down.

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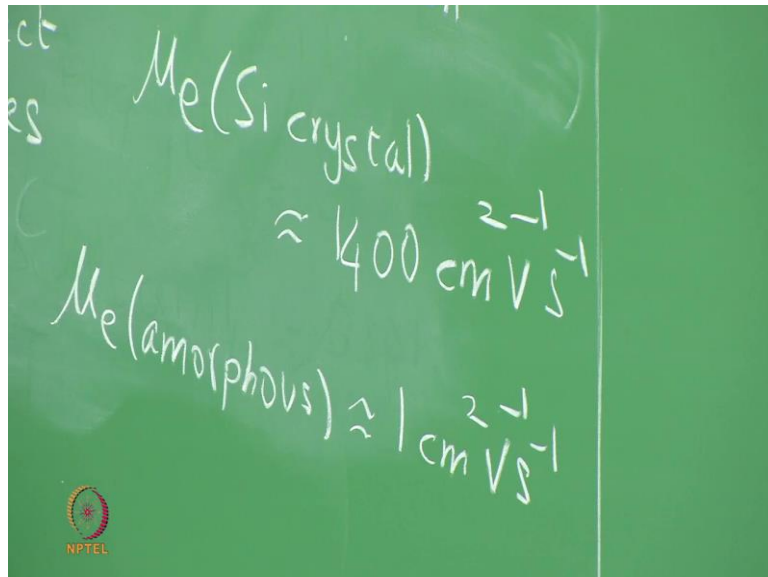


In all the extrinsic semiconductors we have considered so far, we always had a situation n_a or n_d whether these are acceptors or donors is much greater than n_i which is your intrinsic carrier concentration. This means that we can say that the electron concentration is equal to n_d or the whole concentration is equal to n_a .

We also only consider the situations that n_a and n_d are much smaller than the effective density of states n_c and n_v . So, this allows us to think of these impurities as localized states in the band gap. So, your donors form localized states just below the conduction band and the acceptors form localized states just above the valence band these semiconductors are called non degenerate semiconductors.

This is true almost all carrier concentrations that we normally encountered, but if you have really high doping value. So, that n_a and n_d are comparable to n_c and n_v we can no longer think of them as localized states, but we say that a dopants form energy bands. So, these semiconductors called degenerate semiconductors because your dopant forms, it is also possible these bands can overlap with the conduction band or the valence band.

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So, degenerate semiconductors have high conductivity because they have high concentration of impurities, but they also behave very similar to metals. So, most of the devices that we discussed we will essentially deal with non degenerate semiconductors, but for some cases we will find and we can also have high doping. We will also have degenerate semiconductors, the last topic I want to cover, we are talking about electronic material are amorphous semiconductors.

So far, when you talk about intrinsic semiconductor or when we talk about extrinsic semiconductor. We always consider materials that are single crystal which are perfect have no defects this is because defects in a material introduce states in the band gap.

We will change the electronic properties defects will cause defect states we saw earlier that d states can either be shallow state are those that are close to the band edges. They can be close to the conduction band edge or they can close to the valence band edge or they can be deep state. So, these defects state essentially modify the electronic properties the defects can be good or bad. For example, if we are trying to look for higher conductivity, then defects state can essentially act as and electrons and holes. Then, reduce the conductivity in that case defect states are essentially bad. On the other hand, in some direct band semiconductors, you can have defect states in them that can modify the optical property in such cases defect states are good.

So, depending upon the applications, we may or may not want defect states. Amorphous semiconductor is extreme example of a semiconductor with a large number of defect states and amorphous material has essentially no long range order, which means there is a large density of dangling bonds. Dangling bonds are formed when we have 1 silicon atom which has 1 electron, but, there is no opposite silicon atom to supply another electron to form the bond. So, amorphous material characterized by a large density of dangling bonds and these dangling bonds basically act defect states in the band gap. So, we were to draw the band picture in the case of crystalline material, so this is the crystalline material, so let us take crystalline silicon.

So, we will have conduction band, we will have a valence band that is your band gap. So, we have a perfect crystalline material they are no electronic state in the band gap then you have a density of states in the conduction band and the density of states in the valence band. Now, if we have an amorphous semiconductor because you have a large density of dangling bonds there will be a large state of defect states in the band gap and these defect states localized states. So, where to draw band diagram or amorphous material? So, again mark E_c and E_v , so have a large density of states in the bands, but within the band gap we will also have localized edge.

So, these represent conduction band the valence band, so within the conduction band and valence band have extended state, but we also have localized state within the band gap in the case of amorphous semiconductor we know longer talk about a band gap because we have all of this localized state. So, we call the distance between the conduction band and the valence band as mobility gap all this localized defect states also can take part in conduction they can essentially trap the electrons and holes.

So, in the case of an amorphous semiconductor conduction takes place through a hopping mechanism where we think of the electron and holes hopping all of these localized defect states. So, this graphically brings down the mobility and hence the conductivity we have crystalline silicon μ_e is usually around 1350 or 14,100 and the other hand the μ_e for amorphous can be as low as 1.

So, we can have nearly 3 orders of difference magnitude in the mobility in the case of amorphous and crystalline materials. So, with this we have done the electronic materials part of the course. So, we have a look at intrinsic and extrinsic semiconductors, next we will look at the devices and the devices we have to form junction between these materials. So, the next thing we will do is to look at the junctions that we will look starting from next class.