Semiconductor Optoelectronics
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Lecture - 9
Quasi Fermi Levels

In this lecture we will discuss a little bit more about quasi fermi levels. As I had mentioned that quasi fermi levels are very important in optoelectronic devices. Normally in p n junction diodes we do right what quasi fermi levels, but we do not discuss much. But in optoelectronic devices as you will see it is the difference between the quasi fermi levels, which will determine the band width of a semi conductor laser amplifier. So what are quasi fermi level?

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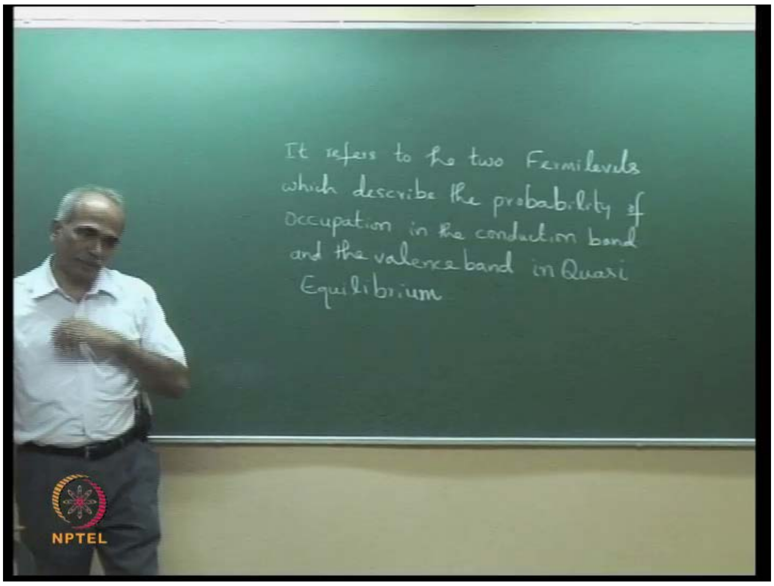

It refers, it refers to the two fermi levels. Two fermi levels which describe which describe the probability of occupation the probability of occupation in the conduction band and the valence band in the conduction band and the valence band. Now, there are two, that is why for quasi fermi levels valence band in quasi equilibrium, in quasi equilibrium.

Hence the name quasi fermi levels so it refers to the two fermi levels that describe the occupation probability of electrons in the conduction band. And in the valence band one fermi level to describe the occupation occupation probability in the conduction band.

And another fermi level to describe the occupation probability in the valence band when the semiconductor is in quasi equilibrium. So we will see what is this quasi equilibrium? But, before we go to quasi equilibrium; let us first discuss the thermal equilibrium thermal equilibrium refers to a steady state an equilibrium.

A steady state at constant temperature and when there are no other sources of excitation. So, the energy is supplied the energy under consideration is mainly thermal energy. So let us first see at thermal equilibrium what are the electronic transition process in a semiconductor.

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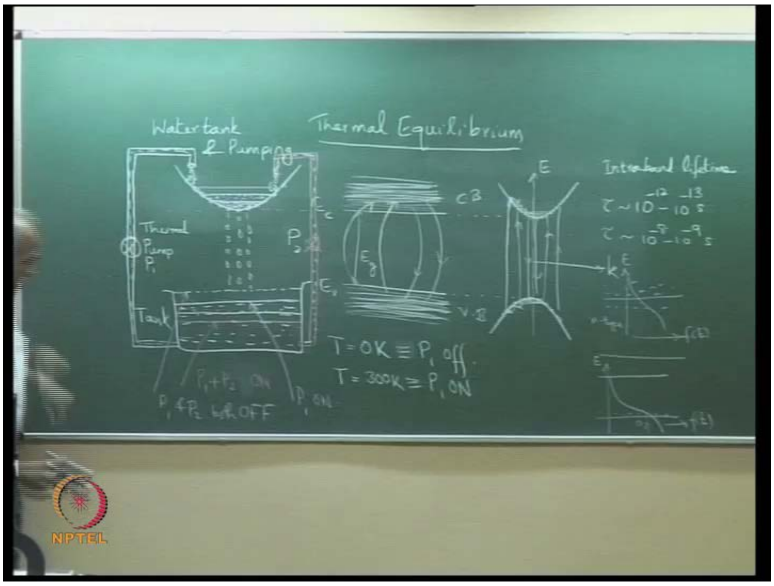

So at thermal equilibrium it is an equilibrium it is not static it is dynamic. But, there is an equilibrium. So, if you recall the energy band diagram; so this is e v e c we have large number of loud states in this band and the density of states go on increasing as you go to higher values. Similarly, there are density of states.

Here and the density of states become more and more which means they are becoming denser and denser as you go further down, so e v e c and separated by e g. This is valence band and this is the conduction band. Along with this, we can also plot the e k diagram. The e k diagram where this is basically a large number of a loud states. Here, almost continue and large number of states in the lower band as well. So, both are equivalent equivalent picture. This is e k at thermal equilibrium when t is equal to zero in a semiconductor. T equal to zero k the lower band is completely full and upper band is completely empty and let finite t.

Then the electrons which are making continuous upward transition. Please remember that it is not that where are some fixed number of electrons here, and fixed number of holes here. It is a dynamic equilibrium. There are electrons which are making upward transition and downward transition in the presents of a finite temperature.

T electrons are continuously getting exited to the conduction band and also there are recombining with the hole. But, there is the study state at study state number of electron making upward transition is equal to number of electron making downward transition. This is the study state; does not mean the electrons are... They are continuously in a state of transition upward and downward but, there is a equilibrium.

At equilibrium the average number of carrier here and average number of carriers which are present here. In this to there are electrons which are making transition upward transition. It could make upward transition here also and also there are electrons which are making downward transition. Usually if an electron which makes an transition, a higher energy level here it will rapidly come down with in the band by a process call thermalisation. This is due to phonon transition an electron exited to an upper level in the conduction band rapidly comes down to lower states by the process of thermalisation. Thermalisation means it gives energy to phonons and phonons are.

Quanta or lattice vibration so and it rapidly comes down here and it accumulate at the bottom of this band. Although it may be making a transmission upward it comes down and accumulates here and electrons as left this place. There is a hole here, the holes it higher energy. So, the electron which is sitting here comes downs position of hole and the hole makes an upward transition here.

So, the hole also similarly, makes transition upward to the top of the band hole as lower energy. Then it is comes to the top of the band. So, the hole accumulates near the top. So, let us study state when the number of electron going up is equal to number of electron going down. There is the certain number of holes here and the certain number of electron in the conduction band.

That is the carrier concentration must be talk of at any given temperature t. The phonons phonon transition are very, very rapidly typical time for this transition is tow is of the order of ten to the power of minus towel to ten to the power of minus thirteen. Second this is the transition time, recombination time that is the time over which the electron comes down by thermalisation. Or this is call the intra band recombination time or intra band carrier time carrier life time with in the band intra band. So, the intra band life time life time here refers to the time over which it is at an exited state is not life time of the electron with in the band intra band life time or it is also the same as recombination time. Or it is also same as the photon transition time.

So, that means this is extremely rapidly to the bottom the transition time. Here, that is form the conduction band to the valence band typical time tow. That is inter band transition time is of the order of ten to the power of minus eight to ten to the power of minus nine seconds. The inter band transition which means the intra band transition is much much faster. Therefore, at any time although there are continuously transition taking place at any time. You see a study state you can imagine this by a an example here.

You take a container. Please see this example, an example of water tank and pump water tank and pump. So I have a container here alright. Let it draw it at the same level easy just it at. This is not band diagram. This is the container. So, there are two containers, two tanks. So this is the tank where there are water.

I am describing the process of thermal equilibrium with the analogy of water in a tanker at t is equal to zero. The lower tank is completely full. Upper tank is completely empty. This upper tank has holes. There are holes here through which if I pump water. It can tickle down. These are holes in the upper tank. The lower tank does not have any hole. I now take a pump.

So this is a pump pump p1. Pump p1 when the pump is off; this tank is full. This tank is empty. I switch on the pump. So, the pump is pumping water here. So, water is falling down and water is flowing down here to the bottom of the tanker and there are holes. And therefore, water is also quickly flowing down. So water is also falling down.

Because an pumping up in to this stand water is getting accumulated here. But, it also following down through this holes. If the holes are sufficiently small; if they are will be some amount of water which is accumulated in this the amount of water, the level of water here depending on the pumping rate. If I pumps very slowly very small amount of water is entering this tank and these also going down. So, the new study state when the pump is on; the new study is this that the water level as come up to this. There is no vacancy here and there is water up to this. You compare this water to electrons and the vacancy is to holes. So, electrons are pumped up.

Because of temperature, because of thermal energy, the thermal pump; so this pump is for thermal energy. So, I want to call this as thermal pump. What? Temperature pump; a pump, because of thermal energy. So, there is the study state here you can imagine bucket of water. Also you take a bucket of water and there is the hole form the side leave the tap in to it depending on the rate which water is falling in the bucket. The hole is very small.

So, there will be some study level. You increase the rate of flow. So, the level will go up and of course, here it will go out at a faster rate. Because whatever come the study state is the amount of water which comes must be equal to the amount of water is exactly like this and thermal at finite t the pump is off is equivalent to…T equal to zero. So, t equal to zero k implies is equivalent is not implies is equivalent to pump p1 off. This tank is completely full and this tank is completely empty. This band is completely full and this band is completely empty. You switch on the pump. Now, for at a finite temperature, some value t equal to let as say 300k which is equal to pump on p1 on at some rate. Therefore, you have level which is study level. If I increasing the pumping rate that is if i increase the temperature from 300 to 400; if I increasing the pumping rate it means it will now go to a new level. So, more water is coming. It will fill here.

This level will go down and you will have a new level which is here and this is here. This is carrier concentration, temperature dependence of carrier concentration. Now, why did I bring this concept at a given temperature? I may have a second pump. Water temperature pump, temperature is fixed 300k. But, I have another pump. So, I use the second pump from here and which is also flowing water in to this. This is pump2.

Pump p2 which is also lifting water and flowing into this. This is not the temperature pump. So, it is not now. Because water is coming from here also the level is now change to a new level. Because there is more water being pump so this comes to a new level.

And similarly, here this goes down to a new level. So, this is the new level. This is width p1 plus p2 both on p1 plus p2 on.

This level is width p1 on same thing is here also, p1 on and this level is when p1 and p2. Both off. What is the point to point is when you have a second pump. There is an new equilibrium. The levels are different. Now, there is a new equilibrium. There was no change in temperature. So, it is not temperature pump. The normal fermi function describes the occupation probability of electrons at thermal equilibrium. It describes occupation probability for both conduction band and the valence band.

But, when you have a new equilibrium in the presence of an additional pumping source; what is an additional pumping source? You will see when you have pumping an additional pumping source. One fermi function can not describes both of them because you have simultaneously very large number of electrons and very large number of holes the large vacancy. In this start water has gone down because half the water is here.

So you have but, this rated which the water is falling is much slower compared to the rate at which water settling down here. Why it this have a study state here? You imagine the bucket. The bottom of the bucket is open. No water at the rate at which you pot there will be no water in that bucket as you no state rate at all. But, the hole is very small at the bucket.

Or if the rate at which the water is going down from here is much smaller then the rate at which it is poring down and settling quickly fit here. Then you have a study state distribution here and a study state distribution here. Each one of them can be described by the fermi function. But, you need two fermi function. One to describe this and the another one to describe this. Why two fermi function? Because the number here, the carrier density here is so large that you have to bring the fermi level here, up you know.

A semiconductor is the number of electrons here, very large liked in n doped semiconductor. The fermi level is shifted up because of I want to describe the probability like this. If it as p type then the fermi level is shifted down. So, if it is p level p type where you have large number of holes. When the fermi function is shifted down so the point five probability, so point five what I plotted f of e verses e always the vertical axis is e. Some times I make not mark at the. What is the vertical axis? But, always every where vertical axis is e. So, this is f of e. So, this is the n type and this is the p type. Now, we have a situation. Now, we have large number of electrons and large number of holes simultaneously and this can be describe and all at steady state. They all at steady state because the time this time here where the rate at which the transition is taking place is much smaller compare to this time.

Which is causing stabilization? Rapid stabilization or rapid thermalization? Therefore, at any time if you see take a photograph you have there is a steady level sitting here. There is a steady level sitting here. It's steady level. Therefore, if you use two fermi functions. One to describe the population of the valence band, one to describe simultaneously one will be here and one will be here. Two fermi functions these are call the quasi fermi levels in the same semiconductor.

Here it was n types another semiconductors; here it is p type separate semiconductor. But, now you have a situation of quasi equilibrium where you have an additional force of pumping; you have two fermi levels to describes the population of the two band. These are call the quasi fermi levels is this picture. Clear that.

This is at zero k. No pump p1 p2. Both of the lower band is full upper band. This have plotted equivalently just by this side. Here the level goes down which means the vacancy here that means there are holes. Here the vacancy here or gap likes holes and water drop is like electron. This is very good energy at every state.

You will see later on they are complicated mm band diagrams where you can understand them every time you think the electron is like a water drop. Because water drop always flows from a higher level to lower level where as air gap air gap always goes lower to higher level. So, you will see the picture will definitely be very helpful so let me rough this all and so under the condition that the intra band transition time or the thermalization time is much smaller compared to the inter band transition.

You will always have a steady state distribution and that steady state distribution in the two bands can be described by can be described by two different fermi function called the quasi fermi level.

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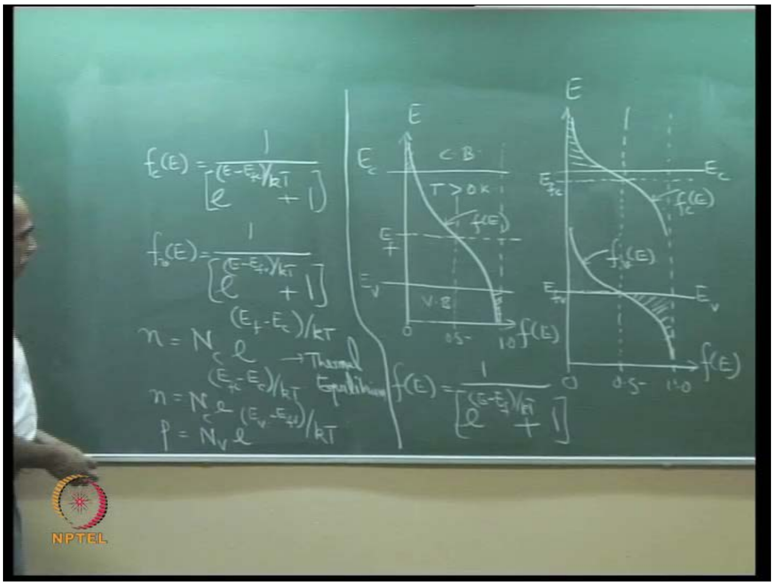

So we have at thermal equilibrium. Again let me plot Ev Ec and e what is as f of e the fermi function and you have a distribution. So, this is 1.0. So at 0.5 f of e equal to 0; 0.5 you draw the vertical line where it intersect that gives Ef. So, this is at particular temperature t; t greater than zero; t greater than zero one f of e describing the probability occupation of the conduction band and the valence band and f of e is given by one divided by e to the power e minus ef by et plus one in quasi equilibrium

And you have and additional source which brings in more electron to the upper band. And therefore, you have, oh I sorry This is where you have do not anything.

I could, I get there drawn figure already for display. But, I got if I plot under view we know what is the difference. So, this is efc fermi level or fermi function describing the conduction band occupation. Probability of the conduction band, this part has no role. Only this upper part role to describe the population of the conduction band occupation probability of the electrons in the conduction band. Here, this is at 0.5. So, happens that comes out at the same value as by chance. It is at ev so efv.

Here this function describes the population of occupation probability of electrons in the valence band. So, this is the f of e and so this is one minus f of e which describes the occupation probability of holes in the valence band. Two functions are separate. This is call f v of e and this f c of e. One fermi function describing the occupation probability of the conduction band and second fermi function describing occupation probability of the valence band f c of e. Let me write this side this me go out of you. Let me erase this picture where f c of e so f c of e is equal to one divide by e to the power e minus efc by kt plus 1.

So, instead of ef we have efc and here we have efv so fv of e is equal to one divide by e to the power e minus efv by kt plus one. Is it if there is any any doubt no. No I went on siding its just by chance in my diagram came out to be co inside it.

It need not it, does not our need not in generally does not but, by chance the wave I have drawn it that 0.5 think came out to be the same value as ev. But, there is no relation at all. So, this is ec and ev by chance it is there. But, the important point that you get is one fermi function characterize to one fermi energy efv will describe the occupation probability of the valance band.

And therefore, one minus fv of e will be give you the occupation probability of holes and a second fermi function simultaneously in the same material. This is not one type one is n type, one is p type. It is the same material but, it is now in quasi (( )). When a materials is in thermal equilibrium you will describe by one single fermi function.

When a material is in quasi equilibrium which means there is an additional source of pumping, additional source of excitation. This additional source of excitation could be radiation, a semiconductor which is eliminated by light or it could be the pn junction where carrier injection is taking place and at the junction in the junction your poring in the electrons and holes. So if you look at that junction region there are simultaneously large number of electron and large number of holes. This is carrier injection and you have two fermi levels in that in that region. Before I proceed to the excitation mechanism more about the excitation mechanism under poles are approximations.

We added an expression for carrier concentration n is equal to nc into e to the power of ef minus ec by kt. At thermal equilibrium in quasi equilibrium everything remain as the same. If we still meet the holes an approximation, this is across across efc. If it is still some where below here then I can still use efc. And I can still use both an approximation and then this will become. So this is at thermal equilibrium. In quasi equilibrium the expression is valid with ef replaced by efc minus ec by kt.

Simply the ef is replaced by efc because what was ef doing? It was describing the fermi function. Now, the fermi function is described by fc of e which means efc of and p the carrier concentration of holes is can be in to the e to the power efv minus ev oh ev minus efv by kt.

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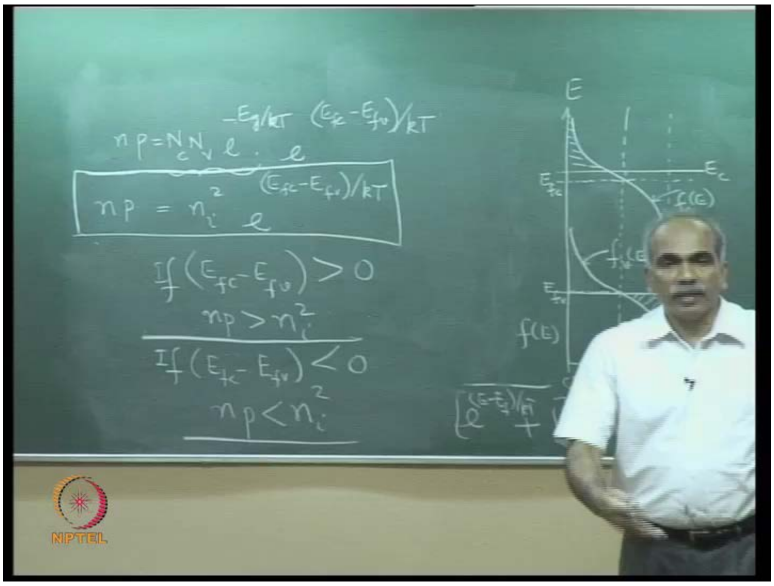

Let me write the two expression again because it littlie congested there and therefore, n in to p is equal to nc into nv in to the product of these is equal to e to the power minus eg by kt n into p is nc in to nv e to the power of ev e to the power of minus ec. Therefore, it is minus ec minus ev. Therefore, minus eg by kt into what we you have at the second term e to the power noise. Let me go for there into e to the power efc minus efv by kt. What is this term? It is ni square. This term is ni square. Therefore, this is equal to ni square into e to the power efc minus efv by kt for n into p is equal to by kt in thermal equilibrium efc is equal to efv is equal to ef is only one ef which means this is zero. The numerator here because efc equal to there is nothing like to fermi function so only one and you are np equal to ni square in thermal equilibrium.

In quasi equilibrium we have two fermi functions and and I mention that is the difference between these. Therefore, if efc efc minus efv efc minus efv is greater than zero; if the difference is greater than zero then np is greater than n (i square), the number of carriers that we have the product of carriers is greater than ni square. And if this is less than zero when will this greater than zero when will be this less than zero. I will show the pn junction now. But, if this is less than zeros.

So if efc minus Efv is less than zero; that means efc is below efv efv is above the less than zero can be have np less than ni square under Boltzmann approximation. Which means we are considering relatively lightly doped pn junction and relatively lightly doped pn material and are quasi equilibrium is quit minute. So, in quasi; oh I erased it In quasi equilibrium, the law of mass action is not np equal to ni square. But, n into p equal to ni square equal to e to the power of efc minus efv by kt.

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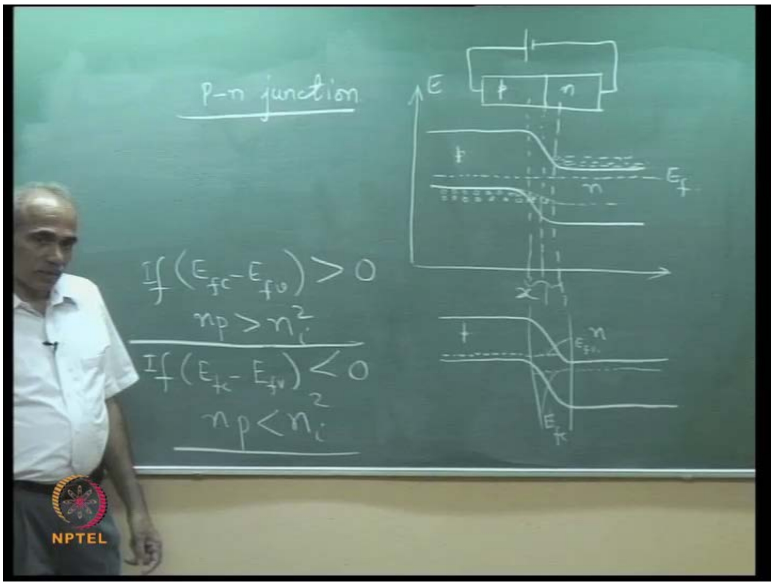

Let us quickly take the band diagram of a pn junction and see what is this we will discuss pn junction a little bit more in a lateral class. But, let us quickly take about the band diagram and see what will be the situation when this is greater than zero and when will be this is less than zero? All of must be familiar the pn band diagram of a pn junction. I hope we will see pn junction from drawing the energy band diagram of typical pn junction.

So this is p type material. So, p and this is n and we have at equilibrium one fermi level ef. So, this is this is energy e and this axis is the distance x. So, x you can take at the joint x equal to zero, at the junction the math logic junction; junction between p type material and n type material. Let there is a energy band variation. So, you have a plenty of electrons here. So, plenty of electrons water. So, when ever electron comes just think a water very easy to fallow and plenty of holes air bubbles.

And near the junction there are by there holes or air bubbles are very little electrons and holes at the junction; it will usually call as the depletion region in electronic. We usually call this region as the depletion region. But, in optoelectronic we done call as depletion region because for optoelectronic devices, this is the most important region and we call it the active region. It is call the active region depletion region is a little bit of negative a. So that of it depleted but, it is the most important region which is the active region. So, you have one fermi function. This is the pn for you. Forward bias this which means to the p n.

So let me show the, so this is the junction p n. Now, you apply a forward bias is entire pn material. I am not assuring the this is the junction. So, p n we have apply a forward bias. So, when we apply a forward bias what happens? The right side goes upwards with respect to the right left side because electrons gets more potential energy is it connected to negative terminal. So, let comes now have a higher potential energy and this is energy axis. So, this and starts moving up relative to this end. So, we have a forward bias pn junction and the band diagram.

Now, so originally it was like this. Now, it has been lifted up from the original position relative to that. So, this was in original position. Let me not sure the original position. This is after forward biasing. So, forward biased junction what happen to the fermi function? So, fermi level in this side remains where it is for away from the junction is no potential built. So, fermi level is here and for away from the junction the fermi level is here. What ever the junction region; so this from the junction region you see there is a.

There are two fermi functions in the junction region. Now, this is the moment new forward bias it which means an addition to temperature you are inject you are giving its supply from outside. Which means you are introducing carrier injection. Then in the junction region you are what is happen thus gone up. So, the when this was gone up water as starting moving here, you see the level as been raised. So, water as come in to the there was earlier the gap depletion region.

Now, when a rise this water is moving this side because the barrier is lower and what happens to their air bubble? So, this as imagine here itself. So, if goes like this the air bubble can come here. So, exactly like that you have air bubbles coming in to this sides which means we look at the same original junction and the new forward bias junction, you have lot of electron and lot of holes in the say at the same value of x insert the same physical position.

You have simultaneously large number of holes and large number of electrons. This is quasi equilibrium. This is come out because of the external power source because of forward biasing and accordingly you see the two fermi functions here and this is now efv. And this is efc for the junction region and therefore, as for as if you focus only on the junction region only. It is a region where you have simultaneously large number of holes and large number of electrons and it is described by two fermi functions.

The separation here efc minus efv is positive efc minus efv is positive. efc minus efv is greater than zero which means in this junction now np is greater than ni square. You have simultaneously large number of carriers when will we have this kind of the second type of a situation, if we reverse bias. So, if we reverse bias the junction then this will further go down which means this will remain there at the other potion goes down. Let me erase the forward bias and the band diagram now becomes v goes down further.

The one's still remains here ef but, in the junction region this is efc and ef is here or away for the p type and n type. But, in the junction region efv is now here. If we look at the junction region; this is efv and this is efc; efc the different now is a negative obviously when you reverses the depletion region further wide and send carriers are pull back and you have much less carrier in the depleted depletion region infect.

This is the forward biasing is the principle of realizing optical sourcing and reverse biasing is the principle of realizing optical detectors as we will see later that this is the case corresponding to optical sources. And this is the case corresponding to optical detectors. So, we will pass for a file here about the basics and a most of the basic essential basics which are required for this course we have review a little bit of pn junction. Let us we will discuss a little later nor because of the normal pn junction which have already studied.

We will have to drill with a homojunction, a hetrojunction and double heterojunctions and we will need to know how the band diagram is of its hetero junctions. It is very easy in the case of a pn junction; is simply draw it like this. But, what happens if you have a hetero junctions that is a junction between two dissimilar semiconductors which have different band gaps? How to plot even the pn junction band diagram energy band diagram?

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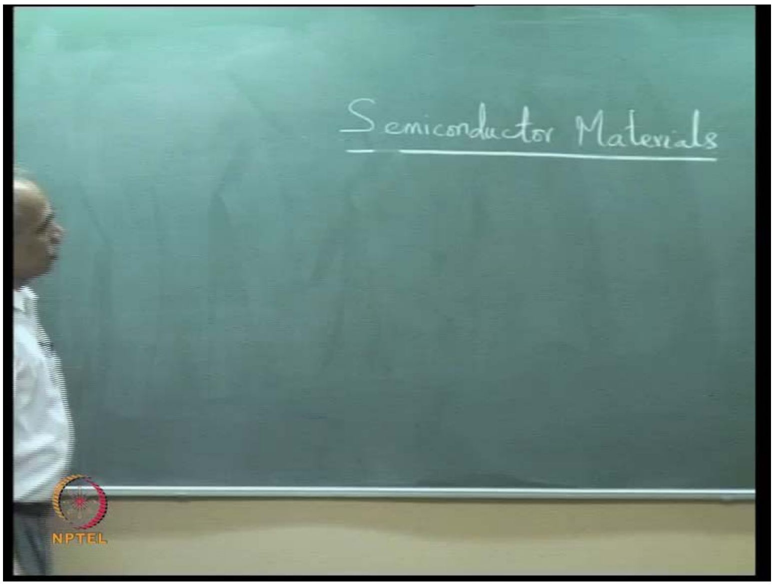

So you will discuss this a little later. But, before that it will taken an next topic semiconductor materials as indicated.

Again that our focus will be mainly on optoelectronic materials. Not all semiconductor materials you be interested particularly material for optoelectronics. We will stop this point because we are now changing over a to the material aspects. So, we will discussed about a hetero structures and ternary compounds quart nary compounds and band gap engineering band gap modification. This will be your topics in next two class. Do you have some questions? Any question? Alright, so I will stop here.