# Semiconductor Devices and Circuits
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## Lecture – 20
## Metal Semiconductor: Junctions

So, so far we have looked at creating junctions, and you know some of the basic ideas behind how to draw a band diagrams. So, we will now start a formal approach to the metal semiconductor junction. So, a metal semiconductor junction is quite important because if you think of any device.

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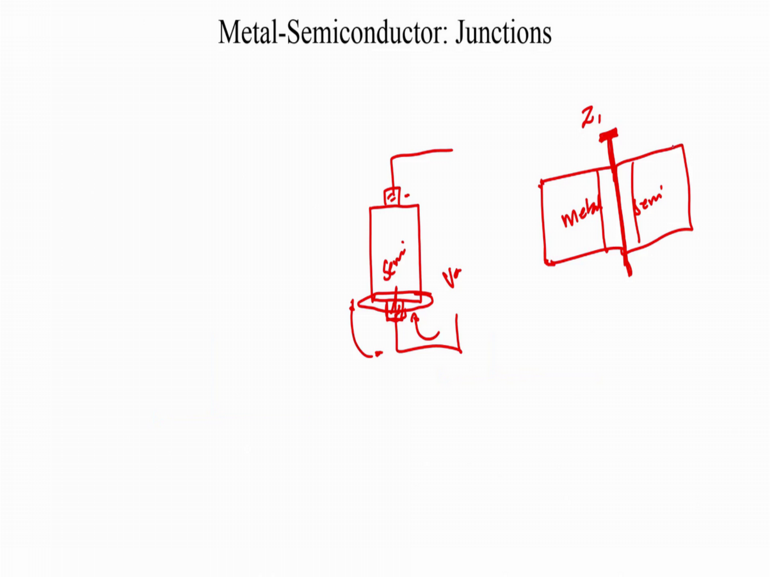

Metal-Semiconductor: Junctions

So, let us say you are building a transistor or you are trying to build a device wherein you will not, you know have these metal contacts and you want to actually apply a voltage or you know send a current through this device. So, this is your semiconductor device.

Now, how do the properties of this metal contact and the semiconductor affect the current voltage characteristics, ok? Ideally what we would like is we want to think of these contacts is very ideal contacts, they should offer no impedance and they should very faithfully transmit any voltage applied to the metal and on to the semiconductor, but that is not really true. And in fact, the depending on the kind of a contact you make between the metal and semiconductor various things could happen.

So therefore, the study of having a metal and interface to the semiconductor, that is to create a metal semiconductor junction is quite important. And what we will do here is first look at and get some qualitative estimate as to what the different metal semiconductor junctions might look like depending upon the work function differences between the metal and semiconductor, and draw the band diagrams for these kind of contacts.

And then we will get into a bit of detailed analytical calculations on estimating a impedance and the particularly the capacitance of a metal semiconductor junction, and also the current voltage characteristics in a metal semiconductor junction, ok.

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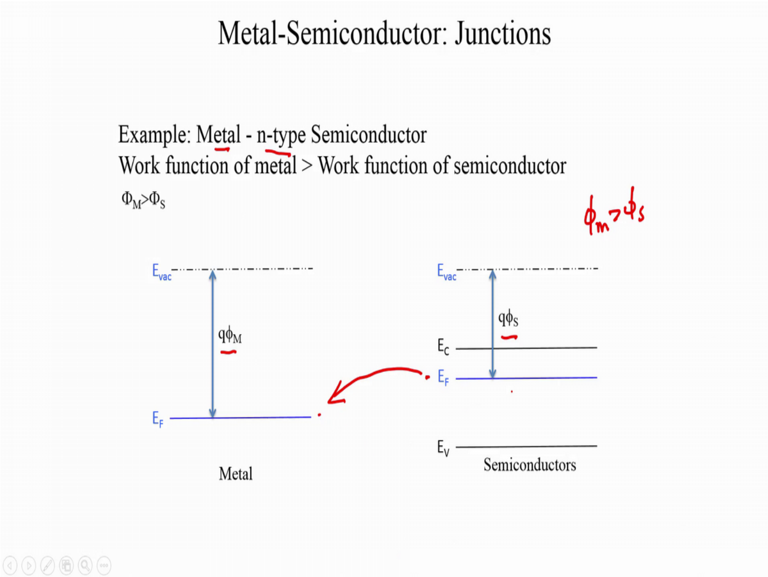

Metal-Semiconductor: Junctions

Example: Metal - n-type Semiconductor

Work function of metal > Work function of semiconductor

$\Phi_M > \Phi_S$

$\phi_m > \phi_s$

So, first let us start with, you know trying to draw some band diagrams ok. So, first let us take the example of a metal and an n-type semiconductor where the Work function of the metal is greater than the Work function of the semiconductor. So, when we looked at the different materials before we noted the fact that the electron affinity of a semiconductor never changes that is always fixed whereas, the work function of a metal is also a fixed parameter. So, irrespective of the kind of contact you make the work function of a metal and the electron affinity of the semiconductor will not change, at any location in space.

So, now let us try to redo this problem. You know we, we discussed we used this as an example when we discuss the, brief study of junctions but let us come back to this problem. Which is we have a metal which has got a work function of q phi M and we have got a semiconductor which is n-type. So, it is an n-type semiconductor and it is got a Fermi level slightly above the mid gap slightly above E i and it is got a work function of q phi S. And the key is in this particular case your phi m is greater than phi s which means that the Fermi level of the metal lies a further away from the vacuum energy level as compared to the Fermi level of the semiconductor.

So, let us, see what happens when we make a contact between these two. Now using our old analogy which is that of water in a bucket for whatever use that analogy is we do realize that since the Fermi level of the semiconductors located above the Fermi level of the metal its very likely that the semiconductor is going to transfer electrons to the metal and the second thing is the Fermi levels will align as long as we are in thermal equilibrium.

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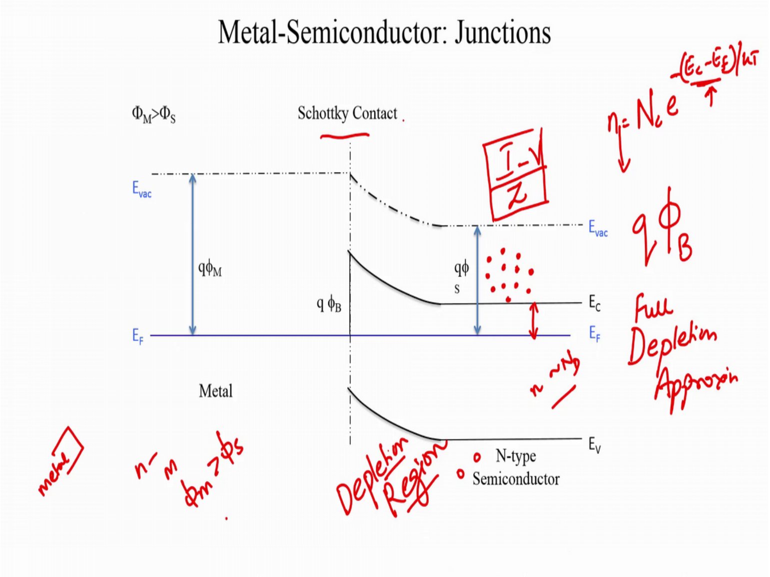
Metal-Semiconductor: Junctions

So, once you make this contact and approve and keep it thermal equilibrium the Fermi levels align. So, that is the common Fermi level for metal and semiconductor. Far away from the contact of the semiconductor does not see anything interesting, it is exactly the way it would be and this is called as the bulk region, ok; this is called as a bulk and this is called as the interface. And since the semiconductor gave up electrons, since the semiconductor gave up electrons to the metal, the conduction band has to move away from the Fermi level near the interface.

So, this region of the semiconductor has lost a lot of electrons. And therefore, the conduction band edge at this region of the semiconductor moves away from the Fermi level. Since n is equal to capital N c e to the power minus E c minus E f by k T. If when n goes down it implies that this term increases because there is a negative sign this term has to increase.

So, E c minus E f has to increase and therefore, the conduction band bends away from the Fermi level. So, the band bending diagram looks like this. So, you have the metal Fermi level and at this point at the junction there is a massive barrier, ok and we call that barrier height. That energy of this barrier is denoted by a special symbol which is called phi B and that is the potential and q phi B is the energy. And after this, there is bands bend away. So, you can see this gradual bending of the band and to a point beyond which the semiconductor does not see any band bending.

So, the region of the semiconductor which does not see any band bending where, where in the semiconductor does not even realize there is a metal semiconductor junction it is called as the bulk semi bulk of the semiconductor ok. So, when we say bulk we automatically imply the, the region of the semiconductor far away from the junction and if you look at, if you look at this contact ok. So, let us, let us think of it let us assume that we have established this kind of a contact in order to study a semiconductor, in order to electrically excited semi conductor by sending in some a current and some voltage. Now how good is this contact?

So, think about the majority carriers the semiconductor. So, we have electrons in the semiconductor there is an n-type semiconductor, we have plenty of electrons and very few holes ok. And you think of the electrons in the metal ok. So, let us say the electron in the metal has to get passed in get into the semiconductor, what does the electron see, it sees a massive barrier. So, as we discussed earlier the band bending diagrams are drawn such that the higher potentials lie at lower points ok.

So, what I mean by that is let us say you have a, you have a Fermi level ok. So, let us say you have a metal and you got a Fermi level and you start increasing the voltage of this metal. So, what would happen is that the Fermi levels start moving downward ok. So, if you see two energy levels in an energy band diagram then the level that is lower has got a higher electrical potential.

So, that is just the way it is drawn. So, that is this convention its drawn thinking of the electron as rolling downhill, ok. So, if you have electrons the electrons would like to roll downhill towards the higher potential and the holes would like to roll uphill towards the lower potential ok. So, you can think of electrons trying to roll down here.

Now, if the electrons, the electrons in the metal they see a massive barrier here, it is like a huge cliff, it is not very friendly for an electron that wants to get across ok. So, therefore, it is not going to help the conduction, it is not going to be very easy to have straight forward drift conduction. On the other hand what about the electrons in the semiconductor the electrons in the semiconductor also see a barrier right. So, not as steep as that of the metal, but they do see a barrier because they have to now roll up the hill in order to get into the metal.

So, therefore, this kind of a contact is not going to give you an Ohmic nature in the sense that an ideal contact. So, you would have a metal and you would have a semiconductor and if you want to model this ideal contact, we would at most want to see a resistor that.

So, that is about; so we would like a contact to be like this. So, that any voltage I apply in the metal is going to have and let us say I send a current through this contact, there is going to be a small voltage drop across this contact but generally the I V characteristics is linear, it is going to behave like a small resistor. So, that is the contact we want but here that is not the contact we are going to get ok. In fact, this contact has a rectifying nature ok.

So, I will tell you what that means when we look at the current voltage characteristics it is, it is got a Rectifying nature and it is something called as a Schottky contact or a and this barrier is something called as the Schottky barrier. So, it is not a contact that is going to give you an ohm, ohmic relation between current and voltage, ok but nevertheless that is the contact you get.

Now, what happens is in reality becomes a semiconductor metal any interface with the semi conductors got a lot of trap states because that is a place where you have cleaved off the semiconductor and or that is the place where you have impurities and therefore, you have a lot of, energy levels sitting inside the band gap.

So, because of that the Fermi levels are not free to move around the Fermi levels cannot move around in the, as easily as described by the mechanics, we discussed for the band bending. And therefore, you have something called as a Fermi level being pinned and due do that you have a lot of interesting effects that come up and it so happens that more likely than not you will end up with a contact that might be rectifying, ok. So, in many practical cases this is a kind of contact you might actually get and that is the best you can probably do.

So, how do we build good devices with such a contact because we already, we have already seen that this kind of a contact is not going to be very friendly for electron transport ok. So, you know because of that we will pay special attention to the Schottky contact and look at the current voltage characteristics of this contact and study what the impedances etcetera and think about mechanisms by which we can improve the nature of this contact; so that we can use such a band bending to our advantage so but anyway.

So, now let us proceed and try to look at all the other possible combinations. So, this is the n-type semiconductor with the metal with phi m greater than phi s. So, that gave you this kind of a band bending diagram. So, let us take a look at the band bending again. So, the bands the E c the conduction band edge moves away from the Fermi level and it slowly bends back downwards and approaches the bulk condition right.

So, till this point we could say that there is band bending and beyond this, the semiconductor does not see anything interesting. Now if you think about this region here, this region in the semiconductor here, what does it have? The region initially had a lot of electrons, because it is an N Doped semiconductor but after the semiconductor transferred electrons to the metal during the contact formation. And after the creation of this band bending, you will see that this region does not encourage or does not have too many electrons, at least particularly very close to the interface. So, the electron count here is now sparse, the hole count is anyway very sparse, because it is an n-type semiconductor, ok.

Therefore this region is in some sense void of free carriers ok. Now void is very powerful word, it does not mean that there are absolutely no free carriers, what it means is that the free carrier count is much smaller compared to the static charges present in this region? So, what are the static charges?

So, since it is an n-type semiconductor, we had initially doped the semiconductor with a lot of donor dopants right. And at 300 Kelvin or the semiconductors extrinsic and all the dopants are ionized and what we have is fixed positive charges in this n-type semiconductor. Now these charges cannot move they are a part of the lattice, and they are all fixed and these ionized donors they gave up an electron which was all which had become a part of your free carrier concentration.

Now, this donor dopant concentration, these ionized charges are how many of them are there we have N d per unit volume of this ok. So, that is the number of ionized charges that we have. And since the semiconductor gave up some electrons to the metal and since the bands are bent in a manner that encouraged the electrons to stay away from this region.

This region has got very few electrons as compared to the bulk, ok. Now the bulk has as many electrons as N d and this region has got much smaller number of electrons as compared to N d. And in order to quantify the number of electrons what we need to do is identify the E c minus E f at every location and we will know the exact count of the electrons.

Therefore, since this region has got very few free carriers ok, holes are anyway low, this region is said to be depleted and this region is called as the depletion region of a metal semiconductor Schottky contact. So, this is a technical term and it is something that people use quite often. Now if you make the assumption that this region has only fixed ions, because of the donors, the ionized donors and it has got no or it has got very negligible N and P. Then the assumption that is made is called as the depletion approximation or full depletion approximation. Now how good is that approximation? Near the interface it is probably a reasonably good approximation but as you start moving towards the bulk, ok.

So, let us look at this region here look at the E c minus E f and let us look at this region here look at the E c minus E f, the E c minus E f here is say much larger than the E c minus E f in the bulk and since it is an exponential dependence of on E c minus E f for the carrier count, we can say that here the N is really very low and it is much lower than the N in the bulk, but as we start approaching as the bands bend and the bending gets more and more gentle and as it start approaching the bulk this approximation begins to fall off for example, we cannot definitely make that assumption at this interface because we are, we are at the bulk.

So, you need to be very careful as to when and where these approximations are made. Now these kinds of approximations are very helpful in sort of simplifying the mathematics. Now in this course, we will consider both aspects we will first simplify the mathematics to get a gauge on how the device behaves etcetera. We will make use of such assumptions ok, but then we will also try to be very careful and point out how we can calculate all these answers out with all the great details, right.

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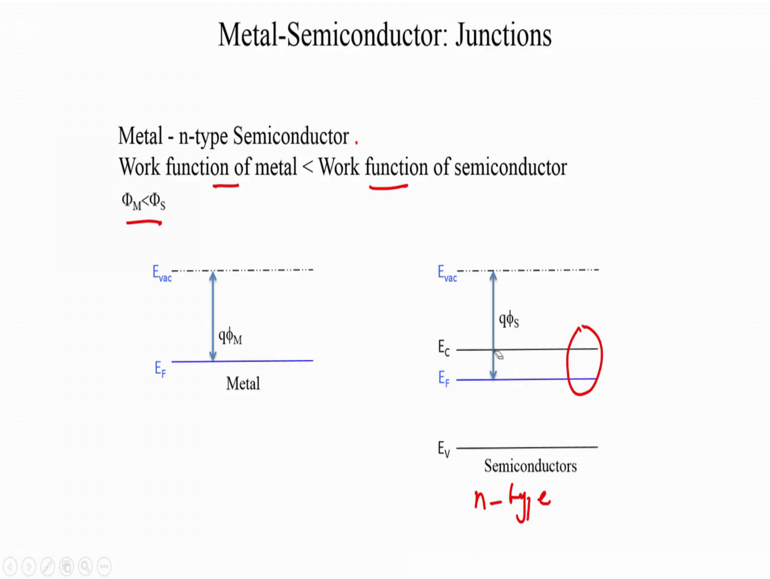

Metal-Semiconductor: Junctions

Metal - n-type Semiconductor .

Work function of metal < Work function of semiconductor

$\Phi_M<\Phi_S$

So, let us say we again have a metal semiconductor junction. And let us say the semiconductors still an n-type semiconductor, but this time we will let the work function of the metal will be less than the work function of the semiconductor which means phi M is less than phi S, ok.

So, in the previous case we had phi M greater than phi S, now since phi M is less than phi S, the metal will start providing electrons to the semiconductor ok. So, it is like two buckets with water level higher here as compared to the other one, that is a semiconductor bucket and this is the metal ok. So, I think this is the last time I will try to use the bucket analogy, we need to refrain ourselves from heading towards that, ok.

So, if you create this junction, the metal will give the electrons to the semiconductor. Once again the Fermi levels will align the metal will give the electrons to the semiconductor. And since this interface is now got more electrons as compared to the bulk, the conduction band will bend towards the Fermi level instead of away, ok.

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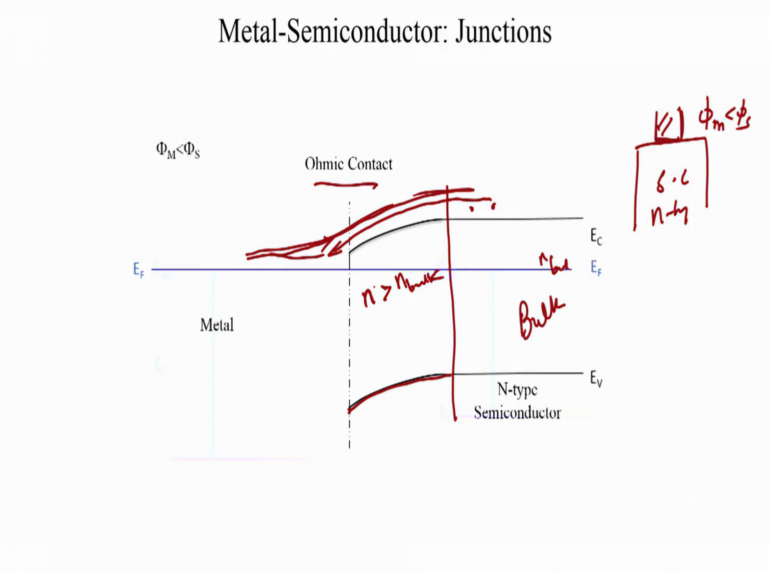

Metal-Semiconductor: Junctions

So, the band bending diagram will look like this ok. So, you have the metal the Fermi level is aligned in the bulk the semiconductor does not know what is going on it sees no change or it is not seen anything specifically interesting, and therefore everything is as it should be. And this is the bulk region but close to the interface since the metal pushed carriers push the electrons into the semiconductor. The conduction band bends towards the semiconductor, towards the Fermi level, sorry and the valence band follows that bending because the energy gap is fixed.

Now, this means that this region has got excess, is got more electrons as compared to the bulk ok. So, this is the electron count here is greater than the bulk. So, most definitely this is the exact opposite of your depletion region, right. This is definitely not a depleted region it is got a lot of free carriers and more interestingly you see that the bending is now favorable for electrons to move through ok. The electrons can easily roll down the hill and you know they do not see much of a barrier in either direction. And you have an easy migration of electrons across from the metal to this semiconductor. This is very much against you know what we saw, this is very much the opposite of what we saw in the case of a Schottky contact wherein we saw a barrier of this kind, the metal the electrons in the metal saw this cliff and the electrons in the semiconductor had to roll up the hill ok, but here it is a very different scenario and this is the kind of contact that we would ideally like ok.

So, if you were to make a contact between a metal and a semiconductor. And let us say this is an n-type semiconductor and you make a contact with the metal whose got a work function less than that of a semiconductor, then you should ideally end up with something called as an Ohmic contact, because here the electrons can easily move across through from the metal to the semiconductor and vice versa.

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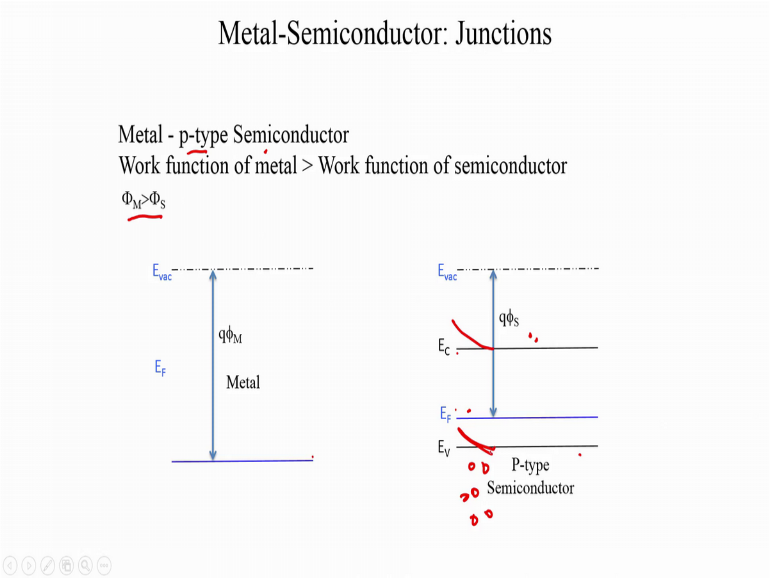

Metal-Semiconductor: Junctions

Metal - p-type Semiconductor

Work function of metal > Work function of semiconductor

$\Phi_M > \Phi_S$

Now, let us go ahead and consider some more examples. Now you will again consider metal semiconductor junction but we will consider a P type semiconductor.

So, P type semiconductor has got a Fermi level that is located closer to the valence band, that is the major difference and let us take the case of phi M being greater than phi S. So, this is your q phi s that is the work function of the semiconductor, this is the work function of the metal. And since q phi m is greater than q phi s, the Fermi level of the metal lies further away from the vacuum energy level as compared to the semiconductor.

So, now what would happen? So, this is a P type semiconductor, the majority carriers here are the holes ok. There are very few electrons, very very few electron and a large number of holes ok. So, you have heavily, it is a large holes of the majority carriers here.

So, if you were to create a junction, the first thing is of course, a Fermi level will build a line, but then where do the electrons go. Since the Fermi level of the semiconductor is higher than the Fermi level the metal the semiconductor will give electrons to the metal ok. There are not very many of them, but the semiconductor will try to give electrons to the metal.

So, what would happen in that case if the semiconductor gives electrons to the metal, E c minus E f has to increase. And therefore, the conduction and way a conduction band edge will try to move away from the Fermi level.

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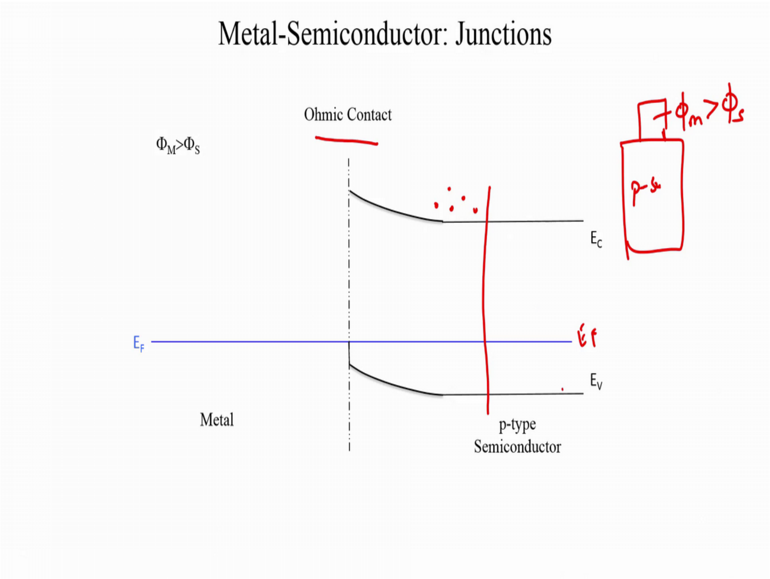

So, the band bending would look like this ok. So, you have your E f, the E f is aligned but since the semiconductor gave electrons to the metal, the conduction band edge moves away from the Fermi level and the valence band edge follows.

Now, what kind of a contact that is going to aid or charge transport or not, ok. Now if these were to be an n-type material and you saw this kind of a barrier it is definitely a Schottky contact but here the majority carriers are the holes. So, we should not worry so much about the electron movement across this junction but rather look at the movement of holes and the holes run up the hill and they see a very nice gentle slope, where and they can easily move and migrate into the metal. So, what about the metal? So, the movement of holes into the metal simply implies that the electrons at this interface recombine therefore, leading to an effective electron flux in this direction.

So, there is good charge transport between the semiconductor and the metal and this is once again an Ohmic contact. So, this is again a kind of contact you would like to have. So, if you have a P type semiconductor and you want to make an Ohmic contact with a metal you must choose a metal whose got a work which has got a work function that is greater than the semiconductor all right.

So, this is an Ohmic contact with a P type semiconductor and far away in the bulk, you see that it is still a P type semiconductor the E f is close to E v and the semiconductor sees nothing interesting.

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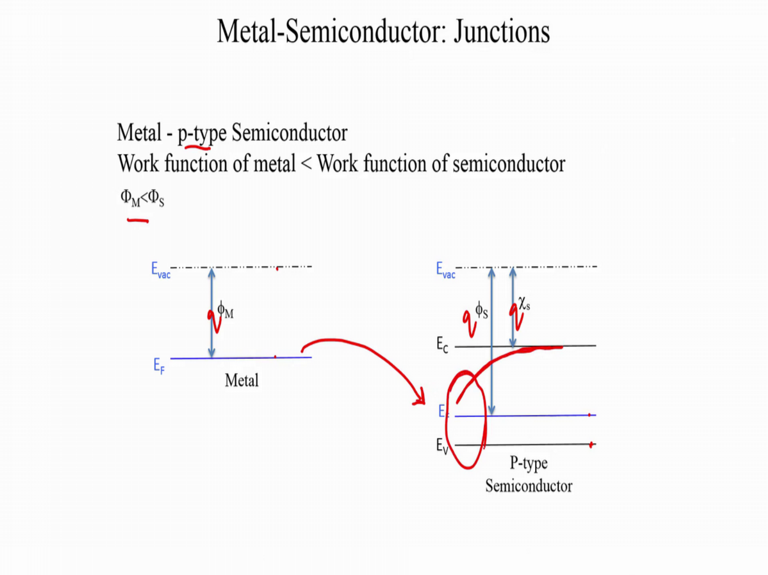

Metal-Semiconductor: Junctions

Metal - p-type Semiconductor

Work function of metal < Work function of semiconductor

$\Phi_M < \Phi_S$

Finally, we will take the fourth of the cases ok. It is a metal P type semiconductor junction but phi M is now less than phi S which means that you have your P type semiconductor ok.

So, this is all these are all energies (Refer Time: 25:23) be q there you have a P type semiconductor that is your Fermi level, it is close to the valence band edge, that is my q phi s and phi M less than phi S implies at the Fermi level of the metal lies closer to the valence band edge. And therefore, this is the situation.

Now if you create a contact you will align the Fermi levels as usual, but now it is going to be the metal that transfers electrons to the semiconductor because the metal has got a higher Fermi level as compared to the semiconductor. And therefore, the bands in the semiconductor will now the conduction band, we will now bend towards the Fermi level, because the semiconductors accepted electrons and there is a large electron population here.

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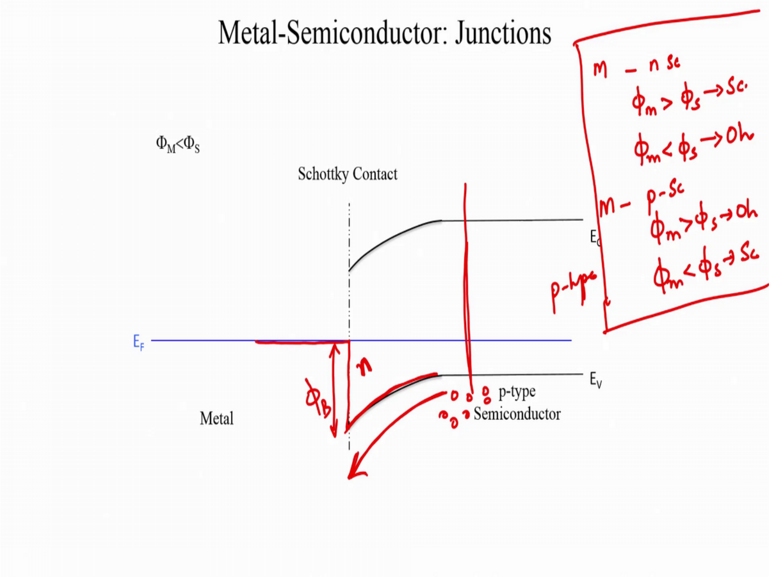

Metal-Semiconductor: Junctions

So, the band bending will look like this. So, you have the Fermi levels that are aligned deep in the bulk, there is nothing interesting it is still your regular P type material but at the interface the semiconductors increased to electron population. And you find that the conduction band bends towards the Fermi level because of this increased electron count but then what kind of a contact is this. So, since holes are the majority carriers let us look at the, let us look at what the holes experience. The holes now see a barrier they, they have to run down, they have to run down the hill ok.

So, in the previous case the holes had to run could run up the hill and into the metal and it was a nice Ohmic contact, but now the holes have been asked to run down the hill they do not like it and they see a barrier. And therefore, this is very much like your barrier or a Schottky contact which we discussed earlier but the only thing is that the barrier is now formed in the between the Fermi level of the metal and the valence band edge and that is your barrier there, ok.

So, just to summarize, we considered four kinds of contacts. We took a metal with an n-type semiconductor and we considered the case of phi m greater than phi s and phi m less than phi s. In the case of a metal, in the case of phi m greater than phi s, we found that we ended up with a Schottky contact or a rectifying contact.

In the case of phi m less than phi s, the metal gave electrons to the semiconductor and we ended up with an Ohmic contact. In the case of a metal P type semiconductor junction when phi m was greater than phi s we had an Ohmic contact, because we are now looking at what the holes are doing at the valence band and when phi m is less than phi s we ended up with a Schottky contact.

So, that is a summary of the four kinds of contacts that we have established, and what we will do from this point on is to study the electrostatics and the current voltage characteristics in each of these contacts.