HIGH SPEED DEVICES AND CIRCUITS

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Lecture – 22

MESFET
Shockley's Model and Velocity Saturation Effect

We have been discussing the MESFET IV characteristics based on a model called Shockley's model.

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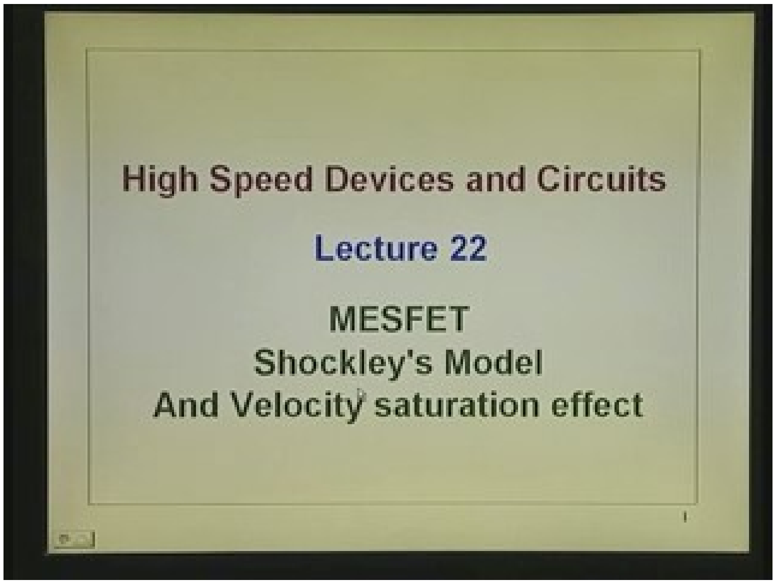

High Speed Devices and Circuits

Lecture 22

MESFET
Shockley's Model
And Velocity saturation effect

These are the original models given at least five decades back, 1950s, but still it holds good for most of the structures unless you have too much reduction in the files.

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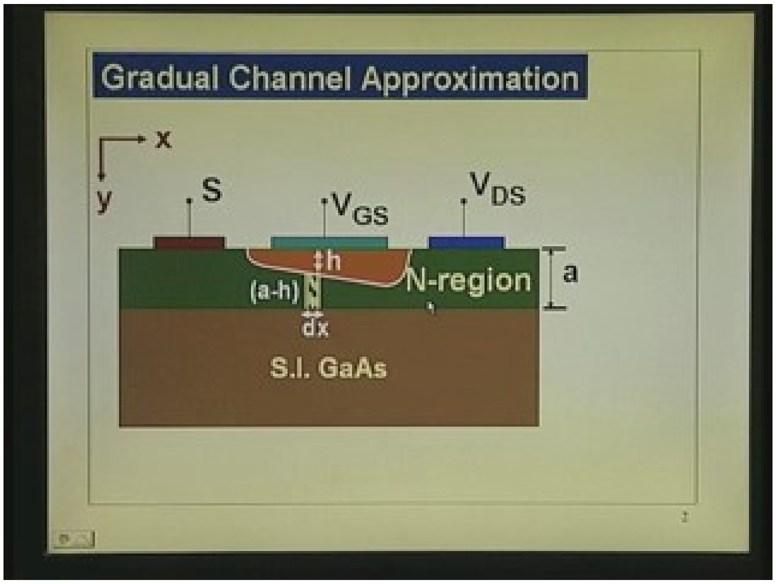

Gradual Channel Approximation

So what we did? I am just projecting the diagram once again. We found out what is the relationship between the drain to source voltage and the drain current. Just go back to what we have drawn; I just draw it side by side, the characteristics here.

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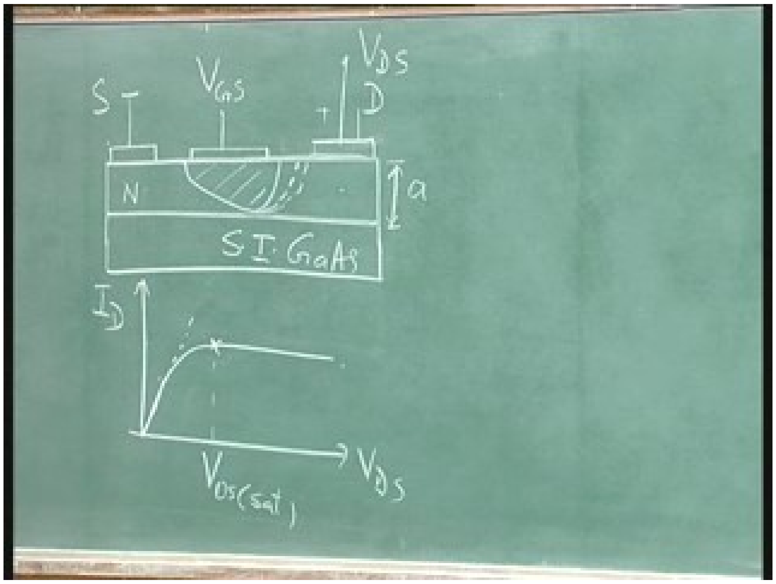

Do not need to do that or I will put it here, in fact what I will do is I will reduce the size here so that we can accommodate everything, semi insulating gallium arsenide (Refer Slide Time: 02:30). Now what we will do is we have this V_{DS} verses I_D characteristics.

So what I want to point out here is initially when the V_{DS} is small compared to V_{bi} minus V_{GS} it is linear characteristics. It is linear because depletion layer is almost flat there. The drop in this region is small compared to the drop across the depletion area. You have seen that. Beyond that point the shape of the depletion layer comes like this and the shape of the resistor becomes narrower and narrower, resistance goes up and therefore the current does not increase linearly it deviates from linearity and goes like that.

And at a particular point when this depletion layer reaches off the channel completely, the voltage drops here that is $V_{DS(sat)}$, we call it $V_{DS(sat)}$ because at that point this has almost closed the channel and there is a small opening left, so that whatever current enters here goes through that layer so that is the saturation voltage.

In fact, we have seen what this saturation voltage is and beyond that point current saturates even though the V_{DS} changes. What we are telling is between these two points the voltage does not change because if it is increasing this will have to widen. There is more scope for widening then the current will fall, so this does not change.

The question is where has that remaining voltage that you have applied gone? That point I did not mention yesterday in the last lecture. This extra voltage goes up; let us take the case where V_{GS} equals to 0. This is connected to that and this has saturated at that point. Extra voltage, this is 0 that if you increase the voltage beyond this point it appears across these two junctions: Shottky's barrier junction and Ohmic contact. It is like a diode.

The reverse bias, this is plus, this is ground, this reverse bias voltage appears, it cannot appear across this because if it appears across that, current would tend to fall. Then it will open up. So that dynamic equilibrium has reached. Beyond that point if I increase the voltage that depletion layer actually will spread like this, leaving that opening still, it will spread like this. I do not have space to show it here but it will go far enough or otherwise it will punch through into that. That is the way the depletion layer will spread out.

The voltage beyond this voltage that is $V_{DS(sat)}$, V_{DS} saturation beyond that point that appears across that. There is a two dimensional effect coming up here, all through it is one dimensional effect. In fact all I have been talking of gradual channel approximation does not hold beyond the point because that is a two dimensional effect. The fields will be going in this direction.

With that introduction or supplementing what we have been talking of yesterday or the previous lecture, we will go ahead further with our discussion. But the key thing to remember is that, this, what we have assumed is this point merges with this region and beyond that point the depletion layer just spreads out in the lateral direction, it does not move in the vertical direction that is the current saturation.

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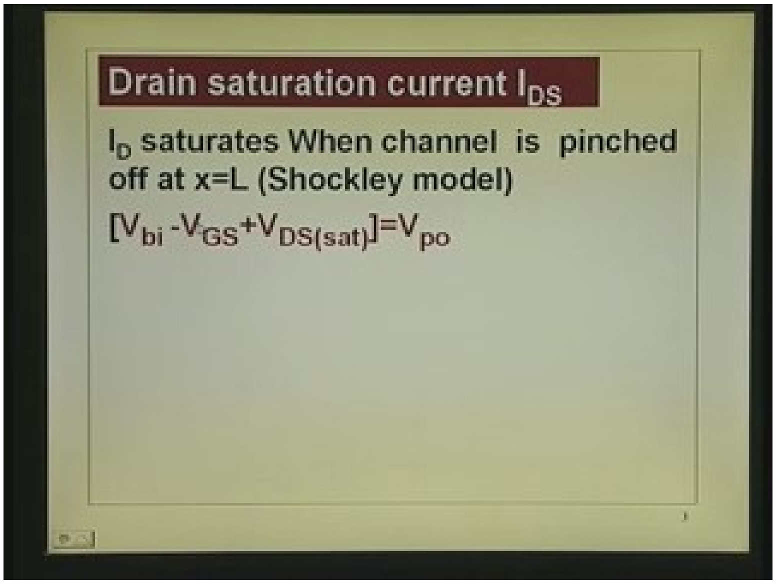

Drain saturation current I_{DS}

I_D saturates When channel is pinched off at x=L (Shockley model)

$[V_{bi} - V_{GS} + V_{DS(sat)}] = V_{po}$

We have also said that we will just quickly go through in a couple of minutes the saturation voltage, drain to source voltage plus the voltage across the depletion layer V_{bi} minus V_{GS} that is V_{p0} that voltage V_{p0} is equal to whatever voltage is present here, which is V_{bi} minus V_{GS} plus that drop that is $V_{DS(sat)}$. That is the Shockley's condition for saturation.

With that assumption we just wrote the equation for IV characteristics using ohm's law and we have arrived at this. I do not want go through it again because we are concentrating detail it is an expression that we get and look at that $V_{DS(sat)}$ we have substituted V_{p0} plus V_{GS} minus V_{bi} substituted from the equation form this here, that is V_{p0} plus V_{GS} minus V_{bi} and I retain other terms as it is. Now one thing that we define at this point is the threshold voltage. It is a very important parameter for the device. That is V_{bi} minus V_{p0}.

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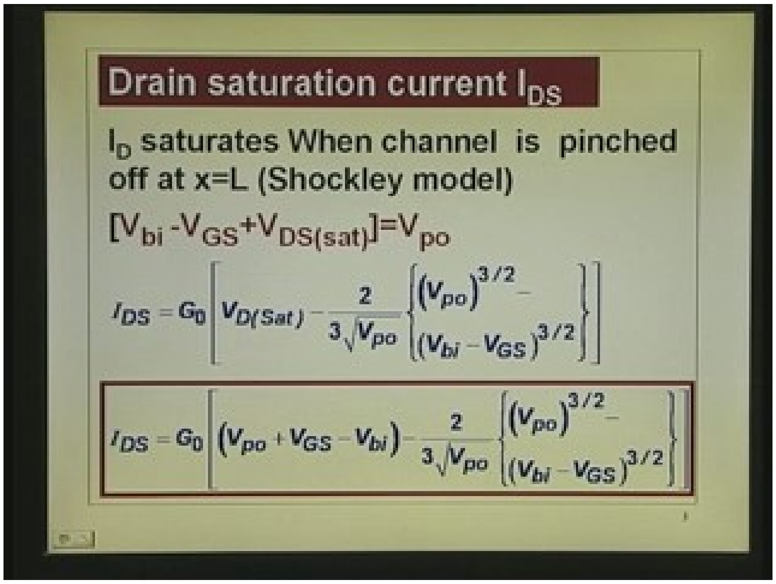

Drain saturation current I_{DS}

I_D saturates When channel is pinched off at x=L (Shockley model)

$[V_{bi} - V_{GS} + V_{DS(sat)}] = V_{po}$

$$I_{DS} = G_0 \left[V_{D(Sat)} - \frac{2}{3\sqrt{V_{po}}} \left\{ \begin{matrix} (V_{po})^{3/2} - \\ ((V_{bi} - V_{GS})^{3/2} \end{matrix} \right\} \right]$$

$$\boxed{I_{DS} = G_0 \left[(V_{po} + V_{GS} - V_{bi}) - \frac{2}{3\sqrt{V_{po}}} \left\{ \begin{matrix} (V_{po})^{3/2} - \\ ((V_{bi} - V_{GS})^{3/2} \end{matrix} \right\} \right]}$$

Actually here see V_{GS} and I can write this term as within bracket V_{bi} minus V_{GS} which is actually V_{GS} minus V_{Th}, threshold voltage. What we have said is the threshold voltage is voltage that we supply to the gate so that the channel just pinches off at the source end. Without any drain voltage if we apply a voltage to the gate that depletion layer all through will move. That is actually threshold voltage that is we found out or we defined yesterday, it is equal to V_{bi} minus V_{p0}.

All that we do is substitute for V_{bi} minus V_{p0}, threshold voltage all that we do and then pullout this V_{p0}, out of that make an approximation of V_{GS} minus V_{Th} is small compared to V_{p0}. Using that relationship you get that.

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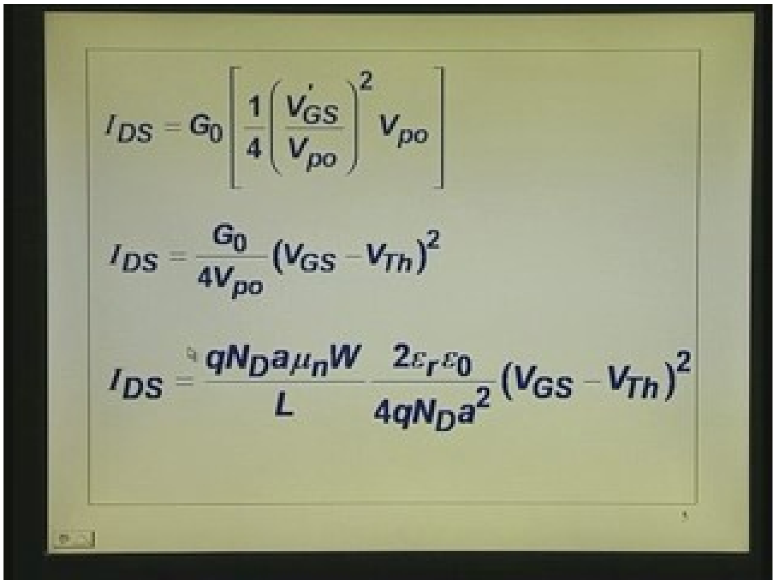

$$I_{DS} = G_0\left[\frac{1}{4}\left(\frac{V'_{GS}}{V_{po}}\right)^2 V_{po}\right]$$

$$I_{DS} = \frac{G_0}{4V_{po}}(V_{GS} - V_{Th})^2$$

$$I_{DS} = \frac{qN_D a\mu_n W}{L}\frac{2\varepsilon_r\varepsilon_0}{4qN_D a^2}(V_{GS} - V_{Th})^2$$

After deriving this expression for the current we said if current saturates then there is pinch off the channel drain end and then we have defined the term threshold voltage V_{bi} minus V_{p0} as threshold voltage substituting that in the equation and made an approximation that V_{GS} minus V_{Th} that is V_{GS} dash is small compare to V_{p0}, we get this. That we rewrite as, pulling out these two terms, this one substitute for G_0 and V_{p0} all that put together and canceling out, G_0 is a channel conductance, and V_{p0} is 4q N_D a squared, write up to epsilon$_r$ epsilon$_0$ and canceling out q N_D into a you get that term, because you have done that in the previous lecture.

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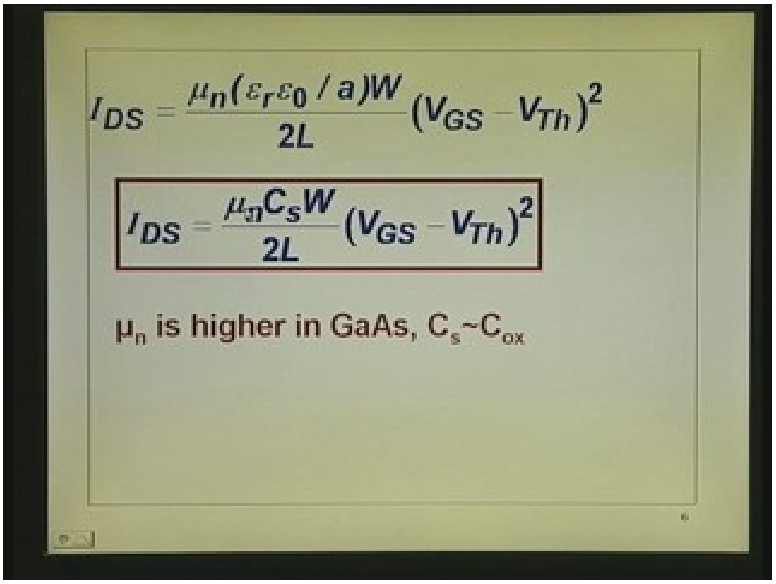

$$I_{DS} = \frac{\mu_n(\varepsilon_r\varepsilon_0 / a)W}{2L}(V_{GS} - V_{Th})^2$$

$$\boxed{I_{DS} = \frac{\mu_n C_s W}{2L}(V_{GS} - V_{Th})^2}$$

μ_n is higher in GaAs, $C_s \sim C_{ox}$

You get this actually is equal to, this is where we stopped at last time, mu$_n$ CsW by 2L V$_{GS}$ minus V threshold voltage squared, then exactly the same as the MOSFET equation.

On the difference is the particular term, capacitance, these are all the capacitance per unit area and here if you take a look at this mu$_n$ we are talking of all silicon meaning the same method of silicon but there will be one difference. This device, the mu$_n$ is governed by bulk mobility, the mobility in the bulk region. In the MOSFET the mobility is governed by mobility at the surface because you invert to that, the inversion. This is not a device which used for inversion. It is a device which is used for bulk conductance, so bulk mobility is placed in the hole here.

Bulk mobility is I have done the surface mobility. If you take silicon 1500 centimeter squared per volt second is the mobility of electrons in the bulk. In a surface due to the scattering in the surface what is the mobility? About thousand, people even worry about getting 1000 if you get 1000 your joy is quite high, because that is what we get if a surface is rough, you will get 900, 800 of that order.

It is not a device whose mobility depends on surface mobility, it is a device whose mobility depends on bulk mobility. Even if you think of silicon device itself MESFET, that will be better, but unfortunately the barrier heights are small in the case of silicon

phi_{BN} because that is 1.1 to take two thirds of that about (12:05) 0.75. That is why here and also your A star etc., is large so J_0 is large in those cases. So not really talk of MESFET in the case of silicon diodes, but we can talk of JFET in the case of silicon diodes.

That we will see the same equation holds good in the case of JFET, absolutely no problem. What is the difference? That short key is replaced by p plus n junction instead of metal semi conductor it will be replaced in p plus n junction. It is understood that all the theory that we have been talking of here, all the equations that we have derived for MESFET or exactly the same as that of JFET.

We are not talking anything different, only thing that has made the difference is, there is an insulating layer below and there is active layer here. You can have a p plus n junction is in the top, we can have it in the bottom also, then you can have depletion layers at both ends. Instead of having a here, you may have 2a there or you can talk about a by 2 and total thing as a. Both are same thing. What we are saying is the mobility that we are talking of here is better and when you switch over to gallium arsenide you can actually make better MESFET compared to a MESFET in silicon. In the case of gallium arsenide the mobility of electrons is 8500 ideally. If it is not 8500, let me get it as 5000 centimeter squared per volt second, so three to four times higher mobility and C_s, what is C_s?

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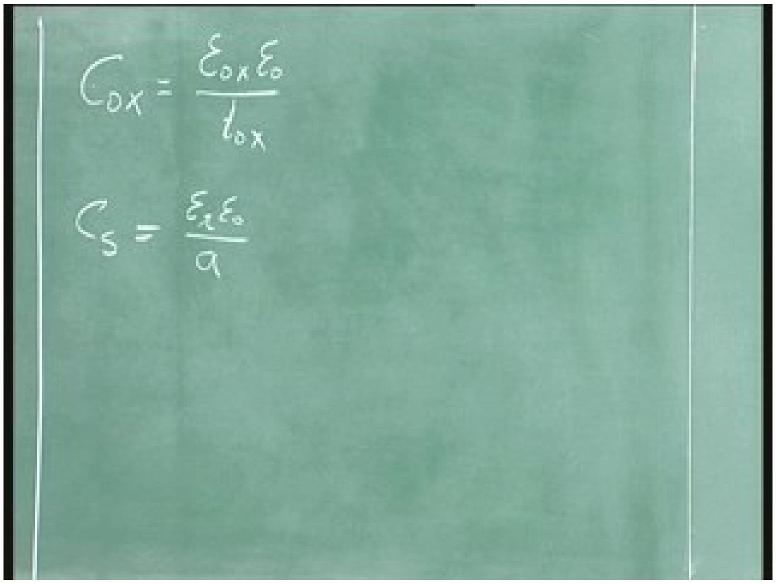

$$C_{ox} = \frac{\varepsilon_{ox}\varepsilon_0}{t_{ox}}$$

$$C_s = \frac{\varepsilon_r\varepsilon_0}{a}$$

It is a C here; C_{oxide} is $epsilon_{oxide}$ into $epsilon_0$ divided by t_{oxide} in the MESFET. t_{oxide} it is an oxide thickness, permittivity of silicon dioxide, $epsilon_0$ is 8.854 into 10 to the power of minus 14 farad per centimeter. I am not multiplying by area because this is per centimeter squared.

C_s what is Cs? (Refer Slide Time: 14:35) Just take a look at here. That is the capacitance of the depletion layer itself, $epsilon_r$ $epsilon_0$ divided by a. That is the capacitance of the channel if the channel is closely depleted per unit area, capacitance for channel per unit area if the channel is fully depleted, totally, uniformly, that is the capacitance. Now that is here between these two, for silicon this is close to 4, we can talk about 3.94 in that range so 4; and this is for gallium arsenide 10.8; silicon it is 12.

We have to talk of silicon MESFET or JFET or silicon MOSFET, this term is larger than that, at least about four times larger, plus you have got the mobility term so all put together you will see here that this particular term altogether is larger. We will have a factor of 10 or more compared to silicon MOSFET. This tells you that you will get I_{DS} larger than for a given voltage source V_{GS}. V_{GS} minus threshold would be representing the voltage swing, for a given voltage swing we will have a larger change in current; it should be mean that you get a better transconductance, for given size.

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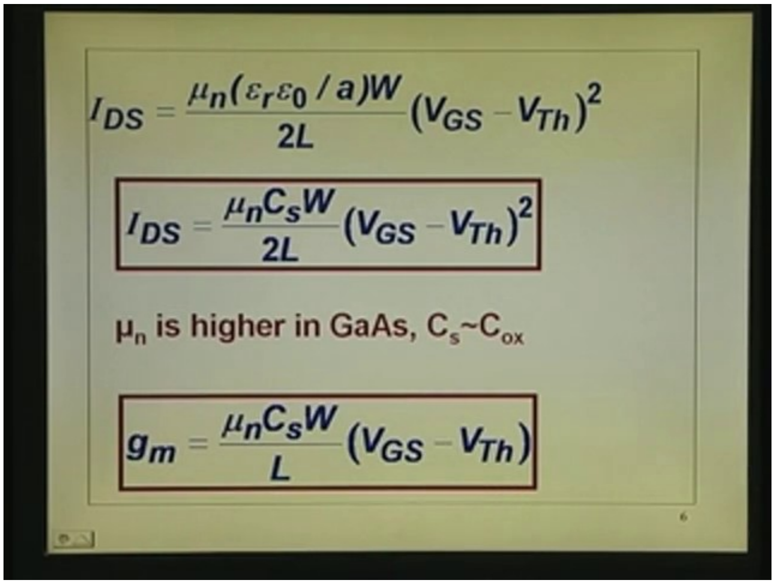

$$I_{DS} = \frac{\mu_n(\varepsilon_r\varepsilon_0 / a)W}{2L}(V_{GS} - V_{Th})^2$$

$$\boxed{I_{DS} = \frac{\mu_n C_s W}{2L}(V_{GS} - V_{Th})^2}$$

μ_n is higher in GaAs, $C_s \sim C_{ox}$

$$\boxed{g_m = \frac{\mu_n C_s W}{L}(V_{GS} - V_{Th})}$$

For given W by L ratio because this is larger than that of C oxide that is Cs and because mu$_n$ is larger in gallium arsenide and also because of the bulk properties it is larger than that of mu$_n$ in silicon, we get this factor much larger. We get it about ten to fifteen times larger because mu$_n$ is still larger and Cs also is larger.

This is one of the better things that have happened; the moment mu$_n$ is larger what the implication of that is? Driving capability of the device is better, that is delta I_D by delta V_{GS} for given change in voltage the current changes larger. The driving capability is better for given size. If the driving capability is better what is the implication of that? It has charged capacitance fast; you can charge capacitance fast because more current can be pumped in at a short time. What does it mean? It implies you are looking in to a device which can make the circuit performance faster. That is where gallium arsenide based devices are better performers, they perform better and better with higher speeds when compared to silicon based devices and also MOSFET based devices.

Infact I was just mentioning the other day, some people in some of the companies in US who were coming here just for a discussion, we are thinking of the MOSFET with thinner and thinner oxides. You remove the oxide we get MESFET. That should be the better performance, because we talk about bulk mobility. It is easily said than done. Then you solve lot of problems associated with that, but I am sure people are moving in that direction.

Finally, remove the oxide. You do not have to worry about all those things. In fact, you can see the flavor of that, when we discuss the gallium arsenide in MESFET properties. One more thing is this; it has better transconductance, better speed.

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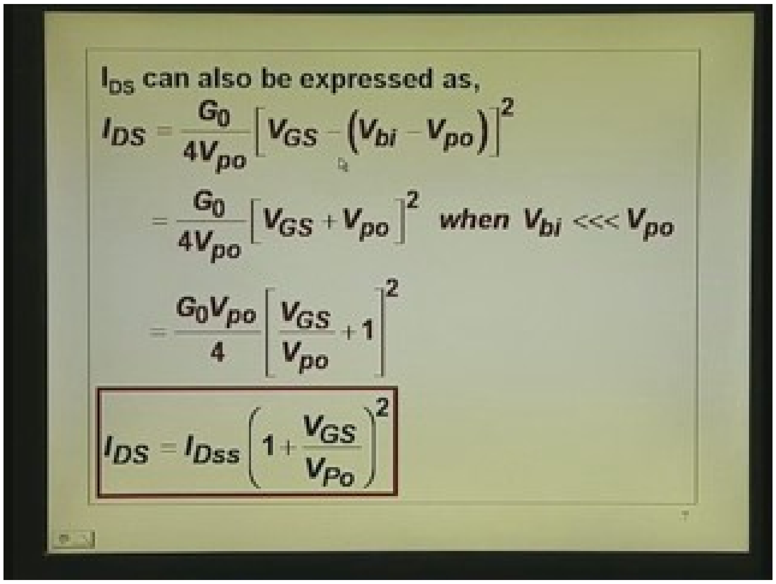

I_{DS} can also be expressed as,

$$I_{DS} = \frac{G_0}{4V_{po}}\left[V_{GS} - \left(V_{bi} - V_{po}\right)\right]^2$$

$$= \frac{G_0}{4V_{po}}\left[V_{GS} + V_{po}\right]^2 \quad when\ V_{bi} <<< V_{po}$$

$$= \frac{G_0 V_{po}}{4}\left[\frac{V_{GS}}{V_{po}} + 1\right]^2$$

$$\boxed{I_{DS} = I_{Dss}\left(1 + \frac{V_{GS}}{V_{Po}}\right)^2}$$

Now in this context I want you not to lose track of what we discuss usually in JFET, particularly in books like, the under graduate books like, Millman and Halkias. You know that you see a different type of form. You do not see the term threshold voltage but let us see whether it is different from that equation that we have derived; under what condition it becomes that equation. The equation that we will see, the equation that we had just known was, let me go back to that once to make sure that what you are doing is right. This is the equation that we wrote that we simplified and put it as mu$_n$ Cs W by two L V_{GS} minus $V_{threshold}$ whole squared.

Same equation G_0 by 4 V_{p0} into V_{GS} minus $V_{threshold}$ whole squared, I am substituting back for V threshold, V_{bi} minus V_{p0}. In fact I am doing back to the equation which we have written in the different form before the final simplification. Here if I remove this V_{bi}, when can I remove the V_{bi}? I can remove it when that is small compared to that. If we are talking of V_{bi} afterwards 0.6, 0.7 or 0.8 volts and if I am talking of V_{p0} 3 to 4 volts, then I can say that the fair amount of accuracy or with less amount of error, I can neglect that.

See on what conditions you get that Millman and Halkias formula? It is a same formula, after all its parallel also put there, so I neglect this I get V_{GS} plus V_{p0} squared. And I substitute it for this, I do not substitute, that is where the simplification is, in the sense you do not worry. This is circuit engineer proof totally; you do not worry what is mobility and all the things. You plug this or combine all these together, into a term call I_{DSS}. This is the term which matters the most, I_{DSS}. What is that? That is that quantity.

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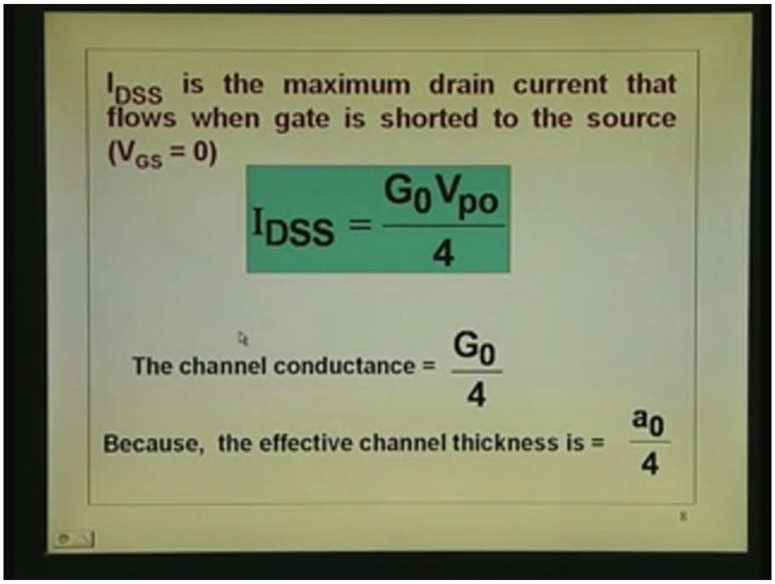

I_{DSS} is the maximum drain current that flows when gate is shorted to the source ($V_{GS} = 0$)

$$I_{DSS} = \frac{G_0 V_{po}}{4}$$

The channel conductance = $\frac{G_0}{4}$

Because, the effective channel thickness is = $\frac{a_0}{4}$

Now what is that I_{DSS}? I_{DSS} is nothing but G_0V_{p0} by 4 and I_{DS} is the saturation current. These are not the formal currents; these are expressions for current in this region. Whatever we are talking of is only the saturation in the region. It is because we may need certain assumption that V_{bi} minus V_{GS} plus $V_{DS(sat)}$ is equal to V_{p0} that assumption we are made. It is in that region. The same equation here hold good. So what we are telling is this current is I_{DSS} into 1 plus V_{GS} by V_{p0} whole squared and if I put in that expression V_{GS} equals to 0 then I get I_{DSS}. Infact you have made two things known: you have neglected V_{bi}, made it equal to 0; and now if V_{GS} equal to 0 the current that shows at the saturation is that I_{DSS} current. Infact it is actually the current which you get a V_{GS}, V_{bi} both are 0, because we neglected all those things.

In other words if we look into this diagram, this is actually 0 here. V_{bi} is 0, V_{GS} is 0, and from there it is moving right up to pinch off here. That is the situation that you have got, like this. See from here if I go on up to this point, right up to this point, this linearly if I go what is the channel area? Effectively it is a by 2, a and 0, a by 2. An average channel conductance will be G_0 by 2.

What is the voltage here? V_{p0}, it is virtually V_{p0}. $V_{DS\ (sat)}$ equal to V_{p0}. In that case, V_{bi} minus V_{DS} equal to 0, that is V_{p0}. So V_{p0} divided by that resistance is a current, saturation current. I_{DSS} would mean that the V_{p0} divided by the resistance of that portion but that would have been G_0 by 2, but it is G_0 by 4 because it is not linear. This is varying as square of the voltage; it is actually coming like this. Instead of being like this, instead of being linear there it is bending down there like that, so that the effective area channel height on an average is a by 4, that is implication.

The Halkias and Millman formula is I_{DSS} into 1 plus V_{GS} by V_{p0} squared it is the same as that what we have got except you put there V_{bi} is small compared to V_{p0}. It is just what we said now; I_{DSS} is the maximum drain current that flows when gate is shorted to the source that is V_{GS} is equal to 0. We just now explained that. I_{DSS} G_0 into V_{p0} by 4, channel conductance is G_0 by 4, if it is linear the G_0 by 2 but it is still less because the curve is down, we like that because the effective channel thickness is a_0 by 4.

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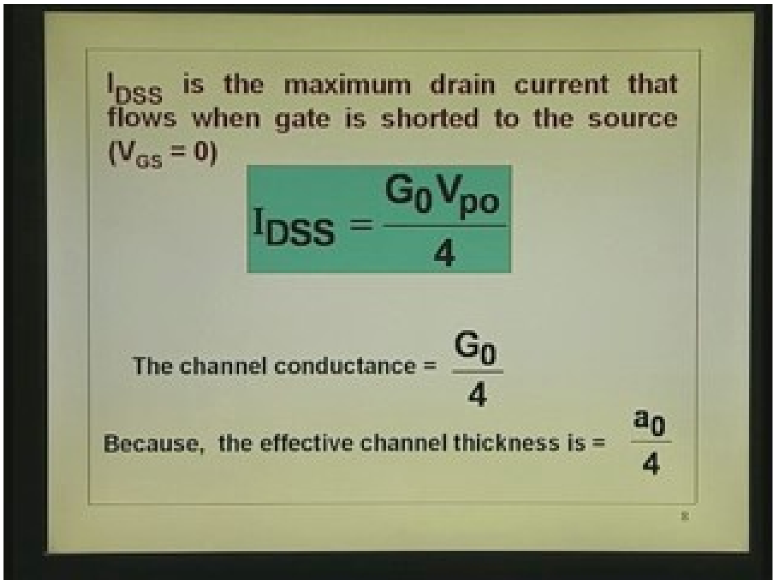

I_{DSS} is the maximum drain current that flows when gate is shorted to the source ($V_{GS} = 0$)

$$\boxed{I_{DSS} = \frac{G_0 V_{po}}{4}}$$

The channel conductance = $\frac{G_0}{4}$

Because, the effective channel thickness is = $\frac{a_0}{4}$

The effective channel thickness is linear; instead of saying effective it is correct to say it is average. It would have been a by 2 but it is a by 4, average. It is just physical meaning into what we are talking of. What we say now is this is actually the current which flows when the channel drop is V_{p0} and the channel conductance is G_0 by 4, all that we have explained.

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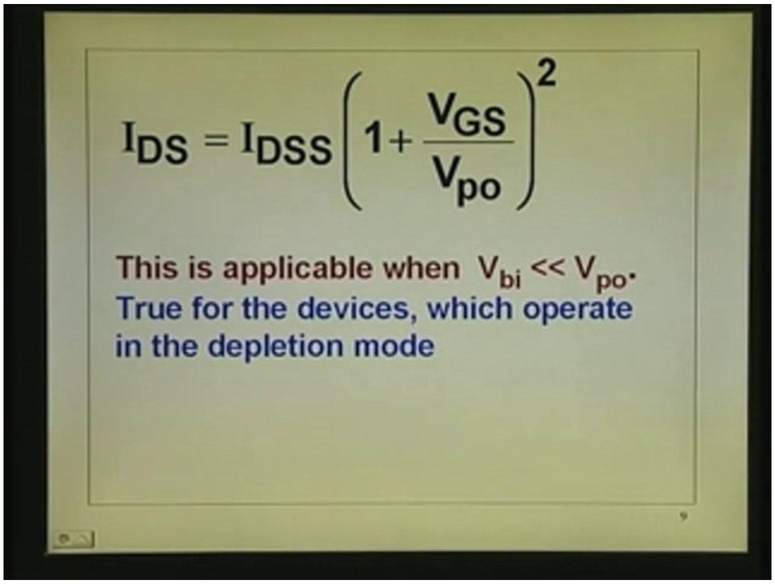

$$I_{DS} = I_{DSS}\left(1 + \frac{V_{GS}}{V_{po}}\right)^2$$

This is applicable when $V_{bi} << V_{po}$.

True for the devices, which operate in the depletion mode

Finally, where is this formula applicable? This formula is applicable when V_{bi} is very small compared to V_{p0} or in devices where V_{p0} is large. You cannot do anything about V_{bi} that is 0.8 volts or 0.75 volts. We can make V_{bi} small; you make a line shorter by drawing a longer line. You can make a small compared to V_{p0} by making V_{p0} larger. This is true for the devices which operate in the depletion mode because when V_{bi} is small, let us put that, when the V_{bi} is small depletion layer.

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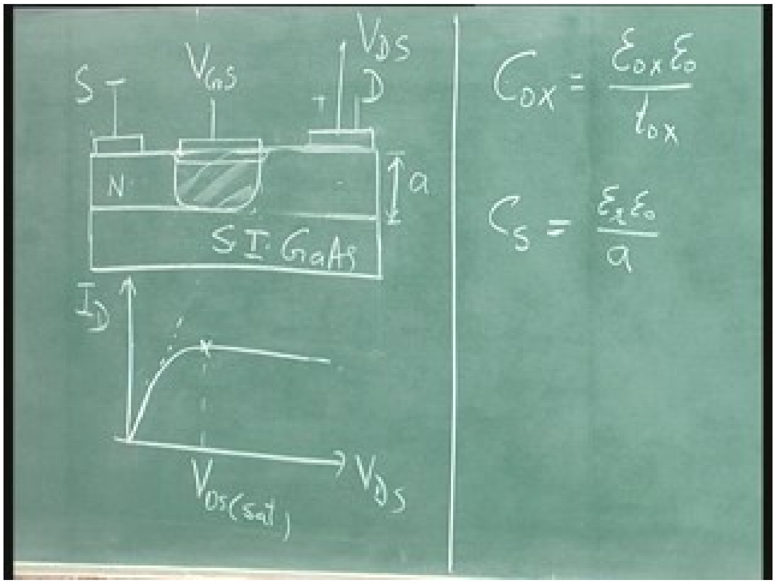

V_{DS} is small, let us say, let us not talk of that V_{DS} without applying V_{DS}, apply V_{GS}. If I do not apply any V_{GS} just V_{bi} itself is there, if I apply a voltage between drain and the source you have current flow. That is if the input voltage is equal to 0, your current because of V_{DS} drains to source voltage.

The device is on without any gate voltage. These are the terminologies which have been beaten up so many times, to turn off the device you must increase that gate voltage negatively so that the depletion layer comes off completely like this. When the depletion layer comes off like this, the channel is closed. It is like closed the valve at the inlet of the fluid pipe there is no output. That is why to turn off the device you must apply the negative voltage. The pinch off voltage is large compared to built-in potential, that is the channel thickness and doping in such that the deletion layer is at pinch off is larger than that depletion layer at V_{bi}. That is the condition for which this formula holds good.

Today we may not be talking of such devices because these are depletion mode devices. We would like to avoid depletion mode type of devices why? Without any gate voltage there is current flow. If there is current flow without get voltage there is power dissipation and the input signal is there not there. You want that device to work when the input signal comes and when the input signal is not there you want it not to perform. It should not perform the input signal is absent. When it is present it should respond.

Now it is responding for the input signal but it is like hitting the fellow to sit down, it is performing making the device not to perform. That is called signal. That is what you are doing. So Millman and Halkias book gives this formula for JFET.

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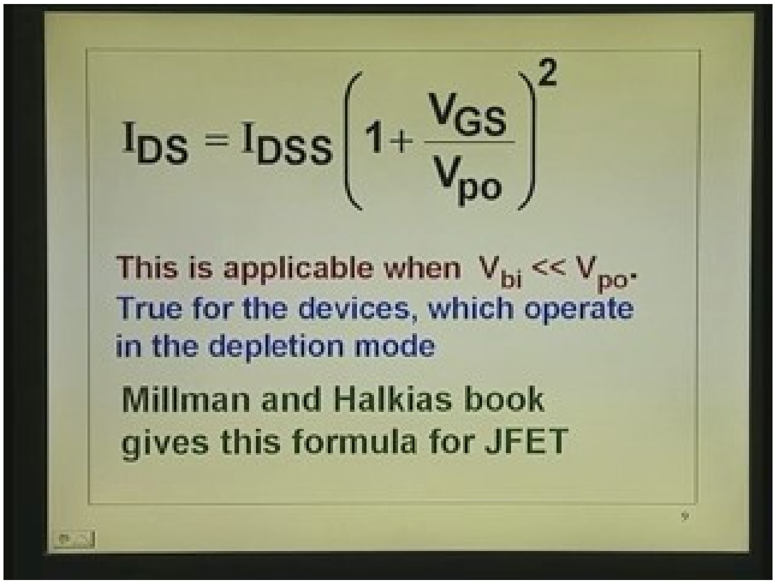

$$I_{DS} = I_{DSS}\left(1+\frac{V_{GS}}{V_{po}}\right)^2$$

This is applicable when $V_{bi} << V_{po}$.
True for the devices, which operate in the depletion mode

Millman and Halkias book gives this formula for JFET

So formulas are the same for JFET and MESFET. Now let us see. This is the formula that we have derived for in general mu C_s W by 2 L into V_{GS} minus $V_{threshold}$ whole squared. Here we have not neglected V_{bi} compared to V_{p0}. That means it would hold good for a situation where V_{p0} is larger than V_{bi}, it will hold good for situation where V_{p0} is not large, it will even hold good for a situation where V_{p0} is less than V_{bi}.

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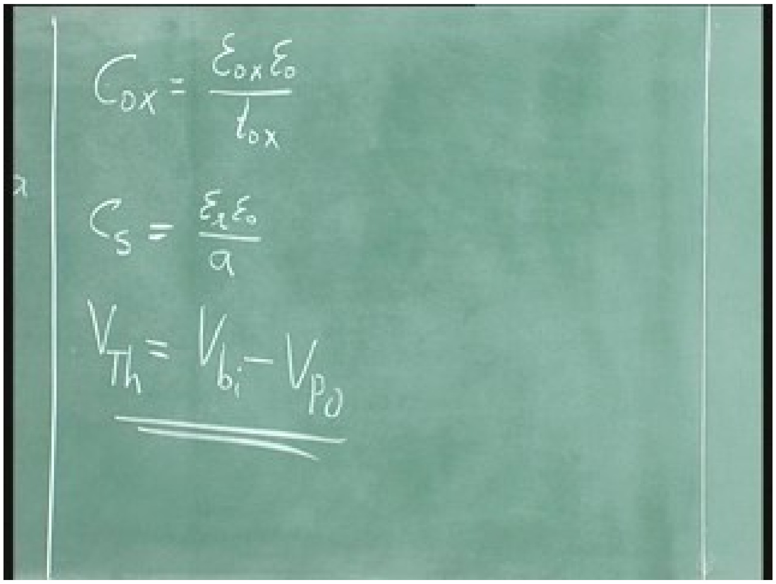

All that happens will be $V_{threshold}$ voltage is equal to V_{bi} minus V_{p0} that is the voltage that must apply. So that the channel is pinched off. If you do not apply any voltage, only V_{bi} will be present. Now if V_{bi} is small or 0 or close to very small compared to V_{p0} threshold voltage is negative that is you must apply the negative voltage so the depletion layer goes through this. V_{bi} is small compared to the pinch off voltage you must apply negative voltage to gate in either JFET or MESFET both.

If it is JFET it is p plus n junction, it is reverse biased. Here it is metal semiconductor contact, it is in reverse bias. Negative voltage is applied so that device is turned off. Threshold voltage is negative. If V_{bi} is equal to V_{p0}, you are not able to believe that, if V_{bi} is equal to V_{p0}, right at 0 voltage just stopping conducting.

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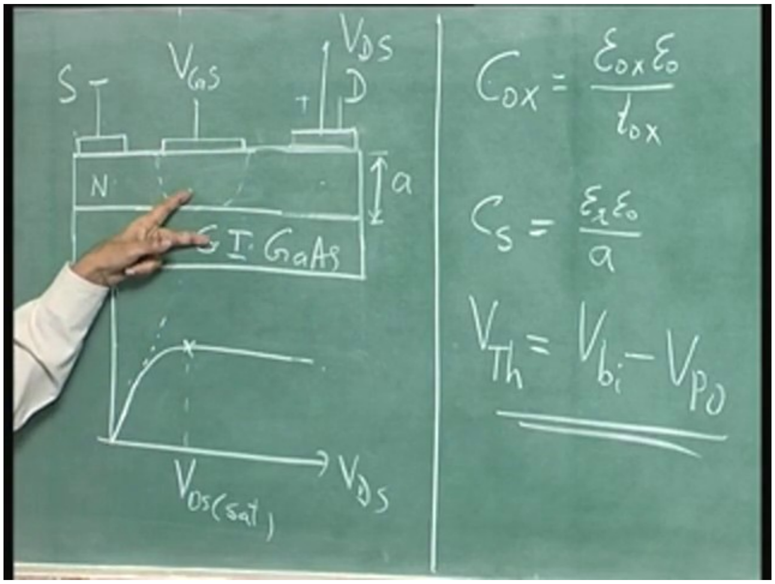

How to make it conduction? Suppose I have a depletion layer. It goes all the way like that because of depletion layer. To make it conduct I must open this channel by decreasing the depletion layer width. How can I decrease the depletion layer width? The voltage across that should be reduced below V_{bi}.

How can I do that? By forward biasing the diode, so we have to forward bias the diode, the Shockley's barrier diode so that the channel is opening, which means I must apply plus voltage to the gate to turn on the device. V_{bi} is equal to V_{p0}. I must apply more than that, with threshold voltage is 0, I must apply the processing voltage. Suppose V_{bi} is larger than the V_{p0} that threshold is positive. That is unless I apply certain threshold plus voltage, see even go beyond that, unless when V_{bi} is positive means I must apply plus voltage so that it is just about to open.

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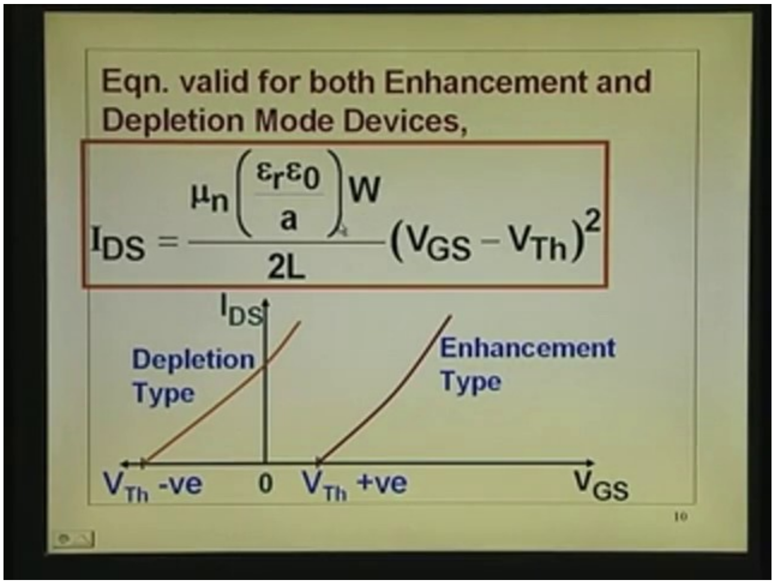

Eqn. valid for both Enhancement and Depletion Mode Devices,

$$\boxed{I_{DS} = \frac{\mu_n \left(\frac{\varepsilon_r \varepsilon_0}{a}\right) W}{2L} (V_{GS} - V_{Th})^2}$$

Now what does this equation say? In the saturation region the drain current is actually increasing as square of V_{GS} minus threshold whole squared. If threshold voltage is positive that is V_{bi} is larger than V_{p0} that is the characteristic voltage. That is called an enhancement type of device. When you say enhancement type of device what it implies is the current enhances when you apply the voltage.

When it is depletion type of device the implication is you are depleting the current, you are reducing the current when you apply voltages. Here you can see threshold voltage is negative, that is when it is zero biased itself the current is there, I must keep on applying negative voltage to cut down the current.

And when you apply the voltage is equal to threshold voltage, the negative voltage it is turned off. The difference is here the threshold voltage, the voltage at which you applied to turn off the device, negative voltage here it is the voltage that you have applied to turn on the device, but even here you can say this is the voltage at with device is about to turn on, about to call it. That is the implication over. Now couple of things I want to discuss before we go further.

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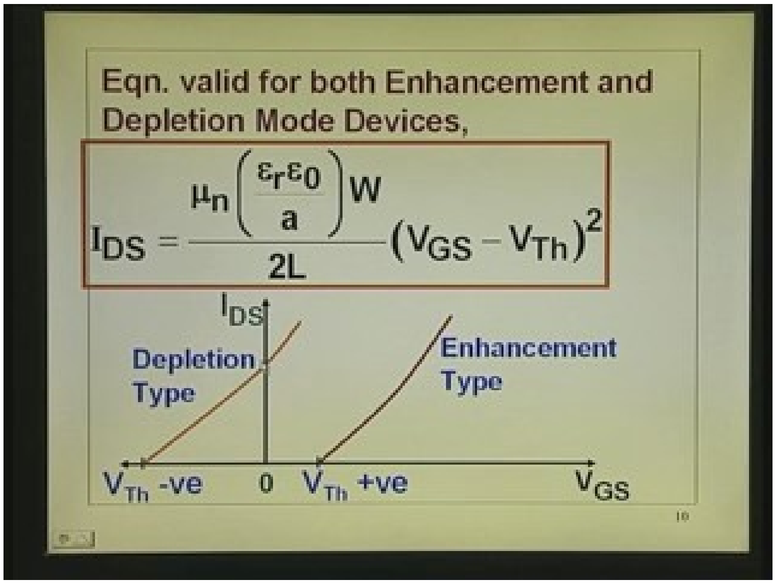

Eqn. valid for both Enhancement and Depletion Mode Devices,

$$\boxed{I_{DS} = \frac{\mu_n \left(\frac{\varepsilon_r \varepsilon_0}{a}\right) W}{2L} (V_{GS} - V_{Th})^2}$$

Please understand the discussion that we are talking of is true for JFET and MESFET both. Well, both of them have the, one is Shockley junction other one is pn junction, both of them do the same job of providing the depletion layer, a barrier. That is why it is the same thing. Now what we are telling is how do I make this threshold voltage positive? See you like this particular device. Why do you like it? When the input signal is 0, current is 0. That is what you want. Power dissipation is 0 when input signal is 0. This is the device that you are looking for. How do we make that positive?

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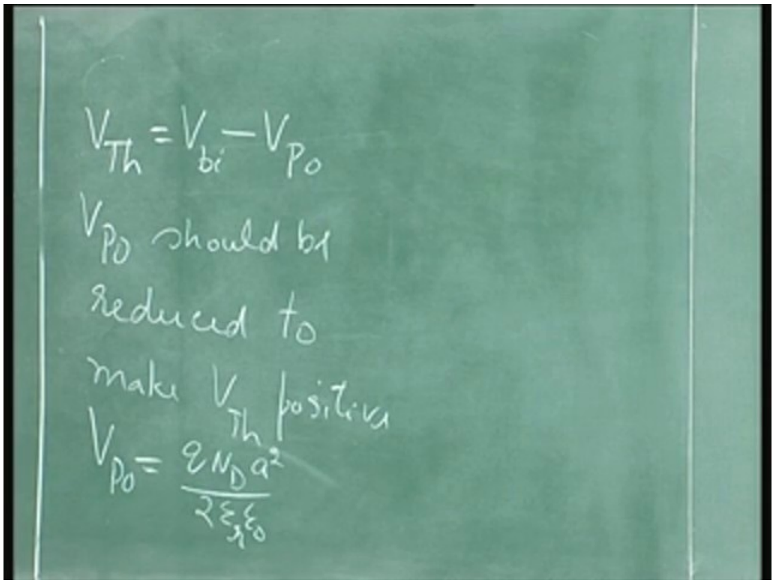

$V_{Th} = V_{bi} - V_{P0}$

V_{P0} should be reduced to make V_{Th} positive

$$V_{P0} = \frac{q N_D a^2}{2 \varepsilon_r \varepsilon_0}$$

We want to make it positive. You can take this V_{p0}. You must reduce the V_{p0} so that it becomes less than this. See for example if this is 0.9 volts V_{bi} to make it positive, I must have V_{p0} 1 volt, now it is 0.9 I must have V_{p0} less than 0.9, 0.8 volts if I have, I have 0.1 volt.

How can you do that? V_{p0} I think there is no need of this diagram right now because we have to write there. $V_{threshold}$ we want to keep positive V_{p0} should be reduced to make $V_{threshold}$ positive. Now V_{p0} is q N_D a square divided by 2 epsilon_r epsilon_0 that is V_{p0}. So if I want to reduce this, how can we do that? The parameter that we can play with is one is doping and the other one is a, which of them will you play? Will you reduce the doping, reduce the threshold voltage or will you reduce a, to reduce the V_{p0}? Reduction of this or this, this is a very tricky question.

If you look back you need not worry in long channel devices much, but if you look back into the MOSFET thing, you will see there, the scaling laws if you see, what you are doing is you are reducing the thickness of the oxide and increasing the doping, control that thing, threshold voltage. Same thing, to control threshold voltage, you prefer to reduce a rather than reduce doping. A very good understanding for this is, why you should reduce a rather than reducing doping?

You prefer to reduce a, what benefit you get straight away? If you reduce a, what benefit you get from this equation, all other things are remaining the same. In fact I would prefer reduce a increase N_D to keep the threshold voltage at some value. Keep the threshold voltage constant at plus 0.1 volts, I can do that by increasing doping or reducing a. So that is kept at plus 0.1 volts.

I would like to do that because I want reduce a that will make this C_S more which actually makes the coupling between gate and the channel better, and that makes also given from the formula I_{DS} becomes larger. For a given voltage swing I_{DS} becomes larger or if you want to see the transconductance becomes larger. So to get a better transconductance device you will prefer to reduce a if you want to reduce V_{p0}. That is what is done.

We will have a better occasion of looking into this little later by the talk of short channel devices. There again we will be thinking of looking into this a reduction.

In the MOSFET the focus is to reduce the thickness of the oxide and we land up in trouble by reducing oxide to Armstrong level. Here the focus is reducing the channel thickness. Please remember when reduce the thickness, you must have that reduced thickness only from everywhere over the entire wafer because a is 0.1 micron.

In one device over here, I want the same a to be 0.1 microns here. Otherwise the performance of the device here the transconductance threshold voltage etcetera here will be different from here. So uniformity, this is the problem which are passing onto technologist, asking the technologist say I want a to be same every where in the case of JFET, MESFET. I want t oxides to be same everywhere in the case of MOSFET. I want the doping to be the same everywhere in the case of JFET, MESFET and MOSFET. Those are the problems which make the life difficult to that technology. The final heat is taken by the rather by technology.

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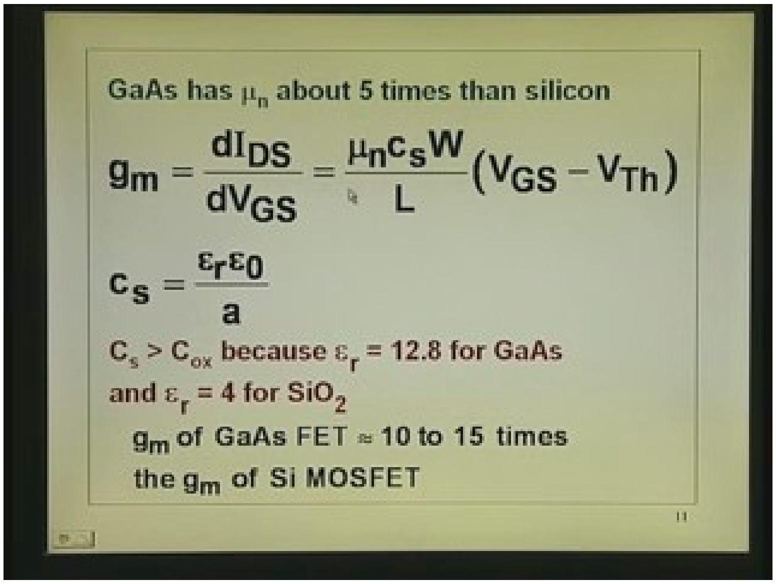

GaAs has μ_n about 5 times than silicon

$$g_m = \frac{dI_{DS}}{dV_{GS}} = \frac{\mu_n c_s W}{L}(V_{GS} - V_{Th})$$

$$c_s = \frac{\varepsilon_r \varepsilon_0}{a}$$

$C_s > C_{ox}$ because $\varepsilon_r = 12.8$ for GaAs
and $\varepsilon_r = 4$ for SiO_2

g_m of GaAs FET ≈ 10 to 15 times
the g_m of Si MOSFET

Now these are the things which we have already mentioned. That is the g_m is better, I have already mentioned this in other reference, g_m is better in the case gallium arsenide FET ten to fifteen times compared to g_m of silicon MOSFET, because mu_n is better, C_S is better, because C_S is larger than C_{oxide} because $epsilon_r$ is 12.8 in gallium arsenide $epsilon_r$ in oxide is 4. We have just told that more than once.

Now let us see what ever we have been talking of how good is that? Do you have to make any changes, and under what circumstances do you have to make changes? That is what we want to see.

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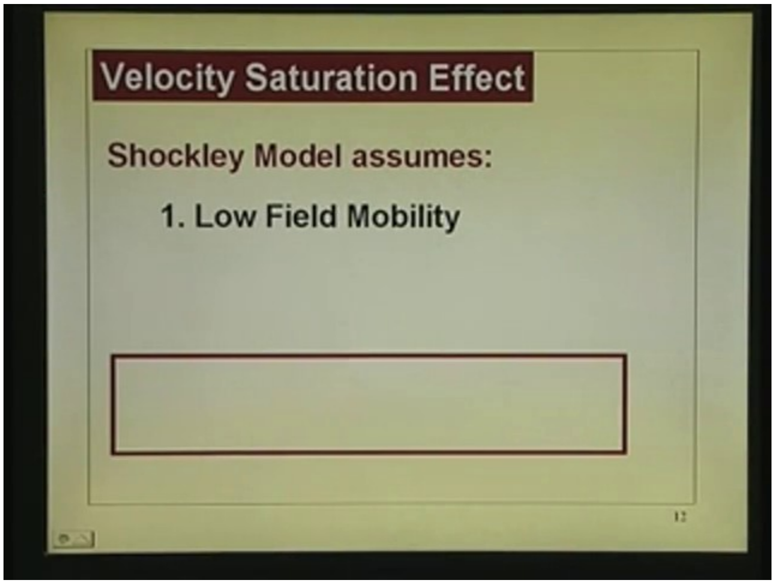

Velocity Saturation Effect

Shockley Model assumes:

1. Low Field Mobility

The assumption in Shockley's model is velocity is proportional to electric field. V is equal to mu into E strictly speaking, that is actually true for low fields. As we go to higher and higher fields, velocity is no longer proportional to the electric field. After all you cannot have the velocity is going onto infinity.

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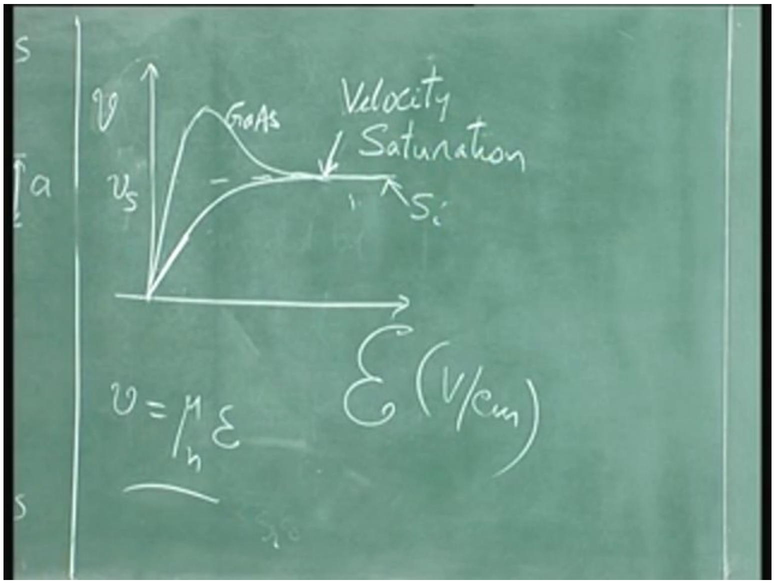

If it is Silicon for example, electric field, volts per centimeter, E is the symbol for electric field then I_D, V velocity, how does it go? It goes on linearly and we have used that it is going to remain right through the electric field, right up to the pinch off point as it is remaining linear and then we came up and said that okay that pinches off, that is the condition. But actually in silicon it goes up like this saturate. You have got saturation velocity. Velocity saturation effect is there, which is about 10 to the power of 7 centimeter per second for silicon. In fact the saturation a phenomenon is true whether we talk of silicon, whether we talk of gallium arsenide lithium phosphide, gallium nitrate anything.

The way it approaches may be slightly different. You may have this going like this or it may go through a thing like this. I am just not plotting at the moment, I am just plotting this for silicon. For gallium arsenide also there will be such saturation. That means just put for the, this is for silicon. For gallium arsenide what we can say about VI characteristic the velocity verses field characteristics? Mobility is higher, that means, this slope will be going up just like that. Delta v by delta E is equal to mu into electric, over here, mu_n is higher implies to be show here. In fact what happens is, we will discuss this later, and it goes like that and come back like that. Whether it goes like that or like this ultimately it saturates. You will have the velocity saturation effect. This is gallium arsenide. We will take a look at it. That is silicon phenomena.

Why it happens to over shoot is there, all that we will discuss in couple of lectures later. That is very interesting and that plays a major role in gallium arsenide device performance, this velocity over shoots here. This is velocity saturation. What we are trying to tell is this will be true whether the fields are low and ultimately it will be velocity saturation.

Let us take a look at this here it is like that, like this, that is the depletion layer. Current can be written as qn into v that is in fact we have used that equation deriving that. v is equal to mu_n into E only in this portion. As the field goes on increasing that proportionality does not hold good. What is the status here? At this point the channel height is large. You will satisfy this condition in most of the portions.

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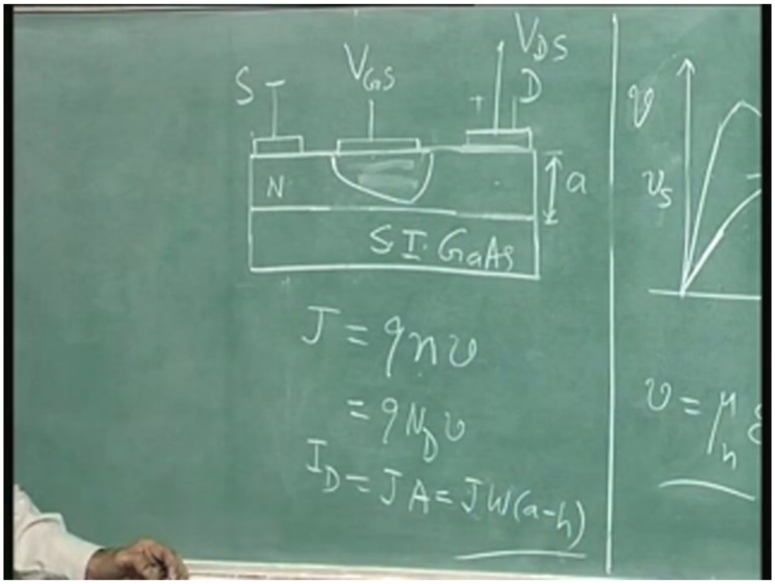

If you recall, J is qn into v, this velocity we are talking of. We substituted that. Now n of course will be equal to, all things are ionized means it will be q into N_D into velocity, doping concentration. This is current density but in the physical device it is the current that we are talking of. Current is actually equal to I_D is J into area and that we wrote it as J into area is how much? See ultimately we are really supposed to use J into W into a minus h. Now you can see this total current is constant. After all there should be current continuity to the device.

Any cross section you take the current cannot just become more in one place and less in the other place. Current density could change. Since the current is constant, in fact in the last lecture we have been discussing about those things, if the current is constant here the current density becomes h is this and this a minus h is this. As you keep on moving from the source to the drain end, a minus h keeps on falling means current density increases if I_D is constant.

If the current density increases what is the thing that is increasing? The velocity which implies as we move from this end to this end, what happens to the velocity? It increases and velocity increases means you are moving along this curve that means you are moving into higher field regions. Supposing you hit this particular region, velocity saturation region, see velocity can become maximum velocity saturation region; this will keep on widening because the voltage drop keeps on increasing.

Now if the velocity has reached saturation here, that is the point of current to saturate. Strictly speaking what Shockley said was not correct. What he said is that if the channel pinches off, current saturates. You can easily get the analytical expression, but what really happens is the current would saturate when the velocity somewhere saturates and where will the velocity saturate? Velocity saturates at a point corresponding where the field is maximum, when you reach that critical field. At a point at which you reach that saturation field we have the velocity saturation. It need not pinch off at that point.

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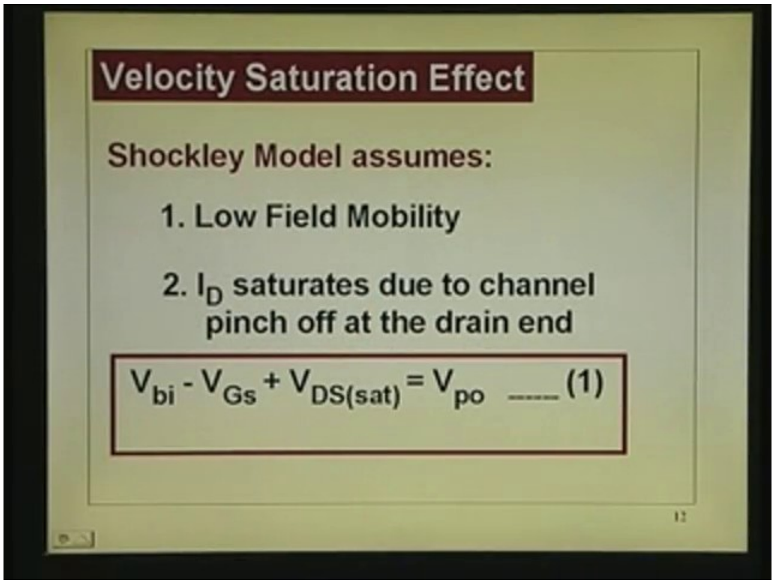

Velocity Saturation Effect

Shockley Model assumes:

1. Low Field Mobility
2. I_D saturates due to channel pinch off at the drain end

$$\boxed{V_{bi} - V_{Gs} + V_{DS(sat)} = V_{po} \quad \text{-----} \ (1)}$$

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Now to illustrate that, so I_D saturates due to channel pinch off at the drain end. That is what Shockley said. What we are telling now is channel need not pinch off. The channel need not pinch off for the current to saturate. That is what we write there. All that it required condition is the velocity is to be saturated.

Now just take a look at this that means you cannot use that equation. Now I will give an example before I go into details of this which I will take in next lecture, in the next few minutes I will just discuss and find out, should we talk about the JFET or MESFET etcetera for this current saturation?

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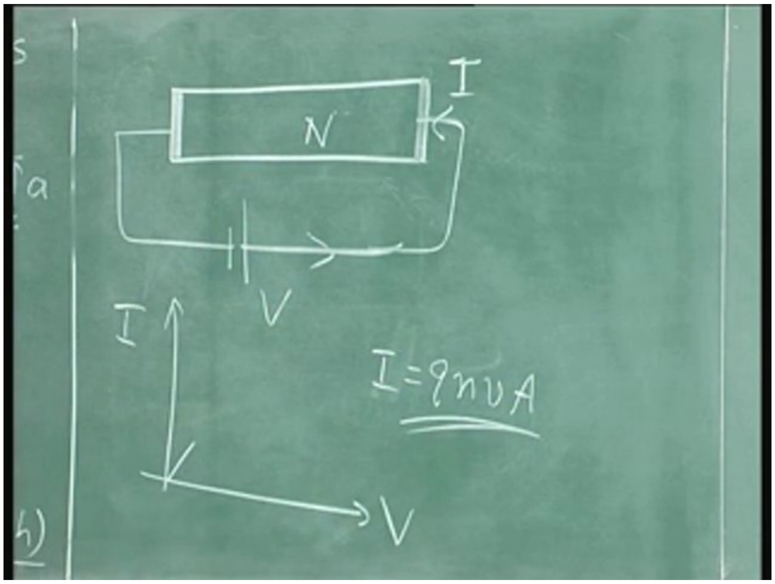

Supposing I take a resistor made up of semiconductors, supposing I take a resistor, like that N type semiconductor, not a metal, not a carbon resistor or anything and I put a contact here, I put a contact here, I apply a voltage here. You will get a current through just like that. This is voltage, this is current. This is a resistor. There is no depletion layer formation therefore chances for depletion formation; I am not talking of surface states and all that. What will happen to the current? What will be the current verses voltage characteristics of this device?

Invariably all of us will say without exception we will say E by I is straight. Ohms law, resistor ohms law but ohms law fails beyond certain point. There is limit up to which you can hold ohms law that is field must be small. In a metal it will hold good very well because carrier concentration is very high. Current density is actually equal to qn into v.

And current is equal to, this current will behave once n is constant, n is decided by doping. In the metal n is decided by metal carrying electrons. This is constant, this is constant here, fills cross section, whereas here you have that cross section varying because of voltage drop and the because of the junction depletion layer widening. Here it is not changing. What will be the IV characteristic here? It follows a velocity variation. As I keep on increasing the voltage the electric field here the electric field there keeps on increasing. When the electric field there keeps on increasing, what about the velocity? I will just put side by side. I will put that.

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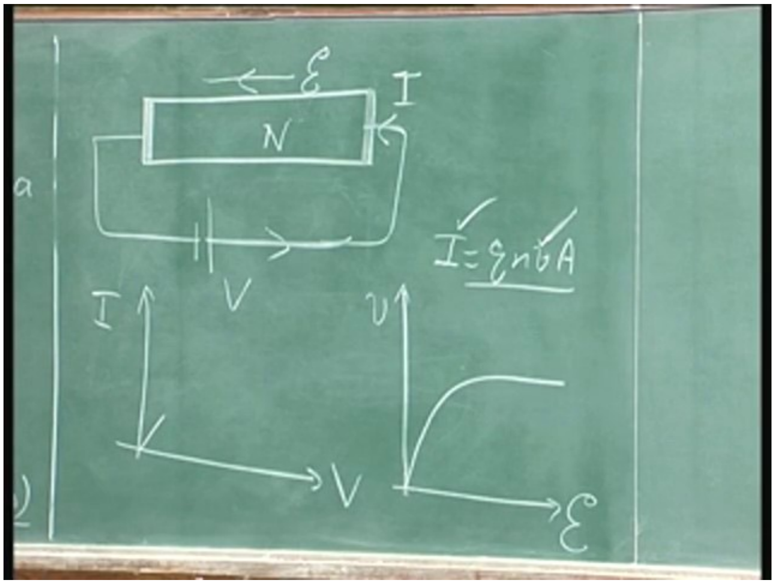

The electric field verses the velocity, if it is like this since I is equal to qnv into area, the current will follow what the velocity follows. You will have the IV characteristics actually of this resistor, which will particularly be true when n is small. You will get a characteristic like this. The current saturation phenomenon is not the propriety of the FET. The current saturation phenomena can take place when velocity saturates.

What we are telling is the current has saturated in the case of FET not because of pinch off. It is because of velocity saturation. But it can therefore happen that pinch off have taken place, velocity saturation has taken place. Here you can see without any pinch off current has saturated that is I_{sat} saturation is equal to qn into v_s into area where v_s is there.

Now where does it land us? It lands us in trouble, in the sense do you accept Shockley's model and under what circumstances can we do that? We will actually have just few things I will point out to you and take it up in our next lecture because in the couple of minutes I will just point out to you. We make an assumption I will just go through this assumption and then we will start analysis afterwards.

Infact finally we will see the Shockley is right under certain conditions. That is why they were able to use that model for so many years. What we do is whether you have gallium arsenide or silicon whatever it is we make an approximation that the velocity v_s field characteristics is linear and saturates. In other words, instead of saying it like this we say it becomes like this. What we do is assumption is a velocity verses electric field; we make it like this, instead of like that or instead of something like that. Whatever is the shape we make this assumption and there are things like this.

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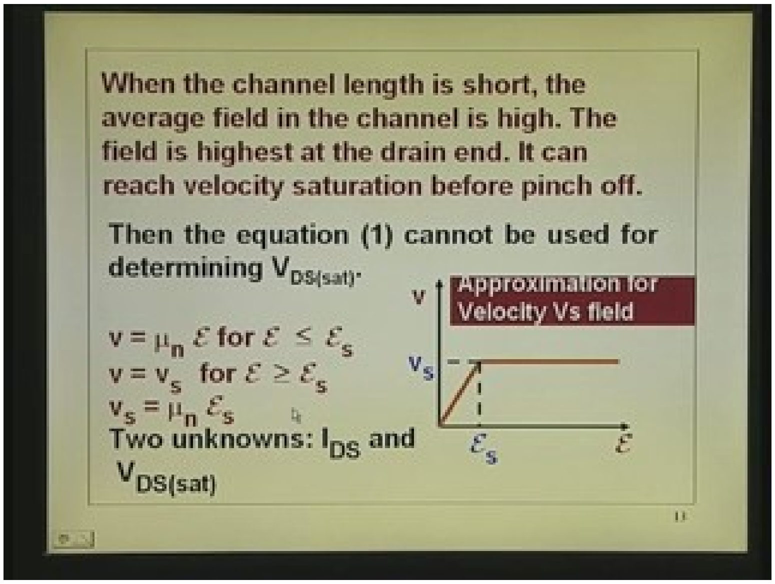

When the channel length is short, the average field in the channel is high. The field is highest at the drain end. It can reach velocity saturation before pinch off.

Then the equation (1) cannot be used for determining $V_{DS(sat)}$.

$v = \mu_n \mathcal{E}$ for $\mathcal{E} \le \mathcal{E}_s$

$v = v_s$ for $\mathcal{E} \ge \mathcal{E}_s$

$v_s = \mu_n \mathcal{E}_s$

Two unknowns: I_{DS} and $V_{DS(sat)}$

The equation one which pinch off condition you cannot use, so you make this approximation for the velocity verses field where velocity is proportional to electric field in this region upto electric field less than v of s, critical field, saturation field and velocity is equal to v of s saturation velocity beyond that, that means piece wise linearization. V is equal to mu$_n$ into E that is the saturation velocity, so once you hold these two, up to that point mu$_n$ into E and from it is saturation and velocity saturation is that quantity. If you use that you have to find out both I_D and $V_{DS\ (sat)}$ which are both known

How to find that out that we will discuss tomorrow, in fact this is the model understanding of this particular device. See you in the next lecture with this approximation straightly we will get into analysis.