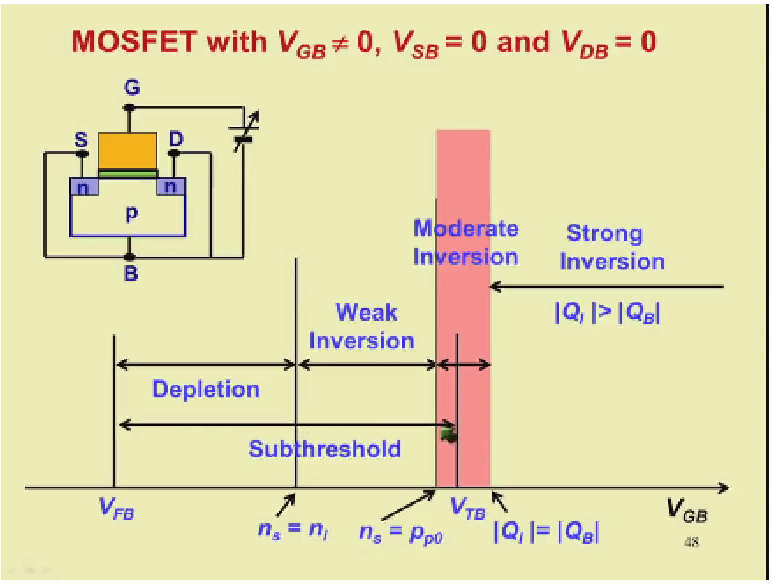
Semiconductor Device Modeling
Prof. Shreepad Karmalkar
Department of Electrical Engineering
Indian Institute of Technology – Madras

Lecture – 42
DC Model of a Large Uniformly Doped Bulk MOSFET: Qualitative Theory

In the previous lecture, we have begun a discussion of the qualitative theory underlying the DC model of a large uniformly dope bulk MOSFET. We have mentioned that qualitative theory for any characteristics is expressed in 5 different ways; these are first you identify the factors responsible for creation and conservation of current flow and electric field, then you identify the factors responsible for imposing boundary conditions on carrier concentration, current distribution, electric field and potential.

The third way to express a qualitative theory is to draw flow lines for current flow and electric field and equipotential lines, then the 4th way is to sketch the distributions of carrier concentration, current density, field potential and energy bands as a function of space in the device and finally you identify the variables, constants and parameters of the model. Now, this is what we want to do for MOSFET, okay which is biased with drain to source voltage, a gate to source voltage and at times bulk to source voltage.

(Refer Slide Time: 02:21)

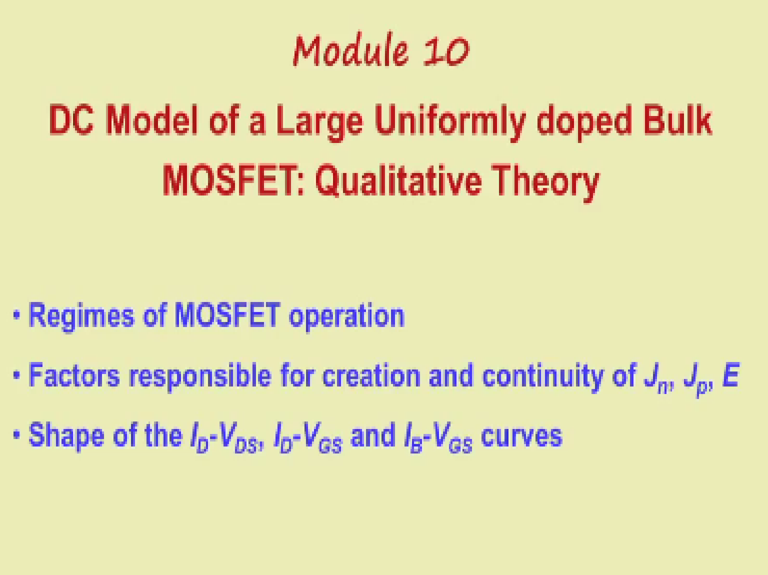


MOSFET with $V_{GB} \neq 0$, $V_{SB} = 0$ and $V_{DB} = 0$

In a previous course titled solid state devices in lectures 33 to 41. We have already discussed a first level model, which includes the qualitative theory for the MOSFET, towards the beginning of this module; we have been summarizing the key features from those lectures. So, that we can proceed further and develop a more advanced model of the MOSFET. Now, so far we have discussed the conditions in a MOSFET with VG be applied.

But source to bulk and drain to bulk are shorted. We identified the following regimes of operation for this device, so this is a VG B axis. The important voltages on this axis are the flat band voltage, the threshold voltage and then you have some other important points, which are based on the surface concentration of minority carriers or electrons in n channel device, so you have depletion region, weak inversion region, moderate inversion region and strong inversion region.

(Refer Slide Time: 03:47)



Module 10

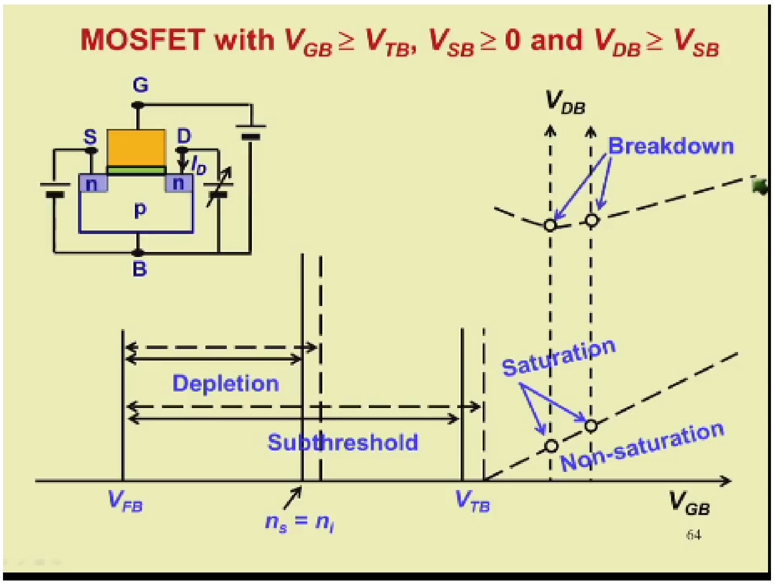
DC Model of a Large Uniformly doped Bulk MOSFET: Qualitative Theory

- Regimes of MOSFET operation
- Factors responsible for creation and continuity of J_n, J_p, E
- Shape of the I_D-V_{DS}, I_D-V_{GS} and I_B-V_{GS} curves

The strong inversion region is that region, where the inversion charge dominates over the depletion charge that is what is indicated here. Now, the region from VGB = VFB to VGB =VTB is referred to as the sub threshold region. In this lecture, we are going to discuss the following points. First, we shall complete the regimes of MOSFET operation, so we will introduce a bulk to source bias.

And later on, drain to bulk bias, right. Then, we shall list out the factors responsible for creation and continuity of JN, JP and E. We shall explain the shape of the ID VDS, ID VGS and IB VGS curves, based on the charge conditions in the device, reverting to the various regimes of operation of a MOSFET for drain to bulk and source to bulk voltage is = 0. Let us see how these regimes get affected, when we introduce a bias between source and bulk.

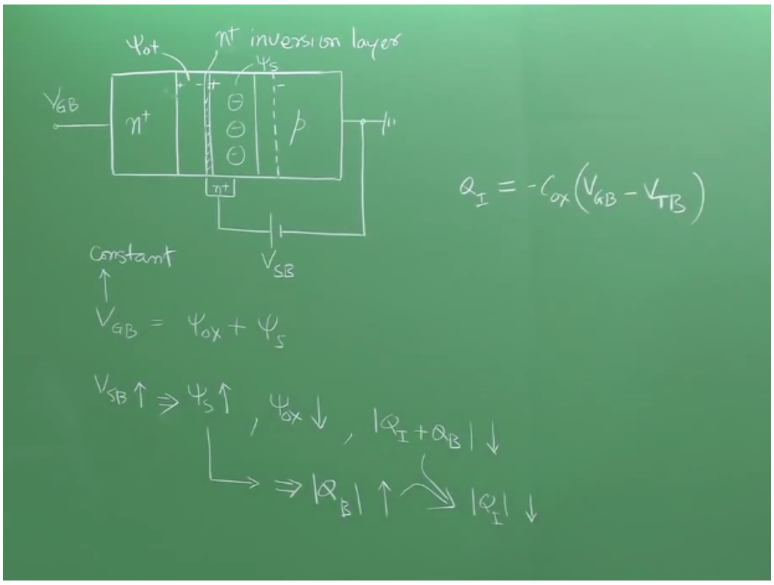
(Refer Slide Time: 04:48)



MOSFET with $V_{GB} \ge V_{TB}$, $V_{SB} \ge 0$ and $V_{DB} \ge V_{SB}$

So, first we clean up the slide and then here, we introduce the bias. We are tying up the drain and source, so that VDB is always = VSB, there is no current flow from drain to source. So, conditions in the channel from source to drain will be uniform. Here, we are ignoring the effects of the depletion region near the source and drain, as we have remarked already because it is a large device, wherein the source to drain distance is much more than the depletion width near source and drain.

(Refer Slide Time: 05:59)



Now, what we find here is the effect of VSB is to widen the depletion and sub threshold regions, your threshold voltage of the N channel device shifts to the right. Similarly, the point where, ns = ni occurs also shifts to the right. Let us see why? So, this is your mass, this is your n+, this is oxide and this is P, you applied a VGB. Let us assume that this VGB is much more than the threshold voltage of the MOSFET.

So, that you have an inversion layer here and a depletion layer, after the inversion layer. Now, let us connect an n+ region here, this is a schematic; an idealized situation where we are using the n+ only to make a contact to the inversion layer. The actual structure of the MOSFET is as shown here. There are 2 n+ regions; drain and source, however we can consider the n+ region only on one side.

Because the potential of this n+ region and this n+ region is the same, therefore the conditions in the MOSFET will not change whether I have just 1 n+ region or I have 2 n+ regions on either side. Another way of looking at the picture is, since this device is symmetric, I can just take one half of this device and then discuss the conditions therein. Now, I am just considering a structure like this right, wherein I have brought an n+ region and contacted it from side.

So, in practice as I had shown on the slide the p region would come here also, right. There will be p region here and this n+ region will be embedded inside. However, to understand this operation, this schematic is very useful and simpler, so you see I have neglected any depletion region that occurs between n+, np here, because my n+ is so small that it is only trying to make a contact to the inversion layer.

And now, I apply a bias so, this is VSB. What will be the effect? Note that this VSB is reverse biasing the n+p junction. Now, as we have remarked earlier that the effect of gate to bulk voltage, a high gate to bulk voltage over and above the threshold voltage is to induce an n+p junction, so this is n+ region inversion layer. Since this is an n+p junction, you can regard it like that, when you apply a VSB here; this VSB not only reverse biases this n+p junction.

But reverse biases the entire inversion layer p substrate junction, okay all along. So, when you reverse bias a junction, what happens the depletion region expands? So, the effect of this reverse bias would be that this depletion region would expand. Now, what would happen to the inversion charge itself? Note that, we are not changing VGB, now if you separate the VGB into the parts of the device, let us neglect the part of V GB that falls across this n+ region assuming this to be heavily doped.

Then, this VGB is falling across the oxide and remaining across this silicon. Let us call this as psi s, so VGB =psi ox+psi s. The effect of VSB is to widen the depletion layer, which means to;

it is increasing the psi s. Now, VGB = psi ox+psi s, wherein as VSB is increased, psi s increases; this upward arrow means increase. So, we can probably write it like this VSB increase results in psi s increase, but VGB is constant, this is being maintained constant.

So, if psi x increases, but this is constant; psi ox decreases. If psi ox decreases, then from the law of capacitor you know that the total charge on the plate of the capacitor should decrease. This means, inversion charge plus depletion charge together should decrease, so QI+QB the magnitude should decreases. However, when psi s increases, QB increases this component increases as you can see here depletion region has widened.

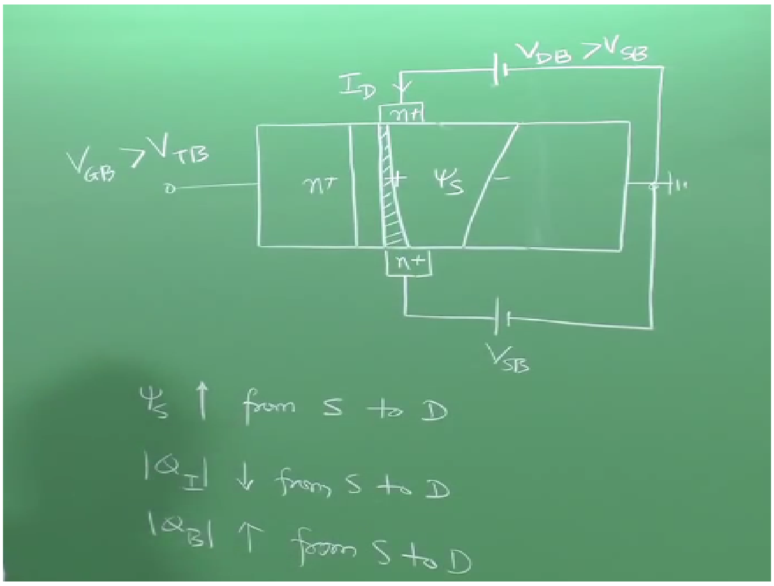
So, psi s increase implies QB increases in magnitude, so if you combine these 2; QI+QB should decrease, but QB increases. This means QI should decrease, so these 2 imply QI decreases. So, inversion charge is going to decrease as you increase VSB. What does this mean? This means that effectively the threshold voltage of the device has increased because the inversion charge is nothing but the oxide capacitance into VGB – VTB.

So, if the inversion charge has decreased, if I write this expression QI = minus of Cox VGB minus VTB, because VGB over and above VTB causes QI. So, if Qi has decreased in magnitude, then evidently because VGB is being maintained constant, VTB has increased. Therefore, this is how you can conclude that the VTB here is going to increase. Now, just as the inversion charge reduces in general, we can say that the electron concentration at the surface here; the electron constitution at the surface reduces when VSB is applied.

Now, this means that a certain condition on electrons such as n = ni, would appear at a higher value of VGB, okay. Now, that is what is shown here, so this how we can conclude that the depletion region widens and the sub threshold region widens because of application of VSB, threshold voltage also increases, when you apply VSB. Now, let us proceed further and apply a VDB, which is greater than VSB.

So, that a current flow is set up between drain and source that is what is shown here. So, VDB > VSB, note that I cannot say VDB can be less than VSB because moment this voltage becomes less than this voltage, this will become the source and this will become the drain. So, since I am calling this terminal as the drain, this should always be more positive than the source okay.

(Refer Slide Time: 15:54)



Now, this is your VDB axis, the lowest value of VDB possible here is = VSB. Now, what is going to happen as I increase VDB? Let us look at that. So, what I have to do now is to bring another n+ contact on this side and apply a voltage to that that is more than this and then see what happens to this charge conditions. So, VGB is > VTB because only then the inversion charge will be there here.

Now, please note that is a condition we are considering here. So, we are drawing this VDB line starting from a value of VGB, which is more than VTB. So, if your VSB 0, then your VTB would be this, if this VSB 0. However, since we are applying a VSB, our VTB would be slightly towards the right of this. So, this VGB that we are now considering is more than the VTB including the effect of VSB.

So, this is your source in an idealized structure; this is VSB and you put another contact at this end and this is your VDB. Now, since there is an inversion layer present because VGB is more than VTB, the voltage between drain and source is going to drop uniformly along this. This means, at any point here; let us say in if I take the inversion layer here at this point; this point the voltage of this interphase compared to the bulk will be higher than the voltage of this point with respect to the bulk.

Now, if you talk in terms of this voltage psi s okay, we can talk in terms of psi s and psi ox. Because the VGB is following partly across oxide partly across the semiconductor across this, were ignoring the voltage drop in the poly. Then, we can say that psi s, goes on increasing from source to drain because the potential along this is going on increasing, VDB is more than VSB.

As a result, we can draw the following picture; the depletion region will go on expanding as you go from source to drain.

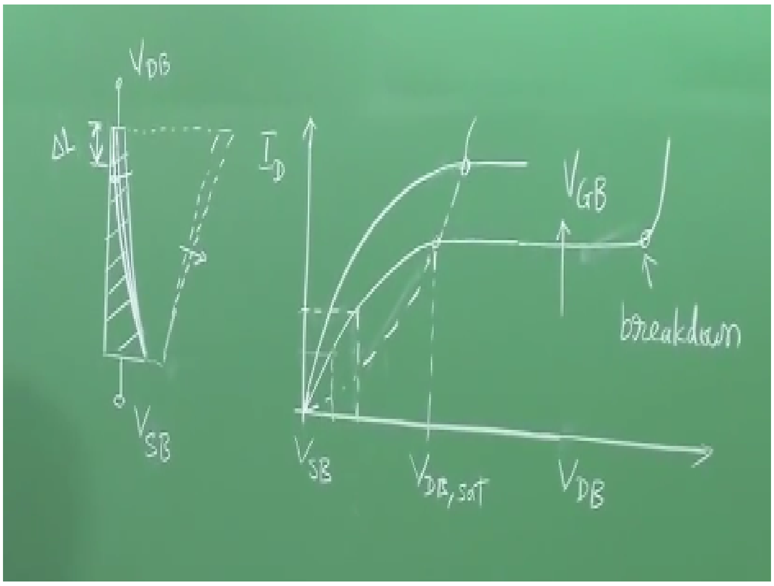
And the inversion charge will go on reducing as you go from source to drain. So, at any point here, this is your psi s; psi s increases from source to drain. Therefore, applying the same explanation okay is incidentally this effect of VSB on inversion charge and so on is referred to as body effect, okay. Because it is a consequence of reverse biasing the body or the bulk with respect to the source.

So we can say that when you apply a VDB > VSB, the result is a change in body effect along the interface from source to drain, so body effect goes on increasing, psi s increases and therefore we can say QI, the magnitude of it falls from source to drain and the magnitude of QB increases from source to drain, so this is the picture. Therefore, what will happen to the current? This is ID.

Now, since the current is flowing through this inversion layer, which is called the channel. We can use a loose analogy of this situation to the current flow in a resistor, as we will see actually the current flow here in this inversion layer is because of 2 factors; drift as well as diffusion. Drift; because there is an electric field directed like this, from drain to source. There is a drift current in response to these electrons move in response to this electric field.

But as you can see inversion layer charge also goes on decreasing from source to drain. Therefore, there is a tendency for diffusion of electrons from source to drain, so there are 2 tendencies; drift as well as diffusion. Nevertheless, to understand what is happening in the device, we can just concentrate on the drift part of the current and say that this is like current flow through a register, whose area of cross section is going on reducing as you move from source to drain.

(Refer Slide Time: 22:00)



Let us separate that out and show it here, so I am showing only the inversion layer and I am slightly expanding; expanding this, right. So, I am making it a little more thick, so that I can show things clearly. So, this is your, at this end you have VDB and at this end you have a VSB applied voltage. Now, clearly if I were to plot the effect of this on a graph, where this axis is VDB and this axis is ID, starting point here is VSB.

Because VDB always has to be more than VSB, then as I apply a VDB, which is slightly higher than VSB, the variation of the inversion charge from source to drain, then will be small, so I could assume an approximately uniform inversion charge. Therefore, for small values of VDB above VSB, my ID will rise like it rises in a register in a linear fashion okay. As you go on increasing your VDB, keeping VSB constant, the inversion charge will reduce more and more towards the drain.

So, if this is the picture for 1 value of VDB, for a higher value of VDB if I were to sketch the picture, it would be like this. I can show it in fact here itself for a higher value of VDB, the inversion charge picture would be something like this. Note that things are not changing at the source end because VSB is not being changed only VDB is being varied, so you are varying this; this means what?

Now, for a higher value of VDB, your effective area of cross section of the resistor has reduced, that means the resistance itself has increased. So, when you increase your VDB, your resistance is more, which means the increment in the ID for any given increment in VDB will be less, therefore you can see that for equal increments in VDB, your increment in ID will progressively reduce.

So, here this is the increment for this much increment in current, for this much increment in VDB, for equal increment in VDB here, I have a somewhat smaller increment in ID and so on. So, I will get a current, which tends to taper off; with rise tends to taper off like this, so that explains the shape, so this is the reason why? Because the inversion charge goes on reducing from source to drain you are getting this effect.

And reduction at the drain is more and more as you increase your VDB. Now, what about the depletion charge? Depletion charge does not affect the current flow because current flows only through the inversion charge, so I am not showing the depletion layer; you want you can show the depletion layer I will show it by dotted line here, diagram is not to scale. So, this is depletion layer for 1 VDB and for higher VDB, this is for higher VDB, right.

So, depletion layer for higher VDB will be more, inversion layer is less but depletion charge will be more here. So, it will be something like this, so it will move in this direction whereas this edge moves in this direction, as you increase your VDB. For some value of VDB, the inversion charge here will become really very very small, okay, as we will see in advanced theory; the inversion charge never becomes 0 at the drain end.

It saturates at a value, where the velocity of the electrons becomes equal to this saturation velocity okay. So, the velocity of the electrons will go on increasing from source to drain because your electric field is increasing, when we plot the electric field as a function of distance from source to drain. We will see that this electric field; this directed electric field goes on increasing; this is evident.

Because my current flow should remain almost the same and if my inversion charge is less to get the same current I should have more velocity of electrons, right. So, velocity of electrons goes on increasing, however you know from an earlier module that the velocity of electron ultimately saturates beyond some critical field. So, once the velocity saturates, then there cannot be a change in the concentration.

So, once that happens, your current will also saturate okay, beyond some point. In the first level course, the saturation was explained based on what is called pinch off; pinch off means that the inversion charge is assumed to go to zero. Now, once the inversion has gone to zero, then there cannot be any change in the current okay, almost no change in the current. There will be a small change; there will be a small slope here, right.

That happens, because actually this point of saturation starts moving inside towards the source, we will just mention this point and deal on this point in detail later. So, what we are saying is for some high value of VDB, your picture would be something like this; the inversion charge is small but constant over some distance and then this is what it is. You apply even more higher VDB, this uniform inversion charge region; small inversion charge region or saturated velocity region as it is called because here the velocity would have saturated.

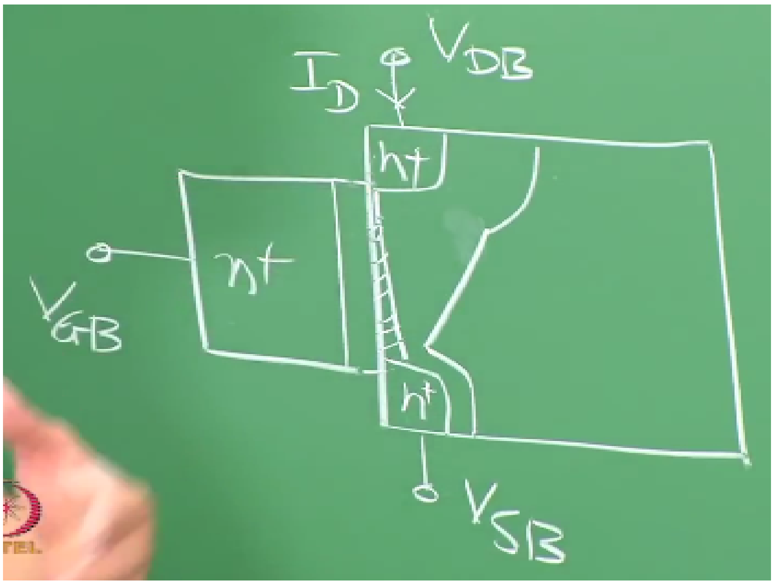
It goes on expanding, so if I denote the region of velocity saturation as delta L, then delta L goes on expanding as you increase your VDB beyond a point called the saturation voltage. Now, this is how we explain the ID VDB shape, if you increase your VGB, then your inversion charge will be more, evidently, your current will be more. So, for a higher VGB, if I want to sketch this, I have to start with a higher slope here, so it will go on like that.

Now, evidently, if the inversion charge here is more, you will have to apply a higher value of VDB to make the inversion charge here go to the same small value at which the velocity saturation occurs and therefore this point beyond which saturation occurs will shift to the right, so this will be your locus of the saturation point. So, the saturation voltage goes on increasing, we can call this voltage as VDB Sat.

So, this goes on increasing, VDB Sat goes on increasing, as you increase your VGB. Now, that is what is shown here; you increase your VDB maintaining VGB constant, you move along this line, you encounter saturation. What happens if you increase your VDB further much further? Then you will encounter what is called the breakdown point. So, if I increase my VDB further, beyond some value of VDB, I have to stretch this VDB axis here, I will find the current increases rapidly.

So, this is the so called break down point. Why does this happen? Because you can think about it in terms of this picture here, there is a depletion region from the drain and the reverse bias between drain and bulk increases so much that a breakdown happens okay, just like the avalanche breakdown of any junction. In other words, the carriers will ionize and there will be impact ionization.

(Refer Slide Time: 31:20)



Note; however, the difference between a simple reverse bias junction and MOSFET is that there is a large amount of current flow through this depletion region. So, here we have not shown the depletion region from the drain, if you want to explain the break down will have to show that region. Let me just draw a simple schematic showing that this is your n+ drain, it is n+ source, this is VGB, this gate; so if I plot the depletion region near here break down, it will be like this,

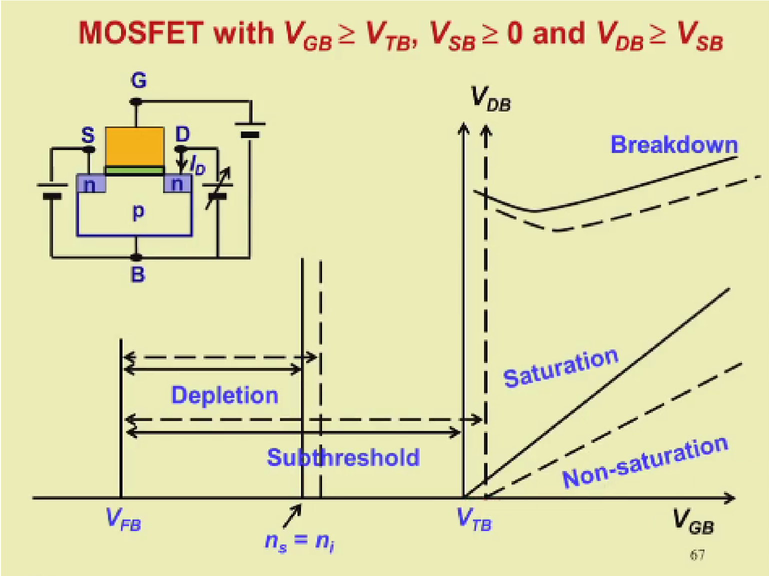
So, you have a wide depletion region here, a small depletion region here, your inversion charge is something like this; this is the so called delta L okay, over which the velocity saturation happens, that is the same as this delta L, okay. So, this is the; there is this current ID, so electrons are flowing in this direction, this is a conventional current. Now, these electrons are encountering a high field here, okay, because there is a high reverse bias.

Now, because of this high field, these electrons will multiply there will be impact ionization okay, and multiplication so that is what causes the breakdown and increase in the current. Supposing, I see the picture for a higher value of VGB, as I increase my VDB from VSB onwards, I will encounter saturation and this saturation will occur at a higher value of VDB, as compared to this case, which was for a lower value of VGB.

So, this is what we explained here that the saturation point moves to the right okay, as your VGB increases. Then, for some high value of VDB, you encounter break down here the breakdown voltage is shown to increase with VGB, more about this behaviour will be explained later. Because we have to consider the various current components in the device in detail; to understand why as you increase VGB in some range in the breakdown voltage increases.

But in some other range increase in VGB would reduce the breakdown voltage, so this detail will be discussed later. Now, if I were to join all these points and try to sketch the locus of the saturation point, then I will find that would be like a straight line, in other words, as you increase your VGB, the saturation voltage increases in a linear fashion almost, okay the shape of this locus will become clear, when you write equations.

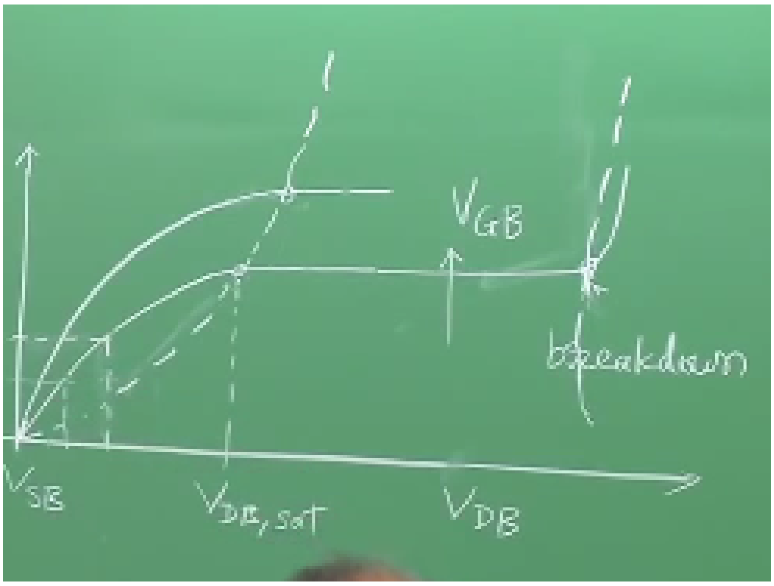
(Refer Slide Time: 34:41)



MOSFET with $V_{GB} \geq V_{TB}$, $V_{SB} \geq 0$ and $V_{DB} \geq V_{SB}$

You start from the point, where VGB is VTB. At that point, the saturation voltage will be zero and for the breakdown point the locus is like this, as I mentioned earlier this shape will be discussed later, when we consider the various current components in the MOSFET. So, we clean up this slide and then show the various regimes completely. So, this is your VDB axis and this point corresponds to VGB = VTB corresponding to the value of VSB.

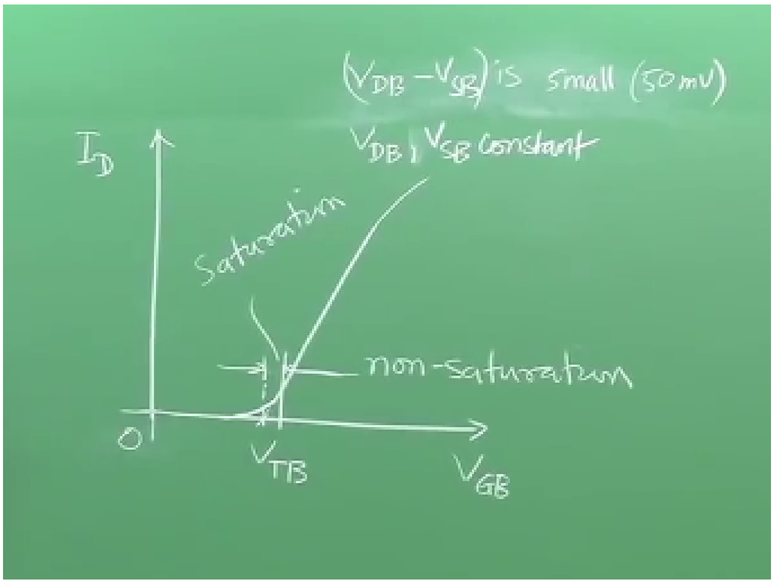
(Refer Slide Time: 35:21)



And on the y axis, the same point corresponds to VDB = VSB, so if I were to show this on this graph here; this region is the non-saturation region this region, here is a saturation region and here you have the breakdown, this favour to show the locus something like this; that is this locus. So, non-saturation, saturation, breakdown, right that is the same thing that is shown here; non saturation, saturation, breakdown.

Here VDB is along this direction; here VDB was in the horizontal direction, right, therefore non saturation, saturation, and breakdown. Please note; that this line is straight here but this line is curved, so you should not confuse this VDB, VGB map with this ID VDB map, right. So, although this VDB axis is common in both cases this VDX axis is horizontal here and the VDB axis on the slide is vertical but the other axis is VGB, whereas here it is ID.

(Refer Slide Time: 36:54)



Now suppose, I fix my VDB at some small value and vary the VGB, what will be the behaviour? This is the so called transfer curve. So, let us explain now the shape of the transfer curve; ID, what is this? VGB, now you are varying VGB, keeping VDB at some small value. VDB and VSB are both kept constant and VDB is small; say about 50 millivolts, right. What will be the shape of your ID VGB curve?

From this graph here, you find that for large values of VGB, you will be in non-saturation region and for some value of VGB; some small value of VGB, you will enter the saturation region as you decrease your VGB okay until the VGB = VTB point. Now, what will be the shape of the curve for ID as a function of VGB that can again be understood from this picture here, the conditions near device?

So, we are maintaining VDB at some small value, which when I say small, I think; I must; when I say VDB is small actually this is the correct way to put it in as follows. VDB is minus VSB is small because the VDB should always be more than VSB. So, i am maintaining as VDB, which is a little above the VSB and therefore the inversion conditions here; inversion layer conditions will be more or less uniform.

In that situation, if I go on increasing VGB that is this; this voltage what is going to happen? The inversion charge here is going to increase progressively and therefore the ID will increase progressively. Now, when the inversion charge is approximately uniform from source to drain you know that the inversion charge increases with VGB according to this formula okay. The VTB will be uniform from source to drain along this.

Because the inversion charge is uniform, because your VDB is only slightly different from VSB. We can assume more or less uniform conditions, so inversion charge increases linearly with VGB and therefore the drain current increases linearly with VGB. So, the picture here would be something like this; now the current will go to zero for VGB = VTB here, for VGB = VTB, inversion charge is zero.

Now, this straight line portion is applicable for values of VGB, somewhat higher than VTB, near VTB, the simple linear law does not hold, so you have a slight smoothening out of the curve here. Similarly, for high values of VGB, this does not remain linear and it tapers little bit, the reason for that is; when your field increases in this direction, as you increase VGB, this field increases, then the scattering of the electrons close to the interface increases.

We have discussed the mobility as a function of electric field. We have said that the mobility of carriers at any point is affected both by the longitudinal electric field and the transverse electric field, so once the transverse electric field is large then you know that the mobility falls. Now, that is the reason why your current is decreasing for high values of VGB. Now, this is your ID VGB shape.

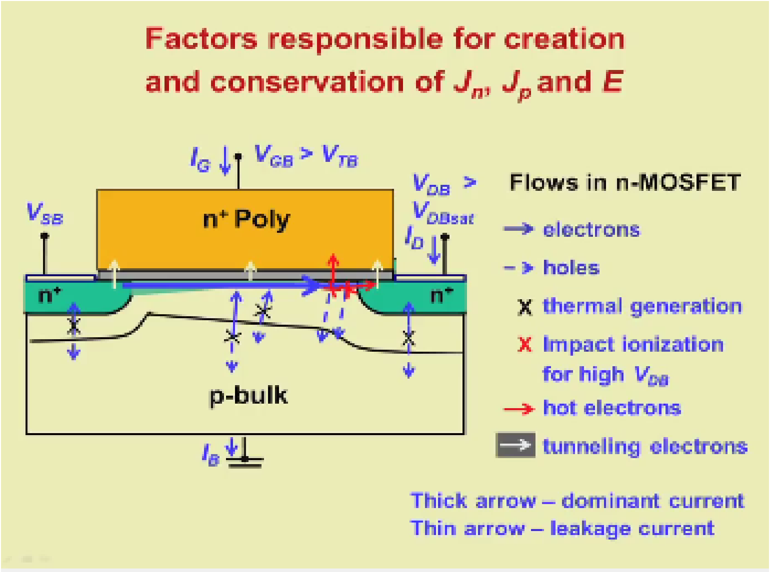
For some range above, VTB here the device would be that is here, the device would be in saturation region and in the remaining region here beyond this, it will be non-saturation okay that is what this shows. For a small range of VGB beyond VTB, you have saturation and then beyond that you have non-saturation. Now, you might wonder; we just now said that the inversion charge is more or less uniform from source to drain.

Then, how can we have for some values of VGB above VTB saturation because that is not the condition for saturation; under saturation in the current is saturating here, you have inversion charge at a very small value at the drain and inversion charge at the source is at a higher value okay, that is the condition during saturation. Now, the point is when we said that the inversion charge is uniform from source to drain, that uniform condition applies when the inversion charge is really large; VGB well above VTB.

When you come to very close to VTB and the entire inversion charge becomes small then the small VDB above VSB, right even though this difference is small that small difference can create a variation in the inversion charge as shown here, right. So, as shown here, when the inversion charge itself is small, then at this point the inversion charge can become even smaller and you can have saturation.

This will however, happen only for VGB very close to VTB, so normally 1 does not bother about this region very much so long as your VDB minus VSB is small. So, let us complete the regimes for a different value of VSB, so if your VSB 0, this is your VTB and therefore your VDB axis will start from here. So, this is how your various regions; saturation, breakdown and non-saturation, they change when you change your VSB, okay.

(Refer Slide Time: 44:21)



Factors responsible for creation and conservation of J_n, J_p and E

Flows in n-MOSFET

→ electrons

-→ holes

X thermal generation

X Impact ionization for high V_{DB}

→ hot electrons

→ tunneling electrons

Thick arrow – dominant current
Thin arrow – leakage current

Let us put our charge conditions on the slide here; for the VDB, which is more than VSB, inversion charge is decreasing from source to drain, depletion charge increasing from source to drain. We are assuming VGB > VTB correspond to this VSB, so that you actually have some inversion charge here at the interface. Now, let us put down the factors responsible for creation and conservation of electron current density, hole current density and electric field.

Now, we shall do that for VDB > VDB Sat. because you have more mechanisms of current flow okay, when you go close to the breakdown point that is why we are trying to consider VDB > VDB Sat and will go close to the breakdown point, so that we can show all the various components of current. So, let us list out the flows in this MOSFET, now there is a dominant flow of current from source to drain.

Dominant flow of electrons that is shown here by this thick arrow then you have electrons provided by thermal generation. These are the electrons; this thick arrow shows electrons provided by source. Now, you have thermal generation throughout the depletion layer okay, as it happens in any pn junction. Now, this thermally generated electron hole pairs they behave as follows; the electrons will move to the interface because there is a field directed from gate to bulk in this direction.

And they will also move towards the drain because there is a field directed from drain to source, so you have 2 fields; drain to source and gate to bulk. So, the net effect of that is electrons move towards the interface and then towards the drain that is why you see this arrow at an angle. So, all the electrons, which are generated here, will try to move to the interface and then if VDB is more than VSB they will try to move towards the drain.

Holes will move out because the direction of the electric field is gate to bulk, the holes will move out and all the holes will get collected by the substrate. So, these holes are actually causing the substrate current. Now note; that there is generation not only within the depletion layer but also just outside the depletion layer within a diffusion length from the depletion layer, so even the electrons which are generated outside the depletion layer within a diffusion length will contribute to current inside here, okay.

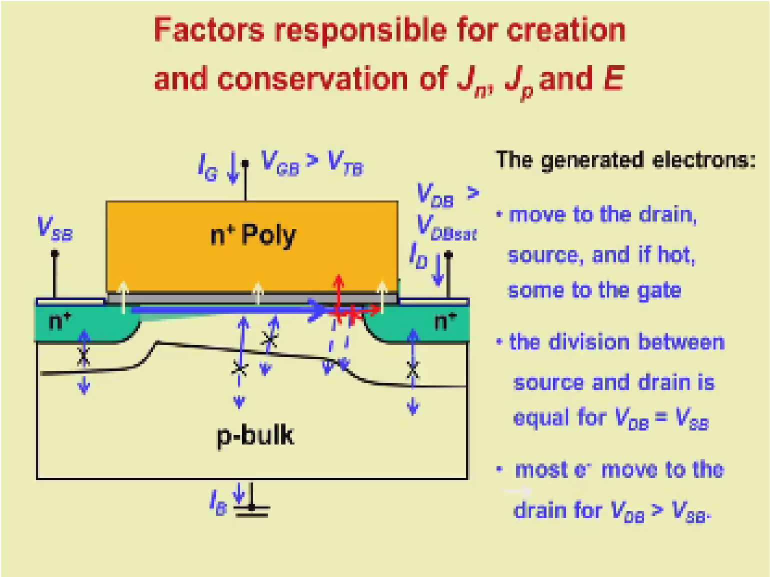
And the holes will move out and contribute to the bulk current. Now, even this generation is similar to that happens in a pn junction; reverse bias pn junction, since we are considering the picture near breakdown, the electric field near the drain is high and therefore all the electrons, which are moving through this high electric field region will tend to multiply because of impact ionization.

So, this red crosses here show impact ionization, the black crosses show thermal generation points. Now, the electrons which are generated out of this impact ionization, some of them move to the drain and some which have high energy because the electric field is high, these are called hot electrons. They can even cross the insulator barrier; the insulator semiconductor barrier and get injected into the gate and they will cause the gate current.

So, they are one of the reasons for the gate current. These hot electrons, which are generated near the drain, because of impact ionization. Finally, you can also have tunneling electrons, you have a high concentration of electrons here and you have a high field from gate to bulk, if the field is really high and an insulator is very thin, you can have tunneling of electrons from substrate into the gate.

So, these will also contribute to the gate current. The thick arrows here show dominant current and thin arrows show leakage current, so the thick arrow here is the current from source to drain that is a dominant current and there are contributions from impact ionization, tunneling and so on but these currents are small. Therefore, they are shown by thin arrows, so that is why here gate current is small and bulk current will also be small.

(Refer Slide Time: 49:52)



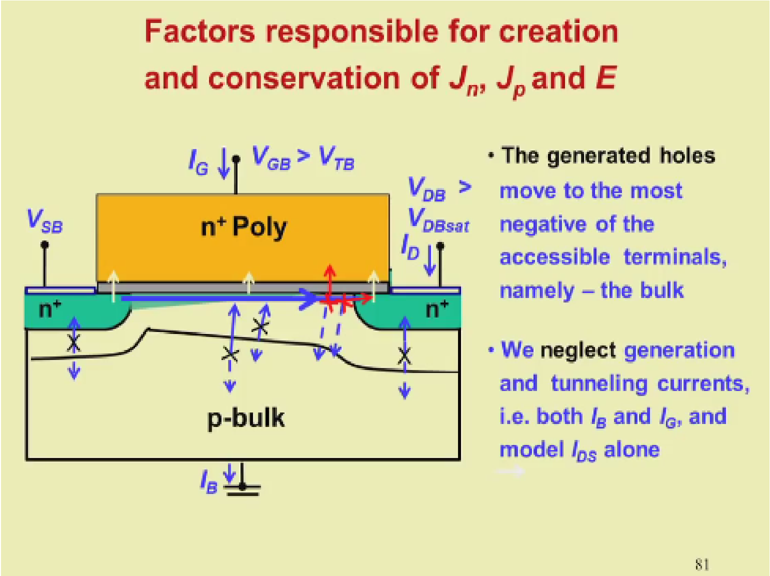
Factors responsible for creation and conservation of J_n, J_p and E

The generated electrons:

- move to the drain, source, and if hot, some to the gate
- the division between source and drain is equal for $V_{DB} = V_{SB}$
- most e⁻ move to the drain for $V_{DB} > V_{SB}$.

Whereas, the drain current will be large. The generated electrons move to the drain, source and if hot, some to the gate. We are summarizing our observations; so here you can see that there are some electrons are moving to the source, right, some are in the gate, if they are hot. The division between source and drain current is equal for VDB = VSB. If I maintain this VDB = VSB, then evidently all the current that is generated will get equally divided between source and drain.

(Refer Slide Time: 50:38)

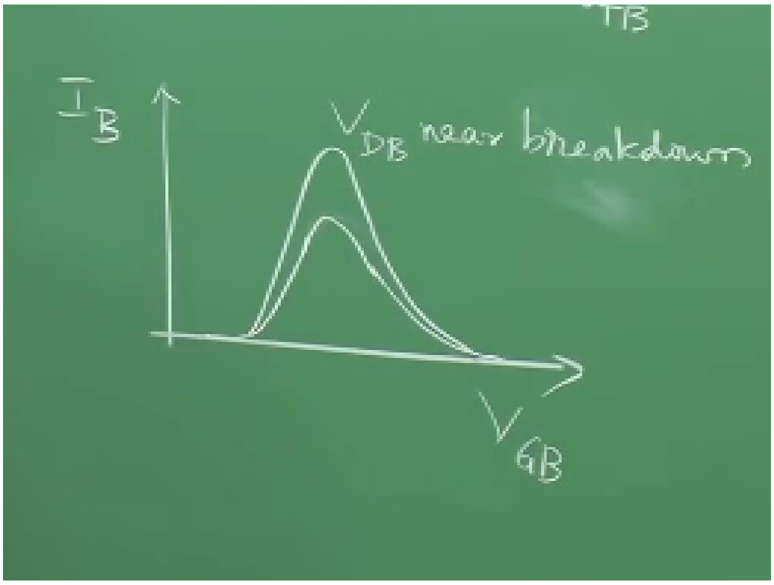


Factors responsible for creation and conservation of J_n, J_p and E

- The generated holes move to the most negative of the accessible terminals, namely – the bulk
- We neglect generation and tunneling currents, i.e. both I_B and I_G, and model I_{DS} alone

Most electrons move to the drain for VDB > VSB, if your VDB is more than VSB, then electrons will prefer to go here rather than going here to the source because electrons will go to the most positive terminal. The generated holes move to the most negative of the accessible terminals namely the bulk, so you can see all the holes here are moving to the bulk terminal and this is what causes the bulk current.

(Refer Slide Time: 51:00)



Now, we can explain the shape of IB VGS curve, based on this picture, Let me, sketch the IB VGS curve now, here we will use VGB because our voltages are applied with respect to bulk, so essentially IB VGB curve. Holes will increase, when the device is nearing breakdown because there are many electron hole pairs generated because of impact ionization that is why we talk about the behaviour of the bulk current near the breakdown point.

So, in other words our VDB is near breakdown because that is where the current will be significant. Now, you can see that if my VGB is small, there is no inversion layer. If there is no inversion layer, there is no current from source to drain, so this dominant current flow is cut off. If this dominant current flow is cut off the electrons, which can multiply their number is very small.

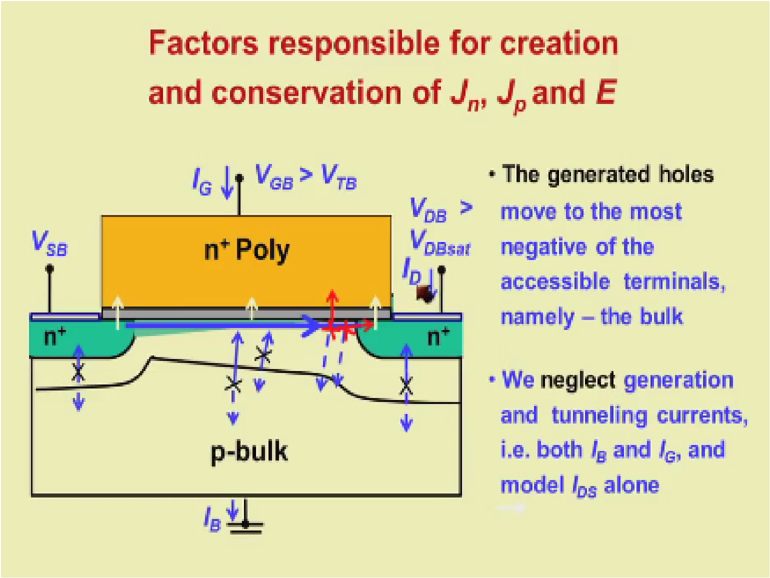
And therefore the current is very small; therefore, for small values of VGB, you will not have much IB. Now, once you increase your VGB and inversion layer forms then your ID s increases and therefore chances of multiplication increases, therefore your IB increases. Now this current is increasing, therefore the source of multiplication is increasing, therefore the IB is increasing, so more electron hole pair is generated here.

And these holes are moving to the bulk. What happens for very high VGB? When the VGB is high, inversion charge is large, then the voltage from drain to source will fall more or less uniformly okay that means the electric field here gets reduced. Note that; when inversion charge is small then the potential drop from drain to source will occur mostly near the drain, whereas when the inversion charge is large then the potential variation becomes more or less homogenized okay.

And the electric field here at the drain decreases. Therefore, for high VGB your IB will tend to decrease something like this, so there will be a peak in between. In other words, for small values of VGB, the source of electrons is small because ID is small, therefore multiplication is not much, therefore IB small; for very high values of VGB, inversion charge is large that decreases the electric field near the drain and again multiplication cannot be much.

Because current may be large but unless electric field is large, you do not have multiplication okay, that is why for low VGA and high VGB, your current is small. Evidently, if you increase your VDB then your current will increase, so it will be something like this; shape will be something like this, so it will increase. Now, finally we will make this comment that we neglect generation and tunnelling currents that is both IB and IG and concentrate on IDs alone.

(Refer Slide Time: 54:44)



Factors responsible for creation and conservation of J_n, J_p and E

- The generated holes move to the most negative of the accessible terminals, namely – the bulk
- We neglect generation and tunneling currents, i.e. both I_B and I_G, and model I_{DS} alone

So, we are going to model only IDs that is this thick arrow, all other currents we are going to neglect for modelling, so which means our picture will be like this. Note that; if only this current is considered then this current can be referred to as I suffix D s because it is flowing between drain and source, we have neglected other components such as ID B and ID G, so gate leakage and bulk currents have been neglected.

Then this current can be called IDs okay. When other current components are present then this current has to be referred to as ID, as we did in the previous slide here. This ID; because it has 3 components IDS, IDG and IDB. With, that we have come to the end of the lecture, so let us make a summary of the important points. Now, in this lecture, we discussed the various regimes of operation namely non saturation, saturation, and breakdown and then we explained the shapes of ID VDB then ID VGB and IB VGB curves, okay in terms of the charge field and current flow conditions in the device.