Semiconductor Device Modeling
Prof. Shreepad Karmalkar
Department of Electrical Engineering
Indian Institute of Technology – Madras

Lecture – 46
DC Model of a Large Uniformly Doped Bulk MOSFET: Qualitative Theory

In the previous lecture, we have sketched the energy bands as a function of position perpendicular to the silicon-silicon dioxide interface. Then we also began sketching the quantities as a function of x that is along the silicon-silicon dioxide interface from source to drain. We have sketched the surface potential as a function x that is along the interface from source to drain and then we have sketched the x and y components of the electric field.

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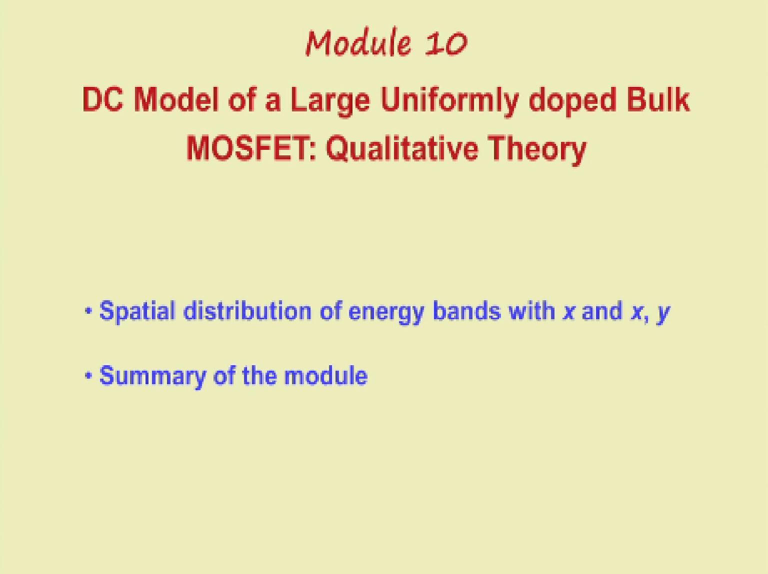

Module 10

DC Model of a Large Uniformly doped Bulk MOSFET: Qualitative Theory

- Spatial distribution of energy bands with *x* and *x*, *y*
- Summary of the module

In this lecture, we shall sketch the spatial distribution of energy bands with x and with x, y that is we shall consider the 2 dimensional energy band diagram also and then we will summarize the module.

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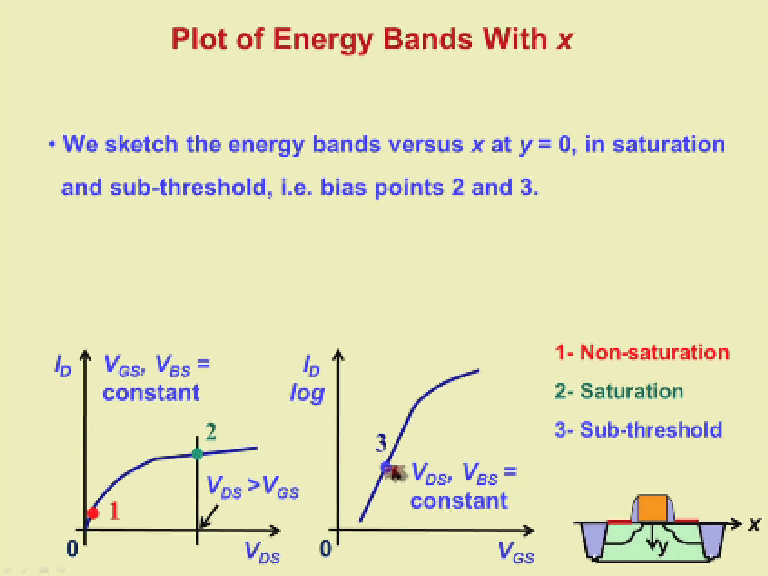

Plot of Energy Bands With x

- We sketch the energy bands versus x at $y = 0$, in saturation and sub-threshold, i.e. bias points 2 and 3.

Let us begin with the plot of energy bands with x. This means we are plotting the energy bands from source to drain along the interface. The interface is nothing but y=0, this is the y direction and y=0 means this interface. Now we shall sketch the energy band in saturation and sub-threshold conditions. This means for bias points 2 and 3, bias point 2 is shown here and bias point 3 is shown here.

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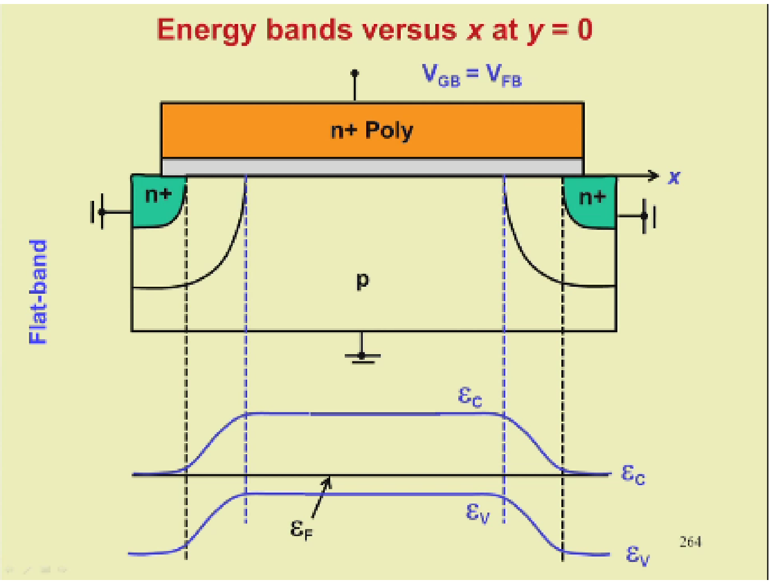

Energy bands versus x at $y = 0$

Let us look at the energy bands versus x at y=0. This is your MOSFET. Let us begin with the Flat-band condition. This means VGB =VFB. The depletion regions at the source and drain are shown here, source is grounded, the drain is grounded and bulk is the reference so that is also grounded. This is your x direction. First we identify the depletion regions then we sketch the constant Fermi level.

Fermi level sketched constant here, because this entire region is in equilibrium. You see for this plain junction this n region is grounded and p region is grounded for this plain junction this N region is grounded and this p region is grounded. Therefore, Ef is grounded, the constant line throughout. Next we locate the conduction band edge in the end region which is shown to be coinciding with the Fermi level because the region is heavily doped.

And we show the valence band region in the p region. So the distance between Ef and Ev depends on the doping in the p region. We have also sketched the Ec in the source region n+ regions, it coincides with the Fermi level. Next we sketch Ec in the p region; Ev in the n+ drain and n+ source regions. So this Ec and Ev are located based on the energy gap. We joined Ec and Ev as a continuous line across the depletion region.

We have not shown the E0 or the vacuum level because in silicon or rather if the entire region is consisting of 1 material then the distance between E0 the vacuum level and Ec is constant that is electron affinity, okay. So if E0 is continuous Ec also will be continuous, E0 and Ec are parallel. Therefore, we do not need E0 if this entire region is made of the same material. We identify this barrier to be Q time Psi not when Psi not is the built-in potential of this n+ p junction.

So, potential drop across the depletion region here along the interface is Psi not. Now let us focus on the Ec alone.

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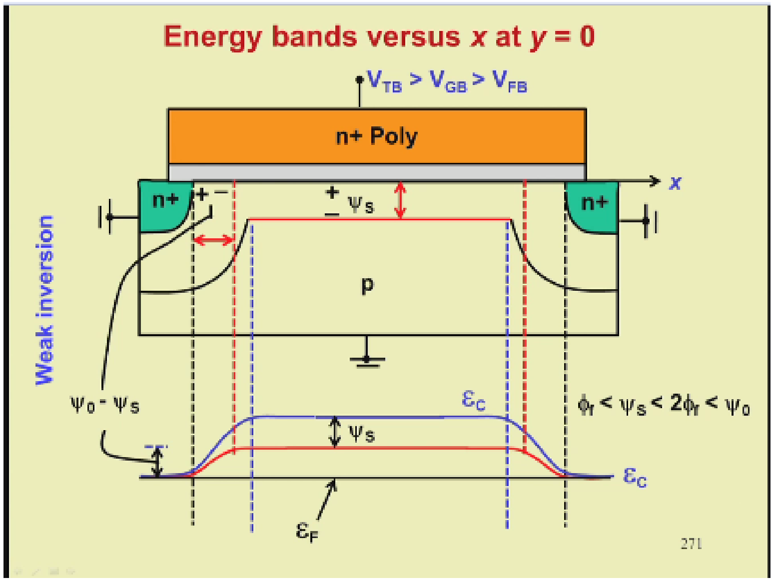

Energy bands versus *x* at *y* = 0

Let us move to the bias point VGB greater than VFD but less than the threshold voltage. This corresponds to the Weak inversion condition. In this case, you will have a depletion region controlled by the gate and this is the edge of the depletion region shown by the red line. The potential drop in this direction is Psi S in other words Psi S is the potential of the surface with respect to bulk.

Now you know that because the device is in weak inversion Psi S will be greater than Phi F but less than twice Phi F which is in turn less than Psi not, which is the built-in potential of an +p junction. Now we identify the regions controlled by the source and drain as you can see from here the consequence of raising the surface potential is that the depletion region controlled by the source has shrink from this blue to this red line.

Because the surface has become positive p type surface has become positive this is equivalent to a forward bias. It is not exactly a forward bias because forward bias there will be a current flow from p to n but in this device there is no current flow. Okay. So from the width of the space charge region that is controlled by the source from this point of view we can say that forward biasing of the rather raising the potential of the p type substrate at the surface has shrink the space charge region that is controlled by the source and similarly by the drain.

Now if you sketch the new variation of Ec it will look something like this as shown by the red line. Clearly, the barrier has decreased from Q time Psi not because the space charge even controlled by the source and drain, these 2 have shrink. The Ec has been lowered as compare to the Flat-bend case by Psi S. Because the Energy-band diagram, shows increasing electronic energies.

If in a certain region the potential becomes more positive, then the conduction band edge is-- in that region will move down. So now the new barrier from the source region to this point in the-- at the silicon-silicon dioxide interface is Psi 0 - Psi S, and thereafter along this entire region until this red line you have the potential Psi S that is what is shown by a constant line, okay, of the Ec. And then in this region also you have a potential drop = Psi 0 - Psi s.

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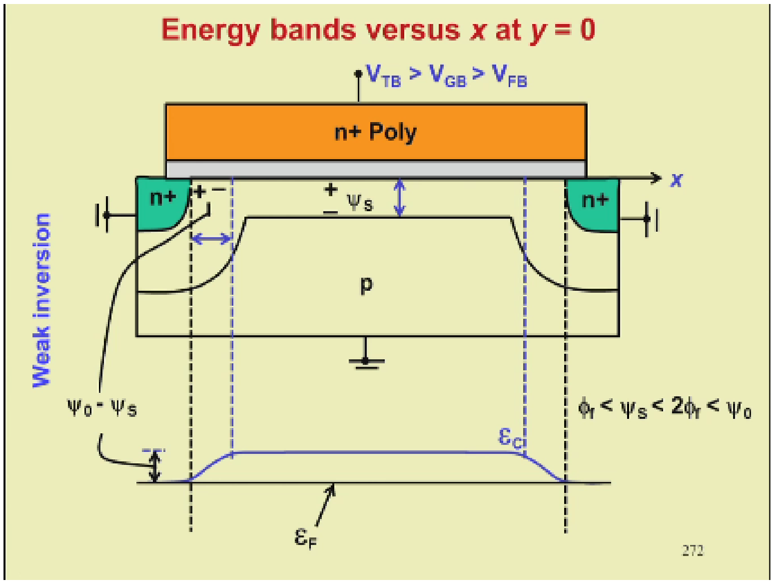

Energy bands versus *x* at *y* = 0

Now let us clear up the slide and every time we show the conditions for a new bias condition those conditions will be shown with red line, okay, so that we can distinguish between the conditions corresponding to the present bias and the previous one. So we can then show the changes very easily. So this is the condition for Weak inversion.

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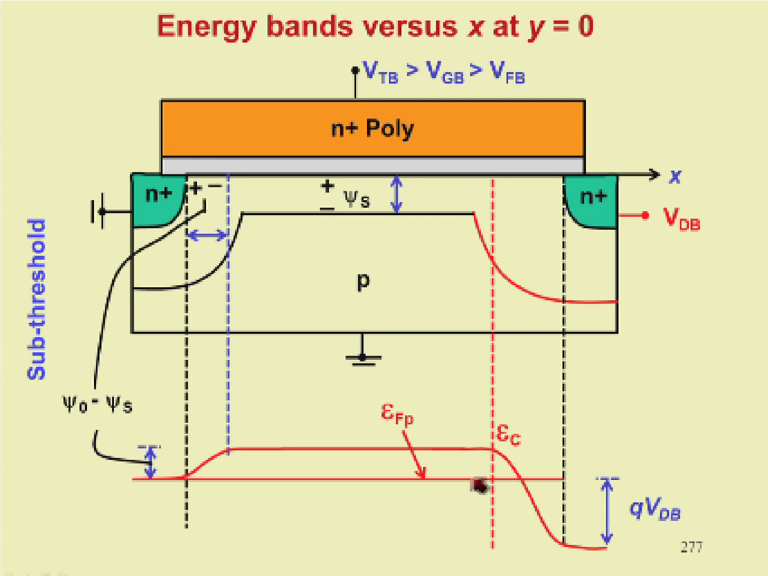

Energy bands versus x at $y = 0$

And now we are going to move to the next point when we apply a drain to bulk voltage. Progressively, you are moving to the bias point conditions that we had shown earlier that is bias point number 2 that was sub-threshold and bias point or rather bias point number 3 that was sub-threshold and bias point number 2 that was saturation. Now because of application of VDB the depletion region at the drain has increased.

Consequently, the space charge region controlled by the drain near the interface this has also got expanded from the blue line to the red line. Now effect of that will be the potential drop across this depletion region controlled by the drain will be more. So that is what is shown here by the red line. Okay. Earlier, the potential drop was shown by this blue line now the depletion region as expanded and this is the new conduction band edge.

The difference between the previous Ec and the new Ec corresponding to non-zero VDB is Q times VDB. So this is the increment in the potential drop across the depletion region controlled by the drain. Now let us clean up the slide. Shown a quasi Fermi level for holes. Notice carefully that the quasi Fermi level for holes is located at the same place as the Efp corresponding to the case VDB = 0.

And this is drawn at the constant line throughout. Let us understanding this point very carefully. Why is Efp drawn as a constant line throughout until this depletion edge, okay but not inside n+

because inside n+Efp corresponds to the Fermi level for minority carriers, right so that we will be consider later. If you recall from our previous module when you are drawing the band diagram of a p n junction we first show the quasi Fermi levels for majority carriers. Okay.

And then we add the minority carrier quasi Fermi level later. Now there is, however no such problem in showing in this Efp region because here the n+ region is grounded p region is grounded and therefore this particular junction is under equilibrium and therefore the Fermi level would continue to be the same throughout for this junction. Whereas, that is not the same for n+p junction here.

This is under applied bias, you applied a VDB and this is reverse bias across this n+ and this p junction that is why when you come to this junction here we show the quasi Fermi level for holes in the p region only.

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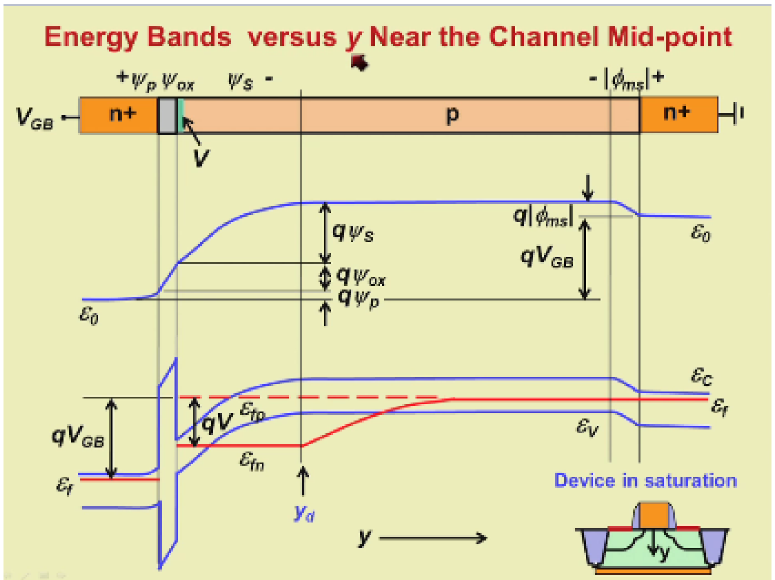

Energy Bands versus y Near the Channel Mid-point

Now let us explain why this Efp is constant throughout. Now if you recall the band diagram that was drawn as a function of y, near the channel meet point you see the Efp was shown as a constant line from the p region right until the interface. Okay.

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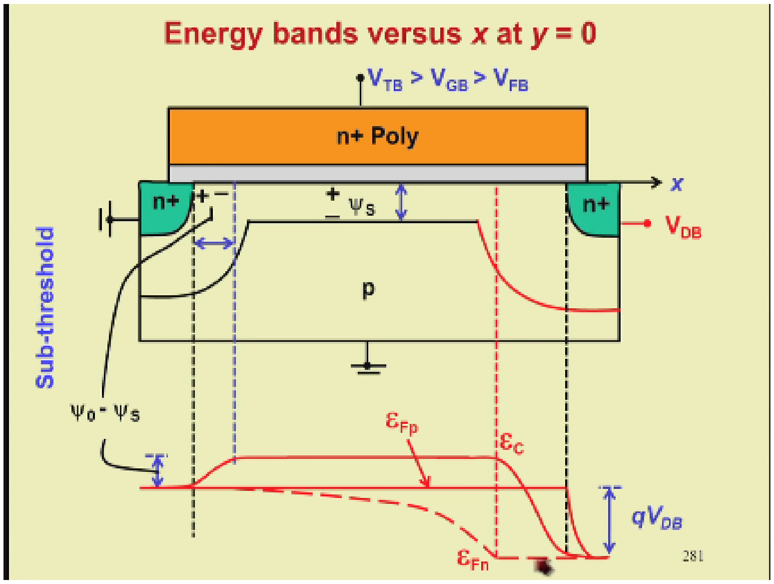

Energy bands versus x at $y = 0$

Now following from here, we can conclude that from any point in the substrate when I move to the surface along this line the Efp will be constant. If I consider the vertical line away somewhere here, here also when I move along this line perpendicular interface Efp should be constant. However, you know that at all points in this neutral p region the Fermi level for the hole should be at the same point.

Therefore, Fermi level for holes at the interface all along the interface should be constant, right. So let me repeat the Efp is constant everywhere here in this region from any point here if I move vertically up to the interface Efp should be constant as we have drawn in the previous lecture and if Efp should be constant along this line and along this line it should be constant along this line also because here Efp is constant everywhere.

Let us now show EFn. Now in the n+ region the Efn coincides with the conduction band edge in the neutral n+ rather the space charge region in the n+ region is really very, very narrow show we are not shown it explicitly. Now as you move into the space charge region on the p side the Efn will continue to be constant throughout this is because of the quasi equilibrium assumption for junctions under bias. So under quasi equilibrium the Fermi levels are constant.

The split between Efp and Efn that is this distance is equal to the applied bias that is Q time VDB. Now we can join the quasi Fermi levels across the-- we can joint or rather we can sketch the quasi Fermi level for minority carriers as a continuous line. So, we know that far away from the junction in the n+ region Efp and Efn should coincide because this region will be under equilibrium away.

And therefore the Efp should be somewhere here far away and Efp until this edge is at this point so I joint/continuous line. So this is how you sketch the minority carrier hole Fermi level, hole quasi Fermi level in n+ region. And you do the same thing for sketching the minority carrier electron quasi Fermi level in the p region, you have come up to this point Efn and thereafter you join it as a continuous line until you reach somewhere here where this p and n+ junction is under equilibriums so Efp and Efn will coincide somewhere here close to this.

Now these are you Efp and Efn, now shown by black lines. Let us clean up the slide.

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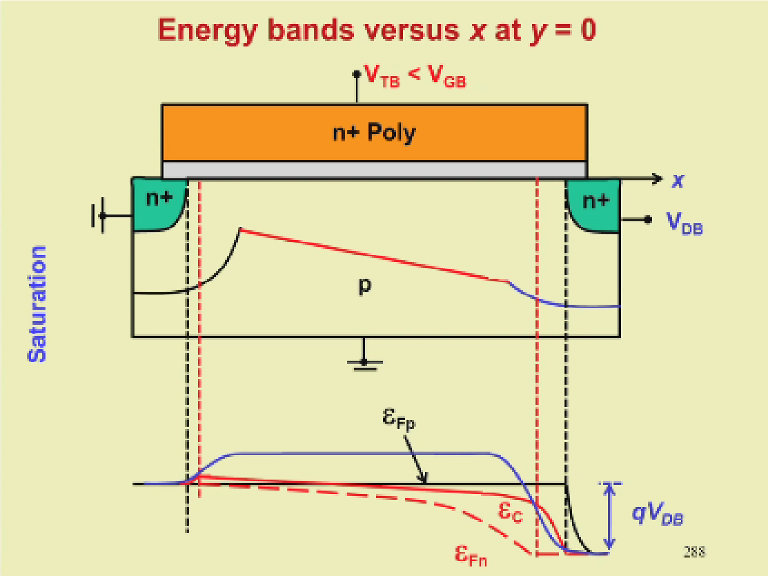

Energy bands versus x at $y = 0$

Now, let us change our bias. We will not go beyond threshold VGB greater than VTB. And if you do that for the VDB condition we will be reaching saturation. The result of that would be expansion of the depletion width from the source to drain because now once your VGB is greater than VTB you have a strong inversion reason here at the interface though inversion charge is varies from source to drain it decreases.

But still you have an inversion charge and therefore the potential will vary continuously, okay along this reason. And therefore the depletion reason will continuously expand so that is what has happened here. Okay. What is the consequence of this energy- band diagram? Now you see when VGB is greater than VTB the portion of the space charge region controlled by the drain has shrink because the control of the gate has widened. Right?

If you keep the VGB constant and increase VDB then the space charge region controlled by the drain will expand. If you keep VDB constant and increase VGB the space charge region controlled by the drain will shrink. Space charge region controlled by the gate will expand and this expansion of the gate controlled reason has shrunk the source control space charge region also here.

Now as a consequence of this we modify the quasi Fermi level position here Efn remain constant until this edge of the space charge region controlled by the drain at the interface and thereafter you have show the variation. Then we show Ec variation. So you see that the barrier from source to the interface in the p region has reduced because the depletion region controlled by the source has shrunk.

Now, similarly if you come to this end, the variation in the Ec, okay less because this space charge region has shrunk. Okay. So this variation across the space charge region is smaller than the variation shown by the blue line which corresponding—which corresponded to sub-threshold condition VGB less than VDB. Also you see, that in sub-threshold the Ec was flat over most of the p region whereas here you see in the saturation there is a continuous variation in Ec right from the source end, okay.

This is because your potential at the surface continuously changes from source to drain because now you have inversion charge, okay which connects the drain and the source region and that is consistent with the fact that the depletion region is also continuously changing. Let us clean up the slide.

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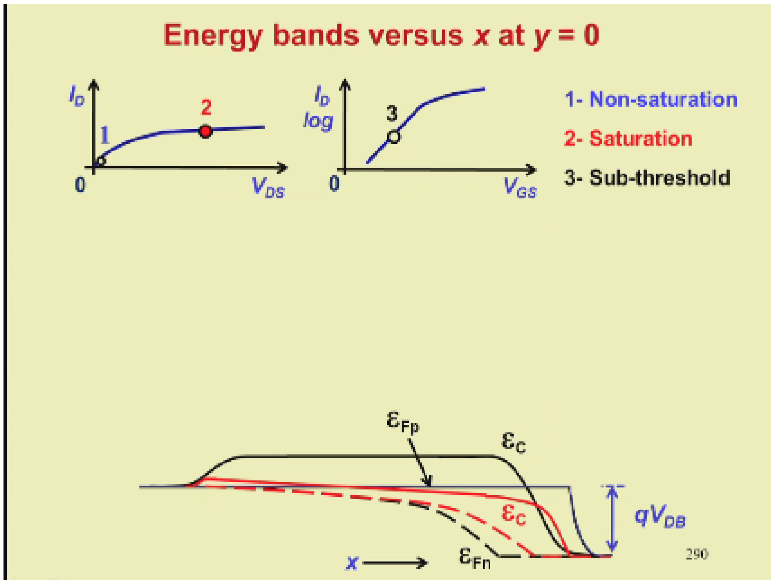

Energy bands versus *x* at *y* = 0

1- Non-saturation

2- Saturation

3- Sub-threshold

Note that the Efp has not really changed, okay throughout all these. Because it is the concentration of electrons which is undergone lot of change because of the change in the VGB above VTB.

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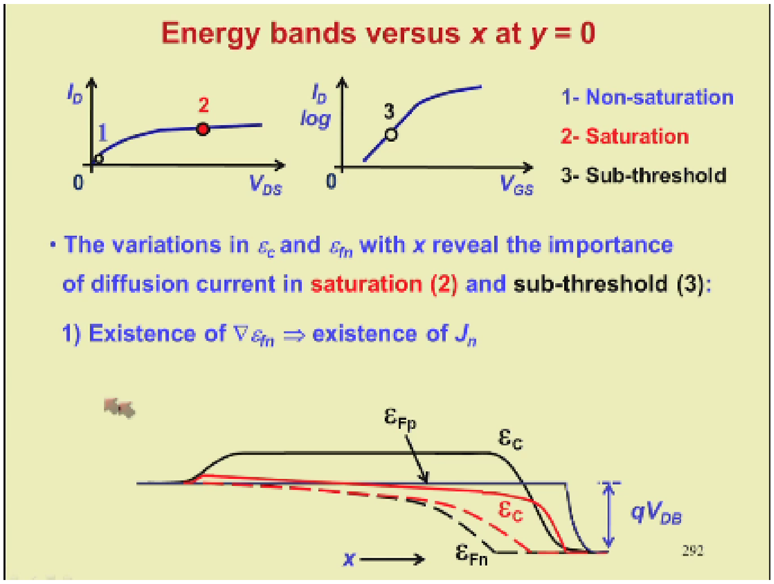

Energy bands versus *x* at *y* = 0

1- Non-saturation

2- Saturation

3- Sub-threshold

- The variations in $\mathcal{E}_c$ and $\mathcal{E}_{fn}$ with x reveal the importance of diffusion current in saturation (2) and sub-threshold (3):

  1) Existence of $\nabla \mathcal{E}_{fn} \Rightarrow$ existence of J_n

Now let us compare the Energy-band levels associated with the sub-threshold and saturation condition. So saturation is shown by the red lines here and sub-threshold that is bias point 3 here is shown by the black lines. What can be infer from this? The variations from Ec and quasi Fermi for electrons with x which are emphasized here reveal the importance of diffusion current in saturation and sub-threshold.

Now let us see how this happens. The first point to note is that if there is an existence of gradient of Efn that is if Efn is varies in x it means that there is a current Jn okay. Because you recall from the previous module that current is reflected in the gradient of the quasi Fermi level associated with the carrier. So now you know, therefore wherever Efn is varying it means that there, there is an electron current.

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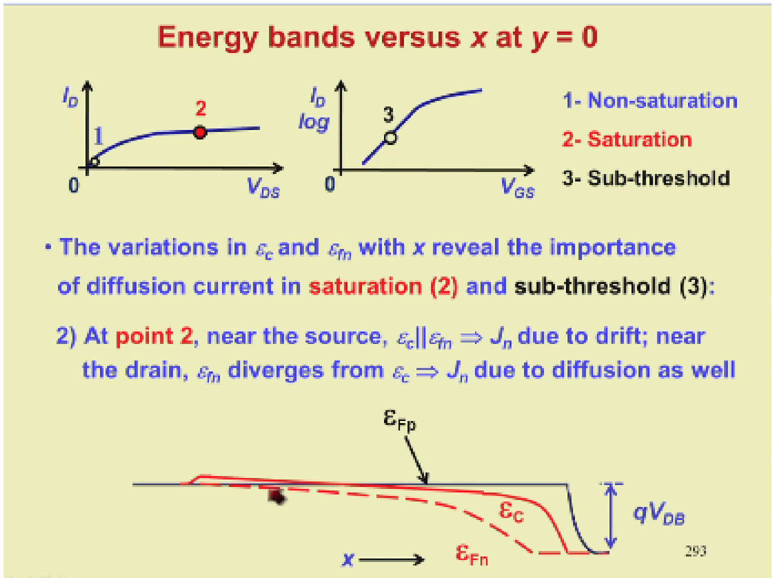

Energy bands versus x at $y = 0$

1- Non-saturation
2- Saturation
3- Sub-threshold

- The variations in ε_c and ε_{fn} with x reveal the importance of diffusion current in saturation (2) and sub-threshold (3):

2) At point 2, near the source, $\varepsilon_c || \varepsilon_{fn} \Rightarrow J_n$ due to drift; near the drain, ε_{fn} diverges from $\varepsilon_c \Rightarrow J_n$ due to diffusion as well

The second point to note is that at point 2 there is a saturation near the source if you see here Ec is parallel to Efn you can see that this Ec which is solid line here and Efn which is the dash line they are parallel near the source here. Now what is it meant? It means that Jn is due to drift. Please recall, the Energy-band diagram under various conditions which we have drawn in the Energy-band module. So if Ec and Efn are parallel it means that the current is because of drift.

Near the drain Efn diverges from Ec. So you can see here in saturation the Efn is going like this whereas the Ec is going like this so distance between Ec and Efn is going on increasing and this increases quite rapid near the drain. Now this means Jn is due to diffusion as well as drift. There is drift no doubt because if Ec is varying with x there is electric field and there is a drift. But difference in Ec and Efn if it changes it means that electron concentration is changing with x and therefore there is diffusion also.

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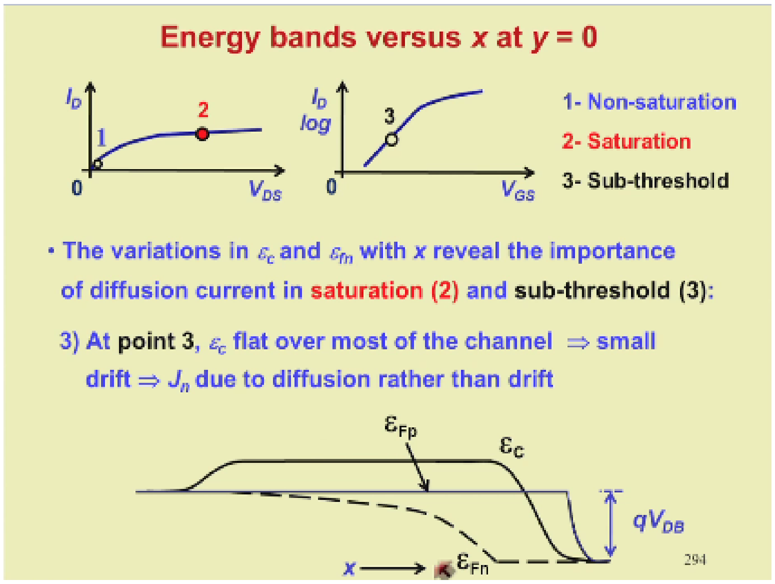

Energy bands versus x at $y = 0$

1- Non-saturation
2- Saturation
3- Sub-threshold

- The variations in ε_c and ε_{fn} with x reveal the importance of diffusion current in saturation (2) and sub-threshold (3):

3) At point 3, ε_c flat over most of the channel $\Rightarrow$ small drift $\Rightarrow$ J_n due to diffusion rather than drift

Point number 3 to note is that, at point 3 that is at this point sub-threshold this is the band diagram shown by the black line. Ec is flat over most of the channel. Okay. Which means that their drift is very small, if Ec is flat the electric field in this region is very small and therefore drift current is very small. And this amongst to saying Jn due to diffusion other than drift because Efn is going on varying with x though Ec does not vary.

So distance between Ec and Efn goes on varying which means electrons concentration is varying in the channel from source to drain and therefore there is a diffusion though there is no drift current, okay. So this is how you can conclude the importance of drift diffusion in saturation near the drain and in sub-threshold throughout the channel.

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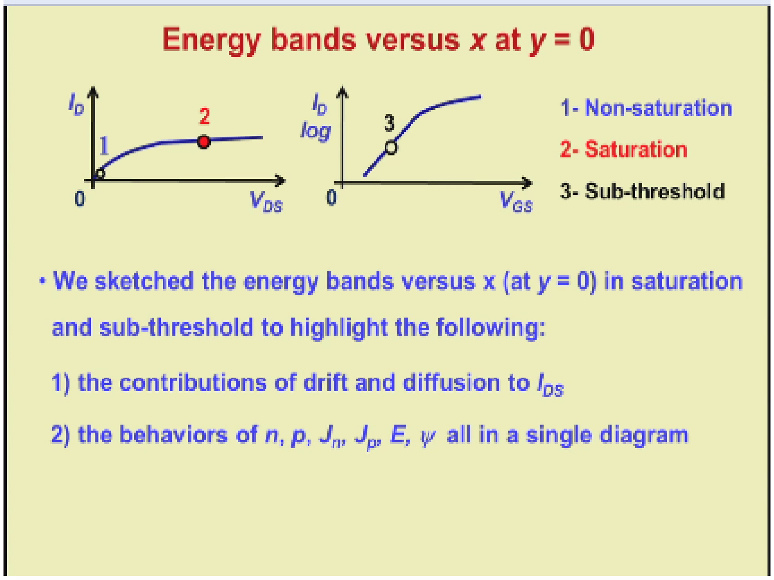

Energy bands versus x at $y = 0$

1- Non-saturation
2- Saturation
3- Sub-threshold

- We sketched the energy bands versus x (at $y = 0$) in saturation and sub-threshold to highlight the following:
  1) the contributions of drift and diffusion to I_{DS}
  2) the behaviors of n, p, J_n, J_p, E, ψ all in a single diagram

We can now summarize by saying, we sketched the Energy-band versus x at y=0 in saturation in sub-threshold to highlight the following. The contributions are drift and diffusion to the current IDS. The behaviours of electron and hole concentration Jn and Jp, E and Psi all in a single diagram.

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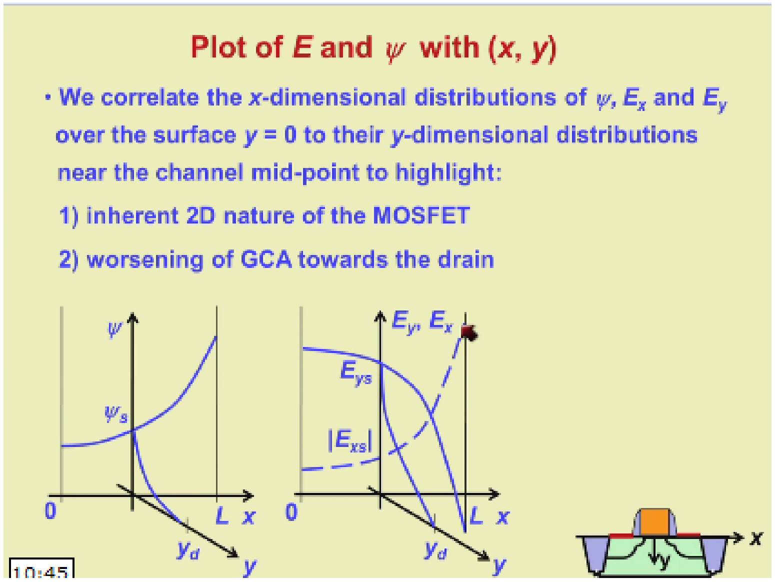

Plot of E and ψ with (x, y)

- We correlate the x-dimensional distributions of ψ, E_x and E_y over the surface $y = 0$ to their y-dimensional distributions near the channel mid-point to highlight:
  1) inherent 2D nature of the MOSFET
  2) worsening of GCA towards the drain

Now let us look at the plot of electric field and Psi with x, y. So we have now completed the 1-dimensional plots along y, along x. Now let us look at the 2-dimensional picture. Okay, so correlate the x and y directional plots. We correlate the x dimensional distribution of Psi, Ex and Ey over the surface y=0 to their y-dimensional distribution near the channel mid-point. So we will try to correlate it here. Okay.

In other words, I will draw distribution of the function of x and then for x corresponding to the middle of the channel we will draw it has a function of y. So here is the reproduction of of the diagrams we have already drawn as a function of x for Psi S, the y component of the electric field at the surface that is the fielding this direction at the surface and Exs that is the field in the x direction along the interface at the surface.

We have put a modulus here because the field is directed from drain into source, drain is more positive with respect to source however, we are sketching only the magnitude of the field. Now we locate the middle of the channel that is somewhere here between 0 and L. And then we draw the y axis. Okay, this is the perpendicular axis that is what is shown here yd shows the edge of the depletion region that is controlled by the gate okay somewhere here.

And we are going to plot the surface potential as a function of y and the electric field as a function of y. Now this is how the picture would be. The surface potential at the interface at this point between 0 and L is shown by this value from this value it decreases and goes to 0 by the time you reach the depletion edge. Similarly, here Eys the y direction field that is the field perpendicular to the interface.

It has this value at the surface which falls on this particular diagram and it decreases, first it decreases rapidly because you are crossing the inversion layer and then relatively slowly when you cross the depletion layer and this field goes to 0 at yd. Please recall the Ey at the surface becomes negative near the drain because we are considering the bias point VDB greater than VGB so drain potential is more positive than the gate potential.

That is the field near the drain is from drain to gate. That is why it is negative. Now what we have achieved using this. The first point is we are able to reflect the inherent 2 dimensional nature of the MOSFET. Second, as we will see later this diagram will illustrate the worsening of the Gradual Channel Approximation towards the drain. We will discuss the Gradual Channel Approximation drain in detail later. Right now, let me just quickly tell you what it is.

This approximation is nothing but the comparison between the gradient of Ey as a function of y and the gradient of Ex as a function of x. Okay. So dou Ex/dou x and dou Ey/dou y. Now you can see here that dou Ex/dou x that is this slope near the drain is rather high. Okay. Whereas if I consider near the source dou ex/dou x is very small; dou Ey/dou y which is actually this slope Ey versus y is this graph. This slope is rather high as you can see.

This will be high both near the source as well as near the drain. However, you see the slope of Ex as a function of x is small near the source whereas it is high near the drain. So when Gradual Channel Approximation valid the slope of Ex versus x is very small compare to slope of Ey versus y. Now because the slope of Ex versus x is increasing near the drain both slopes that is Ex versus x as well as Ey versus y become comparable and therefore we say gradual channel approximation worsens.

Now, this approximation is used to simplify the 2 dimensional Gauss law to 1-dimensional Gauss law. 2 dimensional Gauss law contains 2 terms dou Ex/x and dou Ey/dou y. Well, you will understand this point more clearly when we actually discuss the gradual channel approximation in more detail. Right now just focus on the mathematical properties of the slopes of the field components.

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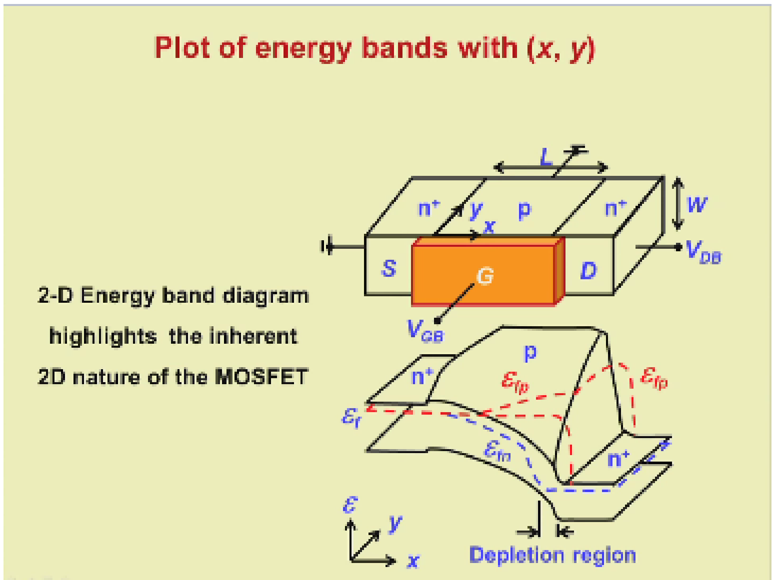

Plot of energy bands with (x, y)

2-D Energy band diagram
highlights the inherent
2D nature of the MOSFET

Now let us plot the energy bands with x, y. That is the 2 dimensional energy bands diagram. The 2 dimensional energy bands diagram highlights the inherent 2 dimensional nature of the MOSFET. Here is the device, source and drain L is the channel length, W is the width of the channel. The source and bulk are shorted also they are grounded; you apply VGB to the gate with respect to the bulk and VDB to the drain with respect to bulk.

Next direction is from source to drain along the interface y direction is perpendicular to the silicon-silicon dioxide interface. Now we are going to plot the energy levels E as a function of y and x. First, we identify the depletion regions controlled by their source and by their drain, then we sketch the quasi Fermi levels. In a 2 dimensional band diagram the quasi Fermi levels and other energy levels would be surfaces. When you draw the energy band diagram in 1-dimension these levels are lines.

So what we have shown here is the intersection of the surfaces corresponding to Efp and Efn with the silicon-silicon dioxide interface, so those will be lines because 2 plains with meet at a line. So if I see over the silicon-silicon dioxide interface Efp and Efn would look something like this. We have sketched this already earlier. And these are the variations of Ec and Ev even these we have sketched. So essentially what we have done is to draw the 2 dimensional bands diagram we have first sketch band over the silicon-silicon dioxide interface as a function of x.

Now slowly we will add the y direction information. So first, we will sketch the surfaces in a neutral n+ source and drain regions corresponding to the Ec. Okay. So this conduction band edge surface in drain and this is a conduction band surface in source. Similarly, we will sketch the valence band edge surfaces Ev surfaces in source and drain. Then we sketch the conduction band edge energy level Ec at the bottom surface that is along this surface here, right.

So you see along this surface, the barrier between n+ and p would be equal to the built-in potential because this grounded and this grounded so that is the built-in potential barrier height. This height is more than the barrier here because application of the positive gate voltage reduces the barrier between source and the interface regions right near the, near the source here because electron concentration is increasing. Okay as you move from bulk to interface.

When you come to this end that is between p and n+ region here along this line the reverse bias = VDB so that is what shown here this is the barrier. Okay which is reverse bias + the built-in potential here. Now you can join the back and the front surfaces by appropriate lines to complete the conduction band surface in the p region. Now, you can show the intersection of the hole quasi Fermi level surface.

Okay, which is in the y direction with the silicon-silicon dioxide interface that is this line and with the conduction band surface that is drawn here that is this curve lines here, okay and this curve line here. So the surface intersects silicon-silicon dioxide interface, the surface corresponding to the Efp intersects the silicon-silicon dioxide interface along this line and it intersect the band surface associated with the p region along this line.

So that is your 2 dimensional energy band diagram.

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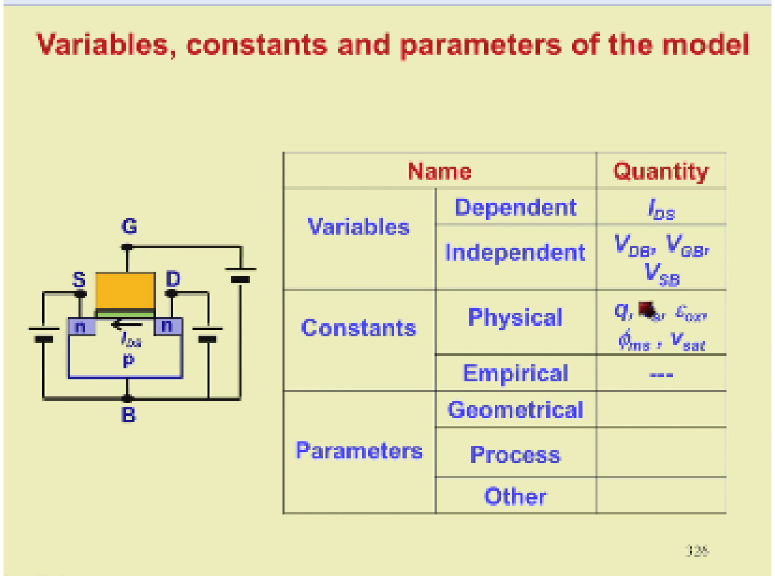

Variables, constants and parameters of the model

Name		Quantity
Variables	Dependent	I_{DS}
	Independent	V_{DB}, V_{GB}, V_{SB}
Constants	Physical	q, [illegible], ε_{ox}, ϕ_{ms} ; v_{sat}
	Empirical	---
Parameters	Geometrical	
	Process	
	Other	

Now finally, let us list the variable constants and parameters of the model. So this is our table reproduced from earlier module so you have Dependent and, Independent variables, Physical and Empirical constants, Geometrical process and other parameters. This is your device where this current IDS is being modelled as a function of drain to bulk, source to bulk and gate to bulk voltages. Therefore, IDS is your dependent variable, VDB, VGB and VSB are your independent variables.

The physical constants that we have come across so far are the electron charge q, dielectric constant of semiconductor S Epsilon s, dielectric constraint of the oxide okay this region that is Epsilon ox , so semiconductor regions are this region and this region. Phi ms, the potential difference, work function difference between the gate and the semiconductor materials, and saturation velocity associate with the electrons in the inversion layer. Okay. There are no empirical constants.

The geometrical parameters are W which is the width of the device in this direction perpendicular to the slide L that is the channel length from source to drain, and t ox that is the oxide thickness here. The process related parameters that is parameter through a controlled by their process are fixed charge of at the silicon-silicon dioxide interface, doping Na of the substrate and mobility Mu of the electrons in the inversion layer that causes the current. At this point we have no other parameters to list.

Now with that we have come to end of the module, so let us summarize very briefly, what have we achieved in this module.

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Solid State Devices

Lecture # 33-37 MOS Junction

Lecture # 38-41 MOSFET

I would like to remind you that a previous course a more fundamental course basic course on Solid State Devices by me has covered the topic of MOS junction and MOSFET in this lectures and what we are discussing here is more advanced version of those details.

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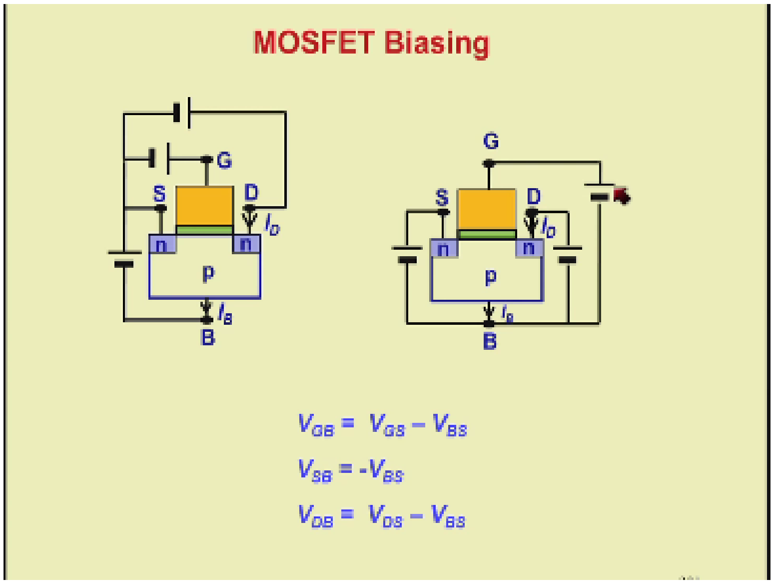

MOSFET Biasing

$$V_{GB} = V_{GS} - V_{BS}$$

$$V_{SB} = -V_{BS}$$

$$V_{DB} = V_{DS} - V_{BS}$$

The first important point to note in this module is that while the device is bias with respect to source in practical applications for device modelling purposes it is more useful to consider the biasing arrangement with respect to the bulk. After we have derived the equations for this biasing arrangements in which we derive the expression for ID, IB as a function of VDB, VSB and VGB we can then express the same model in terms of the voltage with respect to source using these equalities.

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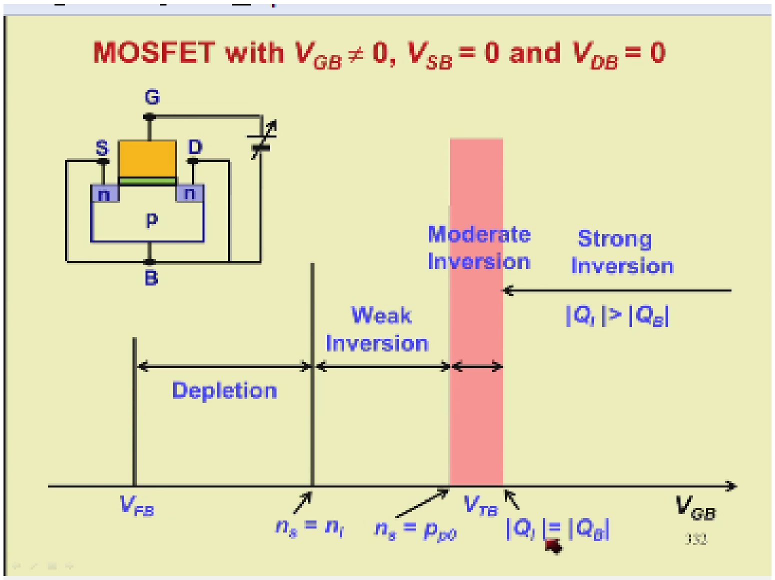

MOSFET with $V_{GB} \neq 0$, $V_{SB} = 0$ and $V_{DB} = 0$

We discussed the bias, we discussed the regions of operation for that purpose we start with the MOSFET in which the VGB is applied but VSB and VDB are zero so drain and source are shorted to bulk. The regions to be identified here are the depletion region which is between the Flat-band point and the point at which the surface concentrations of electrons which is = Ni, that is the depletion region.

Then when you increase the VGB further your surface concentration of electrons at the interface becomes equal to the hole concentration in the bulk and this boundary now is a boundary of so called Weak inversion region. So between Ns = Ni and Ns = Pp0 you can have the weak inversion. Now at the point when inversion charge becomes equal to the bulk charge, this is the charge per unit area that is the area under the electron distribution, okay.

Whereas this is volume charge, this is Arial charge. When Arial and the electron distribution inversion charge becomes equal to the depletion charge per unit area that point we reach strong inversion and for VGB beyond this point the inversion charge per unit area will exceed the depletion charge, this strong inversion, so in Weak and Strong inversion you have the moderate inversion. The threshold voltage VTB falls somewhere in the moderate inversion region. The region from VFB to VTB is referred to as sub-threshold.

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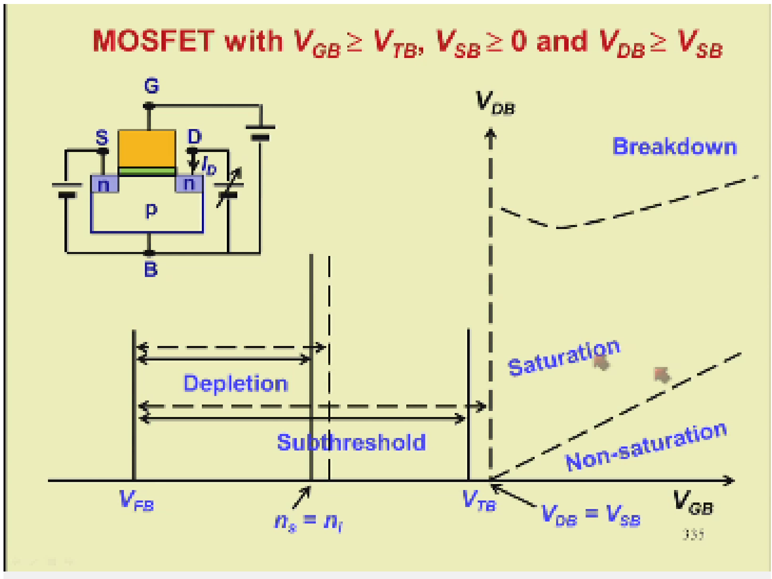

MOSFET with $V_{GB} \geq V_{TB}$, $V_{SB} \geq 0$ and $V_{DB} \geq V_{SB}$

Now if you add a VSB and keep VDB equals to VSB that is short the drain to source. Now what happens is the effect of VSB is to expand the depletion region and sub-threshold region as shown here by these lines. Now when you add a VDB which is greater than VSB now the device has a current drain current flowing between drain and source and maybe small amounts of current between drain and bulk and drain and gate also.

However, we are neglecting the drain bulk and drain gate currents in our course. What is the effect of that? That is shown here. So we now erect a VDB access perpendicular to VGB access; this point corresponds to VGB = VSB when there is no current and then in this VDB, VGB map you have regime such as non-saturation where the current increases linearly in the beginning for small values of VDB.

And then tends to saturate as you enter this region here as increase the VDB and when increase the VDB very much you enter the breakdown region. All these regions are situated for VGB greater than VTB. Now this is your VTB corresponding to non-zero VSB. Your VTB corresponds to 0 VSB is this so, your non-saturation, saturation and breakdown regions will be shown by the solid line if your VSB was 0, okay.

And this will be your VDB, VGB map. So the dotted lines and solid lines here show the change in the non-saturation, saturation, breakdown regions when you change your VSB.

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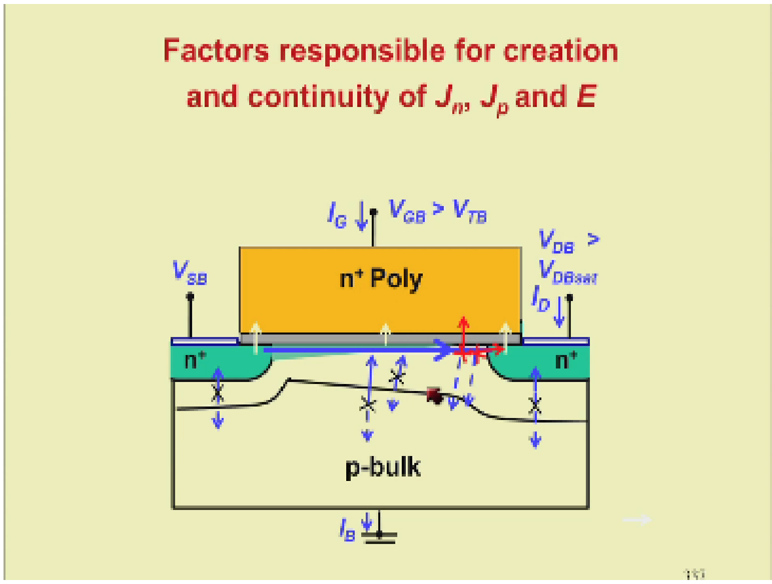

Factors responsible for creation and continuity of J_n, J_p and E

Then we will illustrate the factors responsible for creation and continuity of Jn, Jp and E. So we said that, Jn the electron current which is important in a n channel MOSFET is created by both drift as well as diffusion, so the electric field is created by voltages applied to the gate, source and bulk and this electric field causes several things, one is an inversion layer is created near the interface and this inversion layer then transports current.

So you have variation of the inversion layer from source to drain and therefore current is because of diffusion in addition to drift which is caused by the field between the drain and the source. So that is about the creation of Jn, Jp and E. We really do not bother about Jp because this current is very small in a n channel MOSFET. Now what about the continuity aspects. Now you see that generation of electron hole pairs in this space charge region and within the diffusion region from the space charge region contributes to the drain to source current.

So here you can see that all the electrons which are generated join up with the current that is been supplied from the source and they move to the drain, the holes however move to the bulk and these holes are the responsible for the bulk current. The generation can really increase in the space charge region near the drain at the interface because of high electric fields here which causes impact ionization shown by this red lines.

Okay, then you can have some loss of electrons due to tunnelling. So while generation can the sources of electrons, tunnelling could be loss of electrons, right tunnelling from bulk to gate. As far as electric field is concerned, the continuity is maintained by the space charge here which can be because of depletion as well as inversion.

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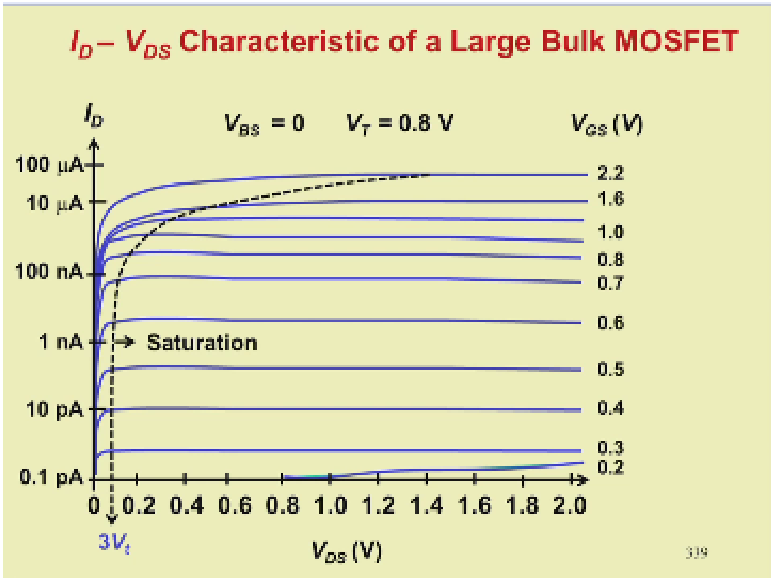

$I_D - V_{DS}$ Characteristic of a Large Bulk MOSFET

Now based on this qualitative understanding we explained the IB, BD characteristics, how the current increases linearly at first and tends to saturate beyond some voltage and how the saturation current increases with VGS. We also explained the IB VGS curves when IB is plotted on a log scale. This was done to emphasis the sub-threshold region of operation where the saturation voltage is constant independent of the gate voltage and it is at value at approximately 3 times Vt.

And on a log plot the current appears to increase linearly with VGS, in other words ID VGS is exponential. This is in the sub-threshold region.

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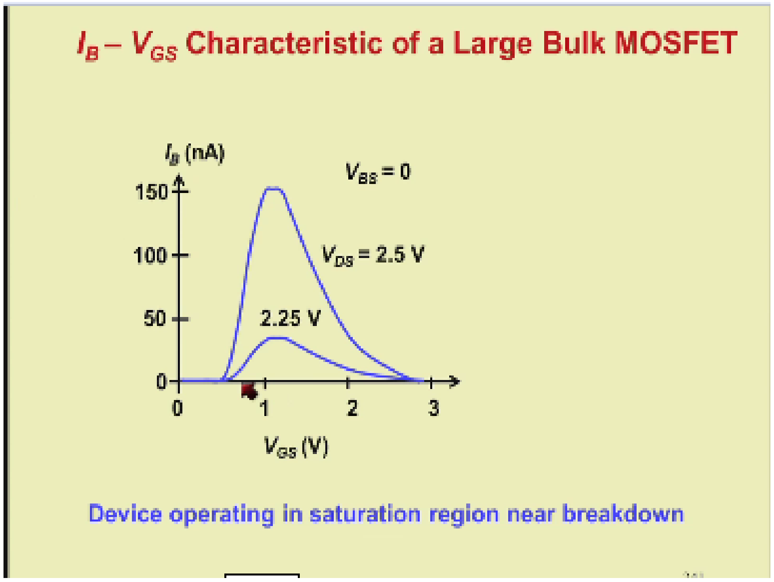

$I_B - V_{GS}$ Characteristic of a Large Bulk MOSFET

Device operating in saturation region near breakdown

Then we explained the IB VGS curves. So when ID is provided on the linear scale the ID VGS graph is a straight line over the significant portion, near the threshold however, there is a rounding of okay of this corner and for high gate source voltages there is a tapering of this slope because of field dependent mobility affects. Now when you plot the IB on a log scale then near the threshold you can see a straight line portion for ID VGS showing the exponential with VGS.

Next we explain the IB VGS curves for a device operating saturation near the breakdown. So what we said is for VGS less than Vt there is no inversion charge and there is no IDS and therefore there is really no subset current because subset current is the consequence of multiplication of the drain to source current because of impact ionization. Okay. So this current depends on 2 factors the amount of electric field available to the impact ionization or simple multiplication and the amount of drain to source current that is the source that can be multiplied.

Now near this end when VGS is small the inversion charges small, the source current that can be multiplied is small and therefore the IB is small. Similarly, for large value of VGS the IB is small again because the electric field in the x direction okay decreases though the current itself is large electric field is small and therefore multiplication is small, so in between you have some maximum value of IB and this IB increases as your VDS increases.

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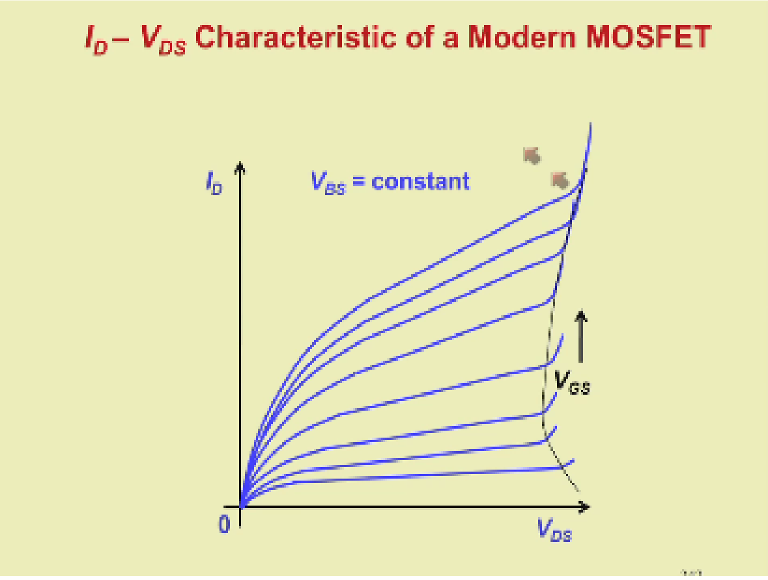

$I_D - V_{DS}$ Characteristic of a Modern MOSFET

Then we also explained, the variations of the breakdown voltage as a function of VGS which follows from the IB, VGS behavior we discussed just now. We however, postpone to a later time the explanation for why the ID VGS reason there is a slope of the characteristics these are short channel affects corresponding to small geometry devices. A modern MOSFET is a small geometric device, whereas we are considering large geometry device here.

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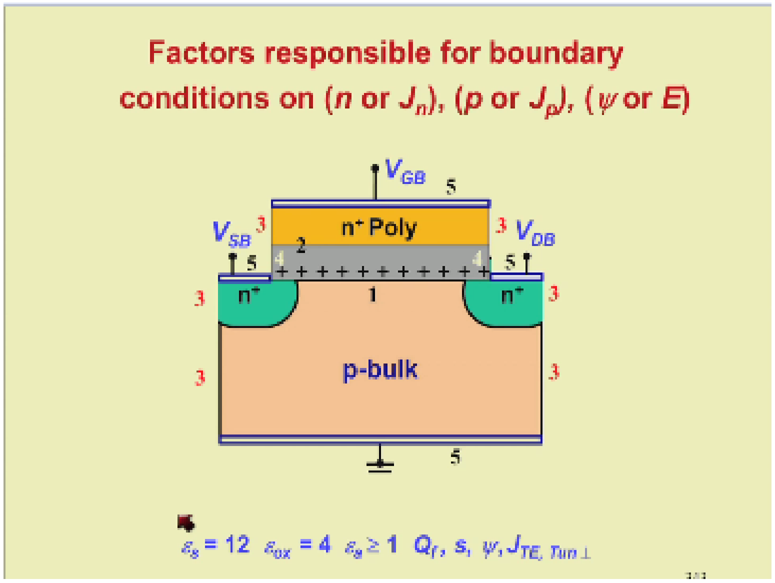

Factors responsible for boundary conditions on (n or J_n), (p or J_p), (ψ or E)

$\varepsilon_s = 12$ $\varepsilon_{ox} = 4$ $\varepsilon_g \geq 1$ Q_f, s, ψ, $J_{TE,\ Tun\perp}$

Then we consider the factors responsible for boundary conditions. Okay, on these quantities. The boundaries we considered were silicon-silicon dioxide interface that is boundary 1, boundary 2 silicon dioxide poly interface, boundary 3 between the device and the ambient, boundary 4 a device and the ambient there are 2 parts one is between silicon and the ambient and the other is between silicon dioxide and the ambient that is 4 and 5 is the electrodes.

At these boundaries the conditions on these quantities are decided by the dielectric constant of silicon, the dielectric constant through a walk side, dielectric constant of the ambient, fixed charge, surface recombination velocity, the potential applied at the electrodes and thermionic emission and tunnelling currents which are negligible perpendicular to the interfaces for the conditions considered.

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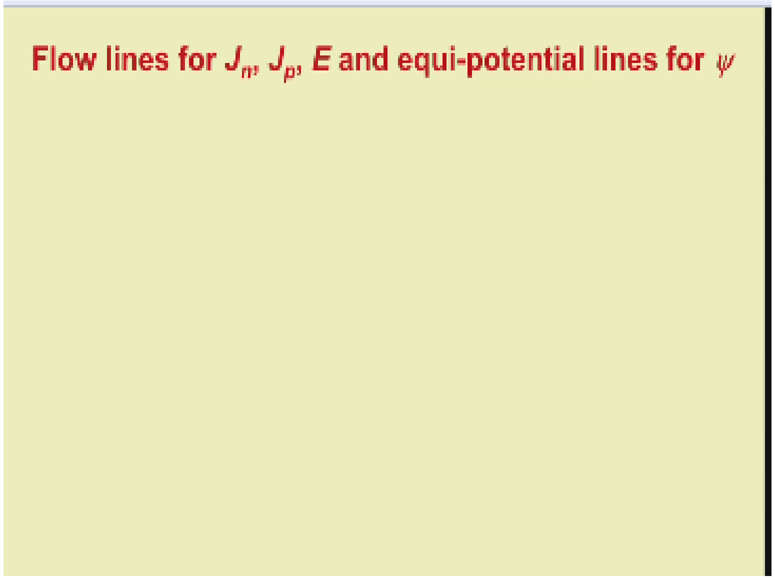

Flow lines for J_n, J_p, E and equi-potential lines for ψ

Then we sketched the flow lines for Jn, Jp, E and equipotential lines for Psi.

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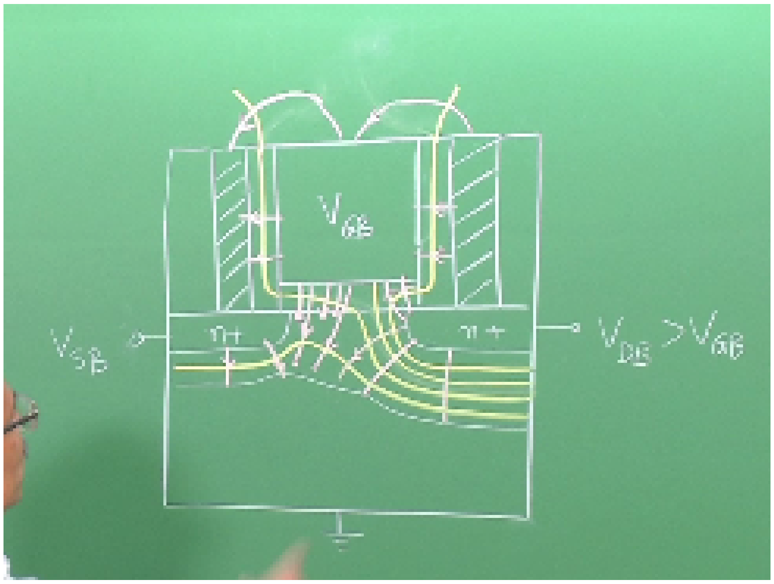

Now that is what is shown here. So you see that the picture is 2 dimensional, these are the equipotential lines and these are the field lines, okay. Similarly, we sketched the current flow lines also.

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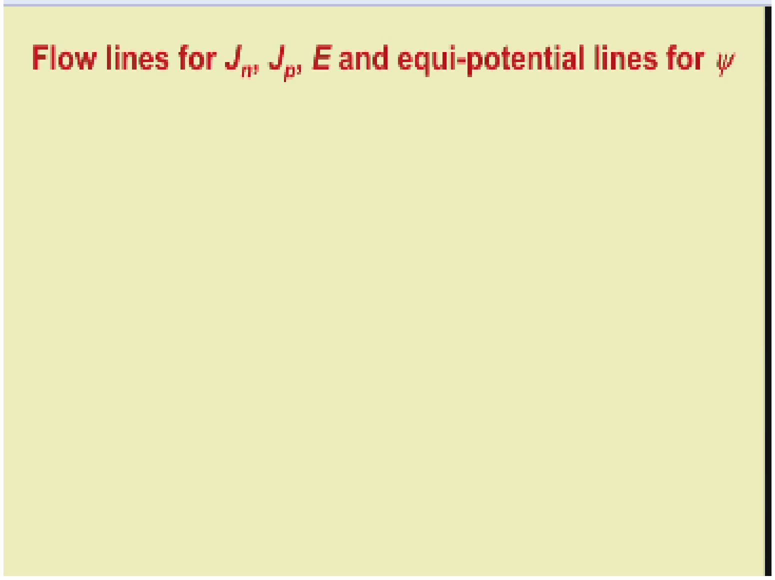

Flow lines for J_n, J_p, E and equi-potential lines for ψ

Based on this, we concluded the MOSFET is inherently a 2-dimensional device.

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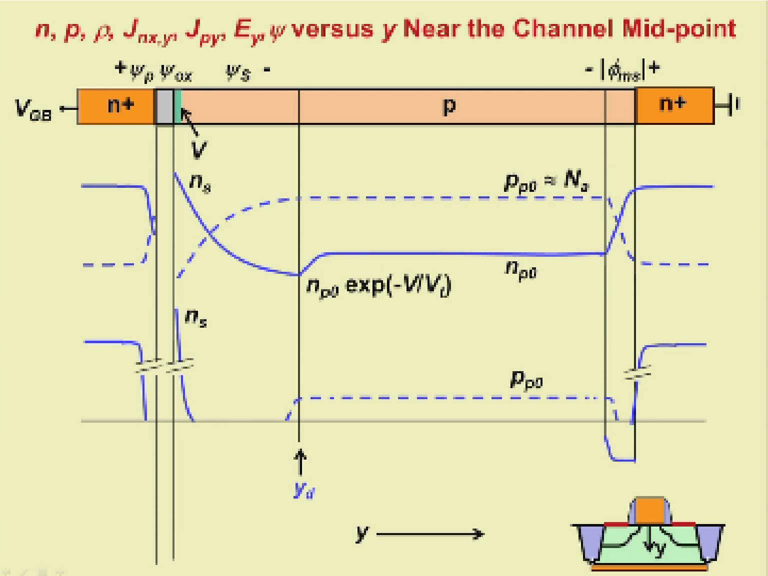

$n, p, \rho, J_{nx,y}, J_{py}, E_y, \psi$ versus y Near the Channel Mid-point

Then we sketched Np, Rho Jnx,y, Jpy and Ey and Psi versus y Near the channel Mid-point and they had this kind of variations.

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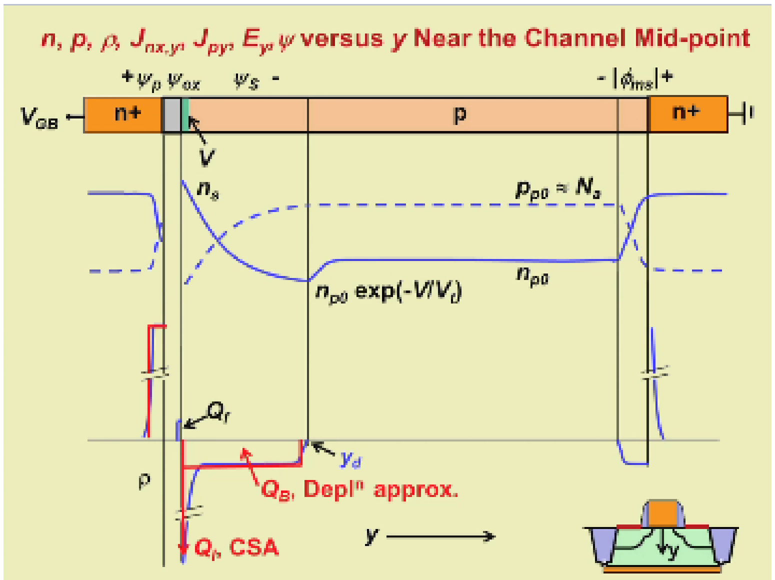

$n, p, \rho, J_{nx,y}, J_{py}, E_y, \psi$ versus y Near the Channel Mid-point

The Jnx that is the current density in the x direction as a function of y was something like this showing that the current is restricted to the inversion layer. In y direction, Jn and Jp are 0 that is current perpendicular to the interface that is 0.

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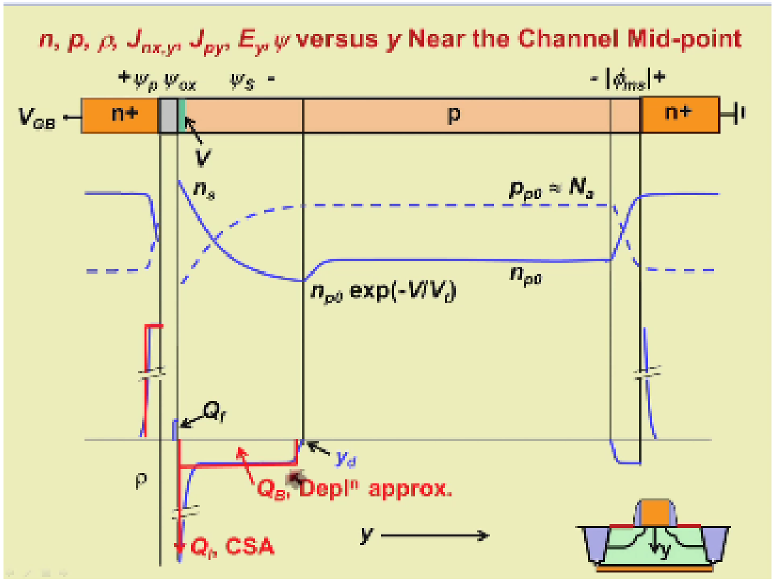

$n, p, \rho, J_{nx,y}, J_{py}, E_y, \psi$ versus y Near the Channel Mid-point

Then we emphasis the depletion approximation of the charge controlled by the gate, and the charge sheet approximation of the inversion layer. Similarly, you have depletion approximation of the charge controlled by the gate in the n+ poly region also.

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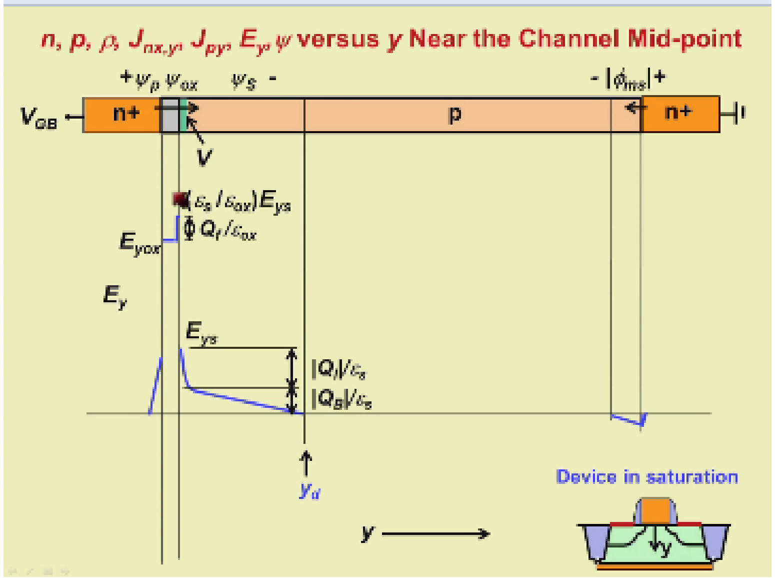

$n, p, \rho, J_{nx,y}, J_{py}, E_y, \psi$ versus y Near the Channel Mid-point

Now this was the picture of the electric field as a function of y, Ey as a function of y.

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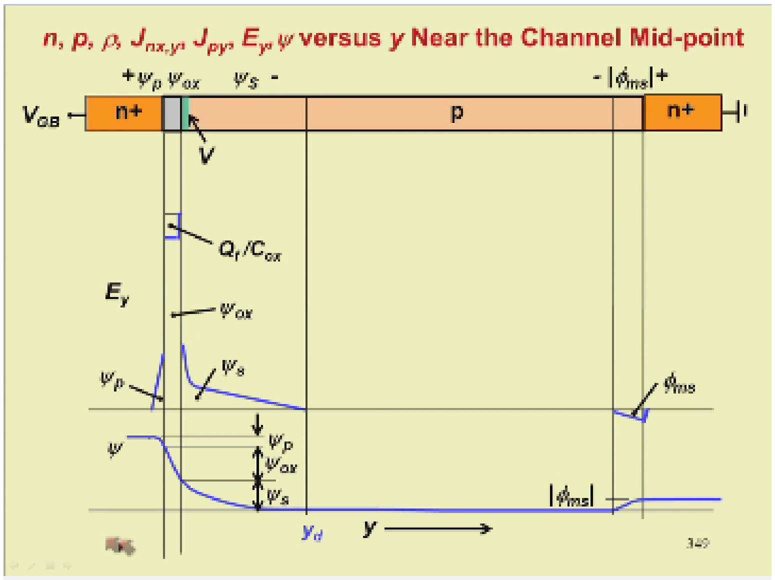

$n, p, \rho, J_{nx,y}, J_{py}, E_y, \psi$ versus y Near the Channel Mid-point

And from Ey as a function of y we also sketched the Psi as a function of y from gate to substrate.

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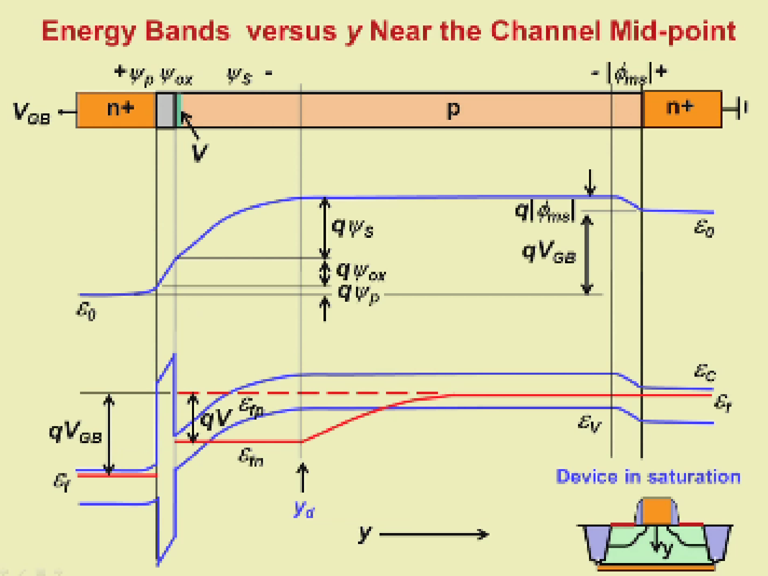

Energy Bands versus y Near the Channel Mid-point

We sketched the Energy-Bands with y that is from gate to substrate and the band picture looks like this which shows E0 Ec, Ef and Ev variations.

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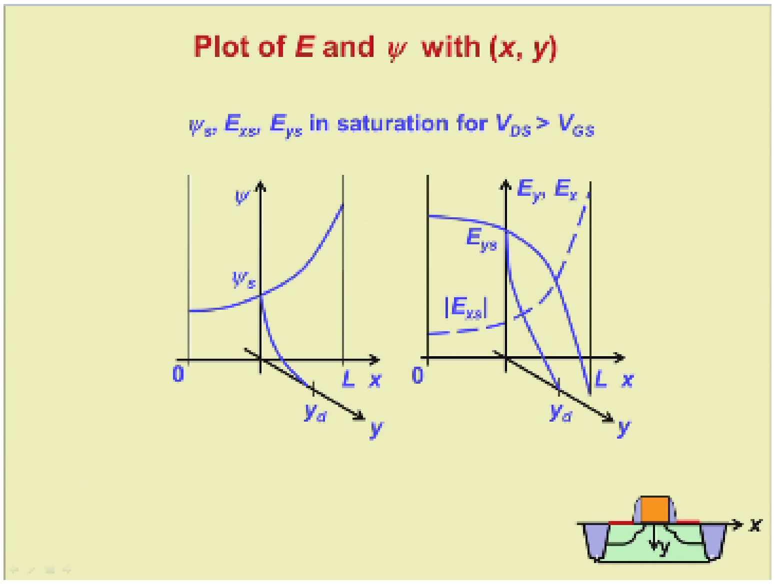

Plot of E and ψ with (x, y)

ψ_s, E_{xs}, E_{ys} in saturation for $V_{DS} > V_{GS}$

And then we sketched the electric field components, Exs, Eys surface potential both with x and with y.

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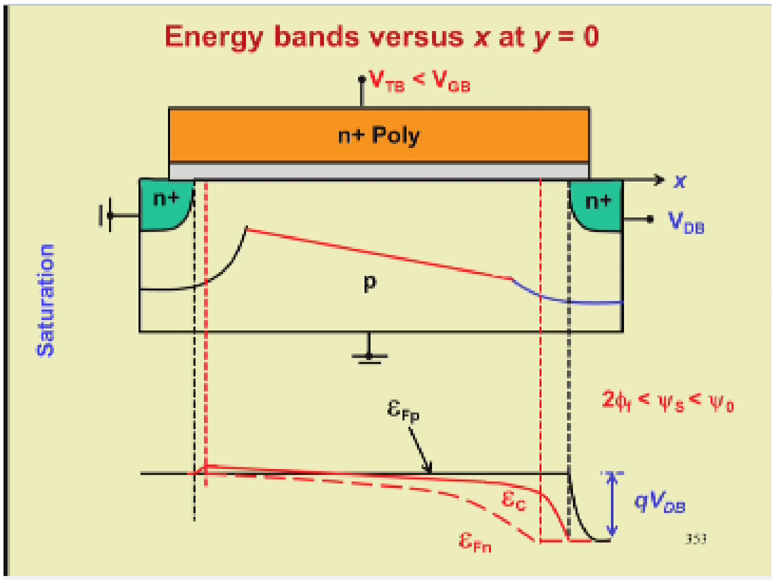

Energy bands versus x at $y = 0$

Finally, we sketched Energy-Bands as a function of x allowing the interface. Okay, for sub-threshold and saturation conditions.

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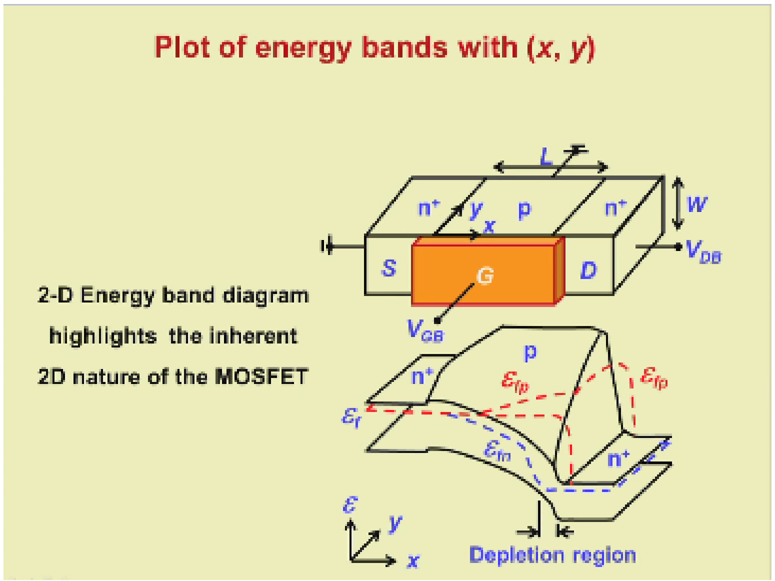

Plot of energy bands with (x, y)

2-D Energy band diagram highlights the inherent 2D nature of the MOSFET

We also sketched the 2 dimensional energy band diagrams.

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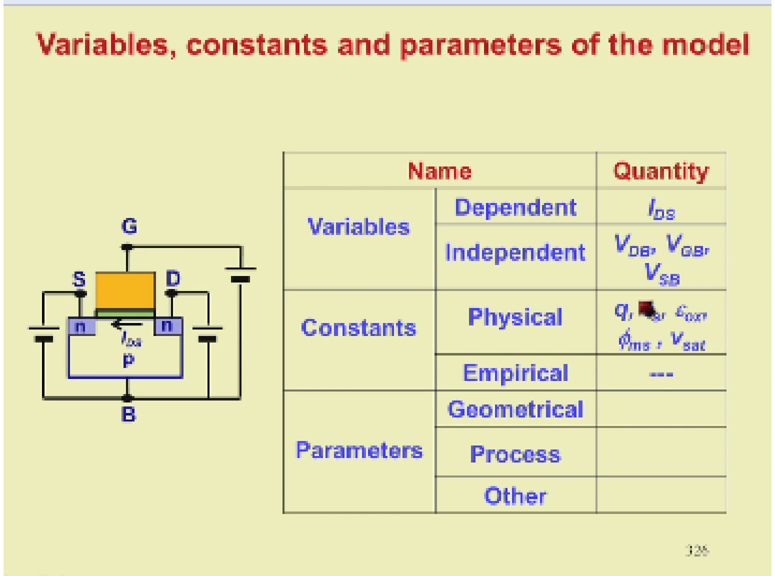

Variables, constants and parameters of the model

Name		Quantity
Variables	Dependent	I_{DS}
	Independent	V_{DB}, V_{GB}, V_{SB}
Constants	Physical	q, [illegible], ε_{ox}, ϕ_{ms} ; v_{sat}
	Empirical	---
Parameters	Geometrical	
	Process	
	Other	

And finally, we listed the variable constants and parameters of the model.

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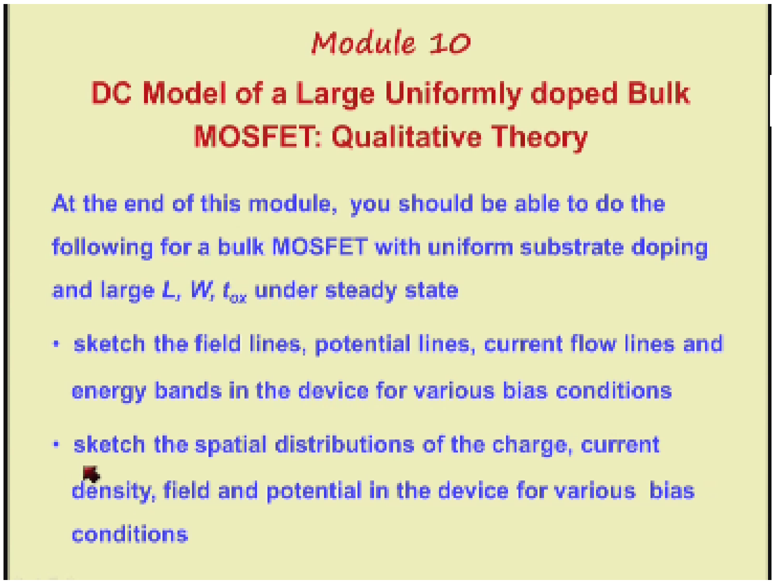

Module 10

DC Model of a Large Uniformly doped Bulk MOSFET: Qualitative Theory

At the end of this module, you should be able to do the following for a bulk MOSFET with uniform substrate doping and large *L*, *W*, t_{ox} under steady state

- sketch the field lines, potential lines, current flow lines and energy bands in the device for various bias conditions
- sketch the spatial distributions of the charge, current density, field and potential in the device for various bias conditions

So I hope that at the end of this module you should be able to do the following for a bulk MOSFET with uniform substrate doping and large L, W, t ox under steady state. First explain the shape of the ID–VDS, ID-VGS and IB-VGS curves in terms of the charge and field condition in a device then sketch the field lines, potential lines, current flow lines and energy-bands in the device for various bias conditions.

Then sketch the spatial distribution of the charge current, density, field and potential in the device for various bias conditions. With that, we come to the end of this module on Qualitative theory underlying the operation of the large uniformly doped bulk MOSFET.