Analog Electronic Circuits
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Lecture - 10
Revisiting MOSFET

So, welcome back to this course on Analog Electronic Circuits. Myself Pradip Mandal associated with Electronics and Electrical Communication Engineering Department of IIT Kharagpur. So, we are still revisiting some of the prerequisites. And, today we are going to talk about MOSFET device, which is essential part of the analog electronics. And, so we will start with some basic concepts. So, let us see the what are the overall plan we do have.

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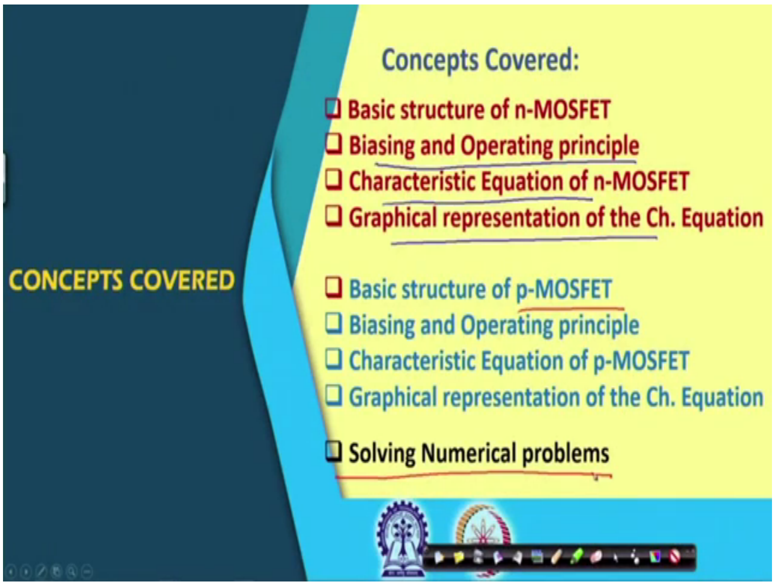

So, we are going to start with basic structure of the MOSFET particularly in MOSFET. And, the then we will be moving to the operating principle, along with the biasing arrangement of the device and then we will be going little detail of the I v characteristic of n MOS transistor n-MOSFET.

And, then we will be going to graphical representation of the I v characteristic of the MOSFET. And, this module it is having essentially 2 parts one is related to n-MOSFET or other n channel MOSFET. In the first part and then say in the second part we will be having p-MOSFET. So, will be subsequently will be covering p-MOSFET.

Many of the concepts here for n MOSFET, it will be applicable for p-MOSFET as well, but there will be definitely certain differences. And, after that we will be addressing the some of the numerical problems to give you an idea that how the I v characteristic equation can be deployed to solve analog electronics containing MOSFET. So, the overall plan again will be seeing that with respect to our overall plan where do we stand.

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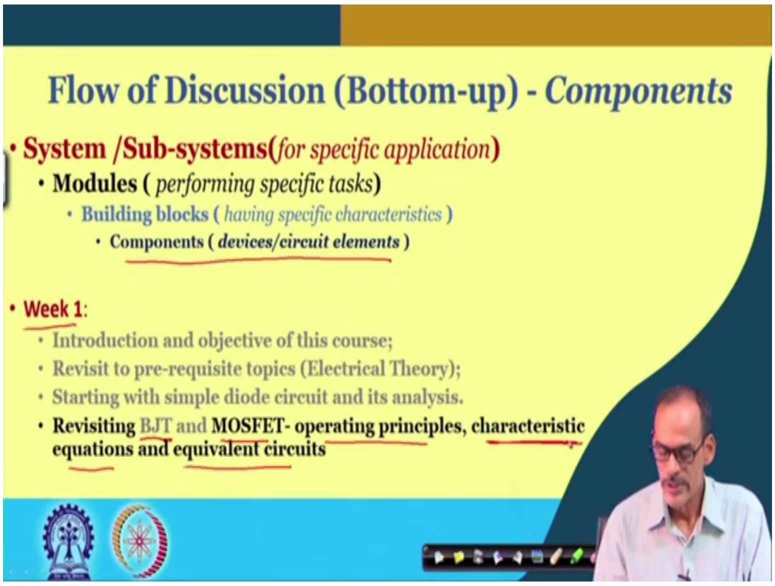

So, as we said that we are in the components or device level, and we are still covering this week 1. We already have covered B J T bipolar transistor and today we are going to start MOSFET. And, the plan is as I say that will be going into the basic structure and then operating principle, characteristic equation, equivalent circuit later on will be seeing, but at least will be going up to the characteristic equation. And, then as I said that today will be covering in channel MOSFET or it is called n type MOSFET and in the next part we will be covering p-MOSFET.

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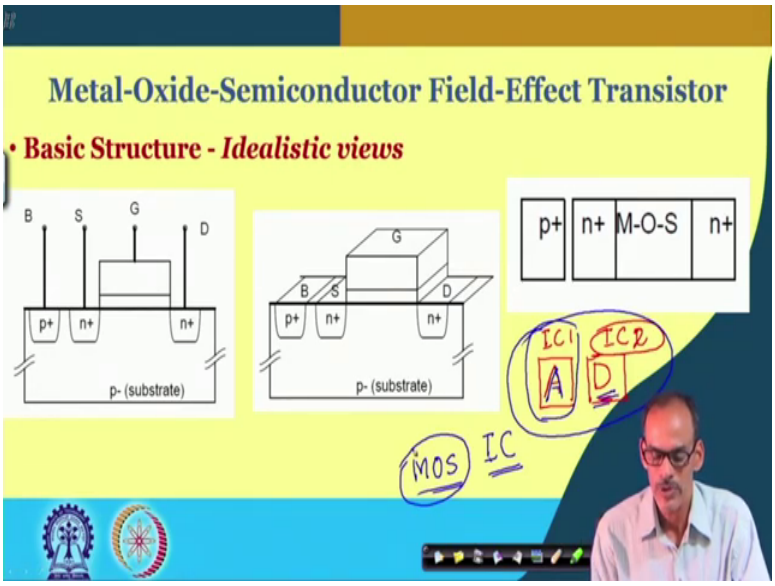

So, let us see the basic structure of say MOSFET. So, as you say that we are going to start with the basic structure of the MOSFET. And, here we do have the basic MOSFET structure. Most transport the metal oxide semiconductor and field effect transistor. So, of course, we do have the structurally we do have metal then silicon dioxide this insulator and then we do have the semiconductor.

And, in addition to that the field-effect transistor where, from the control input we apply voltage to create field on the channel which supposed to modulate the characteristic of the channel. So, here the controlling element is basically electric field. So, that is why it is referred as field effect transistor.

Whereas, for B J T the instead of applying directly voltage we may say it is a combination of voltage and current. And, in fact, it controls the current in the output port by applying current to the controlling port. So, that is a basic difference of MOSFET with respect to bipolar junction transistor.

Anyway, so the MOSFET before I go to the basic structure the MOSFET it is a very important element in today's context. In fact, for analog circuit of course, B J T is a better option compared to MOSFET. However, in the recent scenario or in the present situation, what we have it is whole system it is getting integrated and the system may be having analog and digital.

So, you may say that in a system if we are having say analog counterpart and then also the digital part. And earlier when analog and digital they were implemented differently maybe analog portion it was sitting in one chip I C say 1 and the digital portion it was in I C 2.

So, based on the technologies, whichever it is suitable for digital we were able to select that process to realize this I C 2. Likewise, whatever the process it is suitable for analog circuit, it was used to implement this analog I C. And, invariably as I said that B J T is preferred one for analog implementation. And, as long as this 2 I Cs analog and digital I Cs are independent, it was having fear good option to go for B J T.

However, in last say 2 decades in fact, it may be more than that, the analog and digital counterpart of a system they are getting integrated together within single I C. And, if we consider it is getting implemented within single I C then we have to see which technology is better.

Now, B J T of course, B J Ts technology it is it may be good for analog, but definitely for digital that may not be the good option. In fact, MOSFET it offers many advantages for realizing the digital circuit. As a result as the digital with progress of time as the digital portion of the whole system it is dominating. Naturally, the priority is given more towards the digital circuit to decide the fabrication process. And, this I C the combined I C of course, the MOS technology where basic devices are MOSFET is preferred 1.

Now, so the in this scenario the analog circuit which is of course, it is part of the same system and if we want to make the system on single chip, then this analog circuit need to be implemented and the same technology means the analog circuit need to be realized by using MOSFET transistor. So, whenever you are covering the MOSFET is basically preparing ourselves for technology down the line particularly mix signal implementation of a system.

So, however, as I say that B J T we prefer to keep because at the board level implementation B J T implementation is better, where we can verify some of the basic concepts. Whereas, MOSFET normally it is not really frequently used for analog design on board. So, anyway the now coming to the basic structure of the MOSFET, that as I say that it is having the metal oxide semiconductor.

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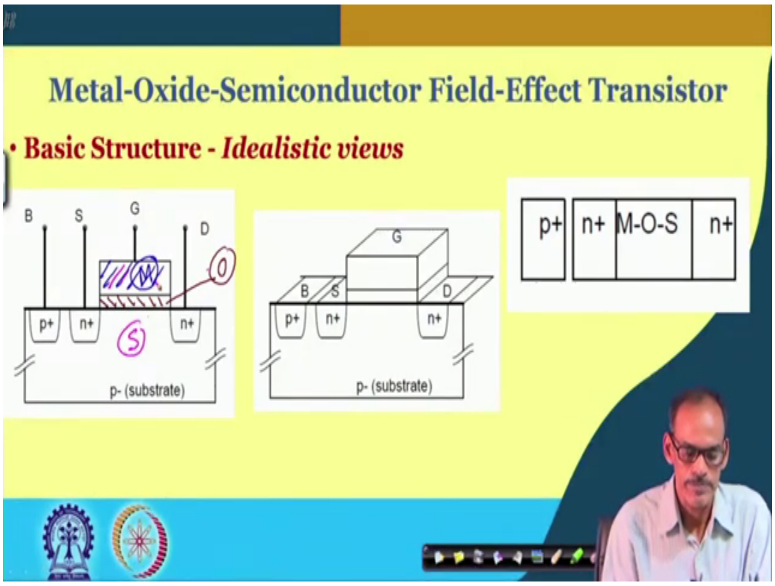

So, this portion this is the cross section of the metal and then the middle thin portion it is the oxide, silicon dioxide. So, you can say this is oxide. And, then this portion it is this portion it is semiconductor. So, that makes the MOS structure. Historically, this portion it was metal, but later on it is observed that so, instead of metal it is better to use polysilicon for tuning the threshold voltage of both n MOS as well as p MOS.

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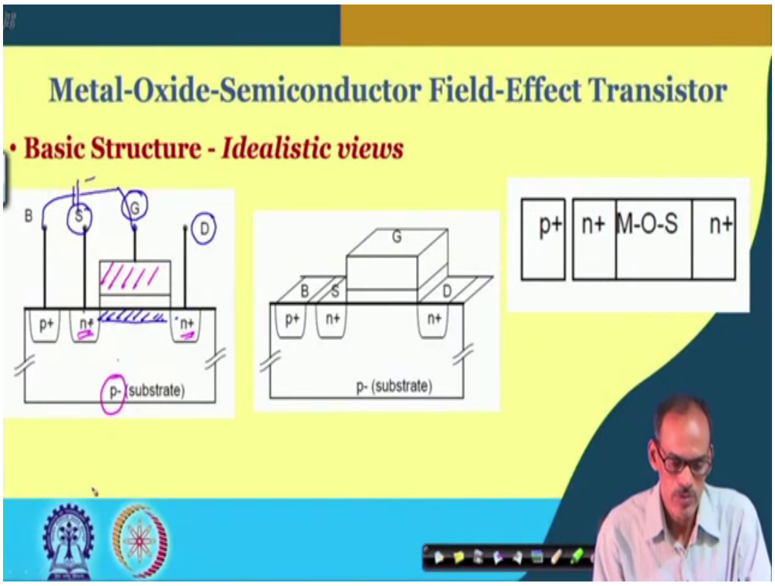

Now, if you see here we do have this is as I say that metal. And, the semiconductor portion it is weakly doped p type semiconductor, then we do have the 2 islands, 2 n plus islands left side, and the right side, and they are forming the I should say 2 terminal. And, if you see here this is n plus and then p weakly dope though it is weakly doped it is p type and then we do have n type.

So, you can say from this island to this island it is complete isolation. And, then by applying a voltage at the whatever this metal region, positive voltage with respect to the substrate. We can change the property of this portion, which is referred as the channel. And, later on we will see that this provides very vital information that, if we apply positive voltage conductivity between these 2 islands can be modulated.

So, as a result we may say that this is the controlling terminal, by applying a voltage here with respect to the substrate p minus substrate, by applying a voltage here. So, in fact, electrically this p plus island is working as port for the substrate. So, if you apply voltage here which is positive, then you can change the characteristic of this region ensuring that these two islands are getting connected.

So, now if I see the conductivity between these two external terminal, that can be modulated by this voltage. So, that is the basic you working principle will be doing little detail.

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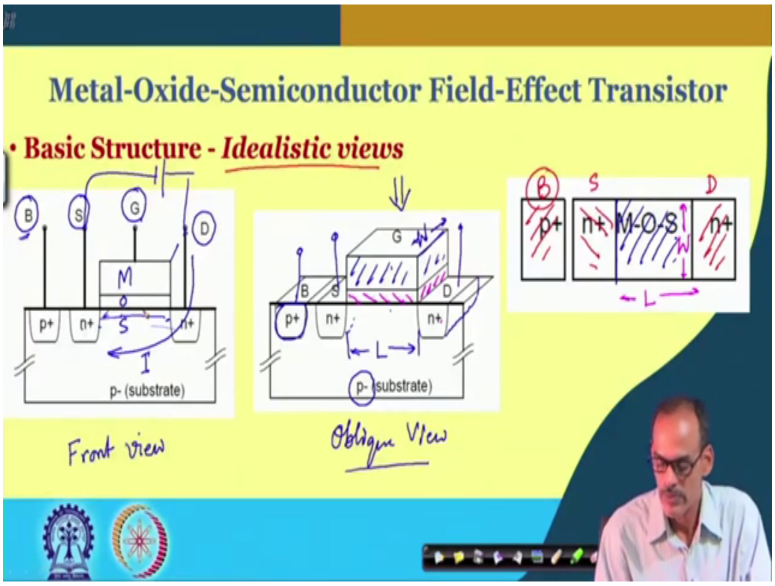

But, structurally as I said that this is having metal oxide and semiconductor. And, this is I should say it is though frequently in textbook it is referred as the MOS structure, but the actual view if you see oblique view it is shown here. So, I should say this is front view or cross sectional view whatever you say you may say that this is front view and this is oblique view.

So, in this oblique view what you can see here? So, this is of course, the metal portion and then we do have the thin oxide. So, we do have the thin oxide here and then we do have 2 islands. So, we do have this island. So, this island in factor it is getting extended like this, this is also getting extended and then we do have the electrically 2 terminals are there.

And, note that the substrate is weakly doped. So, if you directly try to access the substrate from top through metal line, that may create you know schottky diode to avoid. The schottky diode what we can do we can put p plus region and then you will be getting ohmic contact.

So, this p plus island is basically working as terminal for the substrate, it is referred as body. So, that is why we do have we call this is body, we call this is gate. And, this 2 terminal essentially they are interchangeable they are in fact, similar in nature, though this source is in this diagram it is shown close to this p plus region, but actually the these 2 terminals can be interchanged. And, depending on their voltage relative voltage potential; one of them we call source namely whichever is sourcing the carrier and whichever is collecting or wherever it is draining to we call it is drain.

So, that is the naming convention. The controlling terminal you call gate, the substrate tab we call body and then one of these 2 islands between which we are changing the characteristic, one of them we call source and other one is drain.

Now, if you see the top view of this device of course, whenever we are changing the characteristic of this channel, what we are trying to do is that we may be applying a voltage here and then we will see how much the current it is flowing from drain to source? So, this current whatever the current is flowing, it is of course, it is a strong function of whatever the distance we do have and whatever the orthogonal geometry, which means this geometry.

So, the current device wise current is it is a strong function of this spacing called length of this channel and also it is width of the channel. And, why you call it is channel? Because, as I say that once you apply the voltage here current it is flowing through this region that is why it is called channel.

If you see the top view of this device on the other hand what you can see that we do have MOS structure here. So, this is the top view of that main portion metal it is working as gate oxide it is working as insulator through which we are applying the field in the substrate region. And, S stands for the body here and in fact, that is nothing, but the channel.

So, we can see that channel portion it is only here and as I said that the 2 important dimensions one is the length and the width here. And, these 2 islands; these 2 islands are on here. So, we do have one island here in this case we call this is drain and then we do have another island here we call this is source and in the top view we do have the this p plus island we call body.

So, that is the basic structure and I should say this is rather idealistic view of the basic structure. Though it is idealistic view most of the time we will be using refer in this one. And, just for your information the rather realistic views are like this.

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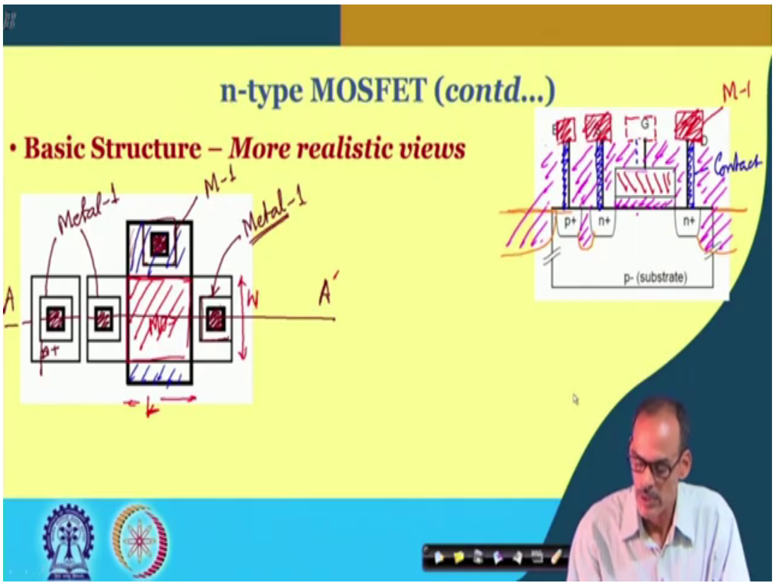

The top view if you see here top view it is. So, this is the channel portion. So, you can say the MOS structure it is here MOS, but then the metal portion it is getting extended beyond this one. So, I should say the channel is of course, within this one and it is length is here and width is this dimension. And, the controlling element or the electrode, that is getting extended beyond this channel for reliability reason.

So, this part the extended portion of the metal is basically helping to improve the reliability of the device. And, then we also have something called connecting terminal. So, we do have this portion it is referred as the contact and on top of that we do have a metal. So, likewise we do have in the drain region we do have contacts here and then we do have the terminal metal.

So, the box here whatever the box we are referring here it is you may say that it is at higher level some metal. Note that this metal it is different from whatever the metal we refer, this metal it is for making the circuit in integrated circuit. So, likewise we do have the contact here and then we do have metal. And, in fact, in integrated circuit there are different layers of metals. So, typically this metal layer it is referred as Metal 1 layer so in fact, this is also Metal-1 layer. So, it is called Met 1 and we do have the p plus region here for the body connection. So, here also you have the contact and then Metal 1.

So, if you see the top view here it is rather like this. So, if you take a cross sectional view along this axis, if I say that a dashed then you can say that cross sectional view it will be similar to whatever it is shown here. However, it will be different slightly different if you are looking for more exact the interpretation say for example, in the drain region. So, the contact portion it is quite say thick here and then on top of that we do have the Metal 1.

So, we may say that on top of that we do have the Metal 1. So, this is the metal one. So, you may say that this is Metal 1 and this is the contact. So, this portion it is also Metal, but it is getting implemented by a different process step. So, that is why it is referred as contact layer of course, it is material is also different. So, we will not be going detail of that. So, likewise for the gate or the resource side also it is like that we do have a contact and then on top of that we do have Metal 1. So, we do have Metal 1.

So, similarly for the body also and it is corresponding Metal 1 connection. So, here if you see along this a dashed line, we are really not crossing this the contact of the gate. So, naturally we are we will not be able to see. So, you may say that it is there.

So, in our engineering drawing whatever the things it is not crossing we may say that it is existing, but probably in different plane different plane of the intersection. So, you may say that this Metal 1 and the corresponding contact particularly for the gate we are not really crossing this one. So, this is rather more from I should say more realistic view of the cross sectional view of the transistor.

And note that this oxide on the other hand let me use different color, this oxide whatever we see thin oxide, this plays very important role, because we are applying a voltage here and through this thin oxide it is trying to influence the substrate in the channel region to change it is characteristic. So, this is very important, but beyond this beyond the this region channel region whatever the portion we do have in fact, they are also we do have the silicon dioxide. In fact, everywhere here it is full of silicon dioxide.

So, if you see the structure wise, it looks like it is a sandwich of the structure and where would you do have the controlling element, though we call it is metal, but actually this is polysilicon as I said. So, this is the gate and everywhere as I said this is silicon dioxide. And, so this is just for your information I am sharing this little realistic view.

In fact, beyond this beyond the that this device if you see, which is part of relatively bigger system in integrated circuit we do have many more devices on this. So, you may say that this is the; this is the top surface of the substrate, and then we do have different devices, and on top of that we have the contacts, and metals to make the connection, and then everywhere silicon dioxide is there to isolate the device above the surface.

So, likewise below also we do have the silicon dioxide. So, it is silicon dioxide is here as well. So, you may say that silicon dioxide it is also here it is also here like that. So, that is rather more in a realistic view of the device, but for simplicity of course, we will be using the simpler version of the cross sectional view namely we will be using this. So, namely we will be using the so, this cross sectional view will be using.

So, we let me. So, in our next discussion we will not be really using this clumsy cross sectional view for simplicity of our analysis we will be going for this schematic view only.

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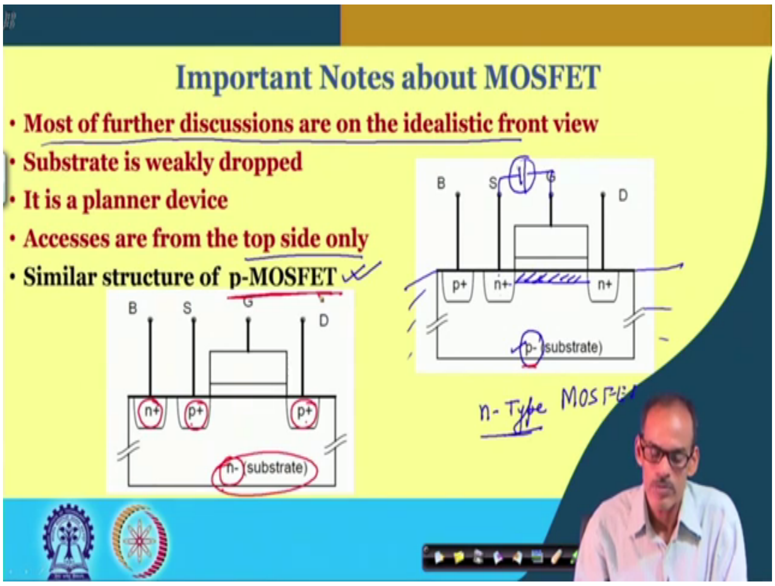

So, this schematic view of the cross sectional you will be frequently referred to. So, there are a few notes to be taken here. So, first of all as I say that for further discussion we will be going to, we will be using this cross sectional view for simplicity. Then the substrate you should be noting that substrate it is not purely complete insulator it is rather weakly doped p type and the device it is planar structure.

So, you can see that the current is flowing horizontally. And, access to different terminals it is coming from the top side of the device. In fact, you may say that this enter portion it is the substrate. So, we cannot directly access this one. So, we have to use access through whatever we discuss the contacts and the top the Metal 1 and so and so. So, all the access it should be from the top.

So, and then the other thing is that in this basic structure we say that the substrate it is p type and by applying a voltage here, we are changing this portion into n type. So, once it is getting changed to n type we may say that channel it is getting converted into n type. So, that is why this device it is referred as n type MOSFET or for simply you may say that n MOSFET.

So, when you say n type it refers to the type of the channel would be created. Of course, originally it was p type, but after applying the voltage here the channel it is getting converted into n-type. So, similar to this structure there is also a counter device or I should say counter part of many circuits and it is structure it is very similar, but it is complementary in nature.

So, if you see here the basic difference in this case for p-MOSFET. The it is body it is I should say body instead of substrate we may prefer to say it is body. Body is weakly n type in contrast to weakly p type and these 2 islands. Drain source islands they are p plus regions islands and of course, to tap the substrate we require n plus region to avoid the schottky diode we can have the ohmic contact.

So, will be later on we will be going further detail for n p type MOSFET. So, let we proceed with n MOSFET for further discussion namely what you can see that the more detail about working principle then i v characteristic and so and so on.

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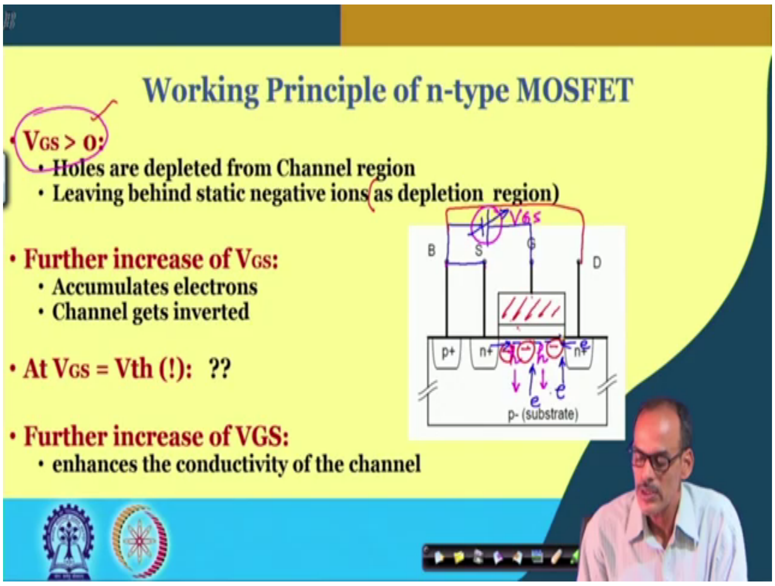

So, let us go into the working principle. So, coming back to the basic device structure and then let you also keep meaningful bias here. So, if we apply a voltage here at the gate with respect to substrate. And, let you consider that this is also at the same potential and try to see what kind of things are happening in this region.

So, for the time being let we also connect this drain region or the drain island together. So, in our whole circuit we do have only this source we do have this source and this source is gate to source. So, we may call this is V GS. So, we may say that this is V GS.

So, if this V GS is positive then let us see what other things are happening. So, if we apply positive voltage here with respect to source and in fact, source is also connected to body. So, what we are expecting that since it is p type substrate there will be holes as majority carriers and because of this positive voltage they may be depleted from the surface region.

So, you may say that whenever we are applying the positive voltage or the gate, it creates a field on the surface across this thin oxide and as a result the holes are getting depleted. So, that is why it is we say that the holes are getting depleted from this region from this channel region and what happens it is effect it is that it is leaving behind negative ions.

So, this negative ions are basically the stuck with the crystals and they cannot move. So, they are basically working as depletion region of diode. So, this static ions whatever the static ions are stuck there of course, they cannot participate for current flow, but they are whenever we are applying positive voltage, they are basically helping that the those fields are getting properly getting terminated to that.

So, if I increase this V GS further then what happens? So, if I increase this voltage V GS further then, whatever the holes it was there near the surface that got pushed away and then what is happening is from the substrate region the electrons though they are minority, they are getting attracted. So, in case if we have this n plus region in fact, most of these electrons may be supplied from this region and this region. So, in as a result in the channel region we do have a thin layer of electrons. So, let me redraw this part again.

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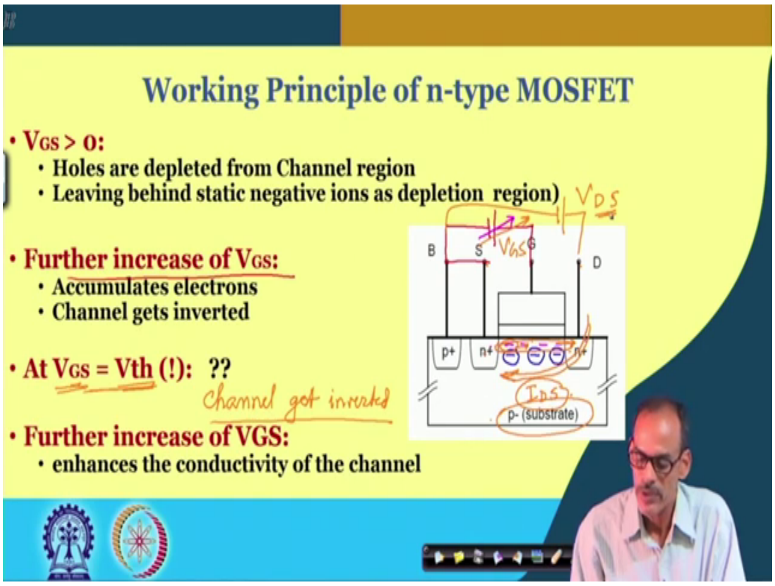

So, we are applying voltage here V GS and we want to see what other things are happening particularly when the V GS it is sufficiently high. We do have the static ions they are not participating for the current flow and in addition to that it is also having electrons. So, these electrons may be coming from these 2 islands.

So, if you see the property of this channel region just below the oxide, it is property is getting changed by applying this meaningful voltage. And, as a result what is happening is more and more while more and more electrons are getting accumulated here, it is providing electrical connection from this island to this island. In fact, that is what it is as I said it is making the conductivity from drain to source or source to drain it is getting modulated by V GS.

Now, if we of course, so, the there is one important value of this V GS. Suppose, this V GS it is reaching to a critical value called V th we will see what is the meaning of this V t h. Such that the concentration of electron whatever the electron concentration in the surface region. If it is exactly equal to holes concentration in the substrate exactly equal to that, then you may say that the channel portion it is completely getting inverted into n type from p type and it is strength is exactly equal to the strength of the substrate.

So, in other words if V GS it is exactly to this critical voltage you may say that this island to this island, it is getting connected and it is strength it is defined by whatever the strength it is there in the substrate region. Of course, within the substrate region the majority carriers are holes and here the majority or other carriers are electron. So, you may say that around this. So, around or beyond this point image or at least at this point you may say that the channel got inverted.

So, if I apply this V GS beyond this V th then what we had expecting is that of course, more amount of electrons it will be there and then they will increase the conductivity of this region further. So, that is what I say that further if we increase this V GS, then what you are expecting is that this portion the conductivity it will be more.

So, then instead of really connecting the drain and source together or keeping this is floating if we apply some voltage here. So, you may call this is V DS. And, then it is expected that since these 2 islands are getting shorted through this channel the electron layer then there is a flow of current. In fact, electrons are moving from left to right. So, these electrons are moving left to right and the current it is flowing on the other hand right to left. So, that is why we call this current is current is flowing from drain to source.

So, whenever we say the I V characteristic or characteristic equation of the device is nothing, but this current how it is changing with the voltage here V GS, how it is changing with V DS? We are going to further detail of how the characteristic equation can be obtained in the next slide.

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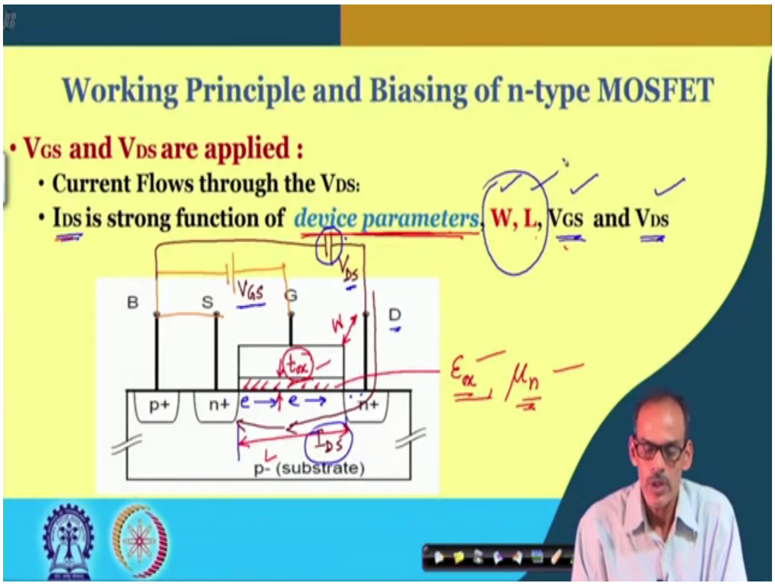

So, here what you see it is that, suppose if we apply the voltage here V GS and also we apply V DS keeping body and source they are connected. So, we call this is V DS and this is V GS the current it will be of course, we do have insulator. So, through this terminal there will not be any current, but then there will be a current flow.

So, this I DS it is flowing here. And, of course, this current it is carried by electrons. So, these electrons are really moving from left to right by this field or by this voltage, you may say this is lateral field. So, we can say this vertical field it is getting created by V GS, which is changing the concentration of the electron on the other hand, the horizontal field getting created by V DS, which is helping for the movement of the electron from left to right and as a result we do have the I DS.

So, note that these electrons are coming from this side. So, that is why you call this is source and it is getting drained to this terminal that is why you call drain. Now, it is very clear that why you call this is drain and source. So, this current flow I DS it is a strong function of this V GS, V DS and also it is strong function of the spacing from here to here namely the length of the device.

So, it is a strong function of the length it is strong function of the other geometry namely width of the device and also it is strong function of the device parameter, which includes the thickness of this oxide. Maybe it is referred as t ox, then dielectric constant here of this portion it is referred as epsilon ox and of course, the mobility of the electrons in the channel region.

So, that is what I say that this I DS it is strong function of all these things. And, as a circuit designer what will be looking for if the device it is already fabricated. So, WS and LS they are already defined then we will be looking for the dependency of I DS as function of V GS and V DS. And, as a device engineer you may try to change this t ox you may try to change probably in the surface so that the mobility it will be better and so and so.

So as a device engineer of course, so, there are different tricks to improve the device performance, but as a circuit designer we may assume that these parameters are given to us and we may consider they are fixed.

On the other hand if it is you are a V L S I circuit designer where the device yet to be implemented. However, technology is fixed; that means, these parameters are fixed. So, you may say that whenever we say technology is fixed device parameters are fixed, but then you also have the flexibility to change the WS and LS of the devices.

So, for V L S I circuit designer not only you will be playing with the applied voltages, but also the geometry of the transistor. So, in the next slide we will be going for the I B characteristic, but let me take a short break and then we will come back.

Thank you.