Semiconductor Optoelectronics
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Lecture-14
Heterostructure p-n junctions

Good morning let us start with the hetero structure p-n junctions this lecture on hetero structure p-n junctions.

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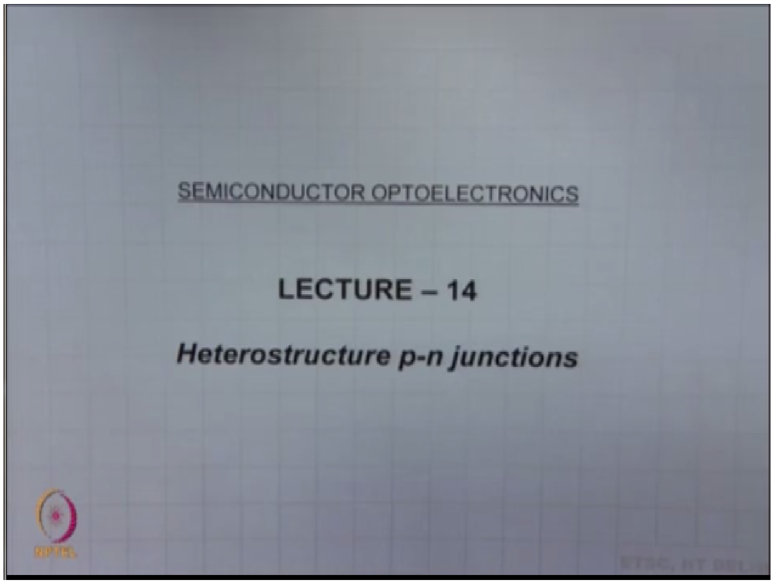

SEMICONDUCTOR OPTOELECTRONICS

LECTURE – 14

Heterostructure p-n junctions

We are familiar with the p-n junctions semi conductor material has such semi conductor material has such is not of much use in any application probably one of the applications were one directly uses semi conductor is a photo conductor we will see later photo conductor 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 semi conductor 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 make any switching there should 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 hetero junctions behave or the band diagram of hetero junctions in the case of hetero structures, band diagram of p-n junctions in the case of hetero structures.

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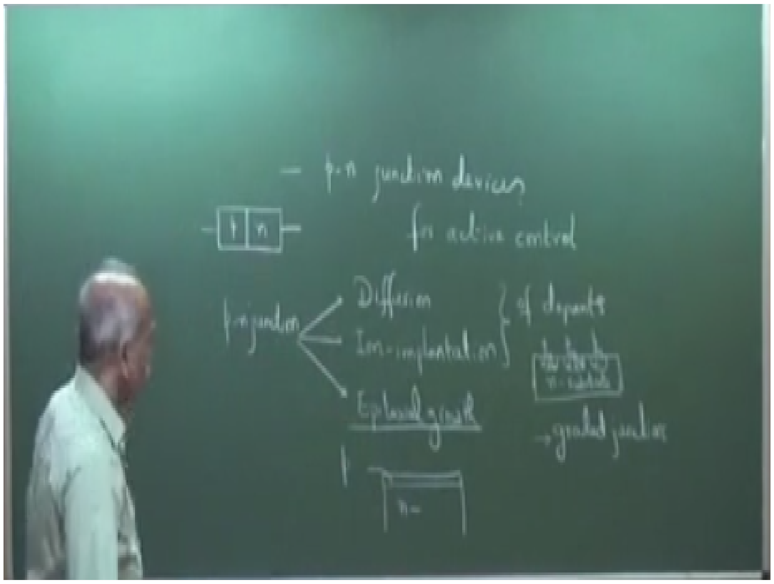

So, the first point is that p-n junction devices, junction devices for active control, control of carriers that is control of current for active control. The second point is when p-n junctions are fabricated or p-n junctions are formed there are usually there are 3 processes which are used for p-n junction. One is diffusion I have briefly discussed about this diffusion Im-implantation and of course epitaxial growth.

Diffusion and Im-implantation of dopants as we discussed you start with the 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 is primarily p if you are doping p material. In Im-implantation there are ion beings which are implanted into the substrate.

But in both cases what you note is the junction is graded it is not an abrupt junction it is graded junction, so both the processes lead to graded junction. Graded in terms of carrier concentration in terms of dopant concentration but epitaxial growth in a epitaxial growth we have already discussed in details you start with the substrate let us say n substrate and then you dope you deposit a layer maybe n+ 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 latest stage. But this is regarding the growth and type of p-n junctions in terms of material and structure.

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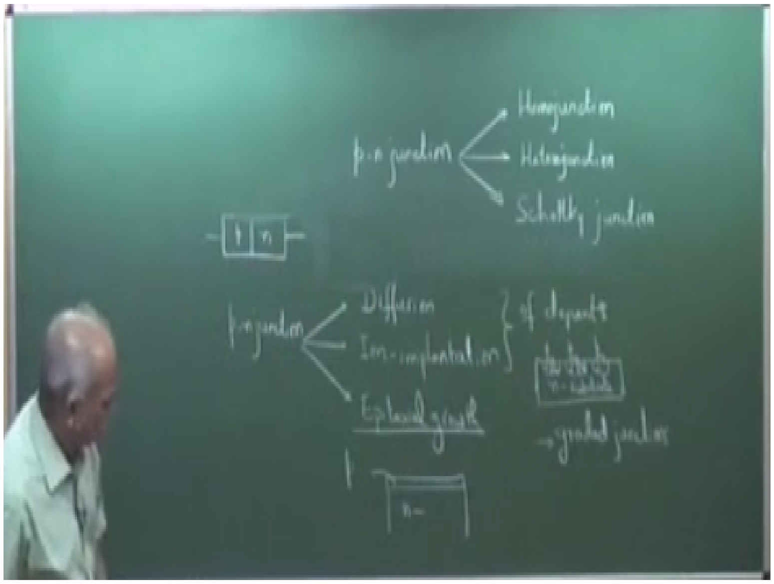

The second type, second type of classification here is homo junction that is junction between same material but p doped n, n doped material, p type silicon, n type silicon, hetero junction, junction between dissimilar materials hetero junction u u and v the different band gap and also schottky junctions this is junction between metal and a semi conductor when you make the device finally you need metal layer for contact and you will always a schottky junction.

And we will see how schottky junctions can behave both as rectifying the junction as well as ohmic contacts that will be our next discussion. So, this classification is based on process and this classification based on structure let me quickly recall the band diagram the energy band diagram.

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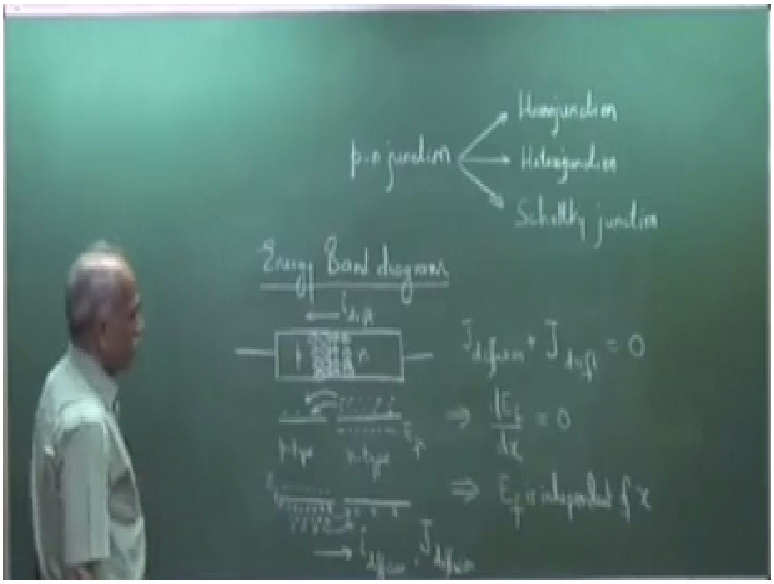

So, energy band diagram is obtain we have a p type material, so this is the p-n junction p, n it a Metrologic contact p-n p type material, n type material and if you draw the let me first discuss one more junction if you draw the energy band diagram before contact p type will have Fermi level somewhere here and n type has Fermi 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.

Now very few electrons here there 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 regions 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 or 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 cleans 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 is these are negative immobile ions. The depletion region and therefore there is a built-in potential here potential difference which leads to drift current wherever 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 a 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 drift current at equilibrium I diffusion.

So, J diffusion+J drift equal to 0 mathematically you can show this corresponds to if you have Eft here and Efn here you can show that this implies def/dx I am showing 1 dimensional x direction df equal to 0 this implies this is pure mathematics and this shows that Ef is independent of x this is a 1 dimensional picture x is in this direction Ef is independent of x which means Ef 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 Ef 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 will the band will bend.

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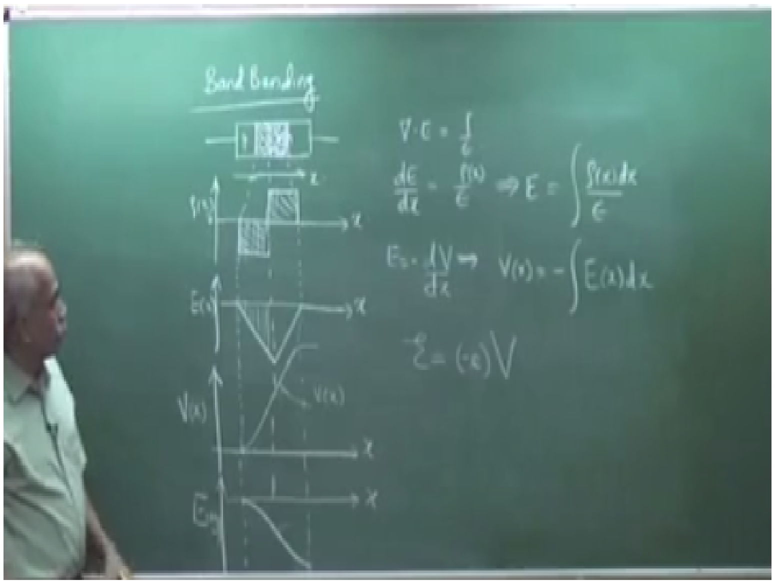

So, let us look at this again band bending some elementary let me redraw these okay let me draw here p type and n type also a little wider depression range here, so you have negative immobile ions here is a quick revision because this is important for us to see the band bending in hetero structures that is why I am just repeating all of you are aware of this, so there is charged distribution here and therefore we use gausi law delta E is equal to row/ upsilon or in one dimensional I can write dE/dx x is this by direction, de/dx is equal to row/ epsilon.

Row is the carrier density charged density so, this is row affects in one dimension actually row is volume density but in a one dimensional simple picture dE/dx is equal to row of x by upsilon which means this implies E the electric field E is equal to row of x dx/upsilon is the simple integration, so we have. So, if I want to plot row of x here, so this direction is x row is negative here I assume that so corresponding to this.

So, there negative row affects and positive row affects, so what are plotted here is row affects this is row is negative, negative charges and here positive charges so this is row affects the electric field if you plot the electric field now Efx is simply integral row affects dx, so again plot x beyond there is no electric field the charge is from here, so electric field is integration, so it is integration and adding row of x dx.

So, you are going on adding segments like this row of x dx which means it will increase as a triangle summing up different segments. So, it is starts from 0 here and then row is so you are it is negative because row 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 gradient but for simplicity I have assumed a uniform distribution.

So, when it comes here it is the you have added area which is are negative now you add positive part of it which means the sum will decrease, so sums starts decreasing please see integration continues from this end to this end and mining out electric field everywhere there are no charges here. So, in charge first starts from here, so electric field is negative like this it comes you are added up to this then you are adding positive to a large negative number.

So, the negative is decreasing 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 dv/dx, dv/dE is equal to –dv/dx so this implies the potential energy v the electric field is related to potential through dv/dx.

Therefore potential v, v of x is equal to –integral e of x dx, v of x is equal to –integral ex dx, so you further integrate so now I want to plot v of x versus x it is –of Ex dx, Ex dx is integration this is again adding area here. So, but with the negative sign therefore this is already negative with the negative sign it is positive therefore the potential starts from here and it is 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 –Ex dx integration summing the area just summing the area and does not get subtracted here it was negative here it was positive that is why if the due stand the field went like this but now it is continuously going up to this, this is potential what about potential energy. So, potential energy is equal to q into v that is –v 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 okay let me write energy. The corresponding potential energy is x and so this is a potential energy variation across the junction from 0 to sum negative value because of charge migration. Because of charge migration across the junction we now have the potential energy variation this very simple now to realise the band diagram.

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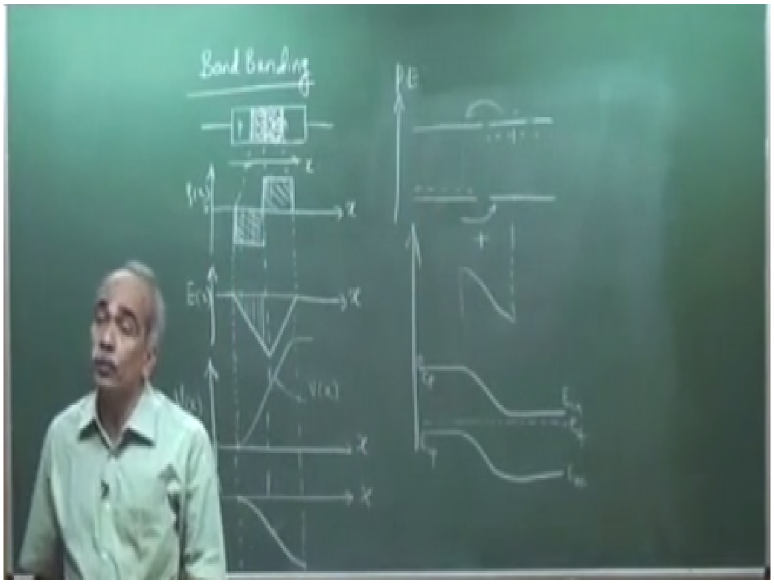

I am sure you all know this, so this was the band diagram before contact now because of charge migration from here and here electron migrating to this idea and holes migrating to other side there is a built-in potential and that corresponding potential energy variation is this therefore now the total potential energy variation across the junction will be this + a negative potential energy variation here across the junction.

This is this axis is energy the edges correspond to potential energy because kinetic energy is 0 band edges. So, this axis is energy+there is a additional potential which is negative and therefore if you add 1+1 that is this+this what you will get is the band diagram of p-n junction and mathematics as already told us that Fermi level remains a constant, this is how we got the energy band diagram. So, this is Ec this is Ev of the p side and this is Ec of the end side.

And this is Fermi level what I want why if have to use this but what I want to 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 hetero structure 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 okay let me erase this, this you have noted.

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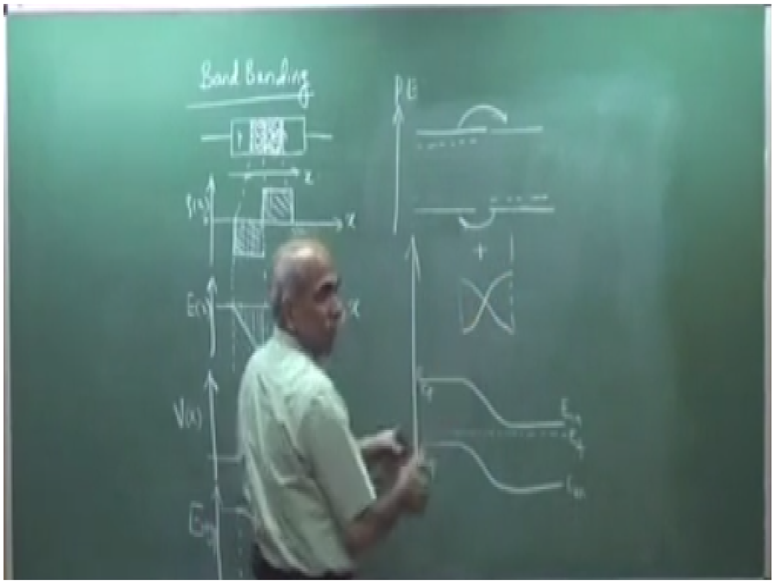

So, suppose let me just make this side p that is here I have n and this side is p, now electrons from here would migrate here and holes from this side would migrate here the charge distribution will reverse that is this side you will have positive this side you will have negative and therefore when you will get a potential energy variation not like this but the inverse of this that is you will get a variation like this.

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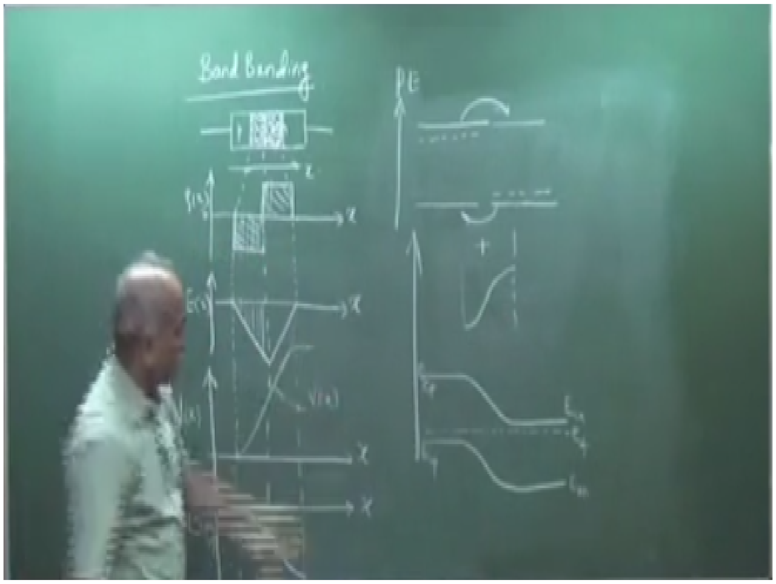

So, if you have p on the other side and n on this side you will have a variation like this and correspondingly the diagram will be.

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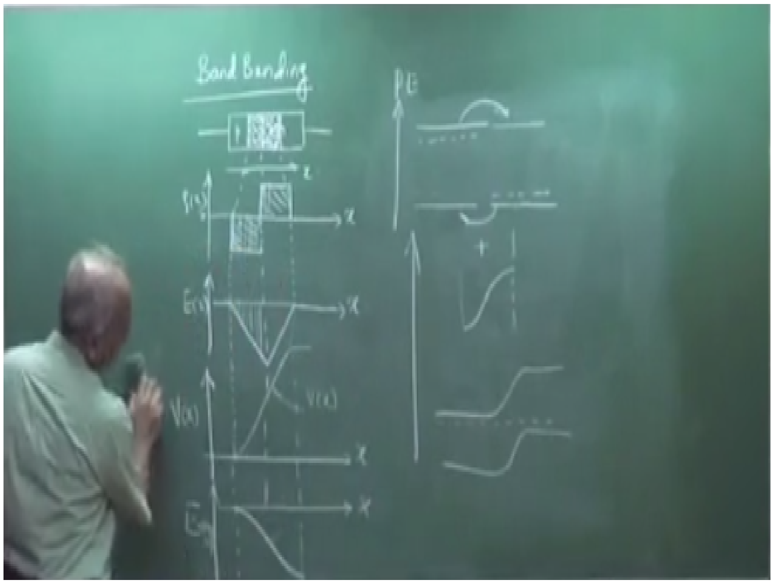

So, we have the band diagram vary in like this, so even ay junction whether p-n o n-p, p-n hetero structure we will see how to draw the band diagram energy band diagram. This is important because we will also see now that within hetero structures we have band gap discontinuities and this makes a difference because when you have p i-n structures or p and 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 hetero structure a single hetero structure that is not double hetero structure 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 okay.

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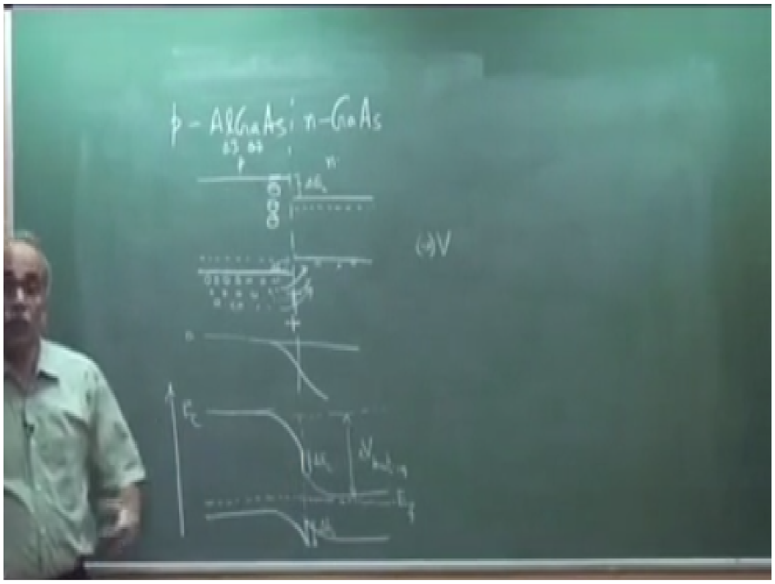

So, let me take alluminum gallium arsenate, let us say Al 0.3, gallium 0.7 arsenate and gallium arsenate let me take this as p type junction between a p-n, so here we are, so you have p type gallium arsenate n type and we know that there is a discontinuity approximately 65% and 35%. So, this is n type gallium arsenate if you take intrinsic material of alluminum gallium arsenate and gallium arsenate and there is no difference in the carrier concentrations.

Then we 35 and uhhh 65 and 35 the difference if you have carrier concentration difference then there is flow of carriers and we will immediately have in addition the band gap variation the a potential energy variation that is this is p type 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 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 compare to this end the potential energy decreases more positive please see v is positive but multiplied by –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+a band gap variation. So, if you plot the sum of these 2 please see, so we have a variation which is coming like this, so it has come this – 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 comes to the junction there is delta Ec 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 Ec because it is a hit way junction this–this so the band was binding like this, so when it has come up to the junction there is a downward discontinuity because of a hetero junction.

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 is I have shown this line only, so this + this keep on adding this+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 were 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 you know. So, this starts bending it comes up to this so it is 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 Ef this discontinuity here is the same as delta Ec which we have here and there is a delta Ev here and this discontinuity here is delta E. So, the band diagram looks like this, so what does happen these 1 the built-in potential is much larger now this is the built-in potential v built-in for E times if it is energy axis E times V built-in some people just call it as built-in potential v sometimes because of energy axis E times v built-in.

In a hetero structure you can see that the net barrier height has become much larger the built-in potential is much larger, you can practise with the any types any different types of any type of a hetero structure hetero junction a single hetero junction you what I have done for p-n you can do for n-p you can also have this smaller this bigger, so see what kind of band diagrams you get just to practise that yes you are able to draw this p-n junction.

So, the discontinuities band gap discontinuities will now at a at the junction the most important thing that we need is what will happen in a double hetero structure we will encounter this later in a laser but let me draw the band gap of a band gap variation of a double hetero structure.

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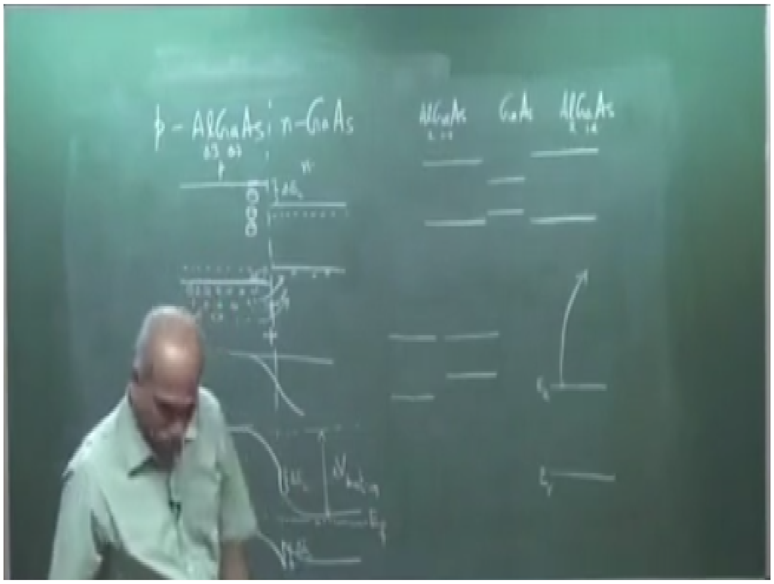

So, again let me take alluminum gallium arsenate, gallium arsenate and alluminum gallium arsenate you can have any composition x, 1-x, ax, x,1-x ax same composition are something different it is possible to have different compositions also. So, we have this and we have sometimes you may also have materials were the upper layers are aligned one of them maybe like this and another maybe like that it depends on the material and the electron affinity.

Electron affinity of alluminum arsenate is much smaller compare to that of gallium arsenate you know what is electron affinity. Electron affinity is the amount of energy required if this is Ec and if this is Ev amount of energy required to free it. So, in the case of alluminum arsenate it is approximately 2.2 or 2.3 electron volts whereas in the case of gallium arsenate it is about 4 electron volts. That is why you see gallium arsenate is sitting below alluminum arsenate is up alright more detail it is a you can refer to books.

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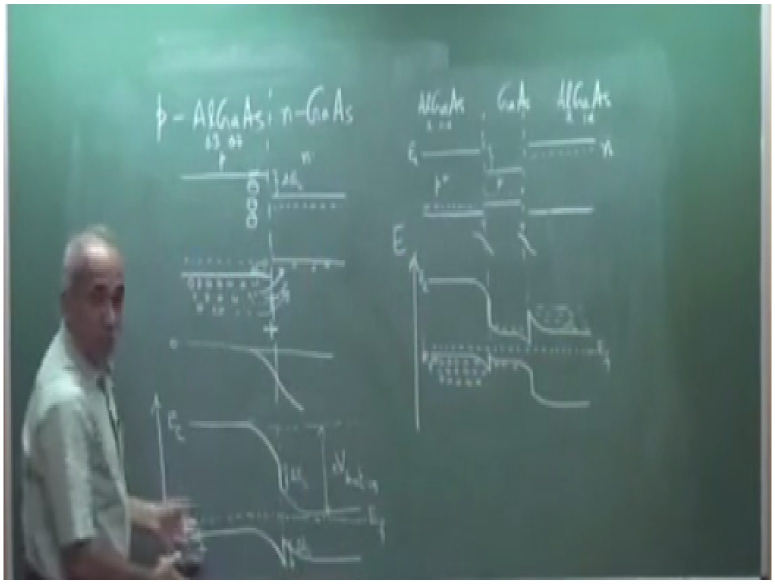

But let me draw the band diagram corresponding to this because this is the kind of structure with we will encounter this is a double hetero structure which means a low band gap material is sandwiched between 2 high band gap materials. So, this is a p type, so I have p type here this maybe let us say so this is p+, this is slightly doped p it could be intrinsic as well and this is n type n.

Try yourself how the band diagram should vary, so there is a delta Ec, delta Ev, so at every junction so this like pn so we have a variation which is like this, so + this potential energy variation because of charge migration this is also a p-n type of variation and therefore I will have an + at this junction also we will have a potential energy variation and the last point is Fermi should become constant when you make the finer junction p+p-n this is a typical structure of a double hetero structure laser we will see later.

That we have to draw the band diagram let us start, so I am drawing this the upper one Ec, so Ec continues it is 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 Ec downward discontinuity please see this is the delta Ec downward discontinuity. So, I have a downward discontinuity and then this continues like this and then it is flat so it is flat.

Now I make the second junction here and therefore there is a second potential energy variation to this starts bending again like this. At this point it has come here, so this is where I am please see I have pass this I have come here now there is an upward discontinuity, so 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.

So, it bends here the discontinuity is upward, so I have an upward discontinuity then I continue for the 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 this is about a little bit p, slightly p doped and this is highly p doped what you see in these structure compare to a normal single homo junction what do you see in a double hetero structure 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 you already had a potential well but there is a bad here, so here you have full of electrons here you have large number of holes some holes are migrated here and some electron has come here. So, this is under no biase is a hetero structure band diagram of a double hetero structure this is E, this is Ec, Ev and this is Ef throughout this is of the p side and similarly Ec of the n side Ev of the n side and this is the intermediate region.

Let us see what happens why am I interested in double hetero structures, once we know this then rest of the physics will follow when we discuss the laser diodes we do not have again come back to band diagram we know yes this is what happens this had a major implications which let to the CW operation of laser diodes and subsequently after many years recognised as one of the finest discoveries and a noble prize was given see such a simple idea.

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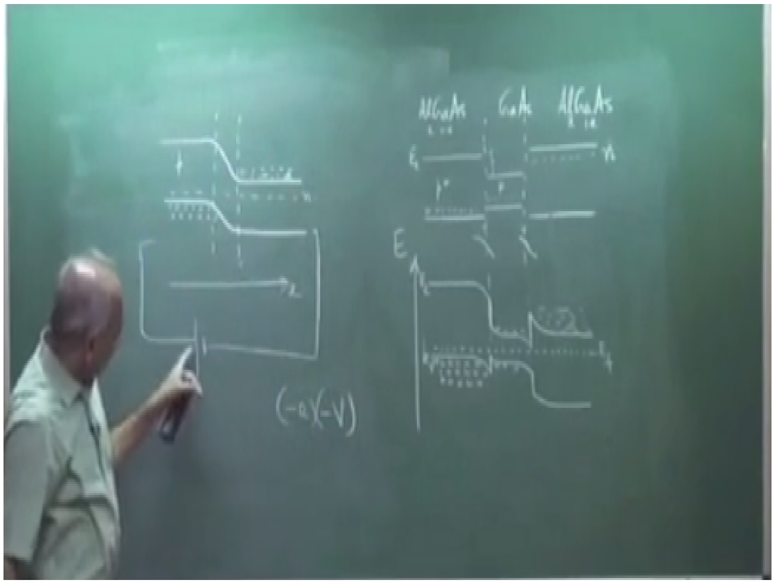

If we take a homo junction there are large number of electrons here and large number of holes here this is the junction region the junction region of a active region. So, this is a p type and this a n type there are very little electrons and holes in this so this x special coordinate they are very little holes or very little electrons in this region which that is why we called it as a depletion region.

If you forward biase 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 –v into –v is positive and therefore there is why this band goes up as you apply a forward biase this n starts going up.

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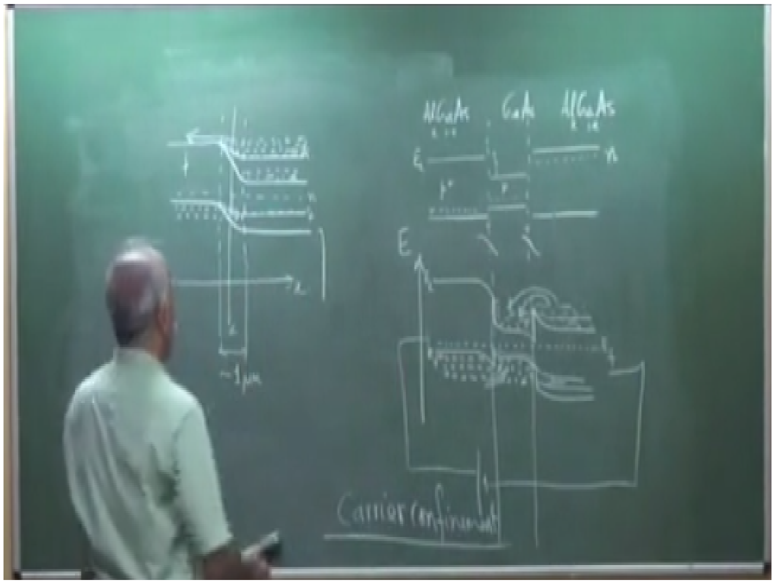

So, when this n starts going up in the same region let me draw in the same diagram I hope you can recognise it, so this has come up here and correspondingly this has come up here this is with forward biase with Vf. This was without Vf, so let me just put a double line to identify that this is after forward biase 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 are 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 biase therefore the carries recombined 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 micrometre in typical semi conductor the width of the depletion region of course it depends on the doping concentration if you if the doping concentration are high the width of the depletion region is small 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 biase this would go up this end goes up you forward biase this when this goes up electrons pour into this right this water we are just, so you just the 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 comes 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 this continuous there is no barrier if you forward biase is faster, then the electrons will go over here and the current would so high that the p-n junction will break down.

But in this case there is a barrier here therefore the electrons are confirmed to this region and holes are confined to this region this region and this region carriers are confined to the junction region and the width of this is in your control because we have fabricated this double hetero structure 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 make it point 2 you can make it point 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 this barriers the electron was not moving this side.

Because of this barriers the carriers are confined this is a very very important advantage of hetero structures. 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 hetero structures, therefore if you understand this band diagram and see that how the discontinuity helps in confine the carriers then you can appreciate that the discontinuities helps in building very large current densities even for small actual current high 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 hetero structures, 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. Otherwise if this barrier was not there we should have been continuing like this in a homo junction.

And then that you hole could have 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 the actual double hetero structure devices. So, carrier confinement have illustrated for a double hetero structure, in the next class we will discuss about schottky junctions and ohmic contact the last of the basic topics are required to understand the device physics device. And operation of the device and then in part 2 we will discuss about how to realise actual devices.