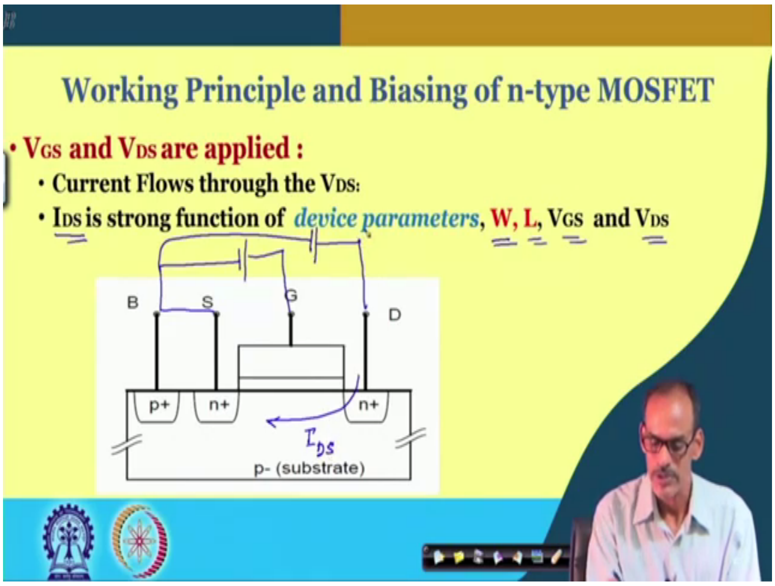
Analog Electronic Circuits
Prof. Pradip Mandal
Department of Electronics and Electrical Communication Engineering
Indian Institute of Technology, Kharagpur

Lecture – 11
Revisiting MOSFET (Contd.)

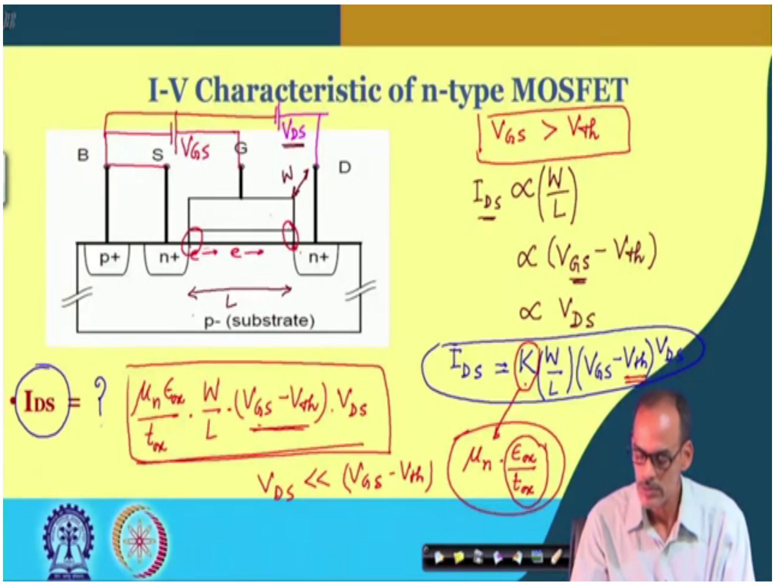
(Refer Slide Time: 00:29)



So, welcome back here again the second part of today's module. What we are looking for it is the expression of the current as function of the Ws and Ls and V GS and V DS. And V GS and V DS of course, they are applied here. And also, just to get an idea that how this current is it depends on the device parameter.

So, in the next slide we will be seeing that how the current while the current it is flowing as I DS how this I DS current it depends on so these parameters.

(Refer Slide Time: 01:12)



So, what will be the expression of this IDS? So, we do have, so this is the big question. First of all let me quickly put the biases. For vertical field we do have V GS here, so that creates vertical field. And let me assume that this V GS it is higher than Vth. So, the first assumption is that this is higher than V th; that means, the channel is existing. And then we apply the other potential, so we do have the V DS which is providing the lateral field.

Then, if you see here I think it is let me go with intuitive way that I DS it is proportional to what? It is proportional to W. In fact, it will be proportional to W by L because if you see here this is the L and this is the orthogonal dimension it is the W. So, if you are having higher length for everything is remaining same it is expected that the resistance here it will increase. So, as a result the corresponding current it will decrease. So, on the other hand if the W is increasing the corresponding resistance it will decrease. So, you may say directly that I DS it is proportional to W by L or you can say that aspect ratio of the channel.

Now, how about the other parameters? So, this will be proportional to the conductivity in the channel regions which is controlled by this V GS minus Vth which means that whatever the excess voltage you do have beyond the threshold voltage that is effectively contributing the to the conductivity or it is helping to increase the conductivity in the channel. So, we can say V GS is, V GS minus Vth it is directly increasing this current. And also we do have the lateral field which is getting produced by V DS, so we can also say that this is proportional to V DS.

So, if I combine all of them, so what we can say here it is I DS it is say proportionality constant say K W by L into V GS minus Vth into V DS, ok. And this K, this K it encapsulates whatever the device parameter is there in fact, this K if you see, if the mobility of the electrons are flowing in this way. So, if the mobility of the electron is higher of course, the current it will be better. So, mobility of the electrons is there. And also the dielectric constant of the oxide epsilon ox divided by t ox. So, intuitively you may say that this represents the capacitance of this structure which is per unit area of course.

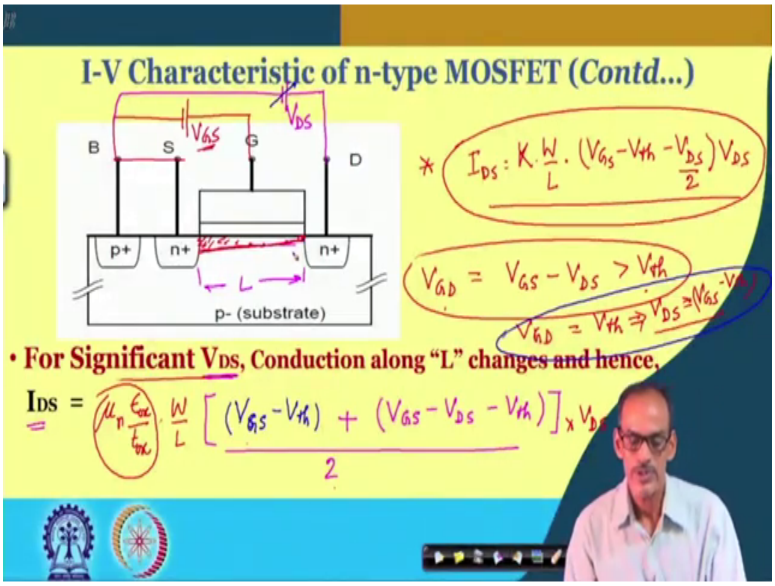
So, for a given supply voltage here the amount of field it is getting created here it directly depends on this epsilon divided by t ox or I should say rather the amount of carrier it will be available it depends on this ratio. So, from that you can say that this K which is basically coming from the device parameter they can be directly written in this form. In addition to that of course, the device parameter is the Vth which is which of course, it depends on whatever the doping concentration is there in the substrate and so and so, but as the circuit designer you may assume that both K is constant Vth is also constant.

So, in summary what you can say that this expression of this I DS it is mu epsilon oxide divided by oxide thickness t ox into W by L into V GS minus Vth into V DS. But one important thing we are missing here it is that, whenever we say that V GS is higher than Vth and whatever the excess amount we have it is contributing for towards the conductivity of the channel, but this is valid probably in this portion. Then if I consider we are applying a voltage

V DS which is say positive, that means, the voltage across this structure it is not same as the V GS here. In fact, that supposed to be V GD which is V GS minus V DS.

So, necessarily the conductivity of the channel towards this drain side and source side they are different. So, this equation it assumes that the V DS is very small compared to V GS minus Vth. And if the V DS is going to be higher and higher or it is significant we need some correction in this equation. So, we are starting with this one with the assumption that V GS is higher than Vth and also we assume that V DS it is much smaller than V GS minus Vth and then only this equation is valid. So, if we increase this V DS let us see what is happening. So, let me go to the probably next slide.

(Refer Slide Time: 08:26)



So, what you are saying here it is the V DS it is significant particularly compared to V GS minus Vth. So, again let me put the quickly put the bias here V GS and we do have the V DS.

So, we do have whatever L and Ws and all these things and as I said that if the length is, so it is sorry, the V DS it is comparable with V GS minus Vth then the conductivity along this length it is changing.

Hence, this I DS its expression as I said need to be rectified or you need to be changed compared to whatever we have derived before. So, we are keeping the device parameter same as mu n then epsilon oxide t ox and W by L those things it is remaining as is, but then the conductivity we need to change. So, let us see: what are the changes we need to make here.

Towards the source side we do have the V GS minus Vth. Whereas, on the on the other side on the other end namely towards the drain side we do have the V GD which is V GS minus V DS minus Vth. So, we need to consider both this part as well as this part and on an average you may say that let me take average of it. So, we just simply add them divided by 2. So, what you are getting here it is we do have.

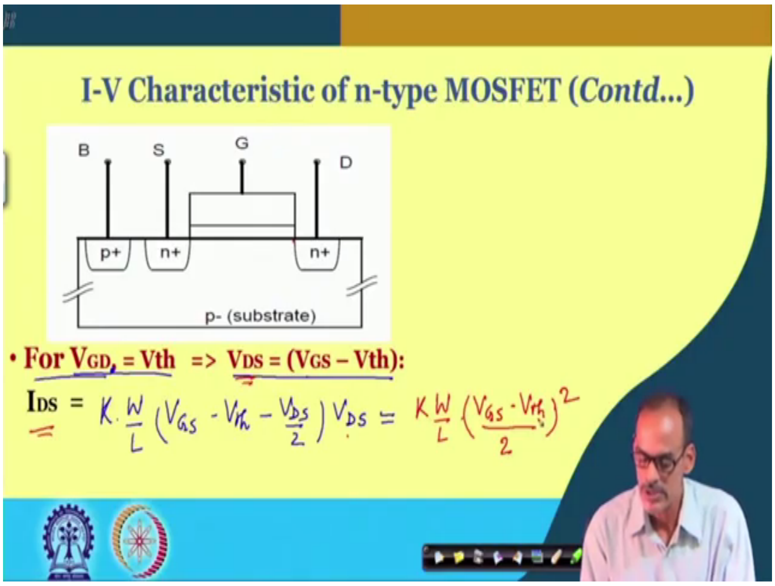
So, then I DS let me write in this space is this part let me let you call this is K and then W by L, and then if you see here we do have two V GS and then two Vth and divide by 2, but then V DS is not there. So, we do have V GS minus Vth minus V DS. And, also along with that this is what it is contributing to the conductivity and then also we do have the V DS appearing as it is providing the lateral field. So, we are applying V DS also. So, we can multiply this by V DS. So, you have V DS by 2 here, this 2 it is coming there.

So, you may say that now the new equation it is like this and this is this is valid as long as V GS minus V DS, it is which is actually V GD it is higher than Vth. So, as long as this is getting satisfied then we can say that the expression of the current is like this. In other words, we can say that the channel is existing here as well as here, but of course, they do have a different strength. So, you may say that the strength of the channel is kind of tapered. So, here it is having strong conductivity, here it is weak.

Now, what happens in a critical situation when we are just making this voltage higher and higher keeping this V GS may be constant and such that the conductivity here it is approaching towards 0, which means that if it is V GD it is exactly is equal to Vth then what happens? In fact, till that point also this equation is valid. So, let me use this equation and let me let me put the condition that V GD equals to Vth or you may say that V DS. So, if I say this is equal, so we can say this is equal to V GS minus Vth. So, then what happens?

So, this is what we will see in the next slide that if we are increasing this V DS and if you are increasing such that this is just at the drain in the conductivity is approaching towards 0.

(Refer Slide Time: 13:37)

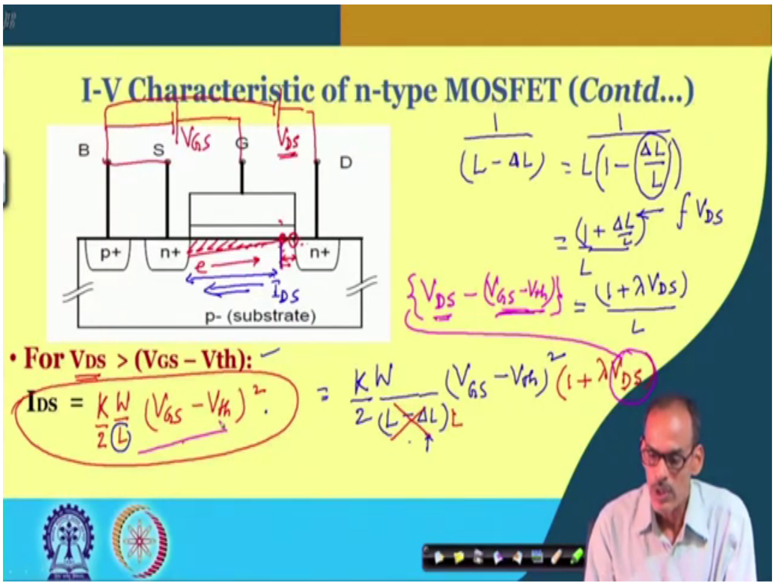


So, so that is what we are saying here that what happens if the V GD equals to Vth sorry this comma should not be there. So, V GD if it is equal to Vth which implies, that V DS is equal to V GS minus Vth and then what we have the current expression is K into W by L and then V GS minus Vth minus V DS by 2 multiplied by V DS. Now, this V DS we can replace by V GS minus Vth, so that gives us the expression here it is K W by L into; so, this portion it is V

GS minus Vth here also we do have V GS minus Vth here we do have divided by 2. So, this portion it becomes V GS minus Vth by 2.

And we do have V DS which is also V GS minus Vth. So, directly you can say this is square. And this is this is what it is happening when at this point the channel is about to disappear. This is referred as something called pinch off will not be going in detail of that, but till this point you may say that this equation of this current is valid. If I take this V DS beyond this point then what happens? So, again let me let you consider this equation in the next slide and then we will see what other things are happening there.

(Refer Slide Time: 15:25)



So, if the in this condition if I take the V DS higher than V GS minus Vth; so, if I consider equal then whatever the equation we do have K into W by L V GS minus Vth square divided by 2. Now, if we exceed this one what is happening is of course, in this portion the channel is disappearing, so obviously, thinks it will be the obvious conclusion or maybe will be having the tendency that we may say that the current is not flowing, right and however, we do have the lateral field V DS.

So, if the current is not flowing then of course, from here to here there is no potential drop. So, then what happens? They will the channel will completely break or what will happen? Practically, what happens is that the channel is here it may be going till some point which may not be really going to the drain end. So, you may say that the point where the channel it is satisfying a condition that the voltage across this structure it is exactly equal to Vth. You may say that till this point or till the left side of this point the channel is existing and beyond this one the channel is not existing.

The natural question is that then how the current is flowing. Of course, there will be a current flow because this voltage major part of the voltage it will appear across a small length or I should say small region of this length and as a result there will be a very strong field. So, you may say that this portion of the device it is working as same as whatever the device we have discussed here where at this age the conductivity is approaching to 0 and whatever the current is flowing here whatever the injection of the carriers are happening that carriers are basically jumping across this injunction from the pinch of point till the age of the drain. As a result you may say that the total current while the electrons are moving in this direction the total current is essentially defined by, so this I DS it will be defined by whatever the current is flowing say through this device and now the device it is getting modified namely its length is getting shortened.

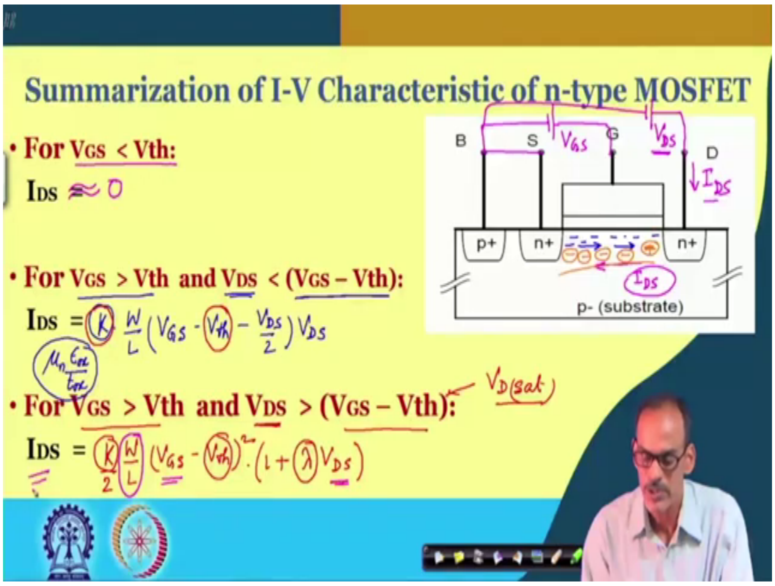
So, you may say that this equation it is again valid even in this condition only thing is that instead of L I will be having shorter length. So, let me write that we do have K W and also 2 here and then L minus shrinkage of the length say delta L, rest of the things it is remaining same. So, V GS minus Vth square; so, then you may say that I do have delta L and how do I express from outside. Of course, this delta L it is getting created by this V DS. So, naturally this delta L it is a function of V DS.

So, we may write this L minus del L as like this, you can L take you can take the L outside, you can make it 1 minus del L divided by L in the denominator and then if you take, so that is the denominator part and then if you take in the numerator what you can say it is 1 by L is remaining there if I assume that this part it is very small compared to 1, so by Taylor series expansion you may take it only one part of it. Let me say that 1 plus del L divided by L. And this del L part it is a strong function of V DS. Since this portion is very small again it is normal it is considered as 1 plus lambda into V DS divided by L.

So, you may say that this part this part it is getting replaced by this. In other words we may say that instead of this one let me directly write L here and let me put this factor 1 plus lambda into V DS. In fact, this is what the equation normally we frequently use and the condition here is of course, the device it is in this region referred as saturation region will be discussing that pretty shown. But please make a note that going from this point to this point it is having some discontinuity if you carefully look into the equation instead of writing this V DS I should have written this is V DS minus whatever the limiting value and then only there will be continuity of then only we will be having continuity of the equation from the previous region to this region.

However, most of the time we considered that this part it is may be small compared to V DS, so we do approximate this whole thing by lambda into V DS. And, if you see that this is the limiting value of the V DS up to which it was having different kind of behavior and if you go beyond this one, the characteristic it is all of a sudden it is having a change. So, we will see that these two regions are having distinct behavior. So, we will be looking into that in detail while will be comparing this characteristic in the across the two regions of operation in the subsequent slides.

(Refer Slide Time: 22:17)



So, if we summarize what we said is that the device characteristic it is, it can be said it is having different regions of operation. Again quickly we do have the V GS here and we do have the V DS here. So, that is producing rather that is V GS is generating the channels, the electrons are moving in these directions and the consequence is that the current is flowing in this direction.

Note that the channel is basically getting created by the electron layers and of course, along with the electron layers we do have the static ions. Those static ions are working as depletion region beyond the channel region, but they do not participate for the current flow, so current is basically carried by the electrons.

Anyway, so the I DS while this I DS is flowing here from terminal side we will see this is the I DS. So, as circuit designer we may not be knowing what other things are happening internally, but from the terminal what we can say that some current is flowing and that current is coming back here, and this current is getting produced by the combination of V DS and V GS. So, let us see for this I-V characteristic for different conditions of these voltages and let me summarize that.

First of all if the V GS is less than V th, so we assume that this channel it is almost very weak and you may say that instead of saying equal we may say approximately equal to 0. On the other hand, when the V GS is higher than Vth and then we are applying V DS is positive, but it is less than this critical voltage, we may say that it is less than the V GS minus Vth which means that even at the drain side we do have the channel may be the channel is stronger here may be here it is weaker.

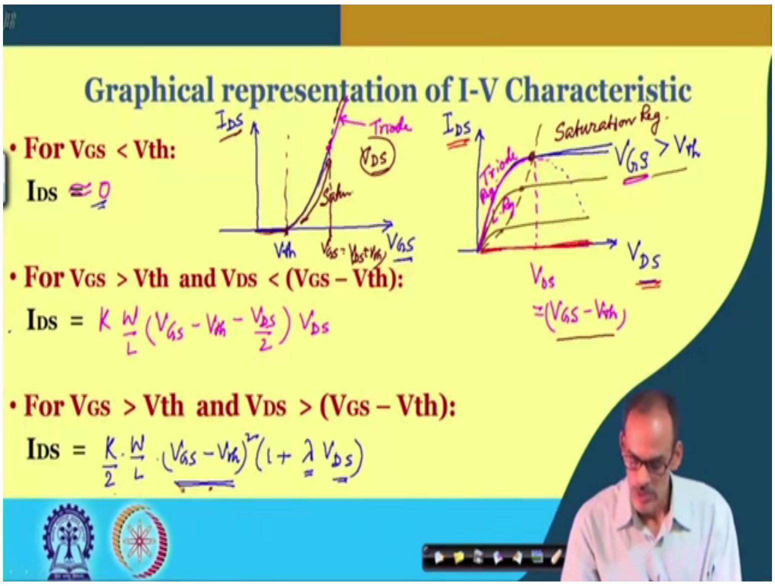
But finally, finally, we do have the channel is spreading across the length and with that condition we may say that the current here it is K W by L V GS minus Vth minus V DS by 2 multiplied by V DS. And of course, this K it is having its own internal device parameter, namely mobility then dielectric constant of the oxide, thickness of the oxide. On the other hand, if the V GS is say higher than Vth however, V DS is higher than V GS minus Vth in fact; this is referred as V D sat.

Of course, this is this is not constant it depends on the V GS sometimes it is referred as V D sat we will see that why it is called V D sat, but whatever it is if the V DS is beyond this one indicating that pinch off already happened towards the near the drain end and the current it is it hardly depends on V DS and the corresponding expression of the current it is K into W by L into V GS minus Vth square by 2 and in addition to that we do have 1 plus lambda into V DS, ok.

So, ideally as I say that I should have written V DS minus V D sat, but all practical purposes most of the time we write V DS. So, this is what the overall I-V characteristic equation of the transistor and if you see here what are the parameters we do have a device parameter, of course, this is one device parameter and then we can say this is also device parameter and also we do have device parameter here. So, these are basically device parameters. The rest of the things are the voltages and the device dimensions.

And as I said that for board level design if the device it is already implemented which means that W and L of the device it is already implemented, then as a circuit designer will be having flexibility to change this V GS and V DS to get a meaningful current flow. So, that is the I-V characteristic. Now, let us look into if I combine all these equations if we consider the graphical interpretation of the this I-V characteristic and the next slide, so let us see the graphical interpretation of that.

(Refer Slide Time: 28:14)



First of all under this condition as I said this current is approximately 0, this is K into W by L quickly, K into W by L V GS minus Vth minus V DS by 2 into V DS and then here we do have K into W by L divided by 2 V GS minus Vth squared into 1 plus lambda into V DS. So, if you plot this current I DS as function of V GS and V DS what you can see here, this is of course, it is 0. So, now if we consider this region so probably you can consider two cases. So, let me keep the V GS constant and then let you observe I DS as function of V DS and assuming this V GS is constant, but higher than Vth.

So, this equation indicates that V DS is appearing here in square form and in fact, it is parabolic relationship. So, if the V DS it is small and if it is smaller than V GS minus Vth then you may say that it is going like a parabolic way. So, this is the equation, I should use the other color to represent this characteristic curve. So, this equation it is getting reflected here. But then this equation is valid till this point where V DS equals to V GS minus Vth and if you go beyond this point the current it hardly depends on V DS in fact.

Typically, this lambda is very small, so you may say that if I ignore this part the current supposed to be remaining constant. And, if I consider some small that the actual value of the lambda it may be having slight slopey kind of things which means that this change is representing the effect of this lambda which is referred as channel length modulation affect. The channel length is getting modulated by V DS; in fact, this is similar to base width modulation of the BJT we have considered.

So, if you see here the different regions of operation from this point beyond the current is getting saturated. So, here we may say that this is saturation region. So, saturation region of operation and before that it is referred as triode region, triode region. Because the current depends on both V GS and V DS sometimes it is also referred as linear, particularly if you see this portion the device behaves like a linear, so either we may say it is triode region or linear region.

Now, this is for a given value of the V GS. Now, if I change this V GS to some other value of course, this point it will be changing. So, if I decrease this V GS, but still maintaining this is higher than Vth we may get lower current and the corresponding current profile it will be like this and so and so. So, the boundary between saturation and triode region; however, for smaller value of this V GS it will come down like this.

So, you may say that the boundary between this linear and saturation region it is having like this equation. In fact, this is a quadratic equation. We will see that what is why it is really a quadratic equation. If you make this V GS smaller and smaller in fact if we take it further down. So, what it will happen is that current it will be almost getting 0; that means, the corresponding characteristic it will be coinciding with V DS line. So, this characteristic it is referred as I DS versus V DS characteristic.

Now, if you see say this equation, in fact, you can try to plot the I DS versus V GS also for a given value of V DS. To start with let me consider the device it is in for a given value of V DS. So, if I increase the V GS beyond Vth then only the current it will flow, but before that the current is approximately 0. And if you if you are increasing this current sorry, if you are increasing this V GS keeping the V DS constant and then you may say that the device starts from this region or saturation region and hence the dependency it is like a quadratic.

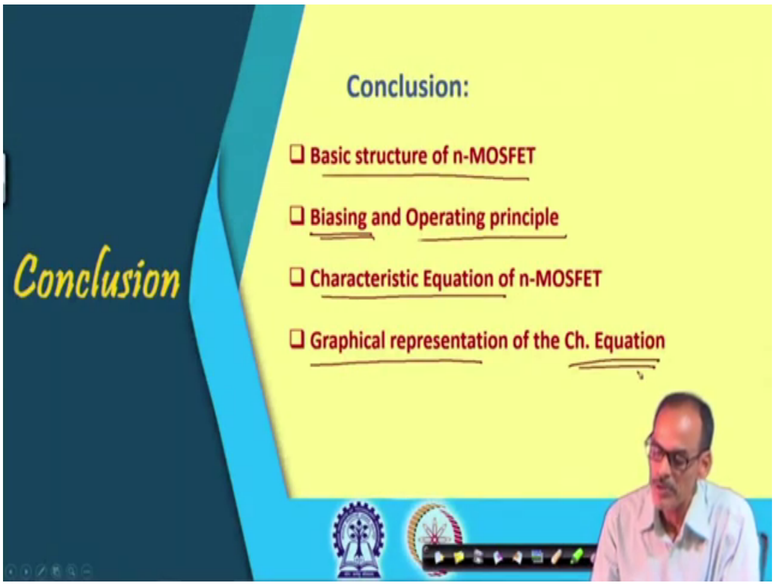
And, if you go beyond some point where probably we are satisfying rather this condition instead of this one and the device instead of really going like this it will bifurcate from that and it may continue to be like a linear one. So, from this point onwards the device enters into triode region or linear region. And before this point the device it was in saturation region. So, here the device it is in saturation region.

So, this is happening for a given value of V DS. So, which means that this point it is at this point the V DS equal to V GS minus Vth or rather you may say that V GS equals to V DS plus Vth, right. So, naturally if I increase this V DS, I will be getting another characteristic curve where this bifurcation it will be probably starting beyond this point and so and so. So, normally these changes we can hardly see. So, in most of the textbook it says that, this is quadratic equation.

Note that this till this point the current is 0, only the current is flowing beyond this one and the boundary of between this triode and saturation region it is nothing, but this portion because this character the boundary point it is nothing, but the V GS minus Vth curve. So, you may say that triode and saturation boundary is nothing, but this profile and this profile it is obtained from this equation where I DS is basically proportional to V GS minus V th square. So, that is about the graphical representation.

So, let us see: what are the things we have covered today or rather so far we have discussed in this topic.

(Refer Slide Time: 36:46)



We have discussed the basic structure of the n-MOSFET, and then we also have discussed about the operating principle of the circuit for different biasing situation. And, then we have discussed about the I I-V characteristic of the MOSFET, and then we have discussed about the graphical representation of the I-V characteristic equation.

Note that, whatever the equation we have obtained here it is not having really a diode kind of equation, but we will be having a tendency to utilize those characteristic equation to represent in the form of you know equivalent circuit. So, later we will see that how those equation can be used to represent the device by means of electrical circuit modules. So, that will be discussed in detail whenever will be going to actual circuit containing MOSFET.

So, in the next module, similar discussion it will be there as we have discussed today, but then for PMOS transistor. I think that is all today.

Thank you for listening.