High Speed Devices and Circuits

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Lecture 18

Schottky Barrier Diode I-V Characteristics And the Non-Idealities -2

We have been discussing the I-V characteristics of the Schottky Barrier Diode. We have shown that it is similar to the PN junction except I_0 is different.

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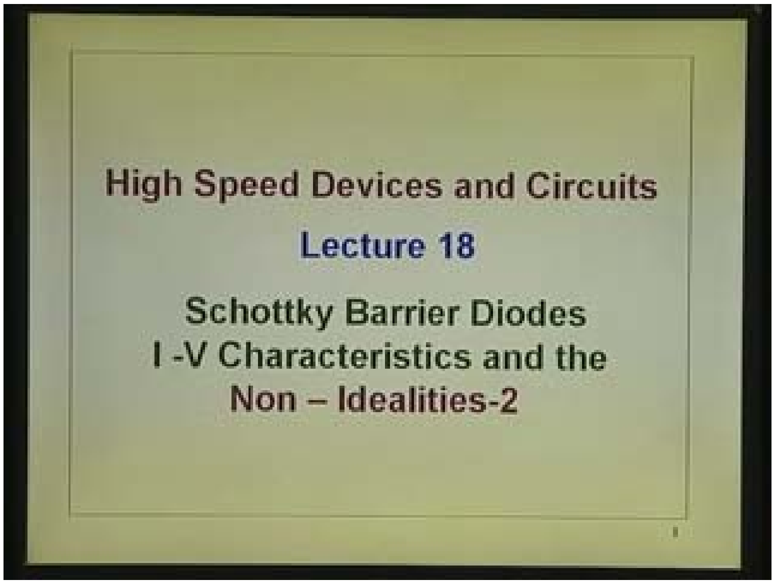

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I -V Characteristics and the
Non – Idealities-2

We have gone into details of that, why I_0 is different? To just say in few words, the difference is actually here, the electrons which are reaching the surface with a velocity; mean velocities are n of s which are smaller than the carrier concentration in the bulk.

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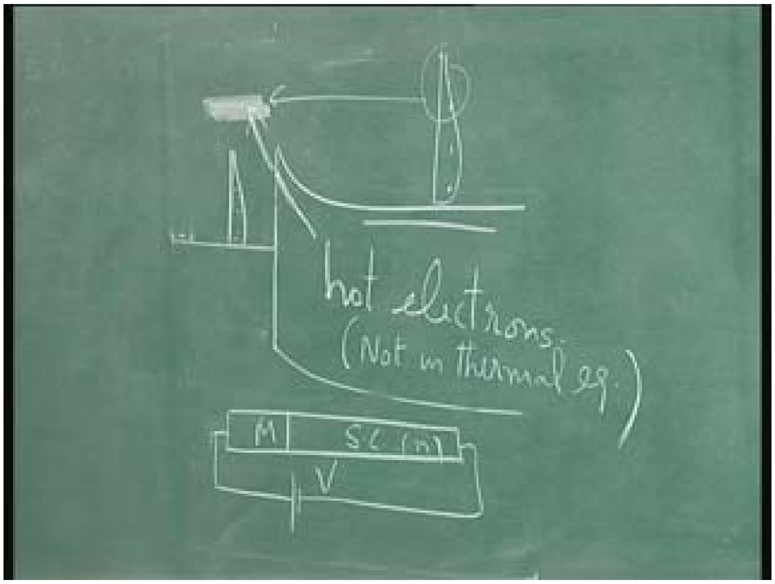

Now once they cross this, once they come in thermal equilibrium with the metal electrons they are very small quantity compared to this total number of electrons. They can be taken away. Same current can be transported with a very small velocity whether it is J is equal to q n into V. Here n is small but V is large. Here n is very large, so with very small V that I am trying to transport it. What we are telling is in this type of the device the transport of carriers is by drift. There are no charge storage effects. We will come back to that thing.

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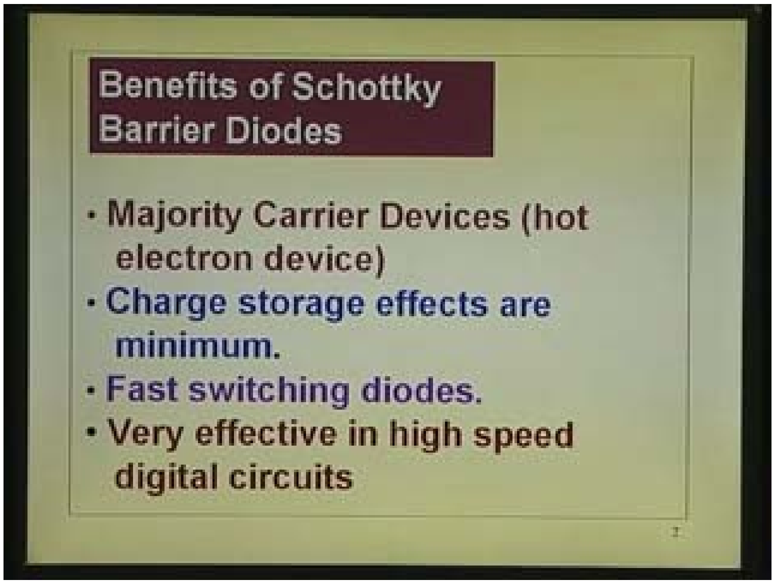

Benefits of Schottky Barrier Diodes

- Majority Carrier Devices (hot electron device)
- Charge storage effects are minimum.
- Fast switching diodes.
- Very effective in high speed digital circuits

I will just go through this once. Referring to that diagram there, what we saw just now. We have seen that the current transport is only due to electrons. Electrons are transported from this semiconductor to the metal and they are taken away by drift. There is no chance for the charges to get accumulated in the metal, because they are very small quantity compared to what is available in the metal. What is 10 to power 22 or 23 per centimeter cube in metal compared to that the injected carriers are very small. Charge storage defects are not there at all and they are not collected there because they are removed immediately.

So, that is why what we say is majority carrier device. The current transport in the n type semiconductor is by the majority electrons and in the metal of course it is again electrons. There are no minority carrier storage effects. We will verify this later with some more details but it holds good even you analyze we will see it.

Other aspect that I want to mention here is which I have also sometimes called schottky barrier, majority carrier device of course, that is general term. It is also called as hot carrier device. That is why I just put this diagram here.

The hot carrier device is called hot carrier because, the electrons which are in this crossing, this barrier having the energy more than this barrier. When they are just at the boundary the energy of these electrons is above that of the electrons in the metal. This is the energy distribution of the metals slightly above the barrier. These are even above that because those are the ones which are giving rise to current. These electrons have energies more than the electrons in the metal which are in the thermal equilibrium.

Usually when you talk of an electron it is in thermal equilibrium with the lattice, so these electrons which belongs to the metal there in thermal equilibrium in the metal, whereas these metal this electron just immediately after they are injected are not in equilibrium. That is their energies are more than those of electrons which belong to the metal. Usually the electron exchanges energy with the lattice and it is in equilibrium with the energy of the lattice that is the room temperature.

Energy corresponding to these electrons is the room temperature or whatever is the temperature of the metal. Whereas this is higher than that, that means, it looks as if the temperature of those electrons has more than the room temperature. That is why it is called as hot electron. It is hot compared to the electrons which are in thermal equilibrium with the metal.

Why we are telling that is this same electrons here, can occupy higher energy levels if you heat up the metal. Here without heating they are at higher energy because they just belong to this metal like across the barrier. That is why these electrons are called hot electrons and they are not in thermal equilibrium in the metal just at the instant of injection. Now it is immediately collide with the lattice within, because I can stand. It will come in to thermal equilibrium with the metal.

Its identity is lost, it is no longer hot. Because its energy is lost it is in lattice equilibrium with lattice. It is hot electrons for a short while. This device is called as hot electron device from that point of view nothing hot about that except that it is hot electron for short while. Now there also we have seen just now. We have discussed, there are charge storage effects are minimum. I am using the word cautiously actually charge storage effects are absent almost totally, now they are minimum.

Also, because the charge storage effects are minimum, the devices can switch very fast. See the switching speed of a diode is larger, if there are stored charges. When they are stored charges it behaves more like a huge capacitor. Lot of charge is stored. Then to turn off the device you must remove the charge completely. That takes time for the on state off state. If you just go, the charges will have to be removed. So the delay times are involved. That is why the PN junction diode is slower because of charge storage effects in the PN junction devices. To make it faster what you do is you actually kill the life time. Reduce the life time, so that a stored charge for a given current is less because currently stored charges divide by life time. If life time is smaller, it can be smaller q, so q by tow is same in PN junction current I. We can say as stored charge divided by life time. I can reduce the life time; I can still have same current with smaller charge.

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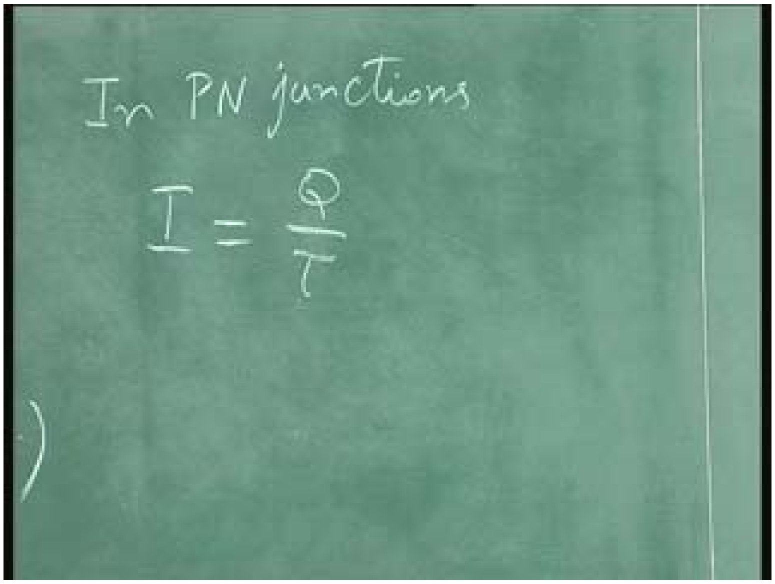

In PN junctions

$$I = \frac{Q}{\tau}$$

That is implication of that. I will not go into details of that this moment. May be when we discuss logic circuits I will come back to this. This will be smaller if life time is smaller. You actually deliberately reduce the life time of carriers by certain methods. Like gold doping etc. To make PN junction faster, you must have life time control techniques. But here there is no stored charge automatically. It is minimum; it is a majority carrier device. That is why these devices schottky barrier diode are faster basically fast devices. In gallium arsenide based logic circuits, you will use quite a bit of this schottky barrier diodes for some level shifting etc. Now it goes without telling all these things together makes that device schottky barrier device without diode, or the devices based on schottky barrier very effective in high speed digital circuits. Now quickly run through what we have been talking, ideal characteristics of a diode. Now we will just see all these characteristics exactly same as we have been talking.

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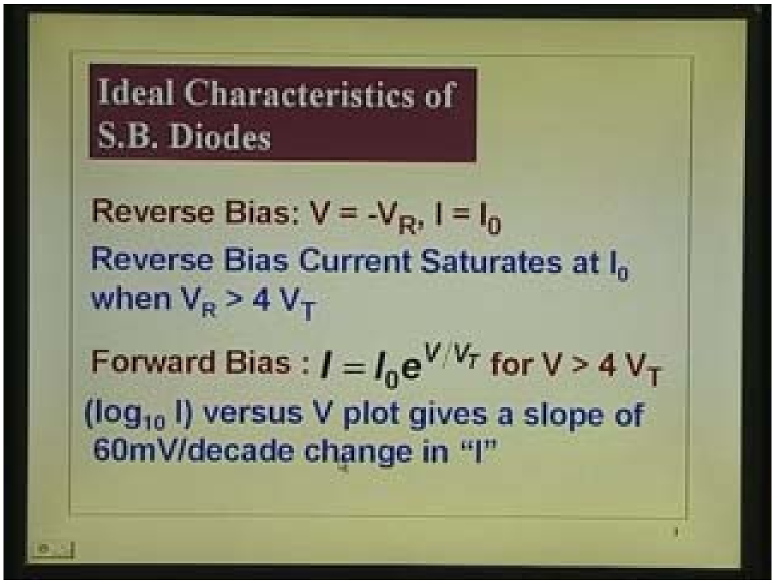

Ideal Characteristics of S.B. Diodes

Reverse Bias: $V = -V_R$, $I = I_0$

Reverse Bias Current Saturates at I_0 when $V_R > 4\ V_T$

Forward Bias : $I = I_0 e^{V/V_T}$ for $V > 4\ V_T$

($\log_{10}$ I) versus V plot gives a slope of 60mV/decade change in "I"

What we said is the reverse bias voltage minus Vr. When you apply, the current reaches a constant. That is one of the characteristics that we said and that is of course when the reverse bias voltage is at least about 100 milli volts. When you apply, see after all it goes from 0, it keeps on increasing. It saturates at I_0 by the time about 100 milli volts. That is about 4 Vt forward bias. We said I is equal to I_0 e to power V by Vt minus 1. I removed that minus 1 there, because that becomes small compared to e to power V by Vt about 100 milli volts 4 Vt.

Now you plot log I versus V log to the base 10 of current versus voltage. It will be linear plot. Because exponential and loss gain and the slope of that will be 60 milli volts per decade. We will see that immediately. What happens further, reverse bias now the non idealities. It is really strictly does not follow this rule. In some cases you have got or in most of the cases reverse bias current does not saturate at I_0.

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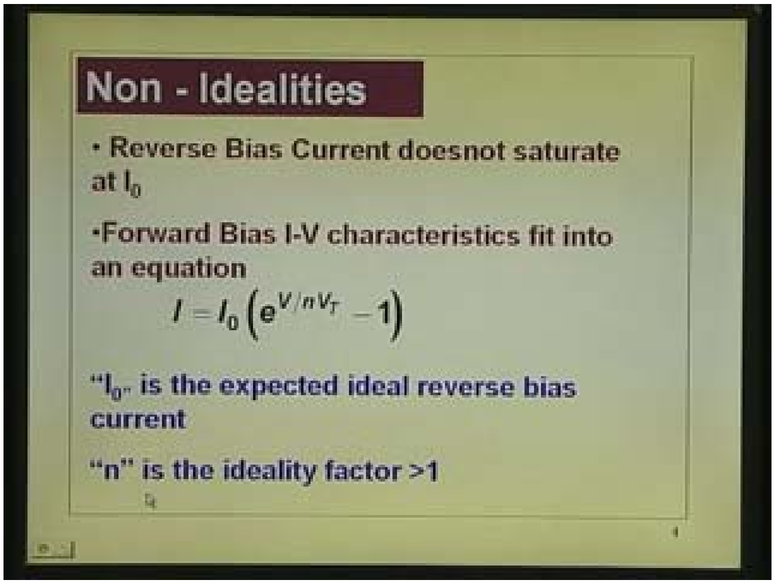

Non - Idealities

- Reverse Bias Current doesnot saturate at I_0
- Forward Bias I-V characteristics fit into an equation

$$I = I_0 \left(e^{V/nV_T} - 1 \right)$$

"I_0" is the expected ideal reverse bias current

"n" is the ideality factor >1

It keeps on increasing and the forward bias I-V characteristics cannot be expressed as I_0 e to power V by Vt minus 1, there will be a factor n coming in the sense it does not increase as deeply as you expect. It increases slightly slowly. That is I_0, where as this term n will be slightly more than one which you call it as ideality factor. We call it ideality factor because, that is the one which tells you how much it is deviating from ideality. Sometimes people confuse and say it is non ideality. It is actually ideality factor. How much it deviates from ideality? If n is 1 it is ideal n is deviating from 1, it is non ideal. So n always is greater than 1. Now to plot on a log scale what we said ideal characteristics is that, I log to the base 10 versus V volts will be I_0 e to power V by Vt will be linear.

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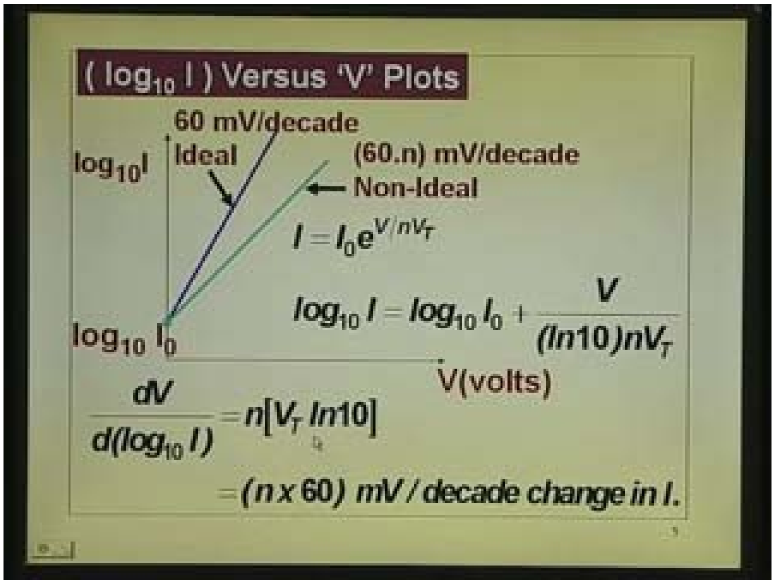

($\log_{10}$ I) Versus 'V' Plots

$$I = I_0 e^{V/nV_T}$$

$$\log_{10} I = \log_{10} I_0 + \frac{V}{(\ln 10)nV_T}$$

$$\frac{dV}{d(\log_{10} I)} = n[V_T \ln 10]$$

$$= (n \times 60) \text{ mV / decade change in } I.$$

Now if the characteristic is in this form, that is I_0 e to power of V by n Vt logarithm of I is equal to, that is what I am putting here. Logarithm of I to the base 10 remember is equal to logarithm of I_0 to the base 10 plus V by Vt V by n Vt. Since you are taking log to base 10, we will have this factor log 10 ln 10 all this to the base 10.

This becomes base to e. What you have now is an equation which is linear and the slope of that. Please remember this is log scale. We will take the slope in a log scale itself. What we are trying to see is I just put it deliberately, because there is some misconception in this here many times. You write it as logarithm. Now you to find the slope in this log semi log scale. What you do is delta V differentiate this with respect to the whole term itself. So delta V divided by delta of logarithm of base 10 I.

This when you do that this term goes off, because it is a constant delta does not vary with voltage. This particular quantity now becomes V by n Vt. What I have done is I have taken this log to that side and the delta V by delta log I that becomes equal to this quantity. Just rearranging the things n Vt into ln 10. This is very well known thing to everybody. But I will just put it in the form of equation. So n is equal to 1, ideal case delta V by d log I will be equal to Vt ln 10 Vt ln 10 Vt. If I take about 25, 6 or so this turns out to be 60 milli volts. If n is equal to 1, it is 60 milli volts. So n is equal to 1.

It is 60 milli volts that is, a current will change by 1 decade. When I say this is 1, it changes by 1 decade for a change in voltage equal to 60 milli volts. The implication of that is if I change the voltage by 60 milli volts, the current will change by 1 decade. Now if ideality factor is 1, if n is more than 1, let us say it is 2. The slope will be if n is equal to 2 that will become 120 milli volts, 120 milli volts per decade meaning if this is giving 1 decade current change in 60 milli volts. This current gives 1 decade change in 120 milli volts. That means it is less change current increases slower compared to the ideal characteristics. These are the things people observed on a log scale. It is like this on a linear scale. That is how the actual thing what happens is the device characteristics.

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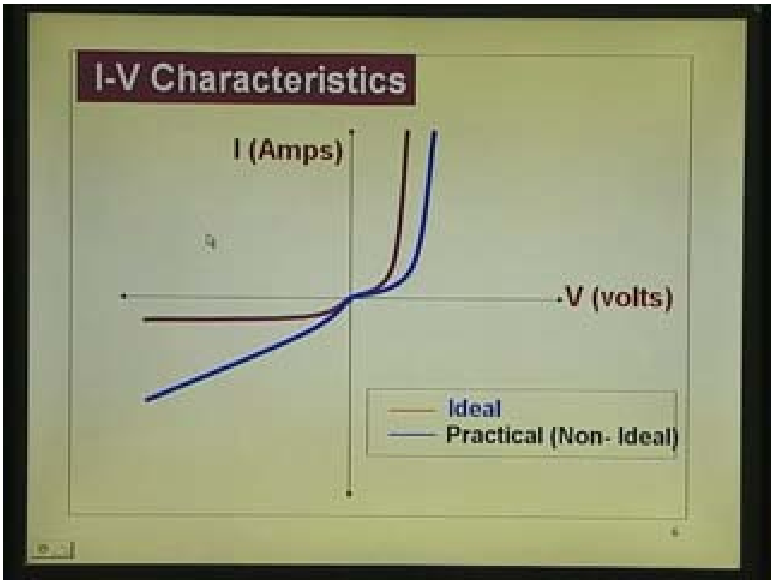

I-V Characteristics

This curve is ideal I_0 is saturating and in non ideal case it does not saturate, keeps on increasing. We will see what the causes of that in the forward case are. Just now we saw the current increases less deeply compared to the ideal case. It is slightly shifted to right hand. Actually to go still exponential expo this is exponential, but less deep. Instead of e to power V by Vt it is e to power V by n Vt. That is the practical situation. It is ideal. I just put this diagram back. What you had seen earlier, to see what are we missing out here?

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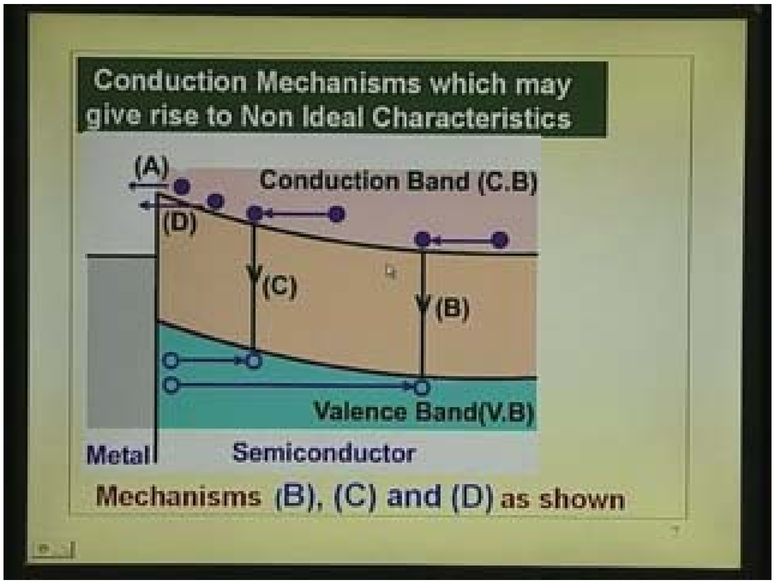

Conduction Mechanisms which may give rise to Non Ideal Characteristics

Mechanisms (B), (C) and (D) as shown

We took into account in the current transport of only of this term that is the electrons, which are able to cross the barrier. That is the thermionic emission current as far as this slide is concerned. Now there are other currents which we have not taken in to account. We will examine and see whether we really should worry about those. What are the other currents? One of them is this current that is the hole injection and recombination in the neutral region. If that is present it is a dangerous situation. If there is hole injection, if the current is controlled by hole injection that means there are stored charges, minority carriers in that region.

We can easily say that will be negligible, but we can compare and see what will be that current comparing to the PN junction model. The other current is actually generation recombination current within the depletion layer, recombination in the case of forward bias generation and in the reverse bias. There is one more current component which actually is the tunneling current. As you go up in this region the barrier width, for example if I take it here, it is large. If I go up here, the barrier width is very small. So once the barrier width is very small, the electrons which are present in that energy like just tunnel through that it is called quantum mechanical tunneling. That becomes probability of finding the electrons here, as well as here becomes same almost. We can find it either here or there. That is the implication of that quantum mechanical tunneling.

Otherwise, you can say that it is very thin layer; it can just go through that. That is very simple in physical explanation. So these are 3. There are other additional things which we have to worry about. So possible causes are summed up, hole injection what I mentioned just now recombination generation in the depletion layer.

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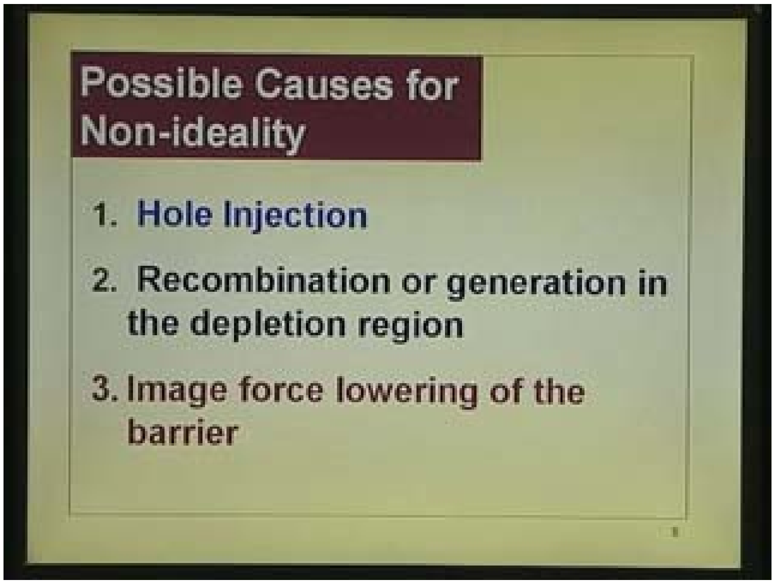

Possible Causes for Non-ideality

1. Hole Injection
2. Recombination or generation in the depletion region
3. Image force lowering of the barrier

There is one more term which I have added here, which is not shown in the diagram. That is image force lowering of barrier. In the sense, go back to the previous thing the barrier here is this, quantity from top to this edge. That barrier gets lowered due to a phenomena called as image force lowering.

We will see that, in fact, if you see open up this book, right on the first page on the schottky barrier what is talked about is the image force lowering which lowers your barrier immediately in the sense it becomes slightly difficult at the distance. I brought it out little later after understanding what the barrier is. We can talk of this barrier height reduction, that barrier reduction due to the image force lowering. Now that is the third one. We will examine that fourth one is, quantum mechanical tunneling which we have just now mentioned at the top. Other one is insulating interfacial layer always will be there.

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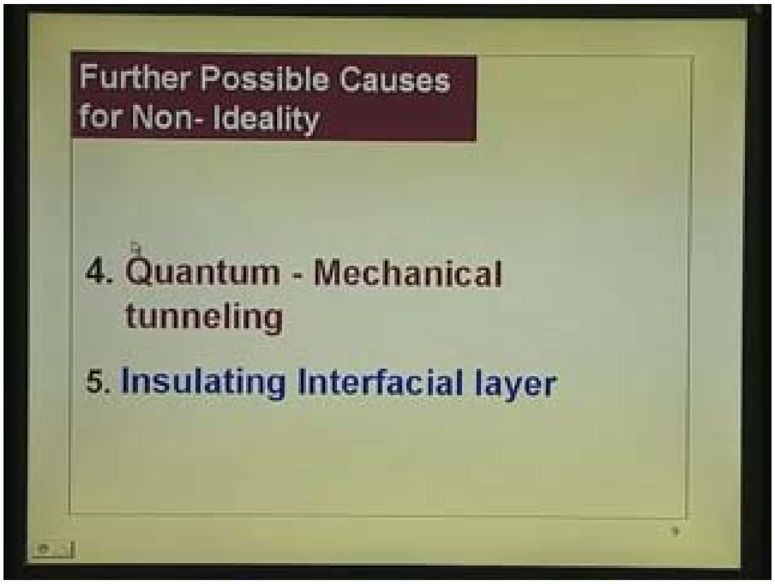

Further Possible Causes for Non- Ideality

4. Quantum - Mechanical tunneling
5. Insulating Interfacial layer

That will affect at some level. We already taken it account that while discussing the I-V characteristics or the phi Bn determination. First we will take the hole injection current in the schottky barrier diode should be worried about that. What I have drawn here is not the energy band diagram.

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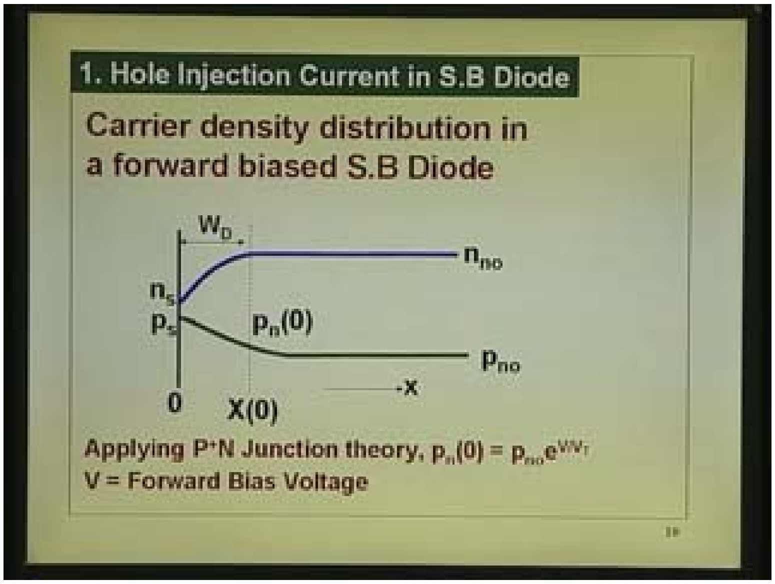

1. Hole Injection Current in S.B Diode

Carrier density distribution in a forward biased S.B Diode

Applying P^+N Junction theory, $p_n(0) = p_{no}e^{V/V_T}$
V = Forward Bias Voltage

I have drawn the carrier concentration in the semiconductor up to this point. It is majority carrier thermal equilibrium, and this is the depletion layer. W_D is the depletion layer width. When you get in to depletion layer width the carrier's concentration drips. You remember we have estimated this quantity n of s and n of s is equal to n_{n0} into e to power of phi by Vt, where phi is negative in this case. That quantity is smaller. I just plotted the whole thing here. Correspondingly, the hole concentration goes up there.

If you take a PN junction, we will see in the PN junction, I am just putting the model exactly same as PN junction without getting into too much complications. In fact people have shown that with this simple model. Hole concentration is changing like that. It will go up in the depletion layer it goes up little bit. It is still small quantity. Just at the boundary we will have hole concentration raised to PN_0.

Like in a PN junction when you forward bias, a PN junction the hole concentration at depletion layer boundary goes up from PN_0. From this value slightly up PN 0 within the bracket at x equal to 0 x_0. And the value of hole concentration here from the simple PN junction theory it can still be written, whatever is the voltage appearing across the depletion layer it is by that quantity that this goes up.

That is the law of the junction. Same law we are using here. Apply PN p plus n junction theory PN_0 that concentration is PN_0 e to the power of V by Vt. Now you may ask why I have not changed it here. That also will go up here. But the change here is very small compared to majority carriers. So it is almost flat. It is like this, may be 10 to power 15 concentration. This will be 10 to power 12. So 10 to power 15 plus 10 to power 12 is 10 to power 15.

I just keep it there. See you are not showing the change here. In PN junction, you see that change increase their majority carrier, if there is high injection level conditions, which you should. We usually discuss in power devices, where high currents are there. Otherwise it is not there. You have got that. Now PN_0 raised by that amount. What will be the current transport due to holes here? Now you saw there is current transport of electrons from here to that due to the barrier. Now if there is a concentration gradient like this, if you have concentration gradient current transport due to the holes will be quite diffusion. It is now to find out what is the hole current? We just all that you do is finding out that. This is straight forward, just like in the case of PN junction. See for example J_p is minus qD_p d PN by dx because the current is by diffusion.

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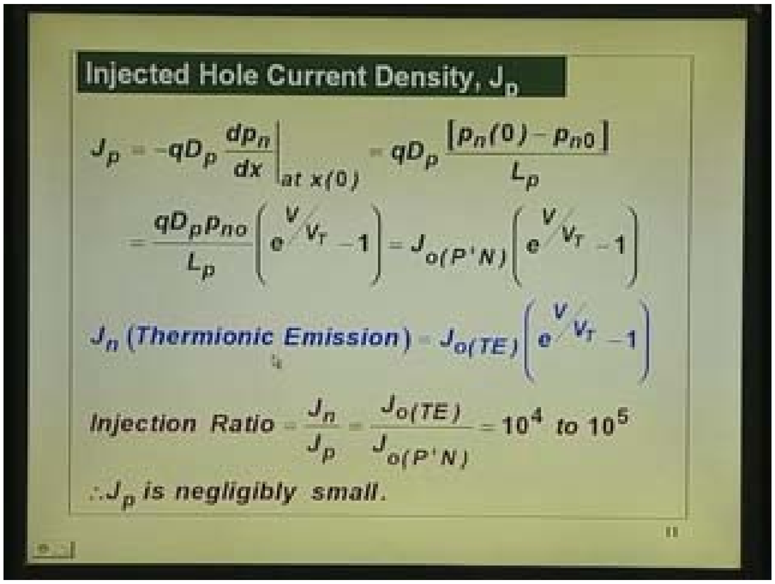

Injected Hole Current Density, J_p

$$J_p = -qD_p \left.\frac{dp_n}{dx}\right|_{at\ x(0)} = qD_p \frac{[p_n(0) - p_{n0}]}{L_p}$$

$$= \frac{qD_p p_{no}}{L_p}\left(e^{V/V_T} - 1\right) = J_{o(P^+N)}\left(e^{V/V_T} - 1\right)$$

$$J_n\ (\text{Thermionic Emission}) = J_{o(TE)}\left(e^{V/V_T} - 1\right)$$

$$\text{Injection Ratio} = \frac{J_n}{J_p} = \frac{J_{o(TE)}}{J_{o(P^+N)}} = 10^4 \text{ to } 10^5$$

$\therefore J_p$ is negligibly small.

There is no field there and that is qD_p PN_0 minus PN_0 by L_p standard PN junction equation. They are making use of hole current injected in the case of p plus n junction for estimating this. Exactly same I do not have to spend too much time on this. This PN_0 is PN bar 0 e to power V by Vt I just substituted for this equation becomes like this. All that I have done is reduce of the expression for PN_0 into in terms of thermal equilibrium value in to e to power V by Vt. So what is this quantity? That quantity is J_0 of the p plus n junction. This quantity, so it is J_0 into of the p plus n junction. Please be careful, this is different from that of the J_0 in the schottky barrier diode whether that mechanism is different. We have spent enough time discussing that. So, that is the quantity.

Now, let us see compared to the J_n what we have estimated as the schottky barrier diode, current totally due to electron current that is J_0. I am using TE here to distinguish from this J_0. There are two J_0s now 1 J_0 will belong in to the hole injection which is p plus n junction. Other J_0 due to the thermionic emission and this is the schottky barrier diode.

What you have to find out is how much is the ratio of this and this. When you divide J_n by J_p which actually you can call it as injection ratio. The e to power V by Vt gets cancelled. The ratio is actually equal to J_0 thermionic emission by J_0 p plus n. How much is order J_0 p plus n is how much for silicon? We saw it is something like 10 to power minus 11, 10 to power minus 12.

And J_0 thermionic emission is something like 10 to power minus 7. We estimated that. this term is much larger to go back to our previous discussion. This we said in silicon it is about 10 to power minus 7. This is about 10 to power minus 12 in the case of gallium arsenide. This is even much smaller than that. Here compared to this is 10 to power minus this be 10 to minus 17 or 10 to power minus 18.

This curve is 10 to power 4 or 10 to power 5. What you are telling is this current. Electron current is much larger compared to hole current. What you are thinking that is could this hole injection current be leading to non ideality will not hold good. We do not have to worry about this at all. The denominator term that means you do not have to worry about J_p compared to Jn. So J_p is negligibly small. We have eliminated that.

Let us go now into the generation recombination current. Second one that we are telling. We are taking look at each of those terms. So generation current, you are familiar about that. In case of PN junction, which is actually given by it is important in reverse bias condition mainly.

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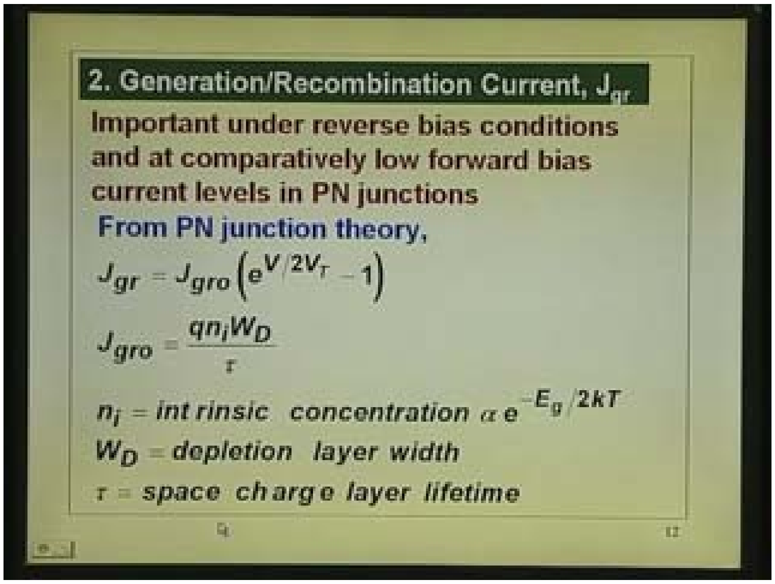

2. Generation/Recombination Current, J_{gr}

Important under reverse bias conditions and at comparatively low forward bias current levels in PN junctions

From PN junction theory,

$$J_{gr} = J_{gro}\left(e^{V/2V_T} - 1\right)$$

$$J_{gro} = \frac{q n_i W_D}{\tau}$$

n_i = int rinsic concentration $\alpha\ e^{-E_g/2kT}$

W_D = depletion layer width

τ = space ch arg e layer lifetime

Comparatively, also when the forward current is very small in PN junctions, we have seen that. For a PN junction theory this generation current is actually equal to some constant J_{gr0} e to power V by 2 V_t minus 1. I am not getting into deriving this. We will just use it, generation current. Because this in PN junction theory we have discussed it in many occasions, or some other course it has been discussed.

But you can take it all that we are trying to see is should we be worrying about this particular component in the case of schottky barrier? This is the generation recombination current. When this constant term is actually q n_i into W_d by tow, where n_i is the carriers generated due to covalent bond breaking. That is why you put it as the intensity concentration. This n_i is proportional to e to power minus E_g by 2 kT. W_D is the depletion layer width tow is the space charge layer life time. Because what we are talking of is what is happening within the depletion layer. Let us compute these values J_{gr0} that is what we are talking of .

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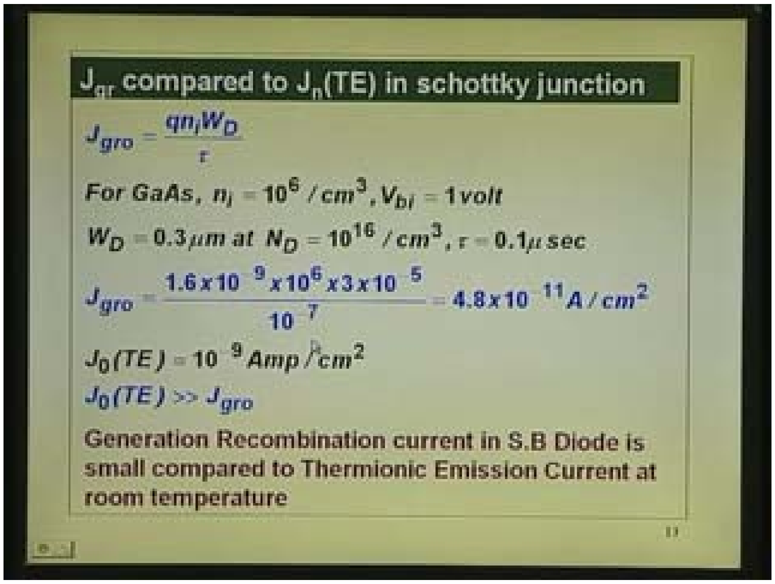

J_{gr} compared to J_n(TE) in schottky junction

$J_{gro} = \frac{qn_iW_D}{\tau}$

For GaAs, $n_i = 10^6/cm^3, V_{bi} = 1\,volt$

$W_D = 0.3\mu m$ at $N_D = 10^{16}/cm^3$, $\tau = 0.1\mu\, sec$

$$J_{gro} = \frac{1.6\times10^{-9}\times10^6\times3\times10^{-5}}{10^{-7}} = 4.8\times10^{-11} A/cm^2$$

$J_0(TE) = 10^{-9}\, Amp/cm^2$

$J_0(TE) >> J_{gro}$

Generation Recombination current in S.B Diode is small compared to Thermionic Emission Current at room temperature

First, let us evaluate that constant. Once you evaluate that constant, then we can find out rest is the varying with voltage gallium arsenide. Let us see in gallium arsenide, n_i is something like 10 to power 6 per centimeter cube and built in potential is almost 1 volt 0.9 volts. 1 volt I am just putting 1 volt for simplification close to that at least very easily 1.43 is the band gap. So 1 volt barrier rate built in potential you can easily get.

All that you have to ensure is you do not say that built in potential is more than the band gap. They will be caught there. If you say silicon has a built in potential of 1. 2 volts and that is it. It is not correct. It is always less than the band gap W_D for doping of about 10 to power 16 is about 0.3 microns it is a rough number tow 0.1 micro second I have taken 0.1 micro second because in gallium arsenide it is a direct band gap semiconductor very easily carriers can recombine just one transition all that you have to do is the energy conservation there is no need of moment of conservation so the life times in gallium arsenide are small so this term J gr_0 am substituting q 1.6 into 10 to power minus 9 n_i 10 to power 6 depletion layer width 3 into 10 to power minus 5 centimeter that is 0.3 microns divided by life time 0.4 micro second 10 to power minus 7 the whole thing turns out to be 4.8 into 10 to power minus 11. Now, what we have to be concerned is how does it compare with J_0 of the thermionic emission? Now you have to recall the numbers that we have worked out in our previous discussion. We have worked out and seen for gallium arsenide that J_0 thermionic emission is about 10 to power minus. In fact exact number we worked out 1.24 into 10 to power minus 9 amperes per centimeter square. I just put a approximated 10 to power minus 9, because we are considering about only that. Now this quantity is minus 11, definitely smaller than that. Actually you may not have to worry at around 0 bias. But when you go on increasing the depletion layer width, what would happen in the reverse bias condition? This quantity keeps on increasing the width of the depletion layer. Suppose in the width of depletion layer goes up from 0.3 micron to 3 micron ten times more this can become ten times more that is 4.8 into 10 to power minus 10 still it is not bad. It will not affect so much that is what we are telling. Forward bias: How will it effect in the forward bias condition? if you recall the diagram that we have been plotting V and I log base 10 if I plot thermionic emission current J I_0 or let me put it as J itself.

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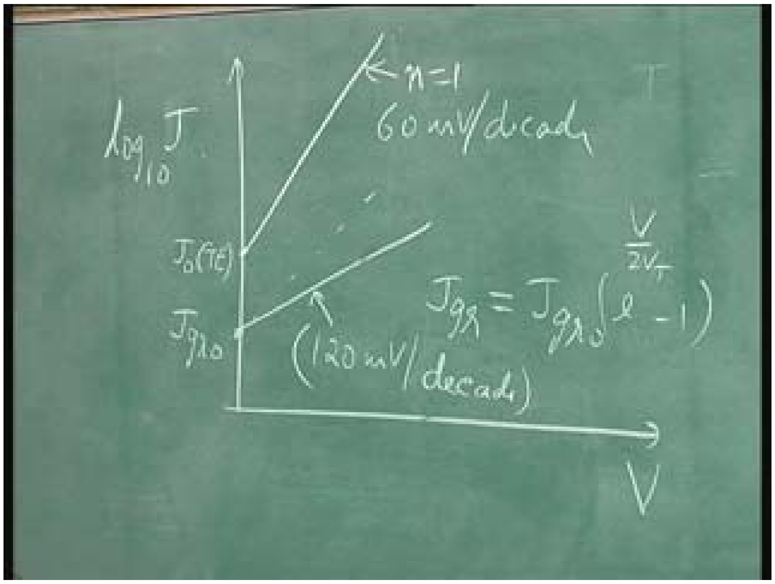

That we can always put J or I it does not matter. Multiply by area you get current so that is that quantity. That is that quantity that we putting here is J_0 thermionic emission. The value of that is about 10 to power of minus 9 and it goes up on the log scale linearly I am putting key where it is e to the power V by V_t so this is n is equal to 1. You would have got ideal characteristics like that. Now we are trying to see whether this term generation recombination current will it be comparable to that at any bias. We have just now calculated it is here this is 10 to power of minus 9 this is 10 to power of minus 11. This quantity in the forward bias is increasing as e to the power of V by 2 Vt, this is n is equal to 1. If n is equal to 2, J_{gr} is going up as J_{gr0} into e to the power of 2 V_t minus 1 of course. I can always neglect that the moment you go to 50 milli volts 100 milli volts forward bias, so where will I put this curve? Supposing this is drawn like that. That means n is equal to 1: n is equal to 2 means it does not increase the slope like that. This is n is equal 2 or let me put it as n is equal to 1,60 milli volts per decade change in current and this one will be 120 milli volts per decade so that is that quantity. Why I plotted this is, you have found out that this value is smaller and it remains smaller right through its not changing that current. The conclusion is in the gallium arsenide based device particularly you do not have to worry about J_{gr} for the schottky barrier diode, all that time it was smaller even in reverse bias case very large reverse bias voltages it is not showing up at all that the conclusion from that. Generation recombination current in fact schottky barrier diode is small particularly in gallium arsenide. If you go to some other material where there is it may become comparable under reverse bias conditions compared to thermionic emission current at room temperature. Let us just go to next, this is the one which is talked of very much and it is simple affecting the I-V characteristics quite a bit

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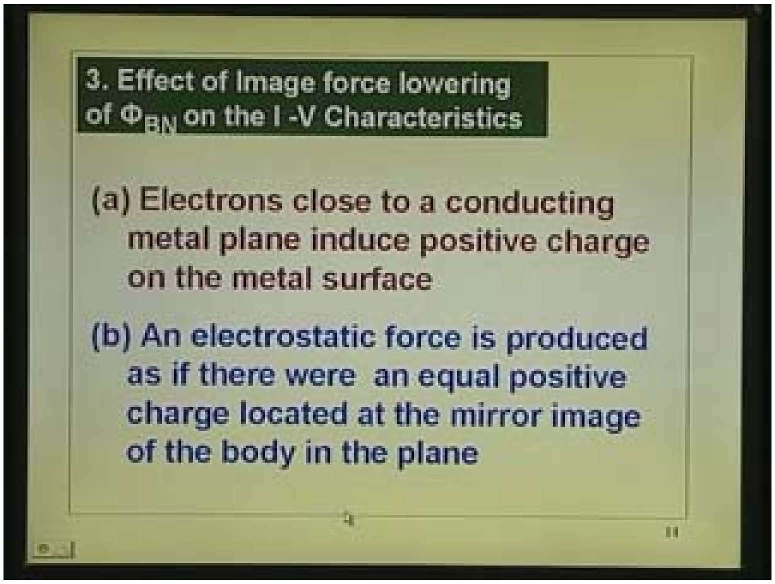

3. Effect of Image force lowering of Φ_{BN} on the I -V Characteristics

(a) Electrons close to a conducting metal plane induce positive charge on the metal surface

(b) An electrostatic force is produced as if there were an equal positive charge located at the mirror image of the body in the plane

The main cause for non ideality is this one which is not there in the case of PN junction this is effect of image force lowering. If you look back always so I do not want to look back now there is a projection here if I have mirror there the projection of that seen on other side exactly the same distance behind. If I have a metal like this and if an electron is coming near that it induces positive charges on the metal. The effect of positive charge it's a distributed charge all over the metal. If minus q is there plus q is there now. You can examine or you can analyze the effect of the plus charge distributed charge by considering that there is no charge here but an image of that on that side that the image it's an electromagnetic theory those who have learned you will know that image charge effect minus charge here plus charge there. You do not have to consider the charge here.

What we are trying to point out is that the negative charge is here because of the induced positive charge there, there will be force of attraction between the two the force this metal won't move this charge experience the force attract the force in that direction. To compute that force an artificial thing that is an image charge plus charge can be put on the back side and compute the force. That is called image force. Strictly there is no charge there is no body there it is only the image the effect of that which you have seen. The charge is actually here plus charge to compute that you resume that there is charge on the other side so we can see electrons close to the conducting metal plane induce a positive charge on the metal surface. This can be taken into account by considering a image charge I just put that diagram.

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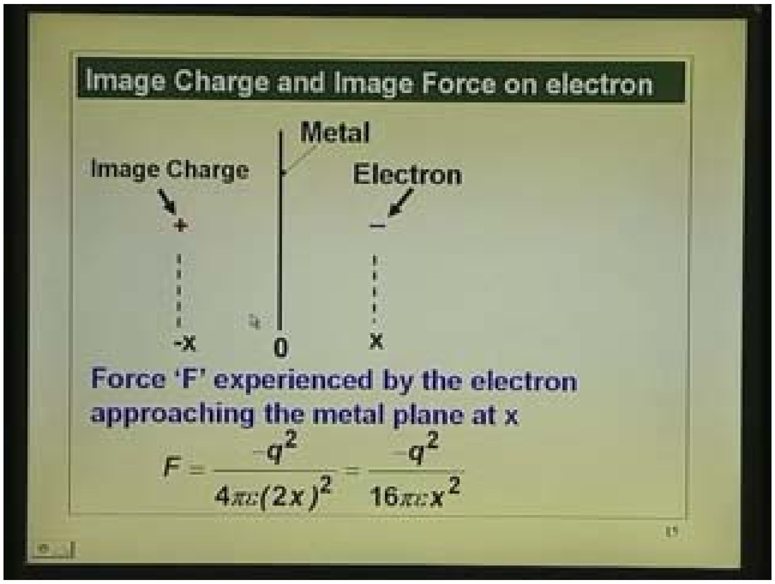

Image Charge and Image Force on electron

Force 'F' experienced by the electron approaching the metal plane at x

$$F = \frac{-q^2}{4\pi\varepsilon(2x)^2} = \frac{-q^2}{16\pi\varepsilon x^2}$$

Whatever I have been telling now put in the diagram. This is the metal surface that is at one charge we have put there. Now it induce a positive charge here but then it is a distributed charge the whole effect analysis become very complicated but instead of considering a positive charge here you put a plus charge here exactly at minus x distance same distance so this is the image charge of this electron. We can compute the force induced force due to induced here by putting this image charge what is the effect of that so that means there is a additional field coming up. When you apply it when you take a look at the energy band diagram in thermal equilibrium or in the under forward bias conditions what you plot there is due to the built in potential due to applied voltage etc.

Now what we are talking of is apart from that. Due to the image charge there is an additional force comes in comes up I do not have to explain this particular term coulombs force law force q one q two divide by 4 phi epsilon distance is 2 x square so minus q squared by 16 phi epsilon x square that is the force that this electron experiences. It is pushing in that direction. That is what we said, an electrostatic force is produced as if there were an equal positive charge located at the mirror image of the body in the plane. When you say is body, this is a body a mirror image is formed in the body of this metal that is what we say there. Now let us go further down, so with that once you know the force we can estimate energy potential etc., of that electron. What we compute is the electronic potential, which is same as the energy band diagram. Electrostatic potential is opposite of electronic potential. So now force you know and the energy is integral of the force. Force into distance is the work done energy that is the energy

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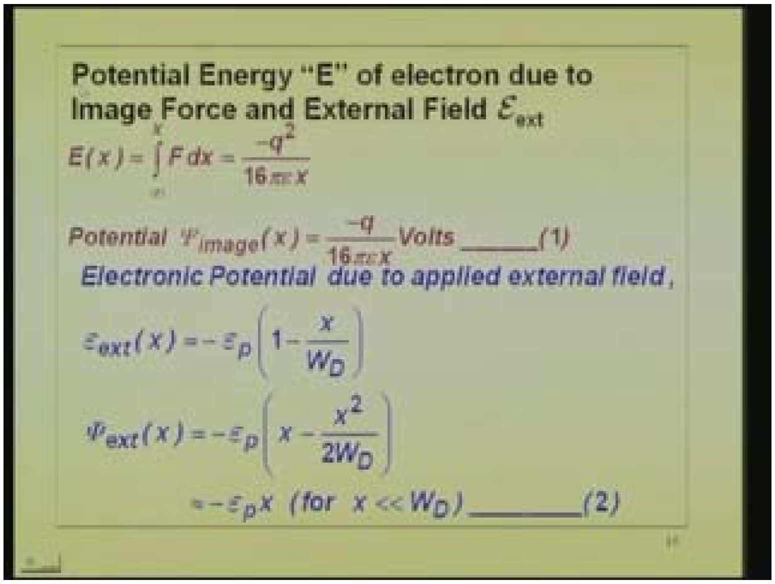

Potential Energy "E" of electron due to Image Force and External Field $\mathcal{E}_{ext}$

$$E(x) = \int_{\infty}^{x} F\,dx = \frac{-q^2}{16\pi\varepsilon x}$$

Potential $\Psi_{image}(x) = \dfrac{-q}{16\pi\varepsilon x}$ Volts ______(1)

Electronic Potential due to applied external field,

$$\mathcal{E}_{ext}(x) = -\mathcal{E}_p\left(1 - \frac{x}{W_D}\right)$$

$$\Psi_{ext}(x) = -\mathcal{E}_p\left(x - \frac{x^2}{2W_D}\right)$$

$$\approx -\mathcal{E}_p x \ \ (\text{for } x << W_D) \_\_\_\_\_\_\_\_(2)$$

When the electron is brought from infinity to that point, all through it is experiencing a force of its own image that a funny thing its whole image is forcing it toward pushing towards this metal. So that force and that energy that we acquire by because of that is actually this one. Integral of that the square goes off and you get that. Now, potential of the image in fact electrostatic electronic potential is you remove that one q from there energy is q into V, I am just finding the electronic potential which is the same variation as the energy band diagram. When you see the plot you will become clearer so I removed that q there it becomes potential. Energy is q into V, I remove the q it becomes potential that is what happened there. Minus sign is there, let us go to the next diagram and see this is the plot of that potential what is the electrostatic potential? Go back to the diagram.

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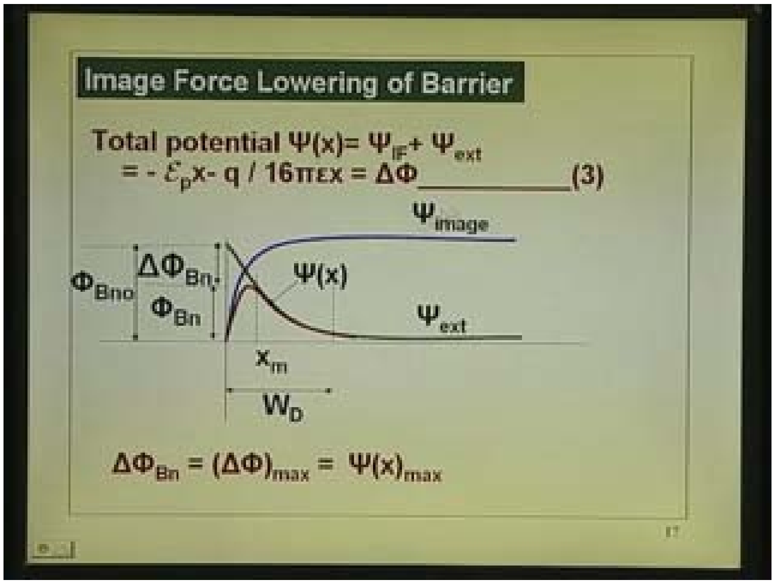

Image Force Lowering of Barrier

Total potential $\Psi(x) = \Psi_{IF} + \Psi_{ext}$

$= -\mathcal{E}_p x - q / 16\pi\varepsilon x = \Delta\Phi$ ___________ (3)

$\Delta\Phi_{Bn} = (\Delta\Phi)_{max} = \Psi(x)_{max}$

That is plus that is minus electrostatic potential is increasing in that direction. That is electronic potential which is negative of that is decreasing. That is actually what is told in this equation also the electronic potential is minus there so as x becomes smaller it becomes larger. At x is infinity the potential of electron is 0. That is what is put here potential is 0 there just putting 0 level is put there shifted down you will get that. The variation of potential is nothing; there start falling as one by x goes down. This is due to the image charge I called it as psi image slightly involve the concept but it is not difficult, all that you have to understand is at apart from the usual energy band diagram or the potential you have got one more term which has to be considered that is that now, if you look at this particular green this particular diagram here that is actually the energy band diagram which we usually see that can be obtained like this that is due to the electric field.

Let us just see that, I must draw that diagram here that is the metal that is the n semiconductor and that is the depletion layer. I will just draw it slightly below, so that we are clearly able to see it depletion layer which has plus charge and there are negative charges here, how is electric field coming up?

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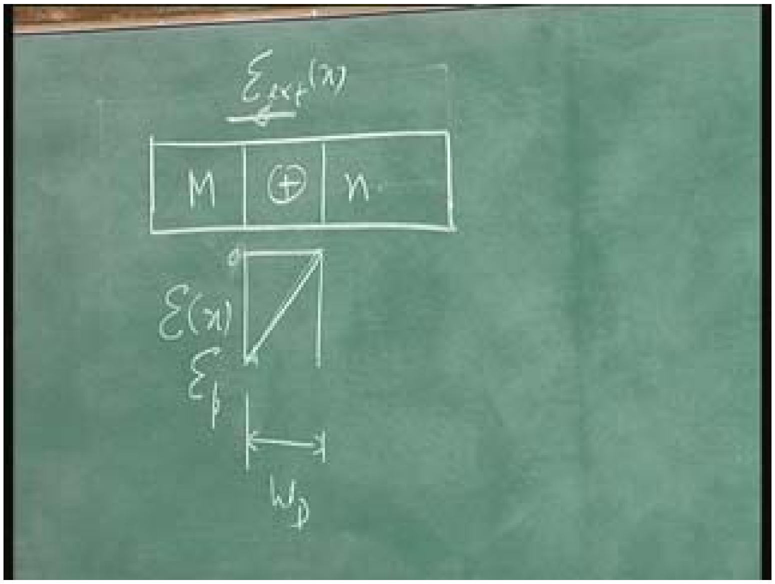

I am just showing whether the bias is there or not bias is there electric field. This is actually the external field which is coming up not due to the charge. You call it as still back the charge is external one but this is the one which may present due to the depletion layer. That electric field is this is negative that is called E external which is actually filled due to depletion layer. I am just calling still as E external because this is the term people have been using in literature, I do not want to deviate from that. So you have the electric field like this. This is the E_p that is the electric field that is 0 to E_p this field is 0.

Here, now we integrate that and this is actually this particular field what you have plotted there is linear. If I want to find out, what is the potential here? That potential in thermal equilibrium is built in potential when I apply forward voltage it is V_{bi} minus V. When I apply reverse voltage that V_{bi} plus Vr so that is all what we have been discussing. So often now, it is I am reiterating what we have been telling. Now E external is in fact this is E external peak the peak value so what we are plotting there peak value into one minus x by W_D where W_D is actually the depletion layer width this is W_D. This is the standard equation for electric field peak value into that and potential due to that is integral of that and I am putting that minus sign. To tell you that, if you go this side electrostatic potential goes up as x increases but when you go towards that side electronic potential decreases. That is how you have to draw the energy band diagram. That is why I put that minus sign there. Otherwise, when you integrate if you are putting electrostatic potential we put integral of that will be minus sign will go because minus E peak into that. In any way you can very easily understand from physical terms that from the x equal to 0 right side when you go electrostatic potential becomes more and more positive electronic potential will become negative just opposite of it. Now just let us plot that so this one more thing I wanted to show you here is this term when you talking of x very small that term will be negligible. What I am trying to point out is you integrate this you get this particular term or you do not have to worry about the whole thing at all compared to one x by W_D is very small when you integrate that you will get first term low we can delete this term completely we can say E peak into one minus x by W_D I can put it as E peak a constant term after some width its like this particular current portion, if I take only a small portion that variation I do not consider its almost a constant that is the meaning of that. In that small region if I plot that will be like that I just putting it because people want to talk in terms of peak value and also what matters us what happens around that peak value.

Now let us take a look at this, so the plot here see here that E peak into x is there it is linear there but as you move away to it deviates from linearity which actually contains the whole integral. Complete integral if you take this is the one. I hope there is no confusion here what we are plotting here is the electronic potential which actually is the energy band diagram which we have been plotting all through. This is the energy band diagram which we have been plotting all through that is the electronic potential that is the psi external. Now this quantity here on the other side is additional shift potential that come comes up. What is the total potential? let me just plot that here because that diagram which may become see what we have is one potential varying like that which actually is the energy band diagram itself what we are talking of linear is only on this portion you do not have to worry about the linear term we can take the full term integrate it you will get it like this. Now, the second term is this is actually psi external we call it. Now, the image force lower image force term that we have been talking that comes from like this as we come closer and closer one by x.

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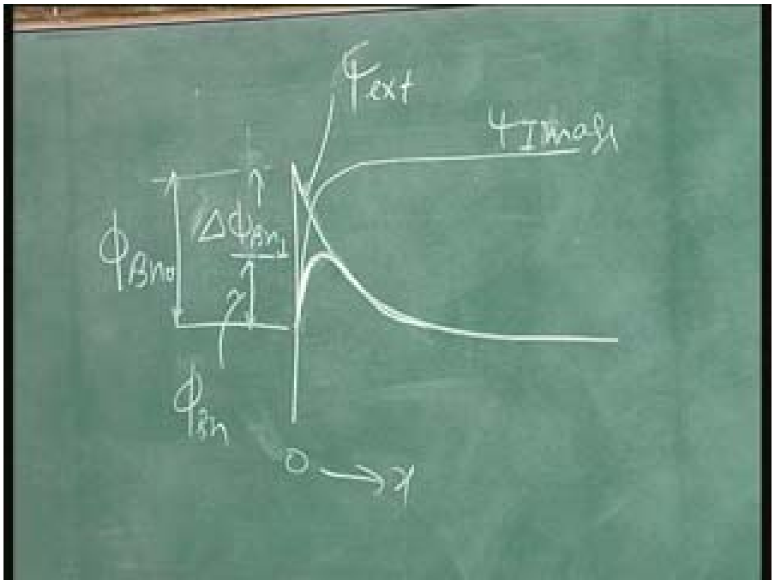

It become more and more negative actually when x become equal to 0 that goes down to minus infinity we are putting it just close to that point so what is the sum of these two this is psi image force or image. So total potential variation or total band diagram will be sum of the two and sum of the two will be here its very large compared to that so it follows that you add this quantity and these two quantities it comes like this and beyond that point that is 0 that is not varying so entire variation comes up now like this that is what I plotted there. Variation total is like this suppose you can take this as 0 its not actually 0 its I take reference as 0 from that point onwards it has come down by this quantity, how much has it come down? This is by how much it has come down usually what we take is you know that is the phi Bn. We take that as the phi Bn.

Now, the new band diagram is like this I have exaggerated it tremendously the new band diagram is like this so what was going earlier like this has become like this. What is the new barrier rate? The entire reduction here is because this has pulled this down. The potential energy of the electrons has been pulled down in this portion because of the image force lowering effect and the new barrier this is without any image force lowering effect when I say put phi Bn_0 that is absent when you take that into effect into account this is actually the phi Bn and the reduction in the barrier height is this is delta phi Bn. So, what we are telling is I hope there is no confusion about the thing we are redrawing the energy band diagram the initial energy band diagram it was due to the electric built integral and the potential is like that depletion layer now superimposed on that we have got this particular potential due to the image force which is force integrated and potential output. So, the actually the barrier gets reduced by this amount. How much is that barrier? The reduction in the barrier delta phi Bn. How do you find out that sum?. If we add these two together differentiate it with respect to x equate it to 0 find out the new phi Bn that is all what you do there when you do that do not worry about the signs and delta phi n just use the delta phi just to show that the reduction in phi is that quantity total sum of them. What we are talking of is the total potential this line here is the psi, psi image, psi external and some of them is psi of x is that all right so maximum value find out by taking this expression here differentiate it I think we will just sum up today some of the things that we have been discussing because let me not get into this

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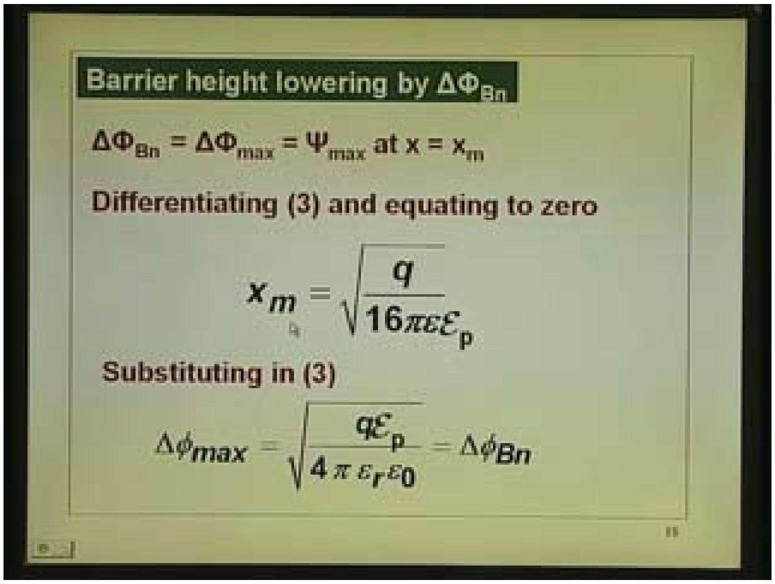

Barrier height lowering by $\Delta\Phi_{Bn}$

$\Delta\Phi_{Bn} = \Delta\Phi_{max} = \Psi_{max}$ at $x = x_m$

Differentiating (3) and equating to zero

$$x_m = \sqrt{\frac{q}{16\pi\varepsilon\mathcal{E}_p}}$$

Substituting in (3)

$$\Delta\phi_{max} = \sqrt{\frac{q\mathcal{E}_p}{4\pi\varepsilon_r\varepsilon_0}} = \Delta\phi_{Bn}$$

Because I will take it up in next lecture once again this particular thing because I will just go back to this point here from there onwards I will just discuss this once again because it will take some time for us to absorb the whole thing the concept of that because this is the one which affects your ideality factor. What you can see from here is the generation component does not effect the hole injection does not effect but they are all small quantities, but image force lowering could effect because from this two diagrams we have seen that the potential barrier which was phi Bn_0 get reduced by an amount like this because this is the only energy band diagram. The energy band diagram instead of being like that now turns out to be like this have exaggerated this so that is the reduction in the barrier

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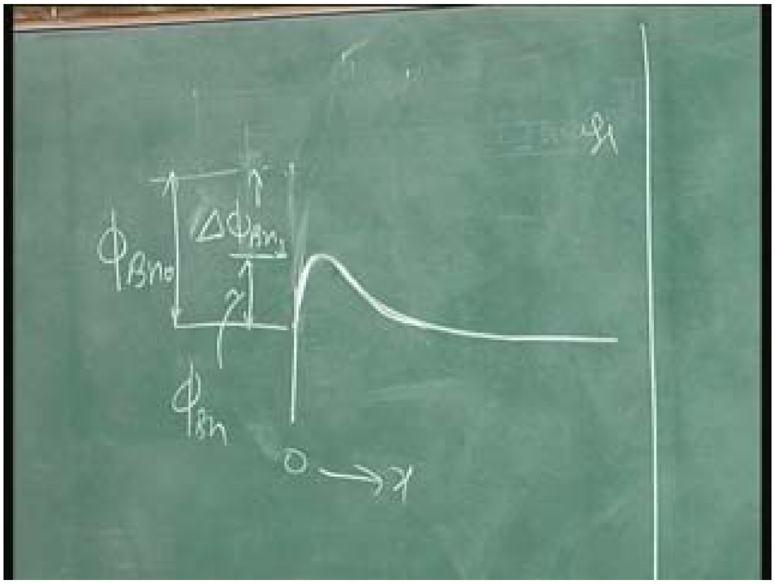

That is called the image force lowering effect on the barrier and then that happens the extent of current that is crossing will change. In fact the J_0 itself will change. See how much is the lowering effect that will affect your J_0? If more is the lowering current will be more J_0 will be more correspondingly the forward current will be changed differently. Now it effects differently in a forward and reverse directions one pulls up one pulls down. This barrier that aspect we will discuss in the next lecture because I want to go back to this bring back to the whole thing details.

See you next time.