

**Optoelectronic Materials and Devices**  
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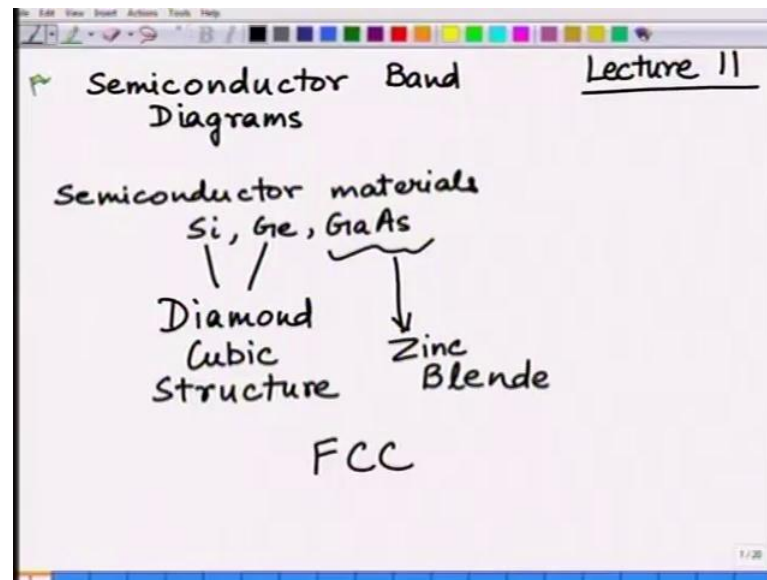
**Module - 2**  
**Electrical Properties of Materials**  
**Lecture - 11**  
**Semiconductor E-k diagrams and their**  
**Material Properties**

Welcome to lecture number 11. Now, we are at the point where we can discuss semiconductor band diagrams; all along so far, we have been trying to figure out how to estimate energies etcetera. Then, also we have been looking at how to represent the k axis, the E-k diagram. Now, that we have learnt all that and the previous lecture, I also gave a quick brief on how you could use these band diagrams to explain some of things such as an aluminum negative hall co-efficient etcetera.

So, in the notion of conductivity in context of band diagrams, so what the things we have learned? It is how to plot decay diagrams. We have learnt how, what kind of some kind of information, some on the electron dynamics, what kind of information we can get from band diagram. In order to do so, we have defined that if we want to use equation such as force equal to mass times acceleration, then what kind of mass we can use?

We have defined a quantity called effective mass. Having put together all these things in this first module, today we are going to start with the second part of the module, where now, we are going to use all this information and start making sense or of them. We will use them and show how this can be applied to devices etcetera. So, today, I will start showing you actual semiconductor band diagrams. We will try to interpret and try to get information out of them about those particular semiconductor materials such as silicon, gallium arsenide, gallium phosphide, germanium, etcetera.

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To begin with, let us start with semiconductor itself. So, let us start with semiconductor materials. When we talk about semiconductor materials, let us name some such as silicon, the most common one, which is extensively used. Notice, of course on optoelectronics, silicon is not one of the materials, which is known for optoelectronic properties. It is not used in optoelectronics. So, it is a good opportunity for us to learn why silicon cannot be used. Another important one is germanium used sometimes in very specialized applications such as detectors.

Why that is a different issue, but again a material not used in optoelectronics, another material gallium arsenide and its derivatives. Several forms of it gallium arsenide or gallium aluminum arsenide when mixed up, these materials you have seen in optoelectronics. You have seen laser pointers made out of it. If not gallium arsenide exactly alloyed form of gallium arsenide, you seen lasers out of it. You seen LEDs made out of gallium arsenide. Those are the common. That means gallium arsenide is an optoelectronic material.

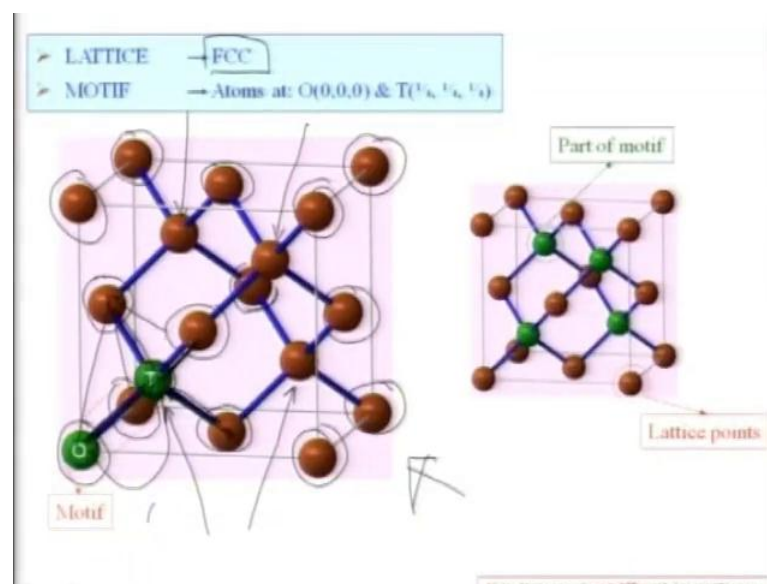
So, the question is why silicon is not an optoelectronic material? Gallium arsenide is an optoelectronic material. These kinds of properties, we are going to be able to decide from band diagram. Hence, we had been studying it, but with these few names, which I have written down here of semiconductors. There are many, many, many semiconductors

around, in fact huge huge, may hundreds of them literally, which around of which practically may be 5, 10, and 15 are at least used semiconductors.

Let us start look at, looking at the crystal structures. So, what will now do is first look at the crystal structure. These all these two semiconductors crystallized in form of what is called as diamond cubic structure. As the name suggests that obviously it is a cubic, but if you recall, if you look at those 14 bravais lattice, lattices, which I had mentioned earlier, part first part of the in the first module. Recall there was the thing called diamond cubic. There was simple cubic. There was face centered cubic. There was body centered cubic, but nothing called diamond cubic structure. Those are lattices. On those lattices, if we put atoms, then they form crystal structure.

So, if we put crystal atoms in certain way, then the structure that emerges, we start calling it as diamond cubic structure. This is because it resembles structure of diamond and therefore, but remember it is not lattice. There is an underlined lattice. The underlined lattice in all these materials is FCC. While we added, let us look at the gallium arsenide. Now, the 2 types of atom gallium and arsenic, this crystallizes and what is called as zinc blende structure. It is very, which mimics in the structure, very close to what is a diamond cubic structure. So, using some 3-D modules and also some pictures, let me try to explain what these structures are, what these materials are. Let us do so.

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Here is an example of diamond cubic structure. So, if you look at this, here is a diamond cubic structure, which I am showing you. Let me show you 3D module. Let me pick it up here in my hand. It is also a same structure, diamond cubic structure. You notice first of all the atoms on the FCC side as it says lattices FCC. So, let me mark the FCC positions. Here is a FCC position, here is a FCC position. Here is a FCC position. These are the cubic positions. These 8 of these are the FCC position, positions of cubic corners. Then, out of that, the face centers right here, right here, right here, right here and 1 more, 2 more right here and 1 in the back, right here this 1.

Now, you see in addition to that, I have 4 more atoms in there, which once those 4 atoms are right here, 1, 2, 3 and another 1 here, 4. Let me show you in this module. Notice, here is FCC lattice; this FCC lattice we look at. Then, you will see it as this this this this corner positions, this this this and this the corner positions. Then, the face centered position right here right here right here right here and right here in back, but then there are 4 more atoms in there, which are right here. These are the 2 atoms in the inside. These are the 2 atoms right here and there are 2 more atoms like this, 2 atoms; 1 here and 1 atom right here. These are the 2 atoms, which are inside this cube, these 4 atoms.

So, the total of 8 atoms are there, 4 from FCC, 4, 4 from FCC and 4 from, 4 there I am showing you inside meaning there by if you think of this structure as 2 inter penetrating lattice, FCC lattices. Imagine like this. Imagine a FCC lattice. FCC lattice, in which you have kept atoms on the, if you you kept the atoms on the FCC positions and then take another FCC lattice take similar cube and then shift it. Let me show you, may be let us like this. Let let us show it like this. Suppose, this we take as origin. Let us think of this as x direction. Right here is the x direction. Right here is the y direction. Let us think of this as a z direction.

If I take this as a cube and this is an origin, I take another FCC lattice, when the where atoms are on the lattice positions only that is at where are the lattice position is FCC lattice position. We keep the atoms there then, where it gives we take another FCC lattice with atoms on the FCC points. Take another cube and place it. We move to one fourth in this direction x direction, one fourth in y direction and one fourth in z direction. I look at this lattice point. So, this point moves right here. If it so moves, then you imagine all other lattice points are also moving.

If you, all other lattice points, if you start looking at, I get an atomic position here. This particular atom, which is a face centered atom, would have moved up here. This particular atom, we show that the bottom of the face centre would have moved right here. This particular atom, which was the face centered on this side would have moved up here. As I moved up here, as I move quarter quarter quarter and all other FCC atoms FCC atoms would have gone out of this cube out of this cube. So, they will not be part of this cube.

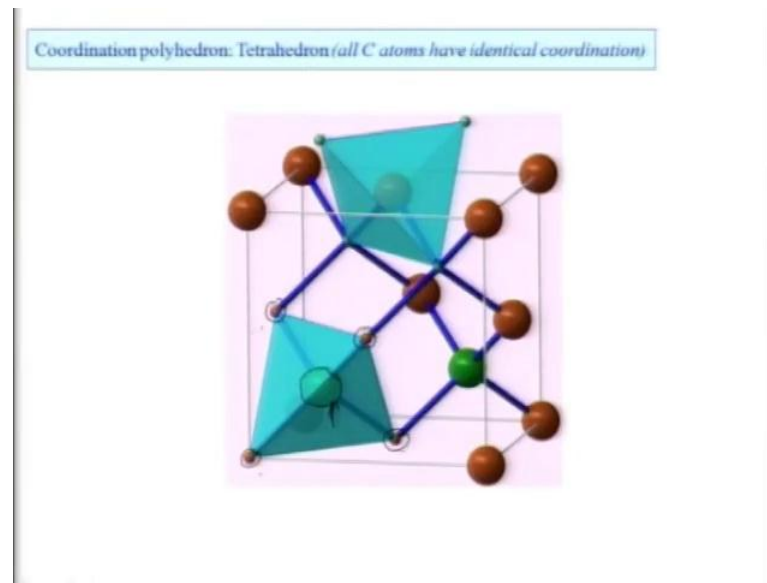
So, if I confine the picture on this cube only, then I will generate, what I will have my original FCC atoms plus these 4 atoms just which I have showed you as the atoms at this centre at the origin. I move quarter quarter quarter. I move here and this face centered atom and this face centered atom and this face centered atom give rise to another 3 atomic positions.

So, that is what our diamond cubic structure is. That is what the structure of silicon is. So, this structure, diamond has a structure of silicon has the structure of germanium as well. So, these all are diamond cubic structure. So, that is what I have described to you. Now, let us go to back to the paper. I will keep this down. I will be looking at the paper, the paper, the one on the screen itself or the paper itself.

Now, if I look at the next page, let us say, let us look at some of them, then what do you see? Let me go back and see. Look at this nature of bonding. The bonding is tetragonal. This is the atom from corner, origin. From origin, it had moved out here. It had moved to this position, new position. The new atom was at quarter quarter quarter. This particular atom if you notice is bonded to what it is bonded to this corner atom. There is a tetrahedral bonding, this bonded to this atom.

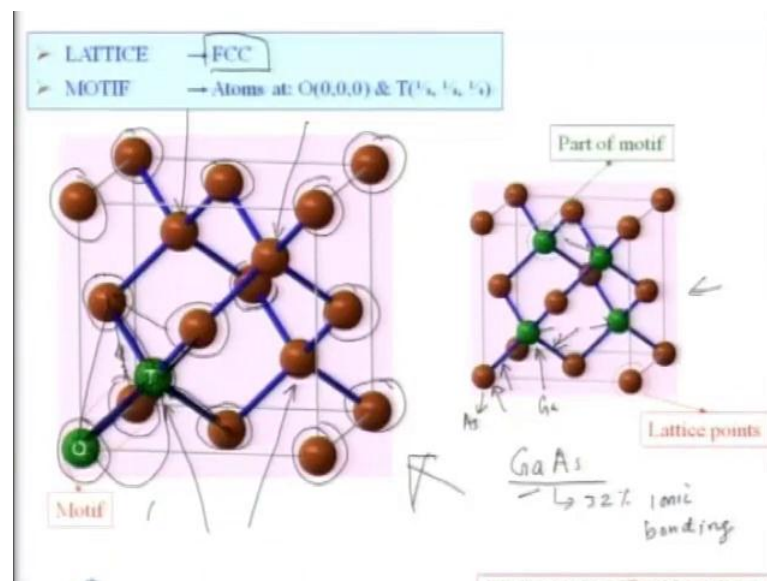
It is bonded to this particular face centre atom, is bonded to this face centered atom on the base and is bonded to this particular face centre, which is on the back, on the face, on towards the screen. So, these are four. You can see an each atom is tetrahedral bonded. So, silicon atom, silicon material essentially, each silicon atom is covalently bonded bonded to other silicon atoms. The nature of bonding is this. Tetrahedrons are forming using this this this and this. We start forming a tetrahedron. Then, we can form a tetrahedron based on this.

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So, notice that what happens that this is the face centre. This is the corner atom. This is a face centre, face which is towards me here. This is a face centre. These form a tetrahedron. In between this tetrahedron sits this particular atom, which is which you see here, this particular one, which is the tetrahedron centre of the tetrahedron. That is the silicon atom as bonded to these 4 smaller ones, which I am showing you here. That is the nature of bonding in silicon. So, that is what we call as silicon diamond cubic structure. Silicon is totally covalently bonded in these also.

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If you wish, we can similarly; we can describe the gallium arsenide structure also. In this gallium arsenide structure, notice now, we have 2 types of atoms; 1 gallium and 1 is arsenic. You can think of in same way like I said 2 FCC lattices, 1 FCC lattice, and 1 FCC cube. Then, take other FCC cube and shift it by one fourth, one fourth, one fourth. You get what is called as diamond cubic structure. You can do the same thing for gallium arsenide.

Then, it is the structure is called zinc blend structure, namely you take a FCC of gallium that means take a FCC lattice. On the lattice point, put gallium. Similarly, take another FCC lattice. On the lattice points, put arsenic atoms. Then, you have these 2 FCC structures displaced from each other by a quarter quarter quarter, just like in diamond cubic structure. What you would get then is essentially a diamond cubic structure, zinc what is called as zinc blend structure. Essentially, it is same. Atomic positions are same like diamond cubic structures, except that two kinds of atoms involved meaning thereby, you can think of it is as follows.

You can think of these as let us say red ones as if you wish to think of arsenic. You think of then green ones as gallium. In this case, so it is arsenic. Now, you think 1 FCC positions of this particular cube, which is shown in this picture. There is a FCC cube here. So, you think of FCC side. There is an arsenic sitting. Then, you think of the gallium sitting in the green atoms is gallium ones. Those are the inside 4 atoms, right here. This this this and this are the inside 4 atoms, which you also saw in diamond cubic structure.

You think of those as gallium. Conversely, equivalent way of thinking would be if you interchange, you should think of this as gallium, these particular red ones as gallium. Then, you start thinking of green ones as arsenic. The structure remains the same anyways because there are 2 interpenetrating FCC lattices. So, it does not matter which FCC lattice. You look at FCC cube. You look at the 1 for arsenic or 1 for gallium; either way whichever you look at the same structure, you are going to get. So, that is a gallium arsenide structure. That is called and that is called the the zinc blend structure.

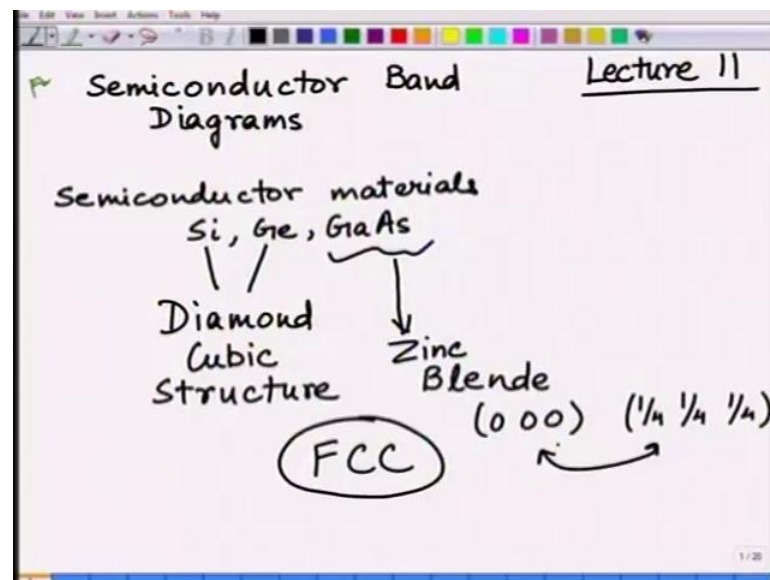
So, this is the nature you can again see in gallium arsenide. It is also covalent covalent bonding going on. There are blue markers, are showing the covalent bonding. The bonding is by enlarging in gallium arsenide also covalent bonding except that arsenic is

more electro negative than gallium. As a result, there is a partly ion-electron cloud shift. As a consequence, there is a partly ionic character to gallium arsenide where as silicon and germanium are purely covalent.

Gallium arsenide is also largely covalent. But, above 32 percent of bonding character is ionic bonding, ionic bonding 32 percent. Rest is all covalent bonding. So, that is the nature of bonding. In some of some of these semiconductors also involve in all these semiconductors essentially show similar bonding though some of are ionic semiconductors as well. But, the ones which will be talking of, we will be talking about are predominantly covalent and partly have some ion, some ionic character in them.

With that let us go to our our screen here, which we are talking about in say FCC, I have shown you. In a FCC, both are FCC lattice with atoms at 0, 0, 0 position and are atoms at one fourth, one fourth and one fourth position. If both are silicon in both the position in FCC lattice, they are both as silicon or germanium that is diamond cubic structure. If one of them is gallium, other one is arsenic, and then it is zinc blend structure.

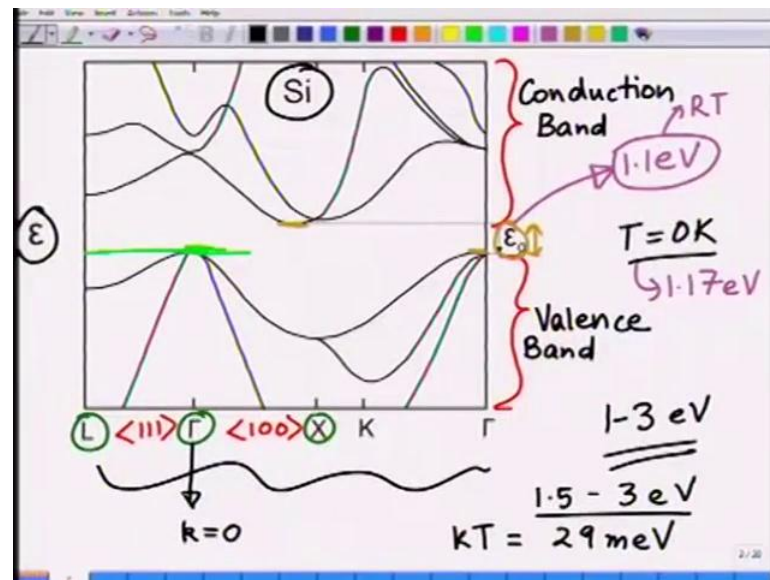
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Having done this, let us go to band structures of semiconductors. Here, it is.



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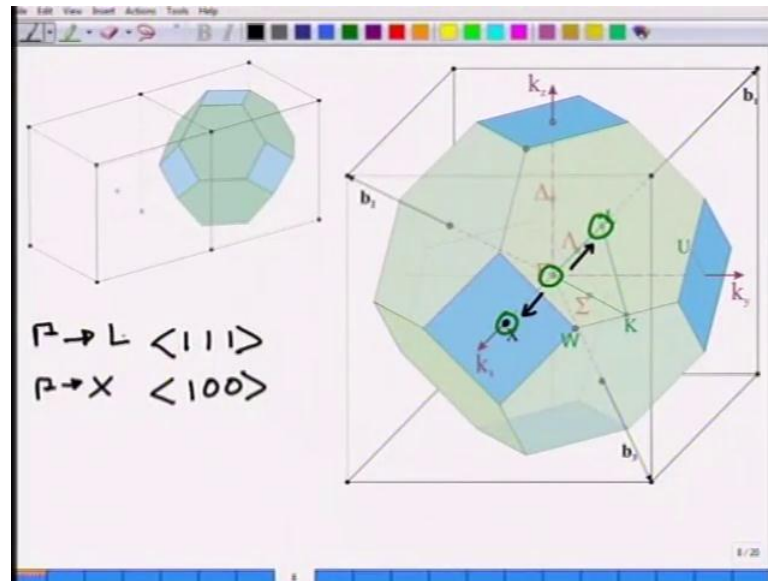


So, this is all will be waiting. For now, remember this I have shown you how the, how these how these band diagrams are plotted. Now, in this case therefore, you have to understand the  $k$  axis. Here is  $k$  axis. I am looking at silicon. This is the silicon semiconductor. You look at the  $k$  axis. Remember, here is a gamma point. The centre point  $k$  equal to 0 corresponds to  $k$  equal to small  $k$  equal to 0. That is what it corresponds to its gamma point the centre of the bullion zone.

Then, you start moving in some major directions. In this case now, these energies are more realistic energies. Energies are estimated by; we have done free electron theory, which does not give a band band gap. Then, we have done nearly free electron theory, a one dimensional theory to show how periodic potential can give band gap. Then, we said that calculations are fairly complicated. So, we are going to use these. Somebody has done the calculation. We will use those calculations to show the realistic band diagrams.

This is what they are here for. They are here for silicon, germanium, gallium arsenide, cadmium telluride, gallium phosphide. So, using these band diagrams now, we are trying to interpret as to what they good for. So, in order to do so, let us start looking at one of them and slowly slowly build up all similarities and and differences between these band diagrams. That is how we are going to look at it. So, if you notice that first, let us define some of the directions; 2 important directions. I am going to define this. This is going from gamma to  $X$  and gamma to  $L$ . These are the two directions you will recall.

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Let us just look at it. Let us look at this. Recall there is a bullion zone. This is the bullion zone we are talking about. So, what is the gamma? Gamma point is right here. Gamma to L, gamma to L direction is what direction? Then, you can clearly see. Let us say 111 type of direction gamma to L. What is gamma to X type of direction? Gamma to x type of direction is 100 type direction gamma to X. This is gamma to L. This is the direction, gamma to X and gamma to L, say 111 and 100 type of direction. So, let us go back. So, gamma to X, as we say is 100 direction.

This is 111 direction. As we go from gamma to L, what do you notice? You notice that that all these energies from here to here are allowed; energies in silicon. Then, you notice there is an energy state at some k value. At some k value, energy is allowed for electron. Therefore, what do you notice in between this this energy which is not allowed? Hence, this is the band gap.

So, this is what we call as band gap of course. So, what do you notice? Hence, a maxima is in this lower band. So, this is one band. Here is a band and here is a band. These are allowed energies. This is a band and there is another band. This is the top of the band right here, is the top of the band right here is the top of the band. It is same as this point. These both are gamma points. This is also gamma and this is also gamma. Therefore, both are same energy. So, you can see this is the top of the band.

Then, you see the other one. The higher one has lowest energies, right here in between these 2 states. Therefore, this is what is called as band gap. So, we see a band gap and indeed therefore, it is semiconductor. The value for this is, about the value for this, is about 1.1eV. So,  $E_g$  is about 1.17. It depends on depends on what temperature you want to talk about. All these calculations by the way are done at 0K.

Though we freely apply them at higher temperatures, at room temperatures also, in all the semiconductors, you will find that energies are all the semiconductors as I go through the energy gap, band gap will be about 1 to 3 electron volt. You out of get sense of what this mean 1 to 3 electron volts. You know visible energy range is somewhere from 4000 nanometers to, from 4000 nanometer, 400 nanometers to about 800 nanometers is a visible range, visible range. That range corresponds to somewhere energy of about to about 1.5, to about 3 eV.

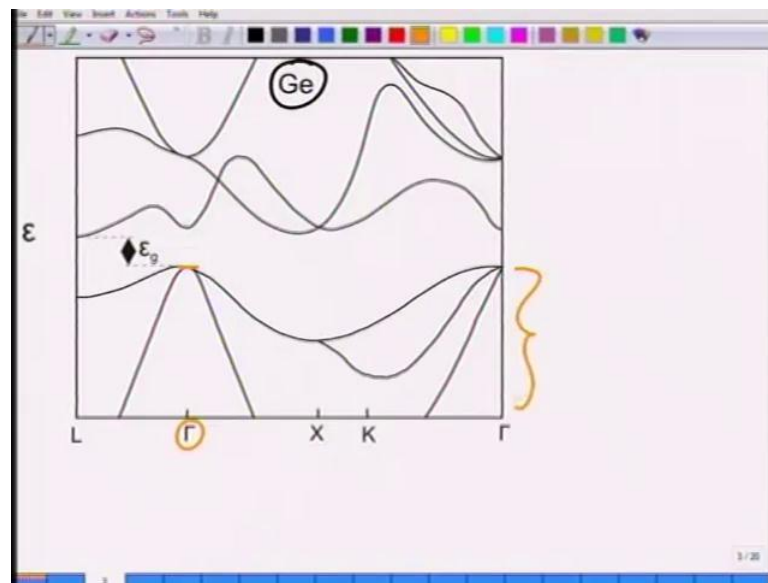
So, 1.5 to 3 eV is about our visible range. What else? At room temperature, if I look at  $kT$ , then it is about 29 or 30 milli electron volts, milli electron volts. So, there is 30 milli electron volts is what this  $kT$  energy is. So, notice that at, when you talk about 1 to 3 eV, and you talk of room temperature, then this 29 milli electron volts is sufficient enough to cause some electrons to jump. This band gap, if band gap is greater than this, then you will find that there will be hardly any electrons able to jump from lower energy state to higher energy state. Anyway, that part we will do later. but, keep this in mind that  $kT$  energy is about 29 meV.

The silicon band gap is about 1.1 e V, 1.1e V at room temperature. At 0K, it is slightly higher. It is about 1.17 e V or so, 1.17 electron volts. Now, if you start putting electrons in silicon, we find that electrons fill up to this energy up to this energy. The electrons are completely up to this energy. Electrons completely fill up. When electrons fill up to this energy and then all this energy higher energy levels, which you see here are empty. That means what we start; therefore, we start calling the lower band as the valence band.

Valence band is completely full of electrons. We start seeing and we start calling the higher band, which is completely empty as the conduction band. As the name, you will see will make sense. As we start doing some carrier statistics also eventually, but, the point at 0 K conduction band in silicon is completely empty. Valence band is completely filled.

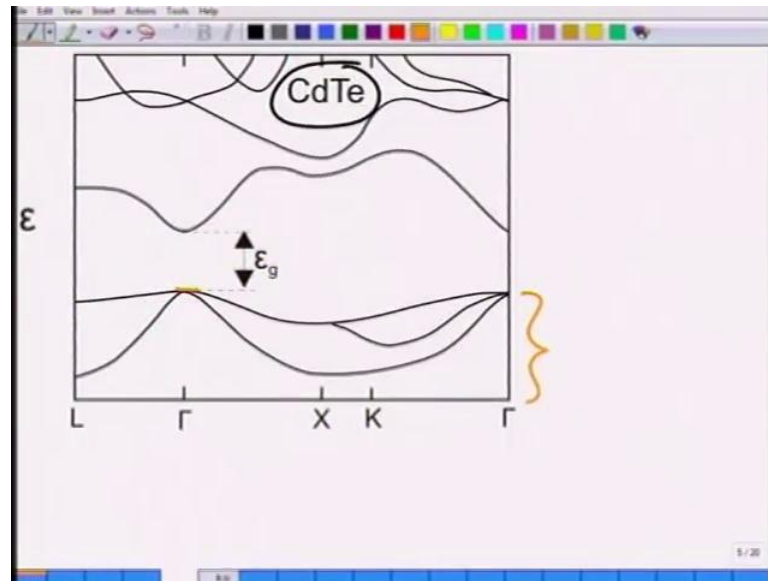
Now, we have been learnt in the previous lecture. You recall that band, which is completely full cannot conduct a band, which is completely empty cannot conduct, which means cannot contribute to conduction. What is that mean? That means silicon at 0 K will therefore, be an insulator. It would not be able to conduct at all because the bands are completely full or bands are completely empty. Now, you start looking at other semi conductors also, germanium or look at germanium. Notice the nature of the band at gamma point.

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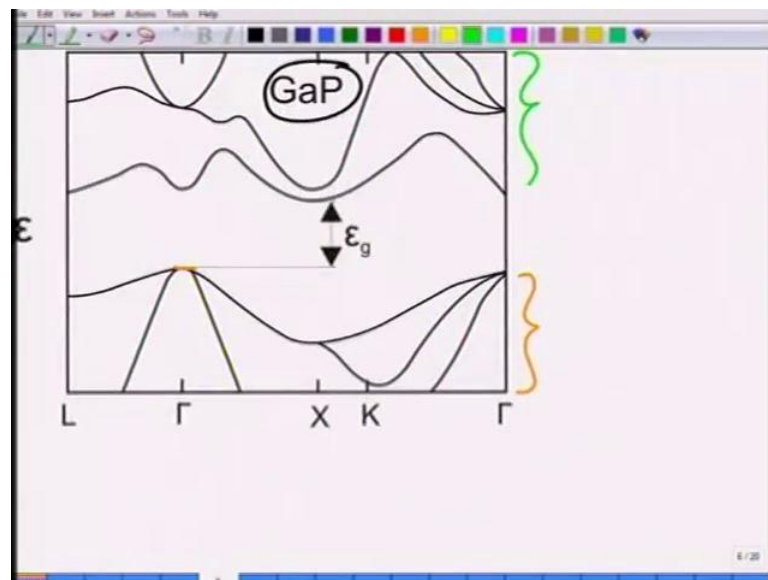
This maximum in the band gap or the valence band always occurs and in all the semiconductors. We find just what find that the, what are the maxima is right here, right here, right here, right here in all these 5 different materials. I am showing you where the maxima are. Maxima occur at gamma point. Maxima in all these cases occur at gamma point. You would notice in all these cases and electrons fill up to this energy level in all cases.

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Therefore, we call these energy levels, these bands here to here to here as the valence band. All these are valence band and across from here from here to here in all these cases, therefore, they are conduction band.

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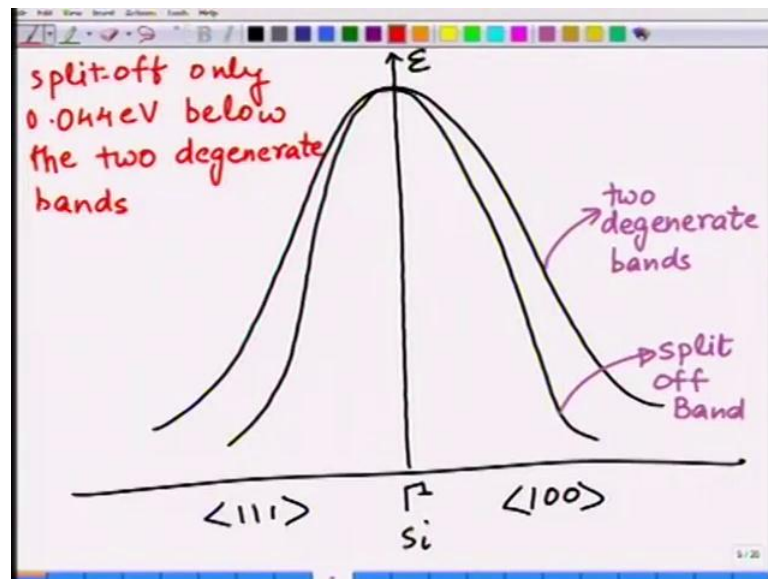


If I look at germanium, this energy  $E_g$  is only 0 point something, like 6, 7 electron volts at room temperature, about 0.74 electron volts at 0 Kelvin. In gallium arsenide, this energy is about 1.43 electron volts. This band gap is 1.43 electron volts, which is  $E_g$  at

room temperature. Remember, this is the room temperature. All these are room temperature, about 1.5 also at 0 Kelvin.

Then, cadmium telluride, this energy gap is 1.49 e V. In case of gallium phosphide, this is equal to 2.26 e V. This band gap is equal to 2.26 e V. What I trying to first start point to the point out to you was that in all the semiconductors, we are noticing that valence band maxima or the band, the lower bands maxima occurs at gamma equal to 0. That is the first point I am noticing in all these band diagrams. So, let us just look at that a little bit in greater detail. So, we find, let us start looking at that.

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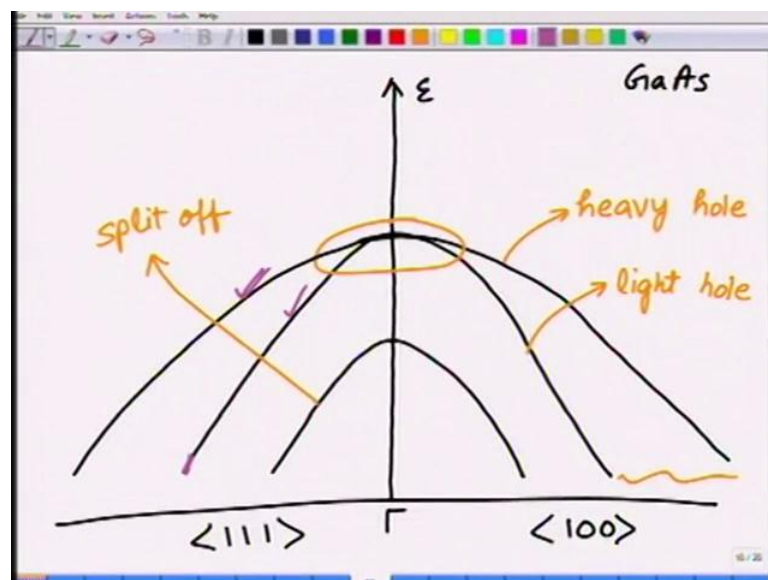
So, first point I want to make is maxima and indeed, all these are showing a maxima, not minima. All these are showing maxima. So, there is a maximum, which is showing up, not a minimum showing up, whereas in conduction band, if you look at all those showing a minimum, not a maximum, there is a minimum here. We talking about minimum, we are talking about not a maximum. In case of valence band, we always show a maximum.

So, we are going to talk about now valence band. I will abbreviate this as v b from now on. So, maxima occur at gamma equal to 0, at gamma point at gamma point, which means k equal to 0. That means k equal to 0. That means a center of the bullion zone always, the maxima in energy is occurring at this point. If I start looking at some detailed structure any other valence band, then it looks like this.

If I now plot like this is gamma point. This direction is let us say in this direction, I am plotting 100 on the right hand side and 111 on the left hand side, left gamma to L and gamma to X. So, let us do that. So, this is 111 direction and this is 100 direction. If I plot this energy clearly, you see that there is a maximum in this. But, if I expand this view, then we find that the structure is more complicated than that.

In fact, we see that something like this in case of germanium. Similarly, this is the energy of course I am plotting. This is basically, this is a expanded view of the picture here of the picture here of the picture here. I am plotting an expanded view. In other words, you can see between this and this I am showing a gap, when I plotting an expanded view, whereas on this scale you are not seeing that.

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So, if I look at that, then there is see a gap in there. If I plot the same thing for gamma point, for silicon in 100 and 100 direction and 111 direction, then we find that there is a band like this. There is a band like this, band like this and band like this. This I am going to name as split-off band. This actually is 2 degenerate bands. What does that mean? That means there are 2 bands overlapping on each other in energy. Therefore, they are degenerate. What is the consequence of it? In a minute, you will see, not consequence right now. We will just show a corrector right now.

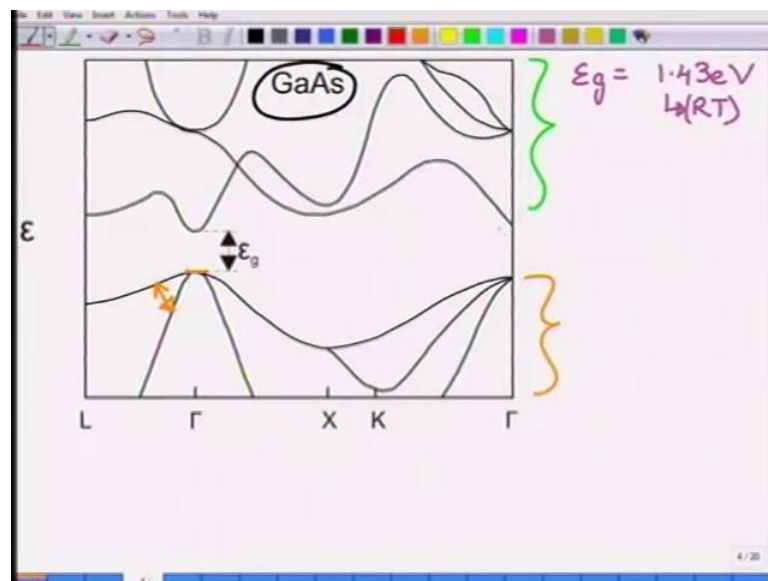
We just are pointing out differences between them, final differences between them. They can be useful. They have been used. They will be use in some context. Some we will use

and some we will not use. But, knowledge of it will help you. In this case, in case of gallium arsenide, this looks something like this. Essentially, what do you see in all these 3 cases? If I, let us just take look at quickly here in all these cases. I am showing you here, here, here, here, here and here, here, here, these I am showing you. But, I am showing you detailed structure.

Now, in all these cases, we are finding that there are 2 bands; right of the top right here. These are the 2 bands in this case. You are going to call it heavy hole, heavy hole. This is a light hole and of course, then split-off. There is a split-off band right here, split-off band. What do you see then? Each of this valence band, where the maxima occurs at gamma point, gamma point you find that these in case of germanium and in case of gallium arsenide at expanded view, we can clearly see separated from the maxima this split-off band.

Hence, the name split-off band in case of silicon, this split-off is only 0.044 electron volts below the 2 degenerate bands. Hence, this seems touching each other because that energy gap is so small whereas, in case of gallium arsenide, germanium is slightly more. Hence, you can clearly see them where as if I go back to full scale picture, where this energy is large scale, you can scale this energy.

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Now, you can see that if this is 1.43, then what all the others energies will be? What the scale of energy will be at this scale? Then, this split-off band cannot be seen as a



separated out. Then, what else you see? What else you see is that all of them have a degeneracy and  $\gamma$  equal to 0 and  $\gamma$  equal to 0. Essentially, the 2 bands are overlying on each other, whereas little far apart in case of germanium. In case of silicon, they are pretty much laying one on top of each other.

Therefore, we are calling at degenerate band normally at  $\gamma$  point. But, through and through around that area, any of the  $\gamma$  area in case of germanium also, they are nearly on top of each other except in this region, right here whether this start splitting off in gallium arsenide. We find that this splitting curvature itself and  $\gamma$  equal to 0 is different of these two. Now, recall what we mean by, recall that nature of this. Since, all this valence bands have this nature where they are concave downwards. Recall yesterday we said concave downward surfaces means they are hole like surfaces, holes like to live there on top of the valence band.

Therefore, electrons will roll down and live in the lower energy state. Of course, the completely full electrons come on top. So, if some electrons have to go to higher energy, simply the top, most electrons goes and jumps. What does it leave behind? It leaves behind leaves behind hole at the top of the valence band. Effectively, we can think of that holes reside on the top of the valence band because all the electrons would have taken the lower energy states. Therefore, we can think. Therefore, such surfaces are called concave downwards or called hole like surfaces.

Once they have called hole like surfaces, then you can think of the effective mass of hole. Also remember, the curvature is more. That means effective mass will be smaller and if curvature is if curvature is large, then in that case, inverse of that with the effective mass. Therefore, it will be like that. So, you can see the one, which has a greater curvature. The one here has a greater curvature, in this curvature where this has a lower curvature. So, it is a lower curvature.

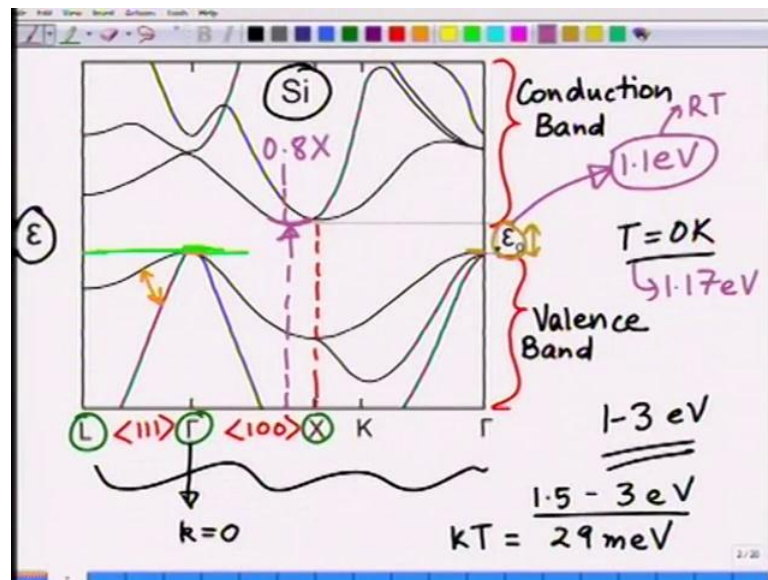
Therefore, inverse of that would have, the hole presiding on that band would have higher effective mass. Then, the one which is on this curve and this is why we call this as a heavy hole band. This is the light hole band. So, this is the differentiation between all these. So, these are similarities we see and differences we see in valence band. Now, let us look at conduction band.

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Now, let us start looking at the conduction band. What do we see? Abbreviate now on as CB, conduction band.

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Again, we go back here. Now, something interesting things happen in this. Now, conduction band has minima. First of all, in all these cases, you see there is a minima, right here is a minima, right here is a minima, right here is a minima. All this have minima. That means when electrons go, they concave upwards. So, that means they are electron like surfaces in a transversal jump and live at the lowest bottom of it and there

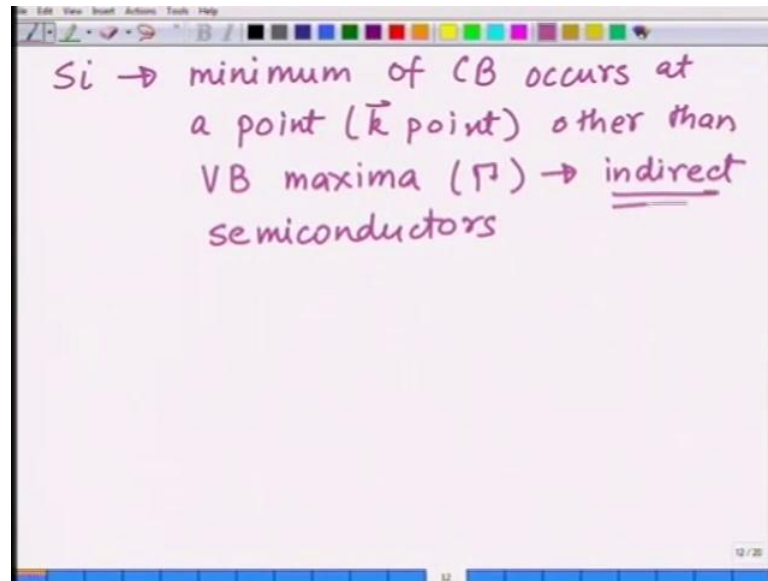
around electron like surfaces. Therefore, we will talk of effective mass of electrons at this at these points.

Now, where does the minimum occur is a very, very important question. We notice for valence band, the minimum and maximum always occur occurs at gamma points. But, in case of conduction band, all these materials have different, their differences. If we look at for example, silicon the most common one, we find that minimum occurs nearly near to the X point, X is here. The minimum occurs somewhere here. This point may be, will change the color of band. Right here is where the minima occur. This minimum occurs as we go from gamma to X at about 0.8 X.

So, this point where the minimum occurs is about 0.8X. It is where this minimum in conduction band is occurring. Now, you can see that 100 give direction are there. They are, this should represent 6 equivalent directions. 100 direction means, what does 100 mean, 100 means; in x direction, in minus x direction, in y direction, in minus y direction, in z direction and in minus z, z direction.

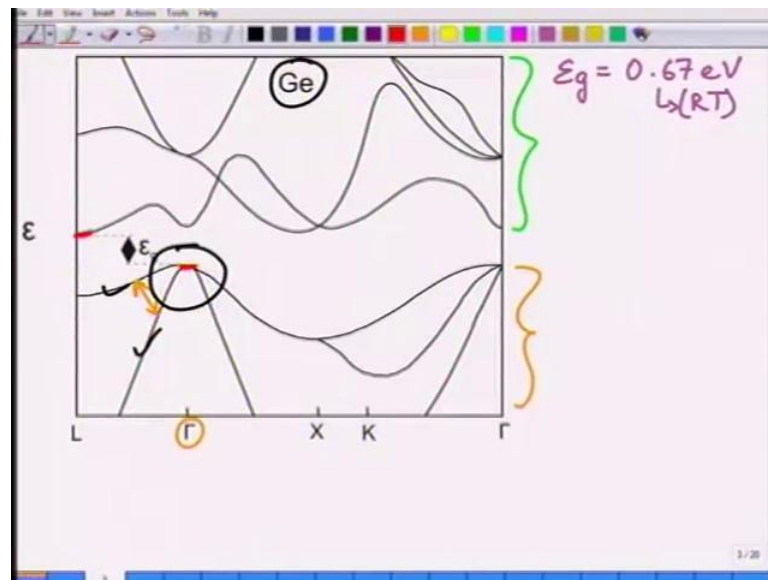
So, there are 6 equivalent 100 types of directions. So, this minimum which you see in silicon really represents 6 equivalent minimas occurring at X, X slightly 0.8 X. As you go from gamma to X at 0.8X is where the minimum in energy of the conduction band occurs. The important point is that minimum of the conduction band occurs at a different point. Then, minimum of conduction band occurs at a point means in k point, on k space, a point other than valence band maxima.

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It is always at gamma point. It is always at gamma point. Such semiconductors are called indirect semiconductors. Such semiconductors are called indirect semiconductors.

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If you look at germanium for example, then we know that this maximum occurs about 0.74 electron volts at 0 K, 0.67 electron volts at room temperature. Where does the minimum occur? Sorry, I should have plotted here. So, where does the minimum occur? Minimum occurs not here, but it occurs right here. Right here is the minimum. Maximum

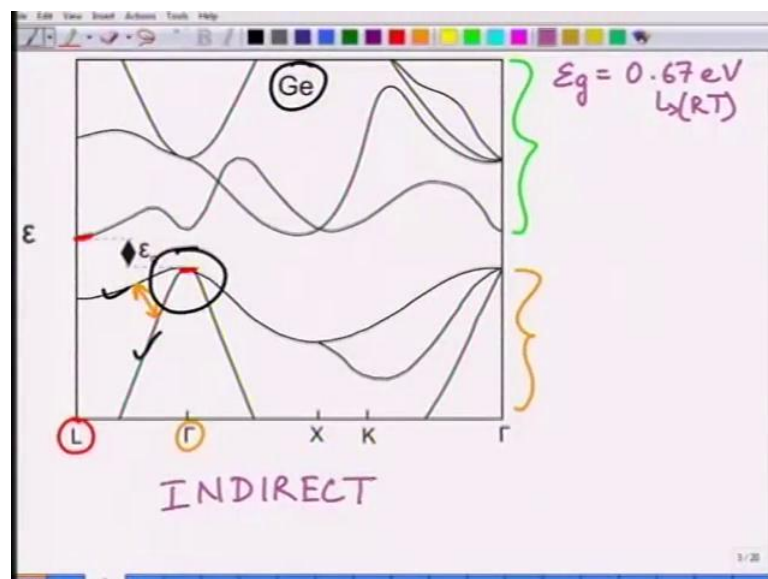
is right here. The minimum energy, which is on the higher band, is right here. I am showing a red point.

So, what does that mean? It means that it occurs at L point at the edge of the bullion zone and L points, L point in 111 direction as you go. Then, if you go in 111 direction, then it, L point, the minimum of the conduction band occurs in germanium. Of course, how many directions are there? There are 8 111 directions. So, you think of diagonal while diagonal of the cube.

So, how many directions are there? So, you can think of plus direction and minus direction. Therefore, you can think of 8 such directions, but because it occurs in the bullion zone boundary, therefore since there are 2 bullion zone, since this is the boundary it shared between 2 bullion zones view, So think of this as 4 equivalent minimas instead of 8 equivalent minimas which you will see, which you see here.

So, this is the degeneracy, idea of degeneracy as to how much how many minimums are there. So, this is the conduction band in germanium. So, what would the semiconductor, be a direct semiconductor, direct band gap semiconductor or indirect? I should say indirect band gap semiconductor. So, there will be indirect or direct band gap semiconductor clearly.

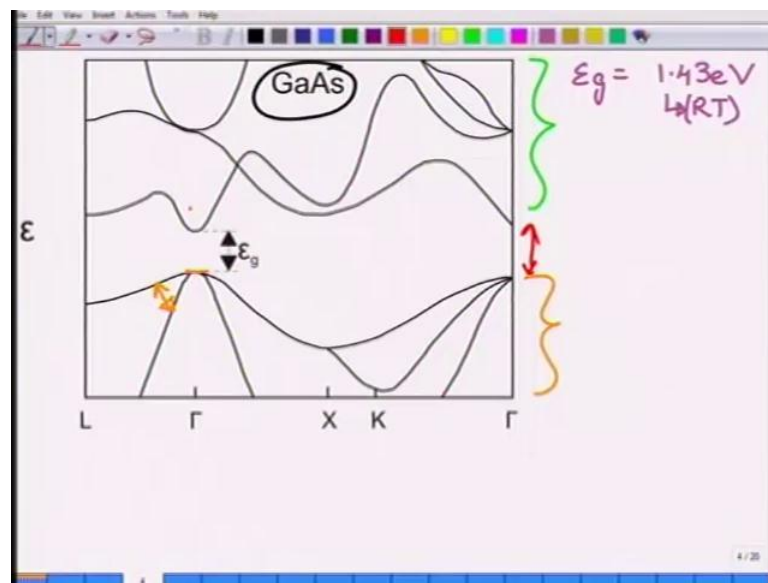
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This would also be indirect band gap semiconductor because the minimum occurs at L point, where the maximum of valence band occurs at gamma point. Now, see striking difference in case of gallium arsenide. Where does the minimum occur? The minimum occurs minimum in conduction band minima is at same gamma point is at gamma point same as where the maxima of conduction band is.

Therefore, this is a important difference. Such a semiconductor is occurs at same k point, we call it direct band gap semiconductor, gap semiconductor. So, that is a direct band gap semiconductor; right here which you see is gallium arsenide. So, let me point out to you I have mentioned or I already mentioned to you that silicon and germanium are not optoelectronic materials. Gallium arsenide, i said is an optoelectronic material. You can see in LEDs and lasers are what I mentioned.

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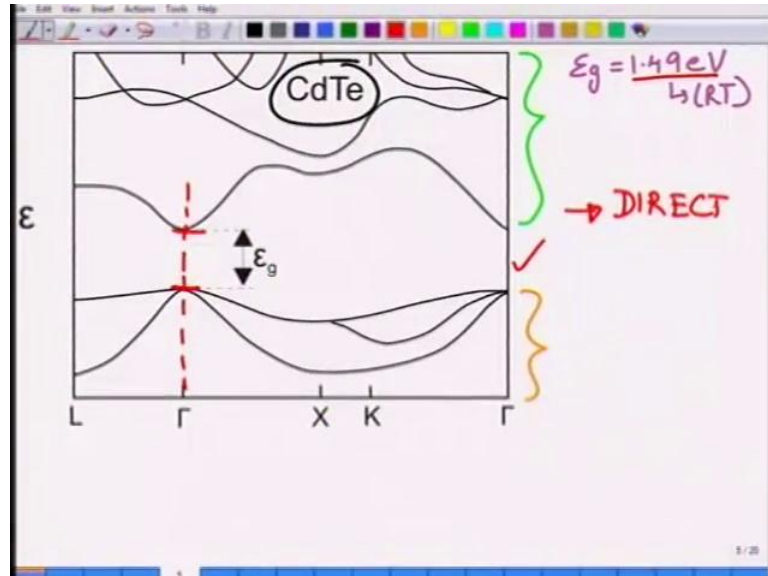


I hope this begins to give you clue why or tells you that this some is something. What I am telling you must be somewhere related to it that silicon and germanium not being indirect band gap semiconductors are not good optoelectronic materials. Something which has a direct band gap is an optoelectronic material. Now, you can hopefully begin to see why we have been doing, why been trying to so hard to understand how band diagrams are to be red.

Let us just move forward little bit further. As we look at cadmium telluride, which has the band gap of 1.49 and notice in this case also, the minimum occurs at same point as

well as valence band maximum is at the gamma point itself. Also remember, the band gap is 1.49.

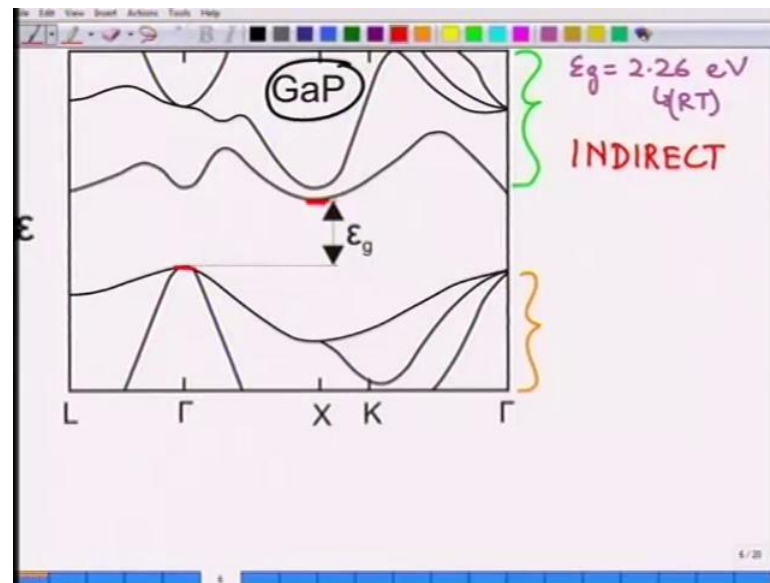
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Really, this is the edge of infrared. Also, clearly this could possibly if I show; if I work my linkage I am not shown you how. But, if you this linkage, that direct band gap semiconductors will be optoelectronic materials. Then, you can see cadmium telluride which has a band gap of 1.49 is just reaching the IR range, infrared range. You can see it is a lower end. It is a lower end, is the near the red end. So, further electron energy means infrared energies.

If you think of cadmium mercury telluride etcetera, then the band gap becomes even less even less and then truly in IR range. If you recall or you, if you not recall rather if you think of what kind of materials, you would make your night vision goggles etcetera. Then, I hope you can begin to see where, what kind of information this band diagrams can give. If they optoelectronic materials in IR range and if IR is what you sense a night vision, and then these materials may be a choice. So, then other material, which is quite important material these days specially we finding it to becoming gaining importance is gallium phosphide in this case of course. So, this is of course, clearly direct band gap. So, this is cadmium telluride right here.

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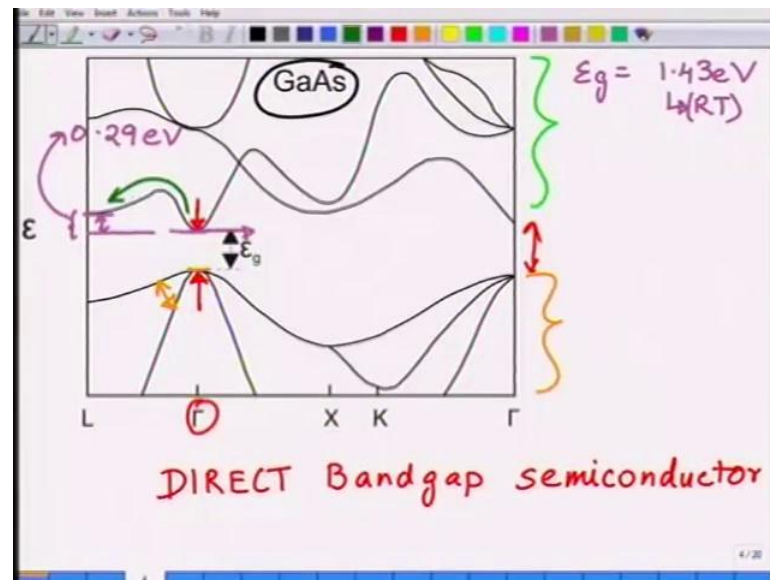


In gallium phosphide, this minimum occurs right here, not at the gamma point. Therefore, this is an indirect band gap semiconductor though on account of different colors of LEDs, gallium phosphide does get used a slight a little bit, but gallium phosphide by itself by including it in gallium arsenide with gallium arsenide, you could retain largely largely direct band gap conductor.

That means if you alloy a gallium phosphide in gallium arsenide and possible retain this structure gallium arsenide, then you could use it as a direct band gap semiconductor, but by itself it is not in optoelectronic material. So, this is the background. Now, let me reduce this whole problem. Therefore, to as follows, let me reduce this whole problem to 2 categories; one, well, one more point I want to make for gallium arsenide.



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One more point let me make. In gallium arsenide, there is a minimum. Of course, I told you at gamma point itself, but where is the next higher minimum? You should look at the next higher minimum. Next higher minimum occurs right here. This is the next higher minimum at the L point. The difference between these 2 energies is only 0.29 electron volts. That is the difference at the L value, what is called as L valley and gamma valley.

Hence, the gamma valley the minimum and hence the L valley, the minimum at the L point and the L point minimum is only 0.29 electron volts higher. So, if sufficient electric fields exist in a device, we made device gallium arsenide, sufficient electric field exist, then remember, electric field application means changing the case stage. So, if you have sufficient electric field, it is possible that you could push. This push some populates some of the electrons in this L valley. If you populate in electron L valley, what you notice?

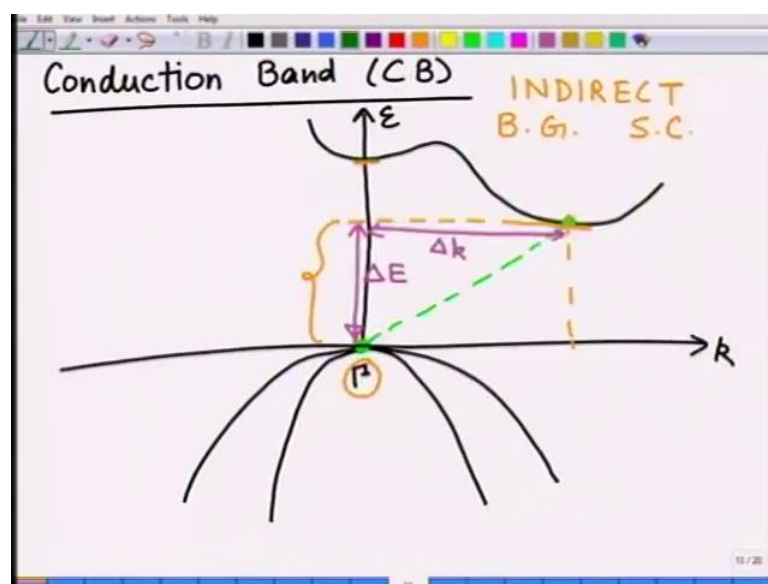
You notice that what is the curvature of it? Its curvature is at L point. The curvature at L point is less than curvature at the gamma point. At the gamma point, the curvature is more. So, what is what about the effective mass? Wherever the curvature is less, inverse of that is effective mass. Then, in that case, effective mass at l point of electric mass of electron and L point will be higher than electron effective mass of electron at in the gamma valley.

So, if I now apply electric field and from more populate some electrons into the L valley, if I do so, what will happen? These electrons, which had a lower effective mass and gamma in gamma valley, when they move to L valley, this start have high effective mass. Now, this, such phenomena can give rise to negative differential resistance. Interesting devices can be made and that can interpret from the band diagram because effective mass from being imagine something is moving and suddenly as it moves from there, it becomes heavy suddenly. It becomes heavy, which means its velocity will decrease.

Now, velocity will decrease. If so happens, then what does mean is in there you have negative. So, what happen it are consequences that will have consequences in the current. So, what would you see? You would see negative differential resistance in this case. You need, can make such devices with gallium arsenide. So, that is the important fact you can, I am trying to point out some tit bits.

I am telling you because of the information, you can kind of information, you can get from the same electron dynamics, we did and this direct indirect business on which I am further expanding on or about optoelectronics based on all these things, you can get lot of based on these things. You can get lot of information from these band diagrams and you can select materials appropriately. So, let us further continue on to this idea.

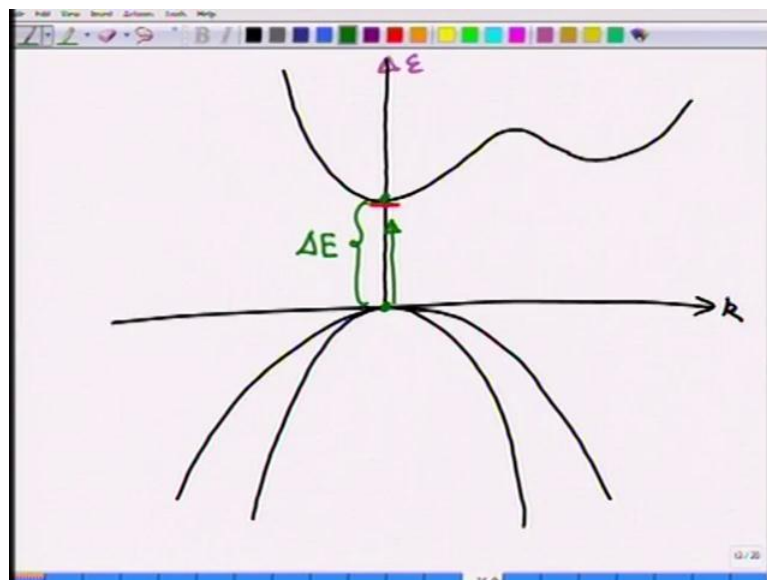
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Let us reduce our band diagrams to 2 categories. It is schematically, in one case, we plot it as follows where we always is to show or valence bands. Here is a  $k$ . Here is a  $k$ . We will show always valence band like this. We may show to, we may show to these 2 curves. Let me show only one. That does not matter, but in one case, I will show a minimum elsewhere from gamma point.

So, this is the gamma point. This is the gamma point. This is the energy. This is the energy. I will show a minimum here from somewhere here and a minimum here. So, this is really the band gap. This is really the band gap we are talking about. Such a band gap minimum occurs at different  $k$  point. Then, it occurs here. So, this is an indirect band gap semiconductor.

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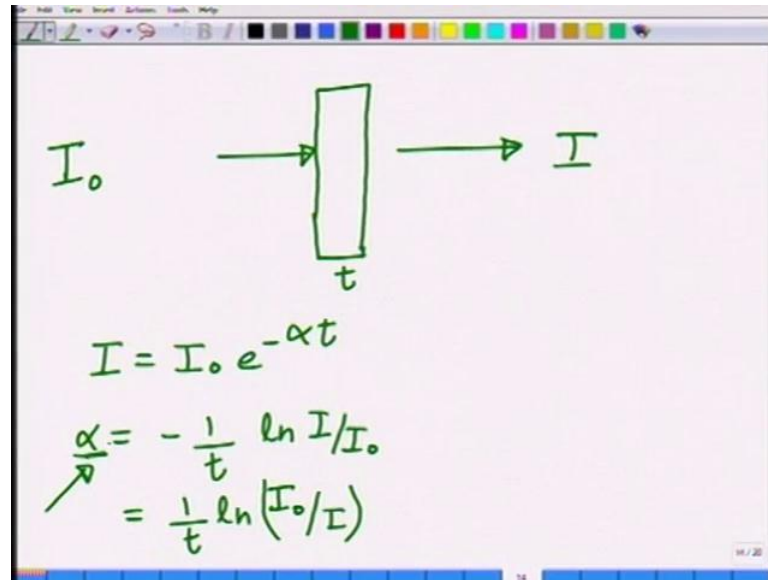


This is band gap semiconductor, indirect band gap semiconductor. Conversely, we can plot it, direct band gap semiconductor. Same way here is a valence band. I am showing there is a valence band and conduction band minima occur here and then here. So, the minimum occurs at the same  $k$  state. Now, you can see if electron sitting here, if an electron sitting right here has to jump has to go here, if it has to move like this, then it can do so by making changes in energy.

This is  $\Delta E$  energy. By making changes in  $\Delta k$ , the  $k$  must also change.  $E$  must also change. In this case, of course, in this case, all you require is  $\Delta E$  change in electron going from here to here. Electron going from here to here would imply that

there is a change in delta E only and no change in delta k. If I look at these 2 semiconductors, I start looking at the absorption profiles of these, so what I am going to do experiments like this.

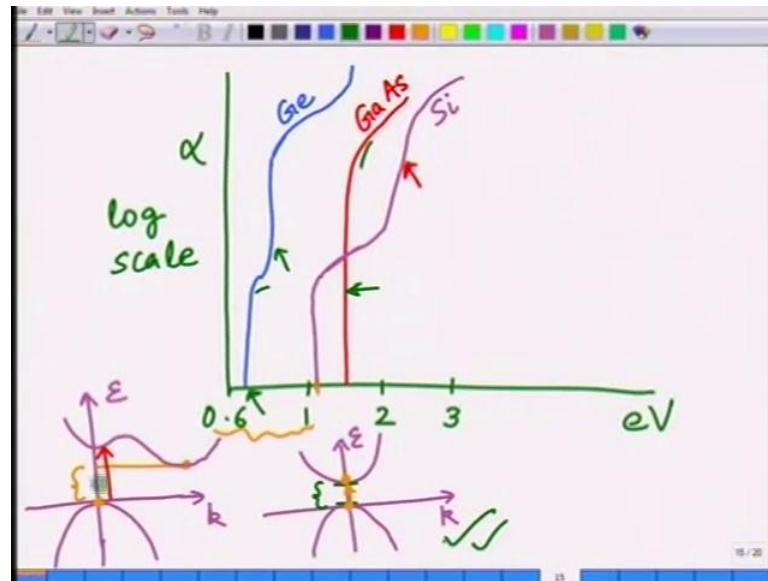
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I am going to do experiment, in which I will take a semiconductor. I will shine light of various wavelengths on to this and this. I will monitor what intensity is transmitted out of this and this. I will do at various wavelengths. If this is the thickness  $t$ , then we say,  $I$  as being equal to  $I_0$  naught  $e^{-\alpha t}$ . I am going to do this experiment for different wavelengths. So, why is that? What I am going to do then is I am going to take, define this  $\alpha$  quantity as equal to that. Then, I am going to find minus 1 over  $t$  times log of huge differentiable,  $\alpha$  does not look nice.

So, this use  $t$  thickness let us use thickness  $t$ ,  $t$  and  $t$  log of  $I$  by  $I_0$  naught. I can plot it  $1/t$  log of  $I_0/I$  by  $I$ . So, this is what we are going define is absorption coefficient absorption coefficient  $\alpha$ . So, I am going to now show you if I have done with experiment like this. I measure  $I$  and  $I_0$  naught for different wavelengths. I therefore, extract what the value of  $\alpha$  is. Then, I am not going to plot value of  $\alpha$  at different wavelengths. That means absorption coefficient at different wavelengths for different semiconductors. See, if I plot that, let me show you plot of it.

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This plot looks something like this. Hence, it is the alpha or a log scale. I am not drawing this scale. Here is energy, so for different wavelengths, there are different energies. I am going to do. So, this is electron volts energy. This is 0.6. I am putting this also at this. Here is one, here is one. It is 2 here. It is, let us say 3 etcetera. Now, if I look at this, what do I find? I will find in case of, I find a line something like this. So, let me draw a line like this first. I will show you different color line. They are shown in different color line. So, from there, here this is for germanium. This is for gallium. This is for gallium arsenide or this for gallium arsenide and this for silicon.

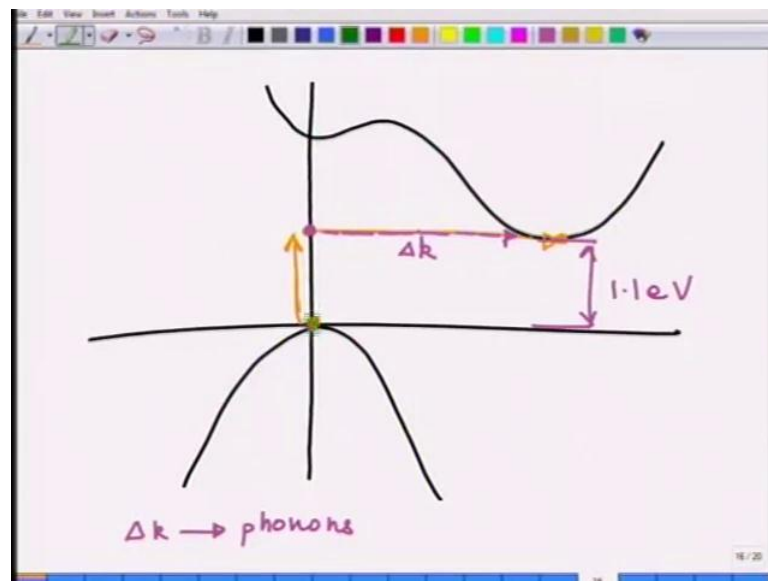
What do we notice? We find that I have, if you indirect band gap semiconductor, then I have something like this. If I would have direct band gap semiconductor, then I have something like this k versus E in case of silicon. In case of silicon, as I shine like clearly as long as energies are less than this, it is 1.1 e V.

So, I cannot have any absorption. I do not have sufficient energy to promote the electron from here to here, but when I get for all value up to 1.1, I do not get absorption hardly in absorption, but when I get 1.1, I get some absorption. I get some absorption. As the photon energy continues to increase, and then it becomes possible for this kind of directly to the higher bands. Also, it is possible to absorb into this. Also, then I get a deep absorption.

One more time same thing happens in germanium. First, absorption occurs with the band gap is about 0.66 electron volts up to here a weak absorption, but when I can absorb into the higher range, higher range directly, then I get a sharp absorption. As in case of gallium arsenide, which is a direct band gap semiconductor notice that, this gap being about 1.5 or 1.43 electron volts and room temperature on 1, 1.5 at 0 k.

This absorption is immense right away. It is an immense absorption straightway. There is a huge amount of absorption going on in gallium arsenide. That is because you can now absorb electron right from here. All you need is photon energy and simply jumps here. This is a 2 particle event namely electron cum electron interacting with a photon. It gets excited into this new state, the higher energy state which is in the conduction band. In case of silicon and germanium, when the photon of 1.1 electron volt in case of silicon, comes by energy, it is possible for this electron to jump.

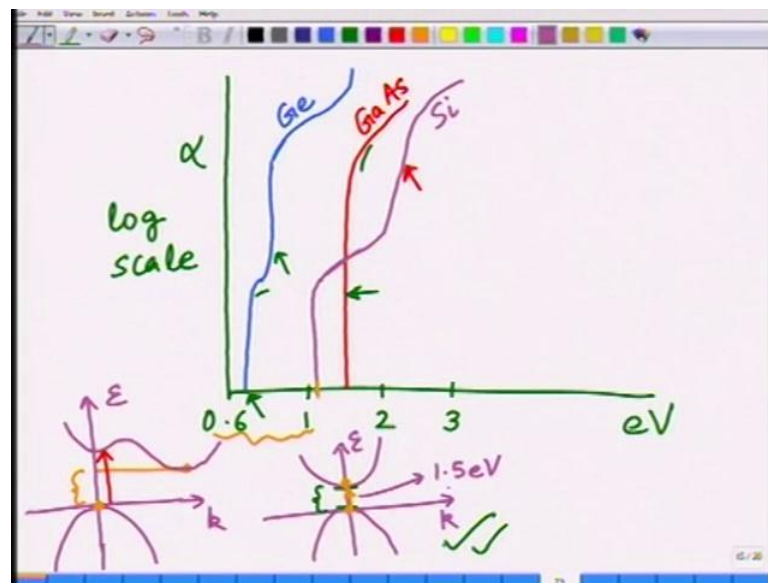
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Let me draw this picture one more time. So, in a different way something like this. Here is 1.1 electron volts. In case of silicon, it is possible for this electron to jump up to here, which is 1.1 e V for electron jump here, but there is no state. There is no state here. So, electron cannot live here. In addition to that, it must change its k value. Also, something must be provided. So, photon and electron alone are not sufficient enough. There must be something else added on that which allows this delta k also.

The  $k$  comes from phonons lattice, quantize lattice vibrations. Phonons must be involved. This quantize lattice vibrations, phonons do not carry much energy. Phonons, the lattice vibrations have very small energy. Remember, you use IR to detect them. So, phonons have very little energy, but they have large crystal momentum. Whereas photons have, very little photons have very little momentum in them, crystal momentum in them, but they have large amount of energy. So, a photon transition when I show in gallium arsenide, I show a vertical transition.

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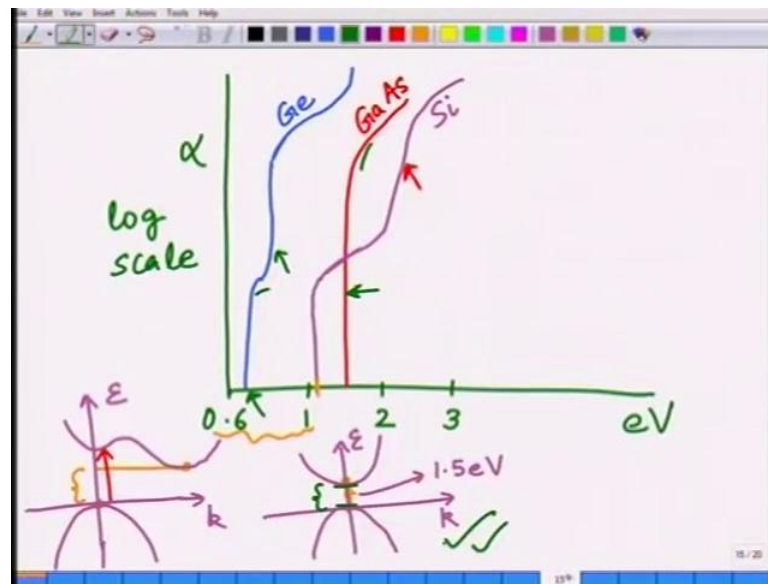


That means if an electron comes and excites this electron, then the energy changes by 1.5 e V or 1.43 e V or so e V in case of gallium arsenide. By this much amount in gallium arsenide, it changes, the energy changes, but there is no change in  $k$  because the photon which came had no, no crystal momentum. It could not change the crystal momentum.  $k$  value did not change.

So, I show it as vertical transition, whereas in the case of silicon and germanium, it is required for me to change  $\Delta k$  also in for this electron to go this much be 1.1. So, a photon of 1.1 e V comes. It has no, it has no crystal momentum. So, all it can cause is jump like this, vertical jump up. When it goes to vertical jump up, there is no state. Simultaneously, third particle should also come in, which is the phonon. We should provide the crystal momentum. Only then, this electron can come here.

The point is that this is three particle events, electron photon and a phonon. Probability of that happening is much lesser. Therefore, absorption in case of silicon and germanium at 1.1 e V and or in case of germanium at 1.66 e V is very weak. We get very weak absorption right here, at those points very little absorption. This is because you require phonon also, but when photon energy becomes, increases, then transition from here to here becomes possible. Even sufficient energy photon has sufficient energy.

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So, these jumps become possible. These jumps becoming possible means that now, I do not need phonon. Now, it becomes 2 particle event because this is a, this is jump, vertical jump only.  $k$  no change in  $k$  states. Therefore, you get a large increase in absorption. When that happens is when this energy becomes equal to the next higher level and  $\gamma$  equal to 0 itself.

And  $\gamma$  point itself at  $k$  equal to 0 itself, then this absorption occurs very rapidly. Clearly, now, you can begin to see that optical materials will be there, those which have good absorption. Hence, they must have direct band gap. With that thought, let me close this right now. Then, we will come back to this opto part again one more time after doing some some carrier statistics.