Low Power VLSI Circuits and Systems

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Lecture No. # 03
MOS Transistors - II

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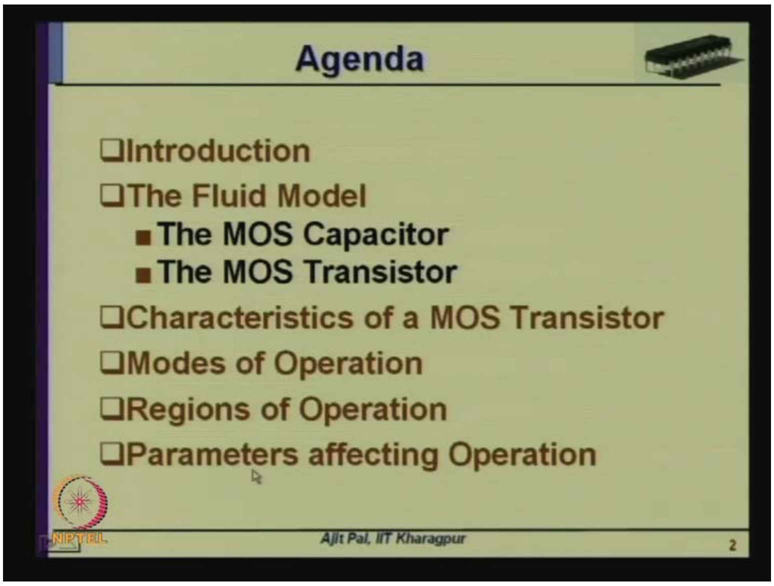

Hello, and welcome to today's lecture on MOS transistors. This is the second lecture on MOS transistor, and today I shall discuss on MOS transistor operation, and here is the agenda of today's lecture. First I shall give a brief introduction about what I have discussed in my previous lectures for the sake of continuity, then I shall discuss the fluid model which has been found to be very useful in understanding the operation of MOS transistors. And as part of the fluid model I shall consider the operation of a MOS capacitor which is the most elementary building block of MOS transistors. Then I shall discuss about the operation of MOS transistor based on fluid model.

And after that I shall discuss the characteristics of MOS transistor without going into any mathematical expression or analytical analysis, I shall simply do that based on the fluid model and after that the various modes of operation of MOS transistors will be discussed, this will be followed by regions of operation of a MOS transistors, you will see there will be three regions of operation of a MOS transistor, and it will be followed by some highlighting some of the important parameters which affect the operation of a MOS transistor.

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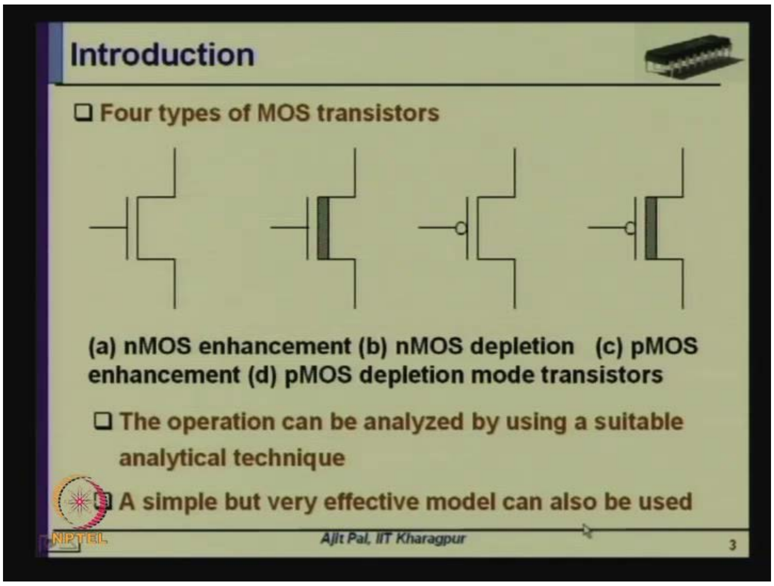

I have already discussed in my last two lectures, I have discussed the structure of MOS transistors, I have also discussed how MOS transistors can be fabricated. And we have seen based on the structure of MOS transistors we have four types of MOS transistors, these are n MOS enhancement type, n MOS depletion type, p MOS enhancement type, and p MOS depletion type. And we have we shall be using these symbols in our lectures as I have mentioned there are other symbols available, which are also used and you will find in different books, different types of symbols are used, but these are the most commonly used symbols, and which I shall follow in my lectures. Now, as I have told today we shall discuss the operation of MOS transistors.

The operation can be analyzed by using suitable analytical technique; that means, the operation of MOS transistors can be done from the, by studying the semiconductor physics, I mean based on semiconductor physics; that means, you have to understand the detailed the detail equations and a I mean a detailed knowledge of semiconductor physics is necessary. And obviously later on we shall do that do derive the analytic expressions, but to start with what we shall do we, shall be using very simple model, which are not based on any analytical expression, complicated equations or anything. And this is somewhat similar to you know whenever we build a building, or a or a bridge, or a campus we make a model. Essentially to visualize the overall layout, or the structure, or the basic functionalities of the system, and this can be very nicely done with the help of a very simple but very effective model based on fluid model.

This fluid model as we shall see can visualize the operation of charge control devices; charge control devices like I mean bucket-brigade devices, then your C C D charge-coupled devices, and MOS transistor transistors are one of them, that means MOS transistors are essentially charged controlled devices as we shall see, and their operation can be very nicely explained without going into detailed semiconductor physics with the help of this fluid model, and you will see you can understand the operation I mean this operation of MOS transistors can be understood even by an obvious.

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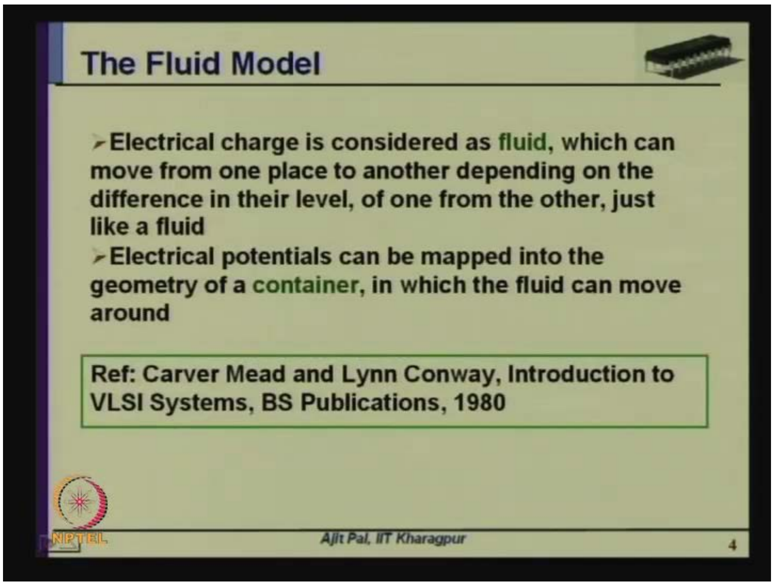

So, what is this fluid model, this fluid model I have that I shall be using is based on two very simple ideas. What are these two ideas? First one is electrical charge is considered as fluid which can move from one place to another depending on the difference in their level of one from the other just like a fluid. As we know whenever we consider that in a container we have a fluid and that fluid as we know if we connect them to another container it will move from one container to another container depending on the difference in level. Similarly, as we shall see charge will move from one place to another place whenever there is a difference in I mean there is potential difference between the two, and so this is the first model electrical charge can be considered as fluid and obviously it is behavior will be very similar to fluid, the way fluid like water, oil and various types of fluid behave as we see in our real world.

Then another very simple idea is electrical potentials can be mapped into the geometry of a container, in which the fluid can move around, that means we shall see that inside the you know that MOS device that you know that we shall be we have discussed the structure of a MOS transistor, and within the geometry of a MOS transistor we shall be applying some voltage and that will create some electric field, electric there will be some potential electrical potential distribution, that electrical potentials can be considered as kind of container. So, the way they will map within the geometry of the device they will be considered as a container, and within that container we can keep charge like a fluid. So, this is the basic simple idea that we shall be using, and this has been taken from a very famous book by Carver Mead and Lynn Conway back in 1980 they published one path breaking book Introduction to VLSI system, and that was the first book on VLSI system, and that actually popularized VLSI fabrication technique among researchers, students, before that it was essentially the houses where a concern with VLSI fabrication, but this book popularized VLSI system design among students, researchers and so on. Anyway so this particular fluid model I have taken from that book.

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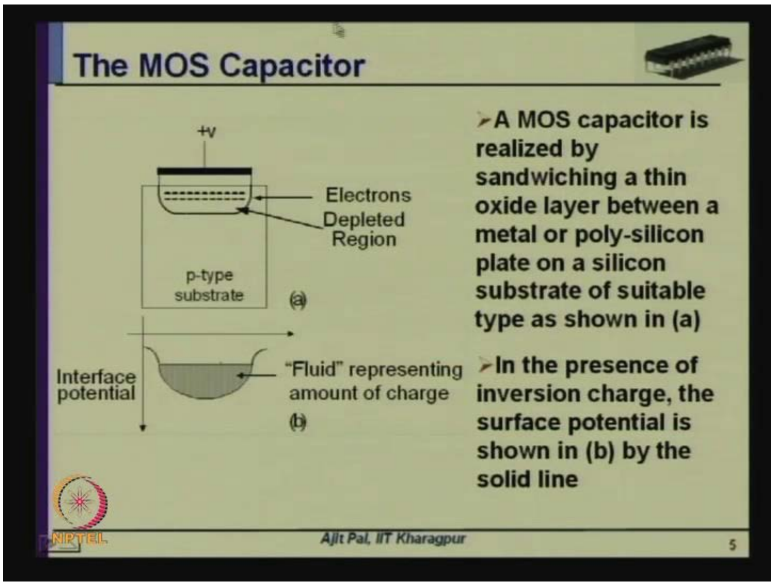

So, based on that fluid model first I shall consider the operation of MOS capacitor, this MOS capacitor is essentially the most elementary building block of MOS transistors or MOS circuits, and a as we have seen a MOS capacitor is realized by sandwiching a thin oxide layer between a metal or poly silicon plate on a silicon substrate of suitable type as show in this figure, let me draw it for your convenience a MOS transistor MOS capacitor.

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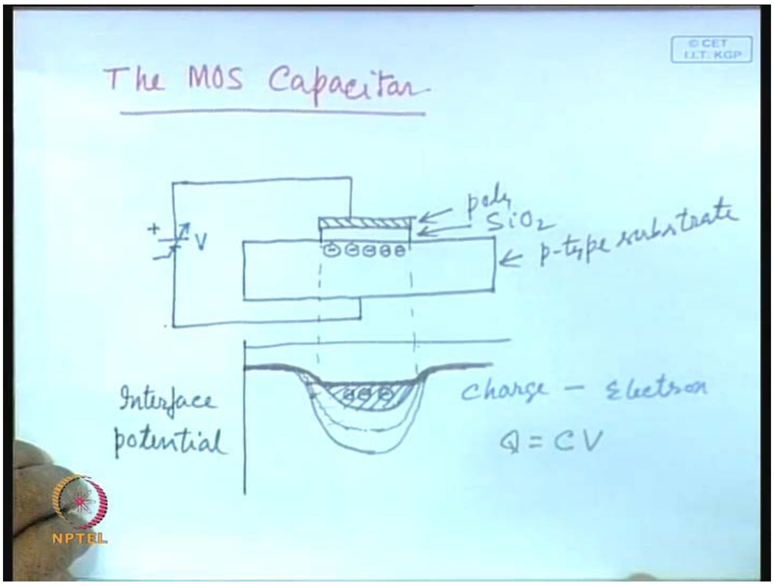

So, the MOS capacitor. So, what we have seen we fabricate MOS devices we start with a wafer, it is the wafer. So, this is the wafer and then we fabricate you know we put a silicon dioxide on top of that, so this is the silicon dioxide, and on top of that we put poly silicon, so this is the poly silicon, poly silicon we can represent it by hatched area, this is the poly silicon; this is silicon dioxide; and this is you substrate or you can p type substrate, it can be any type as well it does not matter. So, here we can consider this particular structure which is nothing but a MOS capacitor as a I mean it can be considered as a MOS capacitor, and these two poly silicon and this p type substrate these two are representing two parallel plates, we know in a capacitor as we know parallel plate capacitor we have two plates, equal two plates and in between two plates you will put some dielectric material.

So, here this dielectric material is silicon dioxide which is an insulator. So, this is realizing a parallel plate capacitor, and normally as you know we apply some voltage across it, and in this particular case we apply positive voltage to this poly silicon, because it is a we have assumed that this is a p type substrate, normally in a n MOS transistor this is what you do. So, this is positive and this is negative, now based on this fluid model what you can do as we apply some positive voltage this can be mapped within the geometry of the MOS structure, first of all you know this voltage whenever you apply a voltage it will create some potential distribution in this substrate. So, it will be somewhat like this, so we can map it within this, so here it will be somewhat like, so this is the potential distribution.

So, we can say this is the interface potential, and here as you can see this has take this potential distribution has taken the shape of a container, so this the container where charge can be stored. How charge is stored? Whenever you apply a positive voltage as you know negative I mean the electrons are induced on this area, so there will be electrons on this just on the opposite side of the insulator, that means in this particular on this plate it will induce this positive voltage will in due charge and that will be present in this area, and we can say these negative charges can be stored in this parallel plate you know in this container. So, here you have got charge, charge means in these particular case electrons.

So, here electrons are present, charge in the form of you can say electron, you could have started with another type of capacitor where you could have applied negative voltage starting with n type substrate, in that case this charge could have been holes, so that is why I am writing charge and then mentioning electron, in this particular case it will be electron because most of our discussion will be around p MOS n MOS transistor, and of course as in when necessary we shall discuss about p MOS transistor.

So, in this particular case this MOS capacitor will be having I mean in this area it will be inducing some charge and this charge will be present here. Now the amount of this charge the amount of this charge will be dependent on what? As you can see here this charge will be dependent on two parameters, first of all this particular area I mean how big is this area essentially capacitance c, capacitance’s value this amount of charge that is being stored here will be proportionate to c, and another it will also depend on another parameter that is your voltage, that is the voltage that you apply here.

How it will vary? Suppose you keep on increasing the voltage, what will happen this will actually push this electric field below, it will be somewhat like this, if you increase it further it will be like this, so that means the size of the container is increasing as we are increasing the voltage, that means more and more charge can be now stored if the voltage is more, charge will be more, and the shape of the container is changing to store more and more charge. So, as we know q is equal to proportional to c and V this is very clearly visualized with the help of this model. Now, after you know this charge is though these are essentially electrons, what will happen these electrons will actually neutralize some of the potential, and as a result in the equilibrium whenever equilibrium condition is reached the potential distribution will be somewhat like this.

So, this red line this is the potential distribution in the equilibrium condition, because these electrons will be if opposite it will be put there it will neutralize the influence of the positive voltage that is being applied on the other side, so you can see in the equilibrium condition you can say these are all filled up with electrons, so the potential will be somewhat like this, so this is how we can explain the operation of MOS capacitor, and as it is mentioned here this fluid representing amount of charge, and the presence of inversion charge, the surface potential is shown in b so this is the line. So, which I have shown in this diagram this, so this is the inversion charge means originally as I mentioned this was a p type substrate, there were holes present here, but this voltage that has been applied to the other side of the plate has induced electrons which are known as inversion charge.

So, this is the this is how the operation of a MOS capacitor can be explained with the help of a fluid model, now let us consider the function of a MOS transistor, we can extend the basis concept of MOS capacitor to MOS transistor.

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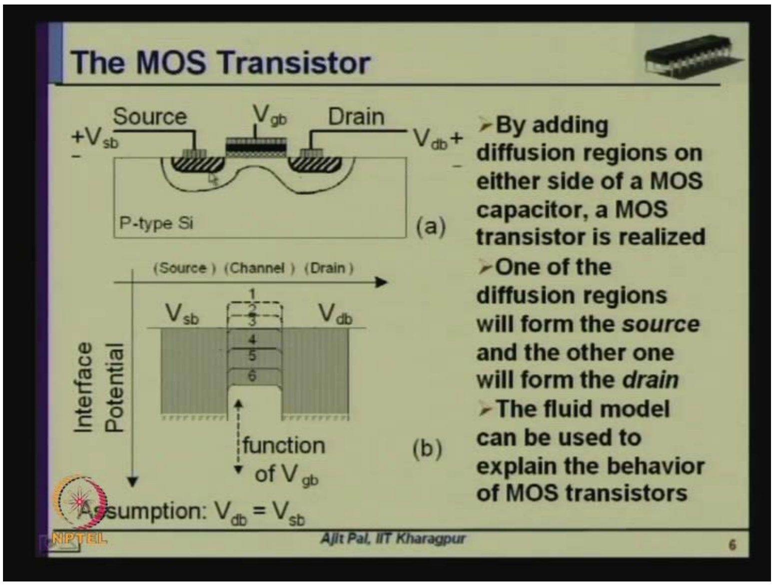

What is the difference between a MOS capacitor and a MOS transistor? As we can see the central portion is essentially the MOS capacitor, and of course on both sides you have got drains and source. So, we can draw it starting from MOS capacitor.

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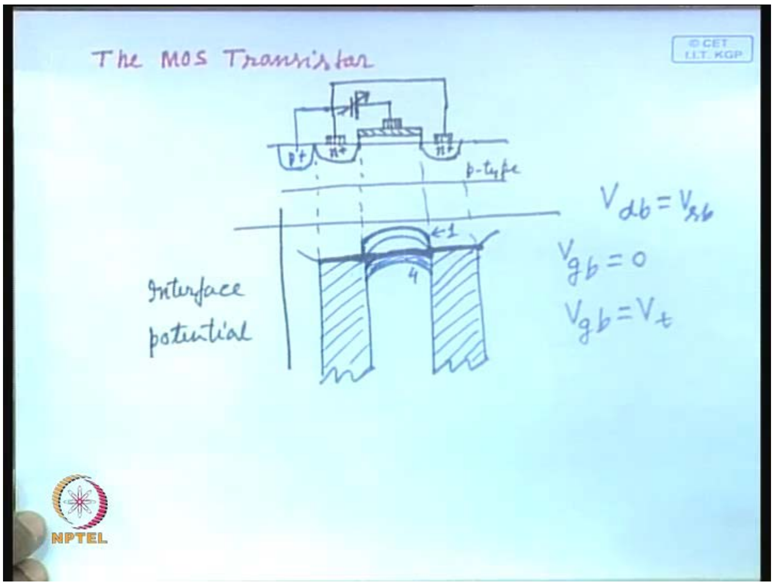

So, here the MOS transistor, so you can start with same thing, so this is the substrate and here you have got your silicon dioxide on top of that you have put the poly silicon, and then on both sides of it you will be having source and drain, so this is p type substrate; then this is n plus; and this is n plus, so this will form you know source; and this will form drain, so I am assuming that I am taking electrical connection, so I have put metals on top of the source and drain. So, this is the structure of a very simple MOS transistor, n MOS transistor, now in this particular case what will be the corresponding interspaced potential let us see, so this is the gate; this is the source; this is the drain let us assume, now in this particular case as you can see this part is essentially the capacitor part, so here you have got the poly silicon on top of that metal has been deposited, this is this is a silicon dioxide layer.

What will be the interface potential here? So, here also you having interface potential, to start with let us assume that you have applied some the voltage that is being applied to the gate and the drain, I mean both the both gate and drain they are at the same potential, they are at the same potential and of course, you can apply that means these two are joined, and you can apply some positive voltage to the gate, so this is the model that we will be using. So, whenever this voltage is 0 and the source and drain these are at the same potential then what will happen, we can say that these two having infinite source of electrons, since the source and drain these are very heavily doped they are considered as infinite source of electrons. How do you really represent and infinite source of electrons? We can consider them as n wells of infinite depth, and of course the so this is the on both sides you have got n wells of infinite depth, and they are since their potential they are tied together there the potential are same. Now, what about the middle portion what will happen to the middle portion? In the middle portion whenever this voltage is 0; obviously, there is no electron present here, and the voltage will be somewhere here, and potential will be somewhere here. So, you can see the potential distribution in the gate region is somewhat like this.

So, you can say that potential distribution will be somewhat like this, it will be somewhat like this, now in this particular condition, say this is this figure number one; this is this corresponds to V gb is equal to 0, that means the gate voltage with respect to this you can say source as you know the source is connected to body, source is connected to body as you have already mentioned by using a p plus contact, since source is connected to body that is why G b is equal to 0, we have assumed that G b is equal to 0, and under this case we have a barrier. So we have a potential distribution here, that means here you have got infinite source of electrons; here you have got infinite source of electrons as if we have got two containers of infinite to I mean two kind of two containers having infinite depth, and lot of electrons are present here in both the cases, but unfortunately since the potential is above this level, these two are separated by this particular barrier.

So, now although the source and drain are having infinite source of electrons they are not connected, so no charge can move from one to the other, now let us let us assume that let us keep on increasing the voltage, this gate voltage, as you increase the gate volte voltage what will happen what you have seen in this particular case, this potential is pushed down, so this interface potential will be pushed down, so here also this will be pushed down, so this will correspond to say 2; this is corresponding to 3, now what is happening whenever it is three, say 3 is a situation where there is a condition as if these two are touching, I mean almost touching, and if it is little more than that, then these two these two will be connected, so this 4, this 1, 2, 3 and 4 this potential 4 corresponding to a little higher gate voltage will correspond to a situation when these 2 will be connected to each other.

But, since their potentials are at the same level there will be no flow of charge that means whenever the gate voltage and source voltage are same, although they are connected by a path as you know that path is channel, there will be no flow of current because their potentials are at the same level, so since they are having the potential at the same level no flow of current will take place, but the position where there you know there for a particular you know whenever this is 0, and whenever these 2 are almost touching, that is actually this what voltage we assign to it, we call it threshold voltage V t. That means a voltage which when we apply to the gate connects creates a channel, creates a conducting path between the source and drain, so that is the minimum voltage that you will require two connect channel, connect the source and drain.

In other words that will create formation of the inversion layer, so electrons are electrons are present here then there are connected to each other, so the surface potential will be somewhat like this now, so in equilibrium it will be like this, so that means it will be like this. So, this is the situation where you are assuming that V db drain voltage is same as base voltage, and we are varying the gate voltage and as you have seen at some point of time these two are connected to each other, but no charge will flow because they are at the same potential.

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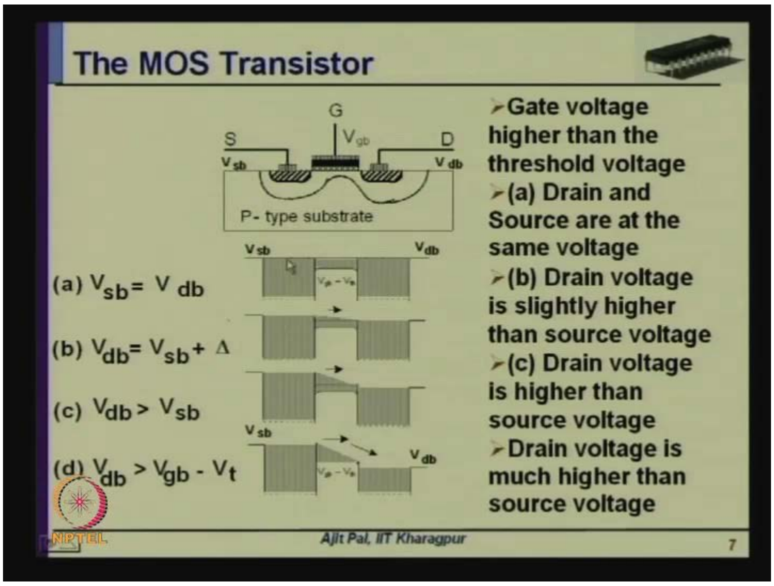

Now, let us go to the second situation, what is the second situation, in the second situation what we shall do, we shall apply some higher voltage to the drain with respect to the source, and apply some voltage which is above the threshold voltage at the gate, so these and then vary to drain voltage, and we shall see what happens in the situation let me redraw these figures to explain that.

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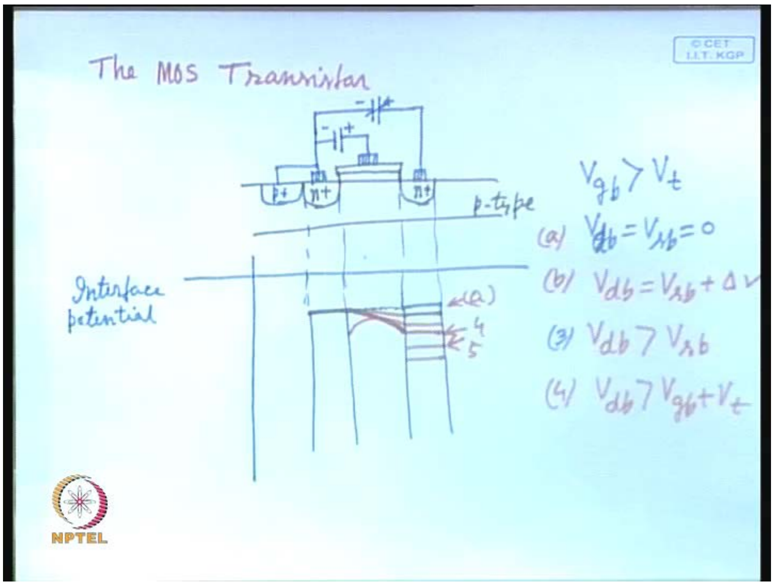

So, again it will be the MOS transistor operation. So, in this particular case we again we use the same structure, that means we have the substrate, and on we have the MOS capacitor, silicon dioxide, poly silicon then source and drain, so you have got n plus; n plus and this is p type substrate, because you are considering a n MOS transistor, and here we have put some metal for taking connections, also some metal for taking connections and here also from metal, now what we shall do uh of course as I have already told this is p plus, so this is connected source is connected to it. Now, with respect to this source we shall apply some positive voltage to the gate, that mans V gb is greater than V t; V t means with a voltage at which channel is created, and what about this voltage, we shall apply a variable voltage this is positive, this is negative, this is positive, this is negative, so and this will this which shall be vary,

So, in this condition what will be the situation in the potential interface, and how the device will behave let us think. So, here also you have got potential distribution interface potential you can say, again we shall be having two wells, but in this particular case, initially let us assume these two this voltage is 0, that means source and drain initial condition is say V gb, sorry V db is equal to V sb is equal to 0. So, this is this is with respect to this body, 0 voltage is applied to the source and drain, and let us assume these are the potentials to start with. And as usual as we shall see these are the infinite wells, now what we do we have applied a gate voltage which is more than the threshold voltage,

So, the gate voltage is somewhere here, gate voltage is somewhere here, now let us consider the situation when we shall be pushing, we shall be pushing increasing this drain voltage, the drain voltage is gradually increased and initially say this is the condition a, this is the condition for a where drain voltage is same at gate voltage, now what we do we simply apply V db is equal to V sb plus delta little more, as we increase it what will happen this in this particular case the chart the distribution was like this, the potential distribution was like this, now as this drain voltage is increased with respect to source it will be pushed downward, so as it push downward it will come here, then what will be the potential distribution in the equilibrium condition, it will be like this, and we increase it further, say 3 is V db is greater than significantly greater than V sb, what will happen in this case, say it has reached this point.

Then another point I shall tell, whenever the drain voltage is made little higher than the gate voltage, and when the gate voltage lower than the threshold voltage, as you can see here there is a slope earlier it was horizontal, now you have got the slope what the slope represents, current; that means rate of flow of charge is indicated by the slope, and this amount of current that will be flow is dependent on the slope, slope is not very high, so current will flow, so in this particular condition current will start flowing, and as we increase it further as you can see the slope will increase, now we have reached this point, the slope is reaching maximum point, and whenever it is say condition 4 V db is greater than V gb plus V t, then what will happen this will be the case whenever it reaches here. So, this is the condition where this V db is equal to V gb plus V t.

So, at this point, now this is the condition 4 this is the condition no this is the condition 4 and this is 5, so at this point if you go further down, you can see at this point the slope is maximum, if it is pushed further there will be no change in slope, it because it has reached the maximum point. So, there will be no further change in slope even if you push it beyond this, that means if the drain voltage is increased beyond this value there will be no further no change in slope, and as a consequence no further increase in current.

So, what is happening we can consider these are mentioned here gate voltage higher than threshold voltage as I have told, drain and source are at the same voltage this is the situation a, then in b drain voltage is slightly higher than the source voltage as I have already explained, so you have got the slope here, and drain voltage is higher than source voltage as you can see here, it is more than the threshold it is more and equal to almost the V db is equal to V sb plus V gb plus V t, and at this point as you can see this drain voltage is much higher than this having V db is greater than V gb minus V t. So, in this case you can see the slope is not slope has not changed from this, between the in these two the slopes are same, so no further increase in current takes place.

So, we have seen how actually current flow occurs in a MOS transistor, can we now construct the characteristics of MOS transistor based on this model

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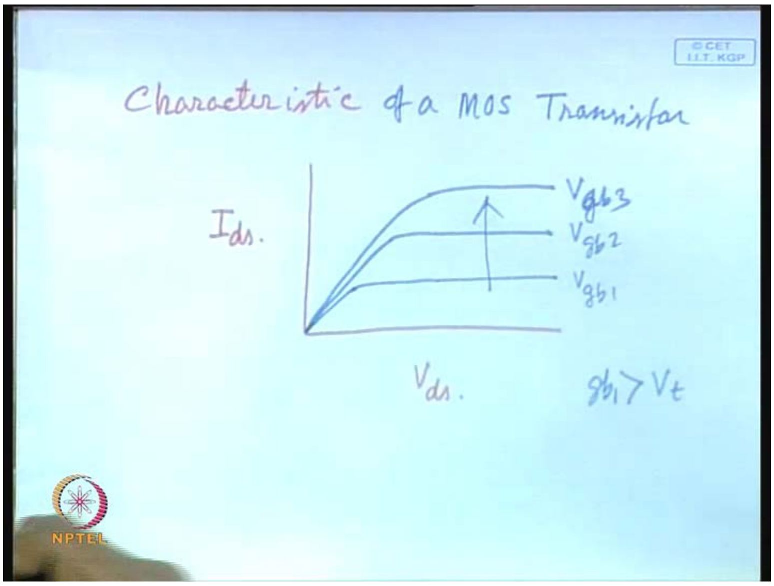

let us see whether we can do it or not, characteristic, so what I shall do on this we shall put on this side we shall put we are interested in drain current, I ds; on this we shall put V ds, so we shall analyze the increase in drain current, as we increase the drain voltage with respect to source or it can be body, if source is connected to body V ds is same as V db and for different gate voltages, so for a particular gate voltage the as we have seen initially the current increases, initially the current increases and as it reaches the point which is equal to V gb plus V t, then it remains constant for a particular gate voltage. Now, if the gate voltage is more in this particular diagram what we could have done, we have we could have applied a higher gate voltage here, so in that case if we if we apply higher gate voltage this will barrier will be at lower, so the maximum current that can flow will be more, because slope will be like this.

So, more current can flow as the gate voltage is more, that means whenever you apply higher gate voltage then the curve will be somewhat like this, so this is for a particular gate voltage, say this is V gb1 this is V gb2, and you can increase it further and it will get you will get a curve like this V gb3, so you can see we have been able to draw the characteristic of a MOS transistor without deriving any mathematical expression, simply based on fluid model we have been able to expressed the operation of a MOS transistor, and how current can flow in a MOS transistor.

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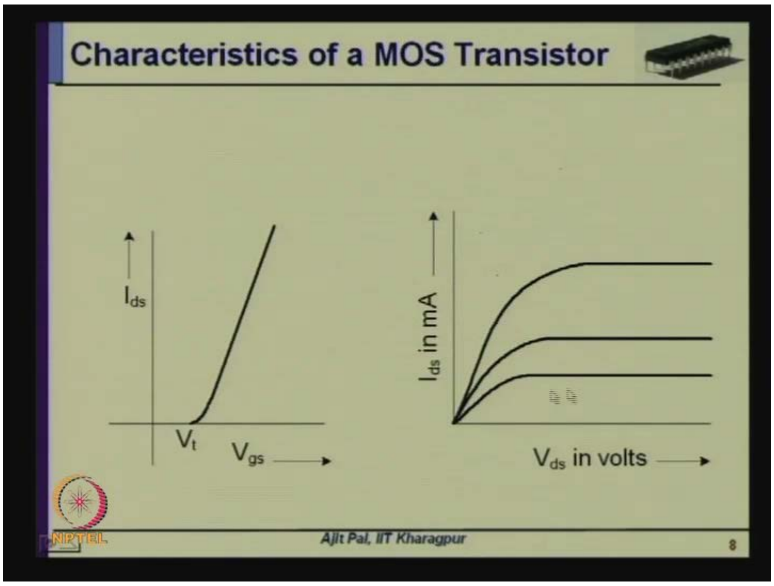

And later on we shall see how it actually happens, I mean derived mathematical expression for this, another plot is here the dependence of current on the gate voltage, so we have seen here this gate this current is increasing as you are changing the gate voltage, sorry this is gb1, gb2, gb3, as we increase the gate voltage the current is increasing, of course this V gb1 has to be greater than V t, all the voltage has to be greater than V t, that is what I being shown here, that means this curve shows that starting with V t as we increase the gate voltage, the these are essentially representing the saturation current, I mean this currents and we can control the current with the help of this gate voltage.

So, what we have learnt from this fluid model, from this fluid model we have learned that MOS transistor can be considered as a voltage control device, and as we have seen the current drain current is dependent on two parameters, What are the two parameters? Electrical parameters gate voltage and drain voltage, with respect to source or body. So, by controlling the gate voltage and drain voltage we can control the flow of current in the channel, and that is how a MOS transistor works. So, this is as simple as this.

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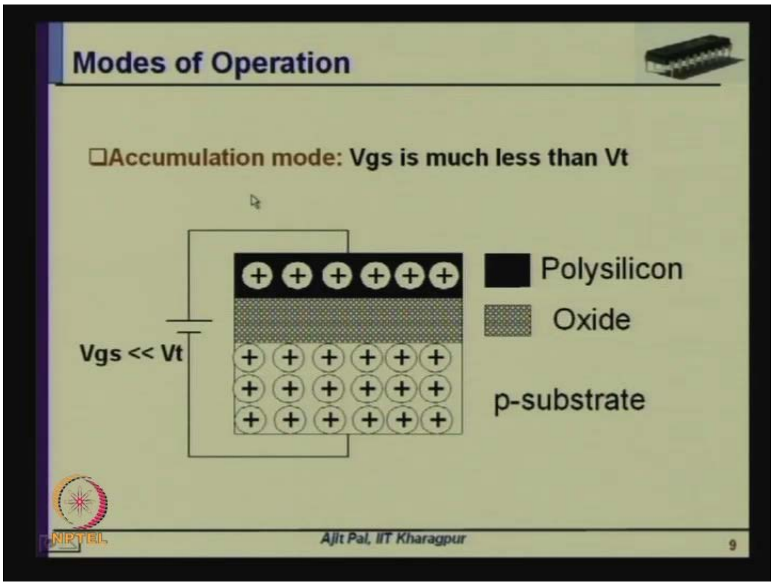

So, after discussing the characteristics of MOS transistors, now we shall focus on another very important aspect, modes of operation. The modes of operation of MOS transistors, we have already explained the operation of a MOS transistor by using fluid model, and we have seen how and when current flow take place, and how the current increases and so on.

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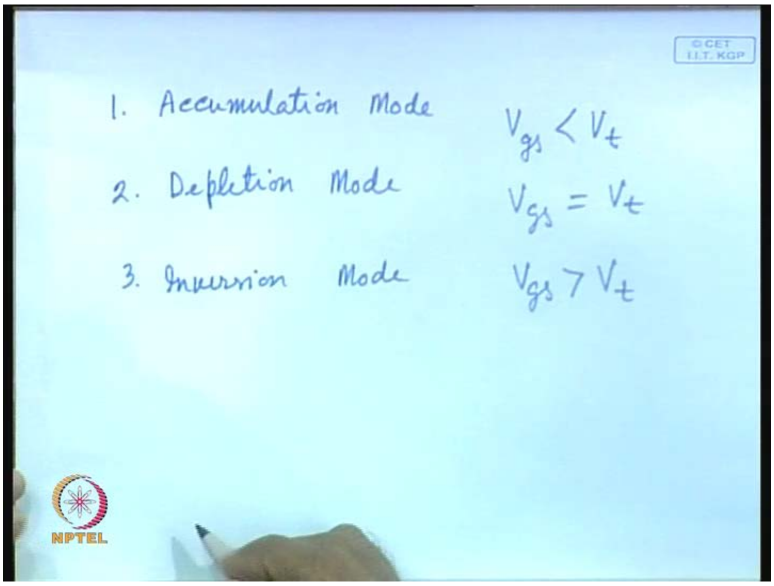

And based on that the operation of MOS transistor can be divided in three modes, first one is known as accumulation mode, number 1 is accumulation mode. What happens this when this mode is represented by what? when this gate voltage V gs is less than V t. What do you really mean by accumulation mode? In the accumulation mode we have seen that initially this is the charge distribution as it is shown in this diagram, that means you have got you know positive charges on the that this poly silicon, poly silicon is heavily doped silicon, so it has got holes.

And then this is a p type substrate, here also you have got holes, and as we increase the initially this portion; this portion also will be having sorry this is the silicon dioxide, you can see the entire portion the p type substrate is filled up with holes. Now, as we increase this voltage what will happen this these portions will be this positive voltage will induced electrons here, and they will neutralized some of these electrons, and as a consequence gradually this part will become will be deferred of any charge carrier, for example

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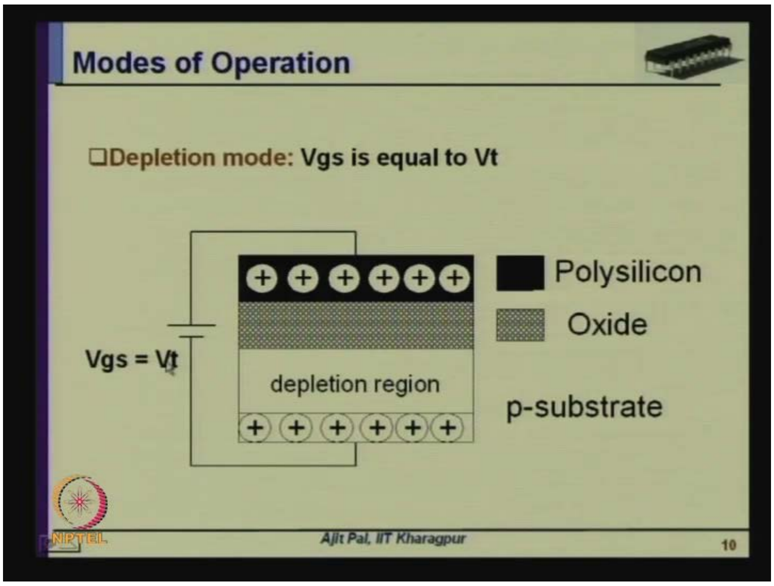

in this case we shall reach depletion mode, depletion mode is reached, depletion mode, depletion mode is reached when V gs is equal to V t, you can see this channel region is completely free of charges, so how you have reached this stage, we have reached this stage by gradually increasing the voltage gate voltage from 0 to V t, as you increase the gate voltage from 0 to V t this is the silicon dioxide; this is the poly silicon and this is the substrate, we can see this the channel region now are having positive charges when this gate voltage is 0, and as it is increased to V t threshold voltage, we define the threshold voltage onset of flow of current, onset of creation of inversion region you can say, this depletion region is there, where there is no charge carrier current carrier I mean those carriers neither hole, nor electron is present here. So, this is the depletion mode where V gs is equal to V t.

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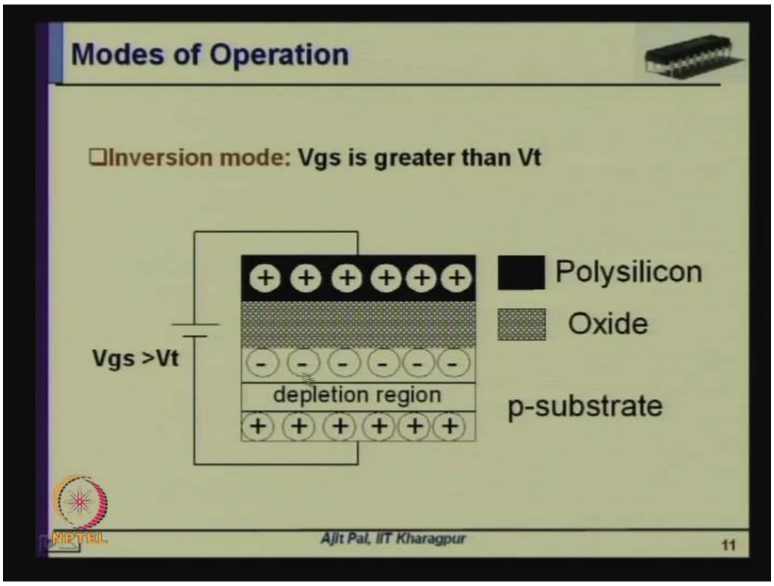

Now, if the gate voltage is increased further what will happen within the geometry of the device, as we shall see it will induce electrons as you have seen, and this will create what is known as inversion layer or and that is why it is known as inversion mode. So, inversion mode is when V gs is greater than V t, when the threshold voltage gate voltage is more than the threshold voltage the device moves to what is known as inversion mode, and in this inversion mode we have got electrons present here, and as we know these electrons will be attracted towards drain if we apply a positive voltage to it and current flow will start. So, for flow of current this inversion mode is necessary, and before that when this device is in depletion mode or in accumulation mode no current flow can take place.

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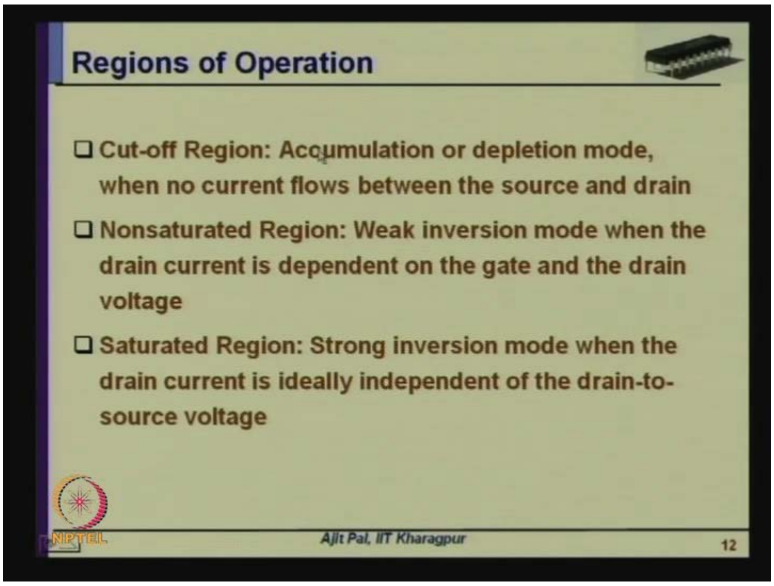

And another operation we shall see regions of operation. We have already discussed the characteristics here, characteristic of a MOS transistor. Now, the operation can be broadly divided into three parts, three regions of operation. What are the three regions of operation? First of all first region is cut-off region, cut-off region is accumulation or depletion mode, when no current flows between the source and drain, as I have already explained. So, in the cut-off region of the characteristic and no current flow, that means this is represented by this point at this corresponds to the cut-off region, that means the no current is flowing in this drain current is flowing, so this is the point which represents the cut-off region.

Then we have got second situation where which is known as non-saturated region. Non-saturated region which is which is known as weak inversion mode, when the drain current is dependent on the gate and drain voltage, that means here it is it is known in several names linear region, weak inversion region, non-saturated region these are essentially same, and in this particular curve this part is essentially b, so this is your non-saturated region, where or it is also known as linear region because current is linearly almost linearly increasing as you can see, current is linearly increasing, that is why it is also known as linear region. So, this is the second region where current can flow, but current is dependent on the gate voltage as you can see, and also on the drain voltage.

So, for example at this point for the same drain voltage for two three different gate voltages, two three different current, similarly for different drain voltage you can see for the same gate voltage the drain current is changing, that means the drain current is dependent on two electrical parameters, the gate voltage and drain voltage, and in this region I mean it is varies for both, that means if drain voltage is changed current will change, gate voltage is changed current will change. Now, what happens to the third region that is your saturated region, this saturated region is known as struck strong inversion mode, I mean you have applied a voltage which is equal to V gb plus V t, so when you have applied a voltage drain voltage which is equal to V gb plus V t, no further increase in current take place that you have already seen.

So, this is represented by strong inversion mode or saturated region, here you can see current does not change as we increase the drain voltage, here also current does not change as we increase the drain voltage, current is not changing as it is as we increase the drain voltage, however it depends on the gate voltage. So, that means in the saturated region the current depends on both drain sorry on only on the gate voltage, on the other hand in linear region current is dependent on both drain voltage and gate voltage. So, we have seen the operation of these I mean three different regions again without any mathematical expression.

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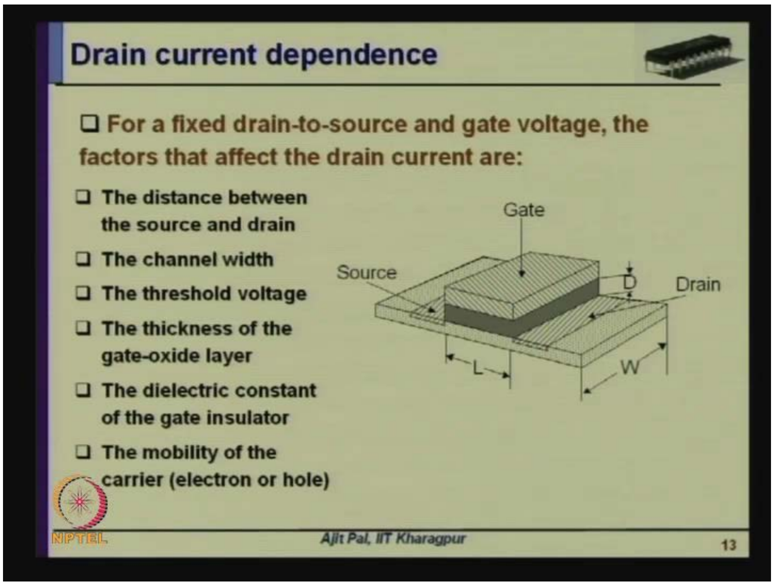

So, in the next lecture we shall discuss we shall derive the mathematical expression, but before we do go to that let us have a look at the look at various parameters on which the drain current is dependant. Now, for a fixed drain to source and gate voltage the factors that affect the drain currents are listed below, so here we have drawn a very simplified structure of a MOS transistor, so here it has been a three dimensional diagram is drawn, so here as you can see you have got a single MOS transistor, and this is your source; this is your drain; and this is the gate; this is the silicon dioxide; this is the poly silicon, here as you can see the channel has a length, that means the source to drain that separation between source and length is represented by L, length of the channel.

On the other hand the width of the channel that is the how long is the drain or source that is known as the width of the device. So, length, width and there is another very important parameter that is your thickness of the silicon dioxide d. So, apart from you know that drain to source voltage, gate voltage depends on this parameter, distance between the source and drain that is your l. So, it is dependent on l which is the distance between the source and drain, because electrons will move from source to drain, and depending on the velocity you know it will take some time, so take some time and the rate at which it will go will be dependent on the distance. So, electrons have to (()) that distance at a particular speed.

And shorter the distance you know that the more electrons will flow and the current will be more, and on the other hand the length is more then it will take longer time and current will be less, than means it is dependent on the parameter distance between source and drain, the channel width w. So, more current will flow if the width is more, because you can see it is wider, it is just like a river when the river is water I mean river is wider more current more water can flow, here also the width is somewhat like the width of a river, and so it will be the w parameter will be there to it will dependent then current will be dependent on the width of the device. Then the threshold voltage, I have already mentioned about the threshold voltage, threshold voltage is essentially at which the onset of the creation of channel starts, inversion-layer formation starts, and only then current flow can start, and that voltage is dependent on many physical parameters, and later on we shall discuss about this.

But, for the time being I have given a simple parameter threshold voltage, then the thickness of the gate-oxide layer, this d. So, smaller the thickness even for smaller gate voltage you know that control be more, that means the thickness will beside the electrical potential in the in the channel region, and that is the region why the thickness of the gate-oxide will control the flow of current within the device, and then the dielectric constant of the gate insulator. So, not only the width, but the dielectric constant will is also very important, and as we know silicon dioxide is the dielectric material that is being used, but I mean in modern devices some high k I mean material with high dielectric constant is being searched, but for the time being we shall consider silicon dioxide as the dielectric that has been used.

Then finally another parameter is there the mobility of carrier. How quickly it can move, how quickly the charge carrier can run, you know we have got two types of carrier electron and hole, and obviously electrons being lighter it can move faster, so n MOS devices will be faster as we shall see, on the other hand holes are heavier, bulky, and as a consequence their mobility will be less. So, these are the parameters on which the drain current will depend apart from the drain and gate voltage, and in my last next lecture I shall derive analytical expression of this drain current in terms of these parameters. So, for the time being we can call it a day. Thank you.