Semiconductor Devices and Circuits
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Lecture – 41
Trapped charge, Body-bias

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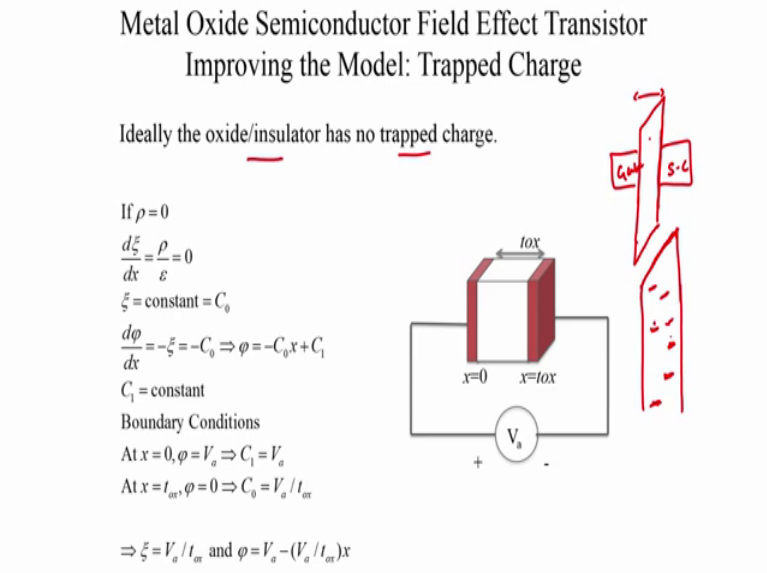

So, let us now come towards a more practical case and that is the case of having charges trapped inside the dielectric ok. And so, fine our discussions with the MOSFET or the MOS capacitor we always assume that the insulator was ideal, and it had no charges trapped inside which implies that the insulator; all the insulator did was to prevent any current from the gate into the semiconductor. And it did that by allowing for a voltage drop across it and by acting like a perfect dielectric with a high band gap.

But in reality the insulator could have charges trapped inside ok. And there are many possible mechanisms by which charges can enter the insulator. And the insulator need not be a perfectly crystalline material, it could be it could have defects in its structure which could result in it is energy band diagram having you know states inside. And all these states as well as any trapped charges inside make the insulator non ideal. And these energy levels or these trap states inside insulator also acts as a home for any free carriers that are floating around.

So, let us now consider what happens you know what happens when you handle an insulator of this kind. So, far in our discussions we always assume that the insulator was ideal ok. So, now, what we are going to do is we are going to improve the model for the MOS capacitor and a MOSFET, by considering the possibility of charges being trapped inside the insulator ok.

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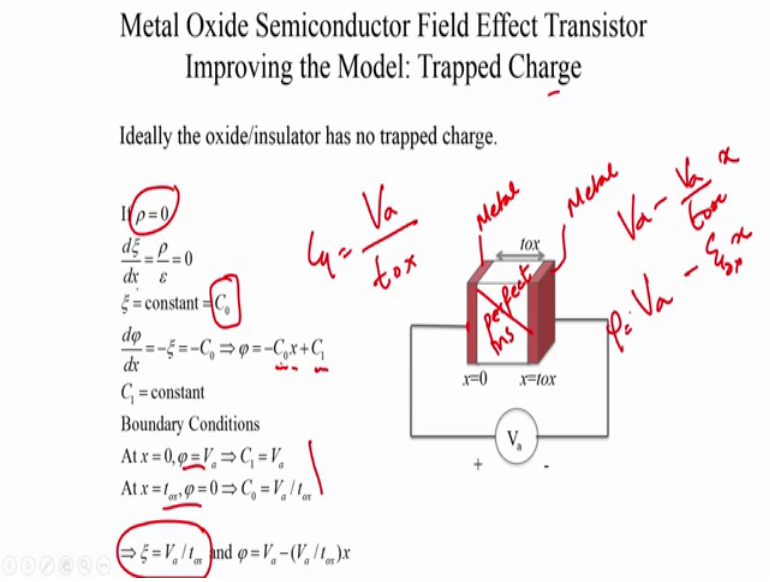

And this could happen due to several reasons and we will address all those reasons. But before we do that, let us consider what happens in an ideal insulator ok. Let us look at the ideal insulator little better and I am sure most of you are familiar with this, but we just doing it to establish continuity between this discussion and the next.

So, if the insulators ideal let us say we build let us keep the MOSFET or the MOS capacitor side and let us just build a parallel plate capacitor. So, you have a metal plate here, and you have an another metal plate here, and you have applied a voltage V a across these metal plates. And you have a perfect insulator, that is an insulator with no defects and no charges inside sitting inside between these two metal plates so it is a perfect capacitor. And you also have the insulator having a thickness of tox.

Now, if the charge concentration in the insulator 0; then you have a Poisson equation which is given by de by dx is equal to 0 which means that the electric field and the insulator has to be a constant. Moreover your potential, the potential term in the insulator

will depend linearly with x. So, you have d phi by dx is equal to minus Co. And therefore, phi is equal to this constant times x, plus another constant which is C1.

And by applying these two boundary conditions there is at x equal to 0 the potential is V a and at x equal to tox the potential is 0, we can establish what C1 and C 0. And therefore, you end up with your electric field being a constant which is V a by tox and you end up with the potential that you know that dk is linearly in space and it is basically your V a minus V a by tox into x where this is nothing, but your electric field in the oxide into x. So, this is the situation in an ideal insulator.

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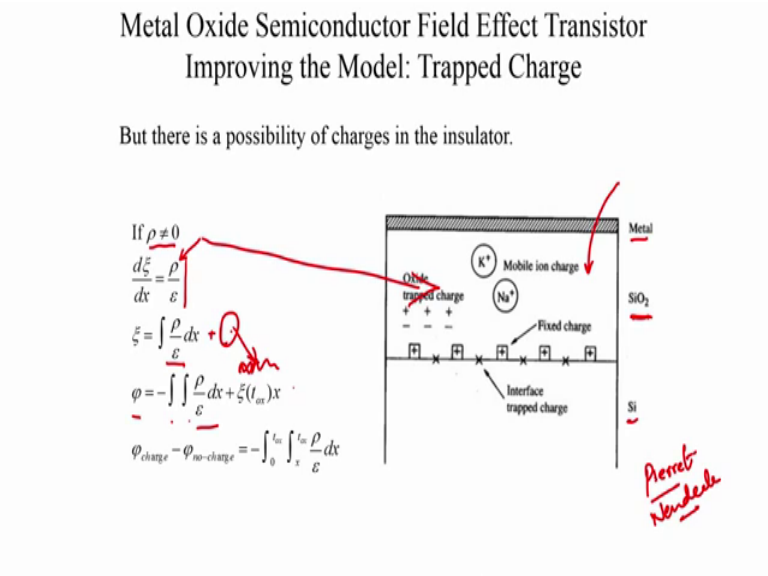

But the moment the insulator gets some charges inside ok, rho is no longer 0. And here is a nice picture taken from one of the reference techs ok. So, I will edit this in edit the correct reference in and this picture has been borrowed from that text. And it shows the shows a more practical scenario of the insulator or in this case a silicon oxide sitting in a MOSFET. So, you have the metal you have the silicon oxide and you have the silicon and you have the insulator in the MOSFET. Now this is a very busy diagram you see a lot of species here.

So, ideally we would like to keep the insulator very clean, but in some practical scenarios it may not always be possible. So, in that case your charge concentration in the insulator is not 0, and your Poisson's equation becomes this, where you have a certain charge concentration depending upon all the species present in the insulator. And the electric

field is simply an integral of this and the potential is therefore, the double integral of this term with the integration constant or with the with the integration constant over here appearing providing a linear dependence on x to the potential. So, this becomes your potential function ok.

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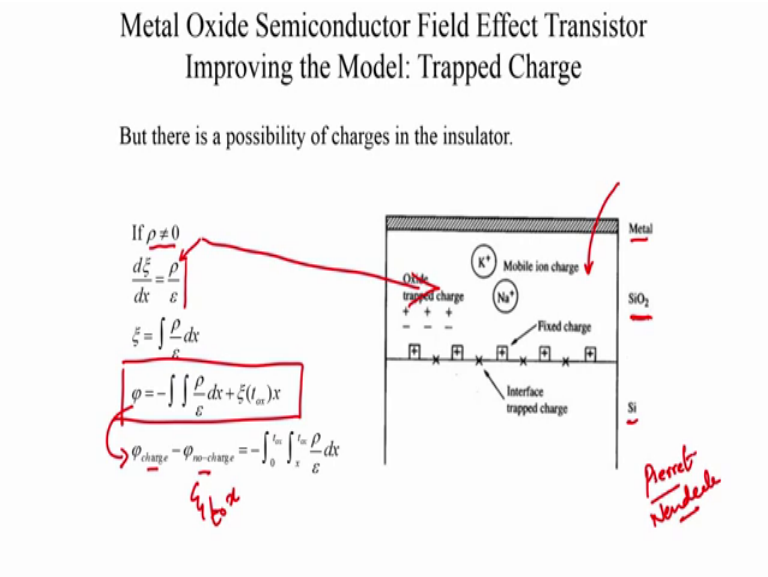

And therefore, if you were to take the potential difference between the case where the insulator has charge trapped inside, and the insulate in the case where the insulator does not have any charge trapped inside. In this case you have this term and in the case of no charge trapped you had this term. So, of course, we have ignored the any constant potential applied across the insulator.

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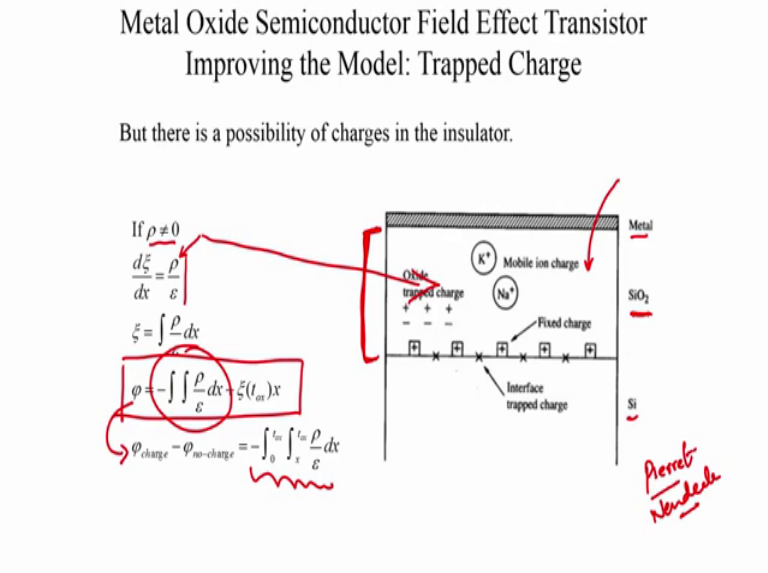

And therefore, that the difference between these two terms the difference between these two terms is this particular entity that crops up here. So, therefore, you do have a potential difference that can vary based on whether they depending on the amount of charge is trapped in the insulator. So, how does all this affect our MOSFET and how does it affect the MOS performance ok? The key is that if you have charges trapped inside you are going to change your flat band voltage, at why does the flat band voltage change. Let us let us consider a simple example ok.

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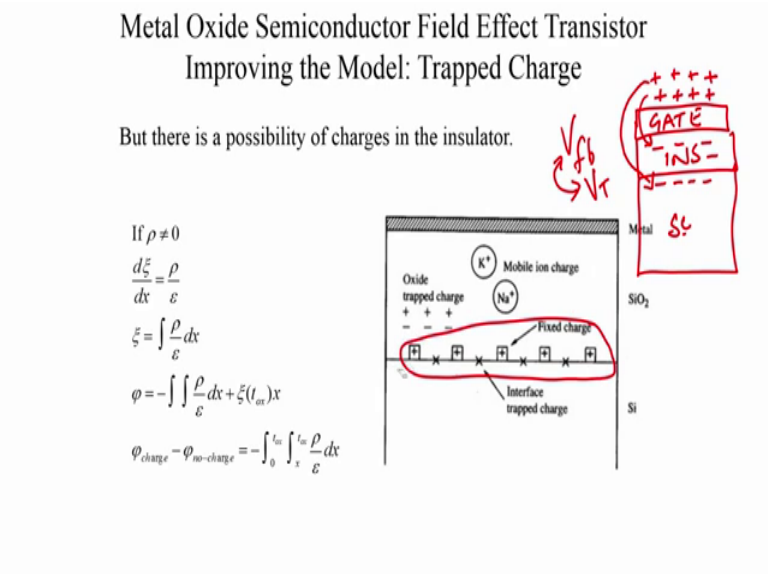

So, let us say you have your ideal MOSFET ok, you have your gate, you have an insulator which is ideal, no trapped charges inside, and you have your semiconductor, so

I am not shown the source train etcetera. So, if I were to apply some positive charge on the gate, then the semiconductor responds by bringing in negative charges close to the semi conductor insulator interface ok. So, this is the only response we looked at. Now these charges could be the depletion or it could be the inversion carriers and depletion, but nevertheless it is all happening in the semi conductor.

But now let us say with the insulator also has some trapped charges; so, in order for me to bring the same amount of charge concentration at this in the semiconductor interface. I need to apply a larger gate voltage because, I need to first compensate for this insulator charge and then bring in the field to establish my inversion layer or the depletion charge. Therefore, it is equivalent to us saying that the flat band voltage is increased or flat band voltages decrease depending on what the charges are in the insulator. And therefore, the V t which depends on the flat band voltage also changes.

So, therefore, charges trapped in the insulator can affect your flat band voltage and can affect the threshold voltage of your transistor. So, what kinds of charges are trapped in the insulator. So, you have you have the you have different kinds ok, you have charges in the insulator and you have lot of charges at the semi conductor insulator interface. So, let us just go through you know what these are and you know how they occur etcetera.

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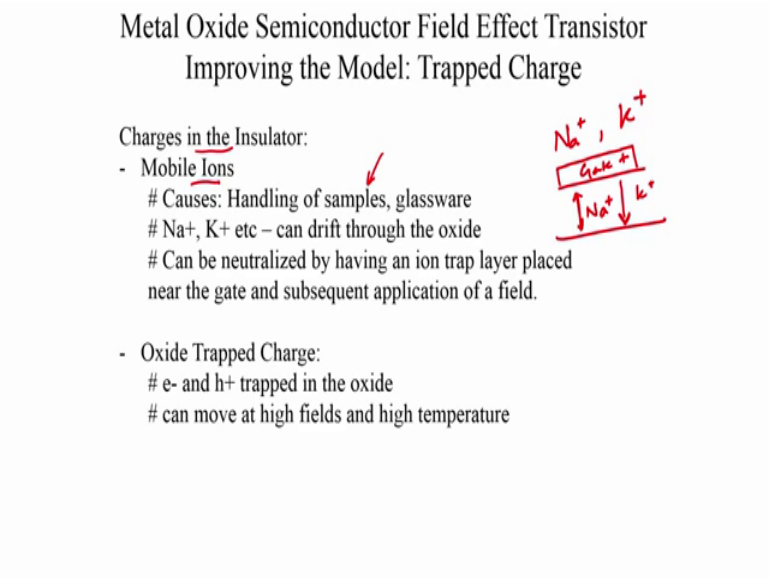

So, the first ones the charges in the insulator you have mobile ions. Now mobile ions are typically you know your sodium and potassium ions basically these are salts that have

ionized. And they occur because of poor handling of the samples or you know use of poor glassware etcetera. So, for example, you know you the ions present on your skin could get into the dielectric if you do not have proper clean room procedures ok.

And these mobile ions once they are inside the oxide they can start drifting inside based on the field is based on the field applied on the through in the oxide. So, if the gate voltage is positive these ions will start drifting towards the semi conductance latent interface, where they will have a larger impact on the threshold voltage. And one way to neutralize these ions is by having a ion trap layer present right at the gate insulator interface.

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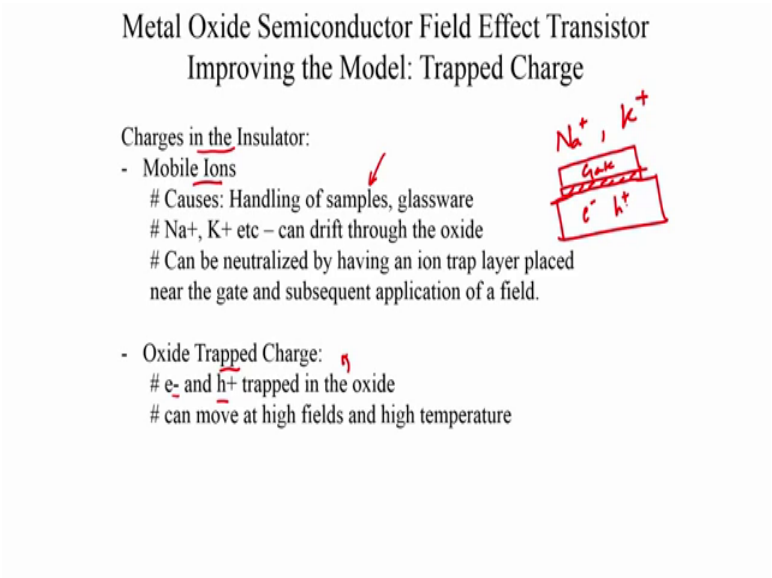

The other kinds of charges in the insulator are something called as the oxide trapped charges. These are basically the electrons and holes from your channel, that had very high energy and that got into the oxide. And once inside the oxide they are trapped and there mobile because they can move at high temperatures and high fields they can move around. So, these are oxide trapped charges essentially refer to electrons and holes as opposed to mobile ions.

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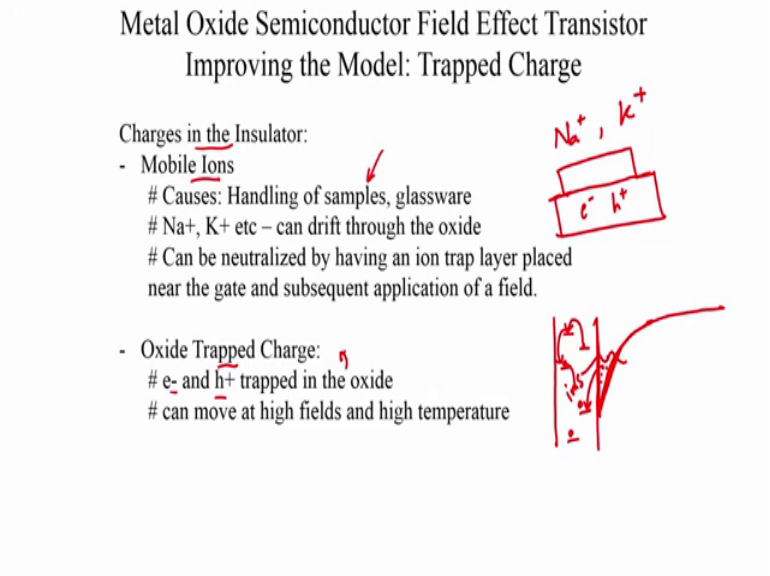

So, these are electrons and holes that are trapped inside the insulator. So, let us let us view the situation little better. So, if you if you remember, you have your insulator and you have the band bending in the semiconductor and you have these electrons here. And these electrons are all basically you know they are all they all have their own wave function.

And therefore, there is a probability of finding an electron in the insulator because these electrons are now trapped in this potential barrier. So, if there are if there are defects in the insulator, the electrons the high energy electrons can actually get in and occupy these defect states ok. And then they could hop around from one state to another and thereby migrate around in the insulator.

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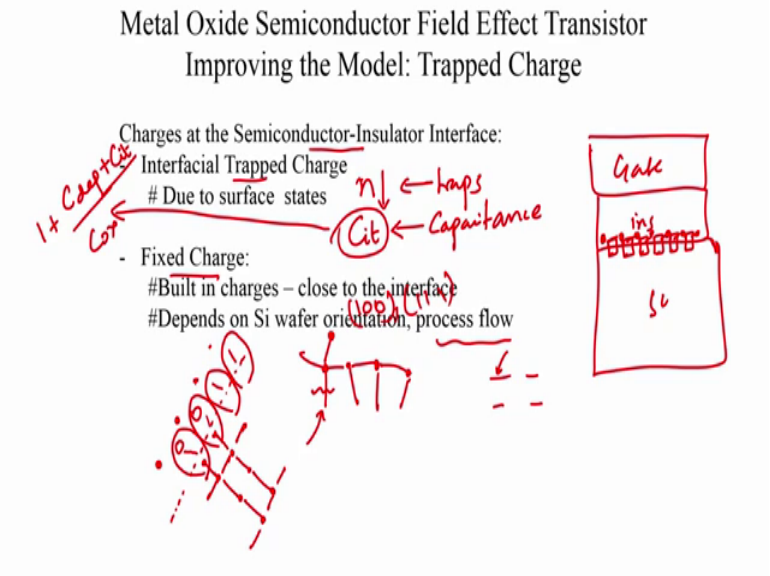

The other kinds of charges on the charges of the semi conductor insulator interface. So, you have your gate metal, you have your insulator and you have your semi conductor and there are these are charges that are located at this interface. They are not inside the insulator, but they are at this interface. The most common and the hardest get rid of is something called as the interfacial trapped charge. So, essentially this is because of dangling bonds. So, you have your silicon lattice or in fact any lattice for that matter ok.

And at the point where we build the insulator, this lattice terminates this lattice structure which was let us say you have a perfectly crystalline lattice. This perfect crystal terminates at this boundary. And now you have a different crystal in this case it is the silicon oxide crystal ok. And this oxide crystal has to now match with the silicon lattice ok. I mean these two have to start sharing electrons to create bonds. Now, depending on the insulate and the semiconductor that is not always very efficiently possible. And what happens is at this interface we are left with a lot of dangling bonds ok.

So, several low the bonds are shared, but then this atom could not find another atom share this bond width ok. So, you end up with a lot of dangling bonds and these dangling bonds are essentially traps. They are they have got a certain energy and they are looking for an electron to trap. And they not only reduce the electron concentration at the interface they act as traps, but they also effectively add on to something called as the interfacial capacitance ok. So, if you recollect the point on sub thresholds swing.

We saw that a key parameter was 1 plus C depletion by Cox. And at that time I had mentioned that if there are trapped charges then it could increases sub threshold swing and therefore, reduce the sub threshold slope. So, these trapped charges can effectively contribute to slowing down the turn on and turn off of the device. And these trap charges also change the flat band voltage. The next kind of charges are something called as fixed charges, and these are charges which are just inside the insulator, but very close to the insulator semiconductor interface ok.

And these are these have got these charges are curved simply because of you know the way for orientation, whether it is a 1 0 0 plane at the surface or 1 1 1 etcetera or the process flow and the temperature at which we had the process flow etcetera. So, these are fixed charges they are not moving anywhere, but they are very close to the semi conductor insulator interface and they also contribute to the trapped charges in the insulator. So, these are different categories and classes of the different kinds of trapped charges you might see in the insulator.

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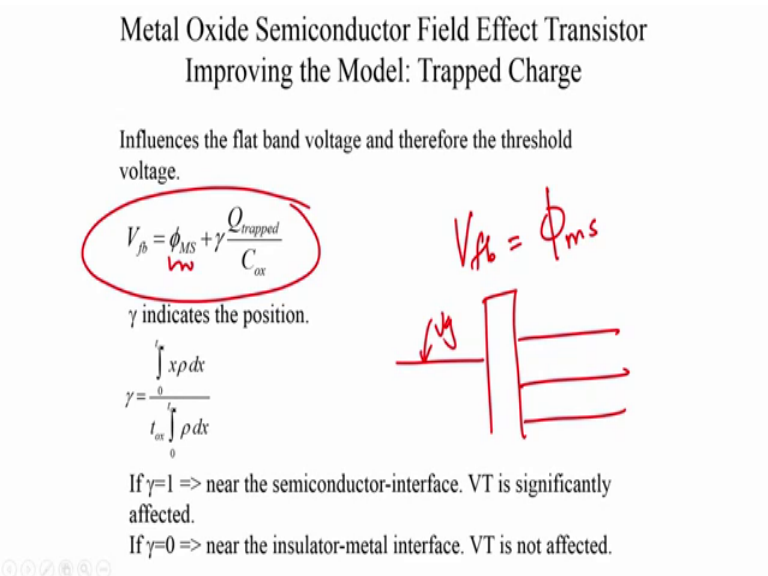

Now, what is the effect of all this the effect of all this is that it is going to change the flat band voltage. So, far the flat band voltage in the insulator was purely because of the metal semiconductor work function difference. So, when we drew the band diagram at the start of the MOS theory. We said that there is a volt Fermi level difference between the metal and semiconductor at thermal equilibrium these Fermi levels will align.

And therefore, you start having you start having bands bending even at equilibrium. And we said that the way to get the flat band voltage was to apply a voltage so as to positive or negative voltage; so, as to get all the bands flat ok. Now, therefore, phi MS, was the only voltage we need it to apply, that was the gate voltage that we need it to apply. But now if you have trapped charges in the insulator you also need to compensate for the trapped charges because if even after applying phi MS.

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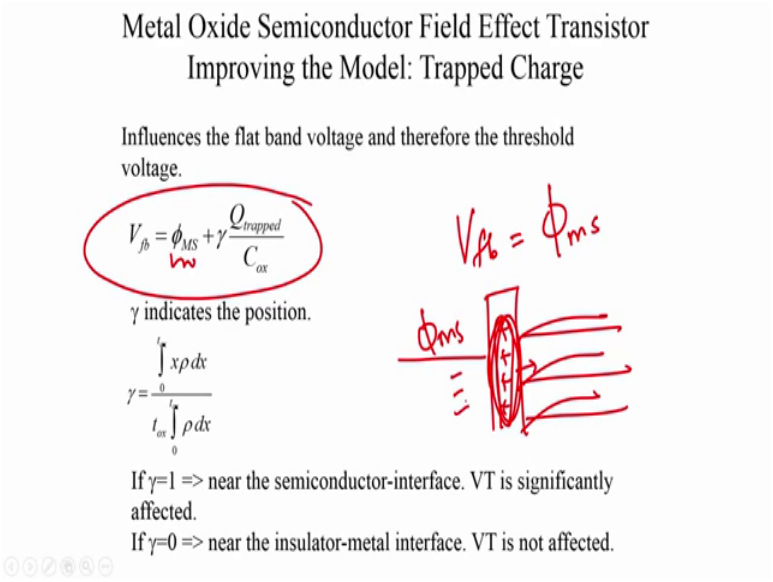

There might still be band bending because there is already a field because of these trapped charges. So, even these could cause a band bending. So, we need to overcome even these charges ok

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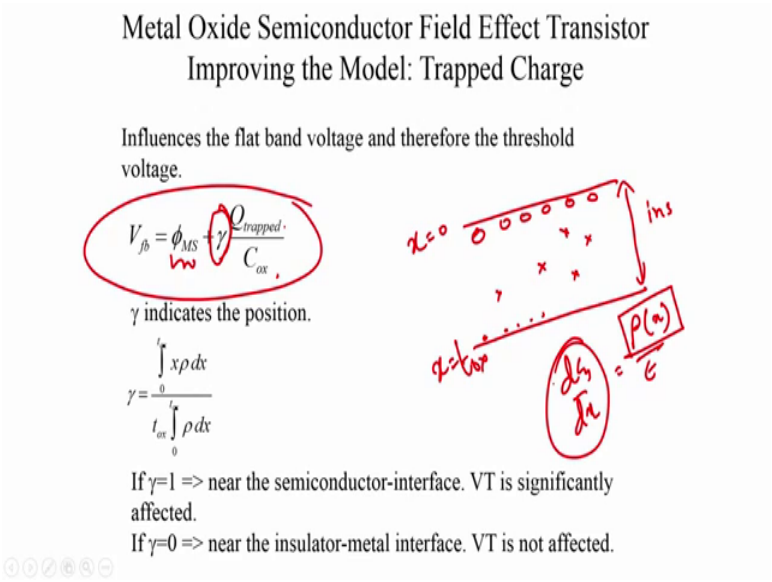

And therefore, the total flat band voltage will now be a summation of phi MS plus Q trapped by C ox into a parameter called gamma. And I will tell you what gamma is? Now gamma is trying to indicate the location of these trap charges. Since these not all charges are present at the insulator interface ok. You have you have charges that could either be located at the semi conductor insulator interface or somewhere in the middle or maybe at near the gate insulator interface etcetera.

So, and this distribution is important because it directly impacts a Poisson equation right. Because your Poisson equation says it is rho of x by epsilon is your de by dx. So, unless you know the distribution of all these charges you cannot solve Poisson's equation accurately. So, good estimate for all these charges is to get the average or the expected value of the location of these charges ok.

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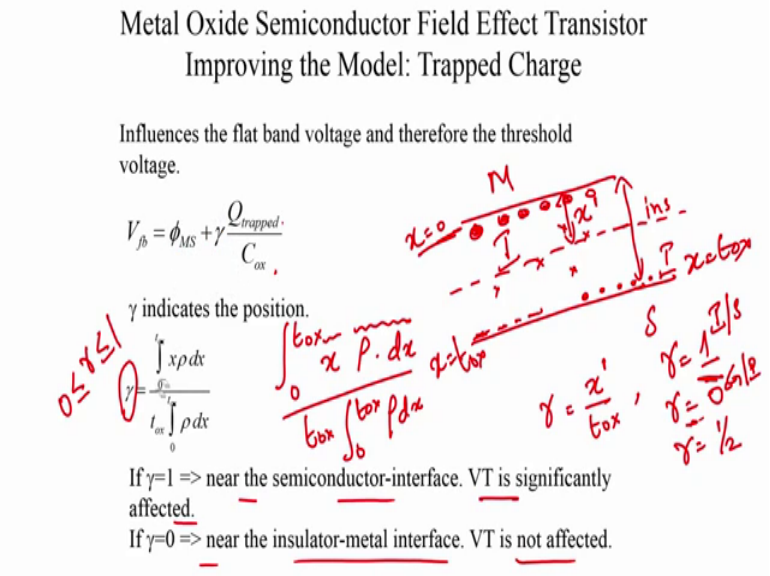

And that expected value is defined by this parameter gamma and this gamma is a dimensionless parameter. And the way it is defined it can take a value between 0 to 1 and the way it is defined is it is. So, in case you cannot see these it is the integral of 0 to t ox of x into rho dx ok. If you think of rho dx as some kind of a distribution a density function, the next times that is the expected location of this charge ok. So, people are familiar with probability theory can think of it is a as a definition of the expectation, divided by tox into integral of 0 to tox of rho dx.

So, this is telling you, so if this so what this is telling you if this is x equal to 0; if the gate metal insulator interfaces x equal to 0 and if the insulator semiconductor interface at x equal to tox. What this is telling you is, it is trying to estimate a mean position for all the charges. So, if you say that the mean position from here to there let us call that as x dash. So, if x dash the mean position then gamma is equal to x dash by tox. So, which means that if the charges are located if most of the charges are located near the insulator semiconductor interface gamma takes a value of 1. And if the charges are located near the gate insulator interface gamma takes a value of 0. And if the charges are located right in the middle gamma takes a value of half ok.

So, this is near the insulator semiconductor interface, and that is sorry this is near the insulator semiconductor interface and that is near the gate insulator interface. So, if gamma 0 then the flat band voltage is not affected ok. So, you can think of it as a part of

the gate metal and it is part of the gate charges. But if gamma is 1; that means, if the charges are located closer to the semi conductor insulator interface, then your flat band voltage is more significantly affected ok.

So, in this case the VT is significantly affected; whereas, in case of gamma equal to 0 VT is not significantly affected. So, this is a simple model it is taking making use of the average location the expected location of all these charges in order to make an estimate on the flat band voltage. So, this is how you handle trapped charges in the insulator. So, this is just our little excursion into handling this non ideality in the MOSFET.

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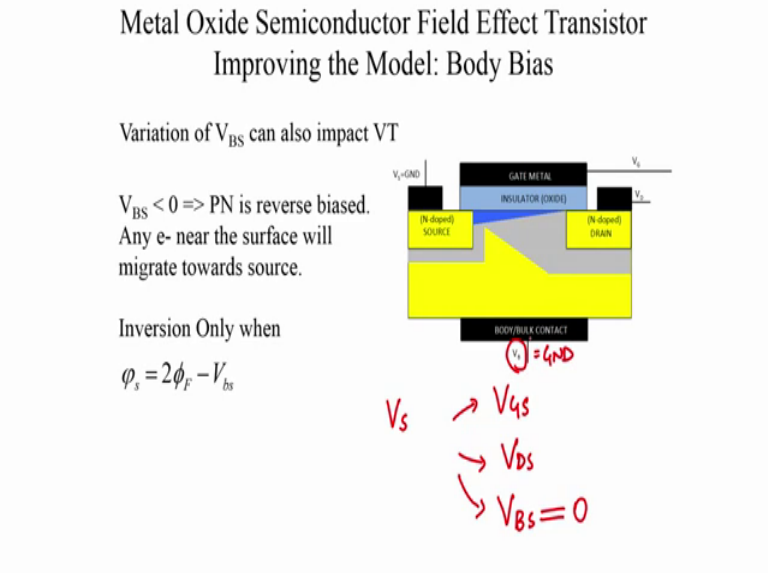

Now, that is not the only thing that can affect the threshold voltage ok. So, now, another key parameter is the body voltage. So, far in our discussion of the MOSFET we said that all potentials are taken with respect to the source. And therefore, what is important is the gate to source potential, drain to source potential, and the body to source potential, which so far we had kept at 0.

So, so far if you remember the body was always at ground we never worried about the body ok. But now let us dislodge this ok, let us not keep it at ground. Let us say that the body has got it is has got a potential that is different from the source. So, how does this affect the performance of your MOSFET.

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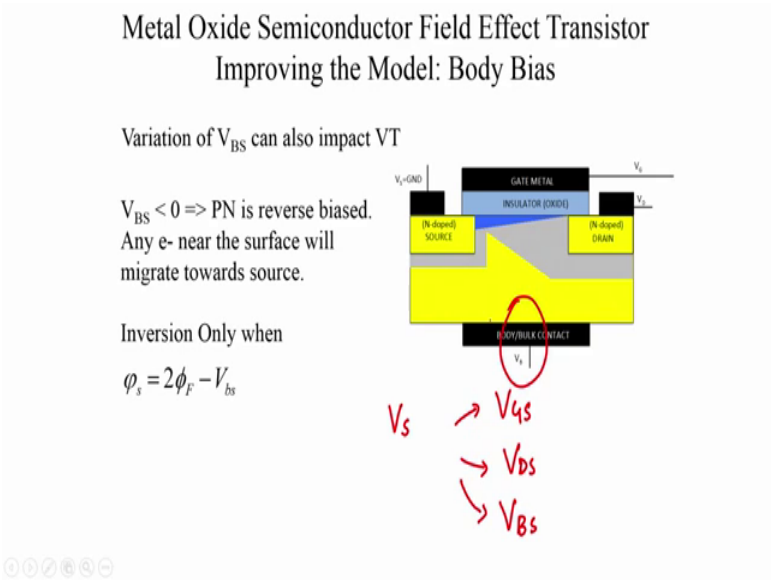

Now this is a very although we spend a very short amount of time on it is simply because of the time constraints on this course, there is actually a very important tool for the circuit designer.

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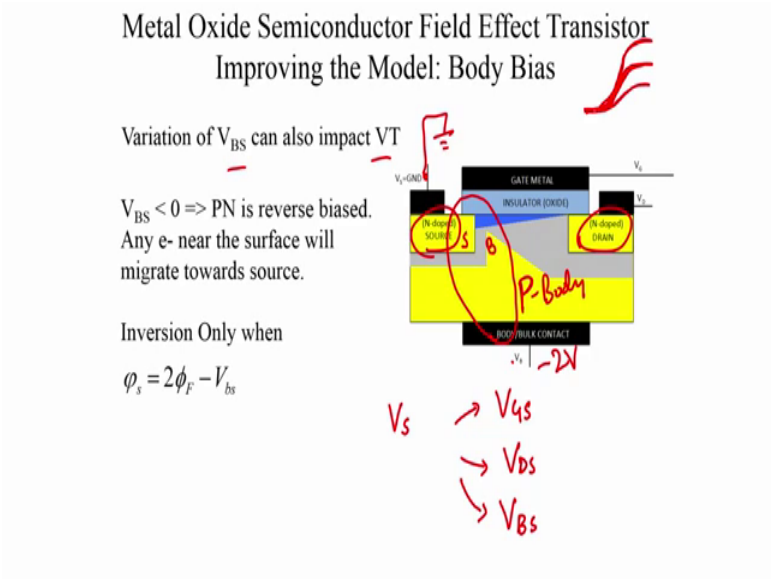

Because, you can control the threshold voltage of the MOSFET by influencing the body to source voltage; so, you can have different MOSFET's having different threshold voltages and we will see why it happens. So, this in the structure the MOSFET so this is the P type body, and you have this N type, N doped source and drain contact. Now, if the

body and source are at a different potential then if we increase the body to source voltage or let us say we decrease the body to source voltage we make the body voltage less than the source. So, if the source is at ground let us say the body voltage is minus 2 volts. So, essentially we reverse bias this PN junction diode ok. If you look at this PN junction diode it is got it is got the source and it is got the body here and that was the barrier ok. So, if we apply a body to source voltage we now start shifting playing around with this barrier. See if you reverse bias set or you forward bias set you can change this barrier right.

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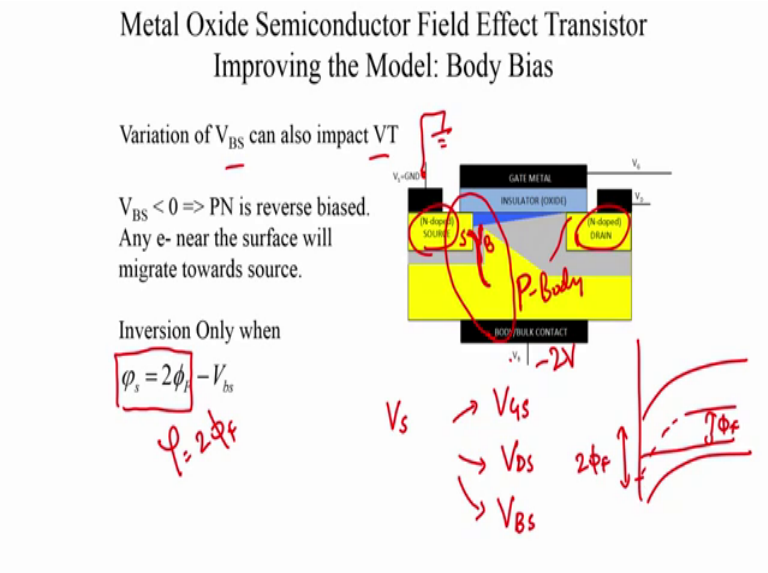

Now, if you reverse bias this PN junction diode, essentially you have made this depletion region have a very high electric field. And therefore, any charges that are trying to appear at the interface will all run runaway because of this high electric field. They will all migrate to the source and drain electrons.

So, in other words so far we were we were getting inversion when my phi s was equal to 2 phi F where phi F is nothing, but the work function insulated difference in the bulk. So, that is your phi F so, when the only when the surface potential hit 2 phi F did we have did we have inversion. But now the surface potential must be equal to 2 phi F minus V BS minus V BS.

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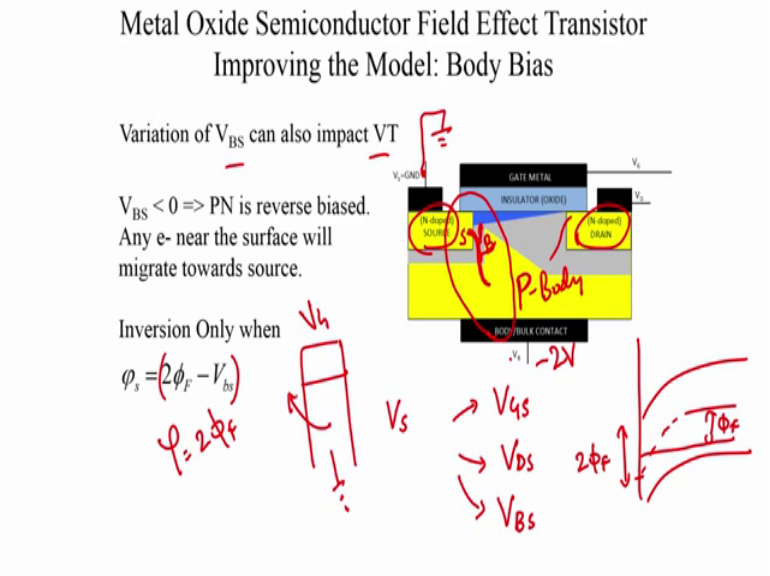

So, the body the body voltage basically changes the back potential of your MOS capacitor. So, your MOS capacitor had a gate voltage it is always with respect to this body which was grounded. But now this is this is offset that potential so, the condition for inversion is now different.

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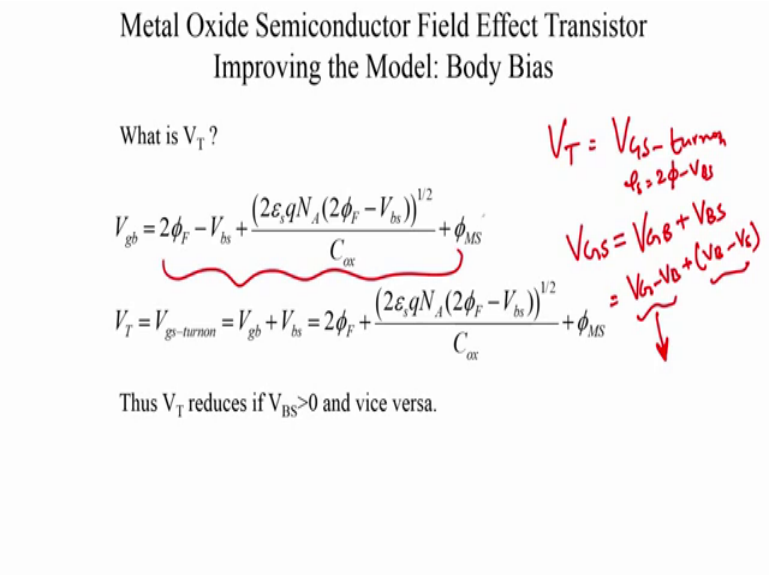

So, how does this impact the threshold voltage? So, if you have to look at the threshold voltage. So, threshold voltage is basically the gate to source voltage at which we achieve turn on right. And this happens in my surface potential hits 2 phi minus V BS now.

But what is the V GS? Now, the body is decoupled the V GS can be now written as VG to body plus V body to source ok which means it is basically VG minus V body plus V body minus V source. So, this is my gate to source voltage. And what is the gate to body voltage? Now, the gate to body voltage has now become this term here. And what does it have? It has your phi MS because of the metal semiconductor work function difference.

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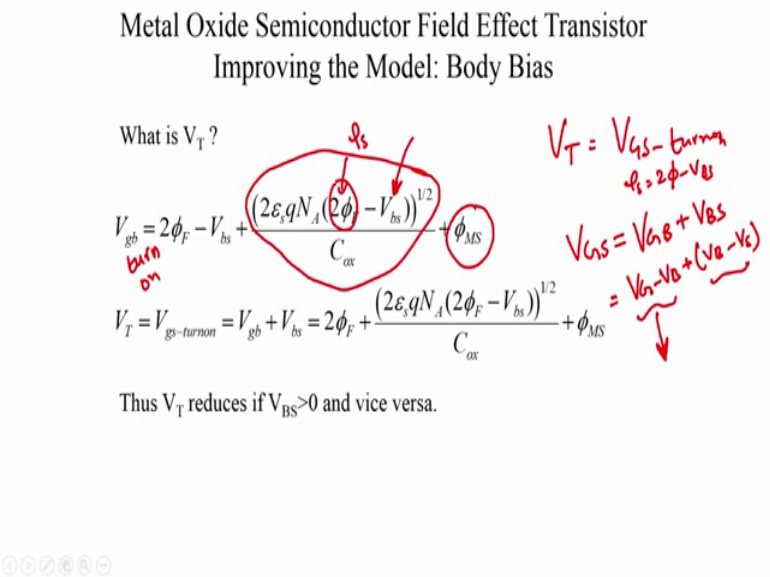

It has your depletion region by C ox depletion charge by C ox, but the depletion charge has to now take into account this extra potential here. So, it is not only 2 phi F so this is V gb during turn on so this is during turn on. And why is it during turn on, because we have said that the phi F is equal to 2 phi F. So, this is the depletion charge by C ox.

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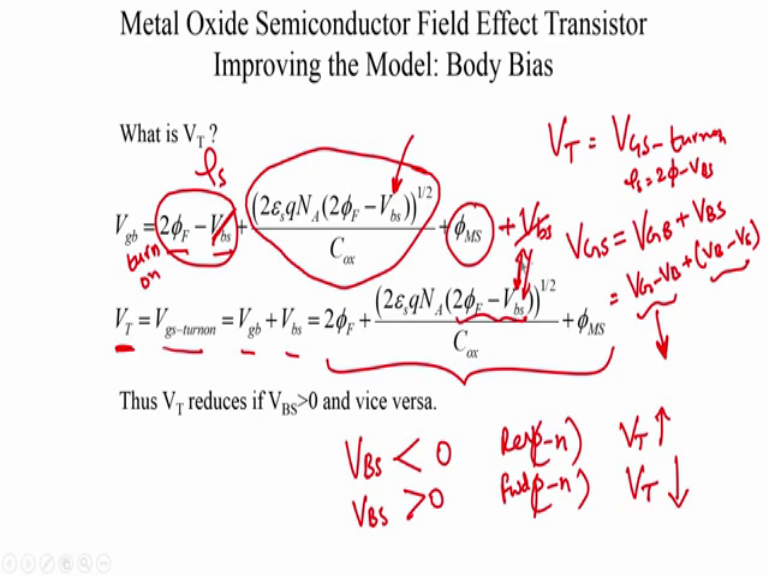

And it is also got the phi s term, which is now 2 phi F minus V bs which is the new phi s needed for turn on. And therefore, Vgs turn on is nothing, but the V T that is become V gb plus V bs which is basically this entire term plus V bs ok. And these two terms cancel off and you end up with this being the expression for threshold voltage.

So, if the body to source voltage is less than 0 which means if you reverse bias your p-n junction then the threshold voltage will have to increase. And if the body to source voltage is greater than 0, which means your forward bias your p-n junction, then your threshold voltage will decrease. And you can see that happening here. So, if you reduce if you make V bs positive then this terms becomes lesser and the threshold voltage decreases.

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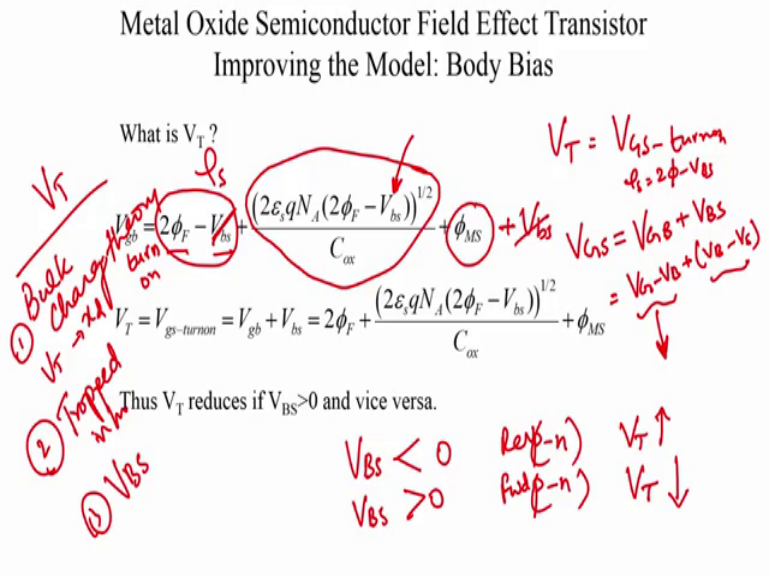

On the other hand if V bs becomes negative and the this term becomes greater than 2 phi F and therefore, the threshold voltage increases ok. So, the body to source voltage can also be used to control the threshold voltage of the device. So, you can see the different things that impact the threshold voltage, particularly through the depletion charge right.

So, you had your you have your bulk charge theory, which said that the bulk charge theory which said that the V T will change along the channel simply because x d is changing. Then you have your trapped charges in the insulator and then now, we have seen the body to source voltage also affect threshold voltage ok. Now, we are going to see more examples particularly when we head towards scaling of the MOSFET.