Analog Circuits and Systems through SPICE Simulation

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Lecture – 02
Basic Analog Design Part – I
Contd.

Hello, and welcome us again to the first part of this course; I am Mrigank. In the introduction session I give you brief overview hint what we have going to cover in the first few lectures on analogue design.

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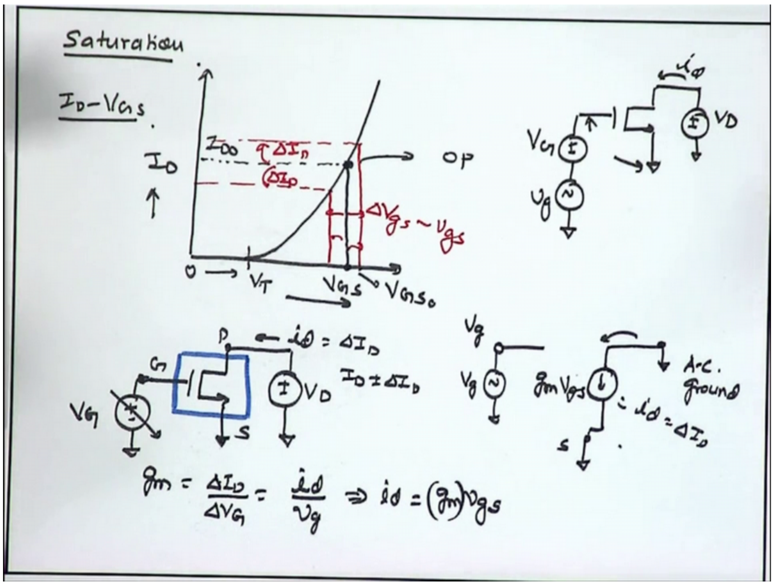

So now, let me talk about the large signal and the small signal characteristics of the MOSFET where that we are going to use in saturation region to arrive at the MOSFET characteristics. So, looking at the squared law equation from the x axis I have V GS on the y axis some plotting the I D. So, how do I obtain this plot? I can apply DC voltage at the gate of the MOSFET call it V G. I can apply a drain voltage source say V D I am not talking about, how to apply that drain volt your, how to generate that gate voltage assume that you have these sources available somehow on the chip or in the test board you are able to generate these required DC voltage is V G and V D and connected to the drain and the gate of the MOSFET.

Source is connected to the reference point, so source is grounded. And now I gradually sweep my gate voltage starting from the minimum value close to 0 going on increasing the gate voltage till I reach a V T the current will be very small it will not be 0 minded, because we are having subthreshold operation and there we know that there is an exponential dependency of current on the voltage.

So, in this region of course, current is very small. For practical purposes if we are operating the devising saturation region we can ignore the current in this region and call it that the MOSFET is of in this region you do not have significant current flow. Once we hit V G equal to V T beyond that point v observes steep increasing current following the square law dependency. And by steeping the V G from minimum all the way to a large value we can obtain this plot. Now how does this link to the small signal parameter of the MOSFET?

So, when we talk about small signal parameter we are talking about processing very (Refer Time: 02:46) very weak signals with the help of this MOSFETs exploiting the device characteristics; exploiting this characteristic curves of the MOSFET.

So, first thing is we need to have the DC operating point; desired DC operating point of these devices no more. What does that means? That means that on this I D V D V GS curve we are going to have a desired V G we are going to have a particular choice of V GS call it V GS naught, corresponding to which we are going to get a particular I D naught. This is the defining my DC bias point of the circuit. I have chosen a certain V GS naught and the I D naught and at this point I am going to operate my MOSFET. So, this is the operating point of the MOSFET.

Now, on the top of this operating point which is determined by the DC voltage I can apply some small signal which is input to my circuit for amplification of processing using the physical characteristics from this MOSFET. So, I can apply a signal delta V. I can increase my gate voltage by small amount or decrease by a small amount which is my small signal I can call it delta V or rather delta V GS. Or in terms of small signal we can just write it as small v gs that is a small signal change that we are imposing on the top of this circuit. So, basically I am applying a small signal in series with this gate terminal and then trying to observe what is happening to the current characteristics.

So, this curves tells us that if you are increasing the gate voltage by little bit my green current will go up, reduces the green current goes down. So, I get a commensurate delta I D on both side; increase and decrease by delta I D. And we can denote this MOSFET as a three put device. So, we can treat this as a black box. So, you have these three terminals that are available to you: the gate, the drain, and the source. We are giving a source at the reference point that is grounded. We are applying some signal between the gate and source that becomes our applied signal V G. On the top of this constant V G we are applying some small v g going up and down. And corresponding to that we expect the current in the output branch I D, we expect some small change in the current in the I D branch that is your delta I D.

So, the net current of course, is going to be I D plus minus delta I D. So, when I am applying V G plus minus delta V G I get a corresponding I D plus minus delta I D flowing into the drain current. So, by changing the voltage across the first two terminals I am getting a change in current flowing across the third terminal. And therefore, there is a transconductance operation going on. Applying a small signal voltage between gate and source we change the current flowing between the third terminal and the device.

So, we can define this three port model in terms of transconductance. So, we can draw the three ports: we have the gate, we can just use the small signal that is applied on the top this DC. So, we can forget about the DC V capital G we can forget about V capital D and look at only this small quantity small v g and the resulting small id that is resulting in our small signal operation.

So, in that case we are just going to apply some small v g over here setting the DC to 0. And we are going to look into the drain terminal; once again in this particular example if I only considered the small signal the V D is constant. So, the drain voltage is a DC it has not having any small signal. So, from the point of view small signal I said it to 0. So, I said this is an AC ground ground because in the corresponding circuit over here we have set the drain to a DC voltage or V D.

And as a result of the applied V G effectively the V GS because the source terminal is also grounded we are getting a transconductance term, we are getting a small change in the current flowing from drain to source and we can denote this as a constant term gm times the small signal v gs and this small change in current which is your small id or delta I D can be obtained from this transfer characteristics from this curve I D V GS curve of the MOSFET.

So, if you look at this curve and say that is your changing the V G by delta V G what is the change in delta I D obtain. So, that can be written as V G times the slope of this curve. So, gn can be defined as delta I D upon delta V G or in terms of small signal small signal id by small signal v g. So, what is the small change in the drain current we will obtained when we are changing the gate voltage by small amount; that is the transconductance term. And the trans comes from the point that we are applying the signal between the first two-ports and we are getting a change in current through the other port.

So, if you have a conductance or a resistance you apply voltage across the two terminals of the resistance and you get change in current across these thing two terminals of the device. But here are applying a small change in voltage across the first two terminals of the device and the current through the other terminal is changing. So, is the trans term community picture, and the slope of this curve at a particular DC point that we have chosen for our circuit operation defines the transconductance of our MOSFET. And therefore, the delta I D or the small signal id can be conveniently written as gm times v g. And remember that in this condition we have taken the source as the reference point, so it is always with respect to the source gm v gs becomes the transconductance.

Now in order to arrive at the expression for gm and look at how it depends upon the device characteristic that we have in our hand we can try to derive the expression and related to the device parameters.

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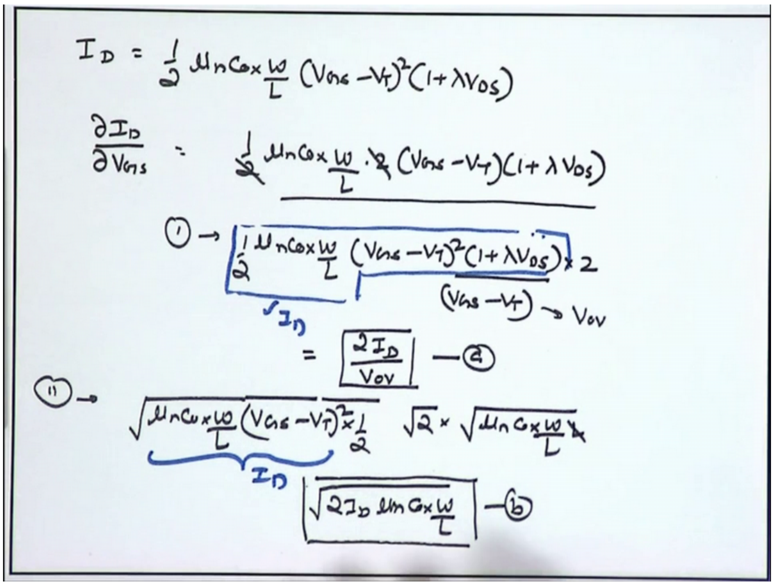

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)^2(1+\lambda V_{DS})$$

$$\frac{\partial I_D}{\partial V_{GS}} = \frac{1}{\cancel{2}}\mu_n C_{ox}\frac{W}{L}\cdot\cancel{2}(V_{GS}-V_T)(1+\lambda V_{DS})$$

$$① \rightarrow \frac{\underbrace{\boxed{\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)^2(1+\lambda V_{DS})}}_{I_D}\times 2}{(V_{GS}-V_T)} \rightarrow V_{ov}$$

$$= \boxed{\frac{2I_D}{V_{ov}}} \text{ — ⓐ}$$

$$(ii) \rightarrow \sqrt{\underbrace{\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)^2}_{I_D}\times\frac{1}{2}} \quad \sqrt{2}\times\sqrt{\mu_n C_{ox}\frac{W}{L}}$$

$$\boxed{\sqrt{2I_D\,\mu_n C_{ox}\frac{W}{L}}} \text{ — ⓑ}$$

So, here once again looking at the saturation region characteristics because that is what we have going to use most of the time. We can differentiate this curve at a desired DC point V GS and V DS. So, we can obtain the slope of I D V GS curve at the particular point has the noted in the last slide and they can write this down as 1 upon 2 mu n Cox W by L 2 times V GS minus V T in 1 plus lambda V DS.

And now I can manipulate this equation that I am getting in different ways to obtain more compact equation for gm and figure out this dependency on the device parameters. So, first case I can multiply this equation and divide by V GS minus V T square. So, I am multiply the numerator as well as denominator by V GS minus V T. Also I can multiply and divide by 2.

So, if I look at the first term. So, within this blue box the term that I am having is same as the DC bias current that we started with that is the I D. And the second term V GS minus V T is call or is generally termed as the V overdrive the overdrive voltage. You need minimum V T with respect to the source at the gate voltage two turn the MOSFET on. The axes voltage V GS minus V T is termed as the overdrive voltage and then this we can express this expression as 2 I D upon V overdrive. This is one expression for gm.

Likewise I can modified in a different way, I can use this equation, I can separate out I can steal the route of mu n Cox W by L take V GS minus V T inside make it a square and we can to some extent. If we can afford to ignore say lambda, we can suppose the channel in more relation is we can ignore lambda then we can drop the second term over here and just use the first term. Multiply and divide by root 2 and also we are left with again another square root term mu n Cox W by L.

So, once again the term under the first square root is our I D. So, what we get over here is route 2 I D mu n Cox W by L of the MOSFET. So, this is another expression of the gm which can be handing, while working on designs, when figuring out what should be the gm what should be the game. So, this is another expression that we should have at our finger tips.

So, it tells us couple of things, it tells us that there is a dependency on I D if you are increasing I D for a given V overdrive your gm is going to increase or vice versa for a particular I D if you are reducing the V overdrive the gm is going to increase. Likewise it also tells us that for a given I D if you are changing the W by L increasing the W by L the gm is going to increase.

Once again as I suggested that it is not good enough to just remember this formula, it is also important that we link this expression to the actual device characteristics. But how this gm change reduction or increases come in when I am changing my I D or V overdrive. So, it is also important to keep that into mind. So, that is look at the two dependency.

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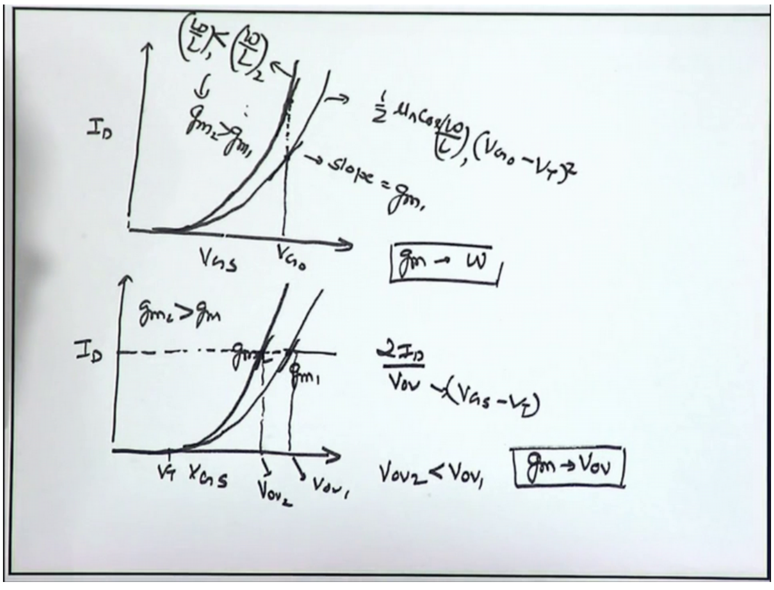

So, if I revisit my I D V GS curve from which we have obtain the definition of gm. So, if I am act a particular V G, so call it V G naught sources grounded. So, as we said the slope of this curve at this particular point is going to giving me the gm. This slope of this curve is the gm. So, as per this equation if I am say increasing the W by L, so, this curve is for 1 upon 2 mu n Cox W by L 1 and times V G naught minus V T square. And if I choose to increase the W by L; as I said W by L is the design parameter available to the IC designer I can tweak my W by L I can change it increase or decrease that to needs certain specs of the circuit.

So, how does this curve change? Definitely if I double my W by L for particular V G naught my curve is going to go up right, V T remains same but the curve goes up. So, at the same value of V G naught we are expecting that this W by L 2 which is greater than W by L 1 we are going to get a larger slope. And hence a larger gm: gm 2 is greater than gm 1 which was opting this point. So, keeping in mind the physical characteristics of the curve becomes are important; we should know why the change in the gm is happening.

Likewise this is a dependency on W. Likewise, we can for the same you know conditions we can also see what is the dependency on the overdrive voltage and conclude that whatever expression we are obtaining is making sense. Once again drawing the I D V GS characteristics for a particular V T; my W by L is fixed, my I D is fixed the second the first equation that I have for gm is I D by V overdrive.

So, this case my I D level is being fixed so I am at a particular I D. So, my horizontal line is fixed. And then if I am reducing my V overdrive the what that mean this is once again V GS minus v T; that means, I am is reducing the V GS. Once again for a particular characteristics if I have to obtain the same value of I D for reduce V GS the curve will be the point will be somewhere over here. And this will be again a part of different I D V GS curve. So, basically we are changing the V GS.

Once again, we can clearly see that gm 2 is going to be greater than gm 1. And clearly the V overdrive 2 is smaller than V overdrive 1. and this gives us the dependency of gm on V overdrive. So, it is important that we are able to link the small signal parameters that we are arriving at with the actual characteristics of the device. Then we can better appreciate what is the dependency of gain on W, what is going to happen if I change my bias current, what is going to happen if I have certain parameters in our hand like V T and so on.

So, this is about the small signal transconductance parameters. Let us now talk about another very important small signal parameters that is ro of the MOSFET, which is very crucial for analog design not so much maybe for the digital part. So, once again if I talk about the saturation region operation and look at the I D V Ds characteristics of the MOSFET.

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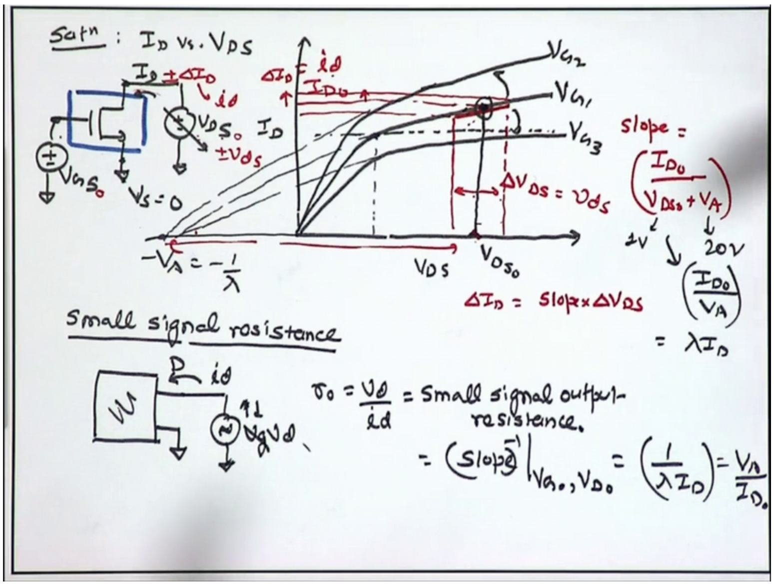

So, in order to obtain this curve saturation region operation for I D versus V DS curve of the MOSFET. So, first of all the question is what is the curve v expect when we have a MOSFET we are fixing the gate voltage to a DC call it capital V G and we are sweeping the drain voltage this time; remember reference point is source voltage, here in all cases we are putting the source as a reference point. So, I can always right V GS V DS in this case v s is equal to 0. And this case once again we are going to sweep the drain voltage starting from 0 to some maximum value dictated by the particular choice of the gate to source voltage.

So, what is the curve we expect the well known I D V DS characteristics? So, we have already seen what happens in the triode region. So, when we start with a very small v gs we said that the MOSFET is in triode region and in that case the equation that is governed is the linear dependency on V GS and V DS. And we will see what is the phenomena that leads to saturation. In ideally in saturation; saturation term means that the current through saturate it should become almost constant and the MOSFET should behave like a ideal current source becomes completely constant, it is not should not have any effect because of changing V DS ones that interns into saturation region.

But the actual MOSFET characteristic tells us something else you do have a finite slope of the MOSFET which means that we do have some finite output impedance looking into the dream. So, let us see what all these term means the small signal output impendence or the slope of this curve the concept of channel length modulation and the requirement of saturation region operation.

So, here this is for a particular V G1. So, what I in do? As I can fixed as V G as to a V G1 and then sweep my drain to source voltage from minimum 0 going all the way to higher value and at each point I can measure what is the current I D flowing through this MOSFET. That is how I obtain this curve. I can change my V G I can go for a larger V G V G 2 an obtain another curve. For a larger V G of course, the saturation region as the triode region expression will tell me that a particular V D in the current is going to be higher if I am having a large V G. And likewise for a smaller V D I can have curve which is lower. And graphically it is known that if you are extrapolating these curves they meet at a particular point on the x axis negative x axis at minus V A which can also be termed as minus 1 upon lambda which is the constant parameter V A as well as lambda I am assuming is a positive constant positive parameter of the device.

And then, if I am talking about a particular V DS V DS naught, I am looking at a particular V G naught. So, I have once again fixing the DC operating point of the device, I am choosing the bias condition the device, I am choosing a certain V G1 I am on the top of that V G1 I am choosing a certain V DS naught. So that fixes my DC operating point it tells me that I am at a particular DC bias current I D naught. This is the operating point of the device. And at this operating point I can figure out what is the slope of this curve at this operating point, because that is going to tell me something about the behaviour of the output port of this MOSFET.

It tells me that if I am keeping my V G constant that is I am sticking to the V G1 curve and changing the V DS little bit across the V DS naught point. So, V DS I have kept it to V DS naught and then I am changing it little bit on both sides; delta V DS you can call it small signal V DS on both sides plus minus delta. So, I am increasing and decreasing V DS by some mechanism maybe just by tuning this knob over here artificially. So, what is the corresponding change in the current that I am going to get? So, this going to lead to delta I D or you can call it the small signal id. So, what is that small signal delta I D or the small id resulting from change in this V DS to plus minus small V D s

How to I going to remind that? So, I can look at this curve once again I can see for a particular V DS the small V DS what is the change in delta I D that I am going to get. This is the small change in I D that I expect. Once again the small change in I D can be expressed as the trans or the slope of this curve delta I D and I can write it as slope of this curve times the delta V DS. So, all we need is to because what is the slope at that particular DC point. If I know the slope I know; what is the small signal behaviour of this device looking at the output port. So, I can say that if I have a DC condition V DS from the top of that I am applying a small signal V DS what is the small change in the current I D so that I can obtain by the slope; slope multiplied by the delta V D gives me the delta I D.

So, I can see some questions coming in, but right now we have question regarding gm, what is the significance of gm. So, once we go towards the application of this device in to circuits we will be able to appreciate what is the significance of gm. So right now we have just looked at the transconductance operation of the device where you are applying the input signal at the gate and getting some change in the drain. So, it is the transistor operation rights you are applying signal that has certain port, you are getting current change at the different port. So, that is the main transistor operation that we are interested in. So, we look into it when we go towards application with revises into circuits.

Now here once again if I talk about the small signal operation: so starting point was we fixed we choose a certain value of V DS; we choose a certain value of V G which landed us on this circle on this point with us fix V DS naught and a fixed V GS naught. And then on the top of that we are changing the V DS. So, looking at this particular simple circuit we are fixing this V GS to V GS naught, we are fixing this V DS to V DS naught and then on the top of that we are changing the V DS by little bit by small amount if small signal and then noticing the small change in I D that is the delta I D (Refer Time: 25:33) MOSFET. And that is easily obtain for this curve.

So, I can write down what is the slope of this curve if I look at this point, the slope can be identified as the y length, the length in the y direction divided by the length in the x direction. Length in the y direction the height of this point is just I D naught. So, I can write the slope as I D naught because this is just I D naught starting from 0 this point is I D naught, divided by the length in the x direction which is V DS naught plus V A in the opposite direction. So, this is the slope.

Approximately in general the V A will be much larger than V DS naught. If I am talking about 180 nanometer technology the supply voltage that we have is 1.8 volt V A can be 10 or 20 volt almost an order of magnitude higher than V DS naught. So for 180 nanometer I can say V A is going to be around 20 volt or higher V DS naught at the max 1 volt of that order. So, we can conveniently ignore this V DS naught term in presence of V A and we can just say that the slope is approximately equal to just I D naught upon V A.

Generally, this is the term this is the expression that is used for the slope. Although in the graph that I have drawn it is not very prominently clear that V DS naught is much smaller than this V A, but generally that is the case V A and V and order of magnitude larger than this V DS naught of desired operating point. So, generally the slope can be just defined as I D naught upon V A. And that can also be written as lambda I D. So, lambda is one upon V A as mentioned over here; so we having the slope given by lambda times I D.

Now if I want to define a quantity that is the small signal resistance seen into the drain terminal; looking into the drain terminal what is a small signal resister. So, what do we mean by looking into the drain terminal? Remember once again treating this MOSFET as the three port device, a black box where you have only three terminals visible to you: the gate the source and the drain. You are treating the source as the reference point grounded it. The gate voltage is fixed at a particular V GS naught and then on the third terminal V DS which we can take it as the output terminal where we are trying to test the device changing the DC voltage over here V DS naught to a small value plus minus delta V DS what is the change in the current.

So, that gives us the quantity small signal resistance. So, for any two-port circuit any two-port network or a model reference point maybe ground. You have one port available, you want to see irrespective of whatever is there in this box, you want to see what is the impedance looking into this terminal of the box, why I am calling this drain? This is the box and I am calling this is the drain terminal which is available to me other ports are fixed at some point I do not care; the gate voltage is think that the some point I do not care. I am just looking at the available port the drain and trying to see what is the impedance, what is the small change in current that I am going to get flowing into this source if I change my voltaire this node by small v g.

So, once again it is very important to distinguish this small v g from capital V G, so this capital V D sorry v d. So, this capital V DS providing me the DC point just like on this x axis we have the DC point corresponding to that we have a DC current I D naught. And if you are talking about the drain terminal here we are trying to change this drain voltage little bit up and down by a amount V D, and what we are trying to do is we are trying to measure the small change in current flowing into the drain terminal. So, we are only looking at the small signal I am forgetting about the DC condition, I am forgetting about this I D naught I am just concerned about this small id which is flowing into the drain terminal; the small change in current.

So, this change in current becomes my small signal; I forget about the DC value bias point. So, what is the change in current the small id which is going to result from changing in the drain voltage by a small amount of v d? So, this v d upon id is going to give me the small signal output resistance; this is going to give me the small signal output resistance. Once again this can be obtained as the inverse of this slope. So, what we obtain from his slope was id upon v d. So, if I have to talk about v d upon id it is just the slope inverse at the particular V G naught and a particular V D naught.

So, once again we have to define the slope but at a particular DC point. So, first of all we have to identify what is the DC point at which the device is operating. So, first is identify this capital V DS naught capital V G naught capital I d so that gives me the operating point. And on that operating point at that point what is my slope, inverse of that slope is giving me the ro. And therefore, this becomes equal to one upon lambda I D or V A upon I D. So, this is the bias point voltage DC current.

Now before we try combine these two parameters gm and ro to arrive at the combined small signal parameter of the MOSFET, let us briefly talk about the channel and modulation. Although many of you might be already aware of it, quite thorough gated, but once again people working racial domain they hardly worry about lambda, hardly worry about ro. So, in those cases it is good to have a brief recap of this might underlying mechanism behind ro or the channel length modulation and the resulting slope that is revisit; that very quickly.

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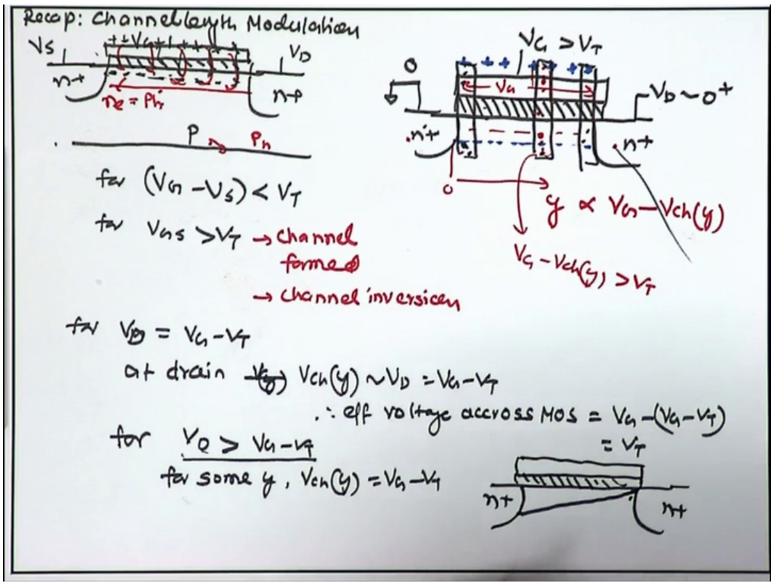

Recap: Channel length Modulation

for $(V_G - V_S) < V_T$

for $V_{GS} > V_T$ → channel formed
→ channel inversion

$y \propto V_G - V_{ch}(y)$

$V_G - V_{ch}(y) > V_T$

for $V_D = V_G - V_T$

at drain ~~$V(y)$~~ $V_{ch}(y) \sim V_D = V_G - V_T$

$\therefore$ eff voltage accross MOS $= V_G - (V_G - V_T)$
$= V_T$

for $\underline{V_D > V_G - V_T}$

for some y, $V_{ch}(y) = V_G - V_T$

So, if I look at the MOSFET structure recap of channel length modulation; so considering the NMOS once again. So, what we have seen is that if you are having a gate voltage V G beyond a certain voltage called V T that is the threshold voltage we have the MOSFET getting on. As long as the V G is lower than the threshold voltage for V G minus V S; V S is a reference point we are assuming it to be grounded. So, for a V GS less than V T there is hardly any current there is hardly any conduction, so practical purposes we can ignore it we do have some threshold current that is always bearing mind that we do have some threshold current, but if we are operating with larger bias current with an ignore that.

So, beyond below V GS less than V T we do not have much conduction in the channel. So, here we have a P type substrate and lot of holes over here, but we do not have electron significant amount of electrons forming the channel. Once we go beyond V T for V GS greater than V T we induce enough number of electrons in the channel. So, when we are increasing the gate voltage essentially what are we doing, we are depositing more and more positive charges on the metal gate. Making a metal terminal positive means you are depositing more and more positive charge. And these positive charge with attract more and more negative charge at this point; more is the positive charge we will require more amount of negative charges over here to balance the electric field created by the positive charging.

So, the moment you are trying to deposit positive charges on the gate terminal trying to make it more positive, we need negative charges on the other side of this oxide to balance the electric field or terminate the electric field. So, they are these positive charges they produce an electric field and they attract the negative charges. So, that they accumulate over here and from the channel. That is a basic mechanism for forming an end type channels. So, beyond the certain point when your V GS is sufficiently larger than V T you have enough number of electrons accumulated over here so that the substrate region has become almost N type as the bulky P type.

So, we say that if the electron concentration in the bulk sorry the whole concentration in the bulk is P; P whole the electron concentration at V G equal to V T almost we can call it n electron is equal to P whole. That is called channel in version that happens only when you are channel is completely inverted beyond V G equal to V T So, that is of course, we can go to more device level operations, and we can drive the exact physical phenomena involved in that, we can derive the physical meaning of V T. But in this limited session of course they cannot do that, we can point of the reference material so that those of who you are interest in going to the device details and brush up the device fundamentals can do that. So, V T itself is the very important parameter that has many important dependencies on other parameters. So, it is important that we aware of V T also the origin of V T also.

So, I would definitely recommend getting into the basic device concepts and be aware of this concept of channel in version that how the P types of state is getting inverted, how you are putting more and more positive charges on the gate and that is attracting more and more electrons on the surface and creating an n type channel connecting the 2 N plus regions. So, once this happens we say that the channel has been formed. You have enough number of negative charges accumulated over here and there density is equal to the whole density in the bulk. So, that is the channel inversion; channel has been inverted.

Now, I reset the channel in version depends upon the relative difference of the voltage between the gate and the silicon. The gate is metal in between you have oxide and then you have the channel which is once again silicon. So, metal oxide and silicon it is forming a capacitor. So, in order do a form of channel any section of the MOSFET; if I redraw this little bit more detail. If I have to talk about any particular locations suppose the sources that are ground voltage and this is oxide we are talking about the gate voltage V G and the drain voltage is small suppose it is close to the 0 it has to be positive right little bit positive voltage is needed to ensure any current flow. If you have both source and drain we know that there is no current flow you need a potential drop you have current flow. So, assume that it is close to 0 little bit 0 plus. So, you have some current flow provide the channel is created.

Now, V G is greater than V T so under that condition as I said you are going to have a channel of electrons created you have deposited, so many positive charges over here to balance those you are having lot of negative charges over here. So, you are having the channel created. At any point in the channel the effective density of these electrons at a particular location y; suppose I call this my reference point 0 and at a particular location y in the channel I am looking at the electron density at this point that is going to depend bit on the difference between the gate potential and the channel potential.

So, this is going to depend upon the difference between the V G at this point and the channel potential V channel at y. V channel means the potential at the y. V G is all port constant right; this is the metal gate metal does not have significant potential drop. So, all throughout V G is constant right. So, this is entire region V G, but in the channel you have a relatively higher resistance. So, we have a potential drop across the channel starting from the source going all the way to drain.

So, the potential is dropping across the channel. This is the higher resistance material silicon. And therefore V y; V channel y is not constant, V channel is dropping from a positive potential on V D side going down all the way to 0 at the drain side. So, V channel y is a variable. As a result at a particular slice if I take out the slice of the MOSFET and try to see; what is the effective potential between this capacitor of metal oxide and silicon at this point? Let us going to be V G minus V channel y that is a we have written over here.

And in order to invert the channel V channel this effective voltage must be greater than V T. So, in order to have the channel at the source side we said that V G should be greater than V T because on the source side the effective potential between the gate and the channel was just V G this is close to 0 because this is adjacent to the source which is having 0 potential. So, at this point we just have the overall potential between the gate and channel as V G, but at a particular location V y it is reduced to V G minus V channel. And therefore, in order to has the channel continuous at the location V y it must have V G minus V channel greater than V T.

Now if you go on increasing V D and make it more and more positive and recheck condition such that- V D has reached say V G minus V T. So, under that condition just adjacent to the channel; just adjacent to the drain terminal if I look at the V channel at drain the V y or you know V channel y is approximately equal to V D which is V G minus V T. And therefore, effective voltage drop across MOS that is the metal oxide semiconductor it is reduced to just V T, because this is going to V G minus V G minus V T.

If we go beyond that if V D increases beyond this then definitely the effective voltage is reduced below V T and once again we are going to lose the channel at that point. So, we say that under that condition the channel has been pinched of, you do not have an effective electron density on the drain site. So, at this time the channel has been pinched of the electron density over here has been reduced to 0, but definitely on the source side you still have the strong channel created.

So, this is basically now creating a depletion region. And what happens if we go on increasing the drain voltage further? So, if my V D is going beyond V G minus V T. So, for some point in the channels or some y in the channel we will have V channel y equal to V G minus V T. So, at some you know location in the channel we will have a condition where, V channel is equal to V G minus V T. If I just continue from here. So, if I am going for larger and larger V D.

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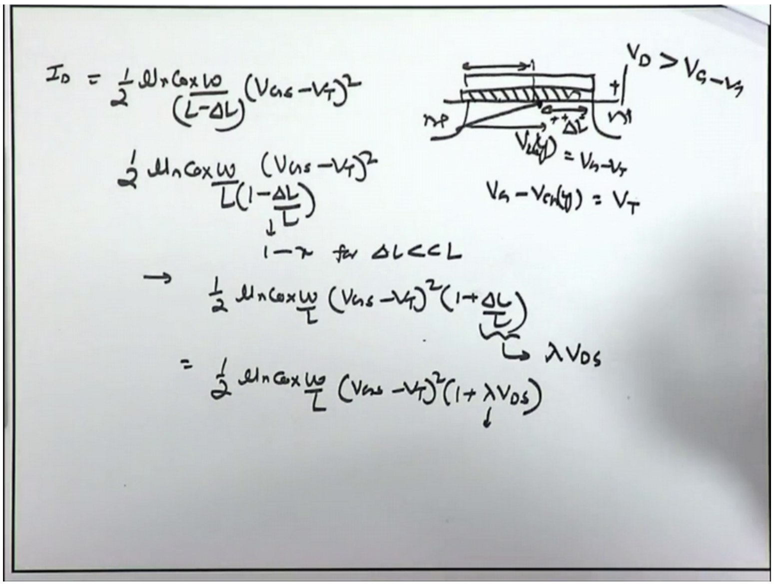

$V_D > V_G - V_T$

$V_{ch}(y) = V_G - V_T$

$V_G - V_{ch}(y) = V_T$

$$I_D = \frac{1}{2}\frac{\mu_n C_{ox} W}{(L-\Delta L)}(V_{GS}-V_T)^2$$

$$\frac{1}{2}\mu_n C_{ox}\frac{W}{L(1-\frac{\Delta L}{L})}(V_{GS}-V_T)^2$$

$\downarrow$ $1-x$ for $\Delta L << L$

$$\rightarrow \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)^2\left(1+\underbrace{\frac{\Delta L}{L}}_{\hookrightarrow \lambda V_{DS}}\right)$$

$$= \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)^2(1+\underset{\downarrow}{\lambda} V_{DS})$$

So, we expect that at some point in the channel definitely down there we are going to have V channel y equal to V G minus V T. And once again at this point we are reaching a condition where V G minus V channel y has been reduced to V T. So, the pinch of point moves further. So, this entire region is depleted of electrons do not have a nap electron in this region we say that this is depleted.

And therefore, the effective we called this delta L, effective channel length across which the length the channel is form is now reduced to L minus delta L. Now it can be shown if it try to derive this equation from the very basics all we need to do in order to capture this effect of reducing L is to modify the channel length the effective channel length appearing in the MOSFET to L minus delta L.

Because, what happens is that you are having a depletion region beyond this point. So, in this region you are having lot of positive charges. So, lot of negative fixed charges over here in the P type region and you have a lot of negative charges in the N plus region. So, here in this depletion region just like in the depletion region of the diode here we have a depletion region and we are going to have a strong electric field in this region. So whatever electrons are able to reach to this point there easily subduing.

So, in order to write down the overall equations for the current I can just write; I can just modify my equations and replace the L by ineffective channel length as if my channel length has been reduce to L minus delta L and imagine that my channel ends over here.

And then whatever current I get that same kind of going to exit out of this channel; that is it is not going to change because current cannot change. So, my modified I D becomes 1 upon 2 mu and Cox W by L minus delta L V GS minus V T square. So, all I have done is the original current equation as modified to L minus delta L, I am assuming the delta L to be relatively small here as exaggerated it is looking largest, but in general if I assume that the delta L is small as compared to the channel length I can take out L lot of (Refer Time: 44:24) 1 minus delta L upon L V GS minus V T square. And this can be expressed as 1 minus x where x is very small assuming x is much much smaller than 1 for delta L much much smaller than L I can express this equation as 1 minus mu n Cox W by L V GS minus V T square 1 plus delta L upon L.

And must again this delta L upon L this is a fractional change in the current can be written as lambda times V DS that is. Once again coming from the device characteristics proportional to V DS we are increasing the V DS making the drain voltage more and more positive the delta L increases the check pinch of point shift further another result the current is supposed to increase slightly. And the proportionality constant is once again coming from that slope I D V DS characteristics.

For the smaller is the lambda smaller will be the change and in that you can ignore this delta L by, but if the lambda is smaller especially we have going for scale technologies lambda degrades another result it becomes more and more significant. The slope in the saturation it becomes more and more prominent, we cannot treated in ideal current source. This is the basic origin behind channel modulation, I can write down the overall current equation as Cox W by L V GS minus V T square 1 plus lambda V DS.

Once again remember that here we have taken such an approximations there is an deriving it from the basics and deriving at the final equation because of lack of time, we have just said that the key point remember is your effective channel length is getting reduced. The length over which you are calculating the current flow it is just L to L minus 0 to L minus delta L. And we are assuming that the drain is shifted to this point, because after this there is no significant electron concentration.

So, whatever mechanism be used to arrive at the original current equation we just change the limit of L to L minus delta L. And whatever current reaches here because of the strong electric field in this region it get sug in towards the drink which is positive potential which is V D get an significantly greater then V G minus V T you have a positive potential over here strong electric field in this direction which sucks in all electron that reaches here. That is the basic mechanism. For more detailed device terminal derivations we can once again provide this an extra nodes, we have defined we do not have though so much time to go through that in this course.

So, this is basically gives us the small signal operation and the characteristics that we used in our previous discussion about the channel length modulation.

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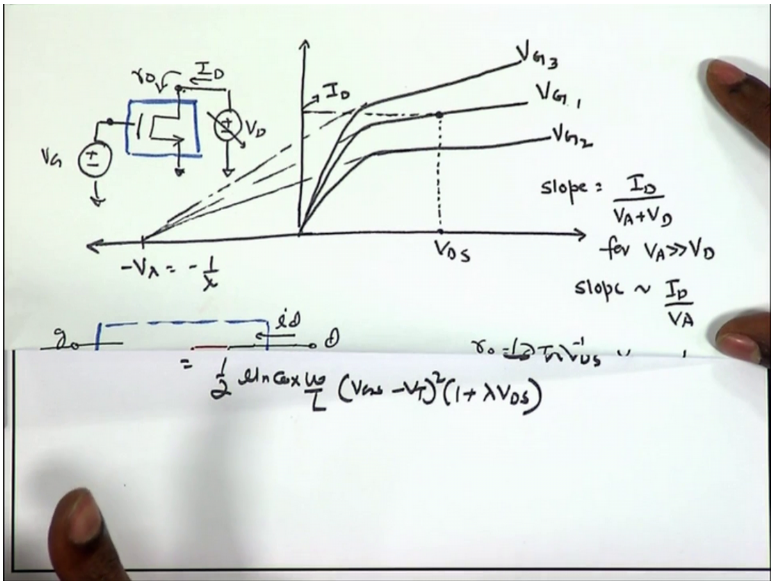

So, this characteristics that we obtain it comes state from this equation or you can say this characteristics is being well captured by this equation: the lambda V DS representing the dependency of the drain current on the drain to source voltage. The good MOSFET and ideal MOSFET will be such that lambda is close to 0. So, that the curves is almost flat so that the channel in modulation is almost negligible delta L is much small as compared to L that is an ideal MOSFET, because what do we need for a good transistor the good transistor is such that the current is being controlled only by the voltage between gate and source then is the good transistor because the transistor operation the voltage across the two-port should control the current flowing cross the third port. The voltage across the third port should not control the current that is a good transistor. So, for our analog operation for good amplification we need good ro. A very small slope, a very small channel and modulations so there is a delta L upon L is very small that gives us better device suitable for analog amplification as we will see in the continuation of this lecture.

So, this is talking about the two small signal parameters gm and ro; we will come back and we will try to combine these two parameters and complete the small signal model of the MOSFET. And on the tau of that we will then try to add the small signal capacitances to develop the high frequency model visit the concept of noise and try to add the noise sources to the MOSFET to complete the model for our circuit analysis. So that is what we are going to do in the next class. And the last session once again we will start with the circuits and try to apply these models for analyzing the circuits for frequency response, for AC analysis, noise analysis, small signal analysis, DC analysis and so on.

So, (Refer Time: 48:56) I will have a introduction section also towards the end, where will try to address some of the key questions that have been posted. So, there is a time for the break right now, we will meet once again after the break; may be after an hour or so at around 1:45 pm.

Thank a lot.