CMOS RF Integrated Circuits
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Module - 04
Review of MOS Device Physics
Lecture - 12
MOS Device Review

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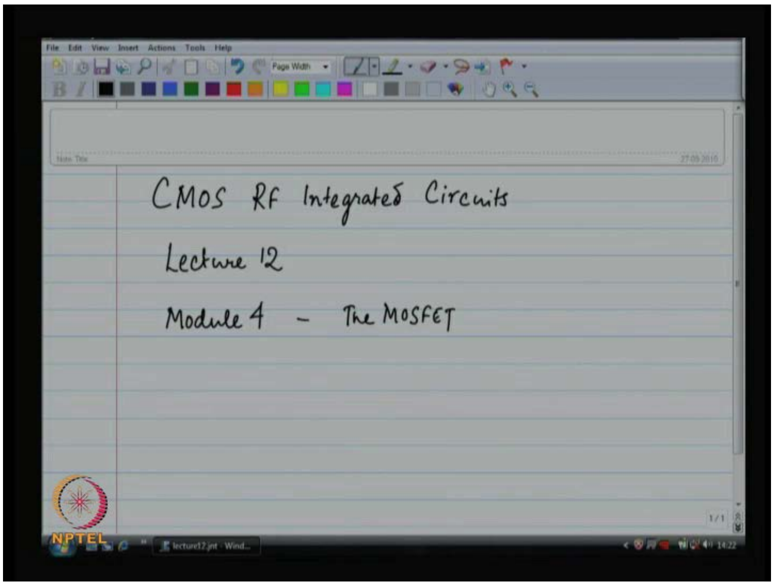

Welcome to CMOS RF integrated circuits. Today, it is the twelfth lecture we are going to start a new module today. And, from today we are going to start talking about the mosfet. Now, the mosfet is the most important component on an integrated circuit right. And, really we talked about lots of different passive elements earlier; in spite of all that when it comes to an integrated circuit the mosfet is the most favored component. Let us say you are working for a company under a boss and you want to use an inductor or capacitor or resistors etcetera. And, you tell your boss that this is my design your boss will tell you that can you make all of these mosfet and show it to me.

I do not want to give you an inductor or capacitor or resistor I want you to use only mosfets. So, mosfets are the cheapest most widely available components on an integrated circuit; the reason being is that the mosfet is it uses plain not technology; it uses minimum number of masks. And, as a result if you stick only mosfets in your design then the fabrication cost of your design is going to be lesser; if the fabrication cost is lesser your design is going to be cheaper right. I mean number of mask said is lesser. So, you will get more yields you will get less you will have to pay less money; when you have to pay less money your overall prize becomes cheaper.

Because it is cheaper it is more widely sold; everything follows on top of each other. And, as a result the mosfet is the most favored component on an integrated circuit. Now, for other RF integrated circuit purposes; foundries also make these special components like capacitors resistors inductors available for you. But remember they are special right; if you want your device, if you want your circuits to be cheap then try to avoid those special components as far as possible anyway. Suppose, it to say we need to study the mosfet; because we are studying on CMOS RF integrated circuits so it is part of the title of the course.

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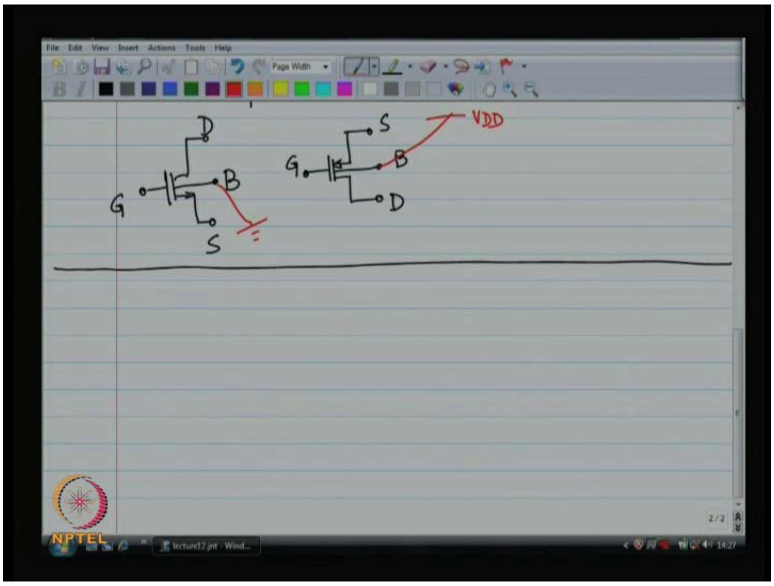

So, the assumption over here is that some part of the mosfet you have already studied. But I am just going to revisit the entire study and to a lot of few this particular module might just be recap. So, the mosfet there is N mosfet N type mosfet P type mosfet it is basically a 4 terminal device; the arrow only indicates the direction of current for which the drain is labeled as the drain and as the source is labeled on the source.

So, will figure it out very soon; these are the symbols of the mosfet there are 4 terminal get source drain and body is the least used terminal usually we like to connect body to ground or the least potential on the integrated circuit in case of N moss. And, we like to connect the body to the highest potential in the integrated circuits for the P mos. So, highest and lowest potentials are V D D and ground respectively.

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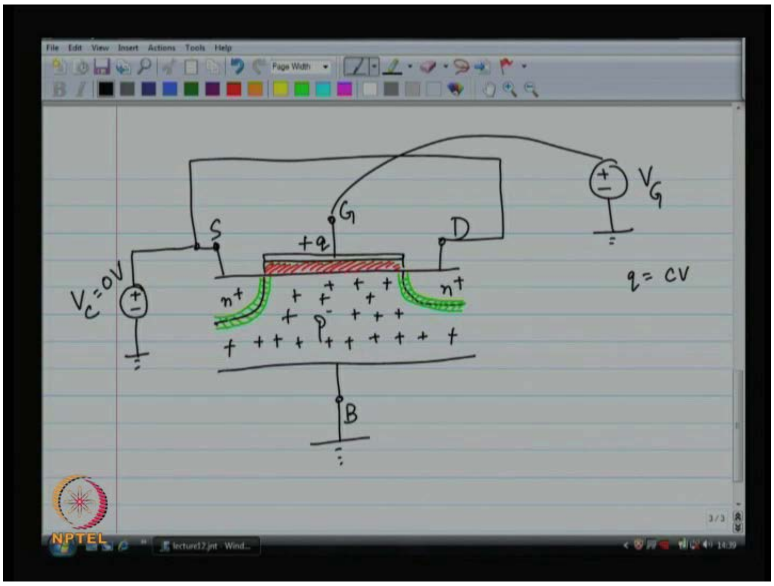

So, that is why we do not like to fiddle around with the body to match in any case how does this mosfet walk? What is it all about? So, to understand the mosfet you can let us first we visualize the structure of the mosfet. So, there is a gate the structure of the mosfet looks very similar to the symbol of the mosfet; but anyway. So, for this discussion I am going to stick to N type mosfet. And, whatever I say about the entire N type exact opposite is for the p type mosfet and in general you can extrapolate from 1 to the other. So, we would not discuss the P type mosfet separately all right.

Now, suppose you are given in a N type mosfet you I have labeled all the doping regions. And, suppose you do nothing with it nothing whatsoever you just keep it like that. Then, the first thing that comes to your mind is that you have created 2 p N junctions; there is a P N junction between source and body there is P N junction between drain and body rather body and drain body and source right; whenever, you have P N junction without thinking too much, without doing anything; something is going to happen at the junction region what happens at the junction region? Yes, what happens at the junction region? Right; some of the majority carriers from one side kind of diffuse over to the other side and recombined with the majority carriers on the side right. And, as a result what happens is that there is a depletion region in between.

So, we have depletion regions along the junction area right and why did this depletion region happen? Because the N carriers from the source side diffused over to the drain, to the body and recombined with the holes in the body. Similarly, the electrons from the drain diffused over to the body and recombined with the holes in the body. And, as a result electron combines with the whole nothing left over there no carrier is left. So, all the majority carriers from the junction area have gone; you have disappeared. Now, what is the result of this; the result of this is that the source is not electrically connected to the body; the body is not electrically connected to the drain. In other words the source is not electrically connected to the drain; what does electrically connected mean?

If I have a wire made out of metal than one side of the wire electrically connected to the other side because; the electrons can freely flow from one side to the other if they need to flow. In our case in the case of mosfet even when they need to flow from one site to the other the electrons or the holes cannot make it we cannot go they are stopped at the junction. Because there is nothing to carry the charge across the junction; there are no carriers over their right. So far, so good; this is just without touching the mosfet; mosfet is left on the table along this is what happens fine.

Now, the first thing you do is you connect the body to the least potential on the integrated circuit why do you do that? Because if you connect p type material to a low potential; then, the p N junction that it fonts is definitely going to be reversed biased. So, the bodies connected to the least potentials. So that these 2 p N junctions which are shown in green those 2 p N junctions remain reversed biased; for good. So, those 2 PN junctions are not going to work like dittos ever. So, you connect the body to ground and you are done. I mean this is assuming the ground is the least potential in the integrated circuits.

So, whatever is the least potential you connect the body to that particular value, that particular voltage. Now, next what I am going to do is for this particular discussion for understanding only what I am going to do is; I am going to connect the source in the drain together with a wire. So, the source and the drain are now connected together with a wire whatever happens to the source the same thing is going to happen to the drain; they will behave in identical fashion. And, I connect the source and drain to a voltage source let us call it V S D actually, let us call it V C, C stands for common. And, I am going to connect the gate to another voltage source labeled as V G all these are with expect to ground; mind you V C as to be positive. Because if not positive then the body is not going to be the least potential right.

So, we do this and let us say V C equal to 0 volts just for simplicity. So, source and drain are both 0 volts. And, let us say I start V G from 0 volts and slowly I start increasing the voltage V G. Now, what is going to happen when V G 0 volts' nothing is going to happen everything will stay stand still just like this. When I start applying little bits of potential on the gate; let us say ten mille volts what is going to happen? So, the first thing that is going to happen is that oh; I hope you know the structure of the mosfet this is not the first time you are seeing this; this is just supposed to be recap.

So, this red materially is silicone dioxide it is an insulator and no current flows through it. So, you are slowly now increasing the potential on the gate. Now, look at it there is a plate; the get has a plate underneath the plate there is an insulator rather there is a dielectric material, underneath that there is a semiconductor. So, what does this look like? Plate then the electric and then something else what does this look like? What does it remind you of? It should remind you of a capacitor right plate dielectric, plate that is a capacitor conductor, the electric conductor, parallel plate capacitor.

So, this should remind you of a parallel plate capacitor; I hope it does remind you. And, if you think about parallel plate capacitor as you increasing the potential across the 2 plates charge is deposited, positive charges is deposited on the positive plate; and an equal and opposite negative charge is deposited on the negative plate. So, plus q and minus q where q is equal to C V right; where is the negative plate here? Negative plate is really not yet making any sense right; negative plate is a mass of semiconducting material remember semiconducting material not conducting material. So, it is really not clear what is going to happen over there.

So, first thing that is going to happen is that you need to recall that the P type material is full of holes. So, what is going to happen if you do computation about of how many holes there are you can assume some? So, this could be a homework problem. Let us say the dimensions of the body or rather the dimensions of the substrates are as follows; substrates under the mosfet the dimensions are like this the length is 1 micro-meter, the width is 1 micro-meter, the depth is 1 micro-meter ok.

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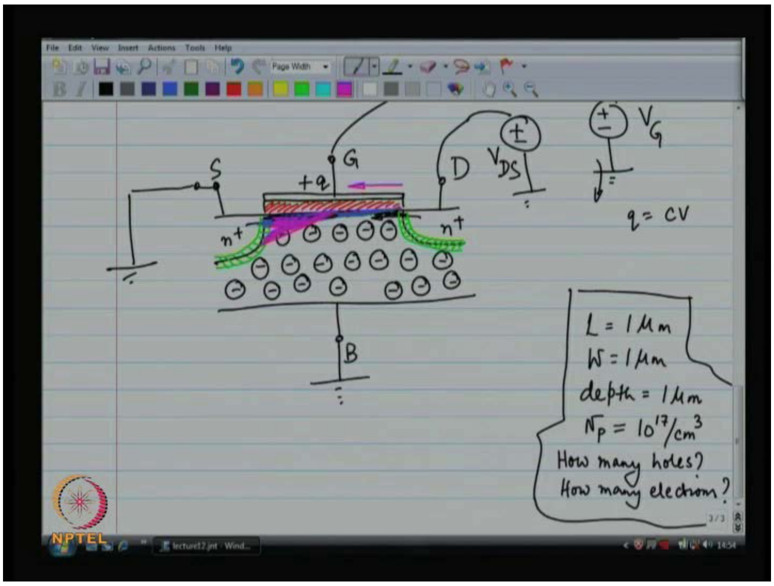

So, this is this is the geometry of the substrate and let us say that the doping concentration is 10 bar 17 per meter cube; the question for you will be at room temperature how many holes are there? And, how many electrons are there? Before I will just give you the rough number; the rough number is not going to be too large. It can maybe 1000 holes will be there no electrons will be there most probably; can do your computations and get back on this all right.

So, there are some holes majority carriers there are some majority carriers available in the bulk in the substrate, there are no minority carriers in this substrate it is too small; minority carriers density is too low. There are no minority carriers available just a few majority carriers may be 1000, may be 100; I do not know the exact number you can find out.

So, accordingly what is going to happen? Well, I am depositing positive charge on the gate. And, what should really happen negative charge should be deposited on the bottom plate of the capacitor. But the bottom plate of the capacitor does not have any electrons; instead it has holes. So, what is really going to happen is that all of these holes are going to go out, they are going to be repelled. So, instead of electrons coming in; all the holes are going to get deactivated first of all. So, when the holes move out as the holes are moving out negative; fixed negative charges are going to become created in the bulk of the subscript.

So, as the holes moves out what remains here are fixed negative charges these are immobile charges; in mobile charges are left alone all the holes have moved out. Now, just a reminder total number of available such immobile charges are something like 1 000 any more available. So as long as this can happen it happens and then once you run out of impulse challenges, once you run out of holes; that need to be evacuated. Now, this body does not have any more holes, does not have any more electrons nothing; only fixed charges are available.

And, then you still increase the gate voltage little bit more what is going to happen you continue increasing the gate voltage. Now, as you continue increasing the get voltage what is going to happen? Do you think the charge on the gate is going to stop increasing? No, that is not going to happen right; the charge in the gate as to increase your increasing the gate voltage. So, the charge on the get is going to increase further; to balance that I need negative charge; I need some electrons to balance that. So, when I increase the charge on the gate even further what is going to happen?

One possibility is that to increase the charge on the gate I have to remove some electrons from the gate and these electrons are going to go all the way to ground and come back to ground and they are going to get injected into the body. And, these electrons are free electrons fine that is one possibility; these electrons have to travel along way to do that right that is the possibility it could happen. However, is a faster way of doing things; some electrons you remember the source and the drain these are N type materials they are rich in electrons; they are very rich in electrons. So, some electrons jump this barrier and stop that is also a possibility right; in fact this is what happens faster.

So, yes, it could be that electrons moving through the ground etcetera and comes through the bulk it could happen that way. But a faster way for the electrons show up would be from the drain and the source. So, that is what happens; electrons hock from drain and the source and the rapidly maven has demanded. So, you demand some more electrons the source and the drain supply electrons. And, remember these electrons are free things, they are free to go wherever they want, where are they going to go; if they are free to go wherever they want where is it that they would like to go? They would like to go as far as possible as closed to the positive charges as possible. So, they are going to go and sit right underneath the oxide layer is that ok.

Now, some of you would have objected to the fact that they electrons jumped the barrier etcetera what happens to the barrier? Now, all the holes have left right there is no more recombining available. So, just keep that in mind. So, that is why the electrons can safely maven from the source and the drain; as they maven from source and the drain the best place that they can go to is to the surface right; underneath the dielectric material that is where the electrons would love to go because it is closest to the positive charges. So, that is exactly where the electrons go. They go and reside right underneath dielectric material and this is called the channel.

So, when these electrons come in a channel is formed this is how we phrase the sentence as you increased the gate voltage; further a channel is formed this formation of the channel is called an inversion layers; why because in p type material even though the materially is p type you are creating a channel made up of electrons. So, this channel now connects the source with the drain; it electrically connects the source to the drain is this idea is clear to everyone that the channel electrically now connects the source and the drain; you have got a continues channel full of electrons it is actually sheets you got a sheet full of electrons connecting the source area and the drain area.

Now, let us disconnect the source and the drain and if I apply a potential on the drain with respect to the source then what is going to happen? Now, at the drain is really connected to the source electrically; if I increase the voltage on the drain charges going to flow through the channel, current is going to flow through the channel right. This connection between the drain and the source this is the basis of using the mosfet as a switch. So, once you have a connection, you have both sides equal potential, you remove the gate voltage both sides are isolated from each other; you apply high gate voltage both sides are now connected to each other. So, you can use the mosfet as an electronic switch of course this piece of wire that is created as its own resistance.

And, there is one more problem that all we analyses is that we did so far, it is assume that the drain and the source voltage are equal. Now, if I apply a drain to source voltage the sheep of a channel is not going to be uniform throughout right; shape of the channel itself is going to change. If the drain has higher potential then electrons would like to get absorbed into the drain the free electrons would like to get absorbed into the drain. So, the sheep of the channel if the drain is higher potential; the shape of the channel is going to look like this, it is going to be more biased towards the source.

Now, what is this blue stuff? Is this really the shape of the channel and all electrons are going to be only on the surface? Yes, all the electrons are going to be on the surface; because the surface is where they can go to they are free moving objects. So, they go has high has possible, they go to the surface, they go has the closest possible to the positive charge. So, the electrons are really going to be a on the surface.

But the density of the electrons is going to be more near the source density of the electrons is going to be less near the drain; because the drain is at a higher potential. So, that is what the figure really tries to communicate any figure with a shape of a channel; channel is not really going into the depth of the bulk of the subscript right. It is not really going deep, it is all at the surface; just an estimate of the charge density of the channel; the channel is really on the surface only.

So, you get a shape of that channel accordingly this particular channel has resistance and accordingly you apply a certain VDS and you get a certain current right; this is how the mosfet works is that it. Well, it is also that you can keep increasing the voltage I am sorry, you can keep increasing VDS. Now, let us keep V G fixed; as you keep increasing VDS what is going to happen is that after sometime the shape of the channel is going to get pinched off. What that really means is that the shape of the channel is going to look like this as a further increase VDS; the shape, the edge will come further and further inwards. So, the edge has come further inwards.

So, you have got channel only for little way across the distance drain to the source; remaining the part the voltage the drain to volt is so, high and if you leave electron over there it will immediately zap across. So, what really is going to happen is that the effective resistance; the total amount of current that can flows through this channel is going to become a constant as you increase the VDS further and further. So, these effects are called there is pinch off. And, then there is something called velocity saturation and there is something called channel length modulation.

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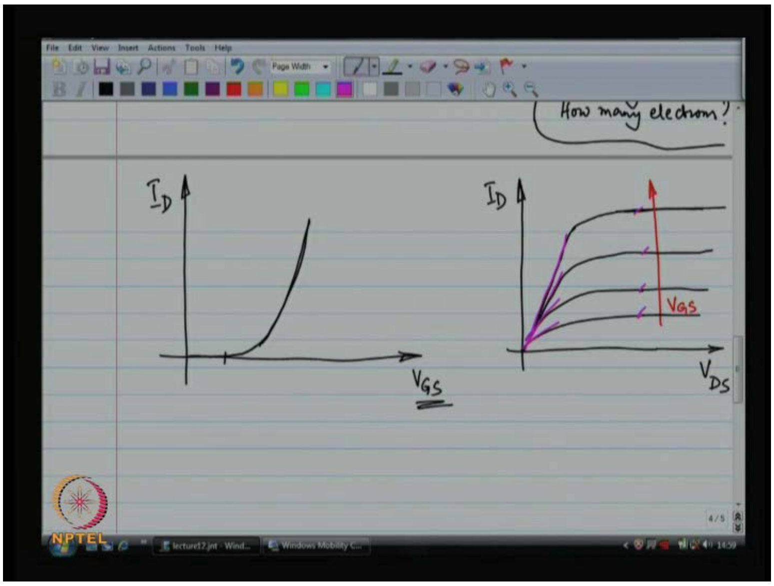

So, you worry about all of these effects and finally these are the covers that we get. So, first of all my first plot is a plot of the current as a function of V G S. Now, when I plot current I really mean the strength of the channel; how strong is the channel I really do not want to plot current. But I am going to plot current for a given drain to source voltage I a m going to pluck current you have already applied drain to source old age; unfortunately, this is not how we just introduce the mosfet; we have drain to source voltage equal to 0 which means that they would not be any current through the drain to source, from drain to source. But anyway this particular curve is just to give you a feeling of how strong the channel is when you. So, when you apply drain to source voltage eventually you will get current characteristics that look like this right.

So, notice at first there is no current, rather at first there is no channel why? Because you are still moving out the holes from the subscript; once you have moved out the holes now channel is being formed right this is very crude. But probably hopefully it is physically it is it gives you the intubation that you need; my model overhear, my explanation overhear is very crude explanation. But I am just hoping that this is going to give you that intubation you need for your thought processes.

So, at first there is no channel you are busy moving out electron of the holes from the subscript then channel is formed. And, then as you increase VGS further and further the channel becomes stronger and stronger all right. So, this is my first graph; the second graph now you assume that you have created a channel as you increase VDS more and more current flows through it starts behaving like resistor. And, very soon the resistive effect is pinched off and the current flats and out. So, these are all for different strengths of the channel. So, has V G S goes up, you go up along that ladder of covers fine so far as so good. So, these are the mosfet characteristics.

Now, from mosfet these characteristics you develop a small signal model for the mosfet. So, the small signal model of the mosfet is basically like this you recognize that the current is basically a function of V G S; the current is a function of V G S. So, add different V G S, you have got different amounts of current. So, the different V G S you get different amounts of current. But of course there is the portion of current that is also attributable; because of V D S. So, the current could also be a function of VDS, it is also a function of V G S.

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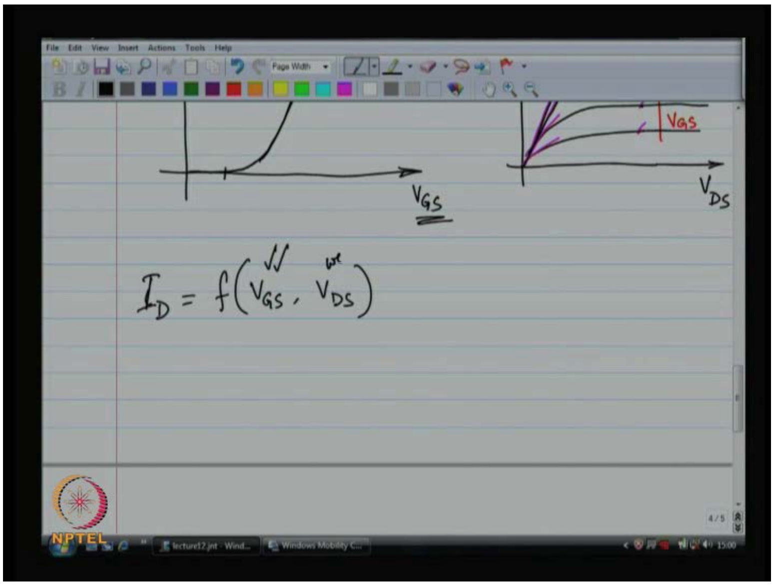

So, that is the model that we are going to built; the current is a strong function of V G S, week function of VDS. And, let us leave the body out of this picture.

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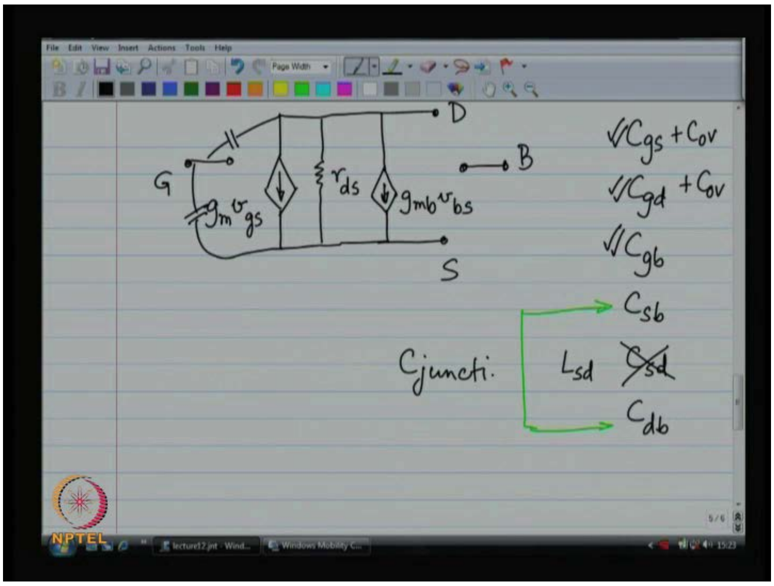

Let us just leave it out for now that is not complicated matters further very shortly I am going to do introduce the body to you. I mean what happens if you start fiddling with the body or what happens if you do not fiddle with the body too much; will talk about it very soon do not worry .So, first of all what is the current through the gate? The current through the gate is 0. Because it looks like an insulator as in looking to the gate there is dielectric material, there is no current into the gate fantastic. And, then there is basically drain to source current.

And, the drain to source current as 2 components; one component is because of V G S. So, I have written, I have drawn voltage control current source and the second component is because of V D S. So, I have drawn a resistor. So, you get current in the drain to source path because you have applied more and more drain to source voltage. So, this is the crudest possible; small signal model for the mosfet.

Now, let us go back little bit and think about the body; the body and the gate are somewhat similar it is like this you are trying to control the charge in the channel. So, you are trying to control the charge in the channel and to do that you have got 2 handles; one is the gate which is very close to the channel, the other is the body which is not that close to the channel. But little further away it is also there.

So, the gate is called the front gate, the body you could call it as the back gate; what you can do from the gate trying to control the channel, you could also try to do the same from the body. So, as far as small signal model goes the gate and the body look like very similar that is all I am going to say about the body. Now, this gives me some refinement on the crudes small signal model that we have developed. Now, these are actually pretty good model this is B model that you are going to use; if we are talking about B,C circuits that operate at D, C or rather circuits that operate at low frequencies this is the model that we are going to use we are talking about R F.

So, when we talk about RF radio frequencies what do we need to incorporate in this model, into this model; well, we have to worry about all the different capacitances remember the mosfet looks like a capacitor we started from a capacitor in the first place right. The set positive plate charge is been deposited. So, negative plate charge will get attracted everything is on I mean is developed on top of a capacitors. So, this got to be a capacitance all over the place right. So, we cannot ignore those capacitors and maybe there is some inductance here and there which we cannot ignore either.

So, we are going to talk about; we need to incorporate all of those into our small signal model all right. So, which are all the possible capacitors you have got 4 terminals; gate drain, source and body which are all the possible capacitors you can have C gate to source, C get to drain, C gate to body, C source to body, C source to drain and C drain to body. I should have covered everything yeah these are all possibilities there is no nothing else that is possible. So, we are going to go 1 by 1 and try to see what all parallel plate to be finding between these 2 nodes and work on this; come up with some kind of intimation, some kind of mathematical formulation for each of those capacitors all right.

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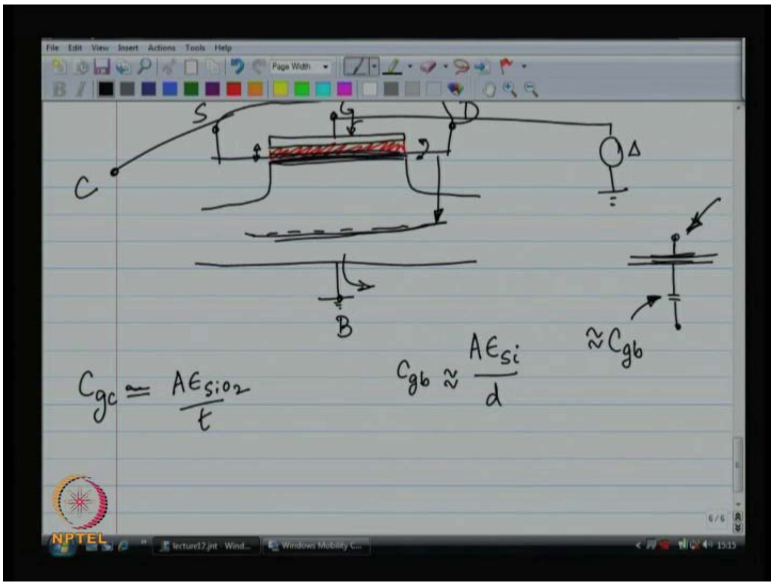

So, before we start. Let us observe the mosfet one more time I am going to redraw because I have so this is I have got gate source drain and body and there is nock side layer in between. And, let us first think about what happens when the source and the drain are connected to each other. So, let us call it common terminal what is going to be the capacitances between the gate and this common terminal. Now, as you increase the voltage on the gate suppose the voltage on the gate the 0 when the old age on the gate is 0; the source and drain are electrically isolated from the body remember these are all isolated right; a lot of P type charges all over the body there is no inversion layer, no channel, no nothing.

So, when you increase the gate voltage a little how much charge would you expect to deposit on the gate. So, I increase the gate voltage little bit how much charge do I expect to deposit on the gate? There is nothing else and where this charge is going to come from? Source and drain are isolated. So, it is almost as if source and drain are not in the picture; I apply little bit of voltage on the gate where how much is the charge that going to be deposited on the gate, where is the charge going to come from; first of all when I deposit plus q from hear the charge as to come out from the body source and drain are isolated how is this charge coming out some p type holes are moving out, some holes are movie out and are creating little pieces of charge, fixed charge in the substrate.

So, the closest holes are going to move out the first; then, you are going to get more and more holes moving out from further deeper point right. So, this particular capacitance is because of gate to body capacitance. And, these charges are exhausted very soon how soon are they exhausted; as soon as all of these material all of the holes move out this capacitance these charges are exhausted. So, let us say that the mean dept of the body is so much this is let us say average depth for the holes. Now, if that is the average depth of the holes I have got so much gate area and this is my dielectric constant what is my dielectric constant? I have got 2 material; first I have got semiconductor zed then I have got some silicon this is silicon right.

So, you have got 2 materials really. So, you got this material you can think of this as to capacitors in series; it is like you have got some strike you have got small capacitor I am sorry, you have got a large capacitor here. And, then you got a small capacitor 2 capacitor in series; net capacitance is going to be smaller than the smaller capacitance. So, you can approximate the whole business as this debt, you can just consider this depth and that will give you the approximate C g b; get the bulk capacitance depth is large area; area underneath the gate.

So, you take area of the gate time epsilon of silicon and the average depth of the holes in the bulk. So, let us say the bulk is 1 micron deep. So, the average depth will be the half a micron; something like that might have to adjust for all of this other infractions like you got some source material, drain material etcetera. But in general this is to engineer this is what is going to work. So, this is going to be yours C get to bulk so far, so, good all right. Now, these charges are exhausted; as these charges are exhausted electrons flood in from the source and the drain and from the channel; electrons come in from the source in the drain and formed the channel.

And, then the capacitance between the gate and the common terminal remember the source in the drain together as the common terminal in our experiment; the capacitance between the gate and the channel, channel is underneath the gate is going to be a epsilon of the silicon dioxide by the separation, the size separation between the get and the channel. So, let us call it that it the thickness of the oxide material; which is going to be more is the get two capacitance is going to be more and gate bulk capacitance is going to be more you look at my picture it should be obvious to you that the gate to channel capacitance is going to be much much much larger than the gate to bulk capacitance, gate to body capacitance. P is much smaller than the average depth of the bulk all right.

So, really when I draw this picture over here; I have done a really good job of it you have got a large capacitor overhear and you got a tiny capacitance in series with it right. So, gate to channel capacitance has been established. Now, you go back over here and you find that get to channel was never listed in the in our objectives; we never really desired to compute the gate to channel capacitance. But remember channel is basically source and drain together.

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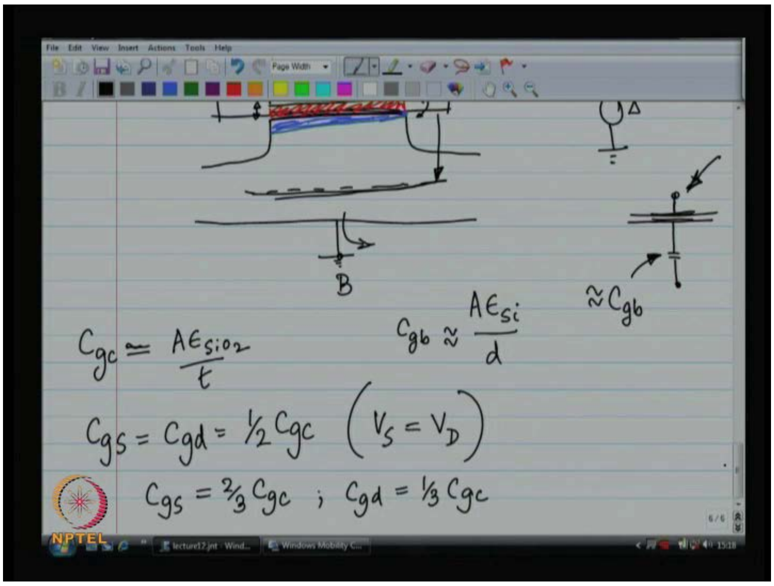

So, if you split up the source on the drain at this point of time you split up the source and drain into 2 different pieces; when the capacitance from the get to source and get to drain should be equal and equal to half of the get the channel capacitance right. Now, as you increase the drain voltage in comparison to the source voltage this no longer remains the case. Because the sheep of a channel changes; you get more charges come towards the source less charges towards the drain. The shape of the channel is tilt at towards the source, more charges towards the source. So, you expect gate to source capacitance to be more then gate to drain.

Now, some sort of triangle perfect triangle is formed at a pinch off; pinch off is when this blue line exactly meets the edge of the channel that the pinch off point; what is VDS; such that the channel is just barely there at a drain. So, at that particular point you can do your computation and you will find that C G S is going to be two-third of the gate to channel capacitance. And, C G D is going to one-third of the gate to channel capacitance all right not at other times. So, this gate to source capacitance and gate to drain capacitance are they depend on the conditions what are the exact voltages on the source drain etc.

However, this is the rough relationship; a lot of simulators just go I at use and two-third and one-third for the simulations voter spies models level 1, level 0, level 2, spice models use this; however, it is not really correct to use this on the face of it; you have to really look at the source voltage, the drain voltage and gate voltage and then only you will be able to figure out the shape of the channel. Once, you have the channel figured out then you should do the computation for the capacitance; what portion of the capacitance is to this, to the source and what portion of it is to the drain.

Now, there is something for over hear that we are not discussed and that is called overlap; while you are fabricating there could be imperfections because of which I mean I have drawn beautiful mosfet. But unfortunately the source could go little bit underneath the gate, the drain good to go a little bit underneath the gate; when this happens you have got overlap between the get and source. And, you got a little bit of overlap between gate and drain and this is going to cause some overlap capacitance. Now, this overlap capacitance as nothing to do with bias voltages; it is something interesting within the mosfet. Because you have made that way; whether you have applied a biers voltage or not the overlap capacitance is going to be there.

So, there is some overlap over here it is a small amount of capacitance. But not something to be neglected; if you apply a very large voltage on the drain you can get rid of C g d altogether, you can really really reduce C g d; you cannot get away reduce, you cannot reduce overlap capacitance at all it is there. So, always going to be there. So, so far we have seen that there is large capacitor between gate to drain; typically a larger capacitance between gate and source, there is a very tiny capacitance between gate and body much much smaller than gate to source, gate to drain.

Now, if you look at this picture do you expect any capacitance to be there between source and drain; source and drain are far apart when the mosfet is on, when there is a channel the source and the drain our connected by a wire, by a sheet charge; you should not have been seen capacitance between source and drain. In fact, you should probably be seen and inductance between source and drain they are connected by a wire; whenever, you got a wire, you got a got small amount of inductance. So, if at all they should be inductance between source and the drain then definitely should not be capacitance between them; they do not look like parallel plates.

Now, what else happens, what else left over here; you have got source to body and drain to body left. And, for that you have got to recall that you created some depletion region along the junctions. Now, what does depletion region means there are no, there is nothing that there are no carriers in the depletion region; it is like you have got dielectric material, insulating material.

So, you got one side a conductor source, you have got some dielectric insulating material, you have got the subscripts, C you will get a capacitor which is parallel plate capacitor right. So, this is called the junction capacitance; we are going to discuss the junction capacitance in the next class all right. So, with this we are going to wrap up for this class. And, we will continue talking about the mosfet in the next lecture.

Thank you.