Course name- Analog VLSI Design (108104193)
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Week- 3
Lecture- 9

Welcome back. In the last lecture, we saw the properties of a required properties of a two port network or the required properties of a device inside a two port network that was necessary to give us amplification of power. So, we saw the properties in terms of the IV characteristics of the input port and the output port and we from the very first principles over the last few lectures, we could come up with a set of properties that we expect from a device that is supposed to give us amplification of power, right. And then we could extrapolate, we could extrapolate those properties that we derived from first principles and hypothesized that if a device exists which has properties similar to the properties that we just derived, right then it is possible to get a amplification of power. And what were the properties? The properties were the incremental input impedance, right Y_{11} or incremental input admittance Y_{11} should have been 0, incremental output admittance that is Y_{22} should also have been 0 , incremental transconductance between the output port and the input port that is Y_{12} that should have been 0 and the incremental trans conductance from the input port to the output port that is Y_{21} that should have been as high as possible, right. And from these first principles we could extrapolate the desired full IV characteristics, in terms of the wish list of an ideal device that could have given us amplification of power.
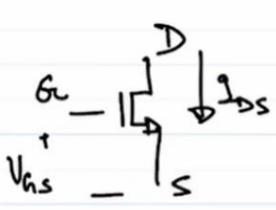
And then as we were at the fag end of lecture 8, we saw that indeed such devices exist. In fact, not only one device, there have been plethora of devices over the last century and there will be plethora of devices in the coming decades which you will see, will have identical or similar similar IV characteristics between their two ports And it is not a coincidence that they all have similar IV characteristics, it is by design because in order to get amplification of power you require certain similarities of the IV characteristics between devices and those similarities are that the small signal parameters in terms of Y parameters should be similar, right. So, in this course as promised we will be concentrating solely on one particular device that is the MOSFET and one of the reasons we will be concentrating on MOSFETs is the fact that most of the VLSI industry as we know it uses MOSFET for their analog and digital designs. Admittedly, this course is not about digital design this course is all about analog design even then almost all of analog circuits that you see almost most of analog circuits that you see uses MOSFETs as their device of choice.

So, simply because MOSFETs are cheap right, they are easy to make comparatively compared to other devices and the ease of making a device has nothing to do with their IV characteristics per se, but it has entirely to do with how it can be fabricated in an IC and that if you are interested I would strongly recommend you take a course on semiconductor device technology where the technology behind making of these devices are covered in detail, right.

So, for this course we will stick to MOSFETs, right. So, in this lecture we will see how the IV characteristics of a MOSFET delve into or lend itself into a good amplifier characteristics of our choice, right and we will see the various operating regions of the MOSFETs and some nuances associated with them, right. So, let us get started. So, as we saw in the last lecture a MOSFET is a device is a three terminal device for now we will treat the MOSFET as a three terminal device, but we should keep in mind that this is a gross simplification will come to will come to more complete model of MOSFETs later on in this course, right.

For now let us assume that we have a three terminals let us call this terminal as drain, source and gate, right and if you apply the current voltage the current between the drain and the source is normally mentioned as IDS and the control terminals of IDS are the voltage between the gate and the source which is often referred to as VGS, right. Even before going into the current between the drain and the source let me talk about one fundamental characteristics of a MOSFET and that is the fact that your IDS in order to get a finite current through a MOSFET, right. We need to so to get a finite current through MOSFET we need to apply minimum voltage some minimum voltage between the gate which is marked as G and the source which is marked as S of the MOSFET and this minimum voltage is called the threshold voltage or VTH. Okay, so by definition if you have a voltage by definition if the G minus VS the voltage between the gate and the source is less than Vth then the current IDS is equal to 0, right. So, often this VG minus VS is denoted as VGS if VGS is less than threshold voltage the current IDS is equal to 0, right.

Note that this has the relationship between is relationship is between the gate and the source and the drain has the other terminal drain has nothing to do with, okay. So, now you might as well as well ask I mean what is this magical terminals gate source drain and why are they named accordingly, right. So, let us take a few minutes and draw the cross section of a device, right. I will caution you before even before getting into this cross section of the device is that

this will be a very rudimentary discussion on the operation of the device operation of the device and this by no means will be a full-blown discussion on the operation of the physics of the operation of a MOSFET, right. So, we will only restrict ourselves to that much understanding of the working of the device of working on the MOSFET as much as it necessary to design analog circuit, right.

So, having said that let us get started. So, when I drew MOSFET terminal like this and I call this a drain, I call this a source and I call this a gate, right. So, one might and on top of that I marked an arrow at this terminal, right. So, we must have been curious as to what these terminals mean and if you already know no harm, you can skip the next few minutes, right. If you have already if you do not know how a MOSFET works then stick along So, I will try to give you a rudimentary understanding of how a MOSFET works, ok.

So, as it turns out in semiconductors everything starts from a wafer which is a dope with a p-type semiconductor. So, we normally call it p minus, right and on top of that what we do? We deposit an oxide layer, ok. If I draw a cross sectional if I instead of drawing a full cross sectional view if I look at it from slightly from a slightly higher vantage point, this cross sectional layer would look will have a width and a length, right. So, this should look somewhat like this, ok. So, similarly this is a this goes on like this.

So, this on top of this we deposit an insulator, right. So, this is an insulator, this is an insulator and as it turns out in a silicon wafer the best insulator that we can make is silicon dioxide. So, oxidation if we oxidize the silicon we automatically get silicon dioxide and that is one of the best insulators that we can make on a silicon wafer. So, often this is called an oxide, ok. So, then on top of this oxide on top of this oxide we deposit another layer of metal or metallic substance, ok.

So, this is this becomes a metal, right. So, pardon my sketch. So, this becomes a this is a metal, ok. And on two sides of the metal what we further do is we dig a portion which and dope it with an n-type silicon. We dope it on both sides with n-type silicon, right.

And these and we take out terminals from one from the metal and we call it gate. We take out terminal one from one of these n-type junctions and one from the other n-type junctions and we call one of them drain and other of them source, right. So, now, you might either already know or might be curious as to which one should I call drain and which one source, I call source simply because they are I mean physically or geometrically they look identical, right. So, as it turns out which one we call we will be calling drain and the which one will be calling its source depends on from which side the carriers are flowing. So, in order to understand that we first need to understand how the carriers are getting generated and how they are how they are flowing.

So, now let us let us pick a let us pick a side and we say that we call the we let us say we call the left hand terminal as source, right. And let us say we put a battery we put a battery Vgs

between the gate and the source, right. Because let us say we put a battery Vgs between the gate and the source. What happens if Vgs is 0? Even before going there even before going there let Let us say that let us assume for the time being the source and the other terminal drain let us call this drain, right . Let us assume that the source and the drain are shorted together, right.

So, if we if we assume the source and the drain are shorted together. So, case 1 Vsd is equal to 0, right. That is the source and the drains are shorted together and Vgs is also equal to 0, right. So, even the gate and the sources are shorted together. So, what do you think what will happen? Will there be any current between any anywhere? Of course, there will be no current we have not applied any voltage, right.

It is a device if we have not applied any voltage hence we should not get any current. If we are getting current even without applying any voltage which means I mean we are getting power out of I mean then it is almost like a perpetual current generator, right which is something that that is probably we are yet to we have to get, right. So, this is very trivial we can say that the current between the drain and the source is 0, right. So, when I say Ids I mean this is the current that flows from one terminal which is marked as drain to the other terminal that is marked as source and this Ids is equal to 0. So, let us say k, now let us move on to the other case that is case 2.

Let us say Vsd is still equal to 0, right and Vgs is greater than 0 and less than threshold voltage. Now, by definition of threshold voltage what do you say by the very definition of threshold voltage that we had in the in the previous page what do you think is going to happen? Ids will be still 0 because the voltage between the gate and the source is below the threshold voltage, right. Now, what is this concept of threshold voltage and why is it at all why is it at all relevant? The concept of threshold voltage and its relevance comes from the

fact that if you apply a voltage between the gate and the source essentially what you are doing you are implying that there are electric fields that are getting generated at the gate and getting So, terminated at the source and given that the source and the drain are at same potential right now. there will be electric fields between the gate and the source and the gate and the drain, correct. So, these are electric fields, right.

Now, what is the effect of this electric field? The effect of this electric field is that it will try to attract it will try to attract electrons underneath the oxide, right. It is almost like a capacitor it is like a capacitor because you have a metal plate on top you have a you have an oxide or an insulator in between and you have something in the bottom, right. Whatever you have something in the bottom on the two sides of the bottom you have some n plus region which is full of electrons. Now, when they are when you apply a positive voltage between the gate and the source in the gate and the drain, right. So, the electrons will tend to will would want to migrate from their locations where they were happily sitting under the source and the drain regions and will try to come to the and would like to come to the gate and come under the gate, right.

So, it would try to the electrons would try to come and reside electrons would try to come and reside under the so these electrons would try to come and reside under the gate, right. So, the concept of threshold voltage is that, right. You need certain amount of electrons under the gate to initiate a current flow, right. For example, if Vgs is less than threshold voltage and I apply a positive Vds, right. So, let us say Vds is greater than 0 and Vgs is between 0 and threshold voltage.

What do you think will happen to Ids? As I just said if you have if you apply a positive voltage between the gate and the source and the gate and the drain, right. There will be a propensity or the invitation of the electrons which are residing under the drain and the source doping regions to come and fill up the space under the gate, right. So, which naturally means that now if I apply a voltage between the drain and the drain and the source, a positive voltage between the drain and the source. So, let us say I have applied a positive voltage between the drain and the source, right. which means i have an another lateral electric field.

So, I have a lateral electric field this way, a vertical electric field this way, right. So, this is Eds going from drain to source and this is E perpendicular, right. So, let us call this E perpendicular, right. So, the electric field is going from drain to source would like to pull the electron towards the drain which means there is a propensity of the current to flow from drain to source. Now, as it turns out in order to get a certain amount, certain density of electrons to appreciably inflict current, right, to get an appreciable current you need to cross a barrier, you need to cross certain amount of minimum concentration of electrons under the drain, right.

So, and that in order to get to that concentration you need to do what you need to apply more and more Vgs, right. The note that the concentration of the electrons under the channel is

getting influenced by the vertical electric field, right. So, concentration of electrons under the gate is determined by the vertical electric field which is E perpendicular which is set by Vgs or Vds in for that matter in the way we have sketched. Now, in order to get to a critical concentration of electrons, so that value of Vgs which creates a threshold concentration of electrons under the gate to contribute to charge flow between the drain and source is called threshold voltage, right. So, hence that is why even if you have applied a voltage between drain and source as long as the Vgs is less than the threshold voltage, right, as long as the Vgs is less than the threshold voltage you will not have any flow of charge between the source and drain, right.

So, that is why your Ids will be 0 as long as Vgs is less than the threshold voltage, ok. So, this is case 3, right. This is case 3. What am I doing? I am saying I will apply Vgs to be greater than threshold voltage. I made a mistake here, I should have said less than equal to, right.

So, let us say Vgs is greater than threshold voltage, right and let us say Vds is almost close to 0. It is positive, but it goes to 0, right. As it turns out, what do you think is going to happen physically? If you have sufficient amount of Vgs which means you have sufficient channel charge, right and you have applied a lateral electric field and the electric field between the drain and the source is present which means the electrons will start flowing, the electrons will start flowing from the source to the drain, right. The electrons will start flowing from the source to the drain and since and you would appreciate the naming conventions now, Y1 is called the source, the another is called the drain. So, the electrons will mark the flow of electrons.

So, electrons will flow from the carriers or the electrons are flowing from one terminal to the other. So, essentially the origin of the electrons is from one terminal and it is getting drained out of another terminal, right. So, that is why the origin terminal is called the source which is sourcing the electrons and the other terminal from which they are making an exit which are getting drained out are called, is called the drain, right. Note that even though geometrically there is no difference between the source and the drain, how is the nomenclature coming? The nomenclature is coming because it is pointing to the direction of current flow or in other words it is pointing towards which side I have applied higher voltage than the other, right. So, if somebody asks you to distinguish between how do you know which terminal is drain and source, what will be your answer? The higher voltage terminal in a MOSFET in this particular device that I have talked about which is in fact called an n MOSFET because electrons in a semiconductor are often referred to as n type, right, n stands for negative and electrons have negative charges.

So, we call this n type MOSFET, the flow of electrons in this particular device is due to electrons, so this is called n type MOSFET. So, in this n type MOSFET whichever is the higher potential is the one where the electrons are being drained out or dragged out, so that is called the drain, right. So, higher potential let me just also write it down here, higher potential terminal in n MOSFETs is the drain, right because electrons are getting dragged out. So, as

long as we understand that there will be a current flow and the higher potential terminal is called the drain. Now, the next region, the next thing that to answer is what will be the value of the current or what will be the governing equation of the current and as it turns out there is a very nice closed form solution of the governing equation and that is called that is as follows.

So, we call this Ids is equal to mu n Cox, I will explain what these terms mean, W over L Vgs minus threshold voltage times Vds minus half of Vds square, ok. So, this terms mu n is called is the mobility of electrons, this term Cox refers to the oxide, the capacitance of the oxide per unit area, right. So, in other words, you can readily appreciate that there is there are three layers, one is a metal on top, right or a metal like substance on top and there is a insulator or an oxide in between, right. So, this metal on top is M, the insulator oxide in between is O and the semiconductor underneath, so S I called as semiconductor underneath is S and hence the structure is called MOS device, right. So, since you have a metal and an insulator and something conducting plate underneath, which means it is natural to assume that there will be a capacitance associated with it, right and surprise surprise this capacitance comes as a term in the current equation.

That value of V_{GS} which creates a threshold concentration of e^- under the gate to contribute to charge flow between the D and S is called V_{TH}.

Case 3: $\quad V_{GS} > V_{TH} \qquad V_{DS} \approx 0$

(Higher potential terminal in N-MOSFET is the D)

$$I_{DS} = \mu_n \, C_{ox} \, \frac{W}{L} \left[\left(V_{GS} - V_{TH} \right) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

Mobility of $\quad C_{ox}$

And we should not be surprised that a capacitance comes because what will be the charge that accumulates under the oxide, it should be proportional to the capacitance, right. If you apply a voltage between two plates of a capacitance, the charge that accumulates on each of these plates is proportional to the capacitance of the plates, right. So, that is why you get a capacitance terms but this capacitance is capacitance per unit area not the total capacitance and hence it is called epsilon ox by T ox, where epsilon ox is the permittivity of the oxide and T ox is the is a thickness, is a thickness of the metal of the oxide. You do not have to worry about these epsilon ox, T ox, mu n these numbers, you do not have to worry about those numbers in this course because everything will be given to you. This is not a device series course, if you were a device designer then definitely you have to worry about that but as since

this is a circuit design course where we have no control absolutely over the mobility of the electrons or the thickness of the oxide or the permittivity of the material with which the oxide is getting made simply because this device will be given to us by our device designers.

So, we will just put our blinders on and say that okay, whatever you have given us we accept it with a without question and we will use those numbers, right. Because we cannot change it we will be using those numbers. However, there are certain things that we can change. What are the things that we can change? That is what we will discuss next. What is this W and what is this L? Let us see L first.

What is this L? This L is nothing but the distance, the physical distance that the electron has to cover between the drain and the source, right. So, this is L. So, this distance that the electron has to cover between the drain and the source is called the L, right. So, naturally what you see is that the electron has to cover longer distance, the value of the current goes down, right. Because I mean you can think of it as a time taken to go from point A to point B if your velocity is constant, right.

If your velocity is constant, if the distance between A and B is long, right, then obviously you will take more time to go. And if the distance between A and B is short, right, in this case the distance between drain and source it is smaller then you can go faster, right. So, naturally the current between the drain and the source is inversely dependent upon, inversely proportional to L. So, it is as long as L becomes larger and larger. If the L becomes larger and larger the current drops proportionately and if the L becomes smaller and smaller the current increases proportionately, right.

And as you might have heard through news flows that we, in the semiconductor industry there is a lot of buzz about this 65 nanometer technology, 45 nanometer technology, 3 nanometer technology, 40, like 28 nanometer technology and so on and so forth. What does that mean? That essentially refers to this value of L, right. So, everybody wants to get to as small a value of L as possible, right. One, because you can reduce the size, right. You can reduce the, if you reduce the distance between drain and source you are definitely reducing the physical size of the device which means on a particular set of given area you can pack in more and more device which means it becomes economical, right.

And the other thing is, the other reason one wants to do this is because the maximum current that the device can now drive will increase because smaller the L larger the current that the device can drive, ok. Now, what is the other thing? So, this L we discussed, what is the, this is length, right. What is W? As it turns out as you can see that the lateral dimension, right, the lateral dimension this dimension, this dimension is called the W, mark it in a better way this dimension is called, it is called the W, ok. And it is basically the width of the device, right.

W stands for width. And why is this relevant? This is relevant because if you, for a fixed L, for a fixed Cox, for a fixed new N and so on, if you want to transport more and more current what

you need to do? You need to ensure that more and more charges travels from drain, source to drain, right. So, more and more electrons travels from source to drain, right. If you simply want to increase, increase the, increase the current, right. So, if you cannot change L, what can you do? You can say that I mean this looks like a pipe, I can make the pipe fatter, right. If I make the pipe fatter, if one pipe gives me, if a thin pipe gives me let us say 1 micro amps of current, a pipe that is 10 times thicker should be able to give me a 10 micro amps of current, right.

That is all that is doing. So, you are making a pipe thicker and thicker, right. So, if a smaller pipe can give me small amount of current, a thicker pipe will can give me larger amount of current and that is essentially what is W doing. So, W is nothing but the width of the MOSFET, right. And you will see this W and L and W by L and W times L repeatedly in this course, right. Why is this important is because as it turns out even though you cannot change mu n, C ox, epsilon ox, T ox and so on, you can change W's and L's to some extent in the sense that as a designer, you can choose your values of W and L.

Granted, note that you will not be able to choose any arbitrary values of W and L because as I said, a technology has some limitation. There is a minimum channel length that you can use. You cannot go beyond that, but you can choose to use a channel length L to be higher than necessary if the design requires it. Similarly, you can also choose different values of W, right. You can choose to make that device wider or thinner depending upon whether you would want it or not.

But note that this you can change only once. You can make this choice only once, right. Once you have made the choice and the device has been put and fabricated on a wafer, you cannot change W and L. So, whole design that when you will be designing, you have to make a wise choice of deciding this W's and L's because you cannot change it once you have, after you have made a choice, right. It is like buying a house, right. Once you bought a house, right, you cannot really change the pillars, right.

You can paint whatever you want in the outside, right. You can change the fans inside and you can put in whatever curtains you want, right. But you cannot really change the structure, right. The basic structure you cannot change, but you can tell your architect that before you build the house, these are the structures that we want. So, you have a control over the design, but you have that control only once that is when you are building it the first time. Similarly, in case of a design of designing with MOSFETs, you have the control once of deciding what the W's and L's will be, right.

But after you have decided and the chip is there, chip has been shipped, fabricated and shipped, you will not be able to change the W's and the L's. However, the voltages are totally in your control, right. The VGAs and VDS are totally in your control. You can change them as and when you please simply because they are voltages that you have, that you can apply. Again, threshold voltage is something that you cannot largely change, right.

So, essentially what are the designer designing knobs which we can use in order to, in order to ensure what, how much current can be flown through a device. You can change W, you can change L, you can change the gate to source voltages and you can change the drain to source voltages, right. Okay. So, note that there is one more nuance to this equation and this equation is valid as he said that this is when VDS is close to zero, right.

Let me be bit more specific. This is when VDS is less than or equal to VGS minus threshold voltage. So, as long as VGS, the voltage between the gate and the source is greater than threshold voltage that is the MOSFET is on, right. So, this is when, let me call this, MOSFET is off. This is when MOSFET is on. So, when the MOSFET is on and VDS is less than equal to VGS minus a threshold voltage then and only then this current equation is valid, okay.

However, what happens if I increase my VDS further that is my MOSFET is on which is VGS is greater than threshold voltage and VDS is greater than VGS minus a threshold voltage, right. What is going to happen? What will be the ideas? As it turns out then governing current equation is, so let me rewrite the old equation, let me rewrite the old equation. So, the governing current equation essentially becomes the equation in the previous case that is mu n Cox W over L VGS minus Vth times VDS minus half of VDS squared for value of VDS is equal to VGS minus Vth. So, as it turns out if you keep on increasing VDS from 0 this equation will hold, okay. However, if you keep on increasing VDS and reach a value of VGS minus threshold voltage, right.

$$\text{Case } 4: \qquad V_{GS} > V_{TH} \qquad\qquad V_{DS} > V_{GS} - V_{TH}$$

$$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \Bigg|_{V_{DS} = V_{GS} - V_{TH}}$$

$$= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2$$

$$(\text{saturation region current})$$

After that this current will get pinned, the current will not increase anymore, right. So, what is this equation telling you? This equation is essentially telling you that if you keep on, if you keep VGS minus threshold voltage or if you keep VGS constant and if you keep increasing VDS this current is supposed to increase, right. Now, what I am telling you is that there is a limit till which this current is going to increase and the limit is when the value of VDS will reach the value of VGS minus threshold voltage, right. And what will be the value when VDS becomes equal to VGS minus Vth? If you just replace VDS with VDS minus Vth you will get half U n C ox W over L VGS minus threshold voltage, right. So, this is when we call the current has

gotten saturated, the current is not increasing anymore and hence this current equation is called saturation region current.

Right and similarly there is a name for this current equation as well and this is called linear region. Okay, so in a nutshell, a MOSFET has three regions of operations, right. So, MOSFET symbolically a MOSFET is now drain source gate where we know the meaning of the, meaning of the drains and the sources and meaning of this arrow. What does this arrow mean? The arrow is pointing to the direction of current flow, right.
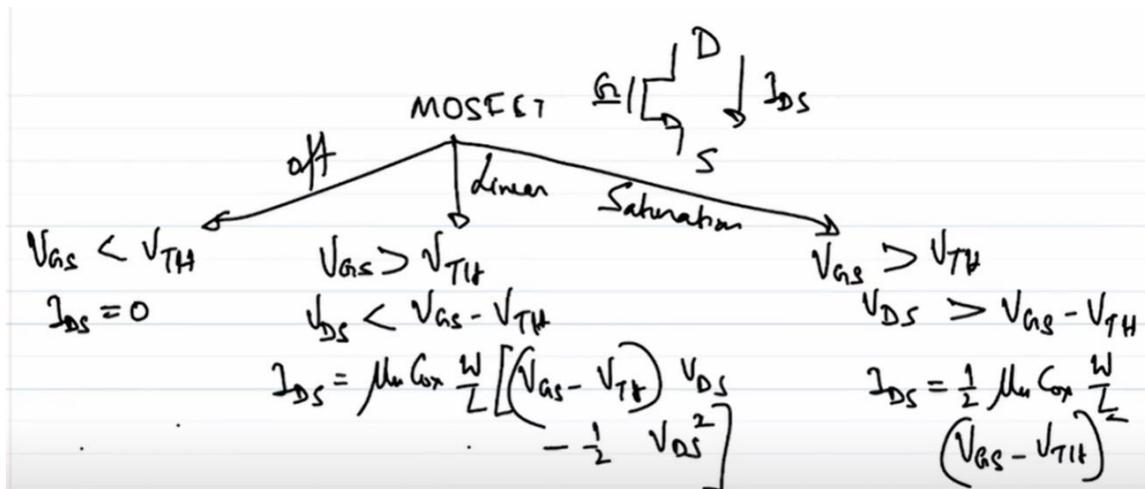
So, the current direction is Ids. The regions of MOSFET are number one which is called off, right. Off region or when in MOSFET is off that is VGS is less than threshold voltage, right. In that case Ids is equal to 0. What is the second equation region? We call this linear region. What is the condition? The MOSFET which has to be on which is VGS is greater than threshold voltage and another condition has to be satisfied that is VGS is less than VGS minus threshold voltage.

In that case what will be the current? The IDS will be U n C ox W over L VGS minus threshold voltage times VDS minus half VDS squared and there will be a third region of operation and we call this saturation region. What is the condition here? Here VGS again has to be greater than threshold voltage because the transistor has to be on otherwise there will not be any current flow and the other critical condition is VDS has to be greater than VGS minus threshold voltage and under this case your Ids is equal to half U n C ox W over L VGS minus threshold voltage, okay. Thank you.