Semiconducter Devices and Circuits
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Lecture - 40
Subthreshold swing, Additional concepts

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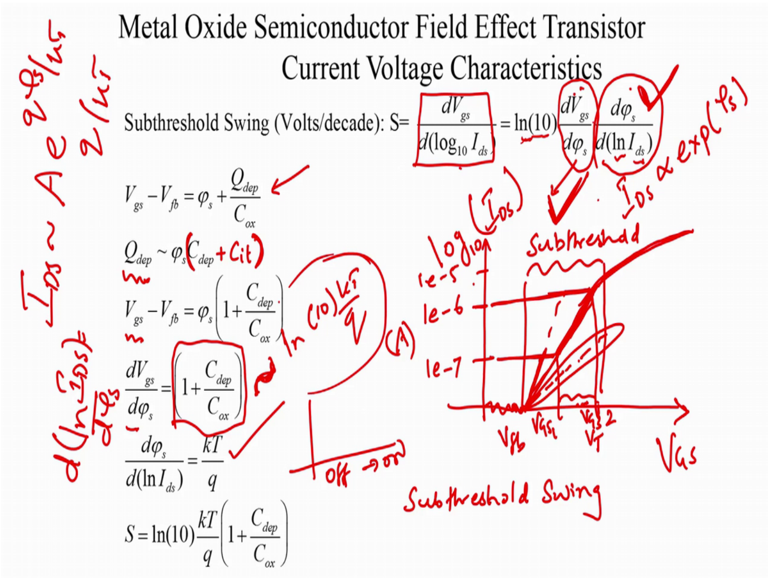

So, the way this region is defined or the way the transition is defined is through a term called as a Subthreshold Swing or in fact, the inverse of it which is the Subthreshold Slope ok. And the subthreshold swing or is measured in terms of the volts per decade and I will tell you what; that means, it means that if we plot if you plot the current voltage characteristics on a log scale.

So, we plot the log I DS ok. So, we say to the base 10 let us say log I DS to the base 10 versus V GS I am sorry V GS the gate to source voltage. So, till a certain point it is all in a basically half and then from here from say V fb to V T well it is not off very far below V G V fb just to keep things a little accurate.

So, let us say it is off around this region and from V fb to V T is start having diffusion defining a current and since the current is proportional to the exponential of the surface potential which in turn is related to the gate voltage, you will find that the characteristics takes a linear relation on a log ID versus V GS scale and then beyond V T you start entering the square law dependence of the current.

So, this region is our subthreshold region of operation, now for us to climb one decade. So, it is a log 10 right. So, let us say this is 1e minus 7 and then that is 1e minus 6 and 1e minus 5 and so, on so many amps of current. So, for us to get from one to one decade that is from 1e minus that is to climbed one order of magnitude ok.

So, 1e minus 7 to 1e minus 6 we need to apply a certain amount of gate voltage. So, we have gone from say V GS1 to V GS2 for us to get past one decade. This voltage difference divided by this one decade is essentially the idea behind your subthreshold swing in, how many volts does it take for us to get the current past one decade ok. So, it is the number of volts per decade.

On the other hand the slope is just the inverse right it is the reciprocal of this parameter ok. So, it is good to have a better estimate of what the subthreshold swing or subthreshold slope right.

So, subthreshold swing is defined by dV gs by d log 10 I ds which we will rewrite as dV gs by d fires because V gs is nicely connected to the surface potential into d phi s by d natural logarithm of I ds and will make a correction for the natural log to base 10 log conversion ok. So, we have redefined this differentially this derivative as with these 2 terms and this coefficient.

Now, how is V gs related to fires, V gs so, we know this relation. So, all the gate voltage that has been applied is equal to the flat band voltage, plus the depletion charge, plus phi s and when phi s heads here 2 phi s is called as the threshold voltage, like a so, we are now at a phi s below the threshold voltage that is the sub thresholds volt.

So, that is the subthreshold region. So, we know that V gs is equal to V gs minus V fb is equal to phi s plus Q depletion by C ox. Now what we will do is, we will define an artefact or parameter which is called as a depletion capacitance ok. So, I would not call it an artefact it is it truly does exist, but the way we will define Q depletion we say depletion capacitance effective and the way we will define Q depletion is by saying that it is the surface potential into C depletion ok. So, what does this mean?

So, this means that ok, in you have your insulator, you have your semiconductor and you now have your depletion layer, because of all the applied gate voltage and the electron concentration is very small they just started to appear ok. So, the way we have defined Q depletion is we say that, this is the depletion this is the band bending and therefore, that is my surface potential or in other words the surface potential is basically the potential drop across this region that is the surface potential. And we say that all the charge here is equal to this potential into this effective capacitance of this region it is be treating this as a capacitor.

So, we define Q depletion as phi s into C depletion and make the substitution here ok. So, you get you get this relation V gs is equal to V fb plus phi s into 1 plus C depletion by C ox and therefore, the dV gs by d phi s becomes this term, it is 1 plus C depletion by C ox.

So, we have solved for this part of or subthreshold swing, now in order to get this derivative let us go back to this relation.

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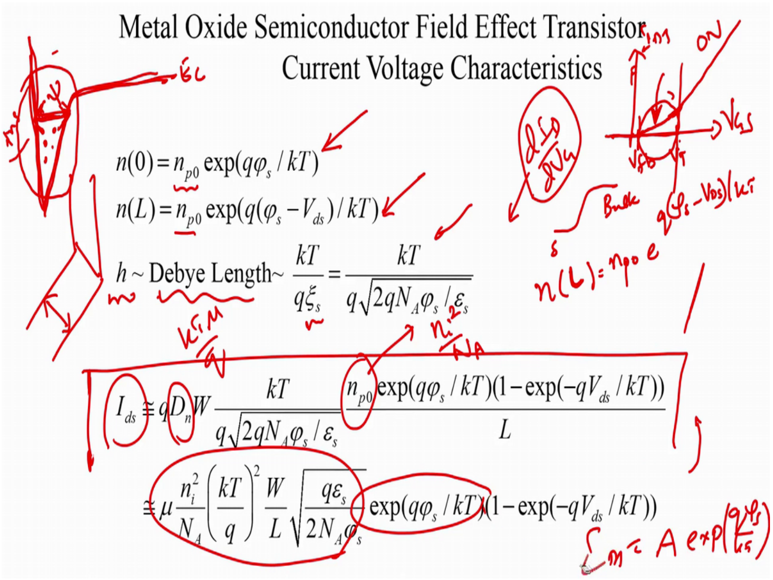

So here you have your dependence of I ds on phi s right. So, this is the only dependence on phi s everything else is independent of phi s right. So, all this is independent of phi s. So, let us just say that all this is equal to some a times exponent of q phi s by kT that is your I DS ok. So, my writing at there does not make it appear on the screen. So, we just say I DS is some constant times e to the power q phi s by Kt, which means which implies that my natural log of I ds is the natural log of A plus q phi s by kT and therefore, d natural log of I DS by d phi s is simply this is a constant and therefore, this is simply q by kT and the inverse of that is kT by q. So, we can get the second part of this definition which is d phi s by d ln of I ds is equal to kT by q.

So, therefore, the subthreshold swing is given by this term here. So, it takes this many volts sorry it takes this many volts to get the current past one decade. So, what does this mean how do we improve the subthreshold swing, we can improve the subthreshold swing by we cannot do much with the temperature and we cannot do much with the Boltzmann coefficient and you cannot do much with q since we will have to change the universe we live in order to do that. Therefore, the only things that are under our control are the depletion charge and the oxide charge.

Now we have although you still not defined these things you will realize that as more parasitic starts developing in the device. So, for example, let us say the interface between the semiconductor and insulator will have interfacial trap charge. So, all that will add on because all those regions will trap charge in them and they will all add on to the charge present in the semiconductor.

So, any parasitic capacitance that traps charge or contains charge at the semi conductor insulator interface and which lies in the at the semiconductor in insulator interface will actually add on to these terms in the numerator and all such parasitics will effectively start increasing your subthreshold swing and decreasing your subthreshold slope.

So, the subthreshold slope probably this is a more popular definition is simply the inverse of the subthreshold swing for and therefore, the subthreshold swing will increase which means you need a larger voltage to head towards one decade ok. So, that is a lower subthreshold swing and that is a higher subthreshold swing. So, the subthreshold swing will increase as we have more and more parasitics and the sub thresholds slope will decrease as we have more and more parasitics.

So, this parameter the subthreshold swing is a very key parameter which determines the rate at which the MOSFET goes from the off to the on state and you can see there is got a very fundamental limit. So, let us say C depletion is 0 or you know let us say the no parasitic, somehow you know you built an architecture where in all this is minimal and you can almost ignore this term compared to one. Even then you have a fundamental limit of ln 10 kT by q being your subthreshold swing, but if let us say C depletion plus C ox is equal to C ox ok.

So, you could say that this is a basic limit for us to what is say, then there is a limitation of this order in the subthreshold swing, you cannot do too much better than this using this present MOSFET configuration. So, therefore, in order to overcome this barrier we need to reengineer the MOSFET architecture and you have many such architectures which try to overcome this barrier although we will not be talking about them in this course.

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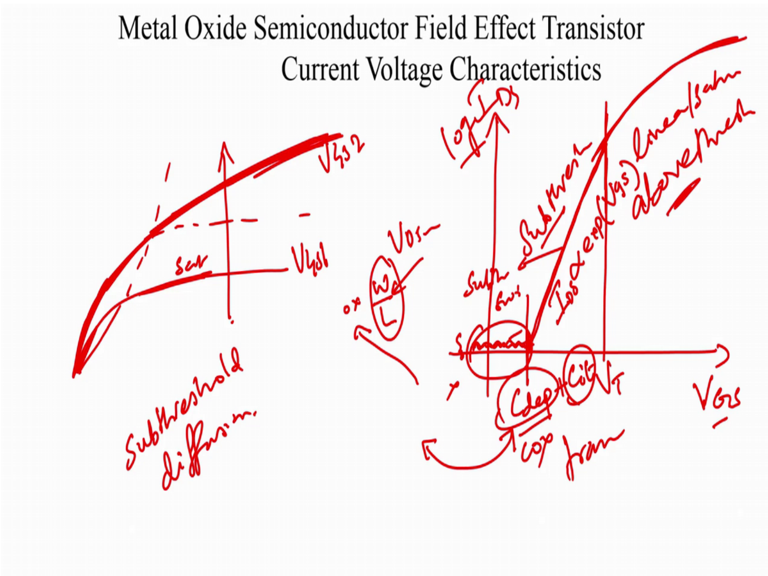

So, just to summarize the subthreshold characteristics, we have we saw that your I DS versus let me just use the space a little better. So, we let us draw 3 characteristics here.

So, we will show I DS versus V GS and we saw that. So, let us say this is the V T. So, we saw that there is a exponential dependence on V GS and then you have an almost square law dependence on V GS after that ok. So, you will find that the characteristics of a MOSFET all look like this as you plot the I DS versus V GS. So, this is the transfer characteristics of the MOSFET for different V DS and as V DS increases the characteristics gets more and more into the saturation region. So, for very low V DS you will find that you remember the subthreshold current also depends on the exponential of the V DS. So, for very low V DS it is going be all most the characteristics would look almost like this because you are very strongly in linear.

Now you could plot the same characteristics on a log. So, this is the subthreshold region right. So, technically let us say from V fb to V T. So, you could plot the same characteristics on a log I DS versus V GS (Refer Time: 13:26) and that is quite useful. So, we will have a complete a lecture on parameter extractions. So, we will actually look at all these things in good detail there, but what are the useful piece of information that you can get from this curve.

From the slope of this curve at very low V DS or even at any other V DS if you know the V DS it is possible to extract this parameter mu C ox W over L and from that we know what mu is ok, if you know the insulator thickness we can guess what C oxs, but in order to get C ox we can always do a capacitance voltage curve and you will find that you know what C oxs.

So, if you know C ox and you know the aspect ratio because we have designed the transistor and we know the geometry of it we can calculate what mu is from the slope of this curve. But from the log I DS it is the same data right you take the transfer characteristics the same experimental data sets and you plot it on a log I DS versus V GS curve and what you will find is that, you will find that the characteristics shows this almost linear relation and then it bends off and this region is the subthreshold region.

And that region is the linear or saturation region of operation that is all above threshold. So, in the subthreshold region you are technically expected to get a straight line because of the purely exponential dependence, but having said that when we talk about non crystalline semiconductors we will see that there are some variations in the subthreshold slope itself because of the existence of states inside the band gap. But for now for this lecture what this lecture tells you is that this should be a straight line because the current is exponentially dependent on the surface potential or there the V GS and then you have a entry into the above threshold region and this mu of the curve sort of defines what your threshold voltages.

So, from this curve we can estimate the subthreshold swing, which tells you which gives you a lot of information on see depletion by C ox and which you can actually correlate with this CV measurement and iterate for this measurement to make sure that you have the right values and therefore, calculate if there are any differential capacitance is or etcetera, etcetera.

Now this log characteristics also gives you another information if you look at the current here which is below V fb. So, have to say if you look at the current here you will understand what the leakage current in the mosfet. So, we have still not approached that boundary so, we will do that, but a little later. It tells you what is the current between the source in the drain then we think that the MOSFET is completely turned off which is when we assume the MOSFET is switched off that is there is no V GS present ok.

So, there is still there is V DS, but there is no V GS and what is the current through the MOSFET or the V GS below V fb so, what is the current through the mosfet. So, we will talk about the leakage mechanisms in the MOSFET a little later. And the third plot that we looked at was the output characteristics, which is very useful when we design circuits because it tells us a lot of things about the resistances.

So, this is I DS versus V DS which is the output characteristics or the MOSFET and that had a form like this and as you increased V GS, you found that you can get these different family of curves, you can get these different curves and as we increased V DS we went from the linear region to the saturation region ok. And also we looked at channel length modulation which did not allow these curves to become perfectly flat, but instead gave at dependence on the saturation provided at dependence of V DS on the for the saturation current.

So, this is summary a quick summary of our current state of knowledge in the with regards to the MOSFET current voltage characteristics. Now so, we at the beginning of this lecture we said that there are 2 aspects that we have still not studied, one is the currents below V T, which we have now you know understood a little better because these are all the subthreshold currents and they are all related, they are all governed by the diffusion of electrons from the source to the drain, the diffusion of minority carriers from one of the electrodes to the other. And second point that we said that we were not we had not covered completely was a variation in the depletion width, which we thought might affect the threshold voltage.

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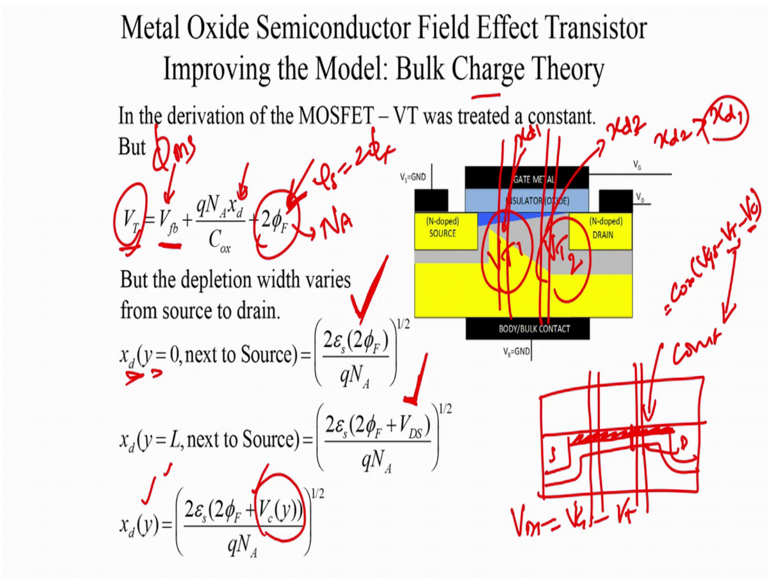

And we are going to now address that point. So, what are we doing we have just we have this very basic model for the current voltage characteristics the MOSFET and we are simply improving this model you know with these details. So, the model the first model we had was from V T till above a 2 gate voltages above V T, which is all the purely strong inversion characteristics where in we looked at linear and saturation regions of operation. And then we defined the regions the current below V T which is the subthreshold currents and we defined the subthreshold swing which was an important parameter.

And now, we are defining the current voltage relation a little more accurately ok. Although we will just introduce this introduce the ideas behind this, but not actually use this for many other purposes, but this is a more accurate model. And this model is something called as a bulk charge theory and it takes into count the variation in the depletion width.

So, as we move from the source to the drain the initial model I mean just to re restate the introduction, as we move from the source to the drain not only it is the channel charge decrease, but that depletion width is also supposed to vary. And because that is because the P-N junction here is this P-N junction is more strongly reverse biased as compared to this P-N junction. And this depletion width variation creates an inaccuracy in the way we defined the channel charge.

So, in the previous case we had assumed that the V DS is very small. So, therefore, we got away with many things we said the V DS is very small and therefore, you know the depletion width does not change too much and that is the channel charge and that qn is simply equal to your C ox into V GS minus V T minus V c by h or you know the charge per unit area is C ox into V S minus V T minus V c, where the V T was treated like as it is a constant, but in reality as if you take a section here and if you take a section here, since the V DS is different or since the V c is different the depletion width is also different ok.

So, it becomes more prominent in this case if I were to take a section here and a section here, the depletion width is suddenly increased right. So, the depletion width here is x d 2, there is a depletion width here is x d 1 and x d 2 is clearly greater than x d 1. And since the depletion charge depends upon the x d, the threshold voltage in this region has to be greater than the threshold voltage here and that variation and threshold voltage is completely missed out in our study, because we went from very low V DS and directly into saturation by simply substituting V DS is equal to V GS minus V T ok.

So, that is the little gap in our model and what we will do now is, we will completely we will try to see how that gap can be corrected for. So, the V T is got 3 milestones it is the flat band you first reach the flat band voltage and then you do Q depletion by C ox you deplete the region and then you bring the surface potential to equal to 2 phi F. Now the problem is with Q depletion right it is not with phi F is purely dependent on the acceptor on concentration V fb is completely dependent on phi ms and it is only the Q depletion that depends on the value of x d and it is qN A times x d by C ox.

So, as x d varies V T must vary. So, near the source side there is at x d at y equal to 0 this is our x d that is the depletion width and near the drain side you have a larger what you say depletion width and that is given by this term. You are all now already very familiar with you know how in how to define depletion width in terms of the surface potential. And at any point y this is the depletion width it depends upon the potential of the channel there.

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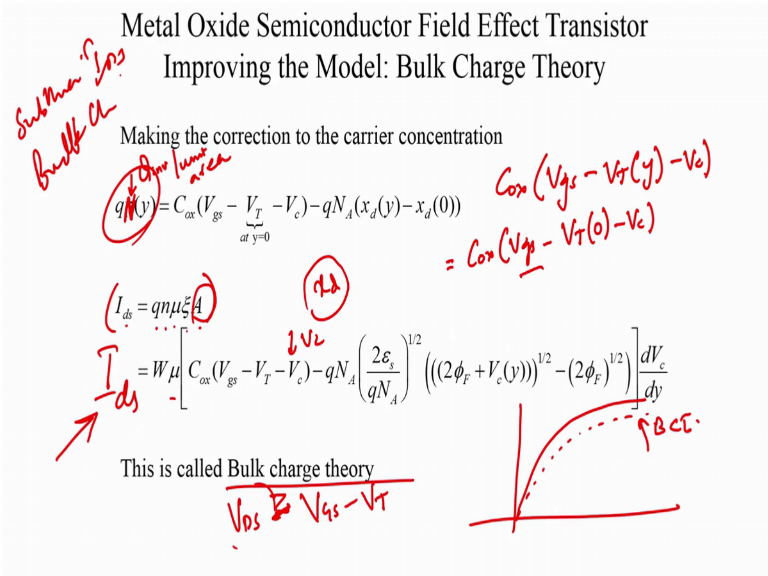

Therefore, we can correct for our relation of qn in this particular manner. So, we will define. So, this should we will try to define this should be qn into h ok, it is the concentrate that free carrier concentration per unit area ok. So, particularly I am looking at all of been say capital N here ok. It is the inversion carrier concentration per unit area and not per unit volume and that is equal to C ox into V gs minus V T minus V c just like the way we defined, but the V T is computed at the source which means using an x d value that is present near the source which is close to the equilibrium x d value of the P-N junctions.

So, we will use that V T, but then we will come to we will correct for it by saying that instead of you should have we should have actually been using V gs minus V T of y minus V c, but we will say that this is equal to C ox into V gs minus V T at y equal to 0 minus V c minus qN A into x d of y minus x d of 0. Because all the other terms the phi in the phi ms and the 2 phi F terms do not change it is only this term that we will correct form ok.

So, essentially we are subtracting qN A x d o and instead adding qN A x d y to this relation here to the V T here. And by making this correction we can now rewrite the differential equation for the drain to source current. We say that I DS is qn mu electric field into area, where this area is your you know once again it is the W into h where the h cancels off and we say that the current voltage relation or the differential equation that you need to solve this I ds is equal to W into mu into this particular term into dV c by dV y ok. And what does this term this term is nothing, but your corrected channel charge per unit area, upper unit volume because the h has cancelled off.

So, this is the h and that is cancelled off so, that is the channel charge ok. And you saw now you if you see the V c, the V c term appears in your differential equation here as well as here. So, earlier we did not have this term and therefore, we ended up with a square law model, but now with this term being present and you have a V c to the power half and a V c term. The model is going to be slightly more complicated than a square law, but it is going to be more accurate because it takes into account the variation in x d.

So, this theory is something called as a bulk charge theory and it generally predicts a lower amount of current ok. So, if that was the square law model the bulk charge theory predicts the current that is slightly lower. And the second point is that the way you define the saturation V DS that is in the square law model the V DS saturation that is the V DS of beyond which the transistor entered saturation was defined as simply any V DS greater than or equal to V GS minus V T.

Then definition will change a bit because your current voltage characteristics has now changed, but it is up to you to solve for this exact differential equation as a homework. Although in one of the assignments I will put out the exact solution we will have this is an assignment question due to which I and it is due to that reason that I have not given our the answers here, but we will discuss the exact answer when the solutions to the assignments are presented.

So, these are the 2 key points the Subthreshold Slope the understanding of the subthreshold current and the Bulk Charge Theory model with sort of refines the current voltage characteristics that we developed.