Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VIII
Module-V
Semiconductor laser diodes

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Hello and welcome to the moke on optical communications. In this module we will discuss fundamentals of semiconductor laser diode. For a proper understanding of this topic namely the semiconductor laser diode you need to actually have a extensive background in PN junction and its associated physics. So semiconductor physics, unfortunately that is not in the scope of this course, so we will be content with qualitative pictures of how a semiconductor laser operates.

And then we will discuss the types of semiconductor laser diodes and I will leave LEDs as something for a reading assignment okay.

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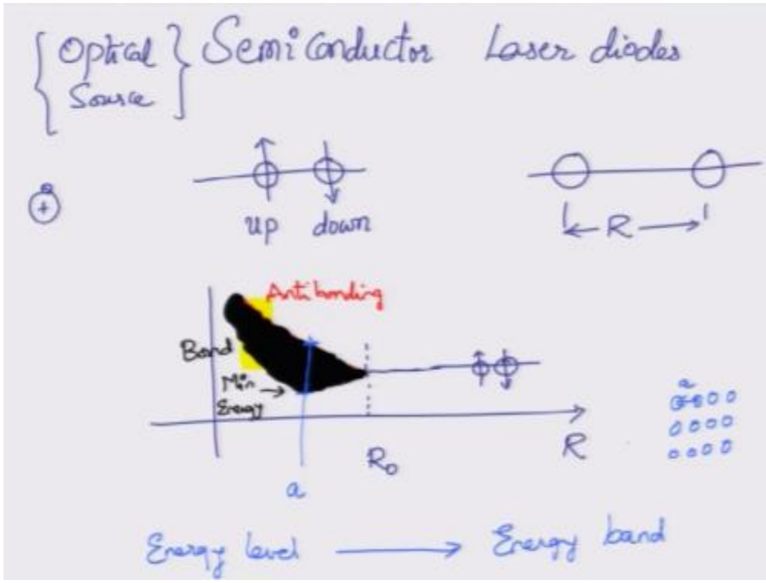

To being with let us consider an atom, you know such as a hydrogen atom which has a positive nucleus and one electron around its orbital right. Now this is the simple picture that we normally think of an atom having a positive nucleus and then an electron that is revolving around. However, the electron cannot reside at arbitrary distance, those distances are essentially quantized.

If you look at the quantum mechanical picture you do have a nucleus that is fine, but there is no fixed orbit or anything, what you instead have is a quantum mechanical state in which there is a certain probability for finding the electron in that okay. And whenever a quantum mechanical objects such as an electron resides in a particular quantum state or has a certain quantum state then there is certain energy associated with it.

In the classical picture this energy could be anything, it can be a continuous number. However, when you are considering the quantum mechanical properties you will soon see that this energy is quantized in fact the word quantum or quantized simply means that you have to have a certain minimum or a certain unit of energy and multiples of that unit is what is allowed for the electrons to be processed.

So in a sense that if you consider a free atom right, there are it is not subjected to any other force except for the force because of the nucleus and the electron attraction, then the energies that this particular electron can have will be some value, but that value will be quantized. And all this can be inferred if you were to solve the Schrodinger equation for this particular system. In fact there is a nice relationship between energy and momentum for a free particle which we will see shortly.

If you look at the energy or the quantum state the energy actually is degenerate in the sense that in one quantum state you can actually fit in two different for other one energy level you can fit in two different electrons. One electron with an arrow upwards is called as a spin up electron and the other electron having the same energy, but its pin is downwards. Spin is a quantum mechanical property it does not have any analogous quantity in the classical mechanics okay.

So spin is completely quantum mechanical you can simply think of this as a label which the electron carries. If the electron label is up, then we pictorially represent it as having a upward vector in case it is a down we will show that pictorially by drawing a vector or an arrow downwards okay. However, important point to note is that for an isolated atom both spin up electron and spin down electron have the same energy.

So any time two different quantities have the same energy we call that degenerate. You might have encountered this degenerate or degeneracy when you look at optical wave guides or microwave wave guides right. It is sometimes possible to have two different modes having the same energy. Then we say that these modes are degenerate, if you go to the optical fiber example, then the X polarize mode and the Y polarize mode have the same energy.

So these are two degenerate modes, they have the same propagation constant atleast in an ideal fiber that we can think of. So for an ideal case they are degenerate, for a non-ideal case they are not, but we are simply looking at the ideal case. So an isolated atom free of any external forces will have a degenerate electric level and you can fit at most two electrons in that energy level, because Pauli's exclusion principle states that you cannot fit in one more in this particular configuration.

So in the electronic configuration finally spin up and spin down can be put in the same energy level okay. But that is the case of a single hydrogen atom entirely in the universe. Unfortunately universe is not like that and especially the semiconductor materials are not going to be looking like a free hydrogen atom right rather what happens is if you bring one atom.

Close to another atom right the separation between these two atoms is called inter atomics spacing and it is denoted various letters so let us choose R as letter to denote inter atomics spacing now if you look at the total energy of the system as a function of this inter atomics spacing you see that for large inter atomic spacing the energy levels are essentially discrete so you have a spine up and a spine down they occupy the same energy levels and this R is very large which simply means that you take these two atoms and then put them as far as possible right.

So the energy of or this particular atom is not talking to this atom and therefore there essentially free and the energy levels there are degenerate okay if there of the same kind then they have the same energy and in each case you can fit in an spine up spine down spine up spine down okay however as the inter atomic distance starts to decrease what happens is that after a certain critical R_0 you will see that the energy levels actually split so you see that one energy level is called as the anti bonding energy level.

And the other energy level is called as the bonding level okay so you will actually see that it is kind splitting but the bonding level initially decreases and then starts to increases so there is a minimum energy configuration over here where in most of your electrons or most of the materials can actually like okay so this is your minimum energy which appears for the bonding levels okay so this is the bond energy level this is a anti bonding energy level this is for two atoms which are close to each other.

Now imagine a solid such as semi conductor silicon germanium in gas aluminum gallium aluminum arsenide so these are all the semi conductor materials and these semi conductor materials are actually solids even among solids they are crystals which means that there is the atoms are going to be placed very closely with respect to each other and what is more they are actually in a defend pattern more or less they actually have nice pattern to them if the crystal where free of defects or impurities then this pattern would go on forever in the 2 dimension or the 3 dimensional depending on what structure you are looking at but this pattern there is a basic lattice and this lattice keeps on repeating itself in all these directions right.

So the key word here is that there are many atoms right you must have head of the Avogadro's number 10^{23} so in a / cm or /mole there is so many number of atoms okay so you can imagine as so many number of atoms are placed together there is going to be interaction among them which what it causes is that when the atomic spacing decreases as you pack in closely and closely these energy levels they will split into 10^{23} values right each energy level wills split into 10^{23} value from the prospective of mathematics this is still discrete because we can still count 1, 2 all the way up to 10^{23}

However for all practical purposes the spacing between this 10^{23} energy levels become o small right this is the total energy that is available this you split into 10^{23} the spacing is going to be so small that for all practical purposes you can simply consider them to be a continuous quantity okay so you end up replacing this discrete energy picture by a band of energy okay so let me try and see if I can do band no I cannot do a band here so you can see that I can I am filling up the entire region over here indicating that this is actually a band okay.

So it bounded between this bonding and anti bonding levels but this as essentially become a band of energies this happens only for the case where you are looking at no solids because your atoms are going to be placed so closely and of course they also have certain pattern this is the inter atomic spacing or the atomic spacing between the atoms and denoted by A so let us say if you are looking at A here then you actually have one energy level down here another energy level down here but there is actually a band of energies in between correct.

So you actually have a band of energies in between so this give rise to concept of energy level going and becoming energy band and you must have heard definitely of two bands one is called as the valence band.

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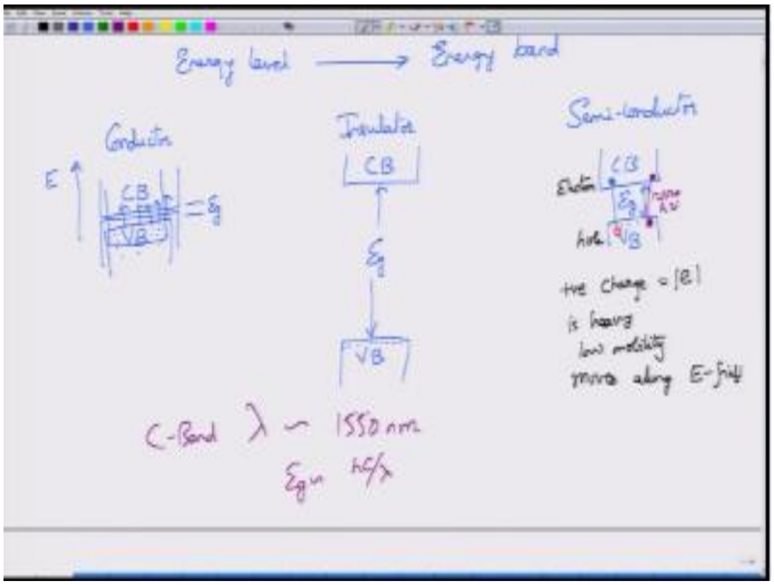

And other is called as the conduction band and based on this band picture we can differentiate three different salts one is a conductor the other is a insulator okay and semi conductor or a semi insulator is something that exists in-between these two quantities, right. So the characteristic of a conductor is that you actually have a conduction band and a valence band which are very close to each other, what do we mean by conduction band and a valence band?

Valence band is the largest occupied energy that you can have energy is going up in this particular wave for the electrons so valence band is the largest band that is occupied by the electrons, okay. And the if you apply an external electric field in the form of a voltage then these electrons will simply skip to the conduction band without any problem in fact in some very good conductors the conduction band actually and a valence band both go inside.

In the sense that they do not really require lot of energy simple temperature increases sufficient to bring about a large number of electrons from the valence band into the conduction band, okay. The gap between valence to conduction band is called as the energy gap, in short while we will discuss where these concepts are coming from, on the other hand on the other extreme is an insulator.

In an insulator the energy gap is pretty large between the conduction and the valence bands, okay. So the electrons here they if you have to promote them into the conduction band require a rather energy to be supplied this can be done by supplying very intense light field, so that the photons are absorbed and then you know it can go to the conduction band right or you have to apply very high temperature so that this insulator breaks down and becomes conducting.

In fact there is a certain electric field that you have to apply in order to break down this particular insulator, okay. So once that happens then of course everything becomes high and high and then you get a nice conductor in place of an insulator but that happens under very extreme conditions, a wood for example under ordinary temperatures would be an insulator right, somewhere in-between is where what you have as a semi-conductor, okay.

So if you have the energy gap as E_g for a semi-conductor it is possible to so normally the electrons are found in the valence band so if you do not apply a volatile they are usually insulators, however when you apply a voltage they will jump from valence band to the conduction band as the electron jump it kind of leave behind an empty space the actual phenomenon is very deeply mathematical to tell you and deeply physical to tell you that.

But this simple picture should be enough for us, okay. In this simple picture whenever an electron leaves the valence band it leaves behind a hole, okay. This promotion from valence band to the conduction band can happen by an external electric field it is not necessary that you have to always apply a photon in order to induce this transition, okay. So this transition can happen by an external current being forced or something like that, okay.

So this is called as a hole and whatever of course is actually here is an electron, okay. So the left one jumps from valence to the conduction band it leads behind a hole the characteristic of hole is that it carries positive charge which is exactly equal to the magnitude of the electron charge so it is exactly equal to the magnitude of the electron charge, okay. It is slightly heavy compared to the electron.

It has a low mobility compared to the electron okay it has a low mobility which means it kind of move slowly compared to the electrons and remember this was the one which was actually limiting our response time in a photo detector because in a photo detector hole response times was considerably longer than the electron response time, right. So this is for all practical purposes behaves as a positively charged quantity.

It is heavy it has low mobility and it when you apply an electric field it moves along the electric field, okay. So that is another characteristic of this while electrons always move opposite to the electric fields so if you apply the electric field along the x-direction this will move in the opposite direction, okay. So these are the semi-conductors this transition where in a electron jump from valence band to conduction band.

Can be reversed under certain conditions where the electron can jump back to you know meet with the hole resulting in a generation of a photon of a certain frequency ν which is dependent on the energy band gap, right. The photon energy that is released if the atoms fall exactly when they recombine the electrons recombine with the holes will be exactly equal to the energy gap. Okay from which you can also calculated what would be the wavelength and everything all this characteristic and see whether these type of material are suitable for optical communication.

Remember, optical communication happens at around 1550nm, right the see band is around 1550 nm therefore, you require semiconductors whose energy gap is around hc/λ, okay. So if you find a semiconductor with this particular thing then you will be seeing when they recombine electrons and wholes recombine you will see a photon coming out, this process is called as electron whole recombination. Let us dig a little more detailed deeper in to this concept of band, right.

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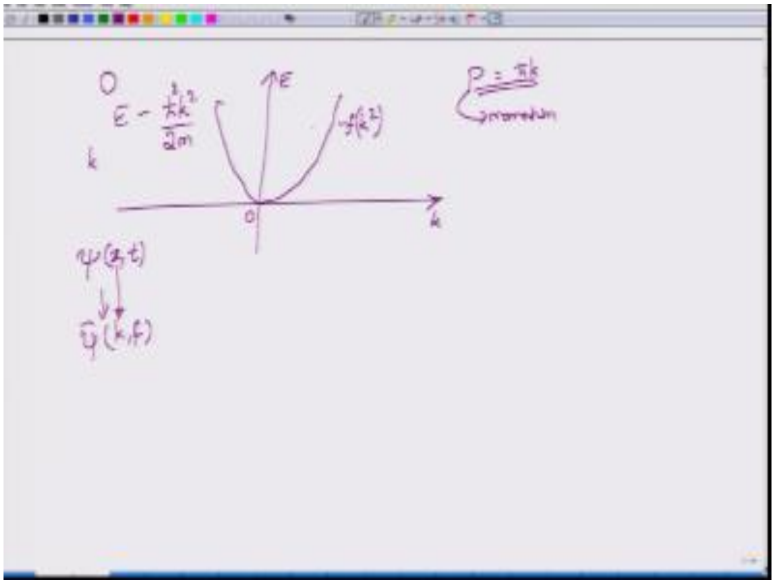

We have already said that free electrons you know that is free atoms which are subjected to know external field will have an energy E which actually can be shown to be given by $\hbar k^2$, sorry $\hbar^2 k^2$ or $\hbar k^2$ there is actually a k^2 dependence yeah, I think this is $\hbar^2 k^2$ for the energy that is there here, if you actually plot this energy as a function k, where k is the wave number so quantum mechanically you picture the electron actually being described by a certain wave function this wave function.

In the time domain can be described by giving its you know in one dimensional wave function can be described by giving x and t assuming that the wave is along the x direction or equivalently you can describe in the momentum picture or in the, so call Fourier space by giving k and frequency f, okay so this is the k that I am actually talking about and in fact turns out that momentum P is related to the k vector or the k number by this relationship.

P is the momentum and energy is basically $P^2/2m$, right therefore this actually energy becomes $\hbar^2 k^2/2m$, so if you sketch this energy verses k what you see is a nice parabolic way in which the energy increases, okay maybe the figures are not very nicely drawn but this is a k^2 dependence, okay this is the function of k^2, this is your energy E it is that okay. So now with energy E depending as a parabolic function or changing as a parabola, right it can have any value of energy you want.

So a given isolated electron can take on any energy level that it wants and corresponding to every energy that it takes there is a corresponding momentum k as well, that is what this particular graph means.

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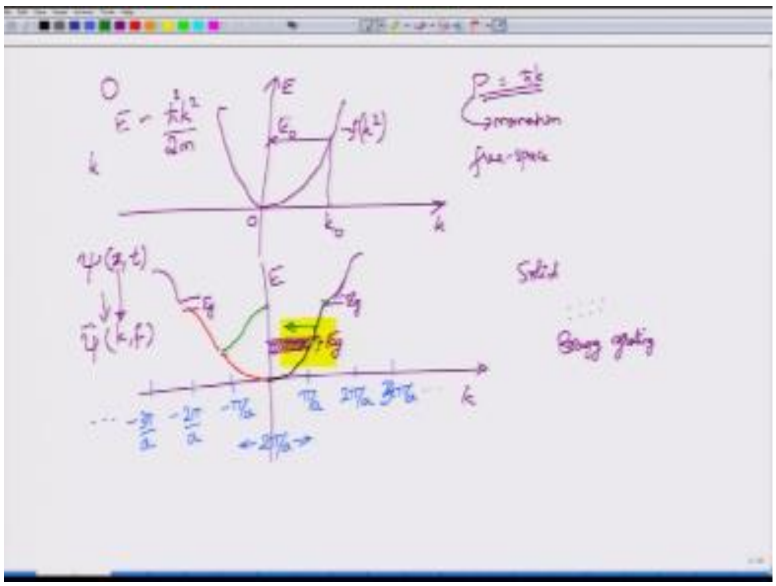

For example, you want this electron E I mean energy E the corresponding momentum so this is say E0 then the corresponding momentum will be k0. Now this picture unfortunately breaks down when you go to a solid, so that was for the free space condition or when there is only one atom in the whole universe, here on a solid unfortunately you have so many atoms which are close by and these atoms in tern talk to each other, okay in fact there is a phenomenon which is very similar to the phenomenon that we talked about a Bragg grating kind of a phenomenon, right remember the fiber Bragg gratings that we talked about there is essentially a reflection of the waves which add in phase crating energy gaps, right.

And a same situation happens over here, so what you get is this momentum gets quantized in terms of this π/a units so this is k the fundamental will be at –π/a to +π/a giving you a total maximum change of 2π/a over this particular range, okay then you have 2π/a you have 4π/a or rather 3π/a and so on, here you have -2π/a -3π/a and so on. So these are the different momentum ranges, okay sorry it is not momentum which get quantized it is energy which gets quantized.

Actually what happens to the energy then, is here it is still parabolic, okay which is fine so that here is still parabolic at the edge this is called as a band edge or the, you know at the edge of the value here at π/a because of the Bragg type of reflection this energy kind of goes or bends slightly, okay then what happens the next energy levels there is actually a gap over here and then the next energy level goes from π/a to 2π/a, okay similarly here it will go from π/a to 2π/a.

So let me try and make this symmetric because the r actually symmetric so here you actually get symmetric condition here at this point you actually get a small bending and this is show you are going to get okay this is because have kind of drawing the graph not vet nicely but this is what happen sp there is a small amount of bending her and this is the kind of type of bending you are going to get.

Look at this in the region right in this region you see that there is a gape correct if you try and find out what would be the corresponding if you want that this particular energy to be there then you see that for this momentum you know the corresponding energy cannot exist in other words electron are for be done to actually have this energy okay this is called as the energy gape there is a next level at which this will change from π/2 to 3π/a.

And then again it will change here there will be the slight bending again but what you see here is a gape right again there will be another g gape this gape may reduce in magnitude compare to the earlier gape and so on so the energy gape also start reducing as you go around as it is right. Now this is the energy momentum diagram oaky or sometimes called as a energy band diagram but then this energy band diagram shows that k can take an infinitive number of values.

But there is an certain periodicity to the crystal the crystal is actually periodic with the period a therefore the fundamental period of the crystal in terms of the frequency unit is 2π /a right if t is if T is the period of the wave form in the fundamental frequency will be 2π/T and the fundamental range is –π/T to +π/T so going with same concept there the fundamental periods will be 2π/a which you can spread it out in to –π/a to +π/a.

So all the other energy band diagrams outside this in travel can be pulled back by translating them by a factor of integral multiple of 2π/a so if you translate this one okay if you translate this by a factor of 2π/a then what happens is this one goes to this is already π/a so you translate this one by -2π/a so this fellow goes to her and this edge the top edge goes to 0.

So this band goes and become something like this band here will be translated by a factor of π/m in when you add a 2π/a brings to the primary region this fellow will go here and this bend edge will go to 0. So you actually get a band that look like this so writing it is separately out this is how the energy and k diagrams would look like.

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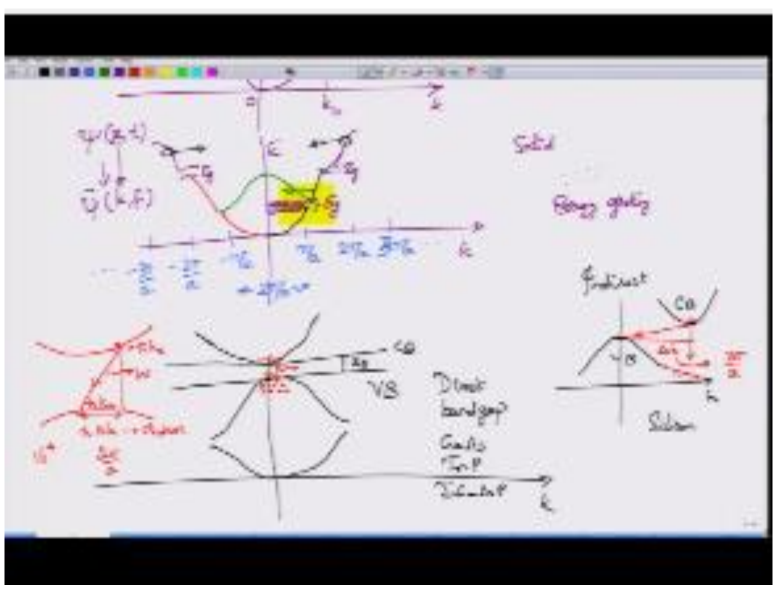

So this is your k this is the fundamental which is almost parabolic and this slightly bending at the edge and then you have the next level which chose like this right and then the next level is again parabolic you can show why that is parabolic by going to the upper picture and then translating these fellows back in to 2π/a range or the in to the fundamental range okay. This again has to be symmetric with the 0 sitting at the origin so let me just draw it here.

So the 09 is sitting here okay so this is your parabolic thing okay suppose in a particular you know semiconductor this happens to be the wave length band edge okay then this happens to be the conduction band edge and the difference between these two is the energy gape that we are looking for, if you look at this energy band gape diagram you see that the top of the way length band s is directly below the bottom of the conduction band.

Okay semiconductor materials which actually have this particular chrematistic or called as direct band gape materials and example of a direct band gape material is gallium arsenide okay or indium phosphide in gas P, right so in gas P is also a material that has direct band gap in contrast there are certain materials for which the wave lengths band edge and the conduction band edge are not at all coinciding with each other. So the top here is way of from the bottom of the conduction band over here, okay.

Then this is a very important situation because this corresponds to silicon for example, and as you know silicon is the base material that is used for all VLSI, ULSI circuits and the silicon technology is very well developed, unfortunately that cannot be directly be used for optical integrated circuit no realization, because silicon is not a direct band gap material, this is called as a indirect band gap material, because the conduction bands it's here and the avalanche band it's here.

Why is this very important? It is important because it is possible for the electrons so here is all the electrons sitting up there, and here is all the holes which are sitting, okay it is possible for these electrons to make a transition from energy you know from the conduction band to the avalanche band, there by generating the photon.

If you dint have a exactly the top level transition, may be the electron sitting here might want to transit down here, if I blow this up and then show it to you it looks like this, so the electron that is sitting here is making a transition to the hole here in the process element, I mean in generating a photon H µ, okay please remember this is highly exaggerated picture, this is not the same scale as this one.

I am just showing it because I can't draw an arrow and make it show it to you in a clear way, so when this happens the photon actually the energy corresponds to a certain momentum ħKe, and this call it as ħKh, okay Kh stands for the hole, Ke stands for the electron, so when the initial state of the momentum is ħ Ke, and the final state of the momentum is ħ Kh, there is a difference between these two momentum right, and this momentum which is ħ Δ k, has to go into the photon.

And what is the maximum such different that can happen, the maximum such momentum change can happen when Δ k changes by 2π/a, right? That is the maximum transfer or the longitudinal or the change in the momentum that can be possible, come back to this indirect band gap material, the electrons which are sitting up here cannot directly fall down here, right? That is because these are all the variance band adjusts there all completely occupied.

These are all occupied over here, there is no way you can transit and then find a final state on the other hand, if it has to make a transition then it has to make a transition this way, you look at the amount of Δ k that is required this Δ k is almost going to its maximum value of 2π/a, whereas here the corresponding Δ k, you know is actually very, very small. This is about 10^{-4} because you can show that the relative Δ k that is necessary will be,

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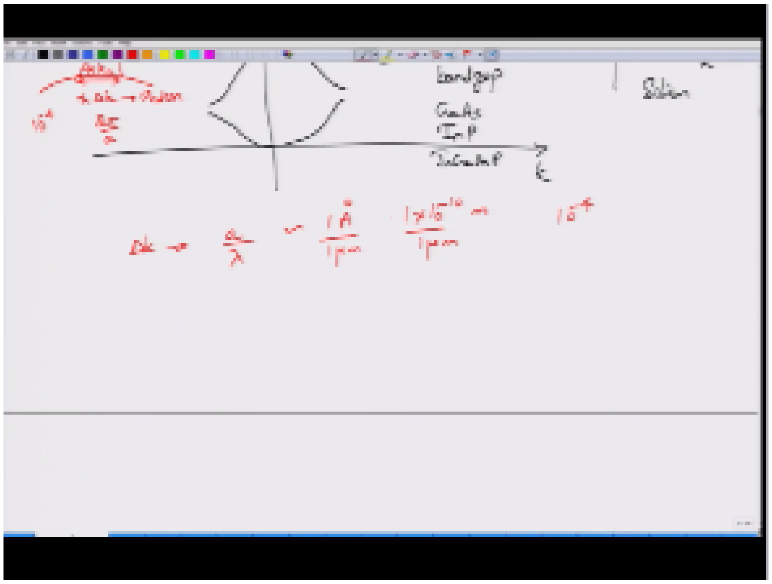

Somehow! I mean will be given by A/λ, where A is the inter atomic spacing, which may be for many cases is one angstrom is 1×10^{-10} meter, and if are looking for emission of 1mm, light so this is that Δ k that change that you want, right the normalized Δ k that change that you want which is around 10^{-4}, on the other hand for a indirect band gap material this change is very large, because Δ k that you have to get should be 2πa times something.

And that would be pretty large, because it is you are in the one bandies to the other bandies to the other bandies transition, so result being most of these transmission is ends up heat rather than actually giving rise to a radioactive transition, so we will stop here and in the next module we will talk about the semi conductor laser diode, okay formed By a PN junction thank you very much.

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