Semiconductor Device Modelling and Simulation

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Lecture – 29
MOS-CV

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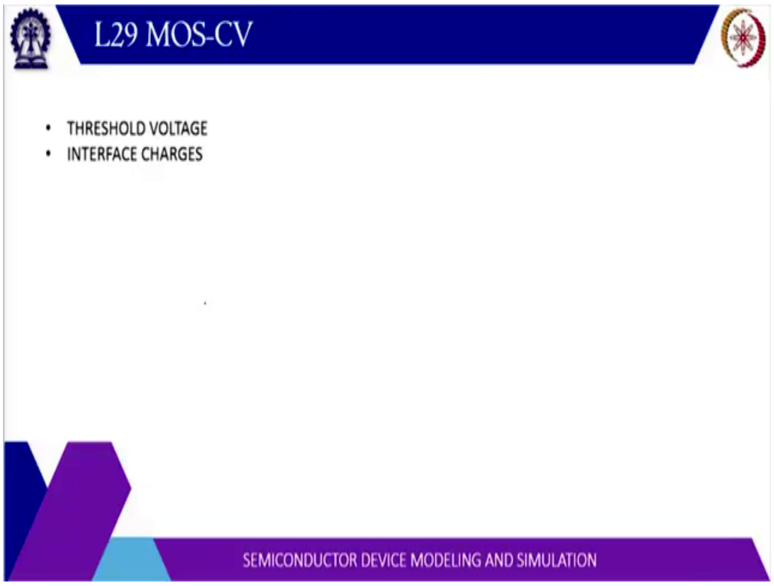

Hello, let us continue our discussion on MOS capacitor. So, again we are dealing with the ideal MOS so far and we have solved the Poisson equation.

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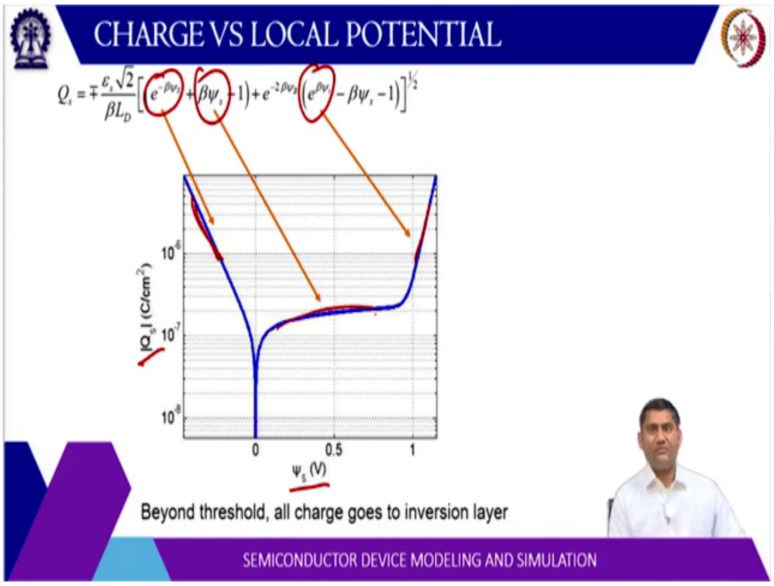

So now, let us define the other parameters that are related to MOSFET, so, this is a typical Q versus surface potential curve for a MOS structure and where we have identified the three regions. This is accumulation, this is depletion region and this is your inversion region. And in inversion region and accumulation region this is exponential term in depletion region. It is inverse proportional to the square root of the voltage.

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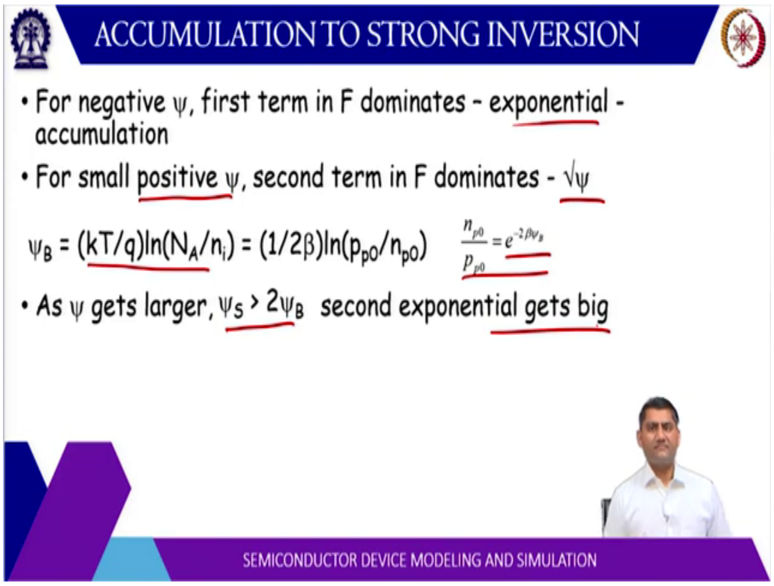

So, for a negative potential first term, in the F. So, this is the first term in the F that dominates and then this is the exponential function and this accumulation. For a small positive side, the second term which is proportional to the square root of psi. The second term beta psi s that actually dominates. And then psi B is the bulk potential that is kT by q lon N A by n i. And so, n p naught by p p naught is a exponential – 2 beta psi B.

That we already discussed and as size most more than 2 psi B. The second exponential starts become active because now it has overcome this term here – 2 beta psi B. So, this becomes big and there is a inversion region basically.

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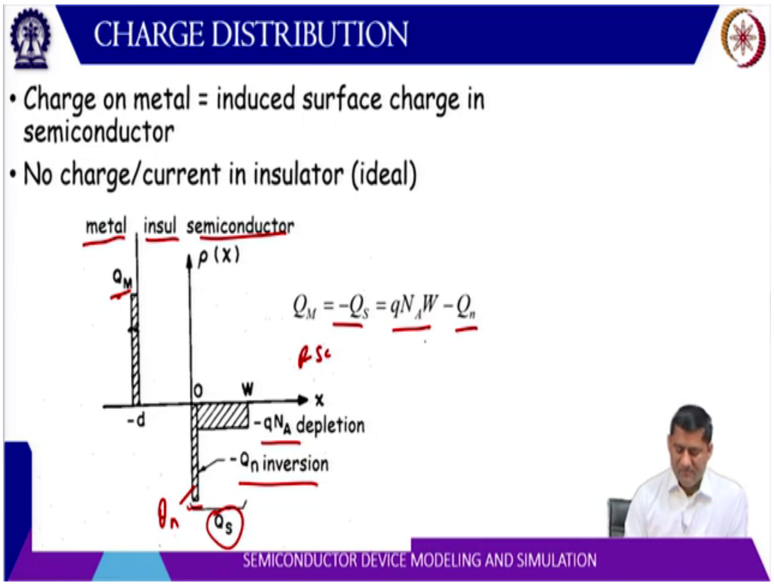

Now, if you look at the total picture, so, there is a metal here. There is an insulator oxide here and there is semiconductor here. So, in the semiconductor there is a depletion region and the charge density can be – q times N A assuming it is p-type semiconductor. Then, when there is a large positive bias here at the metal, it goes into the inversion and then this inversion charge is actually a very thin layer at the semiconductor and oxide interface.

And this charges, let us say, total charge is Q S so, same charge has to be on the metal, so, Q M = Q S what bit opposite polarity, so, Q M is – Q S which is a depletion charge plus the inversion charge. So, depletion charge is – qN A and inverse charge we call it Q n. So that is the expression here.

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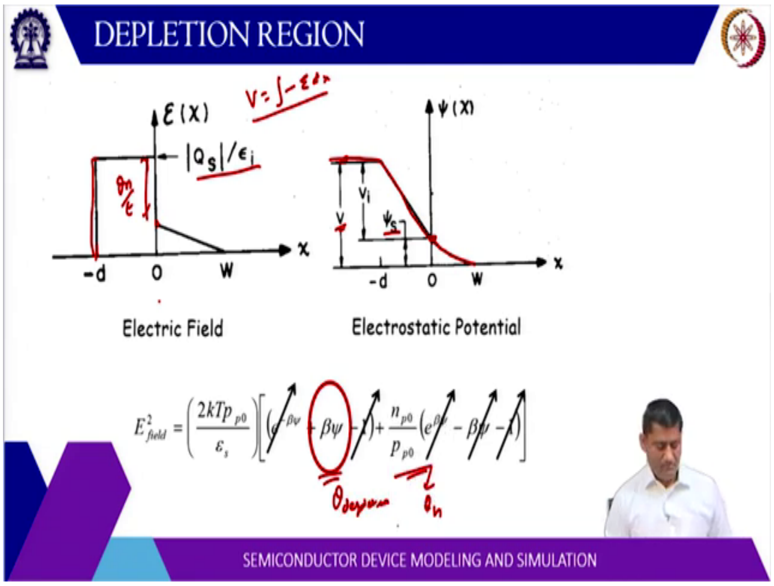

Now, from the charge profile we can also calculate the electric field. So, let us calculate the electric field. Here the electric field is 0 because total charge it is easier is Q M + Q S that is 0. Now, you cross this boundary, the charge is Q M. So, there will be field here that will be Q M by epsilon that electric field will exist here. Now, here there is no charge so that this electric field will be constant here then there is a – Q N here.

So, this will create – Q n by epsilon electric field, so, there will be search jump here. Whenever you encounter a seat of charge there will be a sudden change in the electric field. So, this electric field will reduce now. Then you have this depletion charge which is uniformly distributed. So that means, the electric field will be if you recall del dot e = rho by epsilon. So because rho is constant, so, e will be linear.

So, this electric field will linearly vary here and then beyond this point, this electric field will be 0 so that you can see here. So, this is a metal charge here. So, after this point, electric field is constant that is Q S by epsilon or Q M by epsilon. Then here is Q N by epsilon so, this gap is Q n by epsilon and then this is linear. So, this is electric field curve and then, of course, if you integrate electric field that V = integral – e dx.

You will get a potential here so, for linear it will be parabolic so, from W depletion, width to x = 0 this will be parabolic. Then there is a jump here in the electric field that will not change of potential because potential cannot change instantaneously. So, this potential will be same but now a field is more here. So, the potential will change linearly because field is constant, so, this will be linear and beyond.

This potential is constant because electric field is 0. So, here is the potential psi s and here is the psi that is applied voltage V. Now, here is a depletion region. So, this term is highlighted that controls the depletion region here and this term controls the inversion charge, Q N and that controls the Q depletion region.

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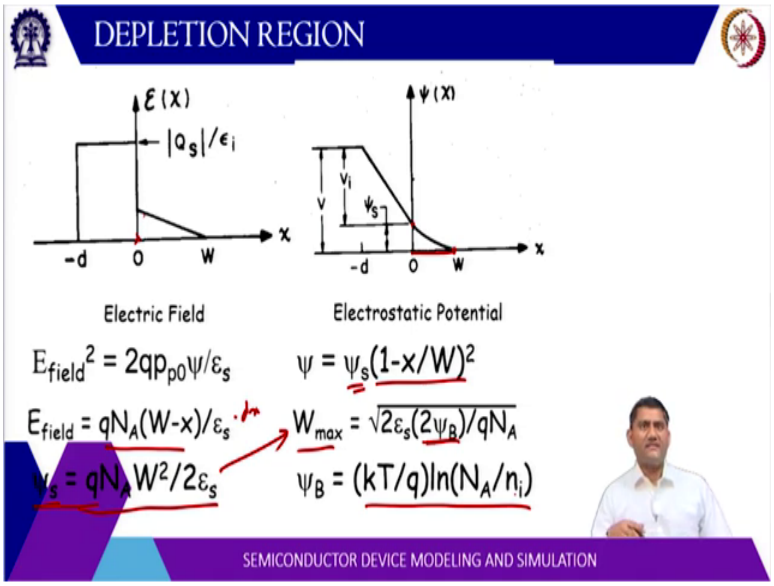

Now we can write some expressions also here. So, E square = q 2 qN A psi by E s epsilon s and if you take the, if you write in terms of the potential width, so, E field can be written as qN A times W – x by epsilon s as a function of position. At surface this x is 0 here. So, the electric field, with qN A W by epsilon and the potential will be area under the electric field. So that will be half height into width.

So, this is the electric field as a surface qN A W by epsilon times half W that will be qN A W square by 2 epsilon. That will be the potential at the semiconductor oxide surface and in the region of semiconductor. This is the field so, if you integrate dot dx, you will get the potential and then, if you separate out the psi s from here, you will get 1 – x by W whole square. That is how the potential is varying.

So, at x = W this potential is 0 and at x = 0 this potential is psi s. And then, of course, you can find out the W max. That is a depletion width, so that can be obtained from here that will be 2 epsilon 2 psi B by qN A. You can substitute psi = 2 psi B so, psi is equal to so, if you substitute here so, from this equation, you can get the W max so, 2 epsilon psi s by qN A and psi s is 2 psi B here.

So, beyond 2 psi B that is means stronger version depletion width does not increase further. So, all the charge that is coming after a strong inversion that is in the inversion layer only. So, we can assume that W max will occur when the surface potential is 2 psi B. And psi B is of course, we know k T by q lon N A by n i. So, this is a handy expression that you can easily evaluate and use them to visualize the field and the potential profile inside MOS metal oxide semiconductor structure.

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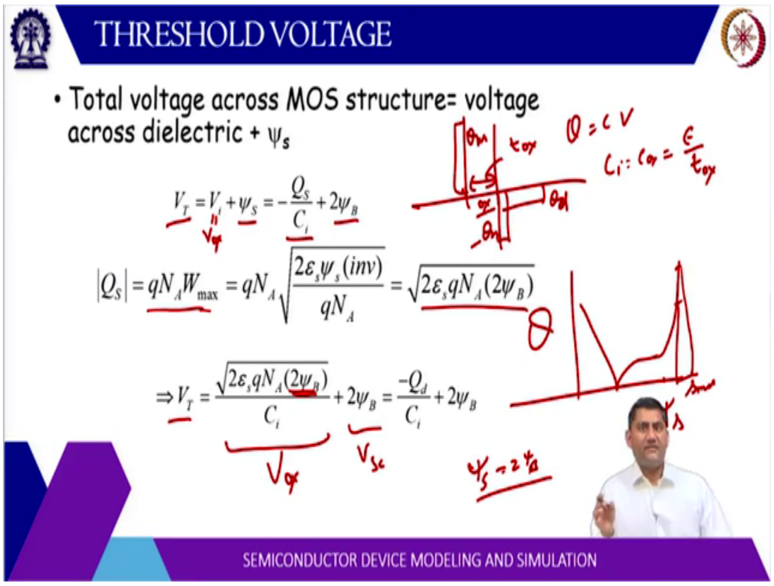

Now, the total applied voltage V T drops across oxide, so, we can write V I insulator or you can write V oxide inside the oxide + psi s the potential drop in the semiconductor. Now, inside the oxide it basically act like a there is a charge here on the metal layer. The inversion charge here is a depletion charge here this is Q n, this is Q depletion. So, this oxide is basically like a capacitor here.

So, the potential can be written as Q = CV. So, V which is basically Q by C. So, Q on either side, let us say – Q S by C I or where C I is same as C ox is in some text. It is C ox it is oxide capacitance or insulated capacitance that is epsilon by the width, so that is t oxide. So, t oxide is a thickness of this oxide region. So, – Q s by C I + 2 psi B. This is at the strong inversion region.

Now, actually if you go beyond strong universal region, the change in potential will be very small because the corresponding change in the charge is exponential. If you look at this curve, Q versus psi s for accumulation, it increases exponentially, for depletion it stays for some time, for certain value then beyond 0.7 it again goes exponential. So, if you see here, the change in charge concentration grows exponentially.

So, for a small change in psi s there is a large change in the charge. So, your Q s is qN A W max. There is a maximum depletion width so that expression we gave already used. So, if you multiply W max by qN A W max we have obtained here, if you multiply this by qN A then you will get qN A 4 epsilon psi B. And then of course, you can express this total voltage which is actually we call it threshold voltage.

So, this is drop across capacitors Q s by C so, you substitute Q s here. So, this is a voltage across oxide and this is a voltage across semiconductor. So, this is just at the threshold, so, threshold is by definition the voltage at which psi s = 2 psi B. So, this is a threshold voltage and this threshold voltage is for ideal MOS structure where we have assumed that phi M s is 0 and we have not considered any charges inside the oxide.

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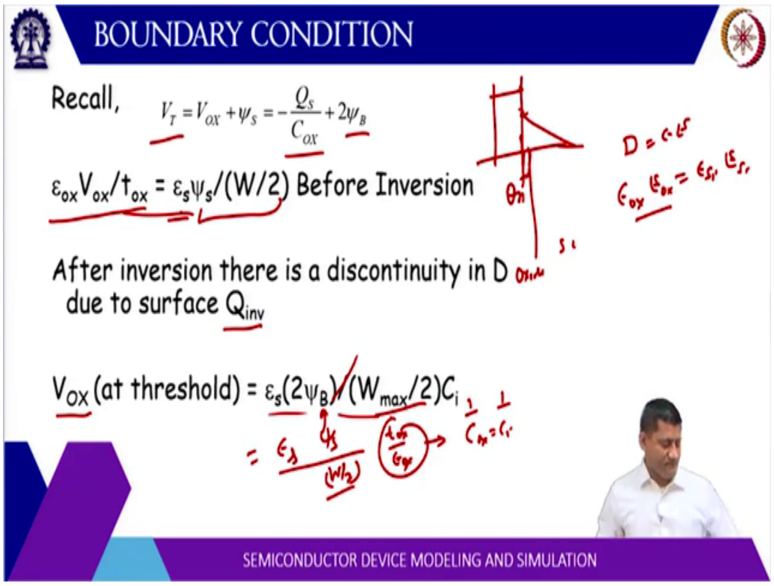

Now, let us recall that threshold voltage is Q s by C x + 2 psi B and at the interface this is oxide here. So, there is a electric field here and then there is a jump in the electric field here and then this goes like this linear. So, since at the interface if you recall that there are two regions, one is oxide, one is semiconductor, the electric field is not continuous but the flux density D the displacement flux density is constant.

So, D = epsilon E so, epsilon on the oxide side and E on the oxide side is equal to epsilon on semiconductor side times E on electric field on semiconductor side. So, this is basically epsilon oxidants v oxide by T oxide that is epsilon E on the oxide side on semiconductor side it is epsilon times psi s by W that is before inversion. So, after inversion there will be discontinued in D also. That is because of this qN charge here.

So, whenever there is a service charge density D will become discontinuous now. As long as there is no infinite sheet of charge or last heat of charge D will be continuous, so, upload depletion region, this device continuous and then, we have to take this Q universe into account there. So, B oxide the voltage drop of across oxide is a threshold is you can say if you write here if you saw rearrange this equation.

So, V ox can be calculated as epsilon s by epsilon oxide. So, this is epsilon s times psi s divided by W by 2 divided by t ox by epsilon oxide that is B oxide. So, psi s is actually 2 psi B and W is W max by 2 and this is C oxide or C i epsilon by T. So, this should be divided by C i basically. So, this is 1 by C, this is 1 by C. So, the voltage across oxide can be estimated at the threshold using this expression.

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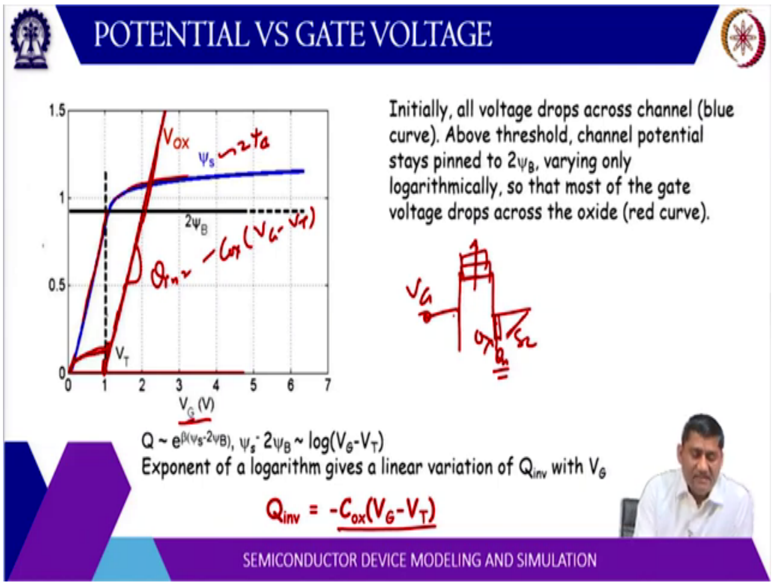

Now, this is a plot again with respect to the gate voltage. So, gate is basically this metal, oxide and semiconductor so, this is the gate voltage. So, a threshold voltage so, this is the threshold voltage here. You can see up to the threshold voltage, the voltage across oxide is almost constant but the voltage across semiconductor actually increases. Because depletion which keep on increasing here.

So, this is a voltage across offside. This is the voltage across semiconductor. But beyond threshold what happens? Here Q n comes into the picture, so, this field actually increases. So now, extra this charge actually appears here, so, this field actually keep on increasing in the oxide. So, beyond threshold, the voltage in the oxide region increases but the surface potential remains more or less constant to is equal to 2 psi B.

So that variation is fairly small. So, we can say that Q inversion is actually C oxide times V G – V T. So, this is V T, here this is a linear line, so, this is basically you can write. This Q inversion is equal to – C ox times, V G – V T, this value is V T, here and this value is V G here. So, V G – V T this region is linear.

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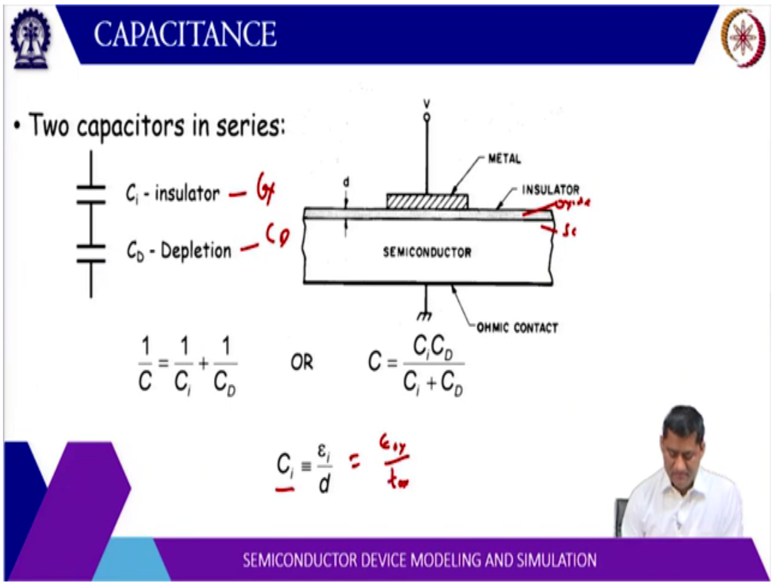

Now, if you look at the metal semiconductor of oxide structure, there are two regions here. One is the oxide here insulator one is the semiconductor. So, inside the semiconductor there is a depletion region. So, there are two capacitors series. This is the insulator oxide capacitance C ox this is the C depletion. So, when the two capacitances are series, so 1 by C is 1 by C 1 + 1 by C 2. So, if C can return as C 1 C 2 by C 1 + C 2.

And we know that oxide capacitors epsilon by D or we write epsilon oxide by oxide thickness where D is the oxide thickness or t ox.

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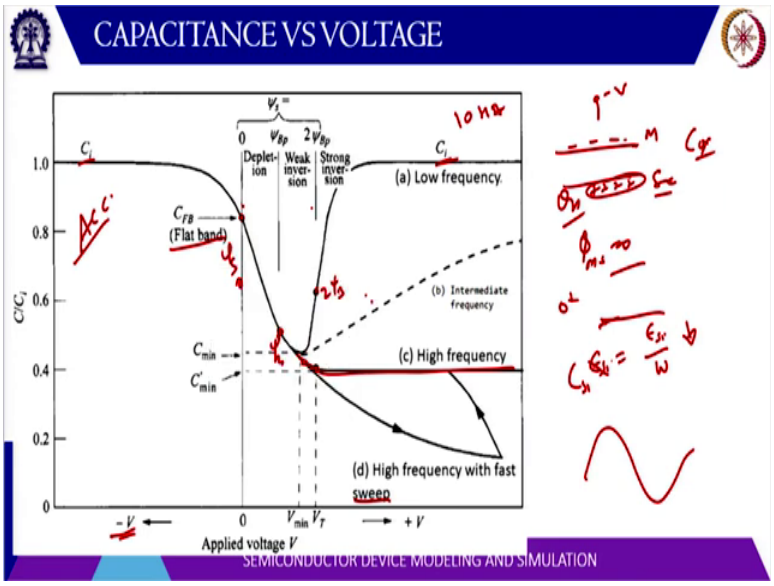

Now let us, look at this picture first so, this is voltage is negative, so that means this is the accumulation region. So, in accumulation region this is metal, this is semiconductor. So, all the holes actually accumulate here and there is a negative charge at the metal surface. So, all the potential falls across the oxide, so, this capacitance is simply C oxide or C I insulator capacitance. Then, so, this is for negative voltage.

Now, let us come down to 0 volt, so, 0 volt there will be some potential across the metal, some potential across the semiconductor. Now, if you look at exactly 0 volt, we have assumed a flat band condition. We have assumed that phi ms is 0. So that is, the bands will be flat. But if you go to 0 + then these bands will bend actually. So, when we say that capacitance at 0 voltage means plus minus variation at this point will give some variation in the depletion charge in the semiconductor.

So, there will be capacitance in the semiconductor that will come into the picture and we call this capacitance a flat band capacitance because your bands are flat and the capacitance is the combination of capacitance of the oxide in series with capacitance in the inside the semiconductor. As the depletion width increases the capacitance inside the silicon is epsilon silicon by W.

So, W increases so, this capacitance of the silicon or the depletion region actually decreases. So, when two capacitances are in series, the overall capacitance will also decrease, so, it actually decreases. And it reaches maximum when it is in the W max. So that is around 2 psi

B but at 2 psi B there is already Q n is there, the inversion layer is already there. So, slightly before that it will peak to the minimum.

And then of course again it will increase and it will be close to the oxide capacitance. Because now, all the charge is getting added here but in the form of electrons because now it is inverted. Now, this capacitance curve actually depends on the frequency because in case of MOS capacitor, this extra charge, when you apply a voltage, a large positive voltage, this electron have to come from somewhere and that takes time.

So, if the frequency is low, let that means around 10 hertz or something then these electron will have submission time to appear there and then at low frequency you will get this curve. But if you got high frequency then this charge carrier will not have time to appear. Because by that time they appear this is again gone to negative side like that. So, at high frequency this will be fixed. So, this will be C ox + C D in series.

And then of course, if you do high frequency with fast sweep then you can get even lower capacitors. So, these are the MOS CV curve for different frequencies and different region. So, beyond flat band capacitance is the accumulation region. Then there is a depletion region. Then there is a weak inversion. So, psi s is between C 0 and 2 psi B. So, this is psi S = 0. Here this is psi B here and this is 2 psi B here and so on.

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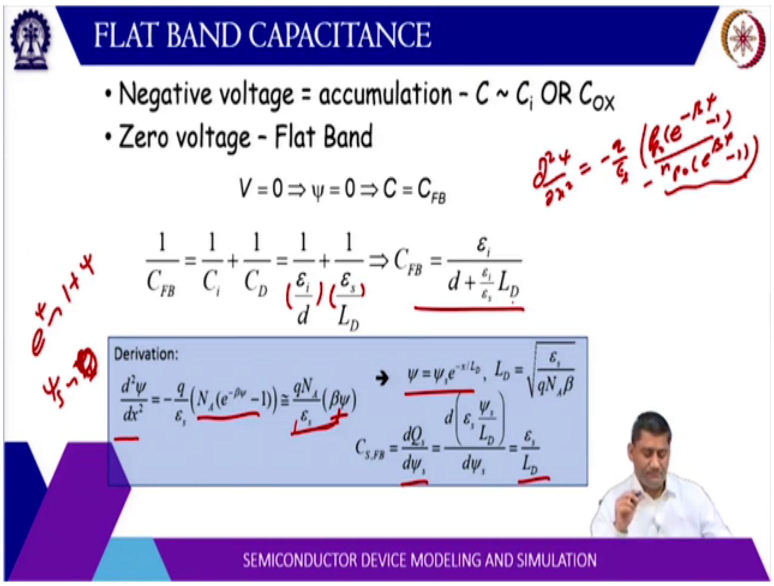

Now, for negative voltage accumulation at flat band voltage, so that we can calculate by solving the Schrodinger equation. So, we know that at psi s = psi B. Sorry at psi s = 0. It is the basically accumulation term that is dominating so, other term we can ignite ignore only we keep the holes from there. So, if you recall, that D 2 psi by dx square = – Q by epsilon silicon times p p naught e to the power – beta psi – 1 – n p naught e to the power beta psi – 1.

So, this term will be insignificant, so only the first term will player all here, so that is, we have kept it here. So that is p p naught is N A exponential – beta psi – 1 and then of course because size is close to 0. So, we can assume the size small so, e to the power psi can we expect expressed as 1 + psi, so, this will be e to the power beta psi can be 1 + beta psi. So, this can written as beta psi only times qN A by epsilon times beta psi.

Now, if you look at this equation, it is some coefficient times I so, the solution can be expressed as psi s e to the power – X by L D, L D is a square root of this coefficient epsilon by qN A beta and of course, if you calculate C that is dQ by dV so, dQ by D psi s. So, Q is epsilon times psi s by L D. So that is the electric field, epsilon e and then that comes out to epsilon around by L D.

So, at flat band capacitance you have oxide capacitance which is epsilon by D or t oxide + 1 over epsilon by L D. That is the capacitors from the depletion region. So, it is a expression for flat band capacitance so, this is slightly less than the oxide capacitance.

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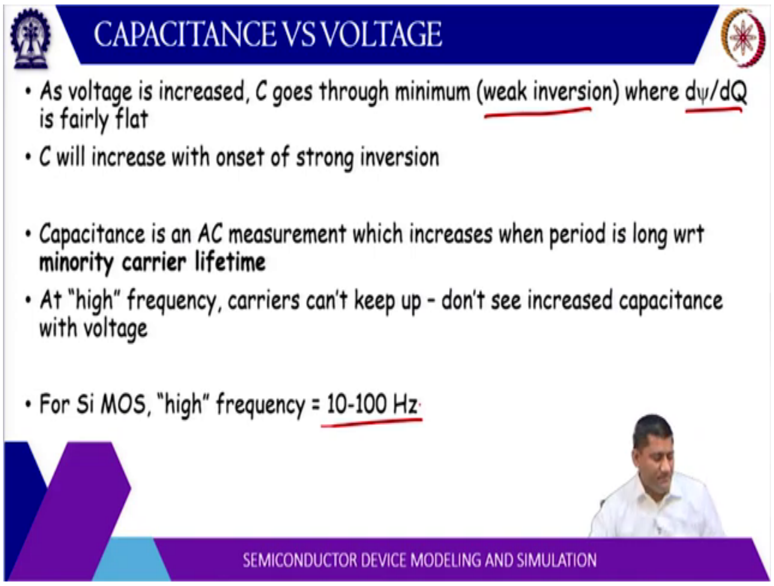

Now so, as the voltage is increased C goes through a minimum during the week inversion, where d psi by dQ is fairly flat. Then of course at the onset of strong inversion C again increases the capacitance again increases because the contribution from the semiconductor side is now not that significant. And of course, when you consider frequency based measurement.

Then if the frequency is much smaller that is comparable to the inverse of minority carrier lifetime. Then, in case of inversion, a strong inversion, the capacitance will be same as the oxide capacitance. But at high frequencies these carriers cannot follow the voltage signal and then that will lead to increased capacitance with the voltage. So, of course, we should remember that for most high frequency is roughly 10 to 100 hertz because that is related to the inverse of the carrier lifetime. So that is quite large basically.

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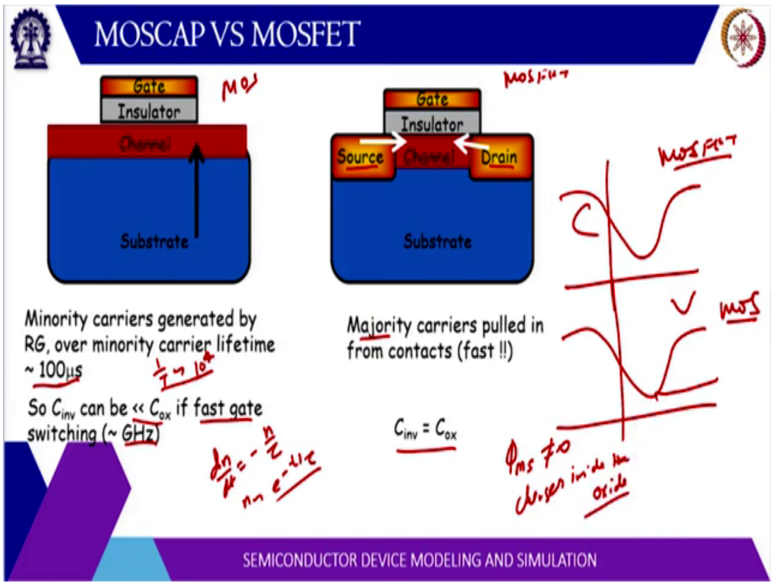

Now, you can compare these two structures one is the mass structure, so, this is metal oxide semiconductor other is MOS field effect transistor. So, here what we have done, we have made the two contacts. There is a source here there is a drain here. So, now, if you compare their CV characteristic, regardless of the frequency the MOSFET will give this curve. Why? Because now, this inverted carriers are they do not need to be generated.

They can be drawn from the source and drain side. So, they can quickly come so, for MOSFET the CV characteristic will be like this but in case of MOS capacitor the curve will be frequency dependent because in case of MOS these carriers have to be generated. So, therefore, because the carry lap time is order of hundred micro second. So that means your 1 over T is basically 10 raised to power 4.

So that is kilohertz so, if you see their lifetime that is quite fast and that means once you go to order of kilowatts, they cannot keep up with the with the carrier consultation. So that means carrier lifetime is basically rated like this dn by dt = – n by tau. So, tau is the carrier lifetime, so, there is a time it takes to recombine or generate so, n can written as e to the power – t by tau.

So, if tau is 100 micro second that is it takes 100 micro second to generate a percentage of carriers. So, your C inverse will be much smaller than the C oxide. If there is a fast switching there order of few megahertz or gigahertz in case of MOSFET this measured carriers are pulled from the source and drain region. So, your inversion capacitors will be same as the oxide capacitance because now, it can easily get the charge from these two sources.

So, thank you very much next class we will discuss about the real diode with difference in the work functions, phi ms will be non-zero and we will also consider the effect of charges inside the oxide region or the insulator region. Thank you.