Advanced Ceramics for Strategic Applications
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Lecture - 13
Electrical Conduction in Ceramics
(Contd.)

Welcome to this continuation class on electrical conduction in ceramics. We have at earlier two classes on the preliminary discussion on the electrical phenomena, and the different theories to explain the conductivity behavior of two different solids. We continue the discussion in this class as well.

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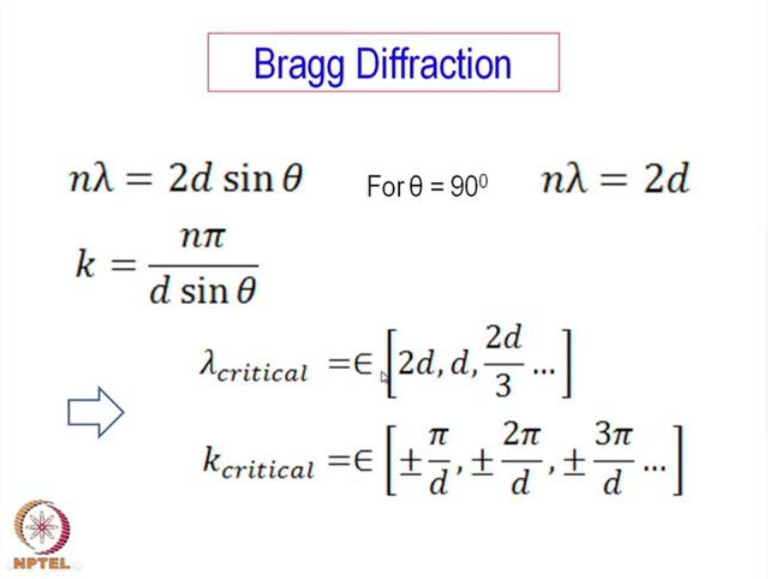

Bragg Diffraction

$$n\lambda = 2d\sin\theta \qquad \text{For } \theta = 90^0 \qquad n\lambda = 2d$$

$$k = \frac{n\pi}{d\sin\theta}$$

$$\Rightarrow \quad \lambda_{critical} = \in \left[2d, d, \frac{2d}{3} \ldots\right]$$

$$k_{critical} = \in \left[\pm\frac{\pi}{d}, \pm\frac{2\pi}{d}, \pm\frac{3\pi}{d} \ldots\right]$$

This is so called Bragg diffraction, the relationship, the formula for Bragg diffraction n lambda equal to 2 d sin theta and for theta equal to 90 degree n lambda equal to 2 d. And k, k equal to k is the wave vector, again n lambda d sin theta. Now, we were discussing this concept of Bragg diffraction, came in because of the consideration of band model, band model of the solids to explain the electrical behavior in particular or the phenomena of electrons, the behavior of the electrons within the solid, and we have considered in a periodic like this the electrons moving in a periodic lattice, this not on a constant potential, but on a periodic potential and because of this periodicity. This Bragg diffraction, the concept of Bragg diffraction also came in that whenever there is a periodic lattice. Any vector in the wave passing through that periodic lattice there is a chance of diffraction and because of the periodicity there is constructive interference.

If the angle of impedance angle of incidence is about 90 degrees, then there will be complete reflection back which means basically the electrons impinging on such kind of surfaces having these having this d spacing and theta of course, 90 degrees. So, if this d spacing the lambda will be completely a d wave particular wave, be completely reflected back, it will not pass through. So, that will be some kind of forbidden barrier to this kind of moment of the electrons and that comes from the periodicity the periodic lattice.

These are the relationship lambda critical that for particular lambda value, this will be satisfied that will be 2 d, d the set of values 2 d, d and 2 d by 3. And then that will be converted to the k value the critical value k, in the k space value the wave vectors. Then at this will be plus minus d plus minus 2 d plus minus pi by d, 2 pi by d and 3 pi by d and these will be clear when we go to the next picture next figure.

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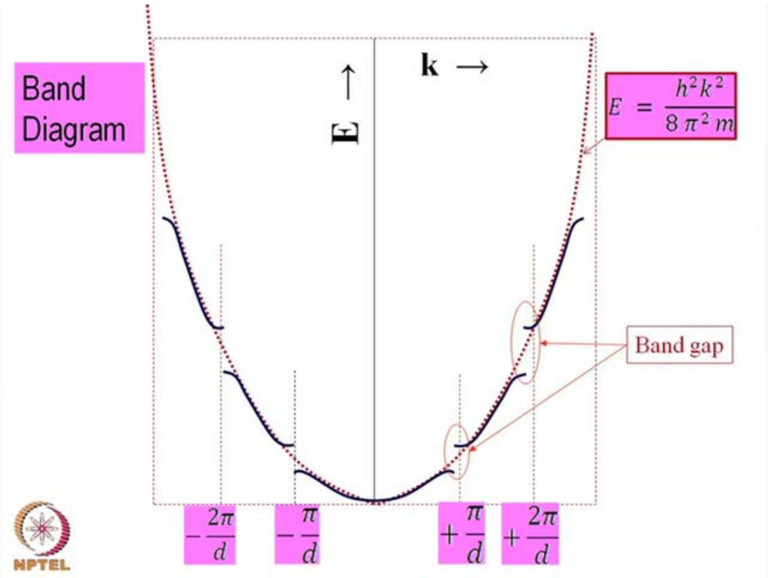

What exactly this is, what exactly is the consequence of the so called periodic lattice followed by the chronic model and the block theorem combine all this what we finally, come up with is the same kind of E k curve. What we have observed in the free electron theory, the parabolic curve and that is our original E k curve, parabolic E k curve which we have earlier drawn and seen and explained. Same thing happens here also, but with some difference, the difference is there is certain amount of discontinuity the certain amount of discontinuity.

The curve is not continuous here, earlier we had seen these are discrete points, but almost a quasi continuous line. These points are discrete point's energy levels, discrete energy levels, but otherwise it is a quasi continuous line, because of this periodic potential of the lattice and the consideration of Bragg diffraction what we have just discussed there is certain amount of discontinuity happens. This discontinuity will not happen anywhere the discontinuity occur at those values of k is critical k values, which we have given here is plus minus pi by d plus minus 2 pi d and plus minus 3 pi by d that kind of particular specific values of k.

We have this discontinuity and we can see towards, one can find out through some mathematical calculation that there is slight amount of bend slight amount of bend in those discontinuities. These are different specific values, critical values of k where there is some amount of discontinuity that means the earlier we have introduced the concept of density of states. The density of states, do change at those points, at those discontinuities at those critical values of k. As a result the E k curve bend, little bit downwards here and here it bends towards upwards considering that there is a discontinuity.

Now, this to this suddenly, if we go on changing the k value then the energy here changes almost on a continuities manner and then suddenly there is a discontinuity there. So, it does not follow the original path of E versus k curve, but there are certain discontinuities that mean here the energy levels are not available. So, if the electrons having this energy level then from this energy level, the next energy level if it acquires some energy it will go it has to acquire this amount of energy and go to the next level. It cannot stay within these energy levels, so these energy levels become forbidden energy levels.

So, this is where it comes from Bragg's reflection, the electrons get reflected from there, so it cannot stay or it cannot occupy any energy level between this values because this is your E n energy access. So, from this energy level it has to jump to this energy level, it has to go the next energy level, the next energy level here these are forbidden energy levels. So, at different level different points, now the k vector different values of the k vector such discontinuities occur so this is one set of discontinuity minus pi by d and plus pi by d. So, one can say this up to this is one volume of the E k curve where there is a continuous, there is a continuity of the energy levels then there is a gap from this one to that and it starts from the next level there.

So, if you draw these horizontal lines here then it starts from there again and it ends in the lower level, it ends there and then suddenly it goes to the higher level and it starts again, so once again there is continuous energy level available from this band. So, this band of energies is continuous then again there is a discontinuity and once again there is a continuous band. So, the energy levels are really not continuous or whatever we have in free electron theory, free electron theory provides the energy levels that are continuous energy levels. Whereas, in reality the energy levels are really not continuous it is discontinuous.

So, it comes in the form of bands, bands are energy levels and that is the reason the particular name band model comes in. So, we have bands of energies and in between the bands there are forbidden energy levels or band gaps. So, this is the main consequence or the main outcome of the band model of solids. We will see later on that this band model can explain many properties and the behavior of different groups of metals or different groups of solids having different ranges of electrical, different ranges of electrical properties whether it is conductivity or resistivity.

So, finally, the outcome is more important for us, because we will only devote to the details of the mathematical calculations, but ultimately the outcome is the main. Outcome is that has to be remembered all the time, this is our main outcome that is the E k curve is not a continuous have does not have a continuous energy levels, energy states available to the electrons. The electrons can have either within the continuous bands, but not in the band gaps, so it cannot stay, so either it stays in the lower band or on the higher band, but not in between the band gaps.

So, that is a very important consequence of the band model and one can this is of course, we have drawn it two dimensional curve, but earlier as I said actually these curves are three dimensional and you have a three dimensional volume which contains a large number of points of different discrete energy levels. So, these are actually different volumes although it has been taken a raw cross section, but these are actually volumes.

So, this is one volume which contains the continuous or semi continuous quasi continuous every level, then there is another volume band.

In this case there is a band, but actually a slice of volume and then there is another of course, the pictures are very, very simplified here they are neither sliced nor the surfaces are plain. So, most of these cases, because this is completely related to the crystallographic directions or crystallographic planes. So, the k values actually relate to the crystallographic planers in the reciprocal lattice particularly, in the reciprocal lattice and from that one can see that the slices, what you see here is actually not a plane cylinder surfaces. But basically, it is a complex three dimensional figures and these regions these regions of where the continuous or semi continuous or quasi continuous energy levels are available, these are called zones.

A particular name has also has been given to these zones these are called the bellowing zones. So, the first level for example, in this picture the first level of continuous energy levels is called the first bellowing zone and then this is the second bellowing zone and the third bellowing zone and so on. It is difficult little bit to visualize the exact shape of these zones, but basically it is a three dimensional cuboids kind of pictures. And, it depends on what kind of crystallographic relationship it has, but the bellowing zones are nothing but these bands in the whatever you seeing in the two dimensional is a band these are actually called the bellowing zones.

Now, there is a consequence of this complexity of these geometric figures, these bands or these band gaps the energy levels are really not uniform throughout in different directions, in the different axis. So, although in a particular section we find they are quite symmetrical, they are not symmetrical the surfaces are complex and not a plane surface at all. So, this is our original expression of the free electron model E equal to h square k square by 8 pi squared m on that it has been superimposed. So, there is lot of similarity over the E k curve is concerned the free electron model and the band model with the exception that there is a discontinuities.

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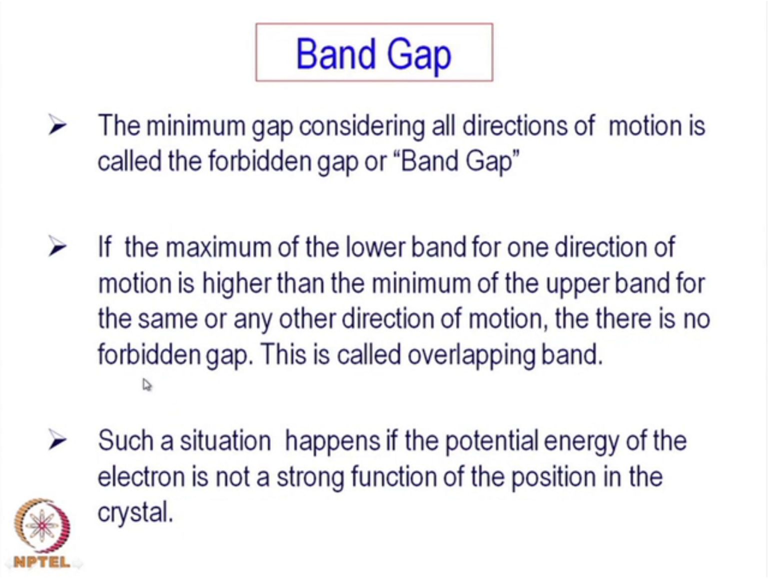

Band Gap

- The minimum gap considering all directions of motion is called the forbidden gap or “Band Gap”
- If the maximum of the lower band for one direction of motion is higher than the minimum of the upper band for the same or any other direction of motion, the there is no forbidden gap. This is called overlapping band.
- Such a situation happens if the potential energy of the electron is not a strong function of the position in the crystal.

This, discontinuity explain many of the properties which we encounter in reality with this we define what is a band gap, because this band gap is of extreme importance to us to understand, the behavior of different solids including ceramic metals which we would discuss later. So, the band gap is the minimum gap considering all directions of motion is called the forbidden gap or the band gap where we have introduced in so called reaction of the motions. In the planes particular crystallographic directions in which the electrons are moving for our mathematical calculation we have taken a reciprocal lattice the k vector is in the reciprocal lattice, but I actually has a correlation with the actual real lattice.

So, the electrons are moving in different directions in different crystallographic directions at the different points, in the direction the electrons encounter different energy levels. So, although these are the two different spaces one is the volume space and that is the energy space there are some kind of a correspondence between them, so when the electron resides in a particular volume space or the actual crystal or real crystallographic site. It also has certain energy level associated with it, so that is although in the energy space you get band gaps, but in the volume space there are absolutely no discontinuities, but energy wise they have discontinuities and some of the energy levels and some of the energy states are forbidden energy states.

So, it cannot stay in everywhere in the crystal we explain exactly how are these means considering all the directions of motion right you take it up. In the next slide may be if the maximum of the lower band, we have different energy levels in the first bellowing zone, in the second bellowing zone, in the third bellowing zone at different levels. One bellowing zone ends, the other bellowing zone starts after with a gap of certain energy levels. So that is what it mean if the maximum of the lower band or for one direction of motion is higher than the minimum of the upper band for the same or any other deduction of motion there is no forbidden gap, this is called overlapping band. Now, if you go back to this diagram, we see that there is a discontinuity here.

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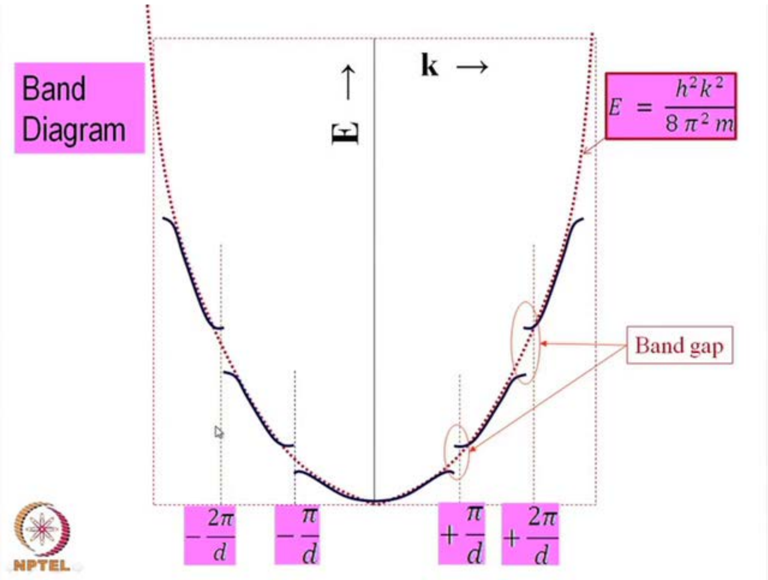

So, if we draw this horizontal line, this horizontal line then all through there is a discontinuity, but this may not be true this may not be a horizontal line at all, it may be a complex line, it may be a complex line like this or something like that. Of course, not in curved surface because it has certain geometry it combination of certain planes. So, if you take any particular say any particular reduction although or a large number of vertical reductions although we are finding a gap here if we draw a line there, there may not be any gap there may not be any gap on that particular axis.

So, it not necessary that all through this gap exists it may or it may not, so if there is no gap or there is some kind of overlapping in a particular direction, but there are gaps in other direction in that case also we can say there is no gap or the bands are getting overlapped with each other. So, we will look into such kind of situations with little space, so that is what in that context we did this paragraph.

If the maximum of one band for one deduction of motion is higher than the minimum of the upper band for the same or any other direction of motion there is no forbidden gap. This is called overlapping band, such a situation happens if the potential energy of the electron is not a string function of the position of the crystal. We have already considered a periodic lattice and depending on the crystal depending on the particular lattice the variation may be less or more.

So, if the variation is more, then such situation forbidden energy gap sorry the overlapping bands may not occur, but if the variations are very strong the forbidden energy overlapping may not occur. So, such a situation overlapping bands happens, if the potential energy of the electrons is not a strong function of the position in the crystal. So, it depends on what is the variation what is it very strong variation or very drastic variation or a very shallow variation depending on that we can expect or not expect a overlapping band.

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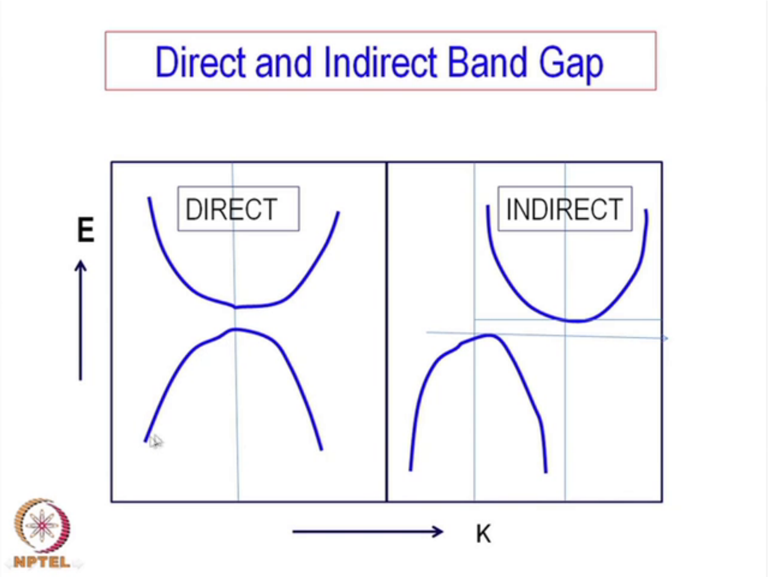

Direct and Indirect Band Gap

We are talking about band gaps and the band gaps are very, very important. Now, this is what we call a direct band gap that means this is the particular direction, this is the direction one can say this is the direction of motion the electron is moving from a lower energy to a higher energy around this deduction. And the bands across this deduction the lower band is like this, it means it is not flat at all as we have visualized here might have visualized there, but a surface of the band is not a flat band or a flat surface it may be a completely curved surface, quite complex curved surfaces.

So, this is a continuous energy band, these are the continuous energy possible here whereas this is continuous that means are bands these are forbidden energy levels or these are forbidden energy levels including these small gaps. So, around this deduction the gap is more as you go from this to the right or the left the gap is increasing, but the minimum gap may be somewhere here. The minimum gap is somewhere here and when you talk about define about the band gap the forbidden energy levels, we will always talk about the minimum gap these are the two different surfaces.

This is in fact one bellowing zone this is another bellowing zone, so the gap is between this and along the vertical line all one can electron can move in the a inclined way also, it can move start there and go in an inclined follow a inclined path as well. But really the vertical direction is here is being shown and the minimum gap is the gap if the forbidden energy gap always we have to remember this is the minimum energy gap. So, if you have to if a particular solid has two different bellowing zones of this nature and we have to say what is the band gap then we will show we have to draw this curve in fact later on, we will see that we do not draw this surfaces as curved surfaces.

We always draw as plane surfaces or as parallel line, but that is only schematic that is not a real situation that is only a schematic situation. It is only for a particular deduction of motion although we give a width to it, but the width does not have any significance. There we will see that, so this is the direct band gap that means along a particular crystallographic direction the minimum occurs before, so this is the maximum the lower band and minimum the upper band is in the same direction same crystallographic direction then only it is called the direct band gap.

Wherever the situation may happen that a situation like this, the maximum a lower band occurs in one particular in one direction with a k vector here whereas, the minimum the upper band occurs as a different k vector. So, there is a gap there is difference between this k value and this k value where this is there is no such distance two k values do not exist. One single k value as the maximum and the minimum whereas, here the maximum is for one k value and the minimum is for another k value. So, this is what we call the indirect band gap although the band gap here is not this neither this band gap is the minimum distance minimum gap between the maximum of this.

The minimum of this that is always the characteristics band gap of this material whereas, this is direct band gap. This is the characteristics band gap and we draw normally if we have to draw a band diagram of this solid, we will draw a line there like this horizontal line and we will draw another horizontal line here. So, that will represent the gap for this material here also, we have just drawn two horizontal line one is this, one this one and this is the band gap. So, we do not draw a curve and we are not concerned what is the band gap away from their maxima or minima this gap may be larger, but we are not concerned about that because the transfer the electron transfer will take place along the direction the minimum gap direction.

So, this is the concept of what do you call a band, a direct band gap, an indirect band gap these are very important when you are talking about any electronic devices some contacts and so on band gap has a very, very important role in designing microelectronic devices or semiconductor devices. So, band gap is one of the most important or utilized concept for designing of different semiconductor devices including the microelectronic of different kinds the laser semiconductor lasers there are many, many devices the concept or the knowledge of the band gap.

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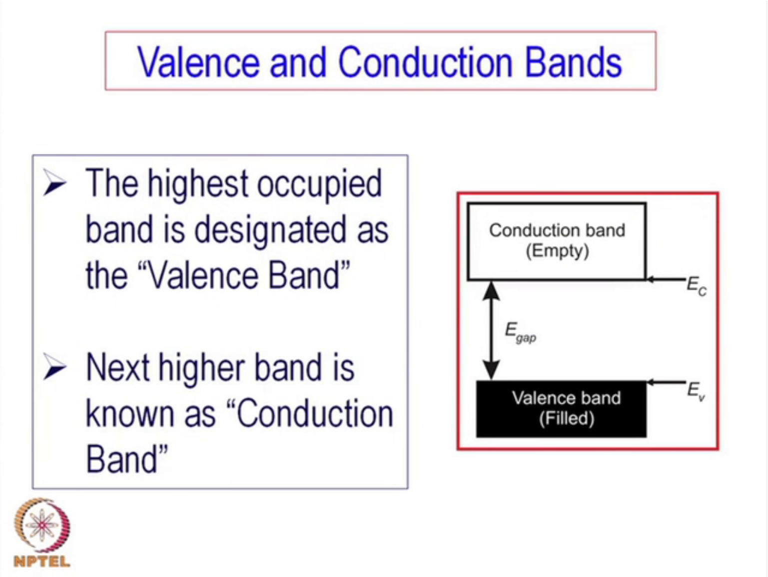

Valence and Conduction Bands

- The highest occupied band is designated as the “Valence Band”
- Next higher band is known as “Conduction Band”

This is what we are talking about the valence and the conduction bands and as we can see here we have drawn a horizontal line a very simplified diagram, extremely simplified diagram. In fact, in reality never such a horizontal gaps, never exists in fact we also remember here that there is no axis here whenever you draw a band diagram we never give a horizontal axis. What is the horizontal axis? It is immaterial in fact, in fact we are talking only about the gap here, and the horizontal axis does not have any significance here. The impact this gap is along a particular vertical line, since vertical drawing a vertical line with a gap is not a very convenient way, good way of drawing something.

So, for better representation we draw a horizontal line, but the width is absolutely immaterial here, any way this is how we draw a band diagram. This is one band diagram one, band for continuous band this is another continuous band of energy levels and in between you have band gaps which is called the forbidden energy gap and no electron can reside on any of these energy levels here. Any of the energy levels, particularly the energy levels are forbidden for that particular system or particular solid with that we also should decide, also define what is the valence band and the conduction band.

These are the two terms, which we extensively use when talk about electronic conduction semi conduction particularly or even in metals and in insulators. So, ultimately it is the valence band and the conduction band the concept of valence band and conduction band are most important. The definition of the valence band is the highest occupied band is denoted as the valence band. Now, once again may be we have to go back to that original picture this one.

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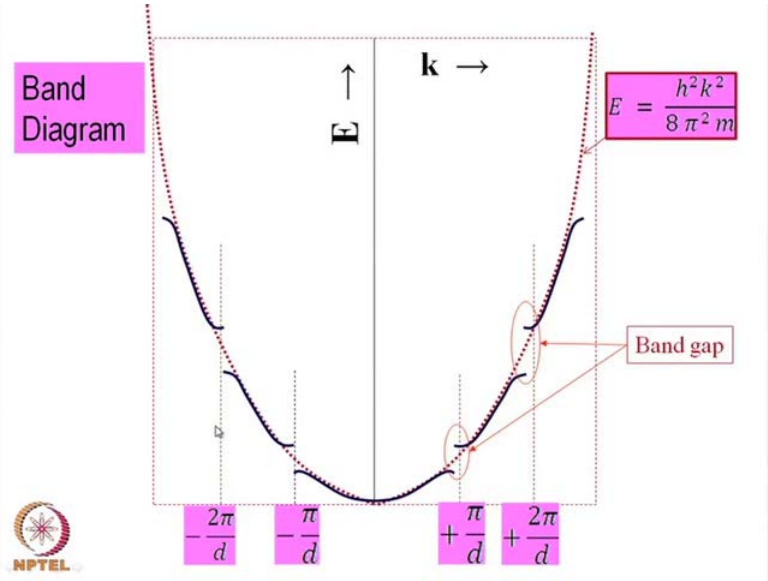

Band Diagram

$$E = \frac{h^2 k^2}{8 \pi^2 m}$$

We say this is one band, the lowest band and lower energy band and then higher energy bands and then it continues. It continues almost indefinitely depending on the number of the structure of the solid and the number of available electrons in that solid free electron of course, now there are one band or one gap here and one gap here. So, we have to understand which one is more important to us or which one actually controls all of them, do not control the property. Mostly one of them control most of the property and that depends on how many number of electrons are available, free electrons are available in that system and how many bands are available.

So, normally the lower, the number the first the lower band will be occupied and then if the number of electrons is more than the number of energy states available here then it will go to the next band that is how it is getting filled up. So, in that context the band gap or the band diagram when you normally draw either you have to draw this one and this one. This one is the lower band and this one is the upper band or we can draw this one as the upper band and that one as the lower band, so for any particular solid there is a band gap.

Now, band gap normally refers to the highest gap or the highest energy gap in that for that particular system, so what we are saying here that the highest occupied band is designated as the valence band. And below that whatever energy levels are available including if there is a band gap does not matter, but all the energy levels are filled up below this level then this would be called valence band, so and the next higher band is known as the conduction.

So, the next higher band will be the conduction band, so we are mostly concerned with these two bands all the time this is your valence band and conduction band. In any kind of literature, any kind of discussion we will always find that there is a mention about the valence band and the conduction band, so we are mentioning here these two bands. So, in that context again going back to the earlier curve, in some material we will see this may be the sorry this is the valence band and that is the conduction band. In some other material one may see that this may be the valence band and above that there will be conduction band.

So, it depends on the particular specific material, but we are more concerned about the gap what is the gap, what is energy gap available and that controls the property of the material to a large extent. So, this is the valence band and conduction band definition and they are also nomenclature here for example, E v the top of the energy level of the valence band is designated as E v, E subscript v whereas, the top of the or bottom of the conduction band. The energy associated with that or the energy corresponding to that is designated as E c and the gap, gap is always e gap here it is written E gap, but it is mostly E g e subscript g it is designation of the band gap.

So, E g e gap or E g is nothing but E c to E v many a times, what happens this because we do not know if we are drawing this particular diagram. We do not know where is our reference where is zero level it is not necessary to known, not necessary to be known actually because many cases take this as the reference this as the zero level and then onwards or upwards becomes our axis. So, reference many most of the time the reference is E v becomes your reference, so that E c becomes E g, so the gap is our concern and it is relative to a particular energy level and normally the top of the valence band is taken as the reference as zero level.

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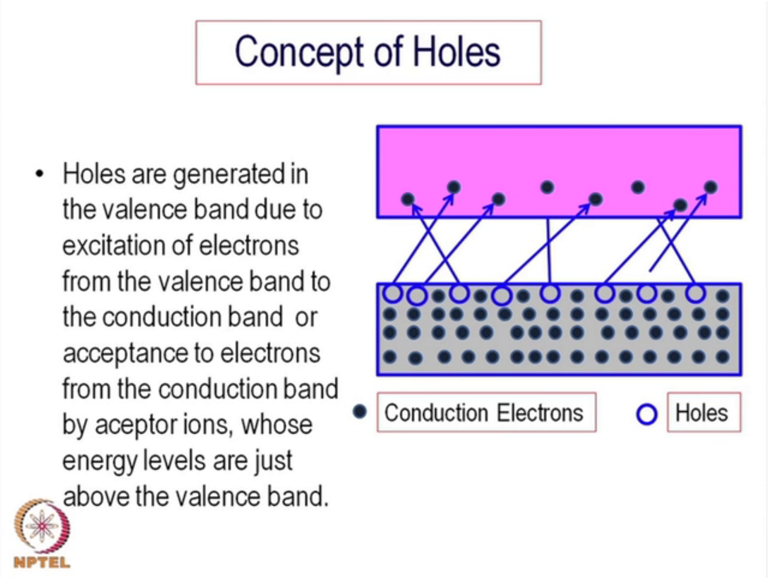

Concept of Holes

- Holes are generated in the valence band due to excitation of electrons from the valence band to the conduction band or acceptance to electrons from the conduction band by aceptor ions, whose energy levels are just above the valence band.

● Conduction Electrons ○ Holes

With this we come to another very important issue now, so far we have discussed the charges, species is basically electron in semiconductor physics. We have some indifferent metals when you are talking about metals electron is the basic species, which is the conducting species or the charge transport species, but in when you talk about band gap then there are another concept comes in holes. The holes are generated in the valence band due to the excitation of the electrons from the valence band to the conduction band or acceptance to the electrons from the conduction band by the acceptor ions. So, holes are generated in the valence bond due to the excitation of the electrons from the valence band to the conduction band.

So, this is our valence band and this is our conduction band, so the valance band is occupied all these are the black dots the black dots are representing the electrons. So, the electrons are available at different energy levels once again there are the horizontal axis does not mean anything. Generally, it is the vertical axis which is of our concern, the horizontal axis is only reduces the kind of the volume not the total number of electrons on that particular energy level. So, from the conduction band by the valence band to the conduction band or acceptance of the electron from the conduction band by the acceptor ions, whose energy levels are just above the valence band sometime.

We come to that later, but before that let us say there is a occupied levels the electrons are here and this is the forbidden energy gap or the band gap be g no electron can reside in this white region because these energy levels are forbidden they electrons cannot accept these energy levels. So, it has to accept sufficient energy, so that it crosses over jumps over to the next band that is the conduction band. So, this is our conduction band this pink one is the conduction band and the black one is the valence band. This is filled up with the electrons and once a thermal energy for example, some thermal energy is provided to it these electrons accept the thermal energy gets energized, so the energy content increases and goes to the next level in the conduction band.

Now, once this electron goes to the conduction band all these electrons are actually got excited from the valence band to the conduction band and consequently there are some vacant sites. So, these circles are actually the vacant sites of the electrons which originally used to be there, because they were excited by additional energy from external sources. So, they have left behind some vacant sites these are actually the electron holes, these are called the electron holes it is basically a vacant sites left over by the electrons which have been excited to the conduction band.

So, it is basically a vacancy of the electrons, so that is the concept of the electron holes the reason why they are important is they can also, act as a species charged species like electrons because once these hole or the hole is created or the site is vacant, it becomes a positively charged species it becomes a positively charged species. So, this hole becomes a positively charged species and these holes can move just like the electron under the application of the electric field just like a vacant can move because of the concentration gradient here, because of the potential gradient of the external applied field.

These holes can move in the particular direction in the direction of the field in fact and the movement is very simple, because if this electron jumps over to the next hole then hole actually moves there. The holes move in direction opposite than that of the hole than that of the electrons, so they are actually equivalent within this array of electrons. If the electron moves in one direction the holes automatically moves in the other direction or the reverse direction. So, we can either concentrate on the movement of the electrons or it is better to in this case to concentrate on the movement of the holes because holes are normally less in number.

So, you can concentrate on the movement of the holes rather than movement of the electrons particularly when the number of holes compared to the available number of electrons. The reverse is true when the available number of electrons is less and the vacant spaces are more that happens when it is near the conduction band, for our purpose we will see the less number of electrons have jumped over to the conduction band. This is the conduction band because originally empty say at lower temperature or close to absolute zero, these sites that means the energy sites are available, but they are not occupied by the electrons, all the electrons were at the valency band.

Now, with the increasing temperature that is one of the ways to excite, there are other ways to excite also providing these electrons will has jumped over and relatively less number of electrons has jumped over because these electrons will never jump over. It is the electrons which is closer to the energy gap here or the highest energy or closest to the highest energy one can say this was the fermi energy, but this not the fermi energy to come to the fermi energy in this case in a different energy. So, closer to the fermi energy have jumped over to this, so this less number of electrons are available here compared to the number of sites available number of energy sites available.

So, it is easier to put our attention on this, so in this case there are vacant sites, there are vacant sites really that is nor our concern here. We will look what is happening to these electrons these are conduction electrons they are negatively charged, they are negatively charges as soon as you apply an electric field they will move to a slightly higher energy level, but not too high. It will not go to that level, it will be at most on the horizontal level slight increase a very small increase in energy because of the application of the electric fields whereas, if you change the temperature then the energy input is much, much larger in any case, so these are electronic charge carriers.

So, our attention will be on this whereas, when you are talking about charge carriers here although electrons are also moving in this our attention will not be on the electrons, it will be on the holes. So, we say the holes are charge carrier here positively charged are the vacant seats of the electrons are the charged carriers rather than saying the electrons are charge carriers here. So, in the valency band the holes will be the charge carriers whereas, the positive charge and here on the conduction band. It is the electrons which will be the charge electrons with the negative charge, so that is what the concept of holes.

So, any semiconducting surface whether whenever there is a band gap and there is a excitation of the electrons from the valence band to the conduction band, holes will be created and holes are almost equivalent to the electrons except that they have a positive charge rather than a negative charge as in case of electrons. So, they can also have mobility they can also be considered concentration hole concentration, electron concentration, electron mobility hole mobility and so on. So, holes are for all practical purposes, a second variety of species which can transport charges.

The holes are generated as explained and once again to read it out, holes are generated in the valence band due to the excitation of the electrons from the valence band top, the conduction band or there is another process also by which the hole can be generated here. We have shown that the electrons are getting excited from the valence band to the conduction band the holes can also be created that means a vacancy can also be created in the valence band, if this electron does move that far, but there is a local site available somewhere here. If there is an absorber or a acceptor of the electrons which has a electron affinity that means it has a tendency to absorb electrons from any source.

Then for example, an ion an impurity ion whose electron affinity is much larger than the host material, this is the band gap or this is the energy diagram for the host material in which we have added some impurity. And that impurity incidentally might have a very strong affinity for very, very strong affinity for the electrons. So, it has tendency to absorb electrons then that will absorb the electrons from the valence band and also will create holes.

So, corresponding to the electrons will be created in the valence in the conduction band, but the holes will be created in the valance band. So, that is what we will mention here or acceptance of the electrons from the conduction band by the acceptor ions, whose energy levels are just. I am sorry, I think is a mistake in this statement for acceptance of the electrons from the not from the conduction band it should be valance band. I am sorry, I am sorry.

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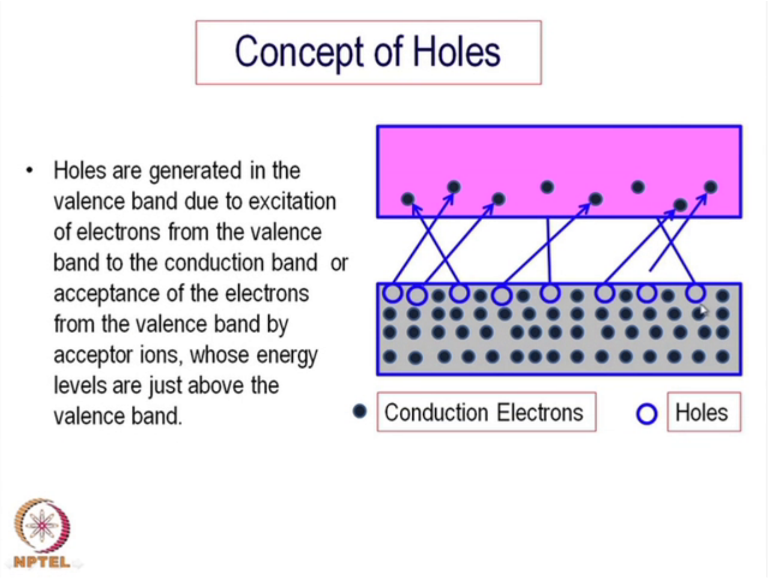

Concept of Holes

- Holes are generated in the valence band due to excitation of electrons from the valence band to the conduction band or acceptance of the electrons from the valence band by acceptor ions, whose energy levels are just above the valence band.

● Conduction Electrons ○ Holes

So, this is the valence band because the holes will be always created in the valence band not in the conduction band, conduction band will always give rise to electronic charge carriers electrons or electrons. So, the acceptance of the electrons forms the valence band by the acceptor ions whose energy levels are just above the valence band. So, this is the top of the valence band and there if you have some ion in the solid in the same host material that means mostly an impurity whose electron affinity is much larger than the host material.

Then it will accept some of the electrons from here to the next level, it will attract some electrons and by that process also you will get some holes generated. So, there are two ways by which holes can be generated in the valence band, one is the electrons jumping over from the valence band to the conduction band because of thermal energy conduction band of the same host material or the electrons going to a foreign material whose energy levels is very close to the valence band. So, we can identify a element or an impurity whose which energy level is somewhere there and it has a great affinity to accept electron and get ionized by itself and by that process also.

It will also take away some electrons and you will get some holes and corresponding electrons will not be available there, because it is not a direct excitation a thermal excitation. It is by a different process the holes are generated and those electrons are not available will not be available for the conduction process. These electrons which are being transferred or excited from the valence band to the conduction band, they are available for electronic or conduction band under the application of electric field. But the electrons which are going to the acceptor level they will not be available completely they will be tightly bound, but that particular atom or ion and they will not be free for movement under the application of electric field.

So, that also have to be recognized that they two processes are slightly different in one case, you will the charge carriers will be same. So, where ever holes number of holes will be created here the same number of electrons will also be created there. Both of them will contribute to the current, both of them will contribute to the charge movement whereas in other case only the holes will be accepted. Holes will be available for charge carrier, but the electrons will be accepted or absorbed by the some other element and that will not be available for the charge carrying purposes. So, this is the concept of hole and this concept of hole is very, very important for understanding the overall conductivity and the behavior of the conduction process.

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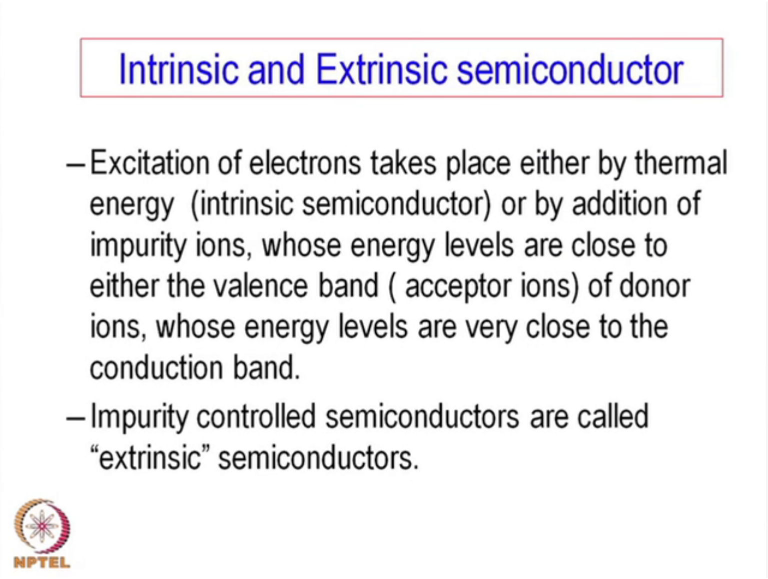

Intrinsic and Extrinsic semiconductor

- 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.
- Impurity controlled semiconductors are called "extrinsic" semiconductors.

In that context we must distinguish between two different types of semiconductors one is intrinsic semiconductor and the other is extrinsic semiconductor. Intrinsic semiconductor is where there is no impurity atoms, so there is no acceptor atoms or there is another form of impurity that is donor atoms. Sometimes, the impurity level or the energy level of the impurity is very close to the just below the conduction case, in which case it will donate electrons and it will have a property of ionization potential.

Its ionization potential will be low, so it will donate electrons to the conduction band, it will not create holes here, but it will donate electrons by that process also, it increases the charge carrier concentration. So, with these are the two different process by adding some impurities of two different kinds, one can either accept electrons which are called acceptors and create holes in the valence band and other variety is donate electrons to the conduction band and there is no question of hole there. So, hole corresponding hole will not be created because a third second element has come in the process and there is no hole is created.

So, such types if the there is no impurity atom present the material is very pure and whatever charge carrier concentration charge carrier creation is concerned is all by thermal excitation. So, the same number of electrons and same number of holes will be created in this process then it is called intrinsic semiconductor, but if you have impurities either acceptor ions or the donor ions they will be called the extrinsic semiconductors. The impurity controlled semiconductors are called extrinsic semiconductor whereas, pure materials or if there is no impurity ions available then it is called intrinsic semiconductor. So, their behavior will be slightly different and there are two different types of impurity ions one is a donor type and another is a acceptor type.

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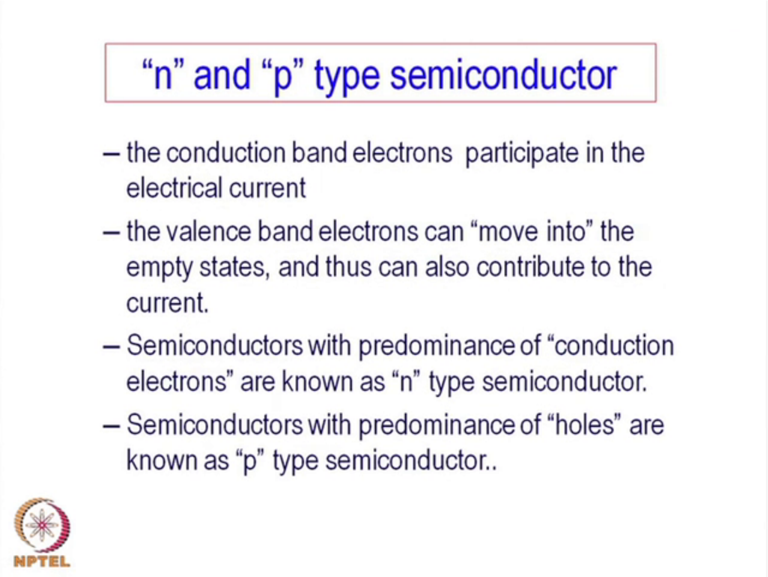

“n” and “p” type semiconductor

- 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..

So, accordingly you have two different types of semiconductors n type semiconductor and p type semiconductor when there are donor ions are available that means the ions are donating electrons from the conduction band. So, then number of electrons or the number of charge carriers or the negative charge carriers is higher than the hole type charge carriers then it becomes n type it is negative type. Whereas, if you have a acceptor type impurity then the number of holes are larger than the number of negatively charged electrons, so it will be called a p type semiconductor.

So, the predominance of holes as the charge carriers are there that will be called p type semiconductors and where there is acceptors if the donors are there if the donors are there then the negative charge are predominant, so that will be n type semiconductor. So, both of them are very important from their point of view and we will see how they are useful may be in the next class, the time is up for the time being. So, thank you very much for your attention and we will continue this discussion in the next class.

Thank you, thank you once again.