Physics of Nanoscale Devices
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Lecture - 36
Introduction to MOSFET

Hello, everyone continuing the discussion of MOSFETs from our previous class we will now see we will today see how the MOSFET actually works, what is its essential physics and what is the traditional understanding of MOSFETs and how it achieves the functionality of a transistor that we need in our electronic systems.

And building on top of this in future we will see or we will sort of see how Nano scale MOSFETs are different from the conventional MOSFETs and that in order to do that we will derive a lot from our understanding of the general model of transport that we gained in last few classes.

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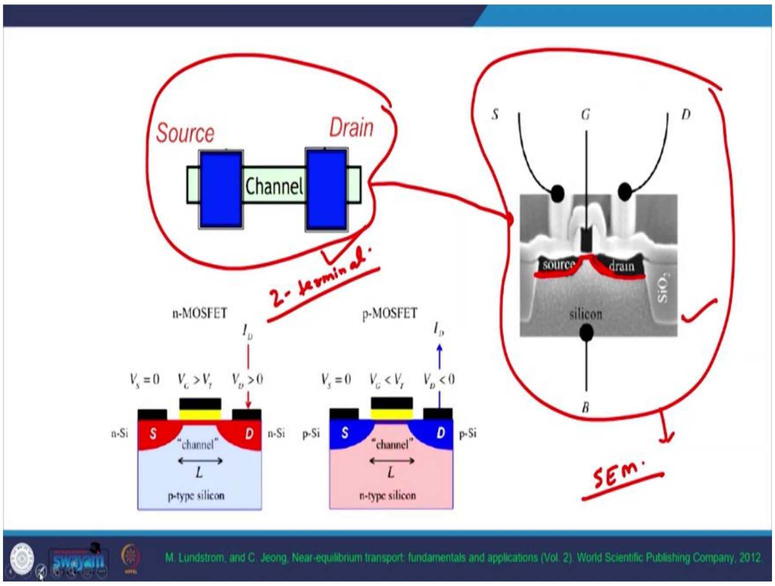

So, this is the device that we actually this is the 2 terminal device that was the main focal point of our discussion on the general model of transport, but an actual MOSFET is like this it is a 3 terminal device and this 2 terminal device can be very easily extended to or the understanding of electron transport from this 2 terminal device can be easily extended to this 3 terminal device ok.

This is the actual or Scanning Electron Microscopic image of the MOSFET this is the this is how it actually looks like and as you might have already noticed and I highlighted this in the last class as well, that the channel region in an actual device is extremely small as compared to the source and the drain regions ok.

So, that is why this needs to be kept in mind ok. And that is why this source and drain contacts are actually dealt as bulk materials and the channel is dealt as a or channel is taken to be small microscopic or even in modern device is a nanoscopic system.

So, this is how it is actually drawn when we try to understand MOSFET and there can be two types of MOSFETs.

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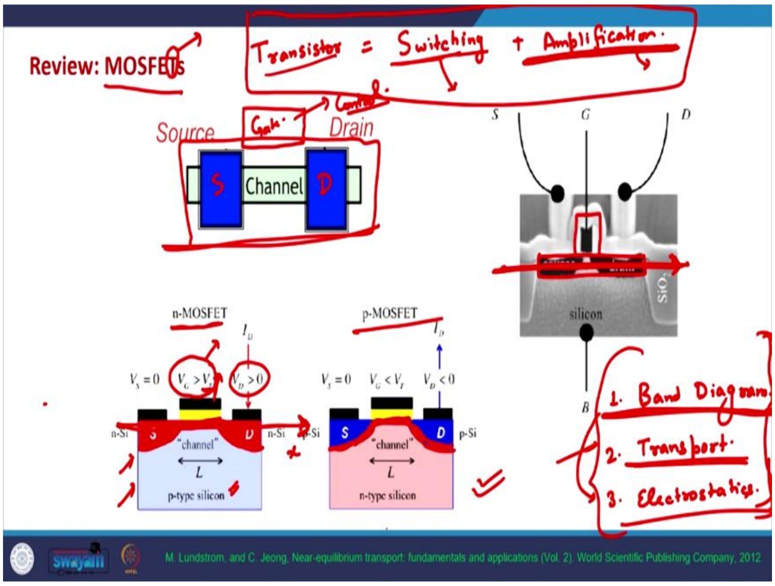

One is the n - MOS and second one is p-MOS, in n -MOS the channel is n type channel that is made out of electrons and the substrate or the body is the p type silicon on which by applying a voltage on the gate terminal or by applying an electric field on the gate terminal we can make a channel or we can enhance or we can sort of make an inversion layer inside the material and by inversion layer we mean that; that originally this body or the substrate is p type silicon.

But, by the electric field produced by the electric field due to the gate voltage now, the electrons concentration very close to the interface between the oxide and the body is so high that it behaves like an n type material and that is why there is a conduction pathway from the source side to the drain side and this is at the heart of the functioning of a MOSFET.

So, please keep this basic thing in mind and similarly in a p MOS we need to apply a negative voltage and the resulting electric field will create a p type channel at the interface and that will make a conducting pathway from the source to the drain via this channel and this will be a p type conducting pathway ok.

So, that is the basic thing about MOSFETs and a MOSFET is a transistor essentially that is what this T stands for basically and a transistor is essentially this how do we just a basic question to all of you to think about. What is a transistor? What is the basic functionality of a transistor?

A transistor is a device let me quickly answer that a transistor is a device which achieves two functionalities one is the switching and second is amplification.

So, we can switch on or off the transistor by in this case in MOSFETs by changing the electric field and we can also achieve amplification and that makes it a transistor and that is essentially these two functionalities are essentially responsible for almost all the operations that we perform in using our electronic devices.

So, almost all the operations that we do they can be broken down in the sequence of switching and amplification operations or they can be broken down in transistor actions ok. So, there are a few things that we need to sort of understand properly if we want to understand either the conventional understanding of MOSFETs or even the nanoscale MOSFETs.

The first thing is the Band Diagram, we need to very appropriately or in a very good way we need to understand the band structure or the band diagram of the transistor especially in the MOSFETs. That gives a very intuitive and extremely important qualitative idea of the entire mechanism of the MOSFETs and so this band diagram is quite important and second is the transport.

This transport part we have already discussed for a 2 terminal device in our general model of transport and this we will extend this idea we will extend from this 2 terminal device to the MOSFETs ok.

Finally, and this is highly correlated with the band diagrams we need to understand the electrostatics of the device, how and where the electric field is there in the device, how it is affecting the electrons movement, the charge in the device, the current in the device, all those things are important.

So, these are few basic ideas that we properly need to understand if we want to understand the MOSFET and before going into those details let me sort of quickly see how a MOSFET can achieve switching and amplification, because that is the most basic task that we want out of this device.

Switching is easy to understand because switching means switching we can understand even from this diagram that if the gate voltage if in the n - MOS if the gate voltage is less than the threshold voltage in that case the channel will not be there and the device will be off and that is how the this off state is that is how this off state is achieved.

When the gate voltage is larger than the threshold voltage we will have a channel below the gate and this will switch on the device. So, by changing the gate voltage we can switch on or off the device. So, that is the basic switching operation of these devices and that is achieved by changing the voltage or the electric field on the gate terminal the third terminal. And that is why this third terminal is like a control terminal in our device.

These two terminals the source and the drain terminals are actually the active terminals because the current flows through these terminals and this third terminal is like a control terminal, it controls whether the current would flow or not in the device. If the gate voltage is less in that case there will not be this inversion layer and the current will not flow from the source to the drain or the electrons will not go from the source to the drain or the current will not flow from drain to the source when we apply a drain voltage.

And if the voltage is higher than the threshold voltage in that case we will have a channel and in that case we will have the and this device will have the capability to conduct currents. But, how are these devices able to achieve amplification and that is what very qualitatively we will see now and then we will try to understand the band diagrams and other properties of the material.

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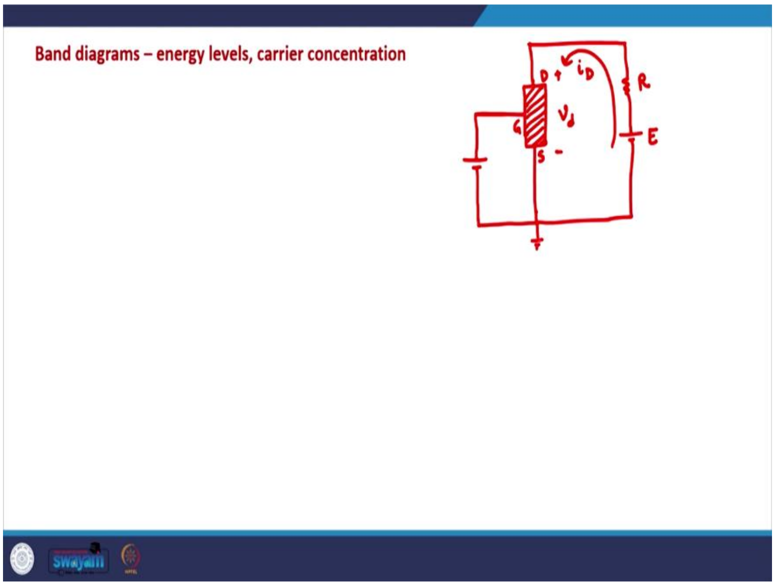

So, let me very in a very qualitative way let me try to sort of explain to you how the amplification is achieved in any transistor I would say and especially in the MOSFETs.

So, MOSFET is like let us say that we have a black box, this black box is our MOSFET device, these are two of its terminals the source and the drain terminals let us say. So, this is let us say this is the source terminal, this is the drain terminal and this is the gate terminal.

And if we apply a battery and a resistor in series this is how it would look like. Let us say the battery voltage is E, the resistor is R, the voltage across the MOSFET is V_d and the current that flows through this device is this circuit is i_D. Let us say this is the situation we are not going into the internal mechanism of current transport in the MOSFET. We are just trying to understand the process of or how the amplification is achieved.

On the gate terminal we can apply a voltage. So, we can apply a separate battery here and this battery is let us say we can connect it to the source and this can be grounded. Generally, this ground is not shown explicitly and it is understood that the negative terminal of the battery is at ground and so this terminal is ground.

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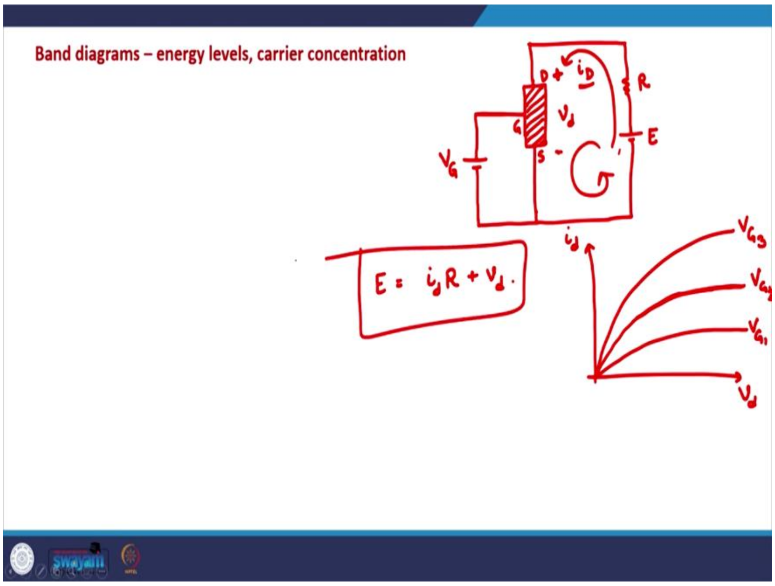

So, this is the gate terminal the gate voltage.

Generally, the MOSFET characteristics, MOSFET I-V characteristics so in this case the current i_D is flowing through the MOSFET between the drain and the source contact and the voltage across the device is V d ok.

Generally, the I-V characteristics of the MOSFET is a non-linear characteristics. So, typically the relationship between i_D and V_d which is the voltage between the drain and source terminal and the current from the drain to the source typically this is how it looks like, this is a part of this is almost linear. So, up to this point it is linear and after that it starts saturating and it becomes almost saturated for higher voltage of drain, higher drain voltages and this is at a specific gate voltage and if the gate voltage is changed this is how it changes sort of.

So, let us say this is V_{G1}, this is V_{G2}, this is V_{G3} and these are various I-V characteristics of the MOSFET ok. So, this is typically how the MOSFET characteristics look like ok. And in this closed circuit here if we right down the KVL this is how it would look like; E is equal to i_D times R plus V_d. So, in this closed loop the KVL will look like this ok.

So, let me redraw this in a proper space.

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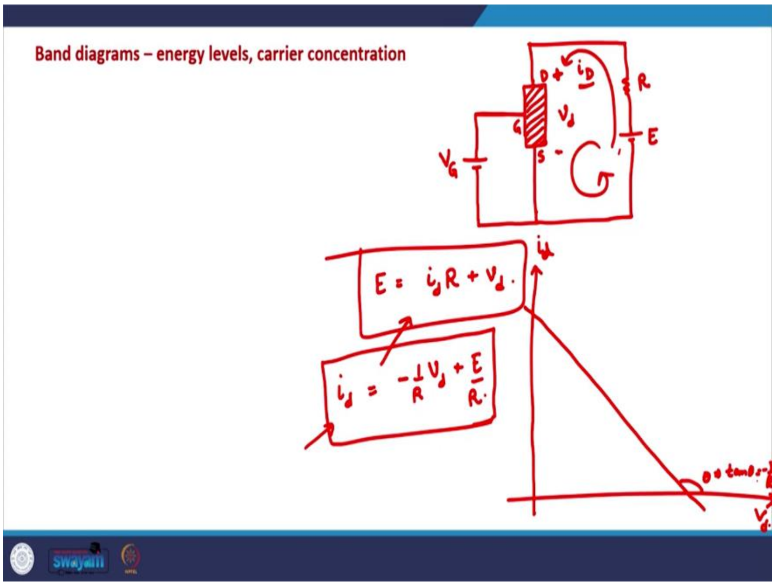

This equation the KVL in this closed loop means that this i_d and V_d will satisfy will always satisfy this constraint this is the basic constraint that the i_d and V_d needs to satisfy.

So, if we plot i_d V_d and if we plot this line this the basic KVL equation this is a line essentially this is a line between i_d and V_d and this can be written as $i_d = -\frac{1}{R}v_d + \frac{E}{R}$.

So, this KVL the basic constraint that the i_d and V_d needs to satisfy this is a line on i_d-V_d on if we plot this relationship on i_d-V_d axis this is a line and the slope of the line is $-\frac{1}{R}$ and the intersection on the y axis is $\frac{E}{R}$. So, this will be a line with negative slope, slope is negative.

The $\tan\theta$ is $-\frac{1}{R}$, but this is not important for us. So, at the same time the i_d and V_d also satisfies the MOSFET characteristics and as we had seen that this is how for let us say low gate voltages this is how it looks like for slightly higher, this is how it looks like for various gate voltages.

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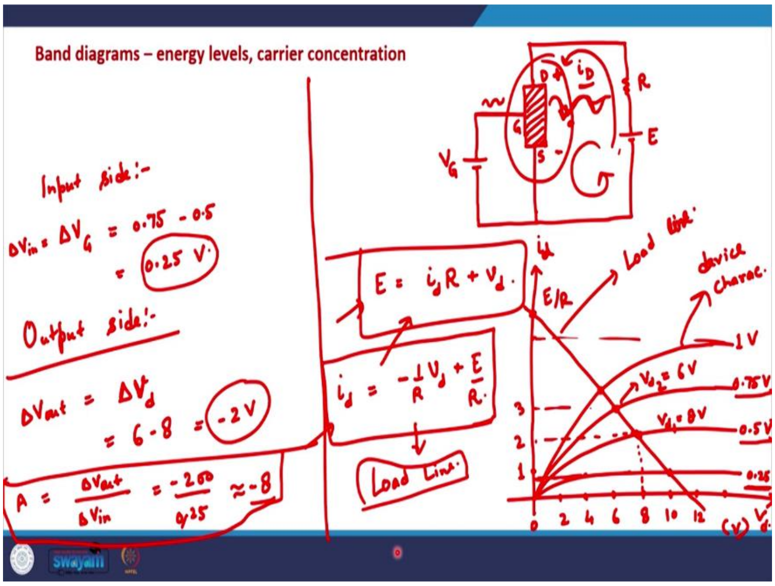

So, and if we talk in terms of real numbers let us say not in real numbers, but let us have a basic idea let us say this if this is the plot or these are at various V_G values. So, here the V_G value is 0.25, let us say 0 point here it is 0.75 sorry 0.5 here, if it is 0.5 volts here, 0.75 volts here and 1 volt here.

And on the i_d- V_d plane if this black box device let us say has although that is not true these are not the real numbers. Please, do not consider them to be the real numbers this intersection here is $\frac{E}{R}$ generally it could be let us say it is 0 volts, it is 2 volts, 4 volts, 6 volts, 8 volts, 10 volts, like this 12 volts all in volts ok.

So, now as you can see that the i_d and V_d values in this circuit will be those values where this KVL line also known as the load line of the circuit this KVL the load line of the circuit intersects with the device characteristics. So, these are the device characteristic lines this is the device characteristics, this is the load line. And the operating point load line the operating point will be at the intersection points because at the intersection points both KVL and device characteristics are satisfied ok.

So, as we can see that let us say if we want if we are changing the gate voltage from 0.5 volts to 0.75 volts ok. It means that now the device characteristics is shifting from this point to this point and at this point the i_d value is let us say there is some i_d value here let us say 2, here it is 3 mili amperes or anything we are just talking quantitative. So, here the

V_d value is around 8 volts, here the V_d value is around 6 volts. So, let us say this is V_{d1}, this is V_{d2}.

So, if we are changing the gate voltage from 0.5 volts to 0.75 volts from this point to this point it is changing the drain voltage from the value of 8 volts to 6 volts ok. So, it means that on the input side the gate voltage is being changed from 0.5 to 0.75.

So, the change in the gate voltage is 0.75 to 0.5 which means 0.25 volts this is the let us say this is the input side Δv_{in}. On the output side the voltage that is reflected through the device here the change the voltage output is Δv_d essentially and the Δv_d value is 6 volts minus 8 volts it is around minus 2 volts.

So, if we are changing the input voltage the gate voltage by 0.25 volts the output voltage is being changed by -2 volts. So, which means that the gain or the amplification it is - 2 divided by 0.25. So, it is around -8. So, the change in the output voltage is 8 times as compared to the change on the input voltage.

So, only a small change here only a small signal here is actually reflecting as a large signal here and that is the amplification mechanism that is very qualitatively the amplification mechanism of the transistors especially the field effect transistors.

And; obviously, proper DC biasing conditions need to be maintained. So, there is in this amplification no energy is getting produced out of 0. So, it is not as if we are able to produce a large signal out of a small signal it is not that because we need to maintain the proper DC biasing conditions. So, there is a net loss of energy, but a small AC signal can be converted into a large AC signal and that is how the amplification can be achieved in the MOSFETs ok.

Similarly, the switching can also be understood from this plot although switching is clear from the device design as well, at 0.25 volts let us say when the gate voltage is 0.25 volts the current across the device is very low and the when the gate voltage is let us say 1 volt the current is extremely high. So, just by changing the gate voltage we are able to switch from a low current state to high current state we are able to switch on the channel in the device, so that the current can flow.

So, this is qualitatively how the amplification is achieved in MOSFETs ok and as you can see this non-linear characteristics the non-linear characteristics of the MOSFET place quite a crucial role in this. One is the non-linear characteristics and second is the sensitivity to the gate voltage.

So, even if there is a small change in the gate voltage the channel can either be there or may not be there and that reflects in a huge change across the drain terminal on the I-V characteristics and that is how this amplification is achieved.

So, now I hope this idea is clear this idea of amplification in these devices is clear. Now, let us see how sort of how the band diagrams or how the energy levels and as a consequence of that how the carrier concentration is there in these devices ok.

So, in this as you can say that the most important part as you can see that the most important part of the device is this essentially, which is essentially this 2 terminal device and this third terminal also plays quite a crucial role, but the current flows in this direction in an n - MOS let us say. So, we need to we first we will see how the band diagrams look like in this direction.

Since, MOSFET is a 3 dimensional device. So, we can have or we can try to understand we can see the band diagrams in different dimensions in different orientations and that will give us different informations. But, the most important direction of operation of MOSFET is this one from the source to the drain because this is the direction in which the current flows ok.

So, in this direction as you can see that we have let us take the case of n - MOS and in the n - MOS in this direction let us call this direction to be the x direction. In this direction we have an n type material here on one side again n type material, on the other side and in between we have a p type material. So, there are sort of two junctions in this direction that we will encounter if we traverse from source to the drain terminal ok.

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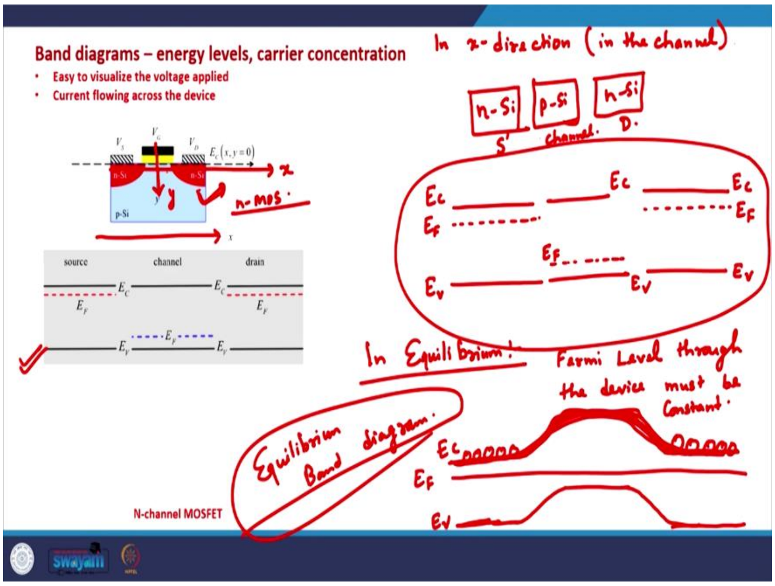

And if we in this direction in the x direction let us say if we are taking the case of n - MOS in which the channel is n type, the body is p type, we have n type source contact, we have n type drain contact and this direction the direction of the current is taken to be the x direction. The direction perpendicular to the current direction or the direction from the gate terminal to the body terminal is taken to be the y direction.

So, if we travels from source to the drain in the x direction we first go through an n type material then a p type material and then n type material. And this is how the bands look like in these materials when they are far apart from each other.

So, in this device in x direction in the channel we have n silicon source, we have p type silicon in channel and again n type silicon in drain ok.

Let us say that let us sort of assume for a moment that they are not joined with each other in that case and they are far apart from each other all these three type of materials are far apart from each other in that case the situation will be something like this. We will have n silicon, p silicon and n silicon far apart from each other. And the band diagrams of these regions of the device in an n silicon, we have a conduction band edge here, the valence band edge here and the fermi level is quite close to the conduction band minima.

In the p type regime we have the valence band maxima, E_v the conduction band minima, E_c and the fermi level is close to the valence band maxima. Similarly, in the n type drain terminal we have the valence band, the conduction band and the fermi level is again quite close to the conduction band minima.

So, this is the sort of the energy levels this is how the energy levels will look like and the most important energy levels in any device is the band edges the conduction band minima and the valence band maxima and the fermi level. So, most important levels are band edges and fermi level and this is what we have shown in the band diagram when these three materials are not joined with each other.

When this we make a MOSFET these three when the MOSFET is sort of fabricated these three regions are joined in that case just sort of think how this band diagram will look like, just take a moment and think about it how this band diagram will look like when n silicon, p silicon and n silicon are joined with each other.

And the source channel and drain are joined with each other in equilibrium, in equilibrium means that we have not applied any voltage and across the device no current is flowing through the device in that case how would the band diagram look like, just think about it for a moment

In equilibrium if you recall our discussion on the fermi level and fermi functions; the fermi level throughout through the device must be constant, which means that we can have only a single level throughout the device in equilibrium.

So, in order to make the equilibrium band diagram we need to sort of draw a single fermi level let us say, this is how let us say this is the fermi level, far away from the junction of source and channel the conduction band edge will be here the valence band edge will be here ok.

Similarly, far away from the junction in the channel the conduction band edge is here, the valence band edge is here. Similarly, far away from the junction in the drain region the conduction band edge is here, the valence band edge is here and at the junctions these edges must be joined with each other ok. So, this is E_c this is E_v and this is the fermi level that is constant throughout the device.

So, this is the equilibrium band diagram and it is an interesting band diagram actually because this explains a lot of things about the MOSFETs. As you can see that in this band diagram we have the conduction band edge here, on source side on the drain side also here in between the conduction band edge is slightly elevated.

So, this is sort of a barrier in the conduction band minima that is there in the channel region and this barrier is actually this barrier is what stops electrons here and here to move to the other side and this barrier is quite central to the functioning of the MOSFET and this is what we will try to understand in the next class ok.

Thank you all. See you in the next class.