Digital IC Design
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Lecture - 05
Body Effect and I-V Plots

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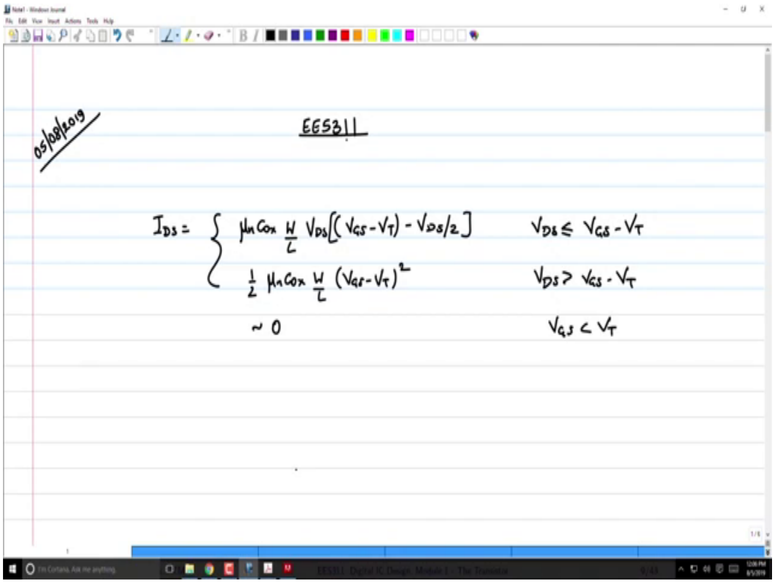

So, good afternoon let us get started last class we were deriving the equation for the on current of a transistor, right. And, we said that the on current we can show for an N MOS transistor is I DS is equal to mu n C ox W by L into, I think the V DS out V GS minus V T minus V DS by 2; this is when, what is the condition on V DS? So, this is V DS is less than or equal to V GS minus V T, right.

And, what happens after that the current just saturates, right and you get half mu n C ox W by L into V GS minus V T the whole square, ok. This is V DS greater than V GS minus V T and this we discussed was because V GS minus V T minus V should be greater than 0 at all points in the channel. So, the worst thing is at the drain end and therefore, if you apply that condition you will find that V DS has to be greater than V G S minus V T for it to be for a current to increase, right.

So, after that it just saturates and what happens, there is one more condition what happens with the V GS is less than V T; the model is basically the current is 0 ok, let me put approximately it is negligible actually, ok. So, now let us just complete. So, this is what we call a long channel transistor which means that the drain and the source are sufficiently far apart that we really do not have to worry about second order effects, ok.

Next we will derive a short channel transistors drain current for by incorporating various second order effects ok, but before that let me deal with what is known as the body effect, ok.

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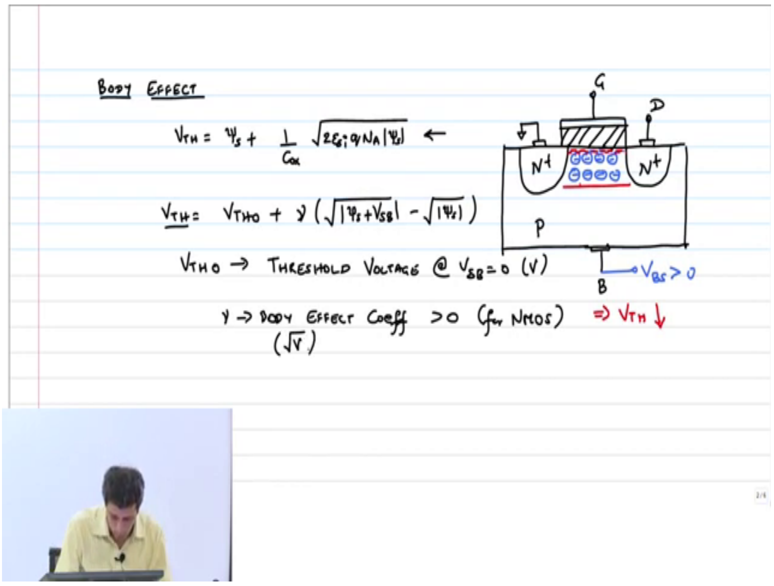

So, what was the expression for the threshold voltage we said it is psi S plus; what? 1 by C ox root of 2 epsilon siq N A into mod psi S, ok. Why the mod psi S, because for an NMOS transistor the surface potential is considered to be positive that is the convention. For a PMOS transistor, the surface potential will be negative, because the, we have to apply a negative potential on the gate and therefore, the surface potential will also be negative.

And therefore, inside the square root you have to put a modulus ok, but for a NMOS transistor it is basically just square root of psi S that is all because psi S itself is supposed to be positive, right. I hope, I got this expression right without missing any other term for the threshold voltage; yes 2 qN A, ok.

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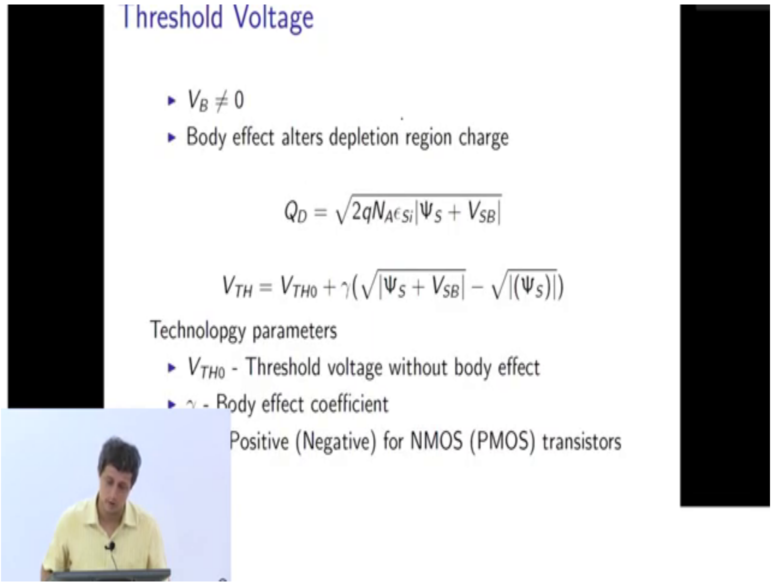

So, what was the structure like we said we had a P substrate then we had our gate with a metal and then the oxide, then we had some depletion like this was N plus, N plus and P, then we applied a gate potential this source we assumed was grounded that was our reference terminal. This is the drain and this contact is basically the body, and we assume that the body was also grounded earlier.

Basically, the body was at the same potential as that of the source, but of course, this is a fourth terminal and there is no need to tie it to the source always, you can always apply a different potential on that body terminal, ok. So, what happens when you do that, right? So, let us now assume that our V GS is some positive voltage. So, what happens is you have some negative immobile charges that have been created here, and then you can have some free electrons; typically, if the body was grounded ok, then all the work that is done to invert the channel is done by the gate, and that was the definition of threshold voltage.

Now, if I apply a positive potential let me say that V BS is greater than 0, I am going to apply some positive potential on the V BS on my body, ok. So, again the theory behind this body effect is very complicated. So, for the purpose of this course we are going to abstract it out and we will treat this body terminal like a back gate, ok.

So, there is a depletion region which is basically like there are no free electrons, you just have an electric field from some positive to negative charges, right. So, what we are going to do is if I apply a body potential V BS which is greater than 0 then this capacitor here, right. This capacitor here is going to act like a back gate capacitor just like the silicon dioxide on top provided control for the gate, this capacitor behind here is providing some control to the gate to the channel, right and that can be controlled by the body terminal.

So, just like we said if gate potential goes positive, you start getting some negative charges at the channel similar thing will happen here, ok. This is again only an abstraction it is not a physical picture that we are talking about, ok. So, you can treat this like a back gate and therefore, if V BS is greater than 0 I will already get some negative charges, ok.

So, now what should happen to the threshold voltage of this transistor? It should decrease because the threshold voltage is defined as the work done by the not work in Joules. It is the work done by the gate potential in order to invert the channel which means I have to get a negative free electron concentration at the surface, which is as much as the hole concentration in the bulk. But now, if the back gate has already provided some electrons or has already depleted the channel partially then the gate needs to do lesser work in order to invert the channel and therefore, the threshold voltage V TH should come down, ok.

So, therefore, I will now modify this threshold voltage term to include this body effect as well, and it is not possible by the way to derive this from scratch or first principles, we are going to I am just going to write an empirical equation, ok. I tell you what the empirical equation means V TH is basically V TH naught ok. I will tell you what V TH naught is plus some term into root of mod of psi S plus V SB, ok; note that I am reversing the term it is not V BS, now I am saying V SB minus root of mod psi S.

So, what is V TH naught, it is the threshold voltage at V BS or V SB equal to 0 which is the earlier expression that we had derived, ok. So, now let us just go through the same analysis that we did if V S, if V BS has to go up what should happen to V SB, it should go down. So, now therefore, the threshold voltage should what should happen which direction should it go V BS greater than 0 we said threshold voltage should decrease.

So, when V SB decreases you want the threshold voltage to decrease therefore, it is basically just; so, what is the sin of this gamma? Positive right, V SB decreases you want threshold voltage to decrease as well, right. So, this gamma is an empirical body f e effect coefficient which means that there is no physical interpretation to this term very accurately, right.

What you do is, you construct a device make measurements in the fab by applying different body potentials on the transistor measures the threshold voltage by some technique, right and then you fit this data to this gamma that is what you mean by an empirical parameter, right. So, this whole device physics modeling equations that we will be talking about are semi physical or semi empirical, you cannot derive everything empiric physically and get an simple equation to deal with, ok.

So, what we are doing is known as a compact model which means that whenever it becomes very complicated or difficult to model something you resort to an empirical model. So, that parameter you will just fit which means that if I just scale you know for example, if I take the previous equation right, if I scale oxide thickness T ox; if I take this equation here if I scale T ox then I can guarantee that the threshold voltage will vary as per this equation.

Now, here when I do this empirical fitting if I change some parameter there is no guarantee that it will work, it is very very specific to what it has been fit to. So, you make measurements on the transistor for certain length, certain widths and all that and then you can guarantee that this is the best fit for these particular parameters. But, if you change it arbitrarily and apply a very large width or a very small width then there is no guarantee that the model will work. This is what and this is the flip side of an empirical model it simplifies the equation, but does not guarantee scalability into all regimes of operation.

So, gamma is body effect coefficient and it is greater than 0 for NMOS, ok. What is the dimension of gamma?

Student: (Refer Time: 12:16).

What is the; what is the dimension of V TH?

Student: (Refer Time: 12:22).

V TH is volts, V TH naught is also volts, ok; so, this is by the way in volts. So, therefore, gamma has to be in a root of volts, ok. So, with that what we have derived is the threshold voltage equation and the on current equation for different regimes linear, saturation and all that for a long channel transistor, ok.

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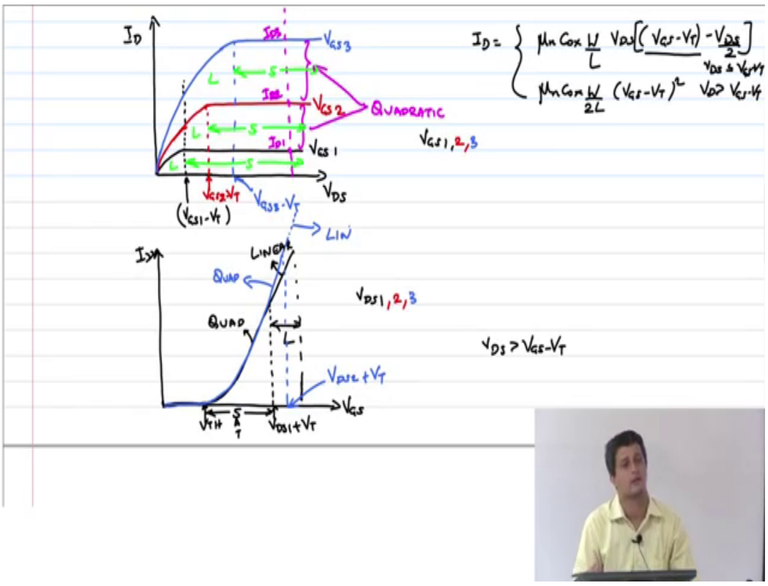

So, before we proceed to the short channel transistor let me quickly look at what will the I D, V GS look like. I am going to look at I D versus V DS for different V GS values, ok. So, I will write the equation here I D is mu n C ox W by L into V DS into V G S minus V T minus V DS by 2 and this is for V DS less than or equal to V GS minus V T. And, after that it is mu n C ox W by I will just say 2 L into V GS minus V T the whole square for V DS greater than V GS minus V T, ok.

So, I am going to now assume that all my V GS values that I consider in this plot are greater than the threshold voltage because before that the current will just be 0; so, I am not interested in that. What will the curve look like as I look at various V GS values?. So, let us consider some V GS 1, 2 and 3 ok, where V GS 1 is less than 2 less than 3; 3 different potentials. So, what will the curve look like initially when V DS just exceeds 0 or just yeah just exceed 0, in what region of operation will the transistor be?.

Student: (Refer Time: 14:48).

It will be in the linear region, because V DS is less than V GS minus V T. So, this will basically be a quadratic thing till what point will it go?.

Student: (Refer Time: 15:00).

Yeah.

Student: (Refer Time: 15:02) it is the minus (Refer Time: 15:03).

So, this is V GS 1 minus V T, this is a quadratic line and what happens after that?

Student: (Refer Time: 15:16).

It just remains like this. So, this is V GS 1.

Now, I increase my V GS to a higher potential; of course, both are beyond V T. So, what will happen, it will again start, ok. Now, the question is will the current be like this or like this or lapin.

Student: (Refer Time: 15:45).

It has to be.

Student: (Refer Time: 15:48) greater than.

Greater than, because if you fix a particular V DS higher V GS means higher current, right; therefore, it cannot be this particular term. Now, I take it till here now let me extend this line. So, will this come and saturate here, why?.

Student: (Refer Time: 16:12) no experience (Refer Time: 16:13).

So, it will proceed to be in the linear region until V DS has hit V GS minus V T and now my V GS is increased. So, this will go further up right and then saturate somewhere here, V GS 2, correct. Now, I consider the third V GS, right similar thing will happen I am going to start; obviously, the current will be much higher by the way let me draw this line here. This is V GS 2 minus V T to start much higher and somewhere here it will saturate, V GS 3.

So, this guy is V G, this is V G S 3 minus V T and this was V GS 2 minus V T. Now, the point to note is that if I fix a particular V DS right in the saturation region where all three transistors are now in saturation, right. So, let me consider this particular point here. What should be the relation of the currents I D 1, I D 2 and I D 3? Let us say this guy is I D 1, I D 2 and this is I D 3.

So, what should be the functional relationship with respect to V GS here, it should be a quadratic relationship, right. So, far a if I increase V GS little bit then the saturation current goes up as square of V GS minus V T, right. So, therefore, this spacing will now be quadratic ok, clear; any questions here because next you will see that when we go to a short channel transistor this quadratic relationship will vanish and it will become a linear relationship.

So, if you want to find out if a transistor is long channel or short channel, this is one of the things that you can look for whether this thing goes quadratically or linearly, ok. Now, how does I DS versus V GS look like for various V DS values and before I even proceed here, let me say this is linear and this is saturation. Now, this is linear and this is saturation this is linear and this is saturation in that plot. So, now, I am going to look at I D versus V GS for various V DS 1, 2 and 3; similarly, like last time V DS 1 is less than V DS 2 is less than V DS 3.

So, what will happen to the current if I if V GS just goes slightly above 0, some small value let us say 1 microvolt; V GS goes to 1 microvolt.

Student: (Refer Time: 20:05).

Has to be 0 right, assuming that the threshold voltage is about a couple of 100 of 100 millivolts 100 of millivolts; obviously, the current is going to be 0. Therefore, this will be 0 right, now at some point this will take off. What is that point?.

Student: Threshold.

The threshold voltage, right and then as soon as my V GS exceeds the threshold voltage if V DS is now fixed in what region of operation will the transistor start?

Student: I think what we (Refer Time: 20:49).

Ah.

Student: How do we (Refer Time: 20:52).

How does it matter, let us say my V DS let us say I have taken it to be some 100 millivolt some small value, V GS just exceeds the threshold voltage.

Student: The threshold (Refer Time: 21:05).

It has to be.

Student: Saturation.

Saturation. So, unlike the I D versus V DS plot where the transistor starts in linear and then goes to saturation, I D versus V GS will start in saturation and then go to linear, right. So, therefore, this is now going to be what kind of curve?

Student: Quadratic.

Quadratic curve, right. So, you will have a quadratic curve until what point right, there is some point where this thing is going to change this behavior will change. So, when will the region of operation change?

Student: (Refer Time: 21:51).

It is starting in this region V DS is greater than V GS minus V T. Now, I am switching sweeping V GS at some point V GS will reach a point where the transistor goes into linear region. So, what V G S is that?

Student: V DS (Refer Time: 22:13).

V DS exactly; so, this is V DS 1 plus V T after that this has to be.

Student: Linear.

It is a linear thing, look at this equation as a function of V GS there is only a linear term; this will simply go linearly I mean let me try it nicely, ok. Since, we are not able to show it, let me explicitly write it this is quadratic and; obviously, in this region this transistor is in saturation S A T and beyond this region it is in linear region, ok.

So, now consider my V DS 2; what should happen, V DS 2 2 comma 3, let me just color code it nicely 2 comma 3; so.

Student: It is not a (Refer Time: 23:42).

So, first until V TH what will happen?.

Student: V (Refer Time: 23:49).

Same thing happens, correct; so, therefore, the current will be 0 all through till here. Now, V DS is higher V GS has just gone beyond V TH, the current will be greater or lesser than V DS 1.

Student: Same.

The current will be.

Student: Same.

Yes, ok. So, you are basically saying that because it starts in saturation, the current will basically be the same till that quadratic region, right interesting; so, then yeah that seems logical. Now so, will there be a point where this curve will not be differentiable. So, what I have what I have drawn is it correct or wrong?.

Student: Wrong.

Why?

Student: Particular (Refer Time: 24:51).

Exactly; because, it has to proceed in the quadratic region even further and then it will switch to the linear region. So, that is where; so, this will go like this until what point?

Student: V (Refer Time: 25:06).

This is V DS 2 plus V T and then it continues in the linear region ok, this will be quadratic and linear.