Ok welcome to into the session of Introduction to Photonics so far we had been talking about light source we started talking about spontaneous emission in stimulated emission of light leading to optical amplifiers and lasers and so far most of the examples that we have taken is for dilute gas of atoms.

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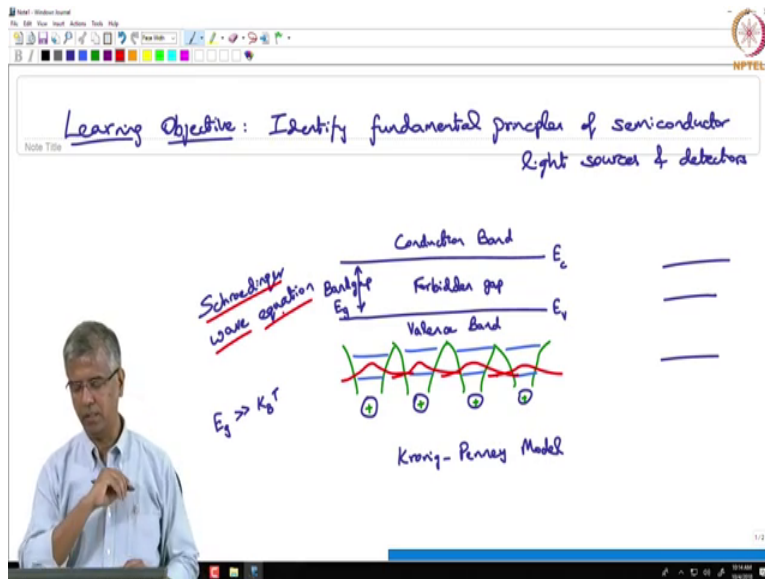
So typically you talk about an atom you say ok you have an isolated atom which may have different orbitals you know and so you have a valence electrons one of the outermost orbitals and from there it can get excited to higher energy levels and we were talking about from the valence orbital to some other energy levels transition between other energy levels.

Now what we will start looking at is you know semiconductor material and when we talk about semiconductor material the model changes a little bit, you starting to talk about electronic charges moving in the semiconductor material which are potentially leaving behind holes that is absence of charges in certain regions and now we going to start talking about recombination of this charges electrons in with holes which may actually give rise to light emission ok and

ofcourse it can also do light detection in which process you have light coming in incident on this material which produces electron hole pairs ok.

So we will look at some of those principles. Now that primary difference is here we are considering system of atoms let us say there are all periodically arranged ok now each of this atoms actually constitutes what is called potential well ok so you would have a potential well associated with each of this atoms. So why do we have this potential well? Essentially what we are saying is this atom at the center of that is going to have this positive charges and then you have this orbitals or this electrons which are quantized in nature so they occupy different levels and it is going to take a lot of work to you know so there is some (attracting) attractive course between the positively charged nucleus and this electrons that are orbiting and that constitutes a certain potential right.

So we are going to have this you know potential wells and the important property of this potential wells is when we talk about existing of an electron right electron is going to have different orbitals so you can basically say it is going to occupy different orbitals that can be represented like this and then ofcourse you can have higher orbitals also but the unique thing is when we talk about the wave function related to another electron so what do I mean by the wave function? I am talking about the probability of existence of an electron ok that would potentially be very high within the potential well so (it will) because it is going to be bound to an atom right but it can also have a finite potential of existing in a nearby in a potential well elsewhere ok.

So what we are saying is when this atoms are closed to each other and they are periodically arranged your valence electron which is typically bound to an atom you would say is ok if it is isolated it is you can say for certainty it is going to be bound to tat atom itself right but when you have a collection of atoms like this there is a finite probability that it may exists in a neighboring potential well as well. So what we are now saying is all this wave functions are going to have this tails that are existing that are extending to this nearby potential wells as well.

So in other words all this potential wells all this atoms are coupled with respect to each other ok so now we are starting to talk about electrons and transport of electrons which is governed by what is call the Schrodinger wave equation right that basically talks about the energy of an electron and then the movement of electron between this material and that is essentially saying

that ok when all this potential wells are coupled with respect to each other ok then you have a slightly different transport mechanism and to give you an idea of this what we can say is when we talk about valence orbitals those can exists upto let us say this level.

So let us say this is Ev ok and then what we will see is it is either bound to this potential wells or bound to his atoms or it is free to move around the lattice if you give it some energy an external energy it can actually unbind itself from the pattern and then it is move free to move around that lattice and that is defined by this energy that you call as Ec that is the conduction band energy and then it can in this region there is it is called the conduction band. So beyond that energy it is free to move around the lattice ok. So there are two distinct states that this electrons can have one is either they are bound to one of this potential wells or collection of this potential wells right which is called the valence band ok and then with a certain level of energy it can unbind itself and then it is move free to move around the lattice and that is what you call as the conduction band ok, is that clear?

So what it also tells is that when you work out the Schrodinger wave equation for this sort of a model this model is actually what is called the Kronig-Penny model so it is clearly named after couple of scientist by name Kronig and Penny who came up with this brilliant idea of modeling this collection of atoms and modeling how the electron transport happens in this collection of atoms so with this model you solved Schrodinger wave equation what you find is there is actually forbidden gap so the electrons cannot exists within this energy level it can either be bound to one of the potential wells in which case you know it is in the valence band or it is completely unbound and it is free to move around the lattice which is the conduction band and then there is a certain energy gap between the two (which is) where the existence of electron is not possible in that material, you understand that?

It is digital, it is either bound or unbound and then in between there is a gap ok and this is actually called the band gap of the semiconductor and that is actually a very unique characteristic of the semiconductor ok. So essentially got this forbidden gap ok and so you ask the question why is it called a semiconductor? Essentially this band gap energy which you can denote as Eg, E g is a semiconductor is typically much larger than KBT, What is KBT? Thermal energy for a given temperature what is the energy that we have. So if E g is greater much greater than KBT what an you say, about an electron existing in a conduction band, you do not expect (sorry) you

do not expect to see any electron in the conduction band because your you know your thermal energy is not enough to take an electron from the valence band to the conduction band ok.

So it essentially acts like an insulator at 0 degree kelvin but as you elevate the temperature you have a finite possibility finite probability of an electron existing in the conduction band in which case it starts conducting right and then it becomes what is called a semiconductor under certain conditions it acts like an insulator certain other conditions it acts like a conductor ok so it is in between a conductor and an insulator. So clearly you can characterize it as an insulator as long as T equal to 0 or may be even for small values of T, maybe even room temperature but as you elevate the temperature it becomes a conductor ok and ofcourse a conductor is one in this model where you can characterize it as conduction band and the valence band are overlapping.

So even at room temperature there is a finite you know density of electrons in the conduction band so they are there is a free electrons they are free to move around so you take one of this wires you have lot of free electrons so it does not take much potential to move them around right you can conduct current whereas the other extreme is the insulator where the band gap energy is so large that you know even when we try to apply a potential between them it does not conduct, a dielectric is a good example right equations about this?

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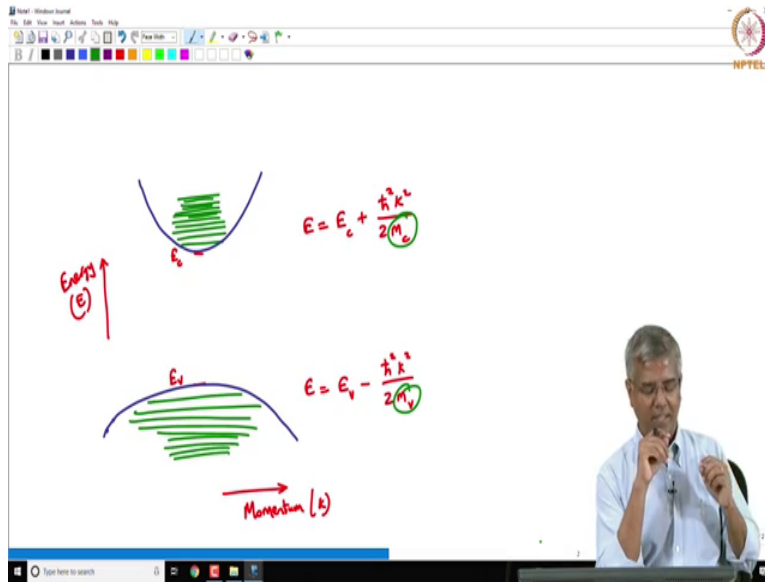
Ok so when you solve this Schrodinger wave equation without going into whole lot of detail, what you also see is something like this sorry I already do this in I am just going to because I am going keep repeating this right.

So you have what is called this is energy and this is momentum represented as K, represented as E right so you have when you solve Schrodinger wave equation you get an expression for the energy of an electron ok which is actually a function of the momentum ok specifically what we will see is if we say this corresponds to Ec and this corresponds to Ev the top most energy level in the valence band we are defining as E va and that bottommost energy level in the conduction band we are defining as Ec then we will see that the energy of an electron in the conduction band has to satisfy this expression I am just giving you a solution of the Schrodinger wave equation I am not solving it here because the interest of time.

But solution would work out to be something like this right and over here the solution is E v minus h square corresponds to the h corresponds to the (())(16:02) constant and h cross corresponds to H over 2 Pie right K is the momentum and then this specific quantity which we are calling as Mc and Mv ok that corresponds to the mass of an electron in the conduction band the effective mass of an electron in the conduction band effective mass of electron in the valence band and what we will see is the curvature so essentially what this equations represent is a equation of what? If it is quadratic like that, it is equation of parabola right.

So you are talking about two parabolas but what we have seeing is one is actually not so curved it is relatively flat with respect to the other right the valence band is typically relatively flat with respect to the conduction band and that is because of the concept that the effective mass of an electron in the valence band is larger compare to the effective mass of an electron in the conduction band. Maybe you can physically understand it from this picture in the conduction band it is free to move so the effective mass is like low right whereas in the valence band it has all the potential wells that are there are speed breakers few may right very crude sense right and so the effective mass is actually reduced so because of I mean the effective mass is larger in this case and mobility is reduced and because of that you have a flatter you know E k yeah you have a question?

Student: (())(18:15)

Professor: no-no so the question is are we talking about particle movement greater than the speed of light? No, we are certainly talking about particles which have a certain mass right the speed of light is where you get this photons which have zero rest mass that are propagating so that is the highest speed that you can achieve but because of the fact that they have a finite mass they cannot certainly achieve that speed right so we are certainly talking about you know in terms of speed of motion in this material it is much lesser than the speed of light.

So it is not like physically the mass is different right what we are saying in the valence band is that it actually says feels a certain field certain attractive force towards the nucleus that effectively reduces the speed reduces the mobility ok so the effectively we say the mass is larger it is not physically the any different in terms of the mass ok.

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So now we are going to just while we stay in this thing when we talking about atomic systems right, dilute atomic systems we were talking about transitions between this energy levels now when we are talking about semiconductors we are going to start talking about transitions between the you know conduction band and valence band.

Having said that also say that there is research going on in intra-band transitions as well ok so people are starting to within a semiconductor you know can you have transition between one part of the valence band to other part of valence band for the simple reason that when you look at this sort of transitions those are much lower in energy right and much lower in energy will correspond to in terms of wavelength what is it correspond to? Very long wave lengths right so now people are requiring mid-infrared like sources, one example of where mid-infrared like sources will be useful is when you consider absorption of the fundamental absorption tones of different gases ok different material in general, different elements you find that the fundamental absorption tone is actually in the mid-infrared region 3to 5 micron region right.

So if you go to that region you find that the absorption is very-very high compared to the absorption that you may have in the near infrared visible region ok. So if you want to pickup trace levels of this elements you want to detect them with very high sensitivity you want to actually use mid-infrared light sources for doing absorptions spectroscopy. Remember we talked about absorption spectroscopy a few weeks ago when we are talking about interaction of photon

within atom we were saying that based on that absorption you can detect different elements absorption in natures and so that detection is much more efficient if go to mid-infrared light sources and to do that people are exploring intra-band transitions but for all the discussion that we are going to have as far as this course is concern we are going to be focusing on inter-band transitions.

Transitions between the conduction band and the valence band, I will come to that so the question is, you know there are certain things called radiative transitions and non-radiative transitions so how do those happen in this things in the semiconductor material I will come and explain that a little more detail but you know from our previous discussion that non-radiative transitions are more likely if your energy difference you know between different levels is very small what do you mean by very small? It is comparable to KBT right then you have non-radiative transitions possible but if you have a pure band gap you know band gap with a energy of 1 Ev your energy corresponding to thermal light a thermal energy at room temperature corresponds to about 25 milli electron volt. So if energy is 1 Ev then you more likely to have radiative transitions you know when we consider jumping between conduction band and valence band ok.

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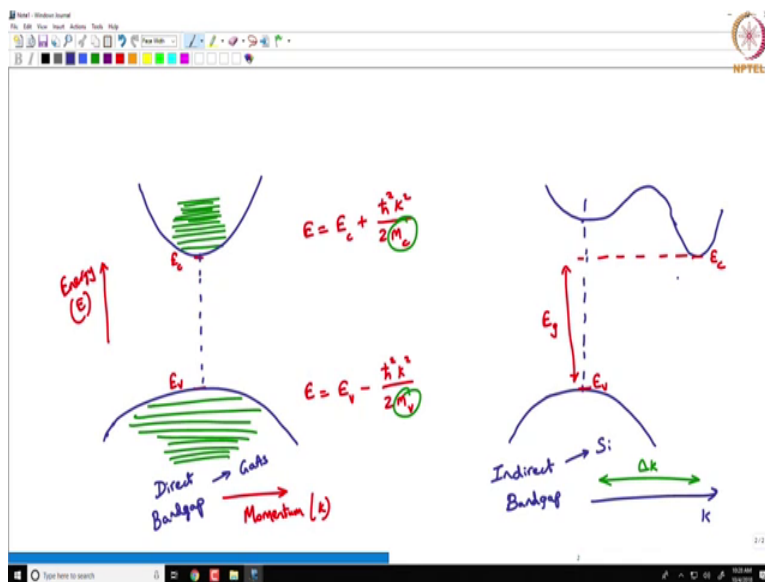
If you have a case where the conduction band bottom right lowest energy level of the conduction band aligning with the top of the valence band you call that as direct band gap semiconductor

because the transitions can be just direct. So if there is something called direct band gap you realize that something is going to be something else called indirect band gap and clearly with indirect band gap what you can say is your valence band and your conduction band minimum there are not happening at the same value of K ok. So you have Ec here and you have Ev here so even in this case the band gap energy is still this, this corresponds to Eg but you do not have direct transition between your conduction band and the valence band so in this case when you have a transition energy is conserved as well as momentum is conserved right.

For any of this things to happen any of this events to happen both energy has to be conserved, momentum has to be conserved ok and that is straightforward in a direct band gap semiconductor but it is not so straightforward in a indirect band gap semiconductor your transitions would have to satisfy energy conservation which can be basically saying that ok transitions occur Eg but also it has to satisfy this momentum gap delta K right so it has to involve some other quantity which you know satisfies the momentum gap as well. So this transitions are relatively relative more involved or little more complex ok. So will comeback and see what is the consequence of that.

Just to give me an idea direct band gap semiconductor one example of that is Gallium arsenide it is a common example that we will keep using and indirect band gap semiconductor very common example is Silicon ok. So it does have it should just complete this picture it does have it may have an (())(27:57) structure like this it is just that the bottom most part of the conduction band is not aligned with the top most part of the valence band ok. So that is one aspect that we need to keep in mind.

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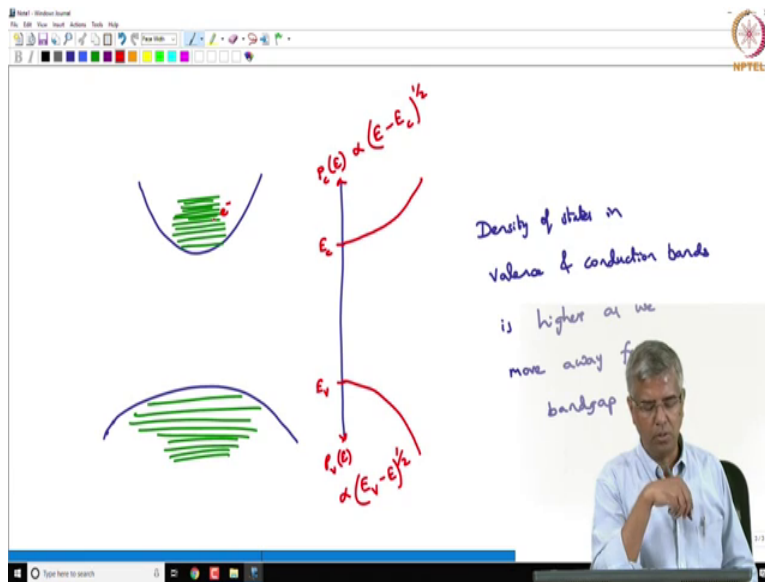
There are couple of other things that we need to keep in mind as well the other aspect is there is a certain so when you actually once again solve the Schrodinger wave equation and look at this energy levels what we will find is you find that the density of energy levels is actually relatively low near the band gap and the density increases when you further away from the band gap.

So we were to represent the densities so this is Ec and this is Ev what you will find is the density let us say I am representing as row c in the conduction band and it is row v the valence band you will have a certain dependence like this and this is this density what we will see is it is proportional to E minus Ec to the power of half and here this is proportional to Ev minus E to the power of half ok. So the what we are saying is density of states in both valence and conduction bands is higher as we move away from the band gap right. So density of states in valence and conduction band is higher as we move away from the band gap energy ok.

So that is with the density of states but there is another important aspect that used to be considered ok and that corresponds to the probability of existence of an electron in any of this states so question is I want to look at what is the probability of an electron existing in this particular energy level right. So how do I find that?

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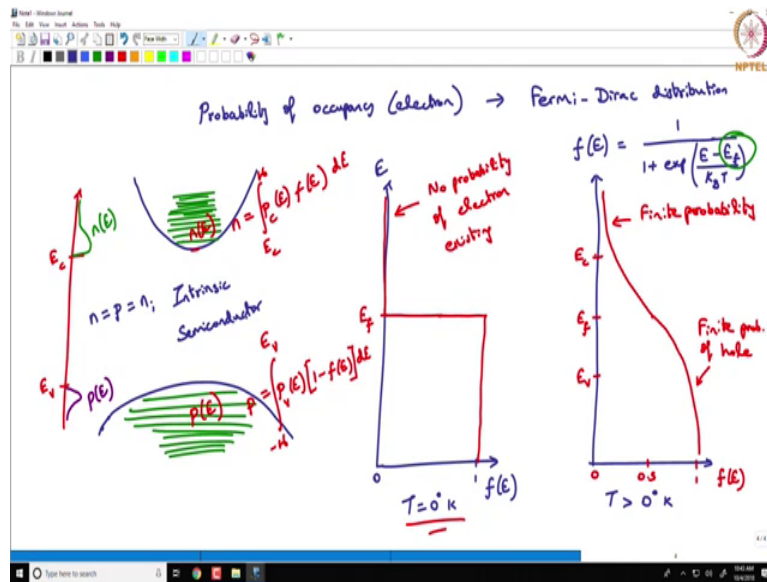
Ok so that has been once again investigated previously and people have come up with (())(31:47) relationship for this so probability of occupancy talking about an electron occupying particular energy level that is this case it is actually given by what is called the Fermi-Dirac distribution ok.

So what the Fermi-Dirac distribution says is F of e is going to be given by 1 over 1 plus exponential of E minus E f over KBT ok so in this what we are seeing is that we are introducing a new quantity that is called Ef so what does that quantity mean? Now will just put this in perspective once again so according to this expression if we plot lets say the this axis we are looking at F of E right the probability of an electron occupying one of this energy levels as a function of E right, E is increasing in that direction ok. So what this says is if you consider so this is going from 0 to let us say 1 if you consider when t equal to 0 degree kelvin ok you get something like this so this would be (use a different color here), this will be f and then it will this is basically saying, so what this means is no probability of electron existing in this regions ok.

Whereas you have a probability of 1 right so you can say for sure that the electron is going to be existing in one of this valence energy levels ok and so that is at T equal to 0 degree kelvin but if you consider T greater than 0 degree kelvin you draw the same expression and this expression now comes into effect now you say this is still your E f so is going from 0 to 1 F of e this about 0.5 that is about this point if you plot that expression it is going to be something like this so what it says is in this case there is a finite probability of electron existing in this conduction band.

So now is to give you a perspective so now we are saying this is your Ec and this is your Ev and there is also a finite probability that in this case over here finite probability that electron does not exists in this valence band ok and if there is actually an absence of an electron in semiconductor physics we call that as a hole ok. So this actually corresponds to the fact that you have a finite probability of holes in the valence band ok. So what we are typically interested in is this quantity we are interested in what is the concentration of electrons in the conduction band and the concentration of holes in the valence band ok.

So that concentration is essentially going to be if you looking at the total so well first of all that concentration is going to be equal to the density of states row c of E multiplied by F of E right so the density of states multiplied by F of E would give you the distribution of electrons in the conduction band and similarly row v that is the density of states in the valence band multiplied by what? 1 minus F of E because we are talking about the existing of a hole, the existence of a hole is when you do not have an electron in those energy levels right. So if you want to look at the total this is the concentration this is the density that is distributed across the different energy levels and if you want to look at the total electron density in the conduction band what you have to do?

You have to integrate over this so in this case integration will happen from Ec to infinity right over all values of D E if you do that integration you get the total density of electrons and similarly the total density of holes in the valence band is given by integral over D E what are the limits? Minus infinity to Ev ok, so what we find in this case is if you look at for example if you look at this is your Ec and this is your Ev if you look at the distribution of electrons it is going be something like this right and the distribution of holes is going to be something like this. So this is basically N of e and this F E. so what are we seeing what do we see in this structure? What we are seeing first of all in N of E is that you have a higher probability of finding an electron near the band gap right but there the density of states is very low ok.

But as you move away from the band gap your density of states is higher but according to the Fermi-Dirac distribution the probability of existence is lower so that is what is you know N of E will let you (())(41:49) of as you go to higher energy levels and similarly with P of E but what we gather from all of this if you look at charged neutrality what you find the is the total number density of electrons is equal to the total number density of holes is equal to this quantity which

we can write as N I so this is what is called an intrinsic semiconductor, intrinsic semiconductor this is a semiconductor without any doping let us say silicon for example without any doping a Gallium Arsenide without doping you know will have equal number of electrons as there are holes in the system and so n equal to p equal to N I ok.

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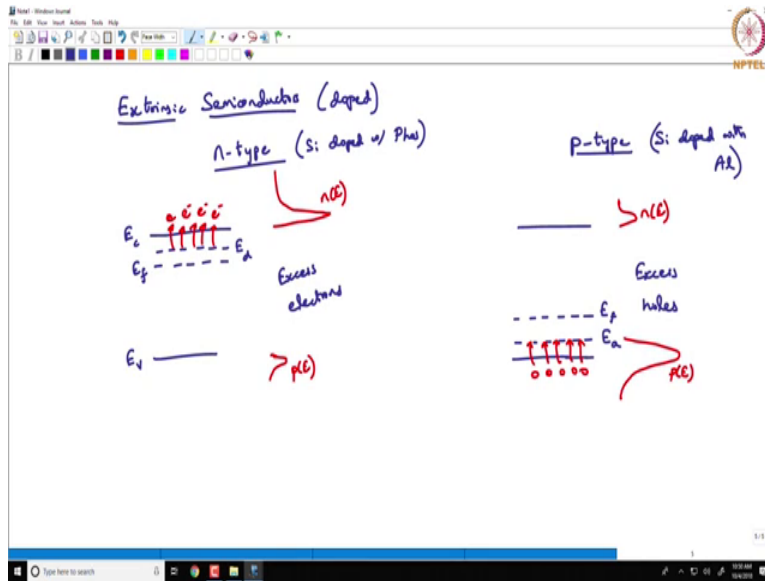
Now interesting things happen when you have doping added to this system ok so you have what is called extrinsic yes one second there is a question somewhere yeah.

Student: (())(43:23)

Professor: yeah I mean you can bind it to specific level but I mean in this is like all possible levels so just say minus infinity but in reality you do not see much happening beyond a certain level yes.

Student: (())(43:46)

Professor: no-no it is not minus infinity so there is no meaning of minus infinity in this case but yeah mathematically you are just trying to do the physically you know you do not attach a meaning to that yeah.

Student: (())(44:15)

Professor: well yeah so it cannot have infinite energy that is basically what he is talking about so you cannot have infinite energy at the lower bound or the upper bound but mathematically you are just trying to account for all possible energy levels right. So yeah that is not physically possible. But interesting things happen when you have doped semiconductors and as far as doped semiconductors go suppose you could have N type or P type semiconductors, N type is where you have let us say example of that is silicon which is actually a quadravalent semiconductor with a spore valence electrons doped with let us say a pentavalent element alike phosphorus right.

So silicon doped with phosphorus can give you some interesting things when what we are talking about is this is let us say a simplicity I will just draw it as a flat line Ec and Ev you have phosphorus when you doped it with phosphorus, phosphorus actually occupies an energy level that is called the Ed somewhere over here such that even at room temperature since it is pentavalent it is got one extra electron to give right so even at room temperature you have electrons that are going into the conduction band right and similarly if you talk about P type semiconductors silicon doped with trivalent element like aluminum and this case the aluminum is going to occupy state over here and it is such that you can have this electrons are accepted by aluminum and in this case what you have what you are leaving behind is holes.

In this case what you have is extra electrons over here ok and that actually changes the electron and hole concentration so you have basically when you are looking at the electron concentration it is going to be much larger like this whereas your hole concentration is still much smaller whereas here your electron concentration is like this but your hole concentration is much larger so this is N of E and that is E of (())(48:21) and to represent that to you know explain this part from a Fermi-Dirac perspective what you can essentially say is that your Fermi energy in this case would have shifted over here right, they are shifted from the Fermi energy in an intrinsic semiconductor is Ec plus Ev divided by 2.

But now with an extrinsic semiconductor the Fermi energy moves up or down depending upon the kind of dope that you have so here the Fermi energy is going to be like this ok. So then you have basically a larger probability of finding an electron in the conduction band in the entire semiconductor and larger probability of finding holes in the valance band as far as the p type pf semiconductor is concern ok. So here you have in N type you have excess electrons and here you

have this is holes ok. Now interesting things happen when you have this excess electrons and holes and before we talk about that now we can also say something else when we are looking at this picture right.

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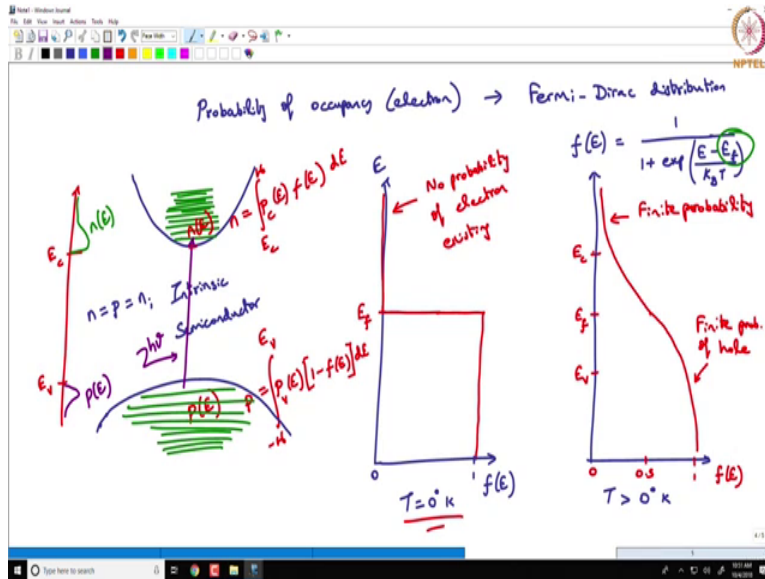
So when we look at this picture what are we saying? There is from a perspective of light absorption an emission you can say that you can have light with H mu (())(50:32) a photon would energy H mu come in such that H mu is if it is greater than the band gap energy then it can actually be absorbed in this material and whenever that absorption event happens it leaves behind the hole in the valence band and it creates a electron in the conduction band right.
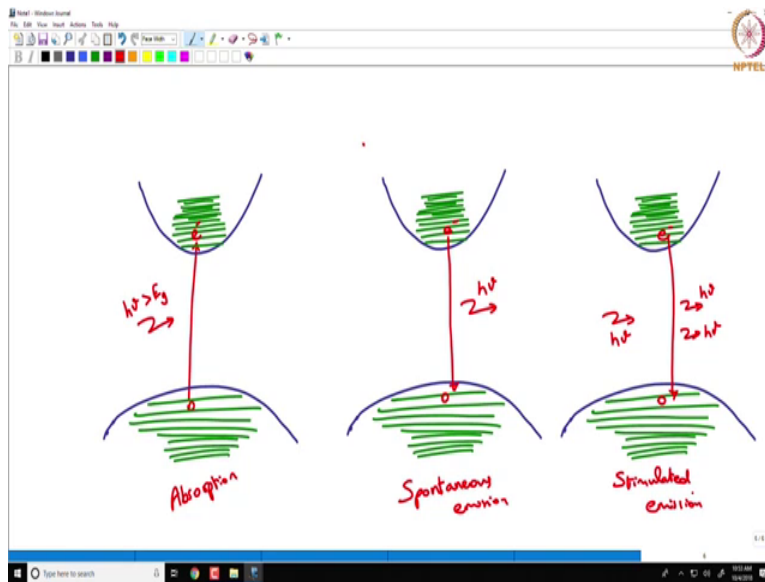
So that can happen maybe I can just represent this in a separate picture over here so let us say you have H mu is greater than E g then you have this transition happening leaving behind the hole here and producing an electron there right.

So this is actually absorption process in a semiconductor whereas now if you say you have an electron over here and a hole over here it actually spend some time and then it can actually come combine kind recombine with the hole which can emit a photon so that is what we call as spontaneous emission and finally you have also this possibility that if you have an electron over here and a hole over here and photon comes around corresponding to the energy difference between where the electron is sitting and where the hole is sitting you can stimulate a transition and in this case you have stimulated emission which essentially means that you could get optical amplification and then with feedback you can actually make a laser ok.

So we are out of time so let us stop over here but this are the things that we are going to be talking about we are going to be talking about light emitting sources which are based on spontaneous emission and stimulated emission of light and we are going to also look at light detectors which are based on absorption of light ok. So that will continue in the next lecture, thank you.