**Analog Electronic Circuits**
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**Lecture - 09**
**The MOSFET and Its Characteristics**

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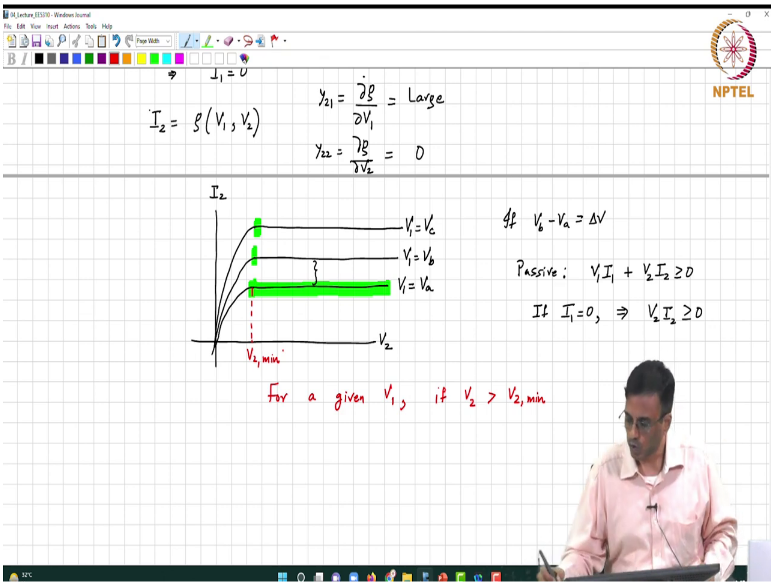


Al, right? It is like saying I know how to drive a Maruti car, right? And tomorrow basically you have a Honda, ok. Now, you do not say, oh, let me go back to driving school and take another 6-month course on how to drive a Honda, because Maruti Honda all basically you know the fact that one is some kind of engine, the other one is some automatic something inside the engine you know all that stuff is irrelevant, right? ok.

You have the steering wheel, you have the accelerator, you have the clutch, you have the brake that is all, right? 4 terminal devices, ok. Same thing here, right? it is actually easier because it is 3 terminals, you understand. So, that is basically the spirit behind the whole thing.

We could have chosen any device as to illustrate all our circuit concepts, but we will choose something that, you know, if you want to drive a car, right? you know will you choose ok, let me learn how to drive Ferrari, right?

I mean you know there is only one Ferrari probably in Chennai or maybe a few more, right? It makes sense to drive a Maruti car, right? because it is cheap and it is everywhere correct.

Likewise, when you are learning about circuit design, you know it makes sense to learn with the Maruti car equivalent of devices which is cheap reliable, right? by the billions, that is CMOS, ok, alright? I mean and you know 30, 40 years ago if I was teaching 40 years ago, we will be talking about the ambassador which is basically the bipolar junction transistor, right? ok.

But, you know I learnt circuit design almost 30 years ago with the Ambassador, right? And, when the Ambassador went off and the Maruti came, there was basically nothing changed, right? The circuit look really pretty much the same, right? the picture of the ambassador is gone and the Maruti comes that is all, right? Otherwise, everything looks the same ok. So, with that background let us quickly say now the only thing to figure out is what is this $g(V_1, V_2)$ alright?

So, clearly there must be several regions of operation. So, there is one region for a specific $V_a$ for a certain value of $V_2$ for a given $V_1$. If $V_2$ is greater than a minimum, alright, what comment can we make let us call this $V_2$ minimum. What comment can we make about $I_2$? $I_2$ is only a function of beyond, for $V_2$ greater than that $V_2$ minimum, what comment can we make about $I_2$?

Student: Constant

It is a constant and is independent of.

Student: $V_2$.

$V_2$ it is only a function of.

Student: $V_1$.

$V_1$, correct, ok. So, you know couple of things first.

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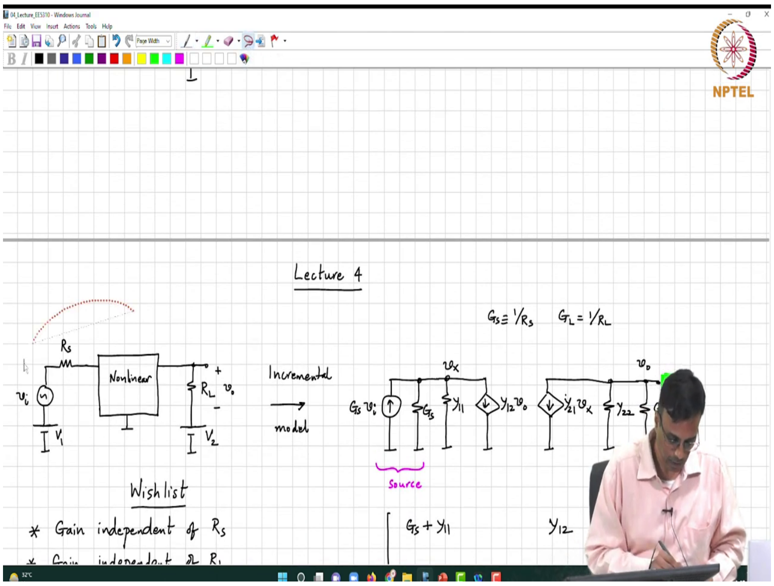


If you recall our amplifier therefore, look like this.

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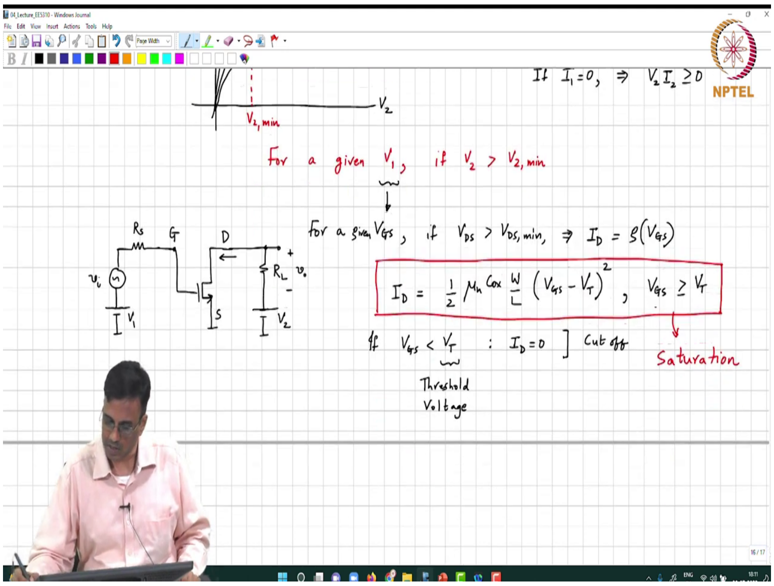


So, now it no longer makes any sense to call this terminal 1 and terminal 2, right? And you know this *dabba* (box) does not make any sense either, right? We can you can basically say this box looks pretty ugly. I might as well come up with my own ugly symbol for the box, right?

So, that is basically this symbol and then rather than call it you know number 1 and number 2, right? It is like addressing you by your roll numbers, I might as well address you by your names. So, like that I will call this, the symbol for this box is this ok, that terminal 1 that which would be called a port 1 is the what we will call the gate, this is the drain and this is the source, alright?

So, what is the in terms of the new terminology, what is $V_1$? It is the difference between the gate and the source. So, that is $V_{GS}$, right? What is $V_2$? If $V_{DS}$ is greater than a $V_{DS}$ minimum then $I_2$ becomes, what is $I_2$ now? Now, but what do you call $I_2$? There is no 2 anymore.

Student: $I_D$

$I_D$, $I_D$ is only a function of $V_{GS}$ alright? and that function happens to be. So, it turns out and this now what I am going to say now is just something which comes from device physics. And, you know I am sure all of you are taking some device course or the other and you know all the gory details of why things are the way they are, are covered in those courses, right?

As far as we are concerned, we are only interested in the equation. If the equation changes, we do not get all flustered, it is just a matter of using the new equations. So, this $I_D$ is nothing but it turns out to be of the form $\mu_n C_{ox}$ W/L, I mean at this point all these symbols you know they appear like Latin and Greek to you, it does not matter.

These are something some parameters related to the details of the construction of the device and some properties of electrons you know inside the device, we do not need to worry about it. These are all given once you are given a device, means you have,

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

Now, let us go carefully term by term, right? So, basically if $V_{GS} < V_T$, $V_T$ by the way is called the.

Student: Threshold.

Threshold voltage of the device. And is not to be confused with the thermal voltage when we use the diode equation. This and that are different. So, if $V_{GS} < V_T$ then the device is dead, right? So, it turns out that $I_D = 0$. And the device is said to be cut off or simply the device is off, ok.

Now, if $V_{GS} \geq V_T$, where that basically means that the device is alive, right? And, if the drain source voltage is greater than certain minimum, then the drain current is independent of the drain source voltage and that is only a function of the gate source voltage and this is basically the that function.

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

And, this region of operation is what is called saturation. Does it make sense people?

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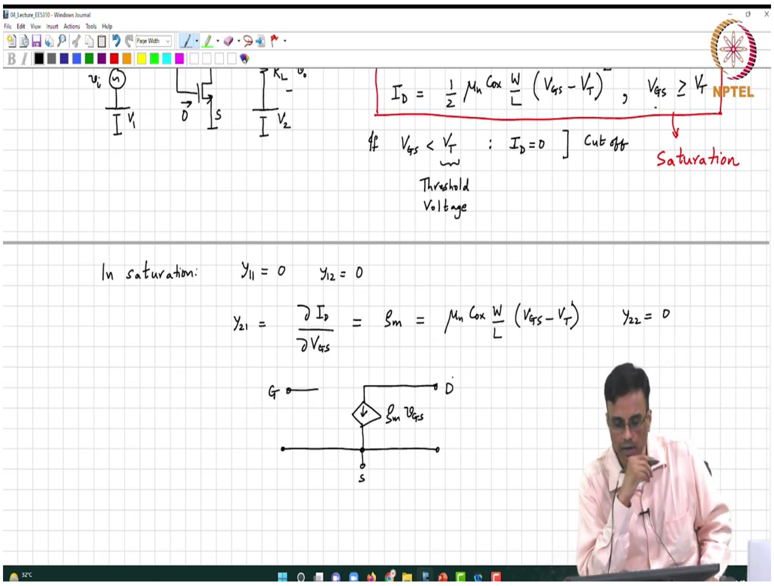


So, in saturation what is the incremental model or what are the incremental Y parameters of the MOSFET? The gate current is always 0. So, $Y_{11}$ is.

Student: 0.

0. $Y_{12}$ is.

Student: 0.

0. $Y_{21}$, what is the definition of $Y_{21}$?

Student: $\frac{\partial I_2}{\partial V_1}$

It was $\frac{\partial I_2}{\partial V_1}$, right? but now $I_2$ is nothing but $I_D$. So, $\frac{\partial I_D}{\partial V_{GS}}$, which is called a special name rather than, now there is no 1, there is no 2. So, is called it denoted by $g_m$ which stands for trans conductance, right? because when you say conductance it refers to voltage and current at the

Student: Same.

Same port. Trans conductance means, the voltage is applied at one place and the current is happening somewhere else, right? So, that is nothing but

$$g_m = \mu_n C_{ox} W/L (V_{GS} - V_T)$$

Alright? And what about $Y_{22}$? What comment can we make about $Y_{22}$?

Look at this equation, box equation in red and tell me, what is the incremental $Y_{22}$?

Student: 0.

0, why?

Student: it is independent of $V_{GS}$.

It is independent of $V_{GS}$ alright? So, what comment can we make about the model for the incremental model for the transistor in the saturation region therefore, is simply it is a voltage controlled

Student: Current source.

Current source, where this small $V_{GS}$ denotes the incremental $V_{GS}$. So, this is gate, this is source and this is drain, alright? ok. Now, the only thing left is what, as far as the transistor is concerned? what else do we need to know?

Sorry, here I need to add another condition, sorry.

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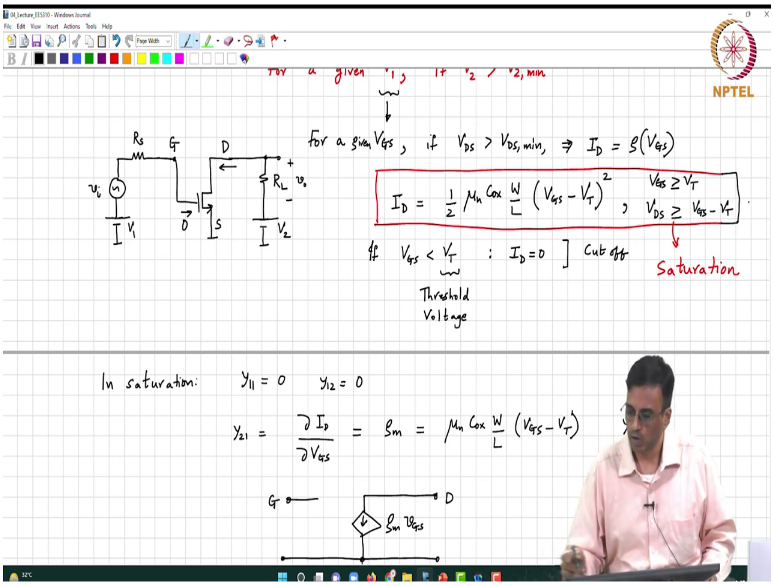


$V_{GS}$ $\geq V_T$ and $V_{DS}$ greater than or equal to; we need to find what that minimum drain source voltage is beyond which the characteristics remain independent of the drain source voltage and that just happens to be $V_{GS}$ - $V_T$, ok. Again, why it has to be greater than $V_{GS}$ - $V_T$ and so on is none of our business, right? You know it is just is god given ok, alright? So, so therefore, if you look at this picture so, this is for $V_{GS1}$. So, now, let us get busy drawing these characteristics.

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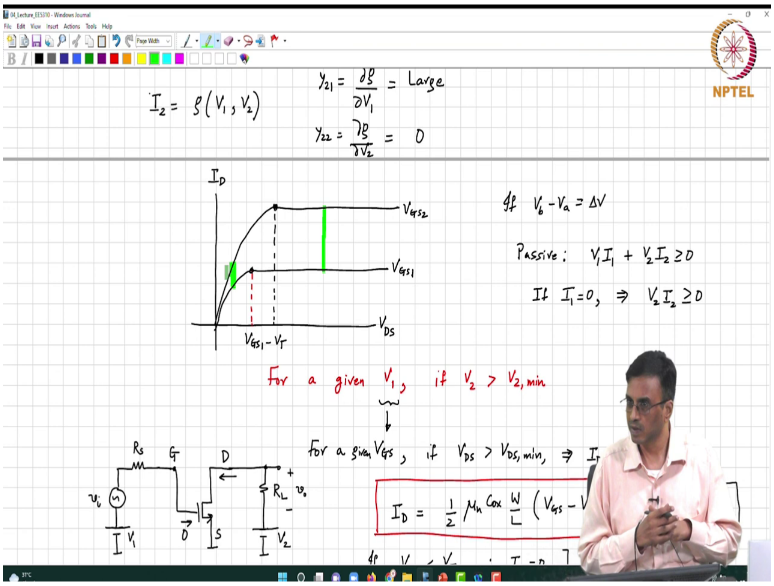

So, this is for $V_{GS1}$ ok. And this minimum is nothing but $V_{GS1}$ - $V_T$. Now, if you increase the gate source voltage, what comment can you make about the drain current?

For large values of $V_{DS}$, what comments? So, this now becomes $I_D$, this is $V_{DS}$. For large values of $V_{DS}$ what happens?

Student: The current is constant.

The current is constant. Will it be greater than the earlier current or less than the earlier current?

Student: Greater than the earlier current.

Greater than the earlier current. And this is for $V_{GS2}$. What comment can you make about the minimum value beyond which the current is constant?

It evidently has the our device colleagues tell us that is greater and beyond below that it does something like that ok, alright? So, as we expected before there is no earthly reason for that boundary between that 0-$Y_{22}$ region and where it drops off to be for that breakpoint to be independent of $V_{GS}$ there is no fundamental reason.

And, for sure enough you know in this particular device it turns out that it is not, ok. So, the only thing left therefore, is to find what the relationship between $I_D$ and $V_{DS}$ is for $V_{DS} < (V_{GS} - V_T)$.

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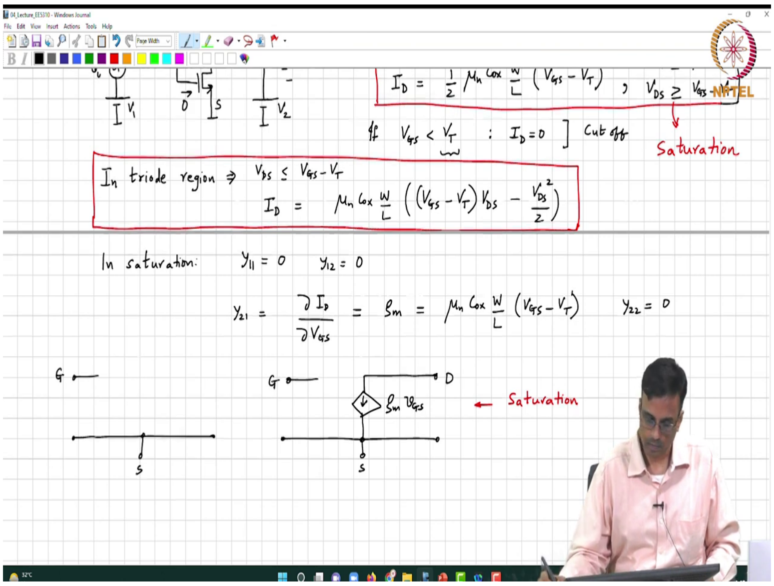


So, in the triode region, that is called the triode region, which implies that $V_{DS} \le V_{GS} - V_T$. What comment can we make about that relationship now?

It must be dependent on $V_{DS}$, because this is falling off. So, this is one more god given equation. There is nothing you can do about it, right? It is $\mu_n C_{ox}$ W/L, where again as I said = $\mu_n C_{ox}$ W/L, they are all device dependent parameters just like how $I_s$ in the diode is a parameter which is dependent on you know some doping somewhere in the diode and all that stuff alright?

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

Technically, actually the correct model is to use minus $\alpha V_{DS}/2$, where that α is slightly more than 1. But you know that is basically for our purposes we will just neglect that and use α = 1. So, this is the behavior in the triode region alright? So, what comment can we make about the model? So, this is the model for the MOSFET in saturation, and the model for the MOSFET in triode, what comment can we make about incremental $Y_{11}$? Yes, people.

Student: $Y_{11}$.

$Y_{11}$.

Student: 0.

Is 0. $Y_{12}$ is?

Student: 0.

$I_1$ =0, right? So, $Y_{11}$ and $Y_{12}$ are 0, as they were before. What comment can you make about $Y_{21}$?

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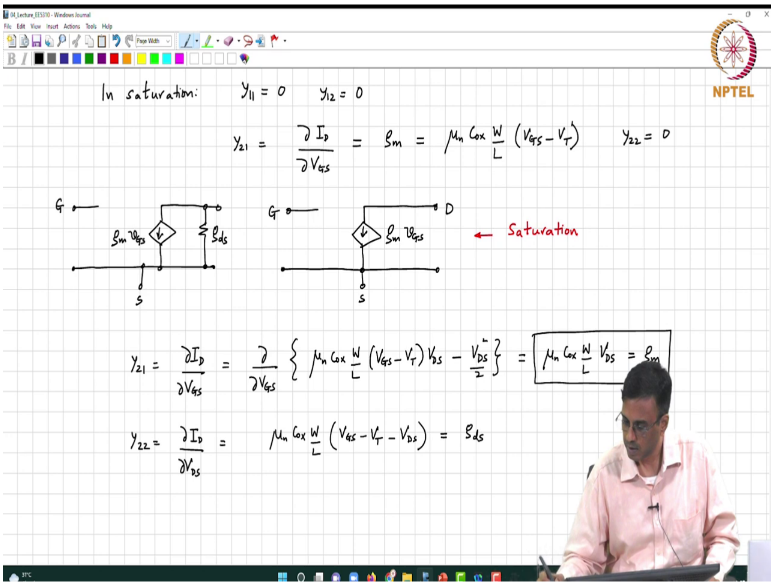


$Y_{21}$ is nothing but

$$Y_{21} = \frac{\partial I_D}{\partial V_{GS}}$$

which is,

$$Y_{21} = \frac{\partial}{\partial V_{GS}}\left\{\mu_n C_{ox}\frac{W}{L}\left(V_{GS} - V_T\right)V_{DS} - \frac{V_{DS}^{\;2}}{2}\right\}$$

Correct? What is this now?

$$\mu_n C_{ox}\frac{W}{L}V_{DS}$$

Ok. So, what is that now? That is basically $\mu_n C_{ox}\frac{W}{L} V_{DS}$, Let us call that $g_m$ x $V_{GS}$, where $g_m$ is this quantity alright? So, quick question is the trans for a given $V_{GS}$ is the trans conductance greater in the triode region or in the saturation region?

Student: Saturation.

Why?

Student: $V_{DS}$.

Yeah. So, $V_{DS}$ is in the triode region you know that $V_{DS}$ is less than.

Student: $V_{GS}$ - $V_T$.

$V_{GS}$ - $V_T$. And therefore, the trans conductance in the triode region is going to be smaller than that you get in.

Student: Saturation.

Saturation, alright? Ok, then, but of course, that comes out of the math. Can you stare at this picture and tell me why that makes sense? Yes.

Student: saturation region.

Very good. So, basically my friend there basically says that if you are in the saturation region, assuming $V_{GS1}$ and $V_{GS2}$ are only very slightly different from each other. What does that distance indicate?

Student: $Y_{21}$.

$g_m$ $\Delta V$, correct, because the transistor is operating in the saturation region, that $g_m$ corresponds to the trans conductance in.

Student: Saturation.

Saturation, right? So, if you want to look at the trans conductance in triode, what are we going to do? Where are we going to look?

Basically, we reduce for the same gate source voltages for the same change in gate source voltage, we are going to reduce the drain source voltage such that the device is in operating in.

Student: Triode.

Triode. So, basically you can see that the spacing between the two curves in the triode region is smaller. Therefore, it is evident that the trans conductance in the triode region is smaller than that in the.

Student: Saturation.

Saturation region, does it make sense? And of course, when $V_{DS} = 0$, what is the trans conductance? Well, the current is 0 and it is not changing. So, therefore, the trans conductance is 0. Now, what comment can we make about $Y_{22}$,

$$Y_{22} = \frac{\partial I_D}{\partial V_{DS}}$$

That is nothing but,

$$Y_{22} = \frac{\partial I_D}{\partial V_{DS}} = \mu_n C_{ox} \frac{W}{L}(V_{GS} - V_T - V_{DS}) = g_{ds}$$

Alright? and this is often called $g_{ds}$, right? which stands for the drain source conductance of the MOSFET, ok. In the saturation region, what comment can we make about $g_{ds}$?

Student: 0.

It is just 0, right? So, when you move from the saturation region to the triode region, you not only have

Student: Smaller $g_m$.

Well, you have it is a double. You not only have a smaller $g_m$, but you also suddenly this output resistance which was infinity before, now becomes fine, ok.

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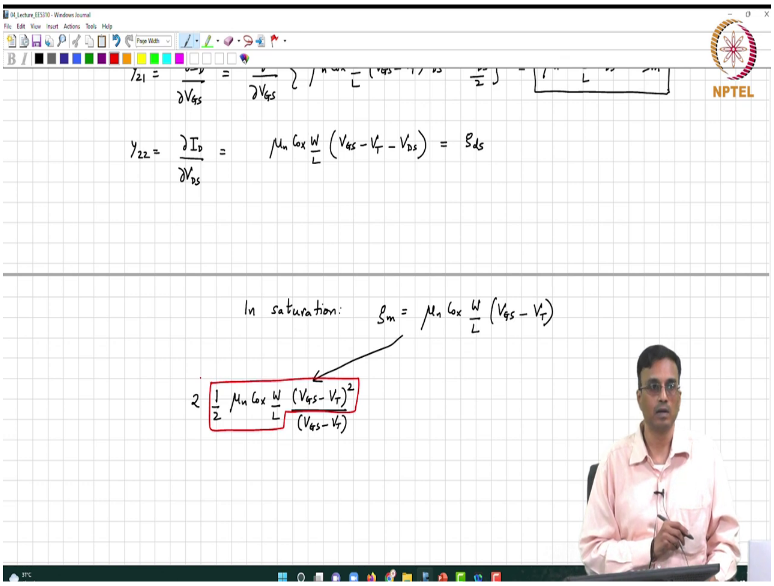


And, as a final thing that I want to tell you in saturation $g_m$ is,

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)$$

which can be written in multiple equivalent forms. One way to do it is to recognize that it is the same as saying,

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

And, what do we recognize that part as?

Student: $I_D$.

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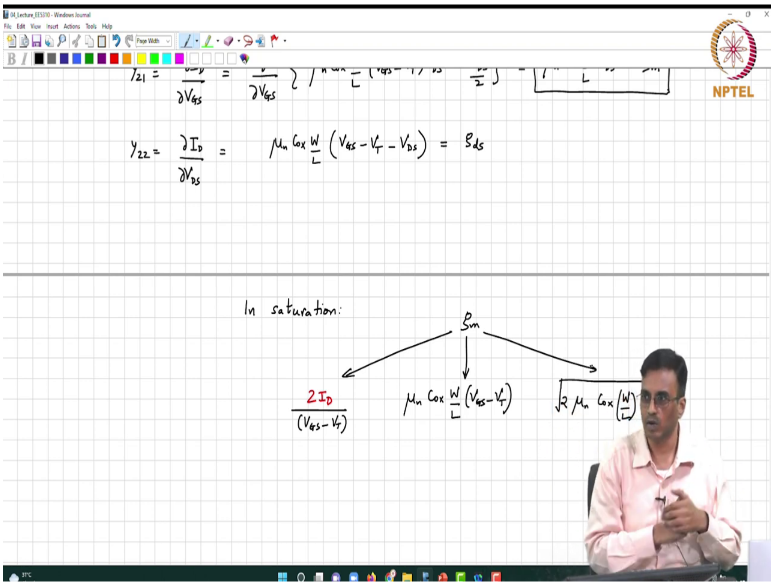


$I_D$. So, that is basically nothing but,

$$g_m = \frac{2\,I_D}{(V_{GS} - V_T)}$$

Ok. And, another equivalent expression is to say well,

$$g_m = \sqrt{2\,\mu_n^{\,2} C_{ox}^{\,2} \left(\frac{W}{L}\right)^2 (V_{GS} - V_T)^2}$$

One of these guys I can knock off and replace this whole thing by $I_D$, ok. And of course, the third way is the original formula.

$$g_m = \sqrt{\mu_n C_{ox} \frac{W}{L} I_D}$$

So, $g_m$ can be written in three equivalent ways, Ok;

$$g_m = \frac{2\,I_D}{(V_{GS} - V_T)}$$

And

$$g_m = \sqrt{\mu_n C_{ox} \frac{W}{L} I_D}$$

Ok. Now, I am going to ask you a question, right? The first formula says it is the trans conductance is inversely proportional to $V_{GS}$ - $V_T$. The second formula seems to be telling you that it is directly proportional to $V_{GS}$ - $V_T$. The third formula is telling you that it is.

Student: Independent.

Independent of $V_{GS}$ - $V_T$, I mean you know what is going on is there?

Student: $I_D$.

Yeah correct. So, basically the thing to understand is that $I_D$ is going as $V_{GS}$ - $V_T$, the whole square. So, $g_m$ is indeed proportional to $V_{GS}$ - $V_T$ and likewise the square say if $I_D$ is going as $V_{GS}$ - $V_T$ the whole square, the square root is still $V_{GS}$ - $V_T$ alright? So, to summarize our discussion today, we figured out what the I-V characteristics of a device must be so that we get amplification in a way which is independent of the source resistance, in a way that there is it is unconditionally stable gain and we get as large a gain is possible, right?

And, another thing on our wish list was that we also wanted the gain to be independent of $R_L$, but evidently it is not possible, right? I mean just because you wish for a lot of things, it does not mean that they all come true, right? and this is you know one such instance, ok.

So, we are happy with you know whatever we get, we move on, right? And, then what did we say? Well, if these are the incremental Y parameters and given that the box has no source of energy inside, it must be passive, correct? And therefore, if the condition that $I_1$ = 0 is satisfied, then the output characteristics of the device must lie in the.

Student: First and third.

First and the.

Student: Third quadrant.

Third quadrant. So, I mean the characteristics cannot remain, the output characteristics cannot remain parallel to the x axis for all values of $V_2$, they must eventually dive into the.

Student: Third quadrant.

Into the third quadrant, right? Of course, I mean you know one way of thinking about it, one possibility is that they dive smoothly, but that is not necessarily. They could basically do some wild thing and get into the third quadrant, right? Our theory basically does not tell us that the transition needs to be smooth.

It just so happens that once you say these are the characteristics I need for a device and you go to people specializing in devices. And, then they say we can make not just one, but many types of devices which do this and one such device is the is the MOSFET, where it in fact, turns out that the transition from saturation is actually when it goes from the first quadrant to the third-one, is a smooth transition, right?

And, beyond that we are you know we are dependent; we are at the mercy of the device folks to give us the work out the equations for those characteristics because that depends on the internal physics of the device, right? So, after doing a lot of mobility, electrons, holes all that fun stuff, they say this is the equation, right? And, we are happy; we do not need to know all the gory details that happen inside, ok. We will work with these equations, correct?

And so and so, we learnt what these equations were and unfortunately this is you know you have to remember the equation correct and you remember all these formulas, right? So, from 10 years from now you know if you have another device, you will have another equation, another formula for trans conductance, another formula for $Y_{22}$, but otherwise it is the same old equation? Bipolar you know that the equation is different, what is that equation?

I mean of course now, the terminals also have to be different, right? You cannot say I invented a new device, but it is still drain, it is still gate is still source, then they say what the hell have you done. So, you say this is collector, this is base, this is.

Student: Emitter.

Emitter, right? And then so, what is the formula that relates? Now, instead of relating the drain current to the gate source voltage, in a bipolar transistor you relate the collector current to the base emitter voltage, right? and for a collector emitter voltage which is larger than a certain minimum, you see that the collector current is independent of the collector emitter voltage, not base emitter voltage ok, alright? The characteristics look you know pretty much the same, right? except that you know there some minor changes.

And, that is what I am saying you know Maruti versus Honda, there is no difference, right? Same steering wheel, same brakes, same clutch, same accelerator, ok, different price tag that is all, you understand? So, that is all that there is to understand, ok. Good.