Electronic Materials, Devices and Fabrication
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Lecture - 10
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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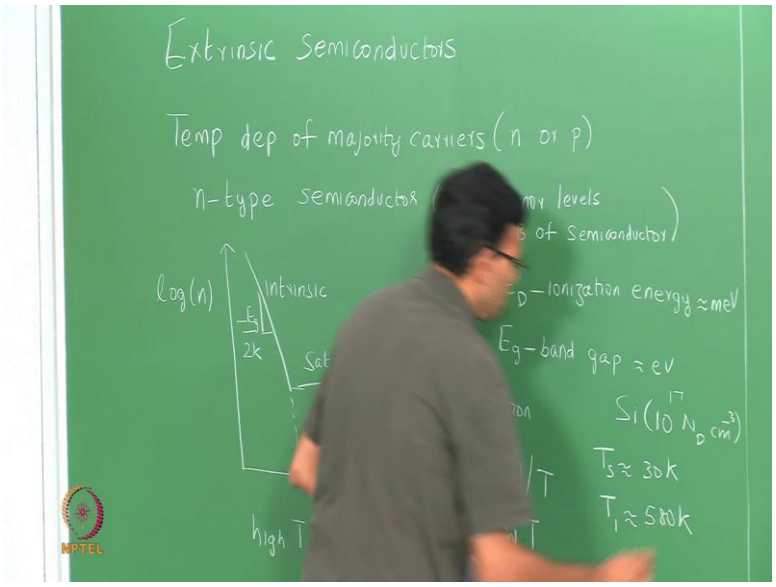

If you remember extrinsic semiconductors are those where we add a small amount with specific impurity in order to selectively increase concentration of either electron on holes. Towards the end of last class, we looked at the temperature dependents of the majority carriers concentrations. So, these would 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 1over t this is log n this is 1 over T.

Since, this is 1ower, 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 digits at low temperature the concentration of electrons is dominated by those electrons that comes from the donor level.

So, we plot n this is 1over 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 1so this is the high temperature behavior and the source is minus E g over 2 k, 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 to the 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 accepter. 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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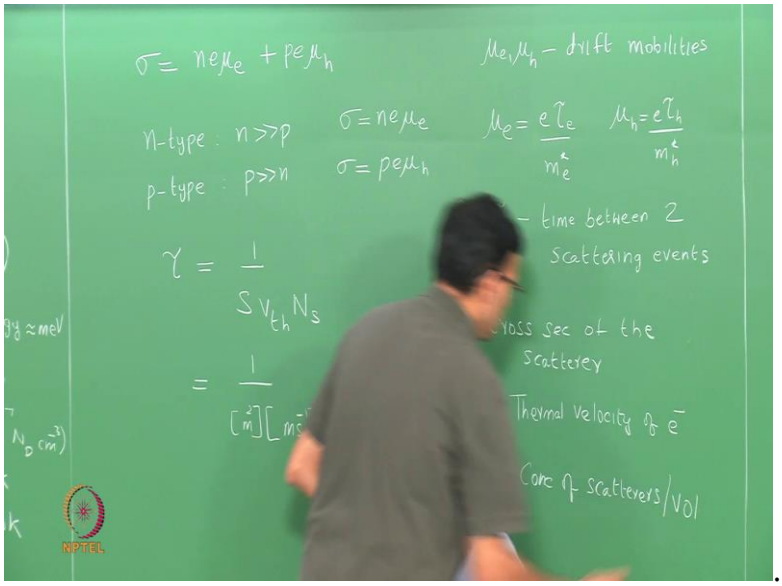

So, today we will go further and talk about conductivity in the case of extrinsic semiconductor and how they depend on temperature. So, we start with the equation of conductivity, we have written this earlier sigma is n e mu e plus p e mu h, this is your general equation for your conductivity. We have 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 hire depending upon the total concentration in which case sigma just be n e mu e. In the other hand, we have p type semiconductor, p is much larger than n in which case sigma just be p e mu h.

We have seen mu e and mu h earlier mu e and mu h are the drift mobility. So, mu e is the mobility of the electron in the conduction band mu h is the mobility of the hole in the valence band. Also, we saw earlier that mu e e tau e over m e star mu h e tau h over m h star, where tau e and tau 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 mmu e and mu 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 1over s v t h time n s. So, what are these terms? S represents cross section of the scatterer, v t h 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 thermal 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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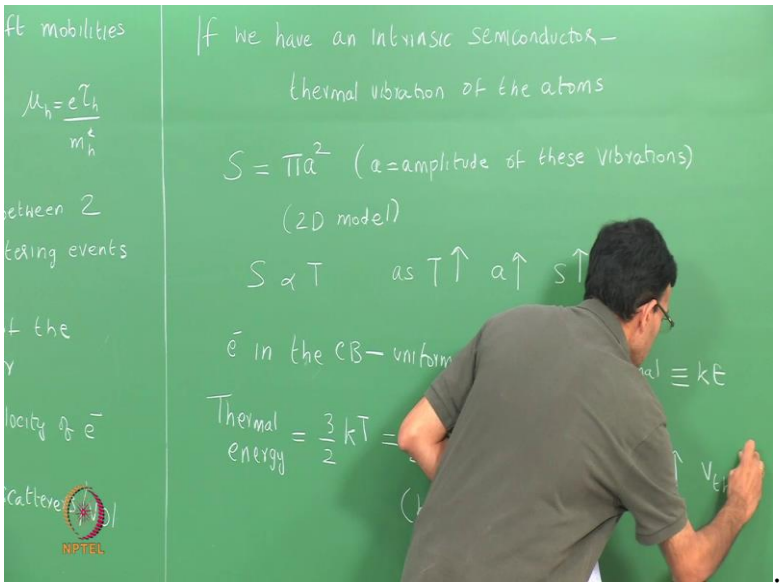

If we have an intrinsic semiconductor, then the electrons will scatter because of the thermal vibrations of the silicon atoms, so we have thermal vibration of the atoms. So, if s is the scattering cross section s can be written as pi a square, where a is the amplitude of these vibrations. So, this is 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 tau 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 3 by 2 k t and the kinetic energy is nothing but one-half m v square. 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 tau which is nothing but 1 over S v 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 1over pi a square v thermal and n s we found that a pi a square is directly proportional to 1 over the temperature v thermal is proportional to square root of the temperature.

This means tau is proportional to 1 over 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 to the three half of the negative sign. So, tau due to the scattering of the lattice and this going to denote as tau l and this proportional to t to the minus 3 over 2 and this. Now, mu is equal to e tau over m and since tau is proportional to temperature minus 3 over 2, you can say that mu is proportional to temperature 3 or 2.

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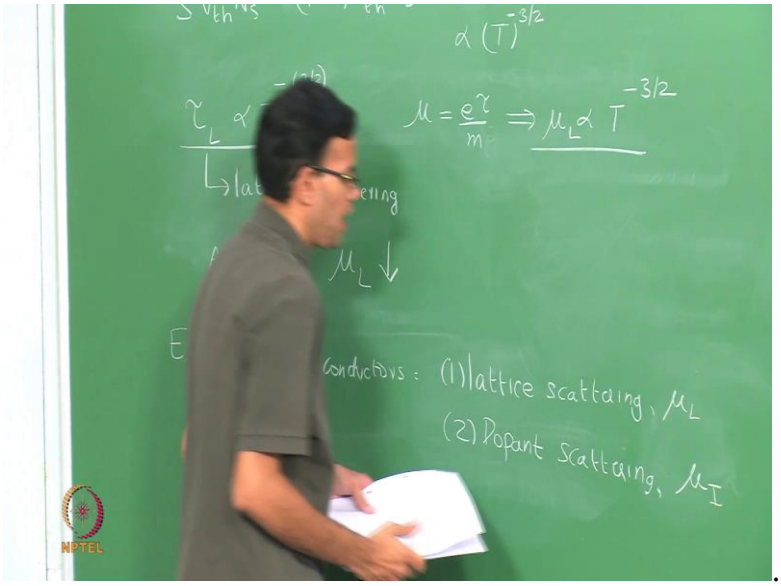

So, we have an intrinsic material, where the conductivity is by the scattering is due to the vibration of the lattice atom as the temperature increases the vibration increases. So, there is small scattering and hence the mobility will go down, so I will write this as mu l to denote that this is due to lattice scattering. So, as temperature increases mu 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 mu l, but you also have a scattering due to your dopants whether they been donors or accepters call that mu 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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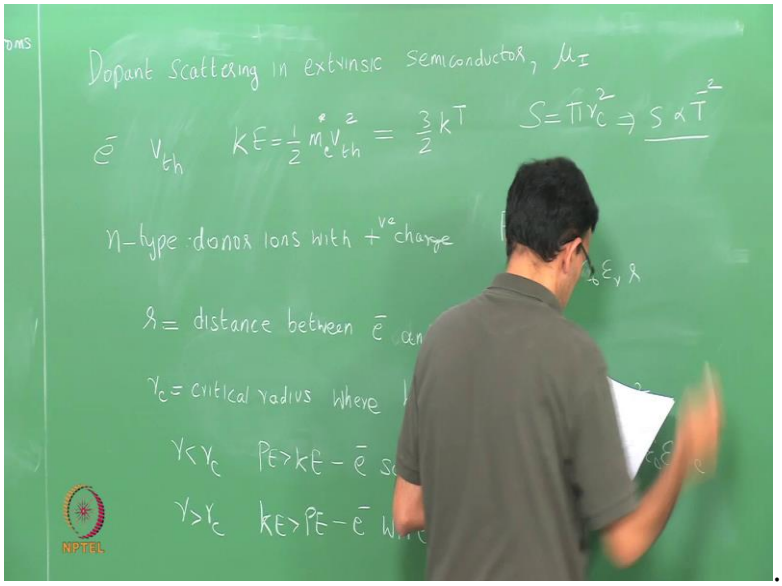

The lattice scattering term is very similar to what we did for intrinsic semiconductors. So, once again mu l is proportional to t to the minus 3 over 2, one thing we have to see is how the dopant scattering changes with temperature. So, we want to look at the dopant scattering in the extrinsic semiconductor, we call this mu 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 accepter atom that can accept an extra electron and create an 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 square or one half m e star v thermal square. 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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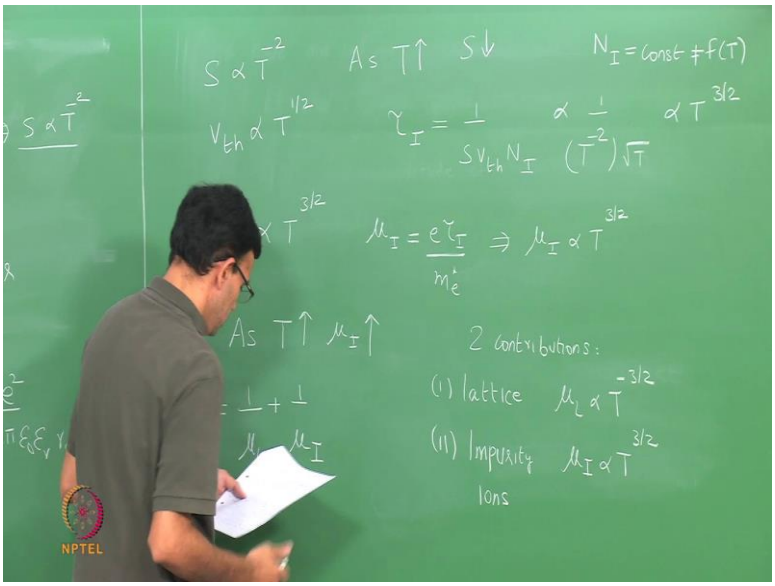

So, this is three half k t, but now you have the electron having an electro static force of attraction with an ionized donor. So, we have a n type, we have donor atoms or donor ions with a positive charge and these can interact with the electrons. So, this electro static force, I will call it a potential energy is nothing but e square over 4 pi epsilon naught 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 3 over 2 k t is equal e square over 4 pi epsilon naught epsilon r r c square 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 pi r c square knowing that r c is proportional to 1 over 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, it is tau i is equal to 1over s v 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 1over t to the minus 2 in the case of s square root of t proportional t to the 3 half. So, tau i which is time due to scattering because of impurities is proportional to t to the 3 half mu i is nothing, but, e tau i over m e star. So, mu i is proportional to 2 half, which means the contribution of the impurities to mobility is such that as the temperature increases mu 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 1is from the lattice and we saw earlier that this is proportional to t to the minus 3 half the other is from the impurity for your dopant and these are ionized. So, I will write these as impurity ions when mu i is proportional to t to the 3 over 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 1over mu e has 1over mu l plus 1over mu i. So, this is in the case of extrinsic semiconductor, where we have contribution over both the impurity atom mu i and the lattice mu l.

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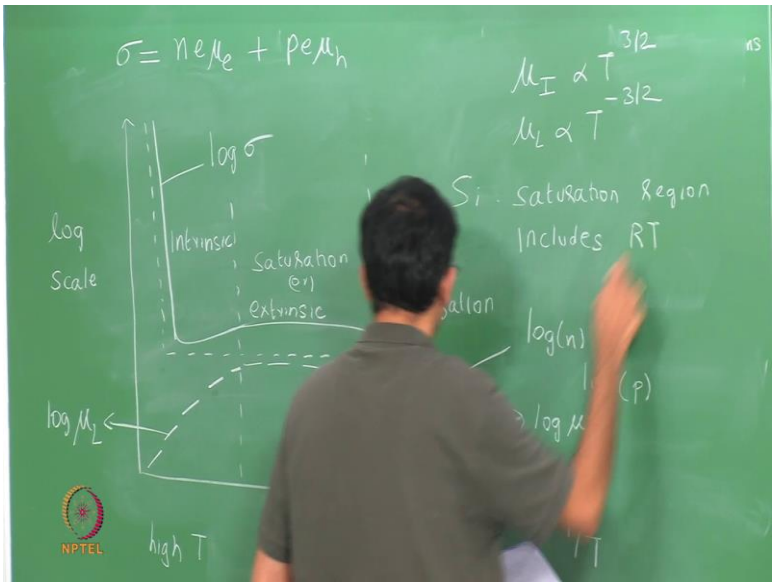

So, let us put this together and then do plots of the conductivity versus 1 over temperature. Again, let me rewrite the equation for the conductivity sigma is n e mu e plus P E mu h. So, in this equation the first thing we will look at is the carrier concentration. So, on a log scale this is 1over t since this is 1over 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 mu i is proportional t to the 3 over 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 mu l is proportional to t to minus 3 over 2, so that as the temperature increases mu value goes down.

So, this is log mu l at intermediate temperature both the scattering from the latter's 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 mu. 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 sigma versus 1over t, we just erase this section and plotted slightly better, so this is log of sigma.

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 sigma 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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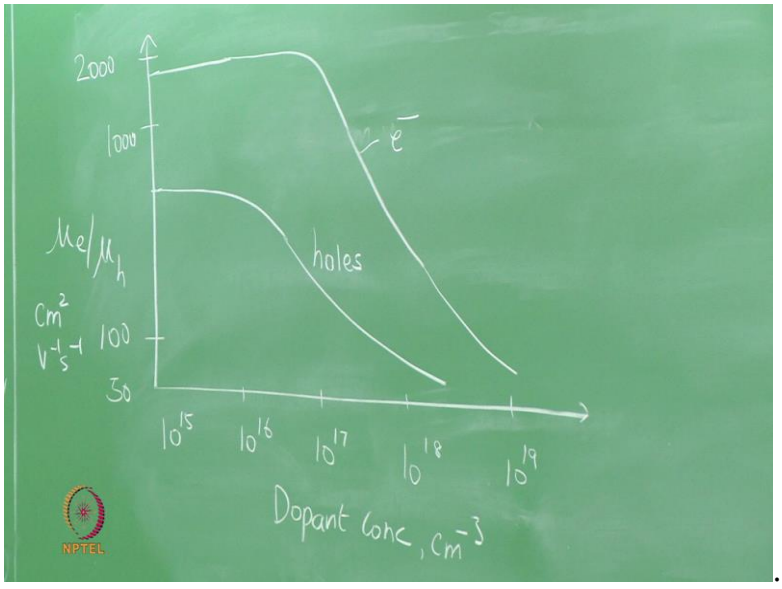

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So, let me just plot log of mu versus dopant concentration. So, I want to plot how mu e or mu h changes with concentration of the dopants this is mu e can be mu h. We use the example of silicon, this is again true for any other semiconductor this is 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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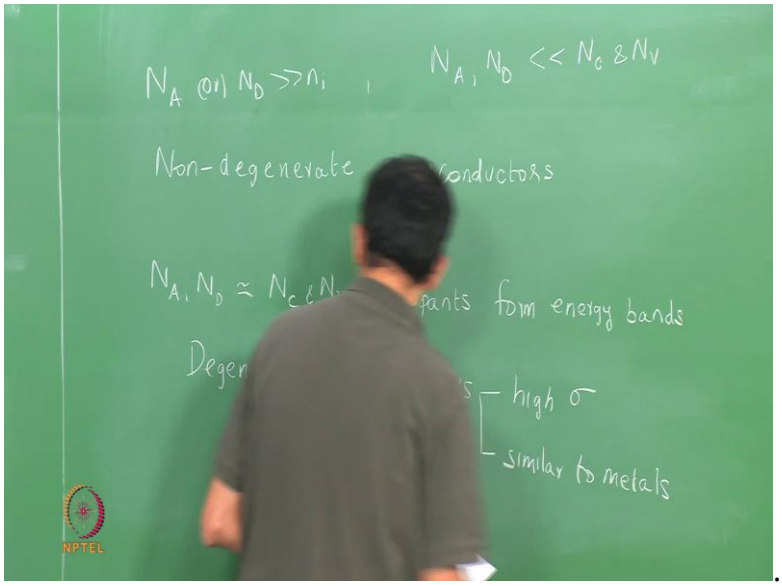

In all the extrinsic semiconductors we have considered so far, we always had a situation n a or n d whether these are acceptors or donors is much greater than n i, which is your intrinsic carrier concentration. This means that we can say that the electron concentration is equal to n d or the whole concentration 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 accepters from 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 is localized states, but we say that a dopants from 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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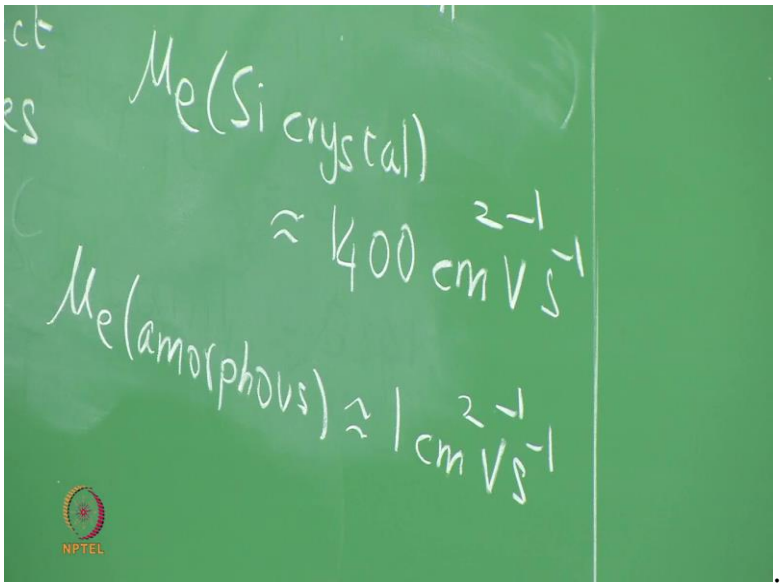

So, degenerate semiconductors have high conductivity because they have high concentration of impurities, but they also behave very similar to metals. So, most of the devices that we discussed we will essentially deal with non degenerate semiconductors, but for some cases we will find and we can also 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 stage 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 1silicon atom which has 1electron, 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 stage 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 mu e is usually around 1350 or 14,100 and the other hand the mu 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.