Nanoelectronics: Devices and Materials
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Lecture - 21
FD SOI MOSFET: Operation Modes and Threshold Voltages and Electric Fields

So we were discussing last time, the silicon on insulator, analysis of that we were discussing and I will just go a little bit back 1 or 2 slides so that because I had rushed a bit during my last lecture on that portion. So we will just start from there 1 or 2 slides.

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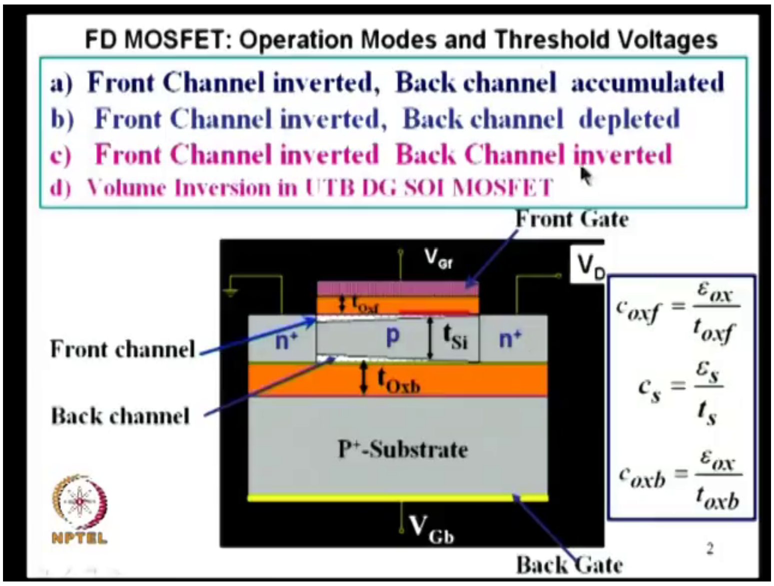

Compared to the bulk MOSFET, there are different modes of operation in the case of SOI. So that we have said, you can have the front channel in order front channel inverted all the time, but back channel can be either accumulated depleted or inverted. So that is 2 channels are there. Now if I make this thickness very very thin, thick or thickness of the SOI layer, t silicon very thin through nanos meter scale, 10 nanometer, 20 nanometer of that order. Then, f lambda called as the Volume Inversion takes place. Entire channel with both the inversion layers will be merging, that also we will discuss.

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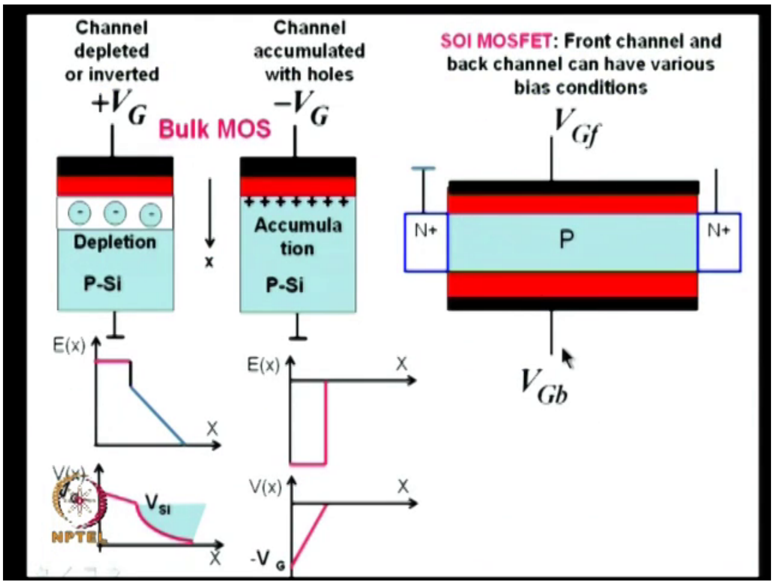

Now I just wanted to bring in some aspect of this depletion and accumulation. To make things clear, if you take a look at this bulk MOSFET, you can see the gate, red is oxide. The silicon will be depleted if I apply plus voltage to the gate, if this is a P type okay. Depletion charge is negative in the P type sub substrate. So this is the depletion plus voltage, if I keep on increasing, you know that you can invert the surface, when the surface potentially is twice Phi f then, you say it is inverted. So I have shown the what last time itself I have discussed this. The voltage drop across the oxide, these to the electric field which is constant, then, the electric field at the oxide and at the interface will be different, there will be discontinuity because the flux is continuous. Epsilon oxide and dioxide is epsilon silicon into E silicon. Since, so this field will be about 3 times more than that because the permittivity of silicon is about 12; that of oxide is about 4. So 12 by 4 that is the ratio is 3. 3 times smaller and if the doping is informed as it happens in most of the cases, the electric field is lenearly falling. The electric field is linear I do not have to derive that because I already know it, that you recall that and the slope of that depends upon the doping, higher the doping there will be is steeper.

Now if we integrate these, you get the voltage. X if integrated it is X square. So if it is linear that will be parabolic in the voltage and if it is constant and integrated with a becomes a straight line. So you have got the voltage drop. Field actually is Vg minus V silicon divided by t oxide that is the field there. So V silicon is like this. Now if it is inverted it is inverted by V silicon becomes twice Phi f. So that is depletion or inversion usually you operate in this region. But if I apply negative voltage to a gate, bulk MOSFET they are still on constant MOSFET.

Black is a gate then, you have got this red oxide then, the silicon. Now you can see when I apply minus here the plus charges can be supplied very easily by this say majority carriers in the P type region. So, they accumulate plus charges, they are mobile charges or remember, what c on the left hand side here when it is depleted, I have put it inside a circle to show that it is not mobile. It is the dope end which has being depleted of the holes whereas, this is the plus charges which have accumulated there and this is the charge sheet on that.

So, whatever voltage you apply, appears completely across the oxide. So the field is actually equal to or the voltage is minus V G here and it is 0 just at this point. So the voltage is linearly falling across the oxide, minus to plus, but that is 0. 0 to minus V G and the electric field of course, is constant. Now charge within the oxide, so V G divided by t oxide, will give you the electric field. So this is the charge sheet. Now when you go to the SOI MOSFET, you have got the front gate, this is almost looks like this. I have shown the MOSFET source, then also here, here I can put a source and drain here, if I want invert and collect carriers. Here I have plus here, minus here.

This is a Schematic diagram. Front gate metal or polysilicon doped, red color is the front gate oxide. This is the SOI layer, P of thickness t silicon and this is the back oxide. So here you have got a front gate and you have also have got the back gate. So front gate oxide, back gate oxide. Now, you can invert the front gate by applying sufficient gate voltage. At the same time you can have the back channel accumulation, depletion or inversion. You can accumulate it by applying any V G b negative like what you saw here. If I apply negative voltage here, it will be accumulated. If I apply plus voltage to back, I can deplete it from the back side. If I apply large voltage, I can invert it that portion you see now.

So these are structure which I did not show, that means, in my previous lecture for analysis.

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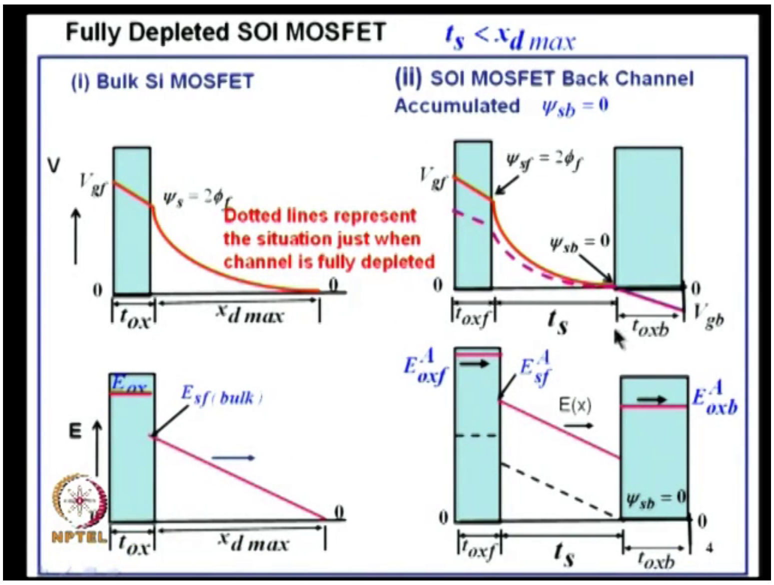

So you can see now here, whatever we have discussed yesterday is here or previous class. That is this diagram is you drawn here, voltage there is a Bulk MOSFET. Now let us see this back channel is accumulated case. So this we have discussed yesterday, what you do is apply a negative voltage to the back gate. I am sorry apply a negative voltage to the back gate so, there will be plus charges here. Now if I apply plus voltages the gate with respect to the source or with respect to the substrate which is somewhere, it is sub cross section on the surface, you will have a contact you can put outside this gate region. Otherwise you can apply voltage between these two also. So if I apply voltage then, this will start depleting, completely depleted and once it depletes, the additional feed lines will cross this and go into the other side that is what we had discussed already. So you get this is the situation, when it has just got depleted dot line dotted line.

I have got actually plus charges here, on this side. On the surface, you have got plus charges. Exactly same way, you have got here, you have got the plus charges here. That is giving rise to the field here. So after this depletion, if I increase the voltage, the field lines across this and the entire field will go up. This portion I think I have discussed this. This is not a very important, need for the SOI MOSFET, but I just showed you, you can get inversion here and you can because you applied a plus minus voltage here, the voltage is the 0 here, because if you recall here, the potential where this accumulated is 0. So you have got 0 potential here. Surface is inverted here and electric field will be, will depends upon twice Phi f minus 0 divided by t silicon that is average field. If these are completely insulated layer then, twice Phi f minus 0 divided by t silicon would have been flat.

Now what happens is, you have got this particular field percent here already. So you superimpose that whatever voltage field was there, you superimpose on that. Original field was like this, varying. Now beyond that a constant field from here, here they both are same, that is gets lifted up by the amount that a regional field. So you can actually find out, how much this field is? How do you find out? Twice Phi f divided by t silicon E is an average field. So it is an average field say for example, for example, if I just draw this like this.

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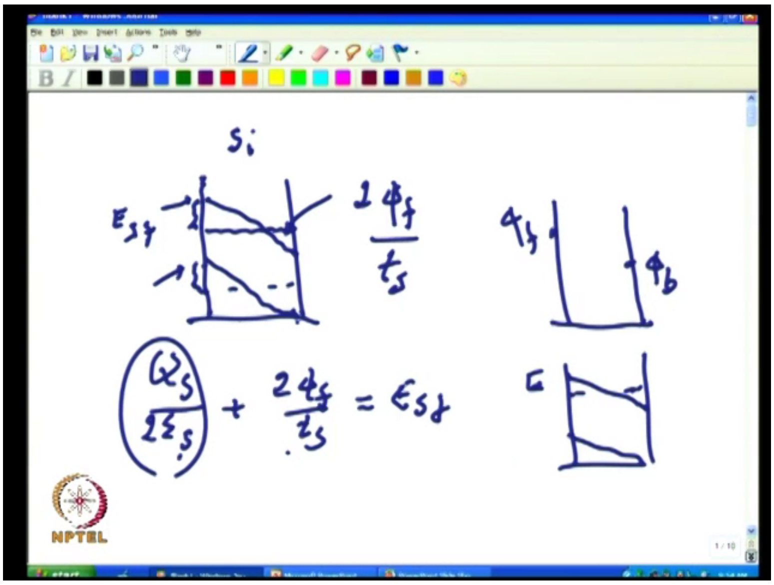

I have at when it this is the silicon, this is a silicon, I have the oxide on either side. Now and it is just depleted it is like this. Lines are not straight actually, I am it is not coming line straight. So if I draw it here like this. Now the, if I take twice Phi f minus 0 and take the average field as like this

This is E s f, this is backside field, so average field is that. Now what I want to find is? So I know this is actually equal to twice Phi f divided by t silicon average field. So voltage drop is that, but now I will not find how much is this quantity is. That quantity is it because this whole thing has got shifted out. So whatever I have here, is half of that as the whole thing is shifted up I get that like this. Now this quantity is the same as half of that. Average is fitting these 2 middle line, here it is maximum s 1 and 0. So, what is this quantity? What is the field here? When it is just depleted, whatever charge is there in silicon divided by epsilon s that is the that is the electric field here, so half of that is that. So if I have this quantity as t ox t s that is the field. Here, this quantity is that is that. So this is the E s f. So I know how much is the field here is. That is E s f, I am writing is that surface front surface. So that is the E s f from here to here total. So that is why you find out average field add to that.

So whatever distribution you have all that you do is supposing I have a potential difference like this, this is Phi f and this is Phi s Phi back, if there is Phi phi b backside. Now this, minus that, divides t f t f s the average field. They may not be equal let me just do it once again. I remove that and I go back to this and oh my god. So you have got let say this is Phi b back channel, this minus that divided by t f s is the average field. To that you know that there if I take the electric field it will be like this. So the average field is whatever I get this minus that divided by t f s. In this case it was twice Phi f only because this voltage of 0. Here it will be some Phi b is there. So I find out the average Phi f minus Phi b divided by t f s is that average field and what is that quantity that is half of this, that is same as this t f by t f s. So this is a general case. So if you understand that there is nothing more to no no voltage difficulty is will be there. So I will just go to back to this ok.

So here you have got the delta field like that, this field is actually twice f by t f s plus whatever field is there half of that you add to that then you will get that. Now let us go to more realistic situations. So you can see I change the whole situation now this was back channel was biased with negatively. So you have got accumulation layer here.

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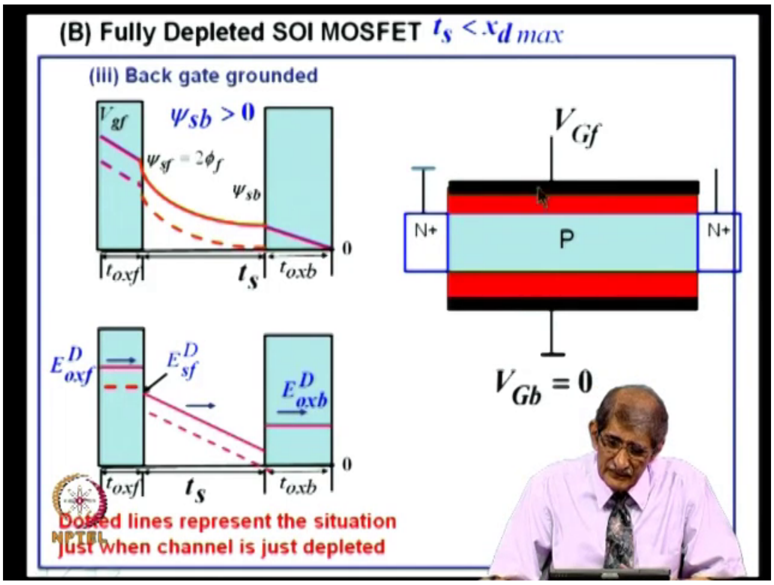

More vertical situation, I have the back gate grounded. This is where I think we started last time and some understanding we needed for bit more analysis. So I apply plus voltage to this, we also change finding a situation where the front channel is inverted back channel is we could apply to the back gate. So it will be depleted. Now, what happens? When I apply a voltage plus voltage to this front gate, this is grounded, this is with respect to that you apply. This is connected to the ground somewhere substrate somewhere else. We are not able to see in the cross sections. So I apply voltage across that. So you see at a particular voltage as I keep on increasing, the depletion layer keeps on moving.

I will just go back to this now. So, let us see where I can do this. So, what we were trying to see is the, if I have the layer like this silicon t silicon.

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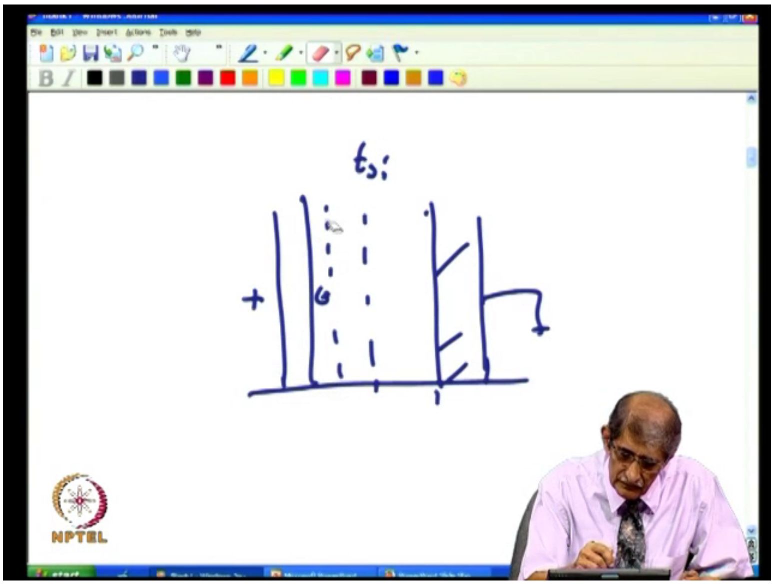

Now if I apply a plus voltage to the gate plus here, I have grounded this. This is a back oxide, this is a oxide. So what happens is the moment you apply voltage, there is a depletion layer formed. That is depleted; they are all negative charges, immobile keep on applying increase in a voltage, this keeps on moving. Ultimately, this merges with that. So when it just reaches this point that is called punch through. The entire depletion the silicon layer is punched through. So then what you will get will be I will just show that at that punch through, you will have the I will just remove this particular thing. So I will go back to this go back to this.

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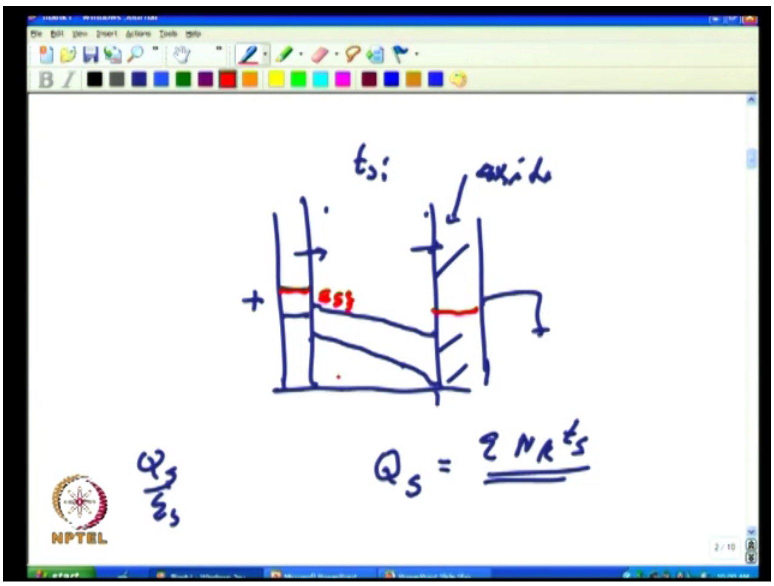

Just when it is punched through I will take field, it is something like this. That is 0, 0 electric field here. This is the maximum field. What happened? So you have got the electric field like that and you know at this point the electric field is Q s by epsilon s. Total charge what is Q of s q n a t of s by t of s, that is charge that divided by epsilon s is the field here, like before. Now if I increase the field voltage further beyond punch then what happens? There is no charge here, there is no charge here, there is no charge in the oxide. This oxide that is the oxide. I hope you can read that, it is an oxide there. So if I increase further, additional field will has a cross here, additional field has a cross there and whatever additional field line is there, there is no charges here it will be down by factor 3, see oxide, field oxide divide by 3 is the charge here field.

So here, if it this has gone up, this will go up by the same amount, but by at 3. Now whatever electric field has increased here everywhere it will increase because there is no charge there or whatever the field line originates from there, terminates there and once it reaches here there are no charges in the oxide. So, what will happen? It will cross the oxide, but the electric field here in the oxide will be higher like the electric field here. The field here will be higher by the factor of 3. So you can see here electric field distribution will be like this now. Now I can found out this is the electric field at the surface E s f. Why are we finding electric field at the surface? If I know the electric field at the surface, I can find out what is the voltage drop across the oxide is. Because of voltage drop across the oxide is E s f into epsilon s that is the total charge beyond that point, divided by c oxide f, charge by c oxide f, charge is E s f into epsilon s divided by c oxide and till voltage drop.

Now, when you go into this situation go back to the diagram now. So, I hope it is clear enough now. So, what we are trying to find out is how much is this field, the ultimate goal is to find out how much is a surface field. When the surface potential is if you take a look at this surface potential, I think I have that here if I take a look at surface potential, see this is the dotted line is the electric field when I just depleted it, that particular thing. Now when I increase the voltage the field has gone up, the entire thing has gone up. The diagram which I have drawn, I put e s f D to tell you that the back channel is depleted. Front field, surface field and the back surface is depleted. So, how are these field here how do you find out? What is the potential here? Psi s f. Because the field lines are crossing these oxide and the because this is grounded there is drop across the oxide.

So the potential here is plus, channel potential on the back surface is plus with respect to the back gate that is Psi sb positive. So the voltage difference between the front channel and the back channel is Psi sf minus Psi sb. I am trying to find out, how much is their threshold voltage of the front gate? At threshold voltage Psi sf will be twice Phi of f kept on increasing voltage till this has reached Psi sf. There is some voltage here, with respect to ground Psi sb. So what is the E s f? How do we find out psi?

Psi sf minus Psi sb divided by t of s you can see that, that is smaller than what you got in the previous case. Previous case it was Psi sf minus 0 divided by ts average field. To that average field you you add half of this field here that is epsilon s. So here, twice Phi f minus some voltage divided by t of s will be smaller average field compared to back channel accumulated. So if you want to find out how much is this average field plus half of this quantity. So I will get in this case also, I will get I will get in this case E s f will be will be twice Phi f minus Psi of s b divided by t of s that is average field ok.

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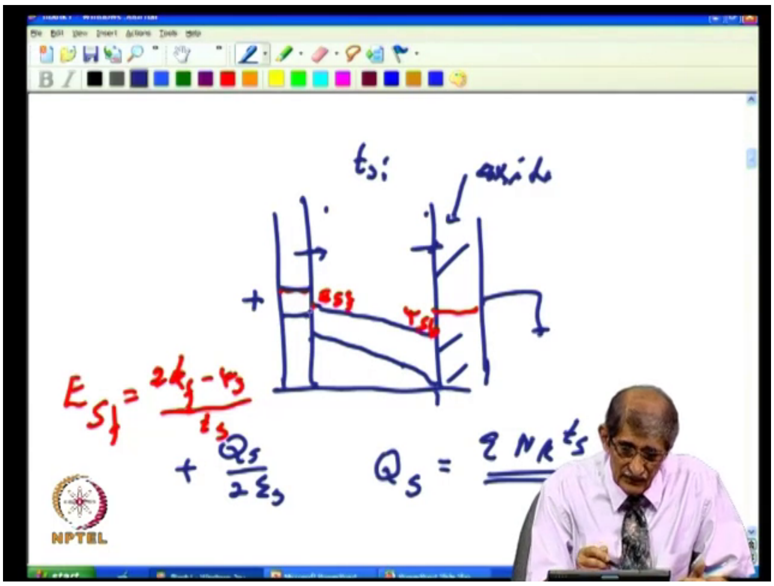

Now, let me just remove that thing. So plus this is the average field, plus what will be the thing? Half of this, this is a just when it had punched through Q s divided by epsilon s is total field. So that is this is the case distribution. So electric field is that. So once you know this multiplied by epsilon s that is charge beyond that point, we do not know where it is all. We know this field how to calculate, multiply it by epsilon s Q s be the charge divided by c oxide of Q s by voltage drop. So threshold voltage at this point is go back to that threshold voltage at this point is actually equal to twice Phi f.

We know that the inversion condition, twice Phi f voltage drop across that is twice Phi f minus Psi sb divided t of s plus half of this field into epsilon s divided by c ox f, see whatever we are telling Q substrate that has got a bigger expression like this. This whole thing is there. So instead of Q, only this charge is there, but there is charge coming under that also whole thing is taken account by this that is the that is the beauty of this using this surface potential that into epsilon s divide by c ox f is the voltage drop.

So that is about the back gate depleted.

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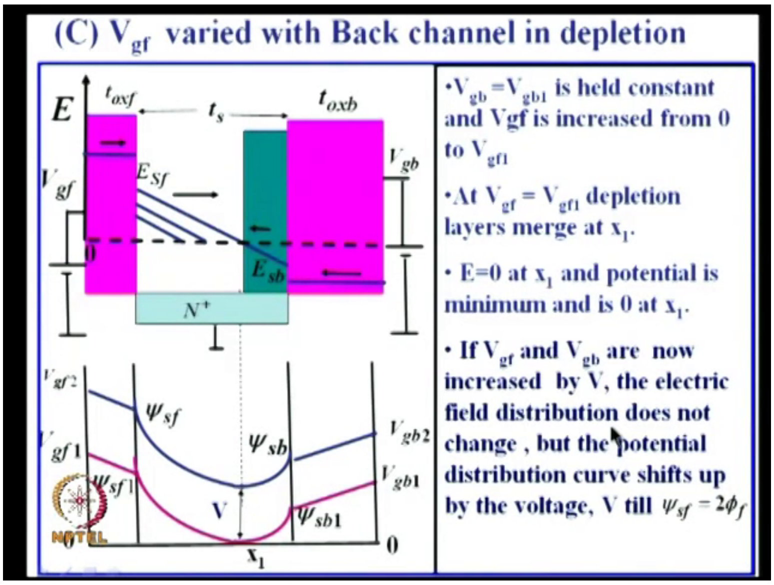

Now let us go and see the situation, when I see here. Here the back surface potential is Psi s b because this is grounded there is a drop across the oxide. Now I will take a situation there, I will deliberately apply voltage to the back gate plus that is, it is a making 0 as a plus here plus there. So I keep the voltage plus here and this green color that I have shown is the depleted region due to the back gate sees, I am applying that with respect to that that is with respect to substrate which is connected to this. So, you have got this is the depletion layer here, up to this point. Now I start applying front gate voltage with respect to this that is substrate. What happens? As I keep on applying the voltage, I am not disturbing this. I fix that at V G b. This may be thick oxide, it is not inverted because to invert depletion layer width is much more than the thickness it is a fully depleted case.

So I start applying the voltage just like in the previous case, you will have the similar situation where, where that situation is slightly different now. So, the situation now is if you see it is like this.

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This is the back channel this is a oxide, and this is a oxide, and part of it that portion is already depleted. Because I have applied plus voltage here, so this two lines are like this in this direction here, now I come from this side as I keep increasing V G f what happens this oxide straightaway there is some voltage drop across oxide that is the electric field.

So, increase of voltage what happens that goes up this goes up at a particular point, I have this coming and that coming like that. Now at this point you see this is the t silicon part of this t silicon has been depletion layer has been occupied by the back gate V G b this has been taken over by that you have fixed that. Now when I have applied up to this point you have got zero field here, because if I plot this electric field lines from the left hand side and right hand side ok, if you draw that was a depletion layer which is already occupied by the back channel.

Now, if I take the electric field now how is it only here, in the channel region t of s over here just one minute up to this point depletion electric field is from right hand side from here, left hand side. So, electric field comes down like this I think I better take a different color for that is like that electric field, and if you the electric field from here that is like this because of the back gate bias. So, that is plus higher here 0 here, so you have got a region where the electric field is 0.

So if I take the potential here, how will that be here it is actually potential the potential here will be 0 it will come from here I think I will just change that. So, the electric the voltage will come like this corresponding to that point that will be 0 and from this side it will come like this, but this potential is smaller depending upon what was the gate oxide thickness what was the back gate bias. So, this is the point at which 0.

So, that is a situation you have got here, now at this point what is the it is not inverted here it is the surface potential is not twice Phyfe. So, I have to increase the voltage further, so what the what I do at this point is I will go back to that slide it contains all the things.

So that is situation that you have got what I have drawn there is this situation the bottom line. So, you have got it like this. Now I see this is V G f 1 and this is V G b 1. This portion belongs to the back gate, this portion belong to the front gate electric field lines you see as I went on doing like this here, I have drawn it like this see instead of drawing it like this, instead of drawing it up like that, this is in this direction that is in that direction, so what we do is we take it like this draw the 0 line, and draw like this it will take it up we draw it like this negative. So, that is what is done there so you have got that continuously there implying that this is 0 here is the negative here by field is in that direction.

So, this is a situation what you got here. Now from here onwards what I do is I increase the front gate voltage by some voltage V, back gate by voltage V see that carries no charge in between completely depleted. The entire layer is depleted all that you have done is now you increase this by same amount the difference between the 2 voltages is not changing, that is the electric field will remain same way the electric field distribution here will not change, where has that extra voltage gone that is the thing. When I apply it like that see here, if I once we have depleted completely and this also V G f from the and this was also bias positively beyond that point, just when it is fully depleted beyond that point I increase both of them by the same amount V that extra V does not appear here, the difference is 0 same, but that extra V appears across with respect to ground that is here. So, that this point becomes plus with respect to that that is the source junction gets forward bias by that extent.

So, if this is forward bias from that point on to the surface whatever drop was there is present, see from here to the midpoint there is some drop. When this situation see from here surface to this point there is a drop. Now if I increase this by V this potential here also is increased by V; that means, the source junction has got by forward bias by that V extra here, but here what is the forward bias voltage whatever V is there plus whatever was generally was there.

There was a potential here see when the point just when it has depleted here potential here, is here the what you have bought in is just outside the surface here, that was 0 it was rising to the that psi f psi s 1, but now it has gone up here this has gone up here, so you can keep on increasing it. So, that this is inverted this becomes psi s f, but this would not have been inverted because that that depletion layer is narrower here.

Suppose you have applied a voltage. So, that the entire thing is at the middle both would be the same potential it will be both will be inverted. So that is the situation that you have got. Now, let us see so, here in this case what will be the field now, psi s f minus psi s b divided by t silicon, that is the average field that is the field there psi s f minus psi s b divided by that that is the average field.

Now, if I want to find out how much is this field what do I do q s by twice epsilon I add, and how do I find out this one E s b epsilon s we subtract that is all. So, it is you got to get the whole thing by solving a Poisson’s equation, but you can see this is very easily you can see for any bias condition. So, this will be inverted this is depleted

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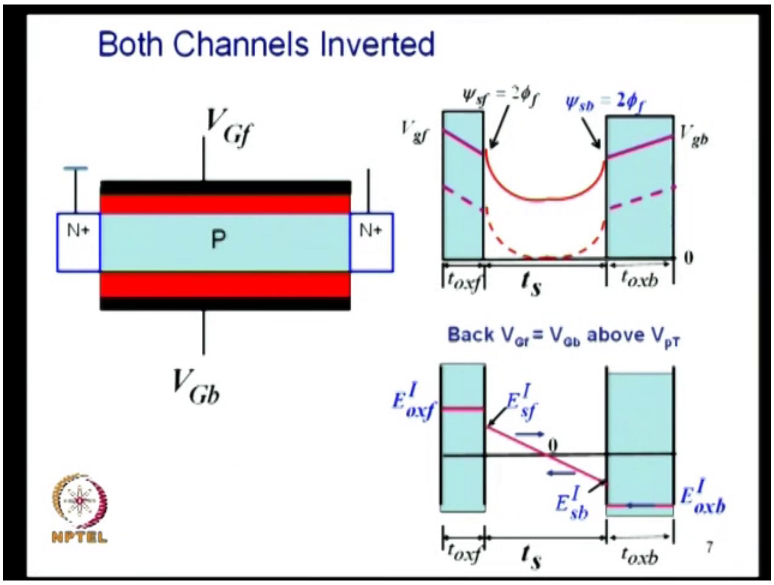

Now, you have got a situation where I have applied a let us say this is a situation where need not be oxide need not be the same thickness, but I can apply a large enough voltage. So, that the depletion layer from backside comes up to the center. Now, I can come from the front gate till the depletion layer merge that is the situation. So, if the depletion layer were coming up to this point the potential will be symmetric, even for thicker back gate I can do that, but the difference will be the back gate voltage will be more.

Because more voltage drop will be in the oxide, so here the drop here from the midpoint to this surface and from midpoint to surface both are equal, but for the same field the voltage drop here will be something here will be more.

Now, beyond this point I increase both the voltages by the amount equal to V till that goes twice phi f because it was symmetric originally when it is depleted, when I have started applying a voltage this also be a twice phi f. So, what is average field here 0 this minus that is 0, so average field is 0, but the field here will be how much the average field is 0 the field here will be this minus this by twice t S that is 0 plus Q s by twice epsilon s that is the field there. So, you can see that q s is actually, what is q s charge in the depleted region q n a t of s. So, if I use lower and lower doping q s by twice epsilon s that is this field will be smaller, if this field is smaller, this field also will be smaller you can see now. We are seeing it like this, but in the device you are able to reduce if you reduce the doping here, and also reduce the thickness here the field here will be reduced.

If the field there is reduced the electric field there also it is reduced; that means, the voltage drop across oxide is reduced that means, your threshold voltage will be lower in this case. When I got the into twice phi f here, the voltage drop was less here correspondingly voltage drop here will be less, because field is less if this field is less this is less drop is less.

So, what we are telling is you can have low electric fields in the in this direction, which you are looking forward to for increasing the immobility. So electric field in this particular direction will be transverse direction will be reduced by reducing the doping, by reducing the thickness. Now, you may question if I reduce the doping will I have a short channel affect that aspect we will address later.

The difference between the bulk MOSFET and this is you can make it thinner and thinner; you can make it thinner, and thinner. So, that these two have a more tighter control on the channel, If the thickness is small, if I have the drain here if this is long compared to this thickness this has a better control gate has a better control like, you know two regions.

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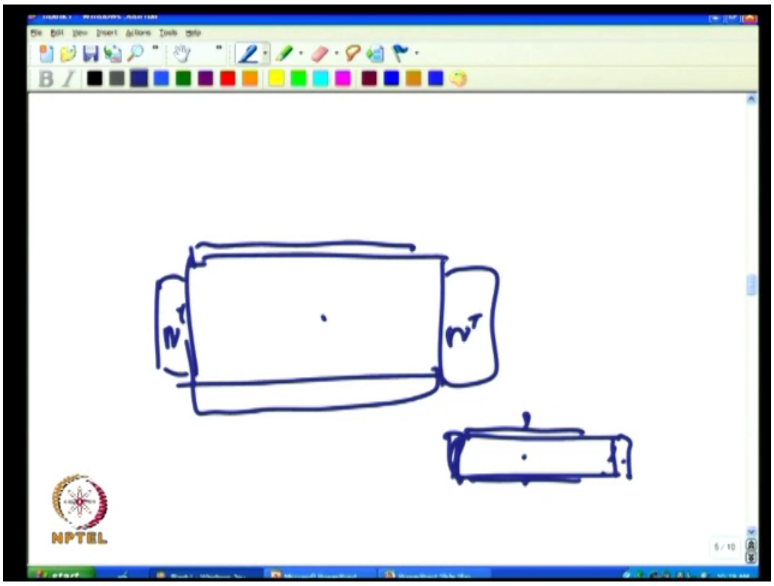

See if I have the gate re here, and if the drain is here, source here. I have the oxide here, I have the oxide here. Suppose this is thick this may have control here this point. Suppose you make it very thin this is a source drain, suppose this is very thin this has a better say on this region than this region.

So, the gate will have more control over this region here than that region. So, you will be able to go much shorter channel lengths, and you will be able to reduce the doping because this region is controlled most mostly by this gate. Even if the doping is reduced the drain depletion area is not able to encourage into the channel. So, that is the situation you can we will see more details of that later, but right now what we are saying is thinner silicon are more likely doped fields in that direction less. If due to invert because of that we get a lower voltage ok.

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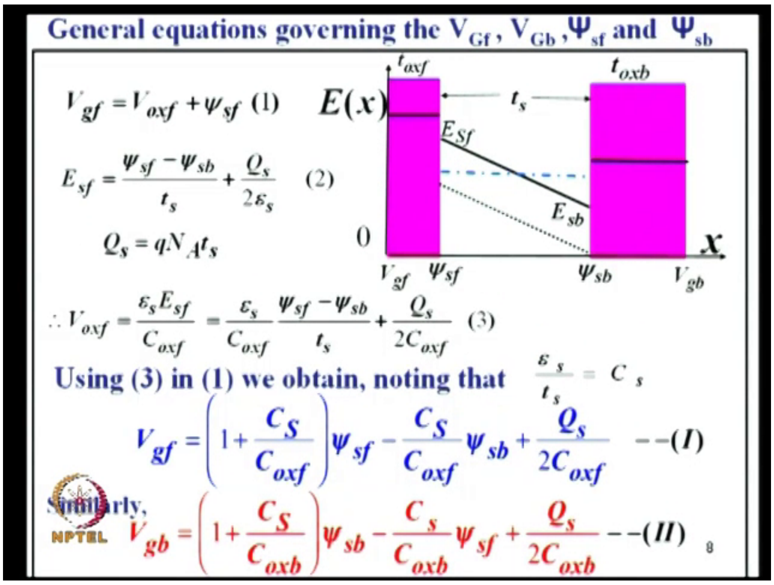

Now a most general case, now since you have understood the whole thing, we will analyze the situation V g f is applied V g b is applied there. I am so calling front oxide back oxide, and this channel gate is here gate is here. And I have got a situation where electric field is across oxide is a across the silicon is like this, and across oxide this situation will be there, when you have got electric field is in that direction electric field in this direction. So, you can see 0 is here it is a general case.

So, we have already discussed this now in the previous slides. So what is electric field here, I will just arbitrarily draw an electric field like that, but how much is the slope here depends upon the doping; electric field doping, this slope depends upon as we start depleting you can see it slope depends upon doping if it is very lightly doped it will be flat. If it is very highly doped it is going like that.

So, I have drawn this diagram here through calculate how much will be the threshold or what is the gate voltage applied to this for this situation, general case. The gate voltage at the front gate is actually equal to oxide drop V xf V oxide front gate plus whatever potential is here psi s f see this is the potential V g f psi s f psi s b V g b all with respect to ground point, all with respect to this ground point.

So, we are drawing that diagram here I may have said had this diagram also, but it is now. So what is the this field now you know how to find out psi s f minus psi s b divided by t silicon is the average field plus Q s by twice epsilon s gives that field, that is a E s f exactly the same way we have argued out difference between the potential divided by silicon thickness gives the average field, the dotted line.

I add that half of that q s by twice epsilon s that is it Q s a that quantity. Now what is the voltage drop; voltage drop is whatever, field is there into epsilon s that represents the charge beyond that point divided by C oxf. So I just substitute this here epsilon s by C oxf into that quantity whole thing, so that you get this quantity just a substitution put this here, substitute that here you get that. Now using this equation three along with that, I will get what is front gate voltage. Is we are now not saying whether back gate is accumulated depleted or, but we know that field distribution is like this.

So, front gate voltage is actually this of this quantity plus psi s f see this quantity the potential here, is whatever potential here, psi s f plus that works at voltage drop. So, add to this quantity this psi s f, when you add that this of this equation there is nothing new here just I am adding this putting it in the form only thing that I have made is epsilon s by t of s is actually the capacitance of its silicon layer when it is fully depleted.

Which we are writing epsilon s by t of s all the time like epsilon oxide by t oxide you say it is the c oxide epsilon silicon by t silicon is C silicon that is the meaning of that, so you replace that by C S, so you will get this equation same way. And I can write here it becomes very simple now, see if you are able to write this equation by drawing this diagram which you can do now you can write for this back gate also.

All that you do is you have to write field here is that minus this quantity average minus that quantity, when you do that you will get V g b is equal to in terms of the psi sb you get this replace C oxf by C oxb, when you want to go to back oxide this symmetric equation psi sf by psi sb, C oxf by C oxb, C S same as C S, psi sb by psi sf all [FL] reverse C oxf by C oxb. So, that is you can talk deal with a situation, whichever channel is accumulated whichever channel is depleted. So, here you can see.

From here, how can I get the I want to see the general equation I want to find out a threshold voltage, when the back channel is accumulated what do I do here, front channel is inverted psi sf will be substitute psi sf back channel is 0, when it is accumulated. It not really 0 slightly negative, but we are putting it very close to 0 25 milli volts, 50 milli volts of that order.

If I remove this, So, then threshold voltage will be 1 plus C S by C oxf plus psi sf plus that quantity, when the back channel is depleted, I will have twice psi sf and psi sb here psi sb here. When the back channel is inverted what will I get how do; I do once it is a equation back channel inverted, front channel accumulated. Substitute psi sf here, here psi sf Psi sb also, psi sf both channels are inverted, then both are psi sb. Then we can see this term and this term cancel out, and you will have twice psi sf plus Q s by twice C oxf it is psi sf by twice psi sf I will have written that thing here.

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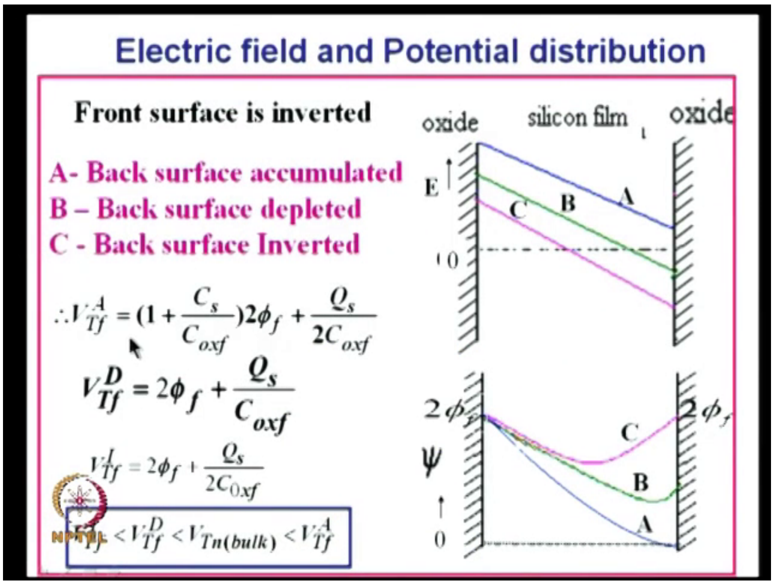

See back channel accumulated you get that substitute and substitute in that equation. If you back to that you will see that, all that I did is put this 0. Then you get that equation basic term is 0. And when the back channel is depleted more or less will be that twice phi f plus Q s by C oxf, but it some of times will comes, but approximately it will be this both channels are inverted.

These two terms are cancelled because both are psi sf, you will have only this term which is psi sf plus that term. So, you can see compared to these things back channel accumulated, back channel depleted, both channel inverted, here only front channel is inverted. When I say these symbols are threshold voltage of the front channel with the back channel accumulated, threshold voltage of the front channel with the back channel depleted, threshold voltage of the front channel back channel inverted both are inverted.

So, if the back channel is accumulated you can see threshold voltage is highest. In the case of bulk MOSFET, if you recall threshold voltage is this twice phi f plus Q depletion by C oxf. So, you can see this twice phi f plus multiplied by a big factor here, so threshold voltage in the accumulation condition will be much more than even the bulk MOSFET. So, that will not work out for you if you are looking for decreasing a threshold voltage, this one and the bulk MOSFET it is look like it is almost like a bulk MOSFET twice phi f plus Q d by C oxd, but in the case of bulk MOSFET what is the Q d, if you see the bulk MOSFET bulk MOSFET mos.

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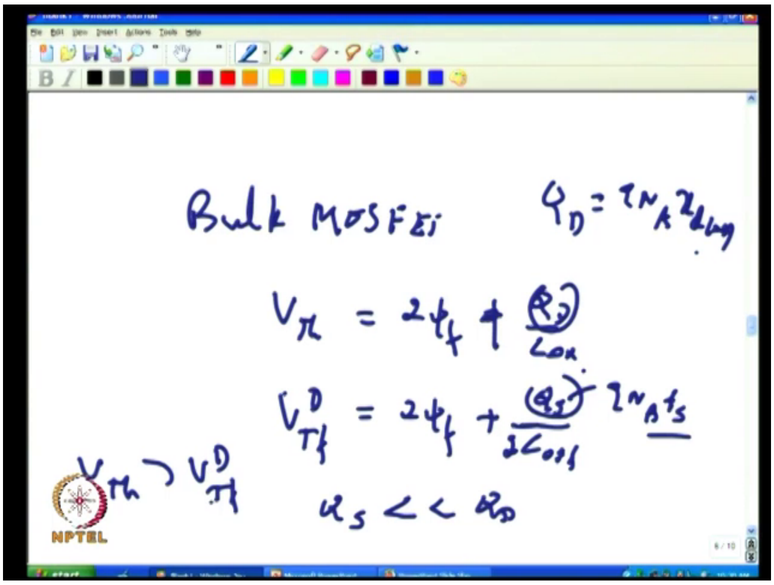

That is the V threshold voltage is twice phi f twice phi f plus Q d by C oxf. Let us say a situation where the oxide thicknesses are same. Now in the case of fully depleted also that is V Tf completely depleted, we saw twice psi f plus Q s by C oxf twice is that right. So, you have got that what is situation now.

So, here differentiate these two terms Q d the bulk MOSFET is Q N A x t maxima at twice psi f, here this is Q N A into t of s t of s is much small compared to x t. So, this is much smaller compared to Q d. So, this will be with threshold voltage of bulk MOSFET will be greater than a threshold voltage of that.

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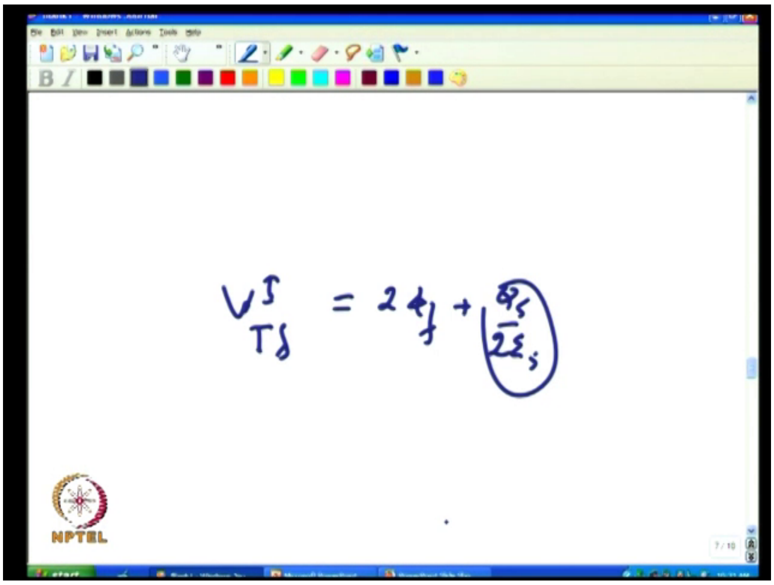

Now when you go to inverted case; I will go to inverted case, you have got V Tf back channel also inverted that was equal to twice phi f plus Q s twice I am sorry, that is good. In fact, if you go I think I have made a mistake there in the previous case it is not there two is not there, but when we go to this now you have got this twice. This is much smaller compared to the bulk MOSFET may be half one forth or even smaller than that, depending upon how thick thickness is reduced divide by twice psi sf twice epsilon S am I correct.

So, this is a term which actually gives rise to voltage drop across oxide. So, in all the cases what you are doing is by taking the situation, what you are doing is see here. In this case the drop across the oxide is small, because the depletion layer charge is small. Now if you reduce the doping this is further can be reduced ultimately, you can get the threshold equal to twice phi f itself very small drop in oxide before inversion just (Refer Time: 50:40) inverting.

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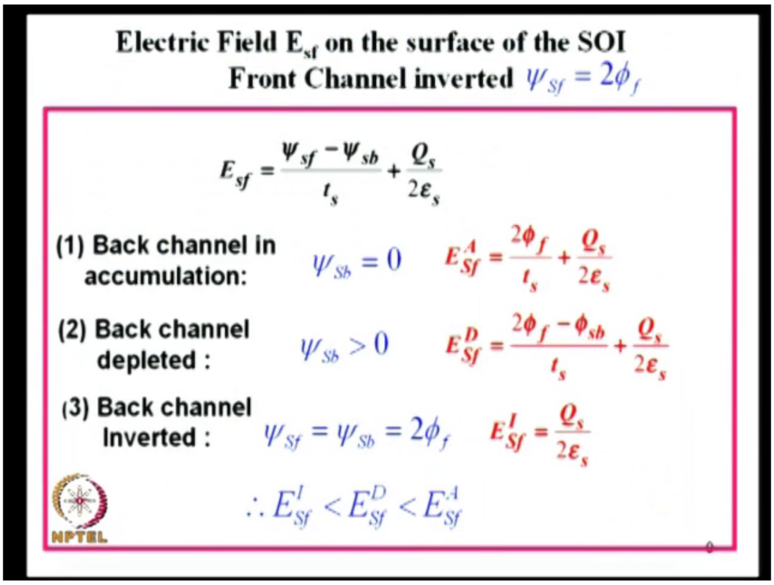

Now, if you see the electric fields, psi sb 0 you see this equation for all the cases this holds good, psi sf minus psi sb by t silicon plus that half of that, it is average field plus this, so if psi sb is 0 that is that field. When psi sf psi sb is greater than 0 this term is practically same thing over even if some factor is there, this is there the difference reduce of that term. When I go to back say inverted both are twice phi f that is the field. Field in silicon, so field in oxide is Q s divided by whatever is the epsilon s into d by C oxf, whatever charge here electric field is there into epsilon s divided by C oxf that is the voltage drop.

So, what we were telling is a field is smallest when the both channels are inverted higher in this case highest in that case. In the bulk it will be in higher, because you take care of the depletion layer which is (Refer Time: 52:09). Now this is the plots which you can see now, electric field is highest there in the case of back channel accumulated. And the whole thing comes down; whole thing comes down to this, electric field is over and the back channel is depleted. And again you can see that the average field is here, corresponding to this field is much slower when the both the channels are inverted, see this diagram you will see everywhere it keeps on lower lower lowest when it is both are inverted. Now you have seen the potential distribution twice phi f your back channel is accumulated potential is 0 here. When the back channel is depleted potential is positive here, the minimum is somewhere in between when the both channels are inverted, that is twice phi f into twice phi f, and it is 0 or is a minimum at a centre, because half of this belongs to the front gate, half of this belongs to the back gate ok.

So threshold voltage the lowest in this case, higher in this case, higher in this case. In all what we were said this summing up in this case is that, you can go to lower threshold voltage with it with the fully depleted channel with both the channels are inverted. And you can make a symmetric gate, symmetric MOSFET, what is symmetric MOSFET front oxide back that is about like this, back oxide thickness and front oxide thickness same everything same. I can connect them together.

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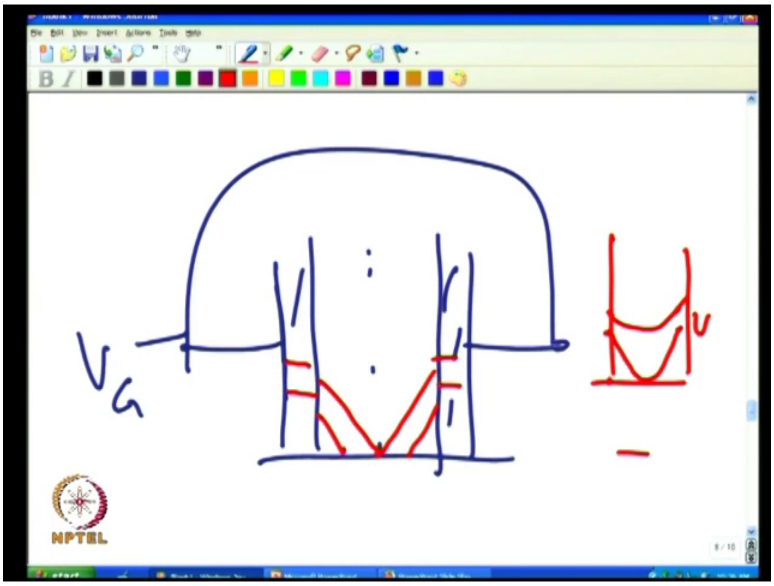

I can have a situation, where I have the back oxide, back oxide everything is same thing. And front of by that, I can connect the back gate and front gate and back gate to the same voltage. Now what happens if you do that, when I start applying the voltage of 0 what happens depletion will starts coming from here, starts coming from here, sorry I think I have to I will come like that.

That is how it comes and from here same way, that is how it comes electric field that is edge of depletion layer. And what will the point come like this. So, whole thing is depleted, and you have the situation where the potential is like this, that is the voltage across the silicon. So, both are same surface potential. Now we arise the both are connected together see both move like that afterward if I increase belong that point you see difference is not there.

Then afterwards it keeps on moving up like this till I get twice phi f all that is the double gate; double gate MOSFET symmetric, so people are looking into devices which are actually realized like this. Both gates connected together and so the other one gate control because after all you do not want to have one supply for a front gate and one supply for back gate make it symmetric connect it together. There are some issues that we will see when you sort out by some other methods. Now, let us go further down.

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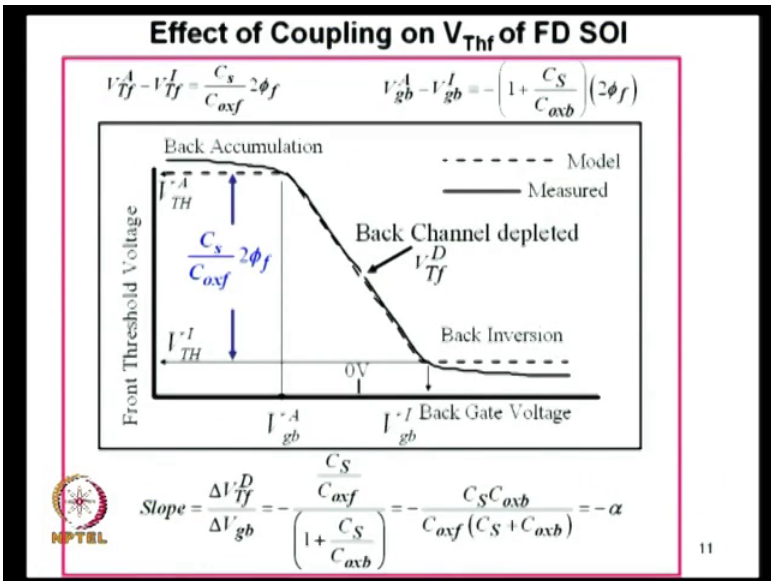

So, you have seen that if you want to see the threshold voltage versus back gate bias. Back gate accumulated threshold is higher, back gate inverted threshold is down in between somewhere it is falling. So, it is just for complete (Refer Time: 56:33) you can control that thing how much is this slope will depend upon the ratio of the oxide thickness front and back.

If they are equal it will comes strictly down like this. If the back oxide is thicker it will come like that, you can analyze yourself sitting down based on whatever we have discussed now it will be like this. And the difference between the front threshold voltage, when the back channel is accumulated and when it is inverted is that C s by C oxf into twice phi f that is the difference, you can see it by substituting in those equations here, this minus that is this quantity that is it ok.

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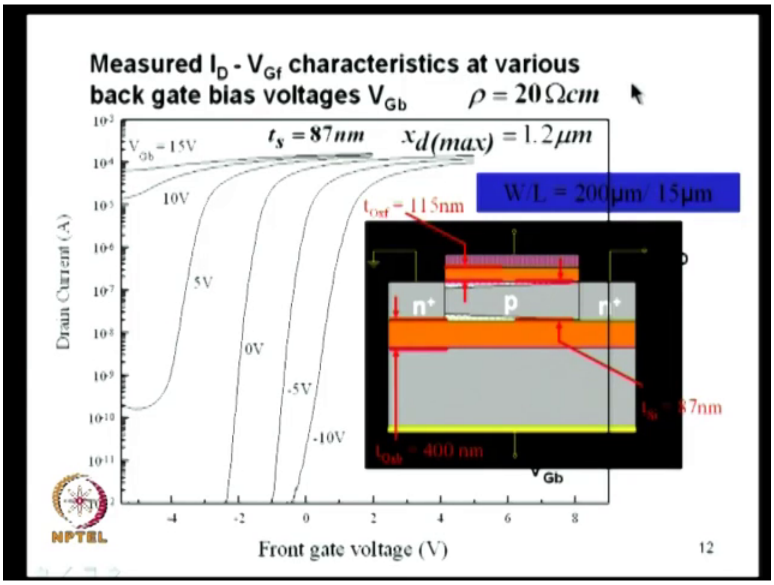

Now that means, you have you can have the transfer characteristic for this MOSFET. I can take the characteristics in the now, I am not showing a symmetric gate we will come back to that afterwards this is one of those experiments which come up for students, in IIT madras had done it complicated these devices. And you can see back gate is thick may be one point four microns, and t silicon is above 87 nanometers fully depleted, something that 10 to the power 14 doping front gate oxide is thin.

Something like may be point of micron or so, and W by L ratio is 200 by 15 while, it is 15 microns 1 channel we are do not want to walk down by the short channel effect. So, the transfer current see that exactly again the bulk MOSFET the only thing is we can change from the accumulation negative we keep on doing that, you can see threshold voltage is becoming less like that. And if you go keep the back gate voltage all the time inverted large voltage is not able to it will not be able to turn off by the front gate.

So, this is just to illustrate that and also you will get now, let us go to the this particular situation, this is just for showing that you can have a good control of the back gate you can convert change the threshold drastically by using that. Unlike in the case of bulk MOSFET you can bias the substrate, but if you can not apply forward bias onto that, because the source things will conduct substrate current will flow.

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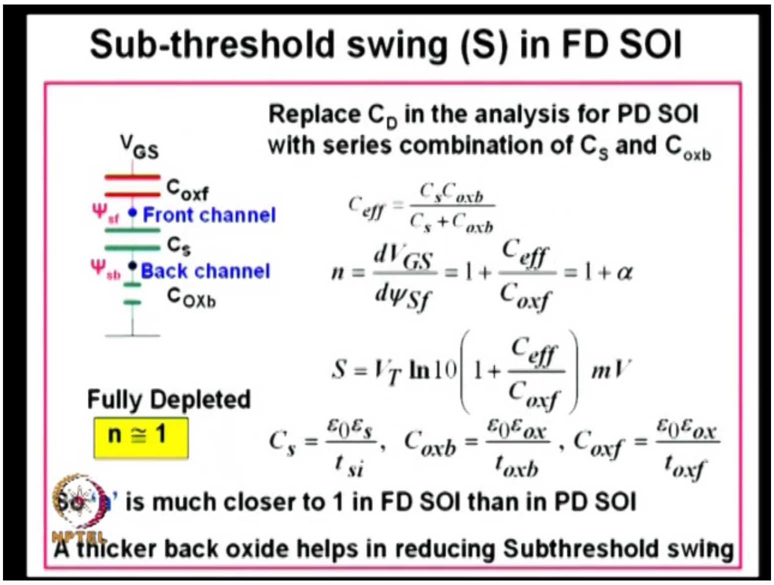

Now what happens to a sub threshold slope, that is what we want to see may be I think I will take on this particular interesting thing on the next class. So, in summary what we have said is that you can get complete control of the back gate bias, you can go from accumulation to inverse from back channel, and you can have a threshold voltage varying like that.

In fact, you will see that you can get also control on sub threshold voltage by using this quantity. And this is the main advantage of this is the threshold voltage can be reduced; the transfers field can be reduced drastically, so that there is a chance for you to get higher mobility. We will continue on this from here onwards the life will be much easier, because we understand how it works out now not much of mathematics from here, but more of what happens in those short channel devices. We will discuss that in next one lecture before we wind up this whole thing.