Advanced Ceramics for Strategic Applications

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Lecture - 14

Electrical Conduction in Ceramics (Contd.)

In this class also, we are going to continue our discussion on electrical phenomena in solids. Particularly, in metals and semiconductors for the timing in this context, we have already introduced the concept of band model. How the bands are separated from one another and why the electrons do not have a continuous energy spectrum. In that context also, we have introduce the concept of hole, particularly for semiconductors, where there are good valence band and conduction band, and when the electrons there exited from the valence band to the conduction band generate holes in the valence band and the electrons in the conduction band.

And both the species contribute to the conductivity move a opposite each other under the application of the electric heat. And this excitation is not by the electric field, because the energy required is not good enough or sufficient enough. Just by applying electric field it is only thermal energy which can excite the electrons from the valence band to the conduction band and there by generate holes.

One of the objectives of considering the band model is to explain the electrical properties particularly the conductivity behavior of all the solids to the same theory. And in that context, we have seen earlier that the two models, which we have considered earlier is not sufficient enough. And not good enough to explain all the properties or the electrical properties of all the solids, the semiconductors, the conductors and the insulators. Here is a model, band model which can be applied universally to all the solids. And it has been successful to explain most of the properties, electrical properties and particularly the conductivity behavior or semi conductivity in the sites.

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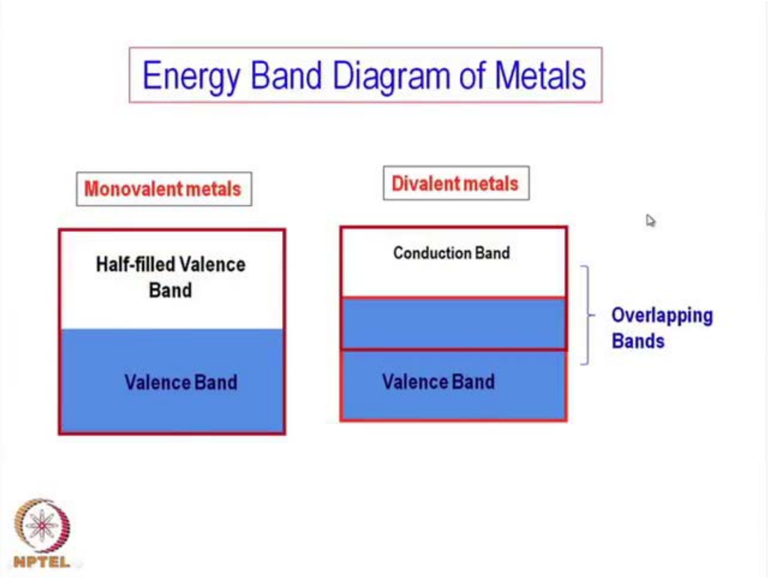

Energy Band Diagram of Metals

Monovalent metals

Half-filled Valence Band

Valence Band

Divalent metals

Conduction Band

Valence Band

Overlapping Bands

In today’s lecture we start with, considering the band model, of or band diagram the energy band diagram of in general metals. What is the situation metals? How the bands look like? And what is their inter relationship so far as the energy spectrum is consider? This is what it looks on the left, we have the monovalent metals and in the right there are divalent metals. This is in fact in the case of monovalent metals, the this is only one band, let it be in fact this is the highest band which can be called valence band or one can say conduction band also.

The characteristics is it is called half-filled valence band, that means the all the not all the energy states available are filled up with the electrons only half of them are filled up and half it is still empty. So, this gives a opportunity for the electrons available in this band to get excited get slight additional energy. When we apply electrical field and they go to a slight high level and then conduct, conduct from one state to the other or slightly above this level.

So, this is how the conduction takes place because there are a lot of empty spaces. So, the electrons get excited can freely move, it can freely move we have much in bands and therefore, the conductivity becomes quite high. So, that is the situation in one group of metals, so called monovalent metals and that is this situation is called half-filled valence band. That means they are within the band, you do not have to go to the other bands, you do not have to go to the conduction band and higher level of bands even if it is there.

Within the band, there are enough space or enough vacancies where the electron can move under the application of electric field.

So, this is what is the situation at a particular temperature, of course, as a temperature increases energy band this level to form the energy they not form the energy, but the highest energy of the electrons may change although the fermi level may be (( )) at this position. So, we have a half field band and that is why an electron can move quite easily and with temperature the conductivity will go up we will go down as per the mobility model (( )) vibration (( )) interaction. That will of course, continue to have only thing is overall level of conductivity will be quite high because large number of electrons large number of free electrons will take part in the conduction process. So, the concentration is very high and the mobility of course, will be determined by the fallen interaction.

In case of divalent metals there is situation is slightly different, we have two bands one is the valence band another is the conduction band. But as such there is no gap normally there is a gap, what we call the band gap, it will the valence band and the conduction band. But, in this case there is no gap there is an overlapping band so, the top of the valence band is higher than the bottom of the conduction band. Normally the bottom of the conduction band is higher than the top of the valance band and that is how you get a band gap. But, in this group of materials or metals, there is a overlap so, immediately although the valance band is filled up there is no space, but because of the overlap immediately get transfer to the conduction band through the overlapping region.

And one's again or one's it goes to the conduction band, the conduction band is basically empty mostly empty. So, the electrons can move with that within that band quite free. So, two situations one is half-filled band another is the overlapping band. One of course, has to remember that this overlapping may not be in fact in the direction in the same direction of motion. Earlier we have seen, direct band gap and indirect band gap so, in an indirect band gap, the minimum and the maximum how correct two different directions, not in the same direction.

So, this kind of overlapping also takes place in two different directions, the top of the valence band is on along one particular direction of motion, but the bottom of the conduction band may be in another direction. So, it is not exactly vertically one over the other so, the, but effectively, effectively irrespective of the direction if there is a overlap we will call it a, we will be useful for conductivity. So, particularly when the divalent metals are there then that is what happened the valance band is most full conduction band is empty.

At the same time there is no band gap effective band gap is nil and therefore, there is a continuous transform of the valence band to the conduction band. So, that is why one’s again we have a large amount of large number of charge carriers or electrons can take part in the conduction procedure and therefore, you have a very high conductivity. That explains are very high the metals to have a very high conductivity of course,

The temperature dependence will remains same, temperature dependence is once again the conductivity will go down inversely proportional to the temperature. And that is the origin is not in their available free electrons, but in the mobility of the free electrons. And that is the region we get where registers are raised with temperature or conductivity decrease with temperature. So this, what is the situation so for as the band diagram is concerned on the metal of the metal conductivity.

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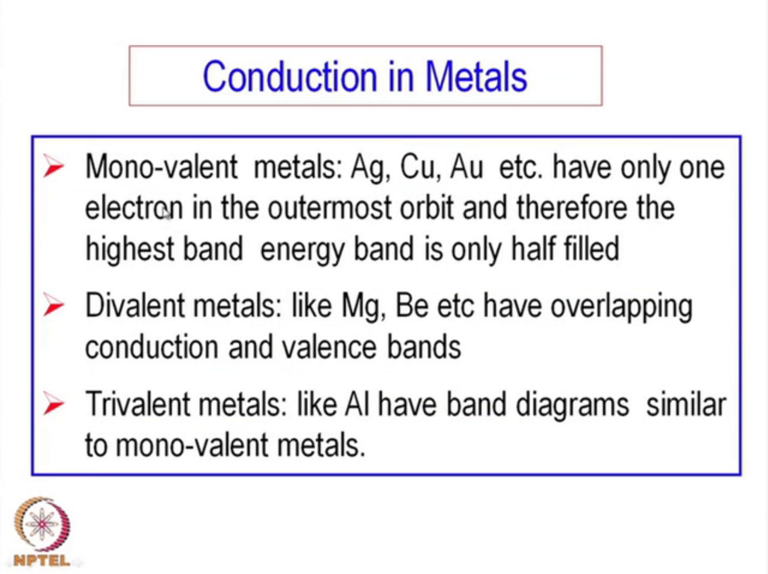

Conduction in Metals

- Mono-valent metals: Ag, Cu, Au etc. have only one electron in the outermost orbit and therefore the highest band energy band is only half filled
- Divalent metals: like Mg, Be etc have overlapping conduction and valence bands
- Trivalent metals: like Al have band diagrams similar to mono-valent metals.

Well there are few points here, what has been morally discussed monovalent metals like silver, copper, gold, etc. have only one electron in the outermost orbit. And therefore, the highest band energy, highest energy band is only half filled, the highest band energy is not band energy it is highest energy band.

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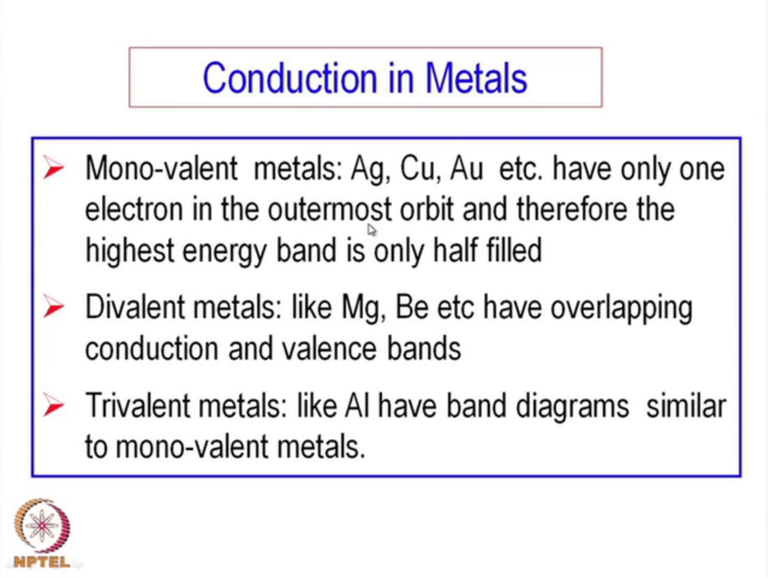

Conduction in Metals

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Yes, its highest energy band is only half filled. In case of divalent metals like magnesium, beryllium, etc. they have overlapping conduction and valence bands. So, in one case of half-filled, another case overlapping bands, trivalent metals like aluminum have band diagrams there is similar to monovalent metals. So, it is only they higher band will be the lower band will be full and higher band will half-filled situation. So, whether is monovalent or trivalent they more or less represent a similar situation.

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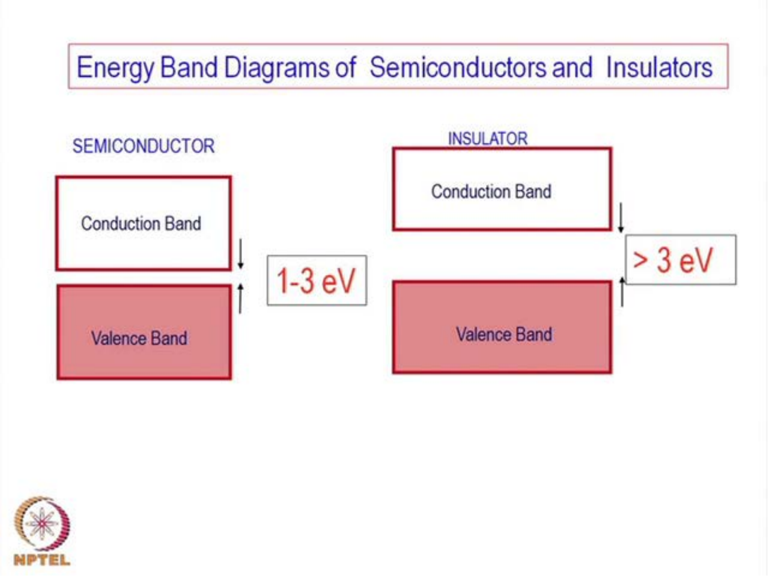

Energy Band Diagrams of Semiconductors and Insulators

This background let us look at the other two groups of materials, how they energy band looks like. In case of semiconductor, this is the situation incidentally in both the cases there is a band gap, there is a gap exists. There is no overlap there is no half-filled situation, valence band is fully, fully occupied, this full in both the cases, the conduction band is completely empty, both the semiconductor and insulator. But, the only difference is the magnitude of the band gap, magnitude to this gap.

In case of semiconductor the band gap, the greatly will small normally, it is about 1 to 3 are slightly less, in some cases may be 0.7, 0.8 particularly. But, the remaining so, it is about 0.5 to 3 electron volt, that is the region where these electrons from the valence band can be thermally excited from the valence band to the conduction band. And as a result in generate, electrons in the band in conduction band and the holes in the valence band and both the species contribute to the conductivity.

So, that is the semiconductor that means semiconductor is a group of material where band gap is relatively small. So, that thermal excitation is good enough or just increasing a temperature to some extend is good enough for some of the electrons in the top of the valence band getting transferred or getting excited to the lower part of the conduction band. So, once they get excited we have vacancy is here, the electron vacancy which are actually holes so, that hole can contribute the conduction process and also the electron in the conduction band, which has been a excited which has been excited they can also take part in the conduction process.

Whereas, in insulator, this gap is much larger and this normally more than 3 volts it may be 8 volts or even after 10, 12 volts so, depending on they what is the compound, what is the structure. So, insulator this since the band gap is very large, it is almost impossible for any electron to get excited to the conduction band because they are not providing that much of energy under normal circumstances. Of course, at a very, very high temperature have a close to melting point things may completely change and everything may become fairly conducting. But, under normal circumstances the electrons cannot be excited by thermal energy from valence band to the conduction band. Particularly even the band gap is larger than 3 electron volts.

So, that is situation where we get insulators so, all the materials metals, semiconductor and insulators can be classified based on the band gap. So, in one case we have overlapping band gap, almost no band gap, in other cases every small band gap and insulators are those materials we have the band gap is very large. So, that is have one can different set between is to group of two materials.

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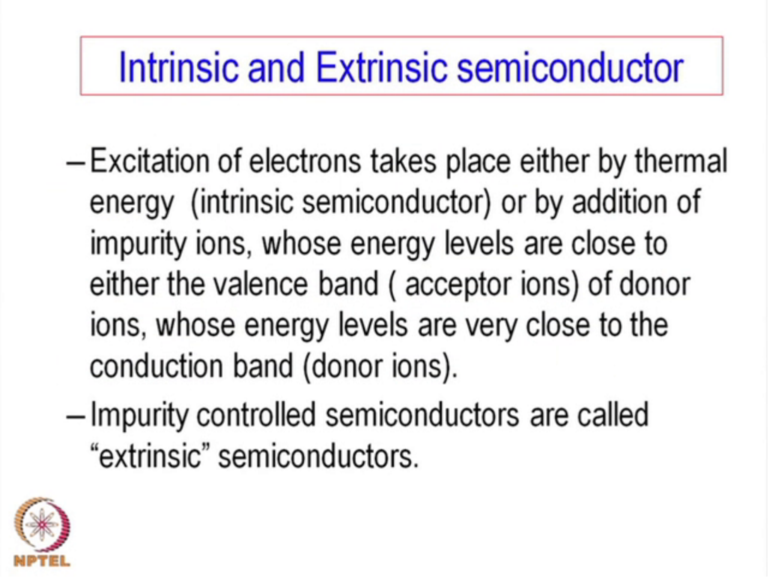

Intrinsic and Extrinsic semiconductor

- Excitation of electrons takes place either by thermal energy (intrinsic semiconductor) or by addition of impurity ions, whose energy levels are close to either the valence band (acceptor ions) of donor ions, whose energy levels are very close to the conduction band (donor ions).
- Impurity controlled semiconductors are called "extrinsic" semiconductors.

Having said that we have two different sub groups of the semiconductors, one is called the intrinsic semiconductor and another is called extrinsic semiconductor. One group is called intrinsic semiconductor and another group is called extrinsic semiconductor.

Excitation of the electron takes place either by thermal energy, that is intrinsic semiconductor or by addition of impurity ions, whose energy levels are close either the valence band acceptor ions or donor ions whose energy levels are very close to the conduction band. So, impurity controlled semiconductor are called the intrinsic semiconductors so, if the material do not have any impurity content. So, all the conduction electrons and the mobile electrons are generated by excitation from the valence band to the conduction band then, that is the intrinsic property of the material and intrinsic semiconductor.

However, you can induce induced conductivity, you can enhance conductivity or you can push or generate electrons in the conduction band. And holes in the valence band by a some other means that is by adding certain some impurities which take part in the process of excitation. We will discuss that in a minute but now, we are basically saying, but we have two groups of semiconductor one is the intrinsic semiconductor that the purest form of semiconductor where impurity effect is not there.

So, all the electrons are getting generated by the excitation of the electrons from the valence band. So, that is the intrinsic semiconductor and once you add certain amount of impurities, particularly when it is elemental semiconductors like silicon, germanium and so on there you add very, very little ppm level concentrations of different elements. Normally, this semiconductors are group four metals or group four elements, we add either group five or group three elements has a impurities which can act as a donors or acceptors, will discuss that.

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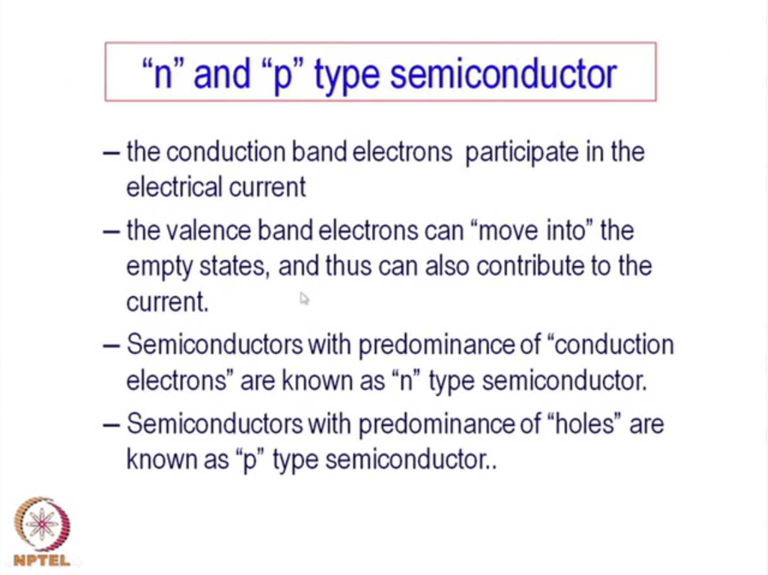

“n” and “p” type semiconductor

- the conduction band electrons participate in the electrical current
- the valence band electrons can “move into” the empty states, and thus can also contribute to the current.
- Semiconductors with predominance of “conduction electrons” are known as “n” type semiconductor.
- Semiconductors with predominance of “holes” are known as “p” type semiconductor..

Once again the semiconductors can be grouped and two some other classifications these are called n type or p type semiconductors. n means electron, that means negatively charged species and negative charge conductors, a charge carriers and p means positively charged carriers, positively in the means in this case basically holes.

Holes are the positively charge occur here where as electrons are the negatively charged charge carriers and that is why where there is a dominance of electrons, electrons because both of them can contribute to the conductivity. So, if both of them are present, but normally one of them particularly in case of extrinsic semiconductor one of them dominates although their numbers or exceeds the other one. So, that is why one is called the n type where the electron concentration is much larger, much, much larger than the hole concentration. Whereas p type semiconductor, their hole concentration is much, much larger than the electrons so, the most of the current is carried by the holes and then electrons so for as the p type conductor is concerned. Whereas n type conductor you have dominance of negatively charged electrons. So, the conduction band electrons participate in the electrical current.

The valence band electron can move into the empty states and thus can also contribute to the current that you have already discussed. Basically, what it say just will come back, there is semiconductor with predominance of conduction electrons and known as n type semiconductor, whereas the semiconductor with predominance of holes are known as p type semiconductors. This is what we have already explained, whenever there is a existed electrons in the conduction from the valance band to the conduction band. Then these electrons which are coming to the conduction band as a lot of empty spaces. Empty energy states, where it can move and these energy states occurs. As you have seen through the k factor, through all these energy states are actually related to some physical space or physical dimension of the solid.

So, the energy states that different sides or different lattice sides, different so it will occupy the higher energy states at a different location and that is how we will contribute to the conduction processes. In a valence band when the holes are created, the electrons remaining electrons also can move to these holes created and in that processes the holes will also move. So, in this case you will say it is a movement of the hole rather than electron impact. One cannot have than the other being on the move that means both of them are related one cannot move without the moment of the other.

So, both in the valance band, the valance sorry, the holes will be moving and in the conduction band the electrons will be moving, the excited electrons will be moving contribute to the conductivity. This is what says the valance band electrons can move into the empty states and thus can also contribute to the current. Semiconductor with predominance of conduction electrons are known as n type semiconductor. And semiconductors with predominance of holes are known as p type semiconductors.

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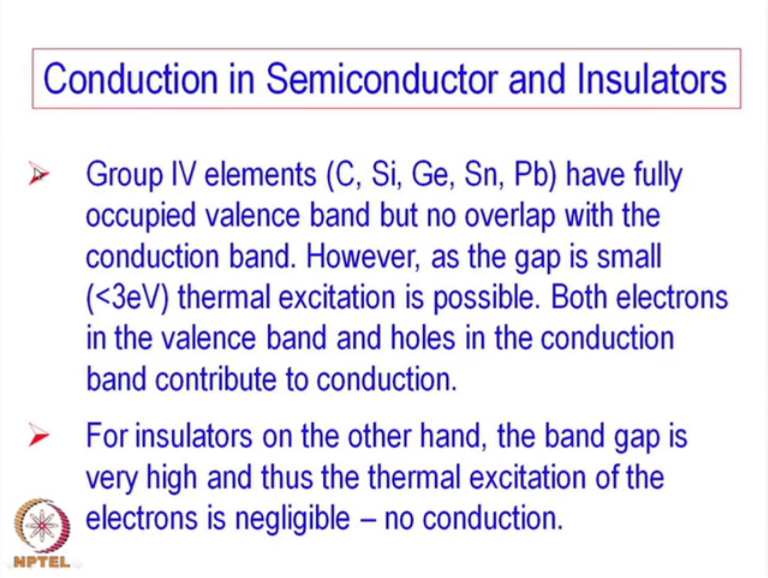

Conduction in Semiconductor and Insulators

- Group IV elements (C, Si, Ge, Sn, Pb) have fully occupied valence band but no overlap with the conduction band. However, as the gap is small (<3eV) thermal excitation is possible. Both electrons in the valence band and holes in the conduction band contribute to conduction.
- For insulators on the other hand, the band gap is very high and thus the thermal excitation of the electrons is negligible – no conduction.

Which are the basic semiconducting materials normally known to us? Is group four elements carbon, silicon, germanium, silicon is the most valued ones. It is not only cheap, but it is been extremely, extensively used in microelectronic industry. So, silicon is the best in building block for the semiconductor industry today. In addition germanium, tin, lead all of them have semiconducting property at different temperatures. They have fully occupied valance band, but no overlap with the conduction band have a has a gap is small, less than 3 electron volt that I have been mentioned earlier. Thermal excitation is possible both electrons and the valence bands and holes in the conduction band contribute to the conduction. For insulators on the other hand, the band gap is very high that you have already said. And thus, the thermal excitation of the electron is negligible no conduction is primarily the band gap which determents the property.

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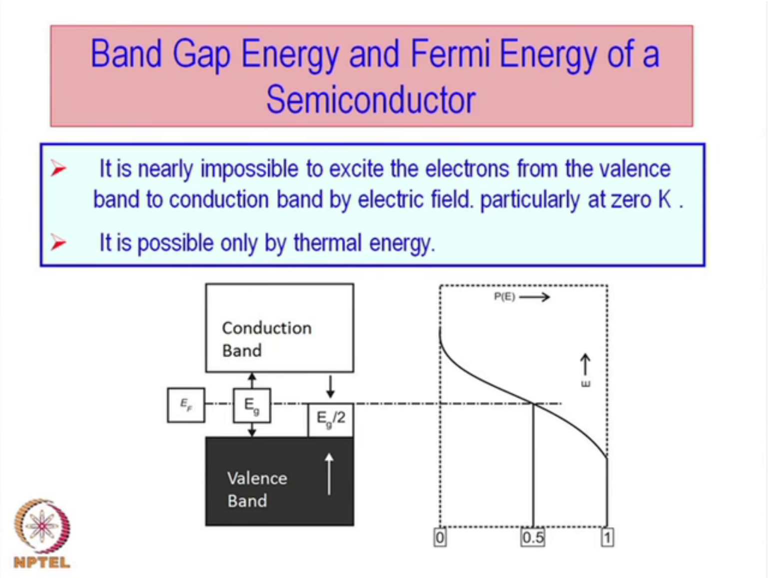

Band Gap Energy and Fermi Energy of a Semiconductor

- It is nearly impossible to excite the electrons from the valence band to conduction band by electric field. particularly at zero K .
- It is possible only by thermal energy.

We will come back to the accepters and donors latter on, before that in the band gap energy fermi energy, we discussed what is fermi energy. And that was the highest energy level up to whose the electrons are fully occupied of this energy states are fully occupied and that to at 0 degree kelvin, in absolute 0. At higher temperature there is at transfer from the transfer of electron from the lower energy states to the higher energy states states, across the fermi level. Now here you right to find out that you have discussed earlier in the, in the context of free electron model.

But here also there is a concept of fermi energy obviously, because the basic concept is same. Really impossible to excite the electrons from the valance band, and to the conduction band by electric field particularly at 0 kelvin. It is possible only by thermal energy that we already mentioned. So, it is the thermal energy which is equal first of all to excite the electrons from the valance band to the conduction band because that is, are the band gap is so. So, if the band gap is such that only with thermal energy one can excite electrons from the valance band to the conduction band with application electric field, electric field is not good enough.

Now, this is we have seen earlier that this band gap is E g and this E g the fermi energy state in at the middle of the band gap. So, this is where the band gap states at E g by 2 this is E g and this a direct band gap material. So, this distance is E g by 2, at that temperature just in the middle, the fermi energy lies or that is for all kind of calculation proposes, designed proposes. This fermi energy is taken as E g by 2.

And as you have seen in the fermidirac statistics that across this fermi energy there is a energy distribution. As you go up or down the, it appears sorry, it changes the probability and at E f that the middle of in the band gap exactly at the middle of the band gap, energy you have a 50 percentage occupancy. And that is the region another definition of fermi energy is where you have all the time irrespective of temperature, you have always a 50 percentage occupancy that is or distribution curve here means.

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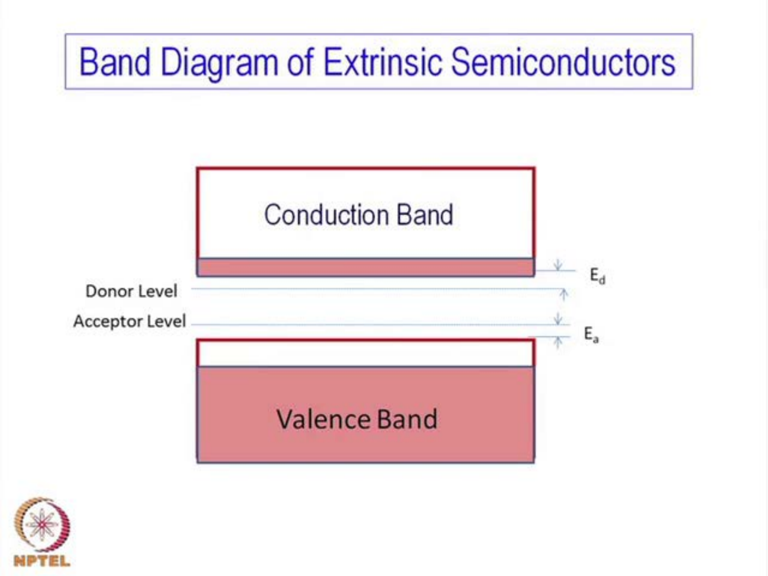

Band Diagram of Extrinsic Semiconductors

So with this, because fermi energy is one of the very important concept when you are talking about junctions, semiconductor junctions either talked about p n junction p n p, n p n junction, p n p junction (( )) is all (( )) circuit diodes and so on. So, junction or junction, the fermi energy concept or the knowledge of fermi energy is very important. Band diagram of extrinsic semiconductors, coming back to the extrinsic semiconductor desecration, where exactly or how band gap band gap looks. Extrinsic semiconductor, within the extrinsic semiconductor there are two types one is the Donor or n type or donor type that is accepted type or accepted impurity or donor impurity. What is exactly means the, these elements has some kind of ionization potential.

That means or electron affinity, that means here if within the band, within the band diagram, we can choose an electron, change choose an element or add to this as an impurity or a solid solution formation. So, that this accepted level of that particular element lies very close to the valence band. That is why it is called acceptors because it has been so chosen that the energy level of that particular element is very close to the valence band. In that case, it is a element it will be a element which has an unfield outer orbital so, it will observe or it will take act it take out some electrons form the valence band. For example, if we have a group 3 this is elemental semiconductors or group 4 and if we add group 3 so, some electron will be transferred to the accepted level. So, electrons will get transferred from here and get observe observed by the accepted level electron.

So, if that band diagram is choose in such a way that the band diagram of the element is closer to the valence band, top of the valence band then this energy gap is very, very small compared to the total energy gap. So, for the thermal excitation you need the total energy to the supplied. Whereas, if there is an accepted level you have to supply a very small amount of voltage or thermal energy, small amount of thermal energy is sufficient for electrons to be ejected from there and get accepted by the accepted level.

That means as accepted must have a very good electron affinity, it has an absorbing capacity so, the its energy levels are such that it will automatically absorb or attract the electrons. So, that the electrons will get excited from here, but instead of going to the conduction band it will just go to the level of the acceptor, because acceptor level is much smaller compare to the band gap here. So, that is the instead of the electrons going from the valence band to the directly with the conduction band, it can go very well the accepted level provided one can choose the accepted level element in such away.

So, these becomes the accepted level and one can see this limit or this energy is quiet small compared to the band gap and even the so called fermi energy, way up here the middle of the intrinsic one. But, we will see later on if there is a accepted doping the fermi energy actually comes down and it lies somewhere in between the top of the valence band and the accepted level. So, the fermi energy intrinsic semiconductor is in the middle whereas fermi energy for the accepted are p type semiconductor is some are here. This will be mainly doping with acceptor, it will be p type semiconductor because most of the charge carriers will be holes, will be holes generated here, not the electrons donated to the conduction band.

Now, reverse happens or something different happens when you have a donor level that means choose an element which whose energy level is very close just below the conduction band. So, it will be just a reverse of what happen in earlier case so, the electron will get donated. Here the ionization potential of the donor is very low once again it is only E d which is very small distance away from the conduction band.

So, only little bit of energy is good enough for ionize the element and the extra electrons will be contributed to the conduction band. So, donor level or donor atoms actually contribute some free electrons to the conduction band. And once they get in to the conduction band then it becomes very easy for it to contribute to the conductivity process. So, these are the band diagrams for the donor levels and the accepted level. Accepted level is very close to the top of the valence band whereas the donor energy is very close to the conduction band if just below the conduction band. And this distance either E d and E d is much, much smaller than the, than the E g E g means this distance so you need much less energy or generation of charge carriers.

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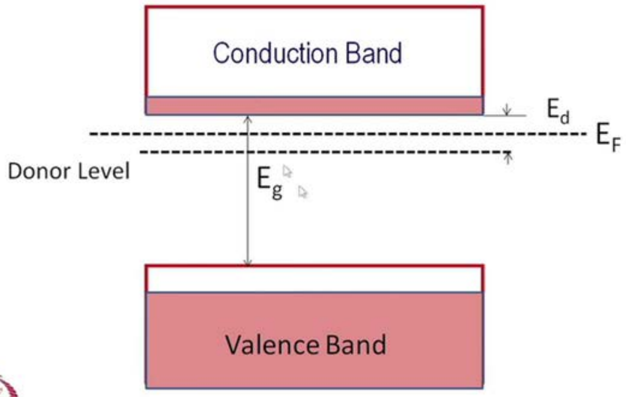
Band Diagram of *n - type* Semiconductor



This is just the expended view of the early discussion that means this is for the donor level and where we just want to. So, that if the intrinsic semiconductor the fermi energy lies exactly at in between that is E g by 2 E g by 2 here where as for accepted doping or donor doping the fermi energy is at a different location. And in case of donor doping fermi energy is larger, closer to the conduction band whereas, for the acceptor level it is closer to the valence band.

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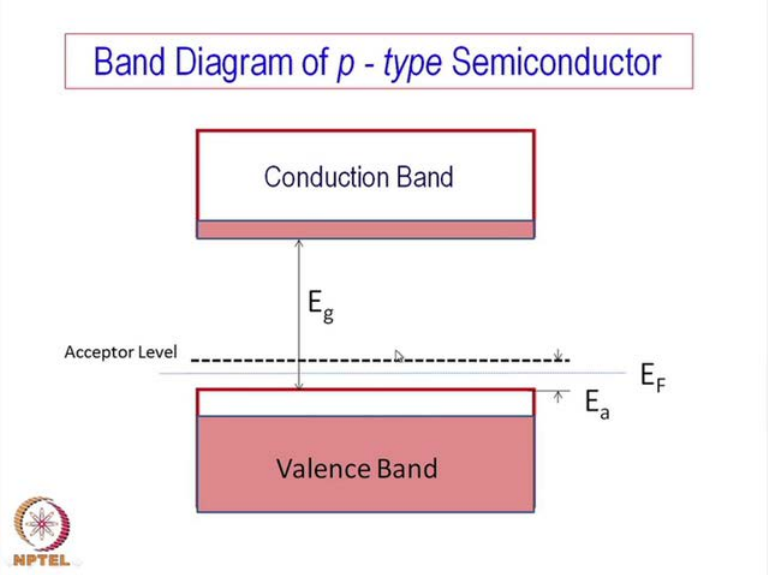

Band Diagram of *p - type* Semiconductor

But that is what given in the next diagram accepted level and the e f E f has come down here. It is exactly between this 2 levels the E a and E f sorry this is E a and this is acceptor level and this is the fermi energy. So, it is just (( )) between the top of the valence band and the energy level of the acceptor ions. So, this is a p type semiconductor because the predominant charge carriers as a hole, both of them will be there it is not that electrons are not completely taking part in the process. Electrons will also be there as well as the holes will be there, but the contribution of holes are much larger than the electrons in this case when it is accepted doping.

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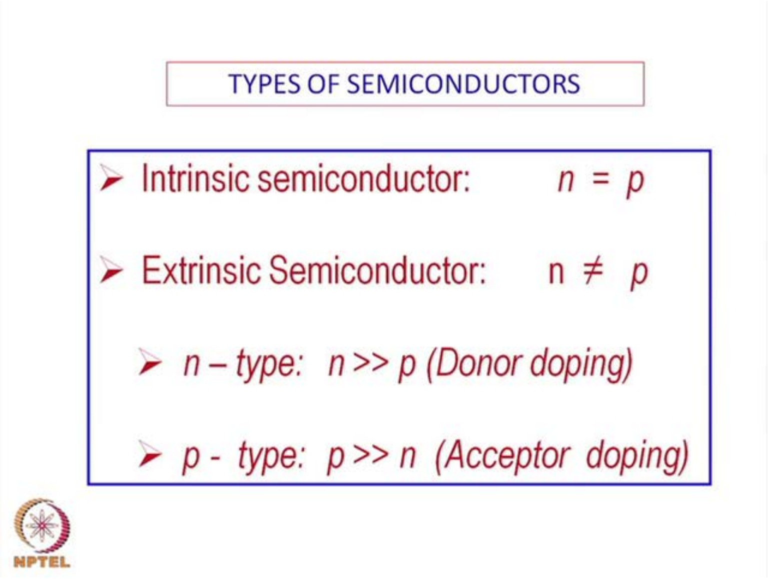

TYPES OF SEMICONDUCTORS

- Intrinsic semiconductor: $n = p$
- Extrinsic Semiconductor: $n \neq p$
  - n – type: $n >> p$ (Donor doping)
  - p - type: $p >> n$ (Acceptor doping)

So, for have learnt three different types of semiconductors one is intrinsic semiconductor, where because intrinsic semiconductor by definition means it is only the thermal excitation we generates the charge carriers. So, by thermal excitation, we are creating charge carrier both of the, at the valence band as well as the conduction band. And since it is the thermal excitation in the transfer is found valence band to the conduction band. The total number of negatively charged electrons and total number of negatively charged holes, the concentration are given by n and p they must be equal because that is one of the very important criteria for designating any semiconductor as intrinsic semiconductor.

Intrinsic semiconductor means that the number of free electrons and number of free hole at exactly same because the source is same. Where as in extrinsic semiconductor either the n is larger or p is larger certainly n is not equal to p. So, if it is terminated by n electrons or negatively charge electrons then it is n type where number of electrons, p electrons are much, much larger than number of hole is the p. And in case of p type, the p electrons hole holes are much larger than the number of electrons free electrons and one can say that is an acceptor doping in the other case the donor doping.

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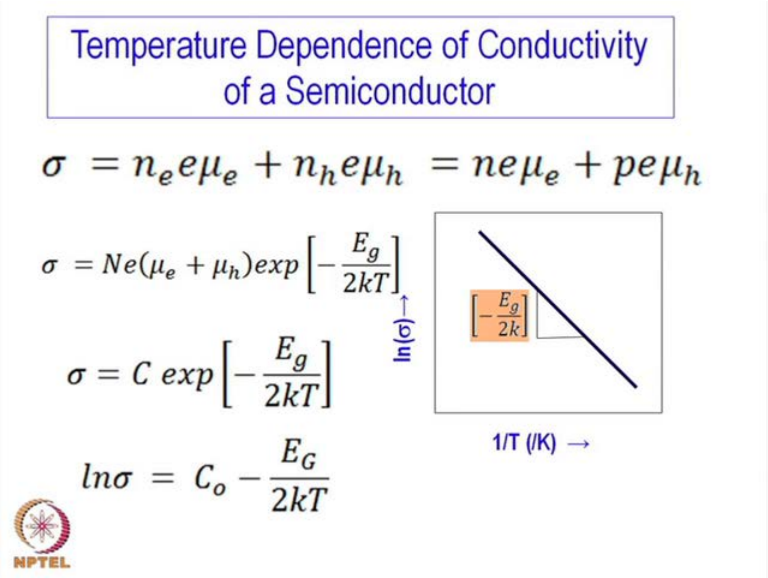

Temperature Dependence of Conductivity of a Semiconductor

$$\sigma = n_e e\mu_e + n_h e\mu_h = ne\mu_e + pe\mu_h$$

$$\sigma = Ne(\mu_e + \mu_h)exp\left[-\frac{E_g}{2kT}\right]$$

$$\sigma = C\ exp\left[-\frac{E_g}{2kT}\right]$$

$$ln\sigma = C_o - \frac{E_G}{2kT}$$

Now, you look at the temperature dependence of conductivity as a semiconductor. These expressions we have introduced very early in this chapter, discussion on electrical conduction. So, it is n e mu basically that is the expression of conductivity n is the number of charge carriers e is the charge per unit charge carrier and mu is the mobility so these are the three terms which multiplied gives us the conductivity. Now we have, since we have two different charge carriers in general, although in n or p type semiconductors one of them will dominate. But, in principle there are both types of charge carrier there and contributing to the overall conductivity. So, you can write n e mu equal to plus n h e mu is equal to n e mu e plus p e mu h so, n e is actually n the number of concentration of electrons and n h is the concentration of holes. We can simplify it by N e mu e plus mu h exponential e g by 2 k T minus e g by 2 k T.

And if you take a log plot log log sorry take a logarithm of that then these becomes a constant and exponential e g by 2 k T. Some kind of an arrhenius kind of equation it is an exponential change as a function of absolute temperature. And taking log this becomes constant another constant of course, and minus e g by 2 k T so, the slope will be, the slope of the straight line it must follow a straight line the conductivity as a function 1 over T. Follow a straight line with a negative slope and quantity of the magnitude of the slope is e g by 2 k.

So, by measuring the conductivity as a function of temperature is a very simple measurement so, by measuring that one can find out what is e g that means what is the band gap. Provided, provided it is an intrinsic semiconductor and both holes and electrons are taking part in the process the conduction. And one can very easily find out what is the value of band gap. Of course, we can only find out the band gap for the two bands involve in the conduction process, not the other band gaps.

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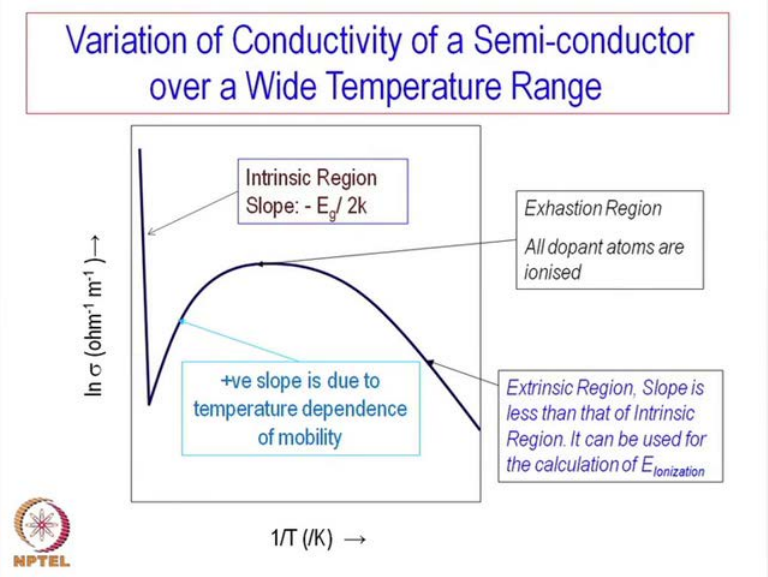

Variation of Conductivity of a Semi-conductor over a Wide Temperature Range

Intrinsic Region
Slope: - E_g/ 2k

Exhastion Region

All dopant atoms are ionised

+ve slope is due to temperature dependence of mobility

Extrinsic Region, Slope is less than that of Intrinsic Region. It can be used for the calculation of $E_{Ionization}$

Now in this curve we are getting a straight line and of course, no particular temperature has been mentioned here it is a typical curve and it is schematic curve. However, if one plots a very the conductivity over a much wider temperature range, one gets this kind of a variation. It is not always a straight line it has some curvature particularly at the low temperature end.

Sorry yes, if you plot a make a plot of log sigma verses 1 over T over a large temperature range then it is really not a straight line. It is really not a straight line it has different regions first of all, at this is of course, the lower temperature end. This is the higher temperature end and will find there is a negative slope here and definition i will come that back later on. There is a negative slope here and then as you increase the temperature the slope decreases and it becomes almost horizontal in some range intermediate temperature range.

And then, it changes in reverse manner that means in this part instead of negative slope we get a positive slope. Once again at the side fairly high temperature you get another negative slope, but very steep slope. So, it is a very interesting behavior and one can explain in this manner. We have seen that the extrinsic semiconductor has a much lower slope because it is not E g by 2 k. It is E i by 2 k, here the conduction process is here, the electron transfer is basically taking place between these two points, valence band and this energy level.

So, the conduction process is really very relatively easy because the activation barrier activation barrier or the energy required for the excitation or transfer is much smaller compare to E g, E g is much larger here. So, this is much smaller so the slope in fact that is what gets reflected in this curve that this slope is much smaller than this slope, in fact, we can go to the next curve and come back.

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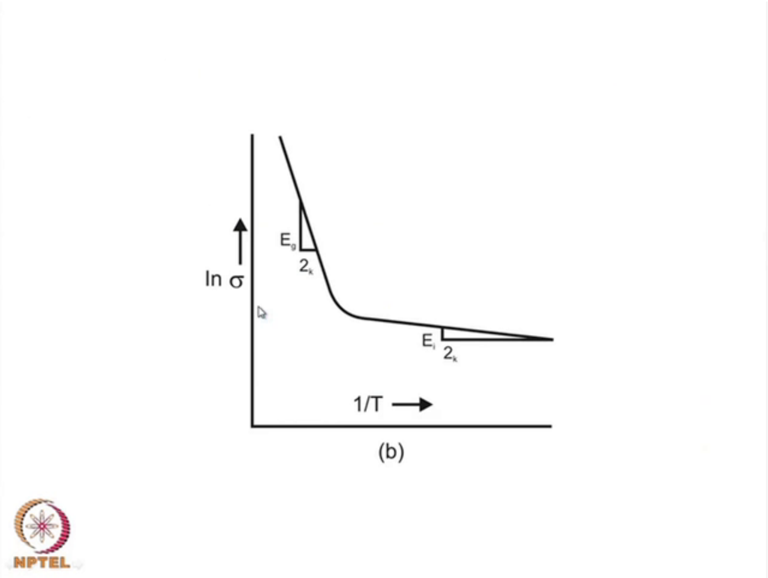

To this, this is another curve where, we will find that the slope change at some temperature. And lower temperature the slope is smaller where the higher temperature slope is larger and this corresponds to E g. E g by 2 K, where as this one corresponds to e i ionization E i ionization or the either the acceptor or the donor energy compare to the valence of conduction band.

So, the extrinsic semiconductor has a much lower activation barrier or activation energy. Whereas, the intrinsic semiconductor has activation energy much larger which is equivalent to E g and E g by 2 K, whereas here it is E i by 2 K an in fact that is, what it is reflected here in this curve, this is the extrinsic region this slope. In fact, this is the extrinsic region, this is the intrinsic region, you do not see such details suppose in the earlier curve or the later curve. Sorry, this one some details are missing here. But, there is a smaller slope at higher temperature and steeper slope at low temperature, high-temperature, this is low temperature and this is high temperature. So, however these details somewhere here are missing in this particular curve which has been shown here.

So, this is what they call the exhaustion region where it becomes more flat and almost becomes horizontal or independent of temperature. The conductivity in this region is actually independent of temperature. Here it is negative slope, here also negative slope, here is a much lower slope much lower than this one, but in between we have a region called exhaustion region. So, this is extrinsic region, this is exhaustion region and then this becomes intrinsic region.

In between we have positive slope that is behaving like a metal conductivity is going down with increase in temperature. And that is because first of all what is exhaustion region, exhaustion is all dopants are ionized because in this the ionization is taking place between either the conduction band between the conduction band and the acceptor or the donor, and the sorry. The ionization is taking place either between the valence band and the acceptor level or the donor level and conduction level. So, in both cases they are very lying very close to the bands bandages and therefore, that slope must be smaller and that is the reason why the extrinsic region, the slope is less than that intrinsic region it can be used for the calculation of e ionization.

So, that is that has been shown here that this is E i by 2 K, so the ionization potential, ionization energy can be calculated in the slope. Whereas at higher temperature the easy can be calculated, the band gap. Then, as we increase the temperature more and more number of electrons of the donors or the acceptor is accepting the electrons or donating the electrons. A donor is donating the electron and accepted is accepting the electron more number of such ions are accepting as the temperature is increased. So, after sometime of course, we have, we cannot see all the time these kind of details because only in certain number when the donor level of the accepted level are very low.

Then one can see this because this relates to the complete ionization of all the elements, all the donors donor of the acceptors level acceptor ions levels. So, it may happen in the number of donor are very large we cannot see that so the exhaustion region comes the number of dopants that is low and all of them that is fully ionized there is no further donation or acceptance of the charge carriers. So, charge carrier concentration do not change much, that is why we get a almost flat region, but then here in this the mobility term dominates because of charge carrier concentration remains constant.

After all of them have been ionized no further increasing concentration of the charge carriers what may change is the mobility. So, mobility as a positive slope so, with respect to temperature and that is the reason which dominates in this region. So, there is a small region after the exhaustion region or after the dopants are all the dopants should be ionized there is the small region where mobility dominates and the conductivity is controlled by the dominance of that by that temperature effect.

However after another temperature rise the intrinsic, intrinsic phenomenon takes over that means they are they have a direct excitation from the valence band to the conduction band. So, in this region there is no direct excitation from the valence band to the conduction band whereas, in this part of the diagram in this temperature range there is a direct conversion. So, once again the number of charge carriers increases, it is exactly it is of course, always exponential wave.

So, as soon as that temperature is reached a very high steep, conductivity change conductive takes over because that is a direct excitation from the valence band to the conduction band and conduction band. And the temperature is sufficient to do that so all others gets suppressed. So, all other variations get suppressed this becomes dominant, so from this slop and can get E g from this slop and can get E i the ionization potential of the acceptor of the donors.

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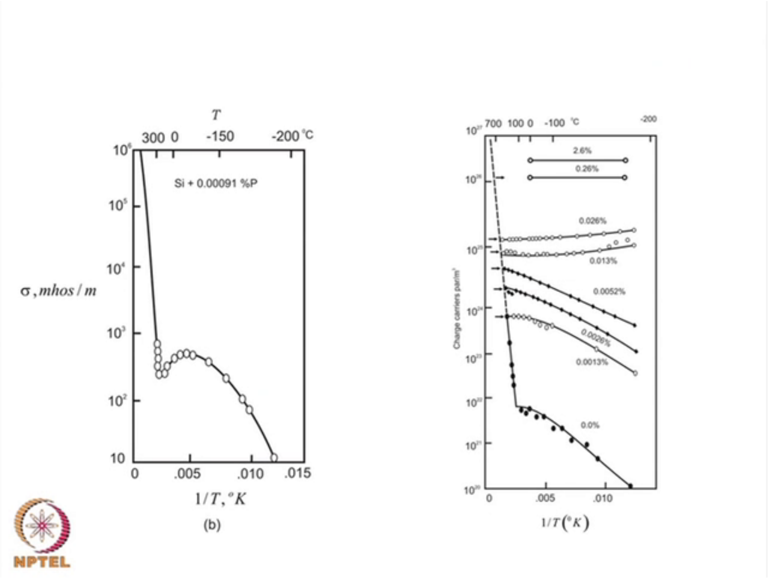

These have already discussed, these are actually some data once again for silicon for example, when phosphorus is added very, very minor quantities you do get in this kind of a variation. What has been idealized or explain earlier this is another curve for different concentration of dopant obviously, when dopant concentration increases more number of charge carrier gets generated. And the conductivity increases and, but at the same time the all the details gets missed out. So, this exhaustion region is no longer there, there is extrinsic region and then followed by the intrinsic region. So, as the concentration of the dopant increases you lose that details these are actual curves.

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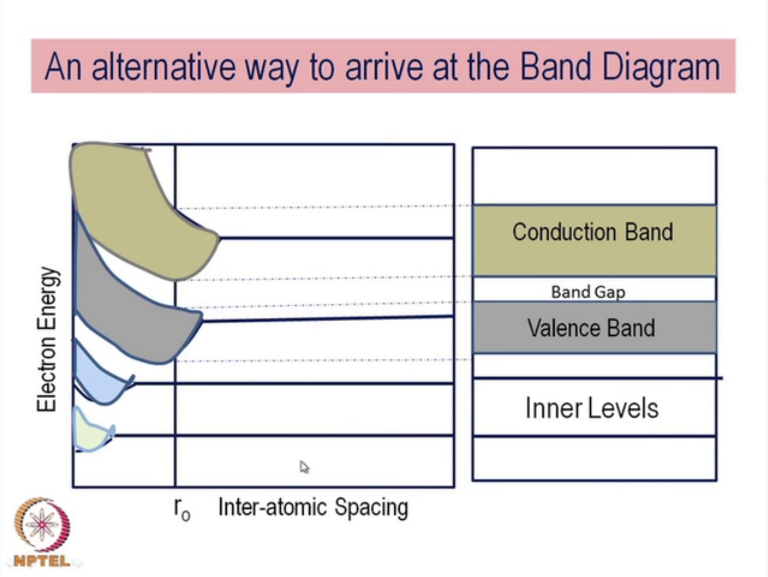
An alternative way to arrive at the Band Diagram

Well, I will just take another couple of minutes may be. We have discussed the band diagram in great details height is generated and so on there is another way one can arrive at the concept of the band diagram. Here what we are describing is actually in inter-atomic spacing, as if the two different atoms are two different ions having some outer free electrons each case coming close, closer to each other from the from a infinite distance. So, initially the, these are the outermost electrons and the inner most electrons inner levels.

So, these are the inner levels and these are the outer levels so, this is the equilibrium distance of separation and till that the equilibrium distance of surface comes there is no interaction between the electron clouds. The electron cloud do not overlap the first electron clouds overlap when the electron interaction takes place and the and the outer (( )). So, ones that interaction takes place there is we called degeneration of the energy levels. Till that interaction is not that between two atoms are isolated so, there is a line energy that means the discrete energy levels are there. Ones there is a interaction the two atoms come closer to each other and the electron clouds starts overlapping each other then there is a degeneration of the energy from the same particular energy level of the discrete energy level.

So, this no longer (( )) discrete energy level it form degenerated levels and that becomes at the intersection of the inter-atomic spacing that is the equilibrium distance of separation there will get the inner level still is not interacting with each other. So, as a result there in the still discrete energy levels where as we have degenerated energy levels here. So, if you plot that on the elevation will get this band diagram, these are the inner levels where that is still no degeneration whereas, in the upper of the outer most of the because of the interaction there is the degeneration there is a semi continuous or quasi continuous energy bands.

Available and the top one could be called the conduction band and the next lower one is called the valence band. And in between the gap which is the gap generated here it was the gap is so much and between the two discrete levels because there we no interaction there no overlap. Whereas, when they come with each other they start rebelling at each other and that a particular point at a particular distance the equilibrium is reached and at that stage there is a overlap. And there is a degeneration, and that is convert into a band gap. So, this is also another simplified way of course, it comes from the same concept, but primarily it is a little different approach from where one can also get a band model. And these models have become more useful when we discuss about the oxides the band diagram oxides and when band, band diagram oxides will be discussed, discuss some of these concepts. So, since the time is up, I must stop it here and thank you for your kind attention, we will continue this discussion in the next class once again.

Thank you.