Analog Electronic Circuits
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Lecture – 12
Revisiting MOSFET (Contd.)

So, welcome back to Analog Electronic Circuits. Today, we are Revisiting MOSFET in fact, it is continuation of the previous lecture. So, previous day we have discussed about n-MOS transistors particularly n-MOSFET and, today we will be going for p channel MOSFET namely p-type MOSFET.

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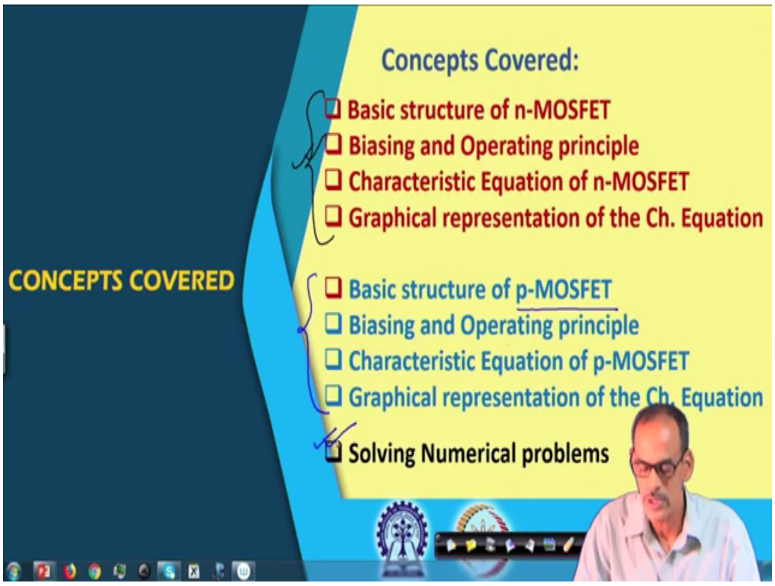

CONCEPTS COVERED

Concepts Covered:

- ☐ Basic structure of n-MOSFET
- ☐ Biasing and Operating principle
- ☐ Characteristic Equation of n-MOSFET
- ☐ Graphical representation of the Ch. Equation
- ☐ Basic structure of p-MOSFET
- ☐ Biasing and Operating principle
- ☐ Characteristic Equation of p-MOSFET
- ☐ Graphical representation of the Ch. Equation
- ☐ Solving Numerical problems

So, the overall plan what is as, I said that we have discussed in the previous class about these 4 topics. So, these things we already has been discussed. And, today we are first we are going to discuss about the similar kind of things, but for p-type MOSFET.

So, some of the things may be a kind of reputation of whatever we have discussed about n-MOS, but then we will try to compare the situation of n-MOSFET and p-MOSFET. So, that you should not get confused while you will be dealing with circuit containing n-type as well as p-type MOSFET. And, then subsequently we will be in case if a time permit then we will be covering some part of the numerical problems.

So, to start with let we go for the basic structure of the p-MOSFET keeping in mind that n-MOSFET in as background information.

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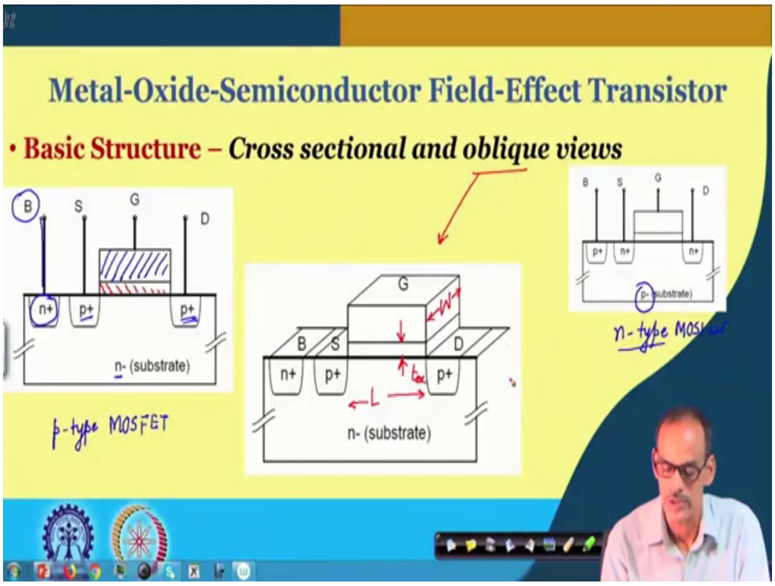

Metal-Oxide-Semiconductor Field-Effect Transistor

- **Basic Structure** – ***Cross sectional and oblique views***

So, here the MOSFET for p-MOS type I should say where the channel it is and the channel it is supposed to be p-type and this is the cross sectional view of p-type MOSFET. Just for your reference I am also keeping the n channel MOSFET. So, I should say just for our reference we are keeping n-type MOSFET.

And, the basic difference here if you see that the substrate or the body here I should say body instead of calling substrate. So, this is n-type, now weakly doped n-type in comparison with p-type body there for n-MOSFET.

And, the 2 islands here they are which are working as source or drain, they are p-type islands and rather highly doped p-type islands. And, similar to n-MOSFET here also we do have the highly doped island for the body connection. In this case the body is n-type so, we required n plus island and so on top of that we do have the metal connection and then we are getting the body terminal.

And, similar to n-MOSFET we do have the gate electrodes here and just below that it is having the silicon dioxide. So, it is having silicon dioxide here and then below that we do have the substrate or the body. And, then in this case to really create the channel we have to see what kind of voltage you have to apply at the gate with respect to source and then we will see that what are the things are happening in detail, but this is what the cross sectional view.

The oblique view on the other hand the oblique view it is shown here where this is the width of the gate or I should say a channel and this is the length of the channel, they are the important parameters to define the behavior of the circuit rather performance of the circuit, this is the oxide thickness t ox that is also a critical parameter and so, this portion is of course, it is substrate and so and so.

So, now let us so this is of course, it is more idealistic cross sectional view. So, we have discussed for n-type device what may be more realistic things and also the top view. So, let us see for p-MOSFET while we do have p islands and then n-type substrate what may be the difference of the top view in comparison with n-MOSFET.

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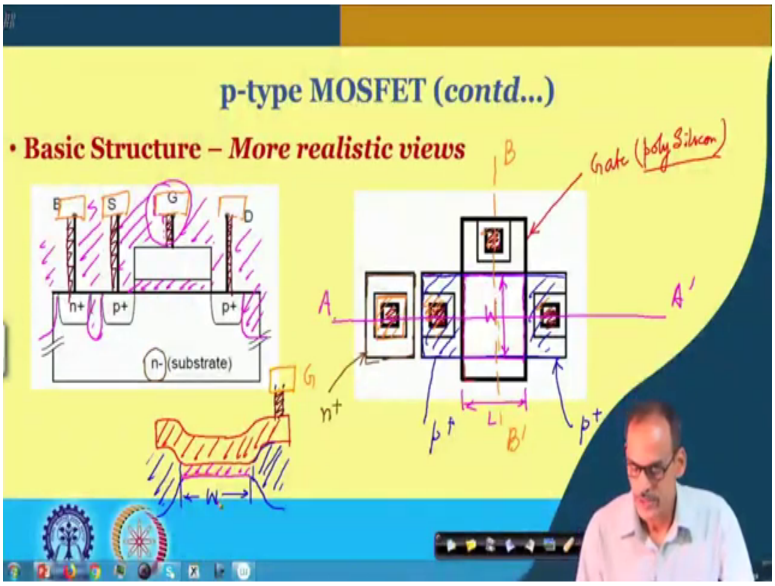

p-type MOSFET (contd...)

- **Basic Structure – *More realistic views***

So, here so this is the cross sectional view of the p-MOSFET and this is the top view of the MOSFET. So, let us see what are the things we do have this is the gate electrode; so, this is gate electrode and the entire thing actually it is polysilicon. And, then we do have the other rectangle here which shows the boundary of the divisions region. In fact, underneath this gate the divisions is not happening only this portion it is having the divisions and this portion is also having divisions. And, in this case those divisions are basically creating the 2 islands p-type islands; p plus islands here and this is also p plus islands.

And, you might have observed that the gate region it is also not only this side, if this side also it is getting extended, but then channel portion it remains the same as you have seen for the n-MOSFET. So, the channel portion is here. And, this is the spacing between the 2 islands, we call length of the device and this is the orthogonal direction of the current flow or it is called width of the device.

On the other hand we do have the n plus island also and this is the boundary of the other diffusion region, but this diffusion it is of n type so you can say n plus and, in fact, the rest of the things; rest of the things here they are weakly doped n-type. And, similar to as you have discussed for the n device we do have the contact here, so this portion is contact, this portion is contact and so and so.

So, this contacts are basically the substrate contacts and then drain contacts then the body contacts and so and so, and, then also we do have the gate contacts here, but this is not really in along this cross sectional view that we have discussed in the previous class. And, on top of that there are different rectangular box here, so if you see here.

So, this portion it is basically representing the metal 1. So, on top of this contact we do have the metal 1 here, we do have another metal 1 here and so and so. So, this portion is metal, this portion is metal and so and so on. So, that is a little bit about the top view of the actual device. In fact, if you see rest of the things it looks like it appears to be hanging, but actually here we do have the silicon dioxide and, but then rest of the things is also having silicon dioxide. In fact, everywhere we do have the silicon dioxide that provides electrical isolation as well as the mechanical stability.

And, in fact, here also at the surface level also we do have the silicon dioxide; it is referred as field oxide which isolates one device to the other on the surface. So, that is the as I said that more realistic view, but we may not be really going in detail of this structure again and again rather we will be preferring to follow the simple cross sectional structure to explain the working principle of the circuit.

In fact, this cross sectional view it is more like cross sectional view along this axis may call A A dash, but you may be you might be observing that along this axis and this is not really getting cut. So, this portion of course, it is not getting cut. So, I should say rather I should draw this portion in dotted line for perfect engineering drawing, but anyway. So, likewise probably you can make an atom to draw cross sectional view along this axis, say it may be called BB dashed ok, along the W. And, you will be seeing that the gate is like it is having a texture like this, it is having up and down.

So, this is the gate portion get electrode and then you do have the contacts here you do have this contact. So, that contact it is here and then it is having the metal connection; metal connection I should use different color yeah. So, this is the gate connection and underneath we do have the channel portion.

So, we can see that here we do have the thin oxide. So, here we do have the thin oxide below of this you know gate region, but beyond this if you see beyond that, this thin oxide is further getting extended like this. In fact, this portion it is also silicon dioxide, but actually beyond the channel region. So, you may say that this is the width of the channel and so, this is the edge of the channel and this is the extension of the gate beyond the channel underneath we do have the field oxide like this one.

In fact, this structure I have not covered for n-MOSFET, but it is there also it is similar. And, for historical reason this gate region earlier it was metal, but then as I said that because of better threshold voltage adjustment for n-type and p-type device, it has been observed that it is better to keep this as polysilicon, because of the work from some difference of the metal to substrate. So, anyway I will not be going detail of that, but probably you can refer to any device course for that. Now, see how we bias the circuit?

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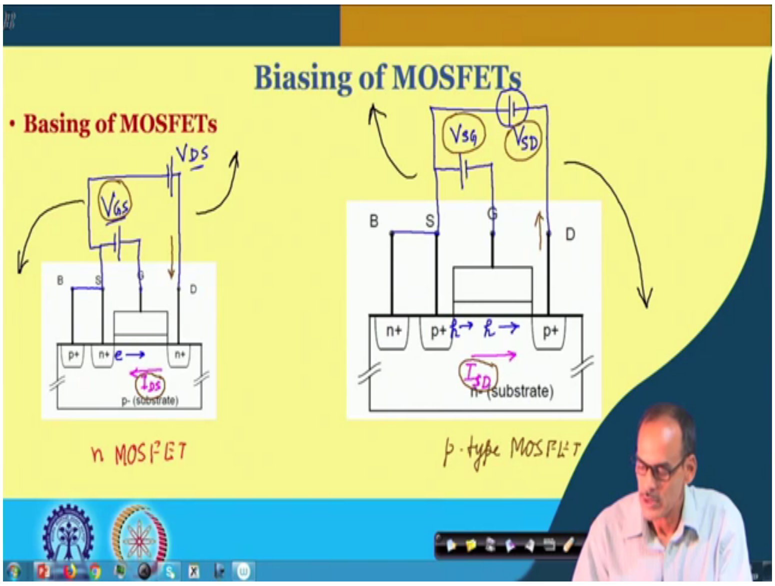

Biasing of MOSFETs

- Basing of MOSFETs

So, let us about think about the biasing. So, primarily we will be covering the n-MOSFET p-MOSFET, but just for our reference we are also keeping the n MOS structure. So, for your reference if you see this is n MOS and if you recall how we have biased it so, for proper operation gate is at higher potential by V GS and most of the time we prefer to keep this body and source connected together and then at the drain we do have another potential source we call V DS.

So, for proper operation V GS should be higher than something called threshold, V DS definitely it should be positive for the electron to flow from the source to dream. So, electrons are moving in this direction and that results the current flow in this direction. Now, this we already have discussed in the previous part. Now, let us see how we bias the p MOS transistor on the other hand.

Now, here at the gate we like to prefer to apply some voltage. So, that the channel supposed to be getting created and we want to convert this channel from n-type to p-type. So, definitely we required to apply negative potential with respect to source as well as body and because of the polarity the other way we may call this is V SG.

And, on the other hand at the drain we can apply negative voltage. So, that; so, anyway I will discuss that. So, we call this is since this is source side it is higher potential, we call this is V SD. And, while you are applying this negative voltage here, it is expected that holes it will be coming into this channel region. And, because of this V SD it is offering lateral field and this holes are moving from left to right.

As a result it produces a current in the same direction. And, now this current since it is flowing from source to drain just to have proper convention of the positive current flow, we may call this is I SD. So, you can see the basic difference here particularly the polarity here we call I DS whereas for p-type device. So, p-type MOSFET we are calling this is I SD.

So, likewise if you see the polarity of the voltage here based on that we are calling this is V GS, on the other hand this bias it is called V SD and likewise instead of V DS we call this is V SD. And, the current flow of course, I SD for this case I DS it is flowing in this direction and whereas, I SD here it is flowing in this direction, ok.

Now, since the current flow as well as the polarity they are different and for our convenience, it is better to keep the device orientation such that the higher potential terminal to be going upper side and lower side we will be having lower potential. Namely, this side it will be pulled towards ground and this may be pulled towards the supply positive supply.

So, a similar thing probably we can do here also; since, this is a lower potential so, probably we can pull it low and then we can pull it high like this one. So, let us see how we; so, let us see how we reorient the device. So, that it will be more convenient to place the device while we do have many circuits; while you do have many devices in the circuit.

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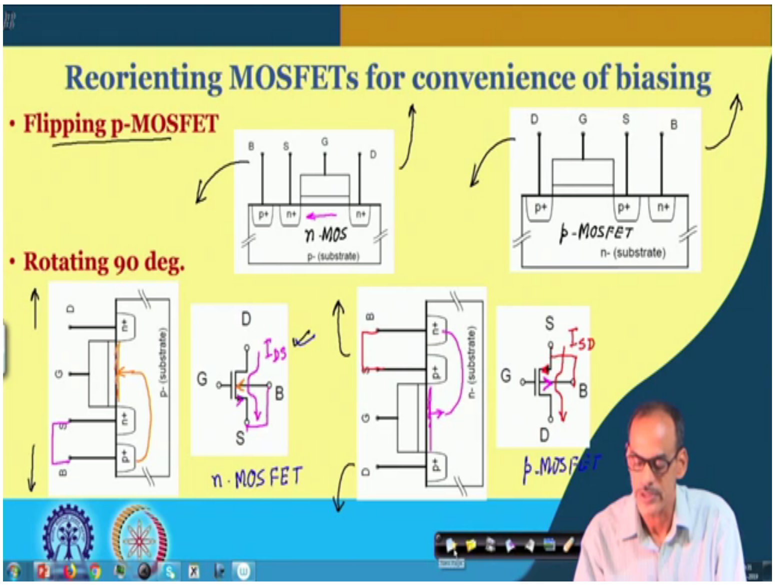

Reorienting MOSFETs for convenience of biasing

- Flipping p-MOSFET
- Rotating 90 deg.

So, what kind of reorientation shall we do? First thing is that we will flip the p-MOS transistor, because here we do have lower potential and here we do have higher potential. And, so, source side as I said we can make it towards the ground and drain side we can make it out.

So, likewise since you have flipped it, source side we have taken towards the right and drain towards the left and we know that drain it will be at a lower potential than the source. So, now, here also we can rotate the device in the same way as we are rotating the n-MOS device. So, this is of course, n-MOS device and this is p-MOS.

So, first thing is we have flipped it compared to the previous diagram and then we rotate it 90 degree. So, as we are showing here. So, the body and source it is coming towards the ground and drain it is going towards the positive supply.

So, here also so, the source and body it is going towards the positive supply, drain it is going towards the ground. So, basically we are reorienting adjusting ourself. So, that the device orientation it will be consistent in the circuit, the whenever we will be discussing with the circuit normally we will be placing the device like this. In addition here I am also showing the corresponding symbol of the devices. So, this is for the n-MOS.

So, this is n-MOSFET symbol and this is p-MOS symbol and if you see here some conventions, if you have observed carefully that the source is having an arrow. In fact, this arrow it is consistent with the flow on the current I DS. So, you may recall that the current is flowing from drain to source I DS though the electron is moving from left to right and the current is flowing from top to down basically drain to source.

So, this arrow it is consistent with the flow of the current and then we also have the body, though the body we are taking along this line, but for our convenience just we are showing like this. And, in the biasing most of the time unless otherwise it is stated, we may connect this source and body together. So, we may connect these two together on the other hand if you see the symbol of the p-MOS.

So, here also we place an arrow, but if you see the polarity of the arrow it is from source towards the drain. So, of course, that is also consistent with the actual current flow and since the current is flowing from source to drain; so, we call this is I SD and as I say that this arrow it is consistent with the current flow.

So, here also we do have the body and unless otherwise it is stated source and body may be connected, but we do have the flexibility, if you are really for some reason if you are not connecting it you have to ensure that this junction it is not getting forward biased. In other words the body should be at higher potential than the source for p-MOS and vice versa for n-MOS.

So, as long as we follow the, that constraint it is not a problem, but for this course unless otherwise it is stated we assume that body and source they are connected. Sometimes, in some books we also place an arrow on the body connection and for n-MOS the arrow of the body connection it is in this direction from body towards the channel. This arrow it is really not consistent with the current flow rather there is no current flow rather in fact, we like to keep this arrow. So, in a direction who is supposed to be representing the polarity of the diode getting formed between the channel and the substrate.

So, the channel is n-type and the substrate is p-type; so, you can say that arrow of the body it is basically in this direction. So, this arrow on the body line it is consistent with that. Please, do not get confused with the arrow on the body line and arrow on the source terminal. So, similarly here also the polarity of course, in this case it is p-type channel and the polarity of this diode it will be from the channel to towards the body. So, the polarity of or direction of the arrow it should be consistent with that namely from channel to body.

So, that is about the symbol that is about the rotation and all and now let us see how we get the I V characteristic of the device.

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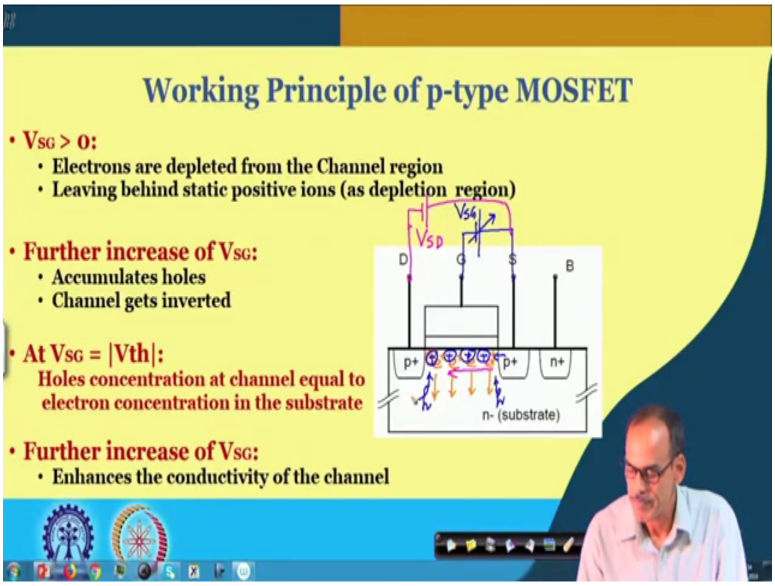

Working Principle of p-type MOSFET

- $V_{SG} > 0$:
  - Electrons are depleted from the Channel region
  - Leaving behind static positive ions (as depletion region)
- Further increase of V_{SG}:
  - Accumulates holes
  - Channel gets inverted
- At $V_{SG} = |V_{th}|$:
  Holes concentration at channel equal to electron concentration in the substrate
- Further increase of V_{SG}:
  - Enhances the conductivity of the channel

So, what is the working principle of the circuit and then that will be helping us to really derive the expression of the current in terms of explain the terminal voltages. So, quickly let us apply the voltages here. So, what we said is that this is the channel it is we have to make it p-type. So, it should be at gate should be at a lower potential than the source by V SG and we have to apply the V SD, yeah. So, we do have the V SD here which makes the drain side at lower potential.

So, this is of course, you know we have to make the drain at a lower potential with respect to source. So, that the current actually it is flowing in this direction and also we said that the hole supposed to be flowing in the same direction. Now, what other things are happening here. If, the V SG; if the V SG it is if you are making it more and more positive.

So, what happens is that the majority carrier namely electrons they are departing the channel portion. So, which means that by this V SG we are forcing this electron to be moving away from the channel as a result it leaves behind positive ions there. So, let me use different color to represent that. So, it leaves behind the positive charges at the end, but they are the static ions of course, they do not participate for the current flow, but they are instead working like a depletion region.

So, then if you further increase this voltage, namely if you make this gate further negative with respect to source, then the holes may be getting attracted from the substrate maybe they are minority carrier, but they will be attracted. In fact, it seems we do have this island holes it may be rather supplied from this island more. And, as a result there will be a thin layer of the ions, I should say it is not ion it is holes. So, there will be free holes.

So, let me redraw the channel portion with the change of this voltage.

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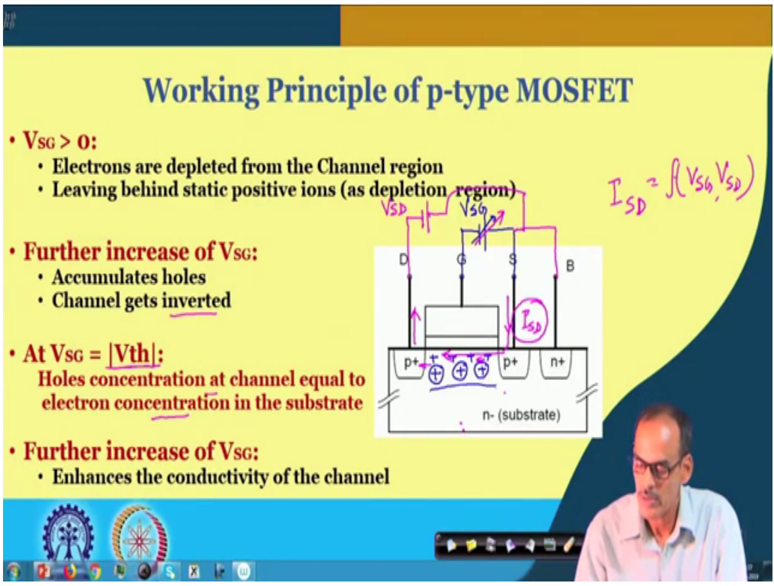

Working Principle of p-type MOSFET

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  - Electrons are depleted from the Channel region
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- Further increase of V_{SG}:
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- At $V_{SG} = |V_{th}|$:
  Holes concentration at channel equal to electron concentration in the substrate
- Further increase of V_{SG}:
  - Enhances the conductivity of the channel

$I_{SD} = f(V_{SG}, V_{SD})$

So, if we further increase this V SG. So, we are expecting that there will be holes just near the surface. And, of course, there will be the static ions as I say that they are not participating for the current flow, but they are basically neutralizing some part of this potential. So, now, if we apply the voltage here, at the drain with negative voltage here with respect to the source and then the holes it starts moving in this direction.

So, as a result there will be a current flow and this current it is flowing from source to drain and then it is going to the drain. So, this I SD it is flowing from source to drain. Now, before we go for this flowing in fact, similar to n-MOS, V SG it reaches to a value a critical value called threshold. And, if the holes concentration here it is exactly equal to the electron concentration deep into the substrate, then we call that channel portion or the surface of the channel got converted from n-type to p-type and their concentrations are exactly equal.

So, you may say that the channel got inverted with this and the channel got inverted to a critical level, where you may say that the channel concentration; channel strength and the substrate strength in terms for the carrier concentration they become equal. And, if you increase this V SG further then of course, there will be more and more holes it will be getting accumulated in the surface. And, of course, they will be contributing more towards the, they will be rather helping this current to be flowing more and of course, we are assuming that the body should be connected the end.

So, that is the basic working principle. Now, we will try to see what is the expression of this current I SD as function of this V SG and V SD, ok? So, we are from let us look into what other things are going to happen if we apply the voltage, yeah.

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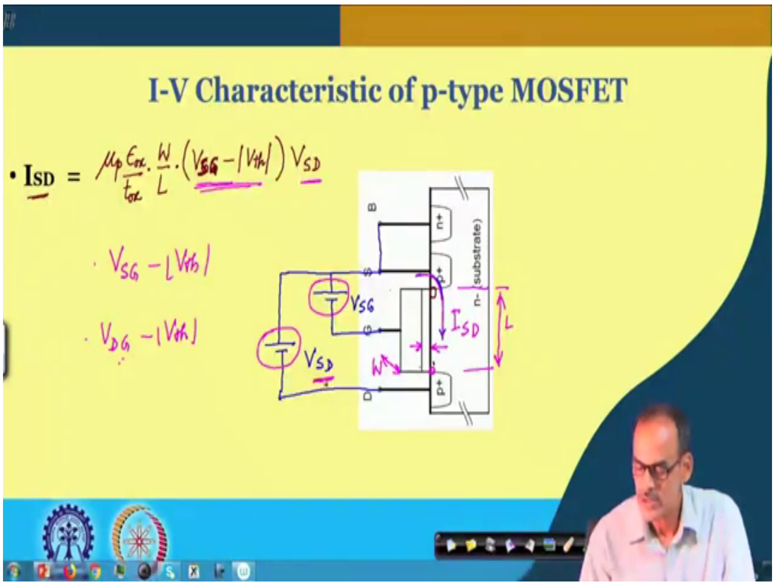

I-V Characteristic of p-type MOSFET

- $I_{SD} = \mu_p \frac{\epsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \cdot \left(V_{SG} - |V_{th}|\right) V_{SD}$

$\cdot\ V_{SG} - |V_{th}|$

$\cdot\ V_{DG} - |V_{th}|$

So, quickly let me apply the voltage. So, we have as I said for our convenience we have rotated the device. So, let me apply this V SG. Now, it is very convenient that the positive side of the potential source, we are connecting towards the upper side and this is V SG body is connected together; body is connected to the source and then we do have the V SD and the current it is flowing in this direction.

So, let me use different color here. So, current it is flowing in this direction and that is I SD and we like to find what will be the expression of this I SD. So, as I said that this current of course, it will be it depends on these two basic potentials and also it depends on the size of the channel namely the length. So, this is the dimension, this is length of the channel and the orthogonal direction is the width W. So, it is function of that in addition to that it depends on the oxide thickness and then dielectric constant of the oxide and then mobility of the holes.

So, the expression of the current in fact, it is let me. So, you may recall that for n-MOS device we say that this is mu p, there it was mu n and in this case it will be mu p. If epsilon oxide divided by thickness of the gate oxide multiplied by W by L the aspect ratio of the channel, multiplied by V GS and this V GS it is entire amount it is really not contributing to the channel.

Some part it is going to the in fact, I should write rather V SG sorry, this should be V SG and some part of it is going to convert or invert the channel. So, we may say that that part it is we have to subtract and then this is what the V SG minus V th that is contributing towards the conductivity of the channel.

And of course, and based on the V SD we do have the current flow due to this whatever the potential we are generating from source to drain. So, this is the expression of the current I SD and this is it looks like valid, but similar to the previous case. In fact, this expression it assumes that the conductivity of the source portion is a function of V SG minus V th, but if you see the other end and if you are applying V SD is positive.

This end, the drain end may not be having the same potential across the assumption. As a result we have to if the V SD is significant compared to V SD minus V th, then you have to apply probably different formula instead of just considering this one. And, the trick is that instead of considering only V SG and the V SG minus V th we also should consider V DG minus V th.

And, this V DG of course, it is function of V SG and V SD. So, if you take average of these two instead of considering V SG minus V th then we will be getting more accurate expression particularly when the V SD is higher. So, let us see what is the corresponding expression we will be getting there?

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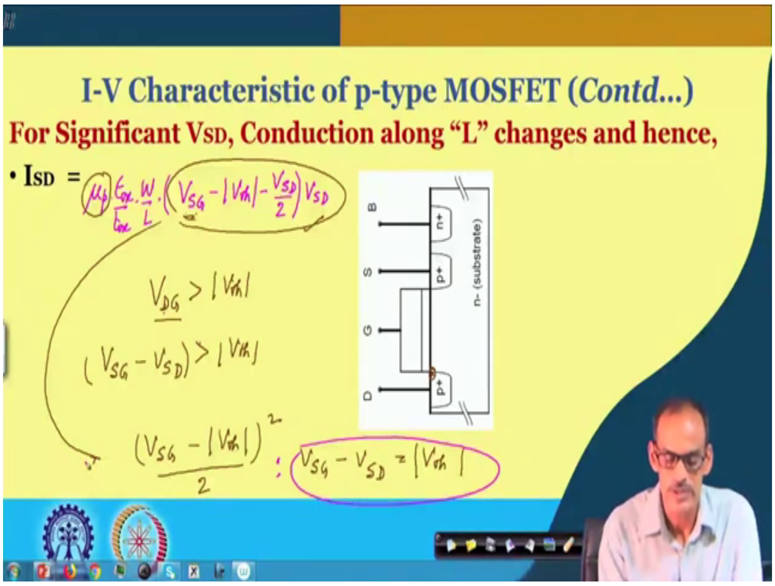

I-V Characteristic of p-type MOSFET (*Contd...*)

For Significant VSD, Conduction along "L" changes and hence,

- $I_{SD} = \mu_p \frac{\epsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \cdot \left(V_{SG} - |V_{th}| - \frac{V_{SD}}{2}\right) V_{SD}$

$V_{DG} > |V_{th}|$

$(V_{SG} - V_{SD}) > |V_{th}|$

$\frac{(V_{SG} - |V_{th}|)^2}{2} \; : \; V_{SG} - V_{SD} = |V_{th}|$

So, for significant V SD what you are expecting there it is the expression of the current it will be mu p into epsilon ox divided by t ox into W by L into V SG minus threshold voltage minus V SD similar to n-MOS device multiplied by V SD. Only difference is that instead of V SG there it was V GS and instead of V SD it was V DS, rest of the things it is similar; of course, we do have the mu also it is different, but we can think of it is just a constant.

So, as long as we are very sure that we have to get the correct polarity of the potential. And, if it is consistent for the operation of the circuit then it is not a problem. And, this is valid as long as the channel is existing at this end, but then and this is true only when the V DG it is higher than the threshold voltage, ok. So, if V DG it is higher than threshold voltage then only we will be having this channel. In fact, we can rearrange this or we can rewrite this expression of V DG in terms of V SG minus V SD.

So, as long as this is higher than the V th, then only we can say that this equation is valid. In fact, at the limiting case when this two are equal this part and this part are equal, then we can say the pinch of it is happening. And, at the limiting case the corresponding current it becomes; so, this portion it becomes, this becomes V SG minus V th square by 2. Particularly when so, we can say that under V SG minus V SD is equal to V th. So, under this condition, we can write that this part it is like this and rest of the things it is coming there.

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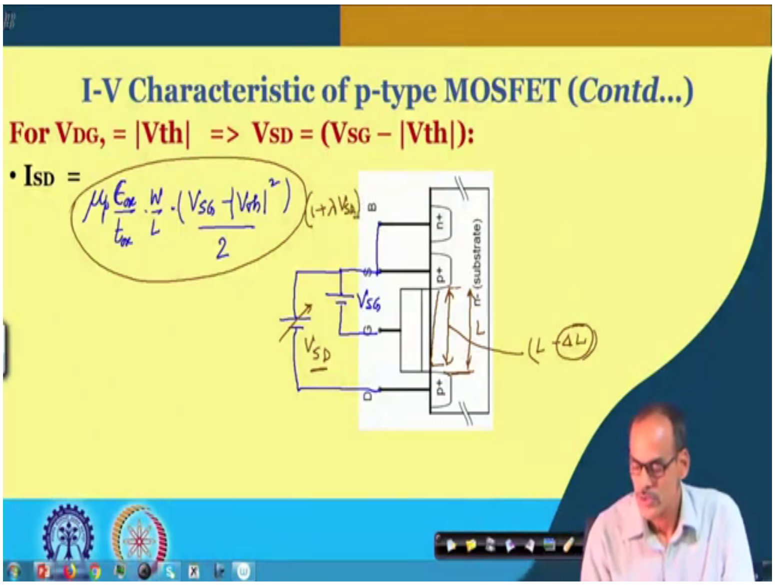

I-V Characteristic of p-type MOSFET (*Contd...*)

For V_{DG}, = $|V_{th}|$ => $V_{SD} = (V_{SG} - |V_{th}|)$:

- I_{SD} = $\mu_p \frac{\epsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \cdot \frac{(V_{SG} - |V_{th}|^2)}{2} (1+\lambda V_{SD})$

So, if you see; so, if I consider how it is as I say that V DG equals to V th the expression of the current it is, expression of the current it is mu p epsilon ox divided by t ox and W by L into V SG minus V th square by 2. And, if you increase this so, beyond this one if you rather if you valid this condition namely, If you retain this V SG to a value and then if you of course, if body is connected to the source.

And, if you increase this V SD beyond some point particularly if you are valuating this one, then the pinch of it will happen here the channel will get tapered like this and all these things it will happen. And, then the corresponding current it will be practically remains the same as this one, but then of course, depending on the value of this V SD the pinch of point it will be departing the drain. And as a result the effective channel length it will get shortened compared to the metallurgical or the otherwise initial length we are having.

So, this length it is getting shortened here to L minus del L as you have discussed earlier. And, this del L it is of course, it depends on what is the V SD we do have beyond this critical value and to capture this effect then we consider 1 plus corresponding lambda V SD part, ok.

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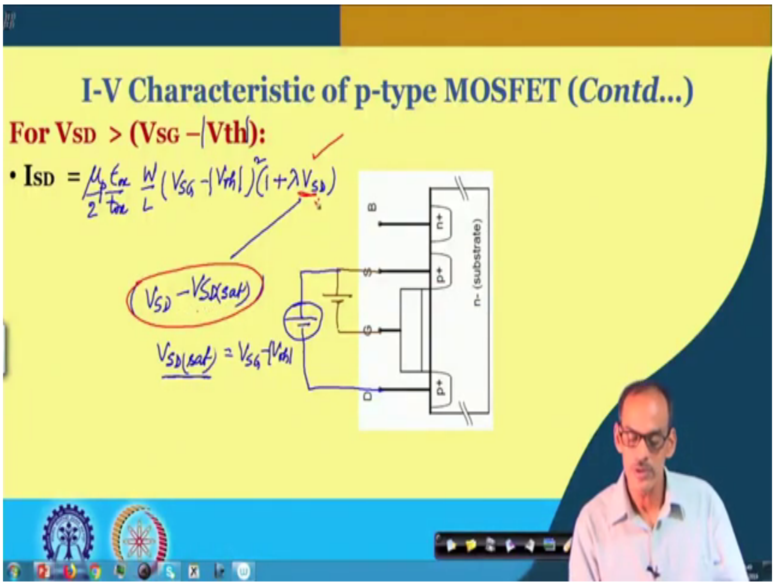

I-V Characteristic of p-type MOSFET (*Contd...*)

For $V_{SD} > (V_{SG} - |V_{th}|)$:

- $I_{SD} = \frac{\mu_p}{2}\frac{\epsilon_{ox}}{t_{ox}}\frac{W}{L}(V_{SG} - |V_{th}|)^2(1 + \lambda V_{SD})$

$V_{SD} - V_{SD(sat)}$

$V_{SD(sat)} = V_{SG} - |V_{th}|$

So, now we to capture this effect we can say that so, the expression of the current under this condition. Namely, whenever pinch off it is happening then we can say that the current here it will be mu p epsilon ox divided by t ox and W by L maybe 2 we can take it here. And, then we do have the V SG minus V th in fact, I should take mod I will explain why we are taking mod here whenever it comes to the situation, but for the time being let me assume that we are dealing with only the magnitude and this multiplied by V SD.

In fact, we should write V SD instead of V SD we should write V SD minus V SD sat where V SD sat equals to V SG minus V th. In fact, that is the value where the pinch of it is happening. So, V SD sat is basically the voltage at this point at the drain source drain. So, that the pinch of it is just happening, but then most of the time we do ignore instead of considering V SD minus V SD sat, we prefer to write only this VSD. So, unless otherwise it is stated at least in this course we will be assuming that V SD minus V SD sat it is approximately equal to V SD.

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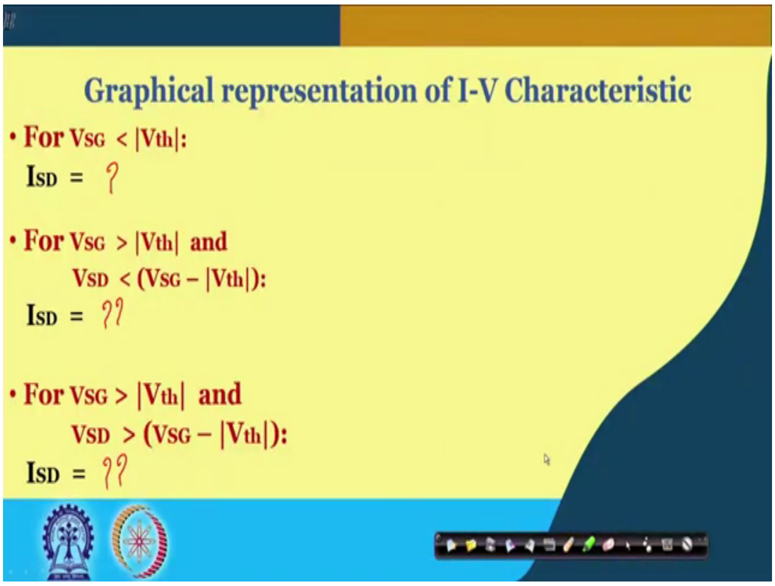

Graphical representation of I-V Characteristic

- For $V_{SG} < |V_{th}|$:
  $I_{SD} = ?$
- For $V_{SG} > |V_{th}|$ and
  $V_{SD} < (V_{SG} - |V_{th}|)$:
  $I_{SD} = ??$
- For $V_{SG} > |V_{th}|$ and
  $V_{SD} > (V_{SG} - |V_{th}|)$:
  $I_{SD} = ??$

So, that basically summarizes the I V characteristic equation. Probably, we already have said can you make an attempt to write this summarize this expression, I will not be again repeating here probably you can do this one and then we will see the graphical interpretation of this one.

So, let me take a break of 5 minutes and then we will get back to you to go for the graphical interpretation of the I V characteristic.

Thank you.