Semiconductor Optoelectronics

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

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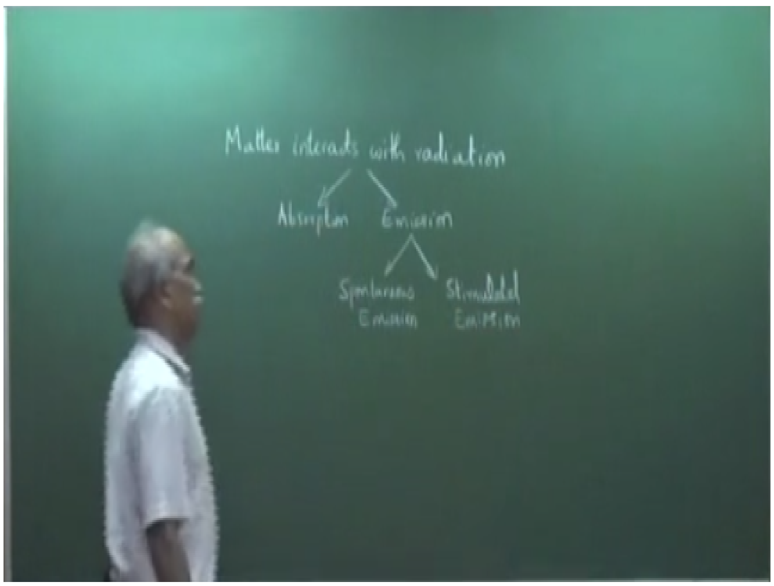

So, matter interacts with radiation through two processes basically two processes. So, emission and absorption, so absorption and emission, in absorption so though emission itself has 2 basic processes one is spontaneous emission and stimulated emission the basic processes of interaction of radiation with matter.

In the context of semi conductors we explain this in the context of semi conductors, so let me rub these we can explain this with the help of the EK diagram, we are interested in interaction of photons with electrons and holes in a semi conductor.

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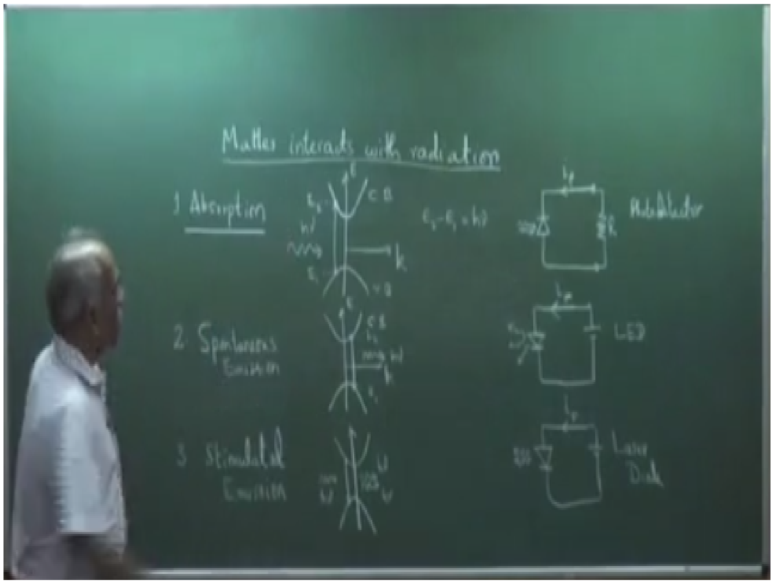

So, first absorption , if you take the EK diagram the EK diagram, so E here and K here consider the incidence of a photon off energy H mu and electron sitting here at energy even, even is an energy level in the valance pack, so this is the valance band and this is the conduction band and electron sitting at energy value even can make an upper transition here to an energy E2 such that E2-E1 the energy difference is equal to H mu.

In fact this is the law of conservation of energy and 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 leads 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, it can be described by a similar EK diagram.

In this case EK an electron sitting in the conduction band makes a downward transition spontaneously, spontaneously means on it is own an electron in the conduction band where is it as 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 to this is E2 and this is E1 here.

The energy difference is given as a photon hb, 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 familiar with these processes in atomic systems, so I am debiting it using the EK diagram in the case of semi conductors. So, stimulated emission normally we discuss this with atomic energy levels.

But in the context of semi conductors I am discussing with EK diagrams, so stimulated emission an electron made a downward transition S to emit a photon but in the presence of a stimulating photon, so if a photon at energy h mu is incident and electron sitting in the conduction band can make a downward transition to the valance band here giving the out an energy h mu a photon of energy h mu which is in phase with the stimulating photon.

This the simple picture to show that 1 photon incident brings down one more photon each one of energy h mu and h mu, so 2 h mu 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 it is own and here it is stimulated by an incident photon.

Basically the interaction is more complicated this is a simple way of illustrating it uhhh it actually the photon interacts with the material system here and comes out with an energy of 2 h mu and this can be described by 2 photons which are coherently emitted with energy h mu so that the net energy is 2 h mu these 3 basic processes are the building blocks of devices in semi conductor.

The first one is absorption, so this is the basis of photo deduction, so, in photo detectors we usually have a reverse biased pn junction and the incident photon in the junction region generates an electron hole pair which leads to a reverse current a reverse photo current IP in the circuit provided of course you connect this let us say the resistance R and 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**.** Spontaneous emission is the basis of operation of LEDs where you have a forward biased diode, a diode which is forward biased. So, there is a forward current now propagating IF 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 of operation of light emitting diodes. Basic principle of operation and stimulated emission is the basic principle of operation of laser diodes again it is forward biased diode with certain conditions which are different from that of an LED which we will discuss later, so you pass a forward current I f and this emits photon which are depicted as coherent photons.

So, in phase here the emission is in random directions whereas in a laser diode the emission is coherent or and directional, so this is the principle of operation of laser diode. So, the basic 3 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 3 basic processes are the basic operating principles of photo detectors, light emitting diodes 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 E2-E1 is equal to h mu, so we will see the conservation laws all these processes have to satisfy the law of conservation of energy and momentum.

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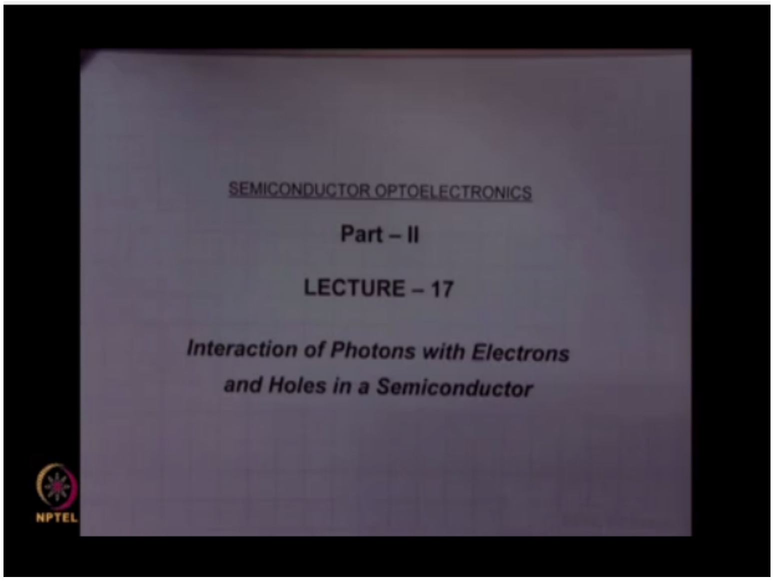

Law of conservation of energy and momentum, so let us discuss the conservation conditions and with the help of the E-k diagram I will illustrate the law of conservation of energy and momentum.

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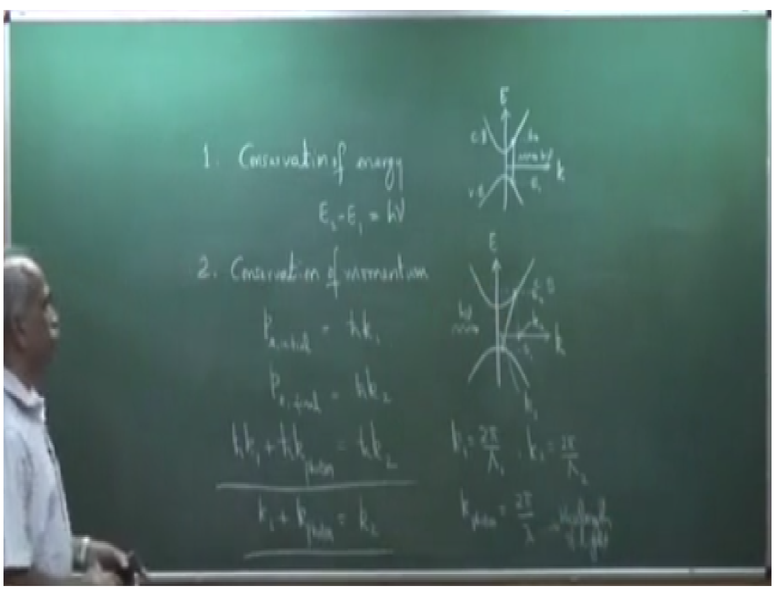

So, the first one is conversation of energy, so conservation of energy again let me use an EK diagram and I consider a direct band gap semi conductor here, a photon **a** an electron which is in the conduction band makes a downward transition could be stimulated or spontaneous emission to a vacant hole here, this gives out energy h mu and h mu must satisfy this is energy value E2, so this is E versus K then this is E1 then we must have E2-E1 is equal to h V.

The same thing is 2 if a photon of energy h mu is incident and you have an upward transition of electron from the valance band to the conduction band. So, this the EK diagram valance band to the conduction band straight forward. Let us see the conservation of momentum, 2 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 and electron sitting at energy value event here making an upward transition to an energy state E2, so this is E2 so this is E axis so E2 and E1, so E1 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 K1 and this electron after the transition has a K value corresponding to this, so this value here this K2 then the electron had a momentum initial momentum which is equal to P of electron initial is equal to H cross K1 and P of electron final that is after transition is equal to h cross K2. So, in this interaction we had 1 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 K2.

Therefore we must have h cross K1 + h cross K of photon, so I will write this as a suffix h cross K of photon is equal to h cross K2 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 K1+K2 K1+K photon is equal to so K1+K photon is equal to K2. What is K1? K1 is 2 pie/lamda 1 where lamda 1 is the debragley wavelength of the electron in the valance band.

K2 is 2 phy/lamda 2 and K photon is K photon is equal to 2 phy/lamda where lamda is the wavelength of light. So, this lamda here is wavelength of length.

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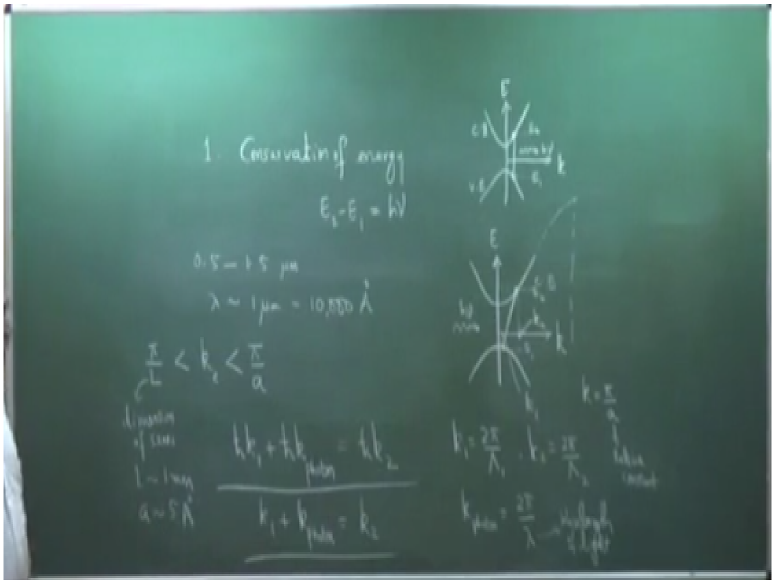

Typically we deal with wavelengths from 0.5 to 1.5 micrometre if it is in communication you have 1.55 micrometer window for optical fibre communication this is in the visible region blue green region and therefore let me assume that lamda is typically 1 micrometer which is equal to 10,000 Armstrong 1 micron 1,000 nanometres or 10,000 Armstrong, what about these lamdas if you see the E-k diagram the band would go and the edge of the first (()) (17:22) zone where a is the lattice constant.

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Therefore typical K here would correspond to so K lies between very small values that is we have discussed pie/L where L is the dimension of the semi conductor, so dimension of semi conductor very small because L is very large compare to a pie/a typical K of electrons. L to a L is of the order of this could of the order of 1 millimetre L is the order of 1 millimetre and a is of the order of 5 Armstrong typically the debragley wavelength of electrons therefore remains somewhere in this range.

So, if you take EK value somewhere here, this may correspond to 10 times a or 5 times a. So, lamda of electrons we had calculated for example the debragely wavelength of electrons in semi conductors corresponding to thermal energy electrons.

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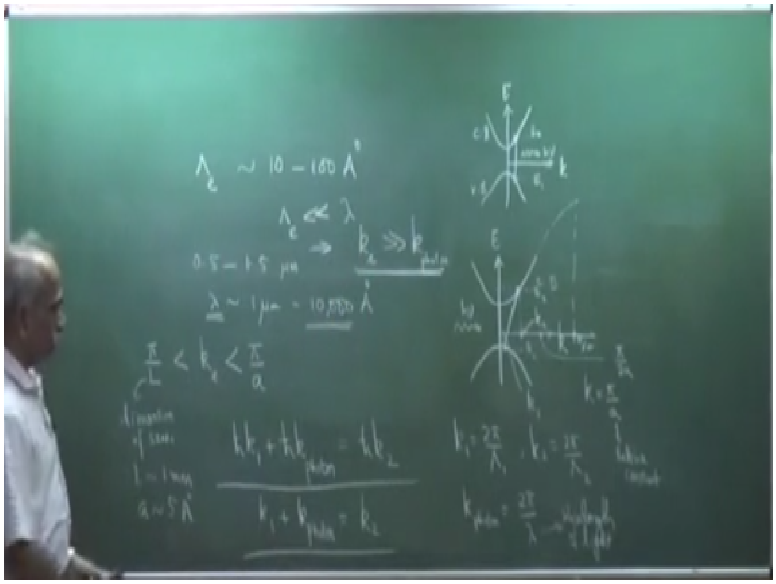

So, lamda for electrons is of the order of typically 10 to 100 times stocking typically lamda of electrons debragley wavelength of electron is in this region we have done an exercise when which I got I think 30 nano meters 300 Armstrong. But if you are in between let us say you are in between here, so it will be pie this is almost 0 this end of the first Belmond zone is pie/a. So, this will be pie/2a, so lamda for an electron which is here will be some this end is pie/a.

So, lamda for electron somewhere in between is pie/2a, 2a is 10 Armstrong because a the lattice constant is approximately 5 Armstrong for an electron which is here the denominator is maybe 10 Armstrong maybe 10 times a 10 times a is 50 Armstrong this is 20 times a about 100 Armstrong. So, the typical numbers for debragley wavelength are 10 to 100 Armstrong. So, even if you wish 1,000 Armstrong for electrons which are close to the bottom.

The point to note is lamda e is much smaller compare to this lamda of photons which is 10,000 Armstrong, so lamda e is much smaller compare to lamda where wavelength of photons. This implies that K of electrons that is K1, K2 is much greater compare to K of photons. K of electrons the numbers just help us to appreciate this point that K of electrons is much greater compare to K of photons.

Therefore if you look at this eequation here then K photon is negligible compare to K1 and K2 and therefore I can write that this implies that K1 is nearly equal to K2 or delta K is nearly equal to 0.

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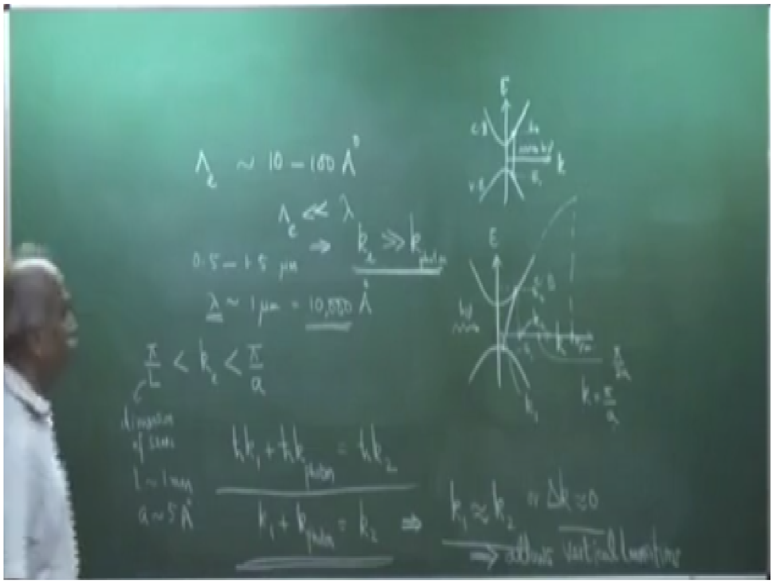

The conservation of momentum the second condition requires that K1 is nearly equal to k2. K1 should be nearly equal to k2 or delta k should be nearly equal to 0 for the transition to take place. K1 equal to k2 means it corresponds to a vertical transition, so the implication of this is this implies that conservation of momentum allows vertical transition**,** vertical in the energy scale vertical in the EK 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 electrons. 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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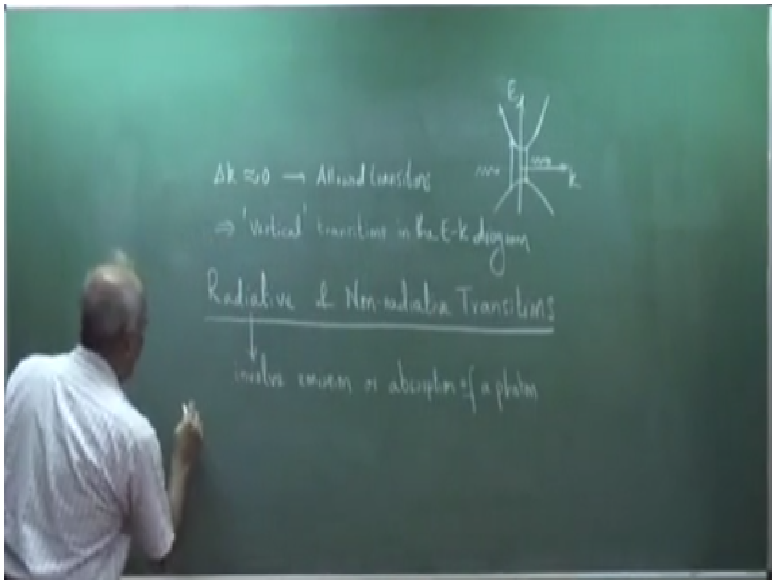

So, delta k nearly equal to 0 or allowed transition this implies vertical transitions, so vertical transitions in the EK diagram. So, I draw the EK diagram here and indicate that the allowed transitions correspond to vertical transitions, so both this state and this state has the same EK value both the 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 transition take place I have been discussing about radiative transitions, so I use the word radiative transitions. So, let us consider radiative and what are radiative transitions radiative and non-radiative transitions. Radiative transitions are transition, radiative transition which involve emission and or emission or absorption of a photon.

Radiative transitions involve emission or absorption of a photon. The phenomenal that I hhad discuss absorption and emission are all radiative transitions which involve emission, absorption or emission of a photon radiative transitions. Non-radiative transition do not involve emission or absorption of a photon, so the law of conservation of energy delta k is equal to 0 conservation of momentum which requires delta k equal to 0 or the allowed transitions for radiative transitions which involve emission or absorption of a photon.

But non-radiative transitions do not involve emission or absorption of a photon. So, can we have, so let me now discuss oblique transition okay let me wipe this discuss oblique transitions, oblique transitions in the EK diagram.

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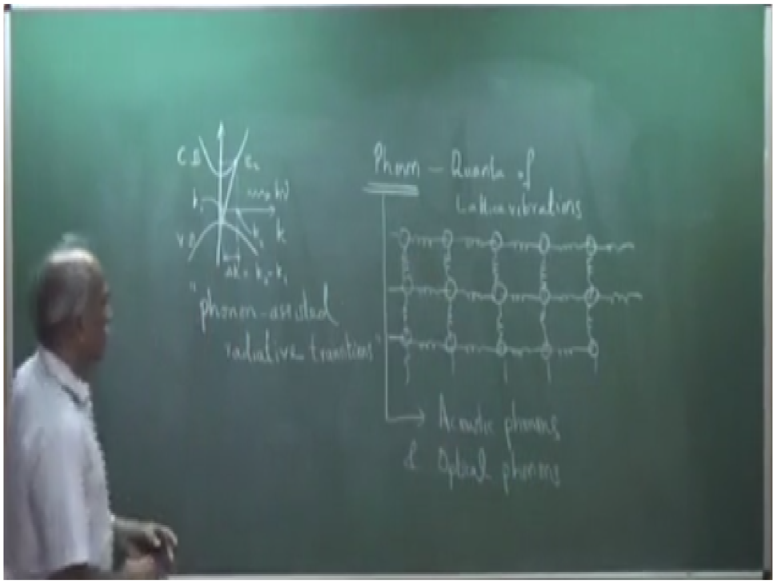

So, in the E-k diagram here k this is the valance band, conduction band and an electron which is sitting here let us say in the excited band makes in oblique transition here and emits a photon is this possible? the answer is yes it is possible it is not an allowed transition, because k k1 is here and k2 the final state is here, so if I call this as the initial because this was, so this corresponds to k2 and this is energy E2 and this comes to k1, so k1 is here see this is k1 value of k1.

So, there is a delta k maybe I will show it here, so there is a difference so this is delta k equal to k2-k1, allowed transitions corresponds to delta k equal to 0 but there is a finite delta k now significant delta k and electron which are sitting here making a downward transition such transitions are possible provided something can compensate for this momentum mismatch this is a mismatch of momentum, mismatch of k vectors.

And these are done by the help of phonons, phonon, phonon assisted radiative transition this is a radiative transition law of conservation of momentum requires the delta k should be 0 and we see that k1-k2 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 and such transitions takes place with the take place with the help of phonons and they are called phonon assisted radiative transition what does this mean?.

Phonon what is a phonon let me now discuss diverse a little bit to discuss about phonons, phonons sorry quanta of lattice vibrations, lattice vibrations 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 springs which a simple picture, so you can imagine I showing spring because the bonds are not rigid.

Basically to indicate that the bonds are not rigid, so the phonons correspond to which means the atoms here can vibrate or fusillade in the lattice. The vibrations have certain an associated energy with them and the quanta of those lattice vibrations are called phonons there are 2 types of phonons let me illustrate this broadly 2 types of phonons which are called acquistic phonons and optical phonons. What are acquistic phonons and optical phonons.

We will come back to the phonon assisted transitions first let us understand little bit about these phonons.

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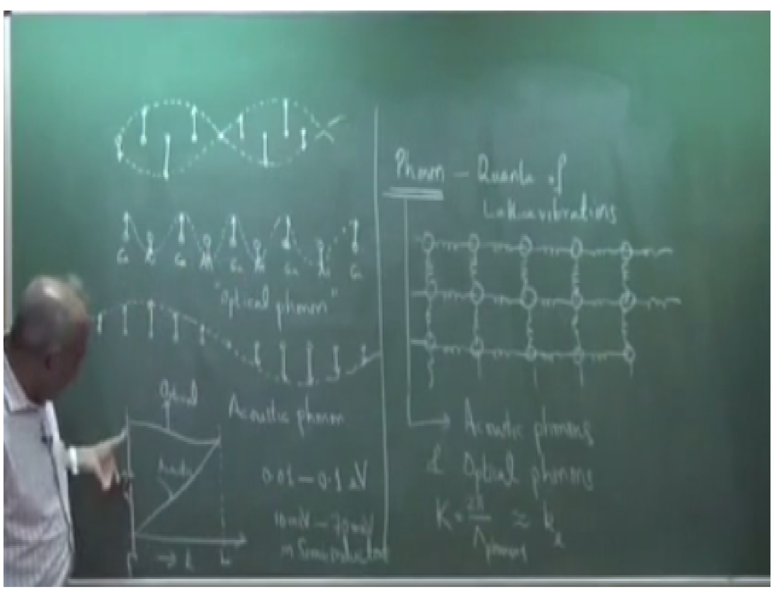

If I take simply a one dimensional lattice which means atoms are raised along 1 line let us say for example this is gallium, this is arsenide, this is gallium arsenic in gallium arsenide gallium arsenic and so on. So, these atoms gallium, arsenic, gallium. Phonon oscillation here the phonons correspond 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, displace like this, displace like this which means the adjacent atoms are displaced in opposite direction if these are displacing 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 a wave here and this is transfers oscillation of atoms and more importantly adjacent atoms displacing in opposite directions.

And this wave corresponds to an optical phonon in contrast in the case of acquistic phonons there are various patterns possible but the displacement adjacent atoms are in opposite direction I can also show you another pattern at another pattern. So, 1 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 remaining 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 direction but the magnitude of displacement is different varying.

Here the magnitude of displacement is the same for all that, this is also an optical phonon this is also an optical phonon. Let me acquistic phonons now, so how would an acquistic phonon look like let me draw in 1 dimension because it is very use to illustrate and imagine what is this phonon. In acquistic phonons atoms adjacent atoms are 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 and then the next group gets displaced in the different direction.

So, the displacement continues which corresponds motion of a wave like this. So, these are mechanical waves which correspond to vibrations of atoms displacement of atoms. So, this is an illustrations of acquistic phonon what you would immediately see is the frequency of the wavelengths are small here the frequency of optical phonons are in general much higher to the frequency this is wavelength.

So, wavelength is large the and you can 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 and hence frequency but the frequency of acquistic phonon in general vary from very small values to very large values.

So, if you see a dispersion plot which you can dispersion, dispersion means k versus omega, frequency versus omega then for acquistic branch for the optical branch generally the frequency varies like this and for the acquistic branch the dispersion curve generally varies and they almost meet this is k equal to 0 in the Bellmore zone picture this corresponds the gamma point and this corresponds to L point or X point L or X.

So, this is the acquits optic this is the acquistic phonons acquistic 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 acquistic branch more details you can see you can go through about phonons and typical phonon energy in semi conductors vary in the range 0.1 electron, 0.1 is also on the higher side generally about 10 millielectron volt to 60 or 70 millielectron volts.

So, generally in that range, so 10 MeV to 70 MeV in semi conductors, the energy of phonons what is this distance is a lattice constant a therefore the wavelength here is 2a, so what you see is the wavelength lamda of phonons can be as smallest to a which means the momentum k is equal to 2pie/lamda of lamda here of phonons lamda of phonons can be as high as this much which means it is of the same order as k of electrons.

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

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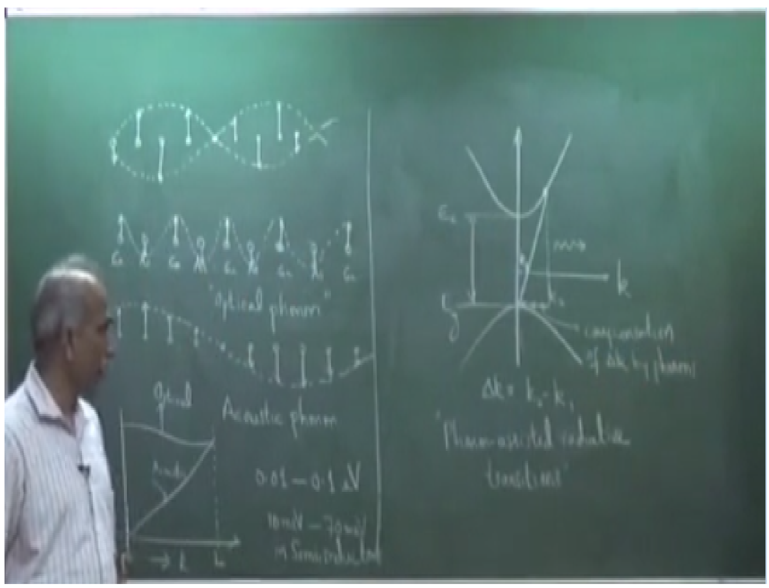

So, let me come back to the phonon assisted transition that I was discussing, so let me draw the figure again here okay let me draw a fresh an electron which was in the conduction band makes a transition to a hole here in the valance band, so this has a value of k here or here let me show this corresponds to k1, and this here corresponds to k2 and delta k is the momentum mismatch and again redrawing it so k2-k1.

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 numbers k1, k2 similar numbers. So, this difference can be made up by phonons however in general for inter band transitions if you take a semi conductor this band gaps this is be see that the remember that this is Ec and this is Eg this band gap Eg 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 conversation has to be satisfied can be by 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 radiative transition.

The probability of occurrence of phonon assisted radiative transitions is much lower compare 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 and the probability of occurrence of such events where the momentum mismatched has to be exactly matched with the certain number of phonons is much lower.

The probability of occurrence of that event is much lower compare to vertical radiations due to vertical transitions which are allowed transitions this is not an allowed transition by momentum condition however the momentum mismatch delta k if it is matched by phonons 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 it is illustrated in this fashion, so from here you show the k by small momentum vectors and this is made up of phonons. So, this small arrows here show momentum of phonons momentum vector of phonons. So, that mismatch is due to phonons, so momentum compensation of delta k by phonons, is this alright. 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 I am show you.

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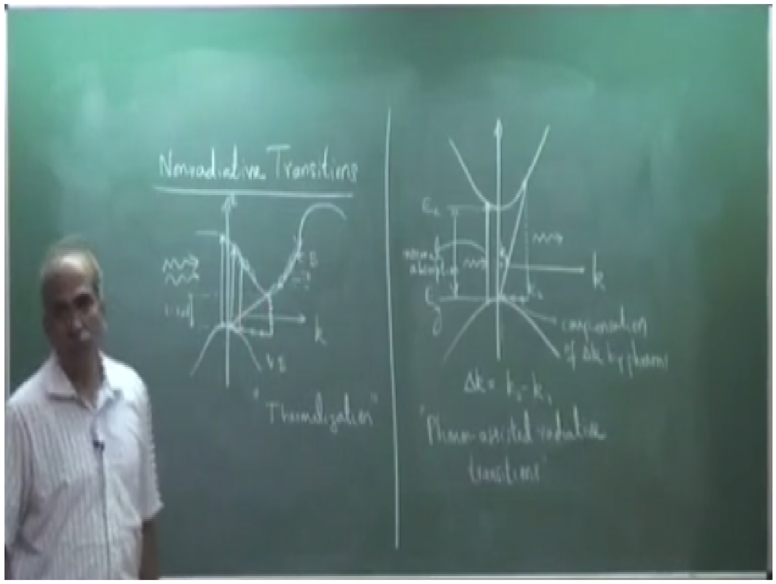

So this is in direct band gap semi conductors, vertical transitions which go from here to here or reverse or allowed transitions this is not an allowed transition unless the mismatch is made up by phonons and this corresponds to a phonon assisted transition this is a normal radiative transition this is a so if you have this, this transition is a normal radiative 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 non-radiative transition we will discuss more at a later stage non-radiative transition as the name indicates this transition do not have emission or absorption of photons. So, if you take a semi conductor like silicon I am showing the EK diagram here of silicon k was the in is the indirect band gap semi conductor the band gap here is approximately 1.1 ev, 1.1 ev 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 thermalisation and tend to accumulate near the bottom, so wherever it is generated it tends to come down by the process of thermalisation, thermalisation 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 energies. So, phonons can easily account for this transition and rapidly if you somehow pour an electron here that is you put an electron high energy electron here then the electron will lose it is energy through phonon transitions and come down to the bottom this is called thermalisation.

So, thermalisation why the thermal because phonons give heat that is energy given to the lattice in the form of heat hence the name thermalisation but basically these are phonon transitions which come down to the bottom. Now an electron which is accumulated here finds that the vacant state here and it makes a transition can it make a transition yes it could with help of phonons.

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 takes place this takes place through phonons there are large number of phonons, so you indicate by small arrows like this, so large number of phonons which are making up for the energy difference although 1 phonon has much smaller energy there are large number of phonons can be emitted.

And they also makeup 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 you see the value here k1, momentum here is k2 there is large momentum mismatch but this momentum mismatch and energy difference energy conservation and momentum conservation both are made up by phonons.

But now it does not involve any photon therefore the probability of the event is not low, probability of this event is low, because electron, hole, phonon and photon whereas here electron, hole and phonons. Therefore this occurrence probability of this occurrence is not low and non-radiative transitions takes place in the case of indirect band gap semi conductor.

So, most of the recombination are due to non-radiative recombination and this immediately tells us that we would like to direct band gap semi conductors if you want to have 4 photon emission and 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 find as absorbers or detectors why if you send photons from here then an electron which is sitting here can make an vertical transition here and electron which is here can make vertical transition here.

An electron can make vertical transitions here because states are available here, so it absorbs photons and makes vertical transitions afterwards it comes down here and accumulates. So, indirect band gap semi conductors are suitable for making detectors as suitable as direct band gap semi conductor, indirect band gap 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, is this clear we will see later on we will see the absorption curves 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 see this at a latest stage, is this okay.

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