Analog Circuits
Prof. Nagendra Krishnapura
Department of Electrical Engineering
Indian Institute of Technology, Madras

Module - 02
Lecture – 07

We know the equations describing the current voltage relationship of a MOS transistor. Now, let us sketch those characteristics and get a better feel for what they are. And as an example, I will take a MOS transistor, whose mu n C ox product is hundred microamperes per volts square; and this W by L, W is some physical dimension of the transistor; L is another physical dimension, and this ratio itself is dimensionless, and this ratio we will take to be one. So, the current factor K n which is mu n C ox W by L, this is hundred microamperes per volt square, and these dimensions do make sense, because we multiply the current factor with square of the voltage to get the current, so the current factor itself has dimension of current divided by volt square.

Now, I will also take the threshold voltage V T to be one volt. This is just for illustration in making some sketches illustrating the characteristics. Now, what are the characteristics we have to sketch, the MOS transistor is a two port, there is a drain current I D, the gate current I G, and each of these has to be sketched as a function of two port voltages V G S gate source voltage, and V D S drain source voltage. Now, the gate current is zero, so there is nothing to sketch there; so we have to look for plots of I D versus V G S, and I D versus V D S. Now, I D versus V G S will be with some constant value of V D S, and then you can choose another constant value of V D S and then keep plotting. Similarly, I D versus V D S would be for constant value of V G S and then you plot it for different constants values of V G S. So, let us do this.

So, let me take I D versus V G S. As usual at this point, I would like you to pause the video and try to sketch the characteristics yourself, for the constant values I have given, and after that you can compare it to what I draw here so that will give you practice in doing these things correctly. So, V G S this is in volts; so let say one, two, three, four and so on. Now, we know that when the gate source voltage is smaller than the threshold voltage, which is one volt, the current is zero. So, the current will be zero up to this point. So, this is the threshold voltage one volt. Now, beyond this, the current will depend on V D S also, but if V D S happens to be more than V G S minus V T; if the transistor is in saturation region then the curve is independent of V D S.

And I will choose that case, that is, I have assumed that the transistor is in saturation region. If I choose V D S to be very large number, this will be the case, regardless of the value of V G S, this will be satisfied and the current will be independent of V D S. Just to remind you this is also called the saturation region. So, clearly for one volt, it will be zero; for V G S equals two volts, this term within parenthesis will be one volt; and this will be one volt square, and it will get multiplied by the current factor K n divided by two. So, the current will be 50 microamperes. So, let say this I D is in microamperes, you can easily verify this. And similarly, if V G S is three volts, this number V G S minus V T whole square will be 4 volts square, so we will get 200 microamperes; and similarly, if V G S is 4 volts, this V G S minus V T whole squared will be 9 volts square, and this product will be 450 microamperes, and it will keep going.

And you can see that for every volt step here, the step in current is larger and larger and that is simply a consequence of this square term over here. So, it will be like this. The crucial assumption here is that for all values of V G S I have shown here, I have assume saturation which means that V D S is greater than V G S minus V T. So, I D does strongly depend on V G S in this region, and this slope only goes on increasing. Now, what does I D versus V D S look like, let say this V D S is also in volts; and this I D is in microamperes. It is first easy to sketch the cut off part, that is, by the way this plot as you know now I have repeated it many times, it will depend on V G S, and you vary V G S as the parameter, and plot this.

For V G S less than V T, the current will be zero. This is cut off. By the way, I should start these plots, earlier said that I will consider V G S and V D S to be positive, so I should start these plots from zero, and go only to the right. Next let us take V G S more than V T; let us take V G S of two volts, and V T is one volt right. It is easiest to plot the saturation region current, when V G S is two volts, and V T is one volt, we know that this expression evaluates to 50 microamperes, but it will be valid only for V D S more than V G S minus V T. And how much is V G S minus V T now, it will be one volt. So, this will be the curve for V D S equals one volt. The current will be 50 microamperes. It is the same as what is evaluated here. Notice that I have made the x axis collinear, so this is fifty microamperes and exactly the same thing is what we see over there. But this is valid only for V D S more than one volt, so this is the value of V G S minus V T.

Next, let us take V G S equals three volts. If V G S equals three volts then this expression evaluates to two hundred microamperes as we have seen here the second point over here, but it will be valid only when V D S is greater than V G S minus V T or V D S greater than two volts. So, in other words, V G S equals 3 volts, we will have this constant current, if V D S is more than V G S minus V T, which is 2 volts. And repeating the exercise for V G S equals four volts, this expression evaluates to 450 microamperes, exactly like here. So, this is the points for V G S equals four volts, and that will be 450 microampere there, but of course, it is valid only for V D S more than V G S minus V T or V D S more than 3 volts.

So, by the way just as an aside, I am trying to sketch these things somewhat to scale although I am drawing it by hand, and this is the very useful thing to do. Now, sketching is not very often practiced these days it looks like, but sketching not for accurate calculations, I mentioned this while talking about graphical analysis of non linear systems, but to get intuition sketching can be extremely helpful. You make something approximately to scale and you get a very good idea of what is going on. And then you use equations to accurately calculate. So, learning to sketch curves well is actually very useful skill in engineering. So, now I D versus V D S we have drawn parts of the curve though, the question is what happens before this. Obviously, this part here, let me draw some sort of a boundary. This part to the right is the saturation region, where V D S is more than V G S minus V T.

Now, what happens before that, before that I have to use these other equations which is this. Now, here clearly the current very much depends on V D S. In fact, you know that for V D S equal to zero, the current will be zero, right; no matter what V G S you have. V G S could be more than V T, but if V D S is zero, this entire number is zero and the current will be zero, and that is the useful thing to remember also. The current flows between drain and source, and just like a resistor if you have the voltage difference between drain and source to be zero, the current will be zero. The resistor of course, is linear for different values of voltage across it, the current will be proportional. In this case, the current is not proportional, but for zero voltage across drain and source, the current will be zero.

So, if you think of the drain source difference as some sort of level difference, if the difference is very small, the current will be very small; and if the difference is zero, the current will be zero. And to operate in saturation region, which is the desirable region for amplifiers, you should have a sufficient separation between drain and source so that is some good intuitive thing to remember. Sometimes while doing algebra especially with negative voltages and other types of transistors, you could get confused, but for every type of transistor, there has to be a sufficiently large drain to source voltage in order to have the transistor in saturation region.

Now, what is this curve look like, clearly you see that there is second order dependence on V D S, which says that it is a parabola. And also the parabola it is an inverted parabola, because the squared term has a negative sign. And again I urge you to evaluate this just evaluate this parabola, you will find that it is something like that. And you can find exactly where the peak of the parabola is, the top of the inverted parabola is. It turns out that the part of the curve below this is that inverted parabola, and the peak of the inverted parabola happens to be exactly here. At that point, the current equals the saturation current, and that is not surprising. If you substitute V D S equals V G S minus V T here, this expression and this expression become the same. So, the current starts from zero then it increases with V D S in some way and up to the point where V D S equals V G S minus V T. And after that this parabola does not continue, this expression is no longer valid, then current will be constant.

Similarly, for the other values; there will be some inverted parabola, slope becomes zero and then it stays constant and same happens for all of them. And the region to the left side of it, this is the triode region. Notice that the boundary between triode and saturation that is not at some fixed value of V D S, V D S itself varies depending on V G S. And this curve here, in the dash green line that itself is a parabola, this you can easily verify. In fact, it is the same parabola is this, but shifted to zero volts. So, this should also give you a feel for first of all how to sketch the characteristics and what the MOS transistor characteristics looks like. In saturation region, clearly you see no variation with V D S, so this exactly what we wanted to have. And you have to operate it in this saturation region for the amplifier to provide a high gain. This region also has its uses; we will look at it in some later lesson.

And this curve here, I D versus V G S, I have drawn only for saturation, and it shows the sharp increase of current with voltage. And as the voltage increases, it becomes sharper and sharper, that is also apparent from the I D versus V D S curve, because when V G S jumps from 2 to 3 volts, there is some increase in current; 3 to 4 volts, there is much larger increase in current; and 4 to 5, will be even larger increase and so on. So, if you draw a MOS transistor characteristics for equal steps in V G S, you will see that the current steps will be unequal, they will become larger and larger. So, this is what the transistor's I V characteristics look like. And for amplifiers, in general you want to be here, that is to the right side of this triode region, saturation region boundary.