High Speed Devices and Circuits

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Lecture - 16

(a) Fermi level pinning
(b) I-V Characteristics of Schottky Barrier Diodes

We have been discussing the ohmic contact in our last lecture and towards the end we touched upon some aspects- one is about the interface state density distribution, why it is distributed across the bandgap we have discussed; and then we also discussed why all those donor levels are towards the valence band side in the bandgap and all the acceptor side levels are towards the conduction band, in the sense they are located above the donor level. This we have illustrated with an example from gold in silicon because gold can be donor or acceptor. There those deep donors are .3 electron volts above the valence band and deep acceptors are mid gap.

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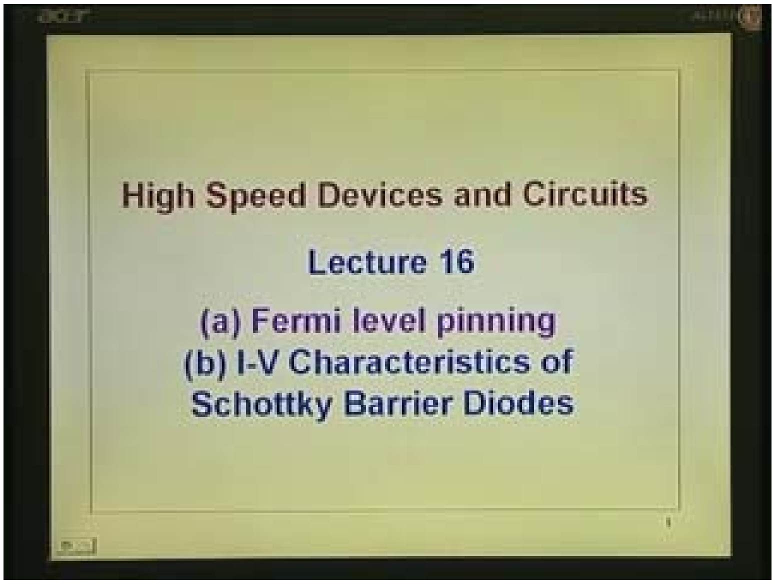

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Lecture 16

(a) Fermi level pinning
(b) I-V Characteristics of
Schottky Barrier Diodes

With that we understood and we also began some discussion on the effect of interface state density on a free surface in the sense if no metal is put, what will happen is what we started on. I have drawn that energy band diagram here. Today we will discuss first a-part on that then we will go on in the b-part on the I-V characteristics of schottky barrier diodes, because this particular aspect what we discuss (a) is very important for a field effect transistors in gallium arsenide, because you can have the devices which are not working due to these effects.

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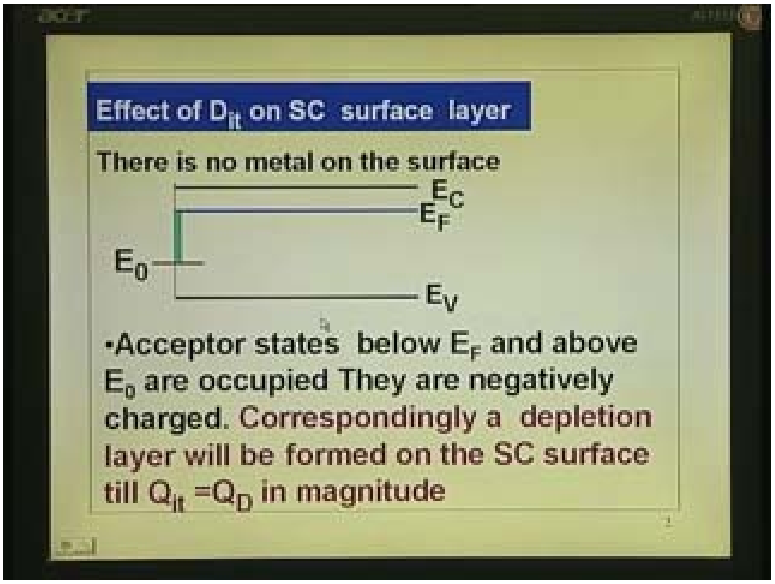

Effect of D_{it} on SC surface layer

There is no metal on the surface

- Acceptor states below E_F and above E_0 are occupied They are negatively charged. Correspondingly a depletion layer will be formed on the SC surface till $Q_{it} = Q_D$ in magnitude

Now let us take look at this diagram which illustrates the conduction band, valence band, Fermi level that is n type material and we have the D_{it} distributed all through the surface here. I just put this E_0 here. Whatever levels are there above E_0 they are all acceptors. Once the Fermi level is in this position, all the levels below the Fermi level will be occupied. I have just marked the region between E_F and E_0 with color, just to tell you that those are the acceptor levels which have been occupied by electrons.

When acceptor level is occupied by electrons the charge is negative. The levels below E_0 they are also occupied with electrons but they are donors. Donor level when it is occupied the charge is 0, it is neutral. We have to consider that this region between E_F and $E_{0,}$ acceptor states below E_F and above E_0 are occupied by electrons. They are negatively charged as a result of occupation of electrons.

Correspondingly, once there is negative charge in the surface it has come from somewhere, it has come from the bulk of the semiconductor and in the bulk it can come from corresponding very close to the point, just near the surface below the surface. If you look at the top of the surface that is the below the surface, those charges have come from there. If those electrons have come from there it leaves behind positive charges. What you mean by that is just below the surface there is a positively charged layer, in the sense there is a depletion layer.

The n type material when it is depleted it has positive charge. It is depleted because those electrons have gone and occupied the surface states here. I have marked the total charge here will be $Q_{it.}$

This particular diagram what I have drawn is actually the beginning. Just the moment this charges the electrons, there will be depletion layer and the depletion layer charge will be equal to whatever charge in the space charge layer. That correct diagram I have drawn next.

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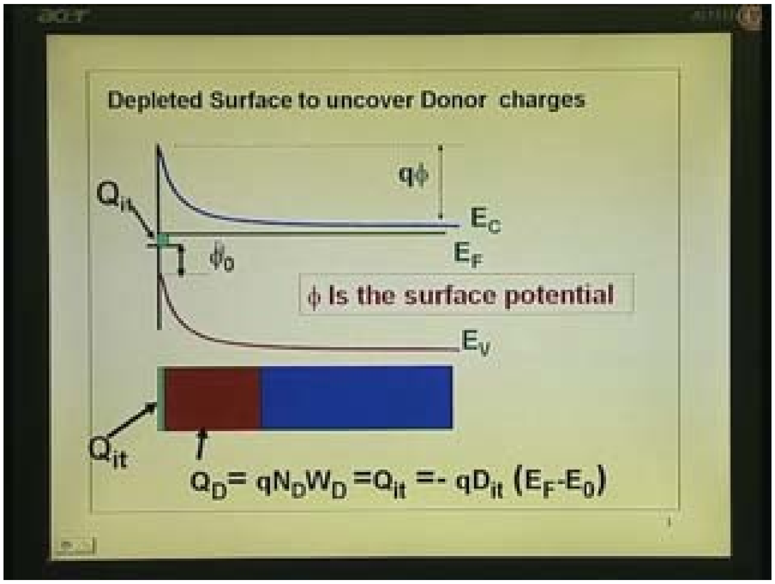

Depleted Surface to uncover Donor charges

ϕ Is the surface potential

$Q_D = qN_DW_D = Q_{it} = -qD_{it}(E_F - E_0)$

You can see if I draw it like this, energy band diagrams are flat which you mean there is no depletion layer, but the very fact that there is depletion layer energy band diagrams will bend and will be like this regular schottky barrier diode. You do not have metal there. Without the metal you have got now a depletion layer formed here up to this point.

The red portion here is the depletion layer, this is the surface state charge Q_{it} and this is neutral region. Notice one thing, as I go back to the original diagram here entire charge was here, but as it starts bending down, this point comes down, along with that the Fermi level in that portion comes down. What happens is as the Fermi level comes down, the occupants here goes down, because levels below E_F and E_0 are occupied. And depletion starts building the Fermi level comes down and less number of charges are occupied.

This process takes place still there is equilibrium between this charge in the interface state and depletion layer. Till that time that band bending goes on taking place. Like that the electrons are transferred from the semiconductor to metal or metal to semiconductor. Here the electrons are transferred from this bulk into the surface till the charge here Q_{it} is exactly equal to the charge here and charge in the depletion layer is equal to per centimeter square of course, you are putting q into N_D is the donor concentration into the depletion layer width W_D is the width of the depletion layer and that is positive. And that positive charge is exactly equal to negative charge within this portion that is that region which is having Q_{it}.

Now Q_{it} is actually equal to E_F minus E_0 into qD_{it}, qD_{it} is number of states per centimeter square per electron volt, still we are keeping it number of states per centimeter square multiplied by E_F minus E_0 you get that. This is exactly similar to what we did in the case of schottky barrier. All that has happened is as the equilibrium takes place till the charge here is equal to charge here.

Now you can see for a given doping concentration what will happen. Here as this D_{it} goes up for a given q N_D W_D, E_F minus E_0 will become see, as qD_{it} goes up if I am keeping this constant it is not a constant slightly varying, if this is constant I am just giving as an example if this is constant that is q N_D W_D if that is constant when D_{it} is large, if it is more in the surface E_F minus E_0 will actually be smaller, that means actually higher D_{it} values the Fermi level gets closer and closer to E_0 because a smaller amount of gap between the two is sufficient to supply those charges.

E_F minus E_0 into D_{it}, if D_{it} is large this gap need not be large. When D_{it} tends closer and closer to infinity which is not realistic but when it becomes very very large E_F becomes almost matches with the E_0 that is what is known as Fermi level pinning. Fermi level tends to pin to the E_0 level, it will not be in exactly but it will go as close as possible to that, so that the small amount of gap there between E_F and E_0 supplies enough some amount of negative charges to the depletion layer.

You can work it out in fact it will be a nice exercise for you to see what will be the potential, see I have marked here as q phi I have not called it as q Bi. Bi is built in potential this also is built in potential, but when you talk of free surface you talk of surface potential. The surface potential is the potential here with respect to the bulk which is same as the $V_{bi.}$ Instead of calling it built in potential, we can call it as surface potential. The potential drop across the depletion layer actually.

Now let us go back to this next diagram. I will just see few things for phi is the surface potential that is what I have marked here. That phi and this is phi_0 is the gap between the neutral level E_0 and E_V. Now let us take look at further.

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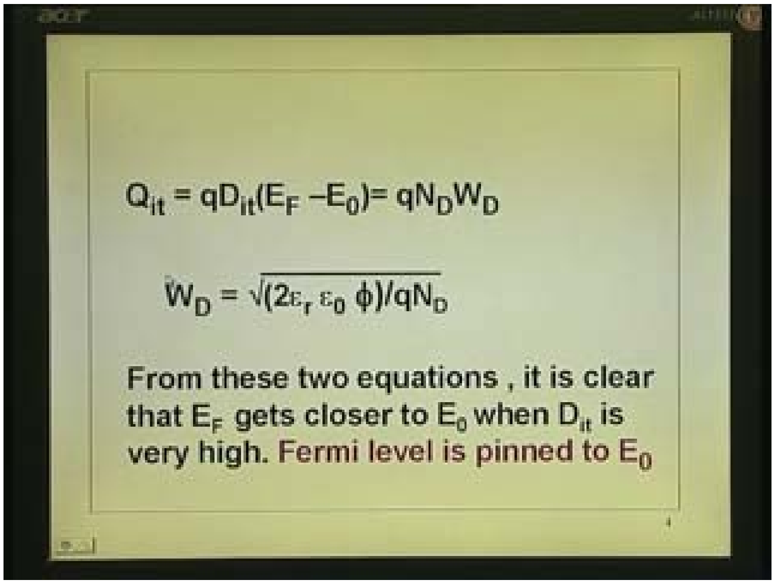

$$Q_{it} = qD_{it}(E_F - E_0) = qN_DW_D$$

$$W_D = \sqrt{(2\varepsilon_r \varepsilon_0 \phi)/qN_D}$$

From these two equations , it is clear that E_F gets closer to E_0 when D_{it} is very high. Fermi level is pinned to E_0

I am rewriting that. I am writing only the magnitudes now. I left out the minus sign; magnitude of charge in the interface state q D_{it} into E_F minus E_0 is equal to q N_D into $W_{D.}$

What is W_D? W_D is depletion layer width and that is decided by how much is the potential drop? The usual law phi is equal to q N_D W_D square divided by twice of epsilon$_r$ epsilon$_0$ very well known formula for depletion approximation. W_D is that.

Now you can see the whole thing has hit equilibrium that location of Fermi level has taken such that E_F minus E_0 is equal to that quantity and that quantity is decided by the potential.

You can now see, substitutes I have not written that deliberately so that you can take it work out and see W_D when I substitute from this, what you get is root of q N_D twice epsilon$_r$ epsilon$_0$ into phi. On the right hand side you will have a constant into root of phi and within the constant you have got N_D.

For a given N_D you have got a phi there. What do you have on the left hand side? Left hand side has got E_F minus $E_{0.}$ E_F has changed its position such that square root of, when you are substituting this, square root of q N_D twice epsilon$_r$ epsilon$_0$ into phi on the right hand side is equal to that quantity E_F minus $E_{0.}$ Can you write E_F minus E_0 in terms of phi? But I would like you can actually sit back and workout this. What is E_F minus E_0? We want in terms of phi, because ultimately the phi has built up such that E_F minus E_0 has taken the proper value. You write E_F minus E_0 in terms of phi.

How do you write that? I have not deliberately written this here so that you can have some exercise to do with yourself.

This quantity now here is the bandgap E_g minus phi$_{0.}$ Bandgap E_g minus phi$_0$ leaves you with total this thing plus this E_F minus E_0. Bandgap E_g minus phi$_0$ minus, this total quantity which is actually equal to q phi and q phi plus E_c minus E_F.

All that you have to do is on the left hand side E_F minus E_0 you can write from this total width subtracts whatever is above which is q of plus E_c minus E_F and also this phi$_{0.}$

So what I am trying to point out is you get an equation, transcendental equation on the left hand side E_F minus E_0 expressed in terms of phi on the right hand side this quantity also expressed in terms of N_D and phi. So the moment to fix up N_D and the moment to fix up $D_{it,}$ you can find out what is phi by solving that equation.

I think I would urge that you would look into as an exercise because that is simple matter to see. All that I am trying to point out from this particular analysis is ultimately the E_F tends to become closer and closer to E_0 if D_{it} is large. What is the maximum value of phi that you can get? Go back to that diagram. What is the maximum value of phi that you can get? You get D_{it} tending to infinity. You can see when D_{it} tends to infinity E_F gets pinned on to $E_{0.}$ What you get will be actually equal to E_g minus phi_0 is that quantity, E_g minus phi_0 minus E_c minus $E_{F.}$

See maximum value is when this merges with that. This gap goes off. This phi will be equal to E_g minus phi_0 minus that quantity. You can figure it out very easily. It is just what you have taken a look into thing. That is what I am trying to point out is whatever be the D_{it} your phi will never become equal to bandgap it will be two thirds of E_g by q.

In an example where the D_{it} is infinite or very large the potential there you can easily immediately be known. The potential there is actually two thirds of E_g by q minus this quantity E_c minus $E_{F.}$ If E_F merges with E_c straight away phi is equal to two thirds of E_g by q potential. Once you know phi you can actually find out what is the depletion layer width is because phi is q N_D W_D squared by twice $epsilon_r$ $epsilon_0$ standard formula.

With that I think I will leave this topic of Fermi level pinning or the effect of interface state density on the barrier height in the schottky and also on the free surface. Please remember that a free surface with high interface state density can lead to a depleted surface below which has profound influence on the MESFET.

When you go to that we will see between the gate and the source there can be depleted layer due to free surface. Just let me put that down so that without leaving you on guessing. For example, if I have a semi insulating gallium arsenide, all our effort was to realize a MESFET. And then I have an n type layer gallium arsenide and here what we will do is you will put a schottky barrier that is a metal gate.

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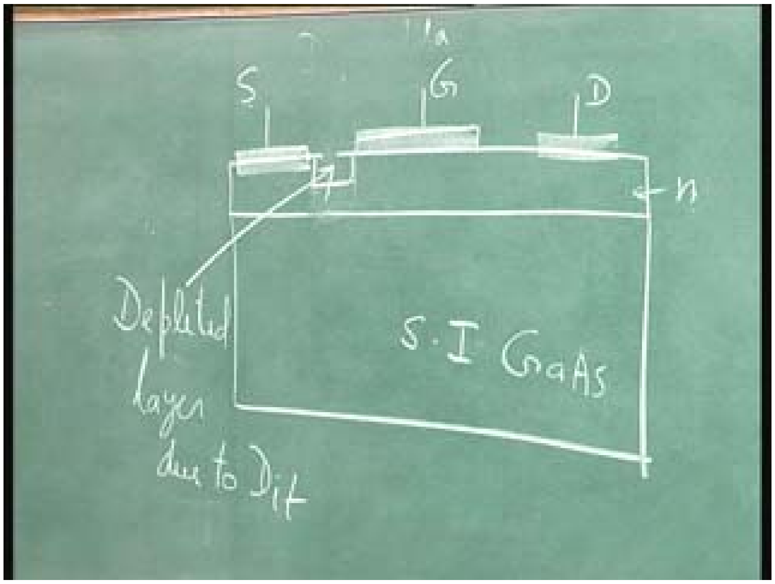

Now you will have ohmic contacts on two sides which will make n plus and metal. You will have a contact here like this. Notice I am putting it buried inside because you alloy it n plus into that and on that you have got the metal, so that is the source. Similarly, I have got drain here and this is the gate, this is the free surface that we are talking of.

In the example that we have considered we first discussed schottky barrier metal semiconductor contact, we saw the impact of the interface state density on barrier height. We will see how the barrier height effects the current or blocking capability soon qualitatively we have discussed we will have quantitative discussion now. These we have discussed make it n plus to make ohmic contact.

Here this free surface what will be the effect of that? This is n type free surface if you allow without any passivation if there are infinite number of tangling bonds you will have depleted layer below that. If you have depleted layer below that you can immediately see the difficulty. What is the difficulty? Suppose in this, depleted layer comes all through like this, what happens? Source is disconnected from the channel. That is the problem that we will face in a MESFET.

This one of the difficulty is that people were facing when making this type of device, particularly, if this layer become thinner and thinner because after all as we said the potential here is equal to two thirds of E_g at the most. Correspondingly, how much is the depletion layer depends upon the doping here, so if I have a thickness only that much.

May be you can say there is still some opening path is there it will lead to increase in resistance, but if the thickness is this much thin of the layer, entire layer is depleted. There is no path between source and the channel. The MESFET would not work. It is like just like the MOSFET without an inversion layer connecting the source and the channel. This is why depleted layer I will just remove that from there let me put it somewhere else. This is the depleted layer due to D_{it} that is all I want to point out right now.

Now we will get back to our discussion on the schottky barrier as I have shown in the first slide itself, what we now do is, take a look at the conduction mechanisms or the I-V characteristics of schottky barrier diodes.

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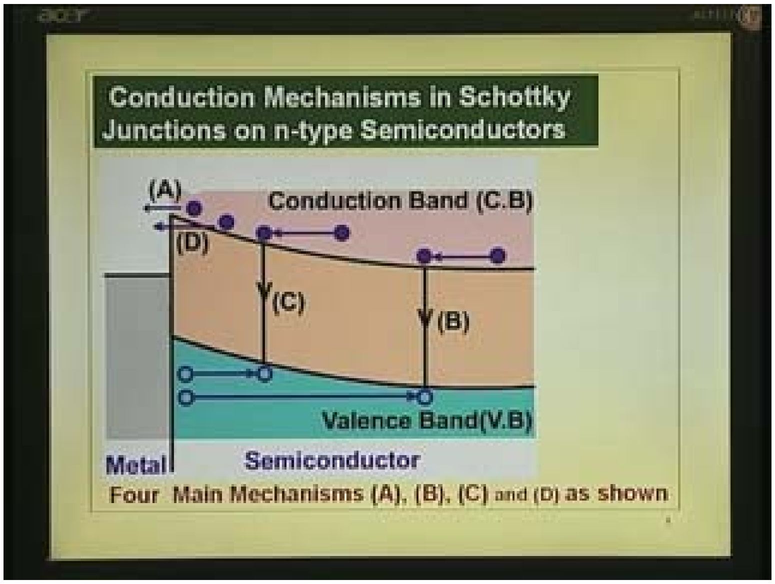

Conduction Mechanisms in Schottky Junctions on n-type Semiconductors

Four Main Mechanisms (A), (B), (C) and (D) as shown

This is the metal and this is the semiconductor on this side. As I pointed out earlier we will be discussing only n type substrate because we are interested in electron transport. Here this is an n type semiconductor and conduction band C.B valence band V.B all this abbreviated because later we will say CB and VB and semiconductor SC these are abbreviations I am following to make it easy to project it here.

The schottky junctions we call it also schottky barrier metal semiconductor contact at the schottky barrier or even schottky junction with a metal with the semiconductor.

You can see here these circles are the electrons. These open circles are the holes in the valence band. Now the current transport, there are different mechanisms by which electrons can be transported from the semiconductor to the metal. From the metal it can be transported if the electrons have energy above that. That we have already discussed that is called thermionic emission.

Thermionic emission means if you heat up or at room temperature several electrons will have energy over and above this barrier. If you look into the old vacuum tubes, I do not know whether I told you the example, if you take the vacuum tube what is the source of electron there? It is a heated filament. A filament is heated, sufficiently heated red hot so that it emits electrons.

If you take a metal and then if it is in vacuum there is a barrier that is zero level and what as you have said that is phi$_{m.}$

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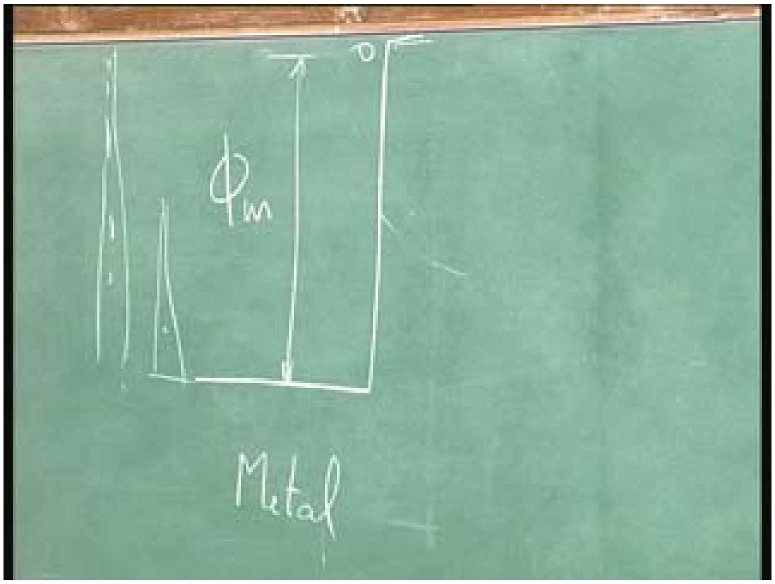

If I heat at room temperature, if you take a metal no electrons are not coming out of that. Electrons are staying within that because they have the energy like this, but I have barrier here like in the case of schottky barrier, these can cross. If I do not have anything only vacuum these electrons energy have to rise up to that.

If it is raised up to that if I heat up them at metal. It is not the schottky barrier that I am talking of; it is the vacuum tube actually. You heat up the filament, this entire distribution will become like this acquire kinetic energy. They can be emitted into the space. In vacuum tube what they do is you have evacuated tube in which there are two electrodes and just close by to the cathode we have this filament is heated.

When I apply voltage the electrons which are emitted can be connected by the plus. So you have the current flow. That is the way the vacuum tube works. In case we do not have chance to talk of vacuum tube these days though that was the main device in olden days, that is the transport of electrons from here to here.

From semiconductor there are different mechanisms, one that we have been talking of transport of electrons across the barrier. I have written that down here, that is the thermionic emission, the A that I am putting here, that A is the transport of carriers across the barrier.

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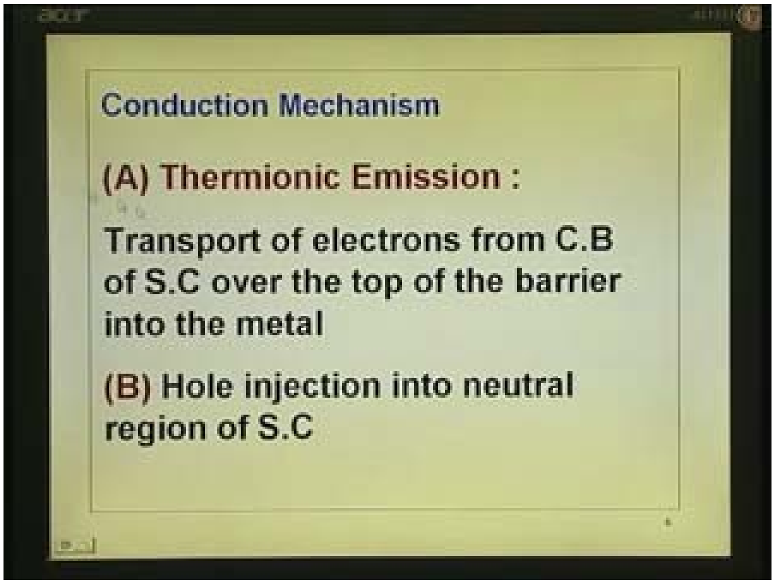

Conduction Mechanism

(A) Thermionic Emission :

Transport of electrons from C.B of S.C over the top of the barrier into the metal

(B) Hole injection into neutral region of S.C

Transport of electrons from the conduction band CB of the semiconductor over the top of the barrier into the metal that is called thermionic emission, that mechanism we are talking about whichever has got energy above the barrier it can cross; second one hole injection into a neutral region of semiconductor, that is this one B. (Refer Slide Time 20:15) Holes injected from here, whatever vacancies are there, it will be injected. They will be transported into the neutral region and you can see it beyond the depletion layer and in a neutral region it will become ionized electron. It is there any combination process.

It is just like in case of pn junction when you forward bias, in fact I have shown here the forward bias device, and it is not thermal equilibrium. In a pn junction when you forward bias you have hole injection from p to n. Similarly, in a hole injection whatever vacancies are there, they are injected into neutral region they will recombine.

We are very silent about it so far. We have been talking of only this transport I have been silent because we will see later on at that. That particular component is very small.

Another component that is present which is negligible in many situations, most of situations is generation recombination C. Notice here, electrons reaching the depletion layer, holes reaching the depletion layer recombination. In the forward bias case it will be recombination if it is a reverse bias case what will be the situation? Electrons will be lifted up from the valence band to conduction band and separated out. That is generation. That is why component C is recombination or generation.

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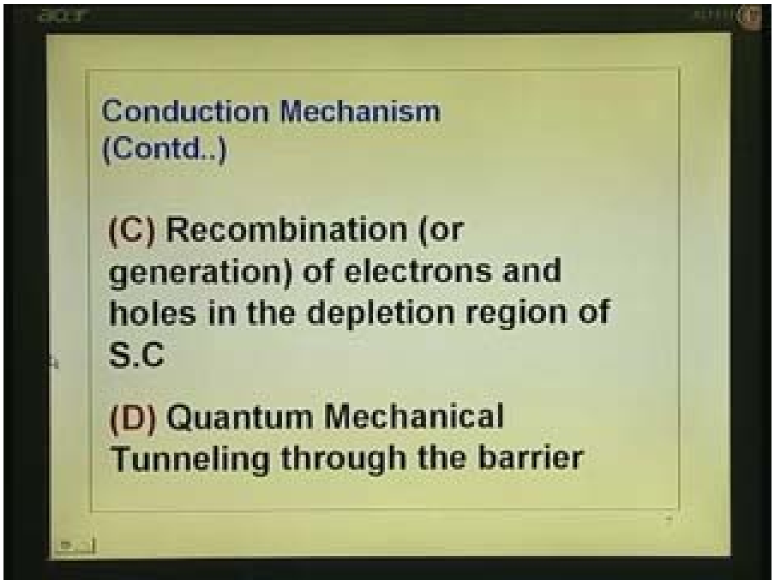

Conduction Mechanism (Contd..)

(C) Recombination (or generation) of electrons and holes in the depletion region of S.C

(D) Quantum Mechanical Tunneling through the barrier

Recombination is in forward bias case generation in the reverse bias case of electrons and holes in the depletion layer. B and C what we have discussed just now, both are same ultimately, it is a forward bias case.

The part B, go back to the diagram, (Refer Slide Time 20:15) here the recombination taking place at neutral region, here C recombination taking place in the depletion region. In the reverse bias case this is absent. This will be generation of current, opposite.

There is one more component here you see, which actually is very close to this top edge electrons which are having energy not above the top of the barrier but very close to that barrier edge. Those electrons find a width of that barrier small. As you go from bottom to top, I will just draw that because it is not very clear effectively there.

Suppose I have a diagram like this and if I have this schottky barrier like this, I am just drawing it to show it now, let me draw slightly differently; it is not like heavily doped surface.

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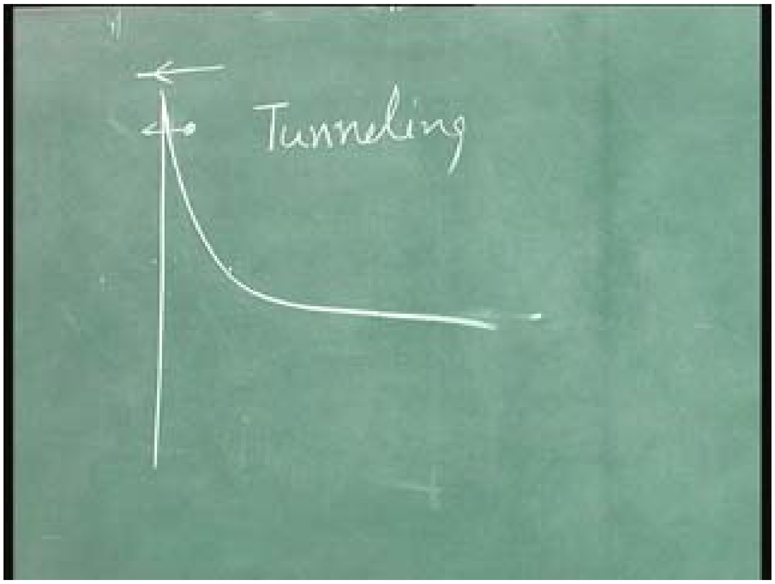

Barrier is wide here maybe 200 armstrongs, 300 armstrongs or even .1 micron but when you go to the top what we are talking of thermionic emission is the injection of electron across that barrier A. What we are talking of is the electrons which have energy here. They find that the barrier width is very small. That is quantum mechanical tunneling.

I think the physics people frighten us by say using jargon term but it is actually the fact showing a request solution gives you all the things.

What I am trying to point out is you will have very easy transfer of electrons from here to here across this thin layer. That is called tunneling. In fact you can call quantum mechanical tunneling.

In fact tunneling actually simple term, the idea is when the layer is very thin the probability in the terms of quantum mechanics, the implication is, if I have a thin layer the probability of finding the electron here and here are the same, because the wave function of this electron, because electrons is particle and also a wave, the wave function overlaps on to other side, that is why easily it can be here or here; and if slight amount of force is there it will find itself on other side.

That is the quantum mechanical tunneling. It is a very simple term. The probability of finding electrons here and here are same, same in the sense it can easily move on to that side because of the wave functions spreading into just neighborhood of wherever the electron is.

So to put it in further simple terms, it looks as if there is no barrier here. That is called tunneling. Sometimes it is also called, as the top one is thermionic emission, this one is called thermionic field emission TFE. These electrons have enough energy because of thermal energy here and this is because of the slightest field, it will push it across that and it can easily occupy the other portion. Because if the wave function goes on to the other side also. Thermionic field emission there is another name given to that. Hence you will hear terms like thermionic emission, thermionic field emission.

These are slightly different mechanisms. Right now what we will see is, among all these three components B, C, D they are not contributing much. The main contribution to the current will be from here. I just included these terms just for the sake of completeness and also they will show up under certain conditions.

If the conditions are favorable they will show up. For example you have already seen if the doping is high that component becomes very high; if the doping is high then the entire layer becomes thin like that. Tunneling becomes very easy.

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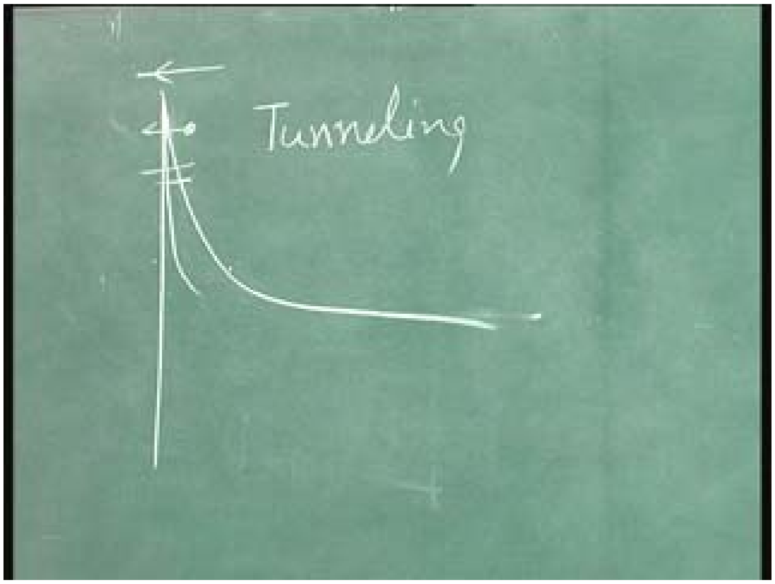

There is one example of telling when you provide a proper condition, other terms will also start bearing its slope. Otherwise normally, for white band semiconductors like gallium arsenide, silicon carbide, gallium nitrate etcetera and even silicon, your main component is A, all that we have to see is that if I want to find out the I-V characteristics. Let us see that.

B is the quantum mechanical tunneling through the barrier. What is that? D. Let me go through that. Thermionic emission generates the recombination current, hole recombination in neutral region and that one is the quantum mechanical tunneling. Among all the four, these are not very important and when they are absent, when this thermionic emission only is present, it shows ideal characteristics; most of the time you get close to ideal characteristics. That is what I said just now. The I-V characteristics of the schottky barrier diode are mostly determined by thermionic emission that is process A that we have said.

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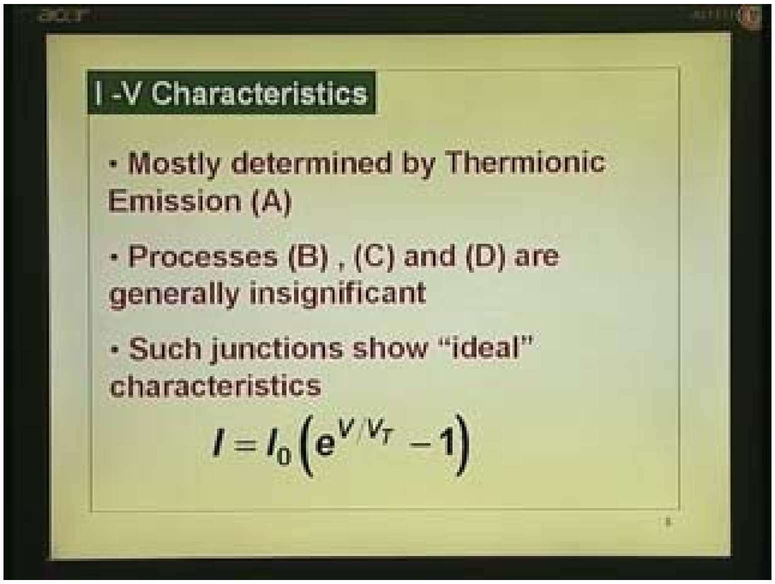

I -V Characteristics

- Mostly determined by Thermionic Emission (A)
- Processes (B) , (C) and (D) are generally insignificant
- Such junctions show "ideal" characteristics

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

Processes B, C, D are generally insignificant. When I say generally insignificant that is generally within quotes, that is if you bring in provides certain circumstances which we have occasionally see later. One of them I have already pointed out- if a barrier becomes very thin you will have tunneling. Such junctions show ideal characteristics. I is equal to $I_{0,}$ e to power of V by V_T minus one.

Now let us see a very quick analysis of this. We come back to that diagram which we have been seeing often. Metal, depletion layer, n type, this is forward biased, this line is E_c under thermal equilibrium conditions. That is what I have shown here. E_F is here.

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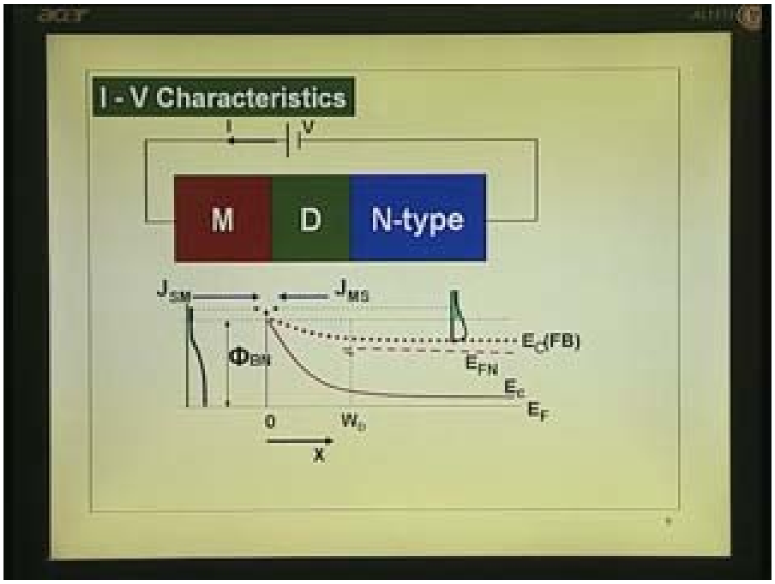

I - V Characteristics

When you forward biased this goes up, that is the dotted line and the Fermi level you can call it as a cozy Fermi level E_{FN} that also goes up. Telling you that you can apply for finding out the total carrier concentration here we can use thermal equilibrium situation and that will be practically equal to the dopant concentration. Entire area under this curve there gives you total concentration n n zero which is virtually equal to ionized dopants. When you forward bias it, this is lifted up and this particular region where I have marked shaded there, this region, that region is having energy above that barrier; all these electrons have energy above that barrier. Before thermal equilibrium that was whole thing was down and now more number of electrons has the barrier energy more.

I am repeating some of the things of course but just get into that, write down equations, that is the one if you have to find out how many electrons are able to cross the barrier what we have to do is find out what are these quantities. You can see that is less than the total quantity area under the curve. It is less than the thermal equilibrium electron concentration. Over here, this region, this shaded portion there, those are the electrons which can cross the barrier, which can give rise to current J_{MS} in this direction due to electron injection from here to here, J_{MS} from here. That is this one.

Whenever I forward biased or reverse biased this quantity is not changing because this phi$_{BN}$ is not changing. All that happens is here. This will give rise to J_{MS} which is J_0 mutually you call that, whereas J_{SM} is due to these electrons. How do you compute the current? It is different from the way you compute the current in the simple pn junction. That is the real difference between the two, why it is we will also see. Now let us see, all that you do is supposing I can find out how many electrons are there above this barrier. That is if I take a move from here to here, how many electrons are there? Here there are the ones which are having energy above that.

As I move from the bulk to this surface, what happens to electron concentration? Keeps on falling and the total concentration here is equal to the one which is above that. If there is electron concentration NS at the surface, if they have a velocity component V_x in this direction, due to their kinetic energy they are above the valence band. Due to their kinetic energy, that is due to the temperature they have got certain velocity $V_{x.}$ Suppose see N is a concentration, V is the velocity, what is the current, N into V into Q, as simple as that.

All that you have to find out, if I want to find out this $J_{MS,}$ that is the current due to the electrons injected from the semiconductor to the metal, all that I have to find out is what is that electron concentration on surface and multiplied by the velocity? This is simple ohms law that we use or simple laws that we use, not merely ohms law. This is all that I have said now.

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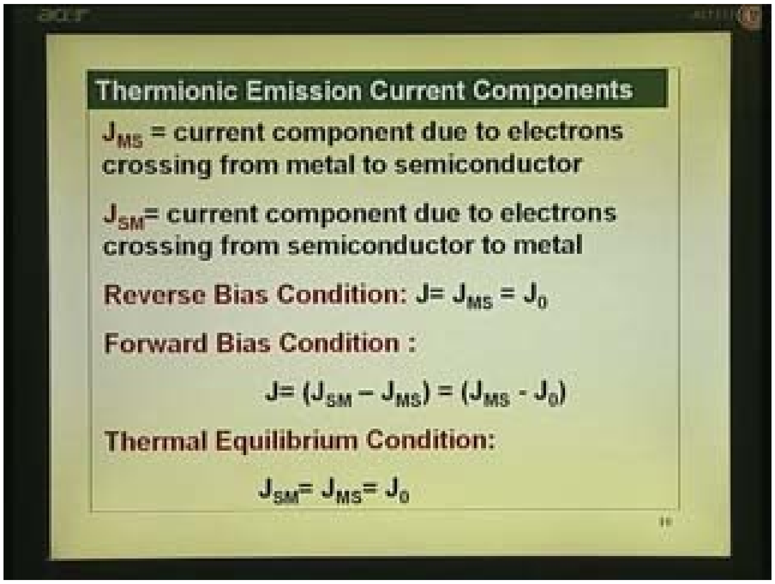

Thermionic Emission Current Components

J_{MS} = current component due to electrons crossing from metal to semiconductor

J_{SM}= current component due to electrons crossing from semiconductor to metal

Reverse Bias Condition: $J= J_{MS} = J_0$

Forward Bias Condition :

$$J= (J_{SM} - J_{MS}) = (J_{MS} - J_0)$$

Thermal Equilibrium Condition:

$$J_{SM}= J_{MS}= J_0$$

J_{MS} the current component due to electrons crossing from the metal to semiconductor, J_{SM} is current component due to electrons crossing from the semiconductor to the metal. Reverse bias condition, total current is actually equal to go back reverse bias condition the whole thing will be pressed down, so none of these carriers will have energy to cross, we have discussed this earlier.

Only these electrons will have the energy to cross that is $J_{MS,}$ see please remember J_{MS} is in that direction due to injection of electrons from here to here, metal to semiconductor. J_{MS} is actually equal to $J_{0.}$ In reverse bias condition you will have current due to the excess electrons which have energy from the metal to the semiconductor that is $J_{0.}$ In forward bias condition J_{MS} remains same thing that is $J_{0.}$ J is actually J_0 which is from which is flowing from semiconductor to metal due to transport of electrons from metal to semiconductor.

And J_{MS} is due to, I think this is other way I think there is a mistake here; just this actually is J_{SM} minus $J_{0.}$ Is it right?

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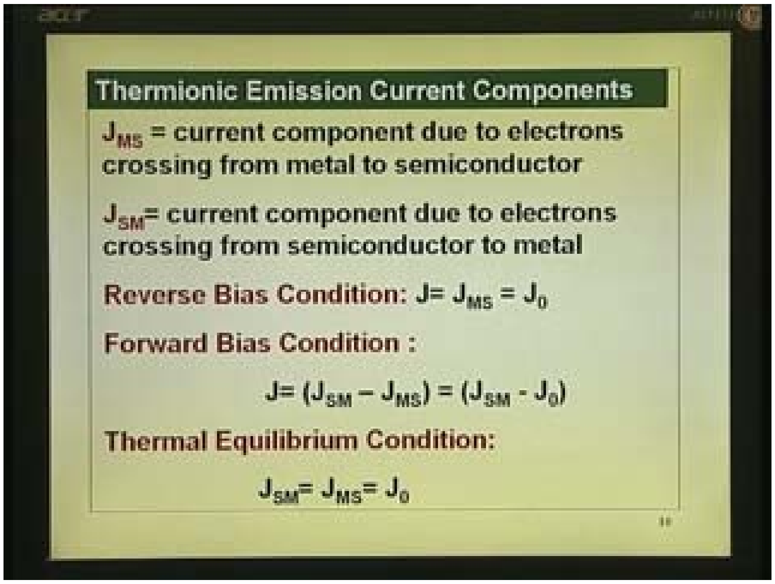

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Thermal Equilibrium Condition:

$$J_{SM}= J_{MS}= J_0$$

That is J_{SM} minus J_0 because J_{MS} is the one which is changing, what we have to find out if I have to find out forward bias condition current is, find out $J_{SM.}$ Make V equal to 0 in the expression what will I get? $J_{0.}$ I do not have to compute J_0 separately find out J_{SM} as a function of forward bias voltage find its value when V equal to 0 that gives me $J_{0.}$ So that is the thing, J_{SM} equal to J_{MS} equal to J_0 at thermal equilibrium. Let us calculate that. I can quickly run through this now, because all the formulae are known to you.

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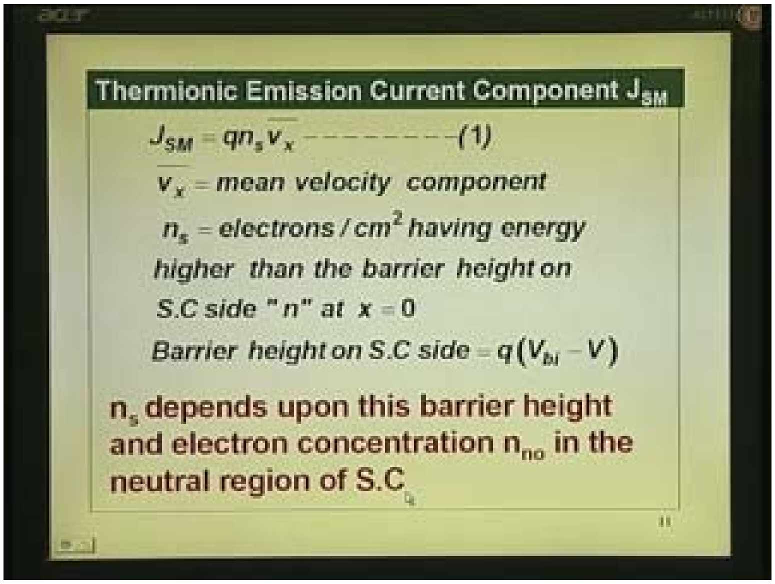

Thermionic Emission Current Component J_{SM}

$J_{SM} = qn_s\overline{v_x}$ --------(1)

$\overline{v_x}$ = mean velocity component

n_s = electrons / cm^2 having energy higher than the barrier height on S.C side "n" at $x = 0$

Barrier height on S.C side $= q(V_{bi} - V)$

n_s depends upon this barrier height and electron concentration n_{no} in the neutral region of S.C

The only formula that you do not know is or you were not applying is J_{SM} current due to the electrons injected from the semiconductor to the metal is number of electrons or electron density near the surface at x equal to zero.

We can go back once. x equal to zero is on surface, metal semiconductor junction at x equal to zero what is electron concentration there? Multiply it by velocity that we are computing. Multiply it by the velocity component that is V_x bar is actually the mean velocity component in the X direction. There is a standard formula for any gas particle from the statistics that comes up.

n_s is the electron concentration is that is per centimeter cube, number again one more error there, I will just correct it right here.

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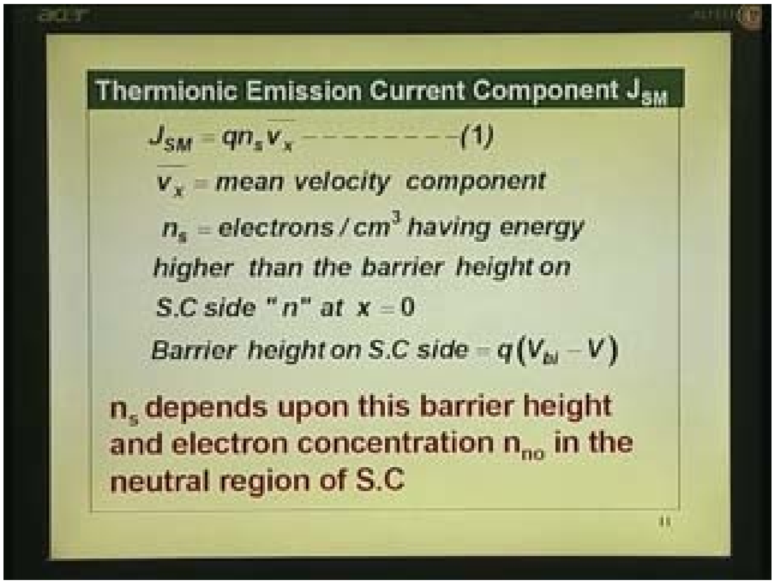

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n_s depends upon this barrier height and electron concentration n_{no} in the neutral region of S.C

These are all per centimeter cube how much it is same. At the very close to that surface in the bulk the carrier concentration is that much having energy higher than the barrier height on semiconductor side.

That is what we are trying to see here. Current is n_s V_x and n_s is per centimeter cube, density, having an energy higher than the barrier height on the n side. What is the barrier height here?

When I apply voltage V thermal equilibrium it is $V_{bi,}$ when I forward bias it is V_{bi} minus V, supposing that is barrier height potential difference what is the n_s?

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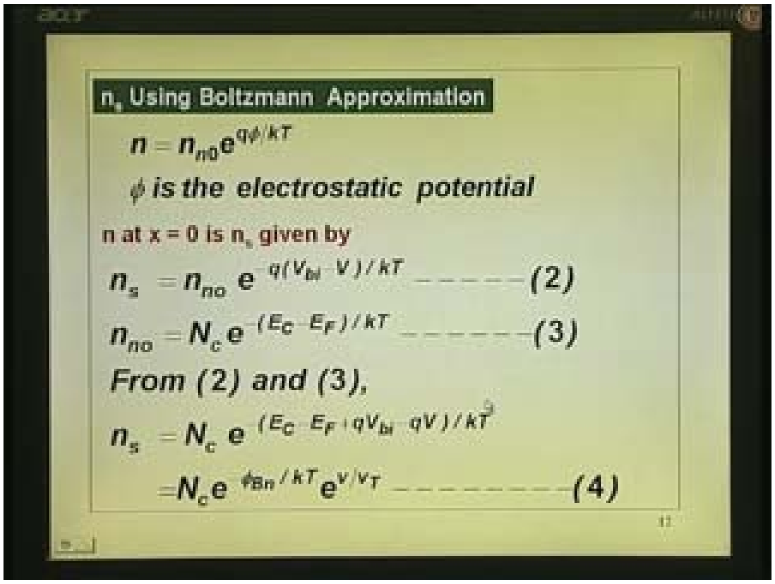

n_s Using Boltzmann Approximation

$n = n_{n0} e^{q\phi/kT}$

ϕ *is the electrostatic potential*

n at x = 0 is n_s given by

$n_s = n_{no}\, e^{-q(V_{bi} - V)/kT}$ ------(2)

$n_{no} = N_c e^{-(E_C - E_F)/kT}$ -------(3)

From (2) and (3),

$n_s = N_c\, e^{-(E_C - E_F + qV_{bi} - qV)/kT}$

$= N_c e^{-\phi_{Bn}/kT} e^{V/V_T}$ ----------(4)

This is the n_{n0} is the carrier concentration in the bulk. From the bulk to the surface if there is a potential difference phi, the carrier concentration surface will be, whatever here is present on the bulk, multiplied by e to power of phi by $V_{T,}$ q phi by kT that is phi by $V_{T,}$ this is Boltzmann approximation. Carrier concentrations vary as exponentially as the potential divided by $V_{T.}$ That is a well known law so I have just used that.

What is phi? Phi is that quantity, minus q V_{bi} minus V by kT. I am using minus V, minus because of the potential, go back from here to here when I go, you have potential drop is negative. If the carrier concentration is n_{n0} here, the potential carrier concentration here is equal to n_{n0} into e to power of minus q V_{bi} minus V by kT because the potential difference is V_{bi} minus V here. That is what we have done.

Very simple actually and once you have written this equation, if you accept that, that is because it is a boltzmann's law which you are have used, carrier concentration between two points can be related by ratio of the carrier concentration is e to power phi by $V_{T,}$ that is what I have used.

The ratio of the carrier concentration here and at the bulk is equal to e to power that. You have to use the sign properly. As you go towards the negative potential the electron concentration low, that tells you that should be minus. Even if you do not understand more than that, that is clear enough.

Now what is n_{n0}? It is thermal equilibrium carrier concentration. That is related to E_C minus E_F and density of states at the conduction band. This again is a standard formula with semiconductors, n_{n0} thermal equilibrium value equal to N_c e to power of minus E_C minus E_F by kT. What I do is I substitute those three into that and then n_s becomes equal to that quantity I have rewritten this, instead of n_{n0} I have put N_c e to power of minus E_C minus E_F and this I have put within that bracket that becomes plus q V_{bi} because minus is there and this becomes minus minus plus. What is this quantity now? If you take a look at this quantity E_C minus E_F plus q V_{bi} let me just put that diagram.

Thermal equilibrium situation if you take, this is thermal equilibrium situation and this is E_C and this is E_F. What is this quantity? q V_{bi}, and what is q V_{bi} plus E_C minus E_F? phi_{BN} that is what we have done.

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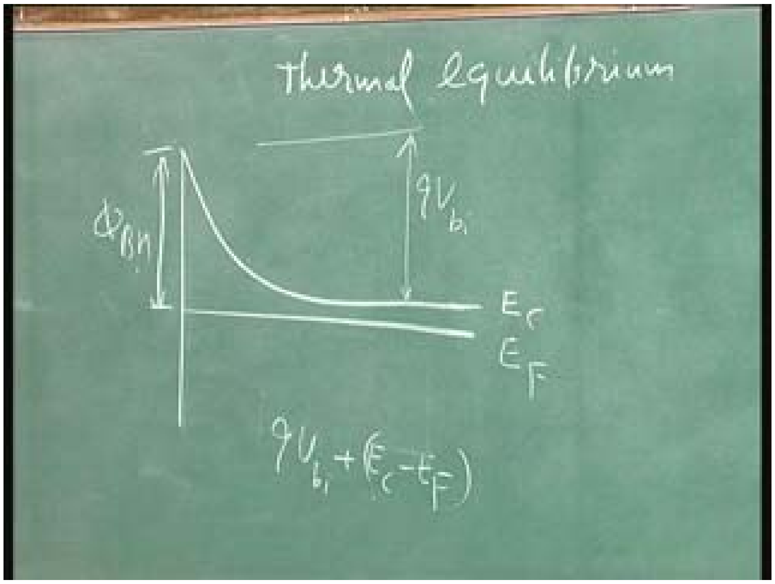

What we have done is, we have substituted for q V_{bi} plus E_C minus E_F is equal to $\text{phi}_{BN;}$ this is in electron volts; this is electron volts, electron volts; this also in electron volts V_{bi}

in volts. We have written that. That is what we have done. I have taken this out all these three quantities together put it as phi$_{BN,}$ so e to power of minus phi$_{BN}$ by kT and this minus and this minus together will become e to power of V by V_T.

Now you can see the whole thing has become simple. These are the electrons which are capable of crossing the barrier, so they are present at the boundary there and they will be hitting the boundary at the velocity, hitting, impinging of the surface with a velocity V of x in that component.

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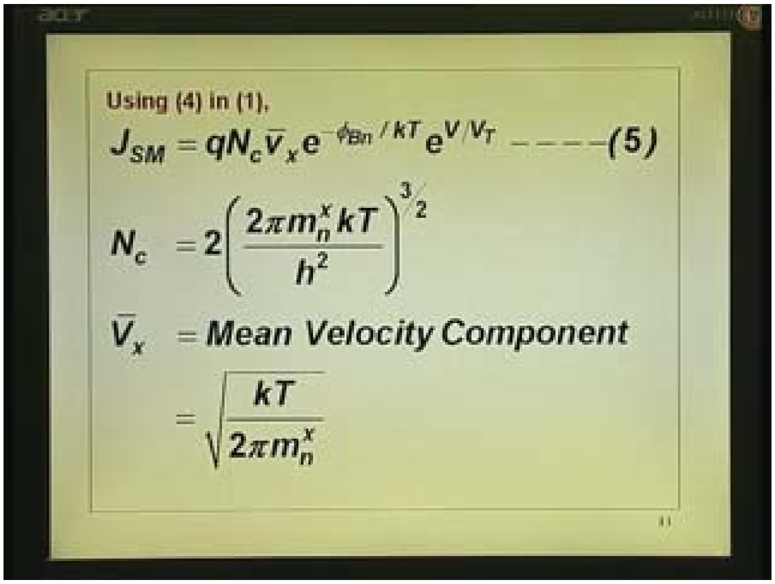

Using (4) in (1),

$$J_{SM} = qN_c\bar{v}_x e^{-\phi_{Bn}/kT} e^{V/V_T} \text{ -----(5)}$$

$$N_c = 2\left(\frac{2\pi m_n^x kT}{h^2}\right)^{3/2}$$

$\bar{V}_x$ = Mean Velocity Component

$$= \sqrt{\frac{kT}{2\pi m_n^x}}$$

Current now is equal to q into V of x and current is this quantity multiplied by V of x into q. That is what I have written there.

Now what you do is, you have to just see substitute for $N_{c,}$ substitute for V of x, you get the equation for current. N_c is this quantity, effective density of states is related to temperature and effective mass, twice 2pi m_n star kT by h square to the power 3 by 2, V of x is the mean velocity component. From the assembly of particles statistics there from the energy considerations people have arrived at the mean velocity component in that direction as proportional to root kT.

That is the quantity so I substitute this quantity and this quantity on to these two. Root kT by 2pi m_n star is mean velocity component, substitute that you get that.

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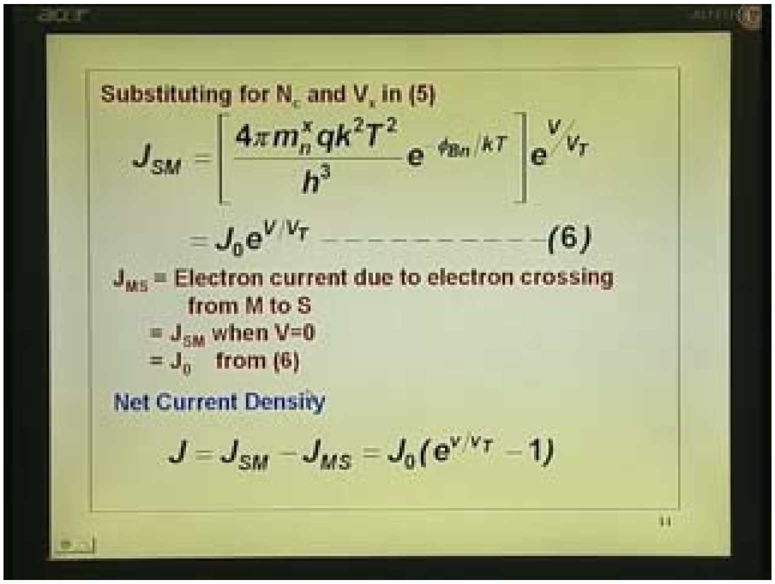

Substituting for N_c and V_x in (5)

$$J_{SM} = \left[\frac{4\pi m_n^x q k^2 T^2}{h^3} e^{-\phi_{Bn}/kT} \right] e^{V/V_T}$$

$$= J_0 e^{V/V_T} \text{-----------} (6)$$

J_{MS} = Electron current due to electron crossing from M to S

= J_{SM} when V=0

= J_0 from (6)

Net Current Density

$$J = J_{SM} - J_{MS} = J_0(e^{V/V_T} - 1)$$

That is all put together, 4pi m_n star q k square T square by h cube e to power of minus phi_{BN} divided by kT e to power V by V_T. Now the whole thing inside that is J_0. Now you see you have got the very famous equation J_0 e to power V by V_T. The whole effort has been to find out what is this J_0 quantitatively. You can see that.

Now let me just go one step further here. If I have put V equal to 0 what do I get? That is J_{SM} at V equal to 0 is thermal equilibrium value. That is exactly balanced by J_{MS}. That is J_{MS} is same J_0, see in thermal equilibrium V equal to 0 and J_{SM} is J_0 and J_{MS} what comes from metal semiconductor must be balanced by that. Total current is actually J_{SM} minus J_{MS}. I have just subtracted J_0 from here because one is in that direction other is in the other direction. These are diode equations where J_0 is given by this expression. Let us take a look at that.

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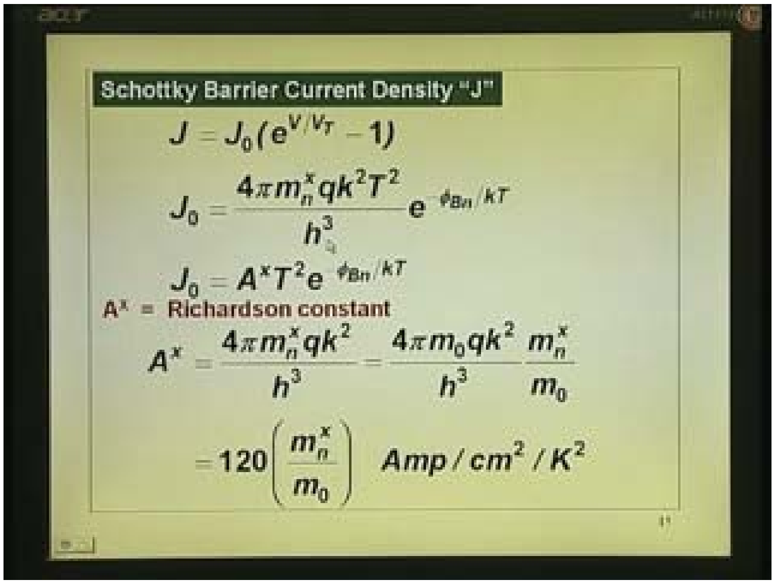

Schottky Barrier Current Density "J"

$$J = J_0(e^{V/V_T} - 1)$$

$$J_0 = \frac{4\pi m_n^x q k^2 T^2}{h^3} e^{-\phi_{Bn}/kT}$$

$$J_0 = A^x T^2 e^{-\phi_{Bn}/kT}$$

A^x = Richardson constant

$$A^x = \frac{4\pi m_n^x q k^2}{h^3} = \frac{4\pi m_0 q k^2}{h^3} \frac{m_n^x}{m_0}$$

$$= 120\left(\frac{m_n^x}{m_0}\right) \quad Amp/cm^2/K^2$$

The J_0 is this quantity whatever I have said just now. Now this is further simplified to make life easy for us. You do not have to remember that big formula. The entire thing here leaving the T that is a constant independent of temperature, you call it as the A star. A star is actually Richardson constant, the person who called it by its name, A star Richardson constant.

The idea is this A star you still could have used it as constant but you can see that there is m_n star coming, that means A star depends upon the semiconductor. For silicon it will be higher because m_n star is higher, for gallium arsenide it will be lower because m_n star is smaller. That into T square into that quantity. You can see that J_0 depends upon barrier height and temperature plus this constant.

Let us now go further down because you do not have to remember even this. What are these quantities? A star is actually this quantity 4pi m_n star q k square by h cube. What I do is you do not like to have that m_n star there. You know always m_n star by m_0 because you know for gallium arsenide it is .067 or so. That is why we multiply this by m_0 divided by m_0. You get a constant independent of the semiconductor multiplied by m_n star by m_0 and this quantity turns out to be 120. I think if you remember that, that is sufficient.

A star is 120 into m_n star by m_0 ampere per centimeter square per k square, degree Kelvin. Now you can compute A star.

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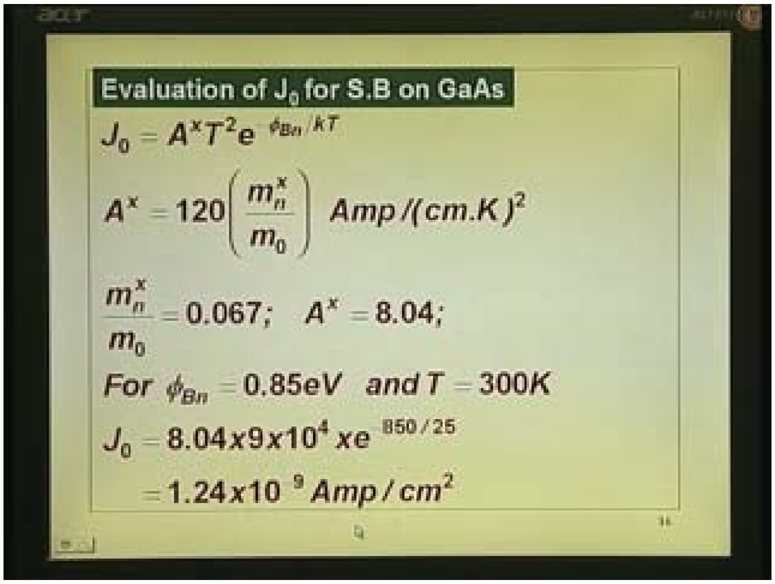

Evaluation of J_0 for S.B on GaAs

$J_0 = A^x T^2 e^{-\phi_{Bn}/kT}$

$A^x = 120\left(\frac{m_n^x}{m_0}\right)$ $Amp/(cm.K)^2$

$\frac{m_n^x}{m_0} = 0.067;\quad A^x = 8.04;$

For $\phi_{Bn} = 0.85eV$ and $T = 300K$

$J_0 = 8.04x9x10^4 xe^{-850/25}$

$= 1.24x10^{-9} Amp/cm^2$

Coming back to this, therefore J_0 is A star T square into e to power minus phi_{BN} by kT. This is the one which decides what is the voltage dropped across this device. A star is 120 m_n star by m_0, you have just now derived, in that quantity. For gallium arsenide we are estimating now evaluation of J_0, how much is J_0 in gallium arsenide?

This quantity is m_n star by m_0 is .067; A star turns out to be 8.04. Once you put that as 8.04 A star, T at room temperature 300 degree Kelvin 300 square, when you do that you get 9 into 10 to the power 4 into e to power minus phi_{BN} kT. I take phi_{BN} as .85 electron volts close to that E_F merging with E_0, you get 1.24 into 10 to power minus 9 ampere per centimeter square.

Let us see just remember this number it is about 10 to power minus 9 amperes per centimeter square.

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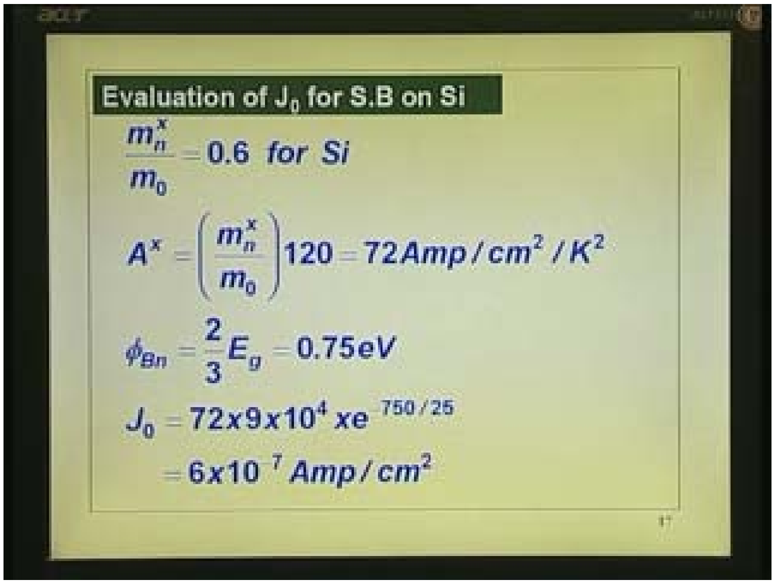

Evaluation of J_0 for S.B on Si

$$\frac{m_n^x}{m_0} = 0.6 \text{ for } Si$$

$$A^x = \left(\frac{m_n^x}{m_0}\right)120 = 72 Amp/cm^2/K^2$$

$$\phi_{Bn} = \frac{2}{3}E_g = 0.75eV$$

$$J_0 = 72x9x10^4 xe^{-750/25}$$

$$= 6x10^{-7} Amp/cm^2$$

Silicon if you take m_n star by m_0 is .6; gallium arsenide it was .067, this is not very close to 1, A star is 72. What was it in gallium arsenide? 8.04 here, it is 72.

Now let us see $phi_{BN,}$ two thirds of E_g I will take, we cannot have better than that. It is about .75 then J_0 is for this case is 72 is A star T square this quantity and e to power this quantity is 6 into 10 to power of minus 7. What you say now? J_0 in gallium arsenide was 10 to power minus 9 because of better phi_{BN} is one; number two A star is smaller. It is A star T square e to power minus phi_{BN} by $V_{T.}$ A star is smaller so J_0 is smaller mainly because of the smaller effective mass, so you get that.

Comparison of characteristics of gallium arsenide you get schottky diodes to do.

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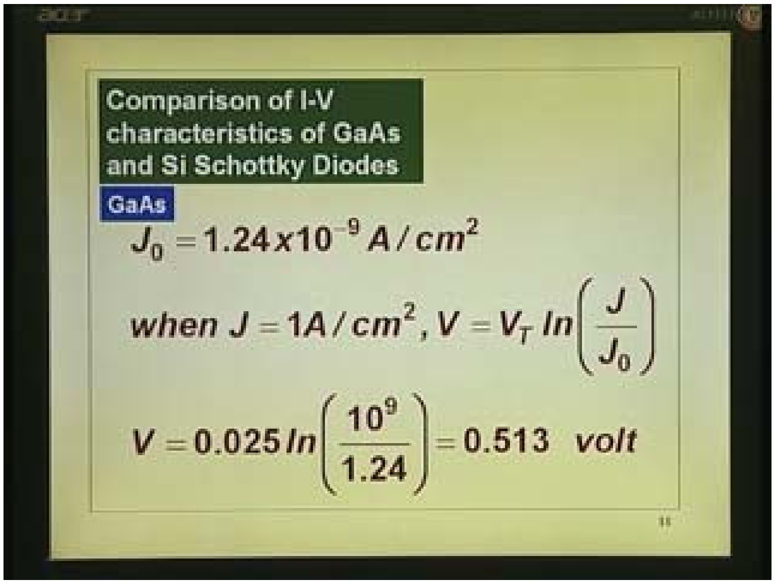

Comparison of I-V characteristics of GaAs and Si Schottky Diodes

GaAs

$$J_0 = 1.24 x 10^{-9} A/cm^2$$

$$\text{when } J = 1A/cm^2, V = V_T \ln\left(\frac{J}{J_0}\right)$$

$$V = 0.025 \ln\left(\frac{10^9}{1.24}\right) = 0.513 \text{ volt}$$

We have just now found out J_0 is 10 to power minus 9 in gallium arsenide, silicon it is 10 to power minus 7, now J_0 is this quantity. Supposing I say J equal to 1 ampere per centimeter square, corresponding voltage across the junction will be V_T long J by J_0 where J is 1 ampere J_0 is that quantity for gallium arsenide it is .513 volts, for silicon it will be, for silicon J_0 is higher therefore V will be smaller .358.

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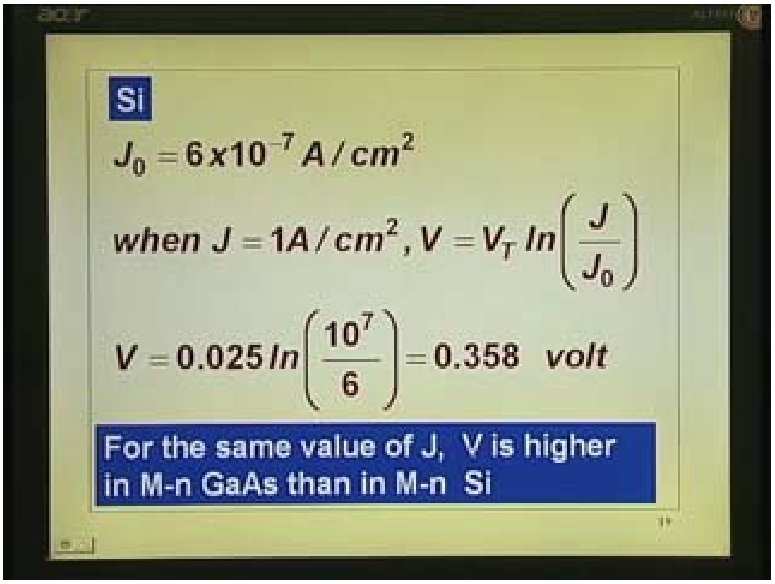

Si

$$J_0 = 6 x 10^{-7} A/cm^2$$

$$\text{when } J = 1A/cm^2, V = V_T \ln\left(\frac{J}{J_0}\right)$$

$$V = 0.025 \ln\left(\frac{10^7}{6}\right) = 0.358 \text{ volt}$$

For the same value of J, V is higher in M-n GaAs than in M-n Si

What you are telling is when you take a silicon schottky barrier and gallium arsenide schottky barrier diode the voltage drop across the gallium arsenide schottky barrier diode for a given current will be larger. In this example of 1 ampere per centimeter square it was .513 this case it is .358. Sum up here.

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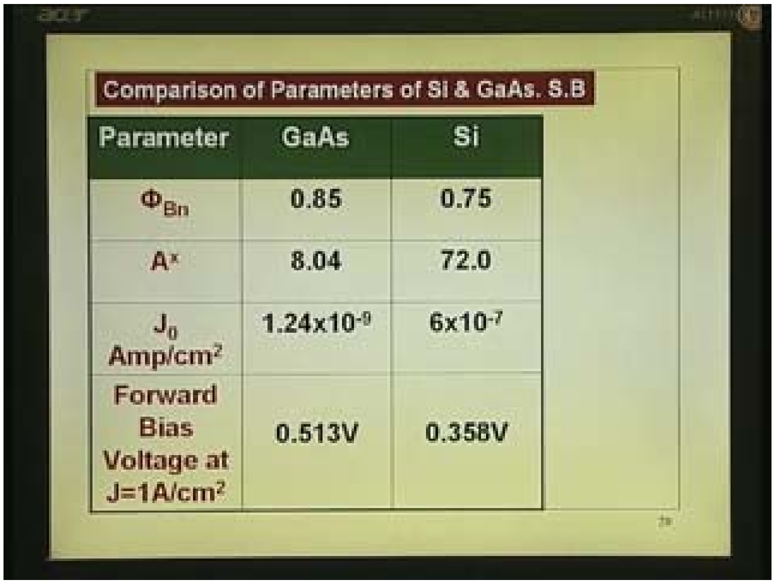

Comparison of Parameters of Si & GaAs. S.B

Parameter	GaAs	Si
Φ_{Bn}	0.85	0.75
A^x	8.04	72.0
J_0 Amp/cm^2	1.24×10^{-9}	6×10^{-7}
Forward Bias Voltage at J=1A/cm^2	0.513V	0.358V

Comparison of gallium arsenide schottky and silicon schottky phi$_{BN}$ is .85 and .75that itself increases this current; A star is 8.04 and 72; J_0 minus 9, minus 7; forward voltage drop at 1 ampere is that quantity. As a result we will get, I will just go one step ahead, only compare these two. These two curves are the I-V characteristics of the schottky barrier.

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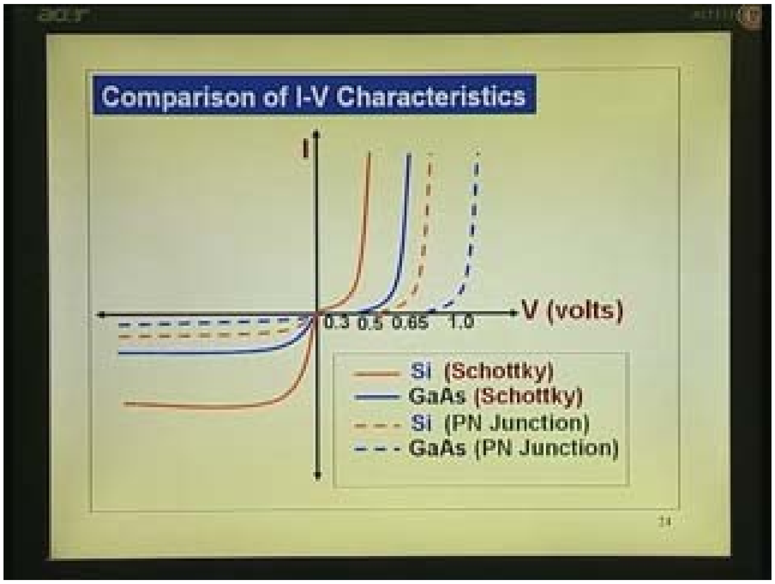

Comparison of I-V Characteristics

Schottky barrier blue that is gallium arsenide about .5 volts for a current of 1 ampere per centimeter square and silicon the forward voltage drop is smaller. Corresponding reverse currents I have shown here, gallium arsenide reverse current is smaller compared to silicon schottky, so these two, we will do the comparisons between the pn junction of gallium arsenide with metal semiconductor contact of gallium arsenide and pn junction of silicon metal semiconductor contact in silicon.

Those things we will compare in the next discussion because right now we have good idea about schottky barrier in gallium arsenide use a cutting voltage of about .5 volts which is close to the cutting voltage of silicon pn junction. It is almost like that.

If I take a semiconductor which has larger bandgap it will get even larger forward voltage drop. So with metal semiconductor contact itself you can get quite close performance as good as pn junction.

With that I think I will close down today, we will continue on this discussion some aspects of this and the non-idealities etc., in the next lecture.