High Speed Devices and Circuits

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Lecture - 19

Causes of Non-Idealities in the Schottky Barrier Diodes I-V Characteristics

We have been discussing the I-V characteristics of schottky barrier diode and when we were doing that we arrived at the ideal characteristics and we have discussed. I will just summarize what we said in last lecture.

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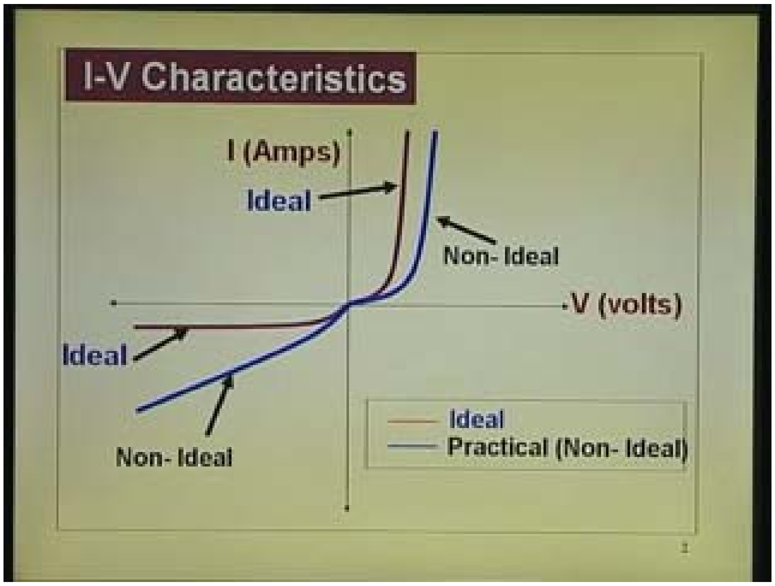

I-V Characteristics

We have seen, or experiments have shown that the I-V characteristics deviate from the ideal characteristics. For example, the reverse current does not saturate, it will keep on increasing. Forward I_0 e to power of, instead of V by Vt, it is V by nVt. That is less increases less rapidly with voltage.

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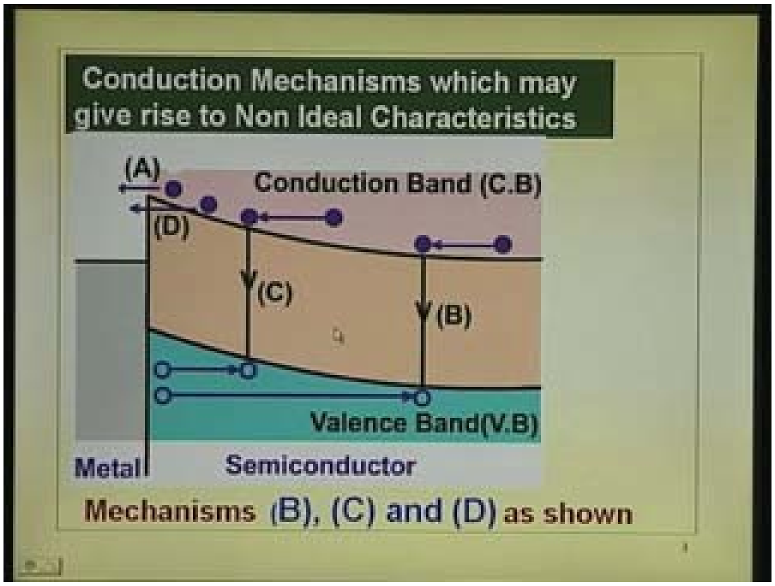

Conduction Mechanisms which may give rise to Non Ideal Characteristics

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

So we just also said, we considered only this current that is the thermionic emission current. B C D is the various terms which were neglected. Out of that, we have seen B and C yesterday, or in previous lecture. That is a hole injection into neutral region and recombination, that we said is not going to matter much, we analyzed it making use of law of the pn junction. Similarly generation recombination current, it is much smaller compared to this particular current, thermionic emission. So we do not have to worry as it is at least one or two hundreds of magnitude smaller in gallium arsenide.

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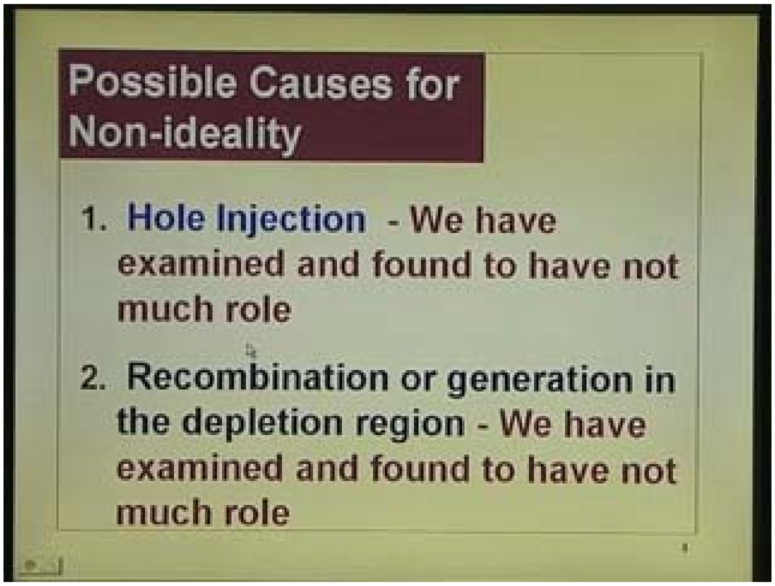

Possible Causes for Non-ideality

1. Hole Injection - We have examined and found to have not much role
2. Recombination or generation in the depletion region - We have examined and found to have not much role

Let us see, the other term that we have put it here (Refer Slide Time: 2:40), which is the quantum mechanical tunneling. These two terms are negligible

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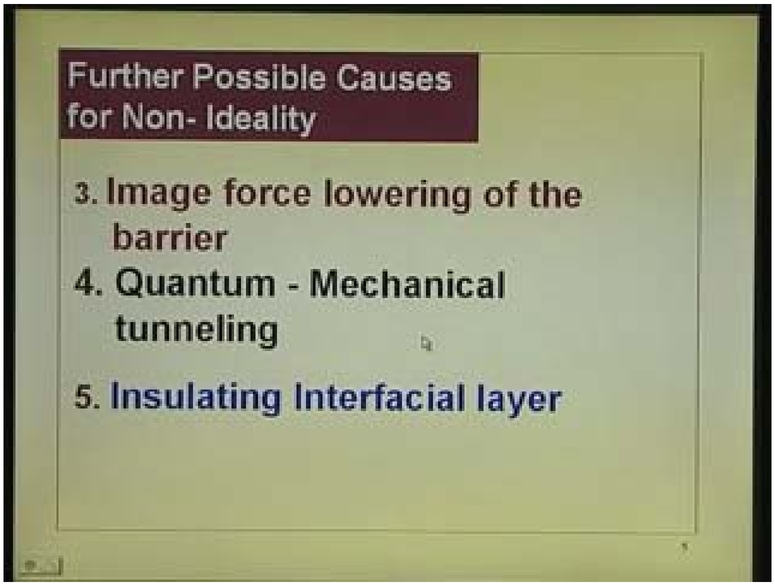

Further Possible Causes for Non- Ideality

3. Image force lowering of the barrier
4. Quantum - Mechanical tunneling
5. Insulating Interfacial layer

Other terms which are there are: image force lowering of the barrier, quantum mechanical tunneling and insulating interfacial layer. These are the three things which we are going to discuss today.

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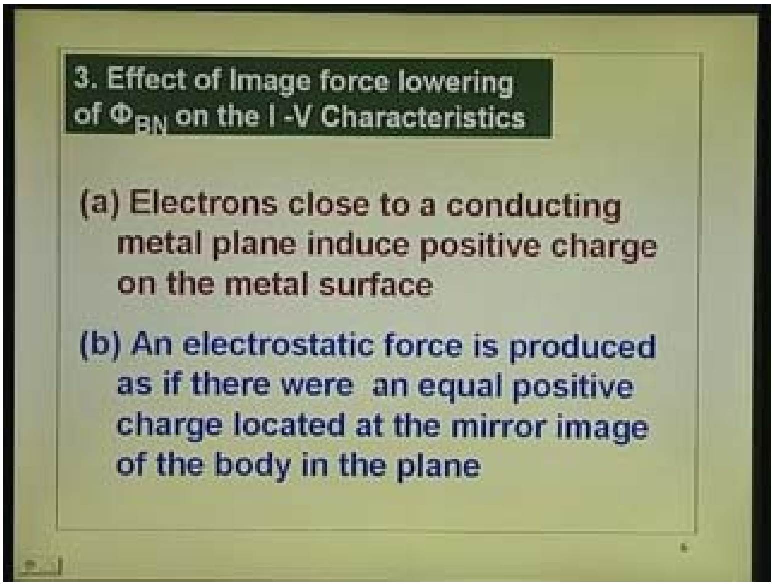

3. Effect of Image force lowering of Φ_{BN} on the I -V Characteristics

(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

Now image force lowering, we have just discussed fairly in detail what it is going to be?

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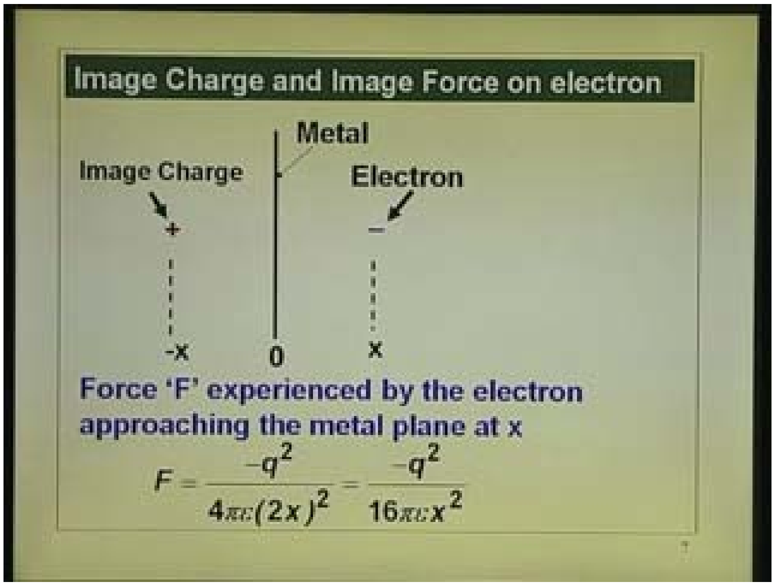

Image Charge and Image Force on electron

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

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

It is due to the negative charge when it comes close to the metal, its mirror image is on the other side. The charges induced on this plane can be the effect of that on this charge can be obtained by considering the image of this charge there, its simplification, it works out very well. Otherwise you have to take… you do not know how the distribution is, but the entire effect can be accommodated by putting the mirror image here. That means actually this charge experience the force, which is actually equal to q square by 16 pi epsilon x squared, where x is the distance.

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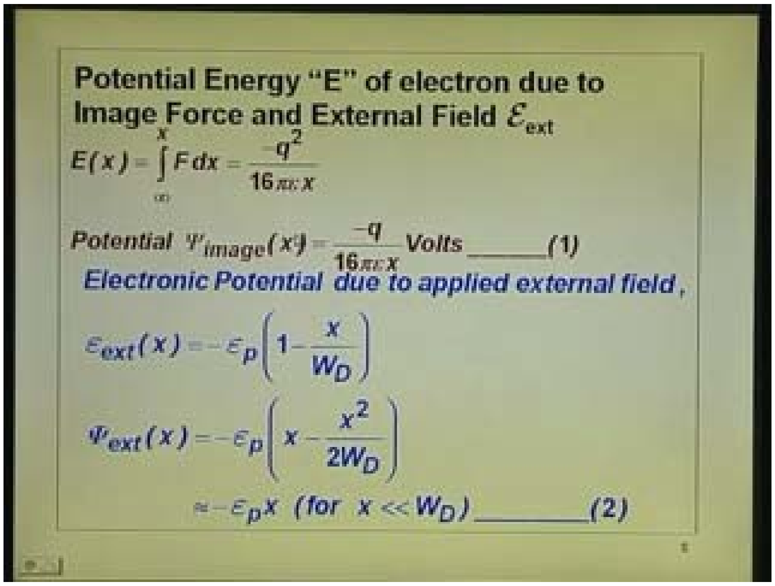

Potential Energy "E" of electron due to Image Force and External Field $\mathcal{E}_{ext}$

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

$$\text{Potential } \Psi_{image}(x) = \frac{-q}{16\pi\varepsilon x} \text{ Volts} \_\_\_\_\_\_ (1)$$

Electronic Potential due to applied external field,

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

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

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

As we go nearer this charge, the energy and the force both of them keep on increasing negatively. That is why energy is integral of that. I am just going through this quickly because we have discussed it yesterday. That is the energy integral of the force. q squared by 4 pi epsilon x, instead of x square. Potential we are talking of the electronic potential that is actually minus. So what we are just trying to point out is, if I move from here to here (Refer Slide Time: 04: 32), the electronic potential is that quantity, that is 16 pi epsilon or epsilon$_0$ into x.

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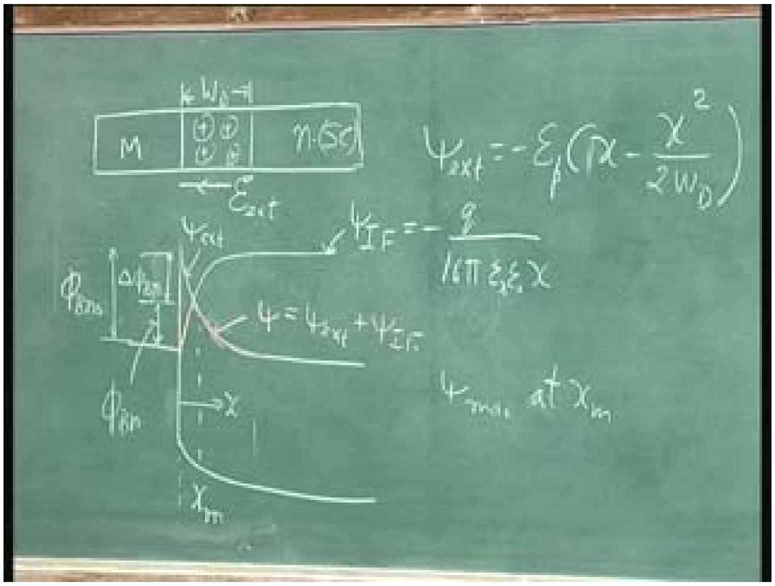

As far as this field is concerned plus there and minus there for this, negative charge and plus charge. So field is in that direction, it moves the energy of the electron lower negative as you go towards the metal surface. That is why we are actually talking of electronic energy and electronic potential. The energy level and electron potential will be following the same path. If energy level is dropping down like that, the electron potential will also drop down like that. These are lower energy for electron. In fact if you recall the 0 energy is there and all other energies are negative. So, that is what we have plotted there.

If you look into that, (Refer Slide Time: 05:25) that is the one which is going down in this fashion. Now in the absence of image force potential, (Refer Slide Time: 05:34) this is the image force potential psi, we usually plot the energy band diagram like this. In fact that is the variation of the electronic potential or variation of electron energy. How to obtain that? You just have the depletion layer there. We call it here as $e_{external}$ because this one is due to its image itself, but this field is due to this depletion layer. If there is no depletion layer, this would have been only the potential. Because of depletion layer present, there is additional external force acting on the electron that is actually given by this. That is electric field $e_{external}$ which is given by e_{peak} into 1 minus x minus by w_D. That is what we put here. That is electric field we call it as $e_{external}$. This is regular depletion field we are talking of. And psi potential is actually integral of that. In fact in my last lecture I just left out this (6:36) but this 2 is there. Now, what we do is, what we trying to find out is, that there are two potentials, that is potential due to this image psi if and the potential due to this depletion layer, which we called as $e_{external}$. The total potential is sum of these two. Now, what I have done here is to simplify matters I just neglected the second term, this term. You can neglect the second term so long as x by w_D is very small compared to 1. We are actually interested in the potential variation just near the boundary.

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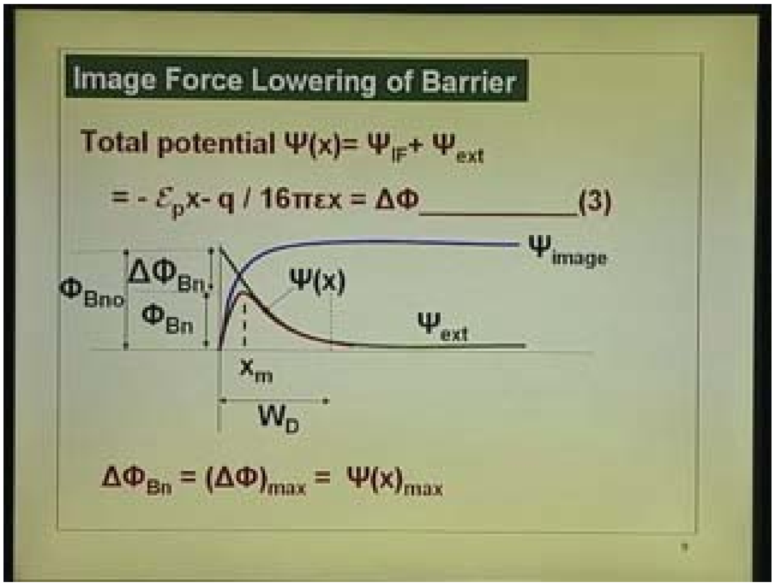

Image Force Lowering of Barrier

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

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

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

Because we are interested in seeing what is the effect of this image force potential and the external potential, add this and this. The sum of the two is given by, if I approximate the external potential by this way (Refer Slide Time: 07:48) e_{peak} into x, then, you have got these two terms. You add up those two, that is, you can call it as delta phi that is the potential with respect to that point or total phi itself, better call it as total potential. The potential is sum of the two. Whatever approximation that we have made here will be true if this x_m is small compared to the total depletion layer width. We will see that is really true. The peak occurs very close to surface in the order of 10 to 15 armstrongs compared to 0.3, 0.4 micron of depletion layer. That is why this approximation is quite good; we are talking just… In this diagram it does not look so, but it is actually very small. What we want to find out is what the total variation potential is? More than that, what we are interested is what the peak value here is? Because after all maybe I can explain here, (Refer Slide Time: 08:58) this potential is varying like that. That is the external potential due to depletion layer. This potential is like this. Total potential is this plus that that is this one. In this portion, suppose you consider this as 0 and this is negative, this follows that and then if you go down here that is 0 and this total potential is 0 here. That is why the variation is like that. To find out this value here, what we do is add up the two and we know that it goes to a maximum differentiate this term with respect to x and when you differentiate with respect to that what you get?

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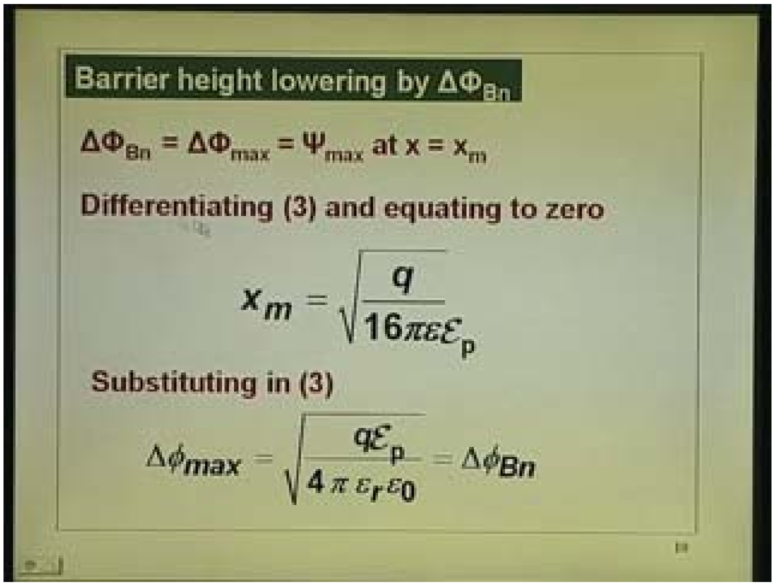

Barrier height lowering by $\Delta\Phi_{Bn}$

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

Differentiating (3) and equating to zero

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

Substituting in (3)

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

You get, x is equal to x is $x_{maximum}$ that is root of that, the simple differentiation. So, this becomes square 1 by x squared, this x goes off. The location of this particular peak electric field is actually given by this quantity. Now once you do that, what you want to find out is, how much is this difference on (Refer Slide Time: 10:12), top to that point, which we call it as delta phi_{Bn}.

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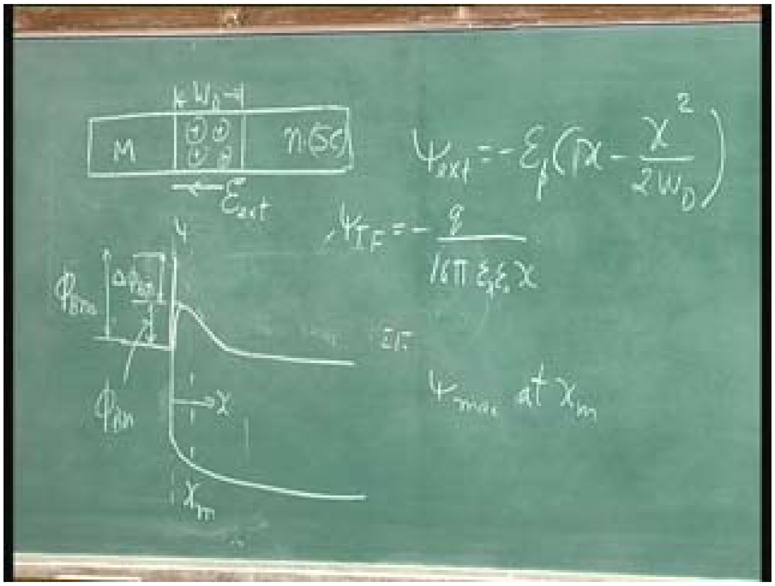

Let me go to the board and show that to you. The actual potential, now instead of being like this it is like this (Refer Slide Time: 10:28); It is like that. So, let me when we draw it slightly better because that is very close by. This entire potential now, instead of being like this, it will be now like this. Now, actually this quantity is delta phi_{Bn}. Why do you call it delta phi_{Bn}? Because, this is the potential barrier which would have been present, but now, because the barrier does not go all the way up to that point it goes only up to this point. As a result, there is a reduction in the phi_{Bn}. This is called the image force lowering effect of the barrier height by that amount. How much is that amount? That is same as this potential. Please remember, the potential we are drawing, taking this as 0 with respect to that how much is that thing. The psi that we put there is the psi with respect to that because that was 0 there and that was psi image force. This is, if I take it as 0 that is the potential. If I find what is the psi value here that straight away gives me delta phi_{Bn}. How do you find psi value their? Add up the two and substitutes that.

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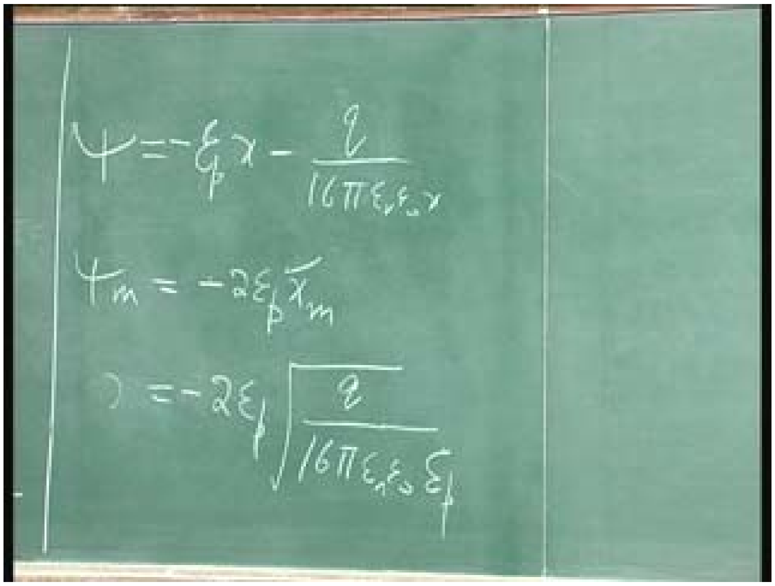

$$\psi = -\mathcal{E}_p x - \frac{q}{16\pi\varepsilon_r\varepsilon_0 x}$$

$$\psi_m = -2\mathcal{E}_p x_m$$

$$= -2\mathcal{E}_p\sqrt{\frac{q}{16\pi\varepsilon_r\varepsilon_0\mathcal{E}_p}}$$

Let me just write that down here. We have got psi is equal to minus e_{peak} into x minus q divided by 16 pi epsilon r $epsilon_0$ into x. We have also seen that… So, $psi_{maximum}$ will be what, when both of them are equal? See, one is coming like this other one coming like that, the peak will correspond to the point and both are equal. That is actually twice e_{peak} into x_m. Substitute value of this quantity we have found out the point at which it is maximum. In fact we can verify that just going through that. That is the value. Substitute for these quantity from the expression for x_m. Let me not right down that, because you already have wrote that. All that I am doing is we are substituting this x_m which we have determined as… by differentiating we have determined as this quantity (Refer Slide Time: 13:15).

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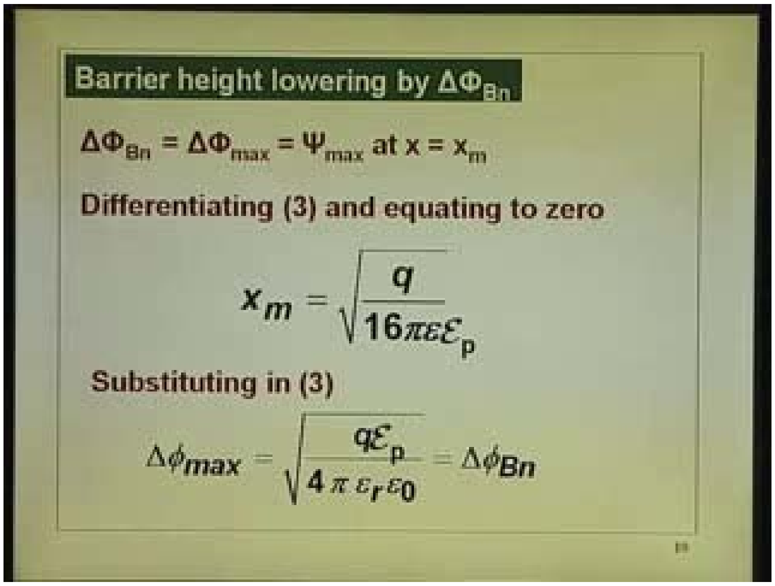

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Differentiating (3) and equating to zero

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

Substituting in (3)

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

So, substitute in that equation phi_{max} is equal to phi c into x_m. So, you do that, all that you have to do is multiply this quantity by $2e_{peak}$. So, 2 goes inside this square root that becomes 4. 4 divided by 16 and that is 4 here. You are multiplying this by e_{peak}, the square root of e_{peak} is their below so, that becomes proportional to e_{peak}. All that we are doing is that. Hope it is alright. What we are doing is (Refer Slide Time: 13:58) x_m that is actually minus $2e_{peak}$ into square root of q divided by 16 pi epsilon_r epsilon_0 into e_{peak}. So this becomes square root of that; this goes inside; this becomes 4. That is how we get that particular term. The key thing to remember here is that this potential I called it as delta $\text{phi}_{maximum}$ that is this quantity. What you have computed is psi; psi is the delta $\text{psi}_{maximum}$. May be unnecessarily I have introduced one more term there just differentiate this related to this barrier. The barrier maximum reduction is delta that; that is delta phi_b the actual barrier is this much. So if the actual barrier is this much, the electrons can go from one end to other end very easily. The current can get affected that what we trying to point out. Let us just take look at the effect of this particular barrier lowering.

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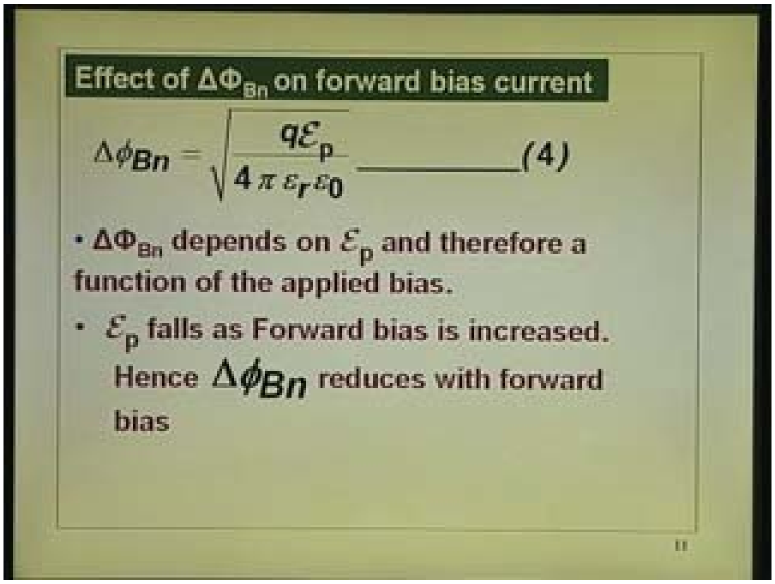

Effect of $\Delta\Phi_{Bn}$ on forward bias current

$$\Delta\phi_{Bn} = \sqrt{\frac{q\mathcal{E}_p}{4\pi\varepsilon_r\varepsilon_0}} \quad \_\_\_\_\_\_\_\_\_\_ (4)$$

- $\Delta\Phi_{Bn}$ depends on $\mathcal{E}_p$ and therefore a function of the applied bias.
- $\mathcal{E}_p$ falls as Forward bias is increased. Hence $\Delta\phi_{Bn}$ reduces with forward bias

The delta phi_{Bn} is a value of phi at x_m, we have determined that is proportional to square root of peak electric field. Now before we go into that, we have derived this by taking the $e_{external}$ is e_{peak} into x. Let us see whether it is valid at x equal to x_m. For that you must find out how much x_m is. Let me just give you some numbers their.

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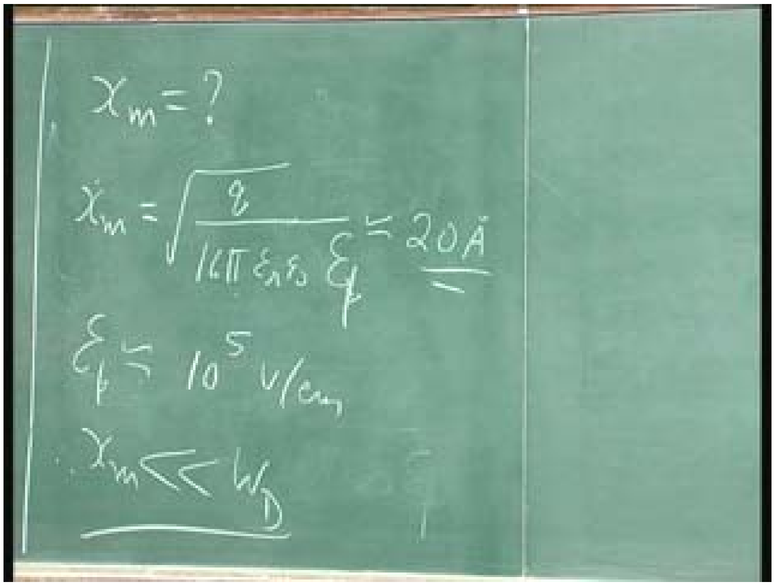

$x_m = ?$

$$x_m = \sqrt{\frac{q}{16\pi\varepsilon_r\varepsilon_0\mathcal{E}_p}} \simeq \underline{20\,Å}$$

$\mathcal{E}_p \simeq 10^5$ V/cm

$\underline{x_m << W_D}$

How much is the value? Say let us just take this, x_m is equal to square root of q divided by 16 pi epsilon_r into $\text{epsolin}_0 e_{peak}$. All that we have to prove is what is the value of e_{peak}

in the depletion layer? See e_{peak} corresponds to that, this peak (Refer Slide Time: 16:41) field that will be roughly 10 to power of 5 volts per centimeter or 10 volts per microns. If you go to 20 volts per microns you may have breakdown. That is why giving that number less than that, but close to that; 10 volts per micron that is 10 to power 5 volts per centimeter. You substitute on to this with epsilon taken as 12.8, 8.8 etc., this is approximately about let us say 20 armstrongs. I can just plug in and see numbers. This is about 20 armstrongs; 2 nanometers. What I am telling is because of that, this peak occurs very close to surface; this x_m is very small compared to W_D. So our assumption that, in the region up to this point (Refer Slide Time: 17:56), this potential is linear is very much valid. By deriving at this expression for delta phi_{Bn}, we took $e_{external}$ is equal to e_{peak} into x. We are talking of that is only up to x equal to x_m. x_m is just very small compared to depletion layer, so that is valid. We are justified in doing that. You are not assuming that the electric field is constant really but we have actually seen that potential is very linearly up to that point. Now other thing that we would like to see is how much will be this barrier lowering? We should be worrying about that. After all we have thrown out other numbers with the hole injection etc, because they were all not comparable to J_0 etc.

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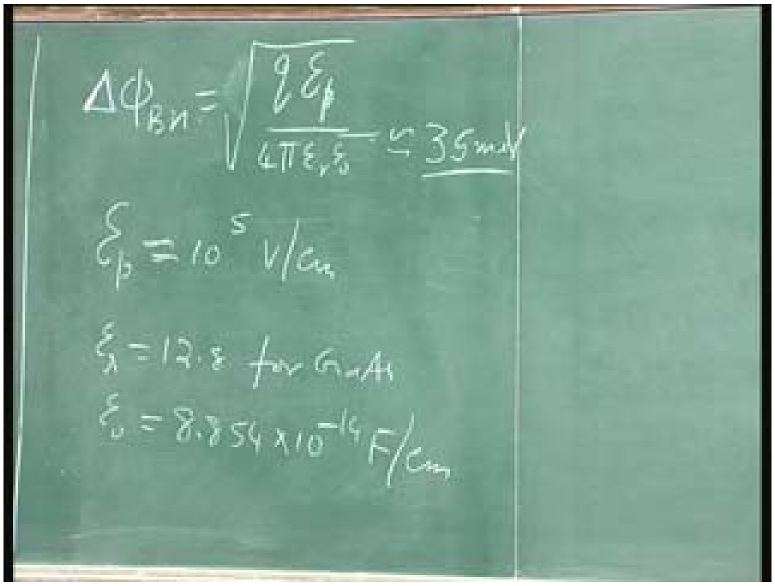

$$\Delta\phi_{Bn} = \sqrt{\frac{q\mathcal{E}_p}{4\pi\epsilon_r\epsilon_0}} \simeq \underline{35\,mV}$$

$$\mathcal{E}_p = 10^5 \ V/cm$$

$$\epsilon_r = 12.8 \text{ for GaAs}$$

$$\epsilon_0 = 8.854\times10^{-14} \ F/cm$$

Let us take a look at how much delta phi_{Bn} is in order of magnitude? delta phi_{Bn} is actually equal to root of q e_{peak} divided by 4 pi $epsilon_r$ $epsilon_0$; this is right here (Refer

S;lide Time: 19:25). Delta phi_{Bn} is that number. Now what you do is substitute for this e_{peak}. It will be about 10 to power of 5 volts per centimeter e_{peak} you have taken that. A depletion layer width is something like 0.3 micron for about 10 to power of 16 doping. For this situation, this turns out to be substituting all these value something like 10 to power of 5 volts per centimeter. If I take substitute for $\mathrm{epsilon}_r$ is 12.8 for gallium arsenide; 12 for silicon; $\mathrm{epsilon}_0$ is 8.854 into 10 to power of minus 14 farads per centimeter. Substitute all that you get in this example about 35 milli electron volts. That is about 35 milli electron volts. That is not negligible because after all the J_0 value that we talk off is proportional to e to power of minus phi_{Bn} by V_t. So if that were phi_{Bn0} and if it is 700 milli volts, this is 35 milli volts. We will say 35 milli volts are small compared to 700 milli volts. But if you take e to the power of that quantity, the currents are proportional to e to power of minus phi_{Bn} by Vt. If it is 25 milli volts reduction, it is e to power 1 which is 2.7. So the current is different by magnitude of 2.7 for 25 milli volts. So even if we are talking about this 10 milli volts change, that J_0 will keep on changing. Because it is exponentially dependent on phi_{Bn}, so any change in phi_{Bn} is reflected on J_0.

So now whatever changes you see in the reverse bias and forward bias are manifestations of delta phi_{Bn} that is effectively J_0 changing. So what is done is let us see how it affects in the case of forward bias? In the forward bias case what happens to delta phi_{Bn}? delta phi_{Bn} depends upon e_{peak}; if delta phi_{Bn} increases what about the phi_{Bn}? Go back to this diagram and see, if this increases phi_{Bn} falls. In forward bias case what happens to e_{peak}, as I keep on increasing the forward bias voltage what happens to external state? It reduces. When you forward bias the depletion layer collapses. So peak electric field falls. When you forward bias and if it falls, delta phi_{Bn} reduces; if e_{peak} falls delta phi_{Bn} reduces. If that happens phi_{Bn} increases. So starting from 0 bias, we take 0 bias as some phi_{Bn}. Let us take the J_0 corresponding to that phi_{Bn}. From there it will either go up or go down.

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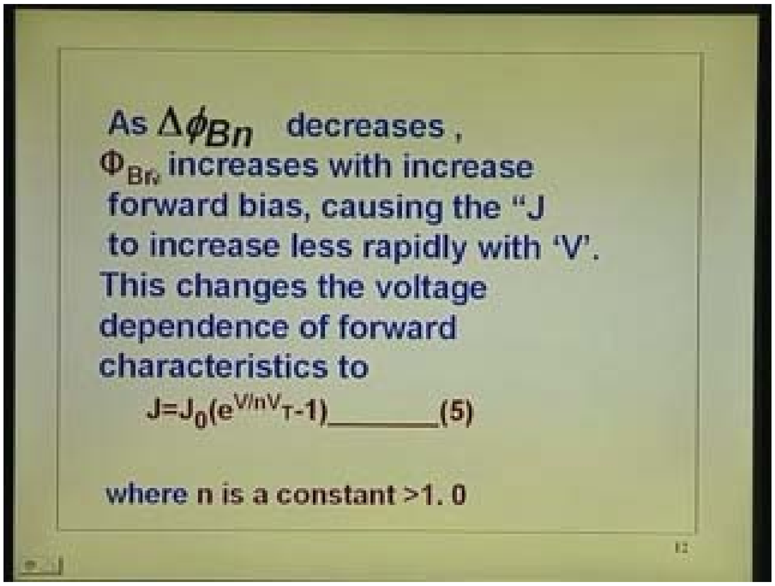

As $\Delta\phi_{Bn}$ decreases ,
Φ_{Bn} increases with increase forward bias, causing the "J to increase less rapidly with 'V'. This changes the voltage dependence of forward characteristics to

$J=J_0(e^{V/nV_T}-1)$_______(5)

where n is a constant >1. 0

What we are telling is even at 0 bias the value that you have is not the same thing, it is different. From that point onwards and it will go up or down depending upon whether you have forward biasing or reverse biasing. If forward bias electric field falls, therefore this falls so that goes up and phi$_{Bn}$ increases. So if phi$_{Bn}$ increases what happens to J_0? J_0 reduces. Now, usually we write the expression for the forward characteristics as J is equal to J_0 e to power V by V_T minus 1. Now what is done here is to take into account the entire characteristics. You keep J_0 constant. Whatever changes that takes places is J_0 you absorb into that term. When you forward bias, the value of J_0 actually what happens? It decreases because barrier rate increases. That decrease in J_0, if you put n is equal to 1 and you have to keep on changing J_0 and that decrease in J_0 will reflect in J_0 increasing as fast as e to power of V by V_T. So if I say J_0 is changing, it is reducing. The implication is current does not increase as much as it would be.

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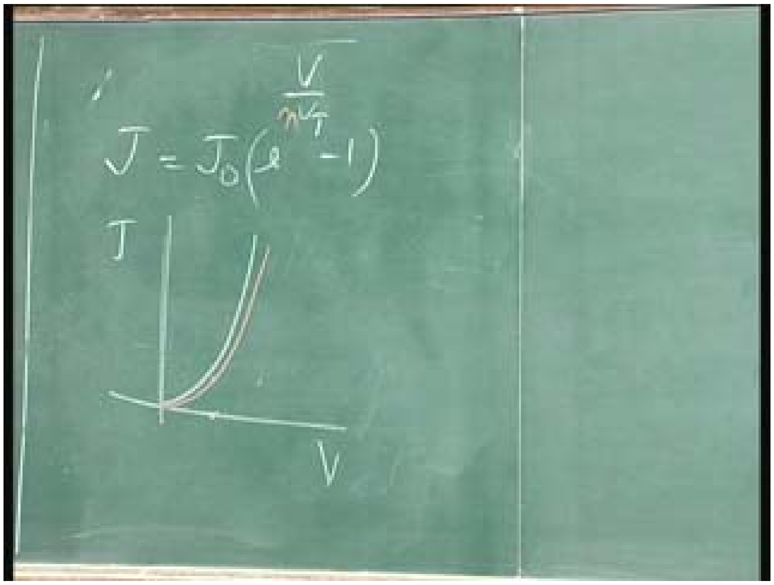

See for example let me remove that temporarily. If I write J is equal to J_0 e to the power of V by V_T minus 1, I get a characteristic which is varying like this and J versus V, if J_0 were constant but if J_0 is going on falling as we increase the forward bias because peak electric field is falling. If J_0 is falling slightly, for a given voltage, this current will be lower. So, you will get actually the current which is slightly lower all through cases. Strictly it is slightly deviated from this particular curve or slightly from ideal exponential curve value. So this reduction is taken into account and you assume that this is constant, absorb that into that factor n (Refer Slide Time: 25:54), this is sort of fur gee. You are just cooking up a number n there, which will be greater than 1 and so current will increase slower than what it would be from the ideal. The entire effect is due to J_0 falling. But you keep J_0 constant corresponding to 0 bias and then say that there is a n which is larger than 1 that is the non-ideality. This term is quite definitely more than 1 because the delta phi_{Bn} from the 0 bias case is always 5 milli volts, 10 milli volts of that order and that will go on changing. It may vary from 1 milli volt, 2 milli volt, 3 milli volt, 4 milli volts like that, but it affects totally. What about reverse bias? It will show up much more.

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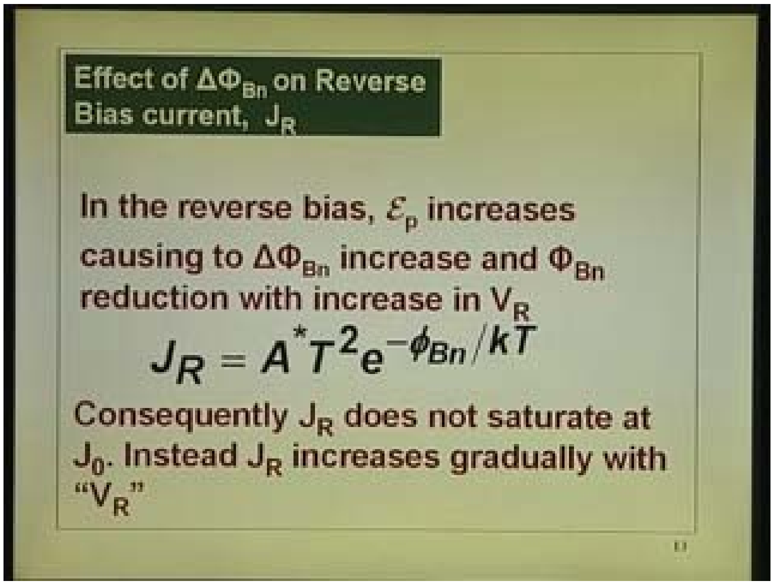

Effect of $\Delta\Phi_{Bn}$ on Reverse Bias current, J_R

In the reverse bias, $\mathcal{E}_p$ increases causing to $\Delta\Phi_{Bn}$ increase and Φ_{Bn} reduction with increase in V_R

$$J_R = A^* T^2 e^{-\phi_{Bn}/kT}$$

Consequently J_R does not saturate at J_0. Instead J_R increases gradually with "V_R"

Reverse bias and what about the peak electric field, it increases. The depletion widens, it increases and if it increases we can see from here (Refer Slide Time: 26:57) delta phi_{Bn} actually increases. If delta phi_{Bn} increases, phi_{Bn} falls. So as we go on keeping reverse bias, the delta phi_{Bn} goes on increasing and phi_{Bn} goes on falling. So this keeps on falling (Refer Slide Time: 27:10). It is e to power minus and so if this keeps on falling, J_R keeps on increasing. This will be much more dominant in this case because if you have a 25 milli volts change in the phi_{Bn}, which is quite possible because the peak fields are more increasing quite a bit, where reverse current can be doubled. That is why we get the reverse saturation current, not saturating, but keeping on increasing. So both the I-V characteristics in the forward direction and also in the reverse direction instead of being like this, this curve (Refer Slide Time: 27:55) will keep on increasing not due to generation recombination but due to image force lowering effect of the barrier. So barrier height keeps on falling. Now we are in trouble if you have devices made in certain portion of device, if there are large fields reverse current will dominate quite a bit. It will leak through those portions because of this image force lowering. Now let us see what other thing is there on here. I hope this explains as a dominant phenomenon for deviation from ideality.

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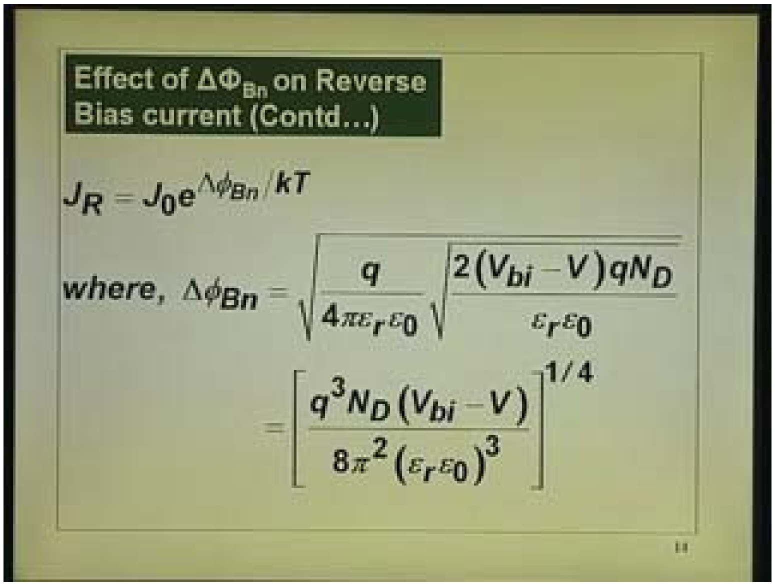

Effect of $\Delta\Phi_{Bn}$ on Reverse Bias current (Contd…)

$$J_R = J_0 e^{\Delta\phi_{Bn}/kT}$$

where, $$\Delta\phi_{Bn} = \sqrt{\frac{q}{4\pi\varepsilon_r\varepsilon_0}\sqrt{\frac{2(V_{bi}-V)qN_D}{\varepsilon_r\varepsilon_0}}}$$

$$= \left[\frac{q^3 N_D (V_{bi}-V)}{8\pi^2(\varepsilon_r\varepsilon_0)^3}\right]^{1/4}$$

This is just a formula which I have just put here. All that we have done here is delta phi$_{Bn}$ is q by this quantity and this whole thing within a square root sign is peak electric field. This peak electric field is let me just put down here. This is for computing numbers that is all.

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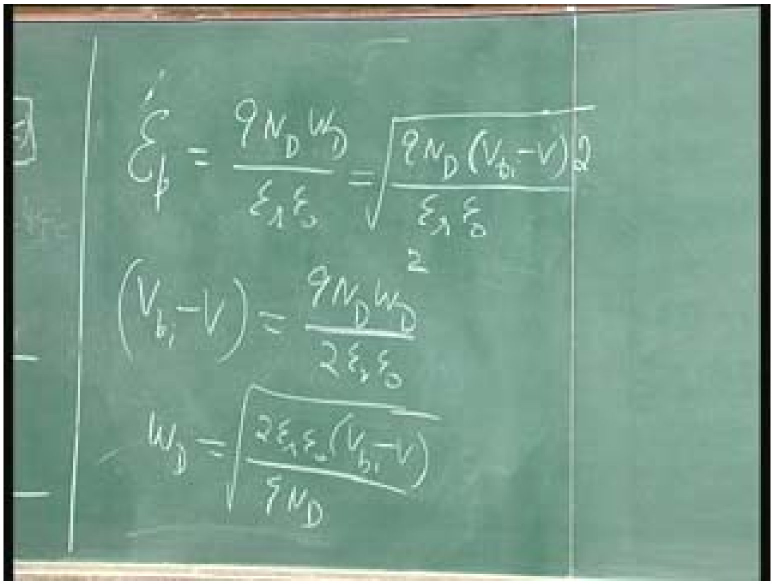

$$\mathcal{E}_p = \frac{qN_DW_D}{\varepsilon_r\varepsilon_0} = \sqrt{\frac{qN_D(V_{bi}-V)2}{\varepsilon_r\varepsilon_0}}$$

$$(V_{bi}-V) = \frac{qN_DW_D^2}{2\varepsilon_r\varepsilon_0}$$

$$W_D = \sqrt{\frac{2\varepsilon_r\varepsilon_0(V_{bi}-V)}{qN_D}}$$

This peak electric field is q N_D W_D divide by epsilon$_r$ epsilon$_0$. V_{bi} minus V in the forward bias case, this is negative. If V is reverse bias, this is adding; that is actually equal to q N_D W_D square by 2 epsilon_r epsilon_0. What we do is substitute that from here. Therefore this is equal to what? So,W_D is the standard formula (Refer Slide Time: 29:50). That is W_D. When you put it here, e_{peak} becomes square root of, substitute from here to there, it becomes equal to root of, this and this cancle there, so q N_D, into V_{bi} minus V divided by epsilon_r epsilon_0 into there is a two term. That term that is 2. So all that I have done is whatever I have written on the board there that is a square root term. Delta phi_{Bn} is square root of q by this quantity into e_{peak} that e_{peak} is this quantity and so the formula looks big but it is actually a simple formula where we have substituted for peak electric field from the well-known law of junction. Then when we will do that together it is a square root of 2 to the power 4 and all that comes because this is square root of to the power of 4.

So delta phi_{Bn} is actually a function of V to the power of 1 by 4th and it does not vary directly as V not as square root of V but it is 1 by 4th total potential. If it is forward biased V_{bi} minus V and V is minus $V_{R,}$ V_{bi} plus V_R that keeps on increasing. So, from here it is very evident that, delta phi_{Bn} will keep on increasing if V is minus V_r, if V is forward biased, this quantity goes on decreasing, delta phi_{Bn} goes on decreasing. Decrease of course will be small in the forward bias case. The impact of will not be too much. So you will get of ideality factor 1 you may get 1.05, 1.06 that is all we get. We are making so much fuss about that but you really have to make fuss about it in the reverse bias, because that current will shoot up. In fact we have seen when you do not take care of some of these things when you make devises you get a schottky barrier which is extremely leaky.

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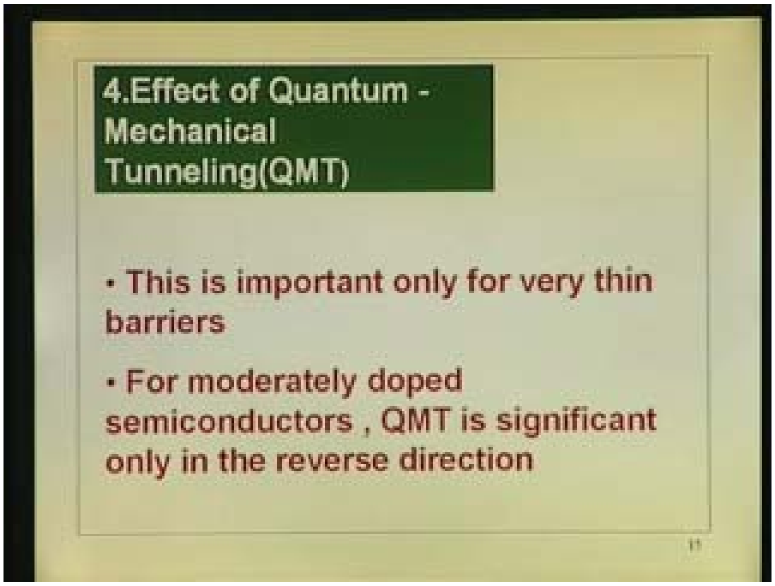

4.Effect of Quantum - Mechanical Tunneling(QMT)

- This is important only for very thin barriers
- For moderately doped semiconductors , QMT is significant only in the reverse direction

So now let us take one more phenomena because these two actually, the image force lowering effect and the quantum mechanical tunneling effect join hands together to spoil the reverse characteristics. Now if you recall what is this quantum mechanical tunneling? This is the fourth phenomena that we are discussing now, the causes for ideality.

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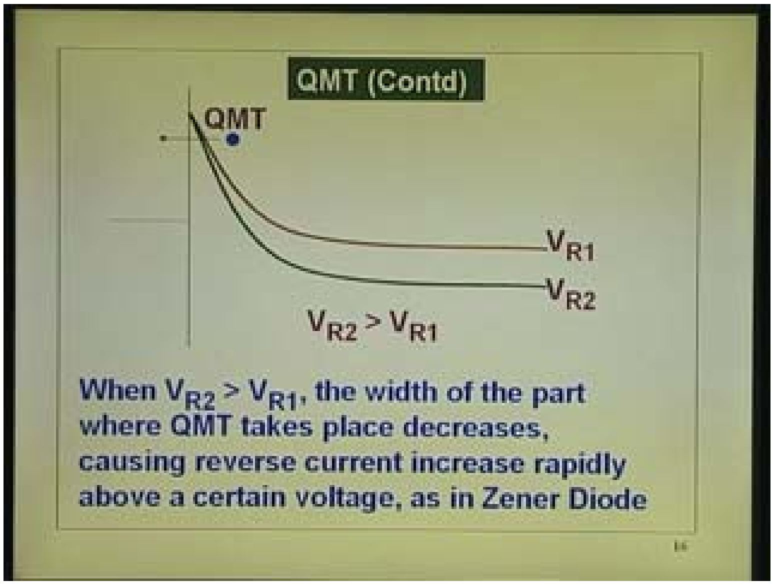

QMT (Contd)

When $V_{R2} > V_{R1}$, the width of the part where QMT takes place decreases, causing reverse current increase rapidly above a certain voltage, as in Zener Diode

In fact by now you must have understood that the non-ideality is more dominating in the reverse direction than in the forward. Forward, there is a factor n coming up and it is slightly more than 1. It will not be 1, 2, 3 and all that is just 1.05, 1.06 of that order because of these effects. Bu it can kill if you do not take care of those peak electric fields. If there is field crowding somewhere, in the junction region, if there is any crowding that e_{peak} will go up, the crowding effect. That e_{peak} goes up; the reverse current will get affected drastically because barrier height will be reduced drastically. After all, barrier height will get reduced more and more if the field is higher. So any field crowding effect or concentration of field will reduce the barrier height in the reverse bias direction and it will increase the leakage current drastically.

Similarly this quantum mechanical tunneling, this is also dominant mostly in the reverse bias. This is due to the electron which is crossing this barrier, where it is thin. If you take the barrier, if it is thin here goes on away from the junction, the barrier is becoming thicker and thicker. In this portion if the electron has energy here, in fact there are a lot of electrons which have energy at this portion from here to up there are electrons occupying. So, at this energy there is sufficient number of electrons. Some of them can cross here because of tunneling effect. This is quantum mechanical tunneling in the sense, there is a probability that good chance that electrons can cross that. I am not getting into those quantum physics but that is what happens.

Now the width of this barrier depends upon the electric field. If the electric field is large, this will vary steeply. The slope of this gives the electric field. Between these two curves, this is at thermal equilibrium or forward bias; whereas, the second curve is at reverse bias. So when the reverse bias is there, the width of the barrier becomes smaller. So chance of tunneling is more if there is more reverse bias or the chance of reverse bias is more, if the peak electric field is more. If the electric field is more this is steeper. So whatever effect which makes the electric field more will decrease the barrier width there and if it decreases the barrier width there, you will have reduction over there. Let us just take a look at that is that. Is the point clear?

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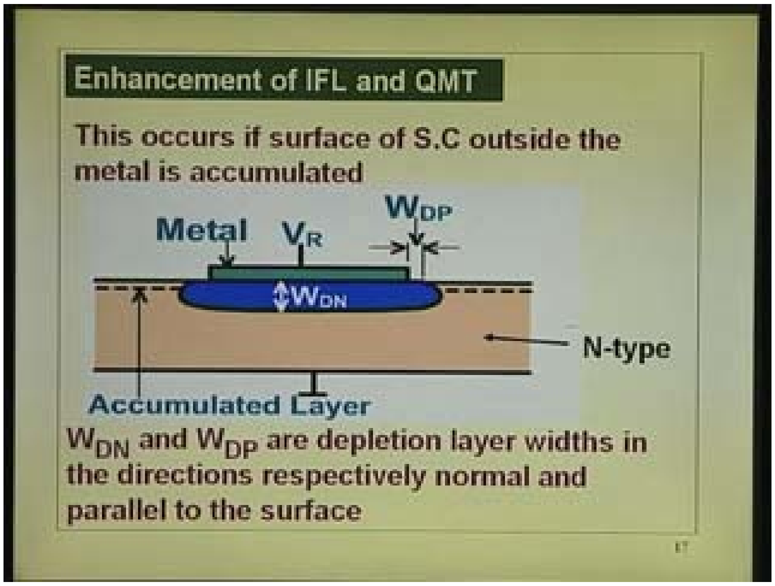

Enhancement of IFL and QMT

This occurs if surface of S.C outside the metal is accumulated

W_{DN} and W_{DP} are depletion layer widths in the directions respectively normal and parallel to the surface

Finally, what we are telling here is, let us get down to the practical things now, so both the effects together will effect if they join hands. Quantum mechanical tunneling is dominant more and more when the field is high. Image force lowering will become more and more if the electric field is high. So both of them become more and more when electric field is high and definitely it is going to affect the reverse bias condition.

Let us look at the junction which is made like that. Particularly, if you take a n type material and this shaded region here, that is the depletion layer. In this portion where the metal is put directly below, in that portion there is a depletion layer which is flat. Now, when you go to the edge, there is a curvature and the depletion layer width on edge is smaller compared to depletion layer width here. It is much more so if there is an accumulation layer here. What I put here is some accumulation layer here, which can be present. There can be accumulation layer that is n becoming n plus there, if there are some positive charges on the surface. It can be contamination or even if you have some oxide there, it can give rise to positive charges but whether the positive charge is there or not. That is, whether the accumulation layer is there or not, the depletion layer crowding effect is there. Let me just draw that once here just to make it more emphatic.

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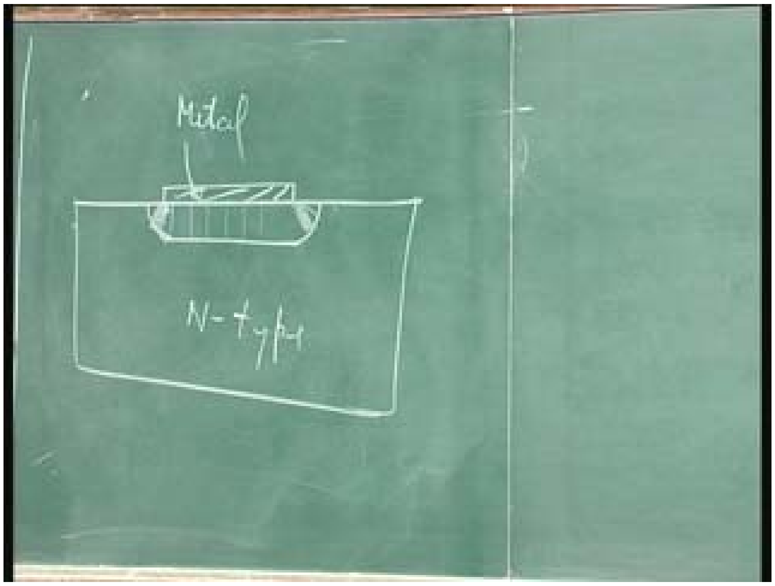

What I am doing is, I have this n type semiconductor on which I just put this metal; that is a metal here, which forms a schottky barrier. What we are talking of now is the depletion layer here will be practically flat, if this width were going like this, then it would have not been that much of a problem but there will be crowding here. Because field lines will all is like this in this portion; whereas, from here, there will be need time crowding there; whether you have an n accumulation layer or not there will be crowding effect here.

So now what we are telling is just like any power device we usually see that wherever junction curvature is there you will get the field crowding. Instead of junction, you have an abrupt ending here. As a result, there will be crowding effect here, field crowding. The moment you have field crowding here what happens? E_{peak} is high there. When e_{peak} is high, both the effects come into picture, the quantum mechanical tunneling due to that extra current and image force lowering is more due to that J_0 becoming high. Both of them join hands together to increase the current here. So if you make a device like this, just put a metal on silicon and make a schottky barrier you end up with the characteristics like this. Because of this crowding, you end up with a characteristic which is very bad.

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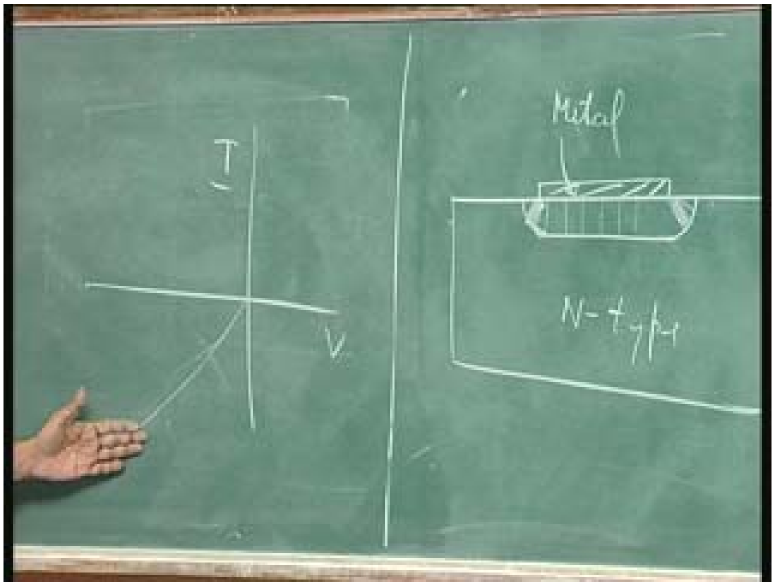

I-V will be something like that. It is a very highly leaky device, so you would not like to see it or you would not like to show it to anybody. That is the state of affairs. In fact I remember when I made my first schottky. I did it like that. After looking into the theory of this what we realized is, you must cut down the field there. If you cut down that field somehow near the edge of the depletion layer you can bring this back into this. One of the methods that are used is shown here.

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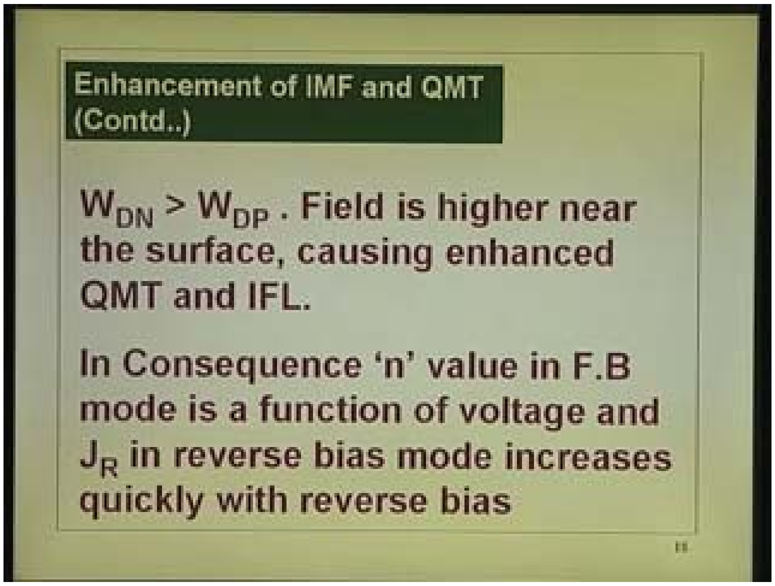

Enhancement of IMF and QMT (Contd..)

$W_{DN} > W_{DP}$. Field is higher near the surface, causing enhanced QMT and IFL.

In Consequence ‘n’ value in F.B mode is a function of voltage and J_R in reverse bias mode increases quickly with reverse bias

This is all what I have been explaining that is W_{DN} here in normal direction is smaller compared to this depletion layer width W_{DP} (Refer Slide Time: 41:34) all that is bringing in the crowding effect. So, I said here W_{DN} field is higher near the surface causing enhanced quantum mechanical tunneling and image force lowering effect. In consequence n value in a forward bias mode is function of voltage and reverse current in the reverse bias mode, J_R or I_R keeps on increasing that is the curve we have shown there.

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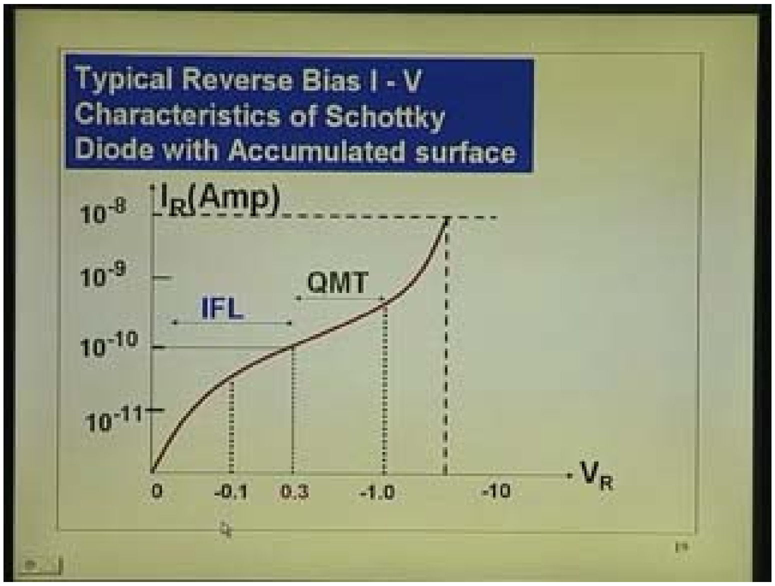

Typical Reverse Bias I - V Characteristics of Schottky Diode with Accumulated surface

This is off course a typical curve that we get. What I have plotted here on the board (Refer Slide Time: 42:08) is shown here in typical devices that people have seen. You can see in this portion the current keeps on increasing, initial to the image force lowering dominant. But when you go to larger values of the electric field, larger reverse bias and the quantum mechanical tunneling takes over. Virtually, it looks like a breakdown like in zener diode that is what happening, it is tunneling. So this portion is quantum mechanical tunneling; this portion is image force lowering effect. So both together is very bad news, in the sense, you get a poor diode.

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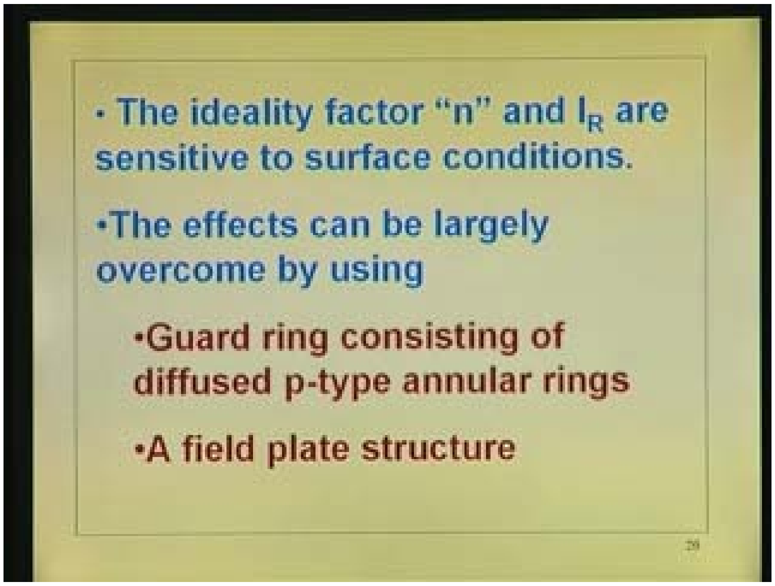

- The ideality factor “n” and I_R are sensitive to surface conditions.
- The effects can be largely overcome by using
  - Guard ring consisting of diffused p-type annular rings
  - A field plate structure

How to overcome that? The ideality factor n is bringing closer to 1. You do not have to worry so much about the ideality factor, so what if it is just 1.01, 1.02 but what you will be more concerned will be reverse current. They can be overcome by two typical methods which are used in practice are: one is actually the guard ring, consisting of a p plus layer put around that; other one is the field plate. Both of them reduce the field kept in that portion. Both of them try to reduce the field here because that is the one which is increasing and it is a cause of increase in the reverse current due to barrier height lowering and due to quantum mechanical tunneling, which are due to the thick electric field increase.

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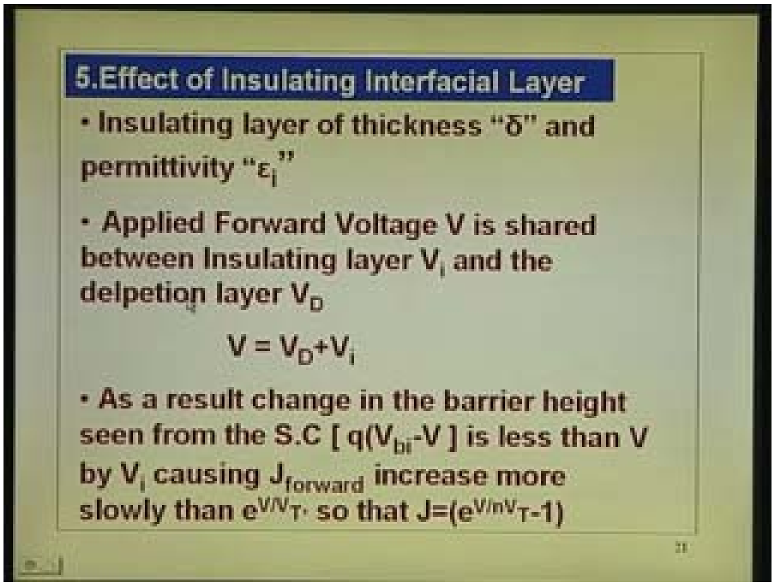

5.Effect of Insulating Interfacial Layer

- Insulating layer of thickness "δ" and permittivity "ε_i"
- Applied Forward Voltage V is shared between Insulating layer V_i and the delpetion layer V_D

$$V = V_D+V_i$$

- As a result change in the barrier height seen from the S.C [$q(V_{bi}-V$] is less than V by V_i causing $J_{forward}$ increase more slowly than e^{V/V_T}, so that $J=(e^{V/nV_T}-1)$

I will just skip this for the time being. Let us come back to this afterwards. That is the fifth phenomena which has some effect in the forward characteristics not in the reverse.

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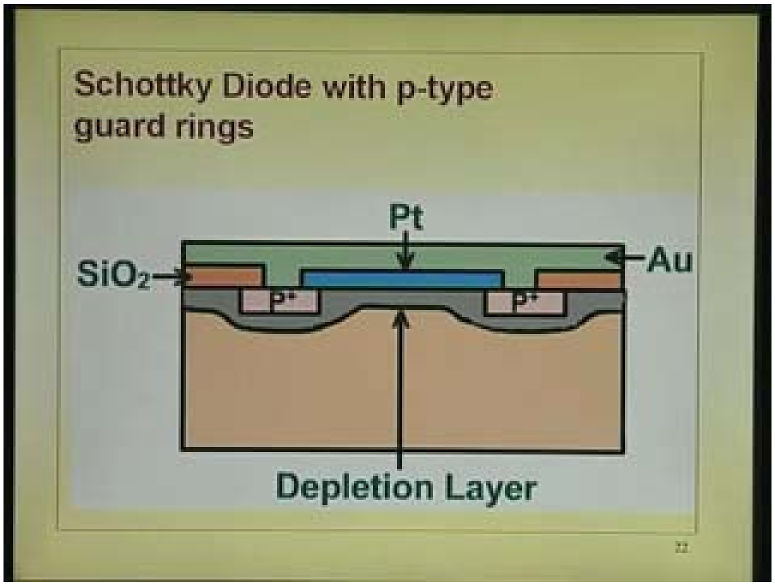

Schottky Diode with p-type guard rings

This is the p-type guard ring or p plus guard ring. You can see the plot here shows the metal here; this is the oxide; this is the metal put over top of that and schottky is only here. This is actually a schottky which is shorting and the junction is shorted out here through this hole. Now how does it help? As far as this diode is concerned, I will just draw that on the board to make a bit clearer.

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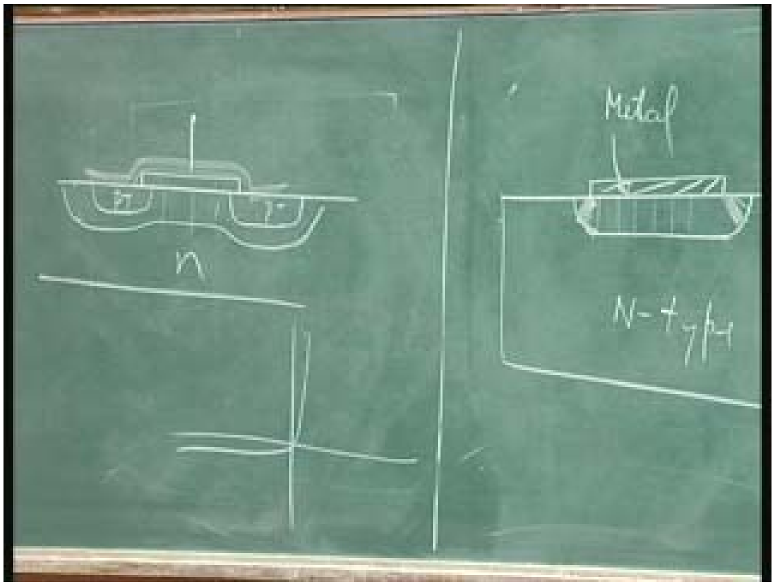

What you do is that the depletion layer is here, and I want to remove the crowding effect and so just put this adjacent to that near p plus guard ring and both are connected together. If you see the diagram, both are shorted together. When I apply voltage here, the depletion layer is formed here. In the absence of this, it would have crowded down like this. There would have been crowding effect. Now there is no crowing effect in this portion and depletion layer moves like that. The depletion layer actually spreads like that.

As far as schottky barrier is concerned, it is being parallel and there is no crowding. All the field lines are vertical. As far as schottky barrier is concerned there is no change in the peak electric field, everywhere it is same thing governed by the one dimensional law. You do not have the increase in the reverse current in that portion, in the schottky diode portion. You will say there is crowding effect coming up here, but now the crowing effect is in the pn junction. The crowing effect in the pn junction; the leakage currents in pn junction are much smaller than that of schottky diode. So you have shifted the crowding effect from the schottky barrier to the pn junction. In the pn junction, even if the field is higher, leakage currents are much smaller than that. Here what we have done is, shifted the crowding effect from the schottky to the pn junction. The current in the pn junction even when its peak electric field is higher is much lower than that of schottky. When you do that you get characteristics which are close to ideal flat. We have seen this. This is a real hard truth about this is the leakage here is what was like that, due to leakage there has shifted up there. Other method which is popular is… Team is to prevent the crowding taking place whatever be the force.

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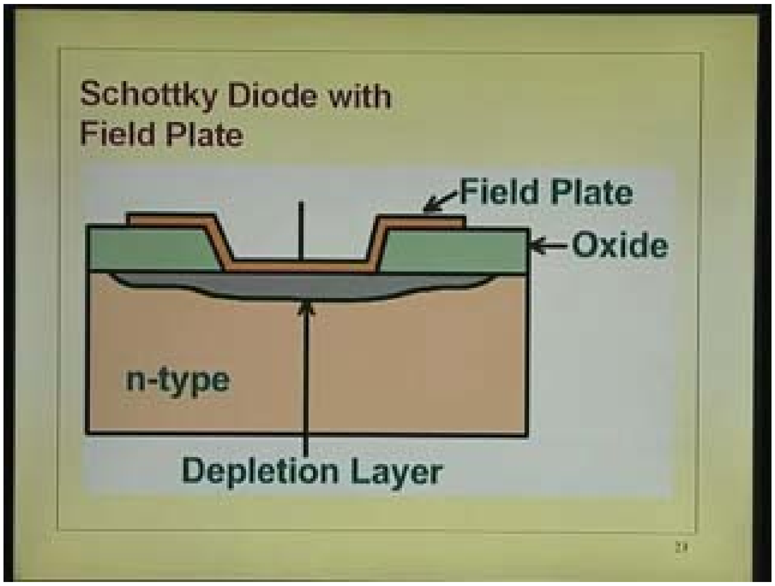

Schottky Diode with Field Plate

This is the field plate structure. If I terminate it here, I would have had the crowding here. Now what I do is, take the metal over the oxide. See you have got a metal here and you have got the oxide and this is the semiconductor. Now, because it is going over the oxide, this portion where it would get crowding here, that voltage gets shared between the oxide and semiconductor. If you see here very carefully, the depletion layer width is wide here and it becomes narrower here like that. I will just draw that here for clarity further.

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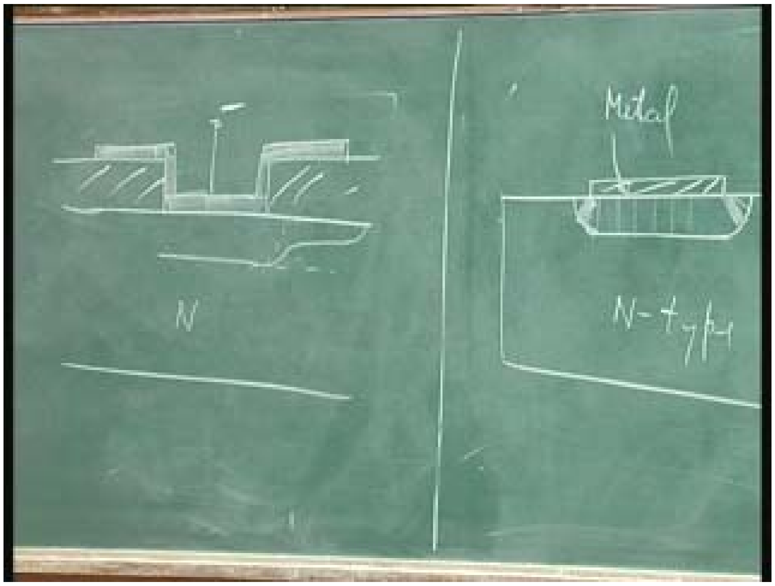

You do not do anything here; all that you do is having an oxide over which this metal will go. So this is N-type region. So that is the metal region. This type of thing people do with splits in power devices where you cut, where ever there is crowding. If crowding is there, take the metal over the oxide. Now when I apply voltage here, reverse bias, depletion layer will be here like this because the total voltage drops across the silicon; whereas, if you go to this side, metal oxide semiconductor, lot of voltage drop into this depending upon how much thick it is. So if I add the metal going all the way up to over here it would have gone like that but because part of the voltage goes into the oxide this is shift down here. Instead of crowding and coming like this, it is spread out. So depletion layer actually is spread out like that, so that you do not have the crowding effect. The moment you do not have the crowding effect there is leakage current here is reduced. We have seen this also reduces current drastically. In fact this is simple to make. Growing oxide, open a window, put a metal which is bigger than a window that cuts down leakage drastically.

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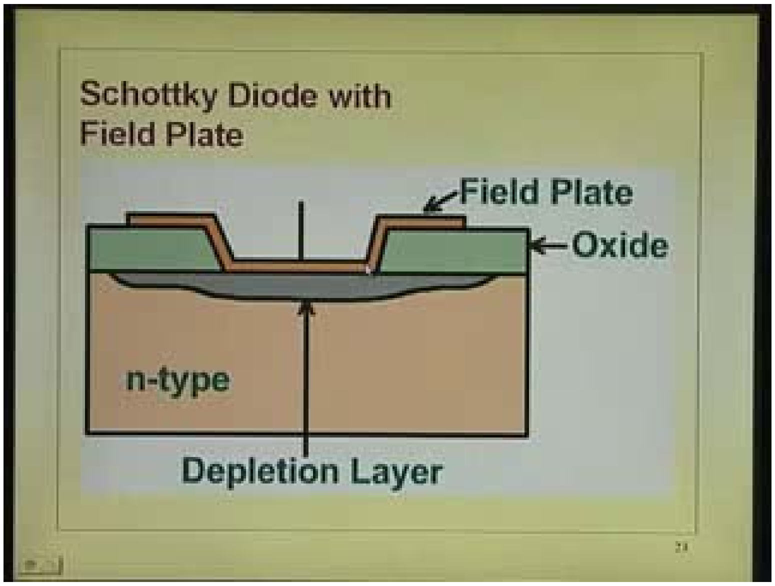

Schottky Diode with Field Plate

This in practice you need to make provision for reducing the field crowding, which would give rise to large current, particularly in the reverse direction due to quantum mechanical tunneling effect and image force lowering effect.

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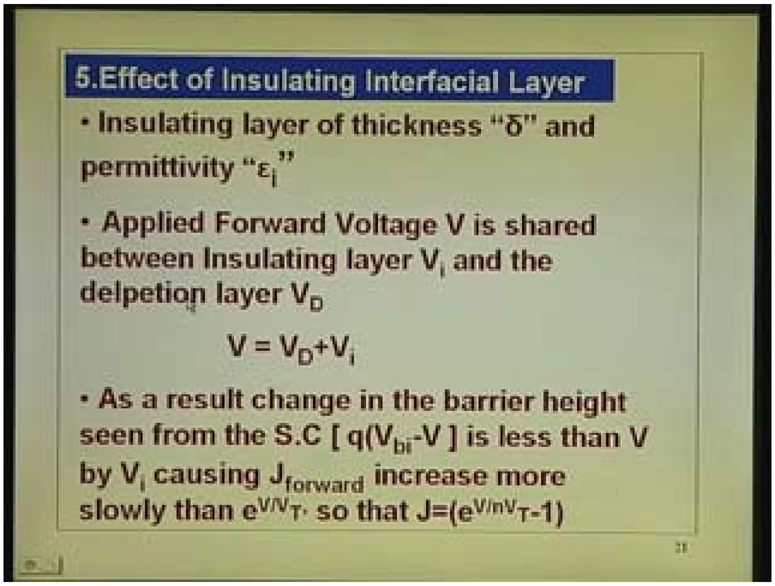

5.Effect of Insulating Interfacial Layer

- Insulating layer of thickness "δ" and permittivity "ε_i"
- Applied Forward Voltage V is shared between Insulating layer V_i and the delpetion layer V_D

$$V = V_D + V_i$$

- As a result change in the barrier height seen from the S.C [$q(V_{bi}-V)$] is less than V by V_i causing $J_{forward}$ increase more slowly than e^{V/V_T}, so that $J=(e^{V/nV_T}-1)$

So one last thing I want to discuss here is the Effect of 5, it is not so important but it is being talked of sometimes. So out of the different effects which effect the ideality, we have seen image force lowering and quantum mechanical tunneling these are the two which really affect particularly in the reverse bias direction. Forward bias direction also will effect because whatever affects this barrier height, additional current, that will affect that. Now the other one is actually insulating layer thickness of delta. I have a thin layer of insulator which is always present due to some native oxide etc that causes slight problem. We have seen it at the beginning, the voltage whatever is present gets shared between that insulating layer and the semiconductor, just like this case (Refer Slide Time: 51:16). If I apply voltage here, that gets shared. What you are talking of is actually a layer here; a thin layer present here.

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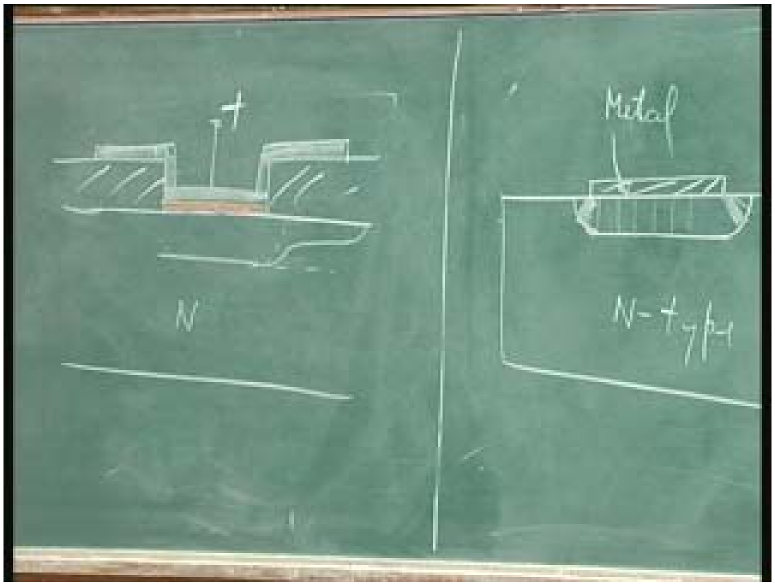

Now let us say, all those effects are overcome by the build plate etc. You put a metal here and what ever changes in voltage you make particularly in forward direction impact is much more reverse direction and it is not going to affect because it is going to cut down leakage current if at all in the region. In forward direction what happens is, when I apply a voltage here v that gets shared between this and this. The voltage that goes to this layer is very small, decause it is after all 5 armstrongs or 10 armstrongs. Its current can tunnel through that and you have got some voltage droping across that. Now what happens is, when I have a delta V, when I increase the voltage in the forward direction by delta V, I expect the current to increase by e to power delta V by V_T, but it would not increase by delta e to power delta V by V_T because that delta V goes completely to the depletion layer. You will have e to power delta V by Vt, but part of it goes to 1 milli volt out of 10 milli volts. The increase in current is not e to power of delta V by V_T, but it is delta V by n V_T where n is greater than 1. That is the reason. If you have an insulating layer there; you get a loose ideality factor to some extent.

In fact in the forward direction apart from the image force is lowering and quantum mechanical tunneling, quantum mechanical tunneling to less extent that plays role in reverse bias. More than these two terms, it is this layer which plays role. If you get1.1, 1.5etc, the ideality factor, then you can say there is a thin layer definitely. If you get 1.01, 1.02, you do not have a thin layer. So this particular quantity V (Refer Slide Time: 53:28) applied voltage is shared between insulating layer V_i and the depletion layer V_D. Delta V will be delta V_D plus delta V_i. If the insulating layer thickness is 0 delta V_i is small and you get ideal factor. In fact I am not deriving this we can get explicit relations between to get the value of n from the I-V characteristics. From the value of n, we can actually find out what is the interface state density. I am not going through that because it involves bit more derivations. May be for time being let me skip that thing. That is why the factor n comes here. So, delta V is not proportional current to e to power delta V by Vt, but it is less than that. That is why that n comes into picture.

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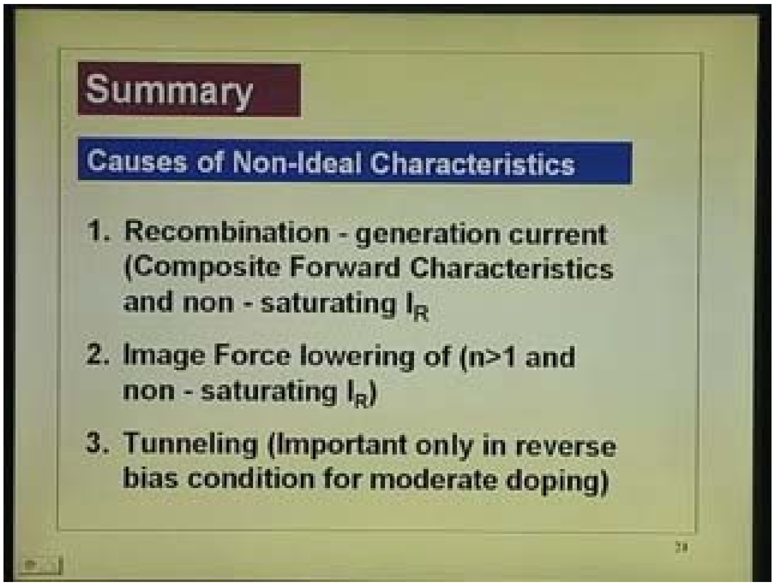

Summary

Causes of Non-Ideal Characteristics

1. Recombination - generation current (Composite Forward Characteristics and non - saturating I_R
2. Image Force lowering of (n>1 and non - saturating I_R)
3. Tunneling (Important only in reverse bias condition for moderate doping)

Finally, what we have seen the summary of all is these non-ideality factors is recombination generation current, it may have composite forward characteristics and non-saturation in I_R in some cases. If you take silicon, it can affect to some extent because the J due to the thermionic emission and this, the difference is less. So it can become more dominant or it will show up as you go to larger reverse currents. But in gallium arsenide, you do not have to worry. Image force lowering makes ideality factor greater than 1 not too much 1; too much more than 1, 1.05, 1.04 in that order and reverse saturation current will not saturate. It will become worse due to the tunneling, quantum mechanical tunneling. Because that comes up if there is field crowding is present. The peak electric field goes up with reverse bias so that is why it is important only in the reverse bias conditions. So, both the things together are very important in the reverse bias directions. That is what I am trying to point out.

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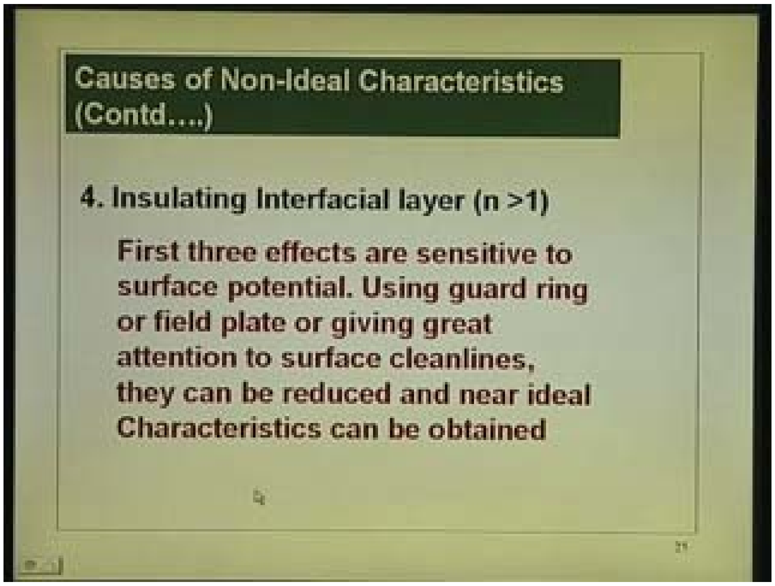

Causes of Non-Ideal Characteristics (Contd….)

4. Insulating Interfacial layer (n >1)

First three effects are sensitive to surface potential. Using guard ring or field plate or giving great attention to surface cleanlines, they can be reduced and near ideal Characteristics can be obtained

If you see the insulating layer presence, you have the insulating layer that will actually affect the forward characteristics because some voltage goes into that. What about hole injection? You do not have to worry at all because it is the order of magnitude is smaller. But still some people have made out cases where they say may be if we go to very high current densities, you may get some hole injection comparable to this one, that is the thermionic emission. Otherwise you do not have to worry about it. I think with that we have completed our discussion on schottky barrier diode, we have seen ideality and non-ideality everything. The main thing that you would require is in the reverse bias operation how does it behave. You should know how to cut down the reverse leakage current. Those techniques also we have seen here like providing field plate, oxide and metal running over the oxide you can reduce that current. So all that we have seen now will take on in the next lecture, the three terminal device which uses the schottky barrier as the gate that is the MESFET. So we will see next time on that.