Introduction to Semiconductor Devices
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Lecture - 6.3
Ohmic vs Rectifying Contacts

This document is intended to accompany the lecture videos of the course "Introduction to Semiconductor Devices" offered by Dr. Naresh Emani on the NPTEL platform. It has been our effort to remove ambiguities and make the document readable. However, there may be some inadvertent errors. The reader is advised to refer to the original lecture video if he/she needs any clarification.

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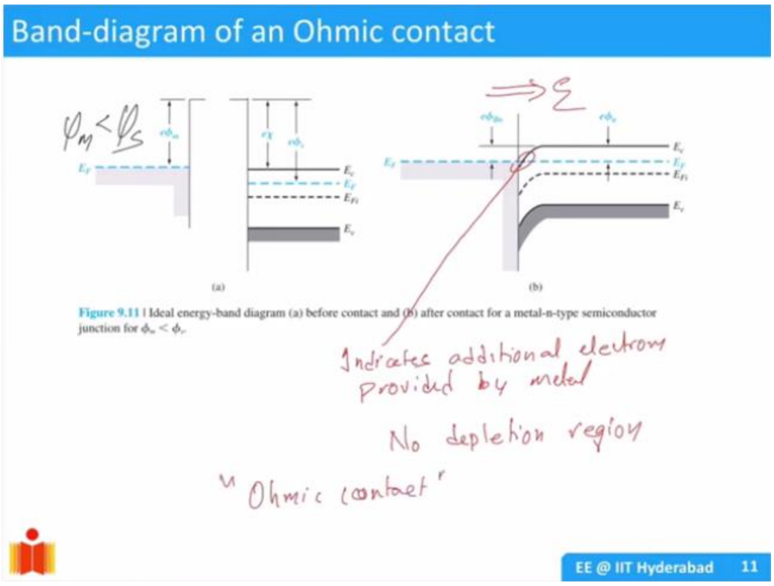

Welcome back. So, in the previous videos, we have considered a Schottky barrier when there is a metal semiconductor junction. We saw that the work function of the metal and the work function of the semiconductor play a crucial role. We have considered n type semiconductor there. But you could also have a situation that you deposit a different material on a metal. For example, we could consider a situation where the work function of the metal now.

Here work function of the metal is smaller than work function of the semiconductor. Remember work function of semiconductor is simply the electron affinity plus the difference of Fermi level from the E_C. So, what happens if your work function of metal is lower? So, in this case, there are higher energy electrons in the metal. And they would enter the semiconductor. This is how electron transfer happens.

The other way it will not happen, because the energy there are the Fermi energy electrons in the semiconductor have smaller energy, they cannot transfer into the other side, but opposite transfer happens. So, when this happens, it is an n type semiconductor, and we are adding more electrons. We are increasing the concentration of electrons in the semiconductor. That is why you will see that in this case the E_F is constant but then the bands are bending low downwards.

So, this point here indicates excess, or you know additional electrons provided by my metal. So, because of that you have additional charge, and the metal will have the positive charge. So, the electric field is going to be in the +x direction. So, what is happening here? This electric field also in some way is causing the electrons to accumulate at the interface. There is nothing like a depletion barrier now or depletion region this.

There is nothing like a no depletion region. So, in this case no depletion region. So, no barrier for current flow you change the voltage, and you will appropriately if you lower the E_F still current flows if you increase it also current flows. So, this sort of a contact you know between metal and semiconductor is known as an Ohmic contact. So, this is called Ohmic contact. So, why do we do this?

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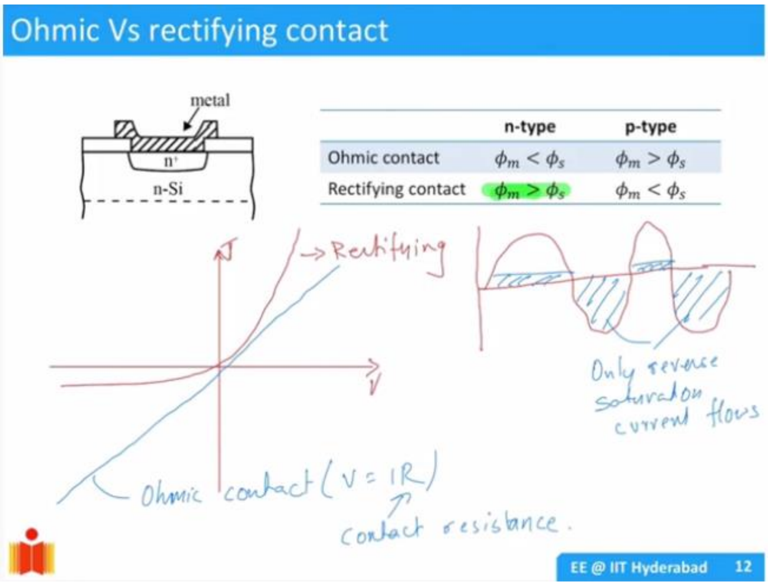

Well, essentially you know it is an important aspect of semiconductor fabrication. You know when you have semiconductors, we always want to make a contact with external world. We cannot simply deal with semiconductors alone. So, we end up contacting a metal. You know, when I mentioned the p-n junctions I mentioned this contact. So, you are going to have another semiconductor device somewhere else.

It is going to connect all that is going to happen through metals. So, the connection between metal and semiconductor is extremely important. And we saw that if your work function of the metal is higher than semiconductor then we found that there is a rectifying contact that is happening. What do we mean by rectifying? You can draw the current voltage characteristics. So, if you draw the current voltage characteristics, voltage versus current J.

For a Schottky diode, it was exponential behavior like this. So, what is happening is if you give a voltage which is you know, let us say a sinusoidal voltage. Whenever you give a negative voltage, for example, here, vary you know only reverse saturation current flows. Of course, there is going to be a small barrier. So, it is going to be slightly positive. Till then it is going to be only reverse saturation.

Above a certain barrier voltage, you can you know above a certain threshold voltage you will have current flowing. So, in a way this behaves this is called as a rectifying behavior. You are removing all the negative going parts of the waveform. That is why we call it a rectifying contact. And this happens whenever you have a Schottky barrier. So, this is for ϕ_m greater than ϕ_s whereas you could also have what is called as an Ohmic contact wherein the current voltage relation is going to be like this.

This is your Ohmic contact, essentially telling you that the current voltage relation is given by Ohm’s law, V equal to IR. This R is called as contact resistance. So, whenever you make this contact with the semiconductor and a metal, there is going to be some contact resistance. And that is going to be a significant feature when you make the contact smaller and smaller.

So, this is a very important aspect experimentally. Whenever we fabricate, we do any research in semiconductor devices, we try to ensure that we evaluate the contact resistances, and we make sure that the contacts are Ohmic and not rectifying. Otherwise, the contact behavior is going to add up to your semiconductor behavior and is going to complicate life. You cannot study what happens at a junction if your contact itself is acting like a junction, or a rectifying behavior.

So, this is for n type semiconductors. We could also do the same analysis for p type semiconductors.

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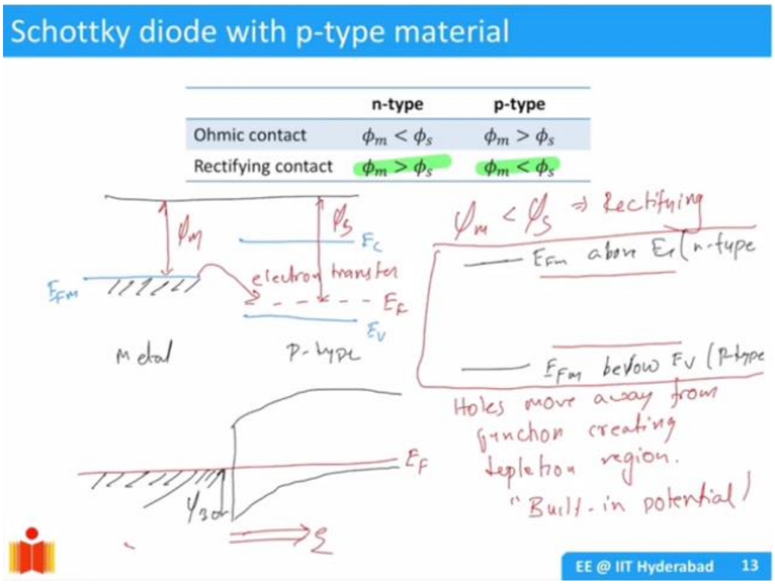

Wherein for example, if you have let us say E_C, E_V, let us say there is a Fermi energy somewhere here, E_F. Now, what happens if I have a metal which is having E_{FM} here? This is your metal Fermi energy. What happens in this case? You are taking a p type here and a metal. In this scenario, of course, electrons are going to go from metal to semiconductor, electron transfer. So, if you transfer electrons, what is happening to the holes?

Because Fermi level is indicating the hole concentration. So, we are in effect reducing the hole concentration. So, in this case, again, you can draw the same band diagrams. You know I will just draw a straight-line E_F. This is going to be your metal and closer to the semiconductor. So, this is going to be your barrier height now, ϕ_{B0}. Why is it a barrier?

Well, immediately you check this is a gradient in the positive direction. So, this is your electric field direction. So, it is going to take your holes away from the junction. So, your holes move away from junction creating depletion region. So, there is a built-in potential, and you have a barrier for electrons and holes to flow.

This is my ϕ_m and this is my ϕ_s. So, ϕ_m less than ϕ_s implies rectifying. That is why we put this here. So, this is exactly opposite. So, this condition is opposite to n type. In the n type semiconductor, ϕ_m must be greater than ϕ_s for forming a rectifying contact. In this case, ϕ_m must be less than ϕ_s. So, an Ohmic contact also same behavior, I would encourage you to see what happens when ϕ_s is less than ϕ_m in a p type material.

Draw the band diagram. That is a good exercise for you. The important point I mean one way I recollect this is a mnemonic that I use maybe it is useful to you or maybe not. So, what I think is whenever I have a semiconductor, the work function of the metal must be, you know for a n type material, work function has to be here in the E_C or above E_C. And in a p type semiconductor, it has to be below E_V.

Only then I can form an Ohmic contact. So, E_{FM} above E_C, E_{FM} below E_V for p type. For n type, it is above E_C. If E_{FM} is above E_C, essentially, ϕ_m is going to be less than ϕ_s. So, this is how I remember it. You can go through the actual electron transfer and analyze it. So, whenever you have rectifying contact, you are going to have depletion regions.

If you are removing majority carriers in the semiconductor, you are going to have rectifying contact. If you are adding majority carriers, you are going to have Ohmic contact. And this is really a lot of significance practically.

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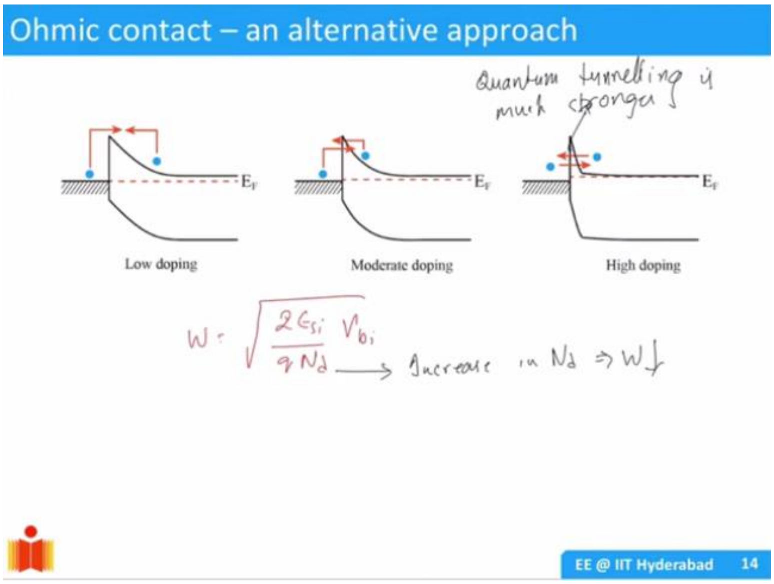

Because as I mentioned already, if you have these metal semiconductor junctions whenever you make a contact, and we want it to be Ohmic. So, sometimes we do not really have a choice you know in this case in the previous example here, what we end up doing is we dope it slightly higher just below the contact. The reason we do that is see here are 3 different scenarios where you know the barrier is shown with an n type semiconductor for different levels of doping, low doping, moderate and high doping.

So, we already studied as the doping density increases the depletion width reduces. So, the depletion width was what.

$$W = \sqrt{\frac{2\epsilon_{si}V_{bi}}{qN_d}}$$

So, if you increase in N_d implies the width of the barrier decreases and that is useful for us.

Because if you have low doping here, you have a large barrier width and electrons must cross this barrier in travel on the other side, thermionic emission process. But as you increase the doping, you see that the barrier width reduces. Once the barrier width reduces here let us for example if you take the high doping it has become much smaller. So, quantum tunneling is much stronger.

So, even though there is a barrier, it still will conduct nicely. The resistance contact resistance will reduce when you have high doping. So, this is a very practical way where you know in the technology, we tend to make a Ohmic contact. Just dope it high just below the contact so that it always forms a Ohmic contact. And there are also other practical considerations because the Fermi energy is not you know going to be so ideal like what you see.

When there is a lot of technological challenges that we must address to make sure that the Fermi energy is changing. There is lot more issues to that. But that will be a topic of a future, you know, master's course. For now, I just want you to understand that shortly contacts are important in a practical way to actually make a Ohmic contact is to simply you know of course, choose a appropriate work function metal that works.

But practically, it might be useful to simply dope just below the contact very highly. So, that is a good way of making Ohmic contacts. So, with that, you know, I would like to stop my discussion on the Schottky diodes. And, you know, we will also post some assignments, you know, from some GATE question papers and all that. So, please try to make sure that you understand. In this course, we are not really dealing with any circuits.

So, I will encourage you to apply these concepts to the, you know, the questions directly question. It is not difficult. I mean that it is not, you know, elementary circuit theory is enough for you to understand and analyze that. So, I am sure you have already studied that. So, you will be able to answer the question so. Thank you so much. I will see you next time, bye.