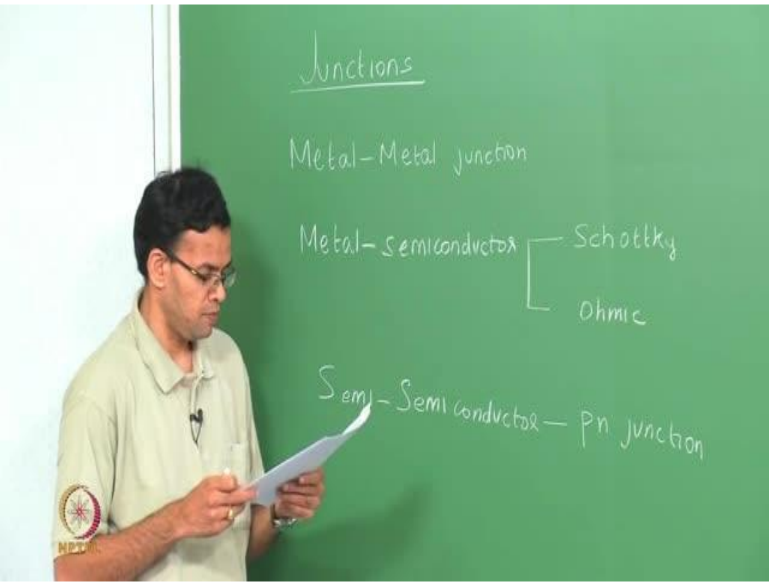
Electronic Materials, Devices and Fabrication
Dr. S. Parasuraman
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture - 12
Metal-Semiconductor Junctions

In the first few classes of this course we have looked at electronic materials. We started with intrinsic semiconductor. 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 semiconductor. So, the next thing which looked that where 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 we put materials together we will form junctions.

(Refer Slide Time: 00:59)

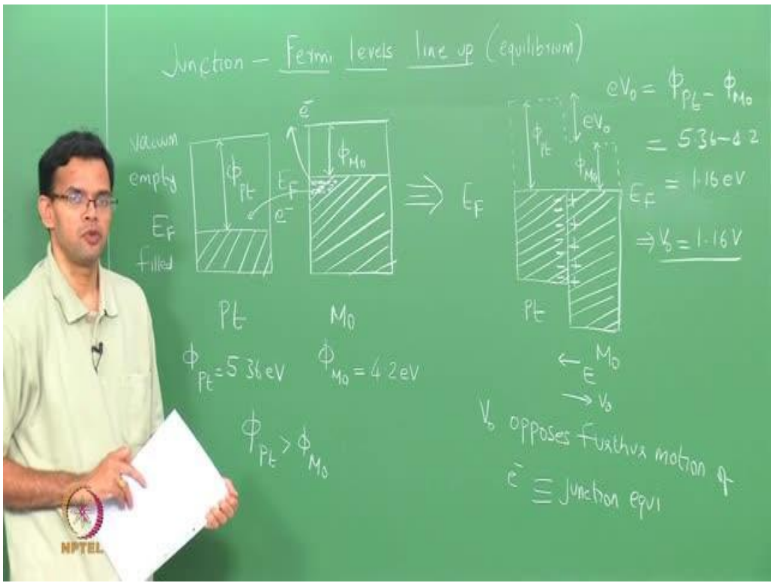


So, in this first lecture on the series of electronic devices, we are going to start by looking at junctions. We will first start with looking at junction between 2 metals. So, we will form metal junction and we will use this to understand the concept of band alignment. From there we will form a junction between a metal and a semiconductor. That 2 types possible here and you will consider them, one is your schottky junction the other is called ohmic.

And from the metal semiconductor will go to your semiconductor, semiconductor junction. And the most famous of this is your p n junction. In today’s call we will focus on the metal

metal and the metal semiconductor junction. So, the most important rule when the junction is formed is that the fermi levels must line up at equilibrium.

(Refer Slide Time: 02:43)



So, whenever you have a junction the fermi levels must line up. And this is at equilibrium, equilibrium here means there is external potential applied to the system. So, consider the case of 2 metals for this particular example I will choose platinum and malignum. So, let me just draw platinum. So, metals are characterized by having a continuous valance and the conduction band. So, that there are fill and 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 states 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 it phi of platinum and platinum has a wok function of 5.36 electron volts. So, I am going to form a junction between platinum and then malignum. Once again this is E f this is phi of the work function of malignum is 4.2 electron volts.

So, here we see platinum has a higher work function then malignum. So, we are going to form a metal, metal junction by putting platinum and malignum together. We will vary later how these junctions are actually formed, now we will just say we form the junction. So, we thing about it malignum has whole bunch of electrons close to the fermi level. And there are whole bunch of empty state in platinum. So, when the junction is formed electrons form malignum with the lower work function can move in to platinum. So, when this happens there be a net positive charge on malignum, 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 set up when a junction is formed between platinum and molly. So, let me form the junction and I said that whenever you form a junction, the fermi level must line up. So, I will put the fermi levels at the same energy level. So, E f in this picture you can think of the malignum levels going down. So, that the E f line up or you can think of platinum going up. So, that the E f line up either case is ok. So, this is platinum and then this is molly.

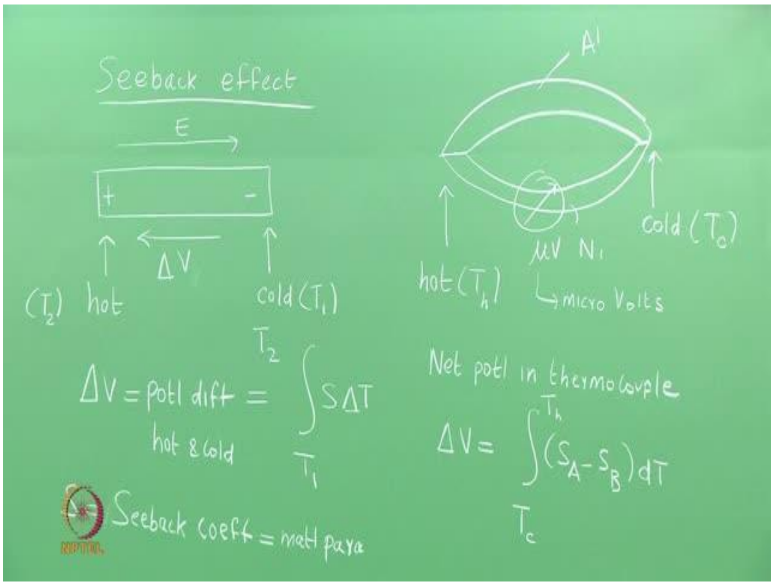
Let me just erase that extra portion here. So, this is the work function of platinum, this is the work function of malignum. So, in this diagram it is said that when we form the junction between platinum and malignum, electrons move from molly to platinum. So, when electrons move and net positive charge is created on the malignum 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 contact potential, potential goes from negative to positive. This contact potential v naught is equal to the difference between the work functions. So, E v naught we write it here is nothing but phi of platinum, phi malignum. We put in the numbers platinum we said was 5.36 molly is 4.2, 1.16 electron volts, implies we naught is 1.164 volts.

So, we can depict contact potential here which is the difference between the work functions. So, this represent E v naught. This contact potential here opposes further movement of electrons. So, that we have a junction that is in equilibrium. So, when we gave 2 metals that come together with different work functions and they form a junction once again we do not look into the mechanics 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 intern 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 in the case of thermocouples to understand that we need to look at something called see back effect.

(Refer Slide Time: 11:00)



So, consider a piece of metal, one end of it is hot the other end of it is cold. So, your cold could be the room temperature, the hot end the hot end could something that is placed in a furnace at elevated temperature. So, 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 3 over 2 k t, which means higher the temperature higher the thermal energy or higher the velocity.

So, these electrons will tend to deft towards the cold end. So, that there will net positive charge on the hot side and net negative charge on the cold side, which means there will be an electric field through your metal and there will a potential, let me just call it v. This potential is dependent on the temperature difference between the hot and the cold end and a coefficient that is called see back coefficient.

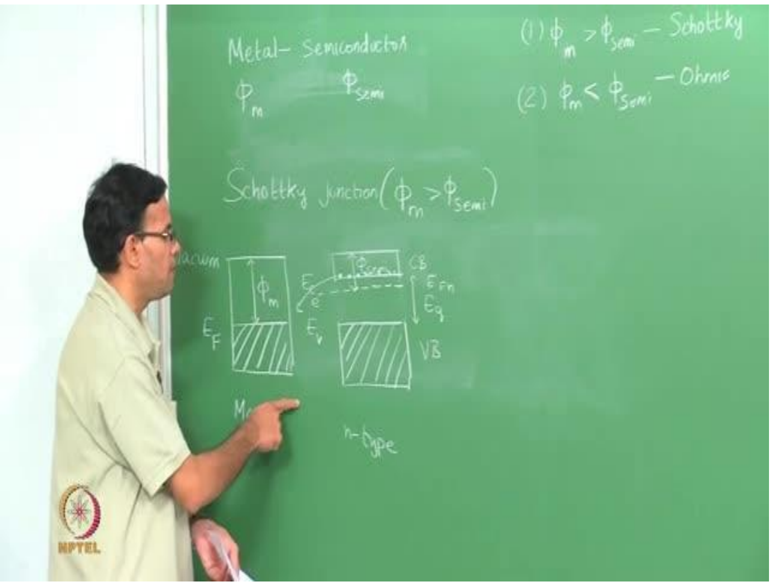
So, delta v let me write delta v here which is the potential difference between hot and cold is nothing but S times delta t the integration is from t 1 which is a temperature at the cold end to t 2 which is temperature at the hot end. And S is called the seeback coefficient. Seeback coefficient is essentially 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 thermocouple. In the case of a thermocouple a junction is formed between 2 dissimilar metals. Give you one 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 this cold. So, typically this could be room temperature. So, let us say the temperature at the hot end is T h temperature, in the cold end is T c. Now, whenever we have a junction between 2 dissimilar materials, we said that there will be a potential which depends upon the work function.

So, there will be 2 potentials here 1 set up at the hot end and the other at the cold end, but they will also be a potential within the material because of the seeback effect. And this potential will be different for other aluminum and nickel because the seeback coefficients are different, which means they will be a net potential in the system that we can measure. This potential is usually very small that is of the order of micro volts, and this net potential in the thermocouple. So, let me call it delta v depends upon the difference in the seeback coefficients. So, if we have 2 material a and b. In this case it is nickel and aluminum is S a minus S b delta t and the integration goes from the cold end to the hot end. So, depending upon the temperature and the difference in the seeback coefficient 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 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 will always be a contact potential. Next let us move to a metal semiconductor junction.

(Refer Slide Time: 16:43)



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 wafer. These devices have to be connected to an external circuit and this is usually done by forming metal contexts with these devices. So, there we will have metal semiconductor junctions. So, in the case of a metal and a semiconductor, let phi m be the work function of metal and phi semiconductor, phi semi be the work function of the semiconductor. So, there are 2 options possible, one you have phi m, you have phi m that is greater than phi semi. This type of junction is called a schottky junction.

On the other hand you have situation phi 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, schottky junction is 1 phi m greater semi. So, let me draw the band diagrams for the metal and the 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.

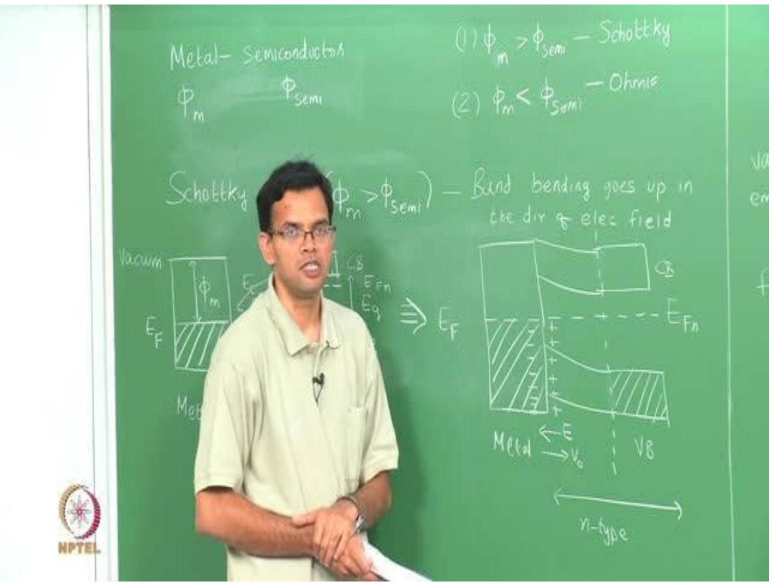
So, have the metal on my left. So, this is my metal has a work function of phi m. This is the fermi energy the top of the metal is you are vacuum level. So, let me form a junction with a semiconductor. For this example I will take an n type semiconductor, but we could use any another material as well me actually write that below. So, I can draw the diagram.

So, in the case of a semiconductor we know we have a valance band, we have a conduction band. There is a band gap let me just erase this. So, this is the band gap E g will denote the top of the valance band as E v the bottom of conduction band as E c. So, this is an n type semiconductor. So, the fermi level will be closer to the conduction band. So, let me call it E f n 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 a whole bunch of empty state in the metal. So, when a 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 we 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 the semiconductor, we have to show the bands bending in the case of semiconductor to explain this contact potential.

(Refer Slide Time: 22:13)



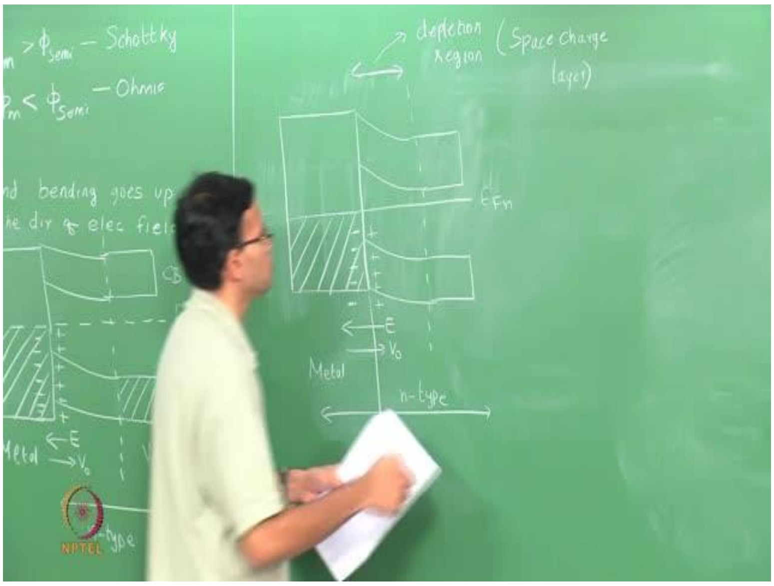
The rule that is to be followed is that band bending goes up in the direction of the electric field. So, we will see in the minute what this means. So, when we form the junction the first thing, I going to do is to line up the fermi levels. And then we are going to bend the bands in the semiconductor 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 f n on the semiconductor side. So, we can say that the semiconductor comes down. So, that the fermi levels lineup. This is your metal for away from the junction the semiconductor behaves like an n type. So, you have conduction band and you have a valance 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 the 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 to the 22. In the case of a semiconductor the electron density is usually lower. So, if we talk about a typical n type semiconductor your electron density is can be around 10 to the 16 to 10 to the 18 per centimeter cube. This means when the electrons move from the semiconductor to the metal they not 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.

(Refer Slide Time: 26:21)

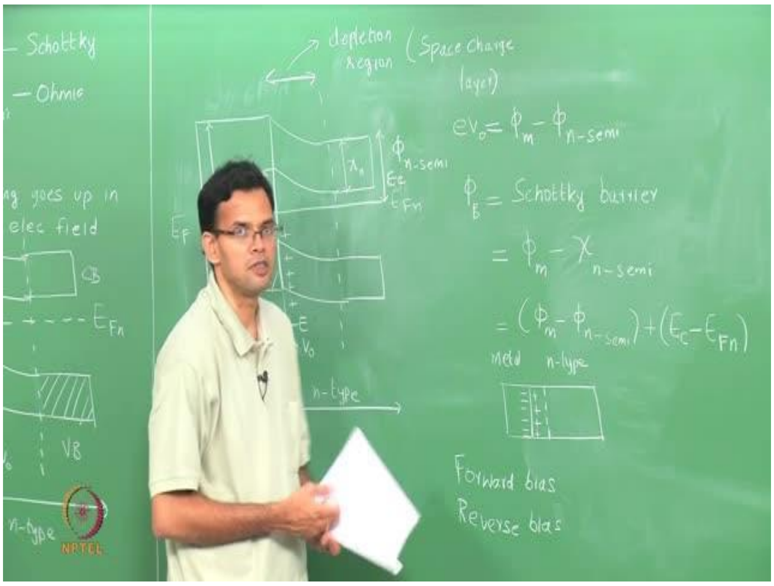


And this region is called the depletion region. So, let me redraw this diagram and mark the various regions here. So, we have formed the junction between metal and the n type semiconductor, the junction is at equilibrium. So, let me just redraw the figure. So, this is the metal side and at equilibrium your 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 you are 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 electrons, from the semiconductor move to the metal is called your depletion region.

Another name for the depletion region called the space charge layer. So, we now have an electric field and the contact potential between the metal and semiconductor. Just like we had in the case of 2 metals, this contact potential depends upon the difference between the work function.

(Refer Slide Time: 28:43)



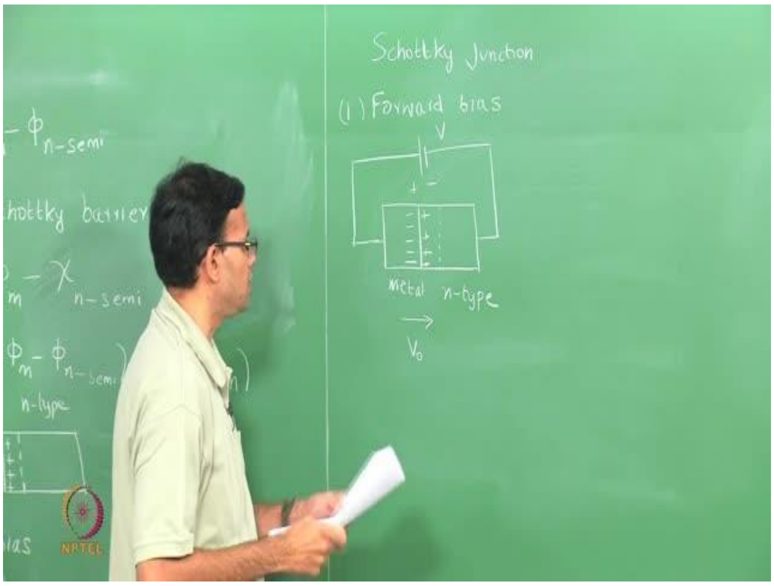
So, E v naught is nothing but phi m minus phi it is an n type semiconductor. So, I will just write it as n slash semi, if you mark the 2 values. This is phi m and this is phi n. So, this contact potential represents the barrier for the electron to move from the semiconductor to the metal. So, at equilibrium you have barrier, that is set up that prevents any further motion. There is also a barrier for the electron to go from metal to the semiconductor. This barrier is called phi 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 top, if the bottom of the conduction band is E c electron affinity is from the bottom of the conduction band to the vacuum level. Another way of writing this this is equal to phi m minus phi 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 semiconductor junction, we have the work function of the metal greater than the work function of the semiconductor.

And when this junction forms 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 a 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.

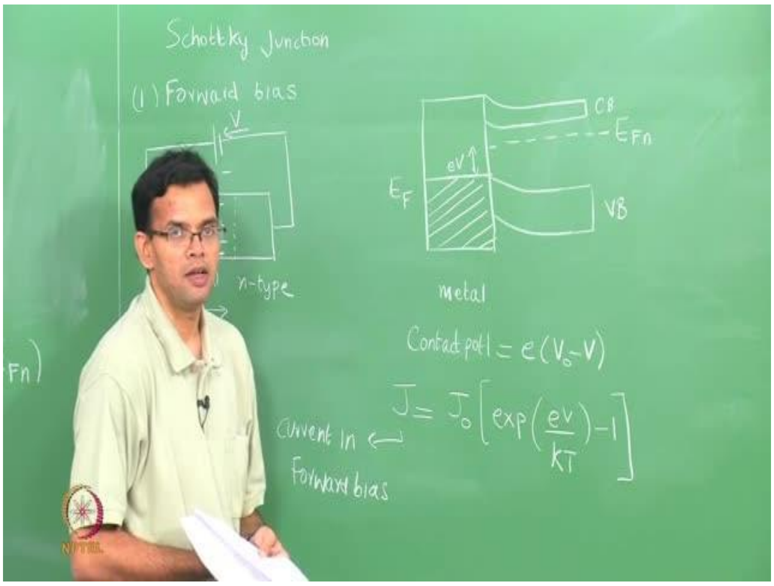
Now, things become more interesting when we try to bias. So, when we try to apply an external potential to this metal semiconductor junction. Now, there are 2 ways of biasing junction first is called forward bias. The next is called reverse bias, when you bias a junction the system is no longer in equilibrium. You have an external potential that is applied, which means you have electrons or volts that are being injected into the system. So, in bias the fermi level will no longer line up, but will be shifted depending upon the applied potential.

(Refer Slide Time: 32:44)



So, let us look at forward bias first and then we will consider reverse bias. So, let us look at a schottky junction in forward bias. So, once again let me draw the metal and the semiconductor. So, on 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, if find that potential is opposite to the contact potential, that is being set up that setup within the junction. So, v naught is the contact potential v is the external potential. And v is opposite v naught. So, the effect of the external potential is to reduce the total contact potential at this, at the interface.

(Refer Slide Time: 34:23)



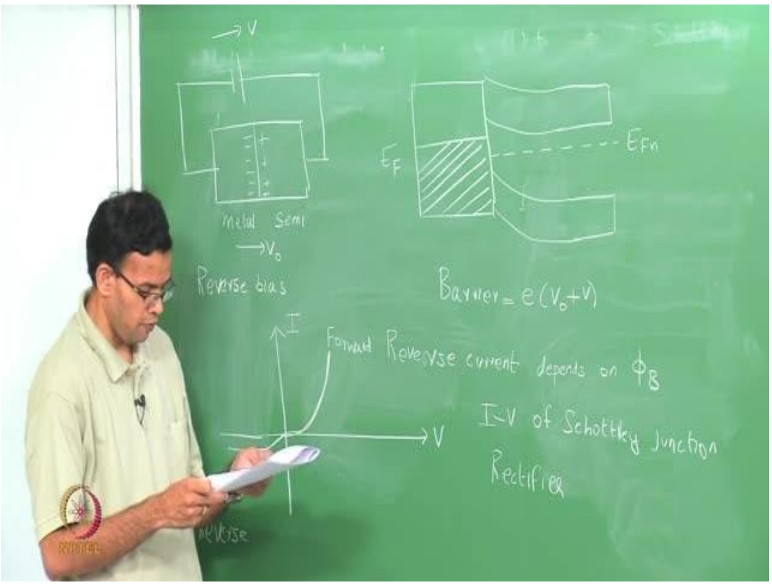
And you can show this in the band diagram by shifting the fermi level of the semiconductor up. So, if I want to show the band diagram of a metal semiconductor junction under forward bias, this is your metal side E f. So, if you have a junction in equilibrium, you would show that the fermi levels line up, but now we have a junction where you have a forward bias which means 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, show the bands. This is the conduction band, this is a valance band. So, this shifting up is proportional to the applied voltage. So, the contact potential of this junction now nothing but E times v naught minus 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 is 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 v. So, higher the value of v, lower the contact potential and higher the current. We can write an expression for the current, J represents the current in forward bias it is nothing but J naught exponential E v over k t minus 1 v here is the applied potential.

So, the current depends exponentially on the applied potential and higher the current when higher the potential higher the current. So, this is the case of p n of metal semiconductor junction a schottky junction in forward bias. So, what happens if we apply a reverse bias.

(Refer Slide Time: 37:39)

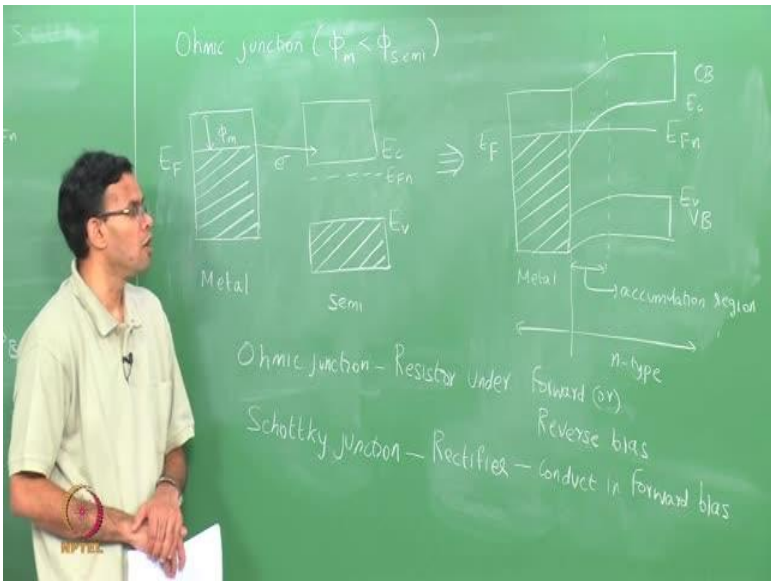


In the case of a reverse bias the metal side is connected to a negative and the semiconductor is connected to a positive. So, this is the metal, this is the semiconductor. So, this is reverse bias in this particular case the external potential v is in the same direction as the contact potential, which 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 level of the semiconductor will go down.

So, if we draw the band diagram for 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 naught plus 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. An i v diagram is onem, where you plot current on the y axis voltage on the x axis. So, the first quadrant is you are forward bias, and the 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 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. So, this is the i v characteristics of a schottky junction. So, in this case you have schottky junction that will conduct in the forward bias because you see a current. And will act as an insulator when you have 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.

(Refer Slide Time: 41:48)



Ohmic junction – Resistor under forward (or) Reverse bias

Schottky junction – Rectifier – conduct in forward bias

So, phi m smaller phi of semi, and you will use the same n type semiconductor as an example. This is the metal side this, phi M E f this is the semiconductor side. So, the valance band E v is the top of the valance band E c is the bottom of the conduction band and it is n type. So, E f n is close to the conduction band h. So, in this case it is the reverse of the schottky junction. So, we have large number of electrons in the metal side.

These electrons can move to the semiconductor. So, an electric field will again be setup and field will be in the direction opposite to that of a schottky junction. So, because you have electrons going from the metal to the semiconductor, you will have an accumulation region.

Remember in the case of 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 valance 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 away.

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 that excesses 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 device under a bias, basically acts as a resistor and the resistance is given by the n type semiconductor.

So, an ohmic junction will behave as resistor under forward or reverse bias. So, the junction will conduct, whether you have a forward or a reverse bias and conductivity is determined by 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 very small reverse current in reverse bias as a rectifier.

So, that it only conducts in forward bias. So, this difference between this 2 junctions depends upon the difference between the work functions of the metal and the semiconductor. All the examples you are worked out today where will an n type semiconductor, but we could draw similar band diagrams be had p type material. So, we can have similar ohmic and schottky junctions. So, today we are see 2 types of junction. One between to 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 look at is the p n junction.