Fundamentals of Semiconductor Devices
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Lecture-36
Substrate-bias effect and subthreshold conduction in MOSFET

Welcome. So, we were continuing our discussion with on MOSFET, we have derived the current voltage equation in last lecture. If you remember a MOSFET I_D V_D, which is the output current versus output voltage relations, we had tried to derive mathematically. I told you that there are two regimes primarily one is the linear regime, one is the saturation regime.

We have derived the expression, so we will have recap of how we have derived, then we will move forward to discuss more you know important aspects like effect of substrate-bias and short channel effects and so on ok, sub-threshold slope. Those are important characteristics in a MOSFET. In modern semiconductor technologies, you know people are moving towards low and low power many circuits and a low power chips, so we need to scale down the power also, when you are scaling down the transistor.

So, sub-threshold slope for example is a very important concept. People are working on steep sub-threshold transistors for extremely low power chips, you know that can work at very low power, but that have very high on-off ratio you know for high speed digital logic for sort of a sort of application. So, we will continue from where we had left the last time which is the I_D V_D relation. And from there, we will go to the effect of substrate effect, and the sub-threshold slope and short channel effect in today and the next lecture ok. So, let us come back to the last slide where we had left.

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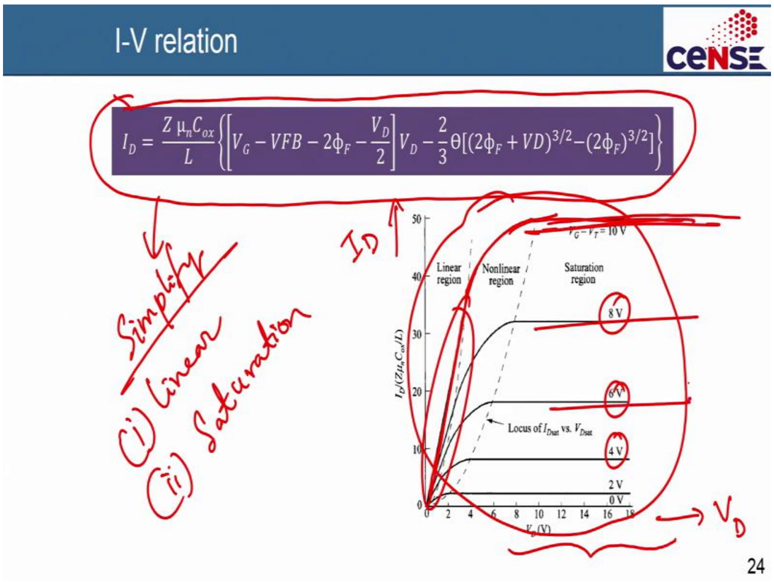

$$I_D = \frac{Z\mu_n C_{ox}}{2L}\left\{\left[V_G - V_{FB} - 2\varphi_F - \frac{V_D}{2}\right]V_D - \frac{2}{3}\theta\left[(2\varphi_F + V_D)^{3/2} - (2\varphi_F)^{3/2}\right]\right\}$$

So, if you recall, this is the I_D V_D characteristics, this is the I_D V_D characteristics that we know for a transistor a MOSFET for example. In fact, for any field effect transistor, it it will look like very similar to this. The y-axis is I_D, which is the drain current. And the x-axis is the V_D, which is the drain voltage. So, it is called output characteristics. You can see the there is a there is a linear regime, when the current increases linearly, and then there is a regime that current saturates.

In this regime, the current does not depend on the voltage that get the drain voltage applying, it is control the gate voltage, these are gate voltages. And there is a non-linear regime, when it transitions from in a you know a linear saturation sort of a point. So, we have derived the expression for the current, the current as a function of the gate bias, as the function of the drain bias. This current was derived in the last lecture, if you recall. And this is the main expression of the current but remembering this expression or using it to solve any problem is very difficult.

So, we said we will simplify this, we will simplify this expression we will simplify this expression, we will have one expression for linear regime right, we will have a one expression for linear regime here this part. And then we will have one an expression for the saturation region right, when the current saturates. So, the current saturates here so the current.

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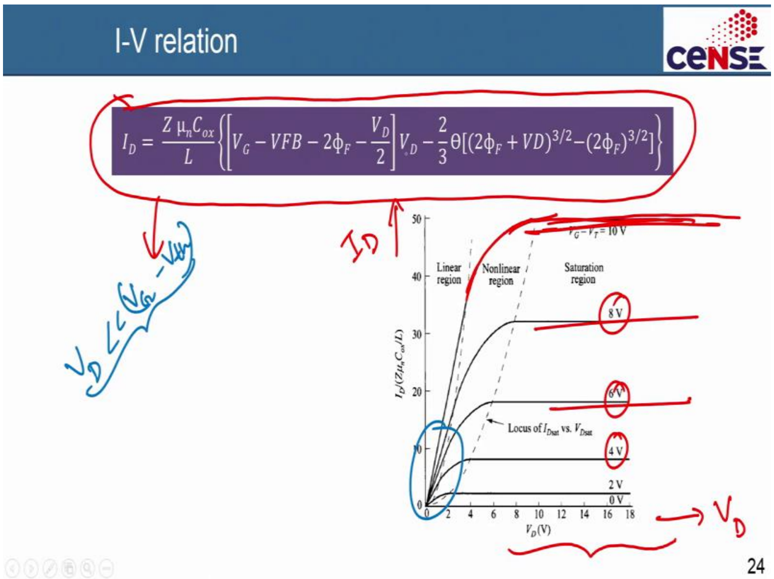

So, if you recall now, we had done some simple approximations. I told you that if you approximate these conditions, for example in the linear regime, you know let me change the color of the pen probably, I will take a blue one for example. So, if you take the linear regime, I can look at very close to you know very close to 0 bias say here. At that point, we can say that the drain voltage that you are applying is very low, it is much lower than the gate voltage times the minus the threshold voltage.

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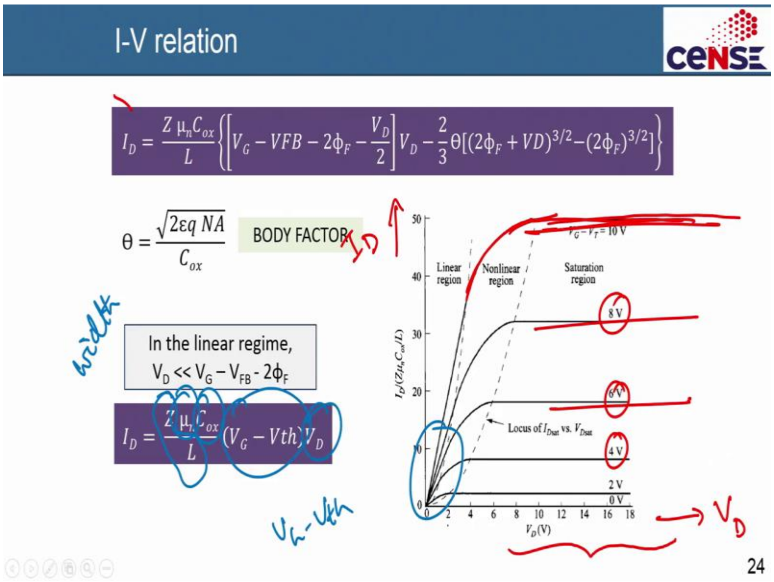

Then in that case we can simplify this expression. And the simplified expression, this is the theta the body factor that comes don't worry about that. So, in the liner regime, the current expression will look like this ok. So, essentially the current goes linearly as a drain voltage, of course it has to go linearly, also it goes sort of linearly, gate minus gate voltage minus the threshold voltage.

So, this quantity this quantity of V_G minus V_{th} is called the gate over drive ok, V_G minus is gate over drive. And then there is this Z, which is essentially W the width of the device; the width of the device, if you recall this that the lateral dimension of the device. So, you have W by L, so you have a Z by L that is the width the dimension of the device that is the length of the device, mu is the mobility, C ox is the oxide capacitance, this is the gate overdrive, and this is the drain voltage, the current increases linearly to drain voltage. So, these are very nice expression that you can keep in mind. And I also told you that in certain textbooks, you know they also give another expression another term here.

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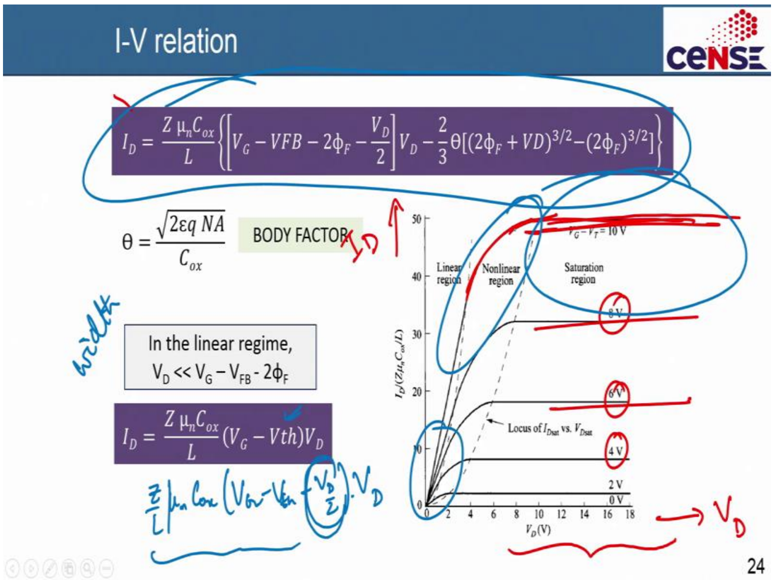

So, what they will write is that they will write Z by L, because it is approximation. You essentially approximating this equation, depending on which terms you choose to leave out or not leave out, your approximation might give you slightly different equations, but more or less it will give you the correct answer. So, this is Z by L μ_n C_{ox}, here I have V_G minus V_{th} into D L. Some also textbooks write V_G minus V_{th} minus V_D by 2 into V_D ok. And this expression becomes this quantity V_D by 2, which is not here you can include that and these becomes more permanent in this regime. When your V_D is little higher ok, before it goes to saturation.

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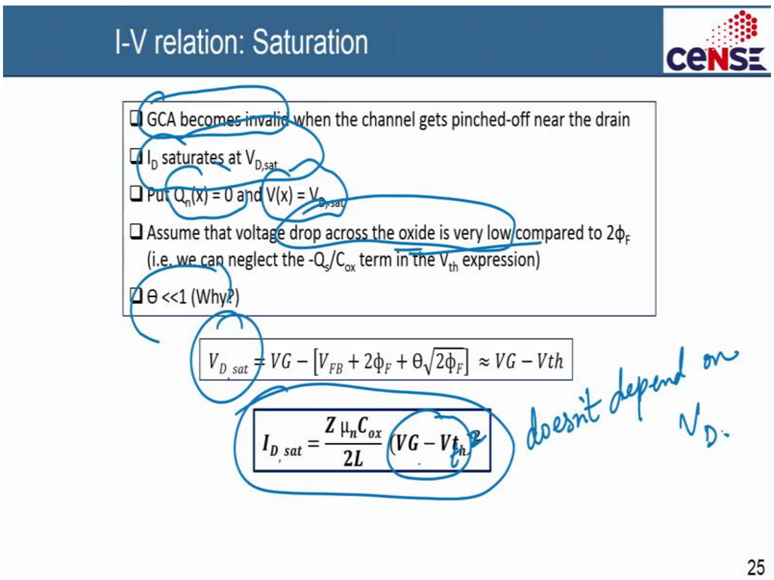

Similarly, for the saturation regime; similarly for the saturation regime, you will also have you know an expression, if you look at that. So, the first thing to understand is that in saturation regime, your gradual channel approximation doesn't hold true, because your channel edge is not pinched off, I mean that they the edge of the gate.

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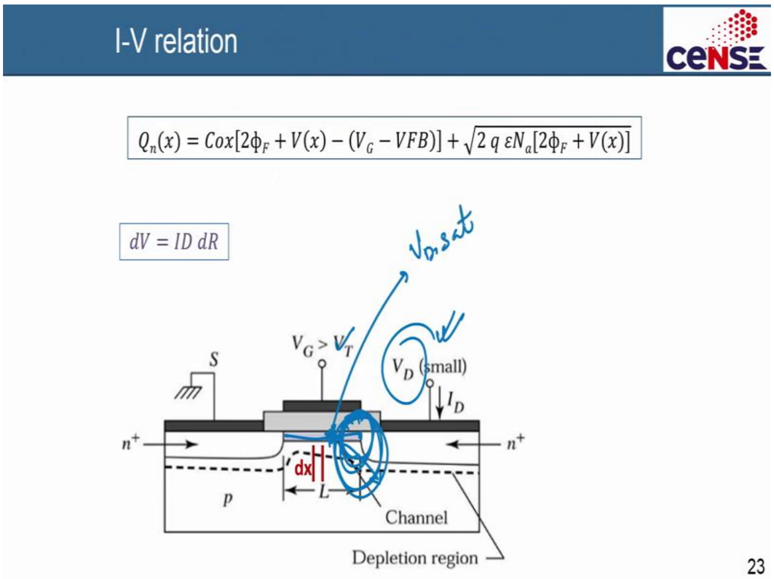

So, I current will saturate, and you have understood the physical basis of saturation is that in a MOSFET. If you look back into the diagram of a MOSFET here, at this point at this point, your gate will be pinched off with respect to the drain, because the drain is at a higher voltage in the gate. So, this point will be pinched off. So, you know you will have very few electrons here, and there is the large depletion region here, careers will be swept here to the depletion region to the drain.

And as we apply more and more drain bias, this pinch of regional move more and more to the left side right. And so your channel length will decrease slightly keep decreasing, but the current will not increase, because the voltage that you applying, extra voltage is dropping across this depletion region, whatever this particular voltage will be fixed at V_D sat, which is the voltage at which the saturation or the pinch off occurs right.

So, anyways so to do to derive the saturation current, we have to what we have to do is that we have to put the current the charge has to be 0 at the edge of the channel, and your potential will be essentially is V_D sat at which it saturates. If you take a thinner oxide, thin oxide, and if you talk about a very low doping, then the voltage dropping across the oxide can be ignored. And in this case, the body factor which you have written down in the previous expression also will be very negligible because if an oxide is thin, then capacitance will be very high. If this is very high, and doping is low this is low.

Then this quantity will be very small compare to one and so we can neglect that in that case we shall be able to derive an expression for the V_{Dsat}, and using that we can derive an expression for $I_{D\ sat}$. And this $I_{D\ sat}$ essentially is V_G minus V_{th} sorry this is V_{th}. So, this is whole square ok, so this is whole square it depends on V_G minus V_{th} whole square, and it doesn't depend on the drain voltage doesn't depend on drain voltage. So, doesn't depend on drain voltage, so of course you remember this part doesn't depend on the drain voltage, it depends this locus of this point moves quadratically, and that is why it comes here as (V_G minus V_{th})square here, this quantity also remains there ok.

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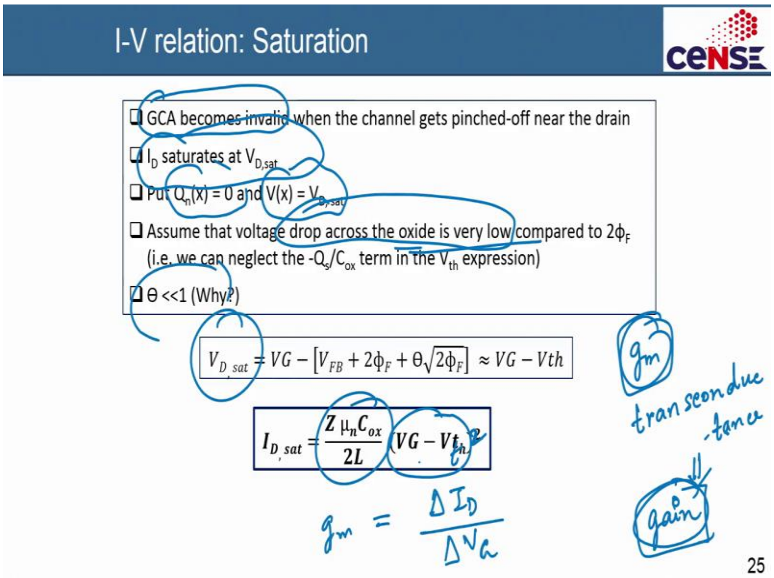

Now, this is your I_D in the saturation regime, remember there is also something call there is also something call. Now this is you have to discussing this there something call a g m of a transistor, which is which you have probably come across in your analog circuits or devices class; g_m is call a transconductance, and transconductance actually transconductance defines the gain of the field effect transistor, it can give you the gain of the transistor. So, you need a higher transconductance, because then you will get a higher gain in the device. And a transconductance is defined by actually the change in the drain current the change in the output current or the drain current is the output current with respect to the input voltage or a gate voltage ok.

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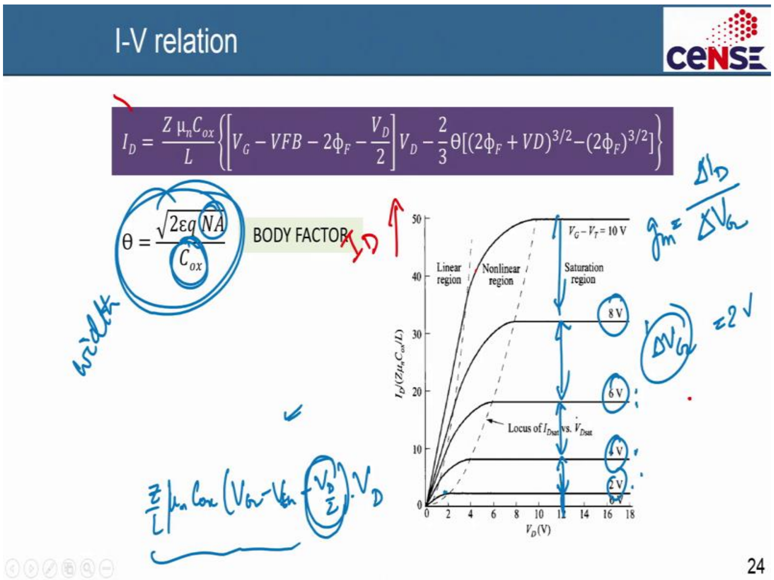

So, what means is that if you look into this plot if you look into this plot ok, so let me erase this part, so it will become clear again. So, if you look into this plot again here, you will see that with different gate biases this is 8 V, 6 V, 4 V, 2 V with different gate voltages, you fix the drain voltage suppose I fix at here. Then a different drain gate voltages from 2 to 4, 4 to 6, 6 to 8, the gate is changing by constant amount, which is 2 volt right.

But, the drain current is changing differently, I am changing here, here I am increasing even more, here it is increasing even more, here it is increasing even more, so the rate at which this drain current or the output current is changing, the rate at which is output current is changing with respect to the gate voltage that is called transconductance. And essentially what is the rate at which this is increasing at a given drain voltage with respect to gate voltage that is called transconductance.

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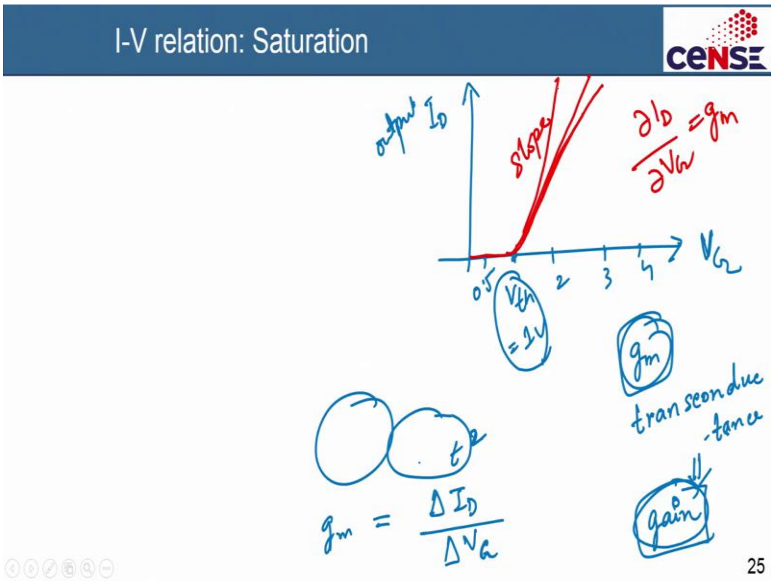

And to understand transconductance, what you do is that you actually you actually plot this is important for any field effect transistor by the way. You plot the drain current, which is the output current with respect to the input voltage which is V_G right.

So, for example the MOSFET threshold voltage, suppose it is 1 volt, this is 2 volt, this is 3 volt, this is 4 volt, this is 0.5 and so on. So, this is threshold voltage for example, the I am just taking an example that a threshold voltage is 1 volt here. So, in I_D versus V_G, this is output current right, and this is input voltage the gate voltage. So, below you know when a gate voltage is below your threshold voltage, when a gate voltage is below your threshold voltage, let me change the color here, and a gate voltage is below threshold voltage, then your current will be very small, it is very negligible.

At the point to this threshold voltage, the current will start increasing, and it will keep increasing right; it will keep increasing with the gate voltage. And this is I_D versus V_G ok, this is I_D versus V_G. And the rate of essentially it is increase, how this is the slope of this, the slope of this I_D versus V_G. This I_D versus V_G plot d (Refer Time: 09:55) V_G is actually g m ok. And the higher g m means, this slope will be higher; this slope will be higher, transconductance will be higher, and the gain will be higher. So, you know if you recall this let me erase this again, so that I can bring on the slide here ok.

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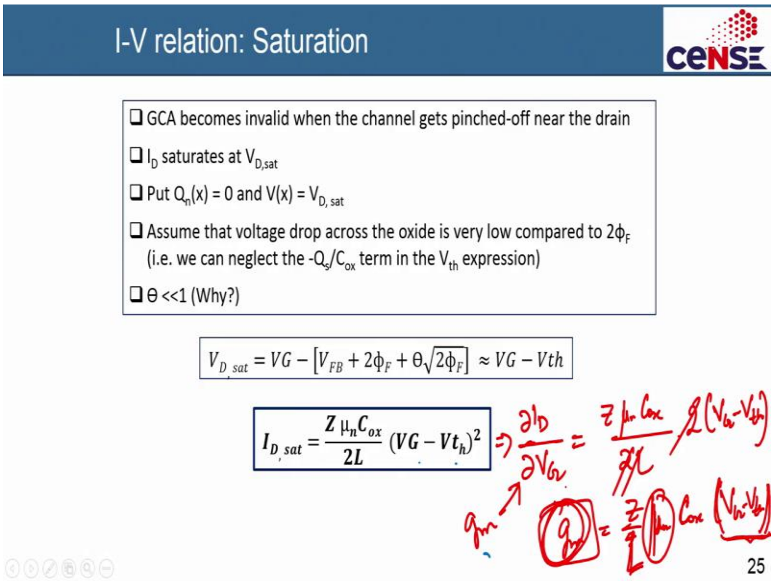

$$I_D = \frac{Z\mu_n C_{ox}}{2L}(V_G - V_{th})^2$$

So, essentially this is your expression for threshold voltage and a saturation current. So, what is the transconductance of a MOSFET in this regime here, so here what you can do is that you can take a derivative of this I_D with respect to V_G. So, what will happen is that this is your g m actually this is your gm. So, what will happen is that if you take a derivative, it will be z mu n and C_{ox} by 2L into this will take a derivative, so it will be 2 V_G minus V_{th} that's all, right.

So, essentially your 2 will cancel out, and so 2 will cancel out, and so what will have g m be is that it will be Z by L μ_n C_{ox} V_G minus V_{th}, so that is your transconductance. So, your transconductance will increase, if your capacitance increases which means epsilon by d, so d has to be smaller. If you are mobility is higher that is your transconductance will increase that is why, you need a higher mobility in a material, so that your gain also can be higher.

Your L is smaller, if your L the short channel length is short, then also your gain will be high that is why you can go to short channel devices, so that you can get higher g m. And also of course, your gate overdrive depends on that you know it depends on the gate overdrive. If you apply higher gate voltage, you typically tend to get a higher g m right.

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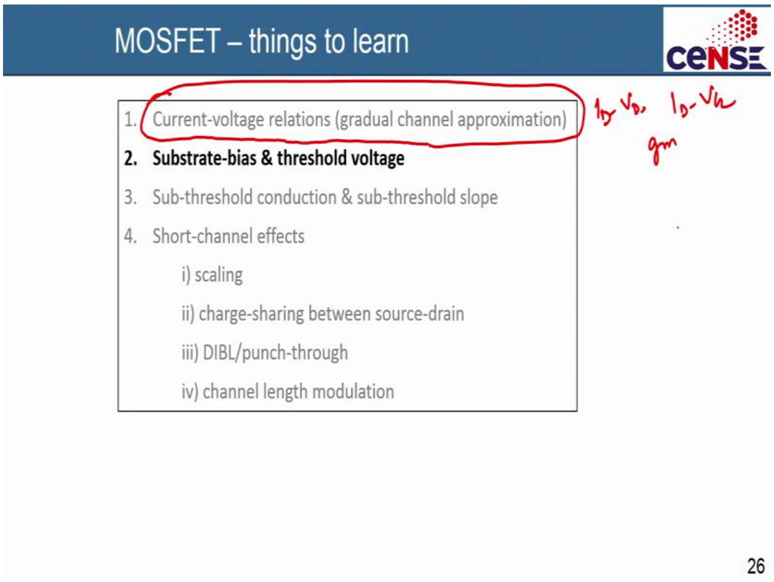

So, this is all about the current saturation. And to what are the other points that we said we will discuss if you remember, we had discussed till now the current-voltage relation or a gradual channel approximation, to derive the expression for I_D V_D essentially right. And also I showed you how I_D V_G looks like the concept of g m and so on. So, this is about the current voltage relation.

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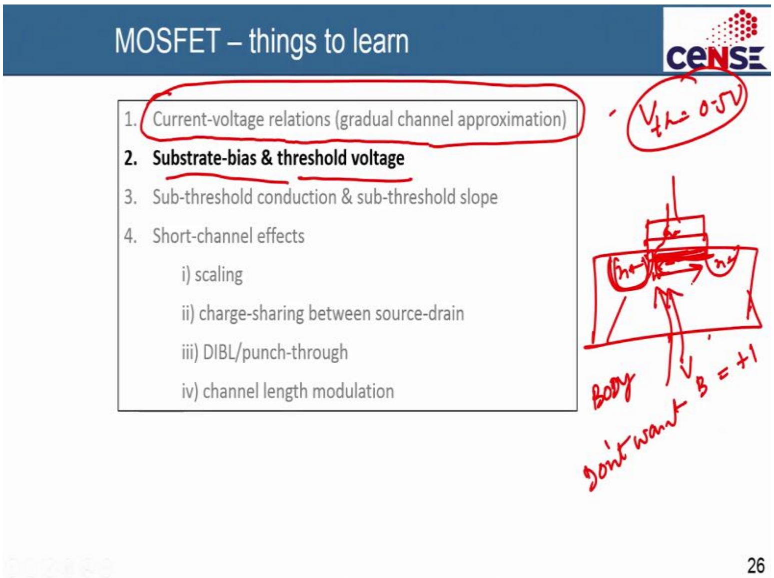

Now, the next point and this will not take so much time here is the effect of substrate-bias on the threshold voltage, you know what is substrate-bias. So, if you recall you know in a MOSFET, you will have this n plus pocket of source, n plus pocket of drain, and then there will be gate dielectric over which you have the gate here right. And this is a p-type substrate for example, it also has a contact here by the way that contact this is called substrate or it is you can call it body or substrate.

So, typically this is contact the body is a substrate, he has actually shorted to the source, and kept it ground. The source is ground of course, and it is a it is also connected to the ground, so it is like shorted. But, incase this is not shorted to the source and grounded. But, if you are applying some voltage here V_B, I am saying B is in the bias the body sorry it a V_B is the body. So, if you apply some voltage to the body, then your threshold voltage, the voltage at which you invert the channel will actually change.

If your threshold voltage was say 0.5 volt, then apply applying the some it is a four terminal you can say. So, you applying some voltage to the substrate, you also going to affect the threshold voltage. So, the question is how much will that affect B, you know how will that threshold voltage change, which essentially some voltage that I am applying on the substrate here. Please remember that if you have a p-type substrate, which is an n-channel device. If you have a p-type substrate, which means this is an n-channel device ok.

If you apply a V_B, which is positive then if you apply V_B which is positive, then what will happen is that this n plus junction this n plus, and p junction will be forward bias. And if it is forward bias, there will be a lot of current injection here, lot of current will inject and that current will essentially go and come here. And it will come up to the gate or it will continue to channel, which is what we do not want ok. We don’t want that we do not want this substrate to inject current electrons, and then I mean holes and which will go here.

And then affect the channel here that we do not want, because then this what will happen is that your substrate will also be a channel, your substrate also will feed electron it will be a channel. It will also be channel, these are also be a channel that will be defeating the purpose of the MOSFET.

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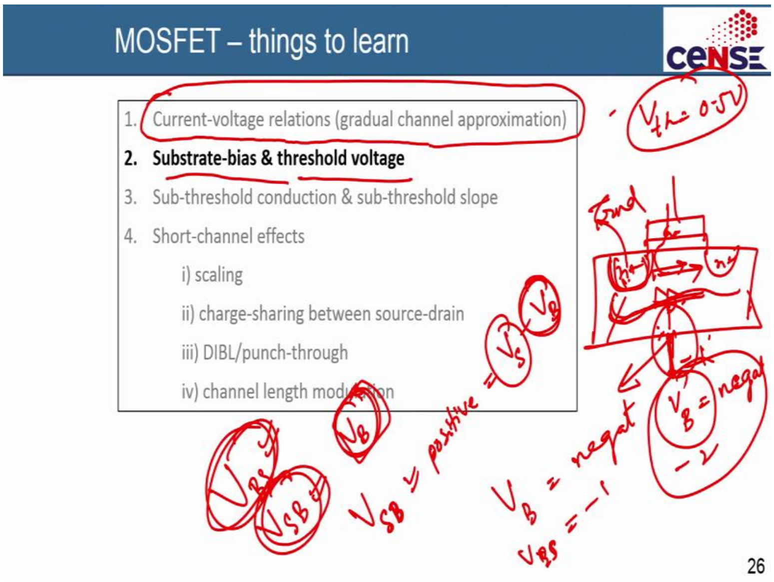

So, what you actually when I say substrate voltage on a p-type substrate, what you mean? And of course, n type the polarity will be different. If I have a p-type substrate here, and then channel is n, then obviously you mean that V_B or the body voltage has to be negative, so that this n plus p junction is actually reverse bias, you are depleting it more and more, you are not actually injecting careers.

So, when I say substrate effect of body voltage or bias, I inherently mean that this is negative may be minus 1 volt, minus 2 volt or whatever ok. So, you applying a negative voltage, so that you are not injecting careers, but you are actually increasing the depletion. And your increase your current here your channel charge and your current that your following in the channel between source and drain actually is going to get affected, so inherently I mean the V_B is negative V_B is negative.

So, I can either say this is V_{BS}, because as S is the source which is grounded which is the same as V_B of course, this will be some negative quantity. In some textbooks, they also say V_{SB}, and that is positive. What does it mean, because V_{SB} is like the body voltage with respect to source. So, V_{SB} essentially means that we source this is S means source minus V body.

If this is positive, essentially what it means is that this is 0 volt, and so this is negative that is what it means essentially ok. This has to be negative is the same thing the convention matters, some text book say V_{BS}, and some text book say V_{SB}, B is the body voltage, and S is the source voltage source is always grounded here. So, when I say V_{BS}, it means I am applying a negative voltage to the substrate.

When I say V_{SB}, still I am applying a negative voltage to the substrate, it has always to be negative voltage. But, because it is V_{SB}, this quantity will be positive, this quantity will be negative. But, the V_B is always negative, you see my point right. V_B is always negative here, it is how you write the convention. If you say V_{SB}, it is negative. If you say V_{SB}, it is positive, but V_B is negative always, so please keep that in mind ok.

So, now question is how will this extra substrate voltage that you applying on the substrate will actually affect the threshold voltage, you will see that actually can affect the threshold voltage. And that is why, this extra body's voltage or the substrate voltage that you apply is an extra knob, and extra tuning factor that can help you tune the threshold voltage independent of the other parameters. So, it is very nice in a way to actually control the threshold voltage.

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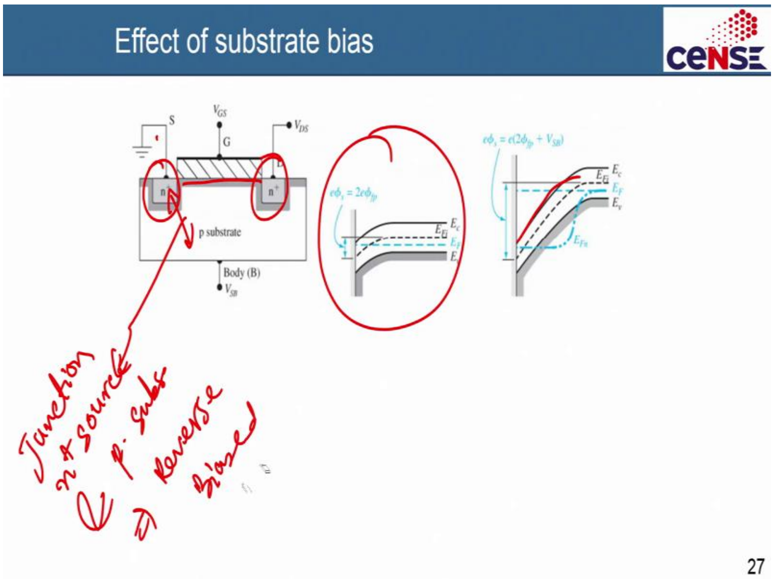

So, let us come to a figure here. You see this is a figure I am taking from internet and many the resources that I will sight in the appropriate times. You know this is the source, this is the drain, and this is the channel that is forming. The substrate actually, you can this is V_{SB}, it says so of course, it is negative V_B is still negative. So, V_{BSB} is positive the convention ok.

So, you are applying some body bias here, what will happen is that if you do not apply any bias here, if you just conduct shortage here to the source to the ground, then this is how the band diagram will look like along the channel. But, the moment you have extra bias, you will be bending the bands even more, because this point, this junction this junction between this junction between the n plus source this junction between n plus source and p substrate, this junction will become reverse biased will become reverse biased ok, and because it becomes reverse biased.

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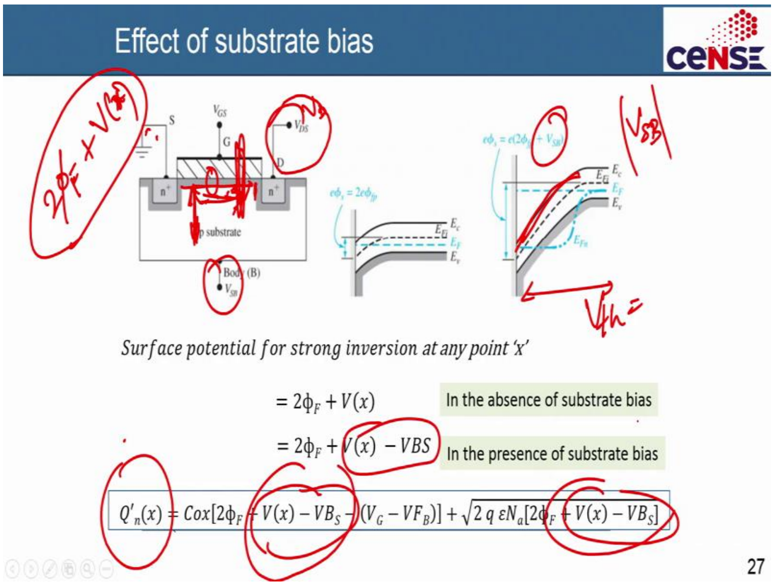

You will have this band bending that is occurring here right, this extra band bending that is occurring here. And that band bending is occurring, because of this term V_{SB}, this V_{SB} term is actually occurring an extra band bending here. And so what you can do is that for example, when you try to solve the gradual channel approximation, and all the equations that you derive, the surface potential along this you know, I told you that the moment you have inversion you have in this direction, you have a band bending of 2 phi F a strong inversion.

But, along this direction, because you also applying a V_{DA} A positive with respect to the source ground along this direction, because you will be applying that; you have to apply the term you know V(x) at any point x here, of course at this point, it will be V(x), but x any point it will be x. So, this is the voltage actually that any point x, we will see here.

In the absence of any body bias, when the body is shorted to the source, but in the case the body bias is also you know there some finite body bias you are applying, you have to that is V_{SB} to be subscript here sorry. So, you have to substrate or the body bias essentially V_{BS} is negative quantity, so that negative, and negative essentially becomes positive ok. So, this quantity will be like minus 1 volt or minus 2 volt, so this minus minus 1 volt, we will make it positive ok, so that is what I am trying to say.

So, what I am trying to say here is that this is typically the voltage that you are dropping at any point x, because of the drain voltage that you are applying and the inversion that is happening here ok, the inversion that is happening in this so potential in this direction, and the band bending in this direction sorry. But because of the substrate voltage, you have to have an extra drop here that because that will increase this to here. So, now, you solve the, way the because of some formatting issue, it is come like that. This is again a VFB essentially, it is the superscript here Cox super script here anyways.

So, you know this is the total charge that will be there in the channel at any point x, we have derived this expression before previously, but here there will be an one extra term here and that is you see this is the expression that you have derived previously in the absence of body bias. In the presence of body bias, this quantity will be replaced by this quantity; and this quantity also will be replaced by that quantity. So, it will become like this sorry ok. You see this it has become like this ok. So, you have V x minus V B s and then again V x minus V B s that you have.

So, now if you know this charge, because it is in the presence of a body effect here, you can actually derive the current voltage characteristics, you can derive the threshold voltage also. And it so happens that in the presence of this kind of a term here now, the threshold voltage will shift by some amount.

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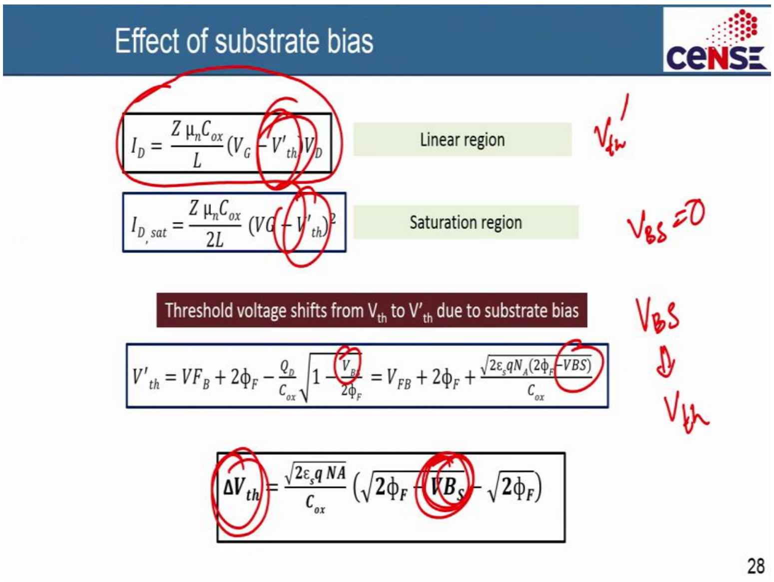

This is the current in the linear regime. This is the current in the saturation regime. Everything says this same except the threshold voltage has changed, it has become V dash V dash V th. So, this threshold voltage has changed, but everything else remain same. And this threshold voltage change is this is the new threshold voltage by the way because of the substrate effect. The you see the substrate effect has come here, then you see that the substrate effect has come here.

If you do not have the substrate, then it will reduce to the original expression that we had. And so this is that extra; this is the extra threshold voltage change that happens because of the substrate effect. This is 2 epsilon q square under square with N A this is the doping of course N A is the doping of the substrate the p-type substrate, C ox is the capacitance value.

And this is 2 phi is the band bending V B s, V B s actually this B should be like this. So, V B s is the extra voltage we are applying, this is the negative quantity typically it has to be negative quantity. So, what I am trying to say is that this negative sign and the negative quantity we will make it positive quantity ok, so that keep it in mind. And if your V B s was 0, which means you are actually grounding it, and there is no difference then this quantity will become 0, and so this quantity will become 0, and there will be delta V h you know the threshold voltage shift will not happen.

So, what basically it means is that by changing the bias on the substrate I am able to change the threshold voltage. So, the threshold voltage will change roughly as the square root of this you know subtracted from this, so that will be. So, if we apply more and more substrate-bias you are able to actually change the threshold voltage as a square root sort of a dependence ok. So, this is an extra nob that designers used to actually tune the sub-threshold not sub-threshold to actually tune the threshold voltage ok, so that is you should keep it in mind.

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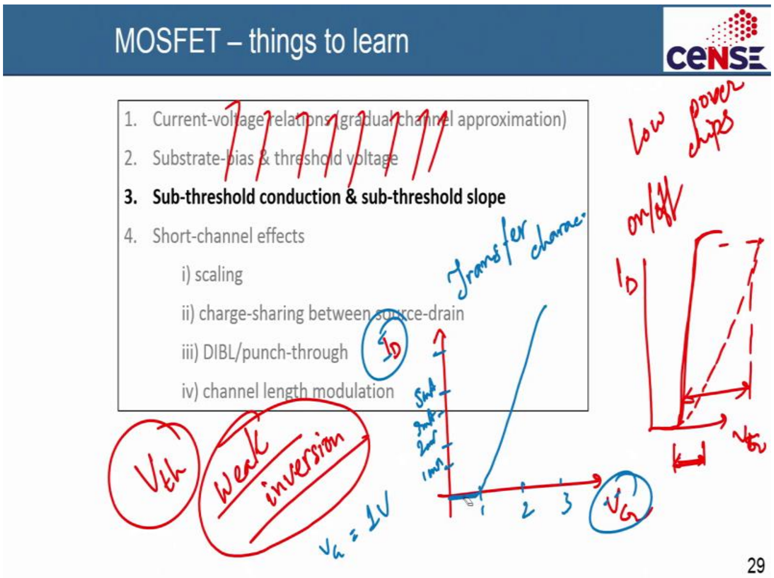

So, we have finished this two part now. We have finished the gradual channel approximation, also we have finished substrate-bias effect. So, the next thing will be sub-threshold slope now. Sub-threshold conduction and sub-threshold slope are very, very important in modern day electronics specially for very low power devices, low power you know low power chips where you want very very low power, ultra low power, extremely low power. But you need a very high on-off ratio which means the current you know if I plot I D versus V G gate voltage I should be able to go from off state to on state very sharply very sharply at very small voltage.

So, if this voltage range is very small, that means, it is a low power device you do not have to go much higher like this, you know to go from very low current to very high current, you do not have to drop much large voltage. So, this you know sharp threshold sort of a this actually is a very important concept and that is why research on this area is very hot even today, new materials are discovered.

What is sub-threshold conduction? Sub-threshold conduction is the conduction below threshold right. It is just conduction below threshold. You know before you go to strong inversion at threshold voltage, before you go to strong inversion at threshold voltage, you have weak inversion. In weak inversion, your bands are bending sufficient such that now your Fermi your intrinsic level, your intrinsic level is touching the Fermi level you know this weak inversion is taking place now.

And it is also going below the Fermi level, the Fermi level it is going below the intrinsic level or the intrinsic level is going below the Fermi level. So, you have some weak inversion you have not you have not reached strong inversion, but still it will carry some current very low current, but it will carry some current that is called sub-threshold conductions.

So, actually if you plot I D versus V G on a linear scale I keep telling you that you know you know threshold voltage if the threshold voltage for example, is say vg is equal to say is equal to say 1 volt. So, this is 1 volt, this is 2, this is 3 and so on, then below 1 volt the current will be almost negligible here; and at 1 volt threshold the current will increase that is what the threshold voltage means in an this is called transfer characteristics by the way I have drawn it is even early transfer characteristics essentially show the output current I D versus input voltage V G.

This part is actually the sub-threshold conduction. You will see that this current is almost 0, this is current for example, maybe this is 1 mill amp, this is 5 milliamp, 2 milliamp, 5 milliamp and so on. So, this point, this point you know below threshold, we see that there is almost no current and so we call it sub-threshold conduction.

Now, you might say that the current is very know almost 0 here. So, how what do you talk about sub-threshold conduction, actually the current is not 0, the current is very low, but it is not 0, and that current will actually come up only in a log scale only if you plot this in a log scale you will see the current actually come up ok.

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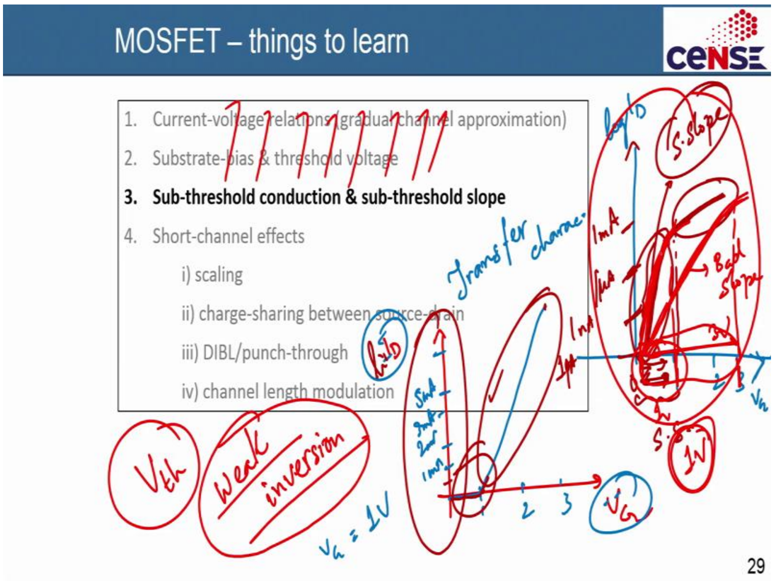

So, what do I mean by that is that n the same plot if I do in a log scale, this is log of I D versus sorry this is log of I D versus V G at 1 volt, 2, 3 volt for example, you see below 1 volt, below 1 volt ok, let me change the color here probably below one volt, it was in a linear scale this was linear scale and so you see that this current is almost 0 here and then it rises at threshold.

But here you will say that this is actually log scale. So, this could be say 1 pico amp, 1 nano amp, 1 micro amp, 1 milli map. So, this is 3, 3 orders of magnitude 1 pico to 1 nano is the 10 to the power 3 difference, I mean time difference 1 pico or 1 nano to 1 micro 1 micro to 1 milli, you know this is like 1, 1 order magnitude difference.

So, what will happen is that is this 3 order, 6 orders difference right. So, what is going on here is that below 1 volt actually with from 0 to 1 volt, your current will actually increase like very sharp, you see on the log scale. This will not show up here because it is can milliamp only linear scale, it will not show up. So, up to 1 volt and then from 1 volt, this slope will change. This is a slope here very sharp and then the slope changes here.

This part is what you see here this part from 1 volt, because it is a linear scale; in this linear scale you can see from 1 milliamp even 0 milliamp sort of to few milliamps current we will see here right. But below that when you have micro amp, nano amp, pico amp of current that will not show up in a linear scale, it will show up in a log scale. This is the sub-threshold; I call it SS. Sub-threshold conduction. There is a conduction and this it is rising by many orders of magnitude. It is rising from pico to like micro hundreds of micro. It is rising by many orders of magnitude in a very less voltage. You do not see it in a linear scale you only see it in log scale.

This slop is actually called sub-threshold slope, sub-threshold conduction. And sub-threshold slope this slope is sub-threshold. The steeper the slope is you know higher lower is the sub-threshold slope and better the device is. If your steeper device here a steeper slope here, if the slope becomes steep much more steeper, it means your device is turning on and off very sharply and; that means, at very small by spending very small gate voltage you are able to turn on the channel by many orders of magnitude that is called steep, steep slope or sharp very sharp on and off. That means, you are able to operate the device at much lower power low voltage and this is sub-threshold conduction this is sub-threshold slope.

If your slope is bad which means suppose you know you have to go from here to there in a very slow, this is a very bad slope right not so steep slope, this is a less steep slope right. So, it will go like this, that means, to go from this pico amps to a sort of milliamps, you have to drop like 3 volts, over here you are dropping only 1 volt. So, you see here you have to drop 3 volts, that means, the power that you supply to your MOSFET and these are like MOSFET these are millions and billions in numbers in your processors in your mobile processors or in your laptops and all. So, you know you have to turn off and on the MOSFET you know digital logic works like 0 and 1 for example a memory devices works many things are there.

So, anytime you have a logic device and you know this all your processors by the way all your cell phones, laptops are working on that only. So, to have this logic devices work in your processors, you have to spend 3 volts of power on each MOSFET actually a voltage on each MOSFET. So, the supply voltage that you are putting on the chip has to be at least 3 voltage, and then only it will come to milliamps from pico amps for example. And that milliamps to pico amps is necessary for defining the on off ratio or for defining the 0 and the 1 state of the digital logic right.

So, you have to spend 3 volt, that is a lot of voltage that is a lot of power, you are wasting power. You would better to have a transistor which can do it in for example, 0 to 1 volt in that case it is such a steep slope transistor that you can supply only 1 volt to your chip your 1 volt your mobile chip. So, your source volt in when I say source you are supplying the voltage the supply voltage to your mobile phones wherever in the chips will be only 1 volt, you are able to turn on the device by so many orders in magnitude it is a sharply.

So, these are called steep you know you want that this slope of the steep. And the steeper the slope is the more low power the device is. Instead of 0 to 1 volt if you actually can go from 0 to 0.5 volt, and you can raise this then that is the even fantastic number ok. So, you want people are trying to go to low and low power this logic and for that you want to do you know of course, low power to your cell phone battery will last longer. If you have to you can go by this order magnitude change in current that is the on-off ratio that digital 0 and 1.

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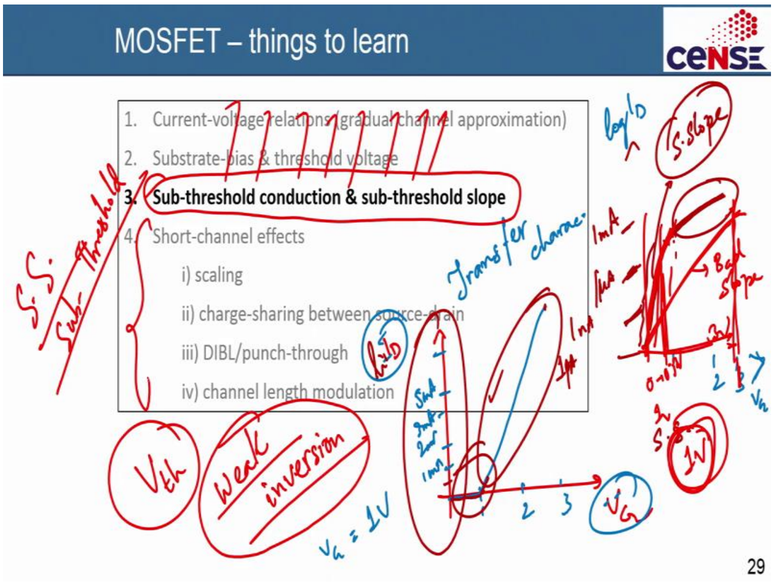

If you can change so many orders of magnitude of current in very low voltage say 0 to 0.5 voltage, that means, your battery has to supply low lower power which means your cell phone battery your smart phone battery will last longer. Your cell phone battery will last longer you have to charge is less right. It will be very convenient. If on the other hand, if your voltage, you are applying 3 volt to turn on and off each MOSFET in your cell phone, there are millions billions of MOSFETS, then you can imagine that your cell phone battery will dry out soon, because you have to apply so much voltage.

So, that is the practical correlation I was talking about in this course that you know whenever we try to understand this devices, we have to also see in the light of practical devices what is going on here. So, this sub-threshold slope I call it SS and sub-threshold conduction are very important concepts that are important in modern day electronics, modern day devices and that is why the next thing that we will study now will be sub-threshold conduction. We will just go through what is sub-threshold conduction I mean what is the equation for sub-threshold slope. And from there we will see that there is a fundamental limit to at what which MOSFETS can actually possibly work ok. And after that we will finish of the short channel effects in the devices ok.

So, with that we will end the class today and we will come back in the next class which we will continue with short sub-threshold conduction and short channel effects. So, that will basically wrap up our lectures for MOSFET we will be done with that. From there we will take up other topics, but I hope that you have understood the basics of MOSFET. We have not gone into very deep advanced mathematics into many of these things, but whatever basic mathematics is required we have used those, so that you are familiar with equations for current voltage relation transconductance and other things ok. So, let us meet in the next class and we will take off from sub-threshold conduction.

Thank you.