Fundamentals of Semiconductor Devices
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Lecture – 33
MOS C-V in More Details

Welcome back. So, if you recall in the last lecture, we were going through the some of the basics of MOS capacitor, MOS C-V and today we shall be finishing up the discussion and studies on MOS capacitor. So, from the next class, we probably can start with MOSFET, which is a transistor right. Till now we are studying a capacitor. Transistor is also similar except that certain things are slightly different.

Anyways, we have studied about things like weak inversion, strong inversion, depletion in the MOS capacitor. You are now familiar with how those things look like and what why happens, why those things happen right. I told you we had started some equations explaining the strong inversion and depletion and so on.

So, today we shall wrap up some of those equations and also look at real MOSFET, because in reality in MOSFETs, in MOS caps sorry in reality MOS capacitors, your work function difference between metal and semiconductor is not 0 and there will be some trap and oxide charges. So, we have to consider all of those to understand the C-V ok.

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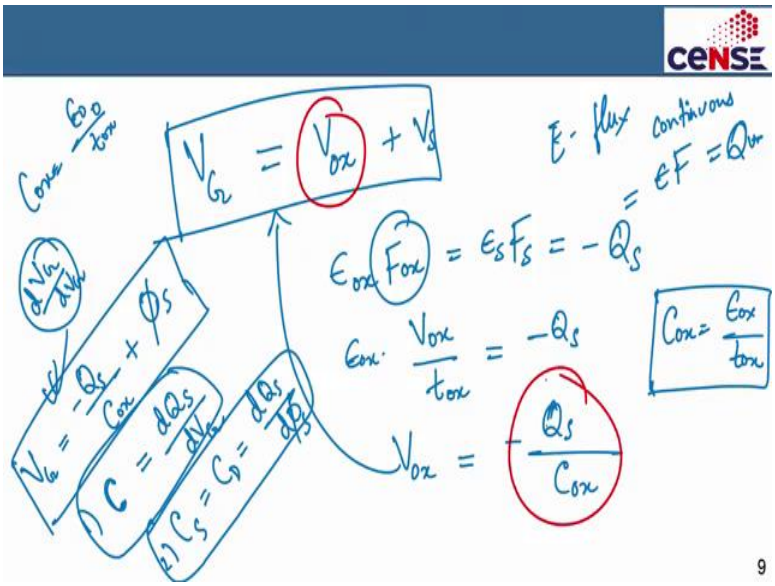

So, let us come back to the last slide where we had left. So, if you recall, I told you that gate voltage that you apply gets divided between the oxide. So, some part of the gate voltage drops on the oxide and some voltage drops on the band bending that is happening in the semiconductor right.

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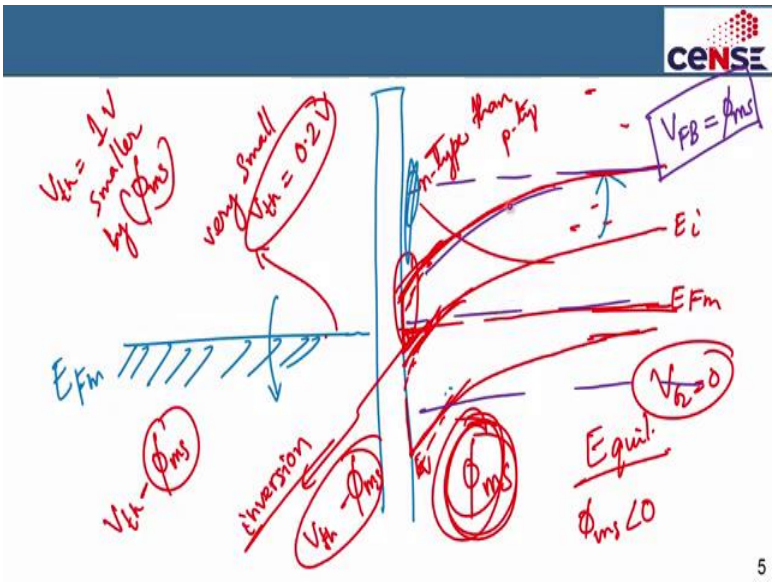

So, what I mean by that is that, if you look at picture, for example, this is for example the MOS that is you know, I am applying a positive bias on the gate so the bands are bending here, so whenever there is a band bending, there is a potential drop across this region. That potential drop in the semiconductor that is causing this band bending is actually this term and the oxide basically means that there is a voltage that is dropping on the oxide. So, the voltage dropped the oxide plus the voltage that is causing this band bending here, that total voltage will give you the gate voltage that you are applying here.

The more you apply voltage here, the more this band will bend. Eventually the Fermi level will come very close to the conduction band, you will start getting electrons here and the moment when the band is such that, I told you this intrinsic level, it is some amount, you know, some energy above the Fermi level, that very quantity, suppose this is 0.2. So, remember this is 0.2 if the intrinsic Fermi level is also 0.2 e V below the Fermi level here, that means, there are as many electrons here as there are holes here, in that case, we call it is a strong inversion and in strong inversion if you recall, the total bending is this that has

bent here and this which is also the same. So, it is a bending has happened for 2 times right.

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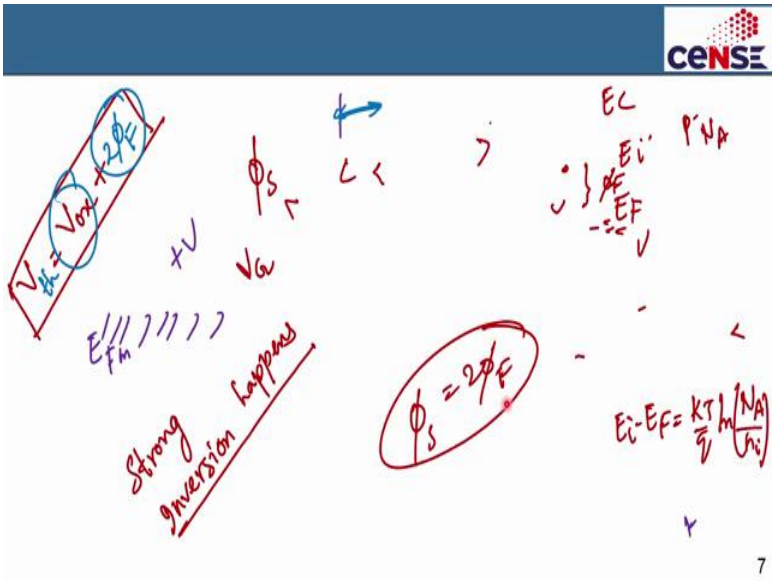

So, in strong inversion, I told you the total bending psi s is the bending on the surface is equal to 2 times φ_F; φ_F essentially is the difference between the intrinsic Fermi level and intrinsic level and the Fermi level. This is φ_F so, 2 times this bending will mean this, again this, which is here right. So, you will get a strong inversion there and that is a condition.

So, if you look in this equation again, I told you this is the voltage that drops on the oxide and this is the voltage that drops on the semiconductor, I told you that electric flux has to be continuous and that will be across the oxide and semiconductor interface. They will be equal to the total depletion charge that is there and if you do some simple math with this conditions that I have written down here, then you will essentially get the capacitance equation eventually.

So, you will see this is the voltage that is dropping on the oxide which is V_{ox} and we get that from the flux here that we did last time, this is the voltage that is dropping that is the band bending in the semiconductor. I told you that the total capacitance of the system; the total capacitance of the system is the change in the charge stored in the semiconductor with respect to the voltage that you are applying to the semiconductor, to the gate right. And the capacitance, this is C_S is the semiconductor capacitance only, actually called also depletion capacitance. So, some textbooks will mention it a C_D.

The depletion capacitance is basically the charge stored in the semiconductor, how is it is modulating with the band bending that is happening here. So, qualitatively speaking, it means what is the charge stored here with respect to what is the band bending here, ok. That is the semiconductor capacitance. The total capacitance is what is the charge stored here with respect to what voltage you are applying here. So, that was the thing.

So, and we know the oxide capacitance is given by nothing, but the dielectric constant times the thickness of the oxide. So, based on this we get the capacitance equation. So, in case, I did not write it down, let me write it down now.

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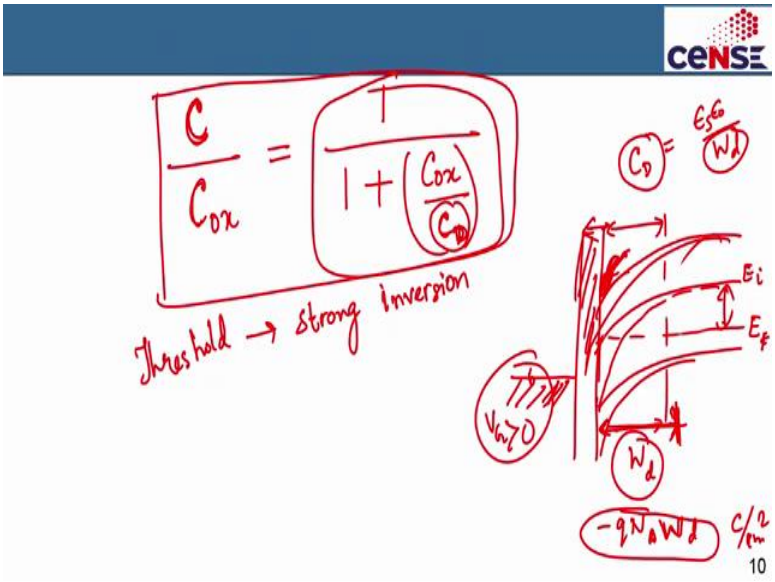

So, if you do that math carefully, then what you will get is that you will get the total capacitance of the system with respect to the oxide capacitance, ok. The total capacitance of the system with respect to that, will come to that actually very quickly, I will show you the equations that have written down also for you here. Eventually, we will have to go to this equation here. So, I will tell you, so, here was I. So, this is the total capacitance of the system and this is the oxide capacitance that is equal to $1 + C_{ox}/C_{depletion}$.

So, essentially this is true not only for inversion; this is true for all circumstances ok. So, this is true for all circumstances. So, when you have oxide here, in applying a gate voltage here and you know positive gate voltage maybe right; positive gate voltage you have applied. So, there is this Fermi level on the semiconductor side here and your intrinsic

Fermi level E_i has bent, maybe it has bent so much. It is probably not in strong inversion nevertheless, right nevertheless, it has bent somehow here.

So, there is some depletion here. The depletion area is where the bands are bending. We call it W say d that is the depletion width and a depletion charge that corresponds to this is basically if you remember - qN_AW_d from your p-n junction basics. The aerial density of the depletion charge is given by the charge times the depletion width.

So, this is the aerial density in coulomb per meter square or centimeter square; that is the depletion charge. The capacitance associated with this area, this is called the depletion capacitance which is this quantity here, depletion capacitance is nothing but the ξ_S/W_d. So, as you keep applying more and more gate bias, I keep telling you the width of the depletion keeps increasing and increasing because you are pushing away holes more and more, which means the width increases, so the depletion capacitance decreases, if the depletion capacitance decreases, then this whole expression decreases. So, this ratio of the total capacitance to the oxide capacitance also decreases.

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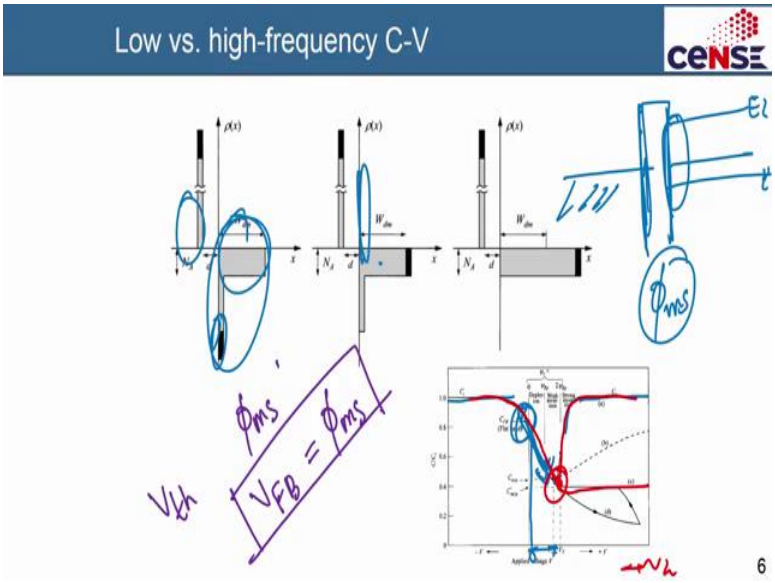

And that is what manifests here in this curve right, it keeps decreasing like this right until it reaches the strong inversion point here. At strong inversion, the band bending is such that you have a very high density of electrons here and it will screen out the field that you are applying essentially. So, you will not be able to get any more a depletion from this

point ok; any more depletion from that point. So, if you are applying a very fast signal, then the minority carrier will not get enough time to generate.

So, all the small changes that you are doing on the gate when you are changing the gate in a small signal, that extra charge has to move in and out here. So, basically your capacitance will become, will be basically get frozen at this point and it will stay like this for a high frequency. If you give enough time, if you do slow frequency, then the electrons and holes the electron minority electrons will get time to generate.

So, again it will come back here because once the minority electron gets time to move in and out of here, then any change here represents a change here. So, you only measure the capacitance of the oxide; that is why you get C/C_{ox} is equal to 1 which is this quantity will become equal to the oxide capacitance.

So, now, we know that in threshold, when you have a strong threshold, when you have a strong threshold or when you say when I when a say threshold, when I say threshold voltage, I mean strong inversion. When I have a strong inversion in the material, a strong inversion in the material means that I have now as many electrons here as I have holes here. So, this gap will become equal to the gap here. So, it will basically drop down here more ok.

Everything will bend more here. So, in that case of strong inversion, we call the gate voltage as a threshold voltage. You see this point we call, this is gate voltage by the way. This point we call the threshold voltage.

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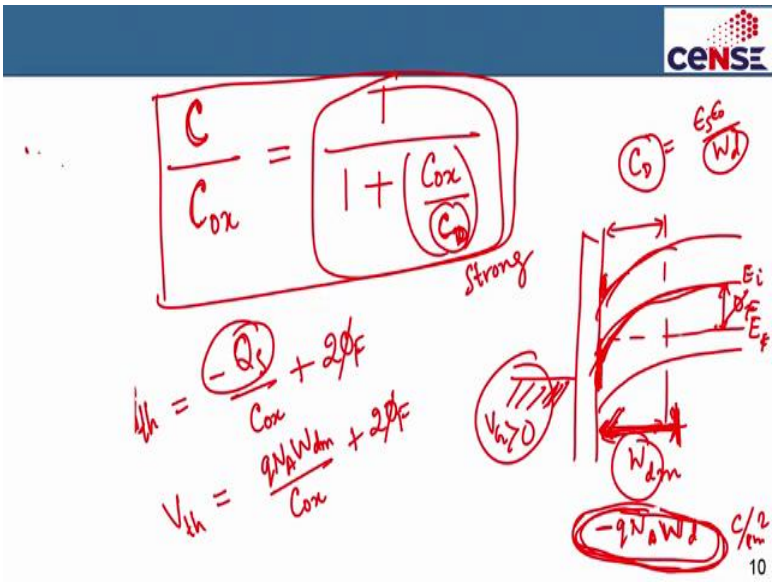

And that threshold voltage will be given by the voltage that has dropped across the oxide which is given by this quantity, where it has gone, this quantity which is basically nothing, but this quantity $-Q_S/C_{ox}$. So, that is given by, where did it go. So, basically your threshold voltage V_{th} will be given by the voltage that is dropping on the oxide. And in strong inversion, and in strong inversion right, this is in the strong inversion, in strong inversion the band that has bent here is actually 2 times this difference φ_F right. Because it has bent this much, again it will bend that much below right.

So, basically it will be 2 times φ_F. Now this quantity is actually the, this quantity ok; this quantity is actually that quantity. That quantity is basically the total depletion charge that has happened and because it is an acceptor p type impurity, the depletion charge is negative. So, the negative sign with the negative makes it positive; that is why actually it becomes positive quantity. It becomes

$$V_{th} = \frac{qN_AW_D}{C_{ox}} + 2\varphi_F$$

This is called the V threshold of course, right.

But of course, you can explain, express the depletion width also in terms of and see this is the point where the depletion is maximum. So, I will call it W_{dm} because the depletion is maximum when the strong inversion happens, after the strong inversion, your voltage you

are applying will not be able to deplete it further unless it is a deep depletion, that is not the case we are talking about here.

So, you know the depletion depth will be maximum when that strong inversion occurs and so, you can find out an expression for that actually right. You can find out an expression for that, that is the depletion depth is maximum.

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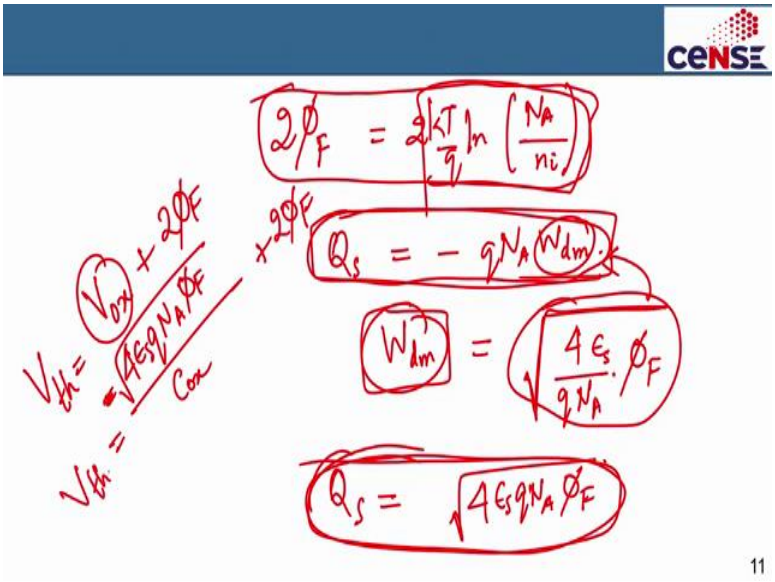

And you have to consider the fact that now, what it is going on here, so now, you will have 2 φ_F as a total band bending which is given by

$2\frac{kT}{q}\ln(\frac{N_A}{n_i})$ so, that is your φ_F. The total charge that is stored here, I already told you that Q_S actually have, because it is a negative charge has already, so eventually it will become negative negative. So, that is equal to qN_AW_{dm} right and then you have at a maximum depletion width here right, the maximum depletion width is happening here. The maximum depletion width will, where is the thing, the maximum depletion width will correspond to the maximum charge that you have in the semiconductor and then in that case, your, under such circumstance, your voltage across the semiconductor is also maximum which is essentially 2 times φ_F ok.

So, now you can actually do some simple math and find out this expression for the maximum depletion width; the expression for the maximum depletion width I mean given the fact that you know this is the case right. This is the case, it will actually turn out to be

a square root of, if I recall correctly, four epsilon actually no, I will I will look at the expression here. It is actually I have written it down later on that is 4 epsilon q by N A.

$$Q_S = \sqrt{4\xi_S q N_A \varphi_F}$$

So, that is 4 ξ_S q N_A into φ_F whereas, φ_F is this quantity right; φ_F is this quantity. So, that is your maximum depletion width that you will have and once you put this value here, you will get the charge in the depletion. This Q_S essentially is the charge that is stored in the depletion, this is Q_S. So, Q_S will turn out to be something like I guess its 4 ξ_S q N_A φ_F, will come out something like that. So, that is your total charge that you store in the semiconductor. This is the maximum depletion width you will have at inversion. This is the total charge you store in the strong inversion, strong inversion when you have threshold voltage, and this is the band bending right.

So, the threshold voltage is now again I can write it as the voltage dropping on oxide plus 2 times the band bending because this is strong inversion. And I can write this quantity if you recall, you can write this, it is gone actually that, I can write that quantity as this quantity which is

$$V_{th} = 2\varphi_F + \frac{\sqrt{4\xi_S q N_A \varphi_F}}{C_{ox}}.$$

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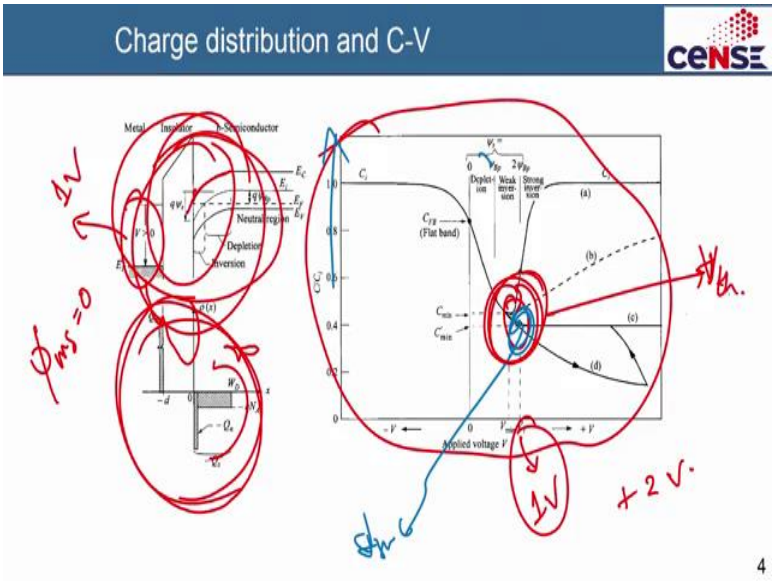

That is your voltage, threshold voltage which will give you this point essentially, this point, which will give you this point, this point, threshold voltage, that is your threshold voltage V_{th} ok. So, essentially some voltage is dropping across the semiconductor; some voltage is dropping across the oxide right.

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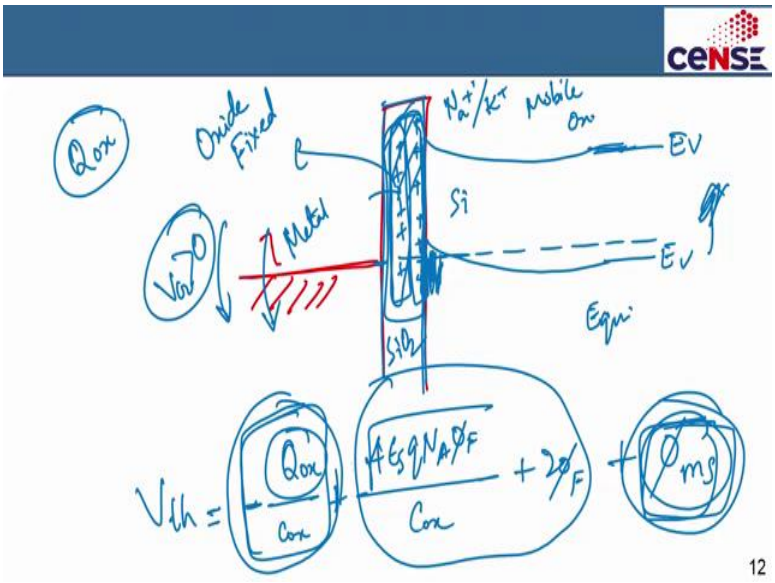

And I told you that in reality; in reality your metal and semiconductor need not be at the same work function before you join. So, we had assumed that the metal work function is here and semiconductor function is here, Fermi level is here. This is the metal Fermi level, semiconductor Fermi level, we have the same work function and so, this condition was a flat band condition at 0 voltage. But in reality, it is not like that; I told you the metal and semiconductor work function could be very different.

So, for example, the semiconductor work function is here, semiconductor Fermi level is here. So, this is when you join without bending like this, but in equilibrium when you join, they will band right. So, the Fermi level will come down here. So, what will happen essentially is that the Fermi level of the semiconductor will come down here and you know it will look like something like this right.

So, initially suppose your Fermi level was here, your valence band was suppose here, suppose this is the valence band here right. Your Fermi level here that you have here will try to align with this metal Fermi function. So, essentially what is happening is that it is going up here. It is going down here like that, right. So, far away from the junction, it will

all be same, you will have, sorry, it is slightly bent here actually. So, eventually I will choose the different color so that this becomes easier.

So, let me choose blue color. So, eventually the Fermi level on both sides will align. Far from the, far from the junction, your valence band and your conduction band will maintain the same difference. What will happen now is that it will look like this ok; it looks like this sorry. So, you will have to remove the, this point, to remove this point remove this point, remove this point ok.

So, this is how your band diagram will look like a lot of accumulation of holes here which means to invert the channel, you have to apply a lot, this is the equilibrium condition; To make it flat to make the bands flat, you have to apply a negative voltage here or even to say you have to apply a positive voltage here, you have to apply positive voltage here to essentially make the bands flat.

So, that extra voltage that you have to may apply to make the bands flat is actually called a flat band voltage I told you and that is equal to the metal semiconductor work function difference that you have. Whatever work function difference initially you had that is the amount by which you have reduced the, you know gap, right I mean you have pulled the bands down, so, that has to be added.

So, in reality, in this expression for threshold voltage, in this expression for threshold voltage which is

$2\varphi_F + \frac{\sqrt{4\xi_s q N_A \varphi_F}}{C_{ox}}$. In this expression, in reality you have to add the term φ_{ms} because that amount of metal semiconductor work function difference needs to be applied additionally on the gate to make it flat and then to invert right.

So, that quantity has to be added, it can be a negative or positive quantity depending on which way the metal semiconductor work function difference is, ok. Now that is one term. So, this is in reality this is a threshold voltage and finally, this oxide that you have here, this oxide can have many types of traps and interface charges which are undesirable. So, for example, this is silicon, this is silicon-dioxide and this is metal right. So, at this interface of silicon-silicon-dioxide you can have some interface traps ok, you can have some interface traps and within this oxide also, you can have some fixed charges. You can

call them either oxide fixed charges right, fixed oxide charges that might be there. There could be also at the interface, there could be some interface charges.

So, they can have many reasons why these have come? Maybe the interface charges might have come because of interface, the nature of the interface and also during very stress operations of this capacitance, you might have hot electron injection, you know that might be injected in the oxide from either the metal or the semiconductor, those might break some bonds, create some point effects. That due to processing issues, there could be some mobile electrons that might come like sodium or potassium ions that are called mobile and not fixed oxide charges, these are mobile oxide charges. All these oxide charges typically club together is a positive quantity; I call it the Q_{ox}.

So, the purpose of this Q_{ox}, what it will do is that this entire positive charge that you have here will further shift the threshold voltage, will further shift the threshold voltage and so, we have to add this term minus Q_{ox}/C_{ox} ok. So, let me write down that better. So, your threshold voltage ok, you have to add that term - Q_{ox}/C_{ox}, capacitance of the oxide, this is the threshold voltage.

Remember, sorry, equal to, remember this quantity, this oxide charges it will be typically positive. So, this quantity the negative sign means that this is a negative quantity. This is a total expression for threshold voltage. These basically shifts the curve; this also shift the curve, this quantity is the ideal threshold voltage, this is because of the metal semiconductor work function difference and this comes because of the oxide charges that are trapped inside the oxide ok. So, what these things will do that this will all shift the your C-V curve.

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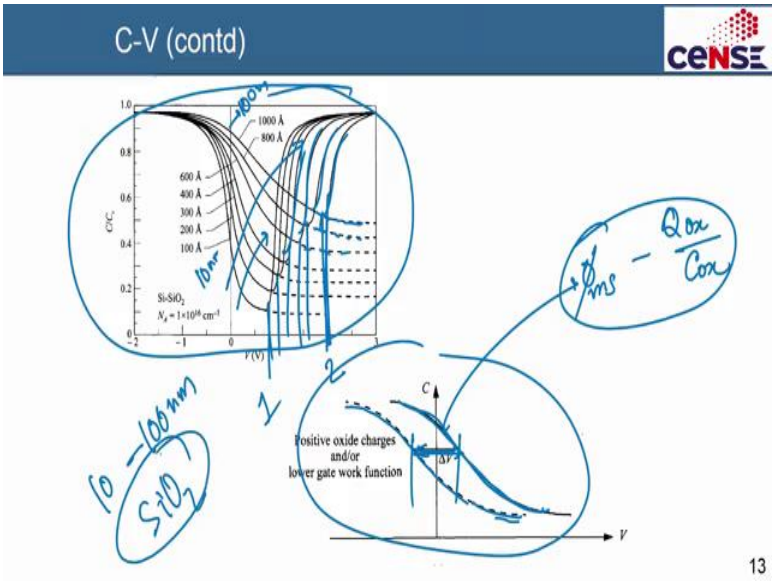

For example if this net quantity is negative, then what will happen is that you see this plot here. This black one was actually the ideal capacitance curve, but it has been shifted; it has been shifted and you get this real practical curve like that. This shift that has happened here, this shift basically is due to this fact that there is a metal semiconductor work function difference and there is also a charge, oxide charges. This shifts the curve; if these were not there, then you would have gotten this ideal curve here and what this plot shows you is that for different thicknesses of the metal, so this 100 Armstrong is in 10 nanometer, 20 nanometer 30 40 and so on and even 80 and 100 the top one is 100 nanometer, so if your gate oxide thickness, if your silicon oxide the gate oxide thickness which is the thickness of this oxide you know; if this thickness keeps increasing, then your C-V looks increasingly like that.

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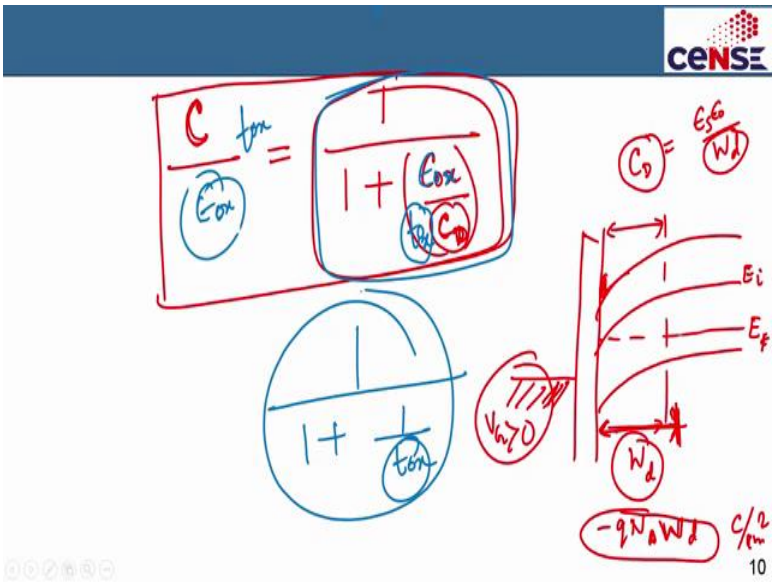

You can look from this expression that I had written down here. You know if your oxide, if your oxide thickness increases, then this is actually nothing but epsilon ox by t_{ox} right. So, this is epsilon ox by t_{ox}, ok. So, if your thickness of the oxide actually you increase the thickness of the oxide, then this ratio also will increase actually ok. You can see that it is like 1 / (1 + ($1/t_{ox}$)) something like that. So, if your t_{ox} increases, then this quantity also increases actually.

So, if a thickness of the oxide increases, your capacitance values also increase; that is why you are getting a slightly upper shifted curve here you see. This is the high frequency curve. This dotted, this dotted line, and this is solid lines and a low frequency curve, solid lines at a low frequency curve. You can see you have higher thicknesses, they moved that way right and the threshold voltage also keeps changing with higher threshold, with higher thickness of the oxide, your threshold voltage also becomes higher. It has gone from almost 1 volt to almost 2 volts if you change it from 10 nanometer to 100 nanometer of silicon dioxide and that is because your threshold voltage, your threshold voltage depends on the oxide know; it depends so much on the oxide.

This is oxide right. So, when oxide capacitance decreases, when your thickness increases, the oxide capacitance decreases and the oxide capacitance being decreasing, this will essentially make this large know, that is why your push is also large. So, your threshold voltage also has become larger essentially.

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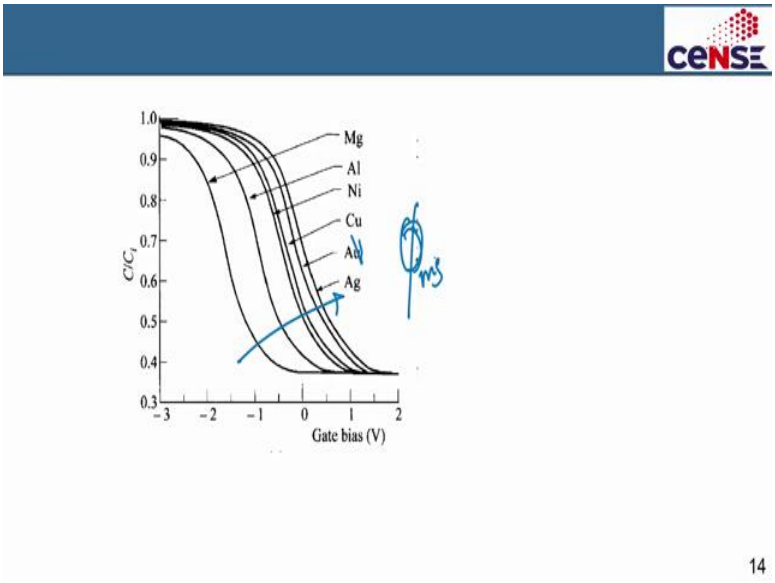

So, let us recap now whatever we have learnt, this is the same thing for different metal work function. So, when your work function of the metal changes, aluminum, nickel, gold and so on, your curves also will shift because your φ_{ms} the metal work function difference also will be different right.

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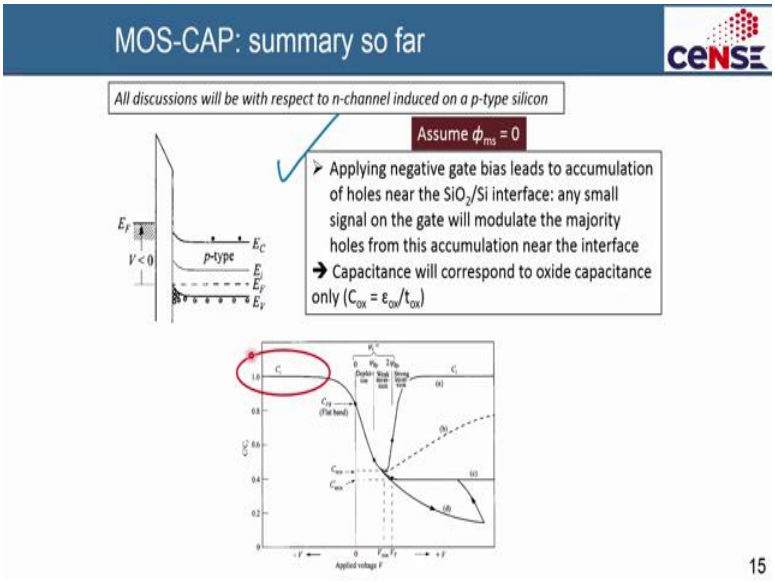

So, the question is now what are the things that we have learned? Let us summarize the MOS capacitor till now. Please be very attentive to this part, MOS capacitance whatever we have assumed till now. We have assumed that the metal work function difference is 0

initially. So, and will discuss that these are all on p type silicon. So, the channel that is formed is an n type channel.

First point that you should remember is that when you apply a negative gate bias. So, let me take the laser pointer here. When you apply a negative gate bias on the gate, it will pull the holes here because it is negative charge right. It is a p type majority, you will have accumulation of holes near the silicon – silicon dioxide interface. Any small signal on the gate will modulate the majority charge here; Thus, only this capacitance will play a role that is why the total capacitance will be equal to the oxide capacitance only, when you apply negative gate voltage and so, this is the capacitance voltage curve at 0. At this negative, at negative gate voltage, you will only get oxide capacitance. So, the ratio of the total capacitance to the oxide capacitance will stay as 1.

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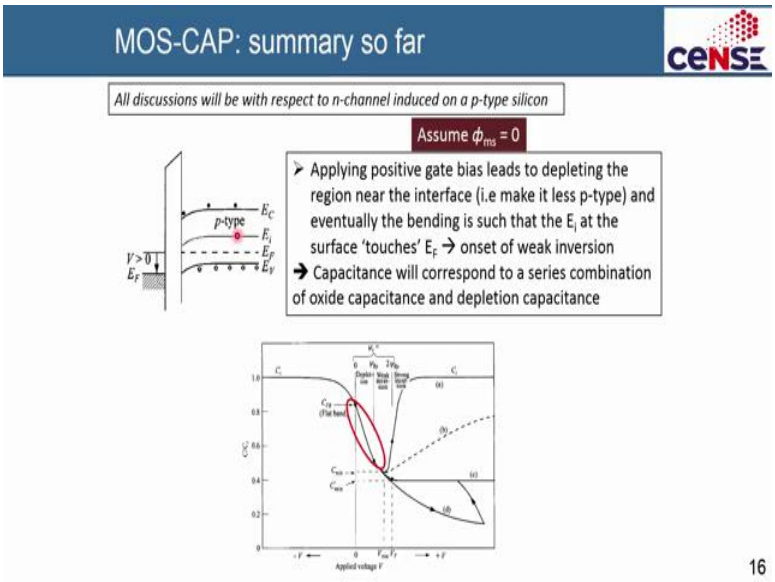

When you apply a small positive bias, you will push away the holes away from here. So, you will create a small depletion, your bands also starting to bend because of that and what will happen is that, as you keep applying more and more positive voltage, your depletion will keep increasing more and more, which means the capacitance associated with this; the depletion capacitance will keep decreasing and the depletion capacitance is in series connection with the oxide capacitance. This is the total capacitance also will decrease. So, we can see this region as you apply more and more positive voltage, the total capacitance, that mean, this is the ratio capacitance of course, this total capacitance is also decreasing

ok. It is also decreasing until you are now almost getting weak inversion which means you are applying such a high potential here, such a high voltage here that your intrinsic Fermi level E_i is now touching the Fermi level, the surface, that is called the onset of the weak inversion after which the intrinsic level will keep pushing down below the Fermi level.

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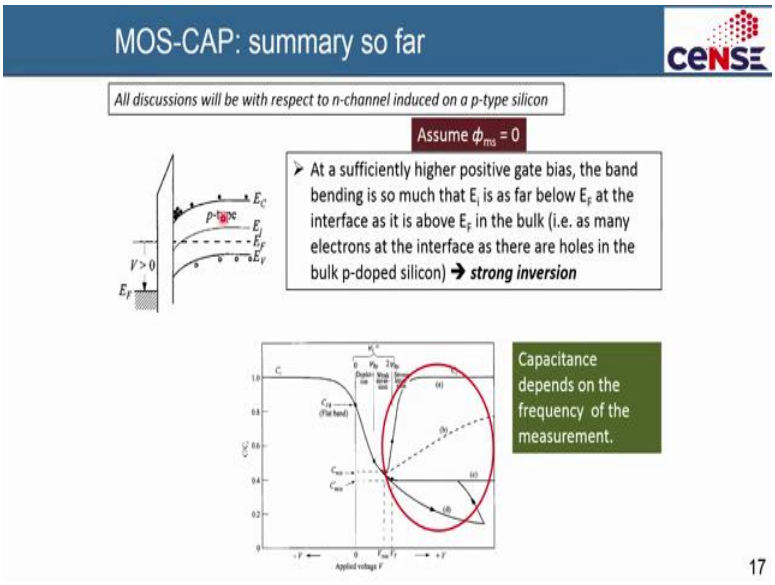

And at one point is such that, the bending below the Fermi intrinsic, the Fermi level of the intrinsic level will be so much that is that the quantities as much as here, which means the difference between the intrinsic level and the Fermi level here is exactly equal to the difference between the Fermi level and the intrinsic level here which means there are as many electrons here as there are holes here. This is the majority carrier p type doped semiconductor.

So, there is a large number of holes here. If you have equal number of electrons here it means it means, you have inverted the channel from p type to n type. So, you have more electrons here, as many electrons here as there are holes here, which is a very you know interesting situation because despite being a p type semiconductor, you are able to invert the channel and you are forming an electron gas here and it is called strong inversion when this bending is 2 times this; which means it has bent this much, again it has bent that much, so it has come here. So, you have the 2 times that bending; it is called strong inversion. One strong inversion form, this metal this high density of electrons that are formed, will screen the electric field that you are applying, will not allow the depletion to go further.

So, your depletion width whatever which has achieved till now is actually the maximum depletion width that corresponds to a minimum depletion capacitance, that corresponds to a minimum total capacitance which is this and the capacitance will stay at this value if your small signal is modulating very fast, so that the minority carrier electrons are not getting time to generate here thermally. So, any change you are doing here will have to be compensated by a change in a majority carrier moving in and out at the edge of the depletion region.

So, the series capacitance of this oxide capacitance and the large depletion region here, that corresponds to a very low the capacitance, will be this value which stays flat with high frequency capacitance profiling. If the capacitance has slowed and electrons the minority electrons will get enough time to generate and you will recover the capacitance once again here. So, because any change here will be changed by the electrons here, so, you will essentially get the oxide capacitance which is this right.

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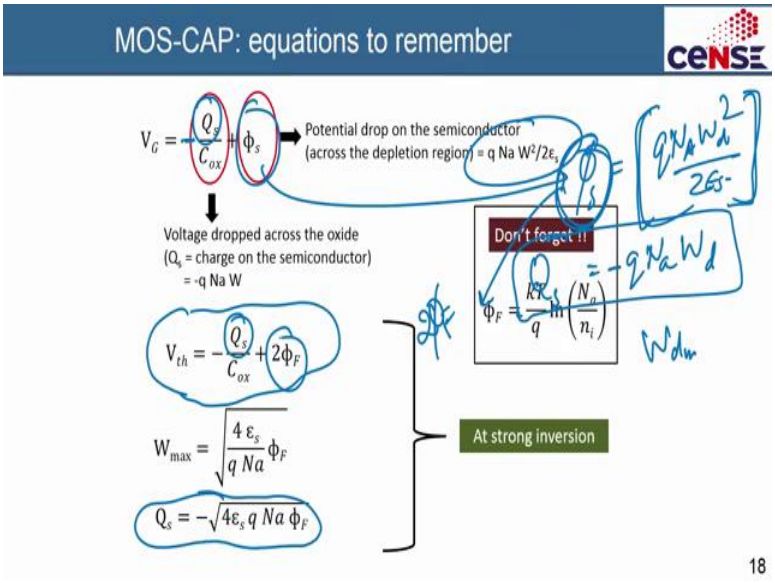

This is the total voltage that you apply on the gate, some of them drop on the oxide, some of them drop on the semiconductor right. So, I have told you that this is the potential drop across the semiconductor. That is the potential across the semiconductor and if you remember this quantity, I will tell you again. So, let me write this down.

This, the potential drop here is psi of s which is equal to this quantity $qN_AW_d^2/2\xi$ and this, that this is the potential that is dropping ok, but the charge that is there, this charge Q_s, this

charge in the semiconductor, this charge is given by this; which is minus qN_AW_{dm} and max. I mean this dm comes in the maximum depletion otherwise its - d. So, this quantity of course, there is a negative sign here. So, the negatives will cancel here. So, this is the total charge in the depletion region.

This is the potential that is dropping in the depletion region, right, and at strong inversion, this becomes equal to 2 φ_F; it becomes equal to 2 φ_F because the band bending is 2 times the band bending is if you recall, the band bending is essentially 2 times this, right, ok. So, from there actually, you find out the expression for the maximum depletion width ok. Anyways, this is the voltage that is dropped here, this is a potential that is dropped here. These are the equations that you should keep in mind; this is the threshold voltage under the ideal condition and I have written that down in a more elaborate fashion also.

This Q_s actually is this quantity which i have written down and this quantity, if it is a negative, so it will become eventually positive and this is the maximum depletion width that will come.

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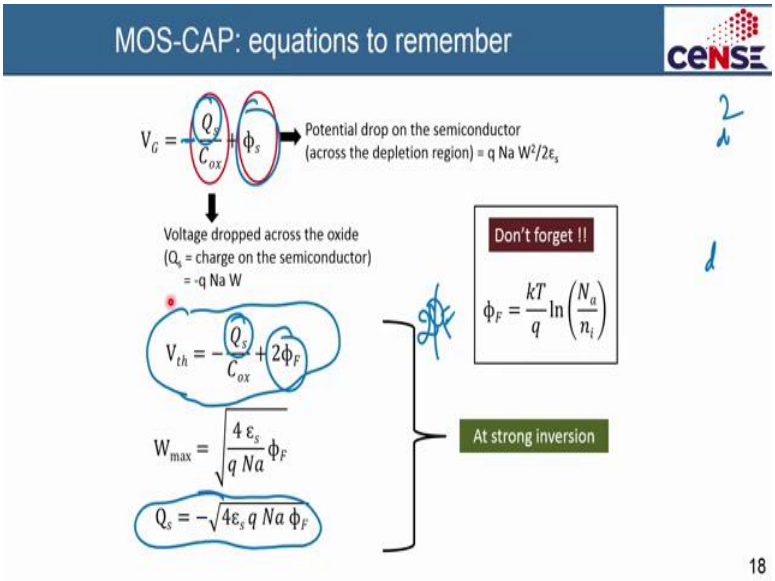

And this of course, you should remember let me rub this out here, do not forget that this quantity φ_F actually represents this quantity ok. It represents this quantity only. So, let me go back to the laser pointer again here. So, you have to plug in these values to get the threshold voltage for any numerical equations that you have.

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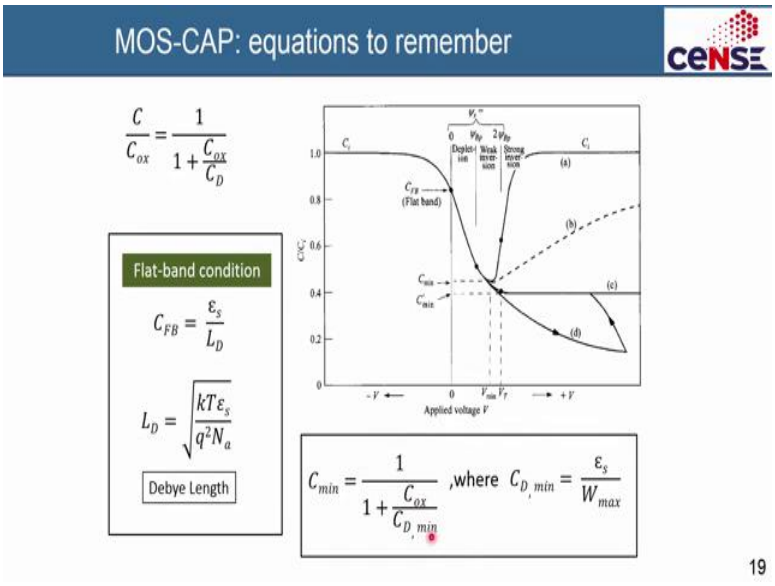

This is the ratio of the capacitance that I have already told you right and this is the eventual C-V plot that you have. I told you at 0 voltage or at any flat this is 0 voltage your flat band, but if you have real MOS capacitor, then the flat band voltage will not be 0. No matter wherever the flat band voltage is, but whenever there is a flat band condition like the bands are completely flat like this, right, I will show you this figure again. This is the total flat band condition, it can come at V_G equal to 0, it can come at V_G equal to negative or positive voltage, does not matter when this is the flat band voltage. And in the flat band condition, in the flat band condition, whenever you apply a small voltage on the gate, you will be able to modulate a small depth of the semiconductor, that is called the Debye depth or Debye length.

And corresponding to that you have a Debye capacitance; this is a Debye length and the Debye capacitance will be in series connection this quantity, you have to put here this expression will still be valid this depletion capacitance instead of that you have to put the Debye capacitance because you will be able to, you will able to modulate only a small thickness of the semiconductor; that is called the Debye length.

And this is of course, the you know the minimum capacitance value is given by here where this is the W_{max} here which we have already discussed in this. So, please remember these slides these equations that am writing here. These are very important on, this will give you all the things that you need to know in a C-V capacitor ok.

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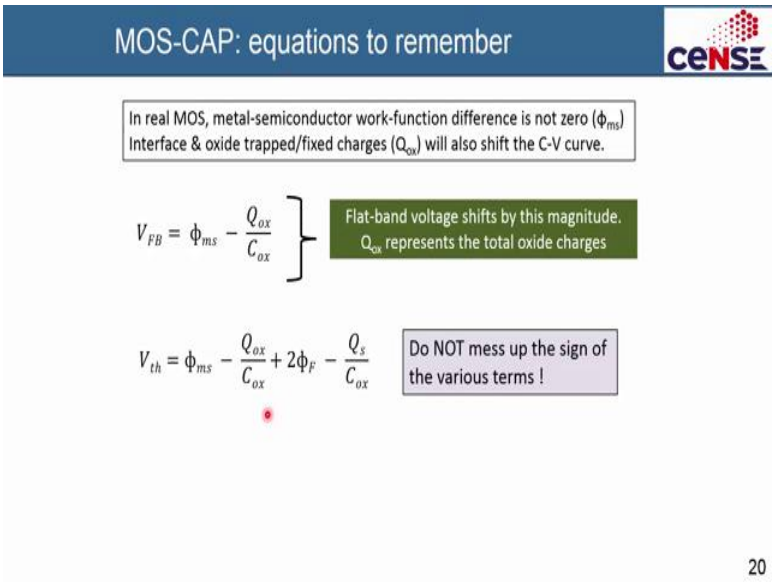

So, in real capacitance the metal semiconductor function will not be 0. There will be some fixed oxide charges. So, this flat band voltage will become, which was ideally 0 in a in an ideal situation the flat band voltage was 0, will actually get shifted by the difference of the metal semiconductor work function and also because of the positive fixed charges that are there in the oxide. So, the total threshold voltage now will be looking like this; I told you this is essentially the same expression that I had written down for you a little bit back.

This is $4\xi_s q N_A \varphi_F$, that is what I had written here. If you remember, $4\xi_s q N_A \varphi_F$; this is the thing right you remember this. This is the expression that I had written here. If you remember right, this expression that I written here, the threshold voltage expression right. This threshold voltage expression will be shifted by the, this is the expression I have written, will be shifted by that oxide charges and the metal semiconductor work function difference. It is essentially the same expression that I am writing here in nicely, but in a neat way.

This is the total threshold voltage, this is the flat band voltage that is the voltage that you have to apply to make the bands flat in the presence of non-idealities like fixed oxide charges and metal semiconductor work function difference. Ideally this should either be 0, but in reality, it is not 0. So, you have to take into account the flat band voltage and you have to add this flat band voltage to the threshold ideal threshold voltage, this is ideal threshold voltage; you are adding these 2 terms here that, so it looks like that. Do not mess

up the signs here and so that basically brings us to the conclusion of the MOS capacitor because in the next chapter, we will start MOS transistor ok.

Once we start MOS transistor, we will realize that this MOS capacitor whatever we have learned till now is very important because we will need them all the time and it becomes a little bit trickier there. So, we will end the class here with our ending the MOS capacitor, all the things that we have learned till now.

We have learned about how accumulation depletion and inversion take place, the different expressions for them, the depletion width the charge it is store in the semiconductor and most importantly the threshold voltage; a threshold voltage basically defines when a semiconductor comes into strong inversion, there are as many electrons on the surface as there are holes in the bulk per unit dense area and that is called strong inversion.

Your semiconductor bands have bent so much that your Fermi level is now as much above the intrinsic level in the surface as it is below the intrinsic level in the bulk. So, that is called strong inversion and you have a strong inversion, your depletion depth has become maximum, your capacitance has become minimum. So, the total capacitance also becomes minimum, the dip comes there, that point is called threshold voltage. The threshold voltage will be given by the 2 times the band bending that has happened. The total band bending that has happened essentially which is 2 times E_i - E_F and the voltage there is dropping on the oxide, but in reality, there is also shift because of metal semiconductor work function difference and also because of the positive oxide charges. So, this is for a p channel device.

For an n channel device, this is for n channel device sorry on a p substrate. If your substrate is n type doped with a channel that is formed of holes and p channel, then everything remains same except that the polarity of the charges would flip because the depletion charges in that case will be positive, because it will be positively charged ionized donor impurities. So, the signs you have to be careful with some of the signs of the expressions, maybe we can do some numerical in a later class to clarify this aspect ok.

So, that brings an end or a conclusion to the MOS capacitor that we have discussed till now. What we next start is MOSFET. So, MOS transistor, so maybe in the next few classes, we will try to wrap up the MOS transistor. We will go in a way that is more simplistic to understand, will not go in too much more complicated depth for advanced learning. We will try to understand how MOSFET works and from there, we will also go

to compound semiconductor that. So, that is the agenda for the course in the next few lectures.

Thank you.