Semiconductor Devices and Circuits
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Lecture – 33
MOSCAP – Continued

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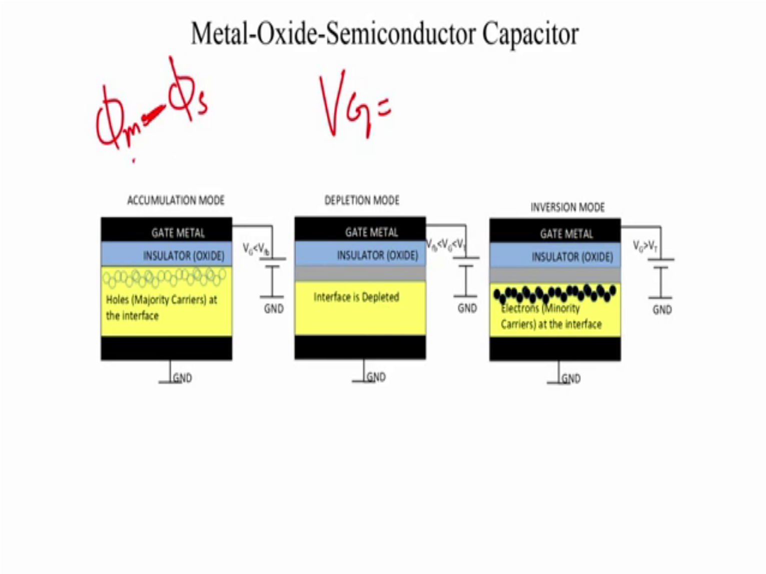

So, we defined something called the flat band voltage. So, at equilibrium the bands need not be flat it will be flat only when phi m is equal to phi s, but that need not be the case. And this phi m minus phi s is the driving force for any band bending at equilibrium, but now when we start applying a gate voltage we take the semiconductor we take the MOS capacitor out of equilibrium and when we make V G equal to V fb.

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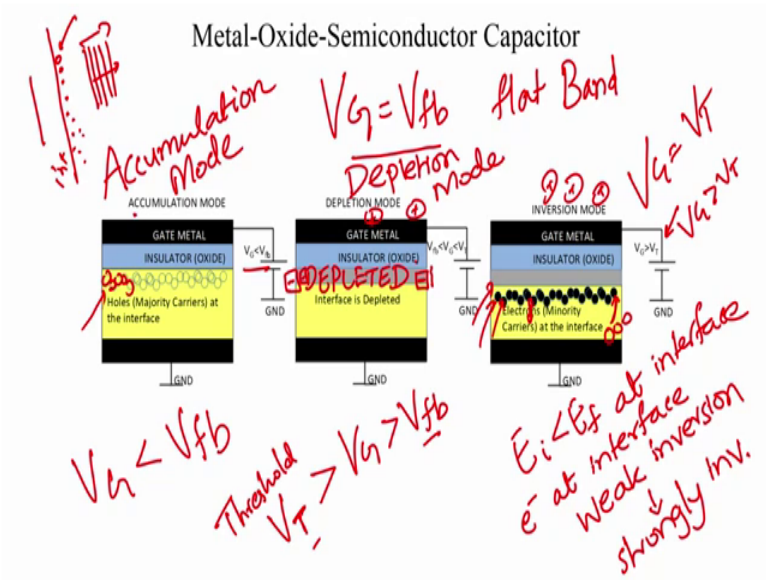

We achieve flat band all the bands become flat. So, that is like a starting point for all our experiments all the bands of flat. And we need to create this kind of an offset voltage to make all the bands flat when we make V G less than V fb we bring the majority carriers at the interface. So, in this case; so here we are all talking about only a p type semiconductor ok. So, the same arguments hold for an n type semiconductor the only thing is you need to watch for the electrons being the majority carriers and holes being the minority carriers ok, but here we are talking about a p type semiconductor

So, when V G is less than V fb we bring holes to the interface ok. So, the hole start appearing at the interface. And this mode of operation is called as an accumulation mode of operation; so is again a technical term. So, when we say that the MOS capacitor is an accumulation mode operation it means that the gate voltage is such that the majority carriers in the semiconductor are at the interface.

Now, let us say we start making V G greater than V fb, but we are still less than V T you know V T is our threshold voltage. So, V G is sitting somewhere between V fb and V T, but what happens in this case is that the gate metal now has positive charge ok. And therefore, it has to be balanced by the negative from the p type semiconductor and that is done by depleting the semiconductor. So, this is the depletion this region is all depleted. So, ideally speaking there are no free carriers in that region. So, the insulator semiconductor interface is depleted. And in this case all the negatively charged acceptor ions are exposed and they are balancing all the positive charge on gate metal.

And this mode of operation is called as the depletion mode of operation depletion mode of operation. And then when you start increasing VG further and further you first you will reach a point where the E i starts going below E f E i starts going below E f at interface and electrons will start appearing at the interface. So, when E i is just started going below E f it is something called as weak inversion weak inversion. And when E i has gone well below E f well below E f and when the when the electrons at the interface when the electron concentration at the interface matches the hole concentration in the bulk. We say that the semiconductors the MOS capacitor strongly inverted strongly inverted strongly inverted.

And this happens at V G equal to V T. And when you make V G greater than V G all the excess positive charge in the gate is now mostly compensated by the electrons rushing at the interface and not so much by the depletion not so much by the depletion charge. The depletion width stops increasing. So, initially this is a story. So, initially you had flat band when you start making V G greater than flat band first the first thing that happens is that depletion width.

So, let us say that is the interface the depletion width starts increasing ok. It uncovers more and more positive charge, but the moment electrons start appearing at the interface this increase in the depletion width more or less stops. Because a small increase in the gate voltage will exponentially increase the number of electrons at the interface. And therefore, you have a lot of electrons coming in there to balance any positive charge.

So, that is the story of everything that is going on in a MOS capacitor.

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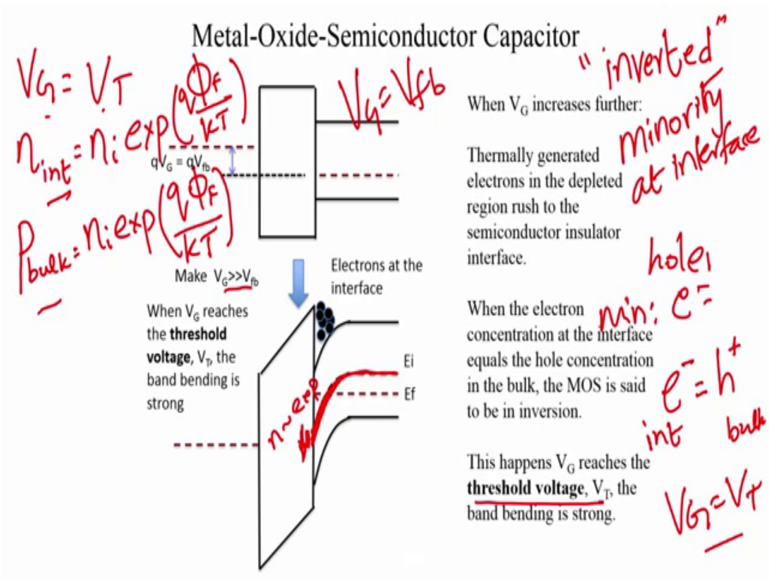

So, go back and look at the band bending picture again just to make things clearer. So, the moment you hit inversion, so you see this bending. So, initially it was just bent like that. So, that was the depletion operation. And the moment it started bending like this you have an equal number of holes and electrons at the interface ok. And then, when you start bending it further down you have more electrons at the interface than the holes. And finally, reach a point when the electron concentration with the interface matches the hole concentration in the bulk and that is what the definition of our threshold voltages.

Now, if you still increase the gate voltage further, this band will not move too much more. It is not going to bend this much, because now the electrons have started appearing at the interface in large numbers. So, beyond at this point this band bending is not going to increase to much more. I mean you need to really make your gate voltage very very large for you to see any significant movement in the band bending that, and that is because for any small movement they export the electron population increases exponentially. And therefore, you have a lot of electrons coming in that easily balance all the charge and the gate.

So, you really need to make a significant amount you need to add a signature amount of positive charge in the gate in order for you to see any movement in the band bending. And therefore, after inversion or after threshold or after strong inversion you could say that the band bending is the bands are almost pinned ok. So, they are almost pinned at this point they are not going to move too much. And another technical term which I should have probably mentioned is that is to define this potential.

So, let us say I create this voltage this built in potential as a reference ok.

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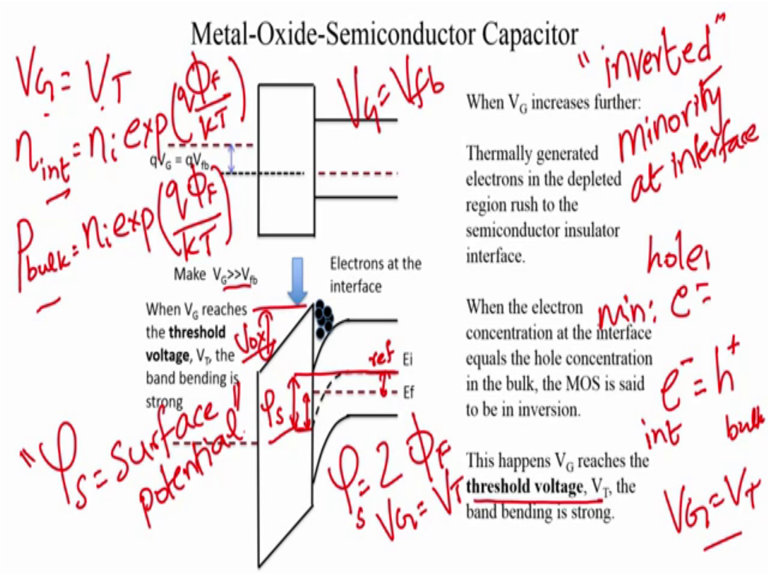

So, let us say that is the reference potential. This potential which is the total amount of band bending in the semiconductor has got a special term, and it is called as the surface potential, phi s is the surface potential ok. So, that is the complete band bending in the semiconductor.

So, at threshold voltage what is the surface potential? The surface potential is going to be 2 phi f, because it is going to be phi f here and phi f there ok. So, meant surface potential is equal to 2 phi f your V G is equal to your threshold voltage. So, this is a very useful term to remember, because we will keep using reference in this particular term. And since, we have defined the surface potential and if you define the voltage drop across the oxide, you can now the summation of the voltage drop across the oxide plus the surface potential has to be equal to V G minus V fb ok.

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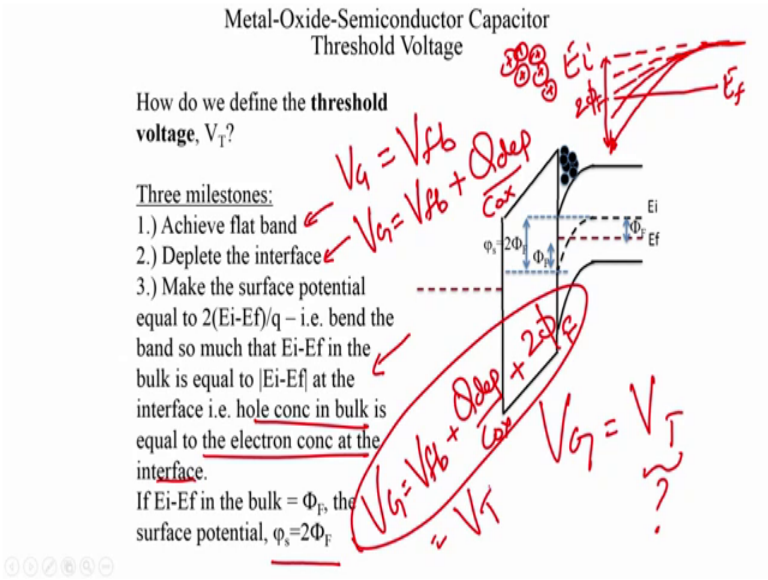

So now how do we define threshold voltage? So, let us now start coming to a more quantitative definition of threshold voltage. Because it is such a useful in modeling parameter, but you must remember as I mentioned the semiconductors the electrons are not waiting for the threshold voltage to you know for the gate voltage across the threshold voltage before; V before they invert. I mean there is some weak inversion happening even before the surface potential reaches to phi f ok. So, the moment the surface potential goes increases beyond phi f you have electrons appearing quite rapidly at the interface. And these are all the thermally generated electrons here.

So now let us say how to define threshold voltage. There are 3 milestones right you need to cross these 3 milestones. So, how do I define V G in a more quantitative manner? So, V T looks good, but what is V T exactly you know what does it depend on. So, there are 3 milestones. Firstly, let us make the bands flat. We do not know what the equilibrium gives you. So, let us first make the bands flat. So, VG has to first cross. So, VG must first equal the flat band voltage ok.

After that we keep increasing VG you start depleting the interface. You know the bands you have E f initially that was E i it was all flat band ok. So, that is let me just draw this clearly. That was E i it is flat band and now you start depleting the interface the E i starts bending a little and you start having depletion. And then you keep bending a bit more you still have depletion. So, you then have to cross the second hurdle which is not only have built put added a flat band voltage, but you start depleting the semiconductor and this total depletion charge by C ox or the insulator capacitance is the effective voltage. That you need to add, and then you still start keep adding more and more positive charges still not enough. You have still not reach threshold you keep add adding more and more positive charge.

And now you will see E i go below E F. And now the electrons have started appearing, but we have still not reached threshold voltage. We reach threshold voltage only when the surface potential equals 2 phi f ok. So, the third milestone is to make E i bend the E i minus E f at the interface have the same magnitude as the E i minus E f in the bulk. Or in other words make the electron concentration of the interface match the hole concentration in the bulk. So, the hole concentration in the bulk and the electron concentration at the interface are the same. At this point the surface potential is 2 phi f and your you have added enough charge to make V G equal to V fb plus the depletion charge plus 2 phi f. And when you have added enough charge to make all this happen then you can say that you have reached threshold voltage.

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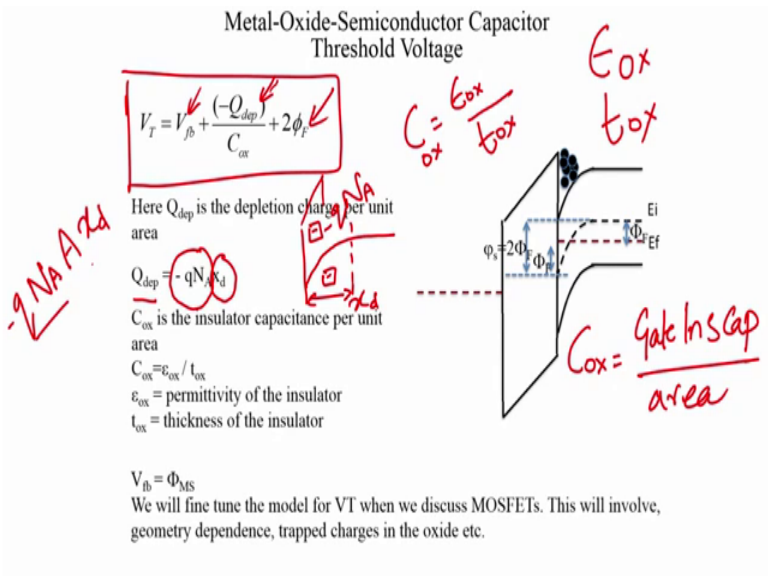

And therefore, the threshold voltage has got these 3 components, it is got V fb which is the flat band voltage it is got q depletion by C ox and I put a minus sign here, because in this case it is all the acceptor ions. You will see because the q depletion has got a negative charge it is negatively charged acceptor ions. So, you first reach V fb, it is the flat band voltage then you deplete the semiconductor. And finally, you make the surface potential reach 2 phi f and it is only when these 3 happen that you could say that that is enough charge in the gate that from this point on the semiconductor strongly inverted or the most capacitor strongly inverted and that voltage is the threshold voltage.

So, in some sense this is the definition of the threshold voltage. Now let us start getting into the details of these little terms here. So, what is V fb, what is q depletion, what is the C ox, what is phi f, ok? So, what are these things? C ox is the gate insulator capacitance per unit area ok. So, it is the gate capacity gate insulator capacitance per unit area. So, it is not the total capacitance.

So, since it is per unit area what does it depend on. So, let us say the insulator has got an permittivity of epsilon ox, ox for the oxide. And it is got a thickness of t ox the total capacitance would be C is equal to epsilon ox A by t ox where A is the total area, but since we are looking at the per unit area capacitance C ox is simply epsilon ox by t ox. So, that is your C ox ok.

So, we understand that in term. What does q depletion? So, this is something you are already familiar with you have solved personas equation enough number of times that you know that in a p type semiconductor which is depleted. You have q NA as the charge minus q NA minus acceptor ions are all negatively charged minus q NA is the charge per unit volume in the semiconductor into the depletion width right. So, you have that is x d and you have this minus q NA is the total charge per unit volume. And there is some area, but since we were looking at charge per unit area we do not really worry about that is a q NA into x d ok.

If you had some area q NA into A into x t would be the total charge present, because this charge per unit volume there is part of it which are you know is not visible on the display here.

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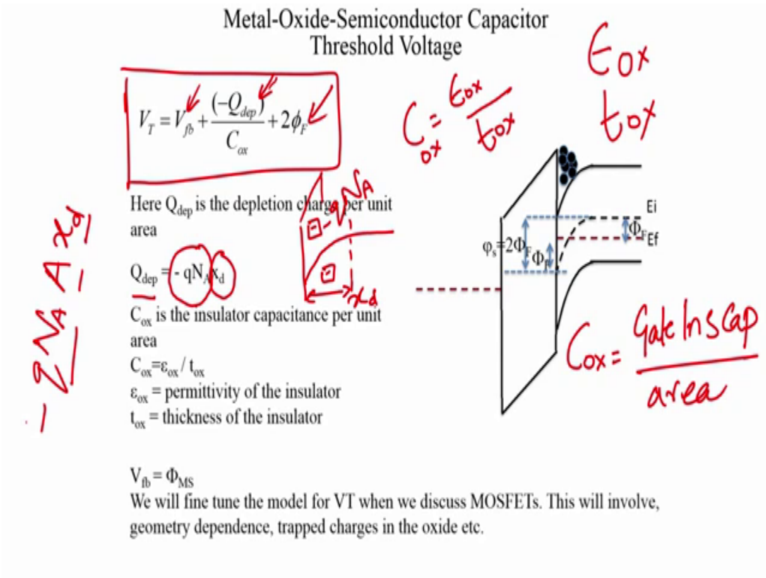

So, minus q NA a into x d is the total charge present, because this is charge per unit volume it is the area and that is the depletion width. So, the charge per unit area is simply this stuff. So, that is your depletion charge. So, that is the amount of charge you need to put on the gate that is completely balanced by the depletion in the semiconductor ok.

So, you understand what this is you understand what this is what is V fb? V f p is simply a phi m s that is what is driving.

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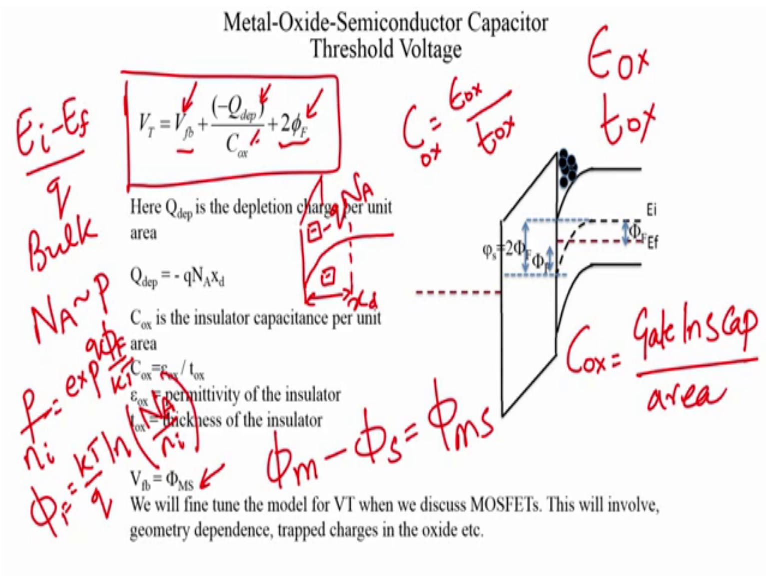

All this it is a phi m minus phi s phi s. Ok we call that as phi m s. So, you understand what V fb is, now V fb can have more complications we will come to these things later on, but for now it is phi m s, and what are these complications. These complications are that you could have charges trapped in the oxide you know you could have. So, that is that is one complication that we will look at. So, that will change the flat band voltage

But for now your V f p is simplify m s that is the driving force for all the band bending at equilibrium. And what is phi f 2 phi f is the surface potential at the interface when you have hit threshold voltage, but what is phi f phi f is the E i minus E f by q in the bulk right. And how do you know what is E i minus E f by q in the bulk. So, if you know the doping concentration, if you know NA you can say NA is approximately your p and p by n I is equal to the exponential of phi f by k t q phi f by k t. And therefore, phi f is nothing, but k t by q into logarithm of your NA by n i. So, that is your that is your phi f, and we have already done these kind of calculations before.

So, if you know the doping concentration you know the intrinsic carrier concentration you know what phi f is ok. So, this is the threshold voltage. Now we are still not happy with this definition right. So, what is x d?

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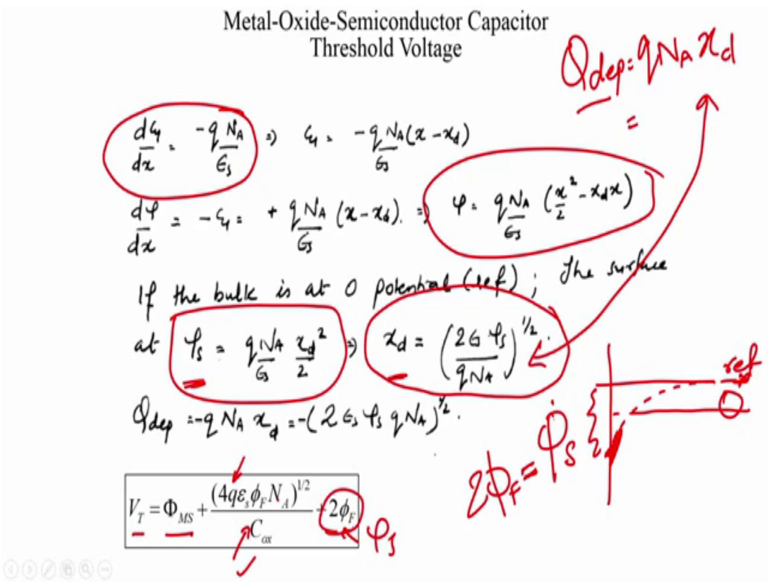

We have not defined x t. And how do you define x t? You solve Poisson’s equation. So, we have done this many times you just write you assume full depletion you make the assumption of full depletion that is there are no free carriers. Therefore, Poisson’s equation is simply this term here and therefore, your x d your potential turns out to be this term. So, I will not go through these details or I think all of you are, now at this point familiar with all this that is the potential and if you say that the bulk is at 0 potential the interface. So, the bulk is that 0 potential the interface will have a potential of this term here and that is the surface potential.

So, that is the surface potential at the interface. And what is x d: x d can be written in terms of the surface potential as this. So, what is the surface potential again? It is you are imagining the intrinsic Fermi level bending this way. So, if you keep your bulk as the reference let us say that is reference or ground. It is this difference. So, that is your surface potential. So, the surface potential equals 2 phi f. Then we have reached threshold voltage. It could be less than to 5, but when you reach 2 phi f it is threshold voltage and when surface potential is greater than 2 phi f you are above threshold ok.

But as I mentioned that after inversion the surface potential is more or less pinned it is not bands are not going to bend too much more. I think the surface potential is more or less pinned and therefore, you can now say the threshold voltage is V fb which is now written out as phi m s. This is q depletion by C ox, because now we have taken into account x d ok. So, you multiply. So, q depletion now becomes q i have taken care of the negative signs we have removed all that; so q NA into x d ok. Let us q depletion is the charge in depletion charge per unit area q NA into x d and for x d you substitute this term here and you will end up with this being the value for q depletion. And that is C ox we already know what C ox is it is the capacitance the oxide capacitance the insulated capacitance per unit area plus phi s and at threshold phi s is 2 phi f ok.

So, that is the threshold voltage. So, if you know the doping concentration you basically know phi f. And so, here again here the surface potential term inside has been.

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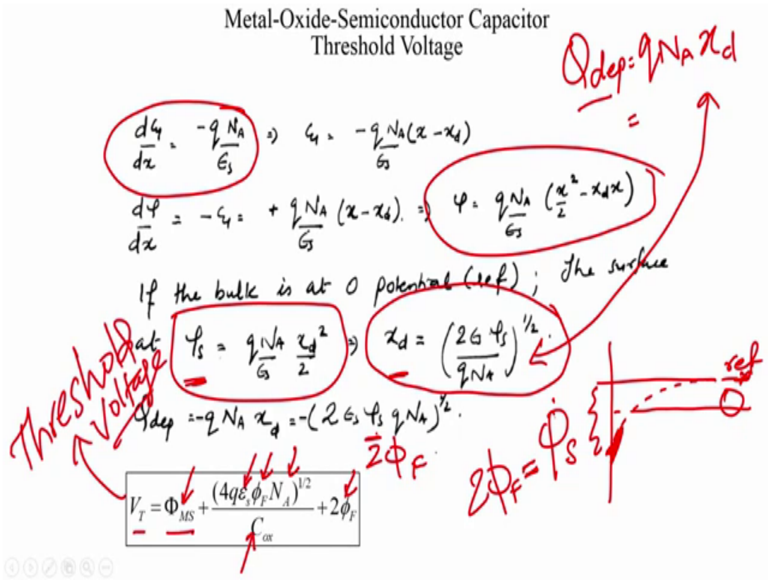

Two 5 f have been substituted for the surface potential term. So, that is why you have phi f there if you know the doping concentration, you know phi f you know this you know if you know epsilon ox and t oxy no C ox that is the permittivity of the semiconductor and that is the work function difference between the metal and the semiconductor. So, this work function difference divided by cube. So, this is the potential term, it is a potential. And you end up with the threshold voltage which is a very useful modeling parameter.

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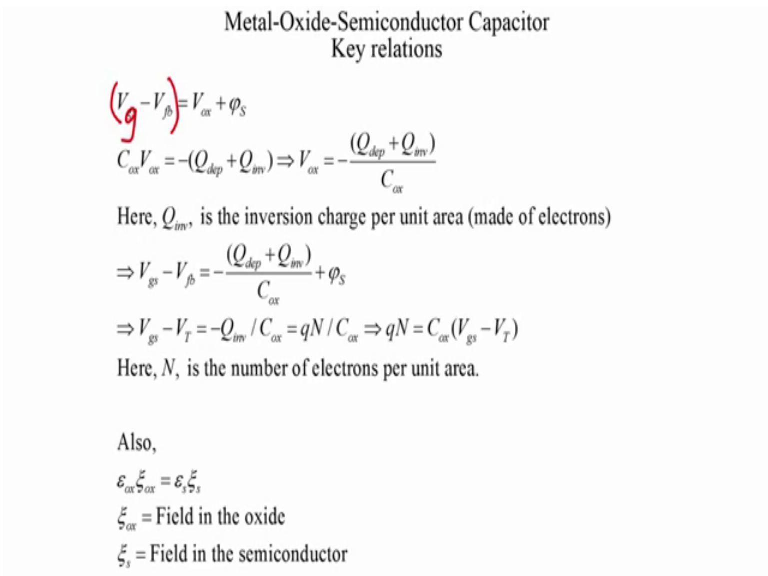

So, here are some very important or useful relations, we will sort of summarize all this by these equations here; so V G s minus V fb. So, let us say. So, let us do pardon this usage of s ok. So, that is just a force of habit. So, you can say s is the reference potential here. So, once we learn MOSFETs you will understand what the V G s is, but just replace all s with just V G ok. So, you have V G minus V fb is the driving force.

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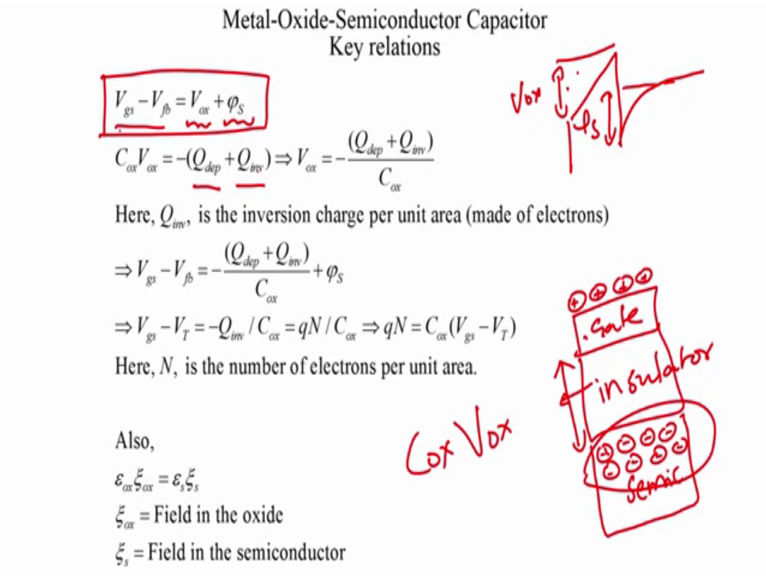

That is the x. So, we have V G is equal to V f p you have flat band there are no voltage drops anywhere, but when V G is different from V fb you start having a you have start having electric fields in the oxide and in the semiconductor. And therefore, you have some voltage drop across the oxide and the semiconductor.

So, the first key relation is that V G minus V f p that voltage has to be split between the oxide and the semiconductor. And in the semiconductor it will be it will appear as the surface potential. So, let us say that is the drop across the oxide the remainder of it will be seen as the built in on the surface potential in the semiconductor. So, V ox plus phi s is equal to your V G minus V fb, but what is V ox? Think of the semiconductor like this ok. So, you have you have the gate metal you have the insulator and you remember this is a MOS capacitor right. And you have the semiconductor and all the charge here is being compensated by some all the negative charges in the semiconductor b depletion charge or b it electrons. So, this is your most capacitor in action right.

So, what is this? If you think of it as a fuse your old, I mean your conventional capacitor notations. That is C ox that is the oxide capacitance per unit area, into V ox is the voltage across this capacitor right as the voltage across the insulator right. That is the voltage difference voltage drop across the insulator that is V ox. So, C ox into V ox has to be the charge stored on the gate ok. And the charge stored on the gate is the charge in the semiconductor ok. And what are the charge in the semiconductor, that it is a summation of the depletion charge and the inversion charge ok.

So, C ox is all per unit area here. So therefore, your C ox into V ox is equal to the depletion charge plus the inversion charge. And I put a negative sign because all this is a negative charge for this example. And therefore, your V ox is simply the depletion charge per unit area plus the inversion charge by inversion charge you mean that you mean the electrons that have appeared at the interface the inversion the minority carriers ok.

So, you have the depletion charge, you have the inversion charge divided by C ox is your V ox. And now, we will substitute for this V ox here and what do you get you get VG minus V fb is V ox plus phi s, but you have already defined the threshold voltage isn't it. So, the threshold voltage is V fb it has the q depletion by C ox and it has got the phi s term in it. So, if you replace these 3 terms with the one term which is the threshold voltage, what we are essentially saying from all these equations is that V G minus V T that is the excess gate voltage above the threshold voltage ok.

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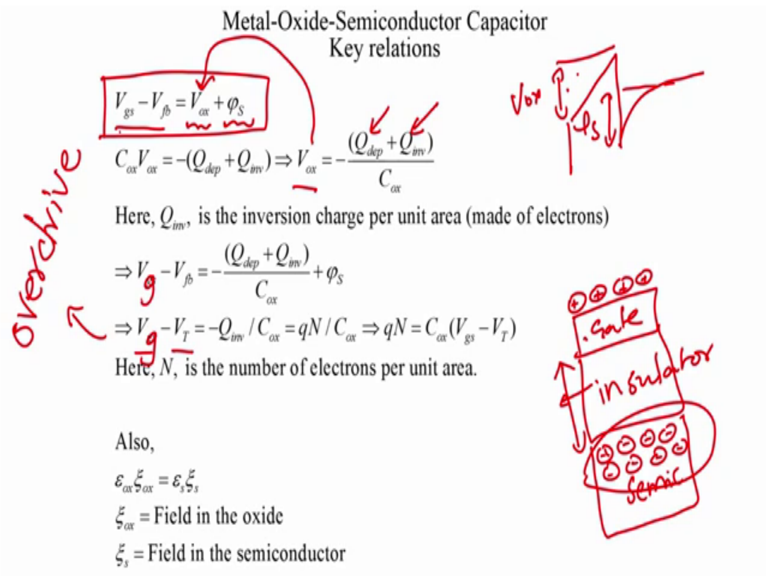

And that is something called as the overdrive voltage it is helpful to know this term in case you hear this in the context of MOSFETs what they are saying is it is V G minus V T ok.

So, again let us just replace all this as V G. So, V G minus V T, because I have now gotten taken care of these 3 terms is simply your q inversion by C ox. So, what you are saying is that.

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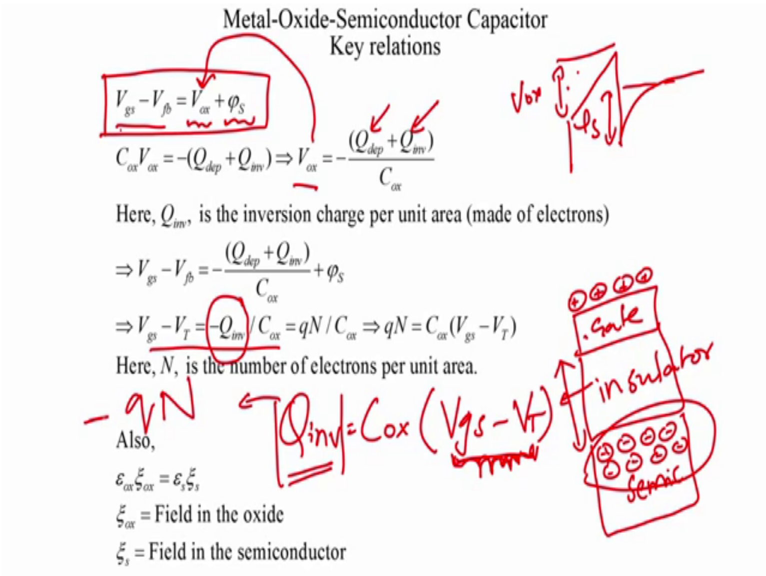

If you want to know how many electrons are there the semiconductor insulator interface, you want to calculate you essentially want to calculate q inversion. What you need to do is simply say that q inversion is equal to C ox into V G s minus V T ok, the magnitude of q. So, V G s minus V T is the voltage access voltage above the threshold voltage because still threshold voltage you did not have inversion charge.

So, you do not have a lot of it, but above the threshold voltage you start having inversion. And therefore, the excess voltage everything that go all the V G s what this is saying is that all the V G above the threshold voltage is creating electrons at the interface. And you can further write q inversion as q into n ok. Where n is the number of electrons per unit area and therefore, here you have the number of electrons if you want to know how many electrons are there per unit area.

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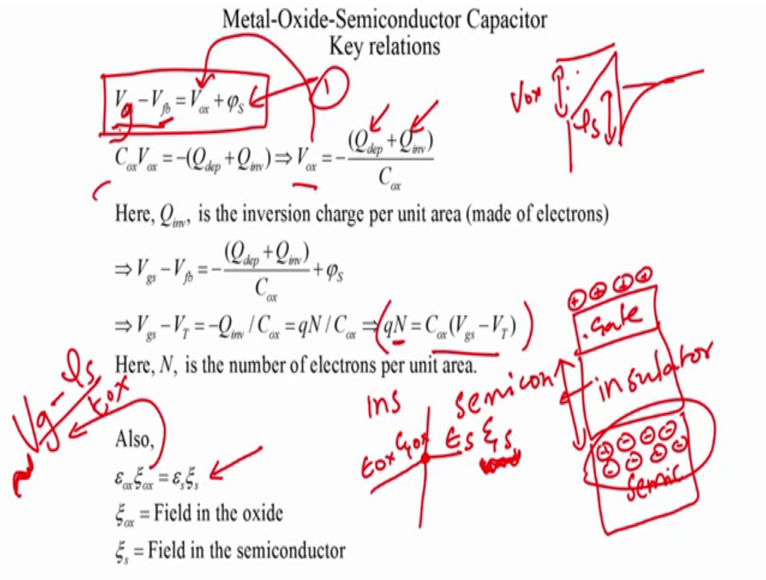

At the interface that is the answer ok. So, that those are some useful relations which will help you imagine the situation a little better.

So, that you are not surprised when we just start writing these equations. So, it all comes from this basic understanding or this description of your device so far. The other relation now how do you find out what phi s because you have one equation, but I still cannot calculate phi I know what V G s because I am applying V G. We can find out what V fb is by looking up the metal and semiconductor work functions, but we still not still do not know what phi s ok. Because we do not know what e ox's here, we ox's V ox all this term, but we cannot calculate it without calculating phi s because your q depletion is also dependent on phi s ok.

So, you see it is a quadratic relation your q depletion does depend on phi s and you also have a phi s there. So, we need another equation. Now the other equation is equating the displacements at the insulator semiconductor interface. So, what this equation says is the epsilon ox epsilon ox, electric field in the oxide this product at this interface must be must be continuous, which means it must match epsilon s into the electric field in the semiconductor.

And you can calculate the electric field in the semiconductor by solving Poisson's equation. And that calculation will have an x d or a phi s dependence on it. And by using this relation you can estimate what phi s ox and what is epsilon ox it is simply going to be your V G minus phi s by t ox in a very crude sense if there are no trapped charges in the oxide that is it. So therefore, you have 2 relations with fires in it and you solve for fires. And these are not easy equations to solve ok.

So, with that we complete the basic understanding of the MOS capacitor, you know how the MOS capacitor works the operation of the MOS capacitor. And from this point on we will start looking at some electrical properties, particularly what is the capacitance or the MOS capacitor. We will start quantifying the capacitance. And this piece of information this knowledge is quite useful when we start talking about MOSFETs.