Physics of Nanoscale Devices
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Lecture - 37
MOSFET: A Barrier Controlled Device

Hello everyone, as you know that we have been discussing the physics of MOSFETs; after discussing the basic theory of transport, we started our discussion on MOSFET theory. And since last class, we started discussing the band diagrams of the MOSFET and today we will see how a MOSFET is a Barrier Control Device.

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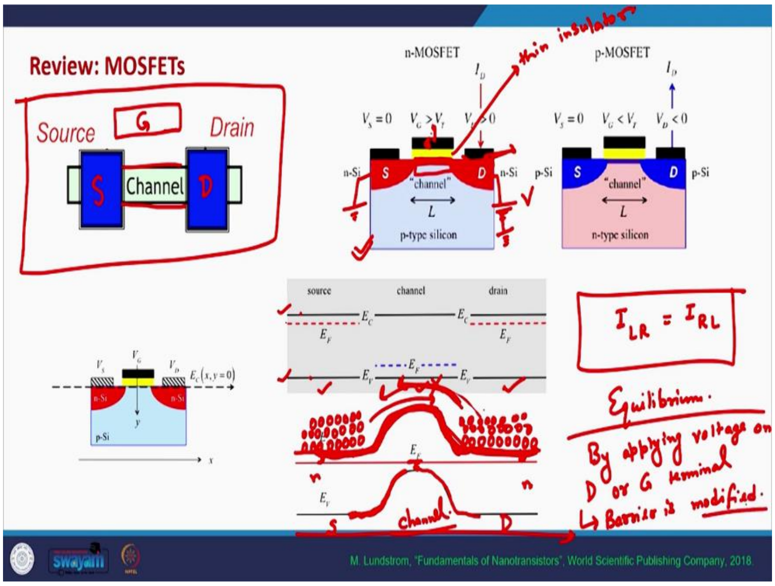

And that is easily visualized from the band diagram of the MOSFET. Let me quickly review, before going into the details of the band diagram, let me quickly review what we have been seeing. In this course in the beginning, we discussed this kind of a two terminal device, in which there is a source terminal, there is a drain terminal and in between them there is a small channel, ok.

So, but an actual transistor is a three terminal device and apart from these two terminals, we have an additional third gate terminal here, ok. So, this is how an actual transistor looks like; this is we have a semiconductor substrate, in this case there is a p type semiconductor substrate and in this substrate we have n type source contact, n type drain contact and between the source and the drain contacts, this region is known as the channel region.

And the channel region is primarily controlled by the third terminal, which is known as the gate terminal, which is isolated from the channel bias very thin, extremely thin oxide or insulator, ok.

And so, that way there cannot be any current from the gate terminal to the channel to the channel in this device, ok. But the effect of the electric field on the gate terminal can be felt in the channel. And using the electric field by applying a voltage on the gate terminal, in fact this entire device, the conduction in this entire device is controlled and that is why it is known as a MOSFET device, ok.

And so, the current conduction takes place from the source contact to the drain contact ok, sorry from the drain to the source contact and the electron transport happens from the source to the drain when we apply a positive voltage on the drain side and the source side is generally assumed to be grounded, ok.

So, we have a positive voltage applied on the drain terminal. So, if we want to understand how electrons are going through various kind of materials while they are travelling from the source to the drain; then it is best to draw the band diagrams of the channel region from the source to the drain via channel region.

And these are the conduction band edges and valence band edges; this is conduction band minima and this is valence band maxima and apart from them we have this Fermi level. And if we plot these three energy levels, that is how we obtain the band diagram, ok.

And so, these are the band diagrams of the source to the channel and the drain separately, assuming that we have not contacted the source to the channel and drain to the channel. So, this is how the band diagrams of the source to the channel and the drain will look like in an n MOSFET, when they are not in touch with each other.

As soon as we make this device, we make this kind of device; the band diagrams, the band diagram of this entire device right from the source to the drain will look like this. So, this is the source part, this is the drain part and this is the channel region, ok.

On the source side, the Fermi level is extremely close to the conduction band; similarly on the drain side, it is also close to the conduction band, because these two are n type materials. So, they are n type materials. This the semiconductor in between the channel region is actually fundamentally a p type material, so that is why it will have the Fermi level close to the valence band maxima.

But because of the junction between the source and the channel, we will have this kind of barrier from the source side to the channel side, both in the conduction band minima and in the valence band maxima. So, this is pretty much similar to the band diagram of a p n junction, ok.

Similarly, in the channel drain contact, the band diagram will be almost exactly like the source channel band diagram. And we will have a barrier between the channel and the drain in this way, because this is the junction between p type material and n type material.

So, in this way we what we see is, if we just look at the conduction band edge; the conduction band edge in the conduction band edge, we have this kind of shape. So, there is, so initially there is a straight line like this; then there is sort of a barrier or a hill, then again we have, again this goes down and again we have a straight line, ok.

And in n type materials as all of us know that there are some electrons sitting in the conduction band. So, there would be some electrons that would be sitting here, because the drain is the n type material. Similarly on the source side as well, we will have electrons sitting in the conduction band.

So, electrons sitting in the conduction band means that, there will be some electrons at the bottom of the conduction band near to the bottom of the conduction band. And now in equilibrium because of this barrier, the electrons on the source side cannot go to the drain side. And similarly the electrons on the drain side they cannot go to the source side; because there is this barrier, which disallows electrons on both sides to go to the opposite side, ok.

So, that is the situation in equilibrium and at max what happens is that, the number of electrons that cross the barrier from left to right is equal to the number of electrons that cross the barrier from right to left; which means that the current from left to right from source side to the drain side is equal to the current from right to left and that is the situation in the equilibrium. So, this is the equilibrium in the device, ok. And in equilibrium as all of us know that this Fermi level is uniform across the entire device, ok.

So, this is what we know. Now, we can apply voltage on two terminals in this device; we can apply voltage on the gate terminal generally and on the drain terminal, typically the source terminal is almost always grounded, ok. Although in some circuits this source may also be connected to high voltage terminal, so that is also allowed, that is not a problem actually.

So, when we apply voltage either on the gate terminal or on the drain terminal; then this barrier inside the device, this barrier is changed, ok. And by changing the barrier, the current inside this devices actually controlled.

So, what we can say is that, by applying voltage on drain or gate terminal, the barrier is modified and that is how this net electron flow starts in the device; whenever the barrier is modified in such a way that the electrons can go from one side to the other side in more number than the electrons can come from other side to the this the previous side.

So, when there is this imbalance between the left flow and the right flow, then the net current is actually flows, net current flows in the device.

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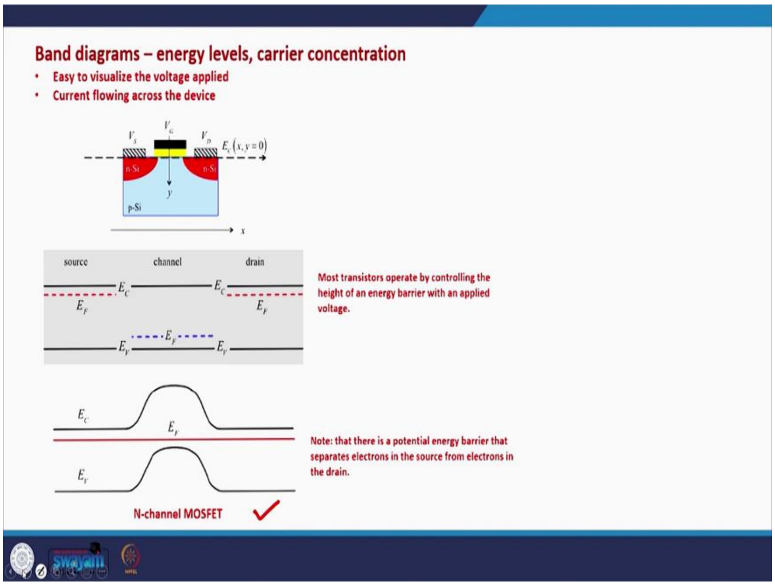

This band diagram is an extremely useful tool in order to understand the MOSFET electrostatics and MOSFET current characteristics. In fact, almost all the, all most of the electrical characteristics can be understood with the band diagrams.

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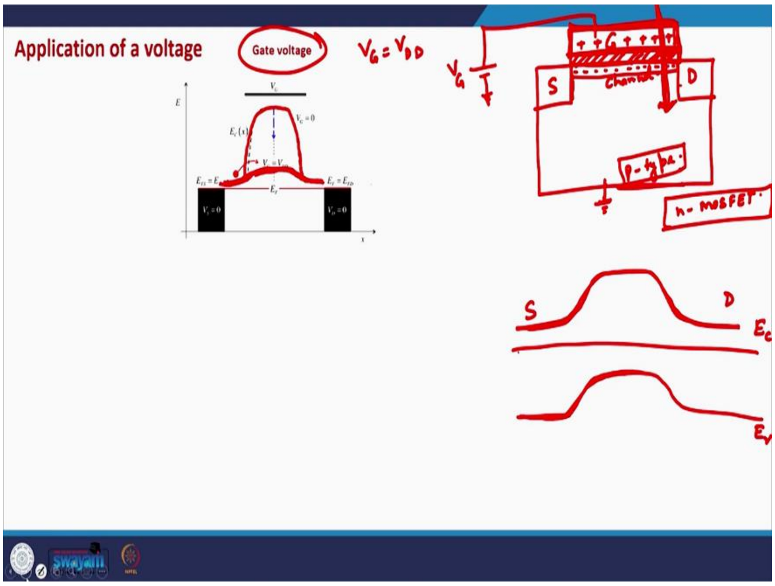

And the way the band diagrams actually work is on how the band diagrams or how this barrier changes with the application of gate voltage and the drain voltage that is what we will see.

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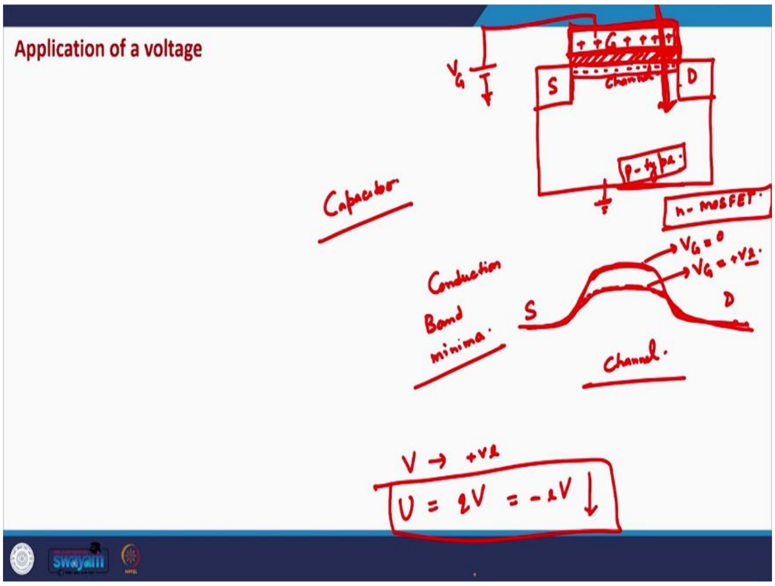

So, finally, we have a device like this; very simplistically we have source, we have drain, we have oxide and we have the gate terminal, ok. And the band diagram, equilibrium band, we just plot the conduction band minima. The valence band maxima will actually follow the conduction band minima exact in exactly the same way. So, the typically this is how this conduction band, sorry this is how this conduction band minima looks like. So, this is the source side, this is the drain side and this is the channel region.

Now, if we apply a gate voltage, let us say that we are connecting a battery to the gate terminal; in this case what happens is, if we apply a positive voltage on the gate terminal, what it will do is and let us say we have we are talking about n type MOSFET. So, generally when this is not specified what kind of MOSFET we are talking about, it is in most of the cases n MOSFET; which means that the substrate material is the p type material and the channel is n type channel, ok.

So, if we apply a positive voltage in the gate terminal, it essentially what it does is that; it produces electric field in the channel, because the body is also let us say grounded. So, there is a net positive voltage on one side of the device and there is a negative voltage on the other side of the device; between the source and the channel, there is this oxide layer.

So, in this direction, the MOSFET works as a capacitor in a way; because we have a metallic plate the gate terminal on one side, in between we have an oxide and on the other side we have a semiconductor material, which can have charge carriers, ok. So, this will behave like a capacitor.

So, the MOSFET in from gate to body, gate to the substrate in this direction the MOSFET behaves like a capacitor. And in this direction, from source to the drain side; when we have a channel, when we have an inversion, then this will act like a conductor, ok.

So, if we are looking at from gate to the body direction, in this case if we apply a positive voltage on one plate of the capacitor; it means that if we put it means that we are putting, let us say we are putting positive charge here, it will attract negative charge on the other side of the plate of the capacitor or it will accumulate or it will attract electrons in the channel.

Or what it does is that because of the this effect of the positive voltage, initially there is a depletion of holes in this p type substrate and then there is an inversion layer, in which a large number of electrons are available very close to the interface and that inversion layer is known as the channel in the MOSFET. And, that acts like a the opposite plate of the this capacitor, ok.

So, if a positive voltage is applied on the gate terminal what it does is that, it will actually and if we look at the electric field in this direction; the potential here there will be a positive potential, because on the other side there is this potential is 0 it is grounded. So, on this terminal there is a large positive potential. So, here also there will be a positive potential.

And because of the positive potential, so this V is positive then electronic potential energy which is given as q times V and q is minus, in the case of electrons it is minus, the charge of electrons is minus e times V. So, this when V is positive, this U will be negative.

So, it means that with the positive voltage, the energy the potential energy of the electrons will go down; which means that this barrier height and please remember that this gate terminal in just over the channel. So, and since the potential energy of the electrons is going down, this barrier will also go down. So, if this was the barrier when gate voltage was 0, this will be the barrier when gate voltage is the positive value. Similarly, this barrier in the valence band side will also be reduced.

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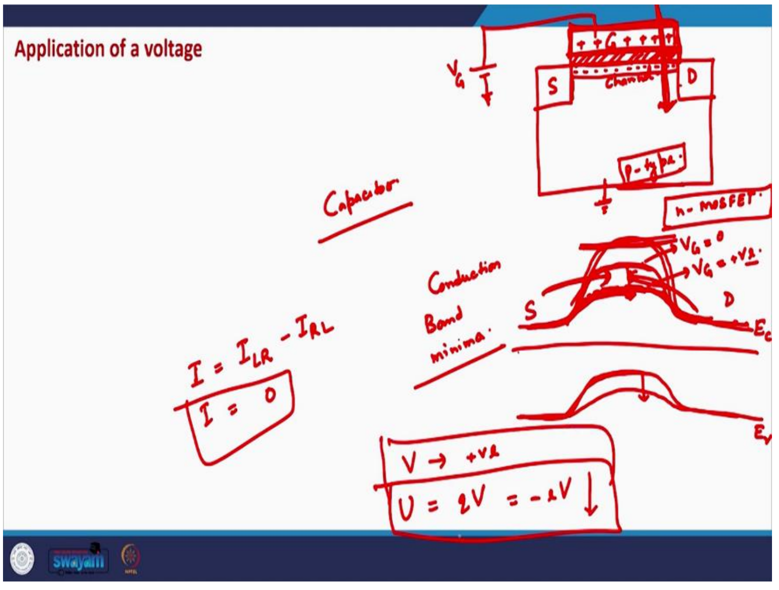

So, if we plot, if we draw this entire band diagram; this is the conduction band edge, this is the valence band edge. So, when there is no voltage on the gate terminal, this is how the barrier looks like; when there is a positive voltage, this will also go down.

So, essentially on application of a positive voltage, the barrier in the channel; the barrier in front of electrons sitting on the source and the drain side, this barrier reduces. So, what it does is that it allows electrons from the source side to cross the barrier; but at the same time, it also allows electrons from the drain side to cross this same barrier.

And if the source and the drain terminals they are identical terminals, they are identically doped; in that case, the number of electrons crossing from source side, crossing the barrier from the source side will be exactly equal to the number of electrons crossing the barrier from the drain side.

So, even then the net current, the current from left to right; the net current is essentially we can right minus right to left. So, the net current will be still 0, because we are assuming that the gate terminal is uniformly put across the channel. So, if there is any positive voltage on the gate terminal; it will uniformly lower the barrier in the channel, so it will allow electrons from both sides to cross the barrier with equal chances.

So, it means that this Fermi level in the device this will not change actually; Fermi level will be a single Fermi level, a uniform Fermi level across the entire device from source to the drain side. So, that is essentially the effect of applying your gate voltage in the MOSFET. So, if we apply a positive voltage in NMOS, this barrier is reduced and if we apply a negative voltage, this barrier height will increase. This can be understood by using the same arguments; because a negative voltage means that the potential energy of the electrons will increase.

So, which means the potential energy of electrons in the channel region will increase, the barrier will increase and the probability of electrons crossing from source to the other side will reduce; similarly the probability of electrons from drain side to cross to the other side will also reduce, ok. So, that is how we can understand the effect of the gate voltage in the MOSFET and as you have seen that by using band diagrams, this can be easily visualized, ok.

So, let us maybe draw, ok. So, this is the barrier. So, as you can also see here that this is the situation when the gate voltage is 0, this is the barrier height and if we apply a maximum gate voltage which is V_G is equal to V_{DD} in that case this barrier is reduced. And because of the reduction of the barrier, now the electrons on both sides will have equal chances of crossing the barrier. So, there will be no net current in the device; although there will be an electric field in the channel, because of the voltage applied on the gate terminal.

Now, the application of a drain voltage; so the application of gate voltage we have understood, the application of drain voltage is also quite interesting is more interesting I would say. But the key take away from here is that, this barrier in the MOSFETs can be controlled by the gate voltage. And as we know that the gate voltage is the control terminal. So, essentially the way gate voltage or the gate terminal exerts its control in the MOSFET is by changing the barrier in the channel, ok.

So, in this case if we apply now, so let us say this is the case when no gate current gate voltage is there.

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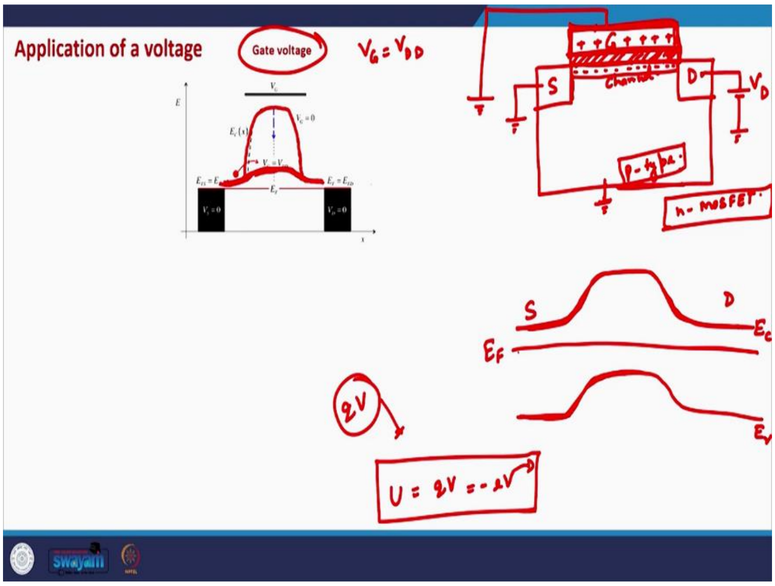

Let us say that gate terminal is grounded, the source terminal is also grounded and we apply a positive voltage on the drain terminal, ok. So, in this case what happens is that, if there is a positive voltage on the drain terminal, again from this relationship -e times V; if V is positive, the potential energy of electrons will be reduced in the drain side, on the drain side and the Fermi level will also go down by few times V on the drain side.

So, any application of voltage on the drain side will alter the Fermi level on the drain side. And, as a consequence it will also change the potential energy or the energy of electrons on the drain side, ok. So, if we are applying a positive voltage in an n MOSFET on the drain terminal let us say, in that case what happens is that now.

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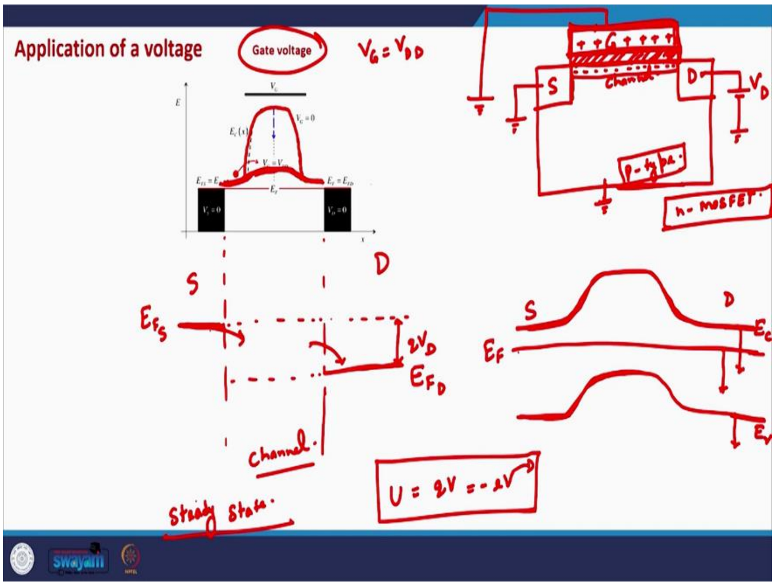

The Fermi level on the source side is this, the Fermi level on the drain side is; let us say this is the device, the Fermi level on the drain side is now lowered by the value of q timesV, that is the or V_D, if the V_D is the applied voltage on the drain terminal. So, this is source, this is drain, let us say this is the channel region.

Now, as you might have already sensed it, this kind of situation we have already seen while discussing a two terminal device, now there is no longer equilibrium in the device. So, application of a gate voltage does not disturb the equilibrium in MOSFET; but application of drain voltage actually takes the device out of the equilibrium. And now if there is a constant current in the system, that state of the system will be known as the steady state, ok.

So, what happens now is that in the channel region and if the source and the drain regions are large; the source terminal tries to fill all the states in the channel region up to the Fermi level of the source. And, the drain terminal will try to fill all the states in the channel up to the Fermi level of the drain.

So, the states in between the source and the drain Fermi levels are now in flux; source is trying to fill them, drain is trying to empty them and that is how a current is sustained in the device and that is how actually the current sets up, that is how the steady state is achieved.

So, in this case what in terms of band diagram what happens is that, now this E_C, E_F and E_V are taken down in a way. And we cannot talk about a single Fermi level in the device, now we need to talk in terms of quasi Fermi level in the system, ok.

So, in terms of band diagram what happens is that, if we apply a positive voltage; it will mean that, that this conduction band minima, the Fermi level and the valence band maxima will go down and the resulting just in terms of. So, if we just have a look at the conduction band minima, on the source side things do not change on the drain .

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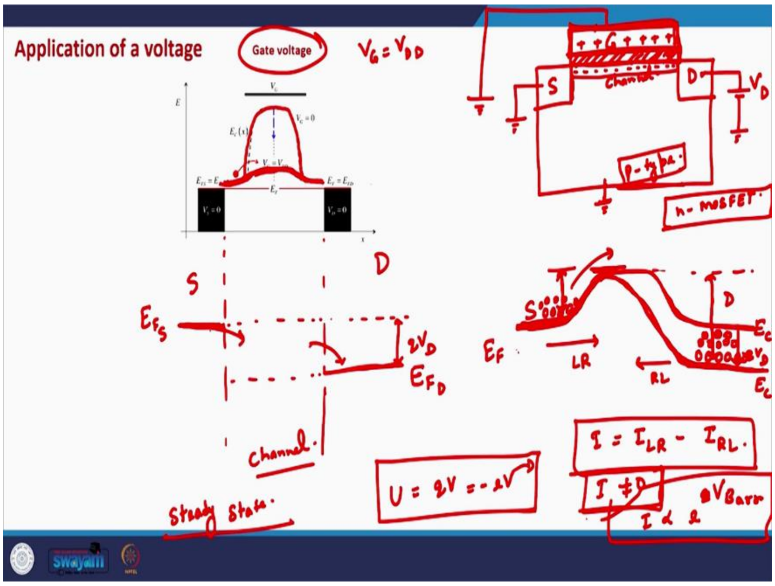

But on the drain side this goes down; now this is the new conduction band minima of the drain terminal this is q times V_D and so, we will have a situation like this. So, if a positive voltage is applied on the drain terminal, this drain side conduction band minima will go down and now interesting situation actually starts happening in the system. Now, what happens is that, this barrier now the barrier from source side to the or the height of the barrier from the source side, which is this height and height of the barrier from the drain side which is this, they are not the same.

What it means is that the current that the chances of electrons sitting on the source terminal, the chances of these electrons crossing the barrier and the chances of electrons sitting on the drain terminal might be now different and that way there might be a net current in the system. So, the current from left to right and the current from right to left might now be different.

So, there might be a net current now; because the chances of the electrons sitting in the drain terminal of crossing the barrier and the chances of electrons from source terminal to cross the barrier are now different, because the barrier heights are different and that is why this these currents might be different. So, it will be a nonzero current and if you remember the p n junction I V characteristics, the current is directly proportional to the barrier height, ok.

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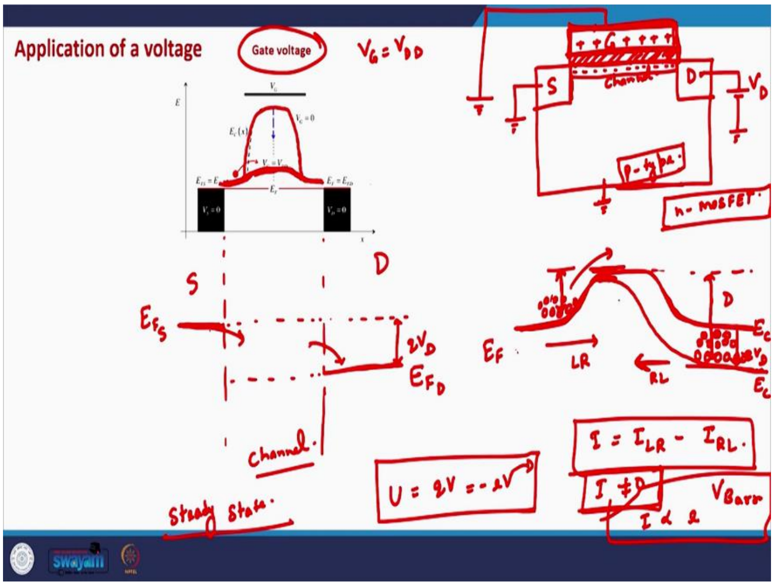

The current from source to the drain side will depend on the barrier height from the source side and the current from drain side to the other side will depend on the barrier height from the drain side.

So as you can easily see here now that now the electrons sitting in the source terminal will now have more chances of crossing the barrier as compared to the electrons sitting on the drain terminal; which means that now there might be a net flow of electrons from the source side to the drain side, which means that there might be a net current from the drain side to the source side, so there might be a net current from right to left, ok.

So, that is essentially what happens when we apply a drain voltage, a positive drain voltage in the MOSFET ok, that is in terms of the band diagram. And now if the drain voltage is applied, the equilibrium might be disturbed and there might be a net current in the system. If the gate terminal is at 0 volt, then this barrier height is extremely high, so only a very less number of electrons can cross the barrier from source terminal and can go to the drain terminal.

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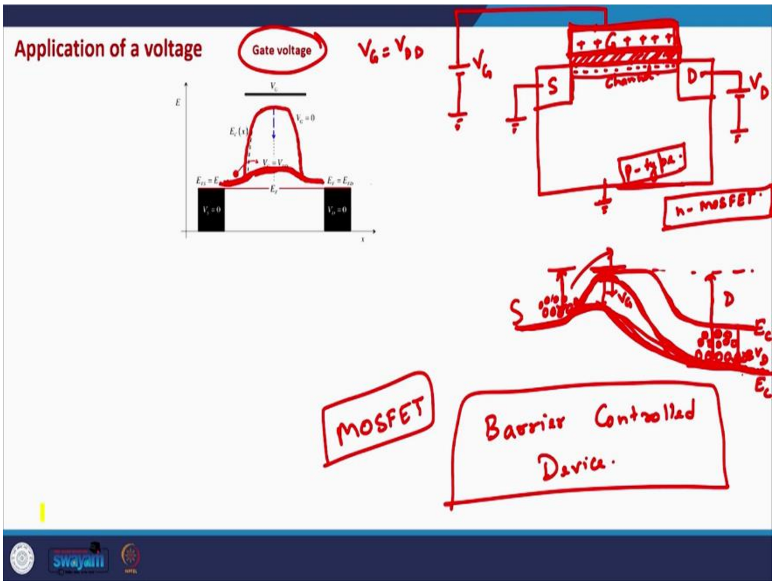

So, the current is extremely small when V_G is 0 volts, ok. So, in addition to a drain voltage, if we also apply a gate voltage. So, now, let us see what happens if we apply in addition to a drain voltage, we also apply a gate voltage. So, we apply a positive gate voltage let us say.

So, if the source is grounded, the gate is positively charged, the drain is also positively charged. What happens is now, because of the gate voltage, this barrier height is reduced and because of the drain voltage, this symmetry around the barrier is broken.

So, now what will happen is that, in this case when both are applied, both gate and drain voltages are applied; in this case what happens is that, this barrier height is reduced as well as. So, this barrier is reduced and the symmetry around the barrier is also changed.

So, now what happens is if this positive gate voltage is there, now it will be more probable for electrons sitting on the source side to cross the barrier and go to the drain side, because now the barrier is less; but since we are also applying a drain voltage, the barrier for electrons on the drain side is more than the barrier for electrons in the source side. And, that is why the probability of electrons crossing the barrier from source side will be more as compared to the probability of electrons crossing the barrier from the drain side. So, there will be a net flow of electrons from the source to the drain side and that way a net current will start in the device.

So, that way we can see that, that ultimately the MOSFET is a or the current in a MOSFET is changed by playing with this barrier. And that is why the MOSFET is also known as a barrier controlled device; because the height of the barrier is controlled by the gate voltage and the symmetry of the barrier or symmetry of conduction band or the symmetry of electronic distribution around the barrier is controlled by the drain voltage. And by playing with both of these voltages, we can set up a net current in the system, ok.

So, that is why the MOSFET is also known as a barrier controlled device; because by controlling this barrier, by controlling its height and the electronic distribution around, it we can control the entire I V characteristics of the MOSFET, ok

So, that is all for today's class and in next class, we will build on these things and we will see how the current can be understood in terms of the barrier height. And, how what is the role of the gate and drain voltages that it, that it plays and we will also discuss about the some threshold characteristics.

So, thank you for your attention, see you in the next class.