Solid State Devices
Dr. S. Karmalkar
Department of Electronics and Communication Engineering
Indian Institute of Technology, Madras
Lecture - 39
MOS Field Effect Transistor (Contd...)

In the last class we started the discussion of the MOS Field Effect Transistor. We shall continue the discussion in this lecture today.

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In the last class we covered the fabrication steps and the device structure. We have also given a simple history of how this device has come into importance. Then we explained the symbol and correlated the various components of the symbol to the device structure. In this particular lecture we will start developing the characteristics of the MOSFET. As we had shown in the previous lecture our goal is to explain the following characteristics.

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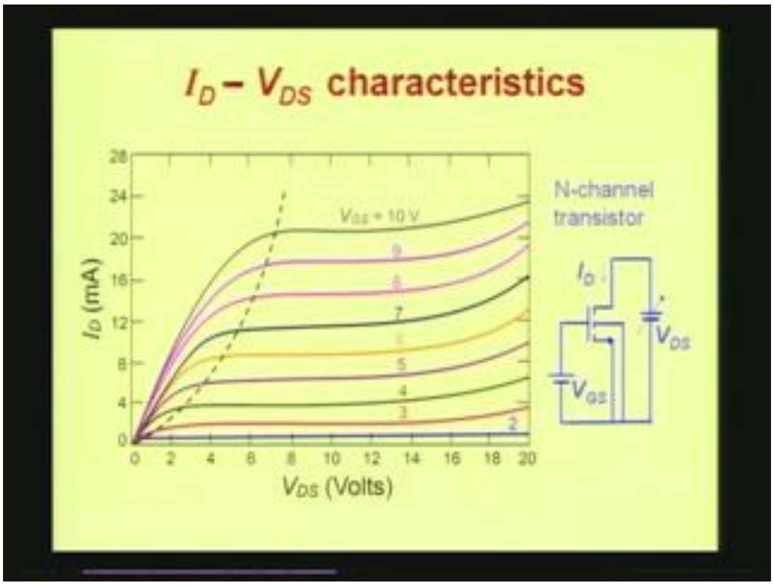

So the biasing arrangement is shown there. There is a gate source voltage then there is a drain source voltage. These particular set of characteristics are shown for bulk to source voltage equal to 0. So you see that the substrate or bulk here, the bulk to source voltage is 0, this is the source. So the characteristics involve drain current versus drain to source voltage for various values of gate source voltage. Now let us see how we can develop these characteristics.

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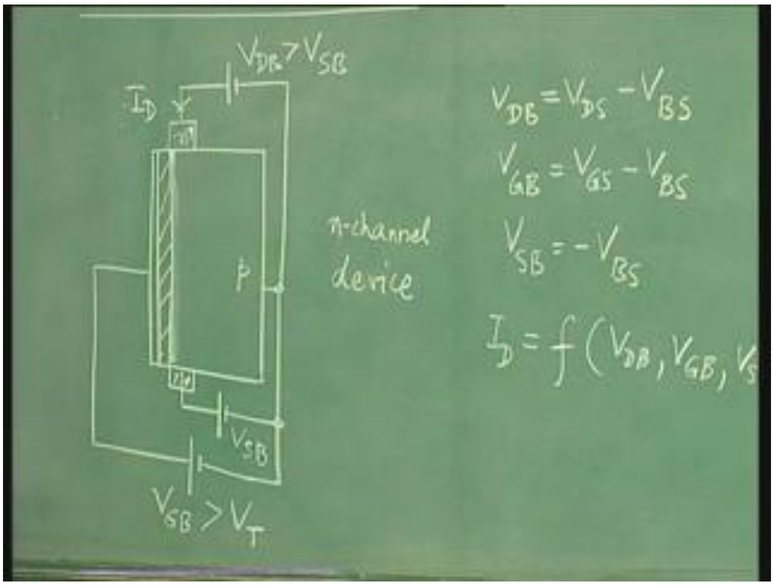

I_D - V_{DS} characteristics:

For this purpose we will draw the MOSFET in this particular fashion. This is your p-type substrate. Now the source and drain will be assumed to be top and bottom. We will assume that this is the source and this is the drain. Now, for simplicity we are showing the source and drain to be very small and just enough to make contact to the inversion layer. In practice your source and drain regions are such that you have a depletion layer from both the source and drain regions coming into the channel. Here you have the oxide layer and this is your gate.

Now an important point to note is that, when you want to develop the current voltage characteristics starting from the device physics then it is convenient to use the bulk as the common terminal. So though in practice the source is shown to be the common terminal to develop the characteristics we will use the bulk as the common terminal and then transform these voltages to the voltages when you use the source as the common terminal which means the following: We will use this as the common terminal and then we apply a voltage to the gate with respect to the bulk so as to create the inversion layer here.

So you have the inversion layer here. Then we apply a voltage to the source with respect to bulk. Now, in our characteristics this particular voltage has been shown to be 0 but that is the characteristics on the slide. But here we will have an equation which will also take into account this voltage then we will set this voltage equal to 0 to see how the equation simplifies, so this is V_{SB} and then we have the drain to bulk voltage V_{DB}. Obviously the V_{DB} is more than the V_{SB} only then this will be called the drain because then the electrons will move from here to here or the current will be from here to here. So whichever n plus terminal is more positive then it is called the drain for n-channel transistor. Here we are considering n-channel device. Once we derive the ID as a function of V_{GB}, V_{SB} and V_{DB} we can always convert these equations to the form when source is the common terminal.

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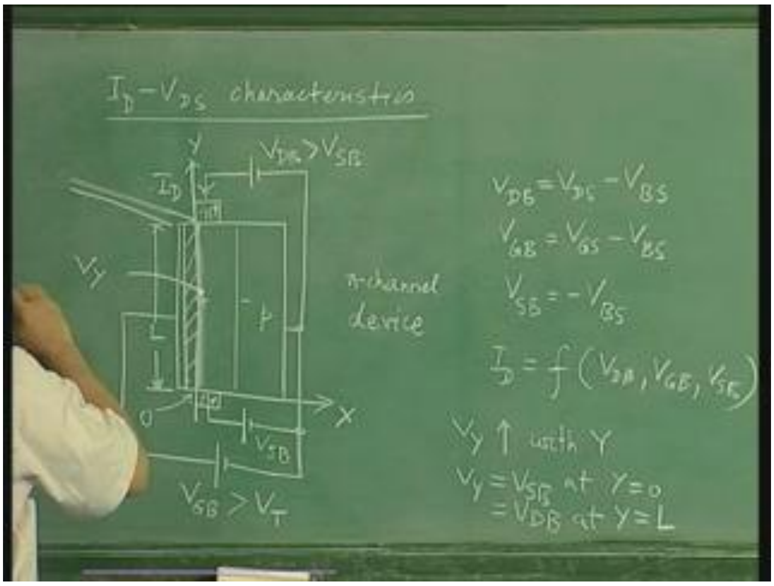

This can be done as follows:
For example, V_{DB} is equal to V_{DS} minus V_{BS}. Similarly, V_{GB} is equal to V_{GS} minus V_{BS} and V_{SB} is equal to minus V_{BS}. Now our approach here will give us ID as a function of V_{DB}, V_{GB} and V_{SB}. Then we will substitute these equations here and the same equation then can be written as a function of V_{DS}, V_{GS} and V_{BS}. So that is the outline of our approach which will be used to find out the characteristics. When we discuss about the charge picture inside the device we will clearly know the advantage of using the bulk as a common terminal. When we do that we will be able to write the equations for various charges very easily in terms of the Physics we have developed for the MOS capacitor.

Now let us look at the charge picture in the device to know how it looks like. Notice that when we do not have any difference between the drain to bulk voltage and source to bulk voltage that is when V_{DB} is equal to V_{SB} then the charge will be uniform because everywhere the potential is the same so you will have the inversion layer and you will have the depletion layer under the inversion layer or next to the inversion layer. Of course we are assuming that gate to bulk voltage is more than the threshold voltage of this capacitor for this particular source to bulk voltage including the body effect. So V_{GB} is greater than V_T which is of course a function of V_{SB} because otherwise you will not have any inversion layer and this is what we will assume.

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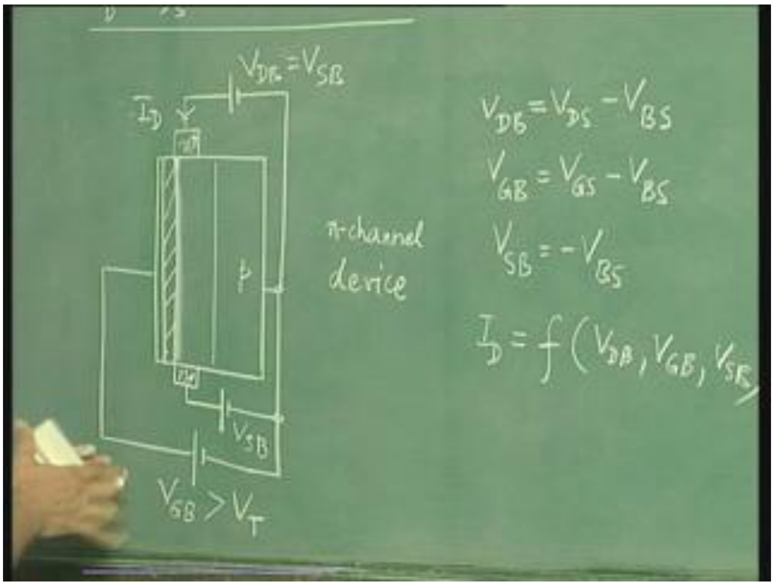

To start with when V_{DB} is equal to V_{SB} your picture is like this, a uniform inversion layer charge and a depletion layer next to the inversion layer which is also uniform. V_{GB} is greater than V_T so that the inversion takes place. Now to pass a current through the inversion layer you will change the V_{DB} to a value more than V_{SB}.

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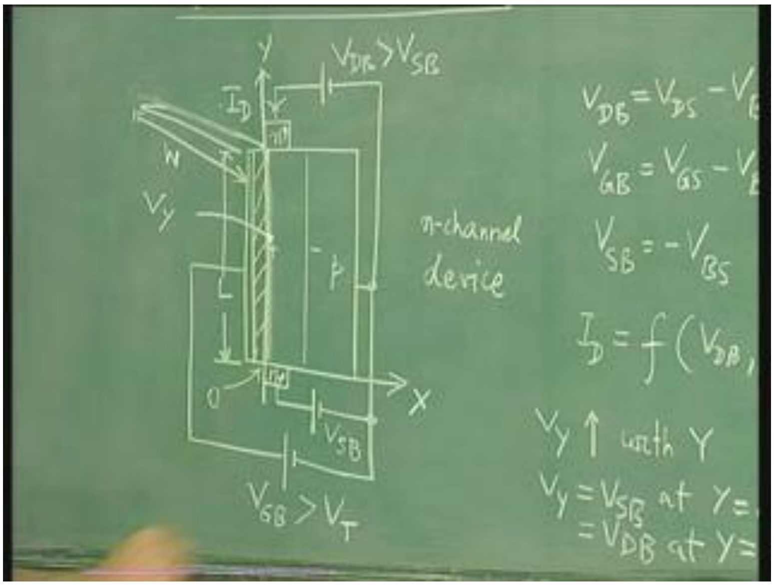

So when you make this more then this picture is going to be changed because the voltage along the channel now is going on increasing from V_{SB} at the source to V_{DB} at the drain. Now what is the effect of increase in voltage on the channel? Clearly if the voltage on the channel increases the voltage difference between the gate and the channel decreases as you move up. Now let us set up a coordinate system. This will be our x axis and this will be our y axis and this will be our origin. So you vary the distance from 0 to x in this direction and 0 to y in this direction. Now we are considering the effect of applying V_{DB} more than V_{SB}. Let us now define a channel voltage V_Y at any point y. Therefore this V_Y is the channel voltage.

Now how does the channel voltage change?
V_Y is equal to V_{SB} at the source and V_{DB} at the drain. Please note that all voltages are reference with respect to the bulk. So V_Y is the voltage between this point channel here and the bulk. Now obviously when V_Y is changing your depletion layer will not be uniform and your inversion region will not be uniform. Now we want to determine how the depletion and inversion charges change. First let us write down the value of V_Y. The V_Y increases with y and its values are V_Y is equal to V_{SB} at y is equal to 0 is equal to V_{DB} at y is equal to L where L is the channel length. So this distance is denoted as the length of the channel L. The width is the distance in the perpendicular direction. The width of the gate is in the direction perpendicular to this so it is something like this. If you take this perpendicular direction then that is the width of the gate.

Coming back to the effect of variation in the voltage along the channel on this particular charge such as the inversion charge and depletion charge as the V_Y increases V_{GB} that is the gate to bulk voltage minus V_Y which is the voltage across the oxide will go on reducing as you move in the y direction. Now, if the voltage across the oxide reduces obviously the total charge that is inversion plus depletion charge in the substrate will decrease. This follows from the parallel plate capacitor analogy. Therefore charge on any plate or electrode depends on the potential drop over the oxide.

We have discussed this in the context of MOS capacitor. We have also discussed in the context of body effect. The total charge here will decrease. But since the voltage across the inversion layer is increasing because there is an increase in V_Y. Obviously voltage drop here is increasing then the depletion layer has to expand. So the depletion charge should increase as you move in y direction. In other words, this is the MOS capacitor with a change in body effect from source to drain. So the body effect is increasing from source to drain. So total charge should reduce but depletion layer charge should increase so inversion charge should definitely reduce as you go from source to drain. So, as your body effect increases from source to drain because of change in V_Y increase in V_Y the inversion charge will reduce and depletion charge will increase.

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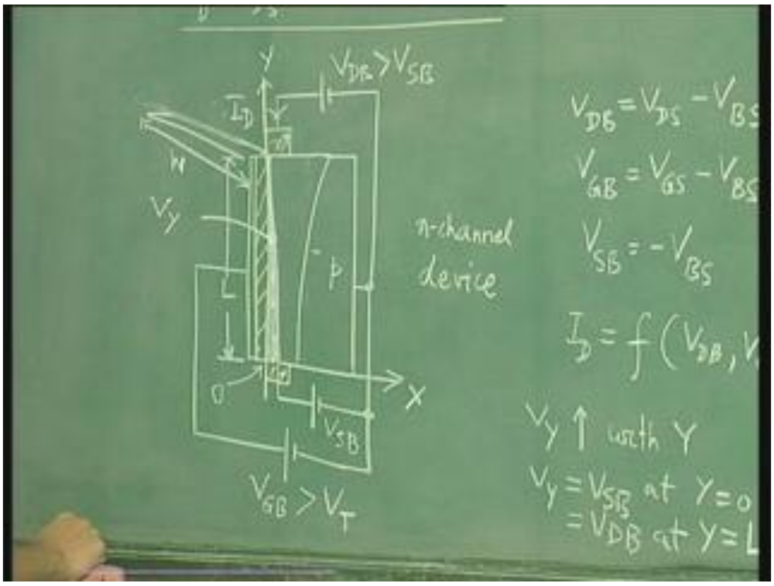

We shall show this as follows:

The inversion charge is something like this. So this shows the decrease in inversion charge. And at the same time you have an increase in depletion charge. So your depletion layer is shown to expand. This is the charge picture in the MOSFET. Now based on this charge picture we must derive the current voltage characteristics. Now we will show a simplified diagram showing only the variation in the charges in the MOS capacitor and see when you change your drain to bulk voltage how the current goes on increasing but then after some time it saturates.

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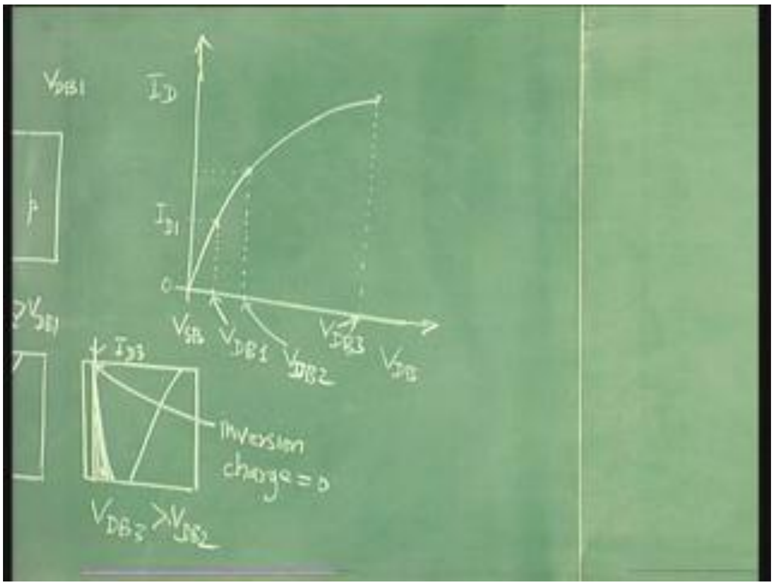

For this purpose let us draw a simplified diagram as follows for different drain voltages. So this is your substrate, this is the inversion charge and this is the depletion charge. This is for one value of V_{DB} so this is V_{DB1}. Now, for another value of voltage V_{DB2} greater than V_{DB1} your picture will be as follows. So this is the p-type substrate, here we are not showing source and drain it is understood this is drain and this is source and of course you have the gate on this side.

Let us just show the insulator. So, for V_{DB2} greater than V_{DB1} your picture would be as follows: Notice that the charge at the source will not change because your source to bulk voltage is not changing. Only the charge at the drain will become even less because the voltage is more. It is something like this. So this charge at the drain is less than this charge. But this depletion layer is wider. So at the source it remains the same but at the drain it is wider. So this V_{DB2} is greater than V_{DB1}.

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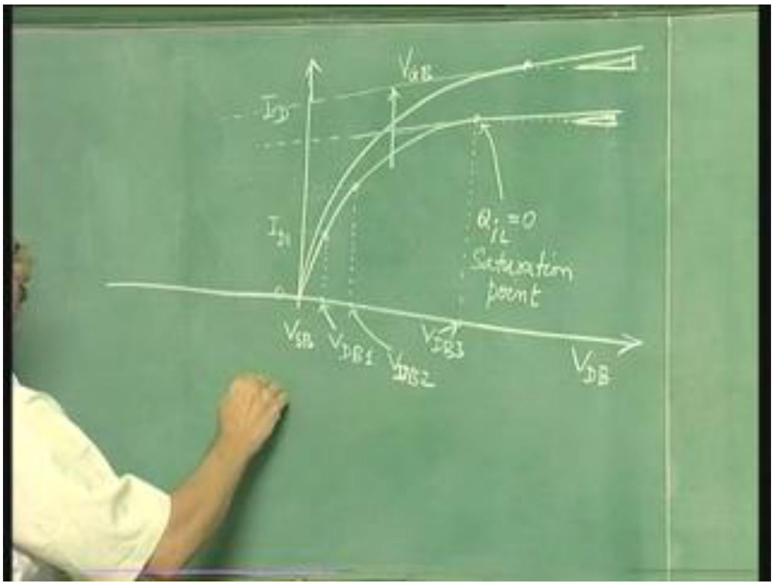

Now clearly from here if you want to show the current variation it will be as follows: We are drawing ID as a function of V_{DB} in this case and this point is V_{DB} is equal to V_{SB} when the current is 0. So we start from here. Now we can assume a simple resistor model and we can say that ID the current flowing in this direction is given by the voltage drop across this resistor. The resistor is formed by this inversion layer. Voltage drop across this resistor which is V_{DB} minus V_{SB} divided by the average resistance of this particular inversion layer will give you the current. Initially you had 0 and as you increase your V_{DB} you get the current. This corresponds to V_{DB1}, this is I_{D1}.

What about I_{D2} that is the current flowing here?
Now the average resistance of this region has increased because the charge at the source is the same but the charge at the drain here is less than this. Since the mobile charge that can participate in conduction is less at the drain here than in this case on average the charge available here for conduction is less than this charge. Since the charge available is less obviously the resistance is more. So now supposing the V_{DB2} is such that V_{DB1} minus V_{SB} is same as V_{DB2} minus V_{DB1} suppose it is an equal increment then for the same increment the increment in the current however will be less than I_{D1} because the resistance of this region is more than the resistance of this and that is because on average the charge has reduced when you increase the drain to bulk voltage.

Hence that being the case your current will increase but it will increase the increment in the current here which will be less than the increment I_{D1} which is something like this. So this increment is same as this increment but this increment in current is less than this increment because the average resistance has increased. Therefore your current tends to reduce. The increment in the current tends to reduce and that explains why you are getting a curve like this which is non-linear. It is an increasing current but it is increasing at a decreasing rate as you go to higher and higher drain to bulk voltage. Now a point will come when for some value of V_{DB} the charge here will become 0 the inversion charge which is going on reducing as you increase your drain to bulk voltage will become 0 so that will be something like this.

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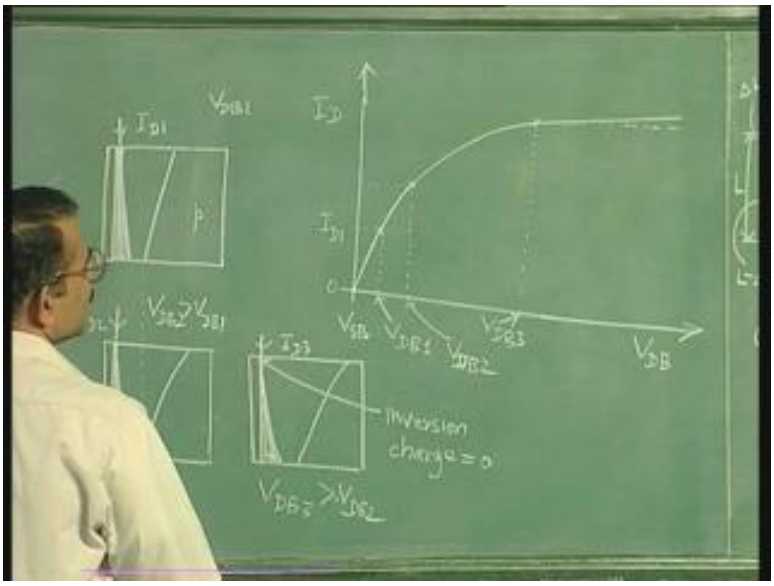

This is your inversion charge and it has become equal to 0 here. So this is I_{D3} and this is V_{DB3} greater than V_{DB2} and of course your depletion region will be even more which is something like this. Now for this case it can be shown that even if you increase your drain voltage after this the amount of charge here cannot reduce because already it has become 0. Therefore what will happen is, beyond this point it can be shown that the current cannot really change significantly if you increase your V_{DB} further the current cannot change.

Let us show this point on the graph here. This is V_{DB3}. Notice that V_{DB3} minus V_{DB2} is not necessarily V_{DB2} minus V_{DB1}. It is some voltage to which you come when the charge becomes 0. So here inversion charge is equal to 0. That is the voltage V_{DB}. Now let us explain why the current cannot change much beyond this point. If you increase your voltage beyond this point the charge picture will look something like this.

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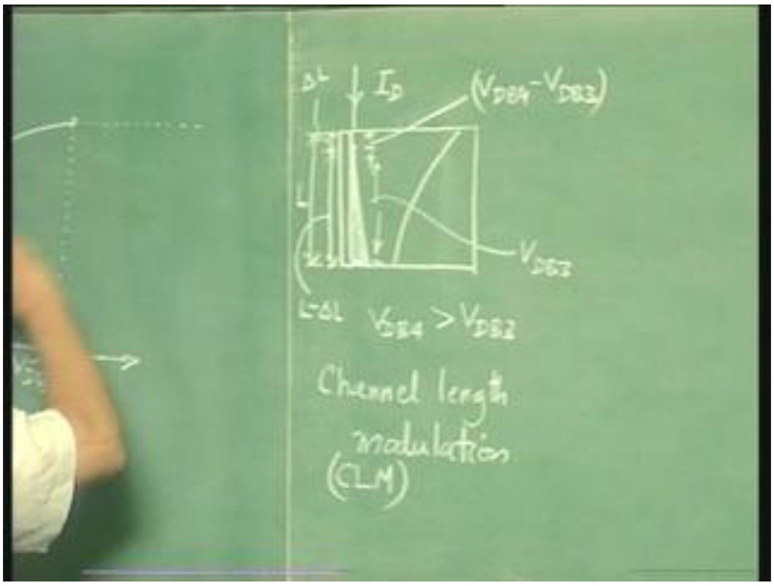

So you have a region delta L here, this is L The channel length over which the voltage beyond the voltage V_{DB3} as shown here. For voltage V_{DB3} the inversion charge becomes 0 right at this point at the drain. Now your voltage is V_{DB4} here greater than V_{DB3}. So, over this delta L you have a drop V_{DB4} minus V_{DB3} so here the situation is as follows: This is delta L so your voltage falling across this delta L region is V_{DB4} minus V_{DB3} the extra voltage beyond V_{DB3} and the voltage V_{DB3} is falling here. So this voltage is V_{DB3} and this is the 0 inversion charge point. So the 0 inversion charge point has shifted away from drain a little bit closer to the source by a value delta L.

We can therefore say that the channel length has now become equal to L minus delta L. In other words, you have what is called as the channel length modulation which we shall abbreviate as CLM. Now what is happening is, over the length of the channel equal to L minus delta L you have a voltage drop V_{DB3}. And since delta L is really small what is happening is the picture here for V_{DB4} greater than V_{DB3} is almost same as the picture for V_{DB3} the charge picture. So even when you change the drain voltage your charge picture is not changing significantly.

Therefore the current picture does not change much. In fact there is a very small increase in current because the resistance of this is a little less than the resistance of this simply because the length here is L whereas the length of the resistance here is L minus delta L, this distance is L minus delta L. So because of this delta L the resistance decreases a little bit and therefore the current increases to a very small value. That is why beyond this if the delta L was not there it would be just constant but in practice it will increase slowly. So, that explains how for a given gate to bulk voltage your current changes as you change your drain to bulk voltage.

The current starts increasing but the rate of increase decreases. Therefore the slope of the curve is decreasing because the average charge in the channel goes on reducing though your drain to bulk voltage is increasing. Ultimately at some point the inversion charge becomes 0 at the drain so this corresponds to the condition when Q_i at y is equal to L that is Q_{iL} is equal to 0. Now this point is normally referred to as the saturation point because beyond this point the current almost saturates though not exactly. It does not saturate totally because of the channel length modulation.

Here this region is normally referred to as the so-called ohmic or sometimes even linear region though it is not exactly linear. In fact only a very small region here near the origin is linear. But still sometimes people refer to the entire region as linear or ohmic region and beyond this you have the saturation region. So the nomenclature of saturation is different in bipolar transistor and MOS field effect transistor. So in the MOS Field Effect Transistor saturation is really referring to the active region of the current voltage characteristics whereas in bipolar transistor saturation is the other than active region that is the before the active region of the current voltage characteristics.

Now these terminologies mean different things in bipolar and MOS transistors because people who have been involved in the development of the bipolar transistor and the MOS Field Effect Transistor have been different. Different people have developed the theories for these two transistors. That is why the nomenclature means different things in the two different cases. Now, to complete the qualitative analysis before we take up writing the equations we must explain what will happen to the current voltage curve if you change your gate to bulk voltage. Now, if you change your gate to bulk voltage obviously the saturation point will also shift. So we would like to know, supposing you increase your gate to bulk voltage.

In what way will this point change on the current direction and on the voltage direction is what we will see next. Now evidently when you increase the gate to bulk voltage your inversion charge will increase. Now the question is what will happen to the saturation point? Let us look at this charge picture here.

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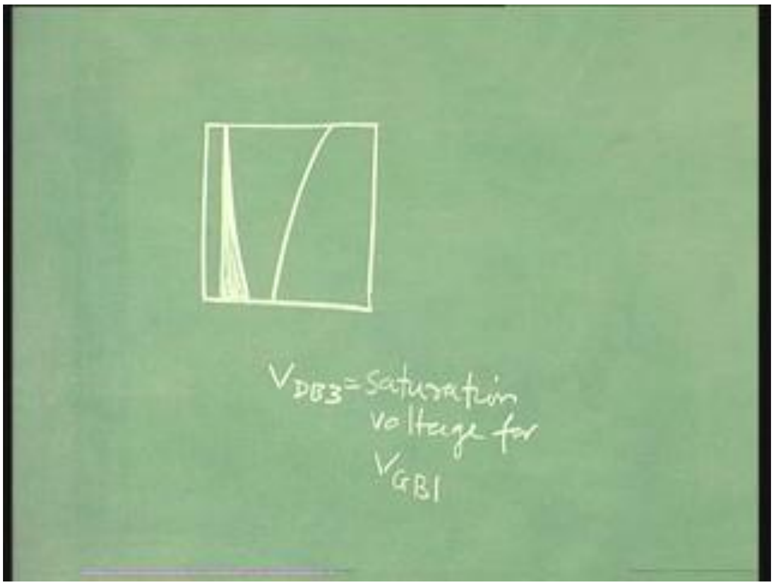

Supposing this is a charge picture for one value of gate to bulk voltage. We are drawing the charge picture at V_{DB3} that is when this device is saturated V_{DB3} is this saturation point for V_{GB1}.

Now you have increased the gate voltage to V_{GB2} gate to bulk voltage. Evidently this point here where the charge was 0 the charge will no more be 0 but it will be increased a little bit and it will go beyond 0. So now, if you want to push this charge condition to 0 evidently you will have to increase the value of V_{DB3} to reach the saturation point. Therefore what we gather is that for a higher value of V_{GB} the current at saturation will be higher and the saturation voltage also will be higher. So this point will shift up and to the right as something like this. This is your curve for a higher value of V_{GB}. So as your V_{GB} increases your curve moves up like this and the saturation point shifts to the right.

Now what happens to the slope of the curve beyond saturation?
When we derive the equation it will be clear that for a higher value of current the slope also will be more. So this slope here is more than this slope here for this curve. And in fact if you where to push all these lines back in this direction then it can be shown they will all intersect at one point in this graph. The voltage axis will all intersect at one point.

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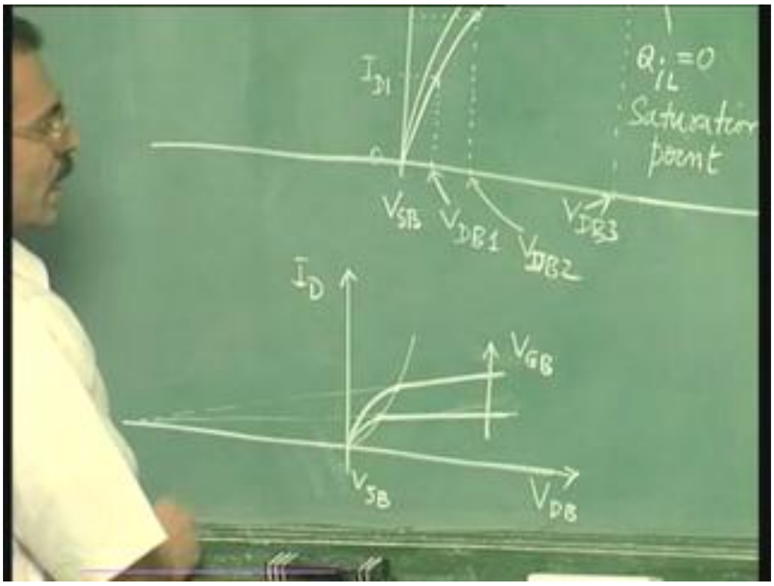

In other words, if I compress this graph then it would be something like this.So, in fact the way to draw the saturation and the ohmic region characteristics clearly is as follows: So qualitatively if a student is asked to sketch the drain current versus drain voltage characteristics, this is V_{SB} here, we are taking the bulk as the common terminal. The current voltage characteristics will look something like this. So we first draw a set of lines like this all starting from one point each of which represent the current in the saturation region for different gate bulk voltages. Then we separate the ohmic and the saturation region so these are your points and these are your curves in saturation. And then we join this to get the complete curve. This is very much like what we did for the bipolar transistor. The only difference being that this region in the bipolar transistor is very narrow whereas here this ohmic region is much wider.

In fact that is why the MOSFET has several applications where it is operated in the ohmic region whereas you do not have any such applications for the bipolar transistor. So in the ohmic region the MOSFET is used as a voltage variable resistor because as you can see from here when you change your gate bulk voltage the resistance which is shown by the slope of this curve goes on changing. So when you increase the gate bulk voltage the slope is more that is the resistance is less. To complete this analysis let us do one more thing.

How will the current change when you change the source to bulk voltage?
So far if you look at the diagram we have seen the change in current with drain to bulk voltage and with gate to bulk voltage. Now what happens when you change the source to bulk voltage? Now clearly let us look at this diagram here. When you change the source to bulk voltage keeping gate to bulk and drain to bulk voltage same the current will decrease because of increased body effect everywhere. So the inversion charge at the source will reduce but the depletion charge will increase.

Now what is of interest to us is the inversion charge because that carries the current. The inversion charge decreases at the source it will decrease everywhere and so the resistance will be more and current will be less. Therefore for increased source to bulk voltage or source to bulk reverse bias your current levels will be lower. So what we have drawn here is the graph for one value of V_{SB}. If you want to draw for another value of V_{SB} then each of this line for a higher value of V_{SB} will be lower.

How will the saturation point change with the source to bulk voltage?
We will discuss this point when we derive the expression for saturation voltage as a function of gate to bulk and source to bulk voltage. Next we will derive an equation for the current voltage characteristics. Now for this purpose we will use a simple diagram shown here.

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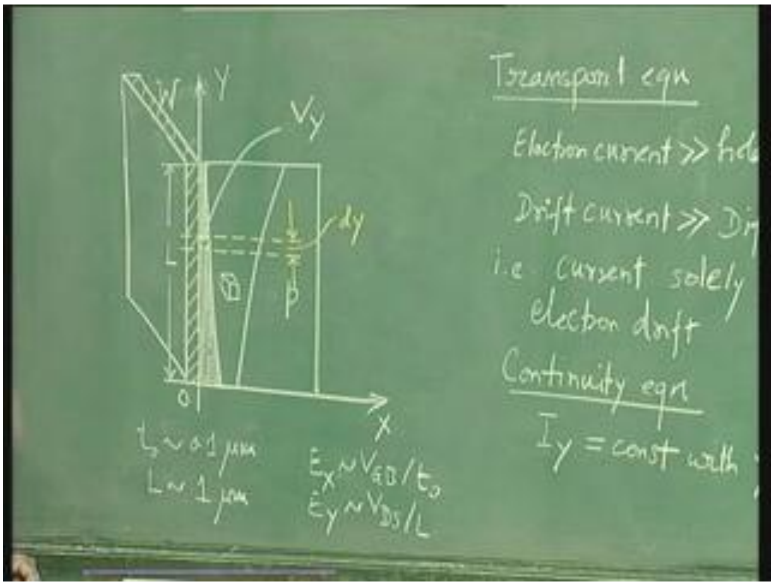

This is our inversion charge changing from source to drain and this is the depletion charge changing from source to drain. So, any point (y) you can take a small element D_Y and the voltage over this element d_y we can assume to be constant so the channel voltage here at this point is V_Y. So we will try to take this small element and then write down the expression for current as a function of voltage for this element. Then we can do integration and then get the picture for this total device. We are following this approach because the charge is continuously changing from source to drain. By analysing a small element and then integrating we can get the total picture.

Now what are the equations that will be used?
Recall what we said in the procedure for device analysis lectures that any device can be analysed using the five basic equations. That is the two transport equations for electrons and holes, the two continuity equations again for electrons and holes and the Gauss's law. We have already shown that using this how we can derive the equation for PN junction and for bipolar transistor which is based on PN junction. Similarly, in a rigours manner one can also show how starting from the five basic equations you can derive the current voltage characteristics. However, we will not follow the rigorous approach because here the picture is two dimensional.

You can see that you have an electric field that is applied in the y direction and you have an electric field along the x direction. The x directed electric field is from the gate to substrate and the y directed electric field is from the drain to source which enables you to pass the current. Therefore in a MOSFET the picture is actually two dimensional. So you will have to write all those five equations that is the transport equation, the continuity equation and the Gauss's law in two dimensions. And then you will have to make approximations and then show how you can reduce a two dimensional situation to a one dimensional situation. Now this process is mathematically a little bit involved.

We will avoid this thing in the first course. However, we will roughly show how the equations are being used. For example, if you take the transport equations we neglect the equation for holes because in a n-channel device the inversion layer is because of electrons and the hole concentration in this inversion layer is really very small.

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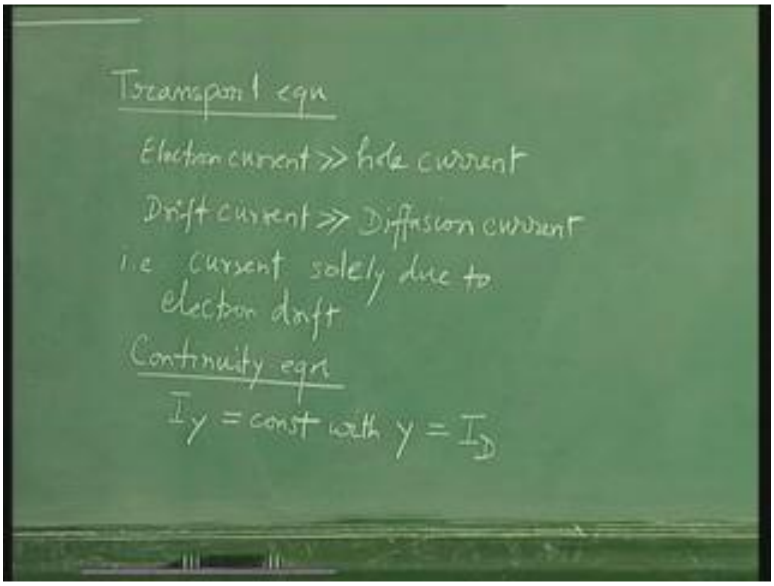

Therefore as far as the transport equation is concerned we are concerned only with the electron transport so one of the equation drops out. Now further in the equation for electron transport you have two terms that is the current because of diffusion and the current because of drift. We shall neglect the current because of diffusion. Please note why can there be a current because of diffusion because your electron concentration is changing from source to drain therefore obviously there is a tendency for diffusion. But then when your gate to bulk voltage is more than threshold voltage and this region is strongly inverted it can be shown that the drift current dominates over the diffusion current. Therefore your transport equation further simplifies to only electron drift.

Here we will write transport equation is electron current much more than whole current. And further drift current is much more than diffusion current. This means that current is because of electron drift. So current is solely due to electron drift. Now let us take the continuity equation. Again we need to consider only the continuity equation for electrons because holes are out of the picture. The electron continuity equation here will reduce to the following statement.

Please note that when you take the cross section a cross section will be perpendicular to this particular board. You take the current flow across any cross section that current will be the same along the y direction and therefore it will be equal to the drain current. That is the statement of continuity equation. So continuity equation is I_y that is the current across the cross section of the channel at any y is constant with (y) and therefore it is equal to the drain current I_D. Now we are left with the Gauss's law.

Where do we you use the Gauss law?
The Gauss's law is required to express the charge concentration here in terms of the gate to bulk voltage because that is a capacitor action. So when you want to express the charge concentration in terms of the voltage you will encounter a two dimensional field and potential distribution again in this case so that two dimensional electric field or potential distribution has to be approximated to one dimensional distribution to simplify the analysis. This simplification of a two dimensional to one dimensional distribution is termed as a gradual channel approximation in the context of MOSFETs. We will first write down what this approximation is and explain it.

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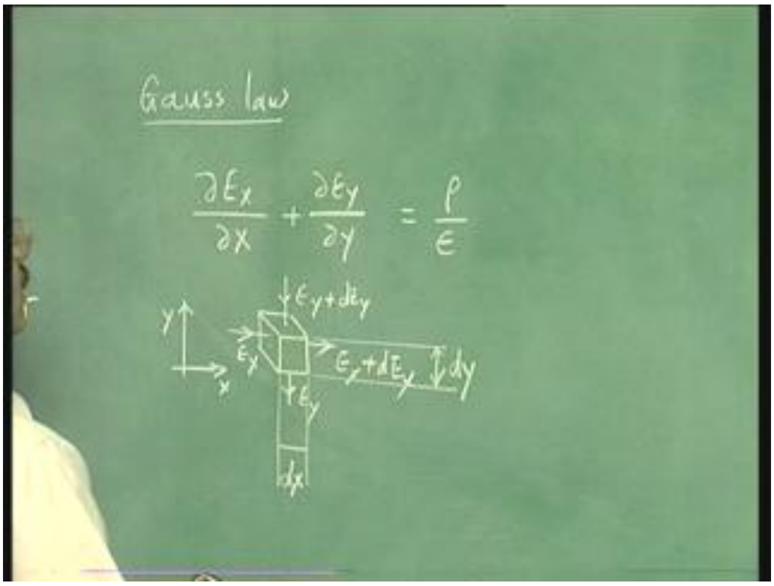

Gauss's law:
So Gauss's law is in this case a two dimensional picture so dowE_x by dowx plus dowE_Y by dowy is equal to rho by epsilon where rho is the space charge including the depletion and inversion charges. So please recall here what is the x and y direction. The x direction is in this direction, so it is the electric field from gate to bulk and that is the x directed electric field. And the field from drain to source is the y directed electric field. So what we are saying here in this formula is; dowE_x by dowx plus dowE_Y by dowy is equal to rho by epsilon is the rate of change of x directed electric field in the x direction plus rate of change of y directed electric field in the y direction is equal to rho by epsilon.

We can show it as follows:
If you take a volume in the substrate near the surface where you have the electric field, for example, if you are choosing the volume from somewhere here and for this volume what this equation says is, this is the x directed electric field going in and coming out, this the y directed electric field so actually this is E_Y and since the field is in this direction y is upward and x is in this way then it is this E_Y and this E_Y plus delta E_Y or d E_Y. Similarly this is E_x and this is E_x plus dE_x. Now this is d_x and this is dy. Now in this direction it is d_z. What we are assuming is that in the d_z or the width direction the fields are not changing. Therefore actually

we can neglect changes in that direction. So we can make this simple and we can show it like this.

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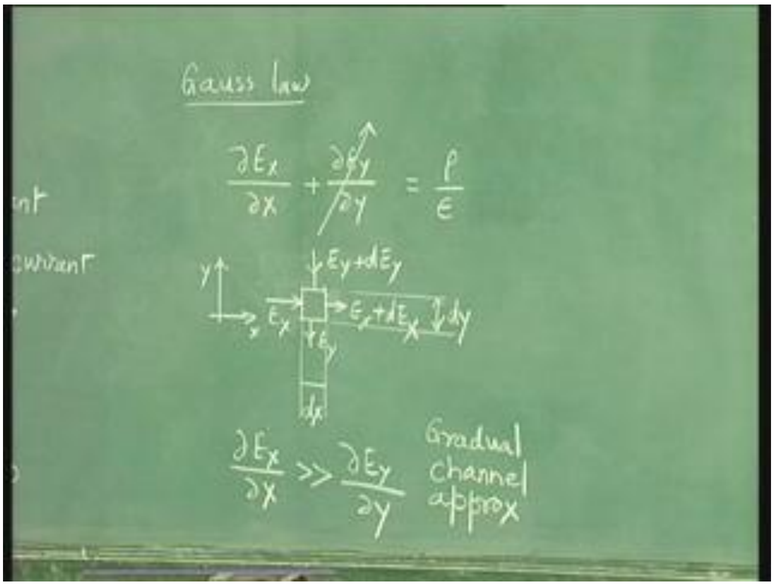

Now you see what this equation says is, the change in electric field here that is this increment dE_x by this dx plus the increment dE_y by this distance dy and this is rho by epsilon where rho is the space charge here. The approximation we will make is that we will assume dowE_x by dowx is much greater than dowE_y by dowy. The rate of change of field in the x direction is much more than rate of change of field in the y direction. This is the so called gradual channel approximation. With this approximation what will happen is this equation this quantity with become negligible. So dowE_x by dowx is approximately equal to rho by epsilon.

Let us understand why this mathematical equation should be called a gradual channel approximation. The reason for this is, what we are assuming is that the electric field is not changing much in the y direction as compared to the change in the x direction. Please note that the electric field is changing definitely in the y direction and in the x direction but the rate of change of electric field in the y direction is much less than the rate of change field in the x direction. If you calculate the fields you will find that the y directed field will be much smaller than the x directed field.

A simple estimate can be done as follows:
You know that the oxide thickness is less than 0.1 micron. The channel length of the device however is of the order of a micron. Now it has of course decreased, it has come to sub micron levels. But to make a simple calculation let us take these values. So oxide thickness t_0 is suppose 0.1 micron and the channel length L is suppose of the order of 1 micron. Now gate to bulk voltage is about 5 volts let us assume that the drain to source voltage is also 5 volts. Now clearly the field in the x direction is approximately gate to bulk voltage by t0 is the approximate order. Whereas the y directed electric field will be of the order of V_{DS} by L. So, if V_{GB} and V_{DS} are equal we assume for simplicity then definitely since t0 is ten times less than L the E_x will be ten times more than E_y.

In other words, the fields in the x direction tend to be higher than the fields in the y direction. Similarly, one can show by a more involved calculation that the rate of change of field in the x direction will also be much more than the rate of change of field in the y direction. That is equivalent to saying that your channel conditions are not changing very rapidly in the y direction. That is the meaning of gradual channel approximation. Gradual channel means a gradually changing channel in the y direction.

So with the help of this gradual channel approximation the charge that is the inversion charge which participates in the current can be calculated using the one dimensional analysis that we have done for the MOS capacitor. This is a great advantage. Though the charge is changing with y at any y you can use a one dimensional approximation and find out the charge in terms of voltages there. Then you can put the changing voltage and that will give the change in the charge concentration. This is the approach of simplifying a two dimensional picture to a one dimensional picture.

In summary the five equations are used as follows:
Transport equation, no hole current and only drift current for electrons. Continuity equation, again no hole current and the current is constant with y that is the statement of continuity equation. And Gauss's law you assume that the picture is really one dimensional that is in the x direction from gate to bulk and based on that you find of the amount of charge. This is the so called gradual channel approximation. Now bringing these results together we will show in the next class how an equation can be derived for the charge as a function of voltages at any element d_y at a distance y and how you can integrate the result from source to drain to get the complete current voltage equation.