Integrated Circuits, MOSFETs, OP-Amps and their Applications

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Lecture - 13
Operation of Depletion type MOSFET

Welcome; to this particular module and this is a continuation of our last lecture in which we have seen the MOSFET. We have seen how the MOSFET can be fabricated using the process flow. Then, we have seen how the enhancement MOSFET works; we have seen some transfer characteristics. In this module we will concentrate on depletion type MOSFET.

So, in the case of enhancement type MOSFET, the channels was the channel was not there between source and drain. If I say that my index finger; then, this one is source and this one is drain; then, the channel which is this pen was not there. That means, channel is not there.

So, this channel can be generated when we apply a negative gate voltage compared to the source, positive gate voltage compared to source of V G S gate is positive compared to source. And then because of the positive voltage at the gate, the electrons will get attract from the base and there will be formation of channel.

Duty formation of this channel as we go on increasing V G S, our current starts increasing for particular value of V D S. For constant V G S when we increase V D S, it will reach to a saturation region; when it starts saturating, the constant voltage or V D saturation, it also called the Pinc- off region.

And then when we keep on increasing suddenly it shoots up after or continuously increase in the V D S and that is your MOSFET may get breakdown or it is a breakdown region or the MOSFET may get affected it may get destroyed. So, we should not exceed V D S more than a particular value.

We have also seen that the gates to source voltage should be greater than equal to threshold voltage to see the flow of current, to see the flow of I D which is drain current. So, in this particular module, let us see how the depletion type MOSFET is there, how we can operate it and what is the construction of depletion type MOSFET?

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So, if you see the screen; today, we will be discussing about depletion-type nmos transistor; its construction and working as well as its drain and transfer characteristics. We will see the drain and transfer characteristics, we will see the construction and Working of the depletion type MOSFET not Enhancement type, Depletion type MOSFET.

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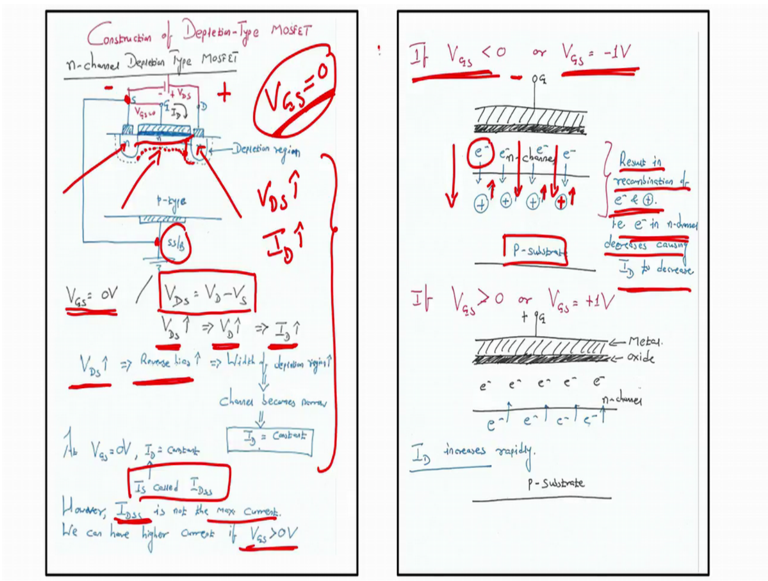

So, you see this slide, we will see or you can see what is here. This particular figure if you see, there is a substrate which is SS slash B; this is internally connected to the source over here. We are applying V D S, where drain is more positive compared to source .And then, right now in this particular condition, the gate is directly connected to source; gate is directly connected to source; that means, that V G S, V G S is 0; V G S is 0.

Now, in this condition you can see, source is here, drain is here and there does already channel exist in between source and drain; there is already channel existing between source and drain. Now; that means, that when my V G S is 0 volt, what is my V D S? V D S is nothing but voltage at the drain minus voltage at the source.

So, if I increase V D S, my V D will increase and correspondingly my I D will increase. Why? Because I already have this channel present between source and drain; so, in particular condition when you have V G S equals to 0, when you have V G S equals to 0 on increasing V D S, on increasing V D S; we can see increase in drain current, we can see increase in drain current.

But in case of enhancement type when V G S equals to 0, even on increasing V D S we were not able to find any drain current because there was no channel between source and drain easy. So, now, in case of depletion type MOSFET, what we see? That when we apply no gate to source voltage gate to source voltage is 0. In this case when we apply, when we increase V D S we can see correspondingly, increase in current I D.

So, what is that? Let us see next one V D S if I keep on increasing then the reverse bias will keep on increasing, width of depletion will keep on increasing and channels becomes narrower and I D becomes constant, I D becomes constant. How? So, if I keep on increasing V D S, if I keep on increasing V D S; then, channel will start getting narrowed like this which you can see from the figure, right over here and because the channel is getting narrow, what will happen, what will happen? The width of depletion region, this width of depletion region is increasing. Now beta depletion region will be see, it is like this. So, the width is increasing, the width of depletion region is increasing.

Now, if the width of depletion region is increasing; that means, channel is becoming narrower; if channel becomes narrower, my current I D will be constant. And in this particular case when V G S equals to 0, V G S equals to 0, when my id that is my drain current which is a constant value; then it is called I D Saturation or I DSS. Ii is called I D Saturation or I DSS.

However, note that the I DSS is not the maximum current; it is not the maximum current. We can have higher current if you increase V G S greater than 0. So, that is not that I D is ID constant id saturation; that means, that we cannot have more than I DSS, it's not a maximum current. We can have more than I DSS, if we start increasing V G S greater than 0 volts. This was a condition, when we have V G S equals to 0 volt, but if I increase V G S greater than 0 volt, I will see the increase in the I DSS or degrade in current I D easy.

Now, if you see the right slide, right side of the slide, what you see; if V G S is less than 0, if V G S is less than 0 or let us say V G S is minus 1 volt; V G S is minus 1 volt. Now what will happen? That means; that V G S; that means, the gate is negative. So, what will happen? The electrons, the electrons will be post down because electron is negatively charged; we applied negative to the gate terminal.

So, negative-negative will cause repulsion. This repulsion will effect in the pushing the electrons down into the substrate. You can see there is a substrate. So, electrons will come down, it will be pushed down like this and because of a negative charge is there holes will have positive charge that we know. So, holes will be pushed up, it will be pulled up; you see holes will be pulled up, electrons will be pushed down.

So, this will result in recombination of electrons and holes that is electron in n-channel decreases causes I D to decrease. So, you get it. So, if I have this particular condition where my V G S is less than 0, when my V G S is less than 0, what will happen? My electrons from the channel will be pushed down the holes will be pulled up and there will be recombination of holes and electrons and ultimately, what I see is decrease in the channel and the current I D will also simultaneously decreased. Now current I D will also decrease.

So, let us consider another condition.

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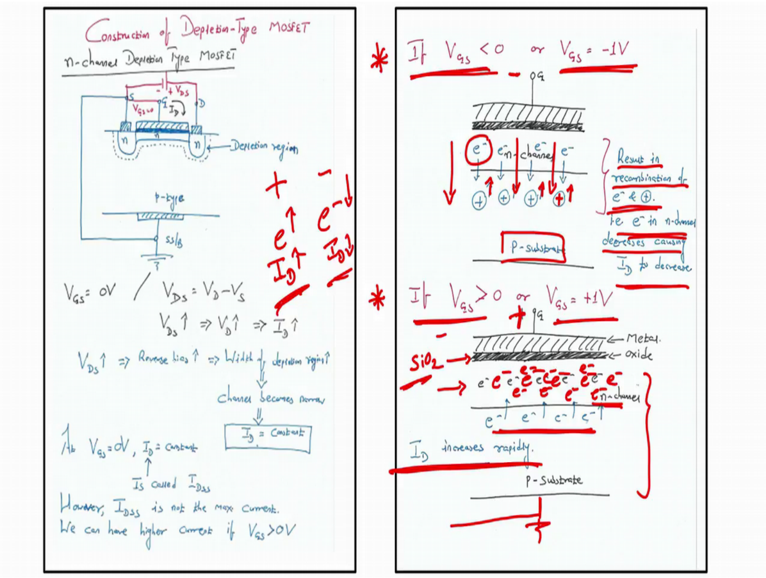

That is in this case my V G S is greater than 0 volt, V G S is greater than 0 volt; see if my V G S is greater than 0 volt, let us assume it is plus 1 volt. You can see here plus at gate terminal; you have substrate, you have substrate which is connected to the ground or it connected to the ground and also internally the connected to the source that we know. So, here if I have gate which is positive compared to source.

Then, what will happen the electrons, the electrons here, in the substrate; in the substrate, this will be pulled up. This already n-channel is there. You see here, n-channel. This is electrons within n-channels. This forms a channel between source and drain. This is your oxide layer S i O 2, thin layer of gate oxide, we already have seen. How can we go gate oxide? We can go grow gate oxide using thermal oxidation; thermal oxidation.

Now, if I apply positive with respect to the substrate. Then, what will happen? The electron that minority carriers from the P-substrate will be pulled up and there will be more number of electrons in the channel, there will be more number of electrons in the channel that will cause, that will cause my I D to increase rapidly, that will cause my I D to increase rapidly, very easy right; see we have to just understand positive apply electron will be attracted negative apply, electron will be pushed down if electrons are push down, the channel will be narrowed and my I D will be decreasing, if my electrons are pushed up I can see my I D increasing. Depletion type MOSFET very easy; very easy.

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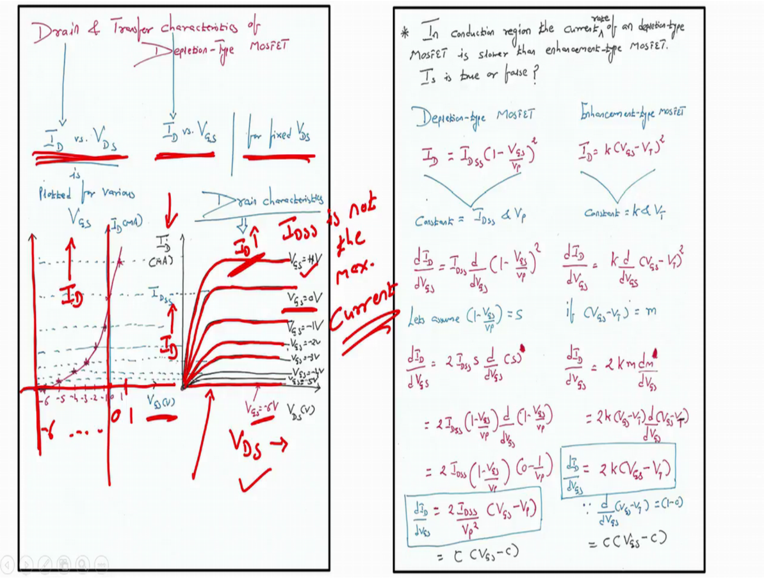

So, in this case if I want to draw a drain transfer characteristics, drain and transfer characteristics for depletion type MOSFET. How can I draw it? Now you see here, see this case here you see at V G S equals to 0 volt I already have on increasing V D S, on increasing V D S, I will see increase in I D. You see here let us consider V G S equals to 0 volt; that means, we have to consider this line and you see here there is a current already flowing right in case when V G S is 0 volt.

So, if I have if I have V G S less than 0 volt, in this case my current will start decreasing; my current start decreasing, you can see. You can see the saturation I DSS is reaching early and at V G S equals to minus 6 volt, you can see here is all almost call, but what if I increase V G S greater than 0 volt? If I increase V G S greater than 0 volt like we discussed, we can see the current still increasing, you can still see the current increasing. The I D is still increasing; that means, my I DSS is not the maximum current, my I DSS is not maximum current, because if I increase my V G S greater than 0 volt, I can still see that the current I D is increasing.

So, what we see here, the drain characteristics is I D versus V D S. Here, I D versus V D S while transfer characteristics would be id versus V G S for fixed V D S; for fixed V D S, let us draw the transfer characteristics. Now in this case what I will do is, I will draw an x and y; x y plot like this. And what I will do? I will write down my value for if this is 0 volt, this is 1 and then so on in this direction. This is minus 6. What is this? V G S.

What is here? Here is I D. So, what I will write? Minus 6, minus 5, minus 4 until 1 because I have applied the similar voltages, I have applied similar V G S in my this plot, this plot.

So, you see these all the voltage is we are writing here in the x axis. Now, you see what we have to do? We have to, we have to just draw because this is I D, this is ID. So, you get and this is also I D, you see this is also I D this is also I D.

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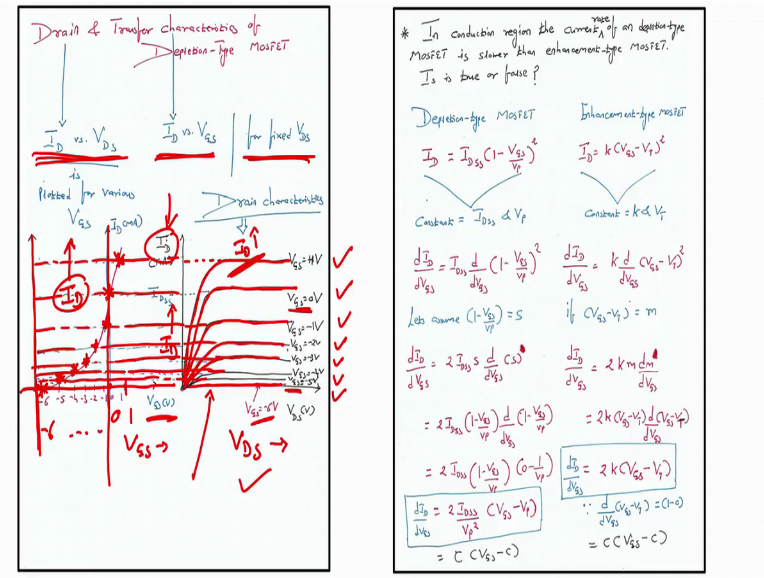

So, what we had to do? We have to just connect this I D values like this, like this, like this.

Now, what we have to do? We have to see. What we have to see? That what is the value here for current for V D S constant, let us say V D S is constant. Now let us consider minus 6, for minus 6 current is 0. So, I will have 0, minus 5; for minus 5 my current is let us say 1. So, I will put a star here. Then 2, then 3 then let's say current is 4 current becomes higher, still higher for 0.

For 1, I can see here my current is somewhere here and let say this value is 8 and 8 milliampere. Then, what I see is I have points on this axis, on this axis just by understanding, what is the current value for particular V G S value. So, here my plot is I D versus V G S; I D versus V G S.

So again, I can draw the transfer characteristics, draw the transfer characteristics if I have or if I know the drain characteristics that is I D versus V D S. If I know I D versus V D S, what we are saying. If we know, what is, how the plot for I D versus V D S looks like for different value of V G S is very easy to plot I D versus V G S.

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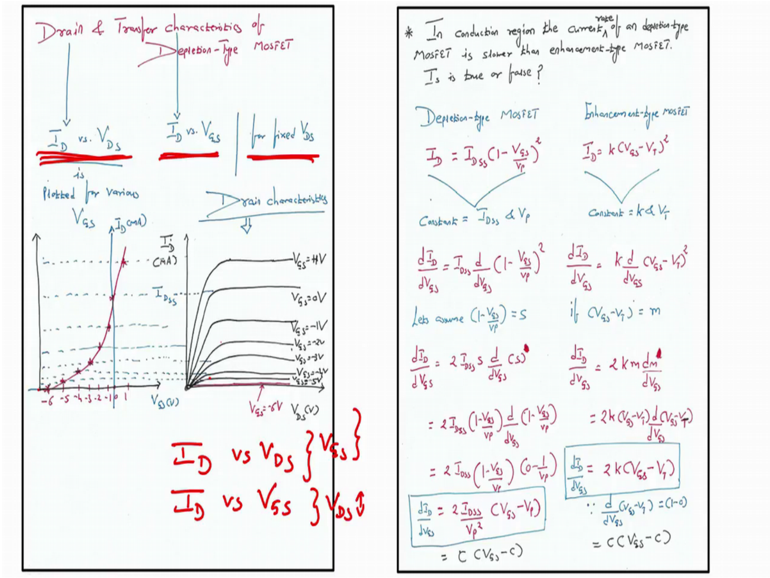

What I am saying is if I know the plot I D versus V D S, how it looks like. It is for different value of V G S; for V G S different values. Then it is extremely easy to plot I D versus V G S for same V D S; for same V D S, very easy is not it; extremely easy.

So, now if I have a problem; if I have a problem which you can see here.

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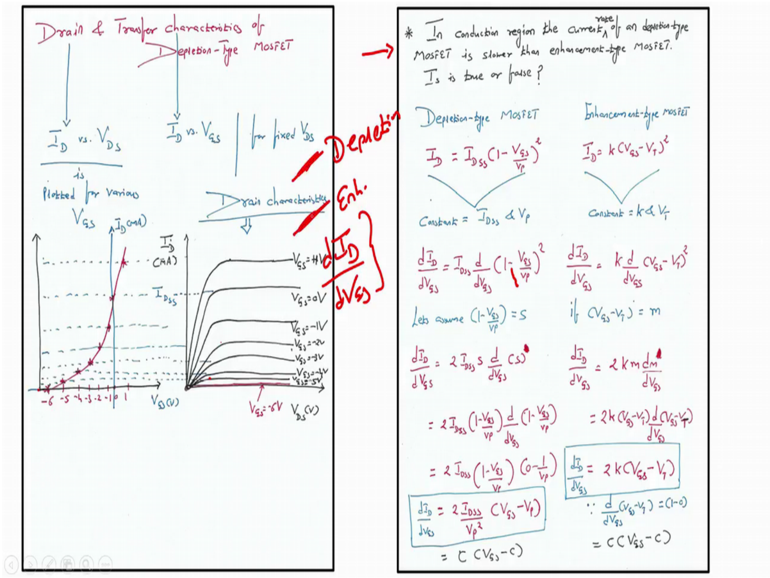

Here, the problem is in the conduction region; in the conduction region the rate of current, the current rate of an depletion type MOSFET; the current rate of an Depletion type MOSFET is slower than Enhancement type MOSFET. What is written? The sentence written is let us read it together in the conduction region, the current rate of an depletion or of a depletion type MOSFET is slower than the current rate in enhancement type MOSFET, is this statement true or false that is a question.

So, let us we have to find out whether the statement is true or false. The statement is if I use my MOSFET, 1 is my depletion MOSFET; 1 is my enhancement MOSFET and what it says that in conduction region triode, in conduction region my rate of change of current that is my I D that is my rate of change. So, d I D by d V G S, rate of change of current is slower when, I use depletion compared to when I use enhancement; is it true or is it false.

So, let us solve it; let us solve it. Now we all know that the I D formula for the depletion type MOSFET is nothing, but I D equals to I DSS 1 minus V G S by V p whole square and if I want to understand enhancement type MOSFET then, my current formula I D will be I D equals to K times V G S minus V T whole square.

We will see derivation of one this, rest you have to do by yourself; try to do by yourself as well. So, one, once I know the formula I D equals to I DSS 1 minus V G S by V p whole square and I D equals to K times V G S minus V p whole square. Then, what is the constant here? Here my constant is I DSS and V p here my constant is K and V T.

Because here I D S S is constant; we know it. Here Pinch-off voltage is constant; I know it. Here K is constant, I know it. Here threshold voltage is constant, I know it.

So, in this case if I do the derivation because I want to see the rate of change or rate of change that is why I had to do derivation. So, D I D this particular equation, equation 1 here is also equation.

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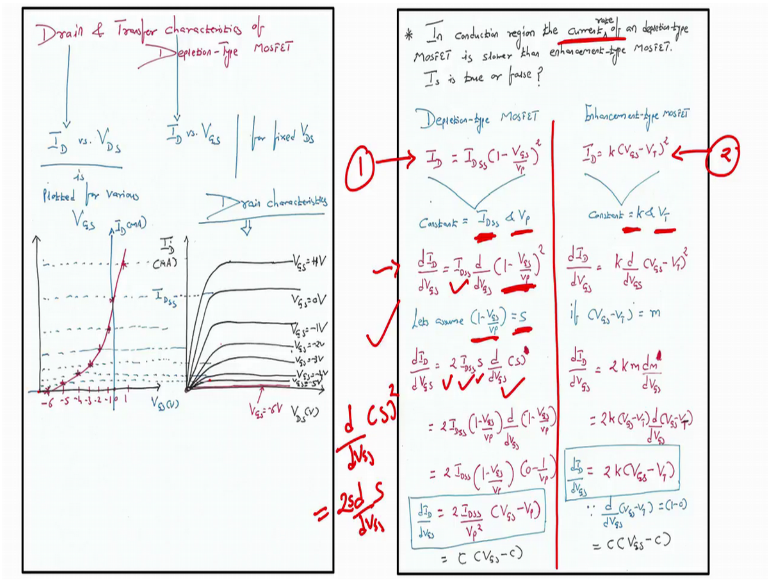

Let's say make it to, let us say this equation number 2. So, we are deriving from 1. So, 1, if you see further d I D by d V G S right to I D S S; I D S S is constant; d by d V G S of 1 minus V G S by V p whole square. So, let us just see this side first; this side first, left side, this side first.

So, let us assume here that 1 minus V G S minus V divide by V p; 1 minus V G S by V p is nothing but my constant S in that case d I D by d V G S equals to 2 times I DSS d by d V G S of S; because d by d V GS of 2 S of S square because we have considered this value, 1 minus V G S by V p equals to S. So, we can have d V G S d by d V G S of S square that can be nothing but 2 times d by d V G S of S. There was we written see 2 times d by d V G S of S and 2 times S, 2S d by d V G S of S.

So, 2 times S d by d V G S of S. And then, we have your I D S S. We have your I D S S; 2 times when you have this derivation of S square is 2 times S d I D by d V G S of S. So, that is only a simple derivation by which we can get this formula, which is right in front of you is nothing but d I D by d V G S is nothing but 2 times I DSS into S into D by d V G S into S.

So, with this formula if I substitute the value of S, my S is nothing, but 1 minus V G S by V p. So, if I substitute value of 1 minus of value S in here, 1 minus V G S by V p then, I get this particular formula. So, if I further understand 2 I D, 1 minus V G S by V p. Now derivation of 1 is 0 and my d by d V G S of V G S by V p will be minus 1 by V p. So, if I further solve this equation, what I have d by d I D by d V G S; d by d I D by d V G S is 2 times I DSS. Now you multiply this and this or you get V p square V G S minus V p; V G S minus V p.

Now, what is constant here? We know see I DSS is constant and V p is constant, we know. So, let us put the constant value. So, this main set, this particular value is constant; 2 is constant, I DS by V p whole square will be constant, V G S minus V p, V p is again constant. So, I will write C as a constant, V G S minus C which is again a constant. So, my role or my equation for the depletion region.

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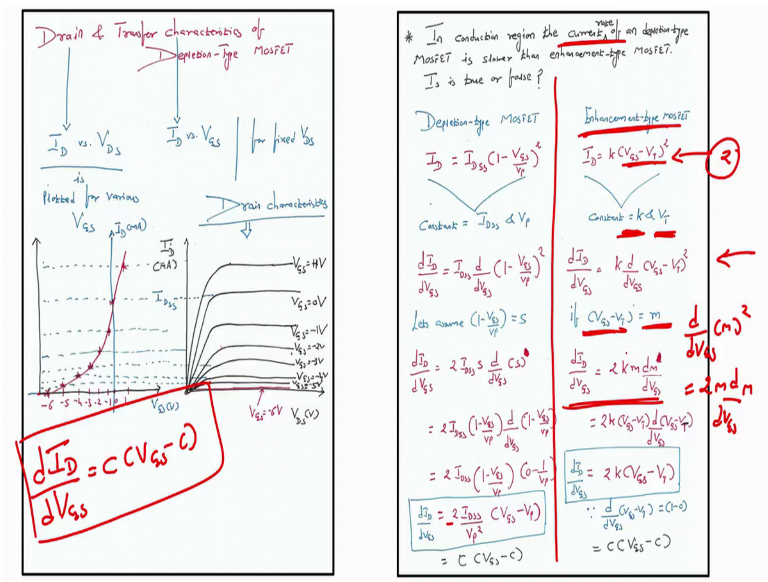

For the depletion MOSFET is C V G S minus C. This is my equation. For what? Depletion type MOSFET and the 2 in conduction region, the great of change of current.

Now, I had to see how the rate of change of current or the current change occurs in the enhancement type MOSFET? I will see how the change of current occurs in enhancement type MOSFET. So, let us consider the right side of the slide and second half that is the equation number 2.

So, now we will just consider this particular side. So, let's start. So, now, we know that enhancement type MOSFET, your current id is K times V G S minus V T whole square. Here K is constant and V T is constant; K is constant VT is constant. So, if I start derivative my d I D by d V G S is multiply K times d by d V G S of V G S minus V T whole square.

Now, if I assume V G S minus V T is equal to m. Then I will have d I D by d V G S equals to 2 times Km dm by V G S. Again which is similar thing, what we have is d by d V G S of m square this is nothing but 2 times m d by d VGS of m. This is what we are written here, this what we are written here. K is there so, we have substituted K also.

Now, once I have this, I will again substitute value of m. So, when I substitute value of m, I will had 2 K; m is what? V G S minus V T. So, 2 K into V G S minus V T; d by V G S of V G S minus V T; when I solve this. I will get 2K V G S minus V T; 2K V G S minus VT.

Now, d by d G V G S of V G S minus VT is nothing but see V G S V G S; so, 1. And VT is constant. So, my 1 minus 0 is 0. So, here my value is nothing but this is constant. This is constant and VT is constant. So, it will be constant into it is writing like constant because K is constant 2 is constant V G S minus VT; VT is constant.

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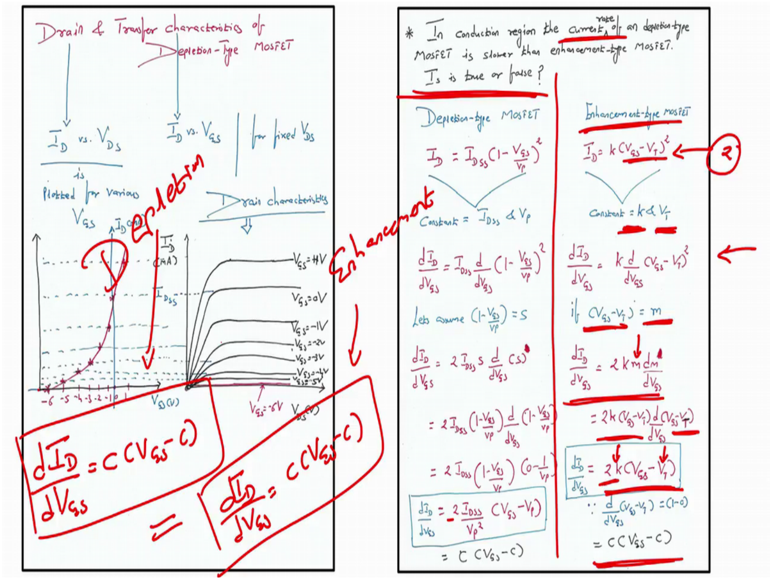

So, I have value d by d I D by d V G S equals to C times V G S minus C. This is what I have derived; this is what I have derived. This is for Enhancement type; Enhancement type. This is for Depletion type; Depletion type MOSFET.

So, what I find is that the in the conduction region, the current rate of an depletion time MOSFET is equal to the enhancement type MOSFET. The in the conduction region the current rate of an depletion time MOSFET is not slower not faster, but its equal to the conduction; the current rate of change in enhancement type MOSFET. So, this statement is false. So, this statement is false, easy; super easy. This is how we can derive whether the rate of change of current in depletion type MOSFET is different than rate of change of current in enhancement type MOSFET.

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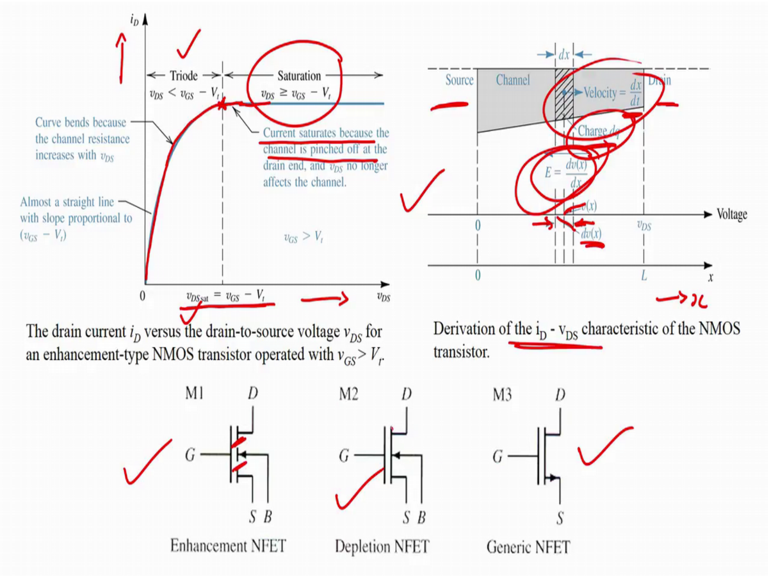

So, if I see the characteristics, it is just to help you out once again. You see V D saturation is V G S minus VT; you just understand this plot. I D you can see almost a straight line and then, the curve bends as the channel resistance increases with V D S. This is your nothing but V D S saturation which is here. This region is your triode region; once you saturate current saturates because the channel is pinched off. So, this is the pinched off voltage and here in saturation region V D S is greater than V G S minus Vt.

So, if I see this particular plot, but I see there is a source; there is a channel, there is a drain. Here there is a drain, here there is a source. And there is a formation of charge, the velocity is nothing but dx by dt. This is my x; my x, velocity is dx by dt. My E will be nothing but dv x by dx; where, this is my voltage vx, this one and this will be my dv x; you see here this one will be my dv x.

So, if I want to draw voltage plot and I am to see how the channel is formed; I can find the velocity, I can see the charge, I can see what is electric filed and that's how we can derive the I D versus V D S characteristics of a MOSFET. You can again see the symbol of enhancement type MOSFET; you can see that depletion type n-channel MOSFET generic and general m MOSFET.

But you here and you see enhancement type there is a break between the drain and source and the reason is that there is no channel at the starting of the MOSFET; when you take a MOSFET enhancement type there is no channel, but in case of depletion type there is a formation of channel and in the starting and that's why we can see this particular line; easy; very easy, very easy.

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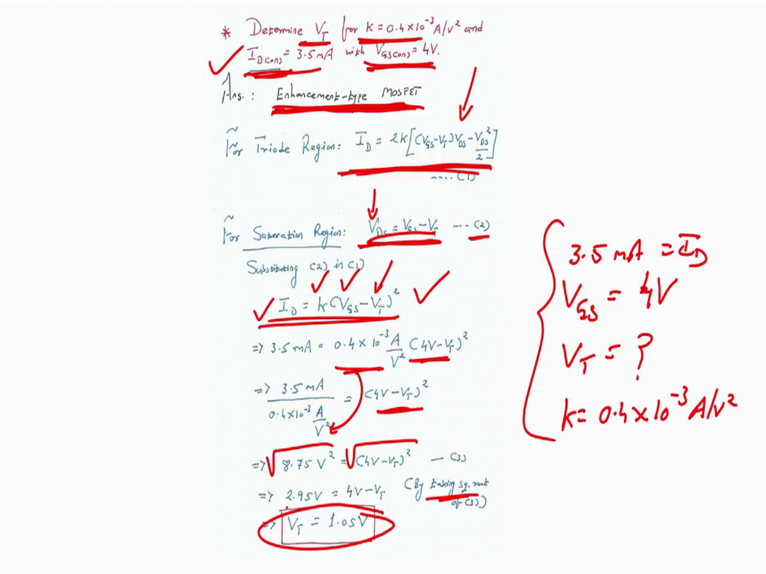

So, let us do one more example and then, we will finish this particular module and we continue in a next module of the same lecture. So, if you are given, determine VT, that is threshold voltage for K of some value, I D on for some value with V G S on for some value. So, first is we should understand that V G S on its 4 volts, I D on its 3.5 milliampere; that means, this is nothing but my enhancement type MOSFET.

For enhancement type MOSFET, my for triode region, I know the equation for triode region I D equals to 2 times K into bracket V G S minus V T into V D S minus V D S square by two bracket over; this is my equation for triode region.

For saturation region, I know V D S equals to V G S minus VT. So, I will substitute this value of V D S into this particular equation, what will I have? Substituting 2 in 1 and I D equals to K times V G S minus VT whole square.

Now, I already have I D, what is I D? 3.5 milliampere. This is already given here. I have V G S 4 volts, V T I do find it out. K is also given 0.4 into 10 to the power minus 3 ampere per Whole Square, this everything is given.

So, if I substitute the value, what I find is if I substitute the value 3.5 equals to this value then, I will have here this particular equation. So, this particular value, I will put it here and I will solve it; I will solve. So, I will have 8.75 V square equals to nothing but 4 V minus VT whole square. Now, this - this gone.

So, 2.95 equals to 4 minus V T. So, we can have by taking square root; by taking square root of this particular equation, if I take square root of this particular equation. Then what will happen? I had 2.95 volts equals to four V minus V T. Then I have V T equals to 1.05 volts, easy very easy.

So, if I know what kind of MOSFET I have, I can find out V T because I know that in saturation region V D S equals to V G S minus V T, triode region; this is the equation. I substitute this equation, I will have a equation for drain current; in the equation of the drain current everything is given. I D is given, V D, K is given, V G S is given; I have to just find out threshold voltage VT.

So, we this is the last slide for this particular module and we will continue in the next module and see the further application of the MOSFET. So, I hope that you guys understood, what is a depletion MOSFET; you understood quickly what are the Drain characteristics. We have seen an example of whether the change in the rate of change of current in the conduction region in depletion type and enhancement type is same or different; we found that both is same. Then we have seen an example of determining the threshold voltage.

So, in the next slides, in the next modules, what we will be looking at? We will looking at the derivation of MOSFET current to voltage characteristics, derivation of MOSFET current to voltage characteristics. We will quickly see, what is channel length modulation? And then, we will move to the important application of this MOSFET which is your current mirror.

So, till then, you just go through the lecture, read it once again how the depletion MOSFET can be used compared to enhancement type MOSFET. The application is very simple in enhancement type; there is no channel. In depletion type, there is a channel. When there is no channel, if I want to attract electron; I have to apply positive gate that is why gate is positive; that means, when I increase V G S my current will start increasing. In this case but, there is already channel.

So, even at V G S equals to 0 that is in depletion type that is a channel between source and drain. So, V G S equals to 0 still I see some current I D and if I decrease this V G S then, I will see a change decrease in the change in the current I D, but if I increase the V G S then it can be more than I DSS because I DSS is not the maximum current. So these much things we have understood till now.

Now let us see, what we can learn in the next class. So, I will see you in the next class; till then you take care. Bye.