Physics of Nanoscale Devices
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Lecture - 38
MOSFET Electrical Characteristics

Hello everyone, today we will discuss Basic Electrical Characteristics of the MOSFET. In the previous class if you recall we discussed how a MOSFET is a barrier control device.

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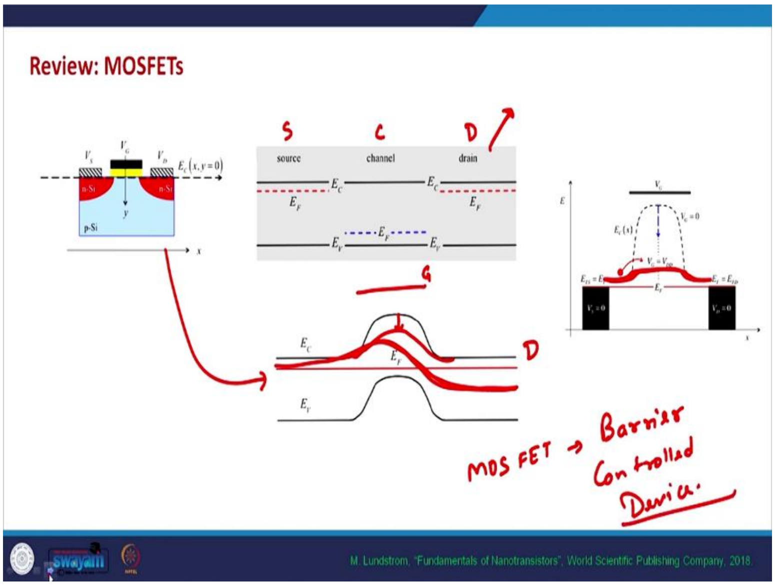

Review: MOSFETs

MOS FET → Barrier Controlled Device.

M. Lundstrom, "Fundamentals of Nanotransistors", World Scientific Publishing Company, 2018.

And the barrier is visualized if we draw the band diagrams of the MOSFET. So, let me quickly review what we have seen so far. So, these are the band diagrams in absence or these are the band diagrams of the source region, the channel region, and the drain region when assuming that they are not connected with each other.

And if in an actual MOSFET where the source, the channel and the drain are actually connected, this is how it looks like. In the previous class what we saw was that; that we have a gate terminal here and if we apply a positive voltage on the gate terminal this barrier height actually reduces this barrier height goes down.

So, that way this gate voltage can control the barrier height; also, we saw that if we apply a drain voltage then what happens is that this drain side conduction band goes down. And this the symmetry of electronic concentration around the barrier is also disturbed ok.

And so, by applying a gate voltage or a drain voltage we can change, by applying a gate voltage we can change the barrier height itself. And by applying a drain voltage we can change the probability of crossing or electrons crossing across the barriers ok. So, and because of these because of this property of the MOSFET, the MOSFET is also known as the is a barrier controlled device that is because of this property of the MOSFET.

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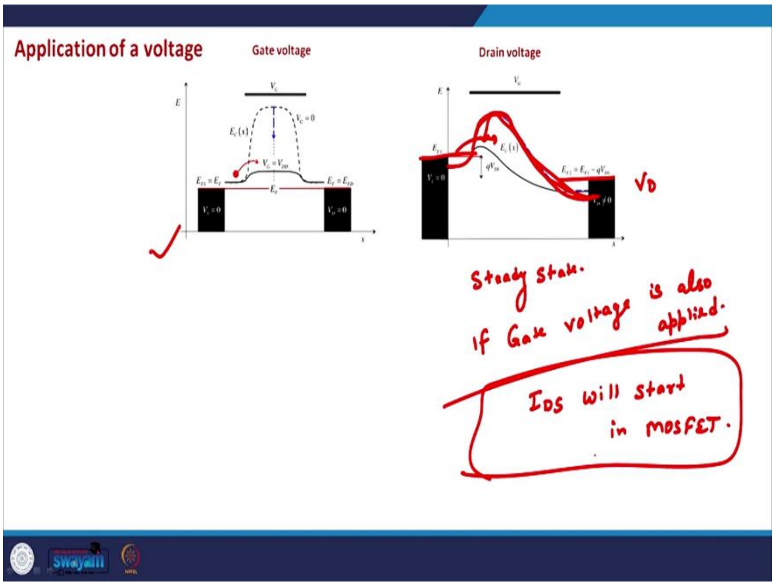

Application of a voltage

Steady State.

If Gate voltage is also applied.

I_{DS} will start in MOSFET.

So, this is the application of the gate voltage on the MOSFET. And if we apply a drain voltage it will change the fermi level as well and the equilibrium is also disturbed; and in this case in steady state this is how it will look like. So, the application of a drain voltage does not change the barrier height in an ideal MOSFET it does not. And in a in conventional MOSFETs it does not actually change the barrier height, because on the source side the voltage is still 0 on the drain side the voltage is V_D let us say.

So, this height which depends on the which actually depends on the voltage across the channel and on the left side of the channel the voltage is still around 0. So, that is why this barrier height does not change, but as we go from the left to the right side, the voltage increases from 0 to V_D and that is why this barrier is now or this barrier changes in this way this follows the potential profile across the channel ok.

So, this is the case when only the drain voltage is applied, but in addition to drain voltage if gate voltage is also applied is also there, in that case this barrier height is reduced. And because of the drain voltage we have more or we have this barrier height which is more on the drain side.

So, that is why now we can see that more number of electrons from the source side can cross the barrier and there will be a current from the drain terminal to the source terminal. So, that is how this I_{DS} will start in the MOSFET ok. And that is essentially the mechanism of current conduction in the MOSFETs.

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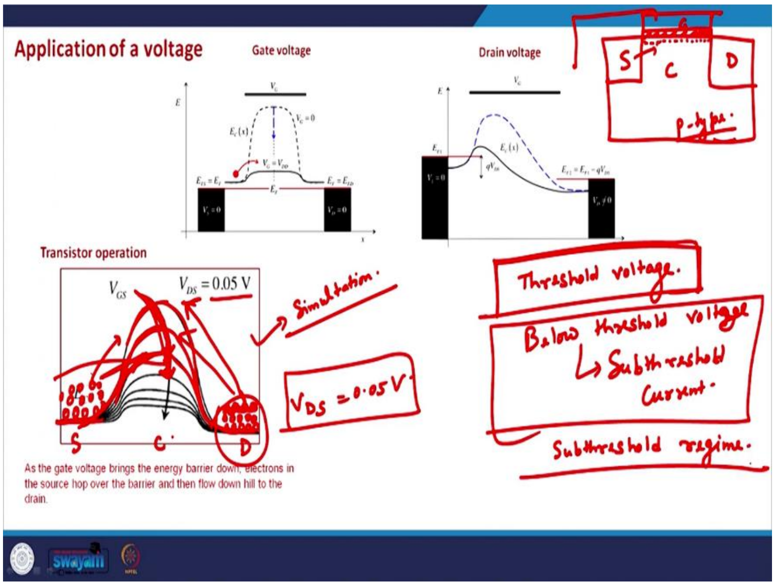

Application of a voltage

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

Simulation.

$V_{DS} = 0.05V$.

Threshold voltage.

Below threshold voltage
↳ Subthreshold current.

Subthreshold regime.

So, this we have already seen from our previous class and this comes from a simulation actually, this is taken from a book by Mark Lundstrom. And here what happens is that the V_{DS} voltage the voltage difference between the source and the drain terminal is assumed to be 0.05 volts. And by changing the gate voltage or for various gate voltages the barrier in the device is shown basically.

And as you can see that by changing the gate voltage, we can actually change the barrier height. And after a certain point actually; so, let us say there are; so, this is the source side, this is the drain side, this is the channel region and gate voltage is changing the barrier height. And there are electrons since, source is n type material; so, there are electrons sitting on the source side and drain is also an n type material; so, electrons are also sitting on the drain side in this way let us say.

So, initially if the barrier is this much high and even if we apply a small drain voltage, even if we have small V_{DS} which is around 0.05 volts, there will not be any current in the system. Because, the probability of these electrons crossing the barrier is extremely small because this barrier is too high for these electrons to cross. Similarly, the probability of these electrons, the electrons on the drain side to cross the barrier will also be extremely small. It will be even smaller than the probability of electrons sitting on the source side ok.

But, as we increase the gate voltage this barrier height is reduced; now, this is the barrier. But, even now it is extremely difficult for the electrons on the source side to cross the barrier; similarly, for the electrons sitting on the drain side. If more gate voltage is applied this will be the situation; so, the barrier is let us say now here. Now, you can see that the energy of the electrons here and the barrier height there is very less difference between the two. So, then the probability of crossing the barrier will now be some non-zero value it will be some.

So, now, some current will at least start in the device because, there is a drain voltage. So, if we apply slightly more drain voltage as well in that case the probability of electrons on the source side will to cross the barrier will be more as compared to the probability of electrons in the drain side to cross the barrier; so, there will be a net current.

So, as you can see that the current only starts after a certain gate voltage in these devices. And if we further increase the gate voltage, now the barrier height is actually less than the energy of the electrons on the source side.

So, now it is not at all difficult for the electrons on the source side to cross the barrier. And if we apply a drain voltage in that case it will be relatively more difficult for the electrons on the drain terminal to cross the barrier.

And there will be this non symmetric crossing of the barrier and that is how a current will be starting in the system. So, as you can see that after a certain gate voltage only after a certain gate voltage a significant current starts in the device and that gate voltage is known as the threshold voltage ok.

Before the threshold voltage if the gate voltage is less than the threshold voltage in that case the current is very small. So, if we have the MOSFET like this we have the source terminal, the drain terminal, the channel region just above the channel we have oxide and on top of oxide we can put gate. So, if the gate voltage is positive enough; so, that it can create an inversion layer of electrons just below the oxide, in that case only the current will start in the system ok.

And so, the voltage at which this inversion is actually inversion happens properly in this channel this that voltage is known as the threshold voltage. So, below the threshold voltage of the gate voltage is less than the threshold voltage, in that case an extremely small current is there it is not that there is no current because, even when the gate voltage is less than the threshold voltage there is a finite probability for electrons to cross the barrier.

So, there will be, but the current will be an extremely small current and below threshold voltage it is known as the sub threshold current; so, it is the sub threshold current that is there in the system ok. And this region or this regime of operation when the gate voltage is less than the threshold voltage this is known as the sub threshold regime ok; so, that is essentially the transistor operation.

So, the transistor operation can be summarized in this way, that it is about playing with the barrier in the device and this is done by applying a gate voltage. So, the gate voltage has contribution in changing the height of the barrier, and the drain voltage has a contribution in having a symmetric distribution of electrons around the barrier and that way a current is actually started in the system.

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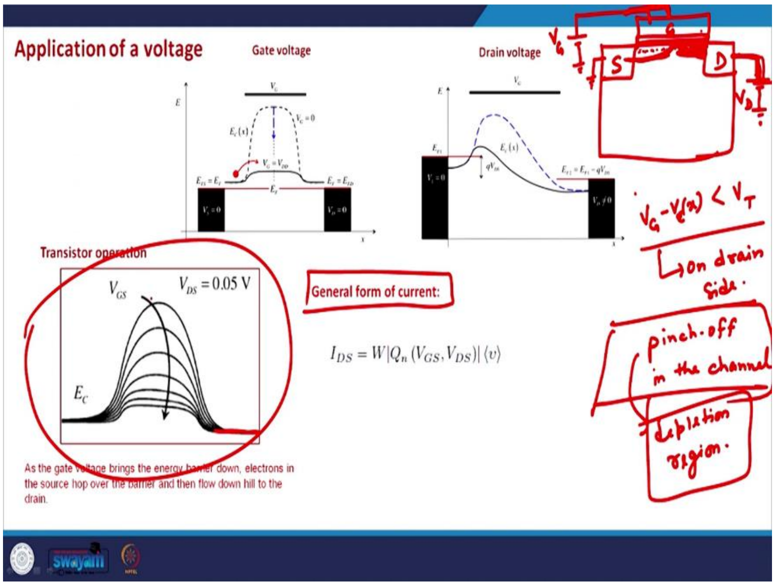

Application of a voltage

Gate voltage

Drain voltage

Transistor operation

General form of current:

$$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\langle v \rangle$$

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

$V_G - V_c(x) < V_T$

↳ on drain side.

pinch-off in the channel

depletion region.

So, now let us; so, before going into the current expression there is one more point that I want to sort of remind you that in conventional MOSFETs what happens is that generally we have source, we have drain, we have a small oxide here and we have a gate here. So, there is a positive voltage in an n MOS there is a positive voltage applied on the gate terminal the source is grounded, there is a positive voltage applied on the drain terminal as well V_D and V_G is positive ok.

So, now this the threshold voltage is the voltage that is applied on the gate terminal; so, that this inversion layer can be formed inside the channel. But, as we apply a drain voltage here; a drain voltage also creates a potential profile in the channel which means that, now the net voltage difference between the gate and the channel on this side on the drain side specially is now less than the. So, the voltage difference between V_G and let us say V_C the channel or let us say let us call it Vx.

So, on the drain side specially it might be less than the threshold voltage, especially on the drain side. So, if a positive drain voltage is applied, it will in a way nullify the effect of the gate voltage. And that way the channel or the inversion layer in the channel on towards the drain terminal might not be present and that is known as the pinch off in the channel or pinch off region of the channel ok.

So, this is just to remind you that because of the drain voltage this the effect of gate voltage is also disturbed in the channel. If there is no drain voltage in that case this gate voltage creates a uniform effect across the channel, but if there is a drain voltage the effect of the gate voltage is now non uniform. On the source side we might have a very good inversion layer, but on the drain side the inversion layer may be weak or there might be a pinch off at all.

So, this pinch off is essentially the depletion region, like the depletion region in the p n junctions and so, the channel when the drain voltage is high in that case the channel consists of a an inversion layer and a pinch off region ok. So, all those things need to be taken into account while calculating the current or while trying to understand the electrical characteristics of the current.

So, there are two concepts that I told you; one is the notion of the threshold voltage that is the gate voltage at which significant current starts in the or significant current can start in the device. Which means that; that is the gate voltage at which the channel is or the inversion layer is formed in the n MOSFET ok and second is the notion of the pinch off.

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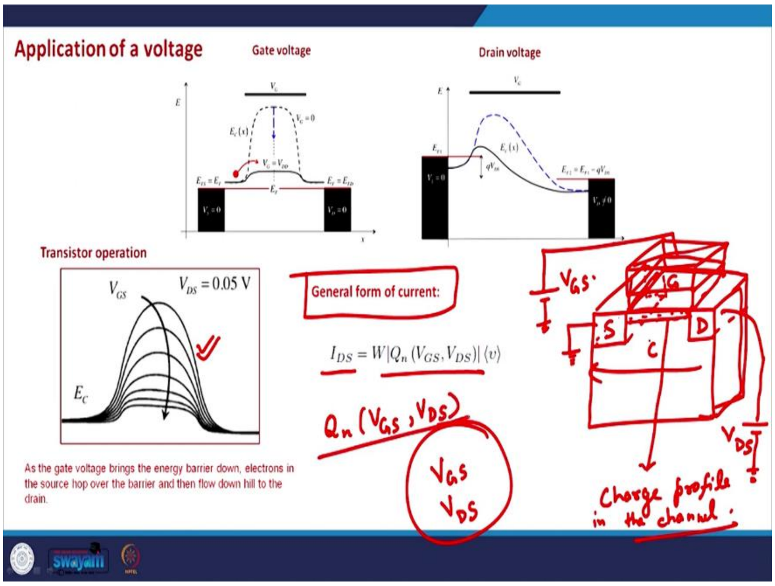

Application of a voltage

Transistor operation

General form of current:

$$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\langle v \rangle$$

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

Now, let us see let us try to understand the current inside the device. So, ultimately we have the MOSFET is like this, we have source, we have drain, we have the channel, and, but in addition to this, this is a actually 3D thing this MOSFET is a 3D entity. So, we this ok; this is how it looks like ok. A general expression of the current from the drain terminal to the source terminal because, typically we apply a positive voltage on the drain terminal.

So, generally source is grounded; so, the voltage applied on the drain side is known as the V_{DS} voltage. And apart from this we have a channel region or we have a an oxide layer here and on top of that we have the gate terminal actually; so, this is the gate terminal. So, the voltage applied on the gate terminal is known as the V_{GS} voltage.

So, now, as we have seen because of the drain voltage and the gate voltage this is how the band diagram will look like and this will create sort of a charge profile in the channel. So, the charge profile in the channel will be dependent on V_{GS} and V_{DS}. So, the charge per unit area; so, because now this channel this inversion layer in the channel that is like a quasi 2D channel that is like almost like a 2D thing.

So, the charge per unit area per unit cross section area that is represented as Qn and this Qn is a function of both V_{GS} and V_{DS} ok. So, this is one important parameter while discussing the MOSFETS that is the charge density or the sheet charge density sorry the charge density in the channel ok, this is the charge per unit area, the units can be coulomb per meter square.

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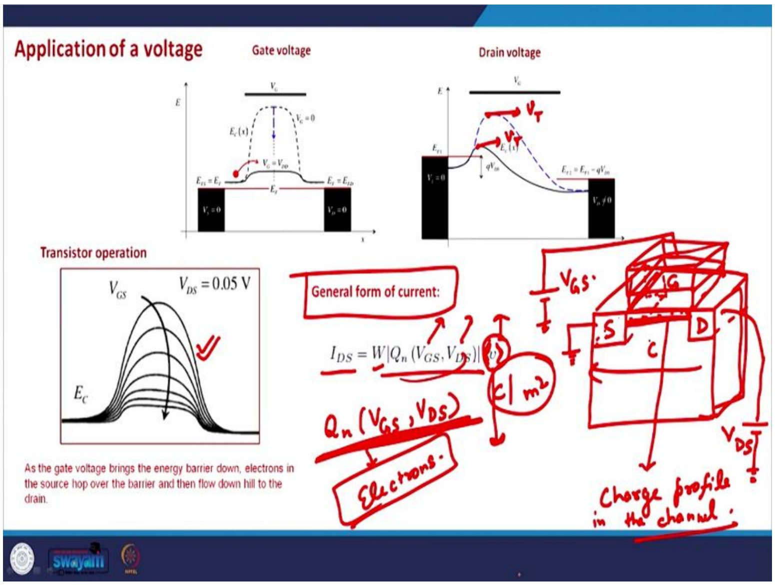

Application of a voltage

Gate voltage

Drain voltage

Transistor operation

General form of current:

$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\,\upsilon$

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

Second important thing is the velocity of the charge carriers. So, this charges because of the electrons in the case of n MOSFET, because of the electrons in the inversion layer. So, the number of electrons as we have also seen during our discussion on the transport theory, that the number of electrons depend on the applied voltage.

So, the number of electrons in this case will depend on both V_{GS} and V_{DS}. And the velocity of electrons crossing this barrier actually will depend on the electric field ideally. And typically this velocity is the velocity of charge carriers, the most important velocity is the velocity of the charge carriers at the top of the barrier at this point actually, also known as the in some cases this is also represented as V_T.

So, that if we have the charge density or the number of electrons in steady state in the channel. And we know that how fast this charge is getting eliminated from the channel, how fast this charge is moving through the channel; then the current will be given by the product of the charge density and the velocity and the width. So, this is a very general definition of the current, and this is true for any arbitrary device this is not true just for the MOSFETs.

Because in any device if we have a charge distribution, if we have a charge density and if we also know how fast that is moving the current through that device will be given by the multiplication of the charge density with the velocity and we also need to multiply by the width ok.

So, this is a very general form of the current in the MOSFET that is given as the multiplication of the charge density and the velocity at which the charge carriers are getting eliminated from the system. Now, let me slightly point out here that since a positive voltage is applied on the gate terminal.

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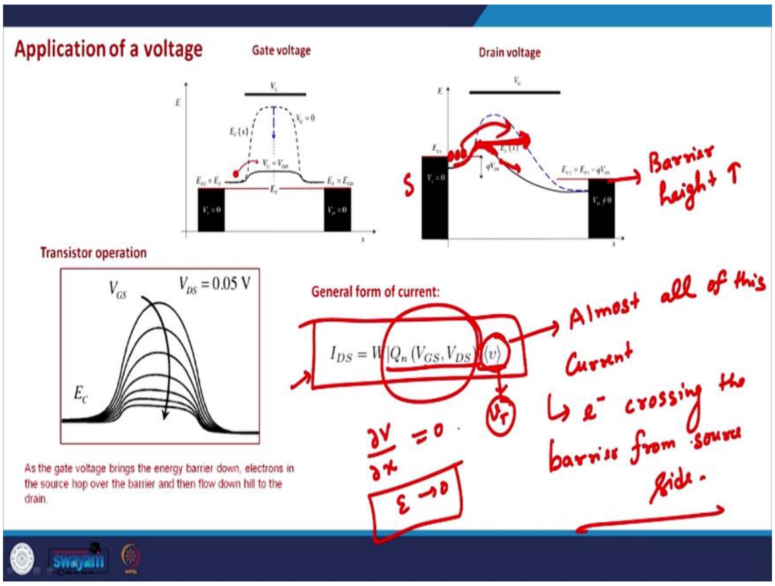

Application of a voltage

Gate voltage

Drain voltage

Transistor operation

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

General form of current:

$$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\langle v\rangle$$

→ Almost all of this Current

↳ e^- crossing the barrier from source side.

v_T

$$\frac{\partial V}{\partial x} = 0 .$$

$$\boxed{\mathcal{E} \to 0}$$

So, this barrier height from the drain side is actually the barrier is very high, barrier height increases from the drain side, barrier height is more from the drain side as compared to the barrier height from the source side ok. So, most of this current is because of the electrons crossing the barrier from the source side. So, almost all of this current is because of the electrons crossing the barrier from source side ok.

So, please keep this in mind and that is why and if we sort of want to see this velocity here we have written the average velocity, but if we try to understand this velocity of electrons crossing the barrier from the source side.

So, just in the beginning they encounter this peak of the barrier and at the peak of the barrier the electric field, what is the electric field at the peak of the barrier? So, at the peak of the barrier we can see that or if we take the gradient of this curve $\frac{\partial V}{\partial x}$ this is 0, so, the electric field tends to 0 at the peak of the barrier.

So, this is the velocity of charge carriers in absence of the any electric field. So, this is the velocity just because of the diffusion of the charge carriers without any external influence of the electric field in a way this is just the thermal velocity of the charge carriers. So, the velocity at the barrier height is without any electric field and velocity at any other point; so, for example, at this point there is an electric field in the channel. So, there is a positive voltage on the drain sides which will attract electrons.

So, that velocity will be more at this point as compared to the velocity at the top of the barrier. So, in a way the limiting factor in current is the velocity at the top of the barrier in the channel, because at all other points the velocity is almost always more than the velocity of electrons at the top of the barriers.

So, that is why in most of the cases instead of this average velocity generally we use $\langle \mathrm{v}(\theta) \rangle$ in order to calculate the current in a MOSFET ok. And this charge profile the charge per unit area is actually because of the application of the gate voltage and the drain voltage.

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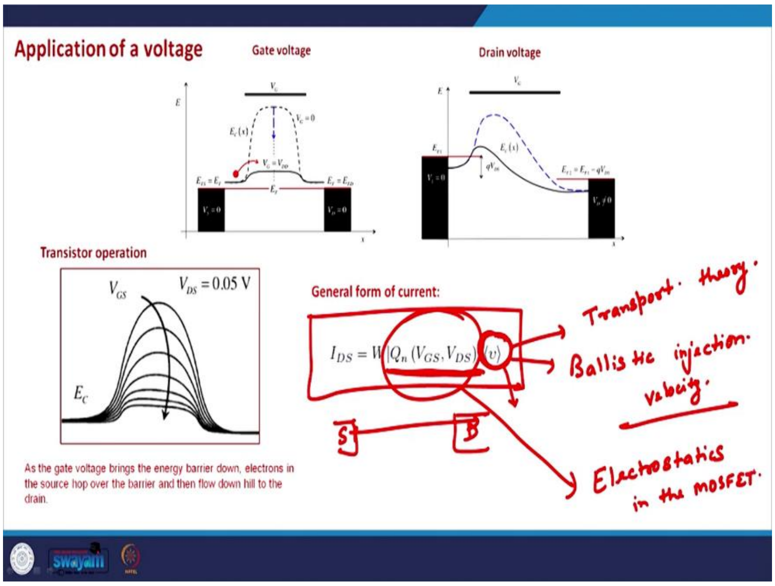

Application of a voltage

Transistor operation

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

General form of current:

$$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\langle v \rangle$$

S

B

Transport. theory.

Ballistic injection. velocity.

Electrostatics in the MOSFET.

So, now with this general form of current; now, as you might have already guessed that there are two distinct things here; one is this charge distribution the charge inside the channel, second is the velocity at which this charge is moving through the channel. And generally, this is the understanding this velocity is a subject matter of the electron transport theory. So, if the electrons are scattering with particles in between this velocity will be we will need to take into account the scattering of electrons.

If the electrons are directly going from the source to the drain side from the source to the drain terminal as we have already seen. If this is a ballistic MOSFET in that case, this velocity will be known as the ballistic injection velocity.

So, understanding this velocity is actually the subject matter of the transport theory is the subject matter of the electron transport. And this charge profile inside the MOSFET is because of the application of the gate voltage and the drain voltage. This is typically the subject matter of the electrostatics or this depends on the electrostatics inside the MOSFET ok.

So, essentially in order to understand MOSFET physics, in order to understand the electrical characteristics of the MOSFET we need to understand the electron transport through the system, and we need to understand the electrostatics in the system here; the transport part we have covered fairly well already. So, we will use that knowledge here in the MOSFET physics and after this basic discussion we will briefly see or we will briefly discuss about the MOSFET electrostatics as well and that way we should be able to understand the entire physics of the MOSFETs ok.

Nowadays, because of the scaling because now the size of the MOSFET is reducing. Nowadays, the transport is changing fundamentally, because in conventional transport theory the diffusive transport is assumed by default. But, it is no longer true because nowadays the channel length is smaller than the mean free path of electrons and nowadays ballistic transport is quite common. So, this needs to be revised properly and that was one of the major goals of this course.

Electrostatics is more or less the fundamental principles of electrostatics are the same, they are not changing. But, the way it is playing role is nowadays slightly different than in long channel MOSFETs, in short channel MOSFETs the electrostatics physics the physics of electrostatics does not change the principles of electrostatics do not change. But, the way this manifest is changing slightly, because nowadays we need to take into account the 2D electrostatics properly in the MOSFET ok.

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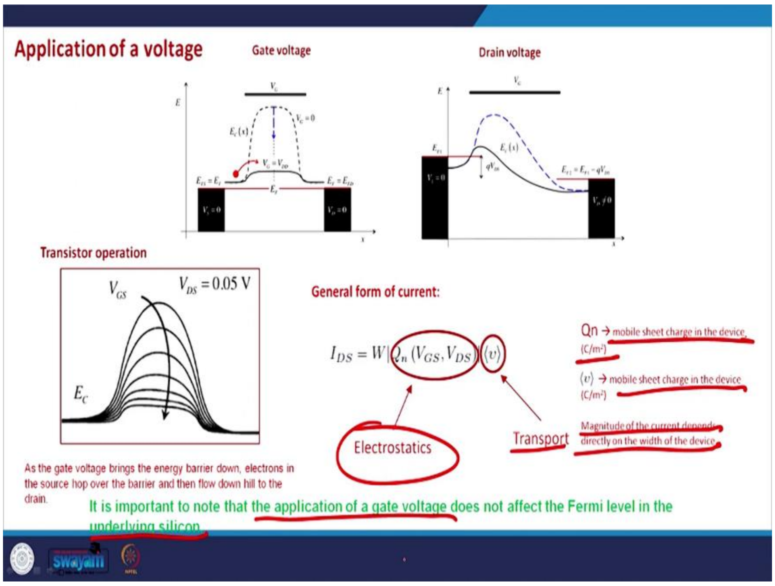

Application of a voltage

Transistor operation

As the gate voltage brings the energy barrier down, electrons in the source hop over the barrier and then flow down hill to the drain.

General form of current:

$$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\langle v\rangle$$

Electrostatics

Transport

Qn → mobile sheet charge in the device (C/m²)

$\langle v\rangle$ → mobile sheet charge in the device (C/m²)

Magnitude of the current depends directly on the width of the device

It is important to note that the application of a gate voltage does not affect the Fermi level in the underlying silicon

So, this is the mobile sheet charge in the device Qn, v is the velocity. So, magnitude of the current depends directly on the width as well, more the width, more will be the current. Velocity is the purview of the transport theory and the Qn is in the purview of the electrostatics. Apart from these things and this we have already sort of highlighted I have already highlighted this that the application of the gate voltage does not affect the fermi level in the channel.

This we have already seen, because the electronic distribution does not change on application of the gate voltage. That is why the fermi level is maintained and that is why this equilibrium the equilibrium is also maintained in the system even when a fermi level is even when a gate voltage is applied.

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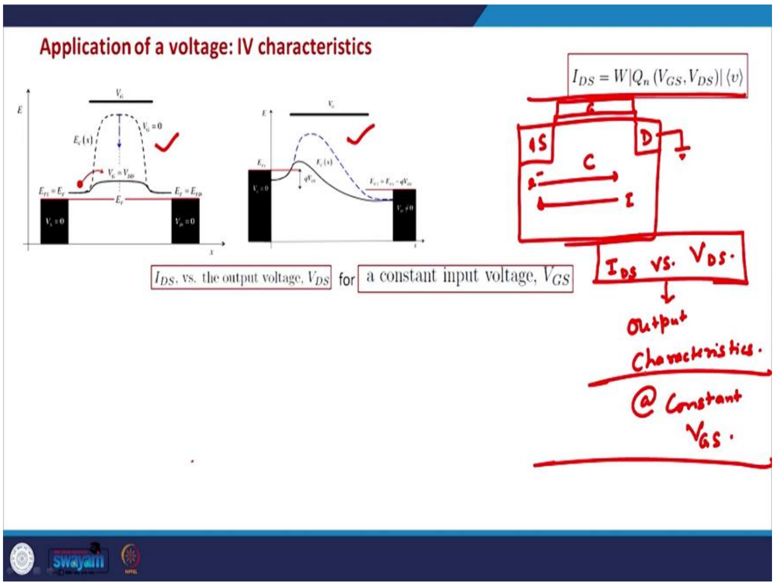

Application of a voltage: IV characteristics

$I_{DS} = W|Q_n(V_{GS}, V_{DS})|\langle v \rangle$

I_{DS}, vs. the output voltage, V_{DS} for a constant input voltage, V_{GS}

I_{DS} vs. V_{DS}.

Output Characteristics.

@ Constant V_{GS}.

So, this now brings us to sort of understanding the I-V characteristics of the MOSFET ok. And this is the source terminal, this is the drain terminal, this is the channel region, this is the gate terminal. Electrons are flowing from source to drain side; so, the current will be flowing from drain to source on application of drain voltage and gate voltage. So, the relationship between I_{DS} and V_{DS} is known as the output characteristics of the MOSFET at a constant V_{GS}.

So, now in the light of the entire discussion that we had this barrier dynamics, how this barrier changes on application of V_{GS} and V_{DS}? Then I would like you to think about the output characteristics of the MOSFET, I_{DS} versus V_{DS} in the light of this entire discussion that we have had. What would be the form of I_{DS} versus V_{DS} for a MOSFET? So, I will let you think about this and we will discuss about this in the next class. I thank you for your attention and see you in the next class.