Basic Electronics

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Module: 3 Field Effect Transistors
Lecture-3
MOSFET UNDER DC OPERATION

Today we will discuss about the MOSFET circuit under DC. When we apply a DC voltage between the gate and source then what will happen is the currents in the different branches can be found out. That DC operation we will take up today. In the last classes we have discussed about the different types of MOSFET. We have discussed about the enhancement type, depletion type and in the enhancement and depletion type MOSFETs there are two types again that is n-channel and p-channel. In our discussion today we will take examples of both these MOSFET's and try to solve examples dealing with the DC operation. For example let us take one circuit. Here we are having a circuit. By the symbol of the MOSFET we know what type of a MOSFET it is.

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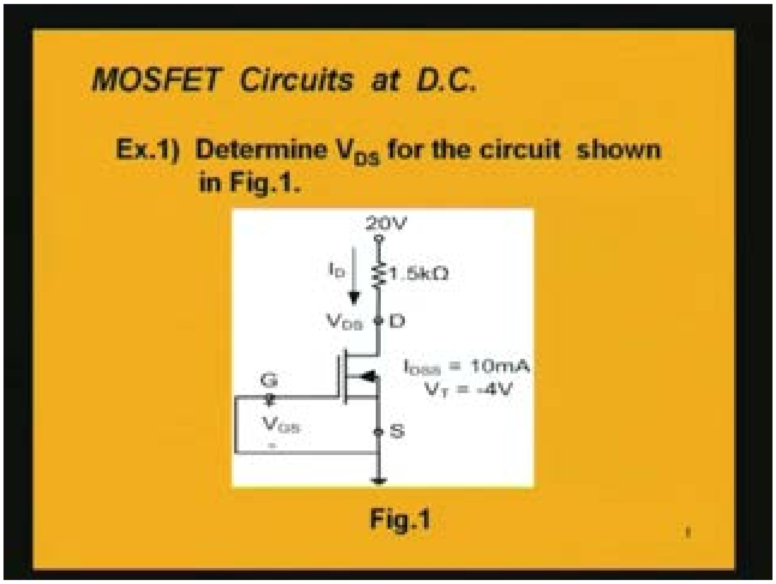

This MOSFET is n-channel depletion type MOSFET. The voltage at the drain is denoted as V_{DS} because S is the source which is grounded. So V_{DS} is also represented by V_D because source is grounded. A 20 volt supply is there and the resistance 1.5 kilo ohm is connected between the voltage and the drain terminal and here the gate terminal is shorted to the source. We are asked to find out the V_{DS}. What will be the voltage between the drain and source that is to be found out? Given that I_{DSS} is equal to 10 milliampere and we know I_{DSS}, the drain current or drain to source current when the voltage between gate and source is zero. This is a value which is specified in the datasheet for a particular depletion type of MOSFET. For this example we are having I_{DSS} value as 10 milliampere.

Also specified is that the MOSFET device has a threshold voltage -4 volt. We have to find out V_{DS}. In order to find out the drain to source voltage we have to solve this circuit.

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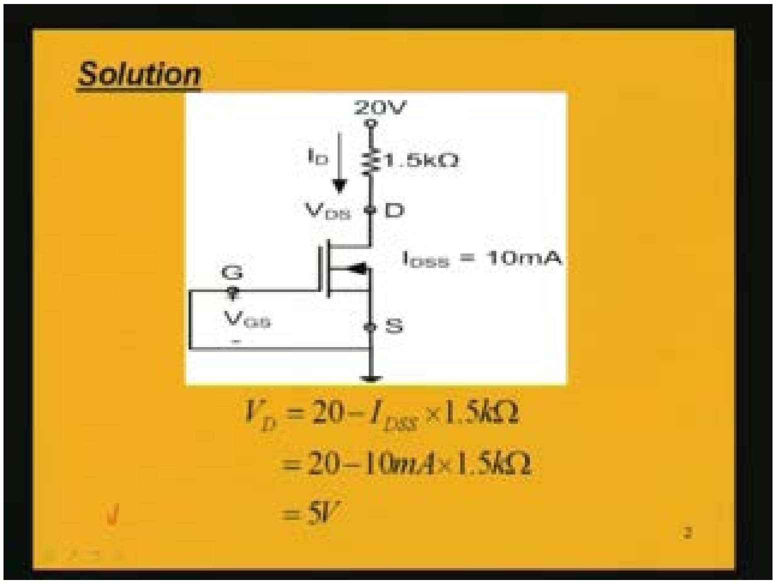

In this circuit which is again drawn we are denoting the drain current by I_D that is the drain to source current and one thing to be noted is that the gate terminal is connected to source as a short circuit and the source is grounded. We now apply the Kirchoff's voltage law to this circuit because we know that this circuit can be solved using the typical laws of electrical engineering like Kirchoff's voltage law, Kirchoff's current law etc. So we will apply Kirchoff's voltage law in the loop. From the end of the 20 volt supply voltage if we travel downwards to ground it will complete one loop starting from here to ground. Traveling along this path if we apply the Kirchoff's voltage law what will it be? It will be equal to V is 20 volt minus I_D into 1.5 kilo ohm –minus V_{DS} is equal to zero.

You have to look into this circuit. Here we are having V_{GS} equal to zero because the circuit itself shows that the voltage between the gate to source is zero. V_{GS} is zero and that is why the drain to source current is the specified I_{DSS}. For this particular circuit as we are having the gate to source voltage zero, the current between the drain and the source is the specified I_{DSS} which is given as 10 milliampere. We can now find out V_{DS}, the drain to source voltage or simply we can write it as V_D. V_D or V_{DS}, this is the same thing because the source is grounded. The voltage between drain and source is nothing but the voltage between the drain and the ground. It is very simple to find out this voltage V_{DS} or V_D which is nothing but 20 minus this drop and this drop is I_{DSS} into 1.5 k. That if we calculate replacing the value of the current which is 10 milliampere, for this particular MOSFET we are given that I_{DSS} is equal to 10 milliampere, this calculation yields a voltage of 5 volt; so 20-15 is 5 volt. That means the voltage at the drain end with respect to the source or ground is 5 volt. This circuit or example is employing the depletion type MOSFET having n-channel that is we are using an n-channel depletion type MOSFET which is very clear from this symbol of the MOSFET. Let us try another example which is given in the circuit shown in the figure. Here you have to design the circuit as shown in figure 2 so that the transistor operates at I_D drain current is equal to 0.4 milliampere and V_D is equal to 1 volt.

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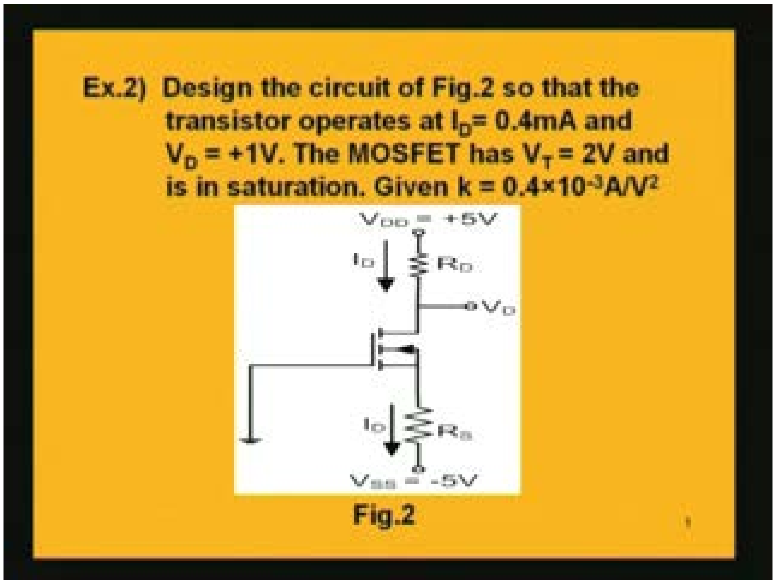

The MOSFET has a threshold voltage V_T is equal to 2 volt and it is in saturation. Given the value of k is equal to 0.4 into 10 to the power -3 ampere per volt square. Here this point is important that the MOSFET is in saturation. As it is in saturation we have to consider that the voltage V_D must be greater than V_{GS}-V_T and the threshold voltage is given as 2 volt. So we will find out V_{GS} corresponding to that condition of saturation.

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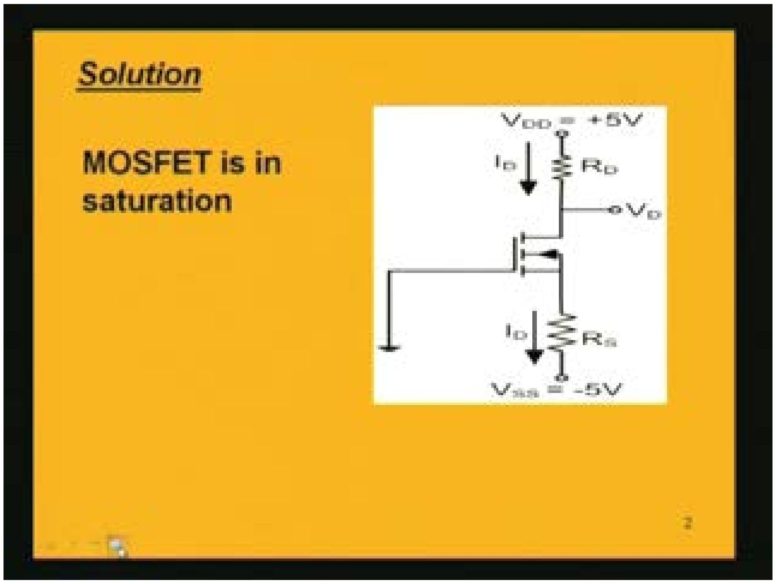

Writing down the relation of the I_D current with respect to V_{GS} and V_T which is this non-linear expression we will find out V_{GS} and this quadratic equation gives two solutions. But out of these two solutions, only one solution will be feasible which will satisfy the conditions for saturation that V_D must be greater than V_{GS}-V_T. We will now solve this quadratic equation and find out that value of V_{GS}. This and this cancel, 0.4 and 0.4; we get an equation 1 equal to V_{GS} minus 2 whole square. Simplifying this we get V_{GS} square minus 4 V_{GS} plus 4 equal to 1. That gives us V_{GS} square minus 4 V_{GS} plus 3 equal to zero. We need to solve this equation for finding out the gate to source voltage for this circuit to be under saturation. For the ON condition we have to find out what is the V_{GS}? This equation is a quadratic equation as we see. It will have two values of V_{GS}. If we solve this equation it will be V_{GS} equal to 4 plus minus under root 16 minus 12 divided by 2. What will it be? It is 4 plus minus 2 by 2. Basically we get 6 by 2 and 2 by 2. That means we have two values 3 volt and 1 volt. But if we have V_{GS} is equal to 1 volt, then our condition that V_{GS} minus V threshold must be less than V_{DS}, that condition will not be satisfied because V_{GS}-V_T will be then how much? 1 minus V_T, we have been given as 2 volt; so 1-2 means it will be -1 but we have V_{DS} is equal plus 1 volt, so this is ruled out.

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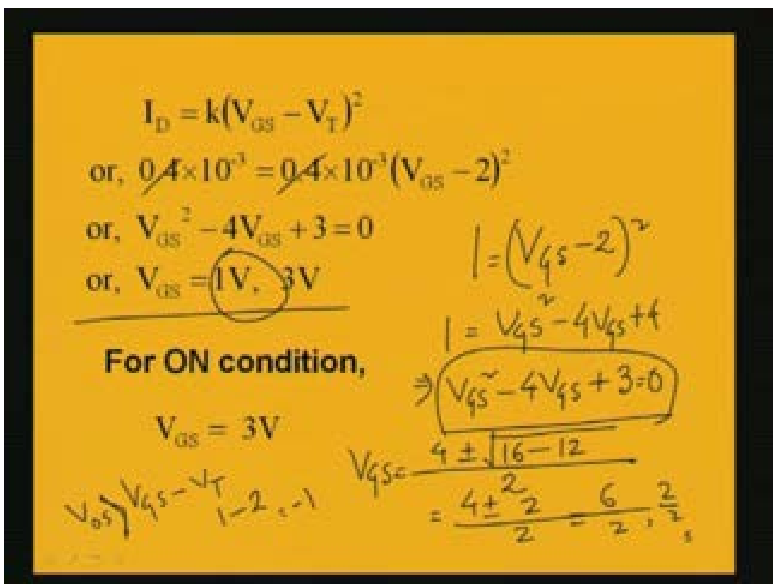

If V_{GS} is equal to 3 volt this condition is met; that is V_{DS} is greater than equal to V_{GS}-V_T that will be met when this is 3 volt. V_{GS} is equal to 3 volt is the critical condition which will make the circuit to be under saturation. We will take that value of V_{GS} which is equal to 3 volt. With this V_{GS} equal to 3 volt we will now proceed to find out the resistances.

In this circuit we now solve in the output circuit V_{DD} minus I_D R_D minus V_D is equal to zero. V_D means with respect to ground. V_D has been given to us as 1 volt. Putting down the values of this V_{DD} and I_D we can find out what is R_D because others are known except for only R_D.

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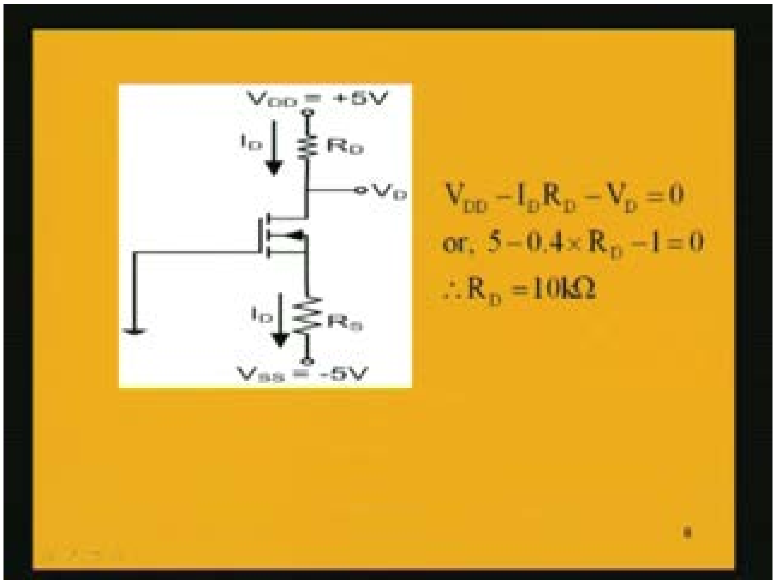

V_{DD} is equal to 5 volt. So 5 minus I_D given to us is 0.4 milliampere, keeping that as 0.4 only then the answer will be in kilo ohm, minus V_D is equal to 1 volt; the voltage at the drain is 1 volt. This gives us the solution of R_D equal to 10 kilo ohm. If we solve this equation it will be 10 kilo ohm. We know what is R_D? What will be R_S? In order to find out R_S we will come through the bottom loop. This is zero minus V_{GS}. This is V_{GS} between this drain and gate. This is drain, this is gate and this is source. With respect to source terminal this voltage is V_{GS}. This is ground point. We will go through this loop zero minus V_{GS} minus I_D into R_S minus V_{SS} is equal to zero. Applying KVL in the bottom loop we get this equation.

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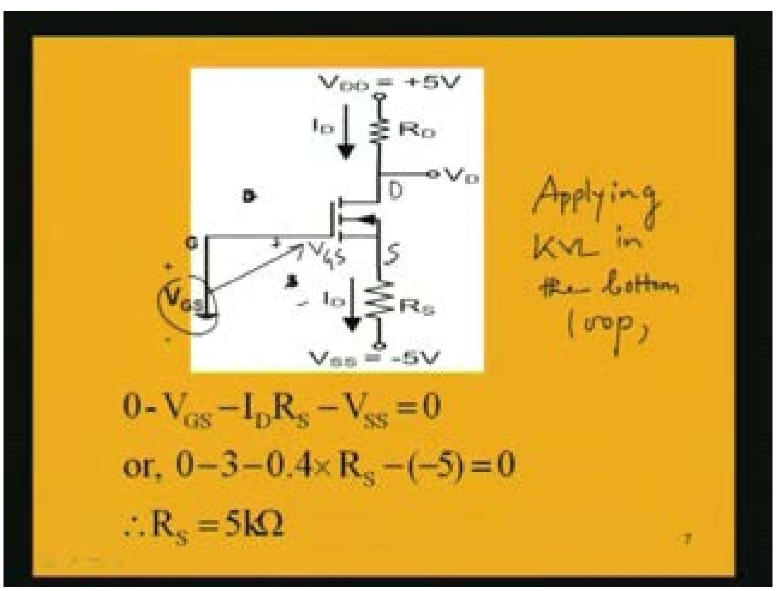

V_{GS} has been found to be equal to 3 volt and I_D is also known. V_{SS} is -5 volt. We will now solve this equation. Only unknown is R_S. R_S is equal to 5 kilo ohm. For this circuit we have found out the two resistances R_D and R_S. In this way the operation of this MOSFET device when only DC voltages are there is illustrated in these two examples.

Why do we use a MOSFET device or for what applications we use a MOSFET device? We use MOSFET for amplification. Earlier when we were discussing BJT, bipolar junction transistor we have studied about the application of the BJT as amplifier. We have seen how amplification of the weak signal takes place. Similarly a MOSFET device also is used as an amplifier. Now we will study about the use of MOSFET as an amplifier. Take for example a simple circuit to illustrate how a MOSFET device is used for amplification. 1856

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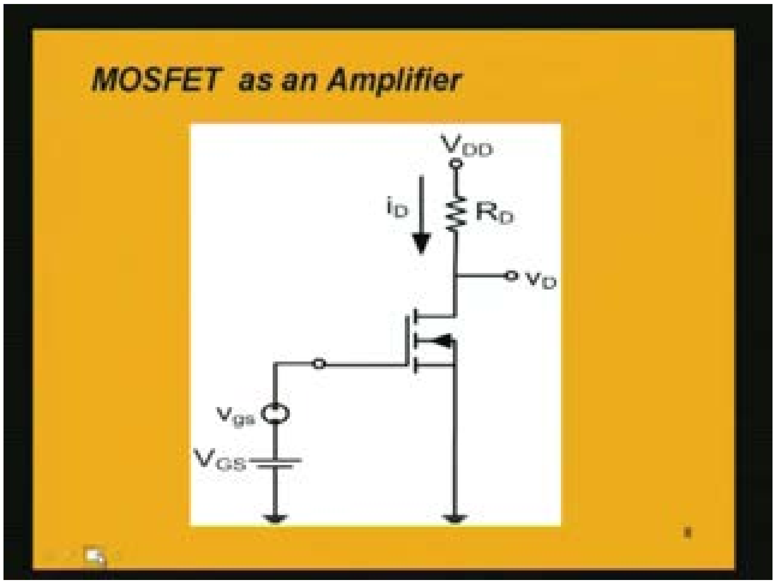

Let us now take this circuit having an n-channel enhancement type of MOSFET device. We are restricting our use to enhancement type MOSFET in this particular discussion but we have depletion type MOSFET also which is used as amplifier. But as we are going to discuss about the basic amplification and other related matters, we will take up the example of enhancement type MOSFET and we will discuss other aspects related to amplification. Instead of discussing different, different type of MOSFET devices let us concentrate on the application of enhancement type and see how the amplification and other related things can be understood. It is not necessary that only enhancement type of MOSFET device be used for amplification but we are taking this example. The amplification and biasing, etc can be also explained for depletion type of MOSFET but we will discuss one particular type of MOSFET and focus on it. We are taking an n-channel enhancement type of MOSFET. What is the amplification? We already know from our earlier studies that amplification means we are trying to increase or enhance the magnitude of a weak signal without distorting its shape. If we have a small or weak signal we will use an amplifier so that at the output we get an amplified form of the input signal. The shape of the input signal should not vary. We need or we desire faithful amplification but its magnitude should be enhanced. That is the basic principle for amplification.

As we were discussing in BJT, the concept of amplification is similar. For this MOSFET device also we will proceed in a similar way. Here we are having this MOSFET which is an n-channel enhancement type MOSFET. In our study we are taking that as an example. We are having DC sources. We are also having a small signal so that we finally get an amplified form of this weak signal. Our aim is to amplify the small signal. This is the gate terminal, this is source and this is the drain. This amplifier is amplifying a signal between gate to source which is small v_{gs}. Apart from this signal there are DC sources which are needed for biasing. We will discuss about the biasing schemes later but in general this figure typically shows one arrangement for amplifying a small signal. The gate to source voltage is if it is varying we know that drain to source current will vary. We have earlier studied about the transfer characteristic or and VI characteristics and we have seen there are three different regions of operation. One is the cut off region one is the triode amplifier region and the other is the saturation region. For saturation region the condition to be satisfied is that the drain to source voltage must be greater than V_{GS} minus V threshold.

In this circuit let us show that drain current is i_D. One important thing to note is that here a combination of both small as well as a capital letter is used just to signify the instantaneous value of voltage and current we use both the small as well as capital symbol because we have two situations here; one is the DC and one is the AC. The DC condition is for biasing and the AC condition is for the signal. If we do not have the signal, as we have earlier discussed in the examples which we did just now, if we have only DC quantities or DC voltages and currents if we have only DC situation then we denote that voltage and current by capital letter say V_D, I_D, etc and if we purely have AC signal we denote this signal by small v small d, small i small d, like this. Now we are having both the DC and AC conditions. What we will have? We will have a superimposition of AC on DC. In the absence of the AC signal we will have a constant DC voltage say V_D or if we consider the gate to source voltage we have V_{GS} which is a DC signal DC voltage. If we now apply this AC signal small v small gs, we will have on this DC voltage superimposed AC voltage like this, small v small gs. At any instant you consider the total voltage between the gate and source. Suppose at this instance what will be the voltage? It will be the total voltage which is having the DC part and an AC part. To know that or to express that instantaneous value of this voltage we use the symbol small v capital GS. Similarly the current component also if we consider, if we have only the gate to source DC value of voltage which is capital V_{GS} then corresponding drain current is say capital I capital D, and when we have the signal applied small v small gs the corresponding current in the drain is small i small d. Then with both of them being applied V_{GS} plus small v_{gs} as is shown in this figure we have corresponding drain current as capital I capital D, plus this small i small d and this quantity is denoted by small i capital D, i_D. That is shown here in this figure.

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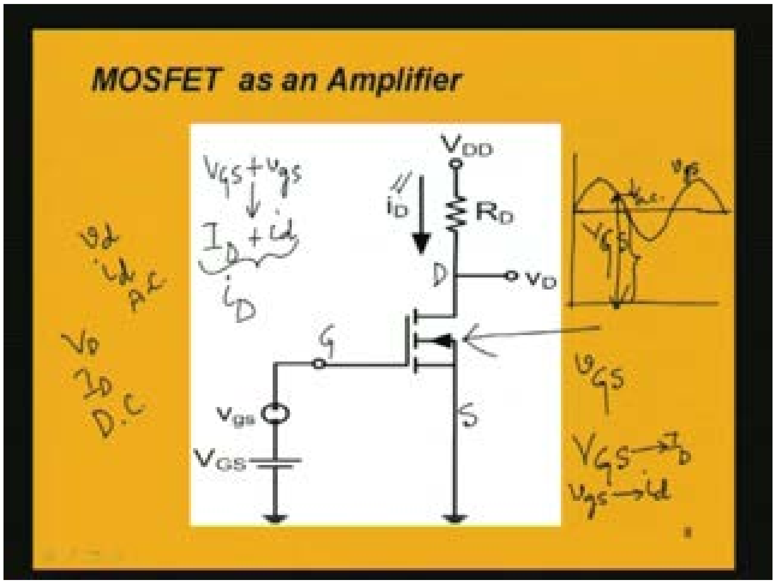

This small i capital D actually means combination of DC current as well as the AC current, DC I_D and AC i_D. When we want to do an amplification that means if we have a small signal here at the drain end we will have to get amplified signal. The voltage at the drain end with respect to ground is small v capital D. By that also we are meaning instantaneous voltage which is a combination of both DC and AC. This circuit is a very simplified version to actually understand the amplification. In practice you may not get such a simple circuit but for understanding purposes we are taking it in a simple manner like this. But in actual while we discuss about biasing, etc we will have a complicated or a different version than this particular small circuit but for the time being we will consider a smaller circuit or a simpler circuit for first of all understanding the basics behind the amplification. At this point we are having a combination of both DC and AC. As it is not having any capacitor, etc to block the DC components we are having both the DC and AC being present here.

One important thing to understand or to remember before going to discuss the amplifier in details is that to operate as an amplifier the MOSFET device must be biased in the saturation region. This is an important thing to note and always remember that we will operate the MOSFET in saturation when you want to apply it as an amplifier. It is just like when we were considering the BJT as an amplifier we operated the transistor in the linear region that is in the active region. The first and foremost condition which has to be met when a transistor BJT is operated as an amplifier is the BJT must be operated in active region. Similarly the MOSFET must be operated or it must be in saturation condition to work as an amplifier. That condition has to be always satisfied that V_{DS} is greater than V_{GS}-V_T so that the MOSFET is under saturation. Here what we are doing is we are varying the gate to source voltage V_{GS}. This is the controlling quantity. In BJT we were controlling the collector current by means of the base current. Here we will control the gate to source voltage and control the drain current i_D. This is the idea which will be applied in amplification.

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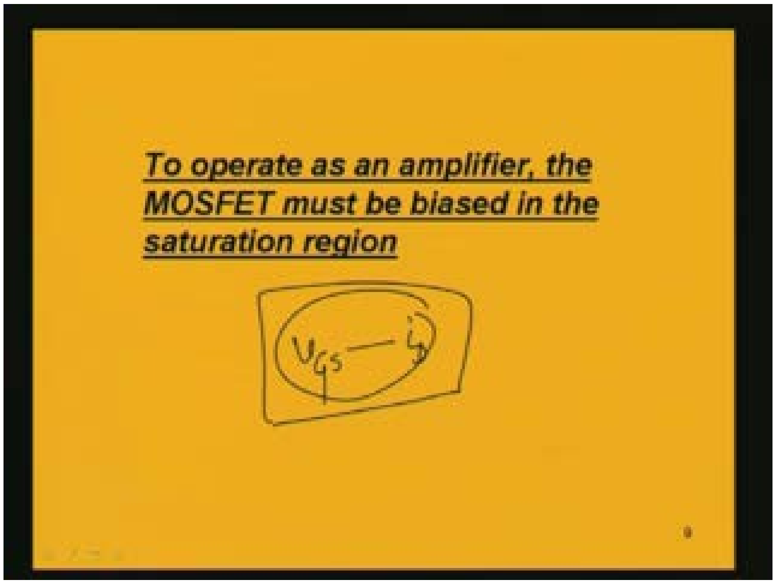

That is we have to control V_{GS} to control i_D. In order to study the amplifier in details we will consider the DC and AC conditions separately. In BJT also we considered the DC biasing condition and then when the signal was applied we combined both of them. We want to analyse the DC condition and then we will go to the small signal model of the MOSFET device so that we can analyse it for being used as an amplifier to know the parameters. But before that let us now see what will be the condition when you do not have the signal and only have the DC condition.

In this particular example first of all we do not have the signal. Without the signal only purely DC condition is prevailing. Then the circuit will have the DC voltages V_{GS} and V_{DD} and the small v_{gs} is absent. In the absence of small v_{gs} we are having this circuit. The current which will flow in the drain to source is capital I capital D now. Without signal if we find out the drain current capital I capital D we know that this is an enhancement type of MOSFET and the relationship from the current and voltage is given by I_D equal to k into V_{GS} minus V_T whole square. This expression we will have to always keep in mind. What is this voltage? You note that this is DC voltage. We are having the DC condition only. This capital V capital D signifies or denotes the DC voltage only. What is V_D? We can apply Kirchoff's voltage law directly; V_{DD} minus capital I capital D into R_D equal to V_D.

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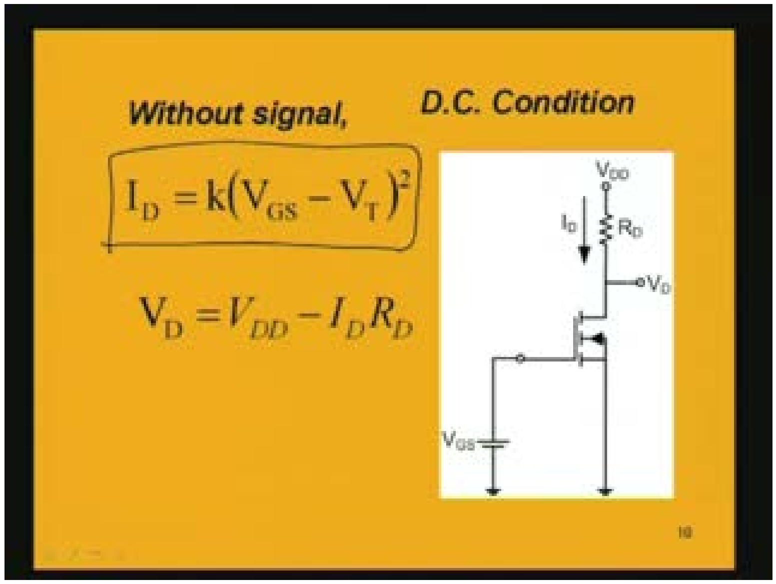

This is as simple as that because we are not having the signal. We are having only DC condition so we are analysing the DC circuit and as the amplifier has to be in saturation at any point during operation it must be satisfying the condition for saturation. So V_D must be greater than the V_{GS}-V_T. We are applying a signal also, that has to be kept in mind. When you apply the signal your V_D whatever we will be getting at the drain end that voltage should be such that at no point the condition for saturation is violated. That is because we are having a signal swing because of the swing in the input AC voltage. This is v_{gs}. If we have a DC V_{GS} here because of the signal we will have the drain current small i small d superimposed on the capital I capital D which is due to V_{GS} only. For only application of capital V capital G capital S that means the DC V_{GS}, suppose we have a V_{DS} as this one that is V_{DS}. Capital V capital DS means it is that DC voltage due to this V_{GS} only. Because of the application of this signal we have a small i small d. Due to this small i small d we will have a corresponding small v small d. So this will come on it. At no point of time the V_{DS} or V_D must be less than this quantity that has to be kept in mind. Because we are dealing with amplification you know that the output voltage will be greater. It will have high magnitude. The biasing should be proper so that under no condition this is violated.

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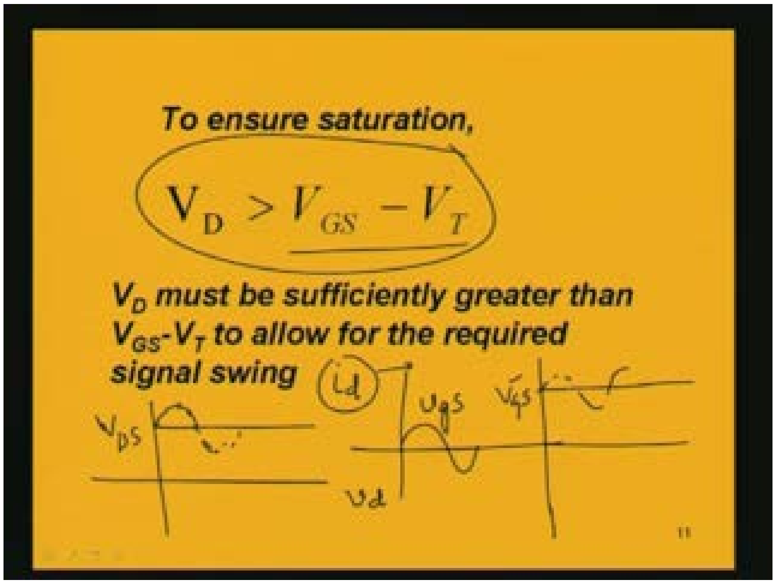

As we have seen in BJT at no point it should go to cut off or saturation. It should be always in the active region so that the input is forward biased. The emitter base junction is forward biased and collector base junction is reverse biased that has to be maintained always. Similarly in MOSFET this condition has to be satisfied for enhancement type of MOSFET which we are dealing with so that it is always in the saturation region because the MOSFET amplifier operates in saturation region. Without the signal we have discussed the DC conditions. If this signal is applied now what will happen is that we will have current at the drain which is denoted by small i capital D because small i capital D means it is DC plus AC.

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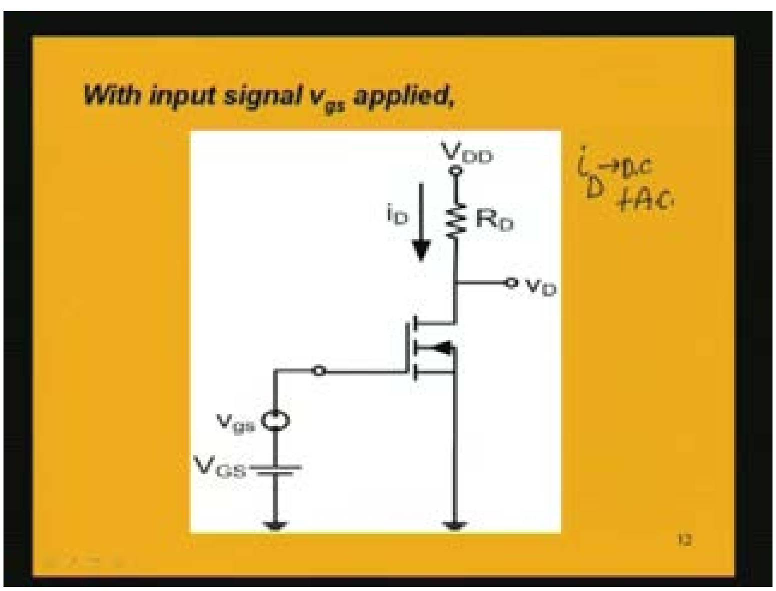

When we have the signal along with the DC signal V_{GS} equal to capital V capital G capital S plus small v_{gs} is the total instantaneous gate to source voltage. Due to this gate to source voltage we have the drain current which is denoted by small i capital D meaning that we are having both DC and AC. That is given by the current law. What is the current law? That is I_D equal to k V_{GS} minus V_T whole square. This is if we have the DC condition. We are not having DC condition because we are having both the DC and AC. If you want to find the instantaneous value of the drain current then the total voltage between gate to source we have to take care of and that voltage is capital V_{GS} plus small v_{gs}. So instead of this V_{GS} we will have to put capital V_{GS} plus small v_{gs} minus V threshold that is specific for a particular MOSFET device which is given in the data sheet itself. Now our relation for the current is this one. Instead of only V_{GS} we are having this voltage.

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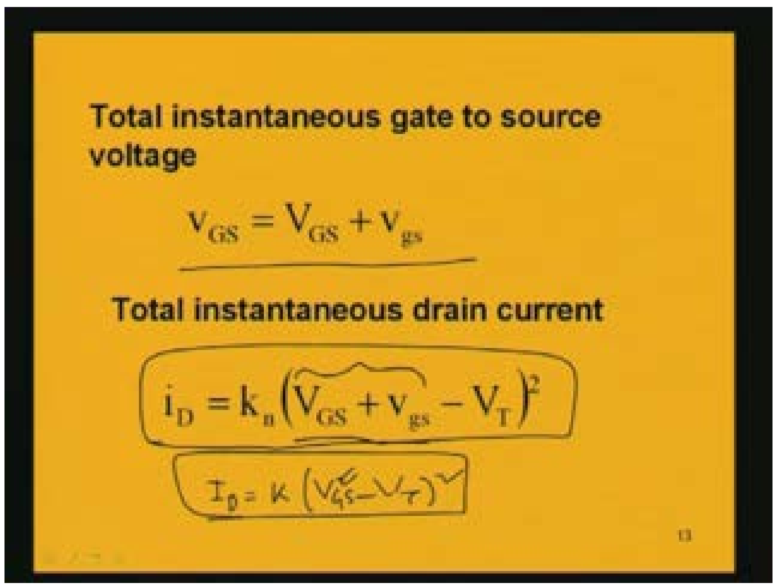

This K_n is the specification constant for the n-channel enhancement type of MOSFET and this is basically a constant which is given or which can be computed given the parameters like length of the channel, width of the channel, etc. In this particular discussion we are using it as a constant. Instead of going into the computation of K_n let us keep in mind that we are using a value for the constant which we are assuming as known. Basically the way to find out the value for K is another topic. We can find this out provided we know about certain other parameters like length, width of the channel mu n etc. We are not going into details but let us assume that we already know or it is given to us in the datasheet.

If we now expand this current expression in the right side it is A+B whole square type of quantity. If we want to break up, A square plus 2AB plus B square kind of expression we will get. So that is equal to K_n into let us keep V_{GS}-V_T together; this whole thing under the bracket is V_{GS} plus small v_{gs} minus V_T but let us take the quantity V_{GS}–V_T together and small v_{gs} separately. That will be now expanded as a square. So it is A square plus twice A into B plus B square. If we closely look into this whole expression, first expression K_n into V_{GS}-V_T whole square is nothing but the DC biasing current capital I capital D.

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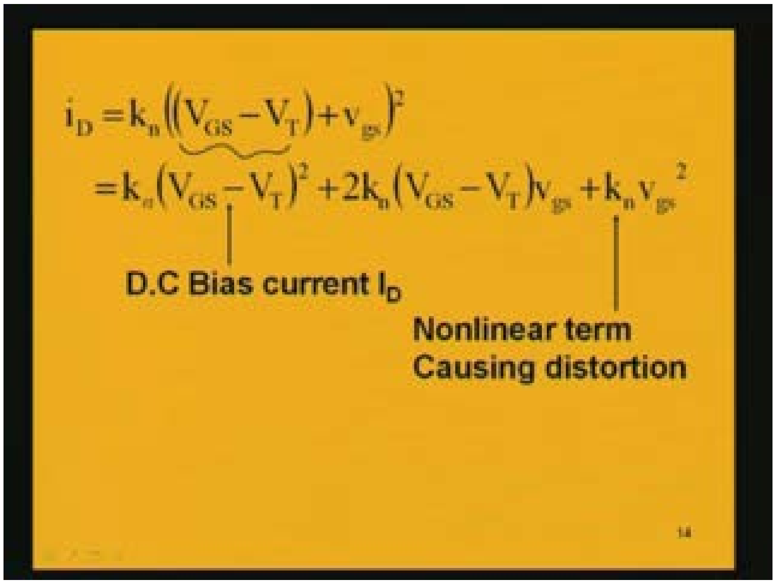

Because if we look into the quantities, this is the DC quantity of the gate to source voltage and this is the threshold voltage. This whole quantity is nothing but the DC drain current. Last term in this expression K_n v_{gs} square, is a square term. Small v_{gs} is the signal. This square means actually it is introducing a non linearity. Because it is a square term it will be a nonlinear term. So it will be causing distortion. In the whole current expression if we have a nonlinear term like this one, the last one will cause a distortion in the current. We have to reduce the effect of this distortion of the nonlinear term and that we can do if we choose the term carefully. That means in comparison with this term suppose we have to neglect this K_n V_{GS} square. So then what we will do?

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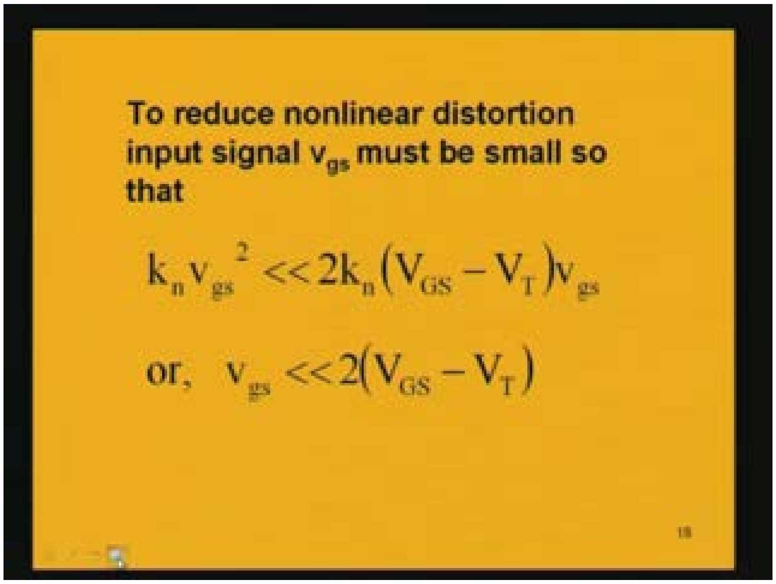

We will make the V_{GS} term or this small signal v_{gs} so small that the square of that small term which is again further smaller and it should be very, very small as compared to the other term which is this one. We are now focusing on these two terms because we did not want the nonlinear distortion which is introduced by this square of the v_{gs} term. We want to get rid of this. This should be very, very small so that we can neglect it in comparison with this one. This plus this is almost equal to this so that this term should be neglected. When can we neglect it? If it is so small in comparison with this other term, then only we can neglect. We must make or we must choose this v_{gs} sufficiently small; sufficiently it should be small so that if it is very small its square will be further smaller; it will be smaller term. $K_n v_{gs}$ square is small in comparison with other term twice K_n into V_{GS} minus V_T into v_{gs} or if we simplify little further it boils down to v_{gs} is less than equal to twice V_{GS}-V_T because this and this cancel and this square term and this term cancel. Finally we get a condition that v_{gs} is very, very less as compared to twice into V_{GS}-V_T.

Then if this small signal condition is satisfied then we can neglect the term $K_n v_{gs}$ square. This is an important condition which we will keep in mind that if the signal which we want to amplify is very, very less as compared to the right hand side expression two times capital V_{GS}-V_T, then the distortion effect can be neglected or it is not causing distortion to the drain current. Then small i capital D or the instantaneous value of the drain current is equal to the original expression if we now again write down and ignore the $K_n v_{gs}$ square term then we get this is the expression for the drain current. What is this current, the drain to source current whose instantaneous value is small i capital D and that is equal to first term is capital I capital D that is the DC drain current and the second term is the AC term, small i small d where this small i and small d is representing this whole term twice K_n into VGS- VT into small v_{gs}.

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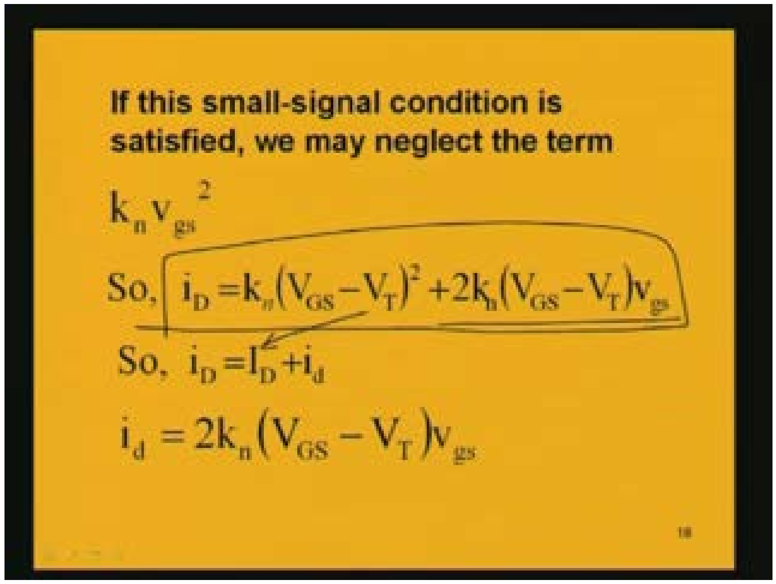

We do one step further and find out the ratio between small i_d and small v_{gs}. If we find this then that is equal to twice K_n V_{GS} minus V_T and that signifies an important parameter which is known as the MOSFET transconductance which is denoted by small g small m, g_m.

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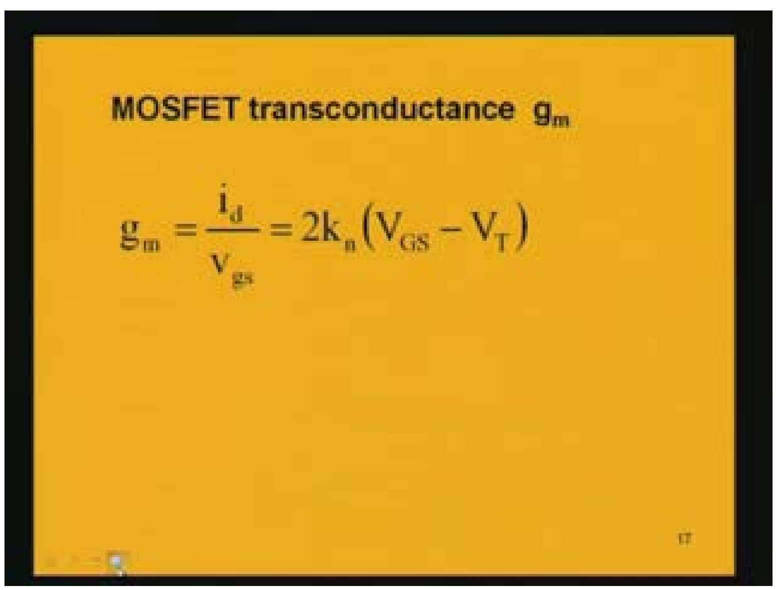

The MOSFET transconductance small g small m is given by small i small d by small v_{gs} which is equal to twice K_n into capital V_{GS}-V_T where this K_n is the fabrication constant for the MOSFET device and this is the DC gate to source voltage and the V_T is the threshold voltage which is known. By transconductance we know a very important parameter for the MOSFET under operation or the MOSFET device which we are using. That transconductance is equal to this right hand term which actually characterises the MOSFET. This will be very important when we go to discuss about the amplifier small signal model.

The characteristic between drain current and the gate to source voltage is nothing but the transfer characteristic. We are familiar with the transfer characteristic which is a nonlinear curve which can be drawn if we know certain points or by joining the points we can draw a nonlinear curve. The starting point will be the threshold voltage when the current is zero and some other points, 3 points or 4 points will be necessary to draw this transfer characteristic and this is the operating point Q. The operating point will be fixed by the biasing circuit and that we are going to discuss very soon. If we have the operating point denoted by Q, then this is having the coordinates V_{GS} and I_D; both are capital to denote the DC condition. For a V_{GS} the corresponding I_D is shown here and the slope of this transfer characteristic at the operating point which is i_d by small v_{gs} that is actually the transconductance.

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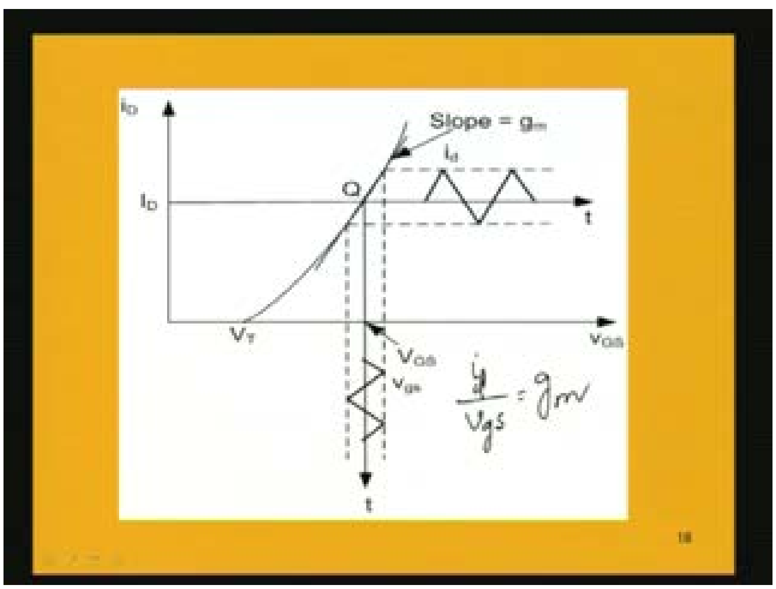

From the transfer characteristic, finding the slope at the operating point we can know the transconductance.

In today's class we have started discussing about the MOSFET as an amplifier. Basically the MOSFET device is used for amplification of weak signal by controlling the gate to source voltage and the MOSFET device must be under saturation to be used as an amplifier. That is one very important condition and we will have the normal biasing arrangements for fixing the operating point and then we will apply a small weak signal between the gate and source to amplify it at the output end or the drain end. Basically we will get a voltage at the drain which will be in an amplified form but we do not want distortion of the input signal which is applied at the gate to source terminal. We will later on discuss about details of amplifier circuits.