Introduction to Semiconductor Devices

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Module No # 13

Lecture No # 65

Current Characteristics of a Short Channel MOSFET

Hello everyone welcome back to introduction to semi-conductor devices so in the previous lecture we have understood the concept of scaling and how it is beneficial to performance of a MOSFET. You know when you scale the MOSFET the performance improves the size reduces and so on. Well, how does that actually back the current characteristic of a MOSFET? So that is the topic that we would like to discuss today.

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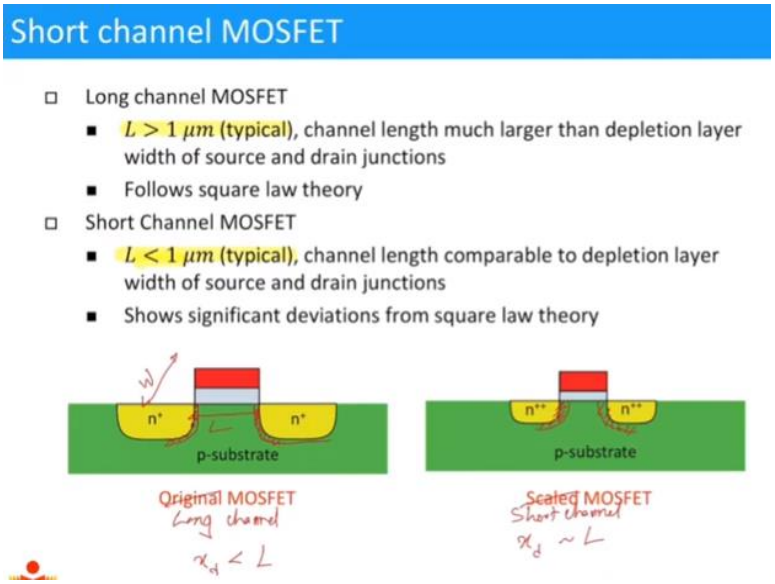

So to do that will have to introduce what is known as short channel MOSFET. So obviously there is a long channel MOSFET and short channel MOSFET so, these are you know we classify these things depending on the channel length. So when you have a MOSFET we define the distance between the source and the drain as the length of the MOSFET. And into to the plane we call it the width so what is the short channel MOSFET?

Well the MOSFET length is much larger than the depletion width of source in the chain junction then we call it long channel MOSFET. So for example here if you; look at the N+ region and surrounding that this going to be depletion region. Because N+ depletion is going to extend mainly into the channel here and on this side you are going to have a depletion region. So in this depletion widths we saw that they are you know 100 nano-meter normally right.

So it depends on the depletion concentrations so if these depletion regions are much smaller than the length of the MOSFET we call it as long channel MOSFET. So typically a long channel MOSFET would be that which has may be about length greater than 1 micro meter typically we take that as it you know there is kind of a limit. If the channel length is greater than 1 micrometer it will call it as a long channel MOSFET.

Essentially means the depletion layer widths are smaller than that and if you have long channel MOSFET we turns out that it follows the square law theory that we discussed for current characteristics. But the moment you go to a short a channel MOSFET essentially where the channel length is not very large you know comparable. For example here if I draw the depletion width you have to a scale MOSFET even such source drainer much highly doped.

So you can top of an Xd which is the depletion width. If Xd is comparable to the length of the channel in the same order of magnitude. Then we will call it a short channel MOSFET whereas in the long channel I should not call original here the long channel , and this is long channel. So in a long channel case Xd is much smaller than the L so when you have a short channel MOSFET then it shows significant deviations on the square law theory that we develop in the past.

So the goal of the medium is understand the deviations you know how the current characteristics of the short channel MOSFET looks like compared to long channel MOSFET. So we will do that by first showing you what happens fully?

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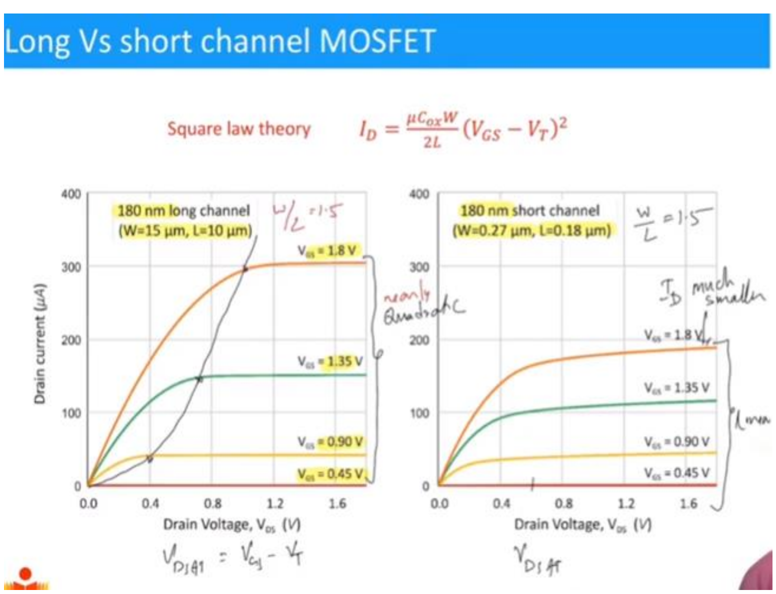

You know so you should compare current characteristics output characteristics of short and long channel they should look like on left you have the long channel device which is the length in microns and width is 15 micron. So $\frac{W}{L}$ of this device is the mobile is 1.5 and this device is fabricated using 180 nano-meter technology. You might wonder how are you fabricating you know long channel with 180 nanometers.

Well 180 nanometers only represents the technology you can always you know that is the smallest feature you can fabricate it. But you can always you know fabricate the devices there is no problem with that you know you can fabricate 10 microns, 20 microns also you can do the formula of course there is going to some restrictions whether manufacturer but typically we can able to do it.

So this is the long channel device and usual typical you know square law theory we have seen this already you know current characteristic in saturation current it is going to be proposal to the

$$(V_{GS} - V_T)^2$$

$$I_D = \frac{\mu C_{OX} W}{2L}(V_{GS} - V_T)^2$$

. And it is saturation you know VDsat which is basically equal to $V_{GS} - V_T$. So if you plot out that you can actually draw the $V_{GS} - V_T$. So if you plot all of that it will behave something like this so this is a point where VD at occurring right.

For every Gate voltage this is different VDsat is going to be equal to $V_{GS} - V_T$. So this is what will happen and you can plot this and it also exhibits the square law behavior that means you know this is actually real MOSFET. So I am using V_{GS} of 180 nano meter technology and V_D is 1.8 volts so I am using equal step 0.5 steps 0.45 to 0.9 to 0.145 to 1.8. Some increasing voltage in the equal steps but my current is actually increasing in a more than super linearly.

You might say this is exactly quadratic you can check it out compute and see there are some facilities involves but essentially it is showing you super linear I would say at least perfectly quadratic. So this is obeying square law theory it is like a typical long channel MOSFET now what happens to the short channel MOSFET? So I have taken another example of a short channel MOSFET here the same technology. But now the channel length is only 0.18 meter and because I want to keep the W /L as same I have chosen 0.27 micrometers as the channel width.

So now in the short channel case also W by L same 1.5 micrometers so now if you nively assume that this square law should obey then you should get the same current the reason is μ is a technology parameter C_{OX} is basically again technology W/L is same ,applying the same $V_{GS} - V_T$ so current should be same, But clearly you see that the current is not same so the current is definitely much smaller here current I_D much smaller that is one of the characteristics, and as you increase the voltage in equal steps the current also seems to be increasing linear.

You know if I say this is basically a quadratic behavior which you will verify of course quadratic here you see that this is linear case. The current is increasing linearly with voltage and also if you notice it you know carefully you would have seen that the V_{DSAT} of the long channel MOSFET was you know small and the square law kind of thing whereas here it seems to be saturating staring the voltage.

So this seems to be V_{DSAT} so initially we have the linear behaviour but once it reaches a certain drain voltage it seems to be saturated why is that? So want to understand all of these things right now that is the goal of this medium. And you know ideally I should have used you know 1 micron technology and calculating the drain currents it would have perfectly quadratic but you know I want you to maintain the same technology that is why I choose this.

So it is nearly quadratic it is you know you will verify this immediate because there are some stabilities because things like you know you and all will not be exactly identical there are some issues anyway we do not have to worry about that right now. So the main differences in the short and long channel we have noted the drain current is much smaller the increase with V_{GS} is linear in short channel and the V_{DSAT} are occurred much low voltage for example.

For comparable V_{GS} of 1.8 in this case the V_{DSAT} occurring at 0.9 or something like that or 1 maybe here it is occurring 0.45 so 0.5 it is much smaller then we have seen saturation. So why is that?

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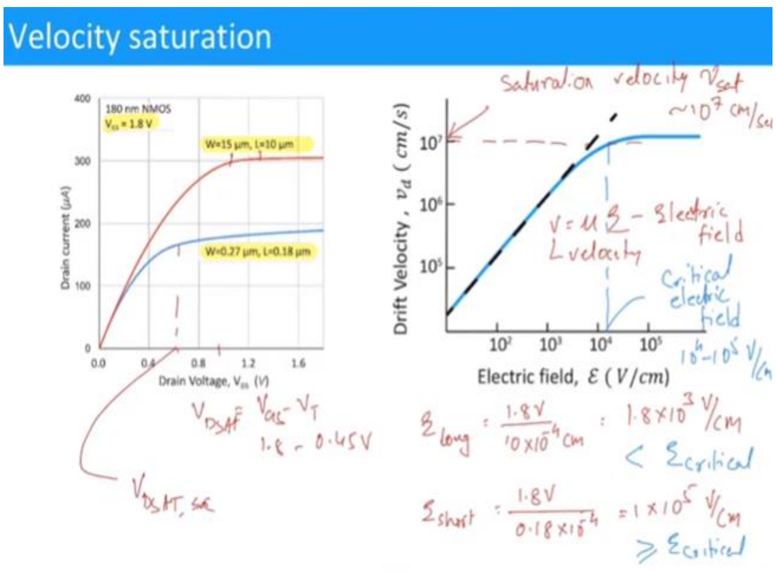

To explain that we have to understand a phenomenal which will call us velocity saturation. Before I do that I just I actually re plotted the same data now it is long channel and short channel but with long channel case and short channel case. And I have chosen V_{GS} of 1.8 so that I can compare so what you see is initially you have the same drain current but at some point the short channel point is seems to be saturated and the long channel is going further ahead.

Once again excuse me so long channel is going much further had before saturated why is that? The reason it turns out is because of what is known as velocity saturation what is this? Well if you remember go back to drift current when we discuss drift current in the PN junction of before PN junctions current in semiconductors we talk about drift diffusion. So the drift current basically is you know if you apply a voltage then with a certain electric field and a velocity of the carrier is proportional to the electric field.

The proportionality concept was actually what we call as mobility so this is velocity and this is electric field and the proportional concept is mobility you can verify the dimension it will work out to be exact. So we assume this linear relation between electric field and velocity and it turns out that this is not quite possible in a MOSFET in a semi-conductor. Because as you increase a electric field what happens?

Well the carriers increase more and more energy and accelerated they go to higher velocities and then once they reach a certain velocity or self-certain you know velocity there is hit another carrier and lose energy. For example because you are not going to have a single electron travel it is like you know 10^{15} right. Let us say you know 10^{15} electron so each electron will travel certain distance is something like this then your velocity you know when you electric field is small it is a query sufficient velocity so a little sort of drift.

But then once it reaches what is known as the saturation velocity? It cannot acquire any more velocity because if it releases the energy to the lattice which hits another carrier this is energy as starts again right. So this particular velocity which is kind of upper limit of a solid material is known as saturation velocity. So in this case here this is basically saturation velocity I will call it as Vsat.

So typically for solids you know for semiconductors silicon it is you know 10^7 centimeters per second. And silicon Gallium Arsenide all of them are typically in the same range you know 1.2 or something like that around 10^7 that is where all the other most semiconductor materials are. This is only you know I am really they are still you know if you go to Gallium Arsenide something else but we do not want to get into all the details of you know. So saturation velocity is this now the electric field at which saturation velocity is reached is known as the critical electric field.

And that typically is going to be around this one I will critical electric field and this typically above 10^4 to 10^5 V/Cm it can be slightly different depending on the material. So there is critical electric field why does it matter to us? When it matters to because when it compute the electric field in the channel you know you are applying the drain voltage between source and the drain.

So essentially voltage is falling across the channel right what is electric field? Well we can easily compute this let us see E long channel how much is that? Let us say I applied 1.8 volts just V_{DS} of 1.8 volts divided by the length of the long channel I said you know this case to be 10 microns means I should write in centimeter units. So 10 into 10 power -4 centimeters right this is going to be if I take this you know 1.8, I think I should be 1.8 into 10 power 3 volts per centimeter.

$$E_{long} = \frac{1.8V}{10 \times 10^{-4}cm} = 1.8 \times 10^3 \frac{V}{Cm}$$

This is the field it the channel so it is actually smaller than the critical electric field this is less than E critical. Whereas if we go to a short channel MOSFET short channel MOSFET how much is that let us take a same voltage apply 1.8 volts. And I am applying now across only 180 nanometers let us say this is 0.18 nanometers so 0.18 microns I should write in centimeters or write it as 10 power -4 centimeters.

$$E_{short} = \frac{1.8V}{0.18 \times 10^{-4}cm} = 1 \times 10^5 \frac{V}{Cm}$$

So this will be you know I will take one more so it will be 1.8 into 10 power not 1.8 1 into 10 power 5 volt per centimeter. So this means that this is almost like equal to or greater or equal to approximately E critical depends on how much exactly is a E critical value. I said it is between 10 power 4 and 10 power 5 so what it means is? I am reaching a short channel device I am reaching my saturation velocity if the saturation velocity is reached then of course my device cannot take any further velocity

So if you have a long channel MOSFET the V_{DS} is going to be you know this V_{DS} we saw was basically $V_{GS} – V_T$ right. So in this V_{GS} is 1.8 and V_T typically lets say 0.45 something like that in this technology that I have used. So it should be about 1.3 or so like that so basically it should be somewhere here well this exact definition is you know debatable , you have some saturation at that point.

But if you look at short channel device the V D channel is this is I should call it as V_{DSAT}. For a short channel device here the saturation is occurring somewhere here V_{DSAT} is actually short channel I do not know S C short channel let us say. So it is occurring at a smaller voltage at what voltage does it occur? Then it occurs at a voltage where the critical field is reached. You know the channel length you know the critical field what is the V_{DSAT}?

So this typically turns out to be that this one is something that carefully model and then they built up a very nice model for calculating current. Alright so what is the current you know you want to get a expression for current and the way to do that would be to go back to the basics.

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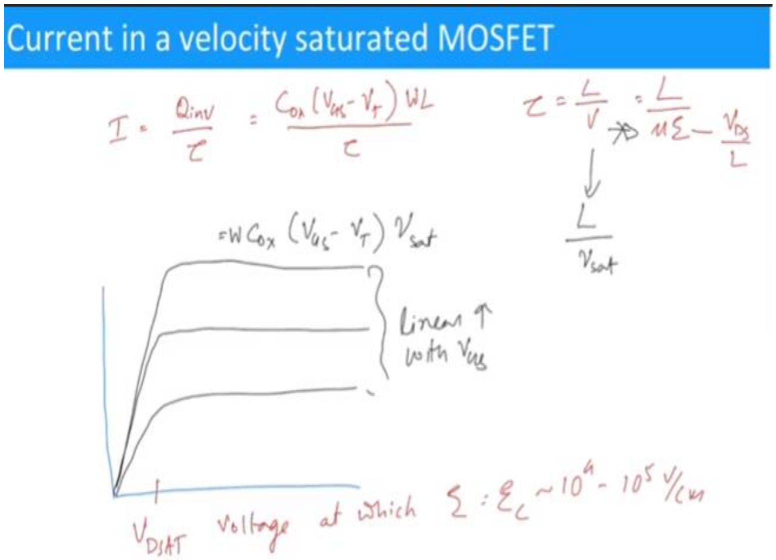

You know how did we calculate the current in a MOSFET we said that one of the basic definition of the current is going to be I is going to be whatever is the inversion charge divided by time it takes to go from source to drain. And we said the charge is simply in the charge supported by parallel plate capacitor and want to take the total charge multiply the area. So this charge is going to be the C×V C is basically oxide capacitance times I will $V_{GS} – V_T$ which is the excess voltage above the threshold.

$$I = \frac{Q_{inv}}{\tau} = \frac{C_{OX}(V_{GS} - V_T)WL}{\tau}$$

$$\tau = \frac{L}{V} = \frac{L}{\mu E}$$

And then W into L which is the area of the you know gate divided by tau so this is the starting point for our derivation. And then the tau in the case of the long channel devices or in a traditional tau is basically going to be L by some velocity, And we said that is velocity is going to be equal to L by mu into E for a typical device. And then we said that this E is going to be V_{DS}/L and then we derive the expression.

Well it turns out that if you have a short channel device this V is not going to be equal so this is not going to be true. The velocity is going to become velocity saturation right. So this will become

L/Vsat which is the saturation velocity instead of regular µ ×E we will put V sat we will substitute it back here. So if you substitute what happens this will be equal to

$$W C_{OX}(V_{GS} - V_T)V_{sat}$$

So this is my current expression for a short channel device so all I need to know what is the saturation velocity and I said typically it is 10^7 centimeter per second. So how will; the current characteristic is look like? Well ideally they should look like you know if I just attempt to draw this you know this is something going to be like this.

So for equal increases in voltage there will be equal jumps so this is linear increase with V_{GS} this is one of the characteristic of a short channel device. And what is my V_{DSAT} now the short channel case it is going to be voltage at which $E = E_C$ the voltage at which the electric channel is going to critical electric field and you can figure it out. This number is said is 10^4 to 10^5 V/Cm

So you can try to compute I mean in terms are these are all you know approximate numbers you would always you know go back and actually simulate this in it circuit simulator that you learn about in different course.

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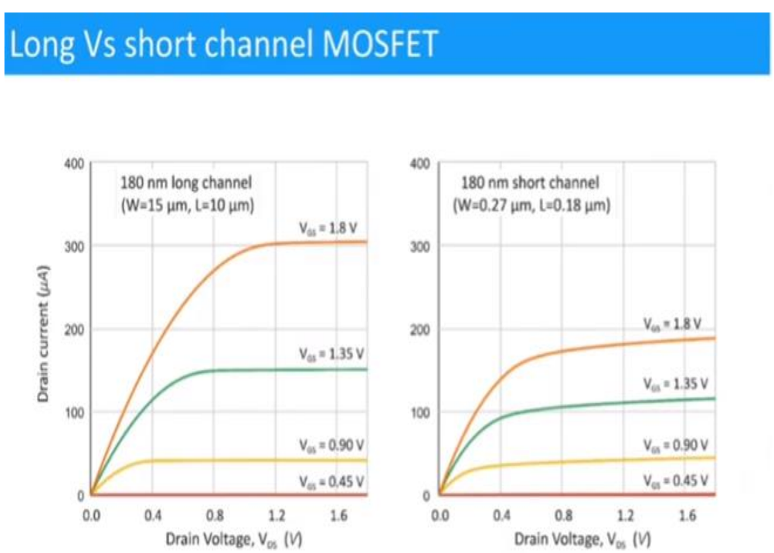

Alright to summarize this is a picture I have already shown so now I think should be you know what is the differences between short channel and long channel you should be able to explain by yourself. So if you want this pause for moment and try to recollect what are the things we have discussed. There are 3 differences the first one is the current saturates at much low voltage.

The V_{DSAT} for a long channel device is $V_{GS} – V_T$ for example for a short channel device is much smaller voltage at which the critical field is reached. And then the increase in current in for linear steps or you know equal steps is going to be quadratic in the case of a long channel MOSFET whereas for a short channel MOSFET is going to be linear increase in the current. These are the main difference so 3 main differences between short channel and long channel devices alright what else it that all?

Well you know the story is always you know there is always something more to a story right it is never ending television serial.

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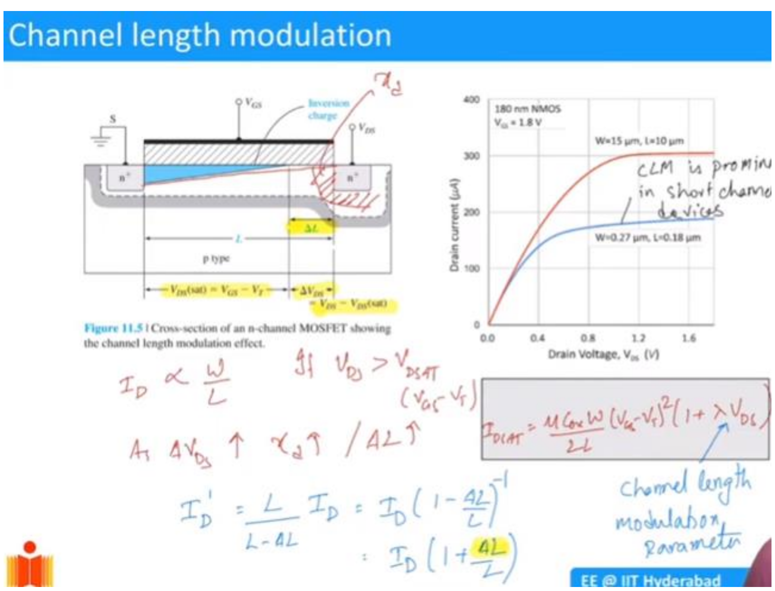

So the next concept that I would like to introduce what is known as channel length modulation. So we have seen this you know some time back when we discussed saturation. We said that as V_{DS} increases the channel gets pinched off because of that we see that you know the saturation we saw in the long channel device. But actually happens is? We saw that I_D is proportional to W/L it is inversely related to length if you have a shorter channel device you current should increase that will anyway happen.

But of course you know there will be that velocity saturation also coming into picture we should keep a W/L constant well only velocity saturation comes into picture. So now what happens if V_{DS} is greater than V_{DSAT}? Let us take the you know the long channel $V_{GS} – V_T$ if the V_{DS} is $V_{DS} – V_T$ then your inversion region is going to look something like this correct we have seen this the pinch off.

We said that the effective potential here is going to be smaller than V_T so it will pinch off. There would not be any remote channel and if you increase your drain voltage above V_{DSAT} then you start seeing this pinch of happening at a much lower length this much before the drain region. And effectively what is happening is your drain is getting more and more positively biased here so your drain depletion is increasing.

As V_{DSAT} increases if I call this as xd depletion width of the drain side as you know I will also call as you know I will call ΔV_{DS} I will define ΔV_{DS} as basically excess voltage lower the saturation voltage. Saturation voltage is a regular you know long channel expression and ΔV_{DS} is excess voltage over that how much we are applying. So if you are excess ΔV_{DS} increases right your xd is going to increase so what?

Well it so happens that we will refer to that as ΔL this excess you know Xd increase in the depletion width of the drain side call it as ΔL. So what happens is if you increase ΔV_{DS} X d increase or you know it could a ΔL increase that means your effective channel length is increasing. So, because once the depletion is just anyway the carriers will drift across the depletion region.

So the effective current you know I will write it as I D prime

$$I_D' = \frac{L}{L - \Delta L} I_D$$

you know I will say I D prime simply to say that effective current and that is going to be your regular long channel I D. But then there will be coefficient which is simply L – delta L. So what am I saying is? Your delta L is increasing so our effective channel length is reducing because of which you drain current increases.

Well I mean this is a very if you look at the textbook I will go to a lot more mathematical derivations I do not think we need all that. I just want you to understand quantitatively what happens. So if I have this what happens here? So L by you know $L - \Delta L$ I can write has you know L I can take it out I can write it L you know basically I D into 1 – ΔL by L to the power of -1 so it is a binomial expansion I can do that that.

$$I_D' = \frac{L}{L - \Delta L} I_D = I_D \left(1 - \frac{\Delta L}{L}\right)^{-1} = I_D \left(1 + \frac{\Delta L}{L}\right)$$

If I do that it is going to be I D into 1 + delta L by L so what it means it if you have this you know delta L is proportional to V_{DS}. So what we do is we say that the I_{DSAT} device is going to be if you introduce the channel length modulation effective channel length is reducing. So you should have.

$$I_{DSAT} = \frac{\mu C_{OX} W}{2L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

In addition I will multiply it by $1 + \lambda V_{DS}$ I will lost the space $1 + \lambda V_{DS}$ so what it means is? As you increase the drain voltage there is going to be an increase in the drain content and this particular parameter I will call as channel length modulation parameter. So what is happening is you know let me take this well let me not stay with it. So this is going to be my current with channel length modulation.

So if you take a long channel device the length is long then the effect of channel length modulation is not going to be significant and that is why you see that the drain current is going to be more or less flat this is small increase but negligible. But if you take a short channel device your depletion width is going to be significant fraction of a channel right length and that is why the channel length modification is significant.

And so even after this you know let us say got a saturation velocity but even then we will still see there is some increase in the current in a short channel MOSFET. It is not going to flat this particular ratio is called as you know this particular increase is called due to channel length modulation. So I will call it channel length modulation CLM is prominent in short channel devices obvious your channel length is comparable to the depletion width so this becomes significant.

This is another kind of you know even though it is truly a short channel effect it is more significant in the short channel devices.

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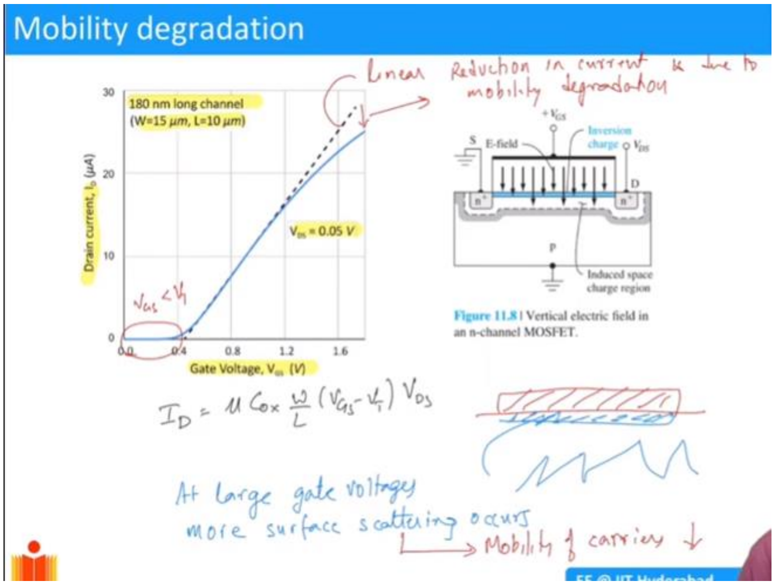

And the last feature of a short channel devices are along to discuss is you know what I will call as mobility degradation it starts again it is not again truly short channel device but it is a non-ideality you could say. So this is a you will see short channel or long channel both so this is current characteristics drain current versus gate voltage plotted for the 180 nanometer long channel device.

So length is 10 microns and width is 15 microns so and I am using only V_{DS} of 0.05, 50 millivolts I am actually using linear drain current right linear regime. So my I_D should be

$$I_D = \mu C_{OX}\frac{W}{L}(V_{GS} - V_T)V_{DS}$$

So if my V_{GS} is less than V_T there is no current so no current here V_{GS} is less than V_T. I mean by we understand that when it is 0 I mean if you plot it on log scale you see some you know some sub threshold slope you know that by now very well.

But above V_T since the drain is fixed this should be linear curve this should be linear current characteristics either my linear current characteristics. So this is what we expect ideally then what happens is you see that current is actually reducing at higher gate voltages. The reason that we are reducing is because of what we call as mobility degradation reduction in current is due to mobility degradation.

What exactly is this? Well we know that you know in a MOSFET there are electric field in a you know there is a vertical electric filed and a horizontal electric field. The horizontal electric field is due to drain voltage but now since the drain voltage is very small it is not going to be that significant compared to the vertical electric field. Vertical electric field is simply voltage across the oxide it is going to be significant so what does it mean?

If you have a stronger electric field the inversion charges are more tightly held to the interface let us say if this is my interface there is an oxide on top if my V_{GS} is large then electrons are more closely held here. The inversion region this is my inversion channel this is much more closely held when compared to gate field which is lower then you know more loosely held. So what if it is more closely held if it is closely held here you can have lot of scattering events.

For example this is my this is not going to be simply some volume of charge rate for the sheet of charge this is going to be just carrier which are scattering with each other. So some of them will hit the surface there might be some scattering events in the surface or with themselves. So here because it is getting more closely held to the surface when you interface there is more surface scattering.

So here at large gate voltages more surface scattering occurs just because of the fact that the inversion channel is more closely held to this surface and because of that the mobility of the carrier is reduces. This implies mobility of the charges of carriers reduces and because of that we see that the gate voltages you see that mobility is not a constant any more. We already a kind of related to this fact you know indirectly and when we said that bulk mobility is 1400 or 1350 centimeters per volt second for silicon.

But when you come to the channel we said that it is 400 well it is 400 but if you go to higher voltage it actually drops even further. So, this is why the current reduces this is one of the important effects that we see. You might wonder now why am I telling you all this is? My motivation is to try to give you a glimpse of various aspects of modern semiconductor devices I do not want to stop with you know application of some formulae I do not like that.

So I want to give a glimpse of it of course in each of there is a lot of detail and I hope that if you take a if you choose to persue the masters level course in semiconductors or in electronic devices or VLSI we can use all of these concepts. You will understand deeper all these things see because our technology has now grown so much that it is time to actually rewrite our curriculum. We should not be happy with you know formulae based question but we need much more physical understanding so that we can work in this areas.

If you are not interest in such areas may be it is okay but at least you can understand what is involved. So I think you know we appreciate the technology better that is what I hope and it will also help you work in a areas of nanotechnology if you are interested in those areas. So with that I will stop the discussion on the current characteristics of a short channel device. So I will record one more video short video again on the threshold voltage characteristics of a short channel device.

With that I will stop the discussion on the short channel MOSFET alright thank you so much I will see you in the next video take care bye.