Semiconductor Optoelectronics
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Lecture - 17
Interaction of Photons with Electrons and Holes in a Semiconductor

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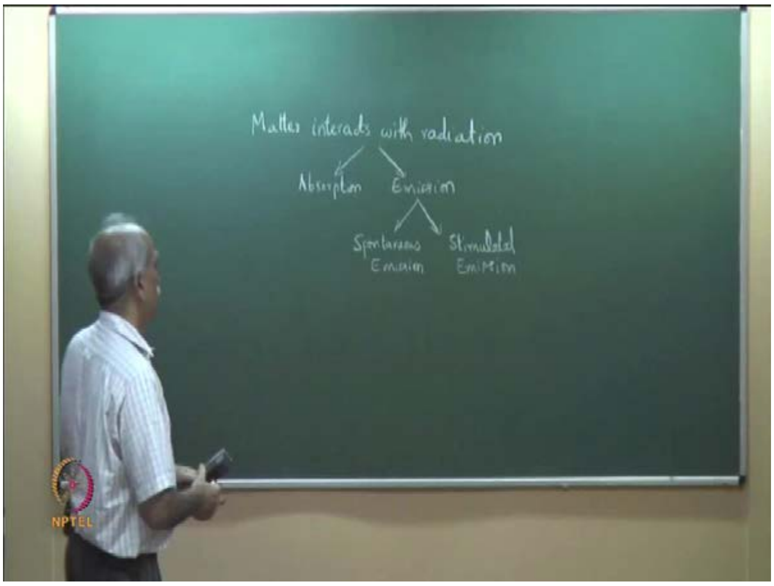

So matter interacts with radiation, matter interacts with radiation through two processes, basically two processes; so emission and absorption, so absorption and emission. In absorption…So, the emission itself has two basic processes; one is spontaneous emission, spontaneous emission and stimulated emission, stimulated emission. So, basic processes are interaction of radiation with matter. In the context of semi conductors, we explain this in the context of semiconductor, so let me rub these, we can explain this with the help of the E k diagram. We are interested in interaction of photons with electrons and holes in a semiconductor.

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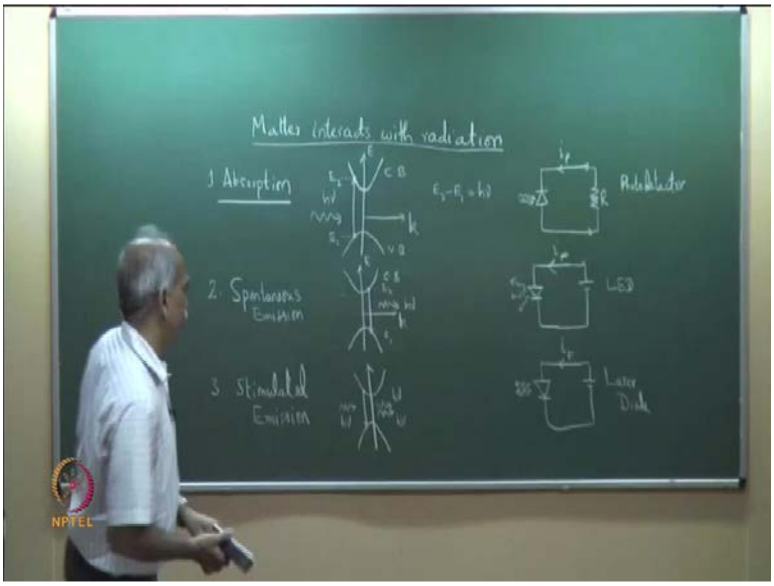

So first, absorption absorption if you take the E k diagram, the E k diagram, so E here and k here consider the incidence of a photon of energy h nu, an electron sitting here at energy E 1, E 1 is an energy level in the valance band, so this is the valance band and this is the conduction band. An electron sitting at energy value E 1 can make an upward transition here to an energy E 2, such that E 2 minus E 1 the energy difference is equal to h nu. In fact this is the law of conservation of energy, an incident photon making an upward transition. In the process the photon got absorbed, so absorption of a photon creates an electron hole pair, when the electron has made an upward transition here it leaves behind a vacant state, which is the hole.

So, generation of electron and hole pairs due to absorption. Emission as I mentioned there is spontaneous emission, spontaneous emission, spontaneous emission. It can be described by a similar E k diagram, in this case E k, an electron sitting in the conduction band makes a downward transition spontaneously. Spontaneously means, on its own. An electron in the conduction band, in the conduction band where it is at a higher energy, makes a downward transition in energy this downward and upward that we are talking is in the domain of energy because the vertical axis is energy, makes a downward transition to a vacant state or a hole in the valance band.

So, this is E 2 and this is E 1 here. The energy difference is even as a photon h nu, so this is spontaneous emission electron making spontaneously a downward transition from an excited state to the valance band. The third part or the third process is stimulated emission, we are similar with these processes in atomic systems. So, I am depicting it using the E k diagram in the case of semiconductors. So, stimulated emission, normally we discuss this with atomic energy levels, but in the context of semiconductors, I am discussing with E k diagram.

So, in stimulated emission, an electron makes a downward transition less to emit a photon, but in the presence of a stimulating photon. So, if a photon at energy h nu is incident an electron sitting in the conduction band can make a downward transition into the valance band here giving out an energy h nu, a photon of energy h nu which is in phase with the stimulating photon.

This is a simple picture to show that, one photon incident brings down one more photon, each one of energy h nu and h nu, so 2 h nu. And the emitted photon is in phase with the incident stimulating photon. So, the downward transition in this case is stimulated by the incident photon. In this case the downward transition was spontaneously on its own and here it is stimulated by an incident photon.

Basically the interaction is more complicated this is a simple way of illustrating it. It actually the photon interacts with the material system here and comes out with an energy of 2 h nu. This can be described by 2 photons, which are coherently emitted with energy h nu, so that the net energy is 2 h nu. These three basic processes are the building blocks of devices in semiconductor, the first one is absorption. So, this is the basis of photo detection.

So, in photo detectors, we usually have a reverse biased p n junction and the incident photon in the junction regiongenerates an electron hole pair, which leads to a reverse current a reverse photo current i p in the circle, provided of course, you connect this let us say it is the resistance R. This is the photo current generated because of the incident photon, the incident photon generating electron hole pairs leading to an external current sometimes. You may reverse bias this for a required characteristics, so this is the principle of a photo detector.

So, photo detector, photo detector spontaneous emission is the basis of operation of LED’s where you have a forward bias diode, a diode which is forward biased. So, there is a forward current, now propagating i f through the diode which then gives out light in the form of photons. So, photons are emitted, when you pass a forward current the electron holes recombine in the junction region leading to emission of photons.

So, this is the principle if operation of light emitting diode, basic principle of operation. Stimulated emission is the basic principle of operation of laser diodes, again it is a forward biased diode with certain conditions,, which are different from that of an LED, which we will discuss later. So, you passed a forward current i F and this emits photons, which are depicted as coherent photons.

So, in phase here the emission is in random directions whereas, in a diode the emission is coherent or n directional. So, this is the principle of operation of laser diode. So, the basic three processes absorption this can also be called as stimulated absorption because the process takes place in the presence of an incident photon, so absorption, spontaneous emission and stimulated emission.

These three basic processes are the basic operating. Principles of photo detectors, light emitting diode and laser diodes in optoelectronics. We will discuss little bit more about the dynamics and the conditions that need to be satisfied for the operation of these devices. So, one condition you can already see that the conservation of energy, which is E 2 minus E 1 is equal to h nu.

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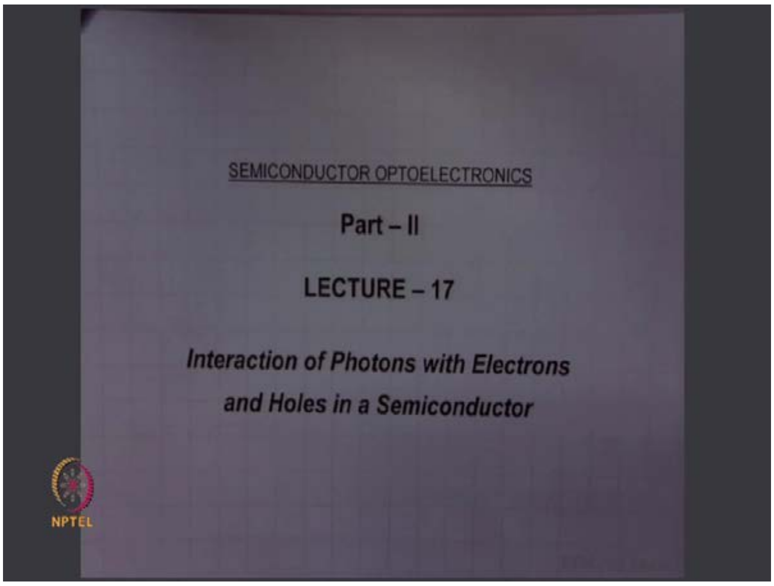

So, we will see the conservation laws all these processes have to satisfied the law of conservation of energy and momentum, law of conservation of energy and momentum.

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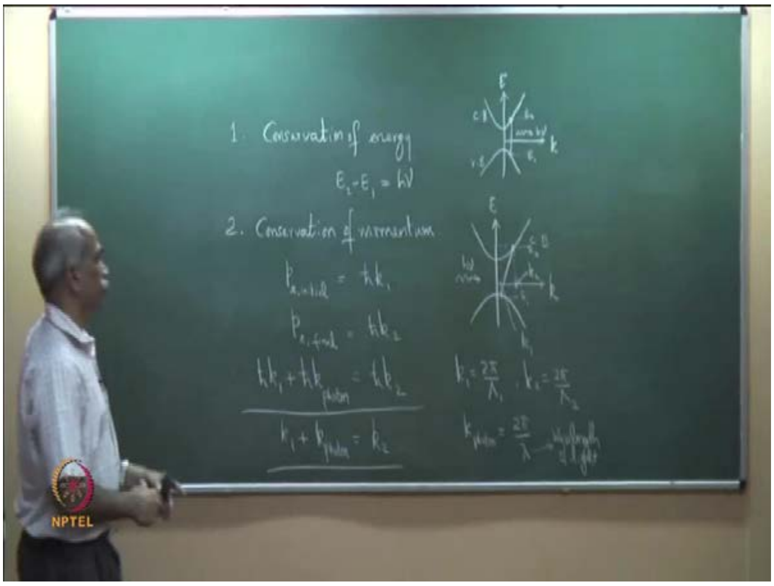

So, let us discuss the conservation conditions and with the help of the E k diagram, I will illustrate the law of conservation of energy and momentum. So, the first one is conservation of energy. So, conservation of energy again let me use an E k diagram and I consider a direct band gap semiconductor here, a photon a, an electron which is in the conduction band makes a downward transition could be stimulated or spontaneous emission to a vacant hole here.

This gives out energy h nu and h nu must satisfy, if this is energy value E two, so this is E versus k, then this thing is E 1 then we must have E 2 minus E 1 is equal to h nu. The same thing is true if the a photon of energy h nu is incident and you have an upward transition of electron from the valance band to the conduction band. So, this is the E k diagram valance band to the conduction band straight forward. Let us see the conservation of momentum, two, conservation of momentum conservation of momentum.

Let me show another process here, I could explain with that itself, but let me show another process. Again E k, consider an electron which is sitting here making an upward transition to the conduction band in the presence of photon that is absorption of a photon, an electron sitting at energy value E 1 here making an upward transition to an energy state E 2, so this is E 2, so this is E axis, so E 2 and E 1. So, E 1 is here, but I have deliberately chosen an oblique transition to indicate that this electron has had before transition, it had a k value here.

So, that is the k value here is, if I designate it as k 1 and this electron after the transition has a k value corresponding to this, so this value here is k 2. Then the electron had a momentum initial momentum, which is equal to p of electron initial is equal to h cross k 1 and p of electron final that is after transition is equal to h cross k 2. So, in this interaction we had one photon, initially we had the momentum of the photon and the electron momentum here, at the end of the absorption process we have an electron with momentum h cross k 2.

Therefore, we must have h cross k 1 plus h cross k of photon. So, I will write this as a suffix, h cross k of photon is equal to h cross k 2, total momentum before the process equal to total momentum after the process. This is the law of conservation of momentum. However, we can we may note that photon, what is the… So, this simply means h cross is common, so we have k 1 plus k 2 k k 1 plus k photon is equal to k 1 plus k photon is equal to k 2, what is k ? k 1 is 2 pi by lambda 1, where lambda 1 is the De Broglie wave length of the electron in the valance band, k 2 is 2 pi by lambda 2 and k photon is k photon is equal 2 pi by lambda, where lambda is the wave length of light. So, this lambda here is wave length of light, wave length of light.

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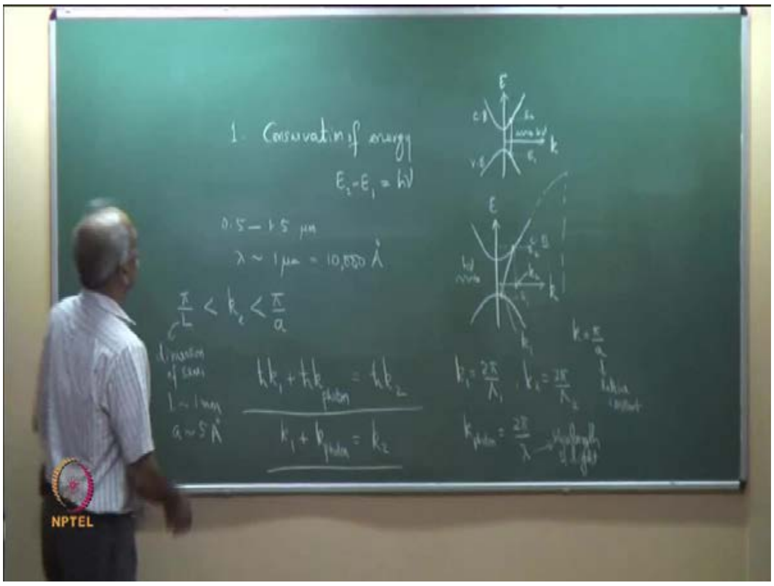

Typically we deal will wave length from 0.5 to 1.5 micro meter, if it is communication you have 1.55 micro meter window for optical fiber communication. This is in the visible region blue green region. Therefore, let me assume that lambda is typically 1 micrometer, which is equal to 10,000 Angstroms 1 micron 1, 1000 nanometers or 10,000 angstroms. What about these lambdas, if you see the E k diagram the band would go and the edge of the first mark zone is k is equal to pi by a is the edge of the first mark zone, where a is the lattice constant, lattice constant. Therefore, typical k here would correspond to, so k lies between very small values that is, we have discussed pi by L, where L is the dimension of the semiconductor. So, the dimension of semi conductor, very small because L is very large compared to a pi by a typical K of electrons L to a

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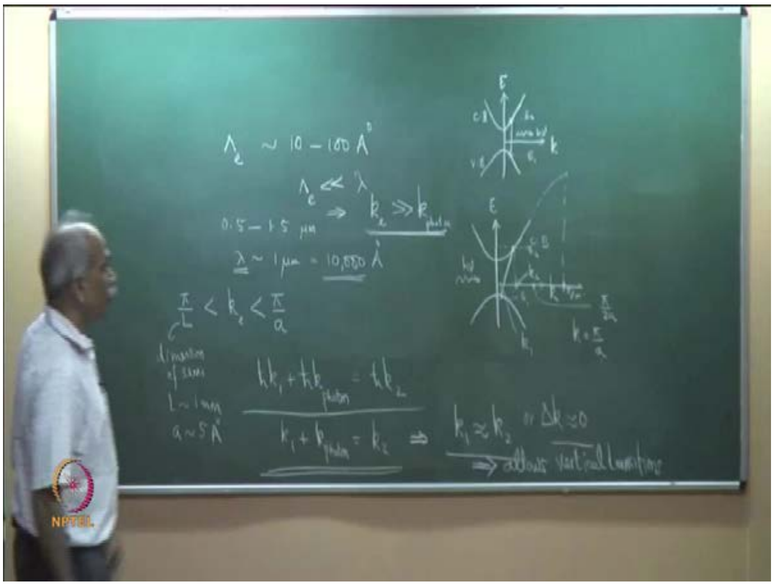

L is of the order of this could be of the order of 1 millimeter, L is of the order of 1 millimeter and a is of the order of 5 Angstrom. Typically the De Broglie wave length of electrons, therefore, remains somewhere in this range. So, if you take a k value somewhere here, this may correspond to 10 times a or 5 times a, so lambda of electrons, we had calculated for example, the De Broglie wavelength of electrons in semiconductors corresponding to thermal energy electrons. So, lambda for electrons is of the order of typically 10 to 100 angstrom.

Typically lambda of electrons De Broglie wavelength of electrons is in this region, we have done an exercise in which we had got, I think 30 nanometers, 300 angstroms. But you are in between, let us say if you have in between here, so it will be pi this is almost 0, this end of the first mark zone is pi by a. So, this will be pi by 2 a. So, lambda for an electron which is here will be, so this end is pi by a. So, lambda for an electron somewhere in between is pi divided by 2 a. 2 a is 10 Angstroms because a the lattice constant is approximately 5 Angstrom.

For an electron which is here the denominator is may be 10 Angstroms, may be 10 times a, 10 times a is 50 Angstrom, this is 20 times a about 100 Angstroms. So, the typical numbers for De Broglie wavelength are 10 to 100 Angstroms or even if you wish 1000 Angstroms, for electrons which are close to the bottom. The point you note is lambda E is much smaller compared to this lambda of photons, which is 10,000 Angstroms, so lambda E is much smaller compared to lambda, where wavelength of photon. This implies, this implies that k of electrons that is k 1 comma k 2 is much greater compared to k of photon. k of electron, the numbers just help us to appreciate this point that k of electrons is much greater compared to k of photons.

Therefore, if you look at this equation here, equation here, then k photon is negligible compared to k 1 and k 2. Therefore, I can write that this implies, this implies that k 1 is nearly equal to k 2 or delta k is nearly equal to 0. The conservation of momentum, the second condition requires that k 1 is nearly equal to k 2, k 1 should be nearly equal to k 2 or delta k should be nearly equal to 0 for the transition to take place. k 1 equal to k 2, means it corresponds to a vertical transition.

So, the implication of this is this implies that conservation of momentum allows vertical transition allows a vertical transition, vertical in the energy scale vertical in the E k diagram. Vertical transitions vertical transitions are allowed transitions allowed by the requirement of momentum conservation. This is the important point to see, when photons interact with electron. In other words when you have radiative interactions, where a photon is absorbed or photon is emitted from a semi conductor, the allowed transitions correspond to delta k equal to 0.

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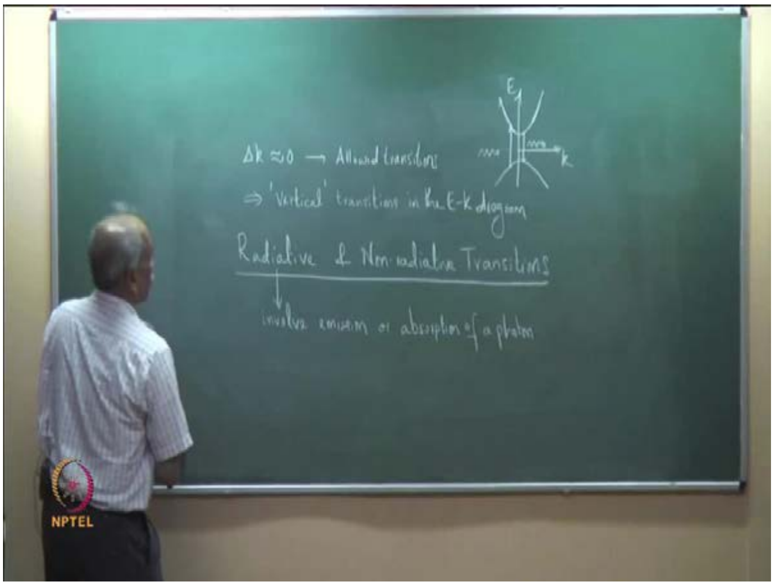

So, delta k nearly equal to zero or allowed transitions allowed transition this implies vertical transitions vertical so vertical transitions in the e k diagram transitions in the e k diagram. So, I draw the E k diagram here and indicate that the allowed transitions correspond to vertical transitions. So, both this state and this state has the same k value both the final state and the initial state has the same value. It could be absorption or it could be emission, but note that the k value is the same.

Let us discuss a little bit more on this that is does, it mean that no oblique transitions take place. I have been discussing about radiating transition, so I use the word radiation transition. So, let us consider radative and what are radiative transitions? So, radiative and non radiative transition, radiative and non-radiative transitions. Radiative transitions are radiative transitions which involve involve emission and or emission or absorption, abosorption of a photon radiative transitions involve emission or absorption of a photon.

The phenomenon that I had discussed absorption and emission are all radiative transitions, which involved emission absorption or emission of a photon radiative transition, non radiative transitions do not involve emission or absorption of a photon. So, the law of conservation of energy delta K equal to 0 in the conservation of momentum, which requires delta K equal to 0 or the allowed transitions.

For radiative transition which involve emission or absorption of a photon but, non radiative transitions non radiative transitions do not involve emission or absorption of a photon. So, can we have, so let me now discuss oblique transition. Let me write this discuss oblique transition oblique transitions in the E k diagram.

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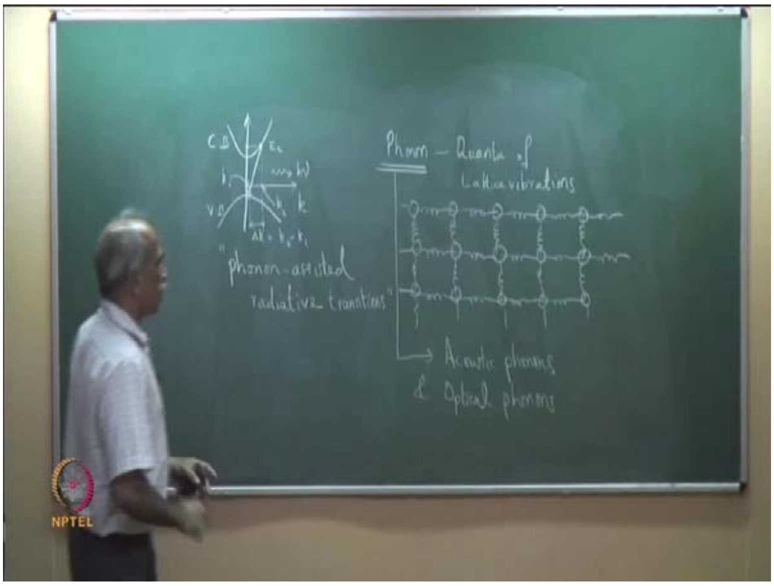

So in the E k diagram here, it is in the valance band conduction band and an electron an electron, which is sitting here. Let us say in the excited band makes an oblique transition here and emits a photon, is this possible? The answer is yes, it is possible. It is not allowed because K K 1 is here and K 2 the final state is here. So, if I call this as the initial because this was this corresponds to k 2 and this is energy E 2 and this comes to K 1. So, K 1 is here you see this is K 1 value of K 1.

So, there is a delta K may be I will show it here, there is a difference. This is delta kequal to K 2 minus K 1. Allowed transitions correspond to delta k equal to 0, but there is a finite delta K, now significant delta K an electron, which was sitting here making a downward transition such transitions are possibleprovided something can compensate for this momentum mismatch. This is a mismatch of momentum mismatch of K vector and these are done by with the help of phonons.

Phonon phonon assisted phonon assisted radiative transition, this is a radiative transition. Law of conservation of momentum requires that delta K should be 0. We see that K 1 minus K 2 is not 0, but if some other particle or some other entity can make up for this momentum mismatch, then we can have radiative transitions. Such transitions takes place with the take place with the help of phonons and they are called phonon assisted radiative transition, phonon assisted radiative transition.

What does this means? Phonons, what is a phonon? Let me now discuss the (( )) a little bit to discuss about phonons, phonon are quanta of lattice vibration, quanta of lattice vibration. Lattice vibration as you know that atoms in a crystal are always are bonded by elastic bonds and they are always in a state of agitation or state of vibration because of finite thermal energy. So, we can imagine these as atoms which are linked by spring; this a simple picture. So, you can imagine am showing string because the bonds are not rigid basically to indicate that the bonds are not rigid. so the phonon correspond to which means the atoms here can vibrate or oscillate in the lattice.

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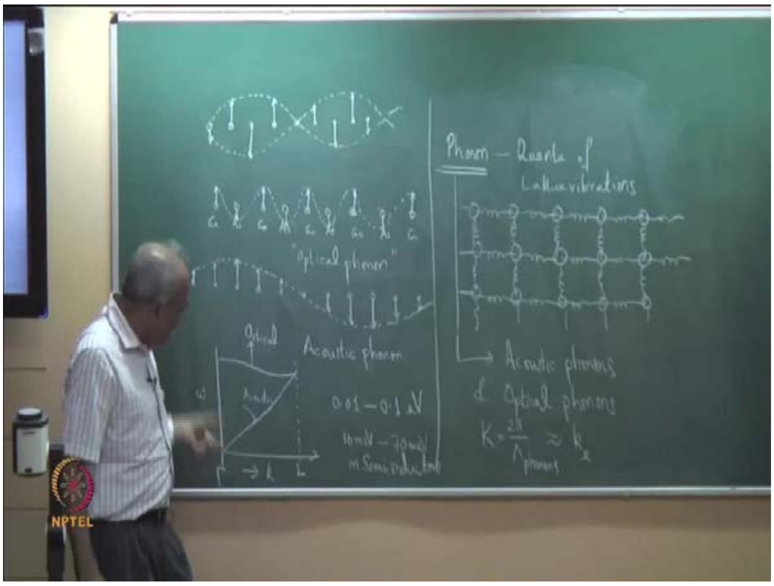

The vibrations, the vibrations have certain associated energy with them and the quanta of those lattice vibrations are called phonons. There are two types of phonons, let me illustrate this broadly two types of phonons, which are called acoustic phonons, acoustic phonons and optical phonons, optical phonons. What are acoustic phonons and optical phonons?

We will come back to this phonons assisted transitions, first let us understand a little bit about this phonons. If I take simply k 1 dimensional lattice, which means atoms are atoms are erased along one line. Let us say for example, this is gallium, this is arsenate, this is gallium, arsenate, in gallium, arsenate, gallium, arsenate and so on; so these atoms gallium, arsenate, gallium. Phonon oscillation here, the phonons correspond to displacement of atoms in the lattice, displacement of atoms in the lattice. For example, if this atom gets displaced in this direction, then this atom could get displaced in this direction.

Displace here, displace like this, displaced like this, displace like this, which means the adjacent atoms are displaced in opposite direction. If these are displacing in this fashion, then it corresponds to motion of a wave. So, you can see a wave nature here, if you see the displacement of atoms the position of atoms what you see is the wave here and this is transverse oscillation of atoms. More importantly adjacent atoms displacing in opposite direction and this wave corresponds to an optical phonon, optical phonon.

In contrast in the case of acoustic phonons, there are various patterns possible, but the displacement of adjacent atoms is in opposite direction. I can also show you another pattern, yet another pattern. So, one atom getting displaced here, this way the next atom getting displaced a little bit more here, the third atom getting displaced here like this, the fourth atom getting displaced here. The fifth atom remain in here, so this forms a wave which is like this. So, what you note is, so this atom here, getting displaced in this direction.

The atom which was here getting displaced to this point, the atom which was here getting displaced, so this is also an optical phonon here it is just adjacent atoms are all atoms are displaced and the wave corresponds to this. Here the wave corresponds to this adjacent atoms are displaced in opposite directions but, the magnitude of displacement is different, varying here the magnitude of displacement is the same for all the atoms. This is also an optical phonon, this is also an optical phonon. Let me show you acoustic phonons now, so how would an acoustic phonons look like?

Let me draw in one dimension because it is very easy to illustrate and imagine what is this acoustic phonon? In acoustic phonons atoms adjacent atoms or group of adjacent atoms get displaced in the same direction like this and the next group gets displaced to opposite direction. So, it is not adjacent atoms are not displaced, but the groups are displaced. So, the corresponding wave would now look like this, you see the difference here. Adjacent atoms are displaced in opposite direction here. Adjacent atoms are displaced by different magnitudes, but in the same direction.

Then the next group gets displaced in the different direction, so the displacement continuous which corresponds to motion of a wave like this. So, these are mechanical waves which correspond to vibrations of atoms displacement of atom. So, this is an illustration of acoustic phonon, what you would immediately see is the frequency of the wave lengths are small here. The frequency of optical phonons are in general much higher compared to the frequency. This is wavelength, so wavelength is large.

They add you can have a variety of wavelengths because you can have 20 atoms displacing here, 20 atoms coming down here, which means the wavelength is very large or frequency is very small. But here the frequency is high. You can at best have some displacements, some variations of wavelength, but enhance frequency. But the frequency of acoustic phonon in general vary from very small values to very large value. So, if you see a dispersion plot which you can dispersion. Dispersion means K verses omega frequency verses omega, then for acoustic branch for the optical branch, generally the frequency varies like this and for the acoustic branch the dispersion curve generally varies.

They almost meet this is K equal to 0 in in the mark zone picture, this corresponds to the gamma point and this corresponds to L point or x point, L or x. So, this is the acoustic, this is the acoustic phonons, acoustic branch and this is the optical branch. What do you see? The frequency of the optical branch is high and almost remaining fixed, whereas the frequency varies for the acoustic branch. More details you can see you can go through about phonons and typically phonon energies in semiconductor vary in the range 0.1 electron. 0.1 is also on the higher side, generally about 10 milli electron volts to 60 or 70 milli electron volts.

So, generally in that range, so 10 m e V to 70 m e V in semi conductors, the energy of phonons. What is this distance is a, lattice constant a. Therefore, the wave length here is 2 a, so what you see is the wavelength lambda of phonons can be as small as to a, which means the momentum K is equal to 2 pi by lambda of lambda here of phonons, lambda of phonons, phonon can be as high as this much, which means it is of the same order as k of electron.

You can have wavelengths, which are small and therefore, momentum very large. Although the energy of phonons are very small in this range, they can have large momentum, which means they can compensate for momentum mismatch. Therefore, in an inter band transition, in an inter band transition phonons can very easily make up for the momentum mismatch.

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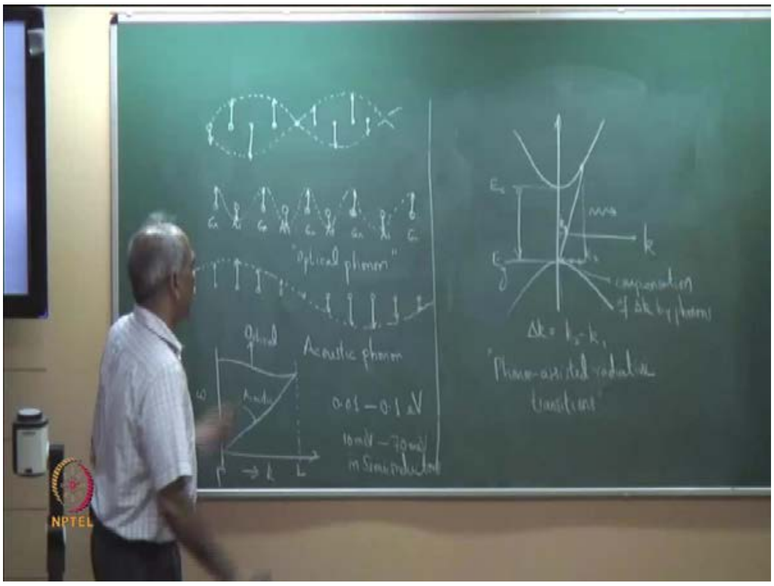

So, now let me come back to the phonon assisted transition that I was discussing. So, let me draw the figure again here. Let me draw a fresh, an electron which was in the conduction band makes a transition to a hole here in the valance band. So, this has a value of K here or here let me show. This corresponds to K 1, K 1 and this here corresponds to K 2 and delta k is the momentum mismatch. Again re drawing it, so K 2 minus K 1 and this can be made up this difference can be made up by 1 or more number of phonons, because phonons have momentum, which are comparable to similar number K 1 K 2 similar number.

So, this difference can be made up by phonon. However in general for inter band transition, if I take a semi conductor, this band gap. So, this is please see the remember that this is E c and this is E g this band gap E g is of the order of 1 electron volt, 1.5 electron volt and so on. But the energy of phonons are very small, so 1 or 2 phonons cannot make up for this gap. You can have large number of phonons making up for the gap, yes.

But the energy difference can be made up by emission energy conservation has to be satisfied can be made up by a photon and the momentum conservation can be made up by participation of 1 or 2 or more phonons and such interactions are called phonon assisted phonon assisted radiative transitions, radiative transition. The probability of occurrence of phonon assisted radiative transition is much lower compared to normal radiative transitions. That is because in this event you have photons, electrons, holes and phonons, an additional entity, an additional particle in this picture. The probability of occurrence of such events where the momentum mismatch has to be exactly matched with the certain number of phonon is much lower.

The probability of occurrence of that event is much lower compared to vertical radiations due to vertical transitions, which are allowed transition. This is not an allowed transition by momentum condition. However, the momentum mismatch delta K if it is matched by phonon, if it is taken care of by participation of phonons, then such a transition can take place. Although, the probability is little lower, this is a momentum, this is a… So, normally a it is illustrated in this fashion, so from here we show the K by small momentum vectors and this is made up of phonon.

So, the small arrows here show momentum of phonon, momentum vector of phonon. So, that mismatch is due to phonon. So, momentum compensation compensation of delta K by phonon phonons, is this all right? So, I come to the last topic that is non radiative transition. What about materials, which are indirect band gap semi conductors such as silicon? So, delta K equal to 0 for emissions are not permitted. So, let me just draw and show you.

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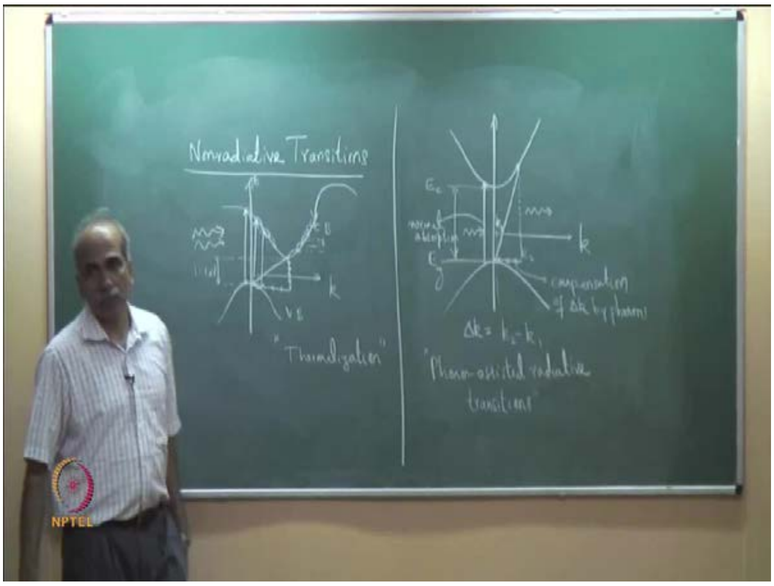

So, this is indirect band semi conductor vertical transitions, which go from here to here or reverse or allowed transitions. This is not an allowed transition unless the mismatch is made up by phonon and this corresponds to a phonon assisted transition. This is a normal radiative transition, this is a. So, if you have this, this transition is a normal radiative trans normal absorption normal. I mean allowed transition vertical transition, whereas this one is a phonon assisted transition.

Now, let me come to very quickly come to the non radiative. We will discuss more at a later stage on radiative transition. As the name indicates these transitions, do not have emission or absorption of photon. So, if you take a semi conductor like silicon. I am showing the E k diagram here of silicon where k versus E, it is a indirect band gap semi conductor. T he band gap here is approximately 1.1 e v one point one e v at room temperature, this is the valance band and this is the conduction band. It is an indirect band gap semi conductor.

So, electrons carriers generated in this come down by thermalization and tend to accumulate near the bottom. So, wherever it is generated it tends to come down by the process of thermalization. Thermalization is a process where energy is carried away by phonons, please see that there are large number of states here allowed states. But you also see that the energy difference between these states, the energy difference is very small. This difference corresponds to phonon energy, so phonons can easily account for this transition. Rapidly if you somehow pour an electron here that is you put an electron high energy electron here.

Then the electron will lose its energy through phonon transitions and come down to the bottom. This is called thermalization. So, thermalization thermalization, why the word thermal because phonons gave heat that is energy given to the lattice in the form of heat. Hence the name thermalization, but basically these are phonon transition, which come down to the bottom. Now, an electron which is accumulated here finds that there is a weaken state here and it makes a transition. Can it make a transition? Yes, it could with the help of hole.

We have all p and silicon diodes where you pass a current and there is recombination of electrons and holes in the junction region. But there is no emission of photons or very little emission of photons, so how does this take place? This takes place through phonon, there are large number of phonons. So, you indicate by small arrows like this to large number of phonons, which are making up for the energy difference. Although one phonon has much smaller energy, there are large number of phonons can be emitted and they also make up for this momentum conservation.

So, participation of large number of phonons to make up for the energy difference as well as to make up for the momentum difference. Please see the value here is k 1 momentum here is k 2 there is a large momentum mismatch. But this momentum mismatch and energy difference energy conservation and momentum conservation. Both are made up by phonon, but now it does not involve any photon. Therefore, the probability of this event is not low probability of this event is low because electron hole phonon and photon.

Whereas, here electron hole and phonon, therefore this occurrence probability of this occurrence is not low. An non radiative transitions take place in the case of direct, indirect band gap semi conductor. So, most of there-combinations are due to non radiative recombination and this immediately tells us that we would like to have direct band gap semi conductors, if we want to have photon emission. Indirect band gap semi conductors are not suitable for photon emission, not suitable for devices to make devices for photon emission. However, these are perfectly fine as absorbers or detector, why?

If you send photons from here, then electron, which is sitting here can make an vertical transition here. An electron which is here can make vertical transitions here, an electron can make vertical transitions here, because states are available here. So, it observes photon and makes vertical transition after words it comes down here and accumulated. So, indirect band gap semi conductors are suitable for making detector, as suitable as direct band gap semi conductors.

In direct band semi conductors also photon energy if the photon energy is larger than band gap, then transition can take place. Here transition can take place and the number of transitions or number of absorptions will be more, if you have larger photon energy; Photon energy larger than the band gap. So, is this clear? We will see later on, we will see the absorption curve and you can explain the absorption curve in a direct band gap semi conductor as well as in an indirect band gap semi conductor. We will this is at a later stage, this is okay.

So, in summary we have seen that interaction of photons with electrons and holes in a semi conductor, satisfied the law of conservation of energy and momentum. Phonon assisted radiative transitions, where phonons make up for the momentum mismatch. Whereas, in the case of indirect band gap, semi conductors it is the phonon which are primarily responsible for the transition. I will stop here and continue.