Analog Electronic Circuits
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Lecture – 03
MOS device, characteristics

Hello and welcome to Analog Electronic Circuits, this is the lecture 3 and today we are going to start working with active circuit elements. Our basic active circuit element is going to be the MOSFET. So, in this course we are not going to get in to the physics of the MOSFET, but we are going to start from the symbol and then work with the MOSFET as if it was a black box and you know we have the operating characteristics of it.

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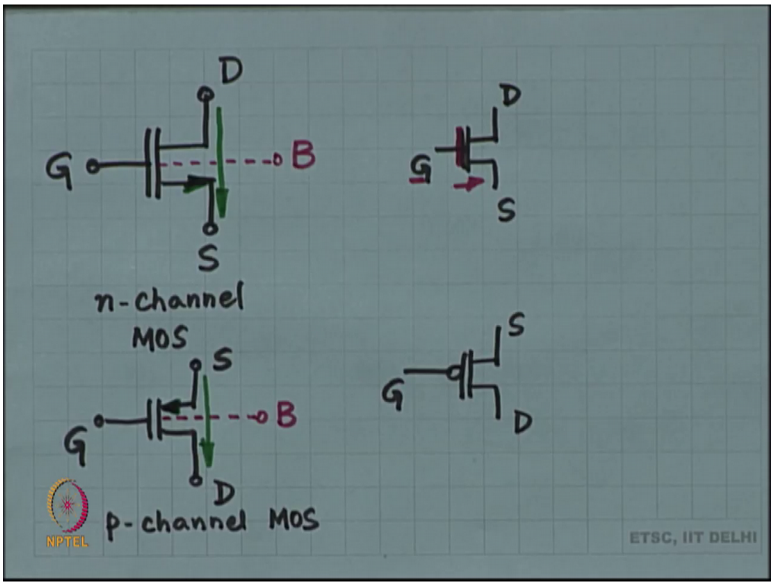

So, here goes so, first of all the symbol that we are going to use is of this fashion. So, there are most importantly three terminals there also happens to be a fourth terminal which is under played. So, we normally do not talk about this fourth terminal there is, but it is also there. So, the terminals are labeled drain, gate and source this fourth terminal is called the body, but as I said do not worry too much about it as of now.

The source is the one with the arrow now there are a lot of other ways to depict the MOSFET, other popular symbols one very popular symbol which is used in digital circuits often used in digital circuits is this with no arrow and the reason why there is no arrow is because the MOSFET is symmetric the source and drain can be interchanged and secondly, in digital circuits the MOSFET operates as a switch. So, the switch is either on or it is off.

So, when the gate voltage is high when the gate voltage is high the electronic switch between drain and source is on when the gate voltage is low, then the electronic switch between drain and source is open ok. So, it is almost like this is pushed in when the voltage is high and you know connection is made between drain and source. So, that is the logic behind this symbol behind the symbol for that is used for digital circuits.

Now there is yet another kind of MOSFET's called so, this is this MOSFET is called the n -channel MOSFET all right. So, all of this applies for the n - channel MOSFET there is also another MOSFET which is called the p channel MOSFET and in digital circuits the p channel MOSFET is shown in this fashion right there is a bubble at the gate which means that when the gate is low then the switch the electronic switch between source and drain turns on that is all.

Now, the equivalent symbol for the MOSFET in analog circuits looks like this and notice I said just now I said a little bit earlier that the arrow is always on the source. So, here the source has the arrow irrespective of whether it is a pmos or in nmos the arrow in the symbol is on the source there also happens to be a fourth terminal called the body, but as I said the fourth terminal is underplayed we do not use it to often it is there. So, this is the p - channel MOSFET ok. Now, there is a reason why the p channel MOSFET the source has been put on top and the drain has been put on the bottom there is a reason.

The reason is that we want to show that the current always flows from top to bottom that is what we like be like the current to flow from top to bottom we like current to flow from top to bottom. So, in the n - channel MOSFET the current flows from D to S in the p - channel MOSFET the current is actually flowing from S to D from source to drain. So, this is why the symbol is flipped and shown where S is on top and D is are the bottom the arrow is always in the direction of the flow of current. So, the arrow over here I am talking with this arrow and this arrow all right.

These two arrows always points in the direction of the flow of current now I told you just now that in digital circuits the symbol does not have an arrow at all and the one of the reasons why is because the MOSFET is a symmetrical device and it does not matter which is source which is drain. So, about that in analog circuits does it matter which is source which is drain how do you figure out which is source which is drain especially when the MOSFET is a symmetrical device right it is perfectly symmetric.

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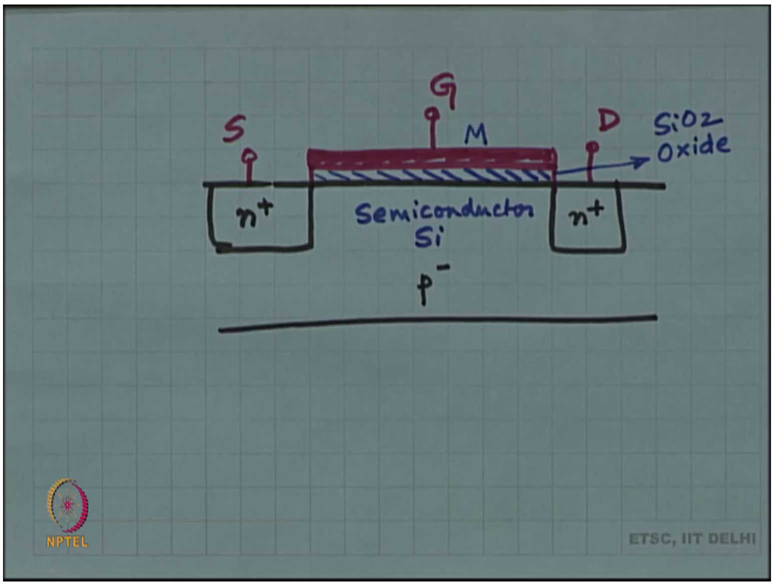

The way the MOSFET is made so, I said that I do not want to show the physics, but I am still showing a little bit of it. So, there is no real distinction between source and the drain, they look exactly the same then what determines which is source which is drain, if on one hand I am saying that as far as manufacturing goes there is no distinction between the source and the drain they are exactly equal in all respects.

Then how do you decide which is the source terminal and which is the drain terminal, what is the answer? The answer is that the flow of current determines which is source which is drain the current always flows from top to bottom just like water ok. So, the way we draw or circuits in electronics in analog electronics also in digital electronics especially in analog electronics the way we draw our circuits. So, there is a particular way we like to draw it the way we like to draw or circuits is that higher potential is above lower potential is below and just like water current will always flow from higher to lower potential.

Which means that if the terminal is drawn higher than that is the origin of the current, if the terminal is drawn at the bottom that is where the current is going and that determines which is source which is drain is this understood. So, in analog circuits the MOSFET this is not the bjt by the way in the bjt the collector is manufactured differently from the emitter there is a difference in terms of manufacturing. So, you cannot flip the bjt and hope that it works there is no way it is going to work, as far as the MOSFET goes you can interchange the terminals if I interchange the terminals of this particular analog MOSFET right S and D if I interchange then what is going to happen if the flow of the current will still remain the same ok.

Let's take an example so, suppose you have got a circuit that looks like this ok.

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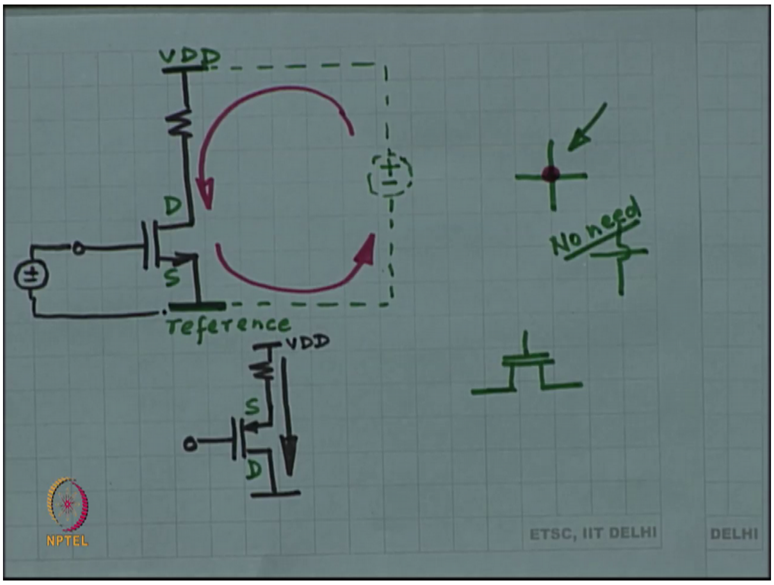

So, this is high potential so, I am going to call this by the way there are a few conventions in electronic circuits we try not to draw the voltage sources ok. So, in your first year on or in your second year you would have learnt to draw a voltage source like this right in electronic circuits this voltage source is implicit we always we do not like to draw this voltage sources. If for example, I write over here VDD then that automatically means that there is a voltage source between these two terminals worth VDD volts and if I do not try it a voltage source for example, at this terminal there is no voltage source or there is nothing written ok.

Then it is implicit that this terminal is connected to 0 volts or ground. So, this is the reference potential so, these are things that no one is going to tell you, but these are implicit when we are dealing with electronic circuits all electronics analog digital we just ignore we just do not draw the voltage sources so, explicitly anymore. So, suppose you have got a circuit like this now; obviously, current is always going to flow from high to low potential. So, what is going to be the direction of flow of current like this ok.

So, right now the gate voltage is something I have applied some volts at the gate I do not know what it is, it does not matter it is not important the gate side what is going on is not important the flow of current is always going to be from high to low potential which means that whichever way you have place the MOSFET. It does not matter if you have put the drain terminal if you have put this terminal over here and this terminal over here, the arrow always points in the direction of flow of current and I know that the direction of flow of current is this way which means current is going to go flow through the arrow and come up, automatically it means that this is the source this is the drain is this understood ok.

So, I spend some time on this is very trivial not many people talk about this at all and the reason I spend some time is to avoid confusion later on when we deal with pmos devices. Because if you had placed a pmos device over here, something the gate potential is somewhere it does not matter what would be the flow of current, the flow of current would be from top to bottom which means that the arrow goes on the top which means that this is the source and this is the drain is this understood great.

So, this is the convention current flows from top to bottom this convention we are going to try to follow in all of are not try to follow we will follow this convention in all of our circuit schematics there are some places of confusion where potentials are equal ok. So, in such scenarios we try to and in sometimes drain and source might have equal potential maybe you are trying to use the MOSFET as a switch just like in digital circuits in such cases in analog circuits we show the MOSFET horizontally.

Because we are not sure which is high potential which is low potential and in such a scenario either left or right it does not matter which site can be drain can be source it really does not matter is this great all right. So, far we have understood the symbols of the MOSFET the conventions of drawing and the conventions of drawing electronic circuits there is one also small point that needs to be mentioned.

When two wires cross and I do not put a dot at the middle then it means that they do not have a contact if I put a dot in the middle then there is a contact ok. So, this is the convention of drawing circuits right do not draw things like this there is no need, no need this is the convention and this convention has been around for the last 50 years. So, let us not draw this funny loops of wires ok. So, this is the engineering practice drawing the dot in case of a contact you draw the dot, if there is not contact then do not put the dot this is engineering practice all right this is nothing ok. So, just pointing these things out because these are conventions that we follow in engineering and practicing these conventions is a good idea all right.

Next let us start using the MOSFET and the first thing that you are going to do is try to understand what the MOSFET does what are it is characteristics right this is the first absolutely rock bottom thing that you would like to do.

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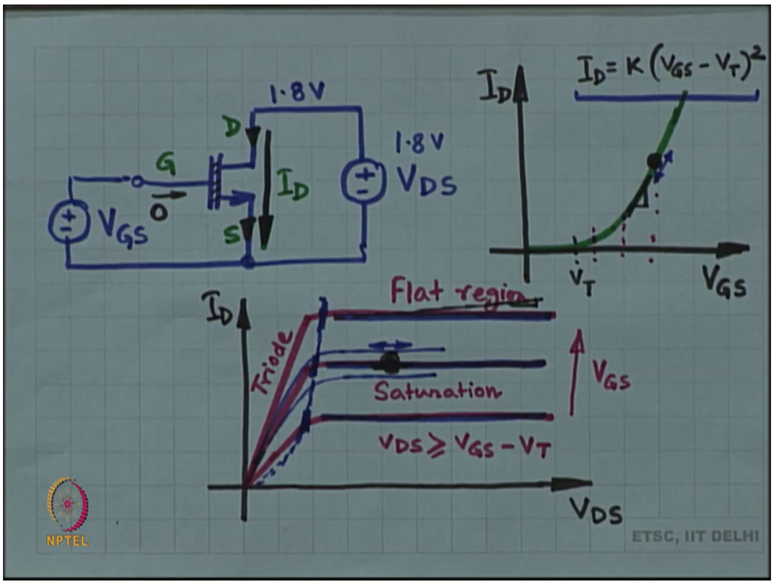

So, what we are going to do is, we are going to use voltage sources and let us start with the nmos and we are going to call this as V DS and this I going to call this as V GS. Now, the first thing that happens let us keep V DS at some large voltage large depends on the rating of the MOSFET. So, if we are talking about let us say 1.8 micron device I will tell you later on what this 1.8 micron means.

But suppose we are using a 1.8 micron device then the absolutely largest voltage that you can operate this MOSFET at is 1.8 volts. So, let us keep V DS at 1.8 volt suppose this is at 1.8 volt you keep it study and now what we are going to do is, we are going to sweep the voltage V GS and find out the corrects all right. So, this current is called I D and unlike the bjt in the MOSFET there is no current in the gate, this is the gate, this is the drain, this is the source. So, the gate is open circuit so, brief recap we go back to the picture over here this gate is metal or. So, called metal modern MOSFET's are no longer made up of metal they are made up of poly silicon.

This area is called the oxide, this is a very thin oxide layer of silicon dioxide and this is semiconductor silicon crystalline silicon which has been doped lightly doped with p minus and then this is silicon what is doped with n plus silicon doped with n plus all right. So, this is the structure you have got metal you have got oxide and then you have a semiconductor. So, you have a stack of metal oxide semiconductor. So, that is what makes the acronym. So, the acronym for MOSFET is m o s f e t metal oxide semiconductor field effect transistor.

So, this is a transistor what kind of transistor is it is a field effect transistor and all of this is what you study in your physical electronics or in your devices course right we are not going to discuss all of these the operation of the MOSFET. What I want to point out over here is that you have got a stack metal oxide semiconductor and this oxide is an insulator oxide is like glass silicon dioxide is like glass, it is a perfect insulator unless you really apply large voltages you are not going to have any current. So, given that it is an insulator the current in the gate terminal is going to be 0.

No current flows into the gate and this is not an approximation we are not talking about an approximation in very very modern devices right, where you when you are working at the age of technology over there. The oxide layer is just a few atoms thick this oxide layer is just a few atoms thick and you can have some quantum tunneling current in such scenarios all right, but ordinary MOSFET's do not worry about it the gate current is going to be 0.

So, as far as this course is concerned we are going to nicely assume that the gate current is perfectly 0 and this is really not an approximation it is not an assumption it is truth gate current is 0 all right. So, therefore, the current in the drain is the same as the current in the source kcl and therefore, I D is all that you need to measure right. You do not have to measure the gate current fine. So, we are going to sweep the voltages V GS V DS right and as we sweep these voltages we are going to understand what is I D.

Now, in our first experiment we have placed V DS at 1.8 volts that has been said and the maximum voltage that this device can tolerate in any of it is terminals is 1.8 volts. Now you sweep V GS and what are you going to measure what are you going to measure I D because that is the only thing to be measured there is no gate current there is no other current there is only I D. So, I am going to sweep V GS measure I D and what we find is that the characteristics looks somewhat like this.

It is mostly quadratic in nature and there is a voltage below which current does not flow. So, this voltage is called V T the threshold voltage all right if you go to a try to make a crude model of this equation you will find that it closely resembles I D equal to sum K constant times V GS minus V T the whole squared ok. It closely resembles this characteristics now as I said I have placed V DS at 1.8 volts, if you change it to 1.6 volts or 1.5 volts or 1.7 volts there is not going to be any change in this curve no change. So, whatever is V DS it does not matter you can middle V DS around there is not going to be any significant change in the drain current this is the characteristics.

Next what we are going to do is we are going to do the opposite we are going to sweep V DS and measure I D all right and for this I have to set a value of V GS. So, let us say I said some value you know let us start with something a little above V T we said we V GS equal to this one all right and then we are going to set V GS equal to this one, then we are going to set V GS equal to this one right. So, a few such V GS points and what you are going to observe is that the current flows like this.

So, there is going to be a region beyond which so, this is my first point of V GS then the second point of V GS so, these are different V GS values. So, for different V GS values you do this measurement and what you are going to find is that as you change V DS beyond the certain point beyond the certain point as you change V DS the current does not change all right. Now we need to know what is the value of a V DS; beyond which the current does not change and if you try to model this curve it looks exactly the same as it looks exactly similar to the other one.

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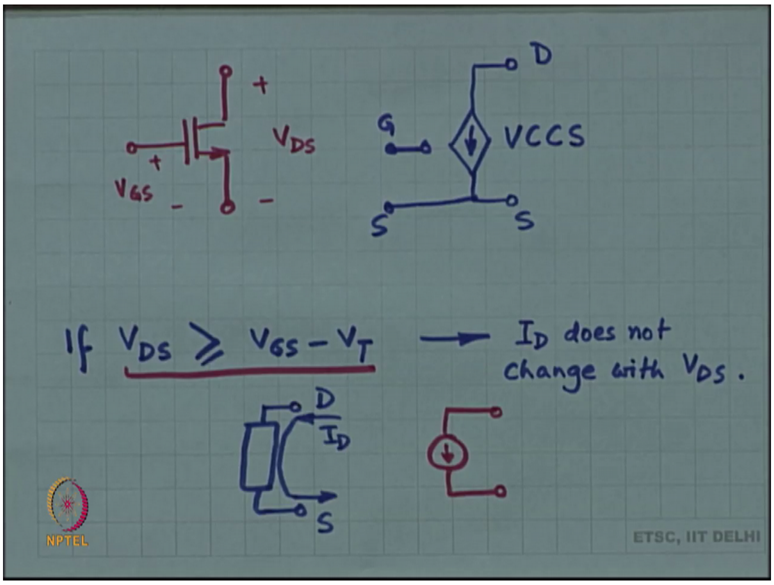

And what you are going to find is that if V DS is greater than or equal to V GS minus V T, then there is no change in ID, all right this is the condition, that you are going to come up with that if V DS is slightly more than V GS minus V T is not slightly more then V GS minus V T that is what this curve is about. Then I D is not going to change at all with V DS it is going to be flat now of course, this is an approximation which we are going to correct later on we are right now going to assume that it is perfectly flat, but later on we are going to modify and say that no it is not really so, flat ok, but for now let us say that I D does not change at all with V DS at least for today's lecture all right.

Now, if I D does not change suppose you have got an element and I do not know what this circuit element is and this is the drain terminal this is the source terminal and I D is going in and coming out all right it is going right through and what you are trying to say over here is that even if I change the voltage between drain and source V DS is the drain to source voltage. Even if I change this voltage I D does not change in that case what is the circuit element inside, what kind of circuit element do you have, here is an element I change the voltage across it the current does not change.

What kind of circuit element is, it is a resistor no, what is it, is it a voltage source no, what is it, it is a current source ok. So, current source is a circuit element across which if I change the voltage it does not matter the current remains the same all right. So, here I have a current source I can change the voltage V DS, but the current does not change all right this is what we want. So, analog circuits operate in this region of the MOSFET almost all analog circuits our entire focus is going to be to make sure that V DS is greater than V GS minus V T. If we can make sure that V DS is greater than V GS minus V T then the drain to source terminal behaves like a current source and that is one of the name strategies in analog circuit design.

So, in analog circuit design make sure V DS is more than V GS minus V T if you do that then you have got a current source hopefully your analog circuit is going to work. So, all the devices in your circuit should obey this principle and why because I am saying so, all right. The only very special analog circuits very special ones which we are not going to cover in this course these special analog circuits sometimes require V DS less than V GS minus V T this otherwise V DS has to be more than V GS minus V T all right.

So, nomenclature this region is V DS greater than equal to V GS minus V T this region is called the saturation region now unfortunately in the bipolar junction transistor. If you have studied the bipolar junction transistor you will get confused because in the bjt the saturation region is the opposite the exact opposite over here right this is called the saturation region in the bjt right.

So, to avoid this confusion we are going to use this word this is not in the books we are going to call this the flat region all right and this region is called the triode region. An analog circuits do not like to be over there only very special situations you are going to operate in the triode region otherwise you are going to be in the flat region of the MOSFET and the flat region is my word right. It is actually called the saturation region why I am not going to use saturation is because a lot of you are very comfortable with bipolar junction devices and bjt is unfortunately saturation means the exact opposite of what we want to convey.

So, I am going to call this is the flat region of the MOSFET and flat means that the characteristics is flat over there that is exactly where we want to be great. Now tell me something here I have suppose my devices in the flat region I have said V GS and V DS such that the device is operating in the flat region some V GS and some V DS so, this devices is already in the flat region.

Now, depending on the value of V GS the current from drain to source is going to change depending on the value of V GS I will either be this current or this current or this current or anything in between right. So, what kind of current source is it, is it what is it, what kind of current source is it, it is a what is it a voltage controlled current source; Where the controlling voltage is the voltage between gate and source fine.

Now normally when you have studied VCCS voltage controlled current source you have said that the current is this voltage times some G right. So, that is not really the case over here the current in this case goes by this equation I D equal to K times V GS minus V T the whole square. So, it is not a straightforward relationship it is not I D equal to sum G times V GS right that is not what it is in state it is I D equal to sum K times V GS minus V T the whole squared. So, this is some not linear equation right it is a quadratic equation and it is not as simple as you are circuit theory voltage controlled current source, but still as far as conceptual understanding goes it is still looks like a voltage controlled current source.

There is a voltage it controls the value of the correct and this current happens to be nonlinearly related quadratically related to the voltage between gate and source that that is just fit is this understood so far all right. Now, a little perspective over here in the bipolar junction transistor those who have studied it we are not really going to discuss. But I just want to point out that in the bipolar junction transistor you end up with the current controlled current source and it depends on the base current remember there is a current in the base in the bjt here there is no current the gate does not have any current this is a voltage controlled current source.

Find any questions, all right now what we have going to do is, we are now going to place the MOSFET all right before I place the MOSFET, I am going to generalize a little bit I am going to write I D is equal to sum function of V GS right remember.

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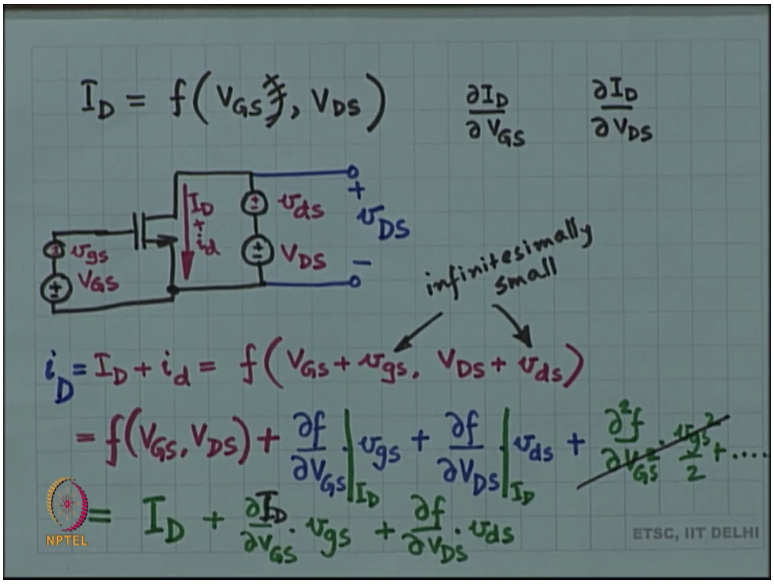

This equation over here I D equal to k times V GS minus V T the whole squared this is model and this model is not necessarily the absolute truth right. In fact, it is not it is just a model it is the model that we are going to use in this course because this is one of the simplest models available ok. So, in general I D is some function of V GS some function it can be quadratic it can be other things also all right.

If I say that this flat region is not absolutely flat there is a slight slope to it right slight slope is there in that case I D is no longer a function only of V GS. It is also a function of V DS it is a very strong function of V GS and a very weak function of V DS, but it is still a function of both V GS and V DS is this all right. What is the slope? Suppose I D is some function of V DS what is the slope over here, the slope is the derivative of I D f with respect to V DS. So, that slope over here is partial derivative so, this slope I am talking about this particular slope right that is the partial derivative of I D with respect to V DS ok.

What is this slope? This slope is partial derivative of I D with respect to V GS thank you ok. Now what we are going to do is, a Taylor series you are comfortable with Taylor series yes. So, we are going to say that suppose so, I had V GS and V DS and now I am going to add a slight small voltage source of value small v sub small d small s in addition to capital V DS and I am going to add small voltage source small v sub small v g small s in addition to capital V GS all right.

And the current over here I am going to call this current has capital I D which was when I had applied V GS and V DS plus small i sub small d. So, the same function of V GS plus a small v gs and V DS plus a small v ds all right and can you do taylor series on this expression. So, f of V GS plus v gs comma V DS plus v ds is equal to f of V GS comma V DS plus partial derivative of f with respect to V GS times small v gs plus partial derivative of f with respect to V DS times small v ds. These are the first order terms and then second order terms, what we are the second order terms lot of other second order terms, second order, third order and then it goes on and on.

If us assume that small v gs is very small and small v ds is very small then these second order terminals do not count ok. So, our examination is going to be that small v gs and small v ds are infinitesimally small. So, let us assume that small v gs small v ds these are very very small quantities and they do not matter the second order higher order terms do not matter as for as the Taylor series is concerned. In which case my derivation over here boils down to f of V GS comma V DS what was that that was nothing, but capital I D plus the slope with respect to V GS let us call it.

So, this is all that we are going to consider all right. So, these two Taylor series us have to be computed at these 2 slopes have to be computed at capital I D ok. So, what does that mean, what it means is as follows what it means is that suppose I have applied capital V GS and capital V DS and for the given value of V GS and V DS, I workout this is to be my point right this is where I am V GS in terms of V GS and in terms of V DS. So, I selects this curve the value of V GS has selected this particular curve and the value of V DS has selected this particular point all right.

Now, I apply and incremental change in V DS and an incremental change in V GS what is going to be the new current. So, the new current is going to be the old current plus something more. So, for that I work out the slope over here and I workout oh sorry correspondingly there is a point over here. So, I workout the slope over here that gives me partial derivative of I D with respect to V DS and I work out the slope over here that gives me partial derivative of I D with respect to V GS. So, these two dou I D by dou V GS dou I D by dou V DS right I compute these two slopes and then I D plus this small i d is nothing, but capital I D plus one slope times the incremental change in voltage v gs plus the other slope times the incremental change in voltage v ds.

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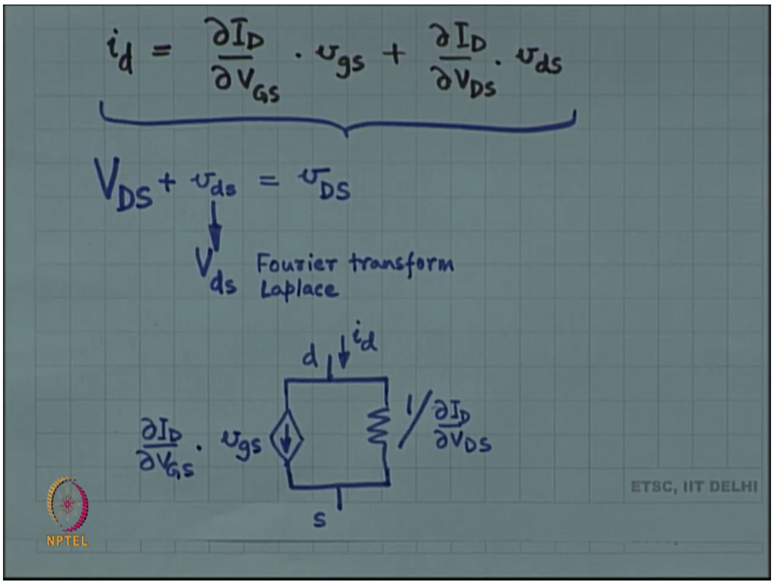

Fine and looking at this I D plus small i d is equal to I D plus some other stuff I D and I D will cancel from both sides and that will imply that small i d is nothing, but one slope time small v gs plus the other slope times small v ds ok. So, few notes about convention So, our convention is going to be that whenever I talk about a capital letter voltage or a capital letter current with a capital subscript.

These voltages or these currents are not going to these are fixed these are fixed voltages and currents, when I talk about a small voltage with a small subscript then that indicates that it is a small incremental voltage riding on top of this big one. This is going to be my convention and then there are two more one is what is the sum of these two and the sum of these two is going to be indicated as a small voltage with capital subscripts.

And the last one which is capital with small subscripts capital with small subscripts is going to be nothing, but the Fourier transform of the small one with small subscripts or Laplace transform whatever is convenient ok. So, these are the four possibilities capital capital, capital small, small small, small capital ok. So, capital capital means it is a fixed quantity, small sub small is an incrementally small voltage or current that is changing with time this is a time domain signal. And if I work out the equivalent frequency domain signal it is capital sub small and the sum of small small with capital capital this is the actual voltage. So, this is small sub capital all right.

So, this voltage and likewise this current I D plus small i d is going to be small i sub capital D fine. So, these are just conventions if you open the books these conventions are add here to normally. So, whenever we are this is just so, that we keep everything clear avoid confusion at all times is this. So far so good all right. So, what have we done so far, we first started with applying two voltages V GS and V DS then I found out that for the given V GS I obtain a certain current I D I pick that value of V GS that value of V DS obtain a certain current I D all right this is what we have done so far.

Then we incrementally changed V DS and V GS if I incrementally change V DS a little wiggle over here means that depending on whether small V DS is positive or negative it is going to move around over here and depending on whether small v gs is positive or negative it is going to move around over there right. So, if I only apply small v ds I keep moving on this curve.

However if I apply small v gs then I move around on this curve which means that I now need to select between other curves depending on the value of the wiggle on V GS ok. A V DS V GS are both moving around then I am not sure I cannot graphically show you exactly what is going to happen, but we know from Taylor series that this is what I will get, I will get a wiggle on the current some extra incremental current and the incremental current is going to come from the Taylor series is going to be one incremental current because of V GS is going to be another incremental current because of V DS.

So, this entire thing this particular equation is modeled in terms of a little circuit. So, what we show is this I D is the sum of two currents small i d is the sum of two currents, one current is one slope times and incremental voltage v gs. So, if this is the drain terminal and this is the source terminal, v gs is not related to the drain and the source terminal. So, this looks like a current source and over here I have v ds times dou I D by dou V DS. So, this looks this looks like a resistor of value 1 by this slope this current source is of value. So, this is what we do let us stop over here and we will continue from here in the next class.

Thank you.