Basic Electronics
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Module: 3 Field Effect Transistors
Lecture-4
MOSFET AS AN AMPLIFIER

In the last class we discussed about the MOSFET device as an amplifier and in continuation with the earlier discussion, today we will go into details of amplification. In relation with the MOSFET device we have got one important parameter which is the transconductance of the MOSFET. The transconductance which is symbolically denoted by small g small m is given by the ratio between the small drain current, that means the small signal or AC drain current and the gate to source AC voltage.

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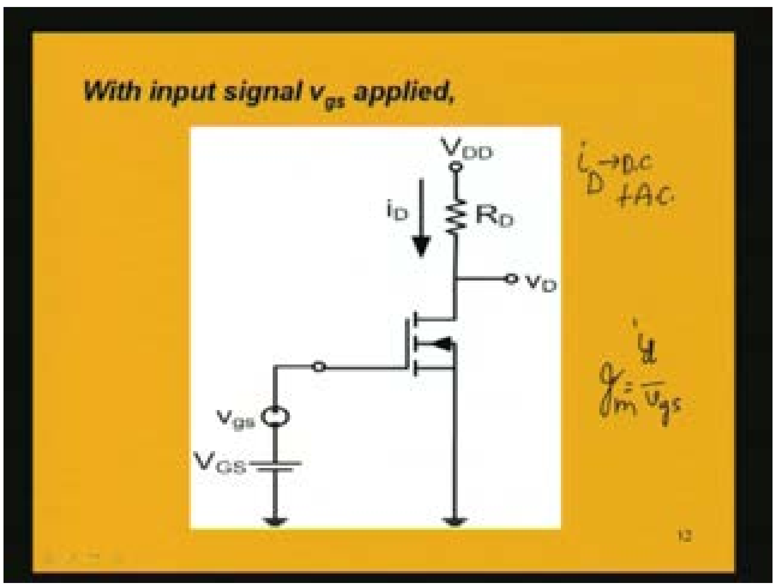

If we look into the transfer characteristic of the MOSFET device, from the transfer characteristic we can find out the transconductance. How to do that? Let us recall the transfer characteristic of the MOSFET device. The drain current verses the gate to source curve is the transfer characteristic starting from the threshold voltage and we should know actually more than one point to draw the transfer characteristic. From the current equation I_D equal to K into V_{GS} minus V_T whole square we can find out some points and join these points to get the transfer characteristic curve. Let Q be the operating point which is fixed by the DC biasing circuit. How the biasing is done in MOSFET amplifier that we have yet to discuss and we are going to do that soon. Let us assume that the Q point is located here and the coordinates of the Q point are given by capital V_{GS} and capital I_D.

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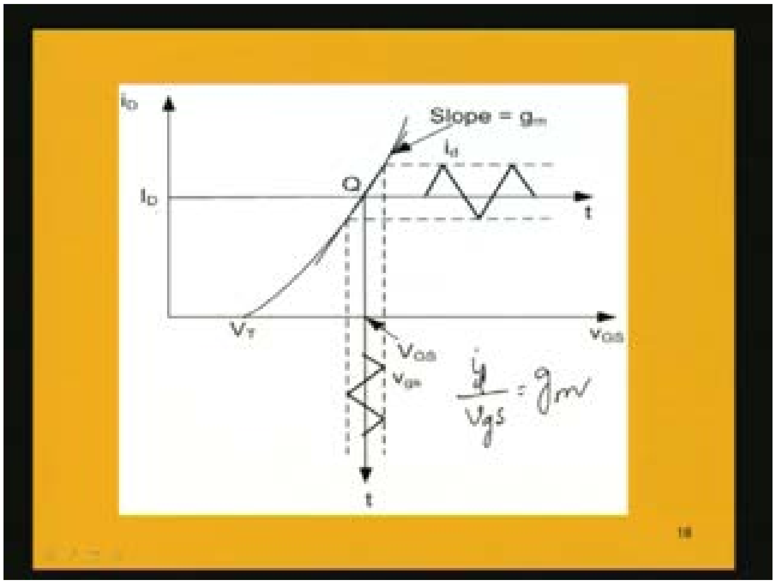

If we now find out the slope of this transfer characteristic at the point Q then that will give us the transconductance g_m. How to find out that slope? Around the operating point we take a small region where the characteristic can be assumed to be linear. Only within a small region around the operating point we can assume that the portion is linear because it is a piecewise linear characteristic, in order to find out the slope. We find the slope of this transfer characteristic at the Q point which is given by the small difference in this current in the drain divided by the difference in this voltage, which is nothing but small i_d by small v_{gs}; that will give the transconductance. We are denoting the small signal drain current by small i small d. For example we are taking a triangular wave form say triangular AC signal which is small i small d and the corresponding gate to source voltage is a small v_{gs}. Corresponding points on the gate to source voltage axis drawn or projected from this current signal are these points which will give us the voltage between gate to source. The slope is denoting the transconductance.

When we are using the MOSFET amplifier to amplify a small signal then we must know the voltage gain. Voltage gain means the ratio between the output voltage and the input voltage. Earlier in discussion of BJT as an amplifier we have found out the voltage gain, current gain, etc. Let us also proceed to find out the voltage gain for the MOSFET and we are taking this small simple circuit as an example. What will be the voltage gain when we are giving an input small v_{gs}? This is the input. It is given at the gate to source terminal. This is the drain terminal, this is the gate terminal and source is grounded. This capital V_{GS} or capital V_{DD} are there which are required for biasing. Because you know it is enhancement type n-channel MOSFET, gate to source voltage must be kept at positive and drain to source voltage also must be kept at positive. To achieve that we need to have the DC biases which are capital V_{GS} and V_{DD}.

Let us find out the voltage gain on the MOSFET amplifier. Because we are discussing the amplification, the gain of the amplifier is the ratio between the output voltage and the input voltage. The output voltage at the drain is small v small d and the input voltage which is applied between the gate and source is small v_{gs}. This ratio will give you the voltage gain of the amplifier.

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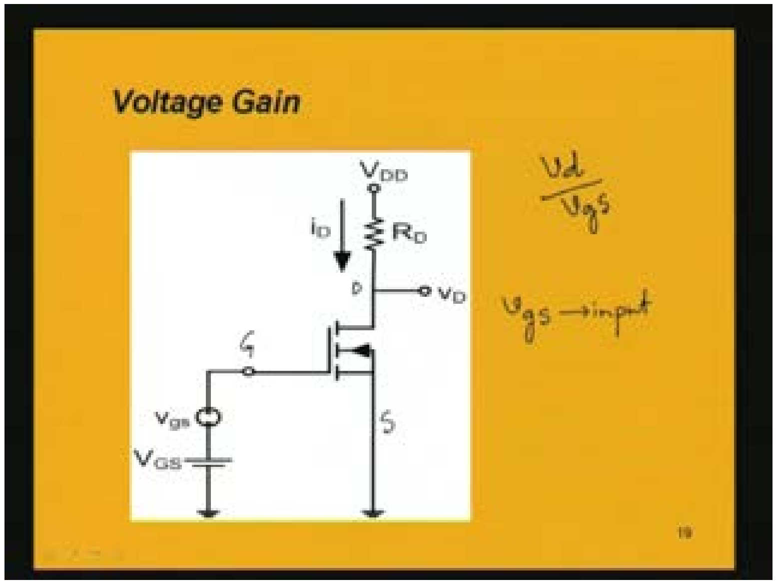

Now let us find out the voltage at this drain end. When we write the voltage equation we will write the instantaneous voltage equation that is small v capital D because apart from the AC signal we are having DC voltages also which are required for biasing the MOSFET properly. Because it is an n-channel enhancement type MOSFET device we need to keep the gate to source voltage at a positive value and drain to source voltage also should be positive. To achieve that we have the two DC voltages as shown here, which are capital V_{GS} and capital V_{DD}. These two voltages are there to make the gate to source voltage positive. Gate is kept at a voltage positive with respect to the source. Similarly the drain is kept at a voltage positive with respect to the source. These two conditions must be met in order to make the MOSFET ON or make it conduct. Apart from this DC biasing voltages we have the signal small v small gs, which we need to amplify.

To write the voltage equation at the drain, in this situation we must write the instantaneous voltage equation. We are not considering DC and AC separately right now. We are going to write the instantaneous voltage equation. That equation will be what? Small v capital D equal to capital V_{DD} minus small i capital D, R_D. So this is the voltage equation. That can be further written down by noting the fact that small i capital D is equal to capital I capital D plus small i small d. Replacing this instantaneous current small i capital D by capital I_D plus small i_d we are rewriting the equation which will give us the instantaneous voltage v_D equal to V_{DD} minus I_DR_D minus small i_d R_D. We note this term V_{DD} minus capital I_D R_D. This term is nothing but capital V capital D. Because if we consider the DC quantity only, the drop V_{DD} minus capital I_D into R_D will give you the DC drop so that is denoted by capital V capital D minus small i_d R_D. If we again look into this equation this is small i_d. If we now consider this whole equation which part will be only AC part? This part small i_d into R_D with a minus sign this is the AC part but other part is the DC part.

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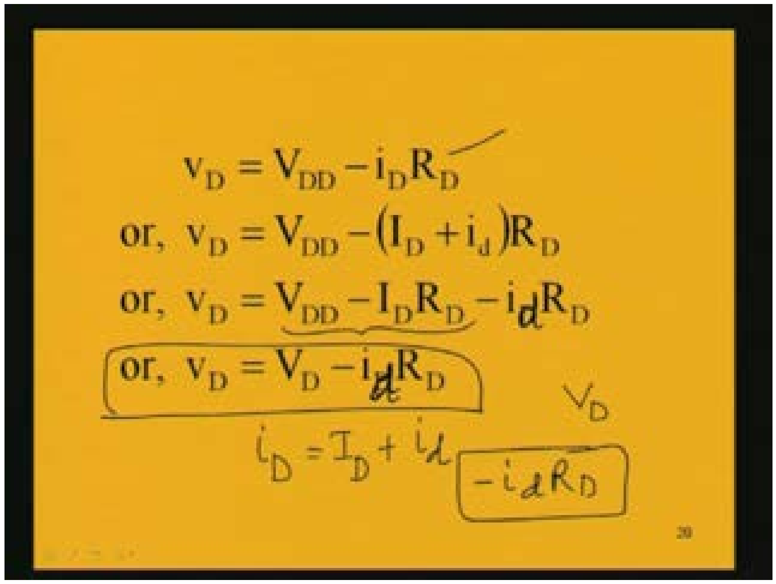

We are now concerned about the AC part only because we are discussing an amplifier. An amplifier is amplifying a weak signal which is AC signal. At the output also we will be concerned about the amplified AC signal. So writing down the AC component or signal component of the drain voltage which is nothing but small i small d into R_D with the minus sign and again this small i small d can be written as g_m into small v_{gs} because we know g_m is small i_d by small v_{gs}. Writing in that way replacing this small id by small g_m into v_{gs} into this R_D, which is already there we can now find out the ratio between the output voltage and the input voltage. Output voltage means small v small d and input voltage means small v small gs. That is equal to what? If you take the ratio between v_d and v_{gs} we have minus g_m R_D. This is the voltage gain of the MOSFET amplifier.

If we look into the term we get the g_m, the transconductance for the MOSFET, a parameter which is defined for a particular MOSFET; the transconductance multiplied by the resistance in the drain with a minus sign. Voltage gain will be minus sign means immediately we know that output voltage and input voltage are 180 degree out of phase. So the phase difference of the output voltage from the input voltage is 180 degree. That is why this minus sign is coming into the term.

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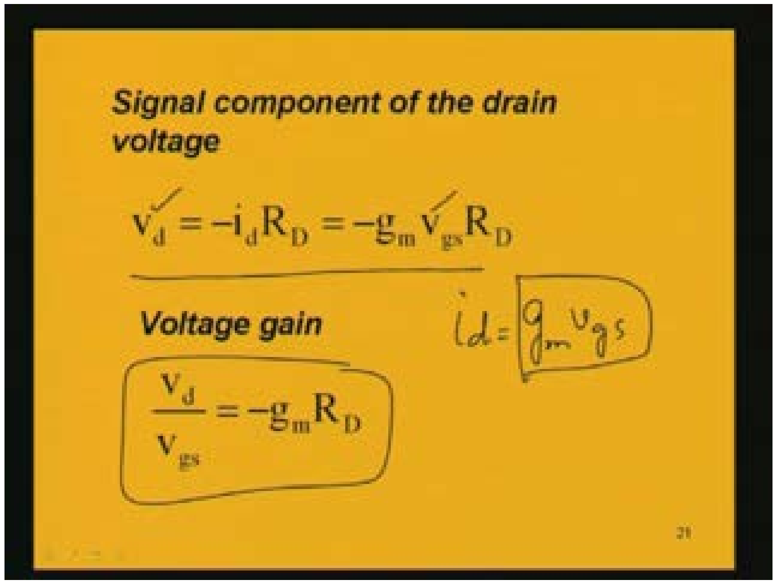

If we look into the output voltage and input voltage let us apply a triangular voltage. We are taking the example of a triangular voltage. It may be a sinusoidal voltage also. Just for easy drawing we are taking a triangular voltage nothing else than that. We are taking a triangular AC voltage which is V_{GS}. This constant voltage capital V capital GS is the DC biasing voltage between gate to source. This will be present. On it is superimposed a small v small gs and the instantaneous value of the voltage between gate to source is capital V_{GS} plus small v_{gs}.

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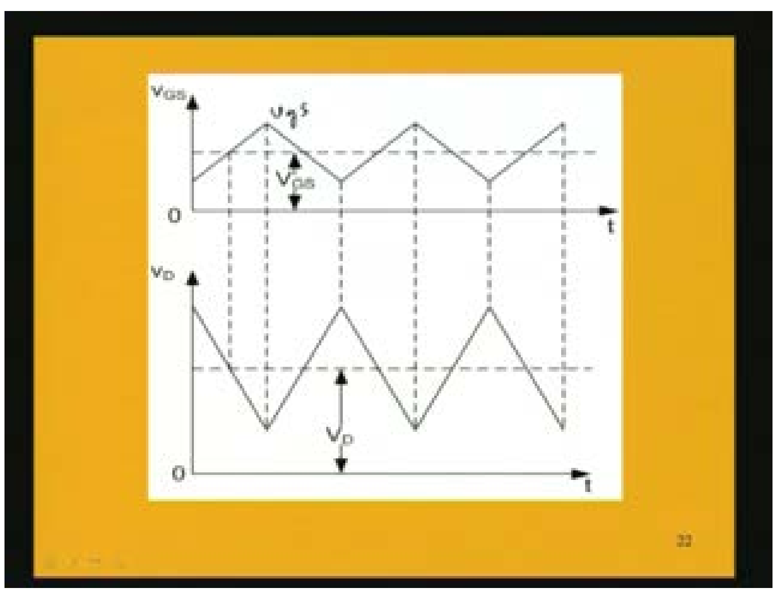

At any instant if we want to find out the instantaneous voltage, at any instance the voltage between gate to source will be found out by adding these two, capital V_{GS} and small v_{gs}. Starting from this DC value it is rising. Because we are applying a triangular voltage it will be rising in this fashion of a triangular wave, rising and then falling. So this will be the profile of the instantaneous voltage between gate to source. Corresponding to that input voltage what will be the voltage at the drain end? The instantaneous voltage at the drain is small v capital D. As shown here it is 180 degree out of phase. When the peak of the gate to source voltage is appearing, corresponding drain voltage will be having the negative peak. This point corresponds to the negative peak and the negative peak of the input voltage will correspond to the positive peak of the drain voltage. We will get the output voltage at the drain as shown here. It is amplified no doubt but out of phase by 180 degree.

In the absence of the signal for the DC V_{GS} we are having the DC V_D. This is the constant part; it is the DC value of the drain voltage and on it is superimposed the AC portion or small v small d. This is actually small v small d which is superimposed on the capital V capital D. The output voltage and input voltage waveforms as we see here they are just having 180 degree out of phase.1925

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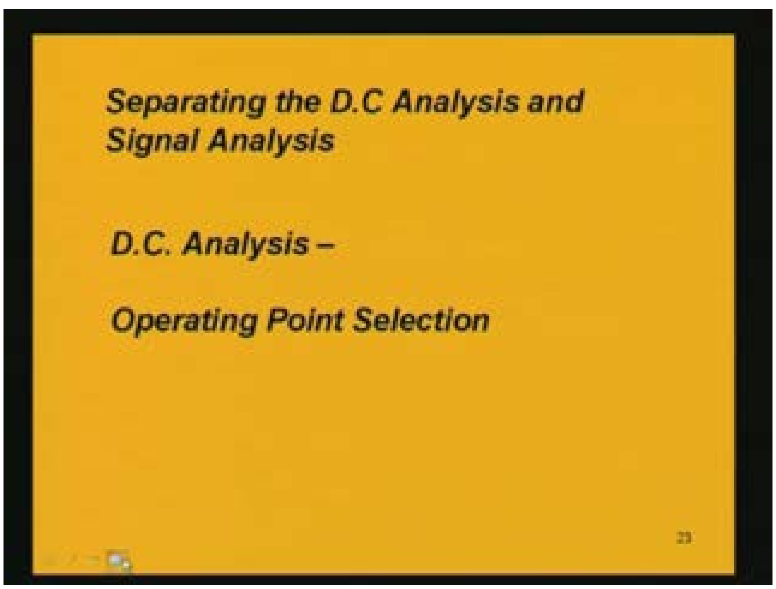

The amplifier as such is amplifying an AC signal and it is having a voltage gain given by minus g_m into R_D, R_D being the resistance of the drain and the minus sign is signifying the phase reversal. As I have mentioned earlier the amplifier is having a DC biasing circuit. In order to analyse the amplifier using the small signal model we must first of all set the operating point properly. The biasing methods which are used for setting the operating point properly will be now discussed. The operating point as you know is the DC point which gives you value of the DC voltage and the DC current when no signal is applied. Unless we fix the operating point at a proper location in the transfer characteristic our amplification may suffer because we know that the MOSFET device is under saturation when it is used as an amplifier. Throughout this operation the condition for saturation should be maintained and in order to maintain the condition for saturation at any point throughout its operation the drain to source voltage must be greater than the difference between the gate to source voltage and the threshold voltage. V_{GS}-V_T should be smaller than V_{DS}.

We can see that in order to satisfy this condition your operating point must be located properly. Because if it is not located properly, if it is towards the upper end or towards the lower end that means if it is too near the cut off like this, if the transfer characteristic is say like this and we are having an operating point which is not properly selected like the middle way; say it is here or above then what will happen? It will be difficult to maintain this condition.

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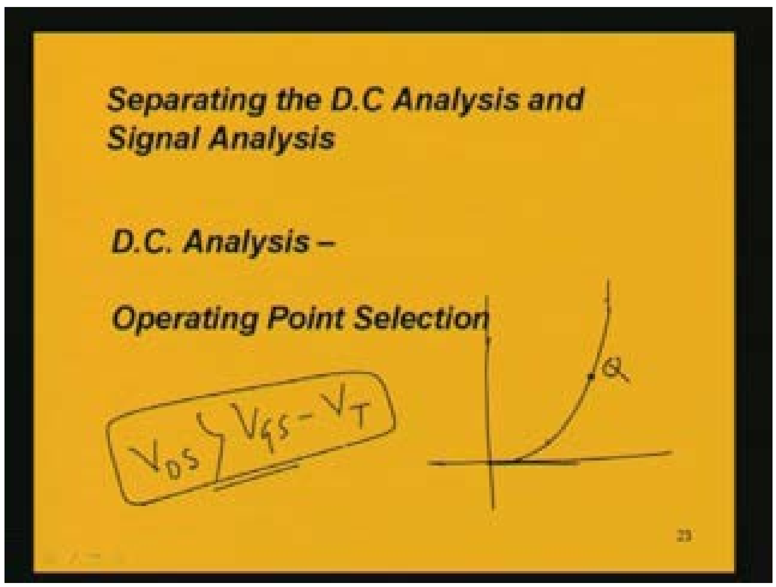

We must first of all fix the operating point properly and for that we must bias the circuit properly. If it is not located properly what will happen? At any point any point when the signal is applied the gate to source voltage may not be sufficient to make this whole quantity less than the drain to source voltage. We will now discuss about the DC biasing schemes which is required for proper selection of the operating point.

First method that we are going to discuss is the feedback biasing method. It is similar to the methods of biasing which we have used in BJT. If we have understood the biasing in BJT then it will not be difficult to understand because it is in a similar way. Even without discussing much we can understand the biasing methods. For example we will take these two biasing methods. One is the feedback biasing method and other is the voltage divider biasing method as applied to the n-channel enhancement type MOSFET device. This circuit here is employing this n-channel enhancement type MOSFET as is clear from the symbol. This is the amplifier circuit.

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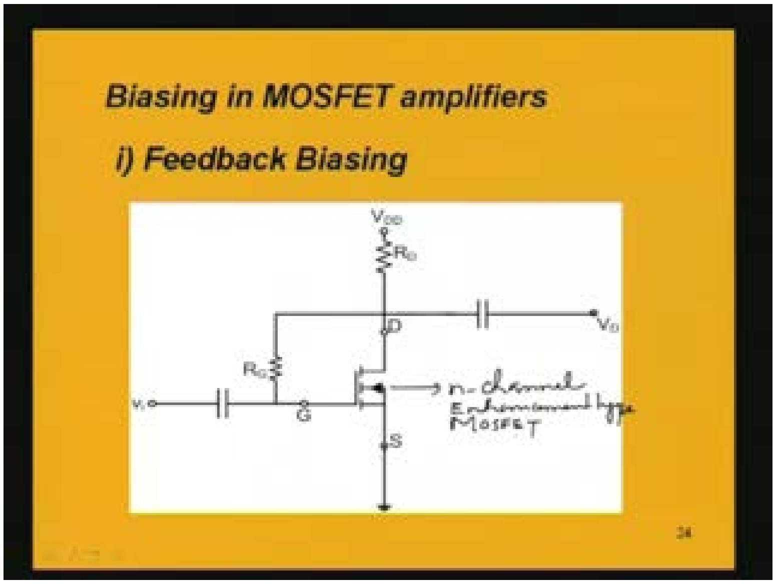

It is having the DC biasing as well as it is employing a small signal which is to be amplified. Feedback biasing means at the drain end we are having resistance R_G to the gate. There are capacitances. The reason for applying this capacitances are that we want to block the DC from the AC because we want to get the amplifier AC output and we do not want it to be corrupted by the DC signal. That is why there are coupling capacitors. The purpose of using the coupling capacitors is to block the DC. In this circuit as we have seen the drain and gate is having a resistance R_G in between them. This is comfortably high resistance R_G which is connected. The output is obtained at this end and this voltage is known as V_D. That is the drain voltage which is the output voltage which should be amplified and not having any change in the shape as regards the input voltage. Input and output voltage must be similar in shape. Although there may be phase reversal, there should not be any distortion. We need to apply the input signal small enough to guarantee that distortionless amplification.

If we are now having the circuit what will happen? If we look into the gate terminal the gate current is zero because we know that I_G is zero for a MOSFET. There cannot be any gate current and the body of the MOSFET or the substrate is having a silicon dioxide in between, which is an insulating layer. So the gate current cannot flow, it is zero. If the gate current is zero, this voltage across this resistance is zero. If this voltage is zero that means the drain and the gate point is like short circuiting. We will say that it is like short circuited part between the drain and the source since I_G is equal to zero. For a MOSFET device we know that I_G or the gate current is zero. This short circuited part exists between drain and the source. If we now draw the DC equivalent circuit forgetting about the AC input we are having this circuit which is having the resistance R_D at the drain, drain and gate being short circuited. This circuit is bereft of the capacitors. It is not having the capacitors since this is equivalent circuit. It is open circuit for DC; capacitor is making it open circuit for DC. The capacitors can simply be removed in the DC equivalent circuit and this simplified DC equivalent circuit appears as it is shown in figure.

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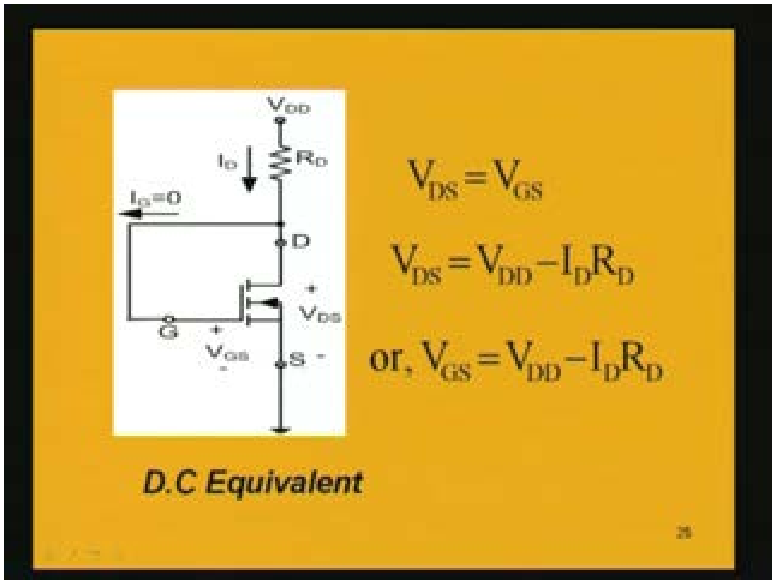

What will be the drain voltage with respect to source? V_{DS} equal to V_{GS} because we know that this point and this point are same. There is no difference as there is no drop. It is short circuited part. V_D equal to V_G or V_{DS} equal to V_{GS}. Source is the reference, so drain to source voltage is equal to gate to source voltage. This voltage and this voltage are same because these two points are equivalent. What is this drain to source voltage? This DS that is drain to source is having the voltage V_{DS}. Applying Kirchoff's law to this part or the loop rather we have V_{DD} minus I_D into R_D that is equal to V_{DS} and mind it this I_D is DC I_D. We are having the DC equivalent circuit, so we are having the DC current. We are having the drain to source voltage as V_{DD} minus I_D into R_D. If this is drain to source voltage that is also equal to the gate to source voltage. V_{GS} is equal to V_{DD} minus I_DR_D.

We can also write then V_{GS} is equal to V_{DD} minus I_DR_D. This expression is one equation which will give us a straight line. This is the equation of a straight line only. This straight line will be obtained or we can draw the straight line provided we know only two points. Two points are required to draw a straight line. What are the two points; the extreme points of the voltage and the current. We are having the axes which are V_{GS} and I_D. These are the axis of our interest because we know that with the change of V_{GS} we are changing the drain current. When we have I_D equal to zero we get V_{GS} equal to V_{DD}. That is one extreme point we get when we have I_D equal to zero that is on the x-axis and when V_{GS} equal to zero we get a point on the y-axis or the I_D axis. This is the extreme point or the maximum drain current point which is nothing but V_{DD} by R_D. V_{DD} by R_D is one extreme point and the other extreme point is V_{DD}. Combining these two we get a straight line. This is the straight line.

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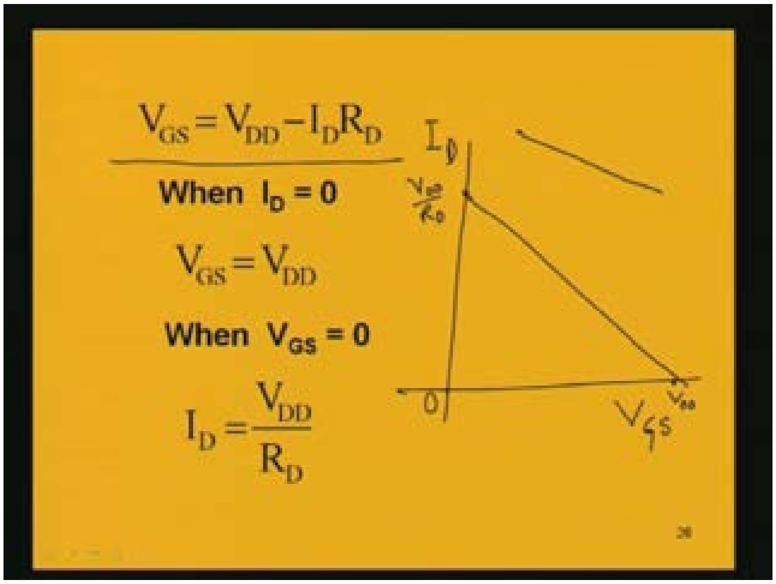

We get from this DC equivalent circuit a straight line which is like your load line when we were discussing about the transistor of BJT amplifier.

Our aim is to locate the operating point Q. How can you find the Q point? We will find the Q point by drawing the transfer characteristics and fixing the I_D V_{GS} line on it. In order to draw the transfer characteristics for this enhancement type MOSFET we know the current relationship which is I_D equal to K into V_{GS} minus V_T whole square. This is in the saturation region because we are employing the MOSFET under saturation only for amplifier. We have to fit the curve which is the transfer characteristics with the help of this equation. Mind it, this is not a straight line. It is a nonlinear equation. A square term is there. So it is not enough to get only two points just as we have drawn for the straight line. We need to have more points in order to fit a curve.

For that one point will help us which is the threshold voltage. Gate to source voltage when it is equal to threshold voltage the current is zero. That means on the same axis as we have drawn right now between I_D and V_{GS}, we will take the same axis I_D and V_{GS}; I_D is in milliampere and V_{GS} is in volt. Start with the threshold voltage that is the voltage between gate to source till when current is zero, drain current is zero. This is the point. One point is on this V_{GS} axis which is the threshold voltage. Another point can be obtained from the specification of the MOSFET given in the data sheet. Generally what is given in the data sheet? They give I_D(On) and V_{GS}(On) values. That means these are the major values for the drain current and the gate to source voltage when the MOSFET is in ON condition or in the saturation region. If we know these two values immediately what you can find out is the constant K that is the fabrication constant K. Because if we look into this expression K is equal to I_D by V_{GS} minus V_T whole square, V_T is known. It is given in the specification.

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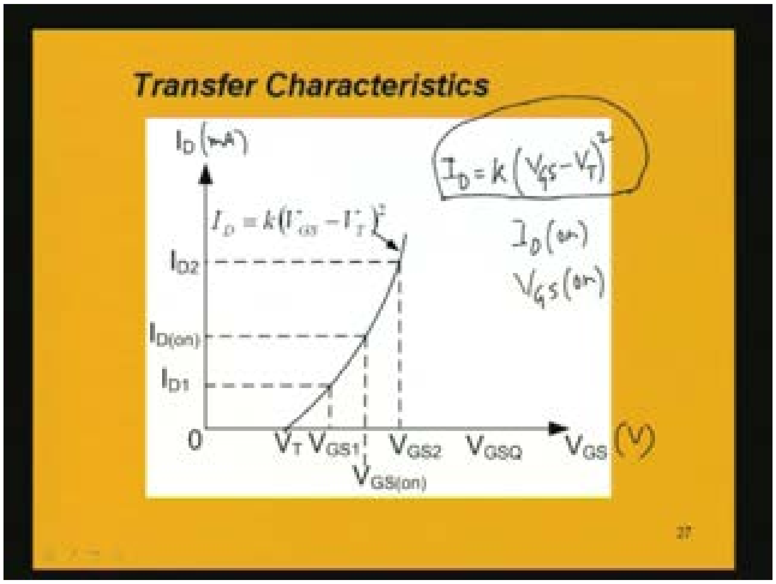

We are given a pair I_D and V_{GS} for ON condition of the MOSFET. If we replace these values here in this equation then we get the value of the K which is a constant. Once we know the constant for any other value of gate to source voltage we can find out the drain current. Let us do that. For any other value say V_{GS1} we are finding out the drain current which is I_{D1}. We are getting another point here and again take a V_{GS} for a current in the higher region. That is say a higher value of I_{D2} is given for V_{GS2} that is another point. We have 4 points right now. Joining these 4 points we get a curve which is the transfer characteristic for this enhancement type MOSFET device. What will we do with this transfer characteristic? We will plot the transfer characteristic and the network characteristic given by this straight line I_D versus V_{GS} on the same axis; on the same axis of I_D and V_{GS} we will be drawing.

What we are doing here is that we are drawing this transfer characteristic. This is the transfer characteristic and this line, straight line is the straight line for the circuit. That is it is describing the network on the circuit and this straight line is drawn by just connecting the two extreme points which are given by the V_{DD} by I_D maximum and this is V_{DD}. Now we have two things. On the same set of axis we are having the transfer characteristic as well we are having the straight line. Both are intersecting at a point which is the Q point.

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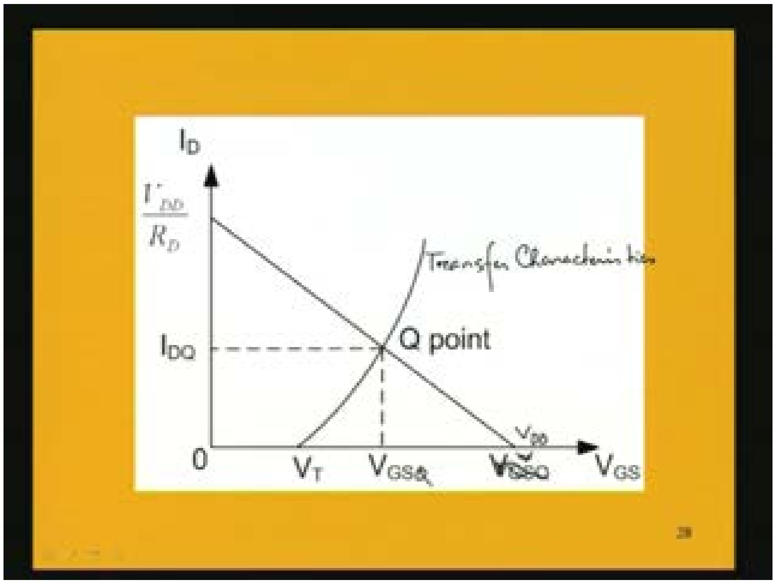

The intersecting point between the transfer characteristic and the network straight line will give us the Q point. We know the DC value of the gate to source voltage and the drain current from this Q point. This Q point selection must be properly done so that during amplification we are having the saturation condition maintained for the amplifier. This is one biasing scheme. Another biasing scheme which is used for this enhancement type of MOSFET is the voltage divider biasing scheme. This also is familiar to us because earlier we have discussed about the voltage divider biasing scheme while discussing the BJT amplifier.

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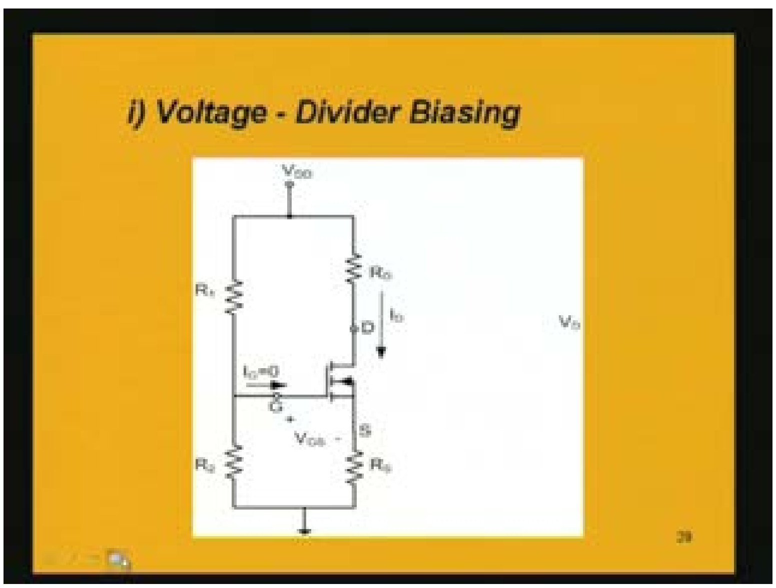

Here there are two resistances given by R_1 and R_2 and there is a drain resistance R_D and source resistance R_S. This is the ground and V_{DD} is the biasing voltage. Let us denote this drain current by I_D drain to source current and here also as I_G equal to zero, gate current is zero for the MOSFET. Then what happens? We can apply the voltage division principle here. What is the voltage across this R_2? That we can immediately write down. That is the voltage across this R_2 is nothing but V_{GS}. V_{GS} equal to V_{DD} into R_2 by R_1 plus R_2. This voltage is available across this gate and ground. So V_G is equal to V_{DD} into R_2 by R_1 plus R_2. If we know this V_G then we can apply KVL, Kirchoff's voltage law in the lower loop, this loop. If we know see into the lower loop we have a voltage V_G given by this one and this gate current is zero. What is this current? This is nothing but I_D. The drain current and source current are same. The drain current will be only flowing and entering the voltage source between drain and source, so the same current I_D and I_S.

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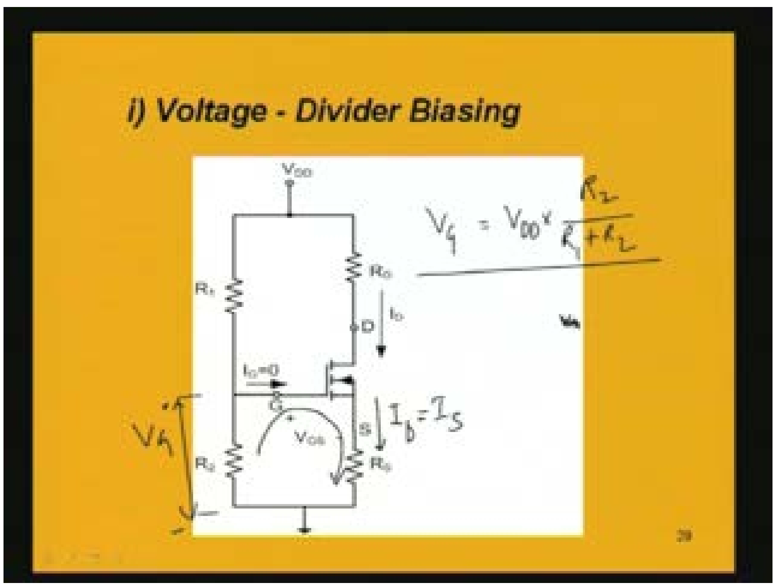

If we are writing this Kirchoff's voltage law in this loop it will be what? V_G minus V_{GS} minus I_D into R_S equal to zero. That is what is written here V_G minus V_{GS} minus V_{RS} means the voltage across the resistance R_S. That is equal to zero using Kirchoff's voltage law or we can simplify it further by writing that V_{GS} equal to V_G minus V_{RS} or V_{GS} equal to V_G minus I_D into R_S.

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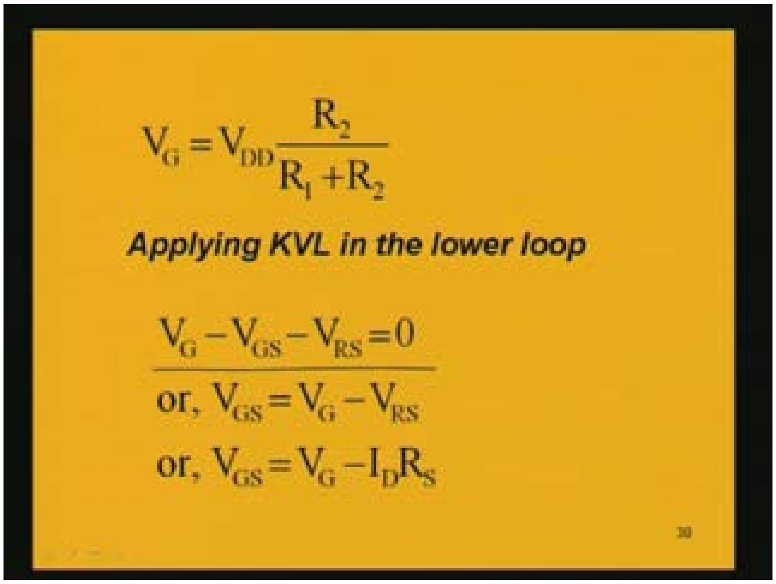

This drop across this R_S is nothing but I_D into R_S. Again if we apply Kirchoff's voltage law in this loop, upper loop what will it be? If we can apply this here in the outer loop V_{DD} minus I_DR_D, we go this way. If we go this way V_{DD} minus I_DR_D minus V_{DS} minus V_{RS} equal to zero. V_{DD} minus I_DR_D minus V_{DS} minus I_DR_S equal to zero because the voltage across this resistance R_S is nothing but I_DR_S and the voltage across this R_D is nothing but I_DR_D. I_D is common because I_D is the source current flowing through this R_S also. We get an equation given by V_{DS} equal to V_{DD} minus I_D into R_D plus R_S. This equation is the key equation governing the drain to source voltage.

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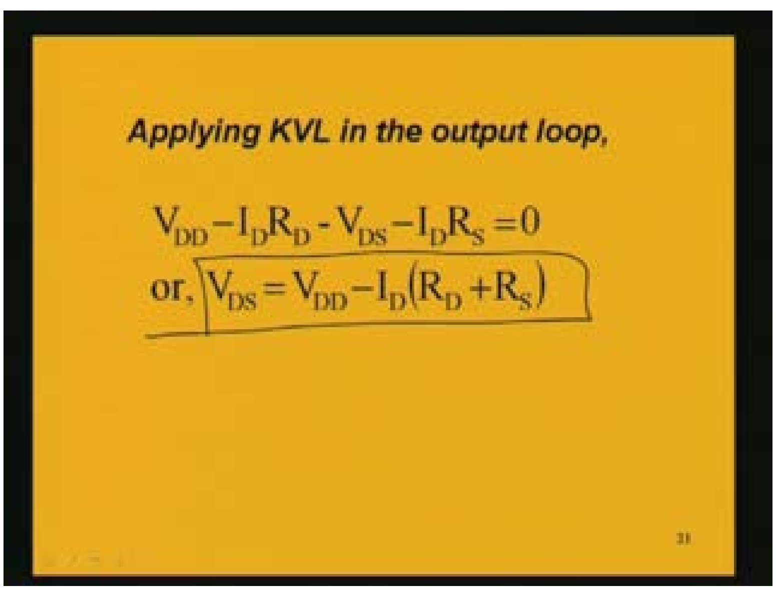

Once you know the DC drain current we can find out the DC drain to source voltage. Let us take one example for the fixed biased DC biasing scheme, fixed biased scheme which we have discussed just now. It is having enhancement type n-channel MOSFET. This is n-channel. This is the symbol for this n-channel. We are taking this only and we are having a resistance 10 mega ohm and the voltage 12 volt is connected through a resistance 2 kilo ohm to the drain. The capacitances are there to block the DC. 1 micro farad capacitance is here, another is here at the output which is say 1 micro farad. This voltage at this output is say v_o. So this is our n-channel enhancement type MOSFET device.

For this circuit it is given that I_D (on) is equal to 6 milliampere and V_{GS} (on) is equal to 8 volt; also given is that V_{GS} threshold equal to 3 volt. You have to find out the operating point. That is you have to find out the DC drain current and the drain to source voltage for the Q point. Here it is GSQ.

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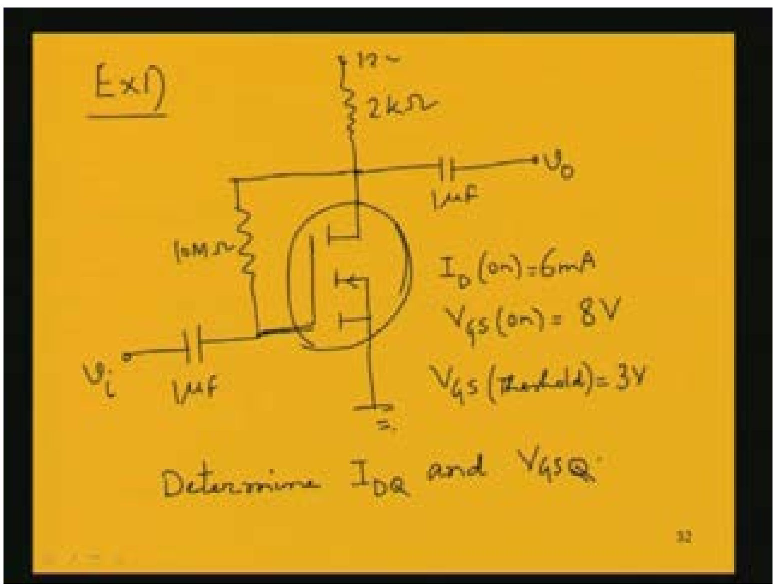

That is the Q point whatever we have seen here this Q point is actually denoting these two; one is the drain current and the other is the gate to source voltage that has to be found out in this problem. We will find out basically the transfer characteristic at the straight line and when they will intersect that point is the operating point. Operating point will give you the voltage and current values under DC. For plotting the transfer characteristic we need to know at least 4 points; that we will try. For plotting the transfer characteristic how many points are required? Atleast we require 4 points because it is not a straight line. We cannot draw it with the help of 2 points. So what are the 4 points?

One point is immediately known from the threshold voltage. One point is V_{GS} threshold that is given to us as 3 volt, so that is known. Second point can be found out from the data given as I_D(on) and V_{GS}(on) which are 6 milliampere and 8 volt because we have this expression for the current given as I_D equal to K into V_{GS} minus V threshold square.

I_D(on) given to us is 6 milliampere for corresponding V_{GS}(on) 8 volt. We know what is K? K is I_D by V_{GS} minus V_T square.

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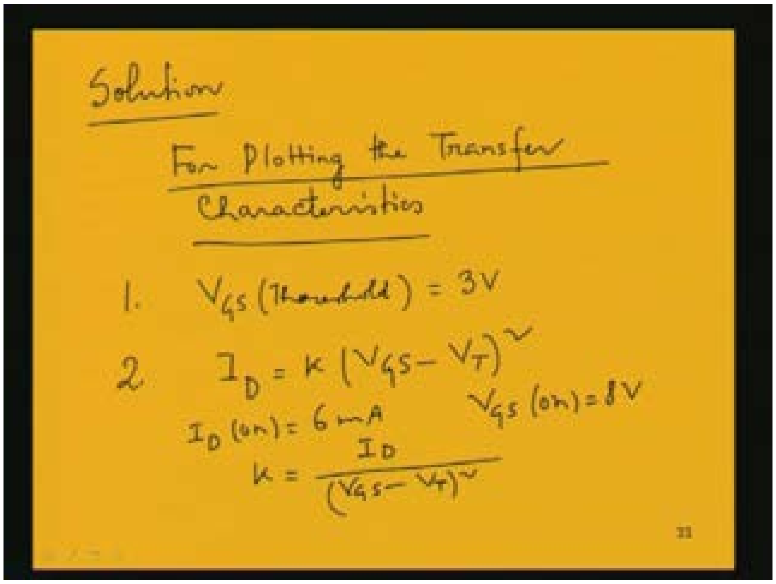

Putting the values here I_D(on) is 6 milliampere which is given to us. V_{GS}(on) is 8 volt, threshold voltage is 3. If you compare this 6 milliampere by 25 we get a value 0.24 into 10 to the power -3 ampere per volt square. Basically it is 0.24 milliampere per volt square. In ampere per volt square if we write it will be the value of K. Once we know K now it is easy for us to find out other points because now we can give a value of V_{GS} and find out the corresponding value of I_D. That we are going to do. But as we have a threshold voltage given by 3 volt and we know for V_{GS} is equal to 8 volt, in between we will find another point. Between 3 volt and 8 volt let us find a point, for example 6 volt. Third point we will find for V_{GS} equal to say 6 volt. That is taken as it is between threshold voltage and the other point which is given by 8 volts. So we take in between point say 6 volt. This you can take 5 volt also but let us take around midpoint.

For 6 volt V_{GS} what will be this value of I_D? K into 6 minus threshold is 3 square. So K is 0.24 into 10 to the power -3 into -3 square. This value comes to 2.16 milliampere. Three points we have known. Another point let us take for a higher value of I_D. Let us take V_{GS} is equal to 10 volt. For V_{GS} is equal to 10 volt I_D will be equal to K is 0.24 into 10 to the power -3 into 10 minus 3 square. If you calculate this value you will get the value to be equal to 11.76 milliampere.

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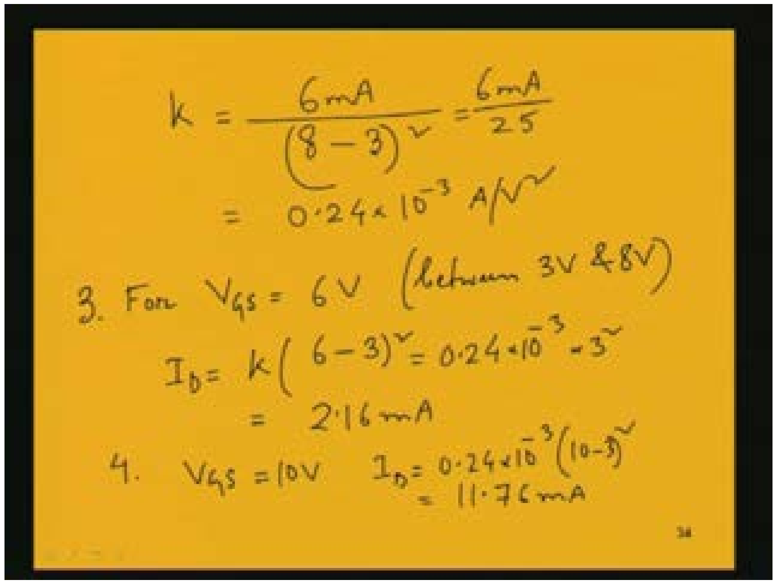

Now we can comfortably draw the transfer characteristics because we know 4 points. This is V_{GS} in volt, this is I_D in milliampere. We have to draw to scale. Let us mark the points, 1, 2, 3, 4, 5, 6. Let us draw the scale. Let us take 1, 2 like this, so it is 4, 5, 6, 7, 8, 9, 10, 11, 12 like that; similarly 1, 2, 3, 4, 5, 6, 7, 8; like that 11, 12. One point is 3, this point. The other point is given by 8 and 6; 8 and 6 here, it is another point. Third point we have taken 6 and 2.16. 6 and 2.16 will be somewhere here. If you draw to scale that will be the correct values. But here I am drawing only with estimation and the last point is 10 and 11.76. 10 is here and 11.76 is say somewhere here. Now joining these four points we get the transfer characteristics.

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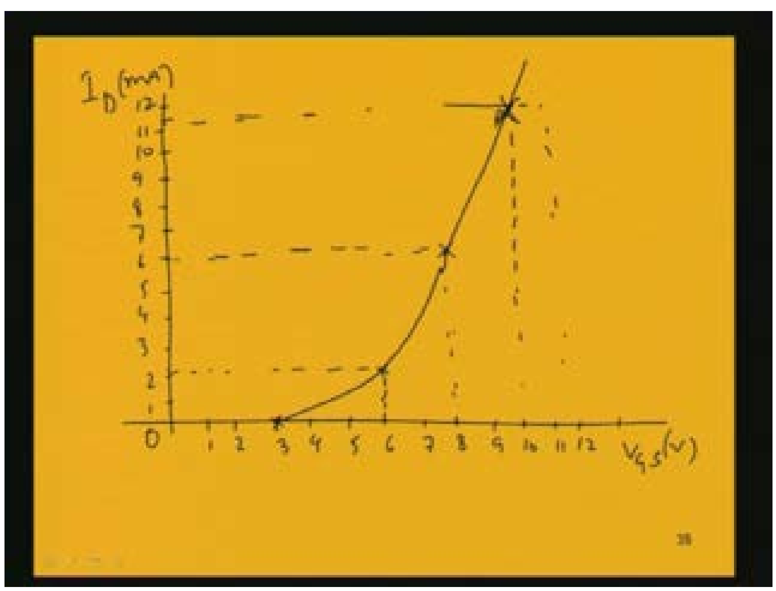

For the biased circuit, the other one, the straight line which is V_{GS} equal to V_{DD} minus I_DR_D. I_D is equal to zero means V_{GS} is equal to 12 volt and V_{GS} is equal to zero means I_D equal to V_{DD} by R_D and that is equal to 12 by 2. R_D is equal to 2 kilo ohm, so we get 6 milliampere.

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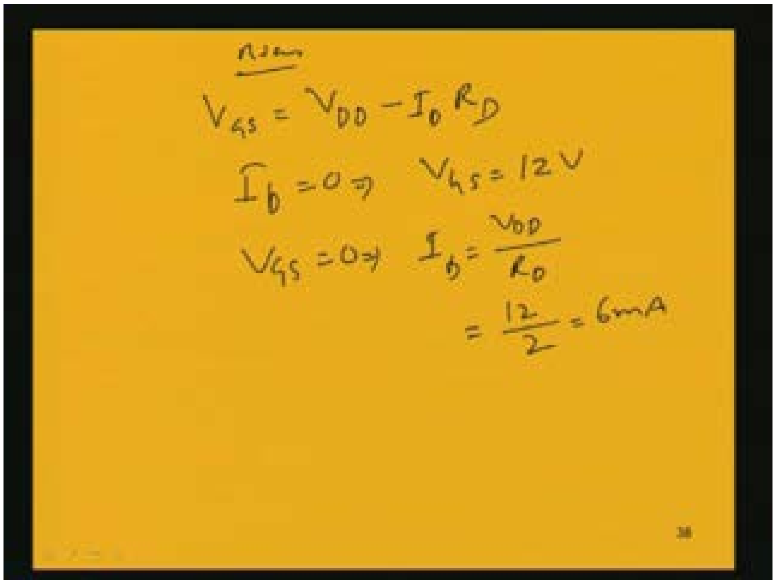

We can draw the straight line; one is at 6 milliampere here and other is the 12 volt. Joining these two we get a straight line. This is for the biased circuit. This is the transfer characteristic. The point where these two are intersecting this point is the Q point and if you draw to scale this point will be given by the voltage and the current at this point. This is your V_{GSQ}. This is your I_{DQ} which will be given by 6.4 volt and 2.75 milliampere.

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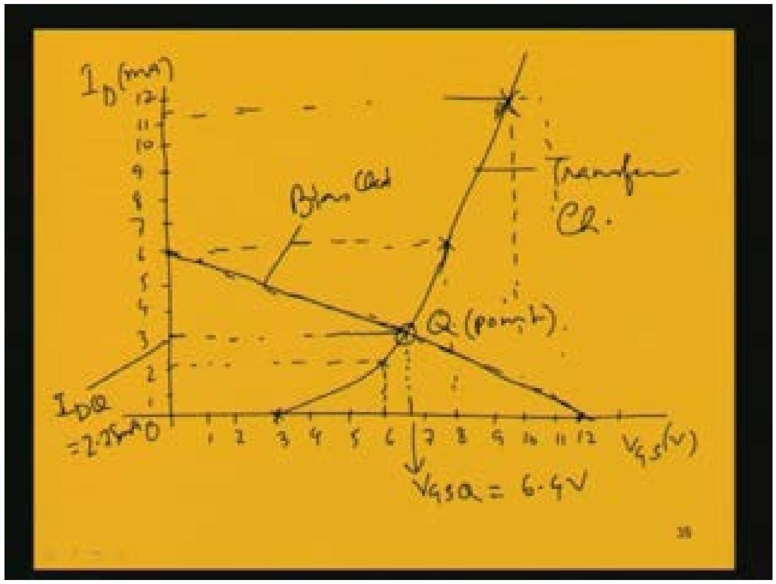

We get the Q point as 6.4 volt and 2.75 milliampere. This is the way we have to solve the problem. We have to draw the transfer characteristic as well as the bias circuit straight line. Then the intersecting point between them will give you the Q point.

In the discussion today we have seen how the MOSFET is used as an amplifier. That is to amplify weak signal how we use the MOSFET in the saturation region and for properly selecting the operating point we need to first use a proper biasing scheme and for that we have seen the two biasing methods. One is the feedback biasing scheme and other is the voltage divider biasing scheme. Once we select the operating point properly then we can now proceed for amplification of the weak signal and so we will analyse the MOSFET amplifier next by using the small signal model of the MOSFET. Next we will discuss about the small signal model of the MOSFET and use it for finding out the parameters of the amplifier.