

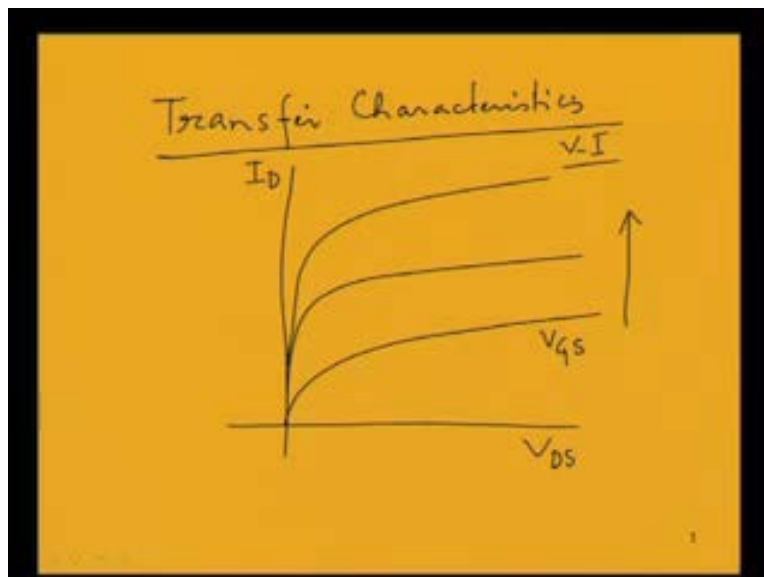
Basic Electronics
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Module: 3 Field Effect Transistors
Lecture-2
Metal Oxide Semiconductor Field Effect Transistor (MOSFET) Part - 2

In the last class we have studied about n-channel enhancement type MOSFET. We have seen the VI characteristic of this n-channel enhancement type MOSFET. Now we will study the transfer characteristic for the n-channel enhancement type MOSFET. We will see how to draw the transfer characteristic. First of all what is a transfer characteristic? What does the transfer characteristic mean? The transfer characteristic is the relation between the input and output. For this n-channel enhancement type MOSFET, the input is the voltage between gate and source and the output is the drain to source current. If we vary the gate to source voltage then the drain to source current will vary. The controlling quantity is the gate to source voltage. From the transfer characteristic we can know about the behaviour of the device.

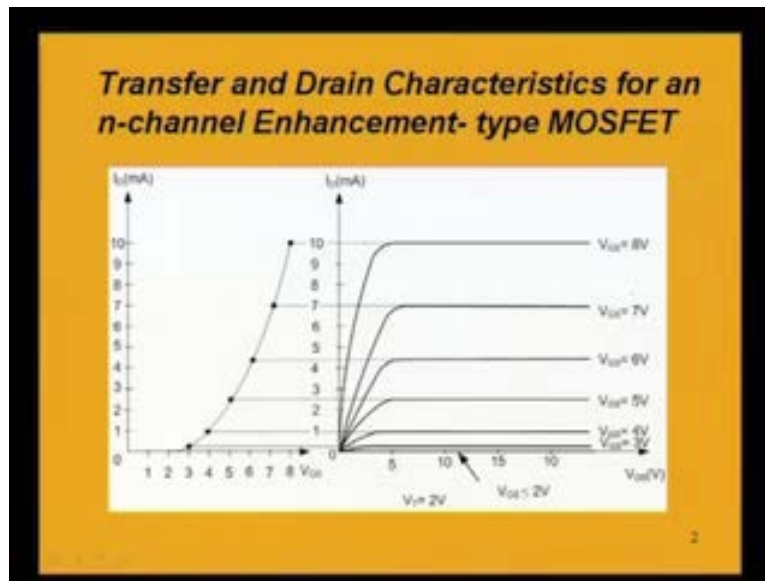
Let us try to draw the transfer characteristic for this n-channel enhancement type MOSFET. We know about the VI characteristic that is the characteristic between the drain current and the drain to source voltage for various values of gate to source voltage. We basically have seen in the last class how for various values of the gate to source voltage we get the plots between the drain current and the drain to source voltage. From this VI characteristic or drain characteristic we can draw the transfer characteristic.

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We are now showing here the drain characteristic for an n-channel enhancement type MOSFET and by the side of this drain characteristic is shown the transfer characteristic. How have we got this transfer characteristic? We have in the drain characteristic or the VI characteristic the plot between the drain current and the drain to source voltage for the various values of the gate to source voltage.

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For a particular n-channel MOSFET device we know the threshold voltage. This particular device what we are considering right now is having a threshold voltage of plus 2 volt. If the gate to source voltage is below that threshold voltage then the current from drain to source will be zero and that we discussed in the last class. For gate to source voltage below 2 volt the current is zero, drain to source current is zero. We are increasing the gate to source voltage beyond 2 volt and we have these different plots, each plot for a particular gate to source voltage. For example we are varying the gate to source voltage from say 3 volt to 8 volt. For 3 volt small drain to source voltage will flow and which will be saturated after some voltage between drain to source. That voltage of saturation between drain to source also we know. That is equal to gate to source minus threshold voltage. If we are giving gate to source voltage 3 volt, $3-2$ equal to 1 volt is the saturation voltage between drain to source at which the saturation current in the drain will flow.

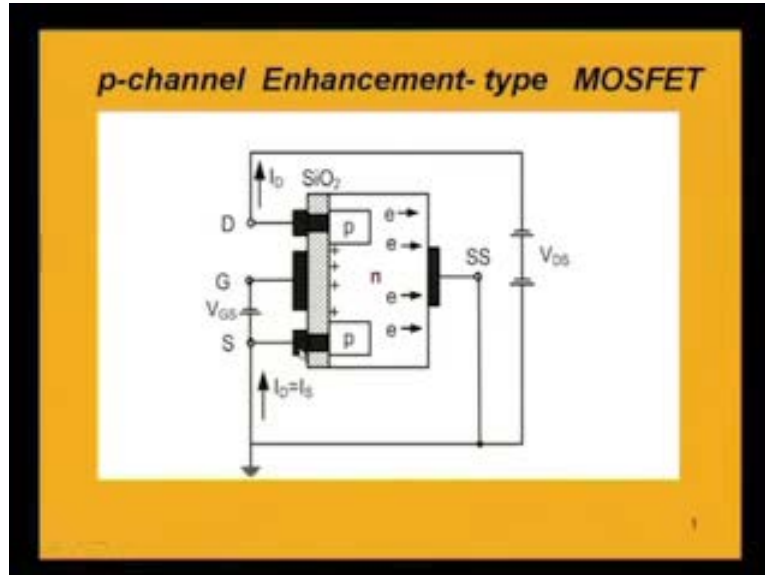
Similarly for different values of the gate to source voltage we have these plots and by the side of it if we want to draw the transfer characteristic then we must plot the points. For a particular gate to source voltage what will be the saturation drain current? That will give a point. Joining all these corresponding points we will get a curve. We will get a non-linear curve and that will be the transfer characteristic, the characteristic between the drain current and the gate to source voltage. Here in this plot we are drawing the transfer characteristic by extending the saturated current and finding out the intersecting point between these values of the saturated current with the corresponding gate to source voltage. The V and I axis will be here, gate to source voltage and the drain current. V_{GS} in

volt and the drain current in milliampere and we are plotting the VI characteristic or the drain characteristic for gate to source voltage from 3 volt onwards, 3, 4, 5, 6, 7, 8 volts. In the V axis that is V_{GS} or gate to source volt, 1, 2, 3, etc up to 8 we are marking in the V_{GS} axis. This is volt and in the y-axis, I_D axis or I_D milliampere, the current axis we are having the corresponding order of the drain current which is from 1 to up to 10. This voltage and current axis are plotted and marked accordingly. For example V_{GS} is equal to 3 volt. This is the saturation current. We extend it and this current is crossing or intersecting the V_{GS} 3 volt at this point. This is one point. The earlier point is zero current and 2 volt because for V_{GS} 2 volt which is the threshold voltage, the drain current is zero. So 2 volt and zero milliampere drain current is one point. Actually it will start from this point and it will continue. That plot can be obtained by joining all the points whose coordinates are V_{GS} and I_D .

In this drain characteristic the saturation current is just extended and the intersecting point between this saturating current and the corresponding gate to source voltage is that point which we have to obtain. For V_{GS} is equal to 4 volt say we are extending this drain current which is the saturation current beyond this axis and it is extended and it is meeting the 4 voltage gate to source at this point. Similarly for 5 voltage V_{GS} , this is the point; the saturation drain current is meeting the corresponding gate to source voltage, 5 voltage at this point. Correspondingly these are the points which can be obtained accordingly and by joining these points we get the transfer characteristic. This transfer characteristic is the characteristic which we have obtained from the VI characteristic. This n-channel enhancement type MOSFET we have discussed and we have already seen how the VI characteristic and the transfer characteristic are obtained.

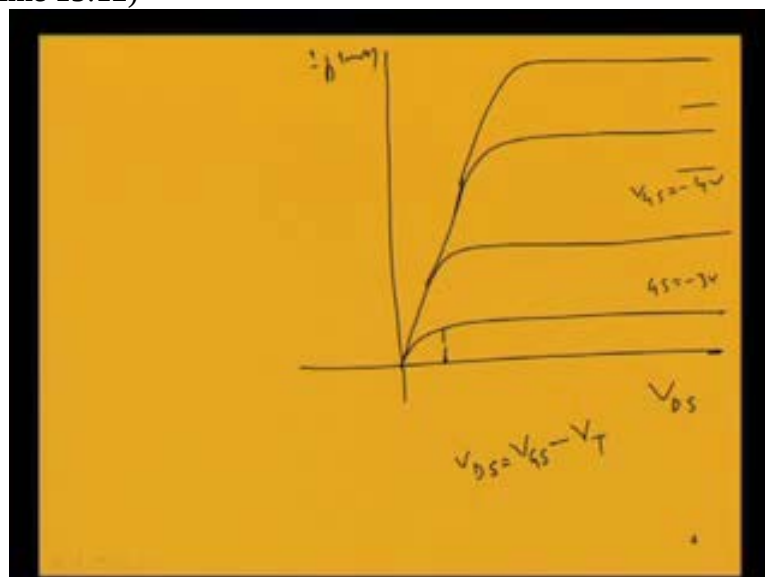
There is another type of MOSFET which we are going to study now. This is the depletion type of MOSFET. Before going to the depletion type of MOSFET, in order to complete the enhancement type MOSFET we will consider the p-channel enhancement type MOSFET because till now we have discussed about the n-channel enhancement type MOSFET. It is enhancement type MOSFET but we are considering the n-channel type. What will be the physical structure like for the p-channel enhancement type MOSFET? If you consider the physical structure of the p-channel enhancement type MOSFET, then we will have the two p-type semiconductors and the substrate will be of n-type. The gate to source voltage will have polarity as shown here. It will be negative, the gate potential will be negative with respect to the source and we will apply the drain to source voltage as shown with such polarity that the drain is negative with respect to the source. Now what will happen? As we are having a negative potential at the gate with respect to the source, the minority carriers of the n substrate which are holes they will be attracted by the gate to source voltage, negative terminal and the majority carriers of the n-type substrate which are electrons they will be repelled by the negative terminal of the gate to source voltage.

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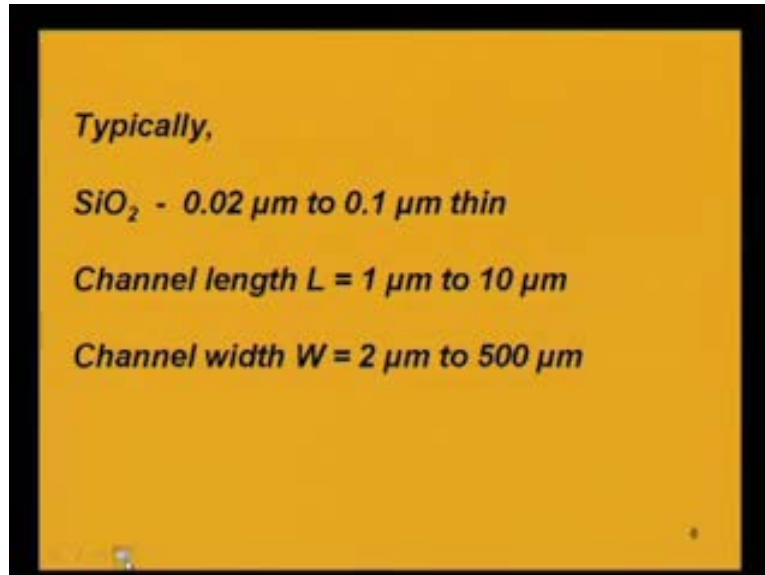
We will have a channel of holes between these two p-types. This will be a channel which will have the charge carriers which are positive and when the number of positive charge carriers are enough to sustain the current, the drain current will flow but the direction of the drain current will be as shown here and which is equal to the source current. This is just reverse of what we got in the n-channel enhancement type MOSFET. For the p-channel enhancement type MOSFET the characteristic or VI characteristic, if we plot the curves will be similar to those we have obtained in the earlier case of the n-channel MOSFET but V_{GS} is negative say -3 volt, -4 volt, etc. This will be horizontal curves like this; saturation is happening. If we have this plot of I_D versus V_{DS} for a particular gate to source voltage, then we will get saturation when V_{DS} equal to V_{GS} minus V threshold.

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Here actually the polarities of the potential are different than the earlier n-channel case and the current directions will also be accordingly. From this plot we can also draw the transfer characteristic for the p-channel enhancement type MOSFET. If we consider the values of the silicon dioxide insulating materials thickness typically it will be around 0.02 micrometer to 0.1 micrometer. That means silicon dioxide material which is the insulating material is having thin layer of around 0.02 micrometer to 0.1 micrometer thickness.

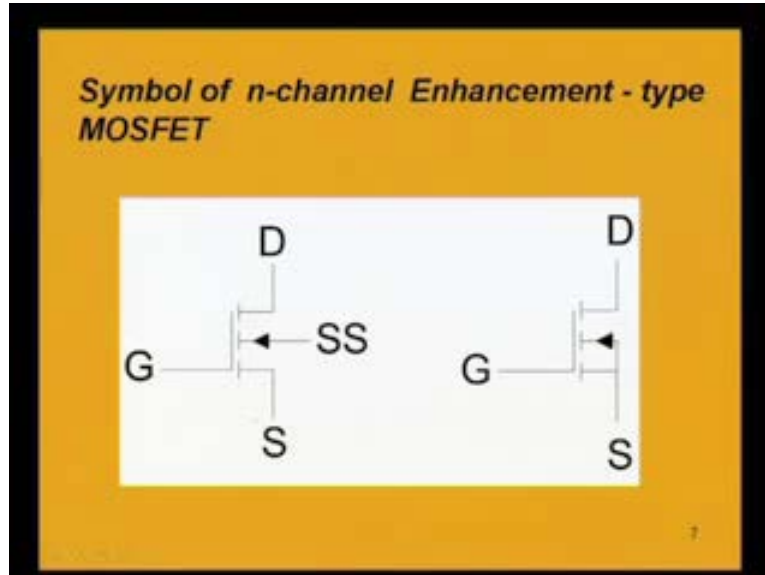
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Typical length of the channel L is from 1 micrometer to 10 micrometer and the channel width which is W is between 2 micrometer to 500 micrometer. These are some typical values or parameters for this MOSFET.

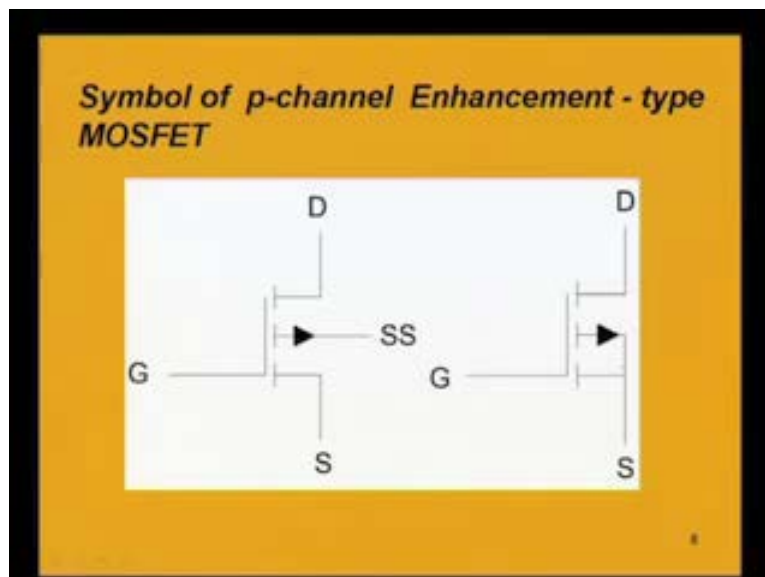
We draw the symbol for the n-channel enhancement type MOSFET. For a four terminal, n-channel enhancement type MOSFET this is the symbol having the four terminals. Here the symbol itself explicitly reflects some of the information. For the n-channel enhancement type MOSFET, this is the symbol. Here we see that there is a gap between the gate and the body. Basically this gap signifies the insulating material silicon dioxide which separates the gate from the body of the MOSFET and these three broken lines are signifying the absence of a channel between the drain and the source. Between drain and source, as you have seen there is no channel established. After we apply the gate to source voltage only we can establish a channel. That is significantly reflected by this broken lines and this is the substrate terminal. This arrow mark is signifying the direction of current between p and n because it is an n channel. In n channel, p is the substrate. So the current is from p to n. It is the normal direction of current in a p-n. That is significantly reflected by this symbol and this symbol is for external connection of the substrate terminal.

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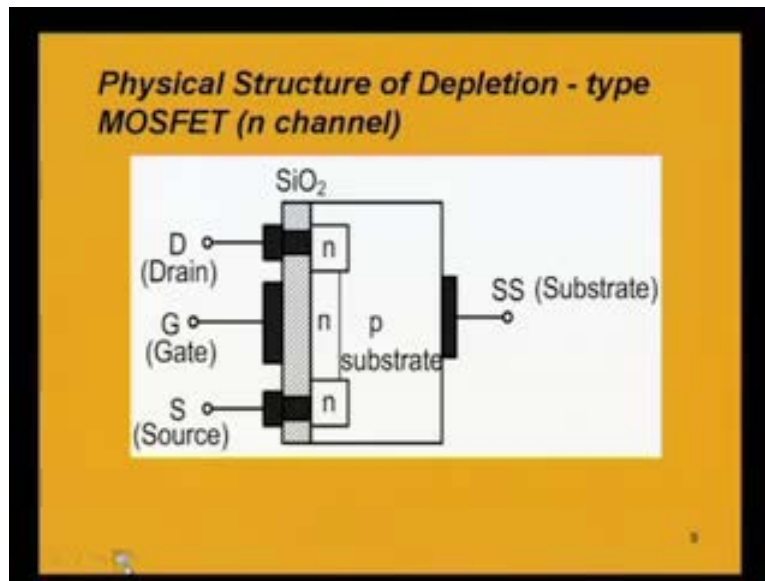
If we have internal connection of the substrate terminal between the substrate and the source then we have this symbol because here we are showing that the substrate and source are connected. This is a 3 terminal, but here it is a 4 terminal. This case is 4 terminal and this case is 3 terminal. This is the symbol for the n-channel enhancement type MOSFET. In the symbol for p-channel enhancement type MOSFET others are same but the direction of the arrow. It is a p-channel means the substrate is n, so the current direction is from p to n and this is the 4 terminal and this is the 3 terminal symbol.

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Now we will discuss about another type of MOSFET which is the depletion type MOSFET. We have discussed about the enhancement type MOSFET. Now we will discuss about the depletion type MOSFET and let us first discuss n-channel depletion type MOSFET. There are n-channel as well as p-channel depletion type MOSFET but we will discuss first about the n-channel depletion type MOSFET.

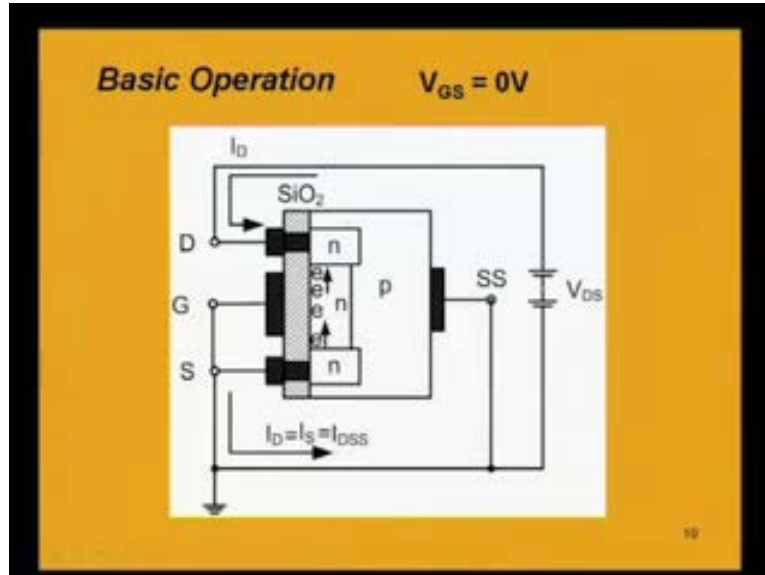
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The physical structure for the n-channel depletion type MOSFET is shown here. The substrate is p. The drain and source are made of n-type materials but one difference from the enhancement type MOSFET is that there is an n-type material as a channel between drain and source which already exists. In enhancement type MOSFET we did not have a channel or we did not have n-type or p-type material in between the drain and source. The region between drain and source was not having any channel but here an n-type material exists between the drain and the source. We already have an n-channel others being same. We have the drain terminal, gate terminal and source terminal taken out from the metal contacts which are grown over the silicon dioxide and the substrate terminal. This is the four terminal case. The physical structure of the depletion type MOSFET is as shown in this figure.

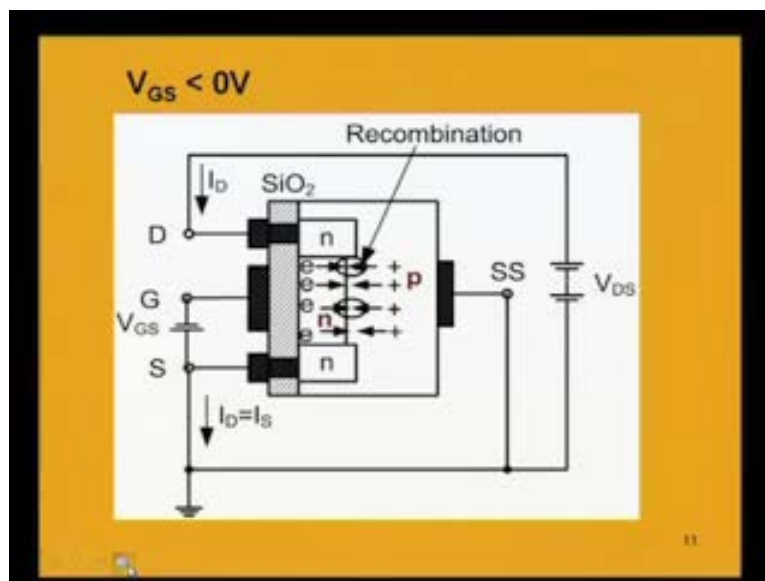
Now let us see how the current conduction takes place. For that let us first consider that gate to source voltage is zero. This MOSFET is having p-type substrate, n-type drain and source and there is an n-channel in between drain and source. The p-type substrate is having holes as the majority carriers and electrons as the minority carriers. Let us apply a positive voltage between the drain and the source. V_{DS} is positive. V_{DS} is positive and we are not having any gate to source voltage. There is abundance of electrons in the n-channel. Because there are free charge carriers, electrons available in the n-channel, these electrons will be attracted by the positive terminal of the drain to source voltage. There will be flow of electrons through the n-channel between the two n-type materials.

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The conventional current flow will be as shown in this arrow mark and that drain current is flowing and it will enter into the negative of the terminal of the V_{DS} . So drain current and the source current both are equal. When V_{DS} is equal to zero that current which flows between drain and source is named as I_{DSS} and this is a specific current failure which is specified in the MOSFET. For a device we know the value of the I_{DSS} from the data sheet. It is specified that this is the value of the I_{DSS} . That means even when the gate to source voltage is zero there is flow of the current between the drain and source. That current is I_{DSS} . What will happen when we have gate to source voltage negative?

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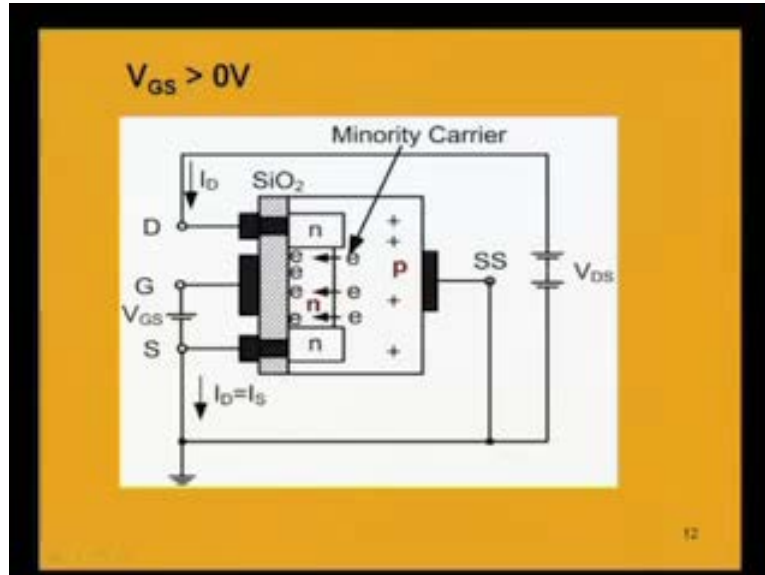


Drain to source voltage is positive but gate to source voltage let us make negative. We are applying negative voltage between gate and source. What will happen? S_D , gate to source voltage is negative. The electrons in the n-channel will be repelled or pushed by the negative terminal of the gate to source voltage and the holes which are the majority carriers in the p substrate will be attracted by the negative terminal of the gate to source voltage. In the process these electrons and these holes when they travel towards each other because of the impact of this gate to source negative voltage there will be some recombination taking place in between the electrons and the holes. Because of that the current I_D will be now decreasing. Some electrons are lost because of the recombination with the holes coming from the p substrate, so total number of free electrons which took part in the conduction of the current will be now reduced. That is why the I_D current will now decrease.

If we go on decreasing the V_{GS} further, if we go on decreasing gate to source voltage even further then the drain to source current will go on decreasing and decreasing and ultimately a point will be reached when it will be zero. The number of free electrons goes on reducing because of the recombination taking place and as we go on increasing the gate to source negative voltage there will be more and more recombination taking place. Ultimately this whole channel will be depleted of any single electron. That means there will be no single electron existing in the channel to take part in the conduction of current. The channel will be totally depleted of the free charge carriers, electrons. The current will diminish to zero. That particular gate to source voltage at which the drain to source current becomes zero because there is a complete depletion of the electrons in the channel is called the threshold voltage and here the threshold voltage is negative, that has to be kept in mind. Because we are applying a negative gate to source voltage and the threshold voltage is that negative voltage between gate to source when the current from drain to source will be zero. This is the reason why this type of MOSFET is known as depletion type MOSFET. The name originates from this depletion. But then there is another phenomenon also which is the enhancement phenomena. That will be clear if we now see the situation when gate to source voltage is positive.

When we apply positive gate to source voltage what will happen is that this positive terminal of the gate to source voltage will attract the minority carriers which are electrons from the p substrate. Because you have the p-type material, the p-type material has majority carriers as holes and minority carriers as electrons. Apart from the electrons which are already present in the n-channel when we apply the gate to source voltage positive, the positive terminal of the gate to source voltage will attract minority carriers, electrons from the p substrate and that is why we now have extra electrons than what were present in the n-channel originally. Because of the increment in the free charge carriers which are electrons there will be increment in the drain to source current.

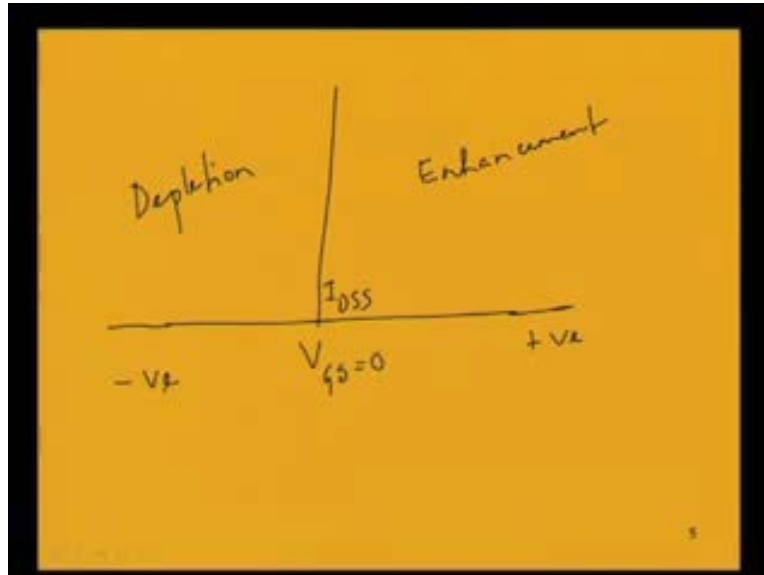
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If we go on increasing this V_{GS} further the current between the drain to source will go on increasing. As V_{GS} is increased, the kinetic energy which is achieved by the electrons will increase. They will knock out more free electrons from the covalent bonds and this process will accumulate. We have much more electrons being given back by this process. Basically what we have? When we have V_{GS} positive, then we have abundance of electrons which are due to the fact that the positive terminal of the V_{GS} is now attracting minority carriers from the p substrate and these minority carriers take part in knocking out more electrons because their kinetic energy is now increased because of the application of the gate to source positive voltage. Basically what we have is that we have a greater drain to source current, so there is enhancement in the current flow. There is enhancement also; there was depletion phenomenon also which was taking place when V_{GS} was negative.

What we notice in this type of MOSFET is that both the phenomena of depletion and the enhancement take place and this can be represented by the regions from gate to source voltage zero to the left and right. If we have gate to source voltage zero then what we have is that, on the one side if we have suppose gate to source V_{GS} zero, here to the right it is positive, to the left it is negative. Then what has been observed is that there are two phenomena, depletion and enhancement. When gate to source voltage was negative, we had the phenomenon of depletion. The depletion phenomenon occurs when the gate to source voltage is negative and the enhancement phenomenon occurs when the gate to source voltage is positive and the current which flows when V_{GS} is equal to zero is I_{DSS} . That is the specific current which has its value given in the data sheet for a particular MOSFET device, which is the depletion type MOSFET.

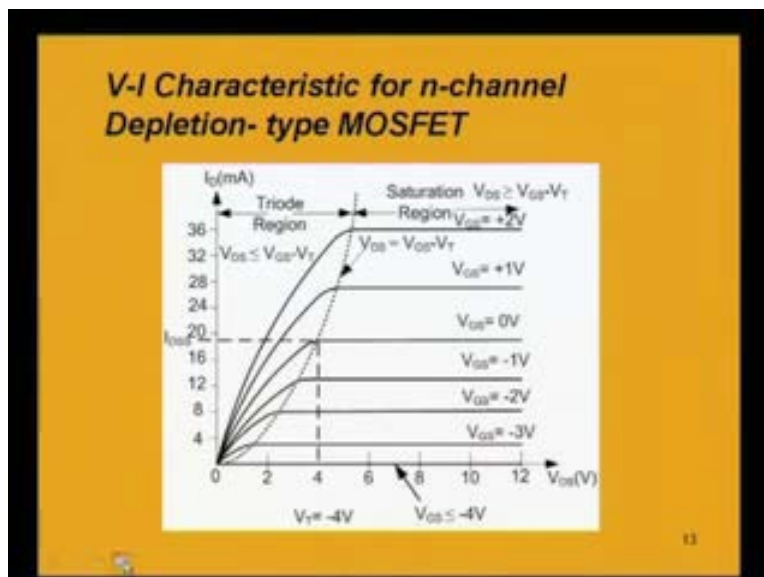
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Although the name of the MOSFET is depletion type, actually both the depletion and enhancement phenomenon are occurring depending upon the gate to source voltage whether it is negative or positive.

If you now see the VI characteristics after knowing all these, about the different regions of operation, knowing about depletion and enhancement that is whether V_{GS} is zero or negative or positive we can now plot very easily the VI characteristics.

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For the depletion type MOSFET, the VI characteristic we draw putting as usual in the x-axis the drain to source voltage and in the y-axis the current I_D in order of milliampere, for different values of the gate to source voltage. When V_{GS} is equal to zero, the current which flows between drain to source is known as I_{DSS} . It has the value given in the data sheet. We have seen that the threshold voltage which is negative for this n channel depletion type MOSFET is that value of the gate to source voltage at which the drain to source current becomes zero and this particular device for which we are plotting the VI characteristic has a threshold voltage -4 volt. This is an example we are taking to draw the VI characteristic. When V_D is -4 volt, threshold voltage is -4 volt, the magnitude of the gate to source voltage is below -4 volt then the current between drain to source is equal to zero. This is the cut off region; cut off means no current, zero current.

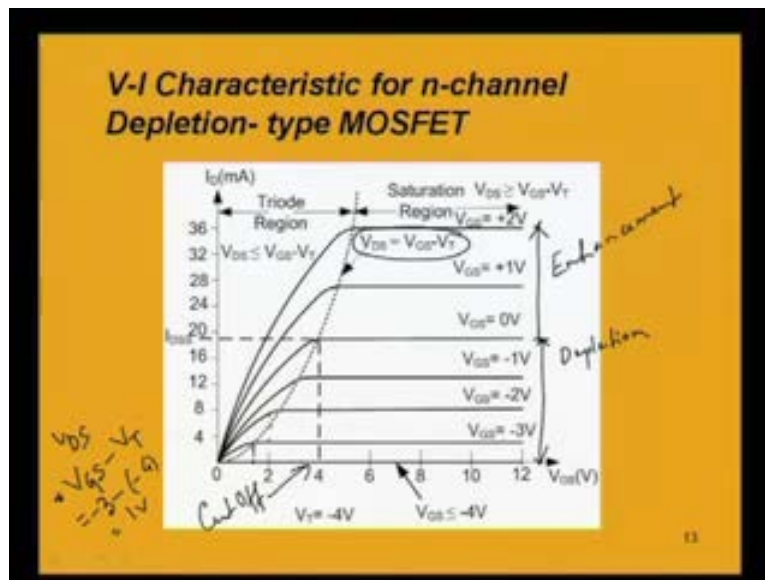
When we have gate to source voltage greater than threshold voltage, it is still negative but it is greater than the threshold voltage -4 volt. Suppose it is -3 volt then current will flow and it will reach the saturation value at a voltage which is defined by $V_{GS}-V_T$. If the drain to source voltage is equal to $V_{GS}-V_T$, mind it that for this particular characteristic or for this particular device under study, threshold voltage is negative. If V_{GS} is equal to -3 volt, we are taking, -3 minus V_T which is -4; so -3 plus 4 means 1 volt. That means that the current between drain to source voltage becomes saturated. It will not increase beyond this value, at a voltage equal to 1 volt. Around 1 volt we get the saturation between the drain to source current.

Similarly if we go on increasing the gate to source voltage, if now gate to source voltage is -2 volt, then the saturation value of the drain to source voltage will be -2 minus threshold; -2 minus -4 that means -2 plus 4 that is 2 volt. Around 2 volt we will have the saturation occurring. That means after this value even if you go on increasing the drain to source voltage the current between drain to source is not going to increase. It will become saturated. Similarly we can carry on. When V_{GS} is equal to zero we know that we have got this I_{DSS} that is the drain to source current. This region between cut off and the drain to source saturation current that is drain to source saturation current when V_{GS} is equal to zero, from this point to this point actually depletion phenomenon is going on. This is the depletion region.

Now we go on increasing the gate to source voltage in the positive direction. Suppose V_{GS} is equal to 1 volt. Now enhancement phenomenon will happen. Current will increase and drain to source current will be very much increased and that fact is reflected in this gap. If you look into the gap between V_{GS} zero volt and $V_{GS} +1$ volt and the gap between V_{GS} zero volt and $V_{GS} -1$ volt, this gap in the positive direction is much, much higher. That signifies that the drain to source current is now much higher. Drain to source current is increasing and this will continue if we go on increasing this drain to source voltage in a positive direction say 2 volt. The drain to source current will increase and increase. Actually in this region enhancement phenomenon is occurring and the saturation voltage between drain and source V_{DS} is equal to $V_{GS}-V_T$. When V_{GS} is equal to positive say for example 1 volt, 1 minus -4 volt will be V_{DS} which is equal to 5 volt positive and the curves will bend towards right because the locus of this drain to source saturation voltage is given by this dotted curve. The equation for this dotted curve is V_{DS} is equal to $V_{GS}-$

V_T . That is the value of the drain to source saturation voltage and to the right saturation is happening where V_{DS} is greater or equal to $V_{GS} - V_T$, in fact it is greater than; equal to is this point and to the left V_{DS} is less than $V_{GS} - V_T$ which region is known as triode region and this region is known as saturation region and actually this is cut off region. This region is cut off region when current is zero and that is when V_{GS} is equal to threshold voltage V_T .

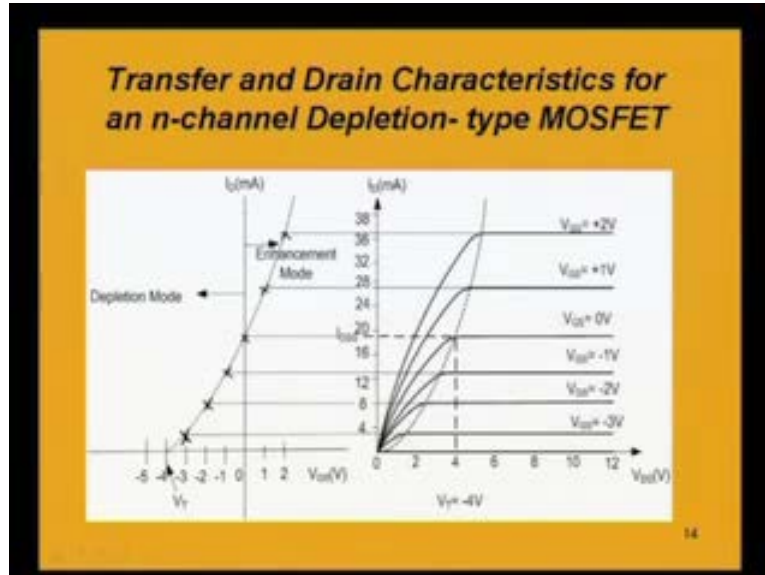
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This plot is explaining the phenomenon of depletion and enhancement occurring in the the depletion type MOSFET. We understand that although the name is depletion type basically it is having both the phenomenon of depletion and enhancement and from this drain characteristic or the VI characteristic we can project it for obtaining the transfer characteristic.

If you want to plot the transfer characteristic that is the characteristic between the drain current and the V_{GS} what you do is that for each of this plots we just extend or project the saturation currents and let it meet with the corresponding V_{GS} . For example here V_{GS} is equal to -3 volt. We extend it to the left. When it is -3 volt in the x-axis or voltage axis we see that this is zero, V_{GS} is equal to zero. To the right this axis is having positive V_{GS} ; to the left this axis is having the negative V_{GS} . Threshold voltage is -4 volt; for this example this is the point. To the left when the depletion phenomenon is occurring or the MOSFET is in the depletion mode of operation, the current meets that -3 volt at this point. We mark this point and next is -2 volt V_{GS} . At this voltage the saturation current is extended to the left and it is meeting the V_{GS} -2 volt at this point. Similarly all these points if we now connect we get a curve and that is the transfer characteristic. 4439

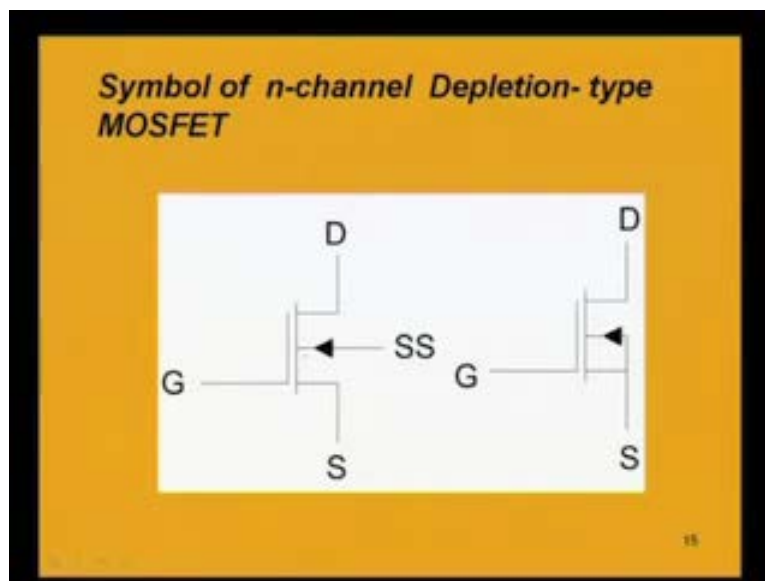
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Here V_{GS} is equal to zero. To the left the MOSFET is under depletion mode of operation and to the right of zero when V_{GS} is equal to positive this is under enhancement mode of operation. From this figure we now have a clear idea how the transfer characteristic can be obtained and that is shown on the side of this VI characteristic or the drain characteristic for easy understanding.

The symbol for the n channel depletion type MOSFET is shown here which is showing the gate having a gap with the body of that device signifying the insulating material.

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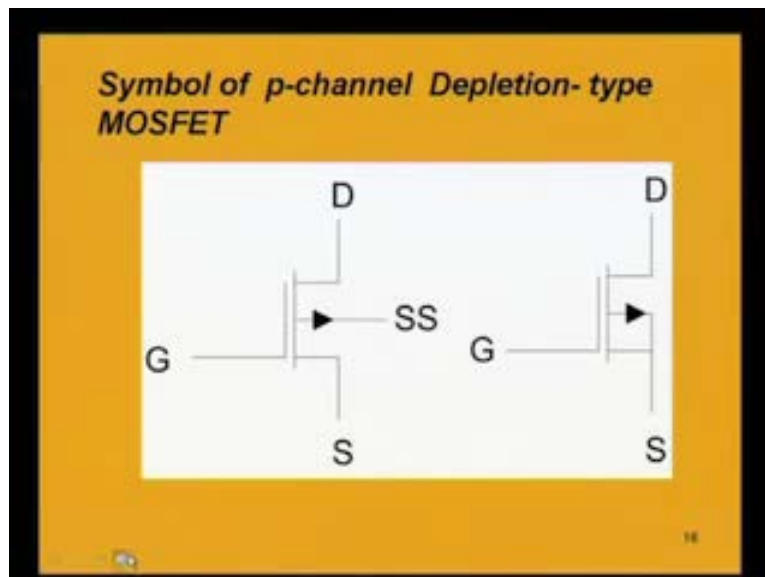


This gap will signify the insulating material as was present in the earlier example that we saw in enhancement type MOSFET. One significant difference between the enhancement and the depletion type MOSFET as far as symbol is concerned is that here we have an unbroken line signifying that there is a channel present between drain and source. If we recall, earlier when we were considering enhancement type MOSFET there was broken line. In between drain and source we did not have a channel. The absence of the channel means the symbol also is reflecting that by showing broken lines. But here there is a channel ever present between the drain and source which is reflected by this continuous and line that is there is a channel between drain and a source. These are the three terminals drain, gate and source. The substrate terminal is this one and it has the direction of the arrow signifying whether the substrate is p or n and we are considering the n-channel MOSFET where the substrate is p. As the substrate is p the current direction is from p to n. That is why it is in this way.

This symbol is for substrate having external connection. That is we have 4 terminals. 1 terminal for the substrate is also available. But what is more common is to show the substrate connected to the source. In this symbol we have seen that the source and the substrate are connected, all others are same. All other parts of the symbol are same. The only difference is that the substrate is connected to the source internally. This is the symbol for internal connection of substrate and this is external connection of the substrate and this is n-channel which is represented by the direction of the arrow. We have a p substrate, so the current will be from p to n normally. That is p to n direction of current is shown by this arrow mark.

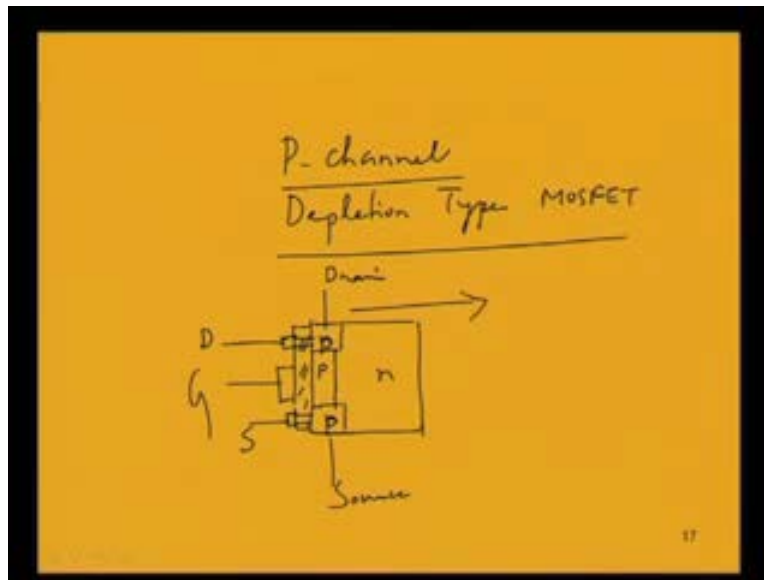
If we have a p-channel depletion type MOSFET, the substrate will have n-type materials and the channel is p.

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Others remaining same, the arrow head of the substrate in the substrate connection or the arrow head will be just opposite to the n-channel. It will be from left to right because in the p-channel depletion type MOSFET we have channel made of p. That is the substrate will be made up of n-type material; this will be silicon dioxide and this will be p, this will be p and this channel will be p, like this. These are the drain, source and gate terminal. We have this connection between metallic contact and p is there, the drain is there and similarly here also between metal and the source there will be a contact, the metallic contact. This is the drain and this is the source. Here channel is made of p. If we look into the direction of current between the substrate and this p-type it will be in this direction.

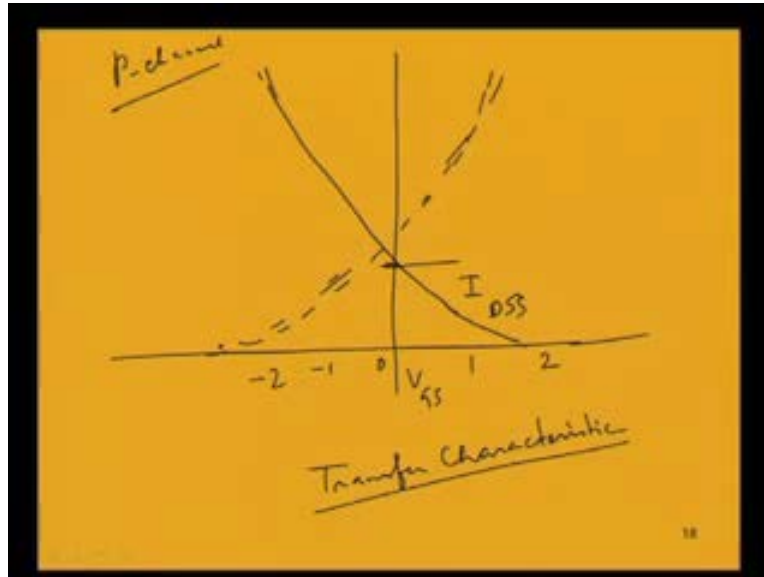
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That is why we have the direction of the arrow from left to right as is shown here and this is 4 terminal case where you have the substrate terminal also available but when you consider internal connection there will be the connection between the substrate and the source. So we have 3 terminals only.

If we consider the transfer characteristic for the p-channel type of MOSFET, it will be just the mirror image for the n-channel but that will be bending towards left. I am considering for p-channel. This is zero. If this is zero then this will be -1, -2; it will be negative. Here this will be positive. The transfer characteristic will be bending towards left. If you flip the n-channel type transfer characteristic it will be something like this. Earlier we got this type when we considered n-channel. Now this is for p-channel, the solid line is for p-channel. This gives you the I_{DSS} .

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The transfer characteristic for a p-channel type MOSFET even for this enhancement type or depletion type if we consider they will be just flipped version to the left or it will bend towards left of what was obtained for the n-channel type. Now we know about the different structures of the MOSFET device. In our lectures we have discussed about basically two different variations of MOSFET. One is the enhancement type MOSFET and the other is the depletion type MOSFET. We have discussed about n-channel and p-channel type of MOSFET both for enhancement as well as for depletion types. We have seen how the current conduction takes place between drain and source and how if we vary the gate to source voltage the drain to source current changes, how saturation is obtained? Depending upon the value of the drain to source voltage we get saturation means the current between drain to source does not vary beyond a point when saturation is reached and from this saturation current and corresponding gate to source voltage we have found out the transfer characteristic. All these studies help us in the understanding the final use where we are going to apply the MOSFET device that is for amplifier.

In the next classes with the background of what we have studied till now, with this understanding we will proceed to study the amplifier using the MOSFET device and for amplifier we know that we have to know the DC biasing also. We will discuss about the DC biasing methods and then we will proceed to find out basically the different parameters related to amplifier where the MOSFET device is used.