Semiconductor Devices and Circuits
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Lecture – 45
MOSFET characterization: Trapped charges, contact resistance

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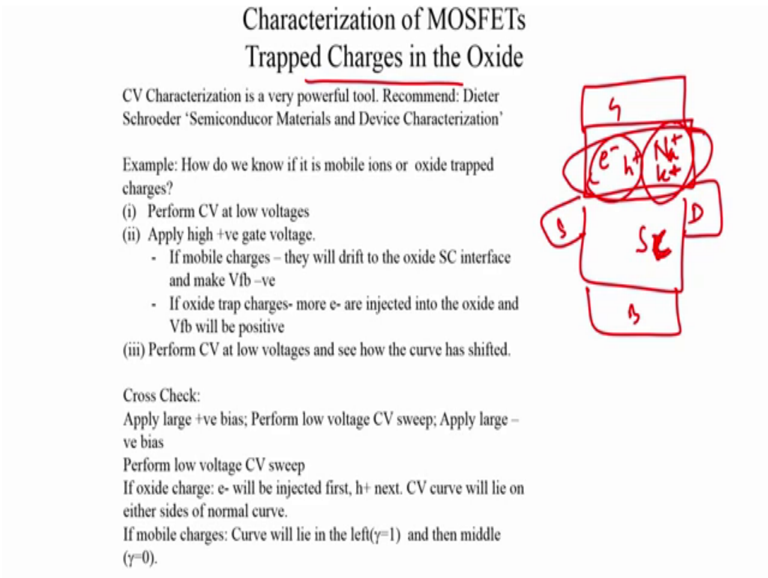

So, next let us come to using the CV characteristics to extract trapped charges and mobile charges in the oxides. So, we looked at the charges in. So, you have your metal insulator, you have your gate insulator semiconductor back contact in the MOS structure and you have your source and drain electrodes there. And we saw that there is a possibility of different kinds of trapped charges in the insulator.

So, we could have electrons holes which are your oxide trapped charges and then we could have mobile ions, which are due to poor handling of the substrate etcetera etcetera. So, how do we is there a possibility to identify the kind or the nature of the trapped charges in the insulator. So, what we do here is we can use the CV characteristics tool as a very powerful tool. And I strongly recommend this textbook, but Dieter Schroeder which is called semi conductor materials and device characterization ok. It is there in the reference list, but I just thought its a good textbook to you know sort of to redefine over here, because it talks about different characterization techniques for semiconductor characterization in general. And this includes the characterization of mobility you know via different techniques, its the hall effect measurement, etcetera etcetera, and it goes all the way to interfacial trap charges and techniques for MOSFET characterization.

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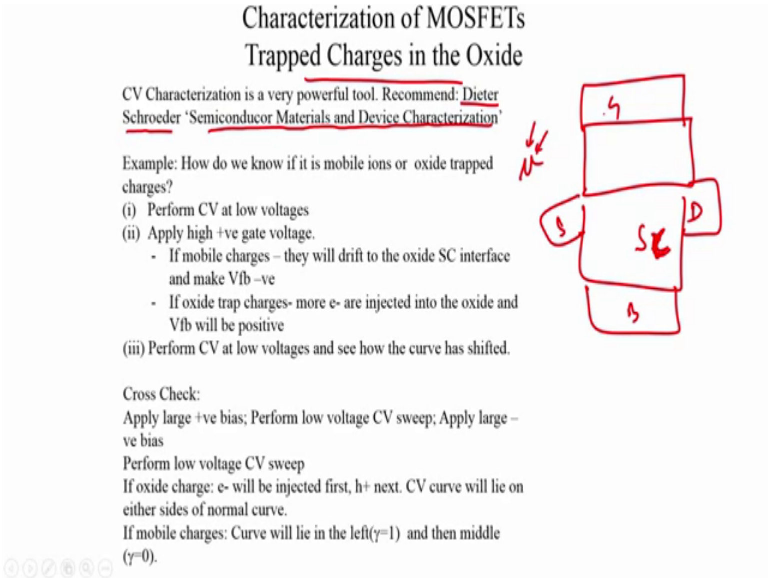

So, it is a good textbook to look at. But once again you know, this is again a very exhaustive topic in a just characterizing insulator track charges, and we do not have the time and nor is it the goal of this course to focus on this aspect for so long.

But I will just give you an example as to why I tell you that CV is a very powerful tool ok. So, if you would remember the impact of trap charges it was influencing the flat band voltage ok.

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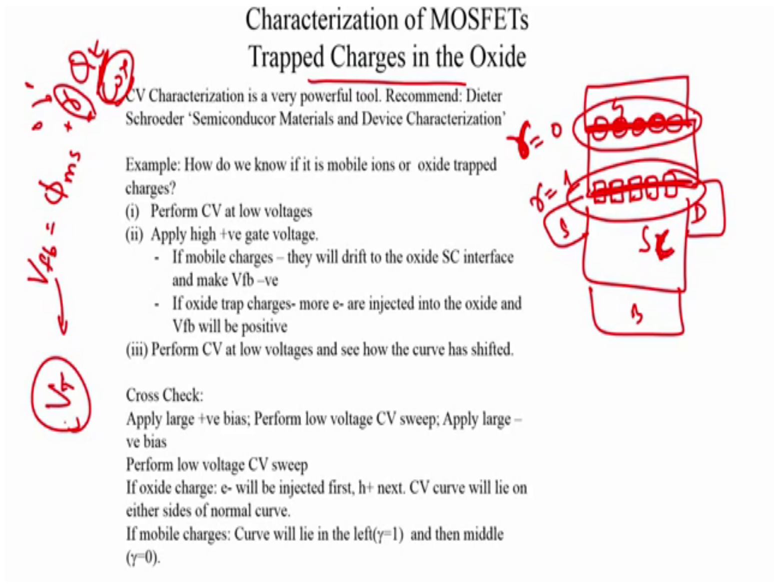

The flat band voltages normally this, but then due to the presence of trap charges we had the possibility of having; we have the possibility of having additional term which was gamma times Q trapped by C ox, but gamma would take a value of 1 or 0 depending on whether these trap charges were present close to the insulator semiconductor interface or whether they were present at the gate insulator interface.

So, the trap charges were present at the gate insulator interface gamma was 0 by gamma was this mean position are estimator ok. So, it was giving you just giving an indicators to the position of these charges. And if when the charges were close to the gate were close to the insulator semiconductor interface, gamma was equal to 1.

So, these were the two extreme values of gamma. So, when the charges are present here they do not impact the flat band voltage and the charges are present here they impact the flat band voltage very significantly. And flat band voltage in turn impacts the threshold voltage of the MOSFET.

So, let us say we want to understand the mechanism of this trap charges in the insulator.

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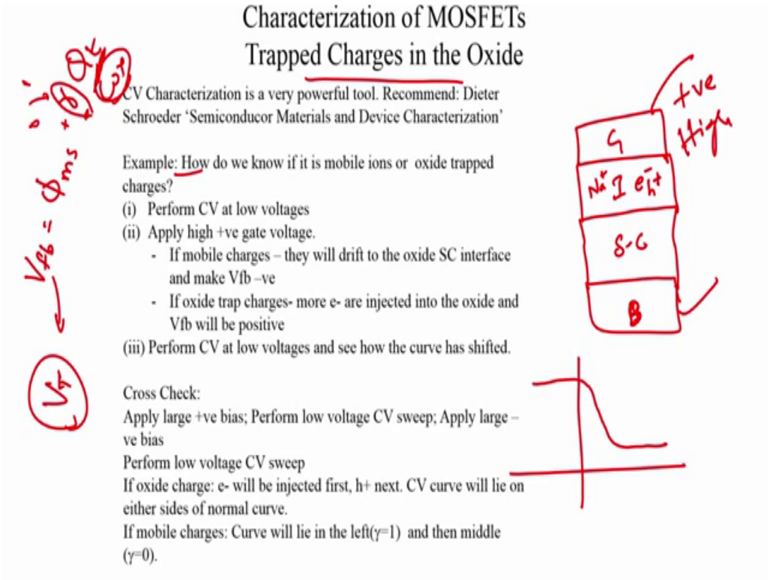

So, let us say we are seeing mobile charges in the insulator, but we do not know whether its because of electrons and holes or whether its due do mobile ions. So, let us say that is the problem. So, we have a semiconductor, you have an insulator and you have a gate and the question is, I do see charges trapped there, but I do not know whether these are oxide trap charges which is electrons and holes or whether it is mobile ions.

So, how do I go about identifying this? So that is that is an example. So, what we do first is? We will perform a low voltage CV characteristic, which is your regular CV characteristics. So, let us say we do a high frequency CV characteristics ok. And the CV characteristics turned out to be this. Now what we do is, we take out the device and we apply a very high voltage; very high voltage applied across the MOS capacitor. So, if you apply a very high voltage if there are mobile ions.

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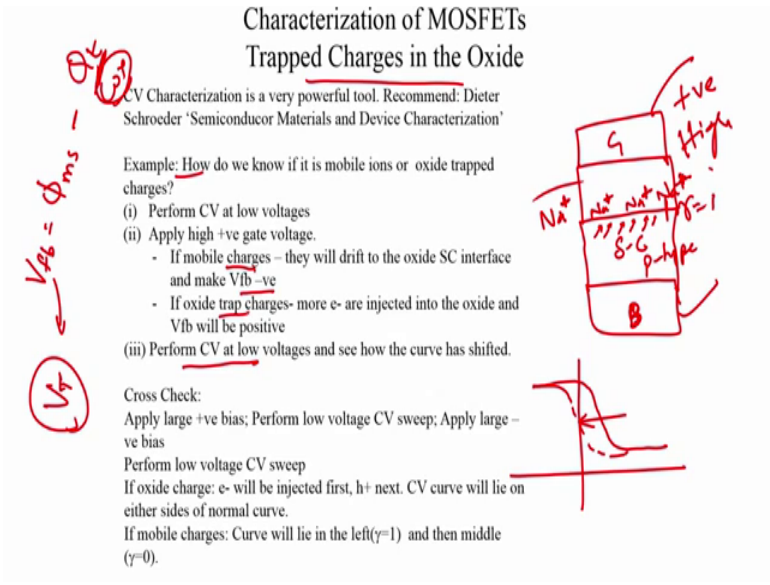

All the mobile ions will drift towards the semi conductor insulator interface; that is they will all take up a value of gamma equal to 1 ok. And if they all take up a value of gamma equal to 1 then the flat band voltage will be significantly influenced and what would happen to the flat band voltage.

So, since these are all positive charges ok. It is like as though without the application of gate voltage. We have already applied a gate voltage ok. So, we are talking about an N MOS devices. So, it is a P type bulk. And these positive charges near the gate insulator interface are playing the same role as adding positive charges on the gate. So, in some sense they have already started inverting or already started creating negative charges inside the semiconductor. And therefore, if we push the mobile ions to the gate insulator interface and to the semi conductor insulator interface, the flat band voltage will reduce.

And now if mobile charges of the cause the flat band voltage would have reduced. And if you now perform a CV characteristics at low voltages, you will find that the CV characteristics are shifted a little bit to the left. And this is an indicator, it is a potential indicator of mobile ions being present in your MOS in your insulator.

On the other hand if it is oxide trapped charges what would happen? So, let us say the cause of tap charges is not mobile ions, but it is oxide trapped charges. Now once again we initially do the low voltage CV measurements ok.

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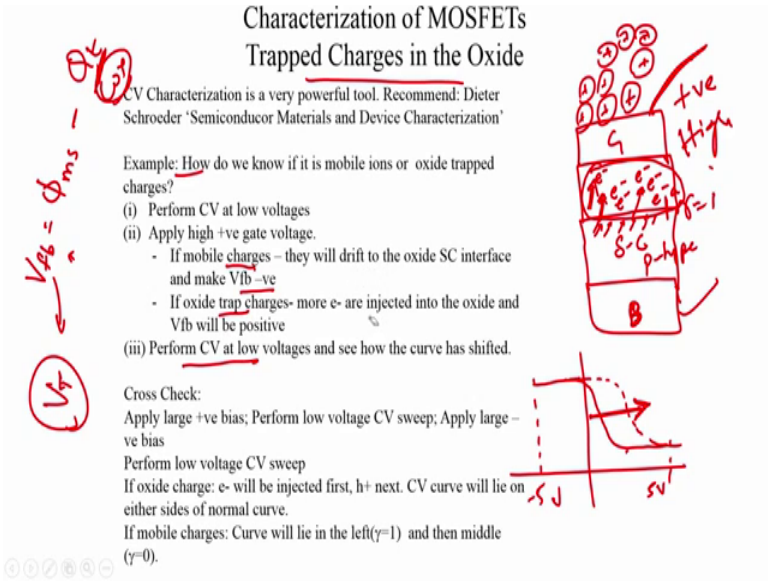

What do you mean by low voltage CV? Simply means that the voltages here are not very high ok. So, let us say we just do your regular CV measurements and now when we apply, we again apply a very high positive voltage.

But now since it is electrons and holes that are responsible, let us say it is not mobile ions, but electrons and holes what would happen? If you have a very positive gate, voltage electrons would be injected into the insulator; so the insulator is weak and therefore, its housing electrons inside. And once electrons are injected into the insulator we now perform another CV characteristics ok; we now remove the high voltage and perform another CV characteristics. And now since it is electrons that have been injected, the flat band voltage would have increased and we will see that the CV characteristic shifts to the right. And why did the flat band voltage increase? It is because even before we applied any positive charge, we already have some negative charge in the insulator.

So therefore, any positive charge you apply on the gate we will first have to compensate for all this negative charge on the insulator before achieving flat band and it is only after that that any additional charge, positive charge you added on the gate will lead to inversion. So, it is as though you have increased the threshold voltage of your MOSFET and therefore, your CV characteristics will shift to the right because the flat band voltage is now increased.

So, that is a very clear indicator as to how the CV characteristics can be used to identify mobile ions and oxide trap charges? You can also do a cross check ok.

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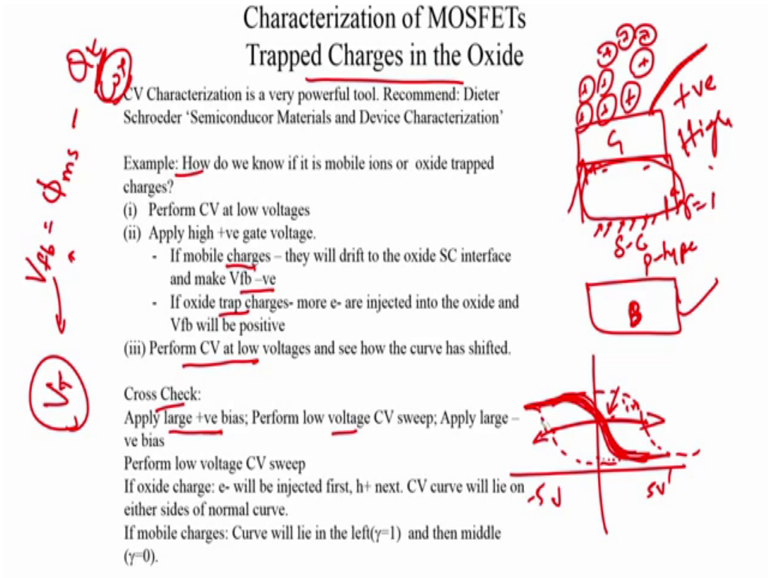

So, what we do is, let us say we apply a very large positive bias and now perform CV characteristic, you then remove the large positive bias and perform CV characteristics.

So, you will find that if it is mobile ions. So, let us say this is the normal, this is the mid characteristics and now we will apply a very large positive bias and perform the CV characteristics and because if it is mobile ions they are all shifted to the left. And now we apply a very large negative bias we take out the device and apply a very large negative bias ok, which means these mobile ions will now start drifting towards the gate insulator interface ok. If it is mobile ions they will all start drifting to the gate insulator interface if we perform, if you apply very large negative bias and when you do the measurement again the curve would have shifted back to where it was.

So, this is the mean position that is without insulator trapped charges ok. We do not know this and therefore, we are oscillating around this point and we apply very large positive bias the curve will go this way and we apply very large negative bias, the curve will go the other way. On the other hand it will go the other way in the sense it will get back to where it was the threshold voltage will not become hugely large, it will not become heavily positive ok.

But the other hand if its oxide trapped charges when we apply very large positive bias and then perform low voltage CV measurement. We would have injected electrons and you will find that the curve has shifted to the right and then when you apply very large negative bias you will inject holes into the device. And then when you perform CV characteristic, the curve would have shifted to the left of the mid position and therefore, if the curve CV characteristic curve swings widely on either sides, it is very likely that you have oxide trap charges and not mobile ions ok.

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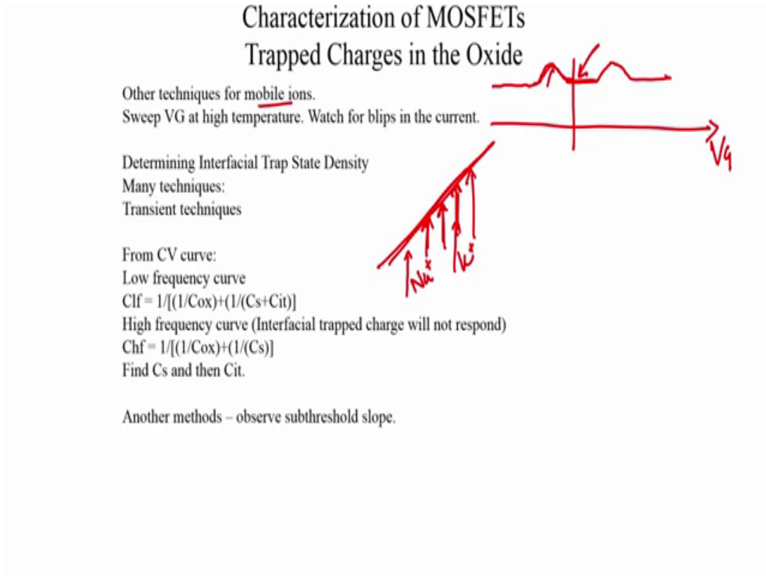

So, these are just some examples to illustrate how the CV characteristics can be used to make these measurements? Now there are other techniques if you want to look at mobile ions you know you also perform IV measurements and you do this at very high temperature. So, for example, if you sweep the gate voltage, you sweep the gate voltage implying that you are changing the field here slowly increasing the field and different mobile species will respond at different velocities to the increased field and why are we sweeping the gate voltage. We not only want to create a field, but we also want to measure the current through the capacitor ok.

So, we will have a steady displacement current and if there are mobile ions that drift in the mobile ions will give some blips in the current and these blips will exist, because the mobile ions start moving and then they reach an interface and then they stop moving and therefore, the current dies out and it will give you the current will get back to the depletion current. So, with this you can identify whether the ions are positively charged, negatively charged you know what is there, what is that drift velocity etcetera?

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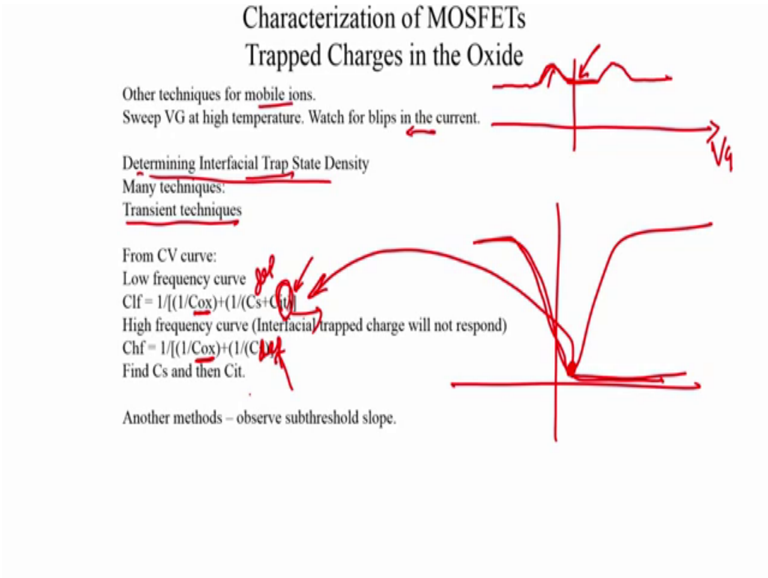

So, it is a again another powerful tool to identify the presence of mobile ions. The other important parameter with regards to trap charges in the oxide is the interfacial trap charge density. So, how do you identify interfacial trap stains ok? So, there are many techniques for this, because it is a very important measurement, there are many techniques and they are very powerful transient techniques.

And I once again recommend the textbook I mentioned for studying these techniques, but since we have been talking about CV curves, here is one simple technique ok, which may or may not work all the time, because you are heavily dependent on the nature of the traps, but the idea is to perform a low frequency CV measurement and then perform a high frequency CV measurement. So, in a low frequency CV measurement at this point you will see the influence of the series capacitance of C ox C depletion and the interfacial trap capacitance, because the charge is trapped in the insulator can respond to the low frequency AC signal. But at high frequency it is unlikely that the interfacial trap capacitance will respond and we will only see the influence of Cox and C depletion. And from the high frequency measurement we calculate, from the accumulation mode region we calculate what Cox is, from the high frequency measurements, we calculate what Cs is, because Cox is known and then we use Cox and Cs to calculate the intubation trap capacitance from the low frequency measurement.

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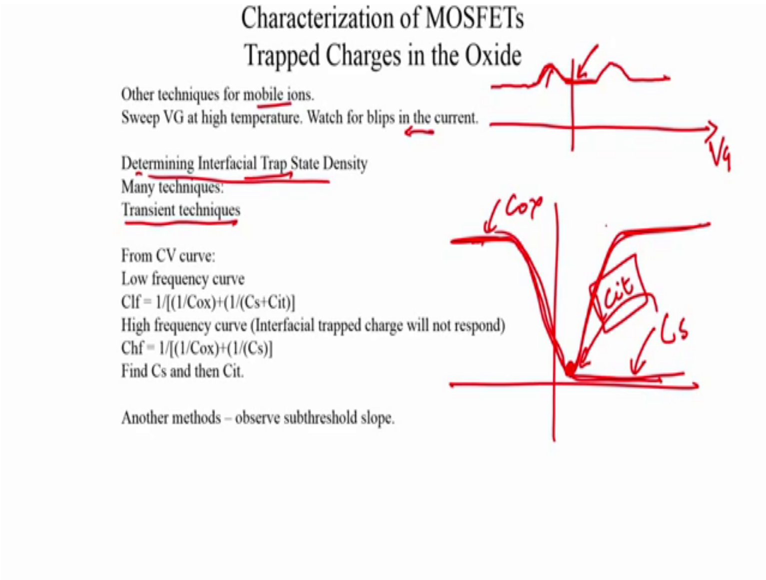

So, this is a technique that works for several devices particularly if it is a disordered semiconductor, but and in disorder semiconductors you will not see a CV curve that looks like that. So, there are other things that we need to do. We will see the impact of frequencies creating different shapes and the CV characteristics.

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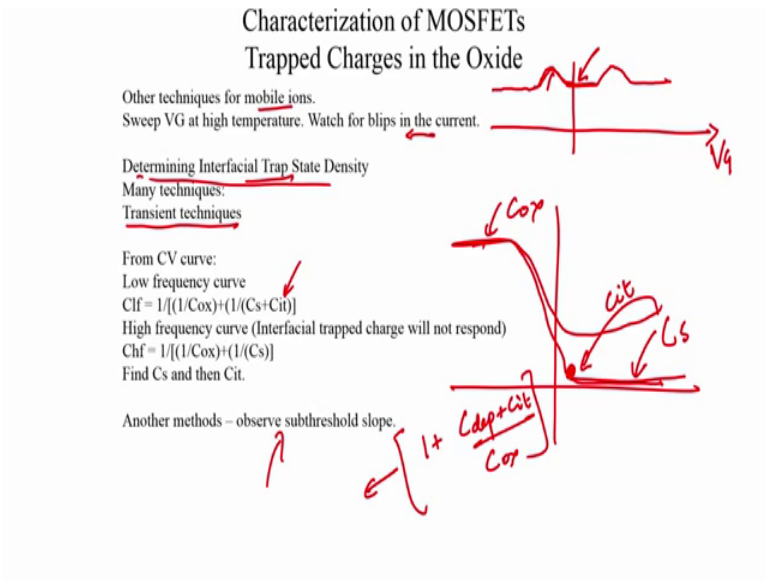

So, it is a technique that can be used to estimate interfacial trap capacitance, but then there are other powerful techniques also available first. And yet another option is to measure the sub threshold slope, because the sub threshold slope has got this term of C depletion plus C interface by Cox built into the definition of the sub threshold swing.

So, this is yet another technique to measure the interfacial trap capacitance. So, that is all with regards to the extraction of trapped charges in the dielectric. And the one last topic that we will look at which is you know which is last, but its quite important is the contact resistance in a MOSFET.

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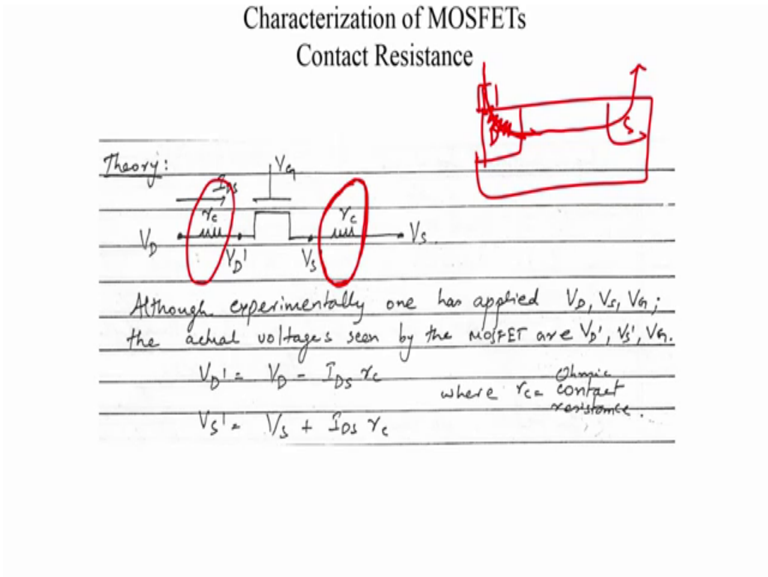

So, this is the very last topic with regards to the device physics of MOSFETs and it is also the last topic with regards to the characterization techniques for MOSFETs. And the point is got to do with regards to the presence and estimation, you know the detection of the presence of any contact resistances in the MOSFET and what do we mean by contact resistance?

So, you have your MOSFET structure, you have your drain and source and the idea of the MOSFET is to have a current flowing between drain to source when it is on. Now it is possible that this pathway from the metal contact through the semiconductor to the channel has got some resistance and this resistance is, it is preferable that this resistance is ohmic, but if you end up having significant barriers, this resistance will not be ohmic and we have issues with regards to the contact. But it is preferable that this resistance be ohmic and if it is ohmic how do we go about extracting that, how do I go about measuring or characterizing that contact resistance?

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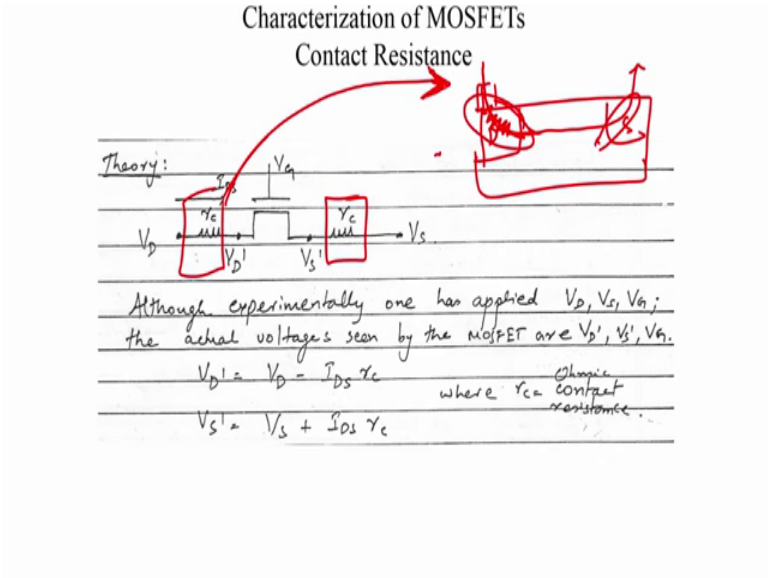

So, it becomes a very useful extraction process to feed back into your process flow because in most of the cases problems with regards to power MOSFET performance can be attributed to poor contacts ok, in most cases therefore, it is a good characterization to perform and to get information with regards to the development of your source and drain electrons.

So, this is a very notorious problem. So, its any student whose trying to fabricate transistors will experience problems with regards to contact resistance and it can end up with the transistors showing very poor performance. Now how do we extract this ok. So, first let us go to the theory of the extraction.

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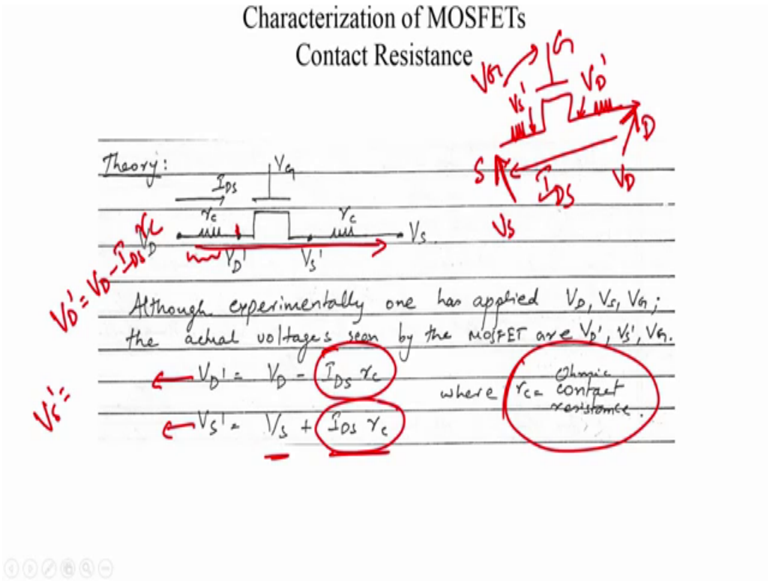

So, what we will do is we need to measure the I V characteristics of the MOSFETs. So, we have the gate source and drain and the point is we are going to apply, we are going to take this MOSFET to a probe station and we are going to apply a drain voltage or source voltage and gate voltage to the MOSFET.

Now, after applying the source drain and gate voltage the MOSFET we are measuring the current the drain to source current in the MOSFET, but if there is a contact resistance present these are not the voltages the MOSFET actually sees. The MOSFET in fact sees is a different voltage, it sees the voltage across this point and across that point. So, we call that voltage is V D dash and V S dash or we know V D prime and V S fine. So, that is the voltage we have applied and that is the voltage that we think that is the drain voltage we think the MOSFET is seen. But in reality due to the presence of contact resistance the MOSFET is seeing a lower drain voltage and it is seeing a larger source voltage.

Because if you have a current flowing through this device, you have a current flowing through this device, it is going to result in a voltage drop here and therefore, V D dash is going to be V D minus I DS r c that is what is given here. And V S dash is going to be at a higher potential with respect to V S and it is going to be V S plus I DS rc where, rc is an ohmic contact resistance that is why we are using this relation to determine the voltage drop across the resistor.

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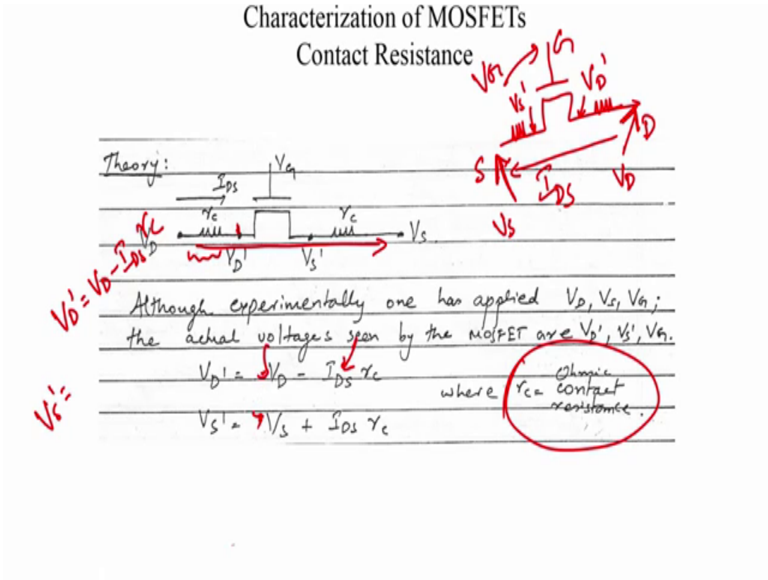

So, this is the situation, we think that the MOSFET is seeing this and we are going to start modeling or MOSFET parameters based on this current voltage characteristics, but in reality because of the contact resistance the MOSFET is seeing a different drain to source voltage, it is seeing a smaller drain to source voltage.

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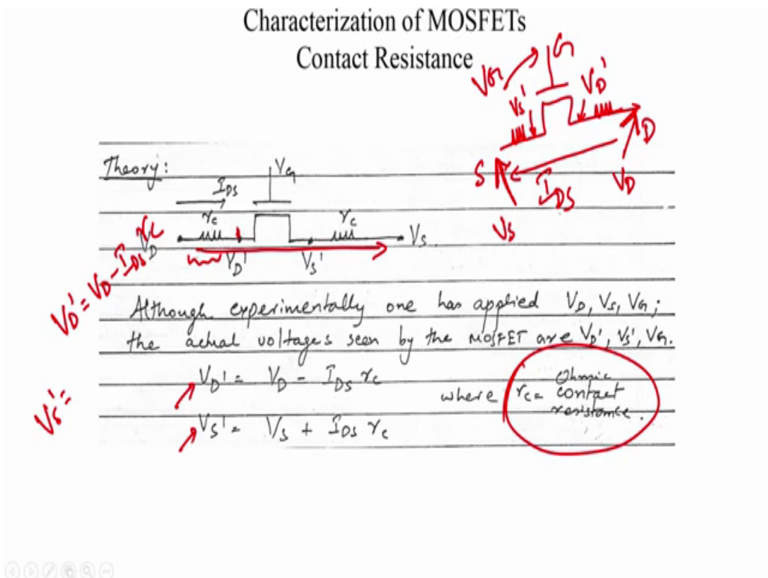

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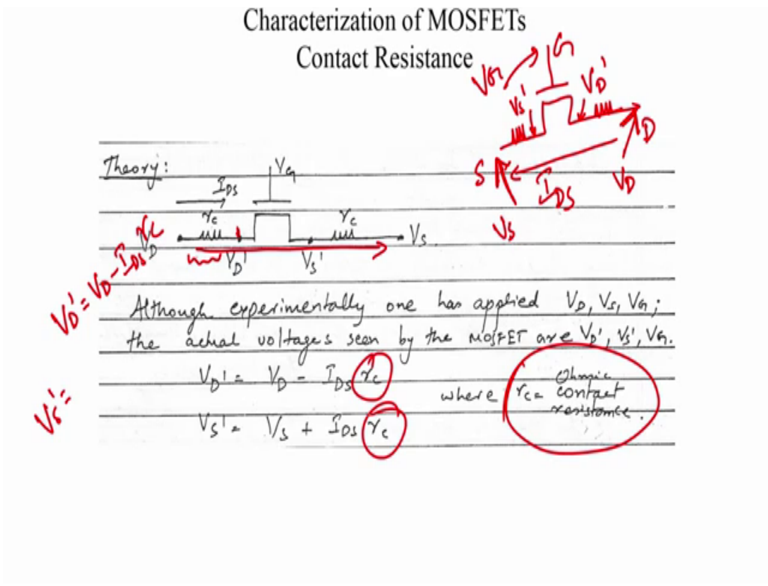

So, how do we extract rc? How do we extract the drain to source voltage?

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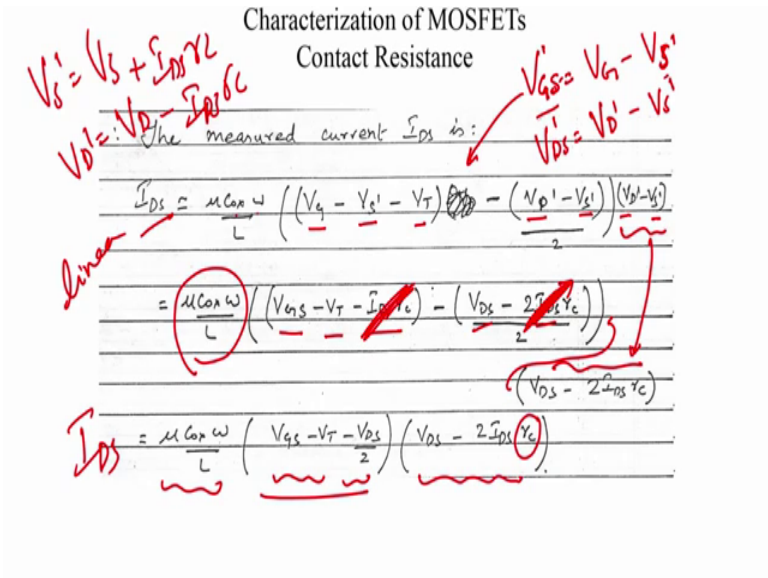

So, let us take the actual, let us write since we are developing a theory let us say that the actual gate to source voltage seen by the MOSFET is V G minus V S dash. VG is there VG seen by the MOSFET will be the VG you applied because the current is too small. There is ideally there should not be any gate current. If you are seeing significant gate current then contact resistance is not your fundamental problem. You need to sort out the insulator first ok.

So, the V GS as seen by the MOSFET is V G minus V S dash and the drain to source voltage seen by the MOSFET is V D dash minus V S dash. So, let us plug in these real parameters as seen by the MOSFET into the MOSFET equation, this MOSFET equation should be correct. So, you have mu Cox w over L, the MOSFET is in linear mode of operation its mu Cox w over L plus and V GS minus V T is V G minus V S dash minus V T and V DS minus V T V DS is V D dash minus V S dash by 2 and the whole thing into V D dash minus V S dash.

So, this is the current voltage relation of the MOSFET, but now we will rewrite V S dash in terms of V S which is V S plus I DS rc and V D dash as V D minus I DS rc. So, we have mu Cox w over L into V GS minus V T minus I DS rc in minus and this is the V D dash minus V S dash. We have V DS minus 2 I DS rc by 2 and the whole thing into V DS minus 2 I DS rc.

So, you find that this minus I DS rc term cancels with this plus I DS rc ok. So, these two make it a plus I DS rc and the two divides and these two terms cancel off ok. So, what we are left with is the actual ideas in the MOSFET is m Cox w over L into V GS minus V T minus V DS by 2.

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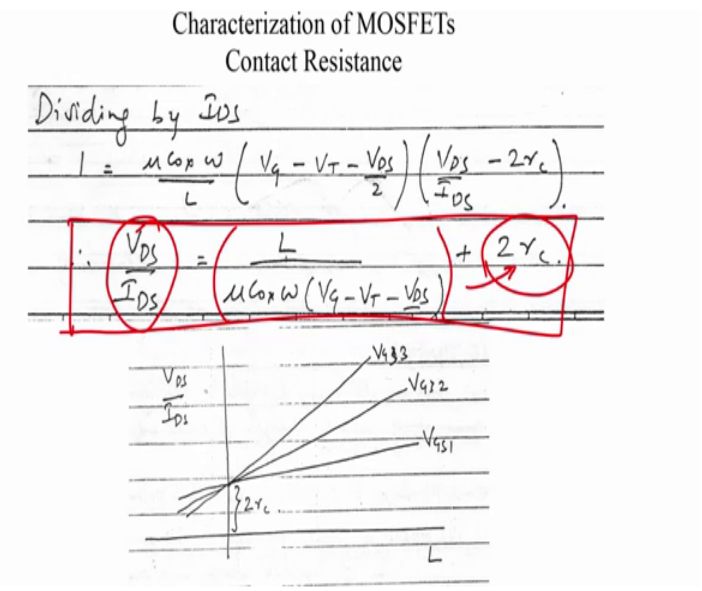

So, this term actually remains unchanged, but the contact resistance influences this term here, it is V DS minus 2 I DS rc and now if you simply divide everything by I DS and you know you separate out this equation, just perform some algebra we want to rewrite that equation, this equation here can be rewritten as this expression here which is V DS by I DS is equal to this term, L divided by mu Cox w into V GS minus V T minus V DS plus 2 rc ok.

So, we have made the rc, the contact resistance component come out as a separate term and now what we do is we build MOSFETs. So, let us say we are developing a process flow where and we want to get the contact resistance right. So, what we do is we develop MOSFETs of different channel lengths ok.

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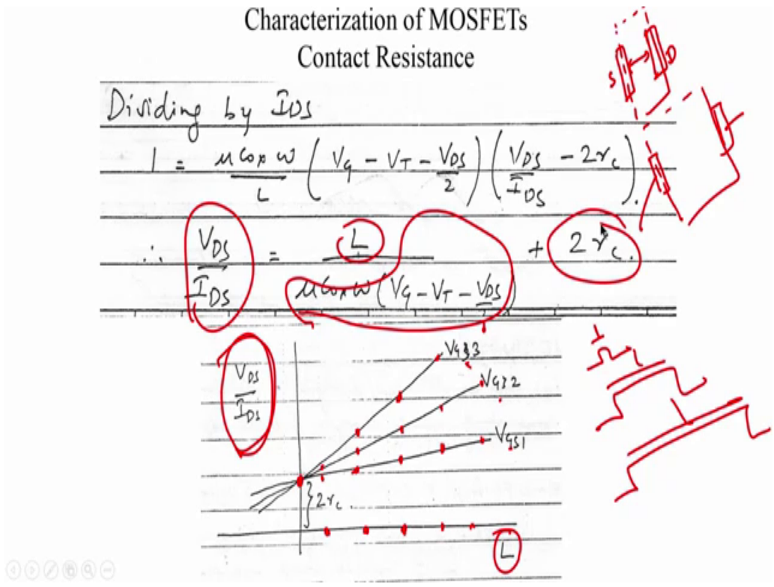

So, we have a wafer with MOSFETs having different channel lengths. So, let me just wrote like that ok. So, essentially what this means is this is the layout of the MOSFET. So, you will have your source, you will have the drain you will have the gate and that is the channel lengths.

So, we will have MOSFETs having different channel lengths and we will perform an IV measurement on all these MOSFETs, in linear mode and then we will take the data and we will plot V DS by I DS for different V GS as a function of channel length. So, we will probably have say five different channel lengths and therefore, we will have these five points, these will be your data points for the different V GS. And we when we plot these data points we will end up with all these theoretically speaking they should all lie on a straight line, and why should they lie on a straight line? Because we are plotting V DS versus I DS versus channel length and you can see that it is linearly dependent and that would be the slope.

So, the slope would be depending on V GS and the intercept the Y intercept will always be constant and its 2 rc. So, if all your devices are well built and they all have the same contact resistance then we will find that all these straight lines of this plot will all intersect at the intercept and it will give you a value of two times rc. And therefore, it is possible to extract the contact resistance which is your rc which is on the drain and source side.

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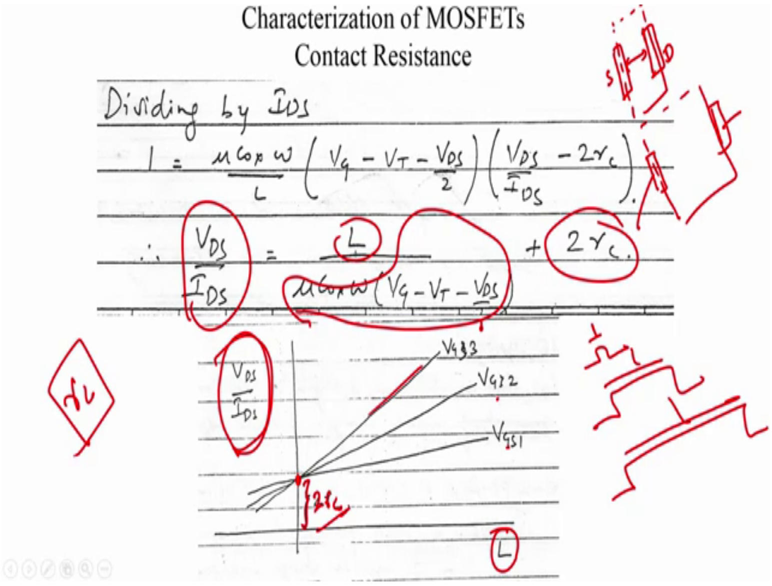

Now, it could so happen that you end up with a plot that looks like this ok.

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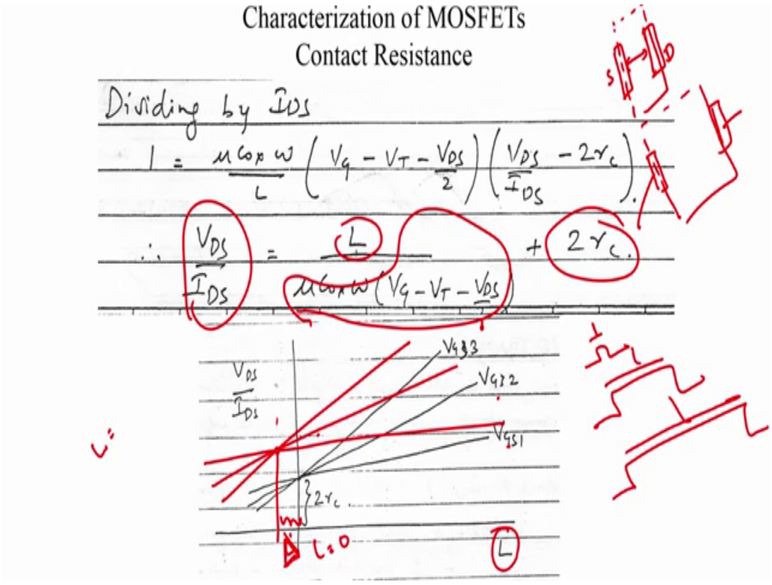

You might have the three lines. Firstly, they might all be lines that is given, but the three lines intersect over here, they do not intersect at L equal to 0. They in fact intersect at some other value of L, what does that mean? It means that it is very likely that we are having a mask error that is when you are doing a photolithography to fabricate your devices it is possible that there is an error in the mask. And what we think as L is actually L minus delta L or you know minus or plus delta depending on whether this point is lying to the right or left.

So, that is indicated above from mask error. So, but this is a general idea behind extract the; behind the process of extracting contact resistance. So, this is the experiments that you need to perform to extract your contact resistance in the device. So, with that we conclude all our discussions on the MOSFETs and I hope you will find this very useful. And from this point on we will change the flavor of the course and we will start we will move from device physics and towards the talks on circuit design with the MOSFET as the prime example.