Physics of Nanoscale Devices
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Lecture - 39
MOSFET IV Characteristics-I

Hello everyone, today we will discuss the MOSFET I-V Characteristics continuing our previous discussion and as you might remember that we have discussed how MOSFET is a barrier control device and the barrier is the barrier for electrons in the energy landscape in the channel. So, that barrier is controlled by the gate voltage and the drain voltage and by manipulating that barrier we can control the current in the MOSFET. So, that is a very qualitative picture of the MOSFET.

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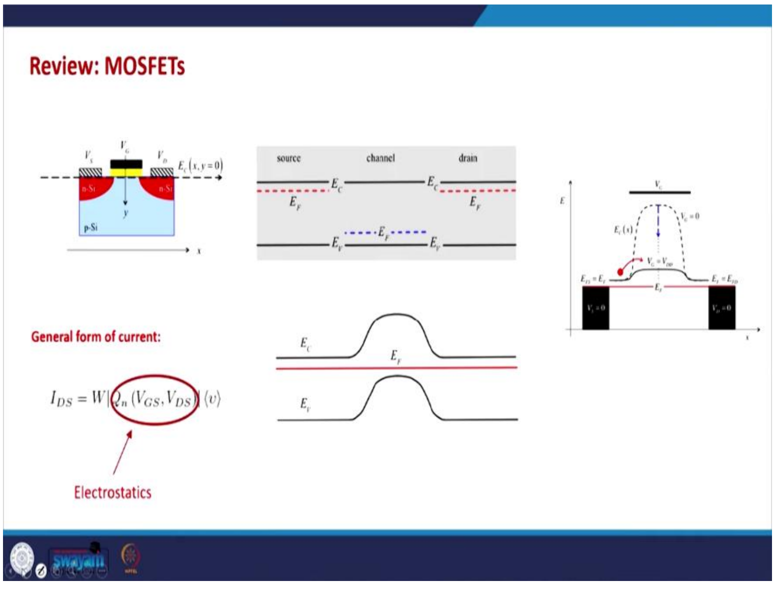

And today we will see how the I-V characteristics is derived or how it looks like, before going into the that detail lets quickly review what we have seen so far.

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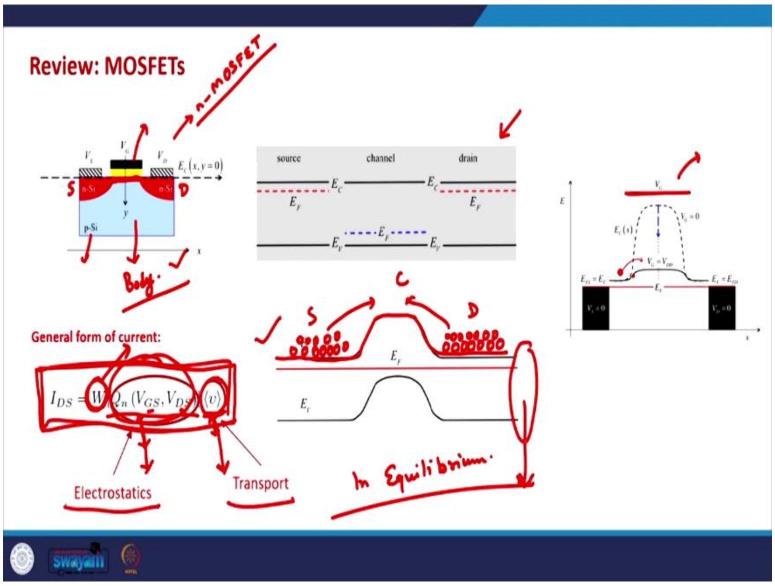

So, this is a typical MOSFET device a MOSFET transistor device, this is n MOSFET which means that the channel or the conducting part of the MOSFET is an n type channel that is formed between two contacts the source and the drain contacts. And everything is sitting on the substrate or body and generally this is a p type semiconductor.

So, when we apply a positive voltage on the gate terminal it basically creates an inversion layer here and that essentially creates a conducting pathway from the source to the drain. So, that is how a MOSFET, a transistor essentially looks like and that is how this conduction in the transistor takes place. If we go to the energy landscape this is how the energy band diagrams of source channel and drain look like when it is assumed that they are not joined.

When we join the source the drain and the channel this is how it looks like and as you can see in equilibrium. So, this is the equilibrium picture and in equilibrium there is a barrier in the channel for electrons to cross from the source or the drain and if we do not apply any drain voltage the barrier for electrons from the source side. So, there are some electrons sitting here because this is n type material the source is n type material.

Similarly, some electrons are sitting here because the drain is also an n type material and if there is no drain voltage the barrier for the source electrons and the barrier for the drain electrons is the same and the probability of the source electrons crossing to the drain side and the probability of drain electrons crossing to the source side is the same essentially.

If we apply a drain voltage the bands on the drain side go down and a barrier asymmetry is created in the device and that is essentially responsible for creating an equal probability distribution for electrons to cross from the source side, as compared to the probability for electrons to cross from the drain side ok.

So, this barrier height; however, is controlled by the gate voltage, as is visible here if we apply a positive voltage this barrier goes down and the probability of electrons crossing the barrier essentially increases.

And if this V_G is negative this barrier height is further increased and the current is further diminished. So, that is essentially what we have seen and also we saw that the drain current in a very general form without sort of assuming anything this can be written as the product of the charge in the channel and the velocity at which this charge is moving through the channel. Note if of course, multiplied by the width of the channel this is the charge density, this is the velocity at which the charge is moving and this is the width.

And the product of these three will give us the current in the channel. So, the charge depends on V_{GS} V_{DS} velocity is actually governed by the scattering in the channel, which means the channel length the electric field in the channel which is because of the electric field is because of the drain voltage or the or in also in some cases the gate voltage.

So, what I highlighted was that this velocity part actually comes from the transport theory of electrons and this charge part actually comes from the electrostatics theory of electrostatics in MOSFETs.

So, that is why if we understand the electrostatics and transport we can understand the entire physics of the MOSFETs and that is essentially what we will be trying to do in this in further few classes in coming few classes.

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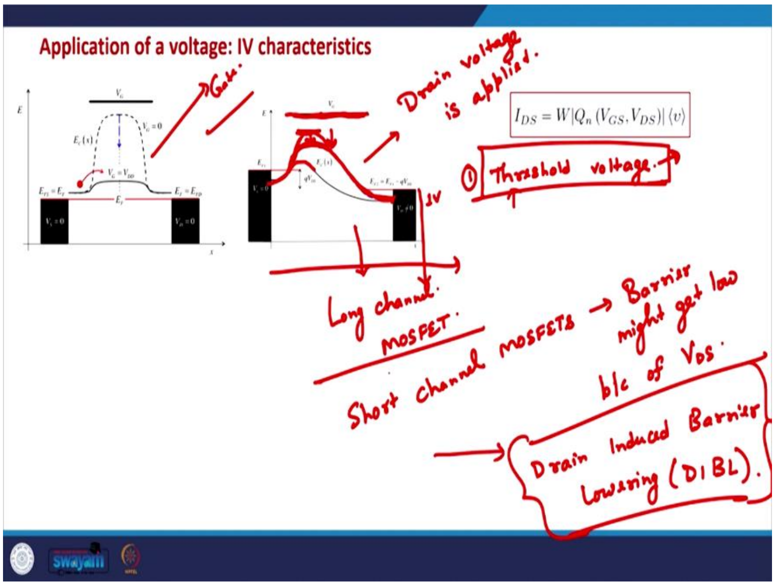

This is the MOSFET barrier when the drain voltage is applied; this is the barrier when drain voltage is applied, this is the barrier when gate voltage is applied ok. So, we also defined a quantity called the threshold voltage.

So, the threshold voltage is the gate voltage at which the charge essentially starts to or the conducting channel starts to appear in the MOSFET. So, this is the voltage after which the conduction can take place through the channel from. So, the electrons can conduct from the source to the drain via channel once the gate voltage is above the threshold voltage in n MOSFET.

So, this is an important quantity and this is one of the main characteristics or one of the main important part or one of the main parameters in MOSFETs theory. We also saw that if we apply a drain voltage it generally does not change the barrier height. So, what it does is that it brings down the energy bands on the drain side which creates a slope or a longer slope from the top of the barrier to the drain side and if we apply a gate voltage. So, this is when gate voltage is 0, this is when gate voltage is positive. So, this is the case in long channel MOSFETs.

So, in long channel MOSFETs the application of drain voltage does not change the barrier height in the channel ok. But in modern MOSFETs in especially in sub micrometer MOSFETs when the channel length is short in that case what happens is if for example, one volt is applied on the drain side the electric field in the channel is so high, that even this barrier is reduced or the electric field can impact even the barrier up to the source side actually. So, this barrier is somehow reduced because of the voltage on the drain terminal which produces high electric field in short channel MOSFETs.

So, in short channel MOSFETs what can happen is that the barrier might get low, because of the drain voltage V DS and this is not what we generally expect in MOSFETs actually this is not what we design our MOSFETs to do. Our design basically dictates that it desires that this barrier height should be controlled by the gate voltage and the electric field in the channel in this direction x direction should be dictated by the drain voltage ok.

But in short channel MOSFETs it might happen that this barrier height even this barrier height is reduced by the drain voltage and this phenomenon is known as the Drain Induced Barrier Lowering. So, or in short it is known as the DIBL ok. So, this is what we what is common in short channel MOSFETs although we would not like this to happen, but this can happen if the design considerations are not properly taken care of ok.

So, we know what is the threshold voltage at least qualitatively we also know what is the drain induced battery lowering. Now, let us see how the I-V characteristics of the MOSFET look like and before going into the I-V characteristics.

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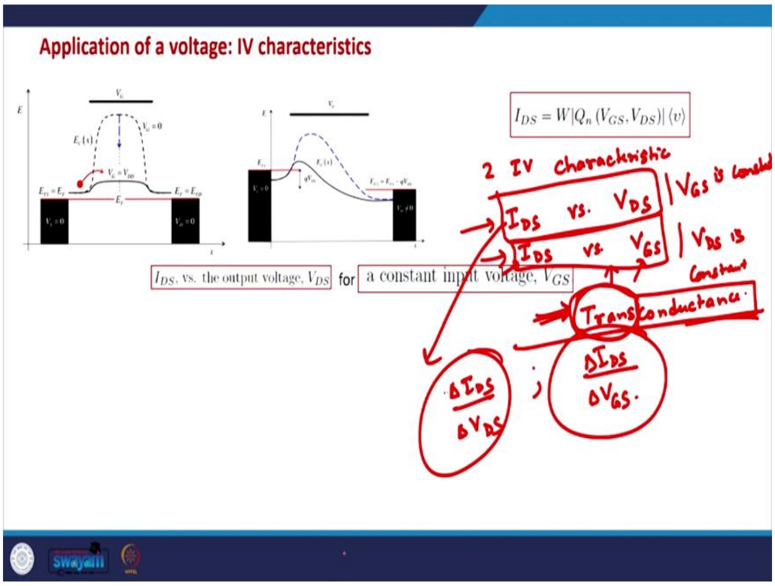

Let me just quickly point it out to you that the I-V characteristics there are 2 kind of I-V characteristics 2 kind of current voltage characteristics in MOSFETs 1 is I_{DS} versus V_{DS}.

Current as a function of the drain voltage and second is I_{DS} versus V_{GS}, the current as a function of gate voltage when V_{DS} is constant and this the first characteristics I_{DS} versus V_{DS} is when V_{GS} is constant ok. So, this I_{DS} versus V_{DS} is known as the output characteristics of the MOSFET and I_{DS} versus V_{GS} is known as the transfer characteristics of the MOSFET. It is as if or it is as if we are trying to understand how this current is related to the voltage applied on the 3rd terminal, which is not the direct terminal .

So, this is not the terminal through which the current flows the current flows between the source and the drain. So, if we are trying to plot I_{DS} versus V_{GS} it means that we are trying to understand the impact of the V_{GS} impact of the third terminal and that is why it is also known as the transfer characteristics. It essentially encodes the transconductance of the MOSFET, what is known as the transconductance the impact of the voltage applied on the third terminal or the controlling terminal.

It is not that typical conductance because we are not considering the voltage applied on the same terminals as through which the current is flowing. So, the conductance is $\frac{\Delta I_{DS}}{\Delta V_{DS}}$ and the trans conductance is $\frac{\Delta I_{DS}}{\Delta V_{GS}}$ ok. Actually the name just to sort of highlight this name transistor also has a correlation with this how this effect of the gate voltage is transferred to the channel.

So, the name transistor has its roots from that action from the action of the gate voltage on the channel actually. So, that is why it is also known as the transconductance and the characteristics is known as the transfer characteristics. Now, the MOSFET characteristics MOSFET I-V characteristics is an interesting one.

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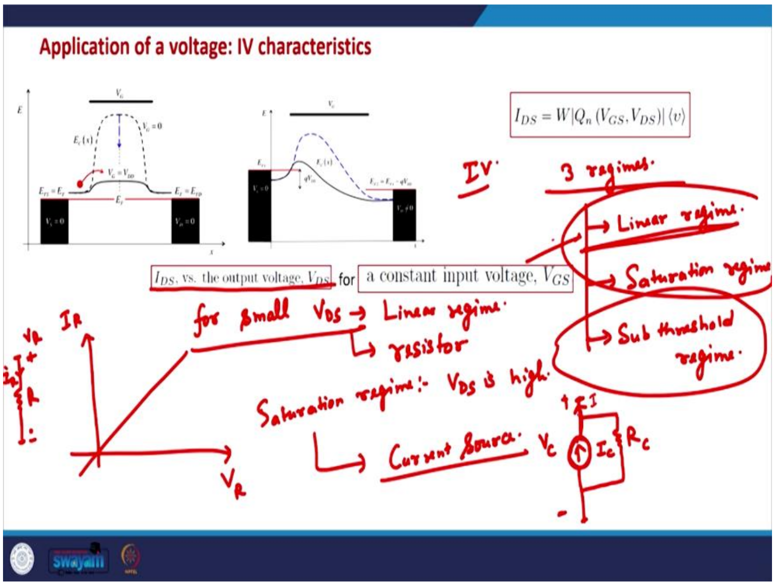

And it can be sort of broken down in 2 parts broadly 2 parts although there are 3 regimes one is in the I-V characteristics there are 3 regimes.

One is the Linear regime, second is the Saturation regime and the third one is known as the Sub threshold regime. So, this we will come a little bit later. So, this I-V characteristics has 2 interesting regimes I would say at the moment let us consider just linear regime and the saturation regime and at the moment we are trying to understand I_{DS} versus V_{DS}. So, for small V_{DS} when the V_{DS} is small the regime is known as the linear regime and the MOSFET behaves as if as a resistor ok.

And how does the I-V characteristics of a resistance resistor looks like. So, if this is the current through the resistor this is the voltage applied across, the resistor this is a typical resistor R if we are applying a voltage across this to be V_R and the current that is flowing is I_R then this will be a linear relationship and the slope is given by the resistance of the device ok.

So, the I-V characteristics of a resistance is a linear one ok and that is how the I-V characteristics of the MOSFET look like in linear regime which is the small V_{DS}. So, for small V_{DS} the MOSFET behaves as if like a resistor. So, in this discussion in this course we are not discussing the MOSFET in a conventional way, the way in which it is discussed in an introductory course. So, a little bit of a background is assumed, but even if you do not have any background you can actually pick it build from these.

But it will be good if you have a basic understanding of the MOSFET in that case it will be easier for you to appreciate all the things that is being discussed here ok. So, in the linear regime for the small V_{DS} the I_{DS} is I_{DS} is a linear characteristics, in the saturation regime the saturation regime is the regime where V_{DS} is a bit high in that case the MOSFET acts like a current source.

And what is a current source, current source is an electronic component or an electronic system that gives constant current irrespective of the voltage applied across it. So, a current source typically looks like this ok. So, if this is having a current I_C this I_C will be independent of any voltage that is applied across this current source I_C.

So, this is the ideal current source, but practically the current source is most of the practical current sources can be approximated by this circuit in which there is an ideal current source and there is resistance in parallel to the current source. In that case this voltage and the current have this kind of characteristics.

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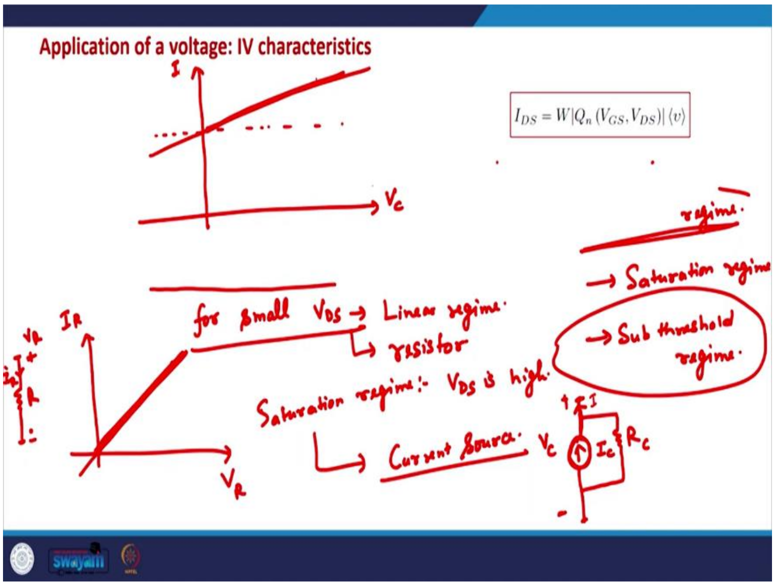

Let me just plot it the current I versus V_C, where V_C is the voltage across the current source I is the current an ideal current source will have characteristics like this, the current will be independent of the voltage applied across it. But a practical current source will have the I-V characteristics that looks something like this.

So, it will be this is the ideal case. So, it will be as slight deviation from the ideal case ok. So, for small V_{DS} this is how I_{DS} versus V_{DS} look like, this is like a resistor for larger V_{DS} in saturation regime this is how I_{DS} versus V_{DS} look like.

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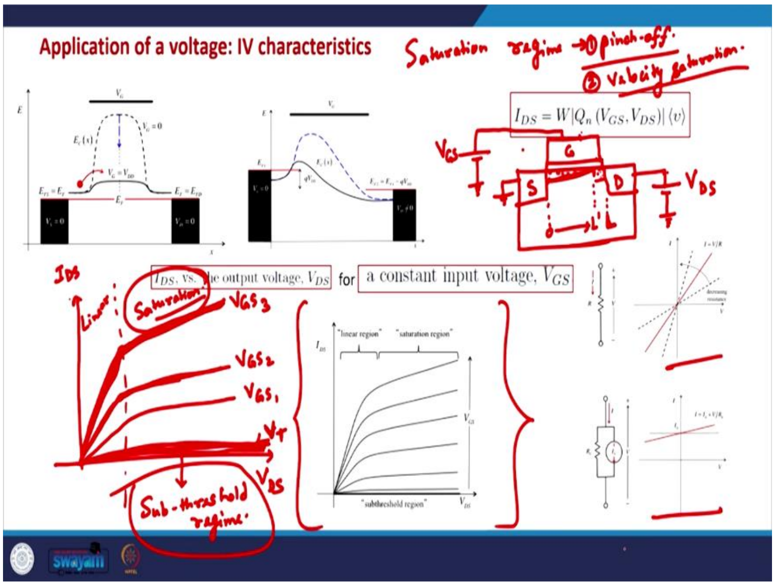

So, if we put everything together this is the resistor characteristics, this is the current source characteristics and if we put everything together this is how the I_{DS} versus V_{DS} the I-V characteristics of the MOSFET will look like.

So, if we have I_{DS} on y axis V_{DS} on the x axis it will be a typical I_{DS} -V_{DS} characteristics for a certain V_G, for small V_{DS} values it will be a linear 1 and for as soon as the I_{DS} becomes large it behaves as if like a current source this way. So, for different V_{GS} values this will be a different plot and when V_{GS} is smaller than the threshold voltage in that case there is not enough charge in the channel to conduct and in that case this current is extremely small. So, the current typically looks like this.

So, that is the case when V_{GS} is less than the V_{TH}, so that is less than V_{TH}. So, this is V_{GS1} this is V_{GS2} and this is let us say V_{GS3}. So, this regime in which the I V characteristic the output characteristics of the MOSFET looks like, a resistor characteristics this is known as the linear regime and the regime in which it does not increase as fast as the voltage increases it almost saturates. Although it does not saturate completely this region is known as the saturation regime ok.

And similarly the regime when V_{GS} is less than V_T and there is not enough charge in the channel to conduct the current in that case also there is a very small current. If we apply a drain voltage and that extremely small current falls in this third regime which is known as the sub threshold regime. So, these are the 3 regimes of current I V characteristics of the output current output characteristics linear regime saturation regime and the sub threshold regime ok.

Please try to note that this sub threshold regime is the regime in which practically the MOSFET is off it is not switched on it is off. But there is a very small current that is flowing through the channel and that is known as the sub threshold regime. So, this regime is also quite important in order to understand the MOSFET characteristics, because it tells us how it or it tells us how much voltage on the gate do we need to apply in order to switch it on in order to switch on the MOSFET ok.

Similarly, the linear region is the region when the gate voltage is above the threshold voltage, but the drain voltage is small. And the saturation regime is the regime, in which the gate voltage is above the threshold voltage, but the drain voltage is also large and the current does not increase as fast as it was increasing in the linear regime and there are many reasons of saturation regime to appear. So, typically in long channel MOSFETs the saturation regime this saturation regime appears because of the pinch off.

So, this we briefly discussed in the last class. So, this is the phenomenon when so for example, if we have applied a gate voltage and there is a channel through the MOSFET and if we have started applying the drain voltage also. So, let us say this is our MOSFET this is the source this is the drain and this is the gate. So, there is a small channel which is because of the V_{GS} voltage. So, let us say this S is grounded, so this is V_{GS} and there is some voltage on drain side as well which is the V_{DS}.

So, we have a constant V_{GS} on the gate terminal as soon as this V_{DS} is increasing the difference between the voltage on the gate terminal and the voltage on the drain side of the channel is reducing. If this V_{DS} is increasing in that case this difference between the V_{GS} and the V_{DS} is reducing if V_{DS} is increasing, it means that the net voltage felt by the channel on the drain side is now less and because of that this channel starts disappearing on the drain side and that phenomenon is known as the pinch off in the MOSFETs in the classical MOSFETs.

So, that is one of the reasons of saturation. So, in the pinch of the channel will look something like this there will be a channel from the source to the to a certain point. Let us say this L’ if the total length of the channel is L this is 0, there will be a inversion layer there will be a conducting channel from 0 to L’. But there will not be a conducting channel from L’ to L and there will be a depletion region here.

So, since it is a depletion region, so while the current is flowing through the MOSFET any electrons that are coming from the source side they will be quickly taken by the drain terminal as well because of the electric field in the depletion region. And that is why after a certain medias this pinch off starts appearing and if V_{DS} is increased this pinch off regime is also increased and that essentially shrinks the channel to an extent and that is why this current starts saturating.

So, that is the reason of saturation current in long channel or conventional MOSFETs. In short channel MOSFETs; however there might be a different reason as well and that is known as the velocity saturation. So, the first reason of saturation is pinch off second regime of second reason of the saturation might be velocity saturation. I guess most of us would know that in semiconductors

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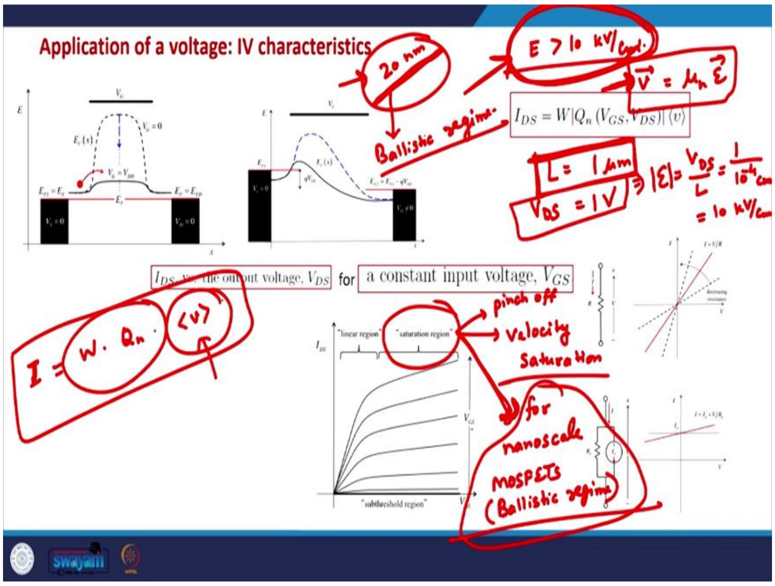

Typically if the electric field is more than 10 kilo volt per centimeter then the velocity starts saturating, because if you know there is a relationship between velocity of electrons and the electric field. So, according to this relationship the velocity should increase as a function of E, but because of the scattering in the channel because of the scattering in the semiconductors after this value typically after this range of electric field the velocity does not increase linearly with electric field it starts saturating ok.

And in MOSFETs if we see that if the channel length of the MOSFET is 1 micrometer and if the V_{DS} that we are applying is around 1 volt in that case the order of the electric field in the channel will V_{DS} by L the electric field will be 1 divided by 10 to the power minus 4 centimeter; which will be around 10 kilo volt per centimeter. So, this kind of electric field is easily generated when the channel length starts going below 1 micrometer and the applied voltage is around 1 volt.

So, in sub micrometer MOSFETs the velocity or the electric field may be well above kilovolt per centimeter and generally in MOSFETs. Where the channel length is 20 nanometer or 40 nanometers in that case it is extremely high as compared to this electric field 10 kilovolt per centimeter and in that case we can expect that this velocity of the electrons will saturate and because of the velocity saturation as you can see that the current is given by I is equal to W times Qn times <v>.

So, this velocity saturates this current will also be saturating given everything else is constant ok. So, these are two reasons of saturation one is the pinch off and second is velocity saturation. But there is an interesting advanced point here in very small channel MOSFETs when the MOSFET channel length is around 20 nanometers or so. So for example, if the MOSFET channel length is 100 nanometer or 500 nanometer around 1 micrometer in that case this velocity saturation argument will hold.

1 micrometer or 0.5 micrometer in that case this velocity saturation argument will hold. But if the MOSFET channel length is around 20 nanometer in that case what happens is that now the scattering of electrons is very low, because this is the ballistic regime this is the ballistic regime of operation. So, the electrons directly go from the source side to the drain side they do not collide with anybody in the channel.

So, this velocity saturation which is appearing because of the electronic collision with other particles atoms in the channel this will not happen. So, in extremely small in channels of this order of length 20 nanometers or so, the velocity saturation will not take place. And it seems that even if this velocity is not saturated even in that case this saturation region appears in the I-V characteristics ok.

So, there is a third factor or there might be a third reason of saturation for nano scale MOSFETs or in Ballistic regime that is not due to either pinch off or the velocity saturation. And that is what we will see while we discuss the transport theory of MOSFETs; we will try to see why the velocity or why the current saturates even if the velocity does not saturate velocity of electrons does not saturate ok.

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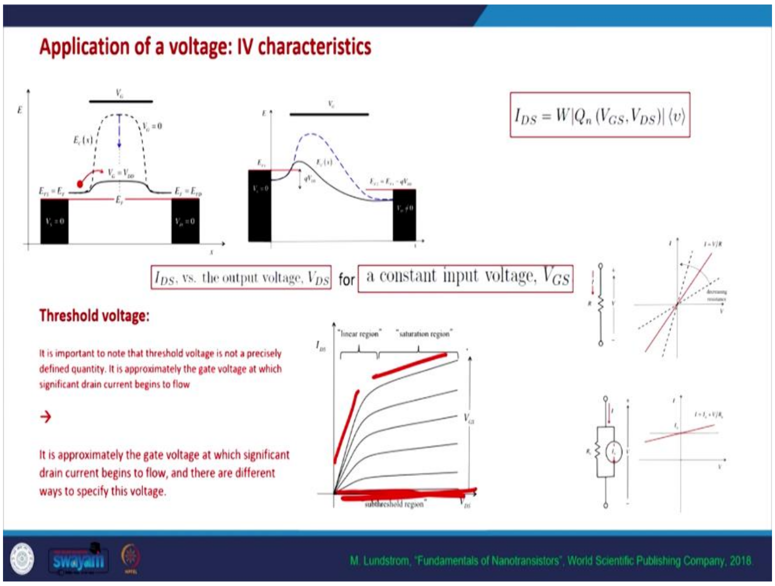

So with this , now we have the I-V characteristics of the MOSFET and this is the output characteristics I_{DS} versus V_{DS} we have the linear region, we have the saturation region and we have a sub threshold region. All these 3 regions are extremely important while trying to understand the MOSFETs and that is what we will try to elaborate in the coming class ok.

So, I would again advise you to go back and read a little bit of conventional MOSFET theory. So, that all these discussions make more sense, although as I said that is not required I will try to make things as comprehensive as possible ok. So, that is all for today's class.

Thank you for your attention, see you in the next class.