Semiconductor Devices and Circuits
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Lecture – 38
MOSFET: I-V characteristics – Continued

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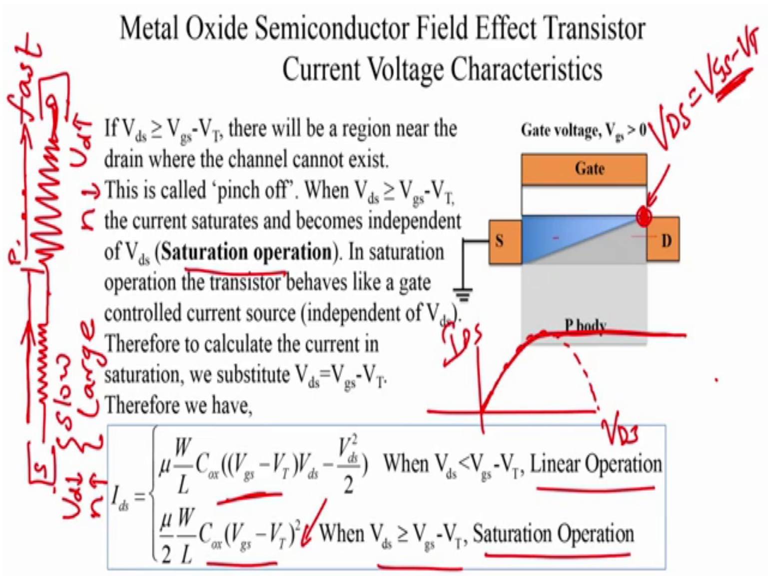

Ok so therefore, we can now write the current voltage characteristics of the MOSFET for 2 conditions, when V ds is less than V gs minus V T which is the linear operation even though this equation is non-linear it is it is linear when V ds is very, very small because you can ignore this term. And when V ds is greater than or equal to V gs minus V T we have saturation operation, and this becomes the current voltage characteristics you see that this current does not depend on V ds it is independent of V ds.

So, if you were to plot these 2 together you would end up with a plot like this you will find that if you plot V DS versus I DS you see this is a parabola. In fact, initially in the early regions it is linear, but in fact, a parabola right so it is something that I will do this, but just when V ds is equal to V gs minus V T the current saturates. And it does not depend on V ds anymore ok.

So, that is what these 2 equations telling you? So, these 2 equations are a good enough first order jump as to what the current voltage characteristics in a MOSFET are, but then we need one more detail ok, which is does V ds really not impact the saturation mode current ok.

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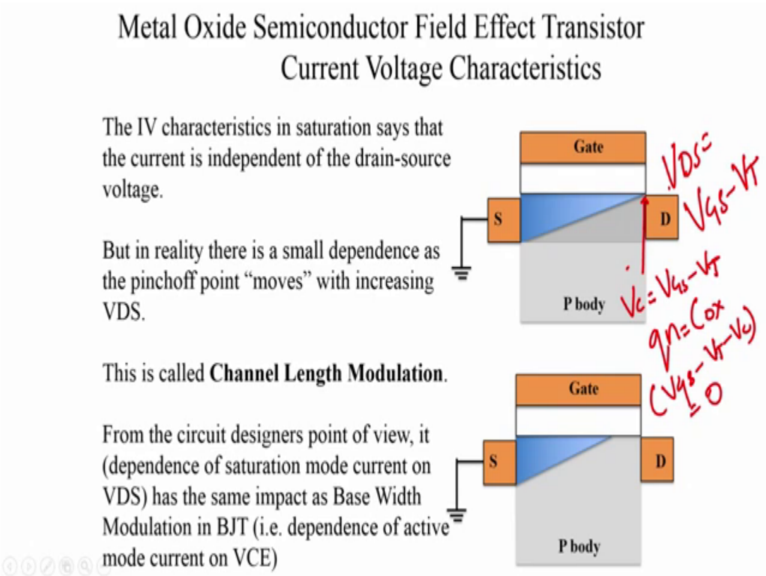

So you think about it so let us take the let us say we have Vd, we have just hit the V DS let us say V DS is equal to V GS minus V T. At this point the channel only this channel potential here, only that region has got the channel potential being equal to V GS minus V T.

And therefore my q n which is C ox into V GS minus V T minus V C is now 0 right. It is only that point which has got 0 electrons, everywhere else the channel potential is less than V GS minus V T because the maximum value it could take is the V DS equal to V GS minus V T. But let us say we increase V DS further, and we keep increasing V GS sorry V DS you keep increasing the drain to source voltage.

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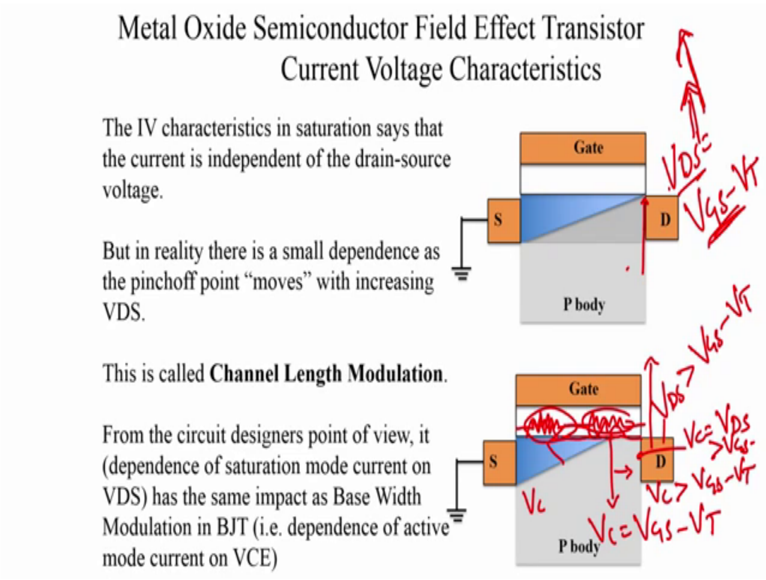

So, the drain to source voltage is now great much greater than V GS minus VT which means that if you look at the channel potential if you were to probe V C there is a point here where V C is already become equal to V GS minus V T. And beyond this V C is greater than V GS minus V T, and at this point my V C is equal to V DS which is of course, greater than V GS minus V T.

So, it is the pinch off point now relocates to a different region and as I keep increasing V DS, the pinch off point was start drifting towards the source side right. So, therefore, we are actually altering this resistor combination. So, if I told you there is a resistor beyond pinch off in the resistor below pinch off by actually moving the pinch off point I am changing the values of these resistances. So, technically speaking my V DS must influence my saturation mode current, but that is not what the equations told us ok.

So, what we are going to do is you are going to add an empirical correction to the current voltage characteristics. Now this fact that the V DS that when a transistor is in saturation the fact that the V DS can actually influence the current voltage characteristics is something called as channel length modulation.

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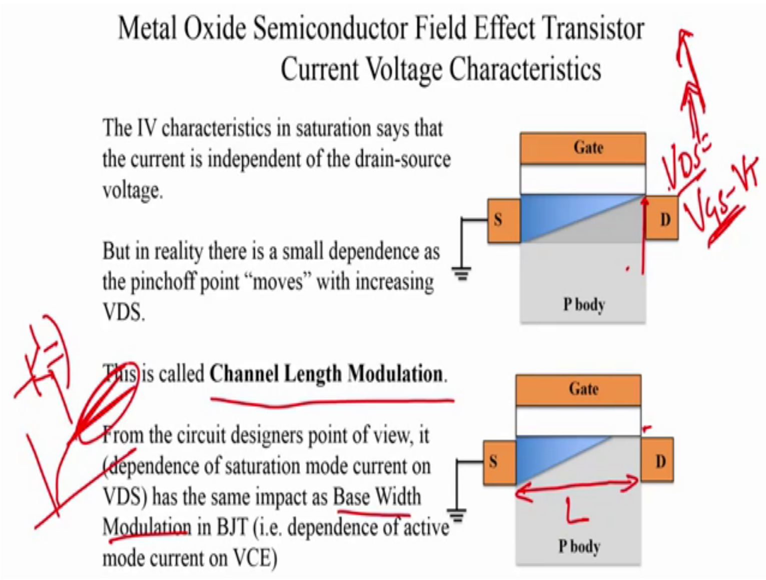

Which means that the effective channel length is being the behaviour of the channel is being modulated by the V DS, even though the device is in saturation. Now this is a very important phenomena because it directly impacts your circuit design particularly if you want to build amplifiers channel length modulation plays an important role in determining the gain etcetera.

Now, from the point of view of a circuit designer this channel length modulation a MOSFET has got a equivalent equivalence. If you remember in the case of a BJT we had the Base Width Modulation. And the base width modulation was you know you had your BJT it was operating an active mode operation, and in active mode operation your V CE was not supposed to influence the current a lot, but even then we saw that the V C does influence the current because the width of the base changes because the depletion thickness is changed.

And we saw that the current versus VCE did have a small trend even in active mode operation. It is exactly the same situation here, the physics is different completely different, but from the point of view of a circuit designer these 2 have the same impact ok. They determine the output impedance of your MOSFET or of the transistor BJT or MOSFET.

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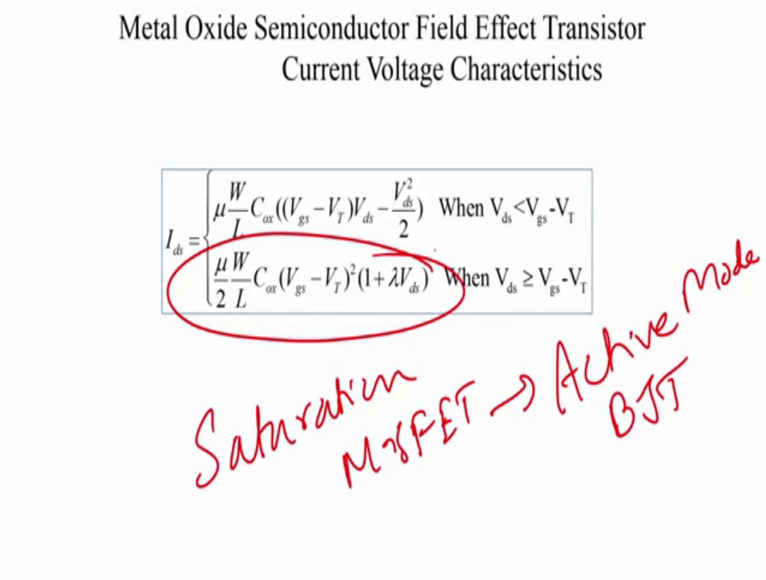

So, the channel length modulation impacts D, it makes the V DS influence the drain current. Not by too much by a little, but by a little, but it is important enough that it impacts the design of your amplifiers.

So now given these 2 equations ok so these are the current voltage characteristics of MOSFET the first order; given these 2 equations what are the plots looks like?

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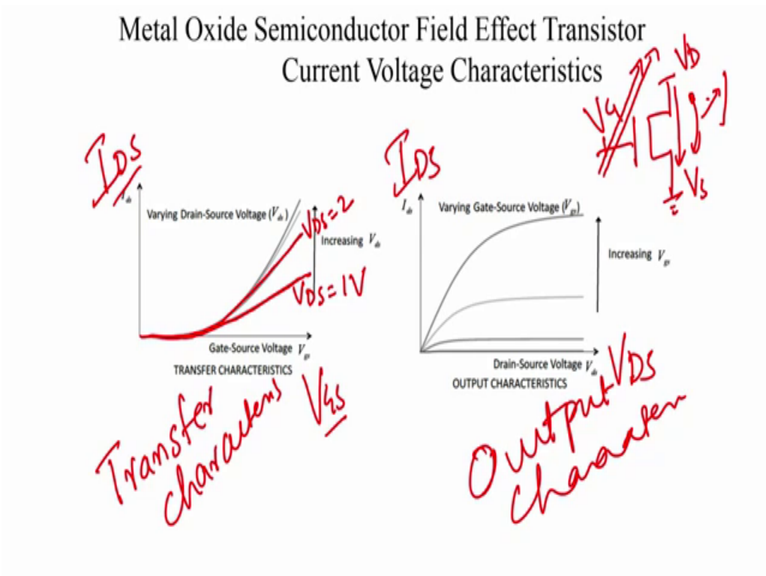

So, we have 2 plots we have the drain to source current versus V GS, which is something called as the transfer characteristics of the MOSFET. And we have the drain to source current versus V DS which is the output characteristics of the MOSFET.

So, what we do, we take the MOSFET. So, let us say I want to plot the transfer characteristics, we have the source, we have the drain, we have the gate the transfer characteristic I DS versus V GS. We set a value for the V DS we set this and then we sweep the V G. And we measure the current and then you change the V DS to a different value, and again sweep the V G and measure the current. So, let us take this particular V DS so here the V DS is let us say 1 volt. And now you sweep the gate voltage and as you sweep the gate voltage you find that the current increases. Now shift the V DS to 2 volts and now as you sweep the gate voltage you get a new curve and so on.

So, you develop that transfer characteristics of their MOSFET. And you can go back here and you can actually see whether you can fit these models into the transfer characteristics. Now for the output characteristics of the MOSFET what do we do we take the MOSFET.

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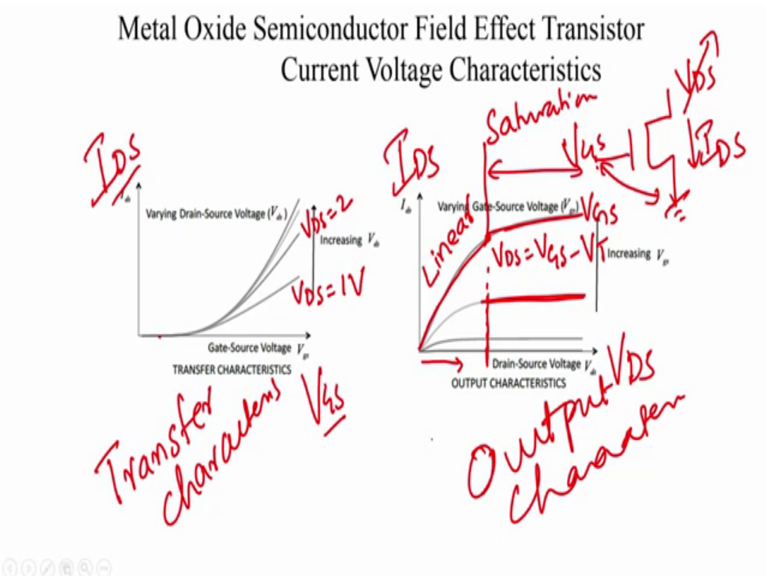

We fix our V GS we say that V GS is fixed we fix this voltage and we sweep the V DS and you measure the current through the device.

So, here let us take a particular value of V GS, and now we sweep the V DS and you trace this particular curve. And then you take another value of V GS and sweep the V DS and you get another characteristics. Now this particular characteristics both of them tell you a lot of things, but let us just look at this particular cap the output characteristics are little.

When V DS is very small you can see that the I DS and V DS relation are almost linear. So, that is the linear here the MOSFET behaves like a resistor, but you can keep increasing. So, we have picked a certain value of V GS isn't it? So, let us say V DS keeps increasing and let us say it reaches a point where the V DS is equal to V GS minus V T. So, let us say that is that point that corresponds to this x coordinate. So, till here the MOSFET is in the linear mode of operation and beyond this point the MOSFET enters a saturation mode of operation.

So, you can see that in saturation the V DS does not change the current a lot. The current is more or less constant, but still because of channel length modulation there is some small increase in the current. So, if you look at it the current does increase a little with increasing V DS, but not by too much ok. And that is sort of empirically added in by this little linear relation.

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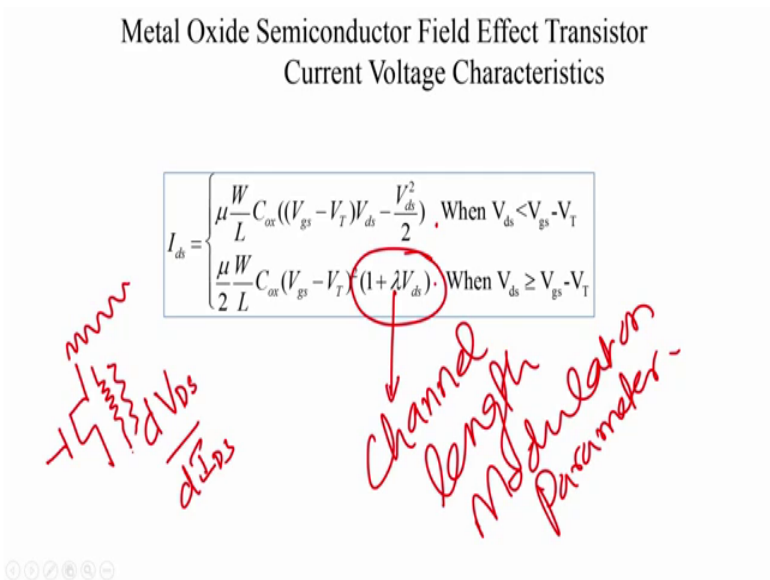

Where this lambda is something called as the channel length modulation parameter. Now if somebody were to ask you as to what is the resistance of the MOSFET or the small signal resistance of the MOSFET, what is the answer ok. So, think let us think of the MOSFET let us take the MOSFET and what we want to know is what is this resistance the small signal resistance here.

So, in other words we want to find out what is d V DS by d I DS, which is if I have a small signal fluctuation in the drain to source voltage, how does the current in the MOSFET fluctuate ok. So now, this strongly depends on whether the MOSFET is in linear or in saturation. So, let us say that the MOSFET is in linear mode operation.

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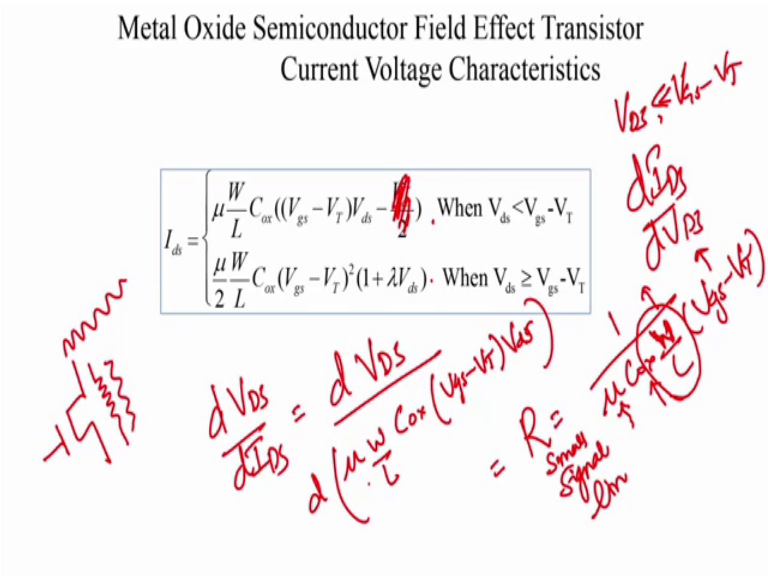

$$I_{ds} = \begin{cases} \mu \frac{W}{L} C_{ox}((V_{gs} - V_T)V_{ds} - \frac{V_{ds}^2}{2}), \text{ When } V_{ds} < V_{gs} - V_T \\ \frac{\mu}{2} \frac{W}{L} C_{ox}(V_{gs} - V_T)^2 (1 + \lambda V_{ds}), \text{ When } V_{ds} \geq V_{gs} - V_T \end{cases}$$

So, what is d V DS by d I DS for a MOSFET in linear. So, if the MOSFET is in deep linear let us ignore this term because V DS is let us say V DS is much much smaller than V GS minus V T so we can just ignore this term. So, what we are asking is; what is for a MOSFET in linear what is d V DS by mu W over L so, d of ids which is mu W over L C ox into V GS minus V T into V DS.

So, you just take this derivative and take the inverse. So, you take you calculate d I DS by d V DS and take the inverse of that, and you will end up with the resistance being small signal resistance; of the MOSFET in linear in linear mode operation being 1 by mu C ox W over L into V GS minus V T. So, that is the small signal resistance of the MOSFET which is operating in linear mode operation.

So, if you increase the mobility of the carriers as the resistance go up or down it definitely it makes a lot of sense that it goes down. If you improve the field effect by increasing C ox the resistance of the MOSFET goes down. If you make the channel width much larger than the channel length and increase the aspect ratio of the MOSFET of course, the distance travelled by the electrons from the source to the drain decreases and the sheet charge area increases and therefore, the channel length resistance will come down, if you increase the aspect ratio.

And if you increase the gate over drive voltage which is the gate to source voltage minus V T if you increase that definitely you have created more inversion more electrons and therefore, the resistance comes down. So, this is the resistance of the MOSFET in linear operation. Now what about saturation? So, what is d V DS by d I DS in saturation.

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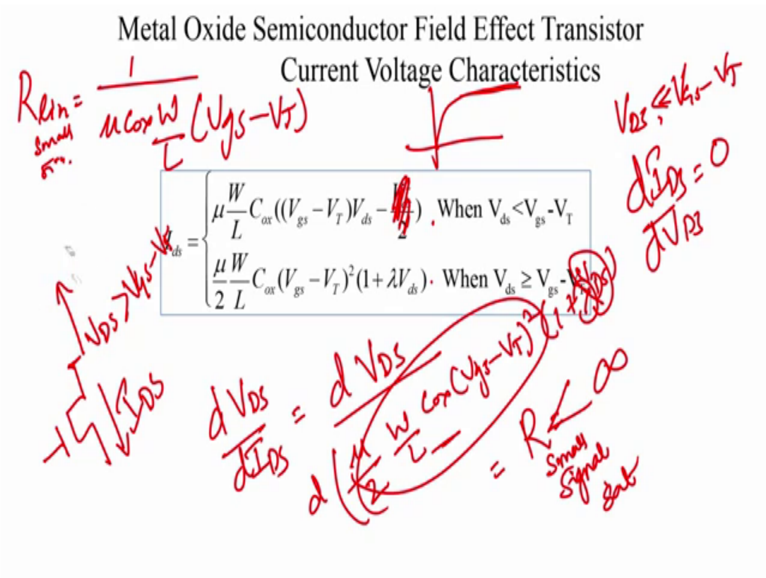

So, let us say the MOSFET does not have channel length modulation let us ignore that ok. So, you have this, now since this current does not depend on so let us write the linear equation first let us just keep it aside. So, that is 1 by mu C ox W over L into V GS minus V T that is the linear small signal ok. Now for saturation they are using a saturation mode current, but we are not going to we assume that it is an ideal MOSFET and there is no channel length modulation.

So, what is this since there is no dependence on V DS in the current this is infinite ok. Because d I DS by d V DS now becomes 0 in the current does not vary with the voltage it becomes 0. We can vary this voltage as much as you want in saturation ok. So, let us say V DS increases in saturation is greater than V GS minus V T and you increase or decreases voltage as much as you want in this region. The current in this will never change ok, it does not depend if there is no channel on modulation.

So, the MOSFET behaves like constant current source, you can change the voltage across it as much as you want and it behaves like a constant current source, and in a constant current source the output impedance is infinite and the MOSFET is telling you that it is got an infinite output impedance, but if you do include channel length modulation ok. So, if you do include this then this is no longer infinite you have a V DS term and therefore, you have a lambda into this particular parameter appearing in as the channel resistance ok.

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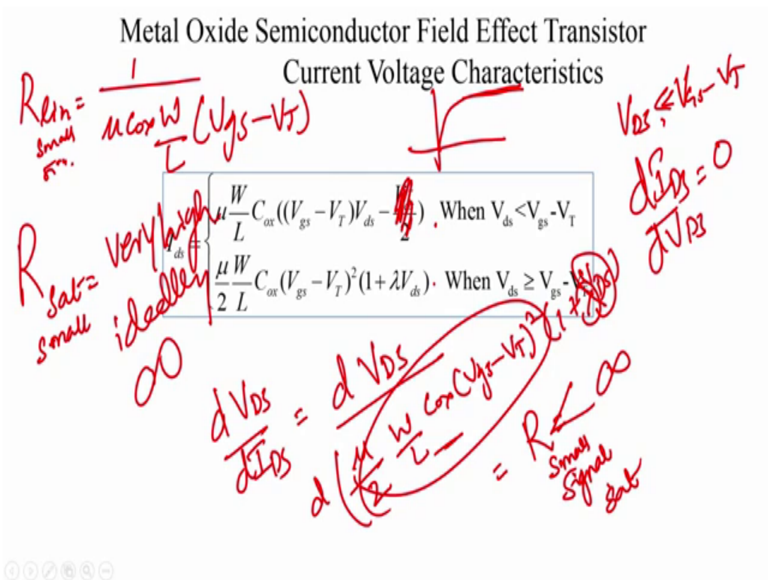

But ideally speaking the small signal resistance of the MOSFET in saturation is very high and ideally infinite ok.

So, if you look at these characteristics here if you take the slope you find that there is a resistance it is a finite resistance, but here you see that there is no change in current irrespective of what the change in V DS is and the resistance is infinite, the small signal resistance is infinite ok. We are not talking about what is V DS divided by I DS because you do have a large enough I DS. And that is I am we are not talking about the large signal resistor we are talking about the small signal resistance, which is if there is a fluctuation here then what is the fluctuation in the current an ideally it should be 0.

Now what are the transfer characteristics tell you; the transfer characteristics tell you that till a certain point there is no increase in current so we could define a threshold voltage somewhere.

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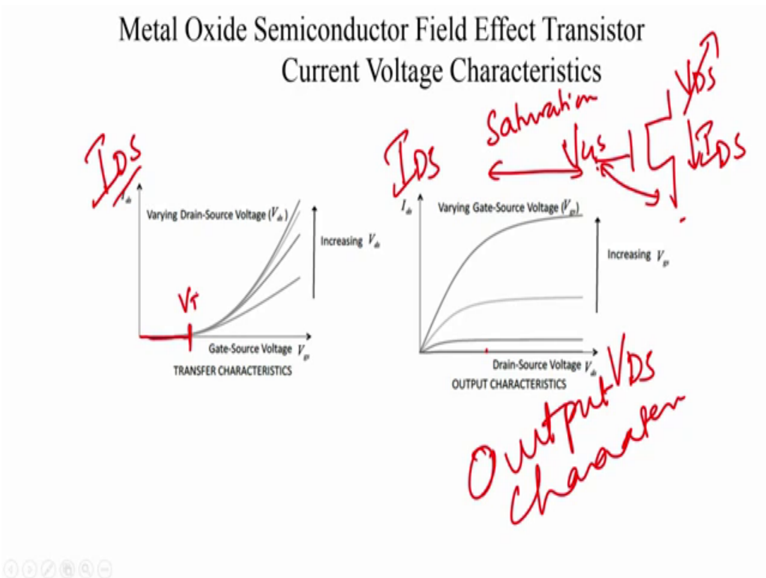

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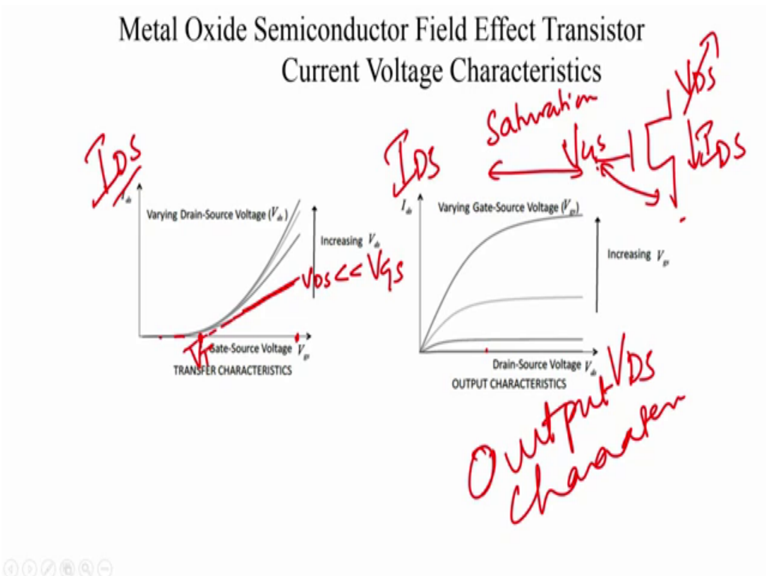

So, if you take a very low V DS if V DS is much smaller than any V GS that you are applying, then that characteristics is almost linear which is what is expected it is almost like a straight line. And if you were to project the straight line all the way back you would intercept the x axis at the point of V T that will be the threshold voltage.

So, we will have a small module on parameter extraction where we can show how to use these characteristics to extract the parameters, but just to look at that just look at that point again. Let us take the linear mode operation of the MOSFET right so here is the MOSFET in linear model.

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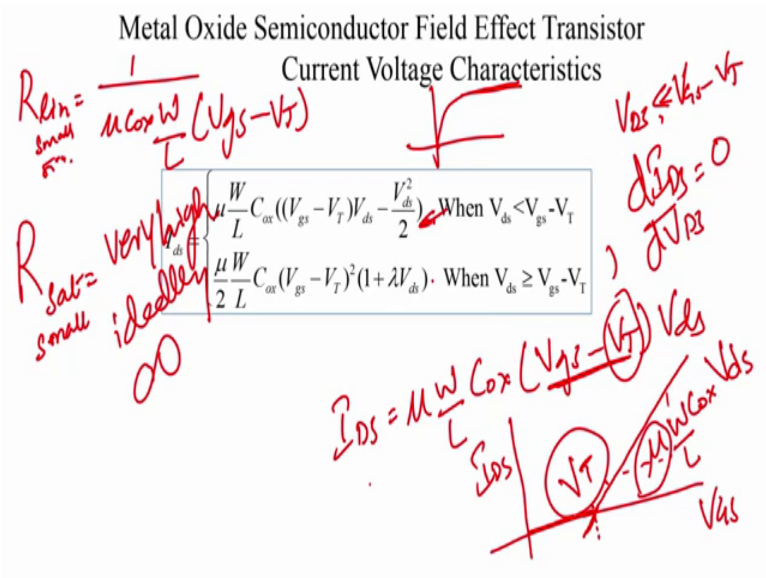

So, you have I DS is we will say it is deep linear where V DS is much smaller than V GS. So, you have mu l C ox into V GS minus V T into V DS. So now, we are plotting the transfer characteristics, how does I DS depend on V GS; it is a straight line. As below V T as long as V GS is below V T the current is 0 we will develop finer models which will tell us exactly what the current should be, but for now it is 0 because there is no inversion layer and after V T the current should linearly increase. And what is the slope of this the slope is simply mu W L C ox into V DS.

So, that is the slope of the current voltage characteristics current the transfer characteristics when the MOSFET is in linear mode operation. And what is the x intercept of this characteristics; it will be V T. So, you can work out and see what the x intercept of this characteristics is. So, this becomes a very useful method to extract both the mobility as well as the threshold voltage. So, it becomes a very powerful tool and you want to extract the parameters of a MOSFET.