Semiconductor Devices and Circuits

Prof. Sanjiv Sambandan
Department of Instrumentation and Applied Physics
Indian Institute of Science, Bangalore

Lecture – 44
MOSFET characterization: Parameter extraction

So, the final bit with regards the very last topic with regards to MOSFETs is with regards to characterizing MOSFETs. So, I felt that this would be a very useful module to have which is the characterization of MOSFETs because in most of your since this course is being offered to students from various disciplines. It is very likely that you are probably making MOSFETs you are fabricating MOSFETs using new materials or new process techniques etcetera. And in order for you to characterize these MOSFETs; we have gone through several ideas through this course, but I do not think it is quite obvious as to how to use those ideas to characterize MOSFETs, ok.

So, these few slides, we will just give you some insights as to what you might need to look out for when you have you know built a MOSFET and you know what you might want to test for after you have built a MOSFET. So, that it gives you some very elementary picture on some very useful or important parameters of the MOSFET that you could use for your research or for your for modeling.

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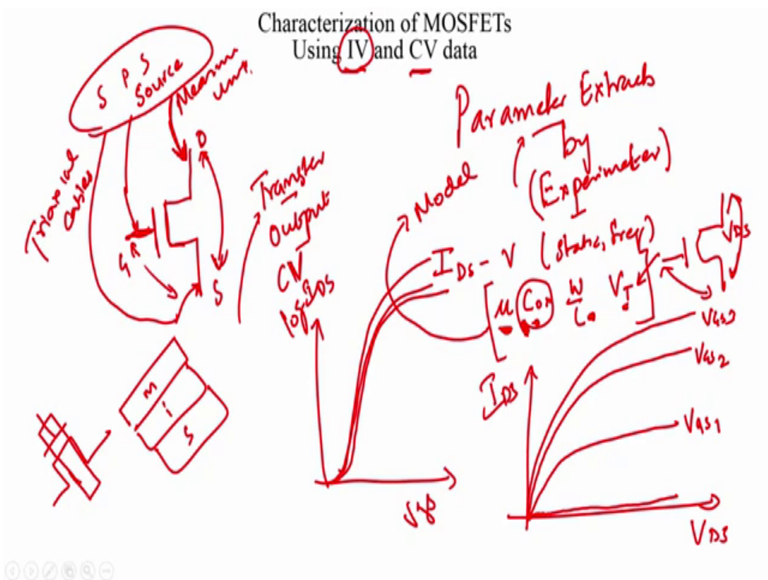

So, essentially let us say you have made a MOSFET, ok. The very first characteristic characterization technique is the most essential, which is using your IV and CV information to extract key parameters of the MOSFET.

So, what is the point of parameter extraction? So, you know, if we want to extract parameters right and we want to extract parameters via experiments. And what is the point of extracting parameters by experiments and what are these parameters? So, ideally the point of parameter extraction is to be able to define your current voltage characteristics in static and in dynamic that is you know low frequency and high frequency characteristics of a MOSFET as accurately as possible, ok.

And we essentially want to identify all these parameters mu Cox W over [laughter], V T so, that we can then start writing equations for the MOSFET and start defining the behavior of the MOSFET. Now after we have built a MOSFET what are the experiments that need to be performed in order to extract these parameters and start using these parameters to build models so, that we can then predict the behavior of MOSFET circuits or behavior of different, you know MOSFETs with different you know mobilities or oxide capacitances, etcetera by simply using these ideas, ok.

So, what I mean is you can extrapolate the behavior of other devices that you make after you have characterized your fabrication process flow, ok. So, that is the whole point of parameter extraction, you can build compact models and you can predict the behavior of MOSFETs. So, what are the experiments? So, the very first one is what we will talk about is the IV and CV measurements and I think this itself would be quite useful for most of you.

So, you have made your MOSFET, ok. So, we will just show three terminals, we will not worry about the body. And this analysis is true for you know any other kind of fet structure you know we have not talked about say for example, thin film transistors yet, we will cover that. But these ideas are valid for any other tft stuff, any of the MOSFETs that is what and the, the key experiments to perform the very first set would be your IV and CV measurements.

So, you have your MOSFET, you got a drain, source and gate. Now, we want to first do experiments to extract the transfer characteristics out and the output characteristics. And then perform experiments to extract the CV characteristics of the MOSFET. Now, how do we do that? For transfer characteristics, we want to obtain a plot of IDS versus Vgs. And this is done by setting by setting the drain to source voltage to a certain value and then connecting, you take the MOSFET to a probe station you add in your probes, ok.

So, make sure that these probes are all connected to high impedance you know, if you are going to measure voltages they need to be connect it to high impedance nodes and we are going to measure currents you want it to have low impedance. So, you typically want to be connecting these probes to a good semiconductor parameter extraction system, or you know very good quality source measure units. And since we are going to be measuring very low currents in the MOSFET, you probably want to be using Tri axial cables for current measurement, ok.

So, after making this connection, you want to be varying the gate to source voltage after setting for a certain drain to source voltage. And we will end up with a characteristic that looks like this. And then we would vary the drain to source voltage and again perform the same experiment so as to get another characteristic. And we can now obtain a family of curves for different drain to source voltages. So, this is the transfer characteristic.

Now you can take all this data and plot it on a log IDS versus Vgs scale. So, you should end up with a bunch of curves that look like this. The next IV characteristics is the output characteristics ,which is the IDS versus VDS curve. So, we would now take the MOSFET, set the Vgs to some particular value say greater than VT, we still do not know what VTS, but you set it to a particular value and we are going to vary that gate voltage and you are going to sweep the drain to source voltage.

So, when the drain to source voltage is swept, you now have a characteristic that looks like this. If the Vgs is below VT, you will probably have a characteristics that is does not show too much of current and for larger gate voltages, we will obtain a family of curves which form the output characteristics of the MOSFET, ok. And finally, we will perform a capacitance voltage measurement, ok. And how do we do that?

So, ideally you want to we would like to do that on a MOS capacitor structure that is a metal, insulator, semiconductor and back contact. But if we have a MOSFET, we make use of the overlap capacitances. So, you have a gate, you have the drain source and we have a small overlap capacitance between the drain and source.

So, if you consider this structure here, we have the gate insulator. So, how do we perform the CV characteristics on a MOSFET? Now, ideally we would like to perform the CV characteristics using a metal insulator semi conductor architecture. But we can obtain such an architecture by simply short circuiting the drain and source making sure that there is no current flowing and then using the moss capacitor in the semi conductor, in the MOSFET.

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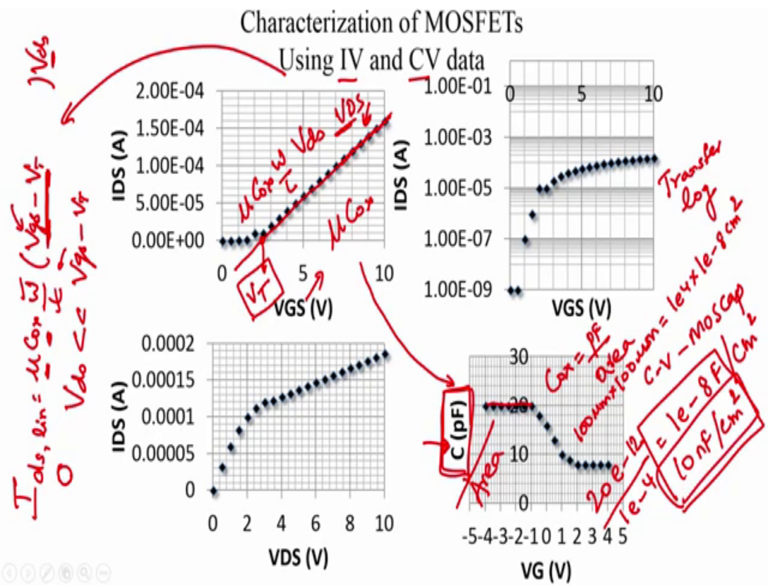

So, at the end of it, we should obtain a family of curves that look like this. So, here I do not, I have not shown a family of curves, but we are we are seeing just one set of one data set, ok. So, here we have the transfer characteristics, we have the transfer characteristics plotted on a log scale. Here we have the output characteristics and here we have the C V characteristics of the MOSFET. So, how do we extract all the parameters required by using this IV and CV measurement?

So, the first point note is let us write down our equations, these our theoretical models help us a long way, ok. So, in linear, in deep linear mode operation so, we have the MOSFET characteristics defined as Mu Cox W over L. Let me just make use of the entire slide here. So, we have the current voltage characteristics and linear operation to be Mu Cox W over L into V gs minus VT minus V ds by 2 into V ds.

Now, if V ds is made much, much smaller than V gs minus VT then we can ignore this term and say that this is our current voltage characteristics. Now, the first thing you could do is once you have these characteristics, you can simply take all these data points, note the appropriate voltages plug them into these curves and just solve those equations to obtain the unknown parameters. And what are the unknown parameters? The unknown parameters are the mobility, Cox and threshold voltage. Vgs is known because we are applying the gate to source voltage, the aspect ratio is known because we have designed the MOSFET, ok.

So, we know the channel width and we know the channel length what remains and Vds is known because we are performing the characteristics by setting it to a certain Vds. So, what remains is Mu Cox and VT. And we are going to use all these characteristics to define all these plots to define these terms and we will use it to cross check and reconfirm these definitions. Now, as I said you could take each point here and plug it in to the equation and obtain the parameters. But then an easier way to do it, is to perform the VDSI VGS I mean that perform the IDS VGS characteristics at very low VDS and make use of this equation here.

So, the slope at any point on this characteristics is simply Mu Cox W over L into Vds, ok. And if you were to extrapolate, if you were to take a tangent if the VDS is really low, we will find that this characteristics is quite linear, you will not see too much of non-linearity. If you take a tangent, let say some point here you know why we are picking a point here because that is where Vgs is the largest and that is were its most likely that Vds by 2 is going to be much less than Vgs minus VT.

So, you take a tangent at that point and you extrapolate the tangent all the way to the x axis, ok. And the point at which it meets the x axis is a very likely value for the threshold voltage, why is that? If you set your Ids as 0, you find that that can happen when your Vgs is equal to VT. So, that is the x intercept. So, from this characteristics what we can obtain is this product which is Mu into C ox and this value which is a likely value for the threshold voltage.

Now, what we need to identify Mu and Cox separately is the CV characteristics or the MOSFET. So, let us now perform a CV characteristics of the MOSFET and it could be low frequency or high frequency CV characteristics, it does not matter, but the point should note is unlike in the case of a mos capacitor, ok. The high frequency CV characteristics of a MOSFET will occur at a higher frequency. So, what I mean by that statement is that if let us take a CV characteristic for MOS capacitor. So, we have the capacitance and voltage curve and what we have done is we first perform the low frequency measurement and we obtained characteristics that looks like this.

So, let us say we performed another measurement, but it is at a higher frequency and at some point let us say when the frequency was say 1 megahertz we obtained the high frequency characteristics of a MOS capacitor. But it is very likely that if you were to take a MOSFET, ok. And perform the high frequency CV characteristics on the moss capacitor and the MOSFET, it is very likely that at the 1 megahertz point that we still obtain the low frequency characteristics. And why is that? It is because the high frequency characteristics flattens out in this region, simply because the electrons thermally generated electrons in the bulk are not able to respond to the change in the applied signal.

The generation rate of electrons is not fast enough and see a MOS capacitor has to rely only on the thermal generation rate, because all the electrons are coming in only from this generation mechanism. But on the other hand in the case of a MOSFET the source can also inject electrons. So, you have the source and drain, the source is also it is also possible for electrons from the source to enter the channel.

And therefore, it is likely that these electrons will appear at the interface at on time and that these electrons can respond to the applied AC signal. And therefore, it is possible that you still see a low frequency measurement in a MOSFET at the same frequency corresponding to a high frequency curve of a MOS capacitor. Nevertheless, so, let us say we have a MOS capacitor or a MOSFET and we have performed the CV measurement, ok.

So, we end up with the CV characteristics that looks like this now where do we obtain our information of C ox? Clearly the C ox can be obtained in accumulation mode in this case. So, that is our C ox, ok. Now, you should be very careful yeah because the CV measurement as performed on a semiconductor parameter analyzer we will give you the complete capacitance, ok, it is the capacitance in farads. It is not C ox it is not the capacitance per unit area.

So, in order to obtain C ox, we need to take this capacitance and divide by the area of the MOS capacitor used and then we obtain Cox. So, in this case, let us say the MOS capacitor used had a 100 microns by 100 Micron length lengths. And therefore, the area is 100 Micron into 100 microns which is 1 e 4 into 1 e minus 8 centimeter square, ok. And therefore, Cox in this case would be 20 Pico Farad that is 1 e minus 12 divided by 1 e minus 4, which is about 1 e minus 8 Farads per centimeter square that is about 10 Nano Farads per centimeter square.

So, that is the value of Cox in this example. So, we need to be careful with how we use the CV data. So, now, we have Cox and we have the product of Cox into Mu and we can extract Mu. So, just as a complete process, you know let us add numbers in a little later, but let us just go through the techniques first, ok.

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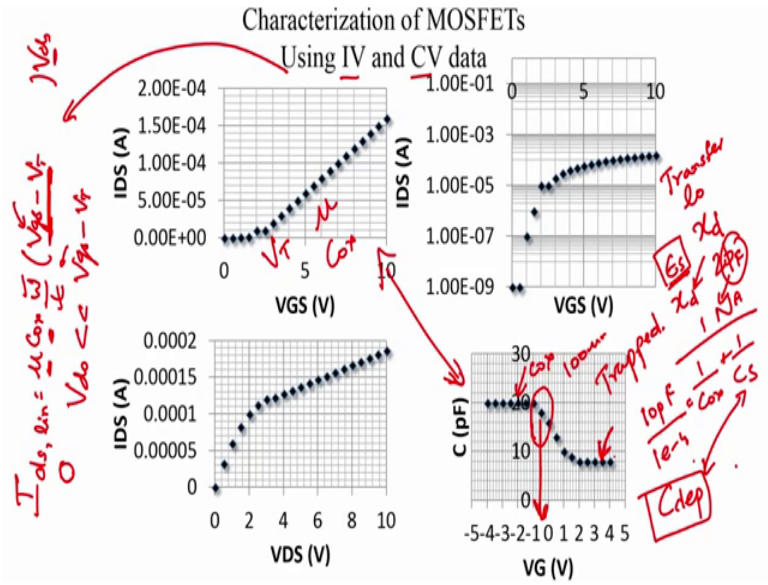

So, we now know what is Mu, we know what is C ox and we know what is VT. And all this has been obtained from these two characteristics. Now, what else can the CV characteristics tell you ? The CV character is a very powerful tool, it can be used to identify through a sequence of experiments, you can use to identify craft charges in the dielectric, ok. We will talk about an example of that in the next slide you can use it identify Cox, ok. But you can also use it to identify the typical flat band voltage.

So, we know that the flat band voltages in and around at this point here, ok. And it is also used to identify the semiconductor capacitance, ok. And what do we mean by that? So, this is the depletion and the interfacial capacitances combined, ok. And how do we do that at the low at the high frequency characteristics here, we know that this is a series combination of Cox and the semiconductor capacitance. And that is basically the capacitance here which is 10 Pico Farad, divided by the area is and we said let us say it is a 100 micron by 100 Micron device.

So, this divided by your 1 e minus 4, 1 e minus 8 is nothing, but oh sorry, 1 e minus 4 is nothing, but the series combination of C ox and Cs and what is Cs? Cs is nothing, but your depletion capacitance plus interfacial trap capacitance. And if interfacial trap capacitance does not exist then it is purely your depletion capacitance, ok.

So, at high in high frequency characteristics, it is very likely that the interfacial trap capacitances will the interfacial trap charge will not respond. And therefore, it is very likely that this is simply the depletion capacitance. And if you know the depletion capacitance, we essentially know Q we essentially know epsilon S by x d. So, that is the depletion capacitance per unit area and if epsilon S is known we essentially know X d which is a depletion width in the semiconductor and since depletion width depends upon 2 phi f. And among several other parameters, we actually know the doping concentration of the semiconductor.

So, CV characters is quite a powerful tool, you can make very good estimates of all these parameters, right.

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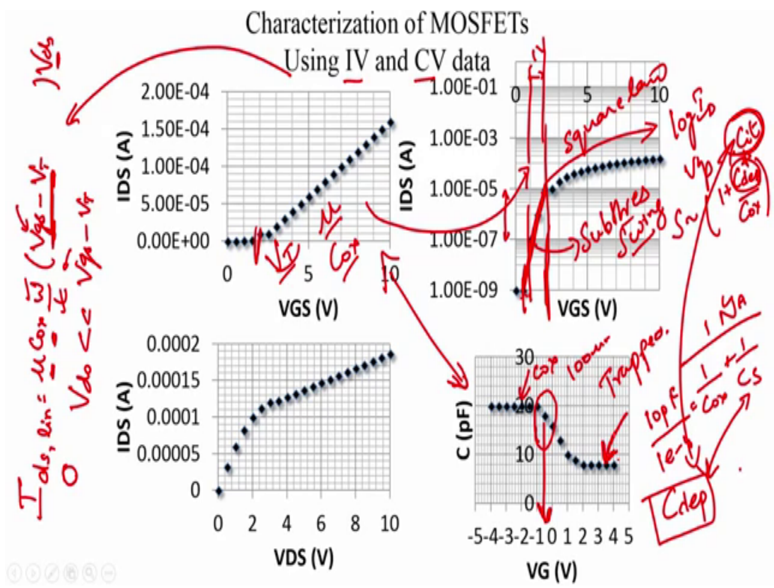

So, now we, we have obtained VT, Mu and C ox and we can now plot the same transfer characteristics on a log I D versus VG scale in order to obtain look at the sub threshold behavior of the MOSFET. So, we know VT, so, we know that in and around let us say about 2 Volves, ok. So, after 2 Volves, the MOSFET enters above threshold operation. So, here it is all given by a square law characteristics and below this below this we know that we are in sub threshold region.

So, here you can see that even though there are a few data points, it is an almost linear dependence. And we can now calculate the the sub threshold swing of the MOSFET and what is the sub threshold swing, it is the Volves per decade. So, how many Volves did it require? What was the gate voltage required for the MOSFET to travel 1 decade up in current, ok.

So, this is 2 decades up in current and the gate voltage required there is about like if we do not have a gate voltage scale well we have a scale here. So, the gate voltage required is about 1 volt for the current to travel up 2 decades. And therefore, it is 1 volt divided by 2 which is 0.5 volts per decade as the sub threshold swing, ok.

So, that is how you calculate the sub threshold swing and sub threshold swing is also related to 1 plus C depletion by Cox and if there is no interface strip capacitance, we can calculate C depletion here. And we can cross check with the C depletion extracted from this place. And if there is a mismatch, it is possible that you have interfacial trap capacitance. And therefore, it is also an indicator for it is also means to combine these two characteristics to extract the interfacial state capacitor.

Because the interfacial trap capacitance will not respond at high frequencies, it is less likely to respond at high frequencies. So, this is one useful parameter, you can get from the log ID versus Vgs characteristics. And the other useful parameter. Since, you are looking at the log scale it is possible to identify the leakage current and by plotting a family of curves at different Vds, here we can identify the gate induced drain leakage drain induced barrier lowering and these phenomena, ok. You can identify the different leakage mechanisms and we know the impact of Vds on leakage and it becomes a very useful tool to study the mechanism of leakage.

So, we know the leakage current. So, in this case for this one characteristics, it is difficult to identify the mechanism, but we can say that the leakage current is 1 Nano Amps. So, that is the leakage current through the MOSFET. So, this is when the MOSFET is supposed to be off and yet it is having a current that is not 0 and that leakage is 1 Nano Amps, ok. So, now, finally, we will plot the output characteristics. So, since we already know Mu Cox and VT, we can cross check to see whether the output characteristics in linear mode matches the use of these parameters. And you can iterate between all these plots in order to see whether we have the right parameter set.

But N saturation mode, we observe for two other features in the saturation characteristics, I mean the in the output characteristics is quite powerful for a circuit designer.

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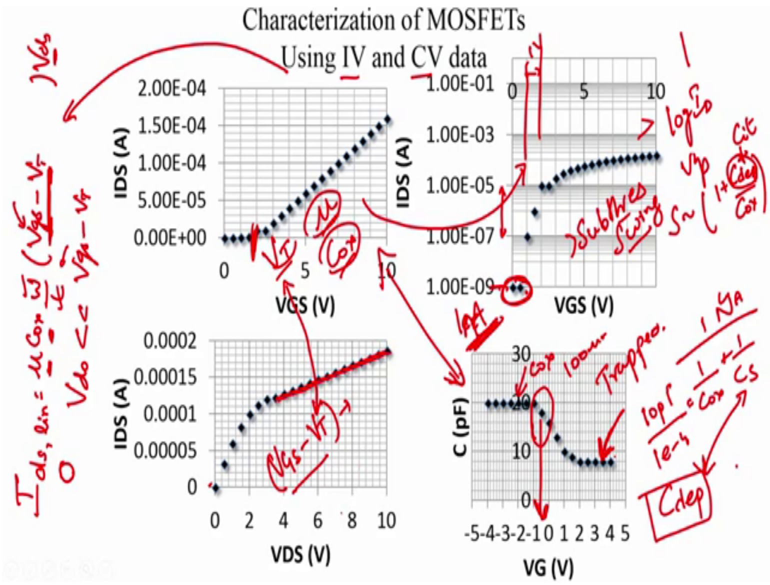

So, in saturation mode we firstly, identify the point at which saturation occurred. So, technically this should be VGS minus VT, but it could be offset by some amount because if you remember the bulk charge theory predicts a different saturation voltage as compared to your square law the simple model.

So, this could give you indicators as to those to those corrections involved, and it is also cross check between this VT and the VT obtained in the transfer characteristics because at it only at VGS minus VT that you enter saturation. The next point is to look at the variation in current due to VDS in saturation, ok. Now, this variation in current due to VDS is theoretically not supposed to exist in an ideal MOSFET.

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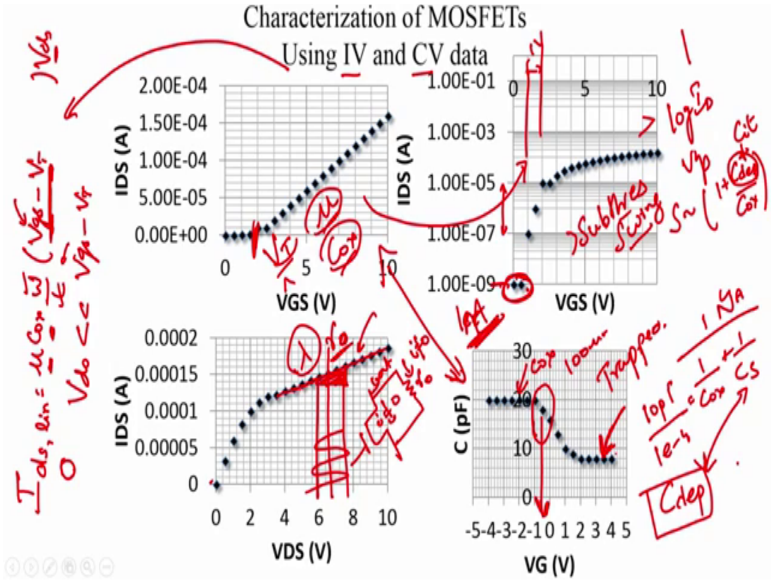

An ideal MOSFET the current supposed to be constant with Vds, but it is because of channel length modulation that you actually have a variation in current in the MOSFET. And therefore, this is a useful plot to identify your channel length modulation parameter and the effective output resistance of the MOSFET, ok.

So, what do you mean by the output resistance of the MOSFET? It is the output small signal resistance of the MOSFET which means that if I were to fluctuate, if I were to set this as my Dc operating point and if I were to fluctuate Vds around this point, what is the fluctuation in the current. And that slope or the inverse slope of that tells you the output impedance of the MOSFET which is to say that if you have an ideal MOSFET with no channel length modulation in saturation operation there is supposed to be no current in this MOSFET.

But we then use this ideal MOSFET and we then add a parallel resistor a resistor in parallel. So, that when the MOSFET operates in saturation, the current here is 0. The small signal current is 0 whereas, the small signal current in the resistor here is not 0. And it is in fact, defined by the current variation in saturation mode, ok. So, just as an example so, since we have already performed a few calculations, just as an example, if ever run through these numbers a bit let us just quickly do that. So, these are the, these are very powerful experimental techniques to extract all these parameters.

So, let us just run through it and through in a few numbers in place, ok. So, this is quite important from the point of view of example problems or you know your assignments, because you will be given assignments with regards to this kind of parameter extracting parameters.

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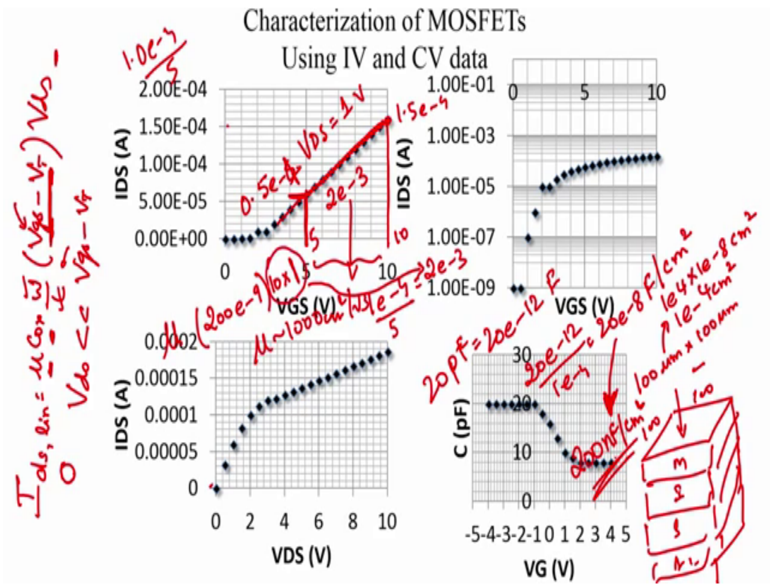

So, firstly, let us say we performed the most capacitances on MOS capacitor having 100 microns by 100 Micron. Those are the dimensions, which means that, that was 100 microns that is 100 microns and you know that was the MOS capacitor that we used, ok. So, as a metal insulator semi conductor back contact. So, what is 100 microns by 100 microns, we would like to represent everything in terms of centimeter square.

So, what is 100 microns into 100 microns? It is 1 e 4 into 1 e minus 8 centimeter square which is about 1 e minus 4 centimeter, sorry, 1 centimeter square. and the capacitance acts, they come to the total capacitance measured here there is a Cox in accumulation mode is 20 Pico Farad.

So, this is all in Pico Farads that is basically your 20 e minus 20 farads. So, therefore, my Cox is essentially this capacitance divided by the area which is 20 e minus 12 divided by 1 e minus 4 which is 20 e minus 8 farads per centimeter square, ok.

And the capacitance here that is basically your Cs in parallel with C depletion is much lower, it is of the order of 10 or maybe less than that, it is about 8 Pico Farads. And therefore, my Cox in series with C depletion is 8 Pico Farad by 1 e minus 4 which is about 8 e minus 8 farads per centimeter square, it is about 80 Nano Farads per centimeter square, ok.

So, do forgive me, if I am making typos here, but I think it is right. So, it is this is about 200 Nano Farads. So, I think, when we had the discussion on CV measurement earlier, I made a mistake, it was one order lesser, but what this tells you is Cox is 200 Nano Farad per centimeter square.

So, now, let us come to the slope. So, what is the slope here? So, let us say this point here is about 1.5 e minus 4 that is the current, that is a 10 volts. And we will go long way because it is quite linear, there is a quite linear characteristics. And let us say this was all plotted at Vds is equal to 1 volt. So, over here, we have a Vgs of 5 here, we have a Vgs of 10 and here the current is about 5 e minus 5,ok or let us say 0.5 e minus 4.

So, the slope that is your D delta ID by delta VG, is essentially 1.5 minus 0.5 which is 1.0 e minus 4 divided by this voltage difference which is 5 volts. So, this slope is about 2 e minus 3, ok. And that is supposed to be our Mu C ox W over L into Vds. So, let us say Vds is 1 volt. So, that is 1 volt, let us say the aspect ratio is also 1 that means, the channel width is equal to the channel length, ok.

Now, we know Cox is 200 Nano Farad per centimeter square, 200 e minus 9 per centimeter square. And that is all and that into Mu is equal to 2 e minus 3 which implies that, that is going to be e 6 and that is going to be e 4, which if I have not made a mistake here say. So, the mobility is quite high it is in fact, dramatically high and it is about 10000 centimeter square per volt second, I am quite sure, I have made a mistake here, but, but nevertheless that is the way you go about calculating this, ok.

So, let us just cross check this 1 e minus 4 by 5 volts, that is 10 e minus 3 by 5 which is 2 e minus 3. And the capacitance was 200 Nano Farad per centimeter square, ok. So, since we have made an assumption on the aspect ratio, the aspect ratio let us say is 10. And let us say the Vds is 1 volt .and let us say we do not know Mu and therefore, this slope must be equal to this number, ok. So, which means that 6 and your mobility will be about 1000 centimeter square per volt second, ok.

So, yes numbers do not make complete physical sense because we are just arbitrarily picking up Vds and aspect ratio. So, there is no typo, it is just a mobility of 1000 centimeter square per volt second is more acceptable considering the fact that we are using silicon as our role model, ok. So, these curves are by no means actual data sets, they are just plots prepared on an excel file using the parameters using a certain, certain number of parameters and using these models, ok. But, it is just for the sake of this exercise.

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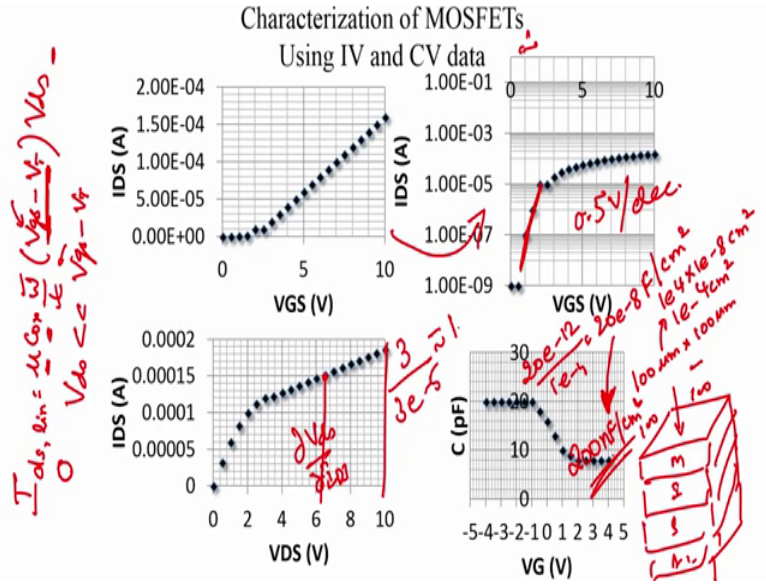

And then let us look at the log Id versus log Vds characteristics we have already looked at this.

So, we saw that the sub threshold swing is in order to get this past 2 decades, you need about 1 volt. And therefore, it is about 0.5 volts per decade. So, that is the swing and let us look at the output resistance or the MOSFET. So, here we can see that the small signal output resistance; you know the Dou Vds by IDS is you can calculate that quite easily. So, let us just mark two points, let us say that we keep one point here at 0.0015 and the next point here which is actually which (Refer Time:36:43) and the next point here which is close to the edge which is say 0.0018 which means the difference is about 0.003,ok.

So, the difference in the currents is the order of 3 minus 5. So, that is the N delta I and that happens for a voltage difference of about 3 volts, ok. So, that is quite a large output resistance, but not large enough. So, it is about 100 kilo ohms, ok. So, this is the way you go about extracting parameters, if I made a mistake in these calculations that I am doing here, I do apologize. But you have the idea you know what has to be done. So, this is a very powerful tool to extract parameters.