Physics of Nanoscale Device
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Lecture - 35
Introduction to MOSFET

Hello everyone today we will be starting a new topic and we will be introducing or we will be discussing the MOSFET as a device. So, MOSFET as we know is a 3 terminal device till now we have been discussing the theory of transport in a 2 terminal device, but now we in order to sort of use that theory in actual devices in actual transistors we will have a look at how the MOSFET looks like and what is the basic physics of the MOSFET.

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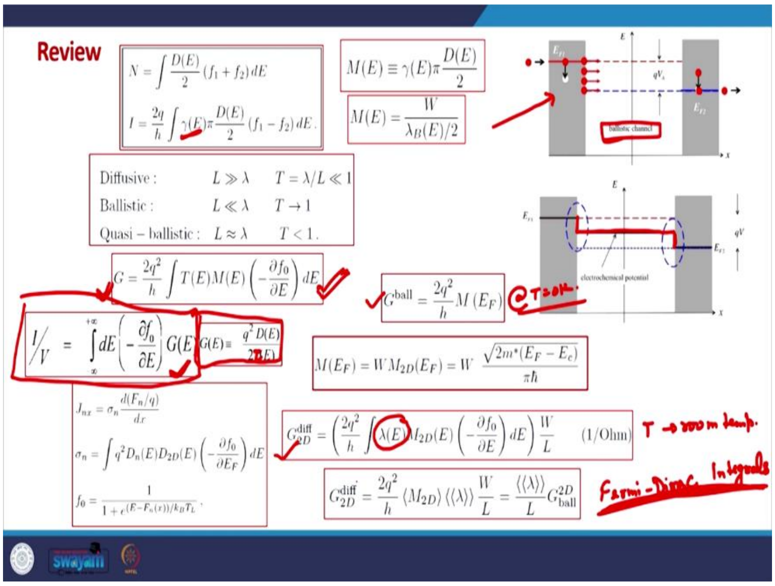

Review

$$N = \int \frac{D(E)}{2}(f_1 + f_2)\,dE$$

$$I = \frac{2q}{h}\int \gamma(E)\pi\frac{D(E)}{2}(f_1 - f_2)\,dE.$$

$$M(E) \equiv \gamma(E)\pi\frac{D(E)}{2}$$

$$M(E) = \frac{W}{\lambda_B(E)/2}$$

Diffusive : $L \gg \lambda$ $T = \lambda/L \ll 1$

Ballistic : $L \ll \lambda$ $T \to 1$

Quasi − ballistic : $L \approx \lambda$ $T < 1.$

$$G = \frac{2q^2}{h}\int T(E)M(E)\left(-\frac{\partial f_0}{\partial E}\right)dE$$

$$G^{\text{ball}} = \frac{2q^2}{h}M(E_F)$$

@ T=0K.

$$I/V = \int_{-\infty}^{+\infty} dE\left(-\frac{\partial f_0}{\partial E}\right)G(E) \qquad G(E) \equiv \frac{q^2 D(E)}{2\tau(E)}$$

$$M(E_F) = W M_{2D}(E_F) = W\frac{\sqrt{2m^*(E_F - E_c)}}{\pi\hbar}$$

$$J_{nx} = \sigma_n\frac{d(F_n/q)}{dx}$$

$$\sigma_n = \int q^2 D_n(E) D_{2D}(E)\left(-\frac{\partial f_0}{\partial E_F}\right)dE$$

$$f_0 = \frac{1}{1 + e^{(E - F_n(x))/k_B T_L}},$$

$$G^{\text{diff}}_{2D} = \left(\frac{2q^2}{h}\int \lambda(E) M_{2D}(E)\left(-\frac{\partial f_0}{\partial E}\right)dE\right)\frac{W}{L} \quad (1/\text{Ohm})$$

T → room temp.

$$G^{\text{diff}}_{2D} = \frac{2q^2}{h}\langle M_{2D}\rangle\langle\langle\lambda\rangle\rangle\frac{W}{L} = \frac{\langle\langle\lambda\rangle\rangle}{L}G^{2D}_{\text{ball}}$$

Fermi-Dirac Integrals

So, before going into this new topic let me quickly review what we have been discussing since last few classes and this is what we have sort of seen in the general model of transport. So, in last few classes we have been discussing in detail the general model of transport and in the general model of transport we saw that this is the steady state number of electrons in the device and this is the steady state current in the device in terms of the density of states in the channel and the Fermi functions of the contacts ok.

So, in terms of basic device parameters we could deduce the steady state number of electrons and steady state current in the device.

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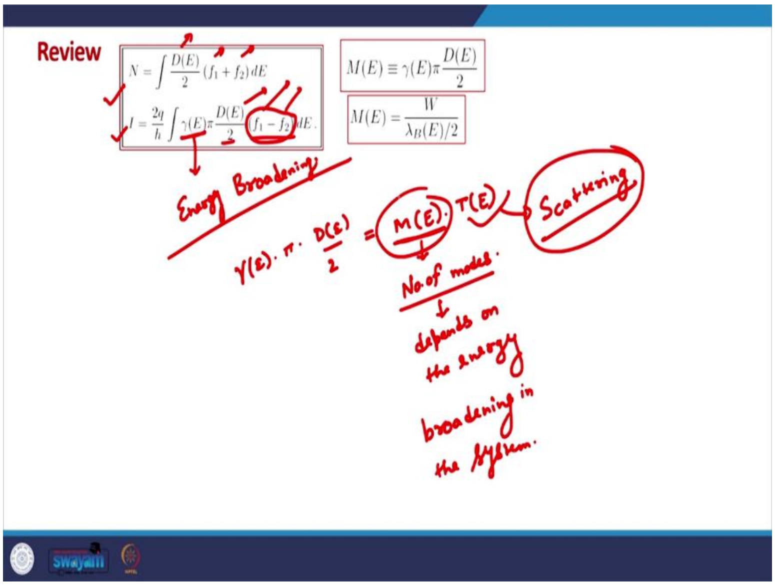

Review

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$$M(E) = \frac{W}{\lambda_B(E)/2}$$

Energy Broadening

$$\gamma(E)\cdot\pi\cdot\frac{D(E)}{2} = \underbrace{M(E)}_{\text{No. of modes}}\cdot T(E) \rightarrow \text{Scattering}$$

No. of modes.
↓
depends on
the energy
broadening in
the system.

Then in the current expression in addition to the density of state and Fermi functions we have this parameter as well which is known as the energy broadening due to electron transport in the device. And in ballistic transport case this is actually this makes sense to call it energy broadening in the case of ballistic transport.

In the case of diffusive transport this term this $\frac{\gamma(E)\pi D(E)}{2}$ is actually written as M(E) times T(E); where M(E) is the number of modes and it depends on the energy broadening in the system ok and this T(E) in the case of diffusive transport it accounts for the scattering in the channel. So, this accounts for the scattering of electrons with the atoms or other impurities in the channel.

So, in a way in the current expression apart from the Fermi functions we account for the scattering and we account for the modes ok. So, this is an extremely important expression that we need to use when we deal with a new device or when we deal with or when we try to understand the transport in a more fundamental way even in our conventional nanoscale devices.

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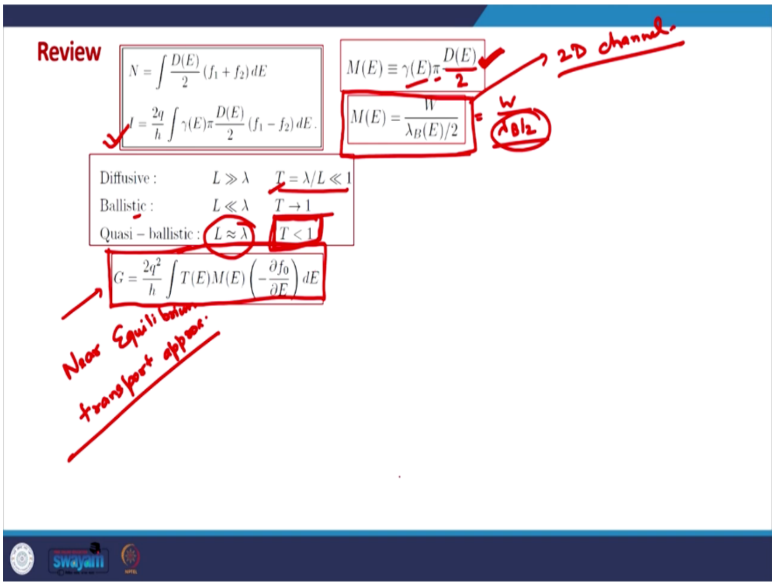

Review

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$$M(E) = \frac{W}{\lambda_B(E)/2} = \frac{W}{\lambda_B/2}$$

2D channel.

Diffusive :	$L \gg \lambda$	$T = \lambda/L \ll 1$
Ballistic :	$L \ll \lambda$	$T \to 1$
Quasi – ballistic :	$L \approx \lambda$	$T < 1$

$$G = \frac{2q^2}{h}\int T(E)M(E)\left(-\frac{\partial f_0}{\partial E}\right)dE$$

Near Equilibrium transport approx.

In this discussion this notion of modes come out which is defined as $\frac{\gamma(E)\pi D(E)}{2}$ ok and this is also written as $\frac{W}{\lambda_B/2}$where λ_B is the De Broglie wavelength of the electrons. So, this is quite an important I would say understanding of the modes; modes is the number of half De Broglie wavelength of electrons that can fit into the width of the device width and in this case it was a 2D channel device ok.

So, after this discussion we saw that we need to introduce the transmission coefficient in the case of diffusive transport and the transmission coefficient is always less than 1. And building on the same lines the transmission coefficient for the ballistic transport approach is 1 and for the quasi ballistic systems which means that when the length of the channel is of the same order as the mean free path this is less than 1, but not far away from 1 it is actually quite close to 1, but less than 1.

Then from this using near equilibrium transport approximation using this approximation we could deduce that the conductance of the device is given by this expression conductance can be written as $\frac{2q^2}{h}\int T(E)M(E)(-\frac{\partial f_0}{\partial E})dE$.

And this is a very important again I would say this is a very important expression because in our discussion of conductance and resistance and we saw that if we start with this expression, then we can account for the resistance or conductance for a ballistic device and as well as for a diffusive device. Our conventional theory of resistance our conventional understanding of resistance or conductance that breaks down when we go to the ballistic regime. And in that regime we need to start with this point.

This conductance function can in other words be written as the average of the conductance function; this conductance can be written as average of the conductance function in the Fermi window using this expression where, the conductance function G(E) is given as $\frac{q^2D(E)}{2\tau(E)}$; where this $\tau(E)$ is essentially the transit time that we have been discussing which is also related to the energy broadening in the channel ok.

So, using this expression we could see that the ballistic conductance at 0 Kelvin at very low temperatures is given by this expression or this is actually and at room temperatures we need to calculate using this kind of expressions. For example, in this expression if we remove λ(E), then this will be the ballistic conductance at room temperature this is the room temperature situation this is at T equal to 0 Kelvin.

While we try to calculate the resistance or conductance at room temperatures we invariably encounter a new kind of integrals and those are known as the Fermi Dirac integrals. And we also saw that in the case of non degenerate semiconductors these integrals can be simplified and the calculations can be done otherwise calculation of those integrals is extremely difficult if you want to do it directly without using any approximations.

But, with the Fermi Dirac integrals and some approximations for example, the Fermi Dirac integral boils down to an exponential function for non degenerate semiconductors using that kind of approximations we can make calculations we can do calculations for the conductance at room temperature both in ballistic transport case and in the diffusive transport case ok.

Then with this we also sort of now with a better understanding we also discussed where is the power dissipated in the device. So, and we could see that the power dissipation happens in the contacts; in the ballistic transport; in the ballistic channel, the power is not dissipated in the channel the power is dissipated in the contacts. And the reason for this is that the contacts are big and the contacts maintain near equilibrium situation because of lot of scattering happening in the contacts ok.

Similarly, in a ballistic channel in a ballistic device the voltage drop is equal to the conventional voltage drop, but the voltage drop now happens only on the contacts, the voltage drop does not happen in the channel. So, the resistance of a ballistic channel is because of the contact or because of the interface between the or this is accounted by the contact and channel combination essentially ok.

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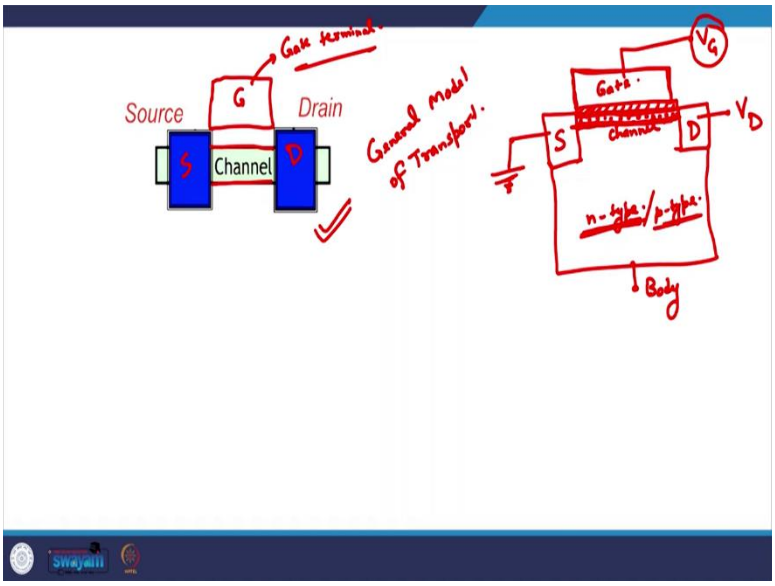

So, with this now this is actually the device that we took for our analysis and took for our analysis in the general model of transport which we discussed in a good detail. This is a 2 terminal device in which there is a source, there is drain and we have a channel in between.

Now, our real transistors the transistors that we use in our cell phones or in our computers those are 3 terminal device and in addition to these two terminals there is an additional third terminal which is somewhere over here and this is known as the gate terminal.

More precisely we have the channel, we have a source, we have a drain, we have a small very thin insulator layer here and on top of this we have the third contact known as the gate contact. And in our conventional semiconductor MOSFETs generally this is how the device is and this remaining contact is known as the body contact and this is the fourth contact it is not extremely important. In order to understand the essential physics of the MOSFETs we will try to understand it from the 3 terminal point of view and then finally, we can account for the body contact as well.

So, this is how typically the MOSFET looks like. So, let us say it has in addition to these two terminals source and drain terminals there is a small very thin generally a very thin layer of insulating material and on top of that insulating material there is this third terminal where we can apply the gate voltage. Generally the source terminal is most of the times grounded and generally we apply voltages on either on drain terminal or on the gate terminal.

So, this between the two terminals the source and the drain terminals we have this semi conducting material this can either be n type material or a p type material and depending on the type of semiconducting material here this channel is actually made of. So, if this is n type material and we want a p type sort of we have a channel in which there is a lot of sort of inversion layer just below the gate contact. This inversion layer will be made of the holes here and that inversion layer comes into picture because of an applied gate voltage.

So, if we have n type body the channel material is n type material and if we apply a negative voltage on the gate terminal it will essentially repel the electrons and it will pull the holes on the interface between the channel and this oxide. And that will lead to a lead to sort of inversion of the channel material from this side at the interface and that will make a small a very thin layer of conducting channel in this device and this thin layer of conducting channel it depends on the applied gate voltage ok.

So, once this thin layer of holes is there once this channel becomes conducting, then if we apply any voltage on drain or source terminals, then it may start a current in the system ok. And similarly if we might also have a p type channel in which on application of a positive gate voltage we can have a small layer of electrons here just below the oxide we can have a thin layer of electrons and in that case the channel becomes conducting because of the electrons just below the insulating material..

And once this small a very thin layer of electrons is there, then this then a current may start if we apply any voltage on the drain terminal or if we apply a voltage difference between the drain or the source terminal.

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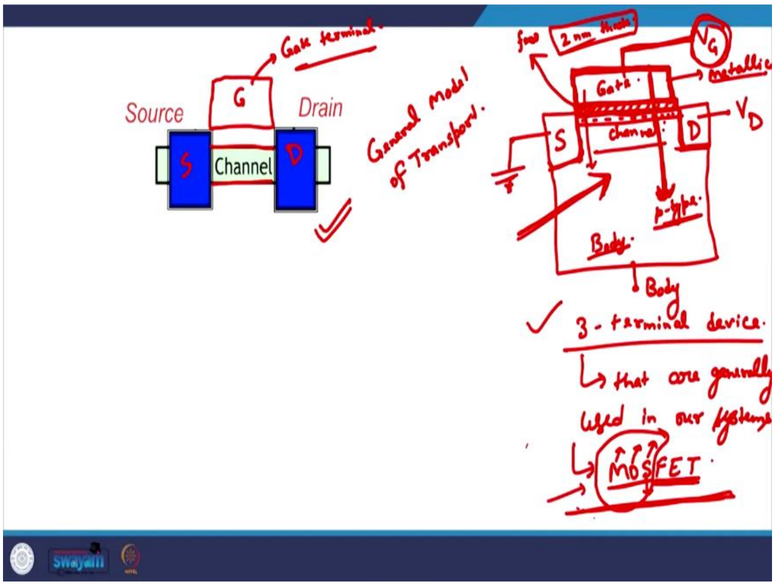

So, this is the sort of 3 terminal device that are generally used in our systems these are known as MOSFETs ok. This the full form of the MOSFET is Metal Oxide Semiconductor Field Effect Transistor. Metal oxide semiconductor means that this terminal gate terminal is like a metallic contact this is metallic in nature. And then we have a thin layer of oxide O, M is for the metallic nature of the gate and below this oxide we have a semiconducting material which is essentially the channel material.

And in a combination with these metal oxide semiconductor if we put two contacts on the sides of this channel this will make a MOSFET and in the MOSFET the second part of the MOSFET essentially means the field effect transistor. The field here means is the electric field. And what is the meaning of field effect transistor? It means that the functioning of this device is dependent on the electric field that is generated by the gate voltage.

So, the gate voltage that we apply that essentially generates an electric field in this direction and that essentially governs the functioning of this kind of device and that is why it is known as the field effect transistor because this electric field because of the gate voltage it either creates a channel or creates a conducting pathway between the source and the drain or it sort of disallow the creation of the conducting pathway or it does not allow the conduction to happen between the source and the drain.

So this mechanism or this the transport of electron or the functioning of this kind of device it is dependent on the electric field that is generated by the voltage applied on the gate terminal and that is why this name is there Metal Oxide Semiconductor Field Effect Transistor. There is a small point that we need to keep in mind here that even though we apply a voltage on this terminal the gate terminal, but there is no current in the device in this direction from the gate to the channel or from the gate to the body.

And the reason for that is that there is this insulating layer of oxide that is sitting just below the gate terminal that essentially disallows the electrons to go from gate terminal to the channel. Although this oxide is nowadays is only few nanometers thick it is it might be around 2 nanometer thick and some electrons if the sufficient energy is available and some electrons in some conditions if they can see the empty states in the right direction they can tunnel through this.

So, there is a small tunneling current that might be there in this direction, but apart from that in an ideal case there is no current that flows from the gate terminal to the body or from gate to the channel.

So, that is why only the electric field plays the role the crucial role in switching on or switching off the MOSFET and that is why this is known as the field effect transistor. If you recall the theory of bipolar junction transistors in bipolar junction transistors it is the current that essentially plays important role in switching the transistor switching it on or switching it off ok.

In this case it is the electric field applied on the electric field due to the voltage on the gate terminal that is extremely important and that is why this nomenclature actually comes from that is where it comes from. So, this is the kind of 3 terminal device that we will be that is extremely important actually that is at the heart of all our electronic systems nowadays most of our electronic systems nowadays and it is a very natural extension or a natural generalization of this kind of 2 terminal device ok.

So, while discussing this 2 terminal device we assume that there are charge carriers available in the channel for conduction ok. In this 3 terminal device these charge carriers essentially that are available for conduction they come from or they arise because there is a voltage applied on the gate terminal there is an electric field due to the voltage on the gate terminal ok.

So, that is why the most of the analysis of the transport that we did for this 2 terminal device that can easily be extended to the 3 terminal device and that was essentially the point of first understanding everything about the 2 terminal device like a device in this figure and then generalizing that to the 3 terminal device that is shown here ok.

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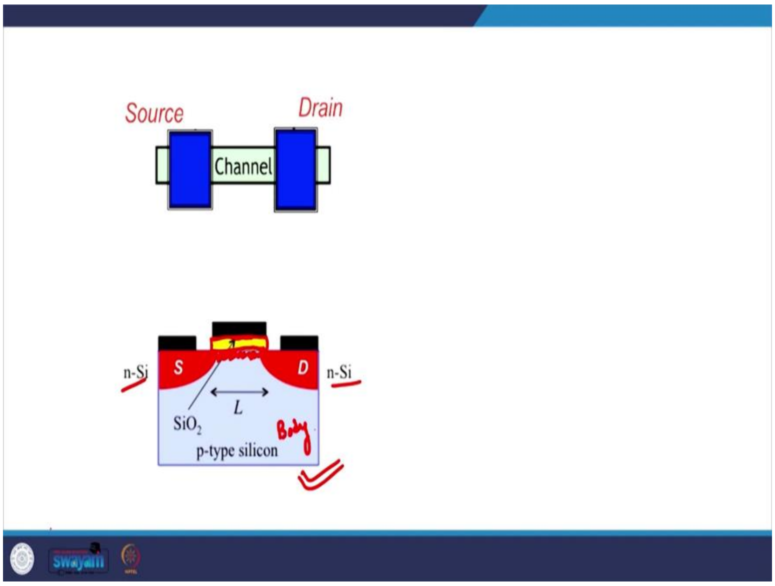

So, this is how actually the MOSFET is generally drawn out, this is a typical picture of a MOSFET we might have a p type as a body of the MOSFET p type semiconductor and with the p type semiconductor the source and the drain terminal are the heavily doped n type silicon.

And between the source and the drain this region is the channel region this region is where the channel will be formed and above this region there is a small a very thick sorry very thin layer of oxide which is the silicon oxide here SiO2 in this case because in this case we are using silicon as the semiconducting material.

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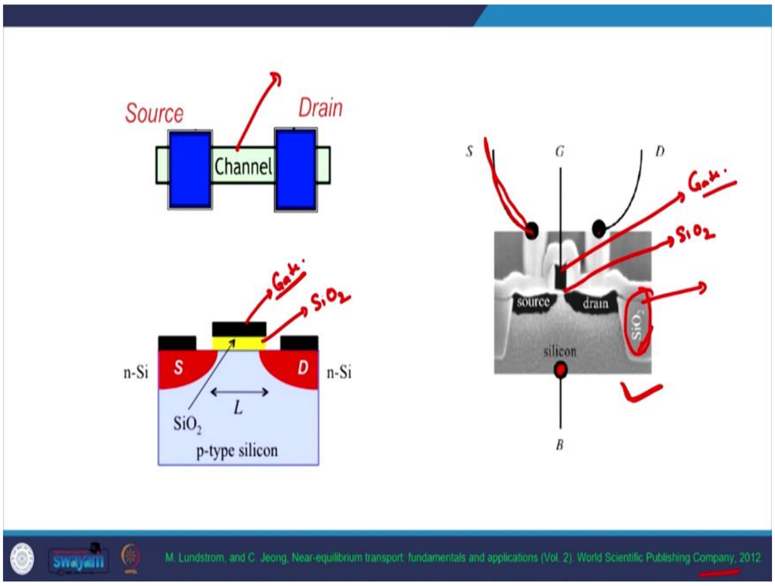

M. Lundstrom, and C. Jeong, Near-equilibrium transport: fundamentals and applications (Vol. 2). World Scientific Publishing Company, 2012.

So, the body is the p type silicon the source and the drain are heavily doped n type silicon this oxide is SiO2 silicon dioxide and on top of that we have a metallic gate or this might also be an extremely heavily doped semiconductor which behaves like a metal. So, and this is a typical picture of a real MOSFET this is how a real MOSFET actually looks like.

So, this picture is now I guess quite old it is around 7, 8 years old and this is taken from this reference or may be around 10 years old. In this case as you can see that this here we have the source contact, we have the drain contact these are heavily doped contacts and in between there is a very small channel region.

And this is what I have always emphasized during our discussions that this channel region is extremely small as compared to the source and the drain in the actual device. And that is evident from here that is evident from a real MOSFET that this channel region is extremely small and the source and the drain regions are quite large as compared to the channel region.

Just above the channel region we have very thin layer of silicon dioxide and on top of that we have the gate terminal. These source and drain terminals they are connected to the external circuitry via the source contact and the drain contacts as is seen in this picture and this rest of the body of this device is known as the B terminal and generally we have a point terminal point on the B terminal as well.

And nowadays typically we fabricate lot of transistors on the same piece of silicon, same piece of semiconductor and in order to separate the adjacent transistors we use the insulating layers in between like the silicon dioxide layer a thick silicon dioxide layer as is shown in the sides of the drain terminal.

So, this is how an actual MOSFET looks like and I would say that this region is an extremely important part of the entire device and this region is very small as compared to the entire device as compared to this big device.

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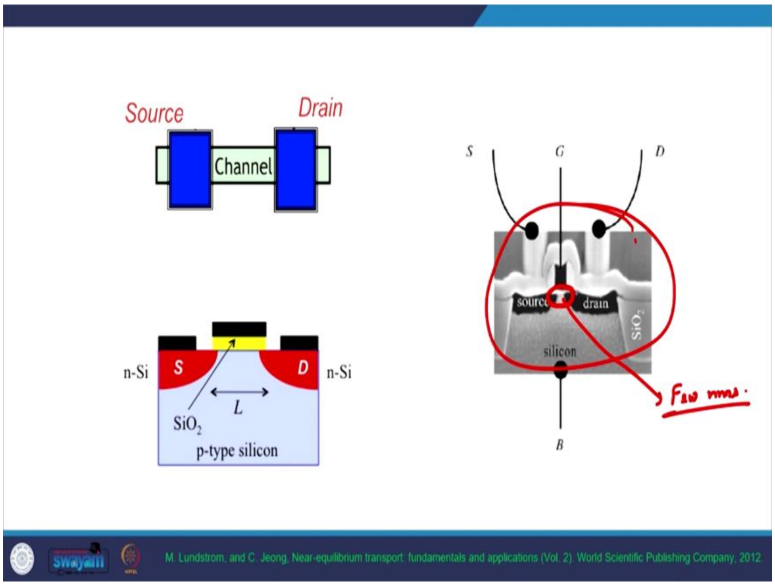

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And typically this is now in modern day devices this is few nanometers around tens of nanometers nowadays, only few nanometers is there. And that is why we need to account for all the nanoscopic nano scale effects that arise because of the quantum mechanical nature or because of the ballistic transport of the electron in these kind of systems.

And that is why we first try to understand the ballistic transport and for that we did a bit of quantum mechanics and how the ideas from quantum mechanics can be used to understand the ballistic transport and the diffusive transport. And that will be extremely important while understanding the modern day nano scale MOSFETs ok.

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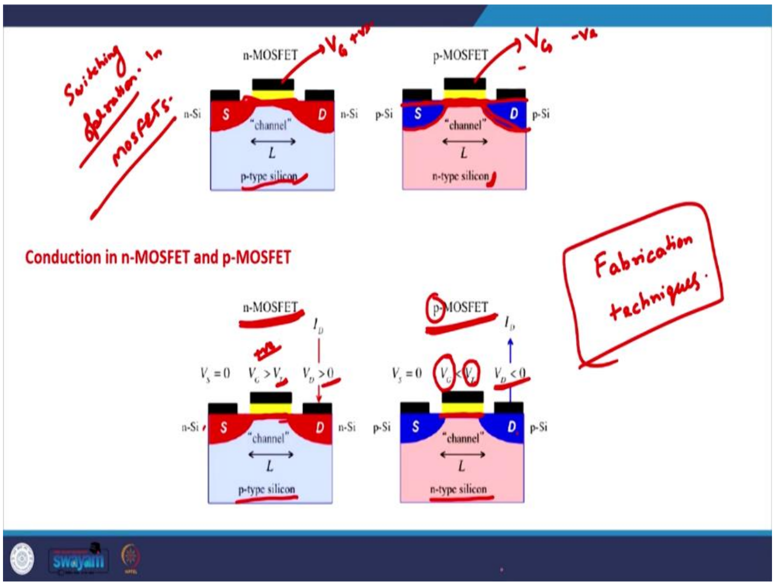

Conduction in n-MOSFET and p-MOSFET

So, there can be two type of MOSFETs actually in one type of MOSFET this body and this point I have also mentioned briefly that the body can be the p type silicon and the source and the drain contacts can be heavily doped n type silicon material from made from the heavily doped n type silicon material. Or we can have the n type the body made out of n type silicon material and source and drain contacts made out of heavily doped p type silicon material ok.

And these two cases have been shown here when the body is p type silicon generally the channel region that we obtain after the inversion of the material after we apply a gate voltage here and we will apply a positive gate voltage in this case that will pull a lot of electrons to the interface between the oxide and this, the body and that will make a n type channel.

And that is how this as you can see that we have the n type source we have n type drain and there will be a very thin layer of electrons here and in this small region this channel or the body will behave as if body will behave like an n type silicon material.

So, there will be this part of the device will behave like a resistor and that is how this is known as the on condition of the device that is how the device is turned on. And if we apply a negative voltage that will essentially turn off the device and that is essentially the switching operation in the MOSFETS.

Similarly, we have when the body is n type silicon material, if we apply a negative voltage on the gate terminal the negative voltage on the gate terminal in that case it will a very thin layer of the channel of any thin layer of the body will become positively charged because it will attract lot of holes towards it.

And from the source right up to the drain we will have a sort of a continuous p type material or a we will have like a conductor sitting between the source and the drain and that is how this transistor is actually operated ok.

So, this is the summary of conduction in n MOSFET and p MOSFET and in n MOSFET; n MOSFET means that the channel is n type channel is made out of electrons which means that the body is p type in this case the gate voltage should be positive and it should be above a certain threshold voltage when the channel is formed.

So, the gate voltage should be above a certain threshold voltage in order to make the channel in the body and this is the positive voltage the source terminal is generally kept at ground and generally we apply a positive voltage on the drain terminal and that is how the electrons go from the source to the drain or the current flows from the drain to the source and that is how this essentially works.

Similarly, in the p MOSFET in which the channel is p type that is where this name p MOSFET comes from which the body is n type silicon, the contacts are p type silicon. And if we apply a sufficiently large negative voltage there will be a p type this body will become p type in a small region just below the oxide and this is known as the p type channel and the voltage that makes a channel in the body is known as the threshold voltage.

And the gate voltage should be below the threshold voltage in the p MOSFET in order to sort of create a channel in the body of the n type silicon material. And then if we apply a negative voltage on the drain terminal and 0 voltage on the source terminal the current will flow from the source to the drain and holes will flow from the source to the drain, ok.

So, the please keep these minute differences in mind that the current direction in p type and in p MOSFET and n MOSFET is reversed to each other ok. So, these are some basic details about the MOSFET, the 3 terminal device that are actually important in our modern day applications and I would recommend you to go back and study about the fabrication techniques of the MOSFETS.

So, that is like a homework reading for you, the fabrication techniques of the MOSFETs and we will discuss more about the theory of conventional MOSFETs and once we understand the conventional MOSFETs, then we will see how things are different in ballistic MOSFET or in modern day nano scale MOSFETS.

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