Semiconductor Optoelectronics
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Lecture-15
Schottky Junction and Ohmic Contacts

We come to this last part of the talk of review talk and we will discuss schottky junctions and Ohmic contacts.

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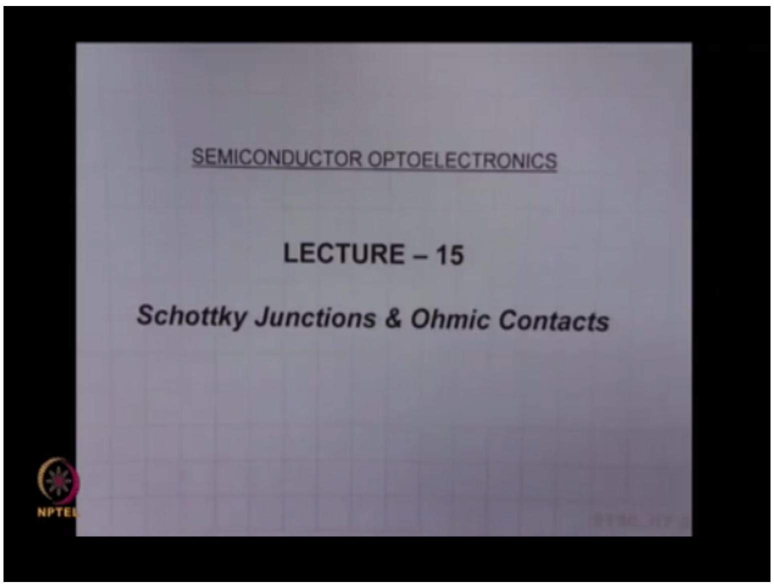

And we will see why it is important in the device.

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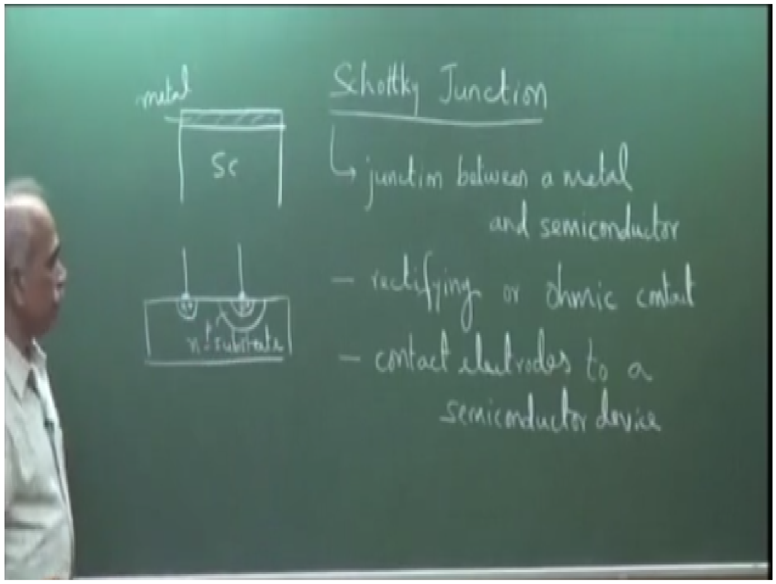

So, schottky junction refers to it refers to junction between a semi conductor and a metal, junction between a metal and semi conductor has we will see the junction could be this could be rectifying it could be a rectifying contact rectifying or Ohmic it could be a rectifying contact like a normal diode or it could be an ohmic contact we will see more on it as you can appreciate this important because it is the it provides contact electrodes or metal contact to the semi conductor.

So, it is important because of contact electrodes to a semi conductor device therefore metal semi conductor junctions are important in device characteristics, so let me briefly talk about this, so it is a junction between a metal and semi conductor, so a semi conductor here and it is a junction so it could be in plain or epitaxial growth it could be a metal layer grown on a semi conductor this is metal or it could be so this is let us say n substrate omega p and junction by diffusion.

So, you do n+ diffusion here and then a metal and you can have p+ so p+ diffusion. So, normally you see that in an n substrate you diffuse first p and then near the contact you either have p+ or n+ at the contact, why is this, we will see from the characteristics. So, let us see, what do I mean by rectifying contacts and ohmic contacts. So, rectifying contact as the name indicates it refers to a contact which allows current flow in 1 direction but blocks it in another direction as it is done in a diode.

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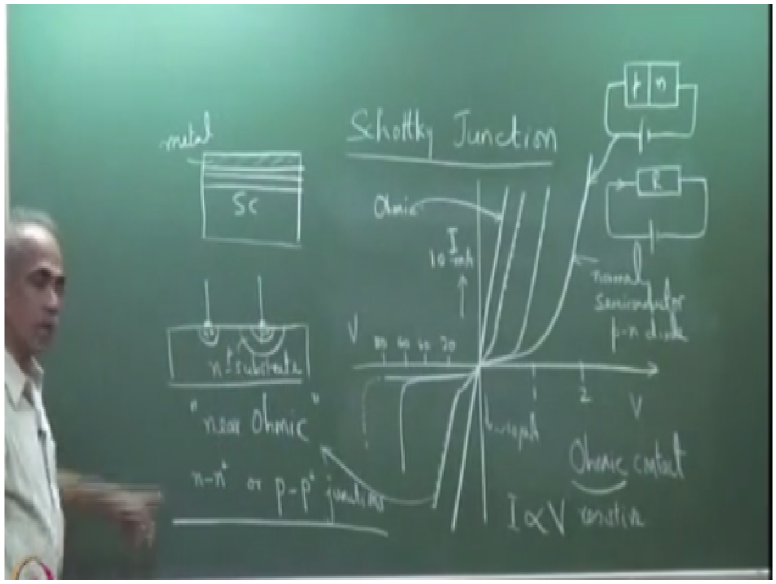

So, if I draw the IV characteristics, so this is voltage versus I current for a device, so if you take a diode we know that the forward characteristic and the reverse characteristic and then almost saturated and finally of course it breaks down. So, this is a typical a normal diode characteristic normal semi conducted diode p and I forward characteristic and reverse characteristic. We will see that when you make a schottky junction then the characteristic normally of course it depends on what kind of a.

So, it starts to go up a little earlier and similarly at the breakdown also it tends to come up come down a little earlier why it happens we will see and what is an ohmic contact, so as you can see this is a rectifying contact because in the forward direction we have good amount of current because if you see the real scales these are in milli amperes tens of milli amperes and the reverse that we see is typically tens of micro amperes.

So, this is tens of micro ampere and this is tens of mill ampere typical diode characteristic which means the current easily flows in the forward direction beyond a certain voltage and it is inhibited in the reverse direction or the current is very small and this they call us rectifying contact or rectifying behaviour characteristic. Now an ohmic contact as the name indicates ohmic which means it is resistive basically resistive for so, ohmic contact which means the current is proportional to the voltage.

So, I is proportional to v and therefore we expect a linear curve, so a linear irrespective of the direction this is pure ohmic the ohmic device if you take a resister for example it is an ohmic whether you take the resister R here and pass current in this direction or in that direction or alternatively if you apply a potential battery in this direction or the other way it does not matter the current behaviour is the same on the either side.

Hence the name ohmic whereas for a diode it does matter, so forward bias and reverse bias does matter to this corresponds to forward bias which is elementary recalling. So, if you so if you take a p and then this corresponds to the forward bias here whereas if you reverse bias the characteristic will like this, this will be tens of holes here and this will be 1,2,3,4 of that all just a couple of holes typical numbers if I want to put this maybe 1 volt this maybe 2 volt.

And if I want to put some typical numbers here this could be 10, 20 or 50, 100 so depends 20, 40, 60, 80 volts reverse volt and as I have written it is therefore you can clearly see that the forward flow is very easy a small voltage applied gives you tens of milli amperes here even if you apply tens of voltages, tens of volts as reverse bias your current is only tens of micro amperes let us for an ohmic contact it is identical it is the same.

In fact in the scale would be same for an ohmic contact it is not really a straight line as I have shown here for this scale the scale has to be identical for ohmic contact in between there are near ohmic, so near ohmic contact and they look like this. So, the curve let me also put a dash line along with a just to differentiate near ohmic contact, so this is near ohmic contact not exactly a straight line but good flow of current is permitted on in both directions near ohmic.

And we will see that by taking a schottky junction there is a junction between metal and semi conductor it is possible to get a schottky behaviour, so this is the schottky characteristic which is slightly smaller built in potential here or it is also possible to have a near ohmic contact. The other methods of getting near ohmic contact include n, n+ junctions or p, p+ junctions, these also behaves like almost ohmic contacts, n, n+ semi conductor or p, p+ semi conductor.

So, before I go to the schottky junction itself characteristics let us first see this n, n+ how is the characteristic qualitatively we will see how is the characteristic of n, n+ and p, p+ whether they behave like why I am interested you can see that here is a n, n+ and then to the metal. Similarly p, p+ and then to the metal same thing you will see in upper electronic structures or almost all devices will have the metal just before the metal there will be a p+ or n+ material.

And then there will be p or n, so you will have a p to p+ and then p+2n to the metal similarly at the other end you will have n+2 the metal and n2, n+. Because they form here ohmic almost very good ohmic contact how do they form we can see from the band diagram. So, from this diagram what I have try to illustrate is what do we mean by schottky junction and ohmic contact what are the characteristics how does it come is very easily understood although qualitatively from the band diagram energy band diagram.

So, that will mine next task, so let us look at the band diagram of an n, n+ semi conductor and exactly like that you can see p, p+ semi conductor, you can try yourself how it would look like why n, n+ would behave like in near ohmic contact and.

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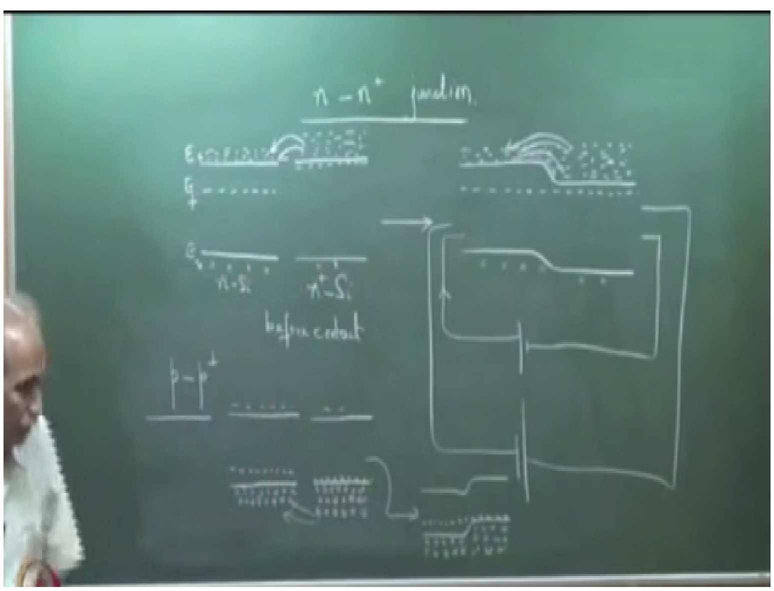

So, n, n+ n+ junction energy band diagram, so before contact this is a n semi conductor whatever it could be could be n silicon and you have an n+ silica so, highly doped, so in the time we will not write Ec, Ev you know what we are referring to so this is n+ silicon + standing for highly doped there is nothing will I get p+ there is nothing like an n-, p, p+ + standing for highly doped this is nothing like n-, n silicon, n+ silicon how do we expect to the band diagram to be when we link the 2.

Remember that this means there is plenty of electrons here it is very, very simple to imagine plenty of water this is also entitle, so there is an few holes here holes, electrons. So, you can see a carrier concentration difference what are here is more from what are would start flowing here electron has a higher concentration there, so it will start migrating to this when a contact is made this is before contact.

So before contact when electron flow to this side this side will become positive which means lower potential energy positive or this side becomes negative which means higher potential energy and therefore lower potential energy means this would start coming down and you know that the ef has to be equal, so what we get is, so this is a n, n+ contact energy band diagram of the n,n+ contact.

Electrons have some electrons have flown here because of carrier concentration difference which has brought down the band here and you have very easy to imagine entrance of water see now junction if we applies a positive +, so forward bias an n, n+ junction is the forward bias which means this end is becoming more negative which means higher potential energy therefore this band will start pushing out if you forward bias in this, it is difficult to say which is forward which is reverse.

But if you connect the battery in this fashion then this will start going up which means more of water can flow easily if you lift this electrons will flow easily in this direction there is very little resist, so water can flow easily in this direction in other words current can flow through the circuit very easily, so the conventional current outside is like this the electron current inside the semi conductor is flowing like this what about negative?.

If you instead of this if you apply reverse bias this fashion then this will go down further because you are applying positive to this end, so electron potential energy will be reduced, so the band will go down now does not matter if this goes down water will flow from here to here if this goes up water will flow from here to here. The main point to see ease in both the places there are plenty of carriers there are plenty of electrons here as well as here.

In other words whether you forward bias or reverse bias the device characteristic that is IV characteristic is almost identical therefore it is near ohmic contact there is very little difference. So, that is why you make n n+ junction the smaller the resistive loss the better it is otherwise there will be potential drop across these junctions what about p, p+ exactly like this if you make p, p+ you can do it yourself and see that this time talking terms of hole currents.

So, this is p, p+, so in plenty of holes now air bubbles, so if you make contact then what will happen if you make contact these air bubbles will start coming here which means this end becomes more positive, so this is going from here positive and therefore this starts going up till you get then you please make it yourself then you will have till, so the majority carrier in this case is hole whereas majority carrier in this case is electron.

But the current flows predominantly due to 1 type of carriers, so same way you make this up make this down it does not matter in either way holes will flow from this side to that side or that side to this side because there are no barriers and there are plenty of holes on both the sides exactly like this plenty of electrons on both the sides lifting little bit this side that side does not make any difference and therefore these are near ohmic contacts.

Let us see the schottky junction now, so if you have understood how to plot the band diagram then most of the time at least qualitatively you can see what type of characteristic that you can expect. So, in the devices we always encounter p, p+ junctions n, n+ junctions and of course to give external contact electrodes to make contact to the contact electrodes we need semi conductor metal junctions.

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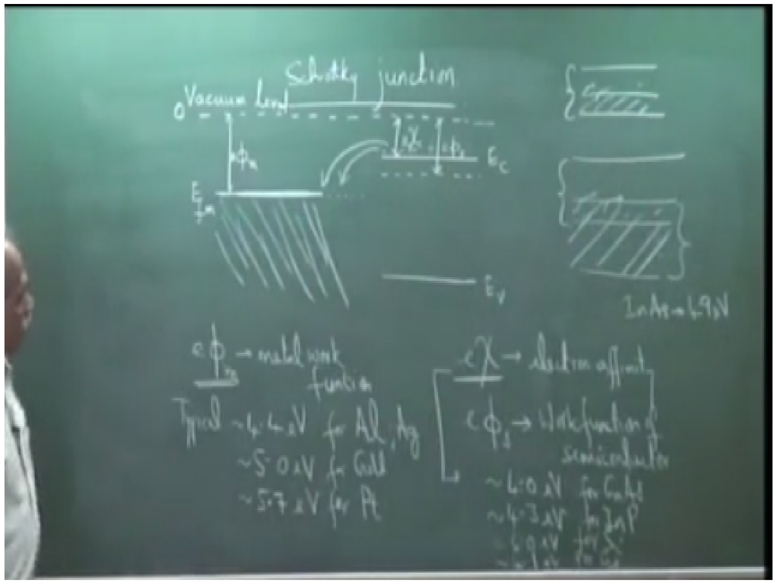

So, let us see the band diagram of a schottky junction, energy band diagram of schottky junction. A metal, metal is characterised by the Fermi function below which normally it could be due to 2 overlapping bands or it could be half filled band but it is characterised by a Fermi level Fermi function below which there are plenty of electrons or at 0 k all electrons remain below this, so typical this work function here okay let me draw this line has the vacuum level that is 0 ev it means this is 0.

So, typical work function here metal work function pie m 3 times higher if the potential pie is normally used as a notation for potential, so e pie m is the metal work function Ef of m fm m for metal Fermi energy for metal, so metal work function, typically so typical values let us have some idea about typical numbers so typical values approximately of the order approximately 4.4 ev for aluminium Al approximately 5 ev for gold, silver is also approximately same 4.4 Ev, 5 ev for gold and above 5.1 ev for I think approximately 5.1 ev or 5.7 ev for platinum.

Typical numbers of e 5 m work function of metals, so this is for Ag also alluminum and Ag approximately 4.4, 5 ev 5.7 ev for platinum. Let me draw a semi conductor here, so Ec, Ev and Ef somewhere if is it end doped then Ef is here and this energy is called the electron affinity E kei, so E kei is the electron affinity sometimes peoples called kei as the as the electron affinity, electron affinity.

And this is e pie s to work function of the semi conductor e pie s although normally we do not use a work function of the semi conductor but this is analogous to this we have work function of semi conductor. Typical numbers for kei of course pie s depends on whether you are doping n dope, p dope or n+ and so on. But kei has typical numbers for e kei is approximately 4 ev for gallimors night approximately 4.3 ev for em phosphate and even for silicon it is approximately 4, 4 ev for silicon for Si.

And about 4.1 ev for the germanium no space here 4.1 ev for germanium typical numbers. So, what you see is in general there are some materials for example indium arsenide this has 4.9 ev closer to matters but in general what you see is kei is smaller compare to the metal bug function, that is why I have shown this above this level in general but there are some variations and we will see implications what are it is implications.

So, when I want to found a metal semi conductor junction let me take this diagram itself metal semi conductor junctions. So, if I am forming a junction here then this is the Fermi level this is the Fermi level here this is a end type semi conductor which means there are plenty of electrons here, plenty of electrons here electrons are up to this level therefore electrons 4 into this, electrons will migrate here because this is a metal therefore there are large number of vacant states above.

It is generally as you know metals comprise of overlapping bands where you have bands overlapping, so this is the conduction band and this is the valance band when they overlap there are plenty of valance states here this is all filled plenty of electrons. But there are also plenty of vacant states therefore electrons can freely move through the vacant states, this is over lapping band or you could also have only half filled band which also means the same.

Half filled means what this is all filled this 1 band but this is completely full which means these are all empty the electrons can easily go to the empty state and move in the small application of potential they can immediately move that is why the conductivity is very high when you make a semi conductor and metal contact this will come down here what would be the result how would the band diagram change we can apply the same methods which we have seen for semi conductor how to when electrons migrate over here. This end will become positive and this will start coming down.

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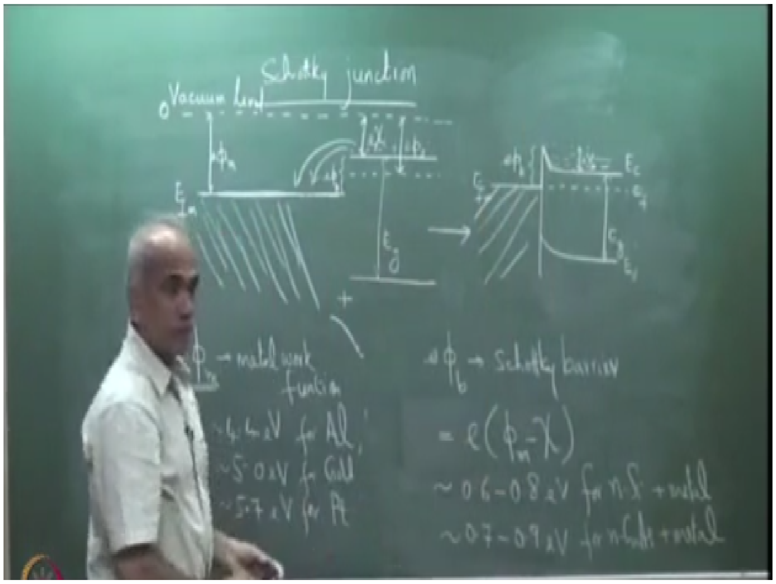

So, what will be the resultant band diagram this is the metal there was a discontinuity here you see there was a discontinuity this was e kei and this is e pie m this the discontinuity, so we have the discontinuity here this is the same as this, so this is actually e pie d this is called the schottky barrier. We will see and then because it has gone down the band starts bending because of migration you remember this has there is a potential energy variation like this here.

And therefore the band starts bend till the 2 Fermi levels that I had shown this little bit more because the gap, so I have similarly here so this is my Ev, Ec and Ef of the semi conductor this is Efm this is all filled with electrons, so Efm. So, we have simply added this but remember there are plenty of electrons it is as if p+ and n junction that is almost like p+ and n junction, so this side we do see this and therefore there is a built-in potential here what do you think this will be V built-in Vb or E times V built-in.

This barrier is called the schottky barrier E pie v please see if this is Eg then this will remain Eg this is Eg if this is some gap here far away from the junction then the gap should be same here. This is the barrier potential when you have made the contact there is a variation which has come because of charge migration but there is a potential barrier here because there was a discontinuity if I extend this up to this you can see there is a discontinuity.

And therefore this is the discontinuity that we have and this discontinuity is called E pie b is called the schottky barrier or pie b is called the schottky barrier potential, so if pie b schottky barrier what will be that be equal to in terms of pie m and kei it will be equal to E times pie n-kei. So, generally we see that because pie m is larger than kei generally this schottky barrier is a positive quantity.

Typically although it looks that it looks theoretically it looks that it is this much in general there are other considerations which come into play and schottky barrier is generally of the order of 0.6 to 0.8 electron volt for silicon and n, n silicon and metals n silicon+metal. And is generally of the order of 0.7 to 0.9 electron volt for n gallium arsenate+metal some idea about what kind of schottky barriers we have barrier heights we have theoretically it is this much.

But generally it does not come out exactly that much but it tells you that in general pie m is greater than kei and therefore there is a barrier. So, we have to see what is the implication of the barrier and how we can control the barrier and how we can get an ohmic contact out of this right what is the contact this is please see there are plenty of electrons here but there is a barrier. So, water cannot flow over there is a barrier unless you forward biase this.

Let me continue with that and try to see what happens if I forward biase and if I reverse biase and then we will understand how to realise schottky barriers which are nearly ohmic in nature. The barrier potential is approximately this but there is a interesting concept which will come we will forward biase this, forward biase this is n type.

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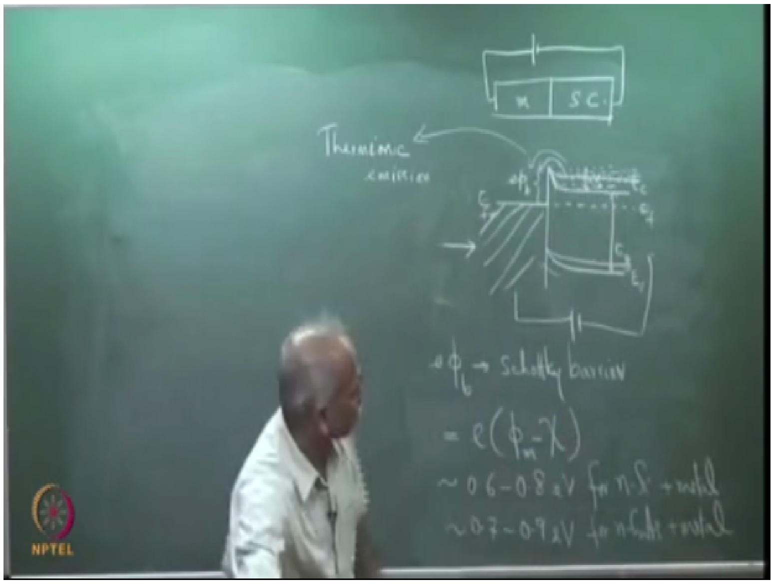

So, we apply, so the end side we are applying negative which means the energy will go up, so this band will start going up and electrons will pour over as this starts going up when I forward biase the new level is here let me show it with the slightly to distinguish let me draw after biasing the band looks like this. The upper one is after forward biasing, so what has happen the band has been lifted which means there were plenty of electrons here.

The electron because we are lifted the electrons are going over the barrier and pouring into this in fact these are called hot carriers because electrons of higher energy being injected into this side. So, as you lift this electrons go over a barrier when electrons go over a barrier to another side it is called thermionic emission this process is called thermionic emission.

We are studied thermionic emission where electrons are emitted from a heated filament its it is not necessarily need to be emitted it has to come out of a barrier there is a potential barrier jumping over a barrier is actually thermionic emission not necessarily you read the material and go. So, this is jumping over a barrier hence the name thermionic emission, so if you forward biase this junction current will flow through this junction this a metal semi conductor emission.

So, what we have in the conventional picture is this so this is the metal and this is the semi conductor and we have forward biased. There are very little holes here some minority carrier some hole current will be there because when you raise this there are very little holes some holes can migrate here and electron can call come down from here because this is a pool of electrons metal is a pool of electrons.

But primarily the current is predominantly due to electrons and due to thermionic emission what will happen if you reverse biase this will go down if we reverse biase if it is not confusing then let me show a reverse biase in the same diagram. So, that was forward biase the diagram is a little smaller. But what would happen this was without this was with forward biase.

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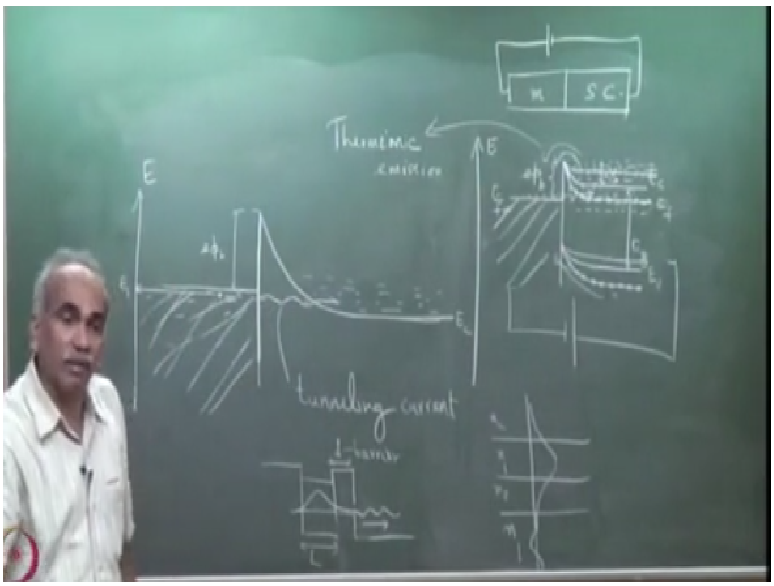

So, if you apply now the reverse biase which means we apply positive to this end electrons will have lower energy so the band will start coming down, so the band will now come like this, so let me show these with dotted line just to distinguish and similarly here this will also come down and the Fermi energy comes down. So, the lower band if you wish you could draw a separate diagram but I want to show in the same diagram.

Because you can see all of them simultaneously, so the electrons have come down further and therefore they cannot any more jump over the barrier, so there is a potential barrier remember that this axis is always energy, so there is a potential energy there barrier, so they cannot jump it has come down, so the electrons are here plenty of electrons are here but they cannot jump and therefore the current will be restricted current cannot move freely but there is some current which will come in this case.

One because it has come down whatever holes which were here they would immediately move up air bubble remember air bubble will go up because there is just been brought down so, air bubble is pushing up but more importantly there is a new current which comes which is called tunnelling current there are electrons here, electrons if they find let us say there are some electrons here if they find at the same energy there are vacant states or there are states permissible states.

Then electron can tunnel through this barrier now this part I will zoom in and show you more clearly I have zoomed in this part for reverse biase to this Ec of the metal and this is E pie v there are plenty of electrons there are electrons here it is a n type material but there are also vacant states there are electrons but there are also vacant states. Here there are plenty of electrons if remember that this axis is energy.

If I take a particular electron here, a particular electron it has energy equal to this much let us say this energy is E1 at E1 if I go to the other side there could be a vacant state there could be a vacant state here because electrons are there and electron and there are vacant states here. So, sometime there could be vacant states here at the same energy there could be vacant state but there is a potential barrier where there are no allowed states, allowed states are on this side.

I note allowed states here but the electron if it finds a state there then there is a probability of electron tunnelling to this side so this is called tunnelling current. This is tunnelling is a quantum mechanical concept I am sure the basic tunnelling all of you have studied at some stage or the other but the important point to see is if you have a potential well let us say there are electrons states which are permitted here and this is called this is the well and this is the barrier.

So, this part is the barrier let us say D is the barrier, barrier width and L is the well width, width of the well if you have a lower potential here which means at this value of energy if that can exist here then this has a probability of tunnelling into that region, it is of course please see let me draw this very carefully you have an evanescent tail here this is the solution which has an evanescent tail which is outside the well because it is a finite well.

The finite well has an evanescent tail at when it reaches here oscillatory solutions are permitted and this means the electron can exist here it can exist here, it can exist here because there is a evanescent tail here it is exactly those of you have studied optical wave lines it is exactly the same you have n1, you have n2 there is a wave the fundamental mode looks like this, oscillatory solution inside and exponentially decaying solution here.

If I now bring in a medium, so this was n2 if I now bring in a medium of refractive index and 1 here then it can have the same oscillatory solution here as well and therefore immediately this starts oscillatory which means the wave can oscillatory solution means it is a propagating solution, so you can have the wave in this region as well you can have energy coming into this region and this is called tunnelling this phenomenal is originally quantum mechanical phenomenal.

But it can be very easily illustrated in light experiments all the prism coupling experiments and directional couplers birth on this method. So, let us not go so much into this the important point is if there is a barrier then tunnelling is possible but the tunnelling probability is proportional to inversely proportional to the width of the barrier smaller the width larger is the tunnelling probability this is the quantum mechanical result which you can show smaller the barrier width larger is the tunnelling probability.

And if you look at this therefore in reverse biase the current is primarily due to tunnelling if I want to increase this right now tunnelling probability is very low because the barrier width is very large if I can somehow reduce the barrier width I have a very large probability of tunnelling and therefore I can increase the reverse time. So, how can I reduce the barrier width, so if I could somehow reduce the barrier width like this.

For example then the tunnelling probability would be much more because barrier width is much smaller, so I can have a much larger reverse current if I could reduce the tunnelling probability if I reduce the barrier width how to reduce the barrier width by doping this semi conductor heavily if you dope this semi conductor heavily then the barrier width will be reduced how?. So, let me draw the energy band diagram corresponding to the metal and a highly doped semi conductor right here.

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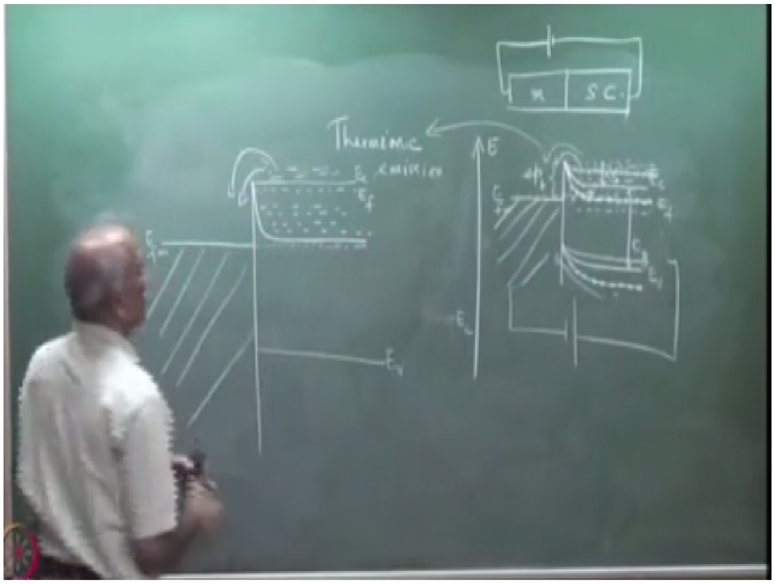

And then we see that the forward current is through we have the metal this is barrier, so we had the semi conductor highly doped and here is the Efm of the metal and Ef of the semi conductor. So, this Ec, this is Ef of the semi conductor Ev of the semi conductor, so as soon as the contact is made the Fermi level has to be align. So, electrons from here the electrons from here go over the barrier and get fold into there is no barrier.

Electrons get fold into this side and this band starts coming down because it is n doped it is n+ doped this is aligned now, there are plenty of electrons here. If you wish you can erase or you can draw a separate diagram.

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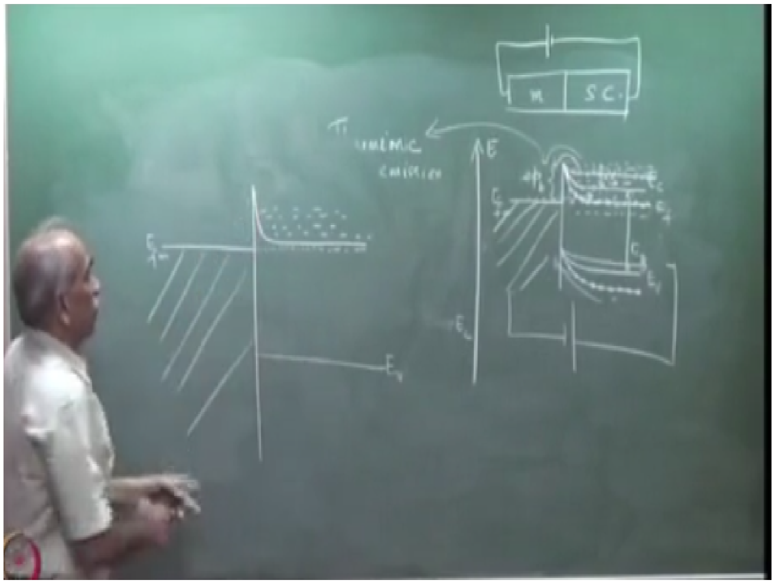

Because it was n + it had large number of electrons right here at this junction, so at the junction region the electrons are primarily have gone from the junction region the electrons are primarily have gone from the junction region and therefore this end has become more positive and you see the barrier has changed into.

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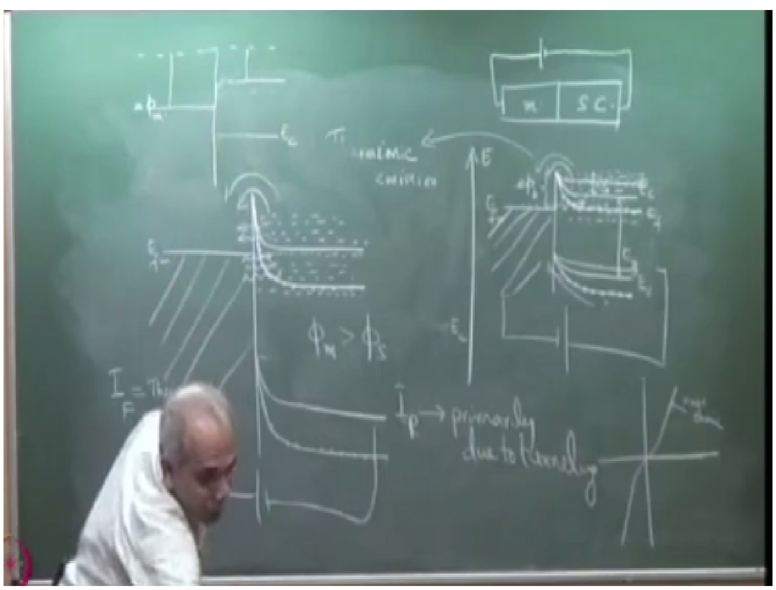

So, this is the new band diagram what I have illustrated is now you see that in this case the barrier width is very small therefore if I apply a small potential, a forward potential like this to this then of course this will get lifted and electrons can subsequently jump over the barrier but also electrons from this direction can also tunnel because the barrier width is very small. If I forward biase this will be raised and subsequently electrons can get fold into this side.

It is like water you are raising this water is getting fold but also because the barrier width is very small tunnelling can take place to this side. There are plenty of vacant states, these all vacant states on this side, this is filled states plenty of electrons. So, you can have electron tunnelling in this direction. So, the forward current If will comprise of thermionic emission+tunnelling**.**

If you reverse biase this then now you reverse biase which means to this side u this is n side therefore to this side you applied positive, so this band will come down further, so let me draw in the same diagram there is difference in the Fermi levels now Ef has separated out, so this is reverse biasing what do you see there is a small plenty of electrons here and there are electrons and states here and current can tunnel through this very easily.

Because the width of the barrier is very small and therefore even in the reverse direction current can flow across the junction but the reverse current is primarily due to tunnelling whereas the forward biase prime it is due to thermionic emission+tunnelling. So, the reverse current Ir will be primarily due to tunnelling. Therefore now if you plot the Iv characteristic in the forward direction also current flows almost freely in the reverse direction also current flows almost freely.

And the characteristic that you would get is a little bend of course here it is not like an ideal ohmic but so this is a near ohmic contact. I have try to explain and the n+ and semi conductor junction. You could as well have a p+ and a semi conductor junction, you do need a p+ because a device has p and junction or a p and device you will have to make metal contacts to n+ also but also to p side.

And therefore there are similarly p+ devices cannot p+ metal semi conductors can also be realised. I will stop here and it would be a good exercise to see I have discuss the case where pie n was greater than pie s that is this difference here was larger compare to the difference to pie s which is up to the Fermi level. Because you remember I started with the metal sitting here and Ec sitting here.

And there was a positive barrier this was pie n E pie n to the vacuum level and this is E pie c. Suppose this level was below this is a case where you have alluminum which is 4.4 and indium arsenate which is 4.9, kei power indium arsenate is 4.0, so this will come down here this is easy for indium arsenate.

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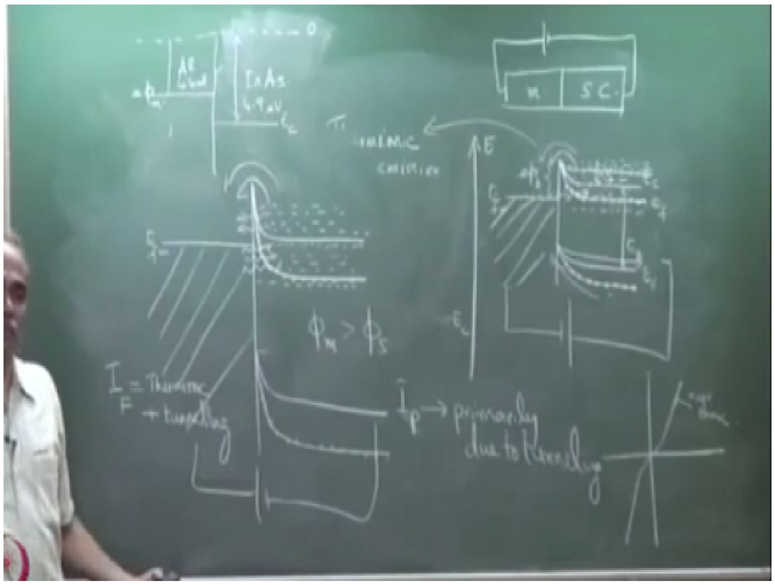

This will be a very interesting problem to see what type of junction will you get if you have Ec of indium arsenate here and alluminum so this difference is 4.4 electron volts and this is the vacuum level 0, so this difference is 4.9 ev, so 4.4 what do you think will it be find out what it is going to be and you will see that there is no schottky barrier in this junction and it will be very ohmic contact current can flow freely in both the directions and this.

But we do not have many metals and semi conductors where you can have this situation where pie m is smaller than kei, o if pie m is smaller than kei then there will be schottky barrier alright. So, we take a quiz today I have already told you what will be the quiz, so it should not take much time for you.

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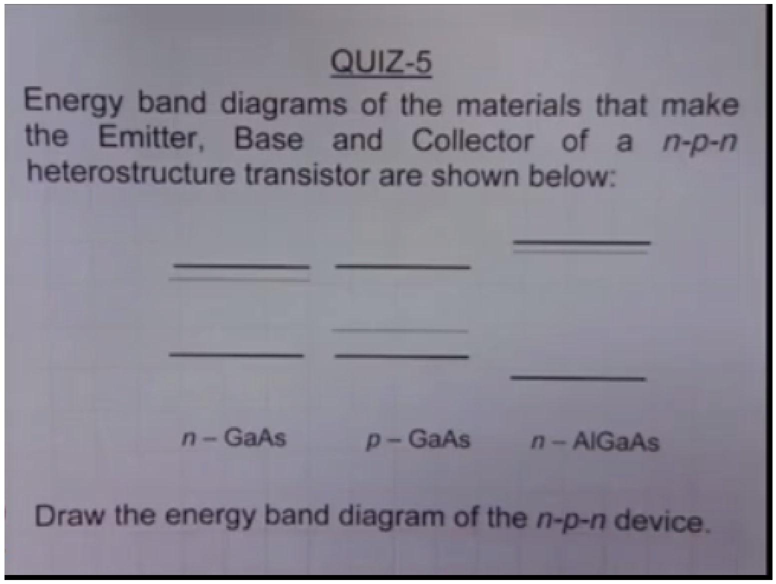

The energy band diagram of the materials that make the emitter base and collector of a n-p-n heterostructure transistor are shown below there are heterostructure transistors exactly like double heterostructure structures that we have in optoelectronics, so n gallium arsenate, p gallium arsenate and n alluminum gallium arsenate. The energy band diagram individually before contact is shown draw the energy band diagram of the n-p-n device.

That is when it is connect when the device is form, so this is the energy band diagram of the individual materials, n gallium arsenate, p gallium arsenate and n alluminum gallium arsenate draw the energy band diagram of the without any biase when there is no external biase what is the energy band diagram of the n-p-n device.