CMOS RF Integrated Circuits
Prof. Dr. S. Chatterjee
Department Electrical Engineering
Indian Institute of Technology, Delhi

Module - 04
Review of MOS Device Physics
Lecture - 13
MOS Capacitances, ft, fmax

Welcome back to CMOS RF integrated circuits; today's lecture we are going to be discussing continuing from where we left of; as far as moss capacitance is goes. Then, we are then going to talk about further non-idealities in the mosfet; then we are going to discuss 2 important parameters; one is ft the other is f max. So, let us just quick recap. So, we are discuss the mosfet and lot of different.

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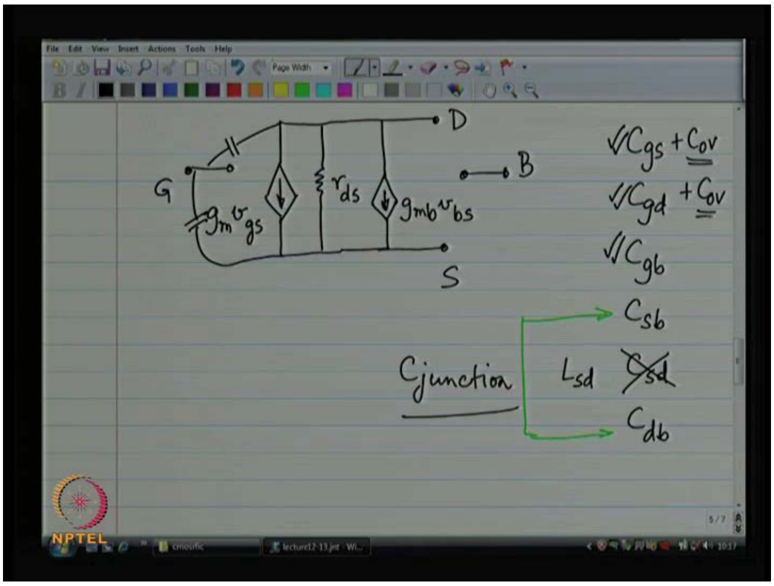

These are all the different possible capacitors C g s get the source; C get to drain, C get to body, C source to body, C drain to body and C source to drain right; of this we were proceeding one by one we evaluated C get the source and get to drain capacitances right. This 2 we evaluated; in addition to what we had evaluated there will also be a small component called the overlap.

So, that is intrinsic to mosfet that is because the gate overlaps with the source little bit. So, you know the gate is like this and the source comes little bit underneath. So, this region of overlap causes an overlap capacitance; and that cannot be avoided. However, you bias the mosfet overlap capacitance is going to be there. So, C g s and C g d and then C get the body is of concern only when the channel has not yet been formed; you got a mean depth of the fixed charges. And, depending on the mean depth of the fixed charges from the gate you get the gate to body capacitance. Now, source to body and drain to body are these are called junction capacitances; we are I am just going to discuss these; source to drain capacitance is of no consequence because source and drain are really far apart.

So, I have got the mosfet; the channel is long source and drain are far apart; in any case they are not really separated by a dielectric material; we are separated by a channel which is conducting. So, as long as the channel is conducting you really cannot call this a capacitor; I do not see a capacitance here alright. Now, let us discuss the junction capacitance; that is drain to body and source to body capacitance.

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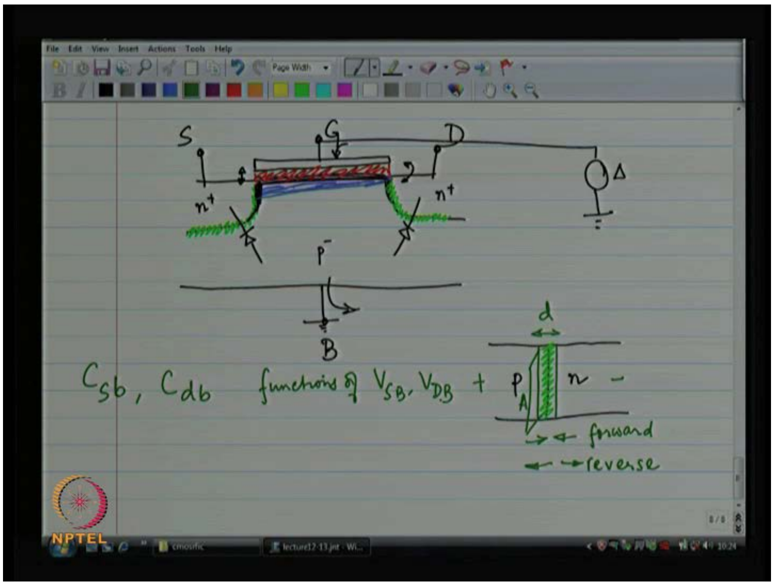

Now, really the drain and the source; these 2 are made out of n plus type of material; especially when I am talking about and n mass. And, the body is made out of p negative type of material when I am talking about the n mass; for the p mass it is exactly the opposite. We are discussing the n mass for generality, p mass you can similarly discuss identical effects will happen; for the p mass you have to remember to connect the body to the most positive voltage in your circuit.

So, that this source body and drain body junctions are reversed biased. So, in our case n mass we have connected the body to the least potential in our circuit. So, the source body and drain body junctions are reversed biased; the p type is at the least potential. So, this is what I have got. Now, whenever you have a P N junction whether or not you apply any voltage across the junction; you always get a depletion region right. And, so whenever you have a P N junction you get a depletion region across the junction; depletion region is the region where the majority carriers of the p side that is the holes go and recombine with the majority carriers of the n side; that is the electrons.

So, the holes and electrons diffuse across the junction and recombine with each other. And, as a result you are left with nothing in that small region right. So, they are no carriers in this region. So, it is like a dielectric material no carriers; so it is an insulator insulating material. So, it is exactly like a dielectric. And, hence the capacitance between p and n is probably going to be given by this cross sectional area times epsilon of the material divided by the depletion width.

So, this is the capacitance of the P N junction. Similarly, we have got a P N junction over here and the capacitance is going to be given by the area of the junction times the epsilon divided by the junction depth. Now, the junction depth of course changes when you apply a voltage. So, right now I have not applied any voltage junction depth is like this; when I make p a little more positive then n then what is going to happen? The junction depth is going to shrink become smaller.

When you make the whole thing conducting then there is no junction depth; junction depth disappears when the devices forward biased when the P N junction is forward biased. So, you can think of it from that prospective. So, the junction keep shrinking, shrinking, shrinking till they hit each other and then devices forward biased; that is how the diode works. And, similarly the more you reversed bias it the more the junction expands.

So, when you reversed biased the diode the junction expands; when you forward biased the diode the junction shrinks. So, when you forward biased the capacitance keeps increasing; when you reversed biased the capacitance keeps decreasing because the depth increases alright. Now, ours is reversed biased; the higher you make the source voltage, the higher you make the drain voltage the more reversed biased it is going to be and the capacitance is going to decrease further and further. So, that is fine. So, first of all C source to body, C drain to body or functions of V source to body and V drain to body right. It is clear modulating the width of the junction, the depth of the junction fine; what else, what is the area of this junction?

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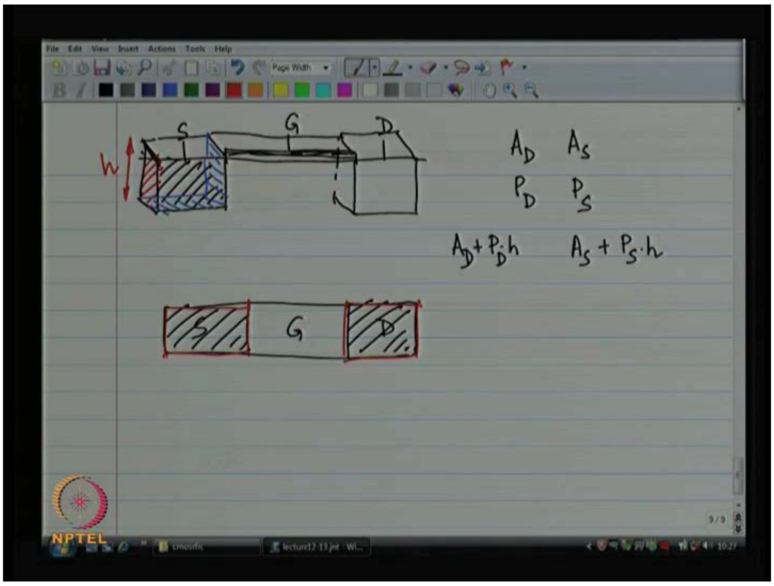

Now, to think about the area what you can do is you can approximate an engineering approximation is to think rectangular is the gate. So, make it look like a box, alright. So, when you make it look like a box all of the surfaces contribute to the source to body capacitance. So, let us say that this distance is h; the area of the source is a no area of the drain is A D, area of the source is A S; the perimeter of the drain is P D, the perimeter of the sources is P S.

So, given this circumstances, given these numbers what is the area of the junction? The area of the junction for the source is going to be A S plus P S times h work it out and find this is correct; in the area of the junction for the on the drain side is A D plus P D times h. So, what is A D and A S? A D is the area of the; so if I look on the top view. So, this is my gate, this is my source, this is my drain.

So, A D I am sorry A D is the area of the drain and S is the area of the source, P D is the perimeter of the drain and P S is the perimeter of the source. So, now you know why this numbers are important when you write here; spice net list A D, A S, P D and P S; I am sure you have done this, right. And, I do not know if you have wondered why these numbers are important? This is why these numbers are important because they determine the junction capacitance between the source and body and between the drain and body, right.

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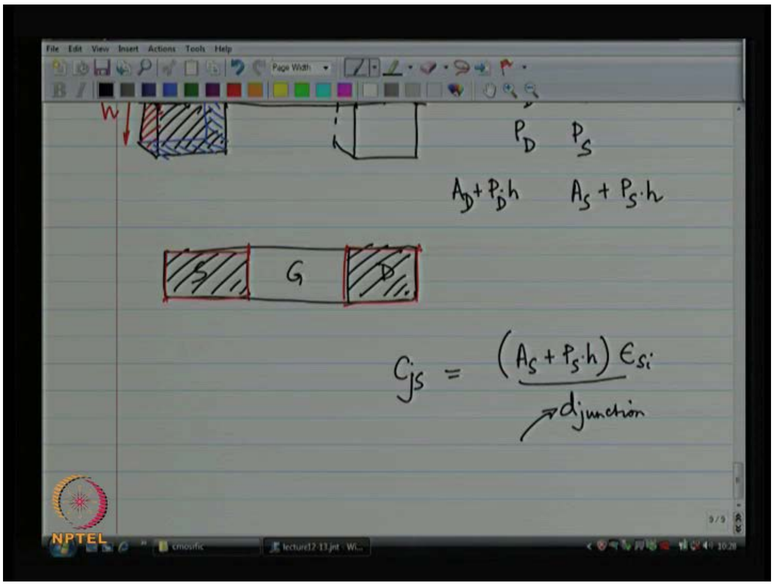

So, C junction source is going to be A S plus P S times h times epsilon of silicon divided by d of the junction; d of the junction is of course function of the source to body voltage; its source to body voltage is if its if the junction is more forward biased this d junction is going to become smaller. If the junction is more reversed biased d junction is going to become larger; that is basically the idea right; same formula applies for both source to body and drain to body capacitance.

So, this 2 are called the junction capacitances right. So, this is basically summarizes all the different capacitors in the mosfet; I have gate to source because of the channel, I have gate to source because of overlap, I have got gate to drain because of the channel, I have got gate to drain because of overlap; usually gate to drain capacitance is going to be much lesser than gate to source capacitance. Because the channel is going to be tilted in favor of the source; hopefully you are operating beyond pinch of and so on and so far.

So, that you get here current voltage control current source characteristics. So, the current is not changing much as you change V D S right saturation. So, if you are operating in saturation typically gate to drain capacitance is going to be much lesser then the gate to source capacitance, fine. Then, you got source to body capacitance, drain to body capacitance; drain is already at all higher voltage then source because you are operating in saturation.

So, that means the drain to body is going to be even more reversed biased. And, that means the drain to body capacitances is going to be substantially lesser then source to body capacitance. Source to body if you have not increased voltage on the source; if sources at the same potential at as body then you get the nominal junction depth for source to body alright.

Then, gate to body is usually not much of concern because the gate to channel is closer than gate to body right. And, typically the body is divide of charges anyway all the fixed charges are usually not going to be present; I mean it is not going to be modulating. So, gate to source, gate to drain is a primary concern; gate to body the body is far away; the depth from the gate to the body is significantly more than gate to the channel.

However, gate to body is important when we are talking about weak inversion; when the channel has not fully formed; that is when gate to body is really serious. In our course over here we are hopefully not going to be dealing with mosfet in weak inversion. So, gate to body is going to be much smaller than other effects; then we have got source to drain; source and drain are hopefully far away from each other. And, this not going to be any capacitance between source and drain, alright. So, now let us summaries our model.

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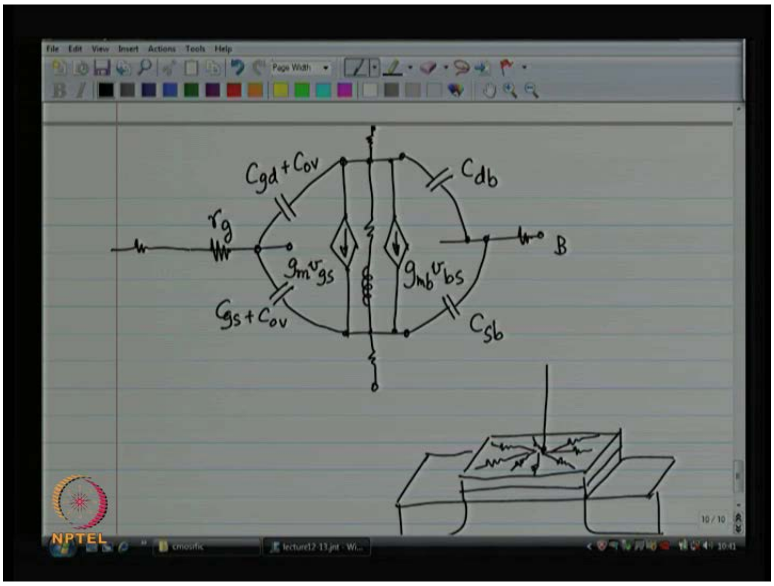

Our model for the mosfet looks like this I have got 4 terminals; gate, source, drain and body. And, between drain and source there is voltage controlled current source; this is the fundamental mosfet; to account for channel link modulation this is going to be a large resistor RDS between drain and source; between gate and source I have got a capacitance which is the sum of overlap which is intrinsic and CGS which can be changed with the biased voltages.

Similarly, between gate and drain I have got a capacitance and then between drain and body have got a capacitance and source and body I have got a capacitance; I am missing something here that is the body effect. And, body effect is accounted by yet another voltage controlled current source which is very similar to the original voltage controlled current source. So, we call it g m b times v b s.

So, this is the model that we have developed so far; is this complete? Well, it is not; there are a lot of other things that we are missing out; number one contact resistances every time you touch something let us see I want to touch the gate; I will have a place to contact and that contact will have its own resistance. So, internally gate source drain body or where I have drawn but if I look from the outside world they are not.

Then, a something call gate resistance; the gate is made out of poly material and if you think about it a resistor also made out of poly material. So, it is like a resistor, right. So, if I touch the gate at the center let us say I touch the gate at the center. Now, for the charge to reach all over the place it has to travel through resistive material; in effect you could think of the gate as a grid of a resistors and corresponding capacitors. Now, such a distributed model cannot be accommodated and it kind of depends on how you contact the gate, where your touching the gate from etcetera.

So, we typically try to lump all of this distributed R Cs together. And, we put something over here called the gate resistance alright. Now, in modern processes the insulating material between the gate and the channel is not really an insulator; it is so thin that charge leaks through; in modern processes is like 45 nanometers, 65 nanometer technology, 32 nanometer technology; the material between the gate and the channel the dioxide layer, silicon dioxide the layer is. So, thin that charge leaks across. So, in that case you cannot isolate the gate from the channel. Now, this gate resistance that I have noted down over here does not account for that; this is not that, this is something else.

This is even if the gate is perfect; just the charge travelling all over the gate and reaching all the different points; all over the gate the charge has to go through resistors. So, that is what this RG is trying to account for; if you want to model further, if you want to model leaking charge across the gate channel boundary. Then, you have to do more stuff over here; you have to kind of change this model to B J T kind of model by polar junction type of model anyway.

So, that is not what we are talking about here this is just the gate to resistance. Because the charge has to travel through the poly material alright; what else are we missing out here? Next, most important thing that we are missing out is the fact that electromagnetic ((Refer Time: 223:16)) takes time to travel it is like this if I say something here you are not listening to me right now; it is taking a little bit of time for sound to propagate from my mouth all the way to your ears.

So, the news that I am giving you is taking a little bit of time to travel; the vibrations that I am setting for the a taking time to travel. Similarly, when I apply a voltage at the drain and electrons start moving the source does not yet no that electrons have started moving at the gate at the drain or think should be moving the sources is not having that knowledge or when thinks start moving at the source things do not yet start moving at the drain right; this is what I am talking about when I say that electromagnetic moves takes a little bit of time to travel; travels at the speed of the light. Now, speed of light is very large our devices have might have long channels, might have short channels I do not know but we are talking about gigahertz. And, when we are talking about gigahertz the time we have is very small; we have a nanosecond of time right.

So, the fact that electromagnetic ((Refer Time: 24:59)) takes a little bit of time to travel is modeled as on inductor in the path of the channel. So, it is like there is exist an inductor over their which tries to continue with the current that was flowing before and slowly allows the buildup of current. So, it is not really liked this; it is distributed inductor resistor network the whole thing is distributed right. So, the channel is like an inductor resistor; inductor the channel is like a transmission line.

So, if the channel is like a transmission line you got put a transmission line there; we cannot just put gm and R D S and so on alright. So, that is what we have. Now, this is the complete model for the mosfet and if we are talking about R F applications if we are talking about 2 gigahertz, 5 gigahertz, 1 gigahertz you have to take into account all of these different effects. And, use them in your model small things going wrong here in their can cause problems. Now, this is the complete model for the mosfet. Now, we are going to move on to couple of important metrics for the mosfet.

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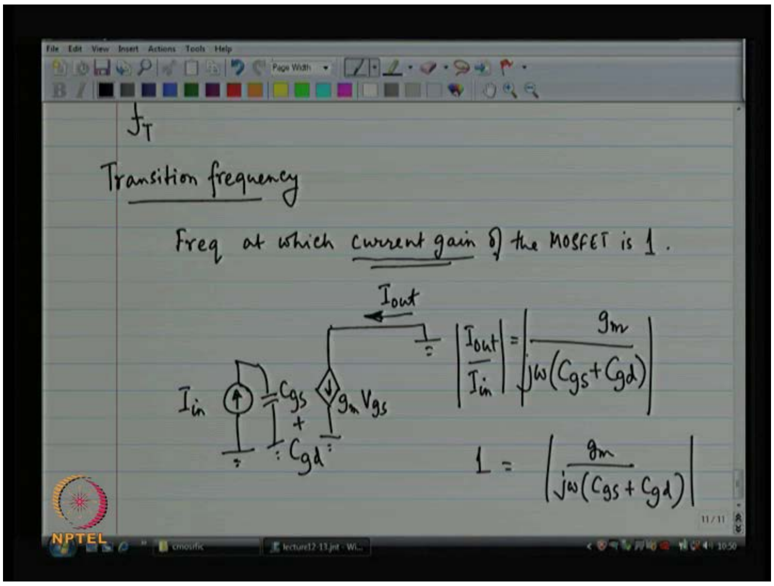

Now, the most important metric you may or may not have heard of this metric is the f T; f T is the frequency the transition frequency. Now, the definition of the transition frequency is that it is the frequency at which the current game of the mosfet is 1. Now, we have something serious over here; what on earth is current game, what do you mean, what are we talking about?

So, imagine an experiment like this; imagine that I biased the mosfet but of course. And, this is the small signal picture mind you not the large signal; I have connected the source to ground, I have connected drain to a biased voltage such that the mosfet is saturated; also the gate is connected to voltage such that the mosfet is in strong inversion. Let us leave alone the body fun of no need to worry about the body you can connect the body to the source to be done with it; in the small signal the drain is at ground because it is at a constant voltage. Now, if I push a current into the gate of the mosfet, how can you push a current into the gate of the mosfet; is it not it on an open circuit? Well, it is an open circuit at d c but for a higher frequencies you have to think about C G S, C G D and so on and so forth right.

So, it is not really an open circuit. So, I am pushing a current into the gate of the mosfet; and the question is how much current does this mosfet generate? And, we are going to sweep the frequency of this input current source; it is a small signal current source. So, they are going to sweep the frequency of the input current source till I out by I in is equal to 1; that frequencies is going to be the transition frequency; that is the definition.

So, let us see what the current game is and then we will easily find out the transition frequency. So, the mosfet is going to be replaced by its model; model for the mosfet is first of all I have got g m I have got R D S right; then I have got C source to body of any concerns both sides are at ground no current is going to flow through it. Similarly, C drain to body is it of any concern both sides are at ground no current is going to flow throughout. Then, I have got C gate to source, I have also got C gate to drain which is going to come in parallel width C gate to source.

So, this is the model for my mosfet I am on throwing out the higher order effects like you know you have got contact resistance and gate resistance and so on so forth. Let us not worry about those right now; those will just add a few more terms here in their also the inductance does not really matter; what is going to happen to R D S both sides are at ground potential. So, no current is going to flow through R D S fine.

Now, I am pushing this current I in as I am pushing this current I in a potential is going to develop across the capacitors; what is the potential that is going develop across the capacitors right? So, we get to source is I in divided by g omega C g s plus C g d and once I know we V g s I know g m times V g s and that is going to give me I out. So, I out by I in is going to be this quantity. So, this is my current game. Now, when I say that I want to find out the frequency at which the current game is going to be 1. Then, that means 1 is equal to g m by g omega C g s plus C g d can this really work? I have got a face problem over here.

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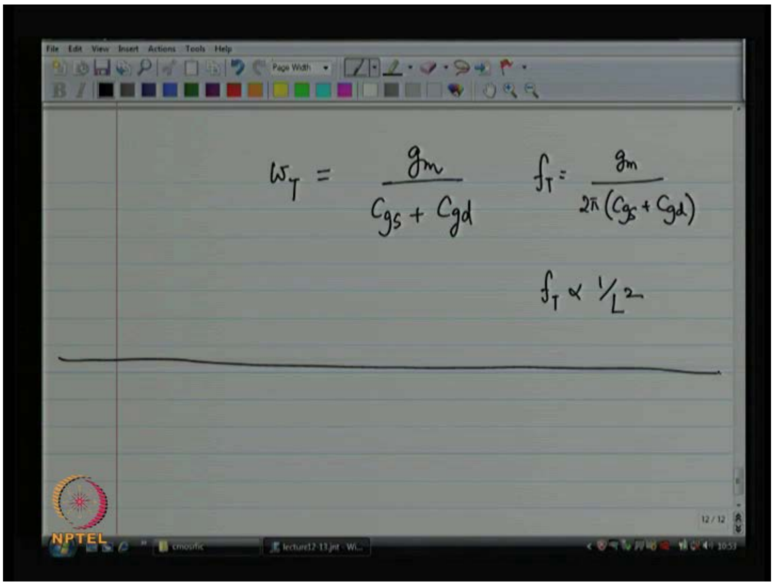

So, clearly is going to be a magnitude over here which means that this is going to be the frequency in radiance per second at which the current game is 1. Now, notice something over here. Suppose I increase the width of the mosfet; if I increase the width of the mosfet g m is going to increase proportional to the width of the mosfet, C g s is also going to increase proportional to the width of the mosfet; C g s is area times epsilon by d capacitor area is proportional to length times width area equal to length times width. So, C g s is proportional to the width C g d is also going to be proportional to the width. And, therefore f T is not going to change at all.

So, f T is not really going to change at all when I change the width of the mosfet; what about length of the mosfet when I increase the length of the mosfet g m is going to decrease, C g s is going to increase proportional to the length. So, f T is going to decrease proportional to length squared. So, that means that is if you want the maximum transition frequency you have to use the minimum size devises that given technology offers. So, suppose you are working at 90 nanometer technology you have to use the minimum length 90 nanometers; that is going to give you the maximum transition frequency.

Now, as you increase length the transition frequency is going to decrease proportional to L square inversely proportional to L square, fine. So, this transition frequency is an important metric; the foundry will tell you or need not tell you can easily compute you just place the model of the mosfet the mosfet in simulation. And, you can easily evaluate the transition frequency; it is an important metric for our R F circuits alright.

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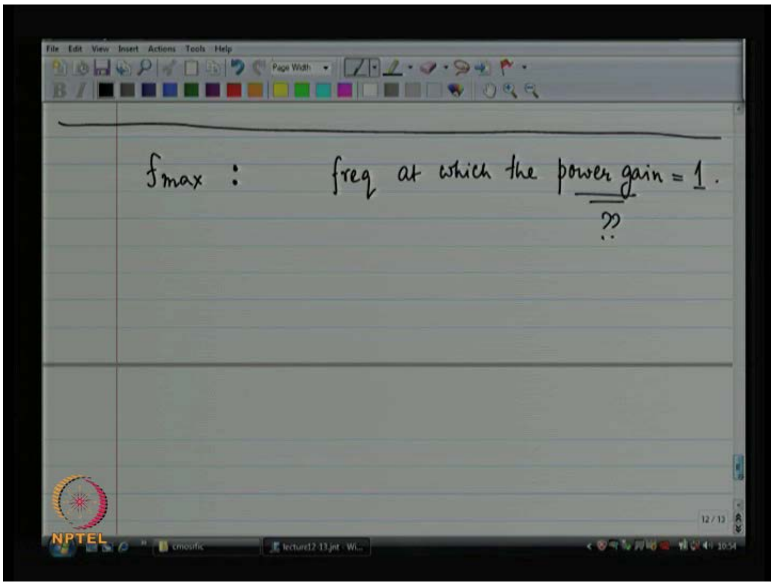

The next important metric is called f max; f max is the maximum frequency at which the power game of the mosfet is equal to 1. So, as you increase in frequency power game is going to decrease and the frequency at which the power game is equal to 1 is called the maximum frequency; what do I mean, what is this power game, what you think is power game? So, first thing you have got to remember is the law of conservation of energy. Law of conservation of energy tells you that if I put in so much power; then I can put out so much power the total power there I can put out is going to be equal to the total power that I have put in plus the power that I have wasted.

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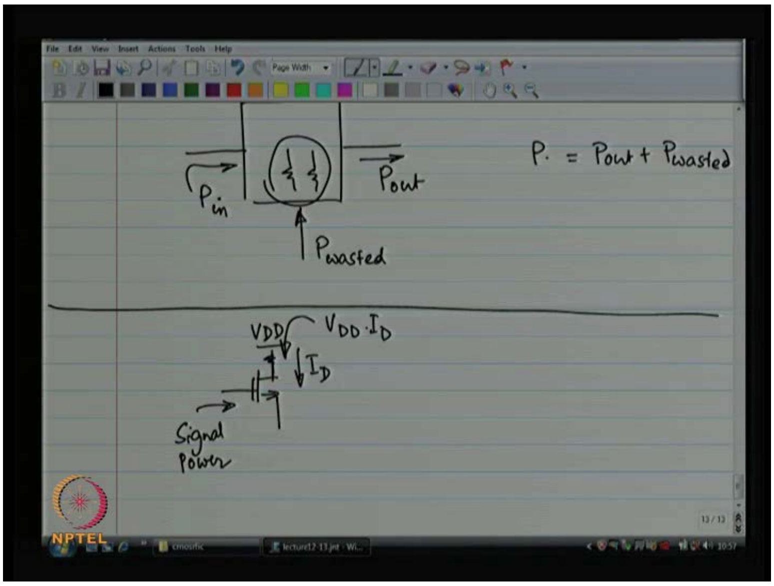

So, if I have got circuit with some resistors I input some power then the output power there is some output power. And, there is some power wasted in the resistors as heat then power in is going to be is equal to power out plus power wasted; which means that power out by power in that is the power game is always going to be less than 1. So, what I am talking about when I say power game? So, this is very confusing right. Well, what you got to remember is that power is coming into the mosfet from a lot of sources; power is coming into the mosfet from the biasing sources, from the signal, from the power supply.

So, I have got my mosfet it is a 3 terminal device; there is power coming in at d c into the drain; this power coming in at the high-frequency into the gate right this current this is voltage. So, power is going inside the gate into the gate at d c I have got a bias current, I have got a bias voltage. So, clearly I have got V D D by V D D times id as the input power right. And, at the high frequency this mosfet is going to output some power to a load hopefully.

So, this total quantity is conserved the power coming into the mosfet at the signal frequency the power coming into the mosfet at d c. And, the power going out of the mosfet at d c as well as at high-frequency all of this together is conserved some part of the power from d c is converted to the high-frequency. And, as a result you get something called this power game unless you have got a game in terms of power; what is point in I am having mosfet, what is the point in using the mosfet at all right unless you can have a game in term power at the signal frequency. So, that is what I mean by power game. So, when we talk about power game we have to talk about the small signal model. Because really we are assuming that power from d c is coming into the mosfet and it is getting translated to the high-frequency ok.

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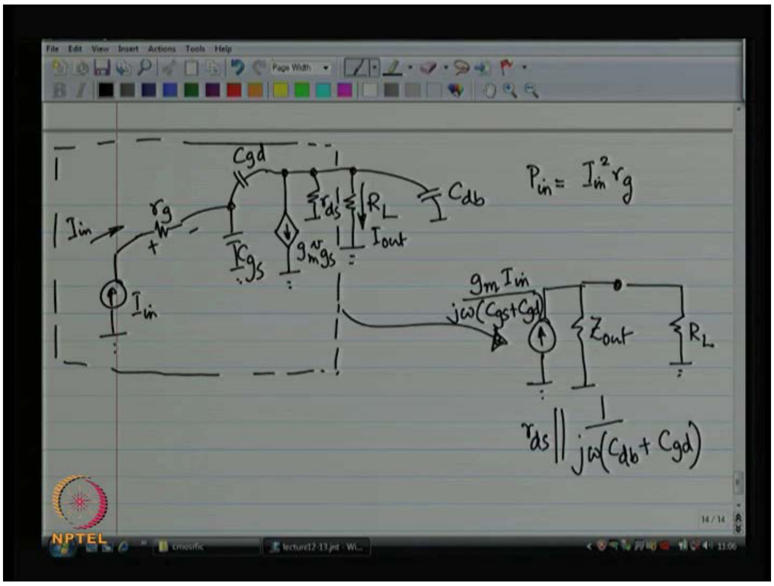

So, let me setup my experiment. So, suppose this is my experiment; power is coming into the mosfet is there power coming into the mosfet at all; is there any current here? Well, there is current not d c at d c there is no power going to the mosfet. So, we cannot really talk about power game but at high frequencies there is a current going into the mosfet; is that current in face with the voltage? Well, if you only think about C g s and C g d the current is never going to be in face with the voltage right; the gate of the mosfet is going to look capacitive.

So, you also got to think about the gate resistance r g voltage drop across the gate resistance means that some power is burnt on the gate of the mosfet; which means there is some power going into the mosfet alright this is ok. Then, the power output is of course whatever the current is current square times R L will give you the output power, alright. So, let us work this out little more organized fashion.

So, let us apply V n and we are going to measure the current that is going in; first of all we have to find out what is the current going in that will give me the power that is going into the system. And, then I have to find out either the voltage at the output or the current at the output; that is going to tell me the power bunt on the load. And, finally that is going to give me my power game, right.

So, instead of starting with V in why do not I start with pushing a current into the into the mosfet; can I push current into the mosfet? I can right. So, that quickly gives me what is the power bunt what is the power going into the mosfet is the voltage drop across r g squared divided by r g right or rather I in squared times r g. Now, what you think is going to be I out; how do you find out I out; is there a shot procedure?

Well, the procedure that I like is by using the not on equal violent circuit models the entire system including C d b etcetera as current source inshant with an output resistance. So, this is going to be the model of the mosfet etcetera right and how do you find out the not an equivalent current by doing the short-circuit test. So, you shot out the output and find out what is the short-circuit current and that will give you the not an equal violent current. So, if I shot out the current its leads me to the previous experiment frequency at which current gain of the mosfet is one. So, that is the experiment I reach right I have done this experiment just a few minutes back.

So, I know that I out is gm times I in divided by g omega C g s plus C g d alright. So, this is my current this is the output current not an equivalent current and what is z out; do I need to know z out? Yes, I need to knows z out z out is a R D S in parallel with C d b what about C g d etcetera? We are going to see the miller effect and you are only going to see basically C g d approximately; this is going to be the output in field outs.

Now, once I have this 2 I can easily put R L inshant and figure out what is going to be the final voltage at the output? And, that is going to lead me to the power game is this ok. So, I do V square by R L that is going to give me the power at the output divided by power at the input; that is going to give me my power game have I made an mistakes over here; is got to be a mistake? If I am asking you the question have I made an any mistakes is going to be a mistake; there is a big mistake here, where is the mistake? Well, this experiment of the finding the short-circuit current is not exactly what I done before it is; not exactly the same and that is going to lead me when erroneous result; the experiment I did before ignored r g. Now, I have got r g over here; as a result V g s is going to be different alright.

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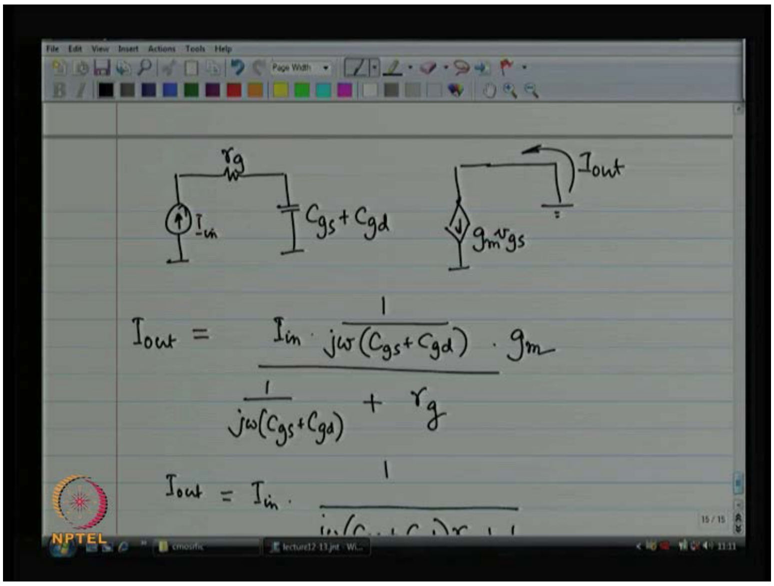

So, this is going to be the real expression which means that I in I out by I in that is your current game; I made a mistake looks like its correct I in no this is correct; I have got to have made a mistake alright that is my corrected version. In fact, which accounts for the presence of the gate resistance. Now, when that is my I out then things will slightly change over here in my previous computation, alright.

Now, why did this affect me why was I keen on making this change? The reason why I was keen on making this change is because I am looking for a power game. And, if my current is not in phase with the voltage that I have developed then I do not really get any power game. So, if my I in over here I am sorry if I out over here going to be something which is not in face with I in then I am going to get a serious problem right. So, that is why I was keen on making this change, alright. So, will summarize this because we are running a little short of time.

So, today what we discussed we went back to all the different capacitors in the mosfet. And, we primarily discussed the junction capacitance effect right; the junction capacitance effect is proportional to the area of the source plus the perimeter of the source times the height of the junction of the source and it is inversely proportional to the depth of the junction. Now, the depth of the junction gets modulated with voltage; that is all you have to remember. Then, we developed a complicated model for the mosfet; we also talked about finite transition time effects. And, as a result of that you have to incorporate an inductance in the channel of the mosfet. And, then we talked about 2 important figures of merit for the mosfet; one is the transition frequency and the second is the frequency at which I obtained maximum power game. Now, when you talked about power game you have to remember that this is power gain at the signal frequency and it ignores power coming into the mosfet at d c. So, with this we are going to close this lecture.

Thank you.