Fundamentals of Semiconductor Devices
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Lecture – 32
Ideal MOS system: derivation of threshold voltage

Welcome back to today's class. So, if you recall from the previous lecture, we are in the full mode for you know understanding MOS capacitor - Metal Oxide Semiconductor capacitor. We have taken example of a p-type silicon on which we have a dielectric oxide and on top of that we have metal. So, this is a classical MOS capacitor, we have had a few discussions on how the capacitance will vary in such a system.

What are the different regions like accumulation, inversion, strong inversion depending on the gate bias that you are applying. I told you that this is the cornerstone, the most important thing that you have to learn to understand MOSFETs and MOSFETs are the most widely used semiconductor devices or transistors that go into all your processors, memory devices logics and so on.

So, we have to understand MOS capacitor first and we have laid down the basic principles of how it works and how the band bends at the interface of oxide and semiconductor. If you recall that, I told you that the capacitance voltage curve will also depend on the frequency of the small signal that you are applying on the gate. So, going ahead, today we shall touch base with a little bit of mathematics that are related to this C-V.

Mathematics we shall try to keep it very simple, the formula and equations, something that are very easy to remember, even if you do not remember, you can always refer to them from the notes and Google, right. And then we will build the base so, that we can start understanding MOSFET from maybe next or next to next class.

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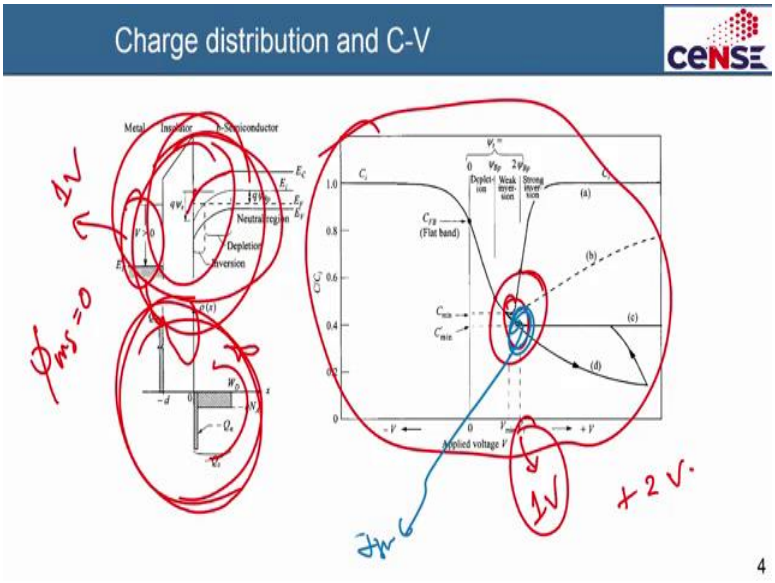

So, it will come to the whiteboard and the slide where we had left yesterday. So, if you recall and I will be using the laser pointer here; if you recall, this is the classical capacitance voltage curve of an MOS capacitor. This is the band bending under inversion and this is the charge distribution under the inversion.

If you recall, on the application of a positive gate bias here your bands will bend, and the conduction band is approaching the Fermi level more than the valence band. So, you will start getting electrons there, we call it inversion. First, weak inversion will happen which means the conduction band will be such that you know that the intrinsic level E_i will essentially touch the Fermi level of the surface.

That is the onset of weak inversion; that means, the Fermi level is now equally distant from the valence and the conduction band at the interface. Then, if you keep applying a positive voltage more and more, you have more and more bending. So, the intrinsic level will go below the Fermi level that is you have seen here, the Fermi level stays flat and we get strong inversion, a very high density of electrons at the interface when the intrinsic level is as much below the Fermi level here as it is above here.

So, if you recall this gap, this gap you recall that gap, I call it φ_f or any you know you can call it any name we want, but that gap will be that $E_i - E_F$ here has to be equal to $E_F - E_i$ at the interface; in which case you are going to get strong inversion.

Once you have strong inversion, then you have a high sheet density of charge here. So, any small signal that you apply to measure the capacitance, it depends on how fast you are changing the signal here. Because, these are minority carrier electrons that are generated here despite this being a p type, they have a finite time to carry, you know, to get generated and to move in and out. So, if you move the signal very fast, then the minority carrier cannot get enough time.

So, your extra charge that you have to modulate will be added to the end of the depletion region here, where the majority carriers, holes can move in and out to essentially adjust for that changing signal that you apply. And once the depletion, once the inversion layer forms here, I told you the depletion that is extending here is the maximum that you can go. So, this is the maximum depletion.

So, your capacitance will be minimum, and the value will stay minimum for a high frequency curve and this is the curve there ok. If your signal is changing very slowly, then minority carriers will get enough time you know and so, you can come back to the original you will basically move in and out of here. So, the exactly, the oxide capacitance is the capacitance that you will measure, which is this oxide capacitance and that is what happens at low frequency sweep.

So, I told you this point, the minimum point where the capacitance becomes minimum or the depletion width becomes maximum is the onset of strong inversion where, strong electron gas density has formed. That is why we call strong inversion, that strong inversion electron density will basically screen the electric field that we are applying; will not allow the depletion region to move further.

That is why you have the maximum depletion region here that corresponds to a minimum capacitance that you can get here ok. The minimum capacitance that you get here, we call it as a threshold voltage, it is a very important number. And, if you recall this capacitance voltage curve, I told you when you apply a negative gate bias, this is the negative side of the 0 axis. So, when you apply negative gate bias here, you are going to attract more holes at the interface.

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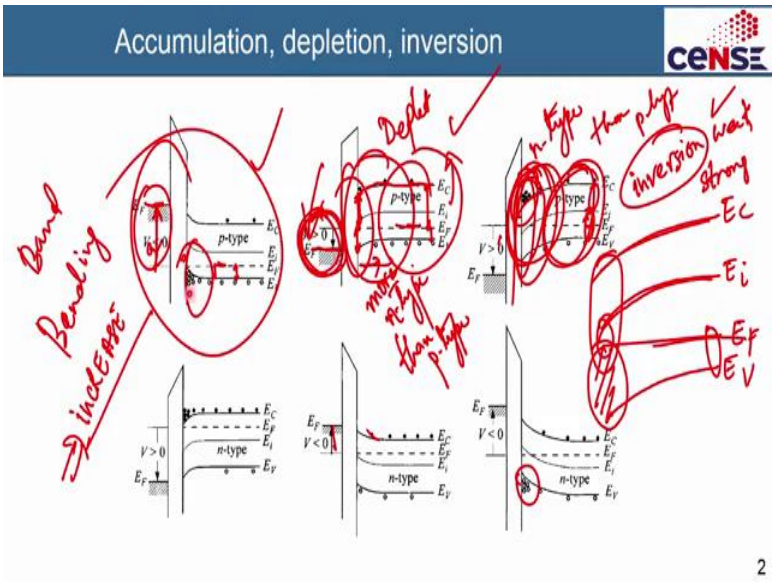

So, what will happen is that, you are going to end up getting a like the similar situation like that, where you have an excess of holes here and that excess holes are majority carriers, they have no problem moving in and out fast. So, no matter how we apply the frequency, any small signal that you are applying here will be able to move in and out, the equivalent ΔQ charge from this interface.

So, effectively you end up getting the capacitance corresponding to that. So, that capacitance is this capacitance which is very high, it is called accumulation capacitance; remember this y axis is in a ratio of the total capacitance to the oxide capacitance. So, when the total capacitance is equal to oxide capacitance the ratio is 1 which is what is plotted here, which is what is plotted here.

But, as you keep increasing the gate bias more and more positive, you know, you are going to deplete the carriers, you are going to deplete the carriers from this interface, because the positive gate bias will push away the holes. The more you deplete, the more that depletion region will widen and if the depletion region widens, then your capacitance which goes inversely as the depletion width will reduce. And, that capacitance here is the depletion capacitance that is in series with the oxide capacitance.

The series combination of those two capacitances also will reduce and that is why the capacitance keeps falling down and down and down; until you have any strong inversion here, at which point you have the maximum depletion width and the minimum capacitance

and after that it will depend on how fast you sweep, it is a small, it is a small signal is a high low frequency it is this curve.

If it is a high frequency, it is this curve and if you are sweeping the DC bias very fast such that you did not give enough time for the electrons to generate here in the first place, for the inversion layer to form, you did not give time, then the depletion will keep extending because there is no inversion layer to screen out the depletion, the field in the depletion.

So, it will basically keep going down, that is what it means. So, till now we are fine, we have not used mathematical expressions till now, right. But, we should start getting some mathematical expressions here; I hope whatever we have discussed till now is clear. So, let me use a marker here and I told you that in our case we had assumed that the metal Fermi level, the Fermi level of the metal, the Fermi level of the metal is here.

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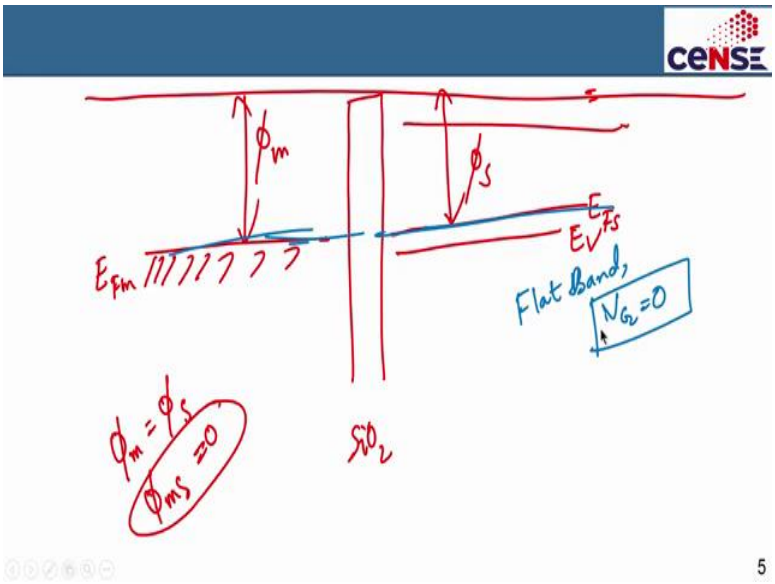

And then there is the dielectric here which is silicon dioxide; we assumed that the semiconductor Fermi level E_F was, and this is p type of course. So, this is the valence band, this is the conduction band; we assumed that the Fermi level of the metal side and the Fermi level of the semiconductor side were already aligned before joining, in which case, we call it the metal work function is equal to the semiconductor work function because the vacuum level will be up there somewhere. It is not a straight line exactly, but it should be a straight line anyways, my drawing is bad. So, you can see this is the semiconductor work functions φ_s this is the metal work functions φ_m.

If the work function of the metal and the semiconductor exactly equal, then your semiconductor metal work function difference will be 0. In which case when you join the two, semiconductor metal and the oxide together alright, you are going to get the perfect equilibrium condition where the Fermi levels are aligned. And, this is called flat band condition because all the bands are flat and in the flat band condition, you are getting at V_G equal to 0. Because you did not have to have to apply any gate voltage to get this, but in reality, I told you this is not a situation that you will encounter in reality right; you will not encounter this situation in reality.

So, in reality what will happen? Right. In reality, the metal and the semiconductor work function will not be same. Your metal and semiconductor work function will not be same. So, the first thing that we should take into account here is that the metal work function could be very different from the semiconductor work function.

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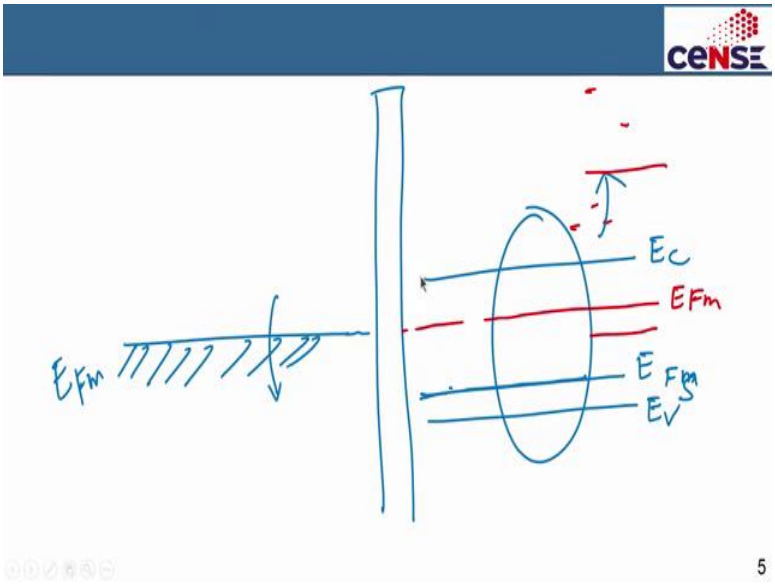

For example the metal is here this is metal Fermi function, right, then there is the dielectric here. Suppose the semiconductor work function, you know the semiconductor work function is here, this is the same in, before you join them, before you join them ok. This is a semiconductor work function, this is a semiconductor valence band, this is a semiconductor conduction band, this is before joining. Now, the moment you join and form the junction, your Fermi levels will have to align because in equilibrium, the Fermi

level is always aligned everywhere which means this Fermi level, this Fermi level will have to come up.

So, this whole thing you are essentially pulling up, this whole thing you are pulling pushing down you can think of that. So, what will happen is that eventually, let me change the color here so that it becomes easier. So, eventually the Fermi level will come here, but far away the valence band will always be here the conduction band will always be here. So, let me erase this part let me erase this part ok.

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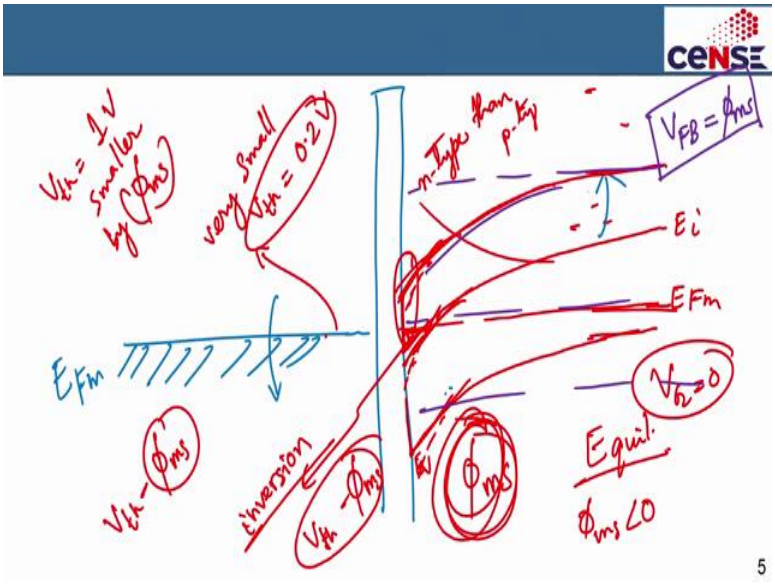

So, the Fermi level will be there. So, what will happen is that it will basically be like that, basically be like that ok. So, this is equilibrium, this is equilibrium and the Fermi levels are aligned, but this is the equilibrium band diagram. Now, you see already, the Fermi level, this is p type, this is p type semiconductor, but over here, the Fermi level and the conduction band spacing is closer than the Fermi level in the valence band spacing. This is E_V at the surface which means this is part has already become more n type than p type; more n type then p type. Because, you know if you draw the mid gap level, your mid gap will be here like E_i, that E_i is probably has already started coming here. And that means, the E_i has already come below the Fermi level here which means there is already inversion that has formed, already inversion has already formed. So, in the previous case, in this case when you are you know, when you had a perfectly metal semiconductor work function difference was 0, in which case you know this point, this threshold voltage for example,

this point is supposing 1 volt ok. You have to apply 1 volt here, you have to apply 1 volt here to basically make the bands bend and create strong inversion. But, over here, even at V_G equal to 0, this is V_G equal to 0 situation you already have a situation like this; so, you already inversion has formed.

So, to get strong inversion, you just have to mildly bend the band more, which means you have to apply a very small positive bias right. Maybe your threshold voltage now will become only 0.2 volt as opposed to 1 volt before; that means, at 0.2 volt it, i am just giving an example, with what I mean to say is that your threshold voltage has become smaller because it is already like this right.

So, this bend that has happened here is actually because of the metal work function difference which was φ_{ms}. So, you are essentially bending the band by φ_{ms}. So, in other words, this φ_{ms} value, your threshold value or voltage, whatever your threshold voltage was before; whatever your threshold voltage was before here which suppose 1 volt will now become smaller; will now become smaller by this quantity of phi ms because of this φ_{ms}, your bands already bend. So, you have to apply a smaller voltage on the gate to get strong inversion right. So, your threshold voltage will now become smaller by φ_{ms}. And, if this was negative which means, if the bands were bending up then you have to apply, this will be negative, so, it will be negative, negative, positive which means instead of 1 volt maybe, you have to apply plus 2 volt higher voltage if your φ_{ms} was negative right and if your φ_{ms} is positive you have to apply a very small voltage. So, essentially your threshold voltage will have shifted by $V_{th} - \varphi_{ms}$. So, in other words, to get a band flat, if you understand what I am trying to say here. So, let me change the color again. If you want to get the band flat here, then you have to apply an extra voltage called the flat band voltage. And that flat band voltage exactly is the bending that has happened and that is the metal semiconductor work function difference that is there, which you have to apply in order to means make the bands flat.

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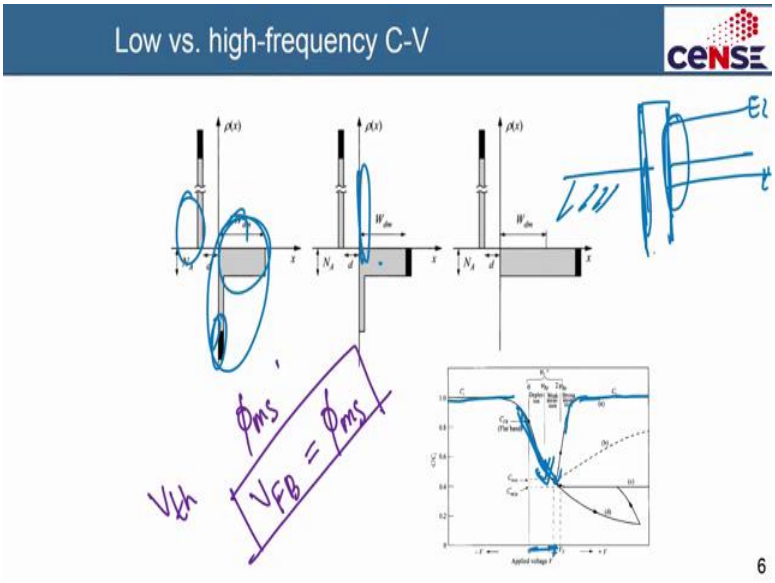

So, what I can say is that whatever the threshold voltage was there, the threshold voltage has become smaller ok, that threshold voltage has become smaller because, you are your its more, has become smaller if your metal from semi, this metal semiconductor work function is positive. If it is negative, it will become larger, that is what it is ok. Please remember that the flat band voltage that you are applying is the voltage that you have to apply to make the bands flat. And so, the threshold voltage will shift by this amount in real semiconductor, ok, that you have to keep in mind ok.

So, there will be some mathematical equations that will come very soon, but you do not have to worry so much because things are basically about logic and understanding the physics behind it. So, once we understand the physics behind it, then the equations will become very simpler. So now, now this is the metal semiconductor work function difference I told you; now let us do some very simple maybe equation.

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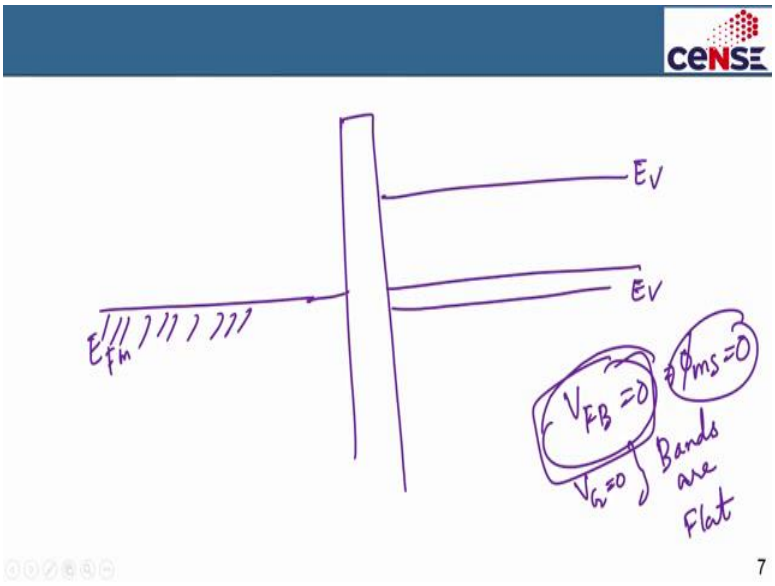

And we will assume the flat band condition is you know at 0, which means I will assume that the metal work function, I am sorry the metal Fermi level and this is the oxide for example, and a semiconductor Fermi level are aligned before joining. So, after joining, they will just be like this, which is flat band voltage is 0, which means at equilibrium, at equilibrium, at V_G equal to 0, bands are flat already; bands are flat already ok.

So, I am assuming that there is no metal. I am assuming basically that metal semiconductor work function difference is 0. So, at 0 gate voltage, I have a flat band condition like this ok. Now, the question is, let me draw it may be little bit straight. So, you know, I have something like that, this is your valence band, suppose there is a conduction band. So, to get strong inversion, I told you, to get strong inversion what you have to do is that, you have to apply the positive voltage here.

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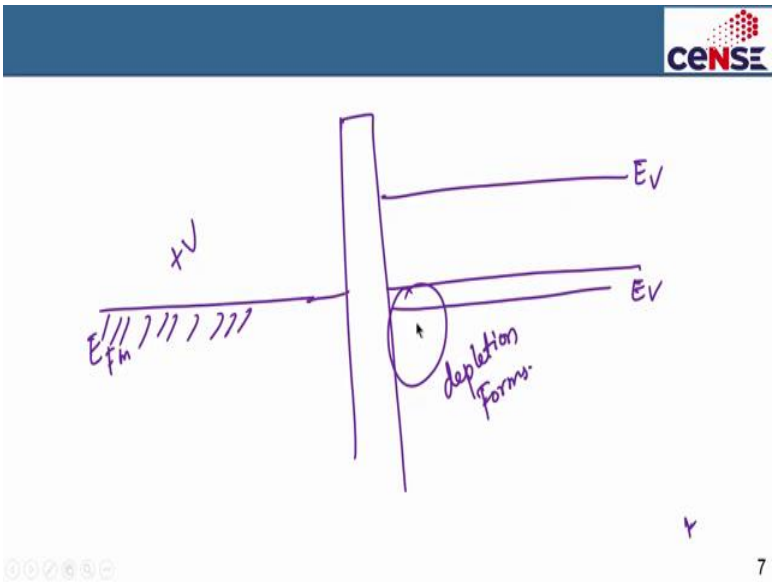

So, that holes are repelled, the holes are repelled, and depletion region forms here, holes are repelled, and depletion region forms here. And, once depletion region forms, p type depletion, your valence band will now move away from the Fermi level. So, what will happen is that and this is what you know will draw some equations and do some stuff here.

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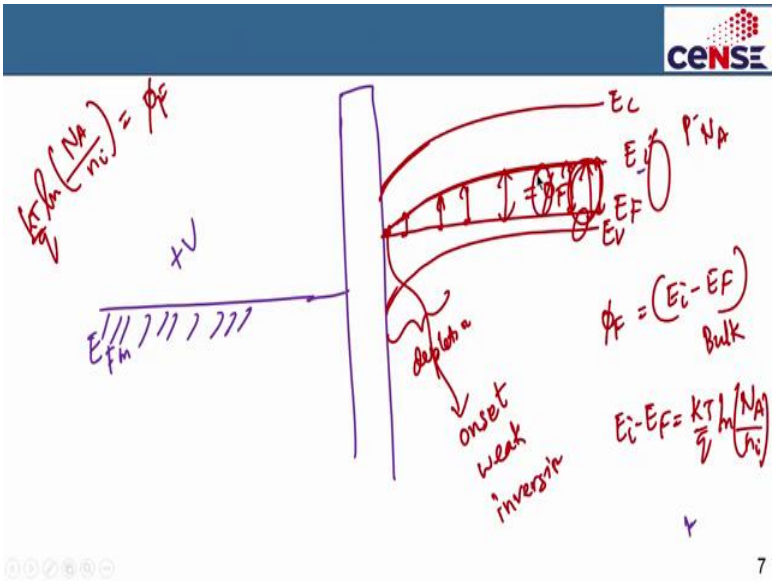

So, this is your oxide for example. So what will happen is that, Fermi level will shift now right. The Fermi level will now shift so, you can see that in a, when you apply positive voltage, your Fermi level this Fermi level will come down. So, the metal Fermi

semiconductor Fermi level will be up here. This is the semiconductor Fermi level right, the valence band will shift like this now, but far away from the junction, the valence band and the Fermi level difference will remain constant. But, here this depletion region has formed because the bands are now bending, and the Fermi level is moved up.

This is the conduction band and the intrinsic level will probably move like this right. So, once the intrinsic level, once the, this is depletion that is creating. So, once the intrinsic level touches this point, once the intrinsic level touches that point, we call it the onset of weak inversion. I keep telling you ok, onset of weak inversion. The total band bending that has happened at the surface is this, this has bent by this amount. And, this amount is called φ_F; you can call ψ_{BF} whatever and that φF is actually $E_i - E_F$ at this bulk because this $E_i - E_F$, this distance at bulk is φF.

This distance decreases at this surf of interface, at the surface, it becomes 0, that is the onset of weak inversion ok. And, this φF you know, your $E_i - E_F$, this $(E_i - E_F)$ quantity if you recall, its actually given by, $(E_i - E_F)$ is given by actually kT/q log of natural log of the doping that you have used by the n_i that you that you have. You have you have this p type doped know, because of p type doping, you have some doping concentration. So, ln of that doping by the intrinsic carrier concentration kT by q; this is equal to actually φ_F or this gap. So, let me erase it again or all of these things. So, so let us make it clean again.

So, $\varphi_F = E_i - E_F = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$

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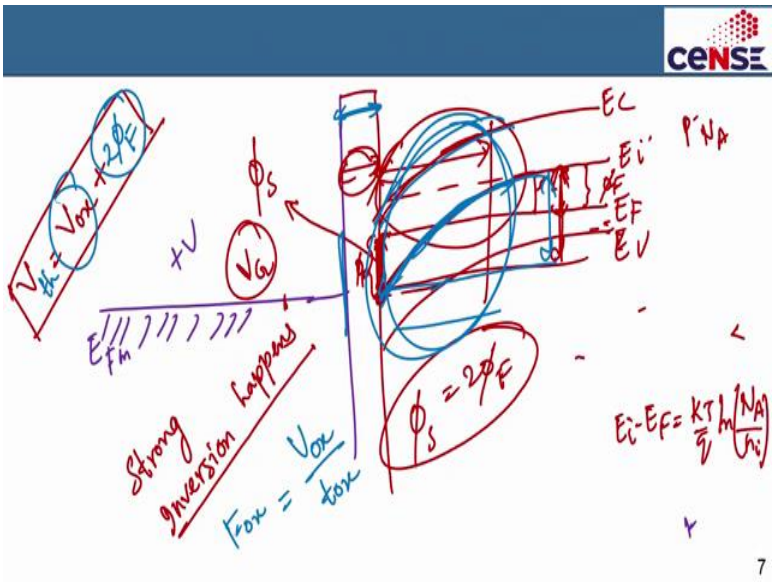

So, now suppose the Fermi level is here, in strong inversion, what will happen is that, this is the Fermi level right. In strong inversion, the reason I am drawing in this again is because we have to write some equations now. So, I will draw it again maybe here, in strong inversion, your intrinsic level E_i will bend as much below this as it is here, which means this is φ_F, this also is φ_F ok. Of course, the conduction band will bend like this the valence band will bend like this ok; if you recall all this. So, the total band bending that has happened is from this point to this point, this is the total band bending that has happened which is 2 times this, this, this is the same as this.

So, at the onset of strong inversion, when strong inversion happens, when strong inversion happens, what will happen is that the total band bending, I call it φ_s at the interface ok, at the interface I call it φ_s, the total band bending that is happening here actually is 2 times, you know, the total band bending that has happened actually is from this point, it has bent to this point.

So, you have bent this much, which is 2 times φ_F. So, when you apply a gate voltage here, you have to apply high gate voltage here so that your band bending happens. When you apply high gate voltage, at any gate voltage for that matter, a part of that voltage drops across the oxide, I call it V_{ox} and a part of that voltage drops across the semiconductor depletion region an inversion layer, I call that V_s, part of the drops in the semiconductor.

Of course, when you have strong inversion, this always holds true because, one no matter what voltage you apply, part of that will always get dropped in the oxide and part of that will always get dropped on the semiconductor depletion and inversion layer totally right. So, no matter what, this holds true, but the moment you have strong inversion, this total voltage that is dropping on the semiconductor here, maybe I should same change the color here. The total band the total voltage that is applying here is actually the band bending that is happening, this band bending that is happening, that is the voltage that is up dropping here.

So, I can write instead of this, I can write it as 2 φ_F that is the total band bending that has happened is equal to the total voltage that has dropped ok. And, this happens at the strong inversion, if you recall, at the strong inversion, I call this point a threshold voltage, threshold voltage. So, I call this as threshold voltage, ok. So, threshold voltage will be some voltage that is dropping on the oxide, we will come to this very quickly. And, the 2 times that whatever extra you know that this on the semiconductor whatever it is dropping. So, let us pause on that and now, what we will do is that we shall think again.

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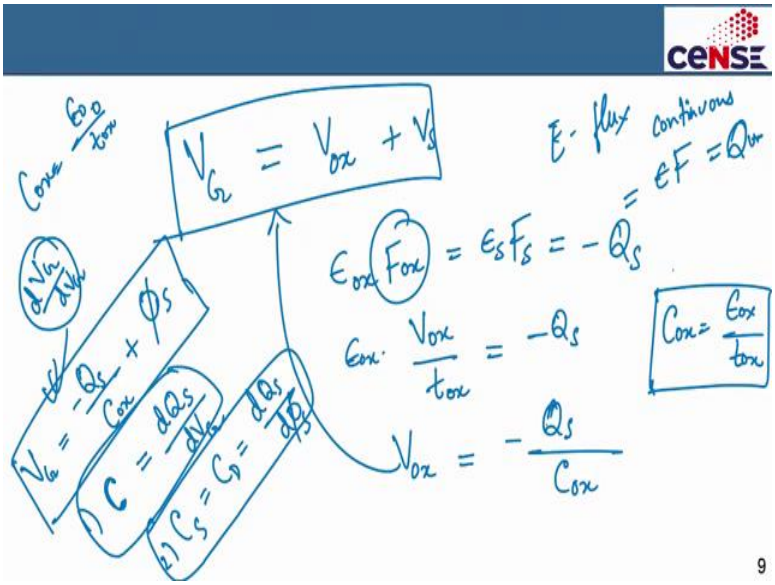

And I will write it that a total gate voltage at any point whether it is whether it is, you know, an inversion, strong inversion or weak inversion does not matter; whatever voltage you are applying on the gate, part of that is dropping on the oxide, part of that is dropping

on the semiconductor. Now, if you recall in a diagram like this, the electric flux has to be continuous right; the electric flux has to be continuous across the interface.

So, the electric flux has to be continuous and that will be given by epsilon times the field and that has to be equal to the total charge, that you are storing ok; the total charge that you are storing. So, let us keep this equation as it is.

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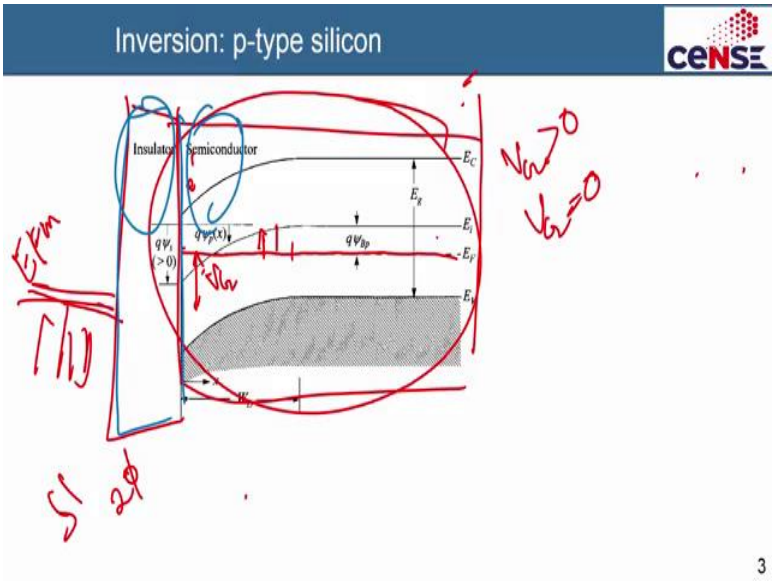

Now, across this interface if you look carefully I mean, you know if you look at this diagram for example, you know there is an insulator here, there is a metal here is. So, the flux, the ξ times the field in the insulator will have to be equal to ξ times the field in the semiconductor. So, I can write that as a, the epsilon in the oxide times the field in the oxide is equal to epsilon times the semiconductor times the field in the semiconductor.

$$\xi_{ox}E_{ox} = \xi_S E_S = Q_S$$

And, this will be equal to the total charge on the gate that we are applying and the total charge on the gate that you are applying is the total charge in the semiconductor because, the total charge in the gate has to be equal to total charge in the semiconductor. Before the inversion is formed, the total charge in the semiconductor is the depletion charge. I can call it also the depletion charge, I will call it $-Q_s$ that represents the total charge in the semiconductor right.

This field in the oxide is nothing actually, this field in the oxide here is nothing but the voltage that is dropping on the oxide divided by, sorry, divided by the voltage that is dropping on the oxide divided by the thickness of the oxide. So, whatever voltage is dropping on the oxide divided by the thickness of the oxide will give you the field in the oxide, field in the oxide.

So, I can write that field in the oxide as ξ_{ox} into the voltage that is dropping on the oxide by the thickness of the oxide, this is equal to $-Q_s$, I can say ok.

$$\frac{\xi_{ox} V_{ox}}{t_{ox}} = -Q_s$$

So, in other words I can say the voltage that is dropping in the oxide is equal to -Q, sorry, $-Q_s$ divided by ξ_{ox} by t_{ox}. Now, this quantity, if you normalize with the area, the ξ by thickness of the oxide is actually the oxide capacitance right. This so, I can write it as the oxide capacitance, ok, oxide capacitance is equal to ξ_{ox} by t_{ox}.

$$C_{ox} = \frac{\xi_{ox}}{t_{ox}} = \frac{-Q_S}{V_{ox}}$$

So, I can write this like this is the voltage that is dropping, now I going to go and put up the equation here.

So, what will you get? You will get V_G, the gate voltage is equal to minus total charge in the semiconductor by the oxide capacitance plus the voltage that is dropping in the semiconductor, which is V_s ok. Or, I can say the voltage dropping in the semiconductor is also φ_s, which is the band bending if you remember.

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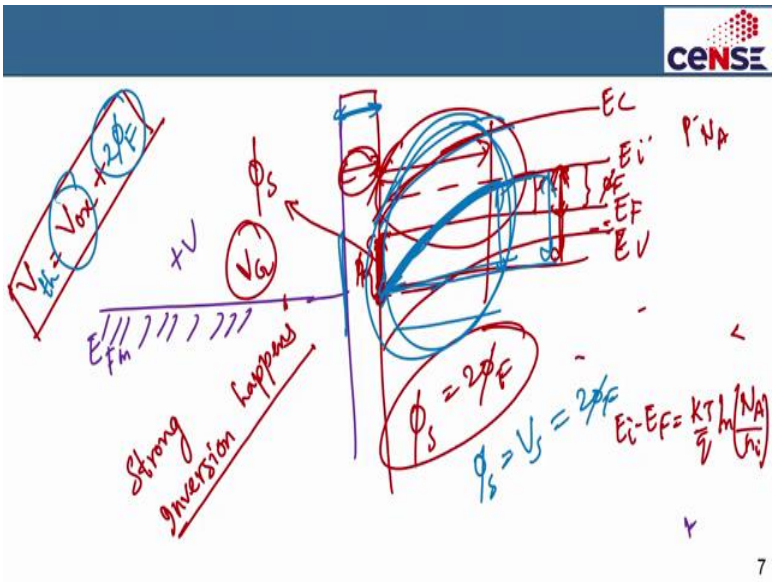

This band bending is actually this quantity, the band bending is called psi s which is the voltage dropping in the semiconductor. In inversion it becomes 2 F, 2 φF because there is twice the band bending right. So, this is the quantity, now, first thing is that we should know that the total capacitance of the system, C, so total capacitance of the system is actually the, you can think of it like the total charge stored in the semiconductor divided by the delta change in the gate voltage.

So, excuse me. So, you can say the total semi the total capacitance in the semiconductor is the total charge in the semiconductor, which is Q_s divided by the total voltage you are applying, ok. The total incremental change in the voltage and the gate that you are applying and what is the change in the charge in the semiconductor, that is the total capacitance.

And this, I define something like a semiconductor capacitance or you can call it depletion capacitance because until the inversion forms, there is a depletion capacitance here remember, this is the deletion, there is a depletion region here no. So, there is a depletion capacitance, I call it right this is the depletion region that is forming, there is the depletion capacitance there. So, I can call that there is a semiconductor capacitance, or you can call it as a depletion capacitance does not matter. That is basically how much if I remove many of these things here it will become probably clear.

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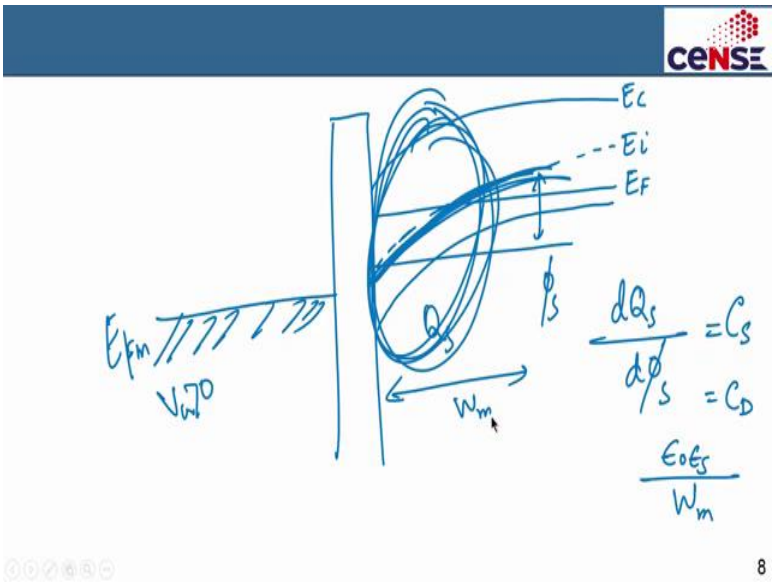

Again, I have to remove this here, right. This is not the Fermi level by the way ok. So, what is happening so, let me I do not know it is not erasing here, this is not getting erased here, but anyways. So, let me use a different actually figure here. So, this is the oxide capacity, this is the oxide, this is the metal Fermi level E_{Fm}, ok, I am applying a positive gate bias here ok. So, your semiconductor Fermi level is up here, your valence band is up to here, your conduction band is up here, and your intrinsic Fermi level is here which has dropped a lot here. So, what is this drop that you are having which is φ_s ok.

The drop that is having, that the band bending that is happening is the total potential you are dropping here, that you know, that the charge that is stored here which is Q_s, the charge that is stored here with respect to what is the change in the charge here with respect to the band bending, with respect to the band bending.

This is called a semiconductor capacitance. In the semiconductor, what is the total charge here and how much you are you modulating with the band bending ok. That is called semiconductor capacitance, you can also call it depletion capacitance ok. And, that essentially boils down to $\xi_0\xi_S$/depletion width ok; this is the depletion width.

So, what I am trying to say here is that this is basically given by $\frac{dQ_S}{d\varphi_s}$. So, if you differentiate this equation, if you differentiate this equation with respect to V_G and take into account that these are the things that you should keep in mind, ok, then what will

happen is that you will get an expression, and keep in mind that your cap oxide capacitance is equal to ξ_{ox}/t_{ox}, then what you will get here is that you will end up getting an expression like ok.

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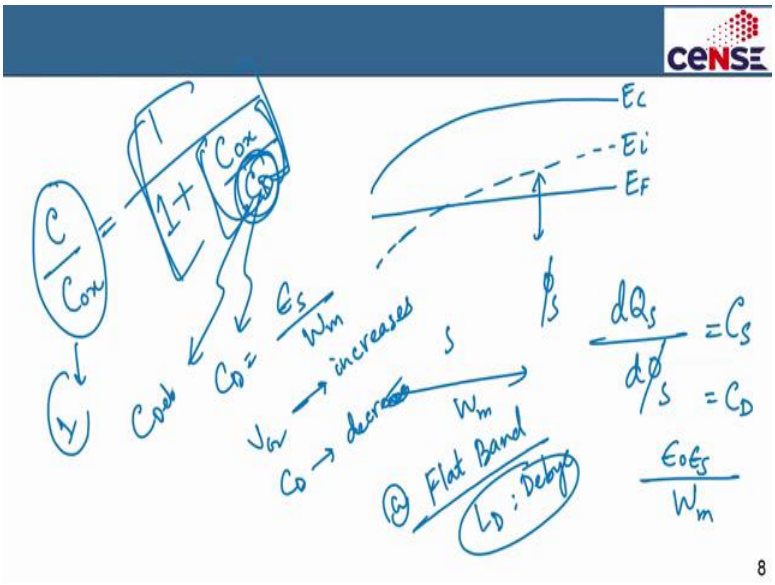

You will end up getting an expression like total capacitance by the oxide capacitance is equal to 1 by 1 plus the oxide capacitance by the semiconductor capacitance, this is what you will get. So, this ratio is basically what is being plotted here, this ratio has been plotted here ok. That ratio has been plotted here, this ratio will be 1; this ratio will be 1 when you are basically going to modulate the charge at this interface only, at this interface at this interface at this interface. If you are going to modulate the charge at this interface only, then your oxide capacitance will show up as the total capacitance; which is what, which is when you will get this ratio as 1 ok.

And, as you make, this is the depletion capacitance you can say and this depletion capacitance, C_D, I told you is epsilon of the semiconductor by the depletion. So, as we apply more and more positive gate bias, as your V_G increases, as your V_G increases your depletion capacitance decreases; if your depletion capacitance decreases, this quantity becomes large. And so, the whole thing becomes small and that is why your capacitance keeps dropping down; your capacitance keeps dropping down as you increase the voltage until threshold reaches and you, strong inversion is formed; until a strong inversion is formed.

So, basically this is the simple expression that tells you that this is the ratio of capacitances that is being plotted here. The maximum this ratio can go is 1 which is what this is 1, this is 1. And in strong inversion also, if the frequency of the signal is small, then it will get 1, otherwise it will be low only. So, that is basically your simple expression for giving the capacitance and I told you that, at 0, at flat band condition, at the flat band condition, when you have flat band condition, you will have every all the bands are flat. And, you will be able to modulate a distance which is only Debye length, I told you in the last class if yesterday.

So, you will be able to modulate only a small part here, which is called the Debye length. No inversion has formed, no accumulation, no depletion, it is just flat band condition. It is like, you know, I have oxide metal here, semiconductor here, conduction band, Valence band it is perfect. There is no depletion, no accumulation, nothing; in that case you will be only able to modulate a small distance that is called Debye length. And so, that Debye length essentially comes in to picture at flat band condition, this quantity will become C_{Debye} ok, the depletion at flat band condition. And, that will manifest itself as this point, but remember this flat band voltage here is 0, but in reality, the flat band voltage will be shifted by the metal semiconductor work function difference ok so, that you should keep in mind.

So, this equation we have learnt now. Going ahead, what we will do in the next class we will wrap up the class here today. So, what we will do in the next class going ahead is that we will take some finite values of metal semiconductor work function difference and we shall try to, you know, see how the different metal semiconductor work function difference will basically change the capacitance voltage curve profile. And secondly, the most important thing is that there are some interface, traps and oxide charges that are there in the silicon dioxide and the interface with silicon.

So, those fixed try or trapped oxide and interface charges will also shift the threshold voltage or the flat band voltage that will also manifest as the C-V profile getting shifted to the right or to the left ok; that is an important thing that is remaining here. So, that will give us a feel for the practical capacitance voltage curve. And, we have written down a couple of mathematical expressions, there are a few more expressions that are remaining. I told you what is the necessary condition for the onset of strong inversion, we shall, I have

written down the expression, it is very simple; 2 times in the bending that has happened plus the voltage that has dropped in the oxide which we shall simplify in the next class.

We shall derive, or we shall not derive, you can say we shall write down the expression for the threshold voltage in an ideal capacitor and in a real capacitor. It is very easy; there is no derivation you have to just think through it. And, we shall write down a couple of expressions for the depletion width that is forming, which you already know by the way.

What is the depletion charge in terms of depletion width and what is the threshold voltage, what is the threshold voltage expression in the presence of oxide trapped charges? So, these are some of the things that we will basically cover in the next class. And, hopefully we will be able to wrap up MOS capacitor portion and we shall be able to move into MOSFET operation from next to next class ok; that is the idea.

So thank you for your time, we will meet you in the next class.