**Semiconductor Optoelectronics**

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**Lecture - 14**
**Heterostructure p-n junctions**

Good morning. Let us start with the heterostructure p-n junctions, this lecture on heterostructure p-n junctions. We are all familiar with the p-n junctions semiconductor material as such semiconductor material as such is not of much use in any application, probably one of the applications where one directly use a semiconductor is a photoconductor, we will see later. Photoconductor is a photo detector which is not a junction device, but most of the devices are p-n junction devices, because if you take a semiconductor of course it has conductivity somewhere in between good conductors and bad conductors.

You can also change the conductivity by doping, but at the stage of fabrication there is no real time control on the conductivity, which means if you want to make any switching devices there has to be real time control something will switch and that is possible by the use of p-n junctions. Therefore, as you know p-n junctions formed the basic building block of all active devices in electronics as well as in optoelectronics. So my objective would be to recall what you already know about p-n junctions, and in particular to see how heterojunctions behave or the band diagram of heterojunctions in the case of heterostructures band diagram of p-n junctions in the case of heterostructures.

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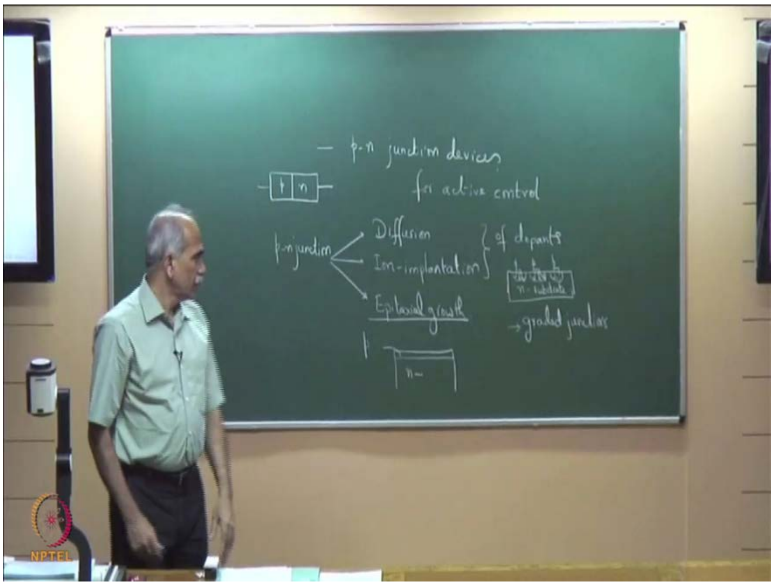


So the first point is that p-n junction devices junction devices for active control active control, control of carriers that is control of current, for active control. The second point is when p-n junctions are fabricated or p-n junctions are formed there are usually there are three processes which are used for p-n junction. One is diffusion I have briefly discussed about this diffusion, ion-implantation, and of course epitaxial growth. Diffusion and ion-implantation of dopants of dopants as we discussed you start with a substrate and you deposit the required dopant and then diffuse this into the substrate. So this is the substrate so maybe n substrate.

And then this forms diffused, the diffused region is primarily p if you are doping p material. In ion-implantation there are ion beams which are implanted into the substrate but in both cases what you notice the junction is graded, it is not an abrupt junction, it is graded junction. So both the processes lead to graded junctions, graded in terms of carrier concentration, in terms of dopant concentration but epitaxial growth in epitaxial growth we have already discussed in detail, you start with a substrate let us say n substrate and then you dope or you deposit a layer may be n plus or you deposit a layer let us say p then the junction is really abrupt. In other words the typical p-n junctions that we show like this schematic which we represent p-n this is an abrupt junction device and by epitaxy indeed you can grow abrupt junction devices otherwise, these processes normally lead to graded junctions, both have their advantages and disadvantages we will discuss probably at a later stage but this is regarding the growth and type of p-n junctions in terms of material and structure.

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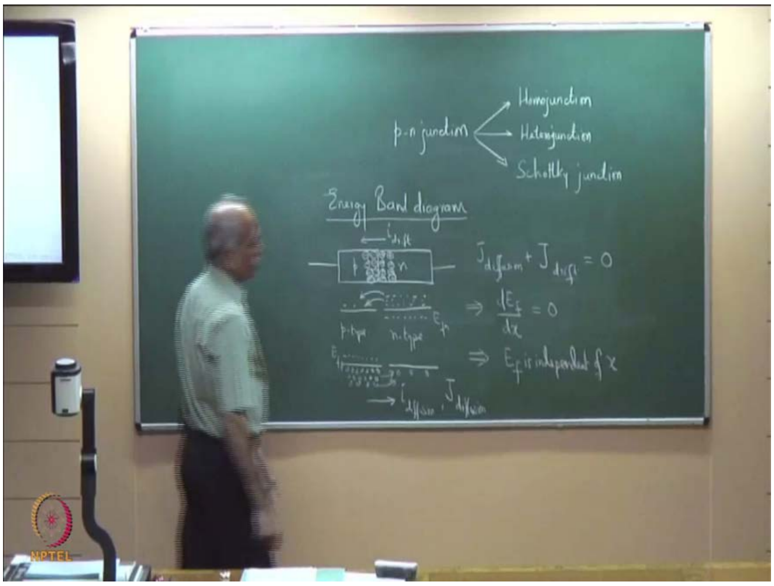


The second type second type of classification here is homojunction, that is junction between same material but p doped and n doped material p-type silicon, n-type silicon. Heterojunction junction between dissimilar materials heterojunction usually with the different band gap and also schottky junction this is junction between metal and a semiconductor. When you make the device finally, you need metal layer for contact and you will always have a Schottky junction and we will see how Schottky junction Schottky junctions can behave both as rectifying junction as well as ohmic contacts that will be our next discussion.

So this classification was based on process and this classification is based on structure. Let me quickly recall the band diagram, the energy band diagram. So energy band diagram of p-n junction, we have a p-type material. So this is the p-n junction p-n so metallurgic contact p-n p-type material, n-type material and if you draw the let me first discuss homojunction. If you draw the energy band diagram before contact p-type will have fermi level somewhere here and n-type has fermi level somewhere here. So this is p-type and n-type, it tells me that there are large number of electrons here in the conduction band a very few electrons here, there are large number of holes here and very few holes here.

So when you form a p-n junction naturally there is a difference in carrier concentration. So electrons when you form junction electrons diffuse from high concentration region to low concentration region and holes diffuse from in this region. So there is a diffusion current, so electrons are moving in this direction which means we have a diffusion current i diffusion. So i diffusion i diffusion or a j diffusion current density j diffusion, because of difference in carrier concentration at the same time when electrons move over to this side or holes move over to this side, this leaves behind immobile ions positive immobile ions all of you have studied this I am just recalling.

And negative immobile ions here because holes have moved. So this these are negative immobile ions, the depletion region and therefore, there is a built-in potential here potential difference which leads to drift current whenever you have a material where there is a potential difference and if there are carriers then there is a drift current. So the drift current will be from positive to negative. So i drift, drift current refers to the current in the presence of an applied potential difference. So there is a drift current because there are always minority carriers in the diffusion region and this leads to a drift current in this direction.

So there is a diffusion current and there is a drift current at equilibrium i diffusion. So j diffusion plus j drift equal to 0 mathematically, you can show that this corresponds to if you have E f p here, E f n here you can show that this implies d E f by d x I am showing one dimensional x direction d x equal to 0 this implies this is pure mathematics and this shows that E f is independent of x.

This is one dimensional picture x is in this direction E f is independent of x which means E f remains constant. So at equilibrium so the drift current is exactly equal to diffusion current in magnitude and in opposite in sign that is why it is 0 and we have all done this that you can show that E f is independent of x; that means, the fermi level is constant throughout. The band has to bend which way the band will bend whether this will go up or this will come down we will see which way the band will bend.

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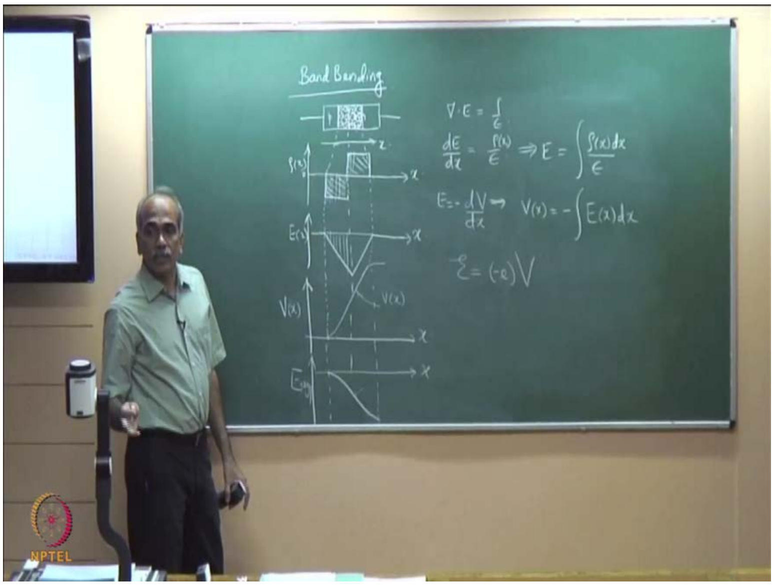


So let us look at this again band bending, some elementary let me redraw these. Let me draw here p-type and n-type I will show a little wider depletion region. So you have negative immobile ions here, it is a quick revision because this is important for us to see the band bending in heterostructures. That is why I am just repeating all of you are aware of this. So there is charge distribution here and therefore, we use gauge law del dot E is equal to rho by epsilon or in 1 dimensional I can write d E by d x, x is this direction d E by d x is equal to rho by epsilon, rho is the carrier density charge density. So this is rho of x in one dimension actually row is volume density but in a one dimensional simple picture d E by d x is equal to rho of x by epsilon which means this implies E the electric field E is equal to rho of x d x by epsilon is the simple integration.

So we have so if I want to plot rho of x here. So this direction is x rho is negative here I assume that so corresponding to this. So there is negative rho of x and positive rho of x. So what I have plotted here is rho of x. This is rho is negative chargers and here positive chargers. So this is rho of x the electric field if we plot the electric field now E f x is simply integral rho of x d x. So again plot x beyond this there is no electric field because a charge is from here, so electric field is integration so it is integration and adding rho of x d x. So you are going on adding segments like this rho of x d x which means it will increase as a triangle summing up different segments. So it starts from 0 here and then rho is so you are its negative because rho is negative. So this is 0, this is negative.

I have assumed that there is a constant distribution uniform distribution, normally in an abrupt normally there is a little bit of gradient but for simplicity I have assumed a uniform distribution. So when it comes here it is the you have added area which is all negative.

Now you add positive part of it which means, the sum will decrease. So the sum starts decreasing please see integration continues from this end to this end I am finding out electric field everywhere there are no chargers here. So, charge first start from here. So electric field is negative like this it comes you have added up to this then you are adding positive to a large negative number. So the negative number is decreased and therefore, the electric field is decreasing. So, the electric field comes down to 0. So this is electric field variation from this end to this end there is no electric field far away from the junction.

Electric field is only here what about the potential energy? V is equal to so d V by d x d V by d E is equal to minus d V by d x. So this implies the potential energy V the electric field is related to potential through d V by d x therefore, potential V, V of x is equal to minus integral E of x d x, V of x is equal to minus integral E x d x. So you further integrate now I want to plot V of x versus x it is minus of E x d x, E x d x is integration, this is again adding area here so but with the negative sign therefore, this is already negative with a negative sign it is positive therefore, the potential starts from here and it starts getting increased. So potential increases like this it increases till you reach up to a maximum.

So this is what I have plotted is V of x, V of x is simply minus E x d x integrations summing the area, just summing the area and area does not get subtracted here it was negative, here it was positive that is why it reduced and the field went like this but now it is continuously going up to this, this is potential what about potential energy? So potential energy E is equal to q into V that is minus E into V, V is positive, E is negative for electrons therefore, the potential energy if I plot E this is not electric field, this is electric field and this is energy. Let me write energy the corresponding potential energy is x and so this is the potential energy variation across the junction from 0 to some negative value because of charge migration because of charge migration across the junction, we now have a potential energy variation it is very simple.

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Now to realize the band diagram I am sure you all know this. So this was the band diagram before contact. Now because of charge migration from here and here the other way electrons migrating to this side and holes migrating to other side, there is a built-in potential and that corresponding potential energy variation is this therefore, now the total potential energy variation across the junction will be this plus in negative potential energy variation here across the junction, this is this axis is energy, the adjust correspond to potential energy because kinetic energy is 0 band adjust.

So this axis is energy plus there is a additional potential energy which is negative and therefore, if you add 1 plus 1 that is this plus this what you will get is the band diagram of the p-n junction and mathematics has already told us that fermi level remains a constant. This is how we got the energy band diagram. So this is E c this is E v of the p side and this is E c of the n side and of and this is fermi level. What I want all of you knew this but what I want you to see is only this point, this is very important now to see the p-n junction variation band diagram to get the band diagram of a heterostructure, that this has come because there was a potential energy variation like this, before charge migration and due to charge migration there is a variation like this please see if this side was p what would happen?.

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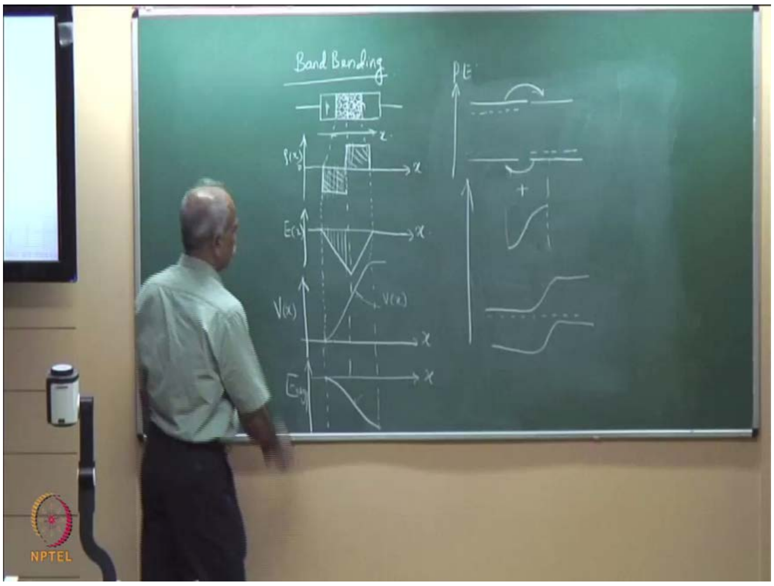


Let me erase this, this you have noted so suppose let me just take this side p, that is here I have n and this side is p. Now electrons from here would migrate here and holes from this side would migrate here, the charged distribution will reverse that is this side you will have positive, this side you will have negative. And therefore, when you integrate you will get a potential energy variation not like this, but the inverse of this that is you will get a variation like this. So if you have p on the other side and n on this side you will have a variation like this and correspondingly the band diagram will be, so we have the band diagram varying like this.

So given any junction whether p-n or n-p or p-n heterostructure we will see how to draw the band diagram energy band diagram. This is important because we will also see now that within heterostructures we have band gap discontinuities and this makes a difference because when you have p i n structures or p n p structures, then there are potential barriers and potential wells which confine or which block the flow of carriers and they have profound importance in the characteristic of the device. So let me take now p-n junction of a heterostructure, a single heterostructure that is not double heterostructure. First let us see the p-n junction corresponding to a hetero junction and then we will see a double hetero junction and the potential barriers and wells which are created there are very important and crucial to the performance of the device.

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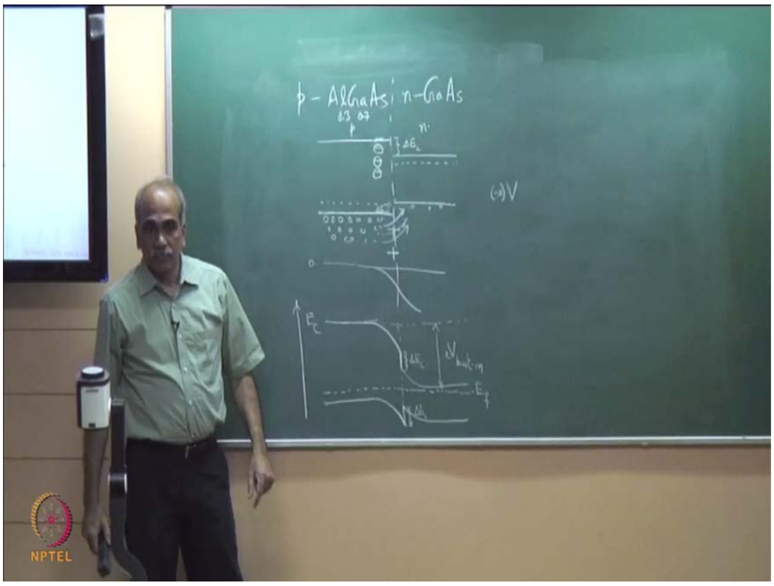


So let me take aluminum gallium arsenide let us say Al 0.3, gallium 0.7, arsenide and gallium arsenide. Let me take this as p-type junction between a p-n so here we are. So you have p-type gallium arsenide n-type and we know that there is a discontinuity approximately 65 percent and 35 percent. So this is n type gallium arsenide, if you take intrinsic material of aluminum gallium arsenide and gallium arsenide and there is no difference in the carrier concentrations then we have 35 and 60 65 and 35 the difference. If you have carrier concentration difference then there is flow of carriers and we will immediately have in addition a band gap variation, a potential energy variation that is this is p-type now and this is n-type and therefore, there are large number of electrons here and large number of holes here.

So you can see very large number of holes and there are very few holes here and immediately, when you make contact this will immediately, start going to the other side the air bubbles are moving to this region. So when holes move to this side this becomes so what you have here. So you will be left with negatively charged negatively charged immobile ions. Let me show in the band gap itself just so because of hole movement or it means electrons are coming from here to here hole is moving that side because electrons are coming this side, one additional electron makes the immobile ion negative that is why you have negatively charged immobile ions. So when this end becomes more positive compared to this end the potential energy decreases more positive.

Please see V is positive but multiplied by minus E is a negative quantity therefore, this end decreases and that is why if you want to find the net band diagram then we have a potential energy variation because of carrier migration. This is the potential energy variation because of carrier migration just now that we have seen this plus a band gap variation. So if we plot the sum of this two please see so we have a variation which is coming like this. So it has come this minus this, this is 0, this level is 0 and there is a negative.

So negative is added therefore, this is going down but when it has come to the junction there is a delta E c, there is a discontinuity here which is downward discontinuity which means I have come up to this and there is a downward discontinuity of delta E c because it is a heterojunction this minus this. So the band was bending like this. So when it has come up to the junction there is a downward discontinuity because of a heterojunction. So the same downward discontinuity will be shown here and then you continue with this. So this continues and finally, so this is the upper one E c I have shown this line only. So this plus this keep on adding this plus this, you come up to this there is a downward discontinuity and then again keep on adding.

So this will go like this, if the discontinuity where not there then it was like a original p-n junction this should have gone like this but because of this additional discontinuity, we have a discontinuity shown in this band, upper band let me draw the lower one it will become clear once the picture is so same gap I keep the same gap here. So this starts bending, it comes up to this. So its bending what will happen at this point? There is an upward discontinuity. So the band has an upward discontinuity and then it continues and the fermi level must remain the same E f, this discontinuity here is the same as delta E c which we had here and there is a delta E v here and this discontinuity here is delta E v. So the band diagram looks like this. So what has happened is one the built-in potential is much larger now, this is the built-in potential V built-in or E times if energy axis E times V built-in, some people just call it as built-in potential V sometimes because energy axis E times v built-in.

In a heterostructure you can see that the net barrier height has become much larger, the built-in potential is much larger. You can practice with the any types of any different types of any type of heterostructure, heterojunction a single heterojunction you what I have done is for p-n, you can do for n-p you can also have this smaller and this bigger.

So see what kind of band diagrams you get? Just practice that yes you are able to draw this p-n junction. So the discontinuities band gap discontinuities will now appear at the junction, the most important thing that we need is what will happen in a double heterostructure? We will encounter this later in a laser, but let me draw the band gap of a band gap variation of a double heterostructure.

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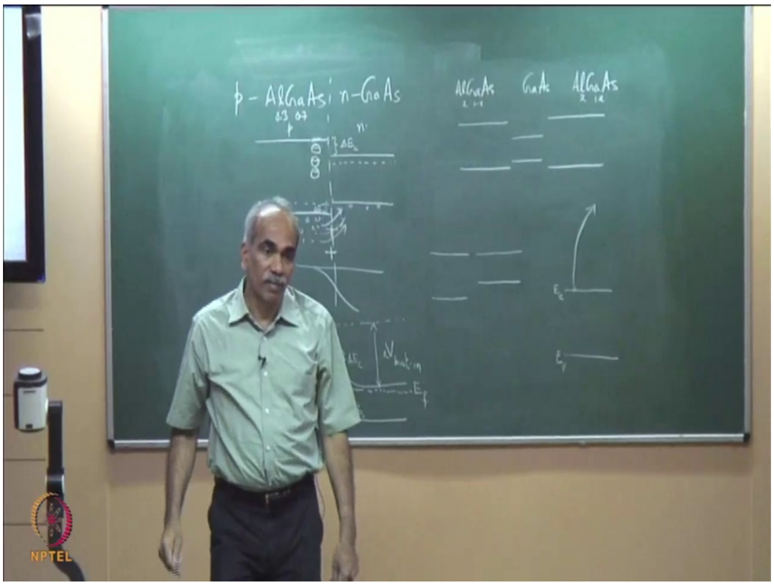

So again let me take aluminum gallium arsenide, gallium arsenide and aluminum gallium arsenide. You can have any composition x 1 minus x As x 1 minus x As same composition or something different it is possible to have different compositions also, so we have this and we have sometimes you may also have materials where the upper layers are aligned one of them may be like this and another may be like that, it depends on the material and the electron affinity, electron affinity of aluminum arsenide is much smaller compared to that of gallium arsenide. You know what is electron affinity? Electron affinity is the amount of energy required if this is E c and if this is E v amount of energy required to free it.

So in the case of aluminum arsenide it is a approximately 2.2 or 2.3 electron volts whereas, in the case of gallium arsenide it is about 4 electron volts that is why you see gallium arsenide is sitting below aluminum arsenide is up all right more details you can refer to books but let me draw the band diagram corresponding to this because this is a kind of structure which we will encounter, this is a double heterostructure which means a low band gap material is sandwiched between two high band gap materials.

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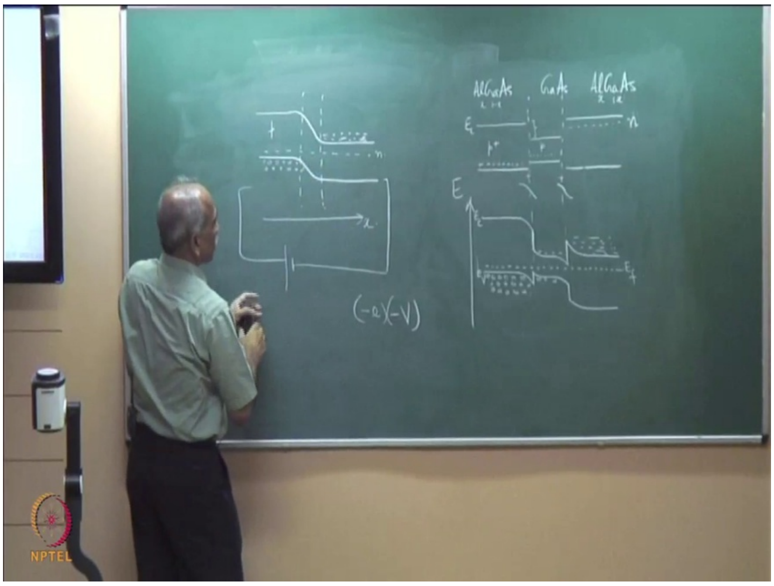


So this is a p-type. I have p-type here this may be let us say so this is p plus, this is slightly doped p, it could be intrinsic as well and this is n-type try yourself how the band diagram should vary? So there is a delta E c delta E v so at every junction. So this is like p-n so we have a variation which is like this. So plus this potential energy variation because of charge migration, this is also a p-n type of variation and therefore, I will have an plus at this junction also, we will have a potential energy variation and the last point is fermi level should become constant. When you make the final junction p plus p-n this is the typical structure for double heterostructure laser we will see later, that we have to draw the band diagram.

Let us start I am drawing this the upper one E c. So E c continues its reaching here therefore, it should start bending now, it bends exactly the bend as it is and then there is a discontinuity downward discontinuity delta E c downward discontinuity please see, this is the delta E c downward discontinuity. So I have a downward discontinuity and then this continues like this and then it is flat. So its flat now I meet the second junction here and therefore, there is a second potential energy variation. So this starts bending again like this at this point it has come here, so this is where I am please see I have passed this I have come here now there is an upward discontinuity.

So upward discontinuity because of this and then this continues, this is only the upper line exactly like this the lower part. So keep the same separation do not worry about fermi level let it come wherever it comes, it bends here the discontinuity is upward. So I have upward discontinuity then I continue further I come here there is a downward discontinuity and then I have the fermi level is constant and you can see that this is n here and this is about a little bit p, slightly p doped and this is highly p doped. What do you see in this structure? Compare to a normal single homojunction what do you see in a double heterostructure? That in the in that intermediate layer which is going to be our active region that you have a potential well you have a potential well here and we already had a potential well but there is a barrier.

So here you have full of electrons full of electrons, here you have large number of holes, some holes have migrated here and some electron has come here. So this is under no bias, this is a double heterostructure band diagram of a double heterostructure this is E this is E c E v and this is E f throughout. This is of the p side and similarly, E c of the n side, E v of the n side and this is the intermediate region. Let us see what happens? Why am I interested in double heterostructures? Once we know this then rest of the physics will follow when we discuss laser diodes we do not have to again come back to band diagram we know yes this is what happens. This had a major implications which led to the c w operation of a laser diodes and subsequently after many years recognized as one of the finest discoveries and noble prize was given, see such a simple idea if we take a homojunction, if we take a homojunction.

There are large number of electrons here and large number of holes here. This is the junction region the junction region or the active region. So there is a p-type and n-type, there are very little electrons and holes in this. So this is x special coordinate there are very little holes or very little electrons in this region which that is why we called it as a depletion region. If you followed by this which means you are applying positive to this side and negative to this side what would happen? This band would go up. Why would it go up? Because electrons are getting additional negative potential, it is negative but the potential energy becomes minus E into minus V is positive and therefore, that is why this band goes up as you apply forward bias this ends start going up. So when this ends starts going up in the same region.

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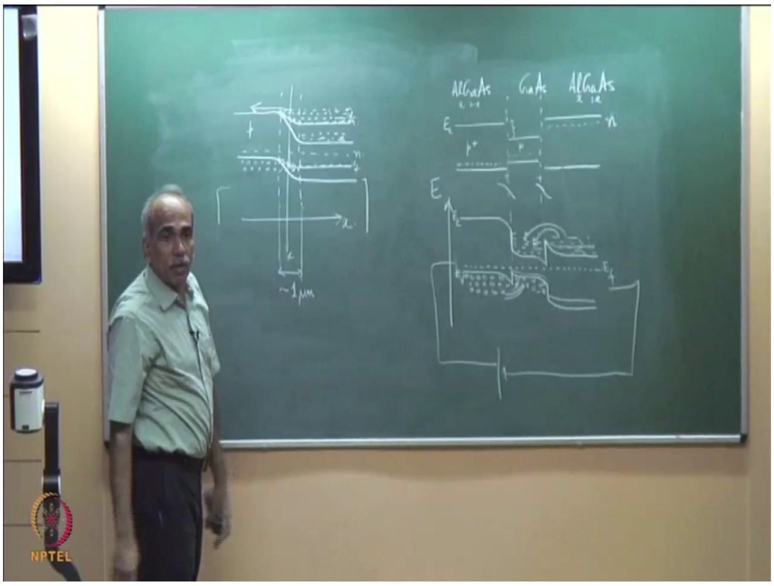

Let me draw in the same diagram I hope you can recognize it. So this has come up here and correspondingly this has come up here, this is with the forward bias with the E f this was without E f. So let me just put a double line to identify that this is after forward bias after forward, you can see water flow into this side which means now the electrons have come up to this, this has been lifted therefore, water is coming up to this and in this case the air bubble is coming up to this, that is holes have moved up to this and therefore, in this junction region now at any value of x, this is any value of x you have simultaneously large number of holes and large number of electrons. Earlier in this junction region you did not have electrons and holes. Now you have large number of electrons and large number of holes which recombine to form the current.

So you forward bias therefore, the carriers recombine and current flows in the external circuit. This is how the p-n junction would work but this region this variation here is approximately 1 micrometer in typical semiconductors, the width of the depletion region of course, it depends on the doping concentration if you if the doping concentrations are high the width of depletion region is smaller and the field is very high there but in general it is of the order of 1 micron, here what would happen if you forward bias? This would go up, this end goes up, you forward bias this, when this goes up electrons pour into this look at this water they are just you just lift this part.

And so water will come there electrons are getting poured. So we have large number of electrons, this end has started moving up, this also moves up because that end moves up, this end moves up and the holes because this end has moved up the holes also come here, large number of holes keep coming because this end also moves. However because of the discontinuity here there is a barrier for electrons, here there is no discontinuity there is continuous, there is no barrier if you forward bias is faster than the electrons will go over here and the current would be so high that the p-n junction will break down but in this case there is a barrier here. Therefore, the electrons are confined to this region and the holes are confined to this region, this region and this region carriers are confined to the junction region.

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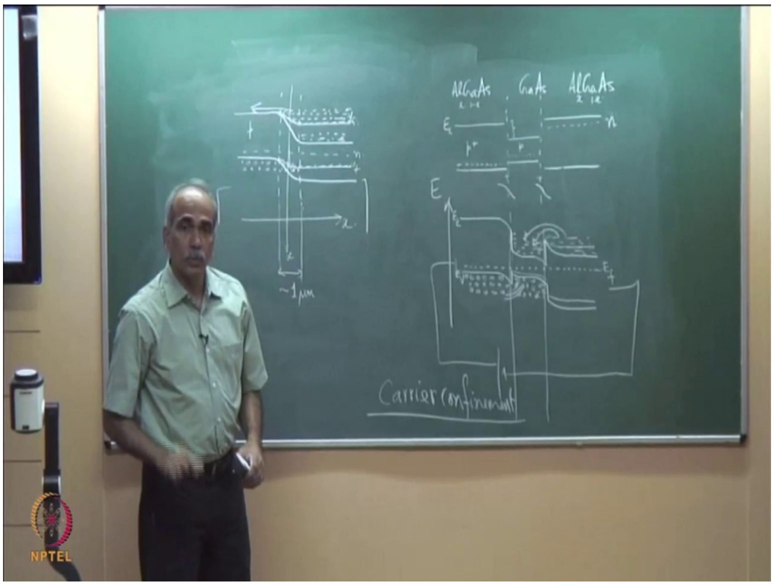


And the width of this is in your control because we have fabricated this double heterostructure, this width we have not got this width, this is because of depletion region because of carrier migration, here this is under your control you can make it 0.2 you can make it 0.1. So for the same current there are large number of electrons and holes in a very small volume, here for the same current, there are electrons and holes which have come, but the volume is larger in this case, because you have made this intermediate layer that you could and because of these barriers the electron was not moving this side, because of this barriers the carriers are confined this is a very, very important advantage of heterostructures. So, this is called carrier confinement there are other advantages we will discuss later.

So what is the point? For the same current you have very large number of carriers in a small volume which means the carrier density is very high as we will see later. The gain of the medium is dependent on carrier density. So if you can have a large carrier density for a small current you can get very high gain for a small current. This is the importance of double heterostructures.

Therefore, if you understand this band diagram and see that how the discontinuity helps in confining the carriers then you can appreciate that the discontinuities help in building very large current densities even for small actual current i through the device. So by passing a small current you can get very large current density because this thickness you have controlled at the time of fabrication. This is the importance of double heterostructures. So please understand drawing of the band diagram and the discontinuities are very important they are the ones which are responsible for the barrier see this one.

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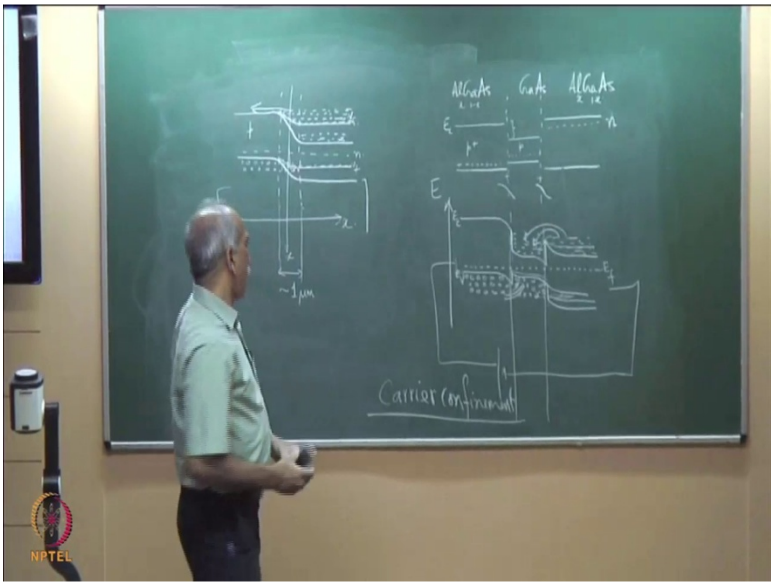


Otherwise, if this barrier was not there this should have been continuing like this in a homojunction and then that the hole would have come here. So you are not able to confine it to a small region, this is one advantage, there are more advantages which we will discuss when we take up actual double heterostructure devices. So carrier confinement have illustrated for a double heterostructure. In the next class we will discuss about Schottky junctions and ohmic contact. The last of the basic topics which are required to understand the device physics, device and operation of the device and then in part two we will discuss about how to realize actual devices? Will stop here.