Fundamentals of electronic materials, devices and fabrication
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Lecture – 09
Metal-semiconductor junctions

In the first few classes of this course, we have looked at Electronic Materials. We started with Intrinsic Semiconductors, so these are pure semiconductors. But, we found out that things could be a lot more interesting, if we added a small amount of dopants to the semiconductors. So, the next thing we looked at were the Extrinsic Semiconductors. Where, we could have selectively either more number of electrons or more number of volts.

In the next few classes, we are going to focus on electronic devices. In order to form a device, we need to put materials together and when we put materials together, we will form Junctions.

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So, in this first lecture on the series of electronic devices we are going to start by looking at Junctions. We will first start with looking at a Junction between 2 Metals. So, we will form a Metal-Metal Junction and we will use this to understand the concepts of band alignment. From there, we will form a junction between a Metal and a Semiconductor.

There 2 types possible here and you will consider them, one is a Schottky Junction and the other is called Ohmic. And from the Metal Semiconductor, we will go to your Semiconductor-Semiconductor Junction and the most famous of this is your p-n Junction.

In today's class, we will focus on the Metal-Metal and Metal-Semiconductor Junction. So, the most important rule, when a junction is formed is that, the Fermi levels must line up at equilibrium.

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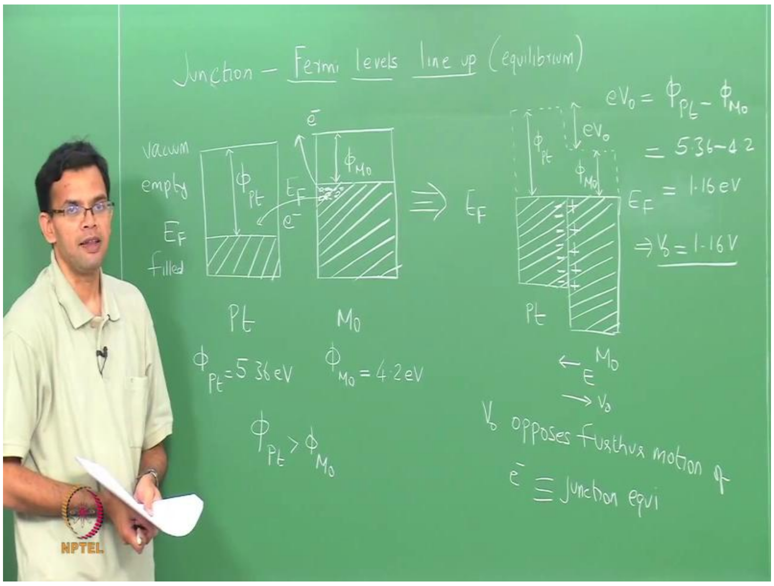

So, whenever you have a Junction, the Fermi levels must line up and this is at equilibrium. Equilibrium here means there is no external potential applied to the system. So, consider the case of 2 metals, for this particular example I will choose platinum and molybdenum. So, let me just draw platinum. So, metals are characterized by having a continuous valence and the conduction band so that, they are filled an empty states and E_F that is the Fermi energy, represents the gap between the filled and empty state. So, this is platinum, these are all filled state, these are all empty state. E_F separates the filled and empty. The distance from the Fermi level to the Vacuum level, the top most is the Vacuum level, is the work function I am going to call phi of platinum and platinum has a work function of 5.36 electron volts. So, I am going to form a junction between platinum and then molybdenum.

So, once again this is E_F, this is φ_{Mo}. The work function of the molybdenum is 4.2 electron volts. So, here we see the platinum has a higher work function than molybdenum. So, we are going to form a Metal-Metal Junction by putting platinum and molybdenum together. We will worry later, how these junctions are actually formed? Right now, we just say that we formed the junction. So, if you think about it molybdenum has a whole bunch of electrons, close to the Fermi level and there are whole bunch of empty states in platinum. So, when a junction is formed electrons from molybdenum with the lower work function can move into platinum. So, when this happens there be a net positive charge on molybdenum and because it is losing electrons there will be a net negative charge on platinum because it is gaining electrons which means, an electric field will be setup when a junction is formed between platinum and molybdenum.

So, let me form the junction. And, as I said that whenever you form a junction, the Fermi levels must line up. So, I will put the Fermi levels at the same energy levels. So, E_F; E_F in this picture you can think of the molybdenum levels going down, so that the E_F 's line up or you can think of the platinum going up so that the E_F 's line up, either case is O K. This is Platinum and then this is Molybdenum. Let me just erase that extra portion here. So, this is the work function of the Platinum, this is the work function of Molybdenum. So, in this diagram we said that when we form the junction between the Platinum and Molybdenum, electrons move from moly to platinum.

So, when electrons move a net positive charge is created on the Molybdenum side and when these electrons move to Platinum and net negative charge is created. So because, you have this positive charge and negative charge, there is an electric field E. The field goes from positive to negative and there is a contact potential. Potential goes from negative to positive. This contact potential V_o is equal to the difference between the work functions. So, eV naught, let me write it here, is nothing but φ_{Pt}, φ_{Mo}. If you put in the numbers platinum we said was 5.36, molly is 4.2, 1.16 electron volts. Implies V_o is 1.16 volts.

So, we can depict the contact potential here which is the difference between the work functions. So, this represents eV naught. This contact potential here opposes further movement of electrons so that we have a junction that is in equilibrium. So, when we have 2 metals, that come together with different work functions and they form a junction.

Once again, we do not look into the mechanics of how the junction is formed; we just say that we have a junction that is ideal, which means there are no defects. In such a case, electrons will go from the metal with the lower work function to the metal with the higher work function, this in turn leads to a contact potential at the surface. And this contact potential opposes further motion of electrons. The value of the contact potential depends upon the difference between the work functions of the 2 Metals.

So, where do we use these Metal-Metal Junctions? One particular example is in the case of Thermocouples, to understand that we need to look at something called the Seeback effect.

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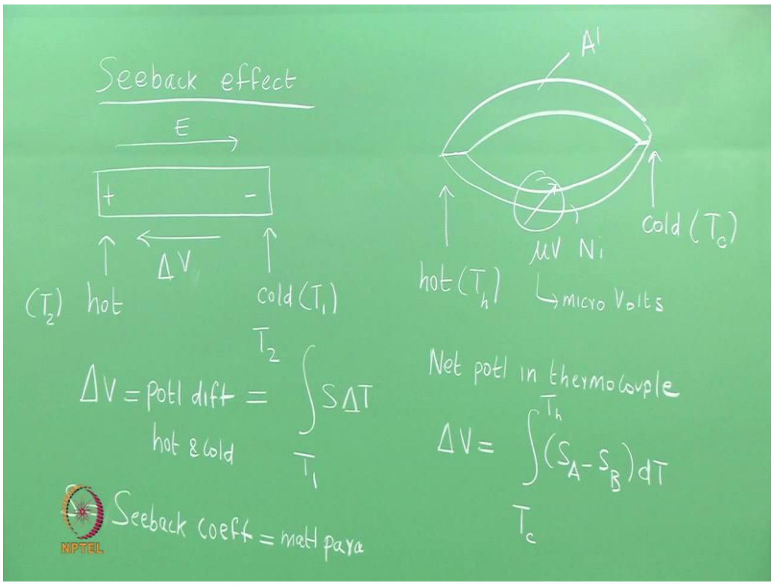

So, consider a piece of metal, one end of it is hot and the other end of it is cold. So, your cold could be the room temperature, the hot end could be something that is placed in a furnace at elevated temperature. So, if we have 2 ends, one that is hot and one that is cold; electrons on the hot side have a higher thermal energy, because yesterday we saw the thermal energy is equal to $\frac{3}{2kT}$, which means higher the temperature, higher the thermal energy or higher the velocity. So, these electrons will tend to drift towards the cold end. So, that there will be a net positive charge on the hot side and net negative charge on the cold side. Which means, there will be an electric field through a metal and there will be a potential, let me just call it V. This potential is dependent on the temperature difference between the hot and cold end and a coefficient that is called

Seeback coefficient. So, ΔV; let me write this is ΔV here, which is the potential difference between hot and cold is nothing but S times ΔT. The integration is from T_1 which is the temperature at the cold end to T_2, which is the temperature of the hot end and S is called the Seeback coefficient.

The Seeback coefficient is essentially a material parameter. So, if you change the material, the value of the coefficient will be different. So, how do we use this in order to understand Thermocouples? In the case of a Thermocouple, a junction is formed between 2 dissimilar metals. Give you an example; consider a junction between Aluminum and Nickel. So, this material is Aluminum and this is Nickel. So, you essentially form 2 junctions at the 2 ends. So, One end of this junction is placed in the hot side, where the temperature we want to measure. The other end is cold, so typically this could be room temperature. So, let us say the temperature of the hot end is T_h, temperature of the cold end T_c. Now, whenever we have a junction between 2 dissimilar materials, we said that there will be potential which depends upon the work function. So, there will be 2 potentials here, one setup at the hot end and the other at the cold end.

But, there will also be a potential within the material because, of the Seeback effect. And this potential will be different for Aluminum and Nickel because the Seeback coefficients are different, which means there will be a net potential in this system that we can measure. This potential is usually very small, it is of the order of micro volts and this net potential in the thermocouple, So, let me call it ΔV. Depends upon the difference in the Seeback coefficient, so if you have 2 materials A and B, in this case it is Nickel and Aluminum. Is S_A - S_B ΔT and the integration goes from the cold end to the hot end. So, depending upon the temperature and the difference in the Seeback coefficients you will have a net potential in the Thermocouple. So, usually there are tabulated values for this potential for a given pair of materials, this will again depend upon the operating range of these materials. So, if you want to find out the temperature of an unknown furnace or an unknown sample, by measuring the potential and then using standard tables we can calculate the temperature. So, this is an example where Metal-Metal Junctions are formed and whenever you have these junctions, there always be a contact potential.

Next, let us move to a Metal-Semiconductor Junction.

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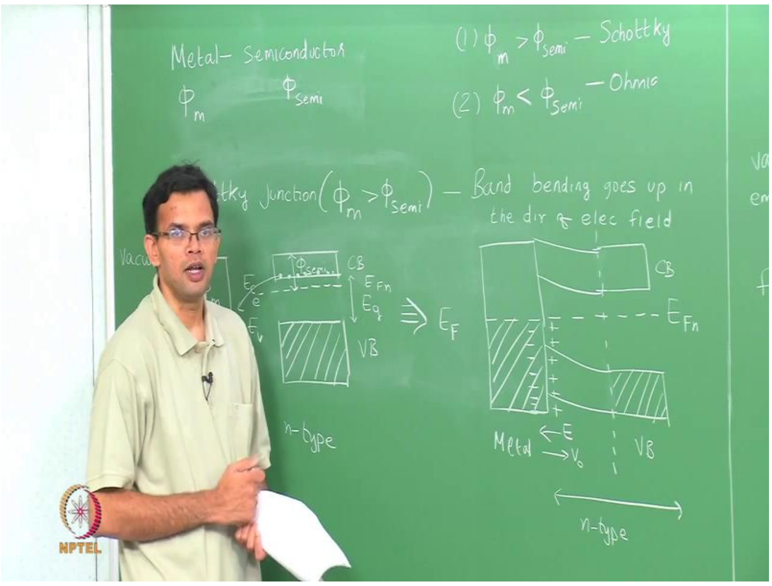

So, we will consider the case of a Junction, formed between a Metal and a Semiconductor. So, this is useful in the case of when we form devices on a vapor, these devices have to be connected to an external circuit and this is usually done by forming metal contacts with these devices. So, there we will have Metal-Semiconductor Junctions. So, in the case of a Metal and Semiconductor, let φ_m be the work function of the metal and φ semiconductor, φ_{semi} be the work function of the semiconductor. So, there are 2 options possible, one you have φ_m; you have φ_m that is $>$ φ_{semi}, this type of a junction is called a Schottky Junction. On the other hand, you have a situation φ_m is less than the work function of the semiconductor this is called an Ohmic Junction.

So, we will start by looking at the Schottky Junction first. So, A Schottky Junction is one, $\varphi_m > \varphi_{semi}$. So, let me draw the band diagrams for the Metal and Semiconductor separately, then we will put them together and draw the band diagram in equilibrium. So, we will follow the same procedure that we used, when we form 2 junctions between metals. So, I have the metal on my left, So, this is my metal it has a work function of a φ_m and this is the Fermi energy. The top of the metal is your vacuum level. So, let me form a junction with a semi conductor for this example, I will take an n-type semiconductor but, we could use any other material as well. Let me actually write that below, so I can draw the diagram. So, in the case of a semiconductor we know we have a valence band, we have a conduction band, there is a band gap. Let me just erase this. So, this is the band gap E_g, we will denote the top of the valence band as E_v, the bottom as a conduction band as E_c. So, this is an n-type semiconductor. So, the Fermi level will be closure to the conduction band so let me call it E_{Fn} and the distance from the Fermi level to vacuum is your work function so, this is the work function of the semiconductor.

So, now we are going to form a junction between this metal, which has a work function, which is greater than the work function of the semiconductor. So, if we look at this picture we can see that this is an n-type semiconductor so there are whole bunch of electrons in the conduction band of the semiconductor. There are whole bunch of empty states in the metal. So, when the junction is formed, electrons can move from the semiconductor to the metal and when this happens there is a net positive charge on the semiconductor and there is a net negative charge in the metal. So, once again we will have an electric field and then you will have a contact potential, and this contact potential will oppose any further motion of electrons.

So, when we draw the band diagram between a metal and a semiconductor, we have to show the bands bending in the case of semiconductor to explain this contact potential. The rule that is to be followed is that band bending goes up in the direction of the electric field. So, we will see in a minute, what this means? So, when you form the junction the first thing we are going to do is to, line up the Fermi levels and then you are going to bend the bands in the semi conductor and this band bending will go up in the direction of the electric field. So, let me put this junction together. So, the first thing I am going to do is line up the Fermi levels, this is E_F on the metal side and E_{Fn} on the semi conductor side. So, we can say that the semi conductor comes down so that the Fermi levels line up. This is a metal, far away from the junction the semiconductor behaves like an n type. So, you have a conduction band and you have a valence band. Let me just erase this line. And, at the junction or near the junction will find that the bands bend. So, this whole region is your n-type semiconductor.

So, let us go back to this picture. We said that when the junction forms between the metal and n-type semiconductor, electrons move from the semiconductor to the metal. So, there is a net positive charge on the semiconductor side and there is a net negative charge on the metal side, which means there is an electric field which goes from the semiconductor to the metal or there is a contact potential. Now, in the case of a metal, the electron density is of the order of 10^{22}, in the case of a semiconductor the electronic density is usually lower. So, if we talk about a typical n-type semiconductor, your electronic densities can be around 10^{16} to the 10^{18} cm^{-3}. This means, when the electrons move from the semiconductor to the metal they not only move from the surface, but they also penetrate at distance within the bulk of the semiconductor. So, there is a region within the semiconductor where electrons are lost as they move into the metal and this region is called the Depletion region. So, let me redraw this diagram and mark the various regions here.

So, we have formed the junction between the metal and n-type semiconductor and the junction is at equilibrium.

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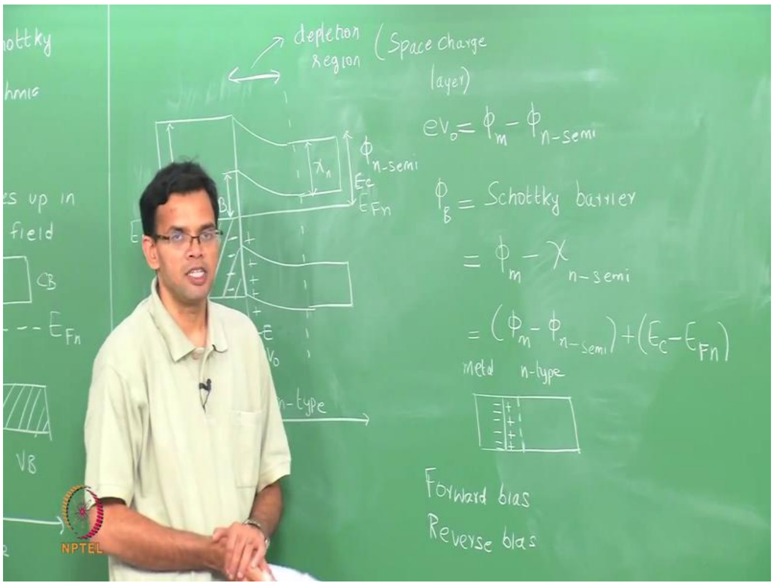

So, let me just redraw that figure. So, this is the metal side and an at equilibrium the Fermi levels line up far away from the junction, it still behaves like a typical n-type semiconductor, but closer to the junction because of electron motion you have band bending. So, this portion is the metal, this side is your n type. There is a net positive charge on the semiconductor side and there is a net negative charge. Now, because of the difference in electron densities, electrons from the semiconductor not only move from the surface but they also move from a certain region within the bulk. So, this distance from where electrons from the semiconductor move to the metal is called your Depletion region. Another name for depletion region is called the Space charge layer.

So, we now have an electric field and the contact potential between the metal and the semiconductor, just like we had in the case of 2 metals this contact potential depends upon the difference between the work functions. So, eV_o is nothing but φ_m - φ, it is n-type semiconductor so I will just write it as n - semi. If you mark those 2 values, this is φ_m and this is φ_n. So, this contact potential represents the barrier for the electrons to move from the semiconductor to the metal. So, at equilibrium you have a barrier that is setup that prevents any further motion. There is also a barrier for the electrons to go from the metal to the semiconductor; this barrier is called φ_b, just call the Schottky barrier. The Schottky barrier is given by the work function of the metal minus the electron affinity of the semiconductor. So, if the bottom of the conduction band is E_c, electron affinity is from bottom of the conduction band to the vacuum level. Another way of writing this is that, this is equal to $\varphi_m - \varphi_n$ which is the contact potential plus the energy difference between the bottom of the conduction band and the location of the Fermi level.

So, if you have a metal and an n-type semi conductor junction, we have the work function of the metal greater than the work function of the semiconductor. And, when this junction forms under equilibrium you have a contact potential that prevents further motion of electrons from the n-type semiconductor to the metal. So, let me just draw this schematically here. So, this is the metal side, this is the n-type semiconductor side, I will draw this with the dotted line to show the depletion region so the metal has a net negative charge and there is a net positive charge on the semiconductor. So, this is the case when you have this system in equilibrium. Now, things become more interesting when we try to bias, so when we try to apply an external potential to this metal semiconductor junction.

Now, there are 2 ways of biasing the junction. First is called Forward bias and the next is called Reverse bias. When you bias a junction, the system is no longer in equilibrium. You have an external potential that is applied, which means you have electrons or holes that have been injected in to the system. So, in bias the Fermi levels will no longer line up but, will be shifted depending upon the applied potential. So, let us look at Forward bias first and then we will consider Reverse bias.

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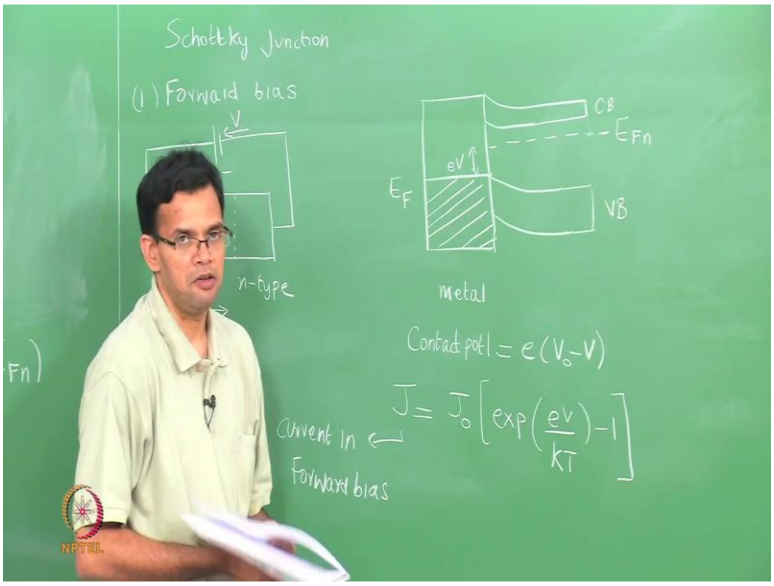

So, let us look at Schottky junction in forward bias. So, once again let me draw the metal and the semiconductor. So, In a forward bias, the metal is connected to the positive side and the semiconductor is connected to the negative side, of an external potential. So, V is the external potential, this is positive, this is negative. If you look at the external potential we find that, that potential is opposite to the contact potential that is being setup; that is setup within the junction. So, V_o is the contact potential, V is the external potential and V is opposite V_o. So, the effect of the external potential is to reduce the total contact potential at the interface and you can show this in the band diagram by shifting the Fermi level of the semiconductor up.

So, if I want to show the band diagram of a Metal-Semiconductor junction under forward bias, this is your metal side E_F. So, if you have a junction in equilibrium, we would show that the Fermi levels line up. But now, we have a junction where you have a forward bias, which means the Fermi level of the semiconductor will be shifted up. So, this will be E_F of the semiconductor. If I show the bands, we just redraw this to show the bands, this is the conduction band, this is the valence band. So, this shifting up is proportional to the applied voltage. So, the contact potential of this junction now, is nothing but $e(V_o - V)$. So, this contact potential we saw earlier was the barrier for the electrons to move from the semiconductor to the metal. By applying a forward bias we have reduced this barrier, which means it easier for the electrons to go from the semiconductor to the metal so we can have a current and the magnitude of this current is depend upon the magnitude of V. So, higher the value of V, lower the contact potential and the higher the current. We can write an expression for the current, J represent the current in forward bias, is nothing but $J_o\left(\left(exp\frac{ev}{kT}\right)-1\right)$, V here is the applied potential.

So, the current depends exponentially on the applied potential and higher the current and the higher the potential, higher the current. So, this is the case of p-n of Metal-Semiconductor junction or Schottky junction in Forward bias.

So, what happens if we apply a Reverse bias? In the case of a Reverse bias, the metal side is connected to a negative and the semiconductor is connected to a positive.

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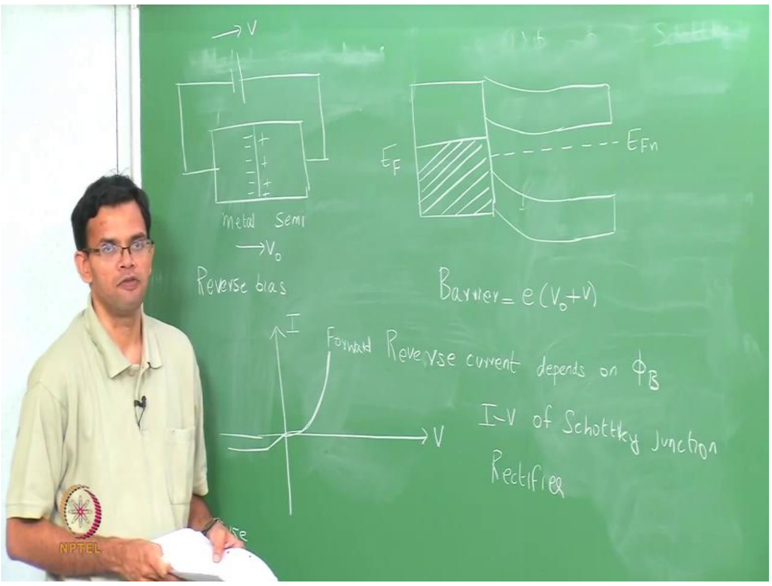

So, this is the metal, this is the semiconductor, so this is Reverse bias. In this particular case, the external potential V is in the same direction as the contact potential, which means the overall barrier goes up. So, in Forward bias we showed that the Fermi level of the semiconductor will go up, in the case of a Reverse bias the Fermi levels of the semiconductor will go down. So, if we draw the band diagram for this, this is your metal, this is E F, this is the Fermi level of the semiconductor it is gone down which means, the overall barrier has now gone up so the barrier is $e(V_o + V)$. In the case of reverse bias, there is a small current that goes from the metal to the semiconductor and this current which is your reverse current, depends upon the schottky barrier.

So, we can draw an I-V diagram for a Schottky Junction. And, I-V diagram is one where we plot current on the y axis and voltage on the x axis. So, the first quadrant is your Forward bias and last quadrant is your Reverse bias. In the case of a forward bias, we found that you have a current that exponentially increases as the applied voltage so, this shows the exponential increase. In the case of a Reverse bias, there is a reverse current which is small and a constant and depends upon the schottky barrier so, this we can show like this. This is the I-V characteristics of a schottky Junction. So, in this case, you have a schottky Junction that will conduct in the forward bias because you see a current and act as an insulator when you have a reverse bias. So, a Schottky Junction will act as a Rectifier. So, let us next consider the Ohmic Junction, where the work function of the metal is smaller than the work function of the semiconductor.

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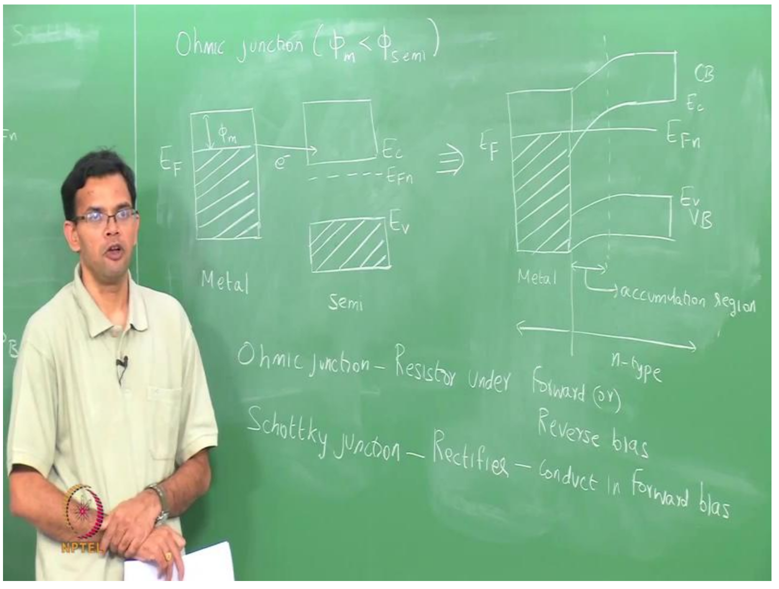

So, phi m is smaller than the φ_{semi}. And you will use the same n-type semiconductor as an example. So, this is the metal side, this φ_m, E F, this is the semiconductor side. So, the valence band E_v is the top of the valence band, E_c is the bottom of the conduction band and it is n-type, so E_{Fn} is close to the conduction band edge. So, in this case it is a reverse of the Schottky Junction. We have a large number of electrons in the metal side, these electrons can move to the semiconductor. So, an electric field will again be setup and the field will be in the direction opposite to that of a Schottky Junction.

So, because you have an electrons going from the metal to the semiconductor, you will have an accumulation region. Remember, in the case of a Schottky junction we had a depletion region, where electrons moved away from the semiconductor. Now, you have electrons moving in so, that you have an accumulation region. We can draw the Ohmic Junction in equilibrium. In equilibrium, the Fermi levels will line up. So now, the bands will bend the other way because the electric field is in the opposite direction. We just redraw this portion, to show the band bending. So, this is your valence band with E_v, this is your conduction band with E_c. So, now you have bands that bend down because the electric field goes in the other way. So, in the case of an Ohmic Junction, this is the metal, this is the n-type semiconductor and you have an accumulation region. So, this is a region where excess electrons go from the metal to the semiconductor.

We can look at the behavior of an Ohmic Junction, in the case of a Forward or a Reverse bias. And this behavior is entirely different from that of a schottky. Now, because you have an accumulation region, the behavior of this device under a bias basically acts as a resistor and the resistance is given by the n-type semiconductor. So, Ohmic Junction will behave as a resistor, under forward or reverse bias. So, the junction will conduct whether you have a forward or a reverse bias and the conductivity is determined by the resistance of the n-type semiconductor. This is opposite to a Schottky Junction, which we saw earlier behaves like a rectifier. So, that it will only conduct in forward bias, but will not conduct during reverse bias or you can say that it has a very small reverse current in reverse bias, as a rectifier. So, that it will only conduct in forward bias.

So, this difference between these 2 junctions depends upon the difference between the work functions of the metal and the semiconductor. All the examples, you have worked out today were with an n-type semiconductor. But, we could draw similar band diagrams if we had a p-type material, so we can have similar Ohmic and Schottky Junctions. So, today we have seen 2 types of junctions; one between 2 metals and the other between a metal and a semiconductor.

In next class, we are going to form junctions between semiconductors and the first one we will look at is the p-n junction.