Introduction to Semiconductor Devices
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Lecture - 6.2
Current Flow Across a Schottky Barrier

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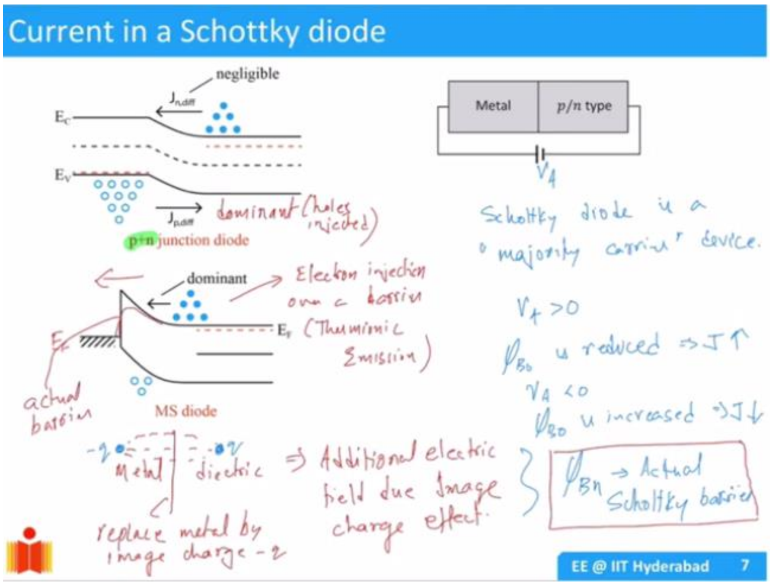
Current in a Schottky diode

Schottky diode is a "majority carrier" device.

$V_A > 0$

ϕ_{B0} is reduced $\Rightarrow J \uparrow$

$V_A < 0$

ϕ_{B0} is increased $\Rightarrow J \downarrow$

$\Rightarrow$ Additional electric field due Image charge effect.

$\phi_{Bn} \rightarrow$ Actual Schottky barrier

In the last video, we were looking at the band diagrams of a Schottky diode. Now, we want to understand how the current flows. And to understand how the current flows, we would like to compare a Schottky diode with a p-n junction. More specifically, we will take the case of a p^+n junction. By which I mean that the p type semiconductor is heavily doped. The reason we are comparing with p^+n is p^+ is going to have a high concentration of holes.

It sorts of mimics a metal. You could think of a highly doped semiconductor as a pseudo metal. So, that will be a more appropriate comparison rather than a simple p-n junction you know with comparable doping. So, when you have a p^+n junction, we have seen this in the past that you know you have a large number of holes here compared to the electrons in the n type. So, the hole diffusion is going to be dominant.

Dominant current compared to the electron injection. So, holes are going to get injected. So, what controls the current in the external circuit? It is the minority carrier injection. Once the minority carriers are injected, they have to recombine with an electron in the n-type semiconductor. And then only that electron will flow in the external circuit. We saw that the minority carrier concentration was decaying exponentially away from the junction.

So, this minority carrier recombination is going to be the determining factor for the current in a p-n junction. What happens in a Schottky diode? So, well, we have seen that. You have this sort of a picture wherein you have barrier, electrons are going to see a barrier and then there is a E_F of metal here. So, now, when will the current flow? Current flows when the electron is able to escape from this when it is able to cross this barrier and flow.

So, this sort of a mechanism is not minority carrier injection. It is actually electron injected injection I would say over a barrier. And this sort of a process is called as thermionic emission. Simply saying that electron is going to cross a barrier and going to the other side. So, this is fundamentally different from what you see in a regular p-n junction. And also Schottky diode is a majority carrier device in a way.

Why do we say this? The reason is there are going to be a finite number of minority carriers. But, how will they move? Will they carry current? Well, to carry current, what should happen? Here, there is a field which is in this direction. So, holes are going to move in this direction. There is going to be some contribution of this. But this is going to be much smaller in number compared to the electron injection over the barrier.

Well, you might say it depends on the barrier height. Of course, it does actually. We will take a few examples and compute the barrier height. And we will see that it is reasonably small. You know in the case of a regular p-n junction, we saw that the barrier heights were like 0.6, 0.5, 0.7 that sort of a range. We will see that the case of a Schottky barrier is much smaller. We will take an example and do this.

So, essentially the majority carrier injection over a barrier is going to play a dominant role. And, what happens with bias? Let us say if you had a applied bias voltage. When V_A is greater than 0, well, the barrier is going to reduce. The barrier that you know Schottky barrier we called it. Φ_{B0} is reduced and current flows. So, J increases, current density increases.

If you have V_A less than 0, Φ_{B0} is increased and J reduces. It is a kind of a constant current actually. Again, there is some complication here. I will let me describe that we are essentially talking about you know this interface. You can think of it like a interface between a metal and a dielectric. Semiconductor is like a dielectric. It has a certain dielectric constant.

So, now, the electrons that are present in the conduction band of a metal, there is an electron let us say here. What will be the field? Well, what happens is in the presence of a metal, metal is like a perfect mirror for electrons I mean electric field. So, the behaviour of electron in this situation can be modelled in terms of what is known as the image charge. We can think of the metal as having an image. If you think of this as a charge q, there will be a -q here.

And there is going to be certain electric field. I do not know if you have seen this but in electrostatics, we call this image charge theory. If not, it is okay. So, essentially since you know metal is having lots of electrons and it is going to be difficult to describe that. If you start calculating Coulomb's law, you know each electron and the electron in the dielectric you have to calculate the forces and all that. It becomes complicated.

So, one of the ways to analyse this problem without doing all that is simply replace this metal by an image charge -q. Replace metal by image charge -q. Anyway, it is not that important right now. What is important is that if you have just a +q and a -q you know how the electric fields will be. And of course, there is a boundary condition that we have to satisfy.

And the consequence of that is essentially there is going to be an electric field due to the image forces. That is the conclusion that I want you to draw from here. So, because of the presence of a metal, that the charge experiences an additional image electric field. Additional electric field due to image charge effect I will say. You follow what I am saying. There is basic because of the transfer because of the doping density you have the space charge.

Because of that, there is an electric field. The band bending happens. But in addition to that because the electron is in presence of a metal, we can describe that as you know replacing the metal and putting an image charge, there is going to be some electric field. And that electric field is going to interfere with your electric field due to the space charge. So, effectively there is going to be a difference in the barrier.

For example, here, the barrier is shown as this black. But because of this metal because of this image charge effect, your actual barrier might be something like this, actual barrier due to image charge. So, there can there is a lowering of the barrier because of the image charge effect here in this case. So, this one we will represent as ϕ_{Bn}, actual Schottky barrier. In the last video, we have seen that the ϕ_{B0} is the difference in the work function and the electron affinity.

That gave you the ϕ_{B0} which is theoretically the Schottky barrier height. But, in reality, the barrier is going to be slightly lower because of the image charge effect. And that one we call it the actual Schottky barrier. We will take a moment and actually compute this as well. So, now, so, in a way, if you apply voltage, the barrier is going to be reduced further. So, there is going to be larger current.

And if you increase it, again the barrier is going to increase and then you have current. You know there is no current that flows in effect. There is going to be some leakage current. So, the actual computations of it we will not do. How the current you know we will not derive an expression for current. But we will simply show you the final answer.

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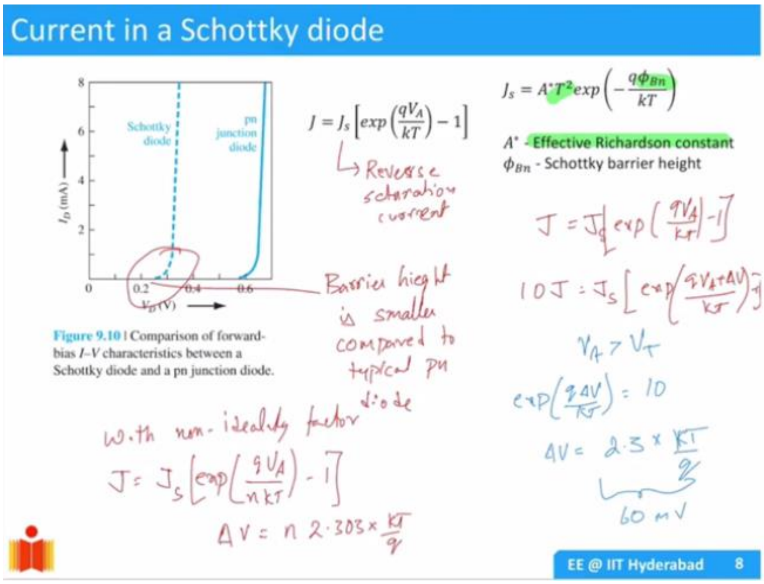

Current in a Schottky diode

Figure 9.10 | Comparison of forward-bias *I–V* characteristics between a Schottky diode and a pn junction diode.

$$J = J_s\left[\exp\left(\frac{qV_A}{kT}\right) - 1\right]$$

Reverse saturation current

Barrier height is smaller compared to typical pn diode

With non-ideality factor

$$J = J_s\left[\exp\left(\frac{qV_A}{nkT}\right) - 1\right]$$

$$\Delta V = n\, 2.303 \times \frac{kT}{q}$$

$$J_s = A^* T^2 \exp\left(-\frac{q\phi_{Bn}}{kT}\right)$$

A^* - Effective Richardson constant

ϕ_{Bn} - Schottky barrier height

$$J = J_s\left[\exp\left(\frac{qV_A}{kT}\right) - 1\right]$$

$$10J = J_s\left[\exp\left(\frac{qV_A + \Delta V}{kT}\right) - 1\right]$$

$$V_A > V_T$$

$$\exp\left(\frac{q\Delta V}{kT}\right) = 10$$

$$\Delta V = 2.3 \times \frac{kT}{q}$$

60 mV

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It turns out that for a Schottky diode you have the same form of expression as a regular p-n junction diode.

$$J = J_S\left[exp\left(\frac{qV_A}{kT}\right) - 1\right]$$

So, the forward bias they look very similar. The IV characteristics look very similar. The only difference is that the barrier height is much lower here typically in the 0.2-0.3 range.

Barrier height is smaller compared to typical p-n junctions, p-n diode. And, what else? Well, the saturation current density expression is different from a regular p-n junction. Here, there is something called as a A* which is known as effective Richardson constant. This is just a number you could say. And there is a time at sorry temperature T square and then there is an exponential and the barrier height.

$$J_S = A^{*}T^{2}exp\left(\frac{q\phi_{Bn}}{kT}\right)$$

ϕ_{Bn} is a actual barrier height of a Schottky, Schottky barrier height actual Schottky barrier height. So, the saturation current is going to be determined on the barrier height. If the barrier height is large, then your Schottky you know the reverse bias current is going to be small. But if your barrier height is small, we will see that this number is going to can be large. So, that is one aspect that we need to analyse.

We will analyse that in a problem in the next couple of minutes. Before I get to that, let us also think about, how the current changes? Now, how much voltage is required to make current 10 times J? I want to increase the current by 10 times. What is the voltage that would be required?

$$10\,J = J_S\left[exp\left(\frac{qV_A + \Delta V}{kT}\right) - 1\right]$$

$$\Delta V = 2.3\frac{kT}{q} = 60mV$$

With non-ideality factor n,

$$\Delta V = 2.3\frac{nkT}{q}$$

This number can be different you know for different situations. Typically, it is in the range of 1 to 2. So, your 1 to 1.5 or so. But this ΔV that is required to cause one order change in the current is a very significant number. We will actually revisit this when we look at MOSFETs. But essentially, you require at least 60 millivolts.

It can be, experimentally it can be 90 millivolts also. So, you need that much of voltage change to cause a change in one order of magnitude in the current. And that is typical for all situations where you have current flow over a barrier. Like, wherever you have a barrier, and we have current increasing. That same thing happens. Even in the p-n junction, it happens. So, we require about 100 millivolts.

Or, you know 60 to 100 millivolts to actually cause one decade increase in the current in the forward bias not in the reverse bias. So, this is an interesting thing. I want you to just make note of it. We will come back, and we will talk about the implications later on when we discuss MOSFETs. So, now, let us try to calculate a problem.

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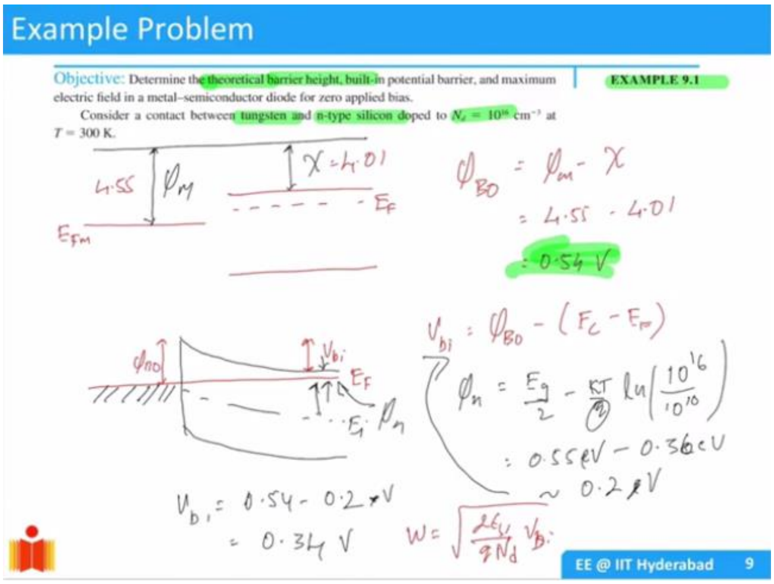

Example Problem

Objective: Determine the theoretical barrier height, built-in potential barrier, and maximum electric field in a metal–semiconductor diode for zero applied bias.

Consider a contact between tungsten and n-type silicon doped to $N_d = 10^{16}$ cm^{-3} at $T = 300$ K.

EXAMPLE 9.1

$$\phi_{B0} = \phi_m - \chi$$
$$= 4.55 - 4.01$$
$$= 0.54\ V$$

$$V_{bi} = \phi_{B0} - (E_c - E_F)$$

$$\phi_n = \frac{E_g}{2} - \frac{kT}{q} \ln\left(\frac{10^{16}}{10^{10}}\right)$$
$$= 0.55\ eV - 0.36\ eV$$
$$\sim 0.2\ V$$

$$V_{bi} = 0.54 - 0.2\ V$$
$$= 0.34\ V$$

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

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So, the problem is again example problem from the textbook Example 9.1. Please refer to the textbook if you have questions. So, what essentially, they are asking is determine the theoretical barrier height and built-in potential and all that for a metal semiconductor junction n-type silicon with some doping density is given to you.

Let us say there is an E_F of metal. And there is going to be some semiconductor. There is going to be some E_F of semiconductor. So, to determine this barrier height, we need to know the electron affinity in the work function. So, the electron, we have to take a reference level. Let us call this as some reference level. So, related to that this is going to be your work function of a metal.

And this distance is going to be your electron affinity for a semiconductor. So, in this case, we are talking about tungsten and n-type silicon. So, tungsten was 4.55 and electron infinity was 4.01 for a silicon. So, the theoretical Schottky barrier height, we are not really doing any Φ_{B0}, the theoretical height was 4.55.

$$\phi_{B0} = \phi_m - \chi = 4.55 - 4.01 = 0.54\ V$$

What is the built-in potential? So, built-in potential is when you know it is an n-type semiconductor. Let us say there is a barrier here. So, what would happen is there is a E_F.

And then there is going to be you know this is your metal and then there is going to be band bending here. This is going to be barrier. So, the built-in potential was, this is your built-in potential V_{bi}. And we saw that this was Φ_{B0}. So, the built-in potential V_{bi} is simply Φ_{B0} minus you know the distance between E_C and E_F. We need to find out that distance. So, in this picture, I want to know what this distance is.

$$V_{bi} = \phi_{B0} - (E_C - E_F)$$

I think we called it ϕ_n also somewhere. So, what is this distance? Well, I mean if you want you can look up the expressions and calculate this. I am sort of more comfortable. I will calculate it relative to E_i.

$$\phi_n = \frac{E_g}{2} - \frac{kT}{q} ln\left(\frac{10^{16}}{10^{10}}\right) = 0.55eV - 0.36eV = 0.2eV$$

So, if you do this, this is going to be turn out to be some I mean this is going to be not exactly 60 millivolts slightly less than that. So, this might be something like 0.2 eV. So, the built-in potential is going to be, we will go back and substitute this into built-in potential.

$$V_{bi} = 0.54eV - 0.2eV = 0.34\ V$$

So, it is going to be point I mean now you know what it is. 0.34 volts is a built-in potential. And then you are also asked to calculate, what is the maximum electric field? Well, if you want to calculate electric field, you need to know the width of the depletion region.

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

So, this is how the barrier potentials will be. This is a theoretical barrier potential. The actual one will be slightly different. Theoretically, we got only 0.54. It is never going to be this much as well.

I mean this is going to be smaller than this because the electric field will be lowered. There is an image electric field which will cause the barrier to be lowered. Let us take one more problem.

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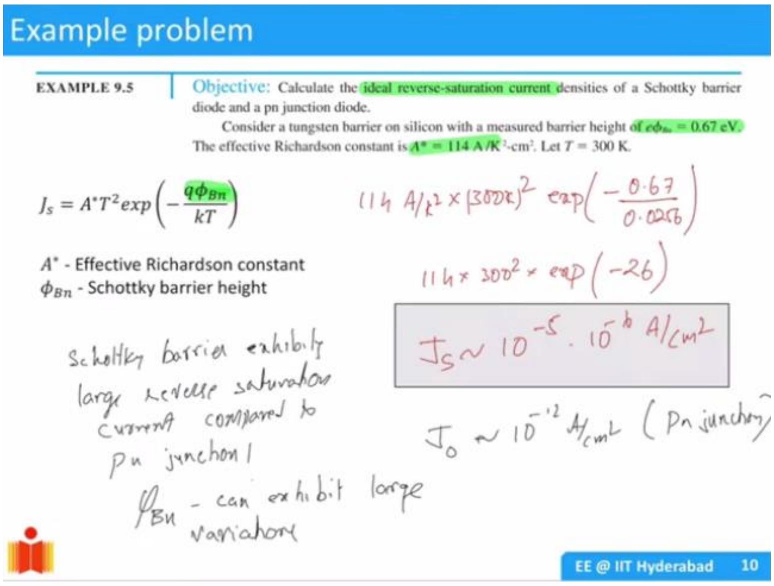

Example problem

EXAMPLE 9.5 Objective: Calculate the ideal reverse-saturation current densities of a Schottky barrier diode and a pn junction diode.

Consider a tungsten barrier on silicon with a measured barrier height of $e\phi_{Bn} = 0.67$ eV. The effective Richardson constant is $A^* = 114$ A/K^2-cm^2. Let $T = 300$ K.

$$J_s = A^* T^2 exp\left(-\frac{q\phi_{Bn}}{kT}\right)$$

A^* - Effective Richardson constant

ϕ_{Bn} - Schottky barrier height

$$114\ A/K^2 \times (300K)^2\ exp\left(-\frac{0.67}{0.0256}\right)$$

$$114 \times 300^2 \times exp(-26)$$

$$\boxed{J_S \sim 10^{-5} . 10^{-6}\ A/cm^2}$$

$$J_0 \sim 10^{-12}\ A/cm^2\ (\text{Pn junction})$$

Schottky barrier exhibits large reverse saturation current compared to pn junction!

ϕ_{Bn} - can exhibit large variations

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So, here the question is to calculate ideal reverse saturation current. Well, there it is going to be some deviation from this. In ideal case, the reverse saturation current is going to be flat. But, in the real case, there is going to be barrier which is going to be affected by the electric field. So, there is going to be some variation in the reverse saturation current. Anyway, we ignored that.

So, there is a tungsten barrier on silicon. And they gave you the effective or measured barrier height as this. So, this is good. And you are given some Richardson constant which is A. And you are asked to calculate, what is the ideal reverse saturation current? Well, this is a very straightforward question. You just have to plug in.

$$J_S \sim (10^{-5} - 10^{-6})\ {}^{A}/_{cm^2}$$

That is the main point I want to make here. The reason for the problem is only this. You remember how much was the reverse saturation current in a diode, p-n junction diode.

$J_0 \sim 10^{-12}\ A/_{cm^2}$ in a p-n junction. This is an important difference between the Schottky barrier and a p-n junction. So, Schottky barrier exhibits large reverse saturation current compared to p-n junction. This is an important take away from here. And also remember, it is dependent strongly on ϕ_{Bn}. ϕ_{Bn} is an experimentally measured quantity depending on the type of interface and you know any non-idealities in the interface.

This ϕ_{Bn} can be different. ϕ_{Bn} can exhibit large variations because of the deposition tools and techniques and so on. Because of that, the reverse saturation current is all over the place. It is actually something that we have to characterize very carefully you know Schottky junction whenever you are fabricating that. p-n junctions are more you know easily reproducible, but Schottky you have to be very careful.

Of course, even Schottky junctions are produced, and they are you know they can be modelled carefully. But, for each production environment, you have to carefully model it and find out what it is. So, this is how the current flows. And you know the main points that you have to take away from here, is that you have the similar current voltage characteristics. But the threshold voltage is much smaller.

You see ideally it was 0.54 but actually when it turned, I mean it is, in this case, it is slightly different. So, it depends on the material actually. Metal and you know semiconductor what type of interface we are talking about. And it can be different. And the voltage generally is actually much smaller at which it turns on. And you have a large change in the current. In the reverse saturation you have a large sorry large saturation current compared to the p-n junction.

So, with that I will stop. In the next video, I just want to quickly discuss the difference between Ohmic contact and rectifying contact because that is a very important thing. And then from there, we will carry on. Thank you very much. I will see you in the next video.