Physics of Materials

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Lecture No. # 37

Electron Compounds; Phonons, Optoelectronic Materials

Hello, welcome to the thirty seventh class in this course the physics of materials, through this course in several of our early classes, we have developed the framework and the theories with which we can attempt to explain material properties and phenomena that we see when we investigate materials or we work with materials. And over the past few classes, we have actually started looking at various, I mean throughout the course itself we looked at specific properties, but we have expanded this scope in the past few classes. We are looking at several properties, and seeing how the framework that we have build is is something that we can apply to these properties, and understand what we have or apply it to the phenomena that we see, and understand what we have.

So we will continue in the same way in in today's class, we will actually look at a particular, we will actually look at compounds that form, we will look at something that we seen certain types of phase diagrams, and certain phenomena we see with respect to when phases form and what is causing them to form. So, this is something that we will look at right now, we will look at the phases that form and what is the driving principle behind those phases that form. What we are going to discuss applies for certain type of components, only certain types of phases. So, it is restricted to that set of phases, so we will, so please bare that in mind as we look at the discussion.

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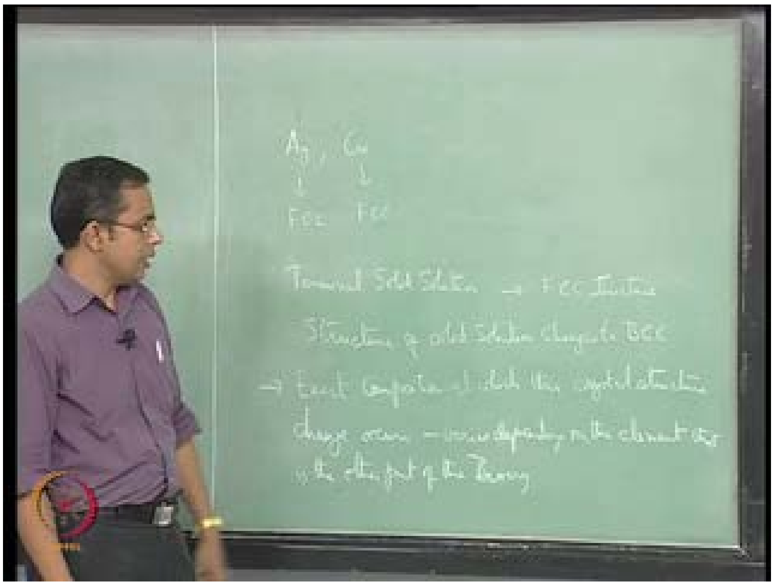

So, it turns out that, if you look at say silver and copper, it turns out that when you look at various binary phase diagrams of silver and copper. Silver and copper several binary phase diagrams you look at, you will you find one general phenomenon showing up, see these two are both FCC structures, so at room temperature they are FCC. And if you take mai binary systems based on this, so you are adding one additional alloying element to this and you start looking at the phase diagram. You invariably find that the terminal solid solution (No audio from 02:25 to 02:35) is since this original structure, terminal solid solution is the solid solution that you have very close to the pure component.

So, we you start from 100 percent silver, you start adding some other alloying element to it, then for the first initial solid solution that forms is called it terminal solid solution, because it is very close to the end of that, the composition scale that we have, so the terminal solid solution that forms will typically have this structure FCC of the parent material, because it still a solid solution, and this is what we have. So, if in both silver and copper, the terminal solid solution is also typically FCC structure, then as you start adding the alloying element, you will cross some composition, some particular percentage of the alloying element that you are adding.

At which point the structure changes to BCC, (No audio from 03:31 to 03:45) so this structure changes to BCC, so this is the… This general trend is seen for silver as well as for copper, for a number of binary systems based on silver and copper, so this is general trend. You start off with FCC structure, the terminal solid solution is is FCC, as you start adding more and more alloying element, it changes to BCC. Now, the point is the the exact composition, at which this change occurs, this crystal structure change occurs (No audio from 04:28 to 04:41) Now, the exact composition at which the crystal structure change occurs, varies from varies from system to system, varies depending on the alloying element (No audio from 04:50 to 05:02)

The other element in the binary the element in the binary, the other element is (No audio from 05:13 to 05:23) by definition binary means, you have only two alloying elements involves, so silver or copper is one of them, and then you are adding some other alloying element. So, based on the alloying element that you are adding at some particular composition some particular percentage of their alloying element, this change in structure occurs from FCC to BCC. So, this is seen in silver and copper, but the and as I mentioned here, the the specific composition at which this change is occurring, is varying will will vary somewhat depending on the element, that you are selecting.

So, in that sense there is no great mystery there, I mean in the sense, you look at various systems, you add elements and changes occur at various composition. So, up until this point, I do not think there is anything immediately standing out that, attracts our attention. At this moment, there is no immediate pattern, that is showing up here except for the fact, that there is a change in structure from FCC to BCC, as you are add an alloying element.

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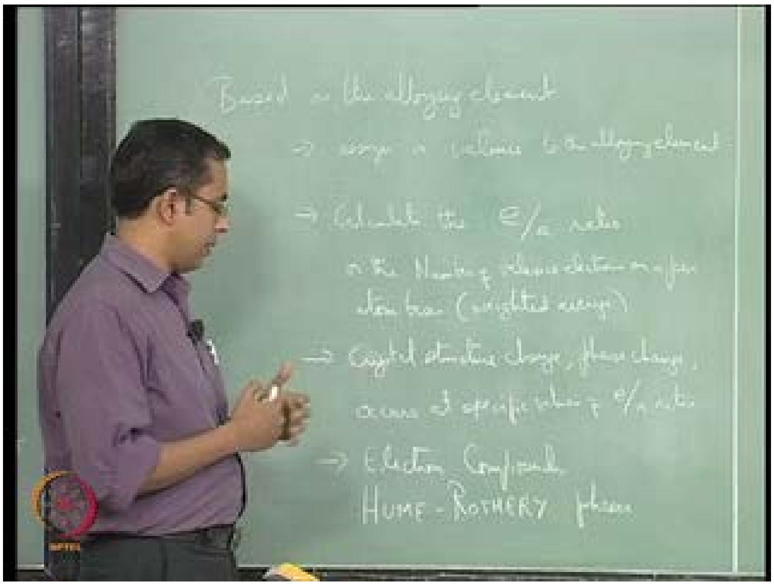

Now, the interesting thing that comes up here, is that these systems, where looked at closely to see, if there was something more common to them, which which indicated some specific reason for this change, and what was found was, that based on the alloying element, (No audio from 06:42 to 06:53) based on the alloying element first thing that you could do is, assign valance, so you can assign a valence state to that alloying element based on what you know of the alloying element, what is it is standard valency that it displays? You can assign to it, so these are substitution solid solutions by the way. And so you can and based on what you know of those elements, you say that you know specific elements tend to show as certain valency, so you can assign a valency to the alloying element (No audio from 07:23 to 07:31)

And then therefore, you can calculate the, what is called the e by a ratio? What is this e by a ratio? It is the ratio of the number of electrons per atom, number of valence electrons per atom. So, you have silver and it will have some valency, you are adding another alloying element, which has a different valency, so you can take a weighted average of these two valencies based on the the number of the number of moles say based on the molar ratio of how you have added these two elements. Based on the molar ratio of these two elements that you have added in the alloying system, you can take a weighted average of the valency of one atom versus the valency of the other atom.

So you can get an averaged valency on a per atom basis right, you can get an average valency on a per atom basis, it is for the straight forward that way. So if you have valency of 2 for one atom, and 3 for another atom, and you have put a 50 50 percent mix, then on average it is 2.5 per atom, so that is the way, you would do it. So that is the way, if we if it is more towards the atom that is with valency 3, you will get a the average valency will be closer to 3 or closer to 2, if you are using the other more of the other atom.

So, in principle you can calculate an e by a ratio, which will take into account, the valency of each of those two atoms, as well as the mole fractions to the two atoms being put in right. So, on a per unit volume basis, whatever so you calculate e by a ratio, this is on a per atom basis, so per atom basis we are getting the e by a ratio. So, we can assign a valency to the alloying element, and we can calculate the e by a ratio or the number of valence electrons per this is the average, number of valence electrons on a per atom basis. (No audio from 09:34 to 06:48)

Appropriately weighted average, we get so you can get this, this is where the problem becomes the situation becomes interesting, because we find that regardless of the alloying element that you are using regardless of the alloying element that you are using, we find that for a specific the, what we found was the composition at which that change occurs from FCC to BCC is varying for from system to system, so depending on the alloying element that you use, the composition at which that change occurs from a FCC to BCC can be a different composition right, but with respect to e by a ratio, we find that the composition change, I am sorry crystal structure change (No audio from 10:27 to 10:38) and therefore the phase change, because the crystal structure is part of the definition of a phase.

The crystal structure change and therefore, the phase change, occurs at specific values of e by a ratio, so this is the very specific value of e by a ratio, at which this change is occurring at in the crystal structure. And the composition corresponding to it may be different, that is simply because the valency of that atom that you are adding is different, so the valency is different, and so you may have to add a more of one atom to get the same e by a ratio, relative to some other atom, given that you are starting with copper, if you add a one alloying element, which has some valance. Suppose to another alloying element, which has twice that valency; obviously you have to add half as much of the second alloying element to get the same e by a ratio right.

So therefore, composition composition wise these two can differ, you may have to add 10 percent of one element, you may only need to add 5 percent of another element to get the same e by a ratio, because their valencies are different and the copper valency or the silver valency is the same. So, so the crystal structure change is seen to occur at specific values of e by ratio, regardless of the alloying element that you put in. So this therefore, means that something about the electronic structure of those compounds is creating a situation that one phase is more stable than the other phase, and and and that is more the fundamental reason, why this phase changes are occur.

So these phases are therefore, called electron phase electron compounds, these phases are also called based they are also called humerothery phases (No audio from 12:30 to 12:42) then since they are something associated with the electron and electron structure of that material, that seems to be impacting the phase change, these are also called electron compound or electron phases, so this is how these names. So now, based… So this is the general phenomenon that exist, so this has been known for a while, so we would like to see now, given that we have some theories for the material and how the material behaves and so on, and what causes the material to have, I mean features in the material, we would like to see, if all the theory that we have build or some aspects of the theory that we have build helps us understand, why this is occurring.

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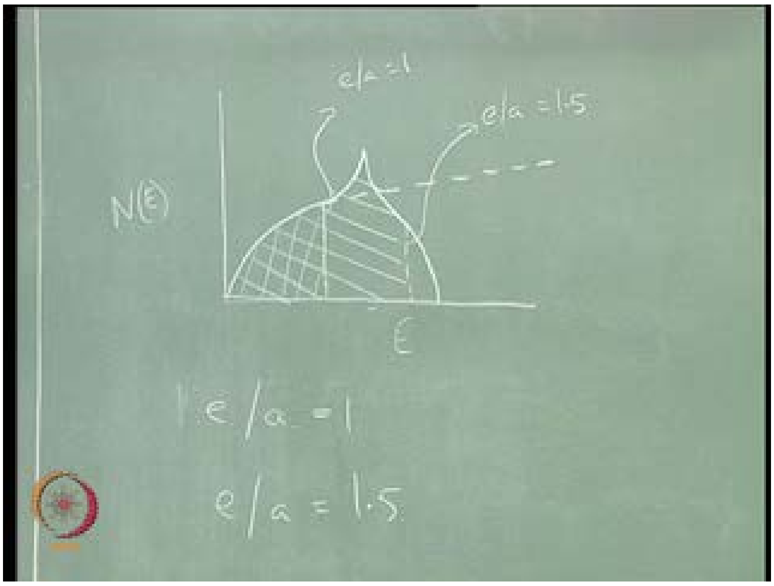

So this is what we will do, so what we will do here is, I will make a plot, on the x axis we have energy, on the y axis we have the density of states right, so this is what we have, density of states and energy. And we will say that, you know at a particular values of energy, we are reaching the (( )) boundaries and such, so what will happen is normally, if if if it is where a free electron system, if it were a free electron behavior, we would see a parabola, so I will just continue this like, so this is what the parabola is, corresponding to a free electron. Now, given that this free electrons, we are always now given that we talk of solids, we are talking of nearly free electrons and so on.

We have we have already examine the fact that when you have a Brillion zone boundary, the free electron parabolas are distorted, so they are distorted, so what actually happens is, so they are they get distorted for two reasons; one you have and of course, this is just the density of available states, the actual density of occupied states will will also include probability of occupancy and so on. So that, we have to include probability of occupancy here, if this this where density of occupied states, this would drop to this would drop abruptly down to 0 at at the Fermi Fermi energy, on the other hand, if it were some other temperature, it will be a, it will have some features corresponding to how it drops to 0, so that issue, that is another parameter we have to add.

Now, given that the e versus k relationship distorts at the Brillion zone boundaries, what you actually see is behavior that looks like this, and the fact that at higher temperatures it is not going abruptly drop to 0, you see a behavior that looks like this, it is like a free electron parabola up to some point, then it is distorts from there, and it comes down like this, this is then the density of states as a function of energy, that actually exist in that material. The taking into account the fact that you know, you have features corresponding to the e versus k relationship, you also have the fact that you are temperature as a room temperature, it is not absolute 0, all those things taken into account plus the bands from various zones and so on, which you see a final picture that looks like this, for e versus k.

So, if you see in now, this is actually the density of available states as a function of energy. Now, you you fill this up with electrons, so supposing you have a filled it up with electrons, supposing you have one electron per atom, so e by a or e by a is equal to 1. It turns out that in in systems such as this; e by a equal to 1 would result in electrons occupying states up to somewhere up to here, so up to here somewhere is where the electrons will exist, so this is what would be occupied, if you have an e by a ratio of 1. On the other hand, if you have an e by a ratio of say 1.5, if you raise the e by a ratio to you have 50 percent more electrons on a per atom basis, so e by a ratio becomes 1.5 this is an average; obviously, so this is an average.

So, if you do that, what will happen? Is it will actually go past this p that you see here, and you would actually fill up to somewhere up to here, so this additional thing will get, so this is up to e by a equals 1 and additionally you will add this. So this whole thing would now be e by a up to 1.5, so this is what we have, e by a equal to 1, this comes comes up to here, e by a equal to 1.5 comes up to here. Now, please note that you know, there are the number of available states has this form, so actually the availability of state begins to climb up kind of sharply very close to the and then drops done abruptly. So that is how we see the available states present Brillion zone within the system, and then it begins to drop down, so this is the general this is the general form of this material, of this information, so this is the form with information.

And based on the number of electrons, we fill up those available states in in this manner, you could either fill it up to here, if you had e by ratio, if 1 are you would have more than e by ratio of of one, then you would have a up to 1.5, you will see in taking into account all the distortions, and such you will find that you are filling it up up to here, so this is the situation. Now, so this is and you are starting for from a terminal, you are starting from an original material, that is FCC structure, so that dominates so if you actually fill is up for on FCC material, this is how it will look. So, on this on this on a similar diagram, we will actually additionally add, what might happen if your, if you plot the same kind of information for for a body centered cubic structure of the same material (No audio from 18:40 to 19:05)

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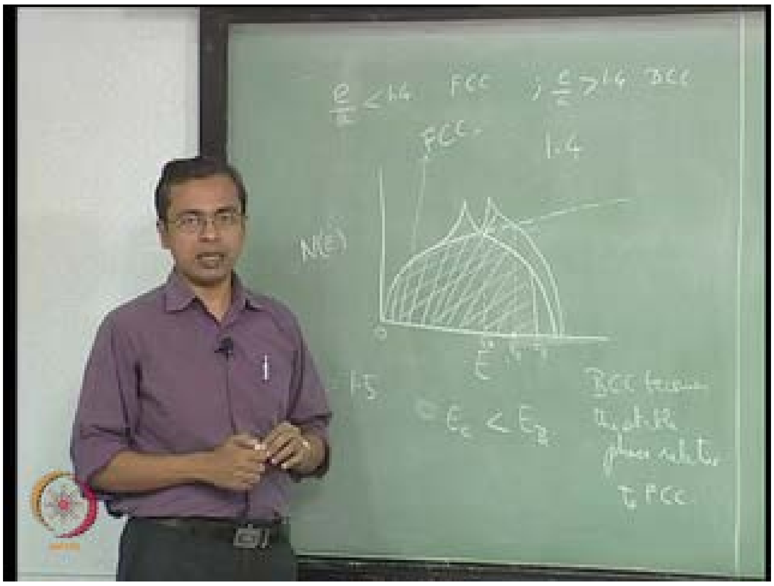

So, this diagram is the same as what we just do, so we will have this is for let us say, now this is for the body centered this is for the face centered cubic material, face centered cubic face FCC face, so this is for FCC. FCC face is this, it is showing you this curve, this is just a trend line from the free electron parabola for, so that we can understand, what we are doing. Now, for BCC structure based on, where the Brillion zone boundaries are for BCC structure, what we see is with respect to a for BCC, if did the same kind of a diagram, what you will see, is it will continue with the free electron parabola little further, and then it will it will sort of climb up here, and then drop down.

So, actually we will we will slightly exaggerate this should, we can I think this would still will exaggerate this little bit, so that it is clearer to follow what we are doing? (No audio from 20:07 to 20:23) So, an FCC would sort of show you, this is the b c FCC structure that comes does this, when you do for BCC the body centered cubic structure, it does this. So, the face centered cubic structure does this or or rather has a number of available states as a function of energy given by this, the diagram that is shown here, and then when you loo draw the same thing for a BCC structure, it looks like this. Now supposing, you have 1.5 electrons per, if e by a is equal to 1.5 if e by a is equal to 1.5, we have already seen that in the original FCC structure, it would fill up up to here, so up to this energy level, so this is what would get filled up. (No audio from 21:15 to 21:22)

If we use the FCC structure, which is the parent structure, you started with that, that is the terminal solid solution and so you building up on the terminal solid solution, you up arrive up to here. On the other hand, if you use the FCC, I am sorry if you use the BCC structure, the curve you have to follow is like this. So, if once you cross this point here, right once you cross this point here, you have the number of states corresponding to BCC is actually climbing as a function of energy as a function of energy, since you are now, only now you are approaching the Brillion zone the Brillion zone shape is different, the location of the boundaries are different and so on.

So therefore, it turns out that for a BCC structure this is where it is, it begins to distorted, so when you cross this energy point, some energy value here, so some arbitrary I will I will will just call it E A, it is a E subscript A, when you cross E subscript A, E A what you find is that, for the FCC structure the number of states per as you, the density of states, density of available states as a function of energy, is a function that is decreasing, it is begin it is already it is decreasing in this place up to here, it was increasing, it increase sharply started decreasing kept keeps on decrease. So for the FCC phase once you cross this point, it it is it is already decreasing from here, but it goes below the free electron parabola around there, and then continues down.

The for the BCC structure, on the other hand, again it follows the free electron parabola up to some point and distorts, and then continues to climb, so you find that there is small region of energies, after that even the BCC structure has it is density of available states beginning to drop right, but there is a small range of energies, where the density of available states for the BCC structure is is climbing continuing to climb, whereas in that same range the density of available states for the FCC structure is decreasing. So, this is very important to note that, the density of available states for the FCC structure has already started decreasing and it is continuing to decrease and this range, whereas that for the BCC structure was increasing, and specifically in this range, this is it is continuing to increase, whereas this is decreasing.

Therefore, in this range of energies and actually little beyond this range also, starting in this range of energies starting in this range of energies more number of electrons can be stored in the BCC structure for the same same amount of energy compare to the FCC structure right. So supposing you take 100, supposing let us say this is a 1000 electrons, so you have to go up to energy this E B, from E A you have to go up to E B, to store those 1000 electrons, just for a some random number that we are we are using for discussion. So, you have to climb up to E B, because that is when you get 1000s states available to you, to fill up those thousands electrons, but if you look at the if BCC structure, because more states are available in this region, compare to the FCC structure.

You may only need to go up to E C, some arbitrary I will just draw it has some E C here, to accommodate the same number of electrons, so we are only looking at the, so if we just see now, (No audio from 24:41 to 24:49) So in the FCC, in the BCC structure, you are able to accommodate more electrons in a smaller energy window relative to the FCC structure, simply because of where the turn off is occurring, where it is beginning to change shape, so it is simply a matter of area under the curve, if you want to look at it that way, the same area in in this curve can be accommodated in a in a smaller energy window, so if this is 0, so 0 to E C is smaller than or effectively E C is less than E B.

We are taking the same number of electrons, we are just populating the number of available states, simply because the number of available states is higher for the BCC structure, in this energy window relative to the FCC structure, you are able to accommodate the electrons in a in a lower number of energy values than relative to the FCC structure. So, and ultimately you know the one of the fundamental driving forces for how things occur in nature is minimization of energy, so that is basically, what is occurring. So therefore, we see that even though you start with an FCC structure, as you start increasing the number of electrons per atom, you reach a stage, where simply because of the energy associated with those electrons the energy associated with those electrons.

We find that one structure corresponds to a lower energy for those electrons relative to the other structure, in this case, the BCC structure corresponds to a lower energy for those electrons, relative to the FCC structure therefore, on the bases of the lower energy being attained for electrons in the BCC structure, BCC becomes stable (No audio from 26:29 to 26:44) so we see clearly from our own diagram from the diagrams, that we have drawn for this this system from all the understanding that we have gained here, in this course, we see clearly how certain type of a phase change occurs as a direct result of what we can see on this diagrams.

So, it turns out that in fact this ratio for for the systems works about 1.4, if e by a is less than 1.4, (No audio from 27:10 to 27:21) then it remains as FCC, if e by a is greater than 1.4, it becomes BCC. And so you just have to actually that 1.4 might work out some some particular location, so some particular location here, you will be able to get that 1.4 as some particular point here, where it really depends on exactly where this curve is going up, and exactly where that curve is coming down. There will be a one particular point, where both of them can whole the same amount of electrons at the same level of energy. After that, the additional electrons should be held in lower amounts of energy by one structure relative to the other structure and therefore, that structure becomes stable.

So therefore, we see a very interesting set of phase changes, which corresponding to this electrons phases, and what are called this humerothery phases as something that we can directly understand, and explain on the bases of the theories, that we have learned. So this is an important thing, that you can you can read up more on electron phases and you will see, how that happens?

Now, we have additional thing that we will look at, which is not (No audio from 28:30 to 29:22) for most of these course, we have actually focused on the electrons, we have focused on the electrons how they behave? What happens to them? What are the conditions under which they, that they are, that they experience, what is their response to those conditions and so on. As I mention you know, some of the properties of the material can be directly related to this electrons, and in many aspects of electronic materials and even many aspects of materials science and engineering, these electrons therefore form a very important aspect of how the material is responding.

The other important constituent of the material is the atoms, so for we have sort of ignore the atoms and we would like, I would like to introduce you at least to one of the concepts associated with, how the atoms are behaving with respect to energy, because that also is a contributed to some of the phenomena, that we see.

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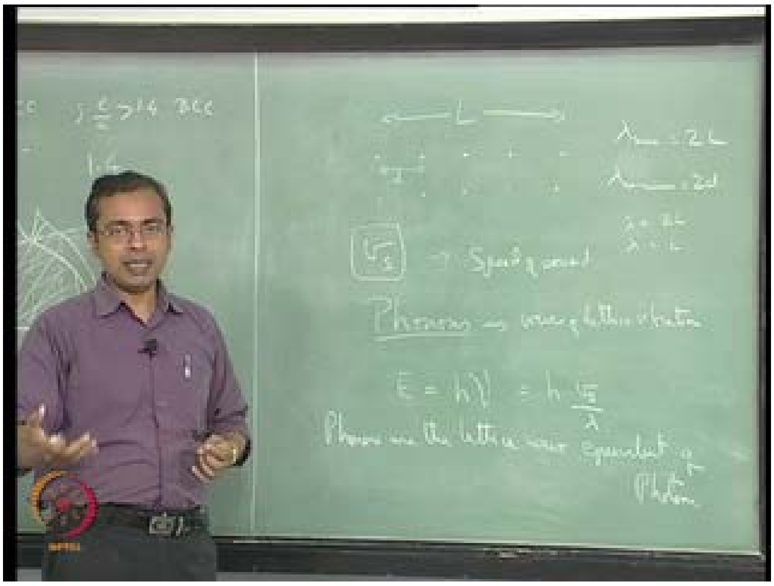

Now, in this structure of the solid, you have atoms at specific locations, so this is how the atoms are and along around this is the free electron cloud, and mostly we have focused on the free electron cloud. Now, but what happens is that, these atoms are not really static, they are not just sitting at it it is a it at exactly specific locations, instead based on the energy available to the system. In fact, they are in a position to move, they are in a position to vibrate about their mean position.

And this is a important way, in which they, the gain energy from as you raise the temperature, and they also release energy as you lower the temperature. So, so so atoms are in a position to accept participate in energy transaction process, and they are actually in terms of an entire crystal, if you take an entire sample full of atoms, they are actually vibrating, so they are all vibrating, they could be vibrating longitudinally, they could be vibrating in a transfers direction, so all these waves are possible in a material. These waves of and in the process you know, energy is getting transferred, it is getting transferred from atom to atom, it is going from one end of the material to other end of material and so on.

And most of these, since they are matter waves, so to speak they all occur at the speed of sound, this is a speed of sound. So, the transfer of energy and such that occurs through this waves, occurs at the speed of sound. So in that sense, you know it we are we are looking at something that is different from, what we have traditionally looked at, where we are looking at speed of light in many of the… In some of the discussions, that we may use, so this is speed of sound is where this information or energy is getting transferred and these matter waves as they are called waves of these matter, they can also actually be converted to…

In principle, some arbitrary wave can go through this, so an arbitrary wave can go through it, but we can analyze the arbitrary wave by looking at it as a set of waves, as a sum of waves, where each wave has a fixed wave length. So, any arbitrary wave that you take, that is what you do, when you do Fourier series, Fourier analysis, you take some arbitrary wave form and that wave form can be actually obtained by summing up series of well defined sinusoidal waves, you just have to take the sinusoidal waves specify their amplitudes, specify any phase differences, if necessary such that they all add up to give you this arbitrary wave from that you have.

So similarly, any arbitrary waves that is passing through this structure can be thought of as all of those waves that are adding up to give you this arbitrary wave, so these matter waves are are referred to as, they are given a name and they are referred to as phonons. Phonons are waves of lattice vibration waves of lattice vibration these are phonons, they are very, they are of interest for several reasons. First of all for example, when we talk of you know specific heat of a solid, they view view in all are calculations we kept focusing on the electronic contribution to the specific heat, what about the all the atoms, the atom also contributed specific heat. And in fact, they do so in the through this, when they do so, you know the energy in the atoms is that you providing to those atoms is held there in the form of those waves, that are present within that system.

So, therefore when you look at, when you underlies the solid for specific heat as an overall concept, you have to look into the phonons contribution to those, thus specific heat, so that is how, we get the overall specific heat of that solid. So, phonons are these lattice vibration interestingly the energy of a phonon is also still related by this equation E equals h nu. So, in that sense actually these phonons are in fact represent one region, where you can actually see one one region in our discussion in so to speak, where you can actually see quantum mechanics very successfully explaining some of the behavior shown by that solid.

So, they two are observing energy, see they are also waves they and they have energy associated with them, and it turns out that they also accept energy only in step functions, just the way we look at photons accepting energy only in steps of h nu, phonons also accept energy only in steps of h nu, only difference is as I said we have they are travelling at speed of sound, so this nu here, is we sound by lambda, so that is a very important difference, we sound by lambda and so that is how they do, so they are quantized so they are quantized that is the very important thing. So, the phonons are the are the lattice wave equivalent of photons, just the way we talk of photons for light, we talk of phonons for waves in the crystal lattice.

So, they are analogues so to speak in terms of, what what they represent, so when it is light and electromagnetic radiation, we talk of photons. So, that is what we have done for most of the course is spoken about photons, but in the lattice, we have phonons. So, this is a this is the thing and they participate like a say in things like these specific heat for example, is explained on the bases of phonons, the the change in specific heat as a function of temperature, there is the schedule the long petit law, we says that you know specific heat is a certain fixed value for all solids, but but actually if you look at specific heat as a function of temperature, then it does have as you get a lower temperature, it does have a certain change in it is form, as a function of temperature, it is not a fixed value.

And those are explained on the strength of phonons and what frequency they can hold, so that is how, you have explained certain things, but also very importantly for form our perspective, there are even the electronic transition that we talk of are sometimes assisted by phonons, so there are times when electron transitions are occurring, which have which are directly associated with phonons, and we will discuss that briefly. I just want to point out that you know in a crystal lattice, when you talk of phonons, there is some restriction on the wavelengths that they can they can look at.

We can look at clearly as we have done before, you know if if this is the length of the material L, the the highest wavelength the that can be supported in this L is such that, this this is half the wavelength, that this length is half the wavelength, so the atoms form half a wave here, and the other half is outside so to speak. So, this can define half a wavelength just the way we did before, so L can be are 2 L lambda can be 2 L, lambda maximum equals 2 L, where L is the extend of that solids so to speak. So, that is the maximum that you can get, the minimum so if this spacing is d, inter atomic spacing is d, so lambda minimum is 2 d, so this is what you will get in between basically you will get, you know if this is 2 L.

The next one, so you can get you know lambda is equal to L by 2 I am sorry lambda is equal to 2 L of and then you the next one you will get is lambda is equal to is equal to L and so on. We can different different possible wavelengths in this solid going from the 2 L to the the 2 d limit, so this is what you will get right and also if if the atoms are so to speak, if if the atoms are actually, if you actually have a 2 atom basis on your unit cell, and let us say those and it is an ironic crystal, if it is an ironic crystal, what you will have is? When you do this kind of a flipping, you are actually changing the field as a function of time.

So, it is it is sort of creating an electromagnetic response, so it can actually interact with infrared radiation, some of this phonons are what they called optically active phonons, because you can send infrared radiation and the material will respond to that infrared radiation. So, some of this phonons are optically active, the others are acoustically active, because they are talking of sound, so that is how this phonons differ from each other. So, this is how they look and as I mention that they actually interact with electrons and allows certain transitions to occurs.

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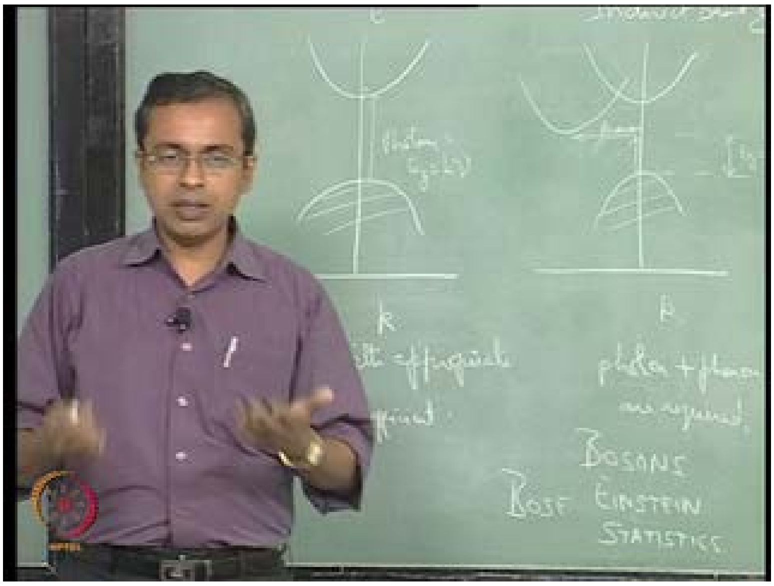

So for example, we looked at direct band gab verses indirect band gab materials right, so in a direct band gab material the highest, so this is K, this is E, so this is one possibility that you have the highest level in energy of one particular in a particular band at the same location as the lowest energy of the next highest band. So therefore, you only need to provide a photon to get this electron to go up here, with E equals h nu, E band gab equals h nu, so you provide this then you can get the electron to go across. On the other hand, if you have a structure for this is K, this is a band (No audio from 40:33 to 40:46) and we will say these are filled, so this is filled, so this is also filled, that is empty, but at some other location in case space you have an even lower band right.

Now, actually instead of you need less energy this this band gab is smaller than this band gab, only difference is this is at the same location in case space, this is at a different location in case space. So, the so electron needs less energy to go up here, this is a smaller E g, but it is not safies if it is goes here, it has to go across to this location in case space, so it has to sort of go up and it has to go across. So, two things have to occur, so it has to go up and it has to go across, this occurs you sing of phonon, so this is phonon based, the lattice vibration enables the electron, which has gone up to, which is gaining energy to also get to the right location in case space, so that it can get into that band.

So for an indirect, so this is direct band gab, this is indirect band gab, and what we see is for a direct band gab, photon is sufficient, photon with enough energy is sufficient with appropriate energy is sufficient, (No audio from 42:17 to 42:30) whereas for an indirect band gab semiconductor, you need a photon plus a phonon. (No audio from 42:35 to 42:45) So, the thing is when you talk of photons and phonons and search they are all at present in the system, they are all occurring at different points and time. So, there is a certain at a given instant, see when you look at this kind of system light is falling on the on the system lets say. So and you would like to see, if some transition is going to occur are some energy is coming transition, where in this case light is falling our system.

You want to see, if there is a transition that is going to occur, will it occur for a specific electrons that is the question, for a given electron will it occur, the whether or not it occurs for a given electron is simply there is an element of chance, so that photons has to strike that electrons, so there is a certain probability associated with it, so there is some element of randomness in this process, photons may be going all over in the sample, they may be striking something else, they something else might be happening. So, certain photons has to arrive and get get in effectively interact with a particular electron, and then enable the transition, so there is a probability associated with that.

Again similarly, lattice waves are travelling through the system and so the right kind of a lattice waves should be available for that electron for it to go from this location in case space, to this location in case space. So, for each of these things that is are probability associated with it, so here you only have the probability associated with the interaction, with the photon and the electron, so that is certain probability, when you look at this system, you need the interaction of the photon with the electron there is a probability associated with it. Immediately after that, you also need the interaction of that electron with the phonon, so there are two separate steps that occurring here, both of them have a probability associated with them. So therefore, the probability of the whole thing occurring is the product of these two probabilities.

So and therefore this this decreases in probability in a very significant sense, so the because this is all these are all some probabilities associated with them, you multiplying them and they are all, they are not they are not close to one, they are much less than one therefore, when you multiply the probability this is drops in a very big way. So, what happens is the point view, I want to highlight here is, it may be that for an indirect band gab semiconductor, the band gab is small. In fact, you will you will find systems, where the indirect band gab semicon this is what is defined as the band gab.

The highest occupied state verses the lowest unoccupied band energy level, so this this gab is now the band gab, so this band gab may be less than this band gab, still when you supply light to this systems. The probability of this transition across this band gab, will be less than the probability of transition across this band gab, because of the fact that phonons are involved in this interaction process. As a result for optical properties direct band gab semiconductors are much more effective than indirect band gab semiconductor, so if you are talking of you know, I mean the number of times this transition occurs and similarly, the number of times transition backward occurs, defines the amount of light you can get out of the system, so you have raise to all the electrons if they begin fall back they release light, you see the light.

The intensity of the light know the intensity of light defends on how many of these electrons at going through the process, the energy of the light is the same, it because that is depend define by the band gab, so here energy will be higher, but you will get a very very week beam in terms of intensity, you will it will be very dull beam, you not be able to see in enough with it, here the intensity will be nice, you will get a very nice intense beam, because several trans several tras I am sorry here you will get a dull beam, because you have to get a two two transactions have to occur, here you will get a bright beam, because you you are you are getting double advantage, band gap is higher, so higher energy is there, at the same time the probability of transition is also high.

So therefore, you get a higher energy beam, which is also intense. In this case, you get a lower energy beam, because the transaction is less, but on top of it, the intensity is also less, because it is a two step process, so that is two step process is reducing the chances that it will occur, you get a dull beam. So, for this and this kind of a process, where you using electronic transitions to get light or interaction with light the these are called optoelectronic materials, so optoelectronic materials is what we are looking at, so for optoelectronic materials direct band gab semiconductors have consider very good, as suppose to indirect band gab semiconductors.

As we saw in the last class gallium arsenide is an example of direct band gab semiconductor, silicon for example, is an example of an indirect band gab semiconductor. So for optoelectronic processes, you use direct band gab semi conductors, so this is one thing, I wanted to point out. And I want to also finish off with one other detail, which will now lead as to what we will discuss in in in fact in the classes ahead, couple of classes ahead, that is that we spoke of you know particles, these statistics associated with particles and so on.

More specifically, when we spoke of electrons, we started off by saying electrons or we started and treated them as classical particles, we use Maxwell Boltzmann statistics, later we recognize that may be that was not the right thing to do, we tried out quantum mechanical approach were we used Fermi Dirac statistics for electrons, and the and the the validity of using a statistics for a given particle really depends on the characteristics of those particles, so you and that is the reason why you know Maxwell Boltzmann statistics fails and Fermi Dirac statistics is succeeds for electrons, because they have all the characteristics that the Fermi Dirac statistics is assuming about that particle.

Similarly, particles are particles such as photons and phonons follow as statistical behavior, which causes them to be called bosons and therefore, they and it they are called bosons, because they follow the Bose Einstein statistics, (No audio from 48:30 to 48:39) so they follow the Bose Einstein statistics, so they are called bosons and and therefore, that is what defines, how they behave and so on. And this is also defines, how they interact with various systems and various phenomena around there. So we will see in the next class next couple of classes, we will also, we will certainly in our next class we will look at another phenomenon of material behavior, where some again the interaction of of phonon will became necessary and phonons are bosons.

So we will actually and certain certain aspects of what we will discuss in the next class, will be related to the fact that certain particles should behave like bosons, so we will look at the phenomena in fact, we will talk of super conductivity in our next class. And we will first look at super conductivity as a phenomenon, and then we will also discuss, since in a couple of different context will there be, we it will involve talking about bosons, we will in the class after that we will look at Bose Einstein statistics of the bosons and that will help as understand certain aspect of it.

So to sum up in today’s class we have been trying to look at more places, where the theories that we have develop the understanding, that we have developed help as follow various aspects of material behavior and in this regard we looked in a reasonable detail at the electron compounds, what causes them to occur, how the diagrams we have drawn, enables us to understand, why this compounds form or what what is the phenomenon that is defining the formation of this compounds. So, we saw that in great detail, we have also additionally added on our on to our understanding by looking at phonons.

We have looked at crystal lattices and the fact that you know waves could travel through those lattices, those waves are have or quantized their energy and they the particle equivalent of those waves is called of phonons. And in that sense it is analogues to a photon, and we have related it to something that we already discussed, which is the direct and indirect band gab semiconductors, we looked at the fact that you know for optoelectronic purposes, direct band gab semiconductors are better, because they do not involve phonons based transactions, whereas indirect band gab semiconductors will will suffer for that reason, because they will involve phonons based transactions, so the probability of the transaction decreases.

So, you you cannot go only by the band gab, the band gab helps you decide that, which which has more energy, which has less energy, and some cases either of them might have higher or lower energy, when you compare direct and indirect band gab semiconductor. Additionally, we also have to look at the probability that that that the transition will occur, which occurs and that probability is much higher, when you look at a direct band gab semiconductor. So, with this we will halt today in this class, and we in in our next class, we will look at at super conductivity as a phenomenon thank you.