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, and we will see why it is important in the device.

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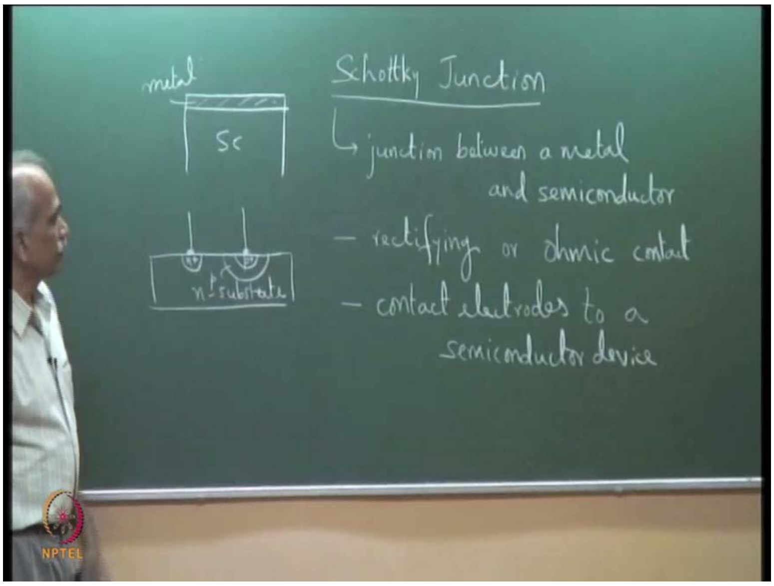

So, Schottky junction, Schottky junction refers to, it refers to junction between a semiconductor and a metal, junction between a metal and semiconductor. As we will see, the junction could be, this could be rectifying, it could be a rectifying contact, rectifying or ohmic, it could be a rectifying contact 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 electrode or metal contact to the semiconductor.

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

So, you do n plus diffusion here and then a metal and you can have p plus, so p plus diffusion, so normally you see, that in an n substrate, you diffuse first p. And then near the contact, you either have p plus or n plus, 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 contacts, as the name indicates, it refers to a contact, which allows current to flow in one direction but blocks it in another direction, as it is done in a diode.

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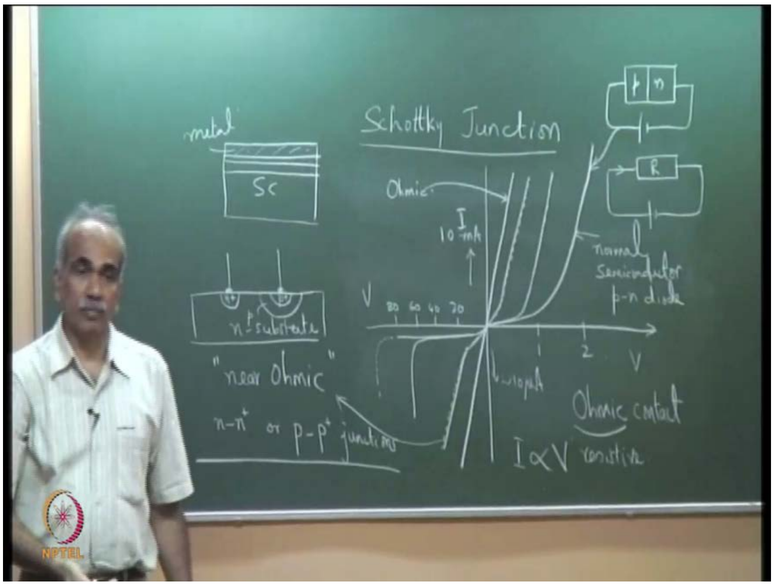

So, if I draw the I V characteristics, so this is voltage versus I, current for a device, so if you take a diode, we know that, the forward characteristics and the reverse characteristics and then, almost saturated and finally, of course, it breaks down. So, this is a typical a normal diode characteristics, normal semiconductor diode, p n diode forward characteristics and reverse characteristics.

We will see that, when you make a Schottky junction then, the characteristics normally of course, it depends on, what kind of so it starts to go up a little earlier and similarly, at the break down al so it tends to come up, come down a little earlier. Why it happens, we will see and what is an ohmic contacts so as you can see, this is a rectifying contacts because in the forward direction, we have good amount of current.

Because, if you see the real scales, these are in milli Ampere, 10’s of milli Amperes and the reverse, we will see is the typically 10’s of micro Amperes. So, this is 10’s of micro Amperes and this is 10’s of milli Ampere, typical diode characteristics 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 we called as rectifying contacts or rectifying behavior characteristics.

Now, an ohmic contact, as the name indicates ohmic which means, this is resistive basically, resistive, 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, a ohmic. A ohmic device, if you take a resistor for example, if it is a ohmic device, whether you take the resistor 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 behavior 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, this corresponds to forward bias, so just elementary recalling. So, if you take a p n diode then, this corresponds to the forward bias here whereas, if you reverse bias, the characteristics will be like this, this will be 10’s of volts here and this will be 1, 2, 3, 4 of that all, just a couple of volts.

Typical numbers, if I want to put, this may be 1 volt, this may be 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 10’s of milli Ampere, here even if you apply 10’s of voltages, 10’s of volts as reverse bias, your current is only 10’s of micro Amperes whereas, for an ohmic contact, it is identical, it is the same.

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

And we will see that, by taking a Schottky junction, that is a junction between a metal and semiconductor, it is possible to get a Schottky behavior. So, this is the Schottky characteristics, which has slightly built in smaller potential here or it is also possible to have a near ohmic contacts. The other methods of getting near ohmic contact include n-n plus junction or p-p plus junctions, this also behave like almost ohmic contacts n-n plus semiconductor or p-p plus semiconductor.

So, before I go to the Schottky junction itself characteristics, let us first see this, n-n plus how is the characteristics qualitatively, we will see how is the characteristics of n-n plus or p-p plus. Whether they behave like, why am I interested, you can see, that here there is a n-n plus and then, to the metal similarly, p-p plus and then, to the metal. Same thing you will see in optoelectronics structure, all almost all devices will have the metal, just before the metal there will be a p plus or n plus material and then, there will be a p or n.

So, you will have a p to p plus and then, p plus to n or to the metal similarly, at other end, we have n plus to the metal and n to n plus because they form near ohmic, almost a 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, it is very easily understood, although qualitatively from the band diagram, the energy band diagram, so that will be my next task So, let us look at the band diagram of n-n plus semiconductor. And exactly like that, you can see p-p plus semiconductor, you can draw yourself how it would look like, why n-n plus would behave like a near ohmic contact and...

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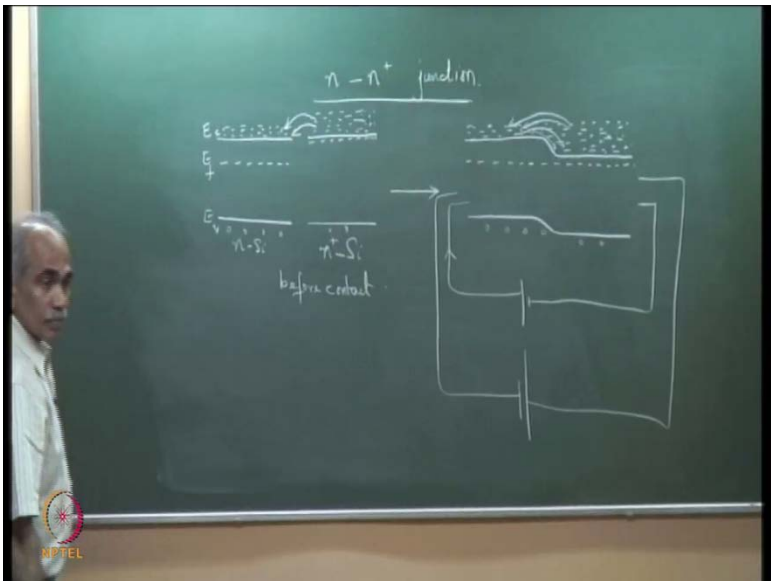

So, n-n plus, n plus junction, energy band diagram. So before contact, this is n semiconductor, whatever it could be, it could be n silicon and you have an n plus silicon, so highly doped. In this time we will not write Ec Ev, you know what we are referring to, so this is n plus silicon, n plus, plus stands for highly doped. There is nothing like a p plus that is, nothing like n minus, p plus, plus standing for highly doped, this nothing like n minus, n silicon, n plus silicon.

So, what do you expect band diagram to be, when we link the two, remember that, this means there is plenty of electrons here, very very simple to imagine plenty of water, this is also n type. So, there is a few holes here holes, electrons. So you can see a carrier concentration difference, water here is more. So, water 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 electrons 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 should start coming down and you know that, the Ef has to be equal, so what we get is...

So, this is the n-n plus contact, energy band diagram of the n-n plus contact, electrons have some electrons are flowing here because of, carrier concentration difference, which has brought down the band here and you have, very easy to imagine in terms of water.

See now, in this junction, if we apply a positive plus, so forward bias in n-n plus junction, if we forward bias which means, this end is becoming more negative which means, higher potential energy therefore, this band will start pushing up.

If you forward bias in this, it is difficult to say, which is forward, which is reversed 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 consistency, 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 semiconductor is flowing like this. What about negative, if you instead of this, if you apply reverse bias in 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, so 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 is, 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 characteristics that is, I V characteristics is almost identical. Therefore, it is near ohmic contact, there is very little difference so that is why, you make n-n plus junction, the smaller the resistive loss, the better it is otherwise, there will be potential drop across the junction.

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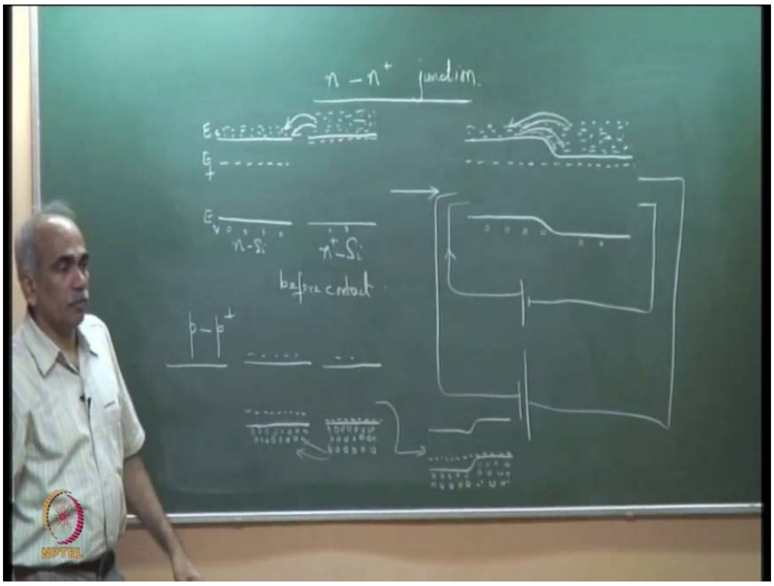

What about p-p plus, exactly like this if you make p-p plus, you can do it yourself and see that, this time you will talk in terms of whole current. So, this is p-p plus so plenty of holes now, air bubbles, so if you make contact then, what will happen, if you make contact, these air bubbles will start 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, you please make it yourself. So, you will have till, so the majority carriers in this case is hole whereas, the majority carriers in this case is electron. But, the current flows predominantly due to one type of carriers, predominantly due to one type of carrier, 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, 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, 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 characteristics that, you can expect.

So in the device, as we always encounter p-p plus junctions, n- n plus junctions and of course, to give external contact electrodes to make contact to the contact electrodes, we need semiconductor metal junctions. So, let us see, the band diagram of a Schottky junction.

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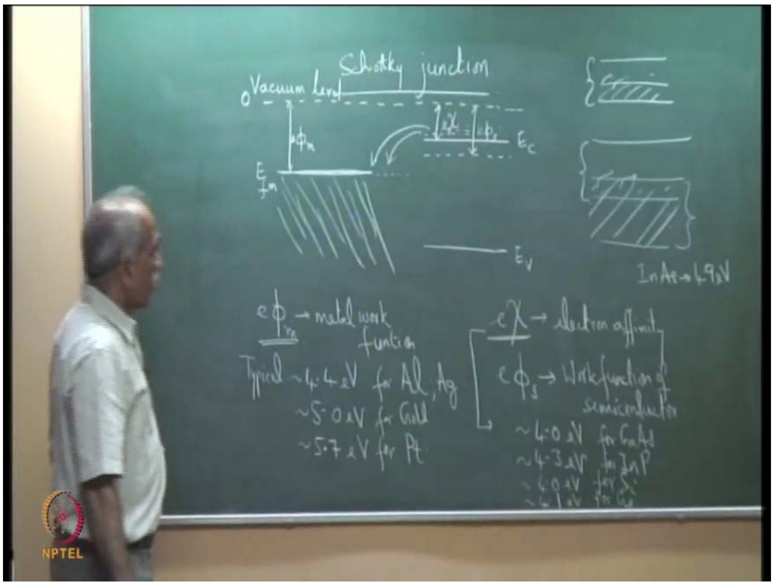

Energy band diagram of Schottky junction, the metal metal is characterized by a Fermi function, below which normally it could be due to two overlapping bands or it could be half filled bands. But, it is characterized by a Fermi level, a Fermi functions, below which there are plenty of electrons or at 0 k, all electrons remains below this. So, typical this work function here, let me draw this line as the vacuum level that is, 0 degree which means it is, 0.

So, typical work function here, metal work function phi m, e times phi m, this is the potential, phi is normally used as a notation for potential. So, e phi m is the metal work function, this is e f of m, f m, m for metal, Fermi energy for metal, so the metal work function metal work function. Typically, for typical values, let us have some idea about typical numbers, so typical values approximately of the order, approximately 4.4 ev for aluminum al, approximately 5 ev for gold, silver is also approximately same 4.4 ev, 5 ev for gold and about 5.1 ev for, I think approximately 5.1 ev or 5.7 ev for platinum 5.7 ev for platinum.

Typical numbers of e phi m, work functions of metals. So this is for Ag al so aluminum and Ag approximately 4.4, 5 ev, 5.7 ev for platinum. Let me draw a semiconductor here, so Ec Ev and Ef somewhere, it is n doped then, Ef is here and this energy is called by electron affinity, e xi. So, e xi is the electron affinity sometimes, people call xi as affinity electron affinity electron affinity and this is e phi s, the work function of the semiconductor, e phi s.

Although normally, we do not use the work function of the semiconductor but this is, analogous to this we have, work function of semiconductor. Typical numbers for xi of course, phi s depends on, whether you are doping n doped or p doped or n plus and so on. But, xi has typical numbers for e xi is approximately 4 ev for gallium arsenide, approximately 4.3 ev for indium phosphide and even for silicon, it is approximately 4, 4 ev for silicon, for Si and about 4.1 ev for 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 indium arsenide, this has 4.9 ev closer to metal. But, in general, what you see is, xi is smaller compared to the metal work functions, 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 form a metal semiconductor junction, let me take this diagram itself, metal semiconductor junction.

So, if I am forming a junction here then, this is the Fermi level, this is the Fermi level here, this is the n type semiconductor which means, there are plenty of electrons here plenty of electrons, here electrons are up to this level. Therefore, electrons will pour 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, metal comprise of overlapping band where, you have bands overlapping.

So, this is the conduction band and this is the valence band, when they overlap, there are plenty of vacant states here, this is all filled plenty of electrons but there also plenty of vacant states therefore, electrons can freely move through the vacant states.

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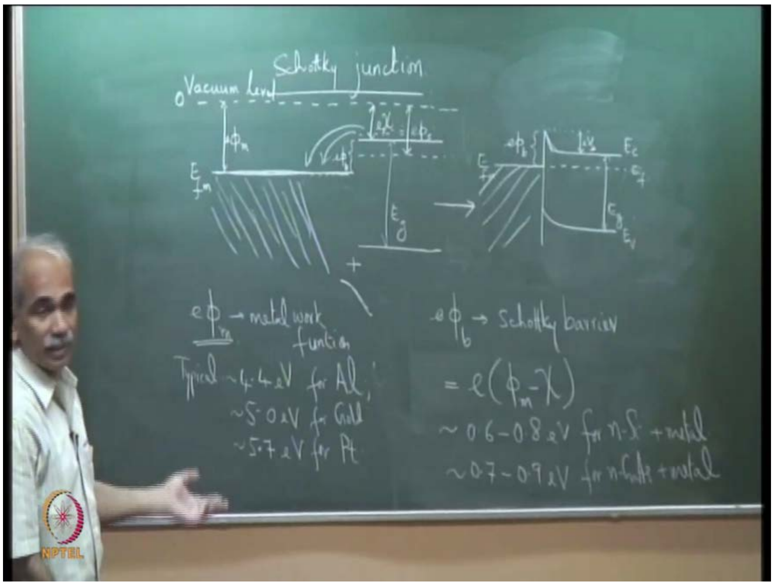

This is overlapping band or you could also have only half filled band, which also means the same, half filled means what, this is all filled this one band but this is completely full which means, these are all empty. So, electrons can easily go to the empty state and move with the small application of potential, they can immediately move that is why, the conductivity is very high.

When you make a semiconductor and a metal contact, this will come down here, what would to be the resultant, how would the band diagram change. We can apply the same method, which we have seen for semiconductor, how to when electrons migrate over here, this end will become positive and this will start coming down. So, what will be the resultant band diagram, this is the metal, there was a discontinuity here, we see thorough the discontinuity, this was e xi and this is e phi m, which was the discontinuity.

So, we have a discontinuity here, this is the same as this, this is actually e phi v, this is called the Schottkey barrier, you will see. And then, because this 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 level, I have shown this little bit more because the gap.

So, I have similarly, here. So this is my Ev Ec and Ef of the semiconductor, this is Ef m, this is all filled with the electrons so Ef m. So, we have simply added this but remember, there are plenty of electrons it is, as if p plus and n junction, it is almost like p plus 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 phi v.

We 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 phi v, is called the Schottky barrier or phi v is called the Schottky barrier potential so e phi v, Schottky barrier.

What will that be equal to, in terms of phi m and xi, it will be equal to e times phi m minus xi so generally, we see that because phi m is larger than xi generally, the Schottky barrier is the positive quantity. Typically, although it looks that, it is genetically it looks that, it is this much in general, there are other considerations, which come into play and Schottkey barrier is generally, of the order of 0.6 to 0.8 electron volt for silicon and n silicon, n metal and silicon plus metal.

And if generally, at the order of 0.7 to 0.9 electron volt for n gallium arsenide plus metal from idea about, what kind of Schottky battier, we have barrier heights we have theoretically, it is this much but generally does not come out exactly that much. But, atleast, it tells you that in general, phi m is greater than xi and therefore, there is a barrier. So, we have to see, what is the implications of the barrier? And how we can control the barrier, and how we can get an ohmic contact out of this.

Right now, what is the contact this is please see, there are plenty of electrons here but there is a barrier so water cannot flow, there is a barrier, unless you forward bias this. Let me continue with that and try to see what happens, if I forward biased and if I reverse biased and then, we will understand, how to realize Schottkey barriers, which are nearly ohmic in nature, barrier potential is approximately this but there is a interesting concept which will come.

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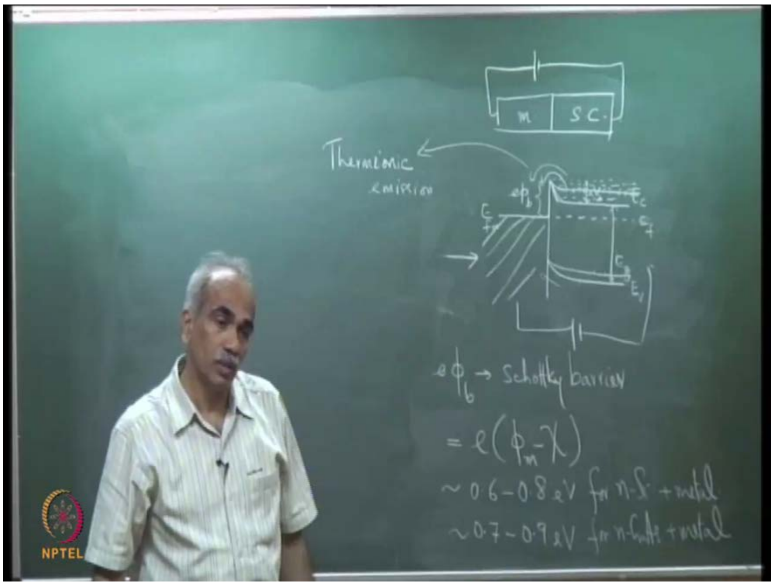

We will forward bias this, forward bias means, this is n type so we apply so the n side we are applying negative which means, the energy will go up. So, this band will start going up and electrons will pour over, as this starts going up. When in forward bias, the new level is here, let me show it with the slightly to distinguish let me draw, after forward biasing, the band look like this, the upper one is after forward biased.

So, what has happen, the band has been lifted which means, there were plenty of electrons here, the electron because we have 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 the barriers. When electrons go over a barrier to another side, it is called thermionic emission, this process is called thermionic emission thermionic emission.

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

This is a metal semiconductor so what we have, the conventional picture is this, to receive the metal and this is the semiconductor, and we have forward biased. There are very little holes here, some minority carriers, some hole current will be there because when you raise this, there are very little holes. Some holes can migrate here and electron can cause 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 we reverse bias, this will go down if we reverse bias, if it is not confusing then, let me try to show that, reverse bias in the same diagram.

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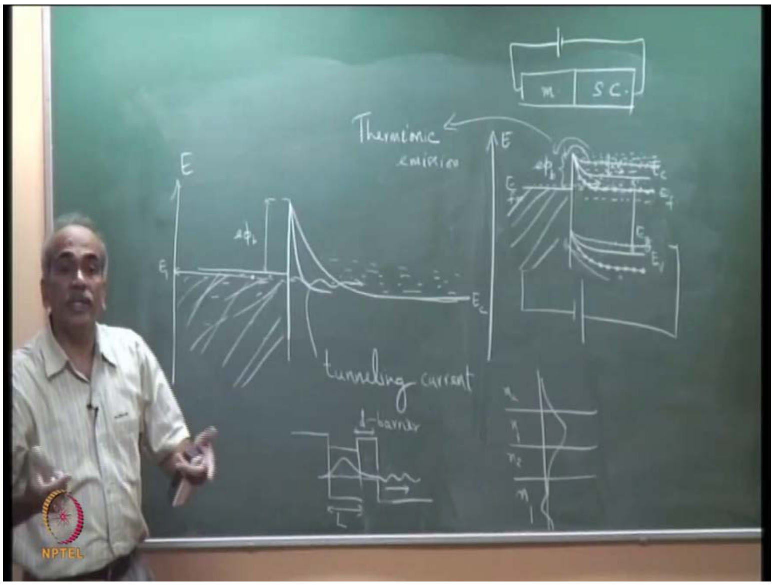

So, that was forward biased, the diagram is a little smaller but what would happen, this was, without bias, this was with forward bias so if you apply now, a reverse bias which means, we applied positive to this end electrons will have lower energy so the band will start coming down. So, the band will 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 anymore jump over the barrier, for 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 this has come down whatever holes, which were here, they would immediately move up. Air bubbles, remember air bubble will go up because there is this has been brought down so air bubble is pushing up.

But, more importantly there is a new current, which comes, which is called tunneling 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 state or there are states, permissible states then, electron can tunnel through this barrier. Now, this part, I will zooming and will show you more clearly, I have zooming this part for reverse bias so this is Ec of the metal and this is e phi b.

There are plenty of electrons, there are electrons here, it is a n type material but there are also vacant states where, electrons but there are also vacant states. Here, there are plenty of electrons, if I remember that, this axis is energy, if take a particular electron here, a particular electron it has energy is equal to this much let us say, this energy as E 1. At E 1, if I go to the other side, there could be a vacant state, there could be a vacant state here because electrons are there but electrons and there are vacant state here so sometimes there could be a vacant state here.

At the same energy, there could be a vacant state but there is a potential barrier potential barrier where, there are no allowed states, allowed states are on this side, no allowed states here. But, the electrons, if it finds a state there then, there is a probability of electrons tunneling to this side so this is called tunneling current. This is tunneling is a quanta mechanical concept, I am sure, the basic tunneling 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 electron states, which are permitted here and this is called this is the well, this is the barrier. So, this part is the barrier, there is a d, is a 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 tunneling 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. A finite well has an evanescent tail and when it reaches here, oscillatory solutions are permitted and this means, the electrons can exist here, it can exist here, it can exist here.

Because, there is an evanescent tail here, it is exactly those of you were studied optical waveguide, it is exactly the same, you have n 1, you have n 2, there is a wave, the fundamental move looks like this. Oscillatory solutions inside, an exponentially decaying solution here, if I now bring in a medium so this was n 2, if I now bring a medium of refractive index n 1 here then, it can have the same oscillatory solutions here as well.

And therefore, immediately this starts oscillating which means, the wave can oscillatory solution means, that is the propagation solutions so you can have the wave in this region as well. You can have energy coming into this region and this is called tunneling, this phenomenon is originally quanta mechanical phenomenon. But, it can be very easily illustrated in light experiments, all the prism coupling experiments and directional couplers comes under this method.

So, let us not go so much into this, the important point is, if there is a barrier then, tunneling is possible but the tunneling probability is proportional to inversely proportional to the width of the barrier. Smaller the width, larger is the tunneling probability, this is the quanta mechanical result, which you can show, smaller the barrier width, larger is the tunneling probability.

And if you look at this therefore, in reverse bias, the current is primarily due to tunneling, if I want to increase this right now, tunneling 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 tunneling and therefore, I can increase the reverse current. So, how can I reduce the barrier width so if I could somehow reduce the barrier width to like this for example, then, the tunneling 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 tunneling probability, if I reduce the barrier width. How to reduce the barrier width, by doping this semiconductor heavily, if you dope this semiconductor 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 semiconductor right here and then, we see that the forward current is through.

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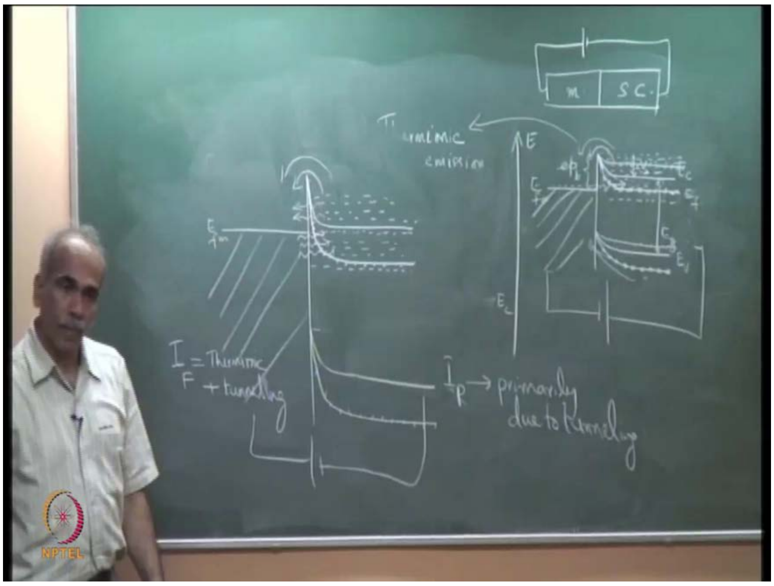

So, we have the metal, this is barrier so we had the semiconductor highly doped and here is the Ef m of the metal and Ef of the semiconductor, so this is Ec, this is Ef of the semiconductor, Ev of the semiconductor. So, as soon as, the contact is made, the Fermi level has to be aligned so electrons from here the electrons from here go over the barrier and get poured into there, there was no barrier, electrons get poured into this side and this band starts coming down.

Because, it is n doped, it is n plus doped, this is aligned now, there are plenty of electrons here, if you wish you can erase or you can draw a separate diagram because it was n plus, 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 and therefore, this end has become more positive and you see, the barrier has now changed into, 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 applied a small potential, a forward potential like this to this then, of course, this will get lifted and electrons can subsequently jump over this barrier. But al so electrons form this direction can also tunnel because the barrier width is very small, if

I forward bias, this will be raised and subsequently, electrons can get poured into this side, this like water, if you are raising this, water is getting poured.

But al so because the barrier width is very small, tunneling can takes place to this side, there are plenty of vacant states, these are all vacant states on this side, this is filled state, plenty of electrons so you can have electrons tunneling in this direction. So, the forward current I f will comprise of thermionic emission plus tunneling plus tunneling, if you reverse bias this then, now you reverse bias which means, to this side, this is n side therefore, to this side you apply positive.

So, this band will come down further so let me drawing the same diagram, difference in the Fermi levels is 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 tunneling. Whereas, the forward bias right, it is due to thermionic emission plus tunneling so the reverse current I R will be primarily due to tunneling.

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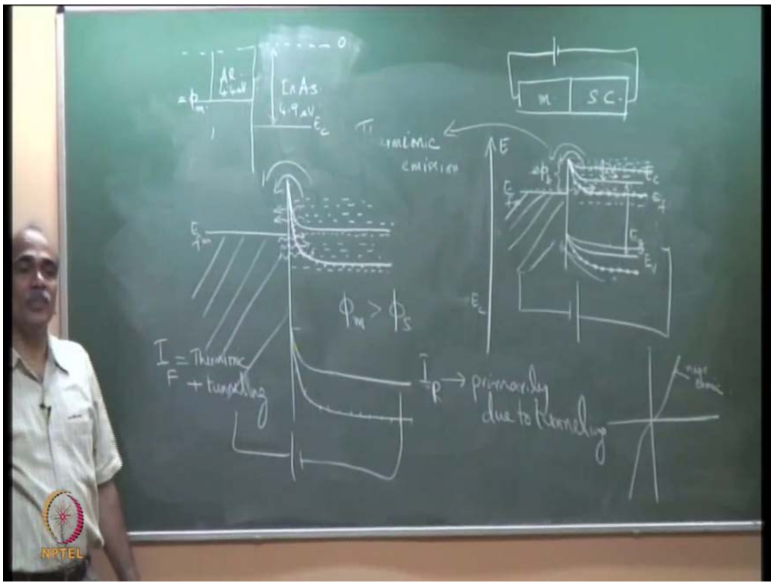

Therefore, now, if you plot the I V characteristics, in the forward direction also current flows almost freely, in the reverse direction also current flows almost freely. And the characteristics that, you would get is a little bend of course, it is not like an ideal ohmic but this is a near ohmic, ohmic contact. I have try to explain, when n plus and semiconductor junction, you could as well have a p plus and a semiconductor junction, you do need a p plus because a device has p n junction or p n device, you will have to make metal contact to n plus also but also to p side.

And therefore, there are similarly, p plus devices can up, p plus metal semiconductor can also be realized. I will stop here and it would be a good exercise to see, I have discussed the case where, phi m was greater than phi s that is, this difference here was larger compared to the difference phi s, which is up to the Fermi level. Because, you remember I started with a metal sitting here and Ec is sitting here, and there was a positive barrier suppose, this was phi m, e phi m to the vacuum level and this is e phi c.

Suppose, this level was below, this is a case where, we have aluminum, which is 4.4 and indium arsenide, which is 4.9, xi for indium arsenide is 4 point. So, this will come down here, this is Ec for indium arsenide, this will be a very interesting problem to see, what type of junction will you get. If you have Ec of indium arsenide here and aluminum here 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 ev.

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 a very good ohmic contact, current can flow freely in both the directions and this but we do not have many metals and semiconductors where, you can have this situation where, phi m is smaller than xi. If phi m is smaller than xi then, there will be no Schottky barrier alright.

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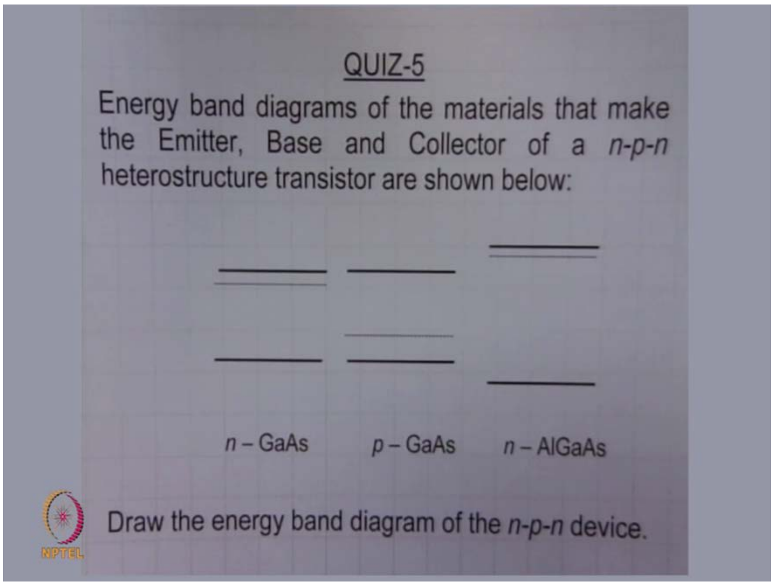

QUIZ-5

Energy band diagrams of the materials that make the Emitter, Base and Collector of a *n-p-n* heterostructure transistor are shown below:

Draw the energy band diagram of the *n-p-n* device.

So, we take a quiz today, I have already told you what will be the quiz so it should not take a much time for you. The energy band diagram of the materials, that make the emitter base and the collector of a n p n hetero structure transistor are shown below. There are hetero structure transistors exactly like double hetero structures, that we have in optoelectronics so n gallium arsenide, p gallium arsenide and n alumna gallium arsenide, the energy band diagram of individually, before contact is shown.

Draw the energy band diagram of the n p n device that is, when it is connect and the device is formed so this is the energy band diagram of the individual materials n gallium arsenide, p gallium arsenide and n alumna gallium arsenide. Draw the energy band diagram of the, without any bias, when there is no external bias, what will the energy band diagram of the n p n device.