Semiconductor Device Modeling
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Lecture - 44
DC Model of a Large Uniformly Doped Bulk MOSFET: Qualitative Theory

Let us continue our discussion regarding the qualitative theory underlying the DC Model of a Large Uniformly Doped Bulk MOSFET. In the precious lecture, we have touched upon the phenomena which govern the sub-threshold drain current behavior as a function of drain to source voltage and the behavior of the drain current as a function of drain to source voltage in breakdown.

We also discussed the behavior of drain current versus get to source voltage in sub-threshold. Then we summarized the factors governing the creation and conversion of the flows namely the electron current density, the hole current density and the electric field. Next we identified the factors which govern the boundary conditions of the device, okay. That is the boundary conditions on the Jn, Jp, E or n, p and psi in the device.

After that we sketched the flow lines for current density and electric field and the equi-potential lines in the MOSFET under saturation.

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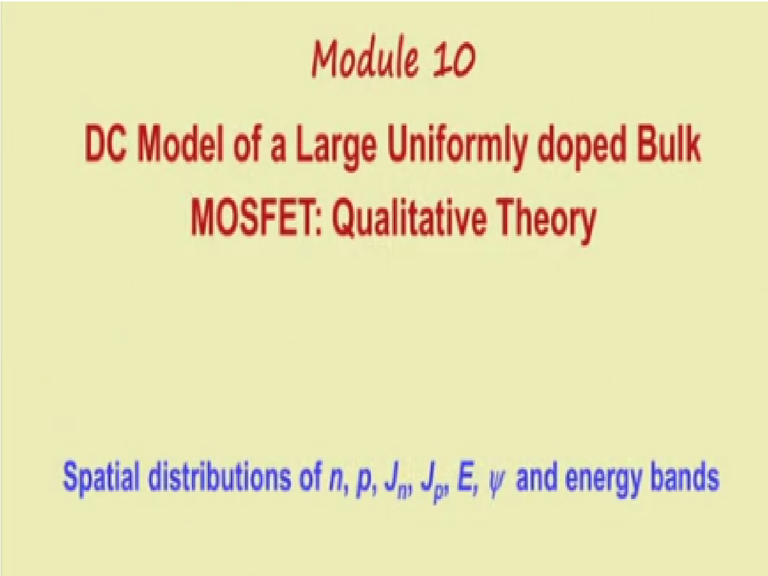

Now in this lecture, we shall discuss the spatial distributions of n, p, Jn, Jp, E, psi and the energy bands.

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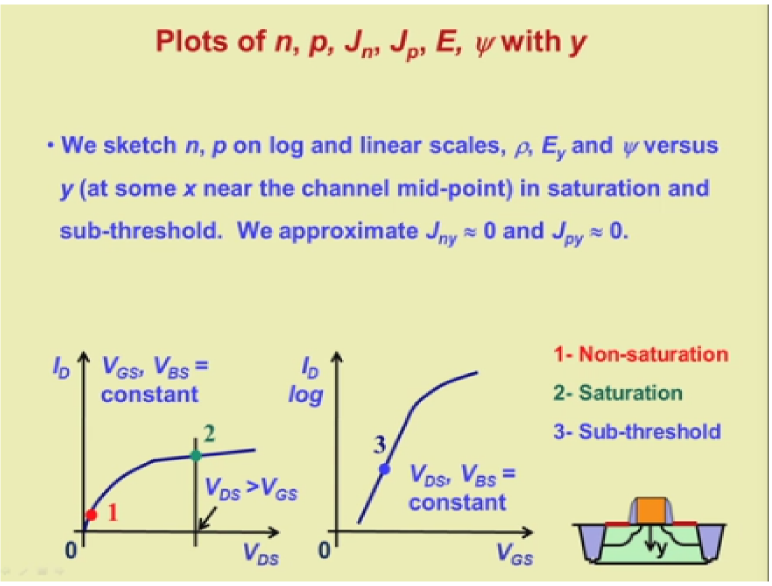

Frist let us concentrate on the plots of n, p, Jn, Jp, E and psi with y. Now y direction is from the interface into the substrate. So, this direction is perpendicular to the silicon, silicon dioxide interface. Now we shall sketch n and p on log and linear scales both and then we shall sketch rho that is the space charge which depends on n and p. Then we shall sketch Ey that is the y component of the electric field.

That means the electric field directed from interface into the bulk or substrate perpendicular to the interface and then the potential psi versus y at some x near the channel mid-point. So, the x direction is from source to drain. So, somewhere near the channel mid-point here we are going to sketch as a function of y, as shown here. Now we shall do that in saturation and sub-threshold conditions.

Now I am going to do this exercise in saturation and I will leave it to you as an exercise to repeat the process for sub-threshold. Now, here are the bias point shown, the saturation point is point number 2. We are going to assume VDS greater than VGS and the sub-threshold point is point number 3 on log ID versus VGS curve. We shall approximate Jny and Jpy to be 0. What does this mean? This means that the electron and hole current densities perpendicular to the interface in this direction would be regarded as 0.

This is because the insulator does not allow any current perpendicular to the interface between itself and the silicon. Therefore, we will not have to discuss the variation of Jn and Jp in the y direction and we are left with n, p, E and psi with y.

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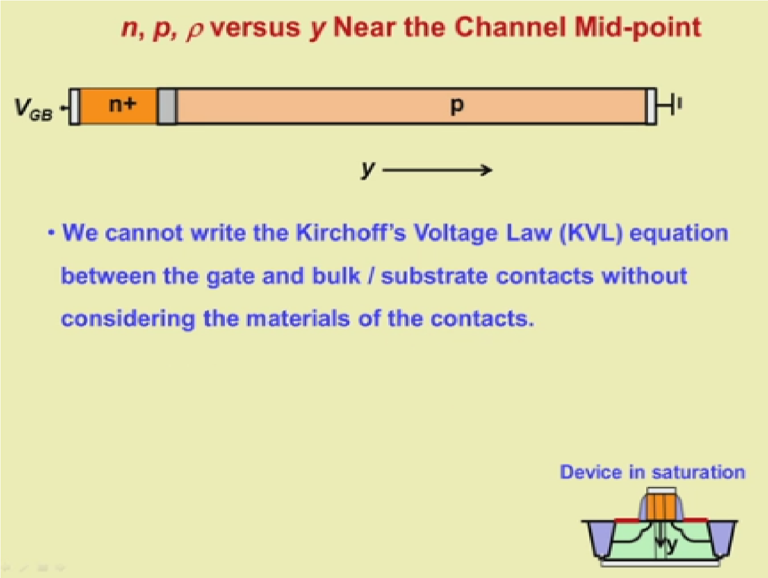

First let us discuss n and p and the space charge which depends on these versus y near the channel mid-point. Now we shall consider a section of the device as shown here between these 2 vertical lines. We shall rotate this section by 90 degrees so that the spatial axis is horizontal. This will help us to sketch n, p, rho, etc. in the vertical axis. Now as we shall see when we are sketching quantities in the y direction.

It is very important to show the electrode materials clearly. So, you have the gate electrode here connected to the n plus poly and the electrode connected to the p-type bulk or substrate. We apply a voltage VGB to the gate electrode with respect to bulk, so bulk is shown as grounded. The same electrodes are also shown here in the diagram. Let us explain why we need to show these electrodes explicitly when we are considering situation in the y direction.

We cannot ride the Kirchoff's Voltage Law that is KVL equation between the gate and bulk substrate contacts without considering the materials of the contacts. Now this is the important point. Now let me explain this with the help of a diagram.

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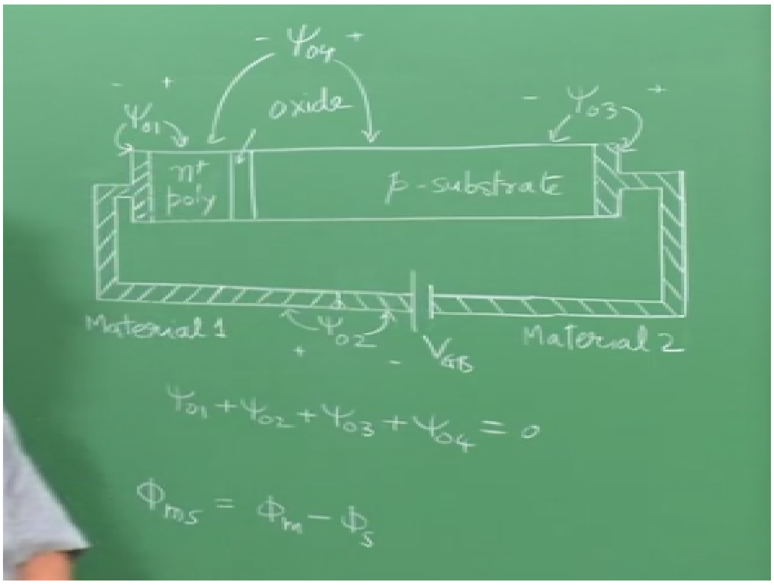

Now here is our mass structure, n plus poly and this is the oxide and this is the substrate. This is the contact to the gate. Now let us assume that the contact to the gate is made of some material 1. So, this is let us say, material 1. On the other hand, contact to the substrate is made of material 2. Now when I close this circuit, I will find following contact potentials. A contact potential between material 1 and n+poly.

Let me denote it as psi 01. A contact potential between material 1 and material 2 let me denote it as psi 02 and a contact potential between material 2 and p-type substrate. Let me denote as psi 03. Now you know that when you apply a KVL to this loop, Kirchoff's Voltage Law then psi 01+psi 02+psi 03 assuming that these are with this polarity+the potential between p substrate and n+poly, okay.

That is shown something like this which is psi 04. Now psi 04 again should be in this direction. So, when I sum up psi 01, psi 02, psi 03, psi 04 I will get it as 0. Now when I want to discuss the conditions in the device when I introduced a VGB, okay I break the things somewhere here let us say and introduce a VGB. Then I will have to consider all these potentials even in the presence of VGB to analyze the structure based on KVL.

What we can do is we can simplify our analysis if we do not try to manage so many contact potentials. So, what we could do for simplicity is assume that for example material 1 and material 2 are made of the same material as n+poly. Now if you do that psi 01 will go away psi 02 will go away and only psi 03 will remain and that potential plus this potential would be 0, okay.

So, we will have to deal with only this potential and which would in fact be equal in magnitude to the potential between n+poly and p substrate and that potential is normally referred to as phi ms. So potential of the gate with respect to substrate where the gate is represented by the simple m because you know when the MOSFET was originally made the gate was made of metal.

So, this simple phi ms has been in vogue since the times when the first MOSFET was made. So, phi ms is really these psi 04 but with appropriate polarity that is phi ms = phi m – phi s. So, work function of the metal - work function of the semiconductor. So, we could then deal with only phi ms, okay and do our analysis and we can avoid too many contact potentials coming in our analysis.

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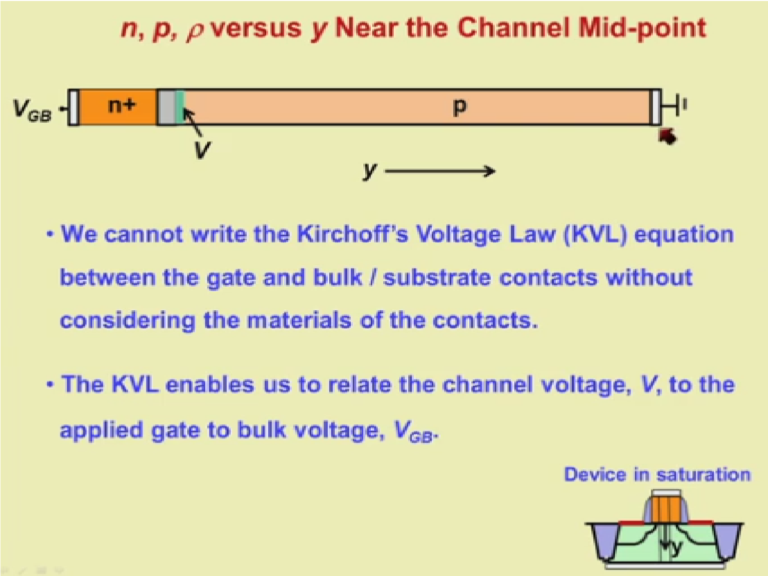

So, let me repeat that point. We cannot write the Kirchoff's Voltage Law equation between the gate and bulks or substrate contacts without considering the materials of the contacts. Now why do we need the KVL, the KVL enables us to relate het channel voltage V to the applied gate to bulk voltage VGB. Channel voltage is the voltage of this inversion layer, okay with respect to bulk and that is represented by the simple V.

So, we can relate this V to the VGB using the KVL and that is why we need to consider the material of the bulk and gate contacts.

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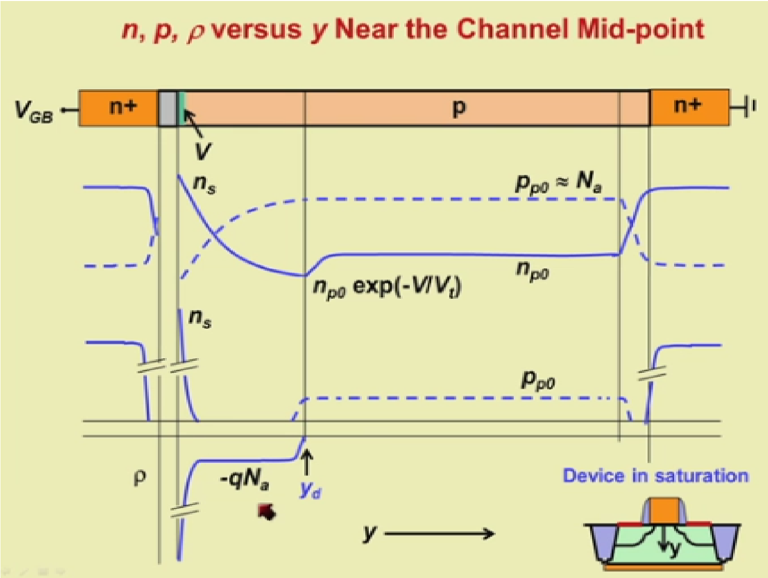

So, as we have said just now, we shall regard the gate electrode to be the same as the n+poly and the substrate electrode also to made of n+poly to simplify our analysis. Now the first step to draw n, p and rho would be to identify the various regions of the device. So, here this is the oxide region and this line represents y suffix d that is the edge of the depletion layer caused by the gate voltage.

Similarly, you have the edge of the depletion or space charge layer cause by the n+p junction that is here. Let us first show the majority carrier concentration in the neutral region. So, this is the concentration of electrons in the n+region. Now a small region here is the space charge region in the n+poly. So, we have not shown the electron concentration there to begin with.

Similarly, here you show the majority carrier concentration namely the hole concentration and this is the electron concentration in the n+bulk contact. Next we show the minority carrier concentration, okay in the n+poly this is the hole concentration. Similarly, this is the hole concentration in the n+poly associated with the gate. Now let us sketch the minority carrier concentration or the electron concentration the p substrate.

So, this would be as follows. Now you see that as remarked earlier the inversion layer p substrate can be regarded as an n+p junction induced by the gate voltage and therefore if the inversion layer has a voltage V with respect to the bulk. It means that V is the reversed bias across the n+p junction and you know from junction theory that if there is a reverse bias across the junction.

Then at the depletion hedge the minority carrier concentration is given by the equilibrium minority carrier concentration into exponential of - of the reverse bias magnitude/Vt. So, you see the electron concentration at the depletion hedge would dip down because of this reverse bias V. Next let us sketch the electron concentration in the depletion layer associated with the gate voltage.

Now here the electron concentration would rise because you see the electric field is directed from get to bulk so that electric field is attracting more and more electrons towards the interface and ns is the surface concentration of electrons. Since the device is in strong inversion this ns is shown to be higher than the bulk majority carrier concentration or the hole concentration.

Now the hole concentration in the depletion layer would fall down as shown here where at each y the product of the electron concentration and hole concentration would be given by Na square into exponential of - V/Vt as in a junction. Here is the electron concentration in the space charge here associated with the substrate contact and substrate junction and this is the hole concentration.

Next, we show the electron concentration in the spatial charge layer of the n+poly gate. So electron concentration is dipping down because you need a positive charge in the gate from where field lines will emanate and terminate on the negative charge in the depletion layer of the substrate. So, positive charge is obtained by depleting electrons near this gate silicon dioxide interface.

And therefore, the hole concentration would go up because here p into n product should be = Na square just as p into n product in this space charge region = Na square. Note that when you apply a gate to bulk voltage that voltage falls partly across the poly and then partly across the oxide and the reaming across the substrate near the interface. However, no voltage falls across the p n+ junction here substrate n+ junction.

Because if any voltage appears across this forward or reversed bias there would be a current through this junction. However, you know that the silicon dioxide insulator will not allow any current perpendicular to itself. We had just remarked sometime back the Jny and Jpy are 0.

And therefore, since a current flowing from substrate perpendicular to the interface has to flow like this through the interface.

And which is not allowed no current can be flowing across n+ p junction and therefore, no bias can appear across this junction, okay. So, even here this p into n product would be Na square. Now let us sketch the same hole and electron concentrations on a linear scale evidently this is log scale because I am showing both electrons and holes.

And for instance, here at the interface the electron concentration is different from the hole concentration by many orders of magnitude and I cannot show both unless I use a log scale. To see the exact shape of the distributions we should sketch the concentrations on linear scale. Now on a linear scale this is your hole concentration approximately constant until you enter the depletion region where the hole concentration falls rapidly.

Now this is the shape on the linear scale for this graph which is shown on log scale. Similarly, hole concentration falls rapidly when you enter this depletion region. Now this is your electron concentration or the linear scale corresponding to this concentration variation on a log scale. So, in a short distance the electron concentration falls by an order of magnitude and that is what we shown here.

Now this explains why we assume the inversion layer to be located very close to the interface and often regard it as a charge sheet. This is clear only when we plot the electron concentration on a linear scale, right. If you consider the electron concentration in log scale, it seems to very continuously over the entire it seems to vary rather slowly over the depletion layer.

However, note that this variation is on a log scale and to see the variation to get a feel for the variation we must sketch it on a linear scale. Only then it is clear that most of the electrons are located very close to the interface. Here is the electron concentration in the n+ region associated with the bulk contact, okay. This is how it falls on a linear scale. Similarly, the electron concentration associated with the n+ gate here falls like this.

This is corresponding to this concentration variation on a log scale. So here you can see clearly the depletion region, why there is a small region where you have neither holes nor electrons. We are not able to show the hole concentration at all here because this is smaller than the electron concentration shown by this line and therefore in a linear scale it cannot be shown.

Similarly, we are not able to show the hole concentration over most of the depletion layer because this is smaller than the hole concentration at the depletion hedge and cannot be shown on a linear scale.

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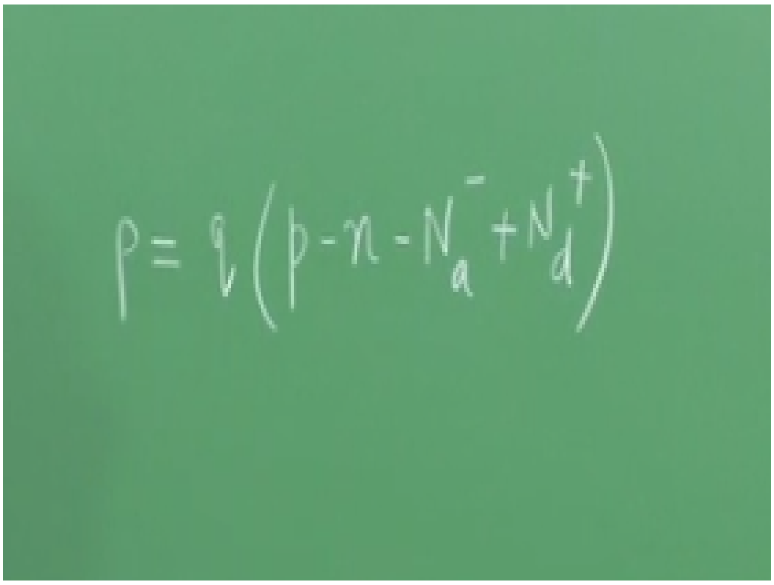

Now let us sketch rho that is the space charge. You know that the space charge is given by rho = q into p - n - Na -+Nd +, okay. Now this is the space charge, in these space charge associated with the substrate. So, this so called depletion charge whose magnitude is - qNa this horizontal line, magnitude of the horizontal line is - qNa and then it rises rapidly near the interface because your electron concentration is rising, okay.

So, this - qNa here is obtained from this formula here because p and n are both very small and there is no Nd+in the p type substrate. Therefore, you are getting - q time Na. However, when you move to the interface that is you come here you get a large electron concentration and therefore this shape corresponds to the formula - N - Na - full concentration is very small and Nd+is absent in a substrate. So, - n -Na -, right is what is shown here.

This is the space charge distribution associated with the depletion layer related to the substrate bulk contact.

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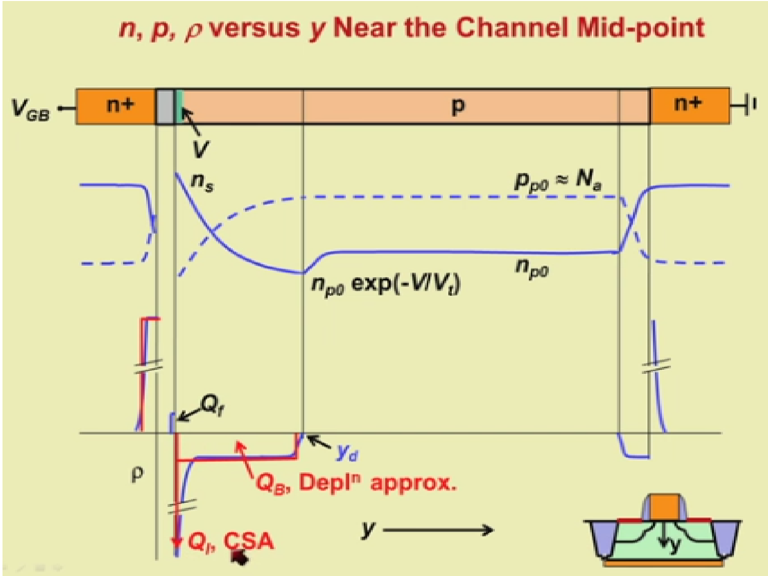

Now, let us clean up the slide and show the space charge in the gate. This is a positive space charge from which we emanate and terminate on the negative space charge shown here. Let us also show Qf the fixed oxide charge near the interface it is shown as a charge sheet. So, this oxide charge is the charge at this interface that is if I will to show on this diagram you have this fix charge.

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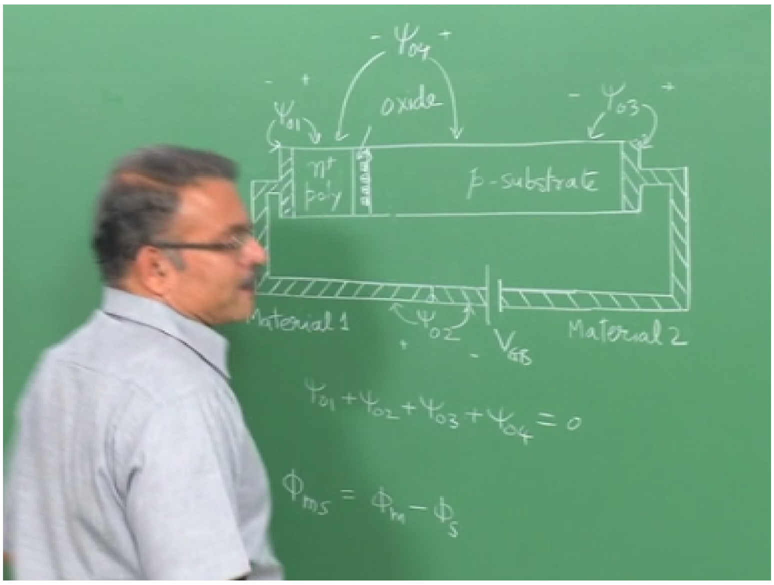

Returning to the slide, we complete the space charge picture by showing the space charge in the n+ bulk contact. This is positive, so field lines emanate from this positive charge and terminates on the negative charge shown here. Now these are the approximations that we normally make, so the depletion charge is assumed to be box type here and represented by the symbol QB.

This is the depletion approximation we are assuming a sharp fall, oaky in the charge and assuming the charge to be constant throughout = -q times Na. Now this is called the depletion approximation. Similarly, even here this blue shape is approximated by the red box in the depletion approximation. And the blue shape that shows the electron concentration variation.

So the inversion layer is approximated as a charge sheet shown by this delta function represented as Qi, CSA stands for Charge Sheet Approximation.

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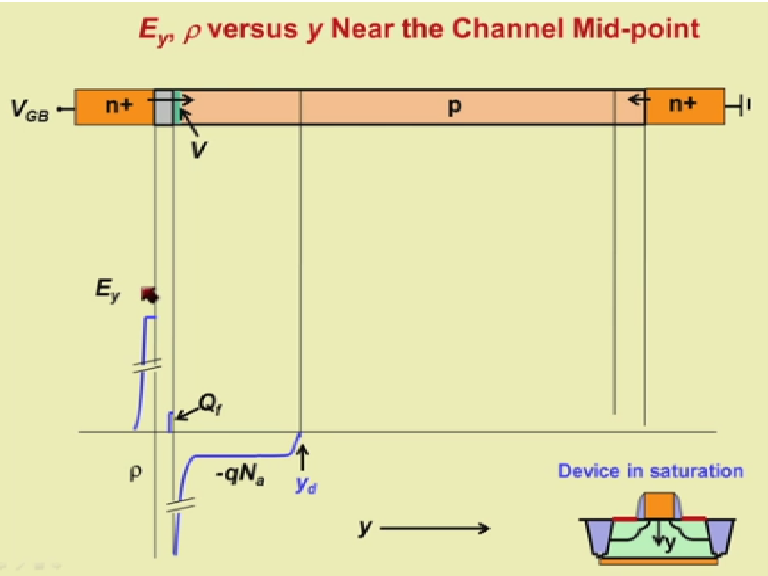

Now let us clean up the slide and now show Ey the electric field in the y direction that is this direction. Now the electric field is shown here by this arrow and similarly there is an electric field associate with the bulk contact junction and that is in this direction because n+ region you will have positive charge. Now let us sketch the Ey that is this fields in this vertical axis as a function of y.

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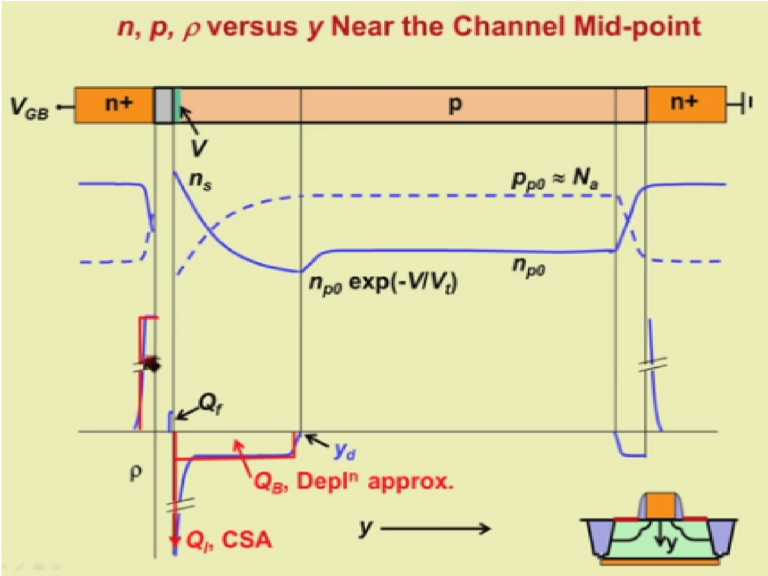

Now cleaning up the slide and showing Ey in the gate region. So, this is the electric field variation in the depletion region. The Ey has a constant slope because in depletion approximation your charge is assumed to be uniform given by q times the doping. So, this straight line Ey as a function of y corresponds to this box type space charge distribution.

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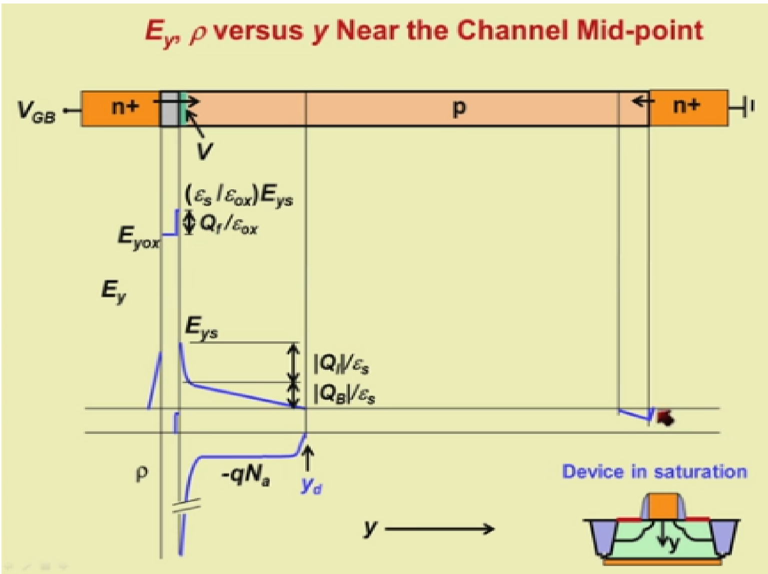

Next let us show the field in the oxide. In the oxide the field is constant because there is no space charge. So by Gauss law where there is no space charge the field is constant. Now this Eyox will be related to the surface field here, okay using the directory constants of oxide and semiconductor. So, since oxide directory constant is about 1/3 of the semiconductor directory constant. Therefore, Eyox is about 3 times the peak value of Ey shown here.

Then as we enter the fix charge, your Ey shows a jump. So, we are drawing the fields starting from the gate because this field is directed from left to right. So, using Gauss law as we start from the depletion **X** the field rises because we are getting more and more positive charges reaches a peak then you enter the oxide it jumps up by a factor of 3 and then when you cross the fix charge here it jumps by Qf/epsilon ox again according to the Gauss law.

So, the field is really maximum at this point where you enter the substrate. Now when you enter the substrate, in the substrate the peak electric field in the y direction denoted as Ey suffix s, okay this is the Ey in the semiconductor at the surface. So, this electric field and this electric field again will be related by dilatory constants of oxide and semiconductor and Eys will be 1/3 of the Ey at this point because of the differences in dilatory constants.

Now that is what is shown here that this peak electric field is related to this electric field by the formula epsilon s/epsilon ox into Eys. Then you cross the inversion layer that is this layer here. The field drops down, okay and the amount of drop again as per Gauss law is given by the modulus of inversion charge per unit area divided by epsilon s. Then you move out of the inversion layer and move into the depletion layer and cross it your Ey is going to fall linearly.

The constant slop of Ey is because in depletion approximation we assume the charge to be constant at - q times Na and the fall in the electric field from the edge of the inversion layer to the edge of the depletion layer would be = modulus of QB that is the depletion charge per unit area divide by epsilon s. We repeat the field picture in the space charge region associated with the bulk contact junction and this is how it would look like.

So, here the field is in negative direction because it is from right to left. You have a line with constant slope associated with the depletion layer in the substrate part of this contact junction and this is the line associated with the depletion layer in the n+ contact.

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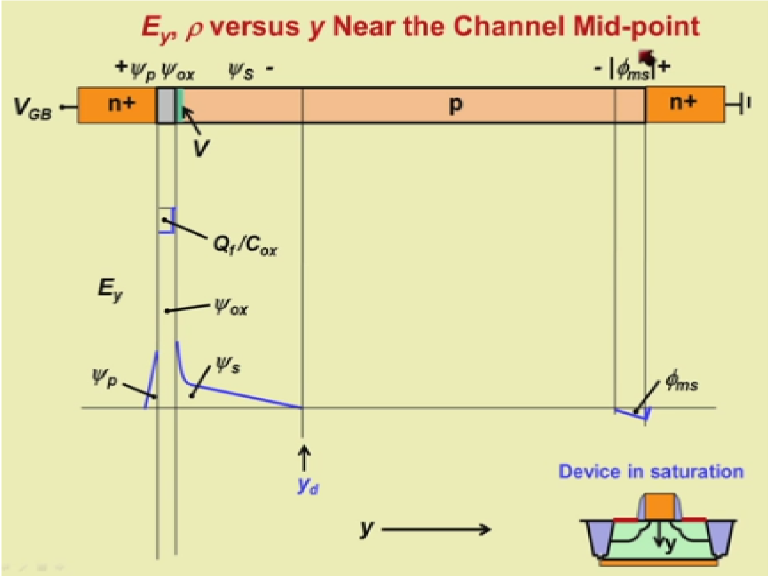

Now let us clean up the slide and now show the various potentials. So, area under the electric field picture in the gate represents the potential drop across the poly that is this potential drop psi p. Then the area under the field picture in the ox side here that represents ox potential drops psi ox that is marked here that is between this edge and this edge, okay. Now this box here represents the area that is given by Qf/C ox.

That is the fixed charge which is available at this interface divide by the oxide capacitances using the parallel plate capacitor law. So, note that psi ox is the distribution, psi ox is the area under this blue line, okay. And the box here is this box, which associated with Qf/Cox potential drop. The area under this field distribution in the substrate is psi s and that is the potential drop from this end that is the silicon dioxide silicon interface to the depletion edge.

Psi s, s stands for semiconductor. Now this is the polarity of the potential drops. So, left hand side is positive and right hand side is negative. For each of the potential drop this polarity applies. Now let us come to this junction here, the area under the field picture here represents the so called phi ms that is the work function difference between the metal or the n+ poly and semiconductor.

Now the polarity of this is as shown here n+ is positive and p is negative. However, the phi ms itself for n+ p junction or phi of n+ p is negative therefore we have put a modulus here.

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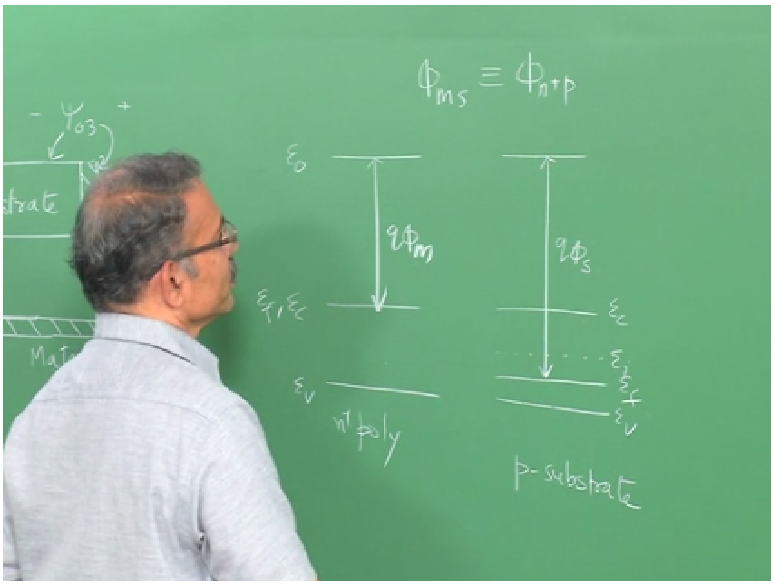

So, let me show here what is phi ms? So, phi ms is nothing but phi n+ poly p. Now let me show the energy brand diagram. So, this is your poly. So, n poly n+ we are assuming Fermi level to be almost coinciding with the conduction bandage and in the p-type substrate your Fermi level is somewhere here below Ei. So, phi m is nothing but this Q phi m or phi n+ and q phi s is this.

So, this is less than this and therefore phi ms is phi m - phi s that is negative. So, this is less than 0. So, that is why it is better to remember the polarity and magnitudes of the potential drops across junctions. That way it is easier to remember. You see the area under this field picture is negative because Ey is on the negative axis. Now let us show the potential psi together with Ey as the function of y.

Now the potential psi is obtained by integrating the electric field picture. The electric field picture itself is obtained by integrating the space charge.

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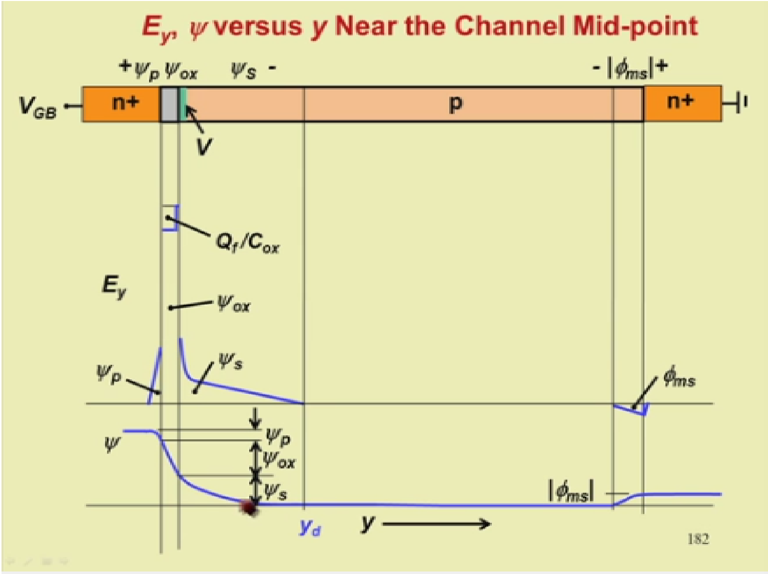

So, this is your psi as a function of y. First we show psi s. So, as you move from this edge towards the interface the potential goes on increasing and this is the potential drop in semiconductor. So, here psi s can be regarded as potential drop in the semiconductor. It can also be regarded as potential of the surface, so s can be regarded as potential of the surface with respect to bulk.

Now as you move inside into the oxide your potential rises by the psi ox the oxide potential. And then when you go into the depletion layer of the gate the potential rises further by a value = psi p. You come to the depletion layer near the bulk or substrate contact, so here the potential will rise as you move from the p-type bulk into the contact because of the direction of the electric field there and the magnitude of the rise is = phi ms.

So, here also when you are moving in this direction you know that the potential is rising because the electric field is directed from left to right. So, when you move against an electric field the potential rises.

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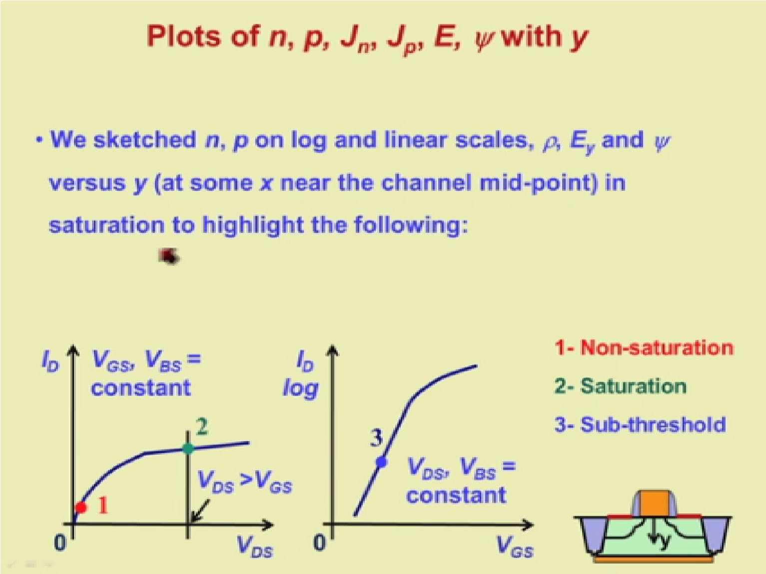

Now let us summarize some important points from this discussion. We sketched n, p on log and linear scales space charge row, y component of the electric field and potential versus y at some x near the channel; mid-point in saturation to highlight the following.

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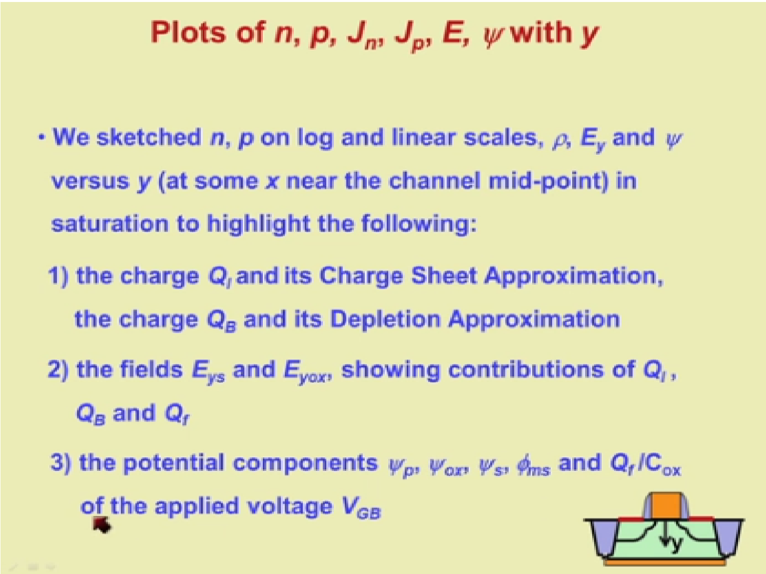

First, the charge QI and its charge sheet approximation the charge QB and its depletion approximation.

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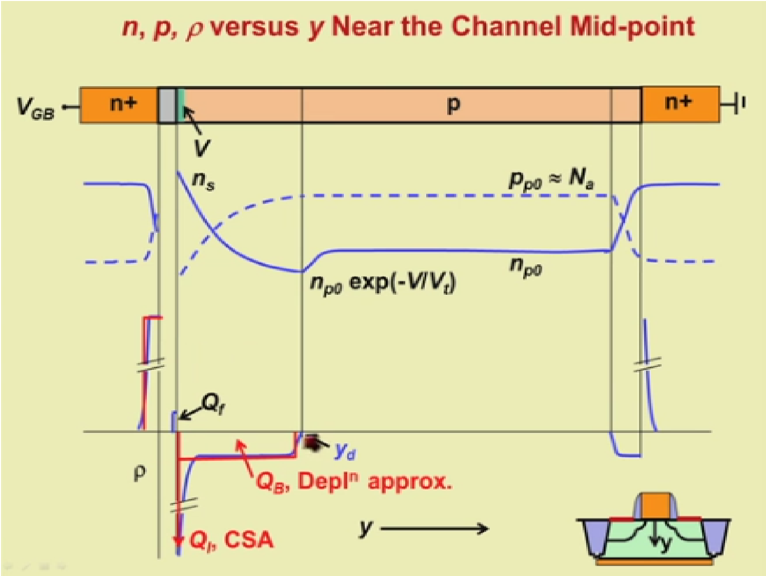

So, here is the charge Qy and its charge sheet approximation and charge QB and its depletion approximation. Next you wanted to highlight the fields Eys and Eyox showing contributions of QI, QB and Qf. So, this is Eyox and this is Eys and these are the contributions of Qy and QB to Eys and this is the contribution of Qf to Qyox. So, this field is related to this field by this formula and then when you come down by Qf/epsilon ox from this field you get the Eyox.

Finally, we wanted to show the potential components psi p that is potential drop in poly psi ox, potential drop in oxide, psi s, potential drop in the semiconductor and phi ms. The work function difference between metal and semiconductor or n+ poly and semiconductor and Qf/Cox where Qf is the fixed charge. So these components of the applied voltage VGB. Now this is the diagram showing the various c components of the applied voltage VGB.

Now you can appreciate how I am able to inter-relate the various potential drops using KVL and in that interrelationship phi ms or the contact potential between the substrate and the electrode whether it is a bulk electrode or the other electrode, right? So, this comes into the picture. For example, using this particular diagram what I get is the following.

So, VGB that is the potential of this gate with respect to bulk is = psi p+psi ox+psi s – phi ms. So, if I assume this to be 0, reference 0 that is what is assumed here. Please note that when I draw this line it does not necessarily mean this is horizontal line is 0. It is just a reference line. So, when I want to talk about the potentials, I should choose any one reference and then talk about the various potential with respect to that reference.

So, here we have assumed the potential of the bulk contact to be 0. So, therefore this is 0. So, when I move like this when I come here I have - phi ms as the potential of this line then when I go up here I have potential - phi ms+psi s then I add another psi ox when I go from here to here and then I add another psi p then I get the gate voltage with respect to bulk. So, let me write it in the form of an equation on the board. So, 0 – phi ms+psi s+psi ox+psi p = to VGB.

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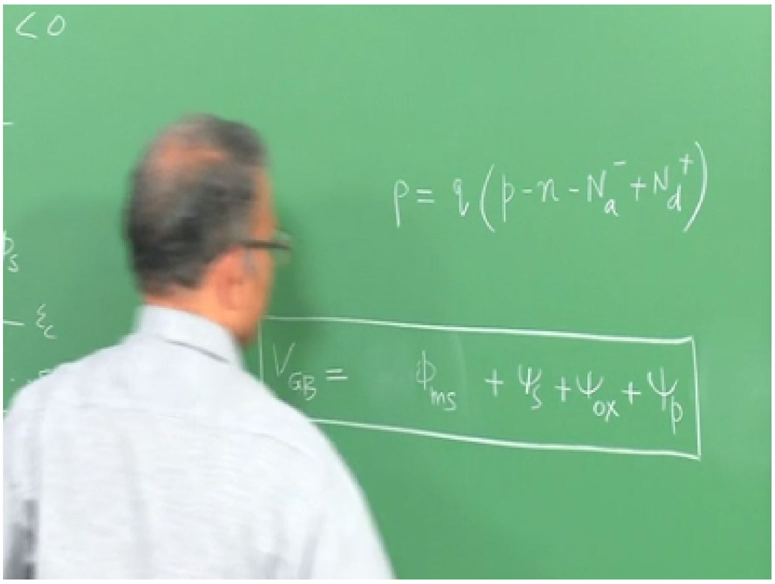

Now I could push this VGB this side and write it in this way which is the way it is written and used normally. Further since psi ms itself is negative modulus of phi ms is - phi ms. So, I can remove this modulus and write it as - phi ms. And - of - phi ms is+phi ms. So I can remove this. So, this is an important relation I get which relates the various potential drops, okay to VGB.

And this also illustrates why I must consider the material of the contacts to these bulk and the gate if I want to write the KVL. So, that material information is available in phi ms.

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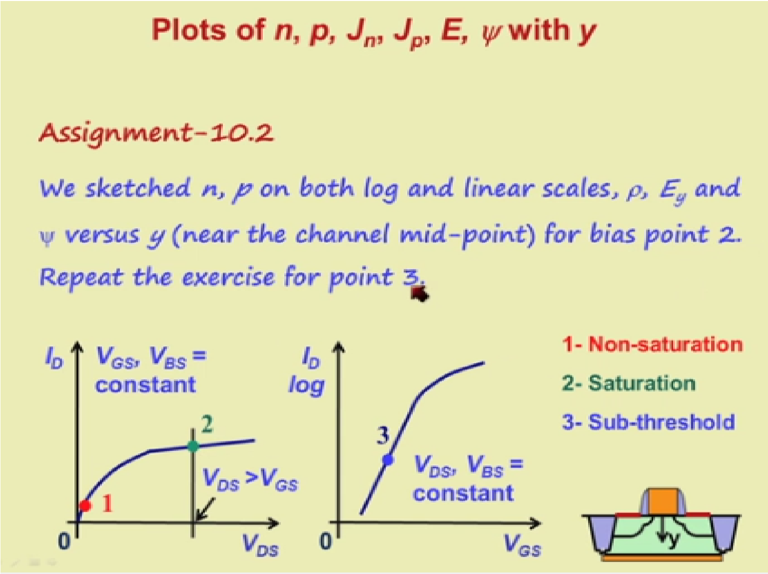

Now here is an assignment. We sketched n, p on both log and liners scales rho, Ey and psi versus y near the channel mid-point for bias point 2. That is this bias point. Now you have to repeat this exercise for bias point 3 that is this.

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Now with that we have come to the end of this lecture and so let us make a summary of the important points. Now in this lecture we have sketched the electron concentration, the hole concentrating, the space charge, the electric field directed from the silicon dioxide interface into the bulk perpendicular to the interface and the potential in a direction perpendicular the interface, okay near the channel mid-point. In the next lecture we shall discuss the variation of the energy bands in the same direction.