Physics of Nanoscale Devices
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Lecture - 40
MOSFET IV Characteristics-II

Hello everyone, today in this lecture we will continue our discussion on MOSFET I-V Characteristics.

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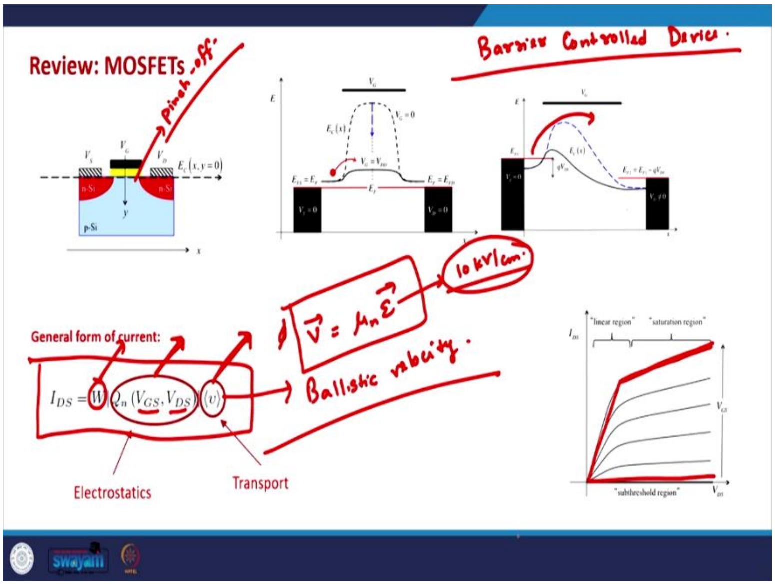

And in the previous lecture if you recall, we have seen how we can understand the I-V characteristics of the MOSFET. And we discussed that there are three important regimes in MOSFET I-V characteristics; one is the linear region, second is the saturation region, and third is the sub threshold region ok. So, and all this can also be understood from the band diagram picture of the MOSFET in which the MOSFET is or MOSFET looks like a barrier control device.

So, if we draw the band diagram of the MOSFET across the channel, the MOSFET looks like a barrier controlled device. And the barrier in the channel can be controlled in this way; so, the gate voltage essentially lowers the barrier or increases the barrier, the drain voltage allows electrons from the source side to cross the barrier and start a current in the system.

So, that is how it looks like and we also have seen in our previous discussions that the general form of the current can be written down in this way where the current is a product of the charge in the channel. The charge density charge per unit area times the average velocity at which this charge is moving through the channel and multiplied by the width of the channel.

So, these three things essentially, out of this W is geometric dependent we can change it by changing the dimension of the transistor. This Q_n depends on the electrostatics, this Q_n is actually governed by the electrostatics of the MOSFET which in turn depends on the gate voltage and the drain voltage.

And this velocity in long channel MOSFETs this velocity the velocity of any charged particle is given as this, in short channel MOSFET this will be a ballistic velocity ok. So, in the long channel MOSFET this velocity is dependent on the is velocity is also a factor of the scattering that is happening in the channel and it is directly proportional to the electric field.

But what happens is as soon as this electric field becomes too high electric field in the channel is around of the order of 10 kilovolt per centimeter in that case the velocity is no longer linearly dependent on the electric field and the velocity starts saturating after this value of the typically after this value of the electric field. And that phenomenon is known as the velocity saturation and that is one of the contributors of saturation current in the output characteristics of the MOSFET. The second contributor is the pinch off in the channel because of the high drain voltage ok.

In ballistic MOSFETs; however, the velocity does not saturate even then the current saturates and we will try to see how or we will try to understand how that happens later on while we discuss the transport theory in nano MOSFETs ok. So, this is the background or this is sort of what we have seen so far.

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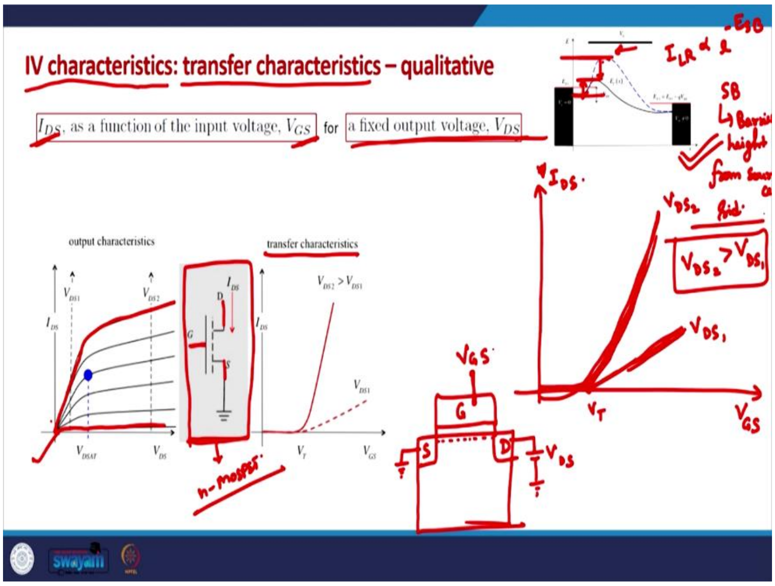

So, let us see; so, we have gone through the output characteristics of the MOSFET. The second important I-V characteristic of the MOSFET is the transfer characteristics. And we will have a qualitative understanding at the moment later on we will also see the quantitative treatment of I-V characteristics, especially the output characteristics ok.

So, the transfer characteristics as we have seen in the last class is the dependence of I_{DS} on V_{GS} for a fixed voltage for a fixed V_{DS} essentially. And the idea of this we can take or this the transfer characteristics in some way we can also deduce it from the output characteristics. So, this is the barrier structure in the MOSFET and effect of drain and gate voltage on the barrier; the gate voltage is lowering the barrier, the drain voltage is creating an asymmetric barrier which is inducing or which is producing a current in the channel.

This is the output characteristics that we have seen that we have discussed. And just to sort of point it out here this is typically the symbol of the MOSFET the n MOSFET ok. We have a gate terminal this is how we write it down in circuits; the gate, the drain, and the source ok. The current direction is shown from drain to source which means electrons are flowing from the source to drain ok.

So, in the output characteristics as you know now that there is this linear regime, there is the saturation regime, and there is this sub threshold regime and if we want to understand the transfer characteristics which is essentially the I_{DS} versus V_{GS}; I_{DS} as a function of V_{GS}, I_{DS} for a constant V_{DS}.

So, let us take the case of an arbitrary V_{DS}; so, for an arbitrary value of V_{DS} for an arbitrarily drained voltage what happens is, when the gate voltage is extremely small in that case this channel in the MOSFET is not formed.

So, generally this is how the MOSFET looks like, this is the source, the drain and we have a channel here this is the channel and only after a certain value of the gate voltage only after the threshold voltage this channel or the significant charge starts appearing in the channel just below the oxide; so, that the MOSFET can conduct.

So, before this voltage which is also known as threshold voltage, before the threshold voltage the current I_{DS} is extremely small whatever be the drain voltage ok. So, this is V_{GS} this current will be extremely small whatever be the value of the V_{DS}, it is not too much dependent on V_{DS} at the moment. As soon as the gate voltage is above the threshold voltage; let us assume the source is grounded, we have a voltage applied on the drain terminal, we have a voltage applied on the gate terminal as well V_{GS}.

As soon as V_{GS} is above V_T, the threshold voltage what happens is that that now the current conduction starts and it is also dependent on the V_{DS}. So, for an arbitrary V_{DS} the current will increase and; so, typically in this way. So, for small V_{DS} it will be like this, for large V_{DS} it will be an exponential kind of increase. So, this is V_{DS1}, this is V_{DS2}, and V_{DS2} is greater than V_{DS1} ok.

This current I_{DS} if we closely look here in this picture in this barrier picture the I_{DS} is the current because of electrons going from the source side to the drain side. So, that depends on the height of the barrier from the source side. So, if the gate voltage is 0 this is the height of the barrier, if the gate voltage is let say some positive value above V_T it is the height of the barrier is reduced and it is this value ok.

So, more the height of the barrier less will be the probability of crossing the barrier by the electrons on the source side and it is an exponential relationship which I guess if you are familiar with p n junction theory you can also deduce it from there. So, this current from the source side or from left to right is directly proportional to the or $e^{-E_{SB}}$ where SB is the barrier height from source side ok.

So, that is why if we increase V_{GS} further, it is almost like an exponential increase in the current ok. For small V_{DS} it will not be so sharp, but for large V_{DS} it will be a very sharp exponential it will be just very sharp exponential ok. So, this is the transfer characteristics of the MOSFET, generally the transfer characteristics is important; so, this is plotted here. In the transfer characteristics the regime below the threshold voltage is known as the sub threshold regime.

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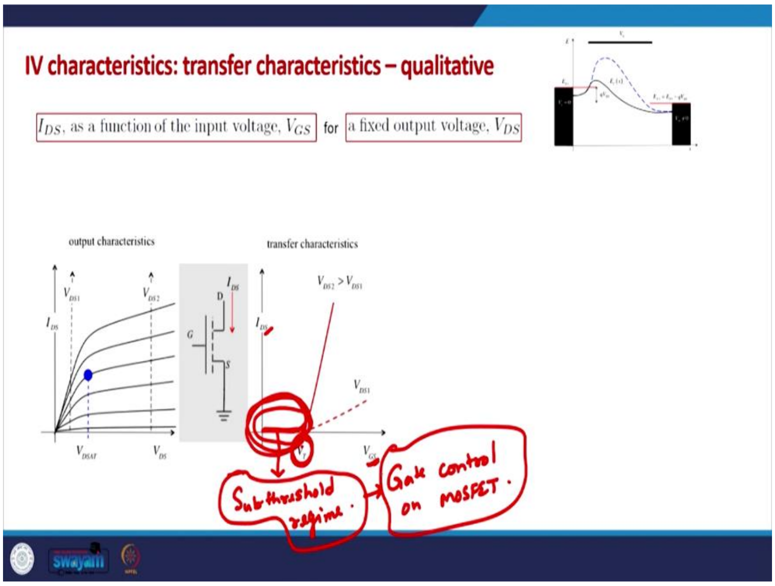

So, this regime is the sub threshold regime and the transfer characteristics is important in understanding the sub threshold regime of the MOSFET ok. And the sub threshold regime is important in trying to understand the gate control on the MOSFET, what do you mean by gate control here?

So, it means that how effectively the gate is able to control the channel in the MOSFET that is broadly known as the gate control. And in the sub threshold regime by understanding the current relationship between the current I_{DS} and V_{GS}, we can see how quickly I_{DS} increases if we increase V_{GS} slightly. And that is the gate control, if we increase gate voltage slightly how quickly the channel is getting formed, how quickly we are switching on the MOSFET, how quickly the current is increasing.

So, that is why this regime is extremely important in trying to understand the sub threshold characteristics. And in some modern day applications; some devices are biased very close to the threshold region, threshold voltage on the gate terminal ok. And in particularly in those devices this is a very important regime to understand, the sub threshold regime is an extremely important regime to understand ok. So, this is about the I-V characteristics and we have taken an extremely qualitative approach in order to understand the I-V characteristics of the MOSFET.

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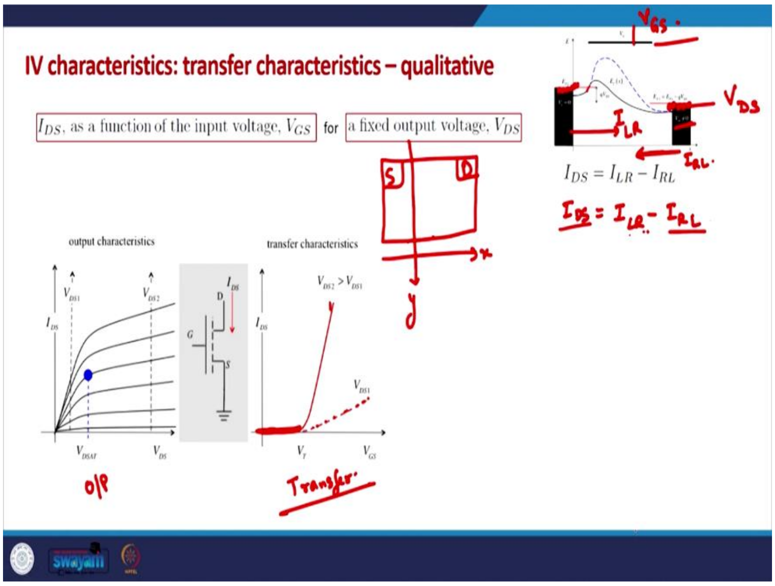

The output characteristics is I_{DS} versus V_{DS}; it has three regimes, linear, saturation, sub threshold. The transfer characteristics has an extremely important regime which is the sub threshold regime. And after the sub threshold regime or this sub threshold regime tells us about how effectively the gate is controlling the channel; after that it tells us about the effect of the drain voltage on the current ok.

Now, let us try to see let us try to have some quantitative understanding of how current is related to various voltages in these MOSFETs ok? So, there is a conventional theory of I-V characteristic conventional way of calculating the I-V characteristics of the MOSFET we will also do that quickly. But before going into that let us quickly see how I_{DS} is related to the various voltages that are applied in the MOSFET, how I_{DS} is related to V_{DS} and V_{GS}.

And in this we will take a this barrier picture, we will start with this barrier picture of the MOSFET in which there is a barrier in the channel. And this barrier is controlled by the barrier height is controlled by the gate voltage and this barrier symmetry so to say is controlled by the drain voltage ok. And as we know that both source and drain they are n type materials; so, they have enough electrons there and similarly the source and the drain will also have enough electrons in it ok.

So, electrons on both sides will have certain probability of crossing the barrier and reach to the other side. So, there will be a current from source to drain from left to right in this way. This is represented as I_{LR} the current from left direction to the right direction and there will be a current from right to left; this is because of the electron movement from the source side to the drain side.

And the net current in the MOSFET I_{DS} or let us not just let us say this I_{DS} will be $I_{LR} – I_{RL}$ ok. So, if left to right current is more in that case I_{DS} will be positive, and if right to left current is more as compared to left to right current in that case I_{DS} will be negative which means current will be from drain side to the source side.

Generally, in MOSFETs just to sort of remind you about the convention the direction from the source to the drain is taken to be the x direction, and the direction from gate to the channel is taken to be the y direction that is typically how it is represented. So, with this we are trying to see quantitatively we are trying to understand how the current is dependent on various voltages.

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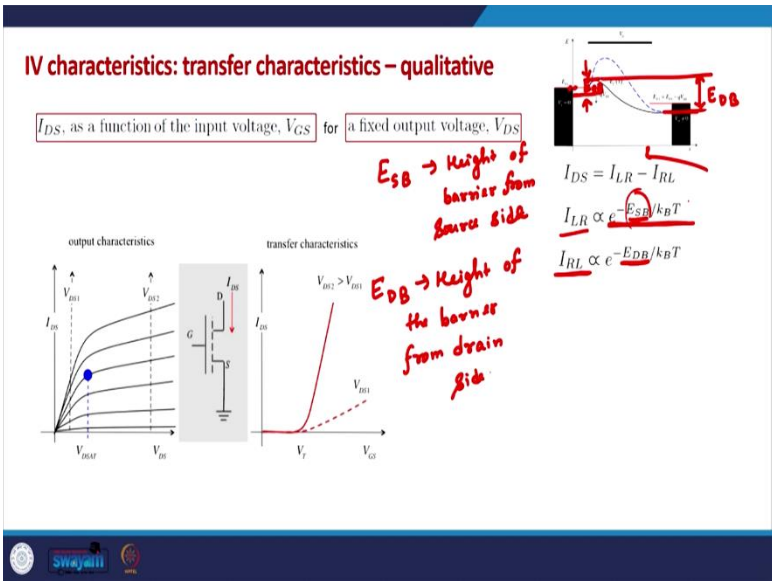

So, as we know that from our basic semiconductor physics, the probability that an electron sitting on the source side will cross the barrier is directly proportional to the exponential of the height of the barrier. So, if $E_{SB}$is the height of the barrier from source side which means essentially this height and E_{DB} is the height of the barrier from the drain side which means it will be this height; so, this will be E_{DB} and this will be E_{SB}.

1. So, the number of electrons crossing from left to right, and as a consequence the current from left to right or the current because of the electrons crossing from left to right will be directly proportional to $e^{-E_{SB}/kT}$; kT is the basic k is the Boltzmann constant, T is the temperature ok. So, if E_{SB} is more, it means that less number of electrons would be able to cross the barrier from left to right and the current because of that because of electrons crossing from left to right will be less.

Similarly, the current due to electrons crossing the barrier from right to left from this side to this side will be dependent on the barrier height from the right side which is E_{DB}. And if this barrier is more, the current will be less barrier is less current will be more ok; so, this is a very I would say this is true very heuristically as well.

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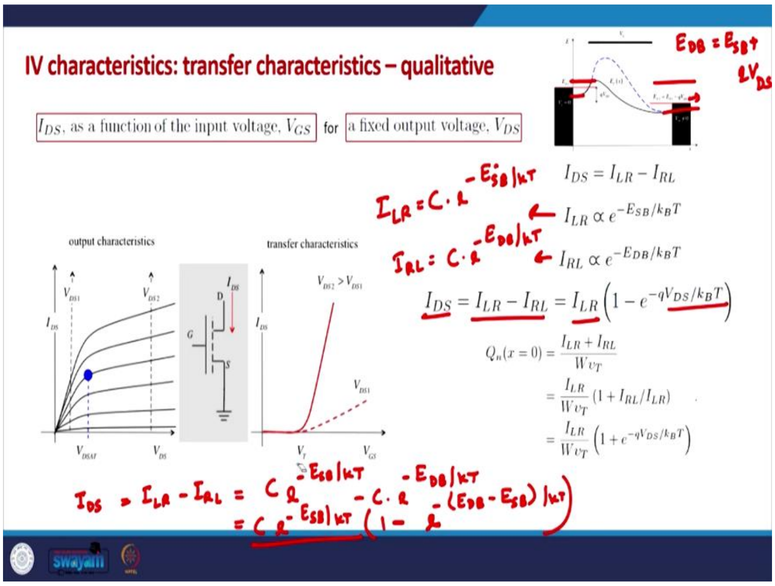

And the net current I_{DS} which is essentially the difference between I_{LR} left to right minus right to left. So, let us see this I_{LR} is equal to some constant C times $e^{-E_{SB}/kT}$ ok. Similarly, this I_{RL} will also be C times $e^{-E_{DB}/kT}$. So, the net current I DS which is the difference between left to right minus right to left it is equal to C $.e^{-E_{SB}/kT}$ - C. $e^{-E_{DB}/kT}$ ok.

So, if you take C times $e^{-E_{SB}/kT}$ out, it will be $1 - e^{-(E_{DB}-E_{SB})/kT}$, and this is I_{LR} which is here. And now there is an interesting thing to observe here; the barrier height from this side is this, the barrier height from this side is this. The difference between the two barrier heights is essentially the V_{DS} voltage because; it is because of the drain voltage that the barrier on the drain side is increasing.

So, this barrier on the drain side is equal to barrier on the source side plus q times V_{DS}. So, this E_{DB} - E_{SB} will be q times V_{DS}; so, it will be exponential this term will be $e^{-qV_{DS}/kT}$ ok. So, that is how we obtain I_{DS} is equal to I_{LR} into $(1 - e^{-qV_{DS}/kT})$.

Now, the charge in the channel or the total charge in the channel is because of the electrons coming from both sides. So, the total charge right at the beginning of the channel on the source side, let us say at the height of the barrier at the peak of the barrier is that is because of the current from the left side and current from the right side.

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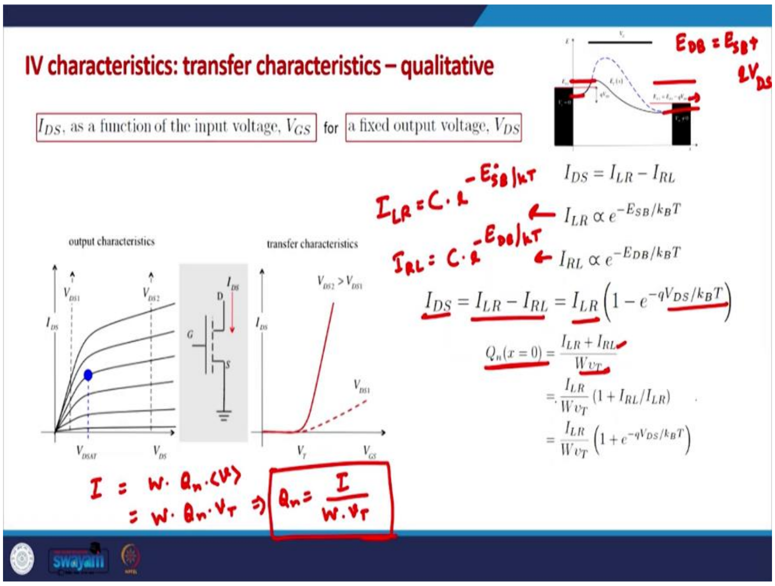

And if you recall the relationship between the current and the charge is this ok. So, if this average velocity if at the peak of the barrier this is taken to be the thermal velocity because, there is no electric field this will be Q_n times V_T which means that Q_n will be I divided by W times V_T.

So, the charge coming from the left side will be I_{LR} divided by W times V_T, and the charge coming from the right side will be I_{RL} divided by W times V_T. So, that way the total charge will be if we take the I_{LR} out it will be I_{LR} divided by; so, let us quickly do it here.

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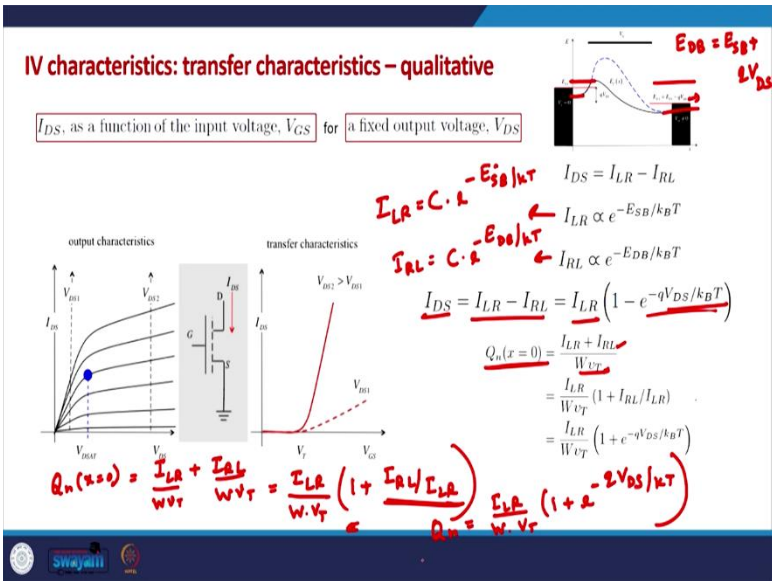

So, this total charge Q_n at the top of the barrier is I, it is the charge due to the left side plus the charge due to the electrons coming from the right side. If we take this as a common factor outside, inside we will have I_{RL} divided by I_{LR}; so, this factor is essentially this parameter. So, this will be ideally this will be I_{LR} divided by W times thermal velocity into $1 + e^{-qV_{DS}/kT}$ ok; so, that is the total charge at the height of the barrier.

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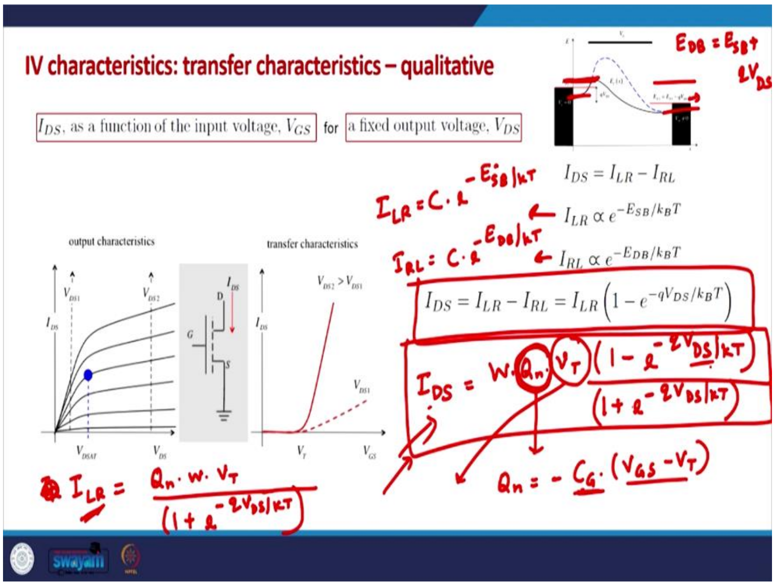

It means that from this expression this I_{LR} can be written as Q_n times W times V_T divided by $1 + e^{-qV_{DS}/kT}$ ok. So, if we put this expression this I_{LR} value in this equation, let us say in this equation. So, the net current I_{DS} will be W times Q_n times V_T into $1 - e^{-qV_{DS}/kT}$ divided by $1 + e^{-qV_{DS}/kT}$.

So, this will be the net charge that will be there in the system oh sorry this will be the net I_{DS} as a function of V_{DS}; apart from this Q_n we have not yet sort of deduced. So, if we also; so, this Q_n will also be dependent on V_{GS} and V_{DS} and typically this Q_n then n MOSFET is given as $-C_G(V_{GS}-V_T)$; where C_G is the gate capacitance or the capacitance of the device looking from the gate side.

Generally, it is assumed to be the C_{ox}; but it is not actually equal to the C_{ox}, we also need to take into account the depletion capacitance of the MOSFET. So, in some cases when that we are not doing the rigorous treatment, it is written down as C_{ox}, but it should be C_G and this thermal velocity this depends on the temperature and other things.

So, from this expression we can see what is the relationship between I_{DS}, V_{GS} and V_{DS}. So, this is the typical or I would say this is the I-V characteristics which include both output characteristics and the transfer characteristics. And this can be derived right from the very simple arguments, the arguments that we can take from the barrier controlled device picture of the MOSFET ok; I hope this is clear and if not let me quickly review it.

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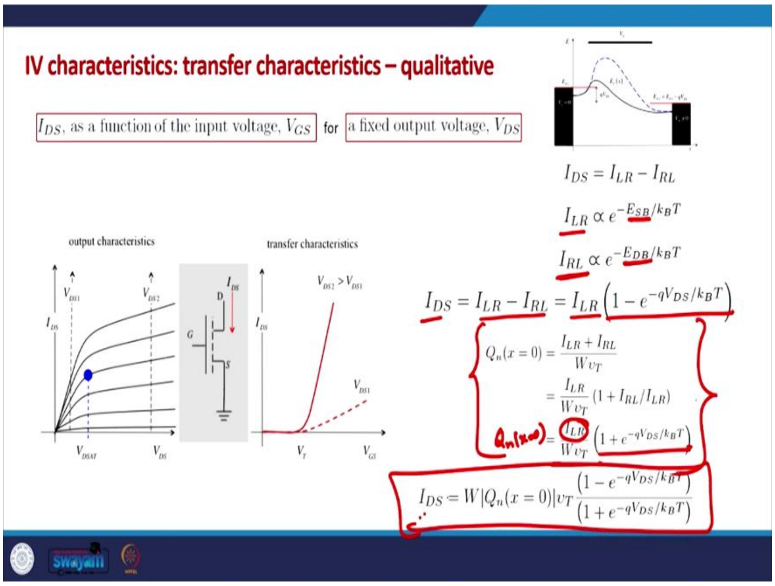

The current because of the electrons coming from the left side to the right side is I_{LR} which is dependent on the barrier height from the source side. The current due to electrons coming from the right side to the left side is dependent on the E_{DB} which is the barrier height from the drain side. The net current is given by the difference of these two currents where if we take I_{LR} common, this is the factor left.

Now, if we look at the total charge especially at the height of the at the peak of the barrier that is that will be due to both electrons coming from the left side and the electrons coming from the right side. So, that is essentially Q_n at x equal to 0 is I_{LR} divided by W times V_T into this and if we put this I_{LR} value in terms of Q_n and V_T in this we obtain this expression for the current.

Here it is might seem that this I_{DS} is independent of the V_{GS}, but it is not so because, this Q_n is pretty much dependent on V_{GS}; and also V_{DS} in some cases. So, this current is intricately dependent on both V_{GS} and V_{DS} and in a way this captures both output characteristics and the transfer characteristics of the MOSFET. Apart from this, this V_T is also important, which is the thermal velocity at the peak of the barrier. So, this picture is quite different from the conventional picture of the I-V characteristics of the MOSFETs.

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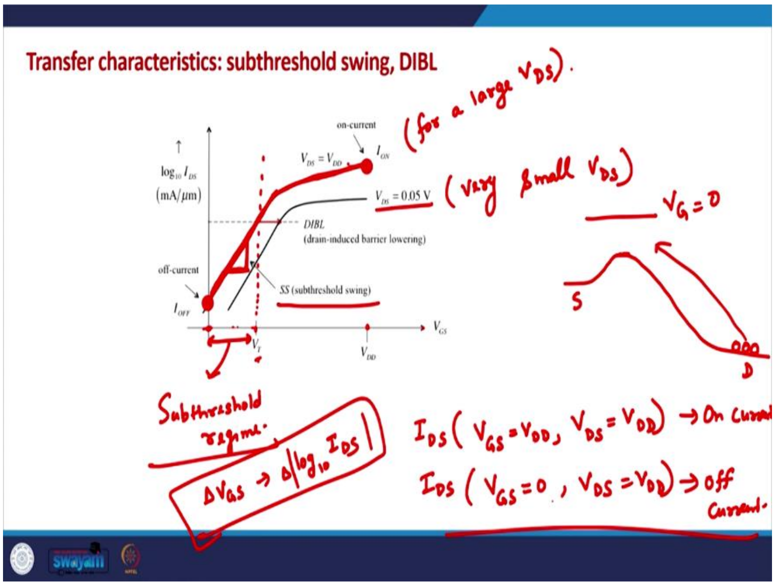

Now, let us see; so, now, this one part is left out that is the sub threshold the I-V characteristics in the sub threshold regime; so, that is what we will try to understand right now. So, if we sort of zoom out only this part of the characteristics if we plot I_{DS} versus V_{GS}, moreover not only I_{DS} we plot log I_{DS} with decimal basis log time I_{DS} as a function of V_{GS}; in that case by doing that we can zoom out the sub threshold part of the transfer characteristics.

So, if we do that this is what we obtain the characteristics this is the V_T below V_T this is how the I-V characteristics look like. And these characteristics have been drawn for two V_{DS} values; one is for V_{DS} S is equal to 0.05 volts which means a very small V_{DS} very small V_{DS} and this is drawn for a large V_{DS} ok. Now, first let us see let us see the I-V characteristics only for V_{DS} is equal to V_{DD}.

In that case; so, there are two important things first two important things that we need to understand, one is even if this V_{GS} is 0 and we have a large V_{DS} in the system. So, at this point when V_{GS} is 0; even then there is a very small current that flows through the device, and if you remember the barrier picture this is the barrier source drain side.

So, even if this V_G voltage is 0, in that case there will be a non-zero probability for some electrons to cross this barrier and reach to the drain side; although the probability for electrons on the drain side to cross the barrier will be extremely small almost 0. So, there will be very small current that will be due to electrons crossing the barrier from the source side and that current is known as the off current. Because, we expect the MOSFET to be off at this value at V_{GS} is equal to 0 value and this is known as the off current.

Similarly, on the similar terms when V_{GS} is V_{DD} the highest value quite above V_T value threshold value and V_{DS} is also V_{DD}. So, I_{DS} when V_{GS} is equal to V_{DD} and V_{DS} is also equal to V_{DD}; in this case it is known as the on current, and I_{DS} when V_{GS} is 0 and V_{DS} is V_{DD}; V_{DD} is the maximum voltage this is known as the off current, nowadays V_{DD} is of the order of 1 volts ok.

So, we have an off current, we have an on current and below the threshold voltage; so, if we draw this line the threshold voltage line. The slope of this curve this tells us about the sub threshold swing, because this regime below V_T regime when V_G is less than V_T this is the sub threshold regime and the slope here this will tell us about how much would the current change if we change the V_{GS} by some value.

If we are changing V_{GS} by ΔV_{GS}, then by the slope we can deduce how much will be the change in I_{DS} and in this case this will be how much will be the change in $\log_{10} I_{DS}$. And see this slope is known as the sub threshold swing and this tells us about the gate control on the device.

This tells us about how well the gate is able to control the channel and that is what we will discuss in a bit more detail in the coming class. So, I recommend you to look into the sub threshold characteristics of MOSFETs in your UG textbooks and then in next class we will start our discussion from this point onwards.

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