Semiconductor Devices and Circuits
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Lecture - 37
MOSFET: I-V characteristics

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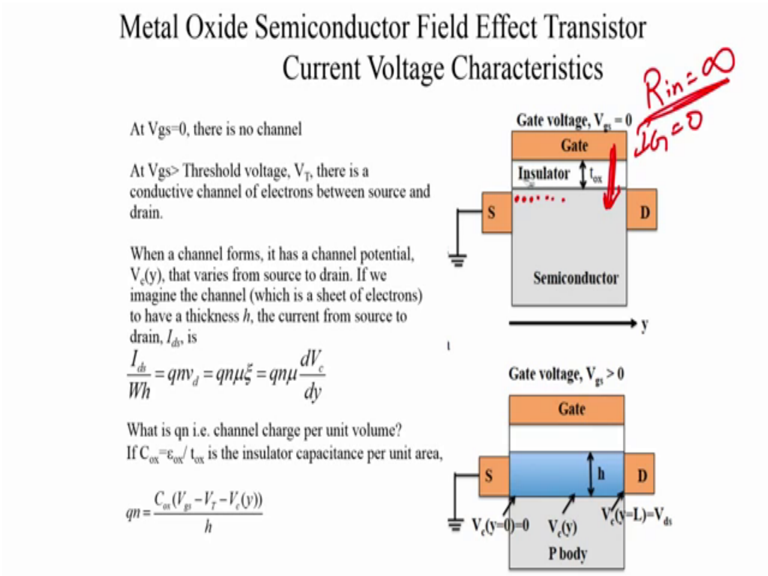

The now let us go ahead and develop the current voltage characteristics. The electrostatics of the MOSFET, it has already been in some sense covered when we discussed the MOS capacitor ok. So, what we will do now is, look at the current voltage characteristics of the MOSFET. Of course, the electrostatics in the MOS capacitor the electrostatics did not include the influence of the source and drain, but that is quite easy to include, and it is just a matter of changing the potential of the semiconductor. What we will look at now is, once you have created the inversion channel what is the current, how what is the current voltage characteristics in particular, what current am I looking for? We are not interested in the gate current, because ideally there should be no gate current ok.

So, we are not interested in the gate current, I G should be 0 and that is the whole point of the MOSFET or the field effect device. If I G is 0 it is, because you have an insulator than the therefore, the input impedance is infinite ok. So, ideally that is what we are trying to achieve. We are trying to achieve a variable resistor with an infinite input impedance variable channel resistance, but the gate input impedance is infinite ok. So, that is the ideal drain. Now what we are trying to look at is this current ok. What is the drain to source current?.

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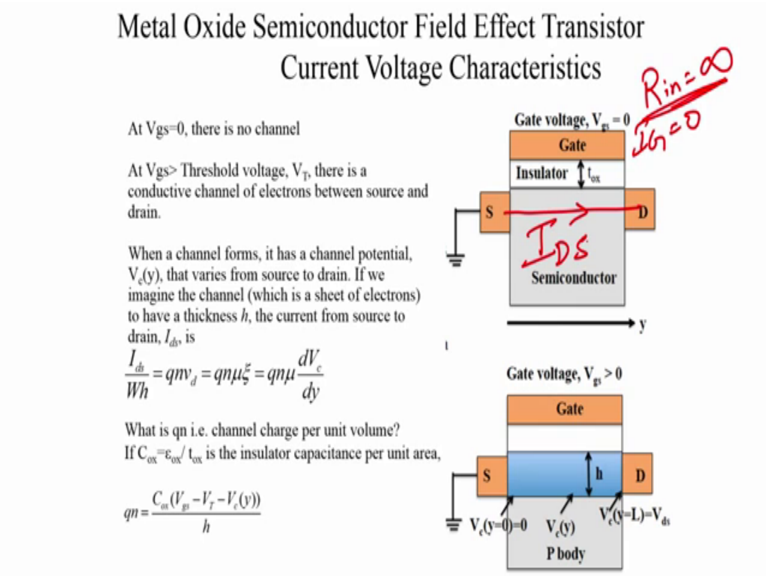

So, if you talking about P channel device, if you talking about the N channel device or an NMOS you have a P type semiconductor and you have electrons there and the electrons and the drain is going to be at a higher potential.

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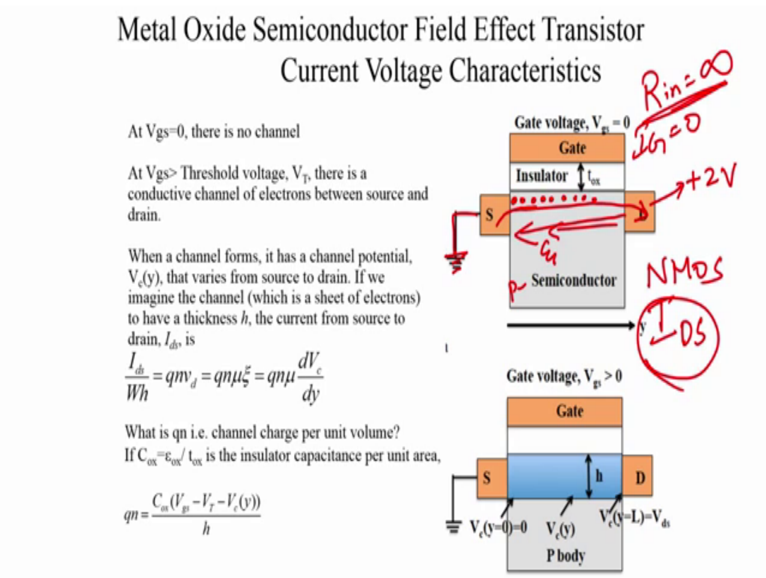

So, let us say at 2 volts, the source is with respect to the source and therefore, the electric field is in this direction and therefore, the electrons will all come in from the source and they will all migrate to the drain which means the current is going to be in this direction. You going to have I from the drain to the source and we want to find out what is the drain to source current all right. So, how do we go about this? And before we continue, this is equal true for an N channel device ok. So, I for a P channel device. So, if it is a P channel device you will have if it is a PMOS, you will have your n type semiconductor and you will have holes of the interface after inversion and these holes that that the source will be at a higher potential with respect to the drain.

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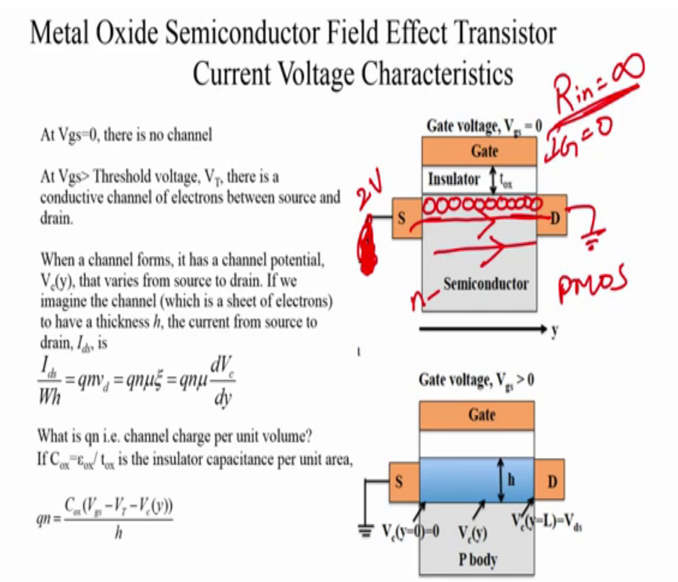

So, for example, let us say look at this is being 2 volts and that is ground. So, the holes will be entering from the source they will migrate to the drain and the direction of the movement of the holes will be this and the current direction will be this ok. So, you will have an ids that is negative V ds that is negative etcetera etcetera ok, but the idea of the physics behind deriving the current voltage characteristics is the same. Now since we have discussed the P type body and since we have discussed the P type MOS capacitor.

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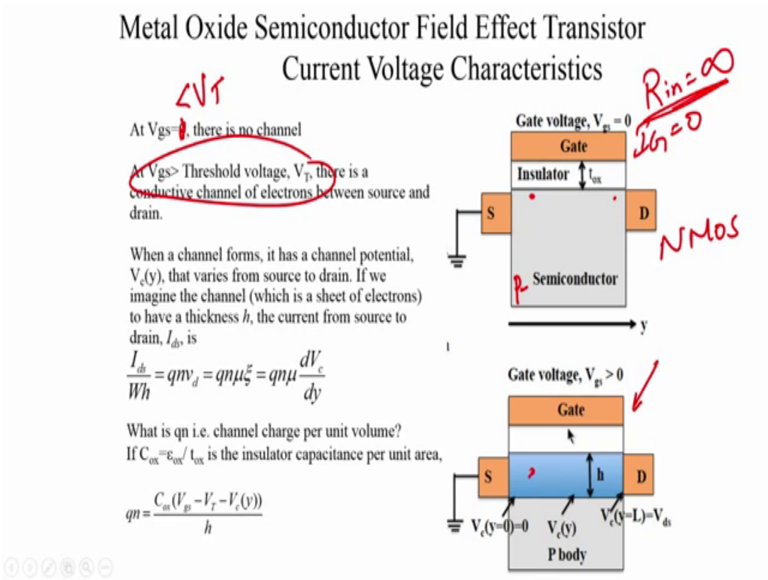

Let us just take with the P type semiconductor and then N MOS device or an electron channel being formed at the interface during inversion.

So, how does this device work? Now when V gs is not 0 when V gs is equal to is less than V T, there is no channel technically because its solved depleted. But once V gs becomes greater than the threshold voltage, you now have inversion and you have a channel that forms. So, the channel it is indicated in this picture and it is indicated as this blue regions; that is the electron channel from source to drain. If we have I a take a voltmeter and head from the source to the drain or for the, from the source to the drain and I were to measure the potential of the channel at every point ok. What is the potential?

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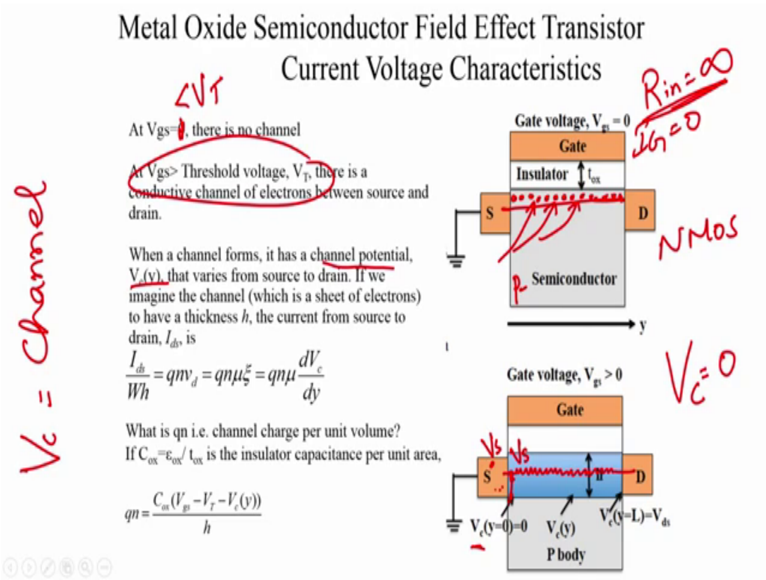

So, let us call that potential as V c which is the channel potential. So, let us give it a name for this particular potential which is V c ok, which is the channel potential which means we have created N channel, we have created an electron interface ok. So, you have electrons here, but then these electrons, we are going to go about go around with the voltmeter and measure the potential of this channel of electrons from the source to the drain and we are going to measure that potential with respect to the source and we are going to call that potential V c. What is that potential?

So, right here so, you can think of this whole path of electrons as a long resistor right. It is got some resistance. So, right at this edge what is the potential? It is 0 it is the same as the source ok. The potential here is V s and this point is V s. So, V c is basically the potential that you measure minus is all with respect to the source and therefore, the V c is 0 ok. So, let us give this a direction. So, we are calling this the y direction and therefore, at y equal to 0 V c is 0.

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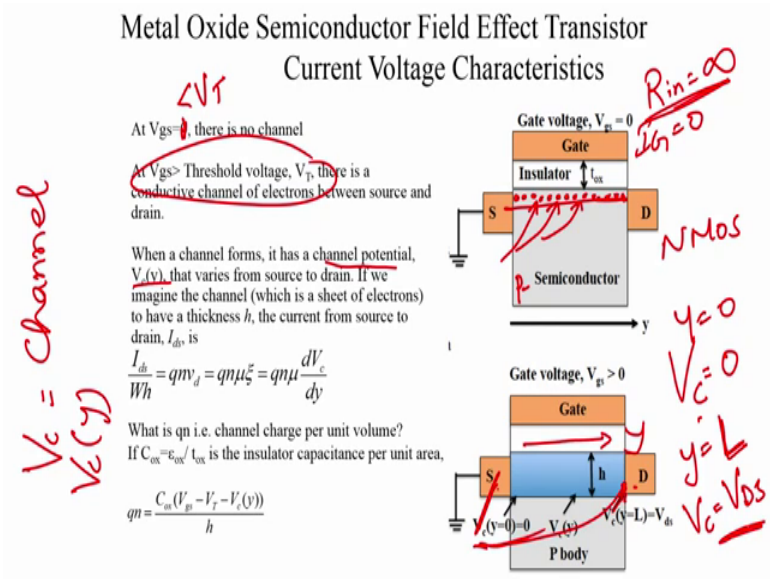

Now let us move ahead, now at some other point the potential difference between these two will be V c of y because its varying with y and as you go to the drain as you approach the drain side the potential here is going to be the same as the drain potential and therefore, at y equal to L which is the channel length V c is going to take a value of V DS which is the drain to source voltage because all these potentials are measured with respect to the source.

So, you are going to keep one probe there another probe here and this potential difference is V ds all right. So, that is your channel potential. So, in order to imagine in order to derive this current, we see that it is the V ds that is providing the electric field and these are in response to the electric field these electrons are going to drift through from the source to the drain

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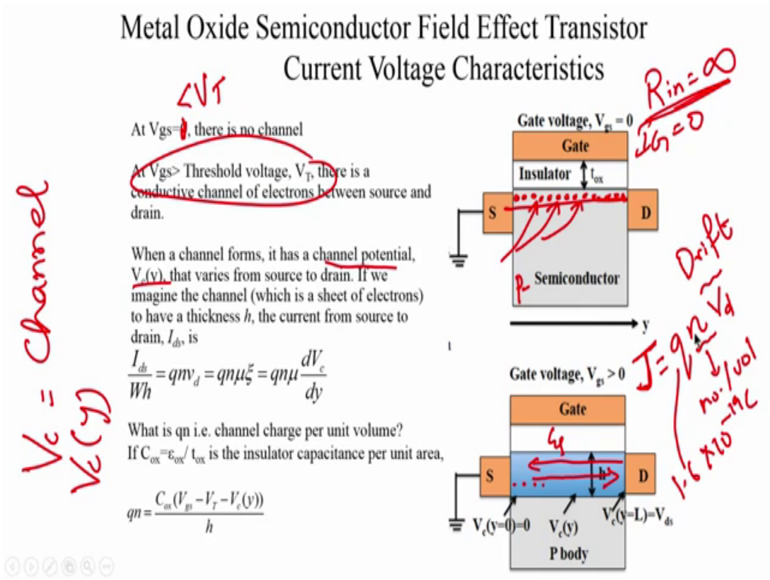

So, what is the drift current density? So, that is J which is the drift current density the current per unit area it is q n V d where V d is the drift velocity of the electrons, n is the number of electrons per unit volume and q is basically your 1.6 into 10 power minus 19 coulombs.

So, that is your drift current density. Now what is the total current? It is the current density times the area of cross section and you want to identify the area of cross section what we are going to do is we are going to define this electron channel as having some thickness h ok. Now that is that is an odd definition because all of you are already familiar the fact that the electrons are all wave particles. So, do you define them as having a certain thickness h is odd, but were going to go ahead and treat these electrons as particles and define the sheet as having a thickness h and this sheet of electrons has got a width which is equal to the channel width of your device ok. You have got you have got this sheet charge which is all migrating towards the, from the source to the, from the source to the drain.

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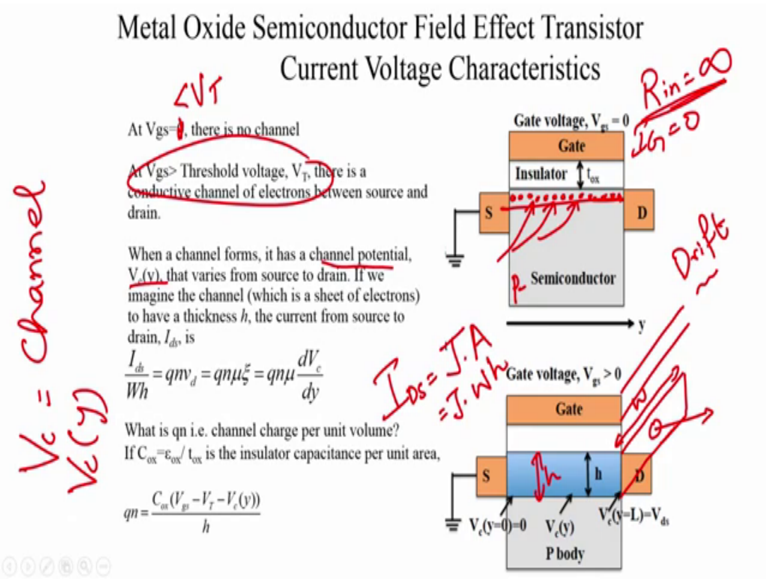

So, all migrating from the source to the drain; so, what is the total current? The total current which is your I ds is basically this current density into the area of cross section and what is the area of cross section? It is basically W into h where W is the channel width and h is your thickness of this electron sheet ok.

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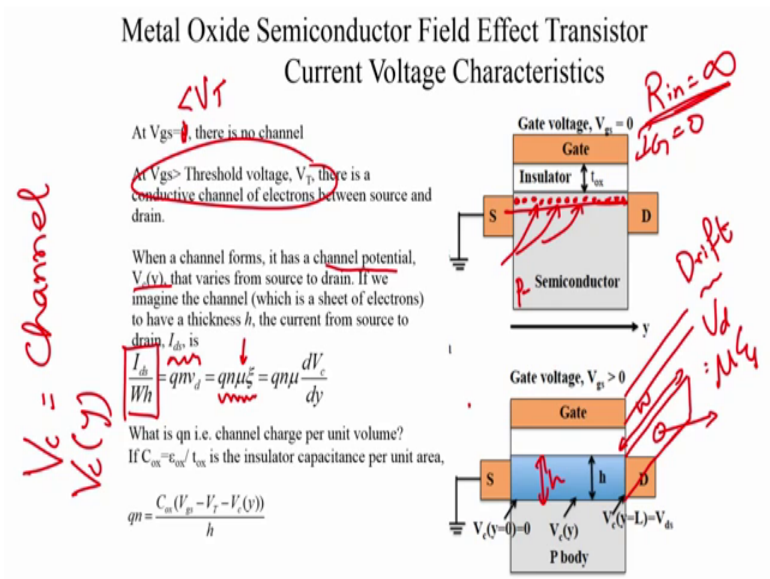

So, we can write this little equation down, which is ids by W h is the current density and that is equal to qn into the drift velocity, but what is drift velocity? The drift velocity is nothing, but the mobility times the electric field. So, we can rewrite that equation as qn mu into the electric field where mu is the mobility of the electrons and furthermore what is the electric field?

So, if I were to now take a little section we already know what the channel potential is right. So, if I were to take a little section, let us take a small section here. So, that is our y direction and let us say the section has got a length dy and we say that the voltage drop across the section is basically d Vc that is a delta of the channel potential.

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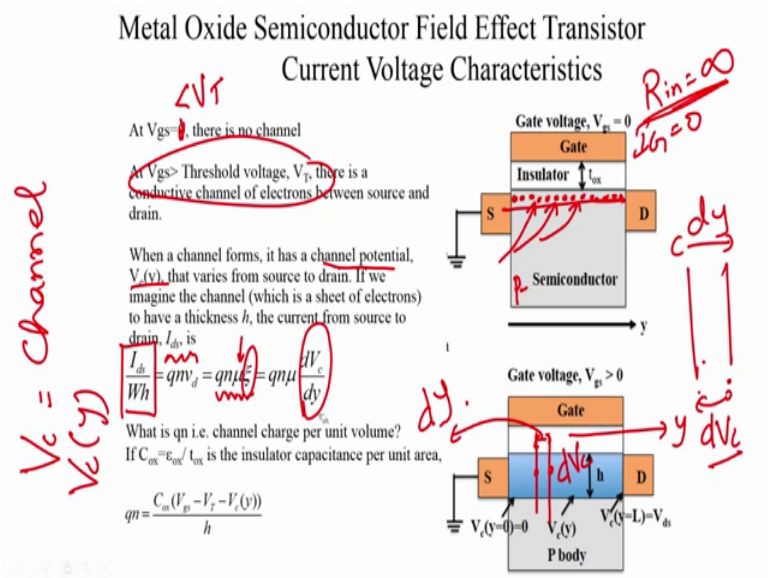

So, you have a section of length dy and the voltage drop across the section is basically dVc. So, what is the electric field across the section it is dVc by dy. So, we replace this electric field term by dVc by dy.

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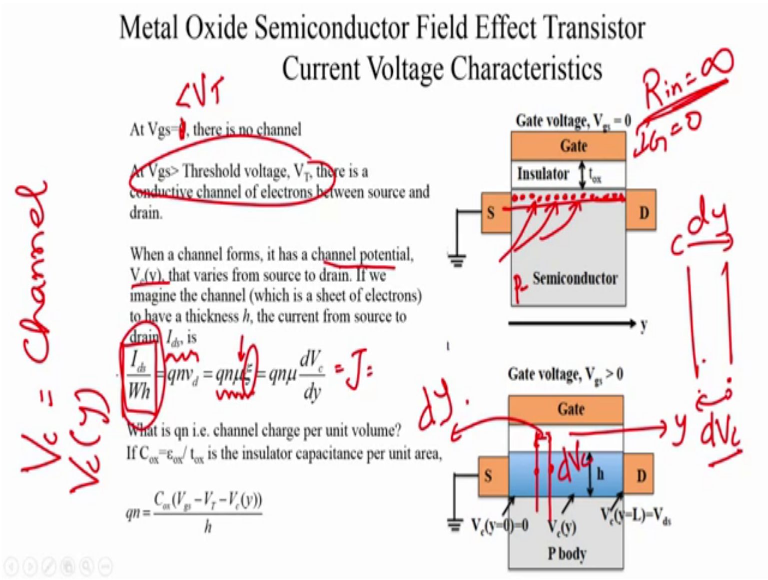

So, you have q n mu dVc by dy as your current density and that is equal to your I ds by Wh ok. Now in order to identify I ds we need to now calculate what is n ok.

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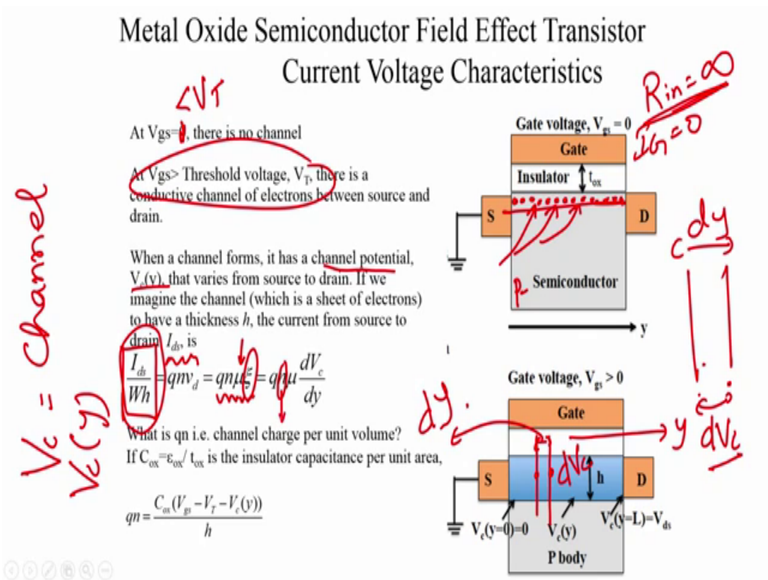

So, how do we find out what is n? n is the number of electrons per unit volume sitting near the channel. So, if you recollect your MOS capacitor we had already identified. So, if you remember the MOS capacitor let us just go back a little bit.

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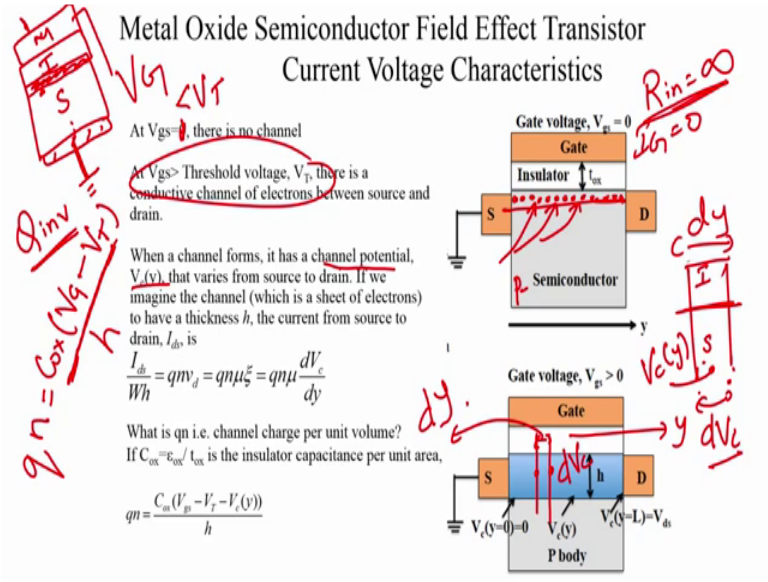

So, we had the MOS capacitor which was a metal insulator semi conductor structure and we had in inversion we had an electron sheet and we had defined that inversion charge is Qinv that was a inversion charge per unit area.

So, the MOS capacitor had a gate voltage V G it had and this also with respect to this grounded back contact and it had it had generated this inversion layer and if you go back you will recollect that this inversion layer was basically qN where N was the number of electrons per unit area which was nothing, but Cox into V G minus V T where V T was the threshold voltage. So, that is the way we defined that the number of electrons per unit area because Cox is per unit area. Now what we want now is the number of electrons per unit volume which is given by small n. So, if this is the number of electrons per unit area, what is the number of electrons per unit volume? It is this number divided by the thickness of the channel which is are h.

So, this is the number of electrons per unit volume at the interface provided the potential in the semiconductor or this channel potential is 0 because in the case of a MOS capacitor what is the difference, what is the voltage difference between the metal and the semiconductor? It is V G minus 0, but now if I were to take this little section here of length dy. So, let us say that is my insulator and that is my semiconductor the potential here is V c of y and the potential drop across the section is dVc and now my gate metal ok.

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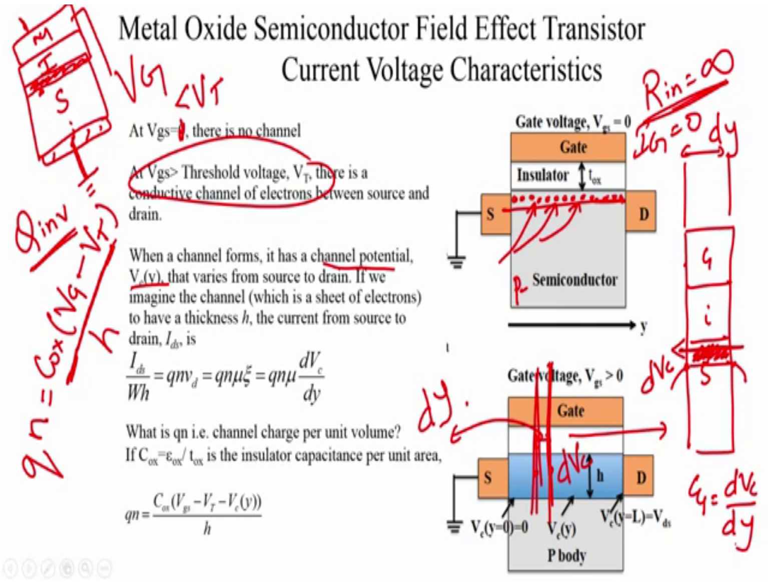

So, let us let us look at the section that we are analyzing here. So, we have, we have to consider this little section you have taken the section all the way through let us cut this little section all the way through you have the gate, you have the insulator, you have the semiconductor, the length of the section is dy the potential drop.

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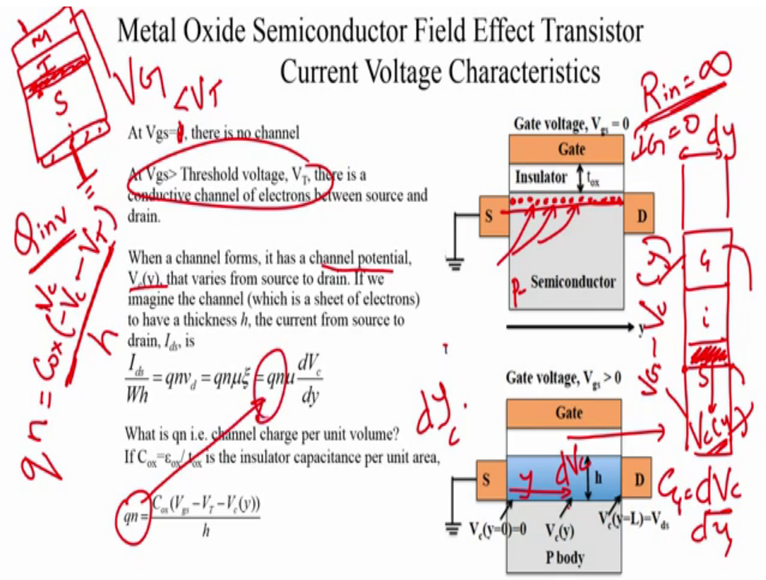

So, you have the channel here, you have the channel here the potential drop across this channel is dVc and therefore, the electric field in that section from here to there is dVc by dy ok. dVc let me just write it clearly dVc by dy that is the electric field and this potential of the channel is some V c of y, because you know its sitting depending on where the y is how far are you from the source depending on what your y is. So, that is that is the source and this distance is y right. So, that is the situation. So, now, if you think of it as MOS capacitor it is a MOS capacitor, but this in the semiconductor is not at ground, but it is some Vc and therefore, the gate to semiconductor voltage difference is not V G, but it is V G minus V C.

So, that difference is so just to tidy up this place a little this difference is V G minus V C of y that is the gate to semiconductor. So, what I am going to do is we are going to replace this little term here instead of saying V G minus ground we are going to say its V G minus V C minus V T into Cox by h is your q into f. So, we now have this equation here it says that q into N where N is the number of electrons per unit volume is Cox into V G minus V T minus V C of y by h and what we are going to do is when are now going to substitute this qn in this expression for the current.

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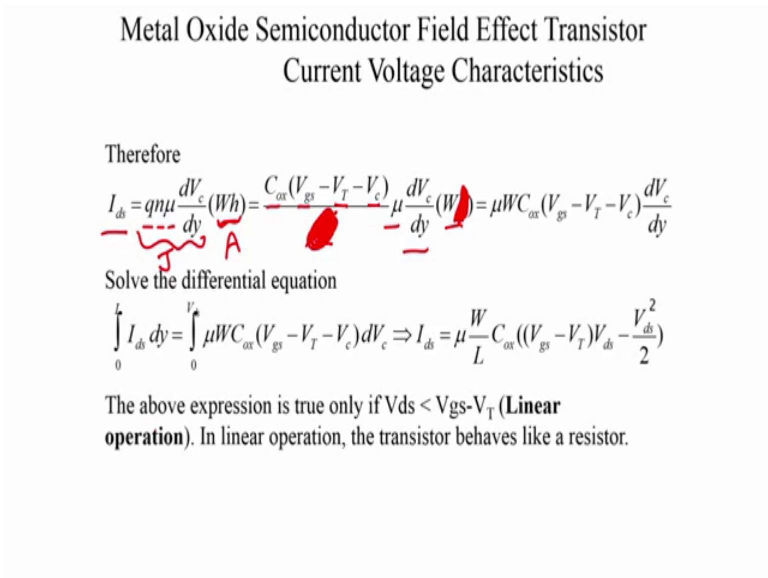

So, we now have Ids we have taken the Wh over to the other side is qn mu dVc by dVy. So, that is the current density into Wh that is the area and qn is nothing, but Cox into V gs minus V t minus V c by h ok. So, it is now the potential with respect to the source into mu into dVc by dy into Wh and see the h cancels off the h was not required. So, even though our assumption on what h is and how we can how we treat h is all was all arbitrary we really do not need it, it just served to explain the situation and therefore, you have this little differential equation that needs to be solved.

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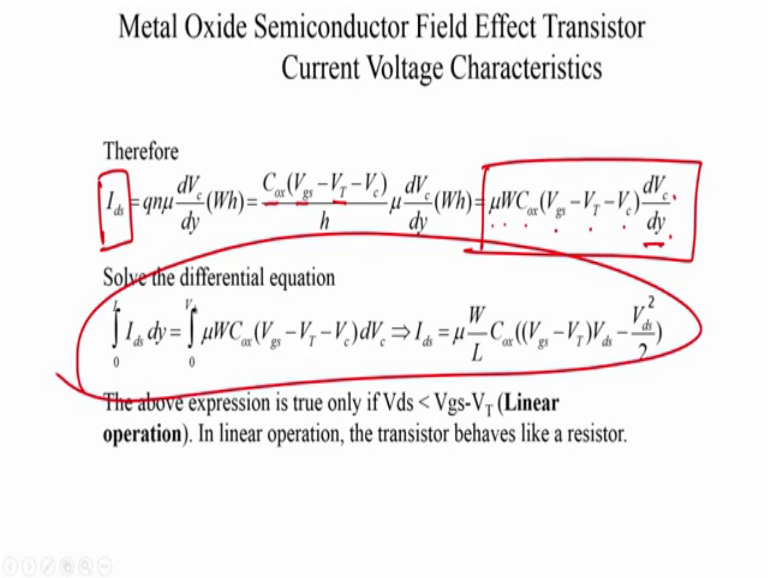

You have I ds is equal to this particular term. So, you have mu WCox V gs minus V t minus V c in a dVc by dVy dy. So, you take dy to the other side and you solve this differential equation. So, you integrate y from 0 to L. This does not is not clear, but this is L. So, as you integrate from 0 to L what are we doing we are moving from the source to the drain and therefore, Vc will vary from 0 to Vds

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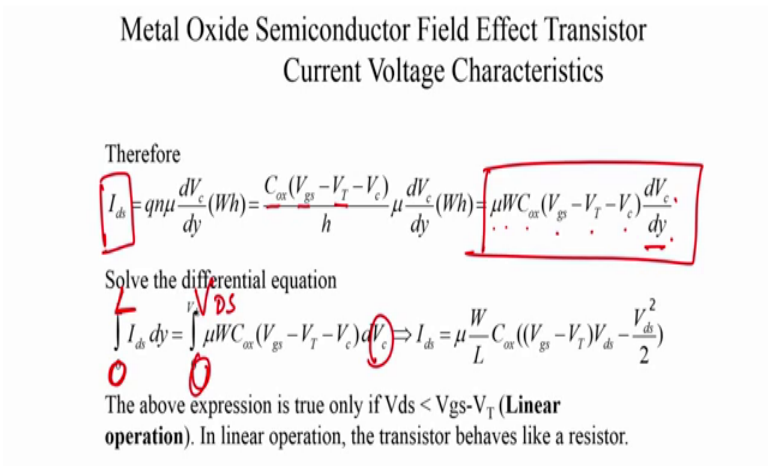

So, if when we did our experiment by moving the voltmeter along the channel we saw that as we moved from the source to the drain L varied x y varied from 0 to L and the channel potential varied from 0 to V ds. So, you apply these limits and solve this equation and you will end up with your current voltage characteristics of the MOSFET ok

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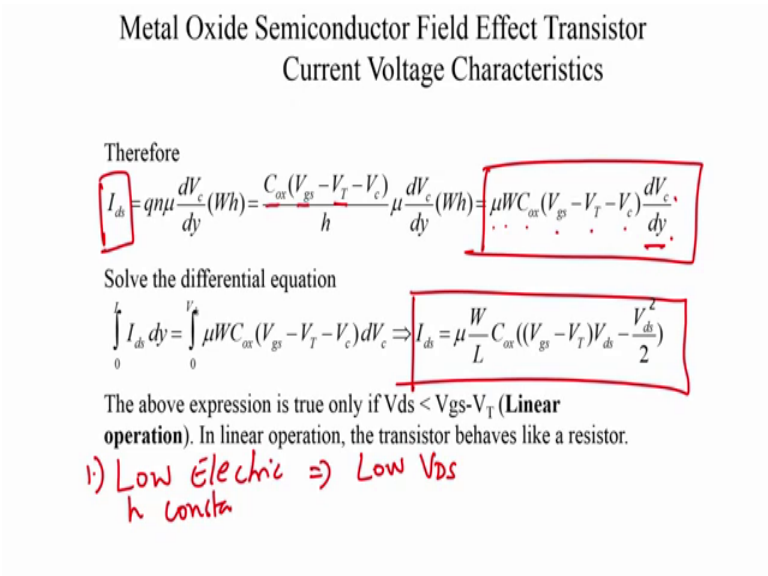

So, that is the derivation of the simplest model for the current voltage characteristics of the MOSFET, but there are problems there are a lot of problems in this ok. So, many assumptions made, many implicit assumptions made. Now what is the first assumption that we have made here? The first assumption is the fact that we have actually used this expression for drift velocity. When is this expression valid? This expression is valid only under low electric fields.

So, that is the first assumption you have assumed low electric fields, which implies low V ds or large L, but I tell you why it implies low V ds in this case. This expression is valid for low V ds because we have made another assumption we have said that this channel thickness remains h throughout from source to drain I mean irrespective of Vc varying a lot ok. Vc is varying from 0 to V ds. We have said that the channel thickness remains h. Normally as we approach as V ds becomes larger and larger as Vc becomes larger and larger, you see qn becomes smaller and smaller ok. So, therefore, this channel should actually taper off as we head towards V ds

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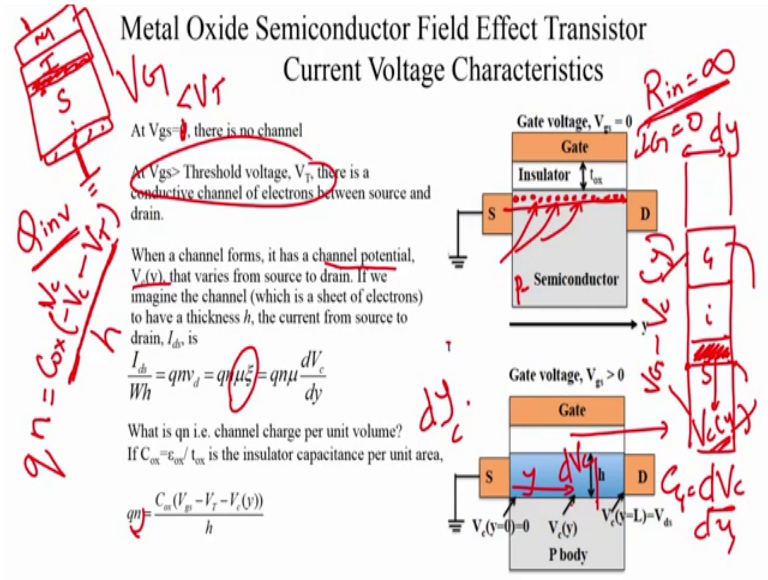

So, we have made this implicit assumption of low Vds and we have assumed we have derived the current voltage characteristics for that condition ok. Now so this region of operation is something called as linear mode of operation ok. So, it is a technical term.

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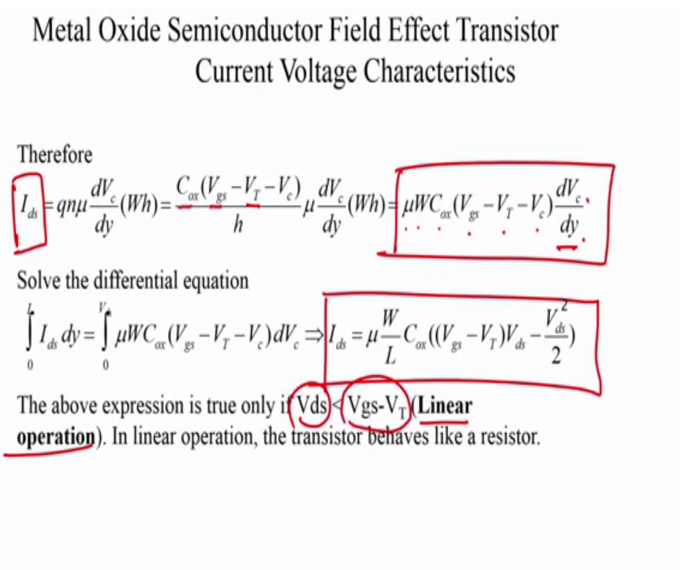

So, when we say the MOSFET is operating in linear mode. What it implies is the V ds is very low and in particular V ds is less than V gs minus V T and I will tell you why.

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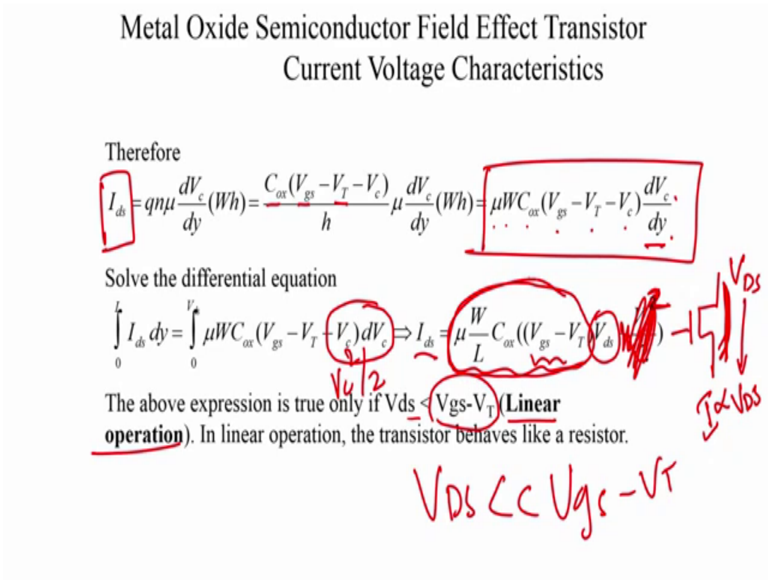

So, why is this, a linear model clearly? This is non-linear right you have a V ds square by 2, but if the V ds is very very small the square compared to V gs is the V ds is much smaller then V gs minus V T then this term can be ignored, and you have only this particular term. So, what you are saying is that you have this device and you have a V ds which is a voltage across this device and you have a current that is more or less proportional to V ds which means that this device despite it being non-linear at low V ds it is behaving like a resistor you see that is the conductance of this resistor. So, you have Ids is equal to the conductance into V ds or inverse of this term is the resistance of the resistor. So, that is why we say, it is the linear mode of operation ok. Now what happens if we start increasing V ds. So, this model is great, but you know it is not really general because we do not know what happens when you start increasing V ds ok.

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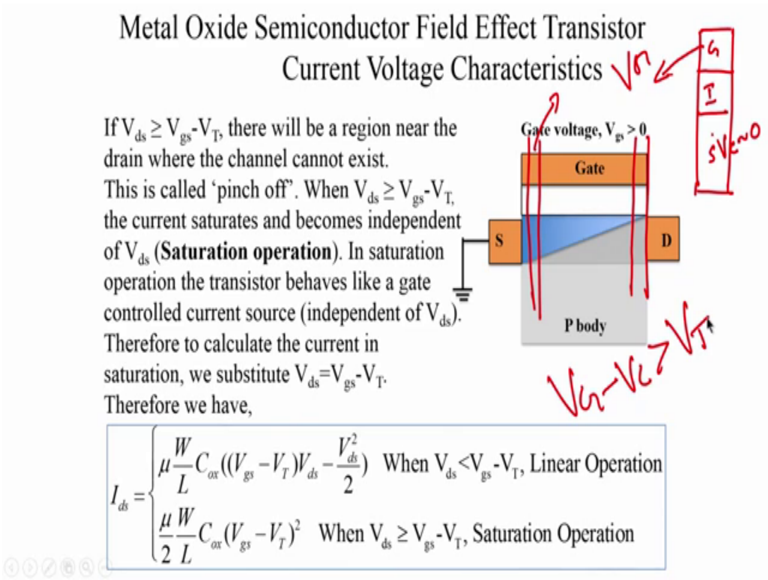

So, when you start increasing V ds the channel or the thickness the so called thickness of the channel will not be constant. My media why is it not constant? So, let us look at two MOS capacitors, let us take a section here and let us take a section here ok. So, let us take so that is that is a very wide section. So, let us take a little thin section here and let us take a thin section here. So, what is the MOS capacitor in this region first? So, that is what we used that is the one we used for all the analysis you have a gate insulator semi conductor. What is the channel potential or what is the potential? Here it is some V c and the V c is approximately 0.

And we know that V g minus V c is greater than V T or in other words let us take let us say V gs V gs minus V c is greater than V T or in other words V gs minus V T is greater than Vc or effectively this gate voltage is strong enough to overcome the channel potential. So, this is large enough and therefore, it is strong enough to pull electrons near the interface, but what happens if my channel potential becomes larger then V gs minus V T.

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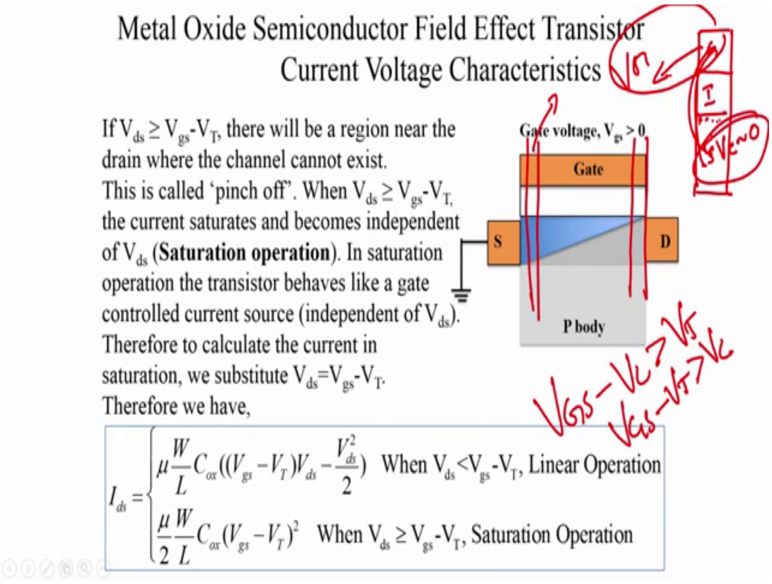

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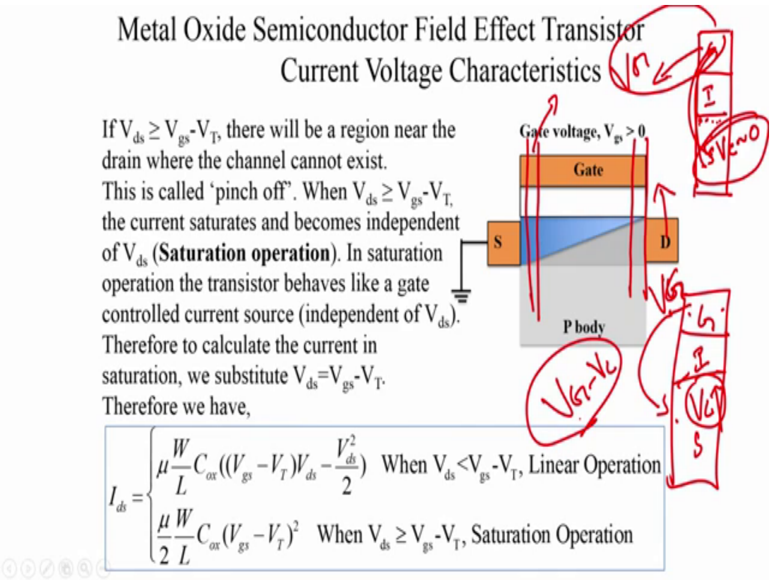

So, let us take a situation where you have gate insulator semiconductor, but the channel potential is very large. Again when can this happen? If this can happen when the V ds is very large the channel potential is very large and now you look at the capacitor you have Vg what is the voltage difference between the gate.

And the semiconductor its V g minus V c now V g minus V c is negative or its in its let us say 0 or in fact, we should be looking at the potential above V T because we have to cross V T to get this.

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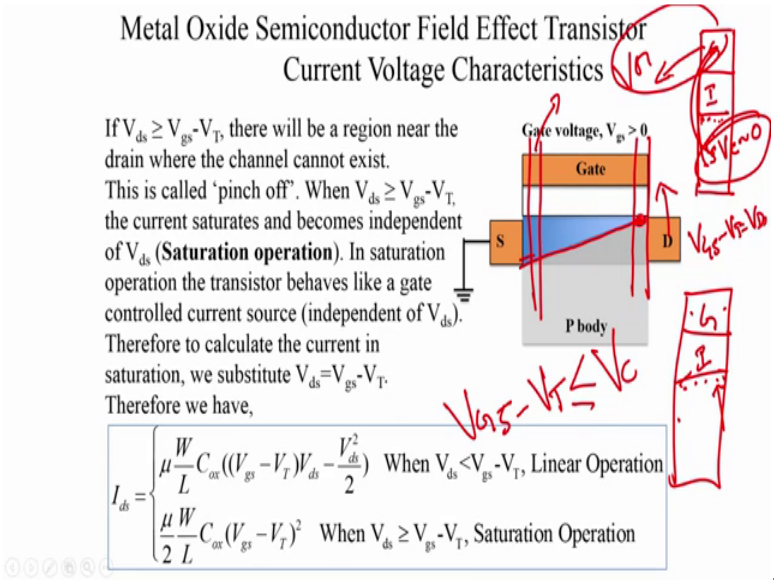

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So, when you have a condition of V gs minus V T being less than the channel potential you cannot have an inversion layer there are no electrons there and therefore, as we start heading towards the drain the channel should actually taper off and the moment V gs becomes V gs minus V T becomes equal to V ds that is when that become when the channel potential heads becomes equal to the channel potentials sorry becomes equal to the channel potential this thing should there should be no more electrons and the channel would simply taper off, it would taper off ok.

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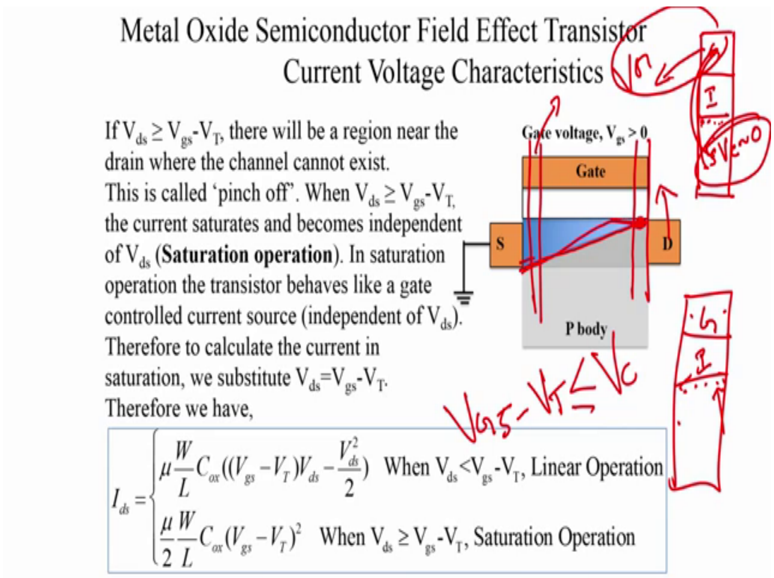

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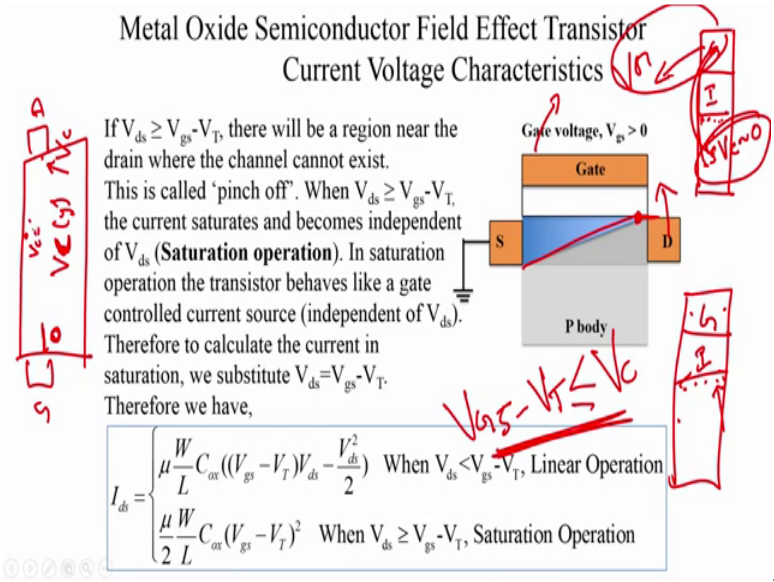

You will not see electrons the anymore and this point where the channel tapers off is called as the pinch off point ok, it is a technical term, it is called pinch off ok. So, I do not know if I was clear enough. So, I am going to repeat this concept. So, the point where so we have a channel you have got a drain, you have got a source and you have got a channel potential that is varying from source to drain. Now the drain voltage is very high, there is a possibility the channel potential is very large particularly near the drain side that is the channel potential is close to 0 near the source side. So, you will have V gs being greater than V gs minus V T being greater than V c near the source side.

So, you will have electrons there, but there will be a point where the V c becomes equal to V gs minus V t.

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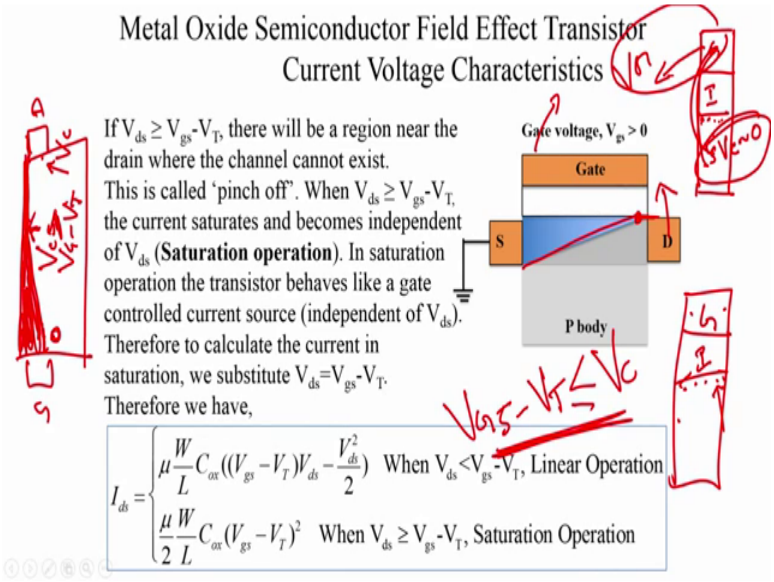

So, let us say that happens at some location where V c becomes equal to V gs minus VT and as you move between that location and the drain the V c is always going to be greater than V gs minus V T. So, throughout that region you cannot have an inversion and the channel is said to be pinched off. So, you have electrons here, but suddenly beyond this pinch off point beyond this point, there are no electrons because inversion has not happened. Now the let us do this experiment its thought experiment, let us say we are running the transistor in linear operation, in linear mode of operation; that means, the V ds was very low.

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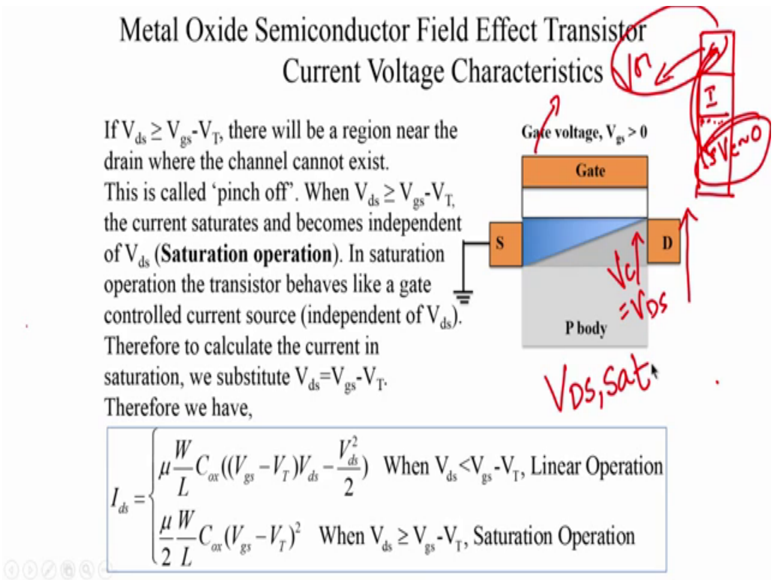

And we now start tweaking up the V ds, we start increasing the drain to source voltage the drain to source voltage at which. So, as you are increase the drain to source the channel potential is increasing. So, let us watch the channel potential near the drain, let us only focus on this section here.

So, this channel potential is increasing as you increase the drain to source voltage. This is in fact equal to V d V ds right. So, the drain voltage at which the channel potential becomes equal to V gs minus V T or you know that particular drain voltage is given a special symbol it is called the V d sat and I will tell you what that is at that particular drain voltage the channel is just pinched off near the drain end ok.

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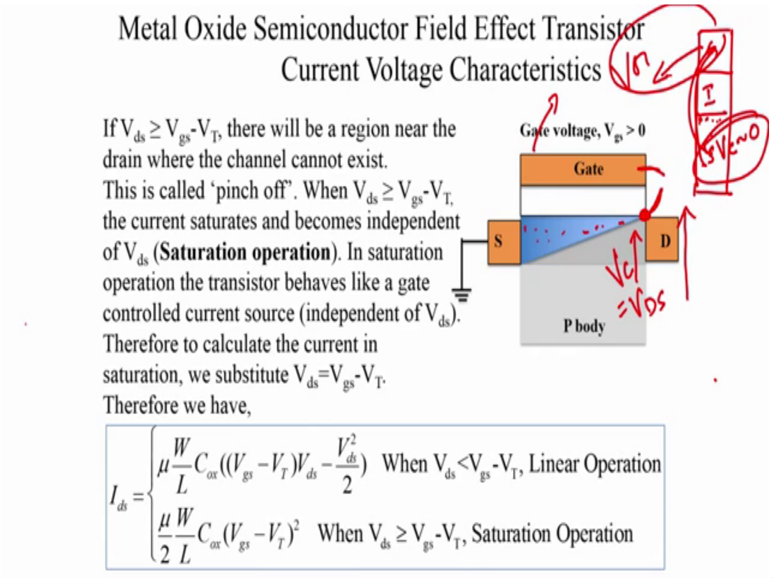

There are electrons every other region is inverted, but just this end near the drain is you do not find electrons because the V g V gs minus V T is now no longer greater than the channel potential. Your V gs minus V T minus channel potential has become equal to 0 and therefore, qn has become equal to 0. So, this end is now pinched off.

And we say that the transistor has entered has gone away from linear mode of operation because now our model is no longer valid. It is going away from linear mode operation and it has entered something called as saturation mode operation.

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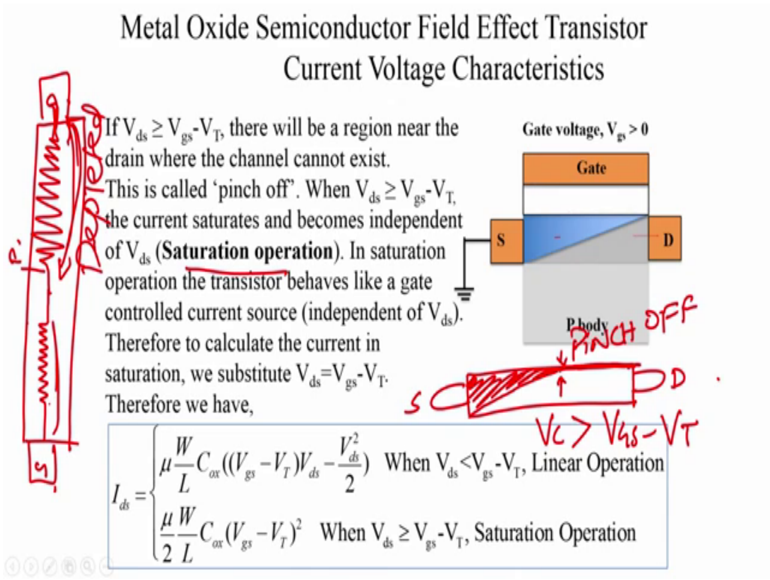

And now if we keep increasing V ds further the transistor we will continue to remain in saturation mode operation. Now in saturation mode operation so what saturates we find that the current through the transistor saturates and I will explain what happens.

So, you have you think of this channel as a resistor this entire region between source and drain as a resistor. So, let us say we have hit the pinch off ok. So, the drain is sitting there, the source is sitting here and there were electrons all the way till this point, but then the channel potential at this point is now greater than V gs minus V T. And therefore, this region is all pinched off, all this is the pinch off point and there is no electrons from here all the way till the drain. So, let us imagine this to be a large resistor between source and drain.

So, how would the resist what would the resistance look like? You have a lot of electrons between from the source to the pinch off point I am sorry I have run out of space there is a lot of explanation here, but there is not much space for me to write anything. So, do bear with me. So, let us say you have this as a resistor you have electrons all the way and then you hit the pinch off point and beyond this you have a large resistor because you do not have an electron channel anymore. So, now, when you have a drain to source voltage, most of the voltage drops across the large resistor in the region that is actually depleted, all those region is not depleted the region is beyond the pinch off point is all depleted right. So, you have a large resistor here and you have a much smaller resistor here. So, you have most of the voltage drop across this region. So, what happens to the electron current? You have a large number of electrons.

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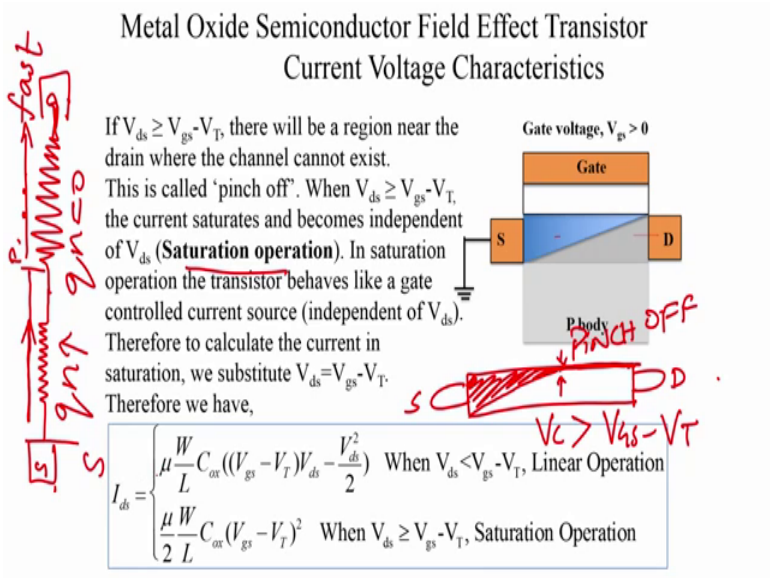

So, qn is good; it is larger and then qn becomes 0 beyond this point. So, you have a large number of electrons, look at the electron traffic, you have a large number of electrons moving at low electric field all the way till the pinch off point and then after that the electric field is very large, but there are not many electrons. So, you have a few electrons that are shooting fast that are racing fast this depleted region that are racing fast this region because of the high electric field. So, you have fast electrons and you have slow, but larger number of electrons ok. So, that is what is going on.

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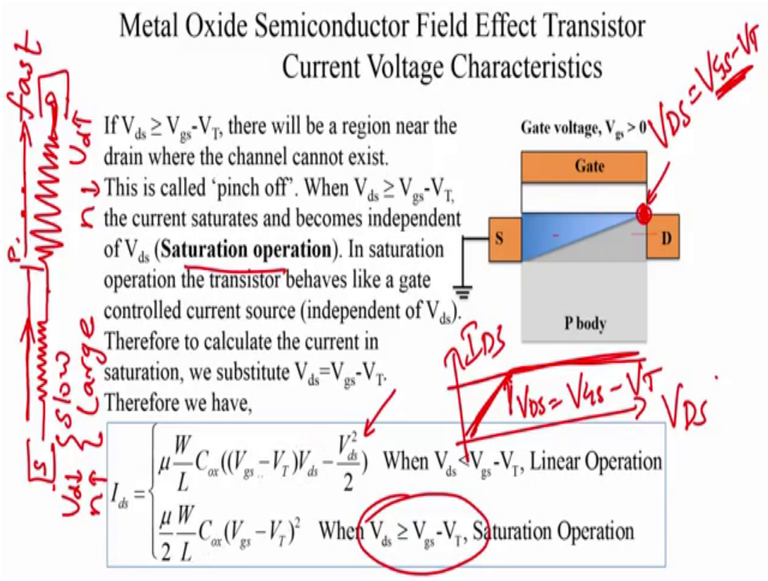

So, you have slow electrons, but a large number of them. So, which means that the entire flux has got low velocity, but large number beyond this the number becomes very small, but the velocity becomes very large. So, never the less the current is maintained, but the current does not increase very significantly if you increase V ds because it is not it is a non-linear device in some sense ok. So, the V ds does not impact current beyond the pinch off operation and therefore, the current has increased all the way in the linear mode in the linear region the current kept increasing, but then after that the V ds stopped impacting the current.

So, we say that the current has saturated, the current is not going to be impact impacted by the V ds anymore and what is the equation for saturation we simply say that the moment this point is pinched off the current is the same as the last value of the linear current ok. So, which is what which is when V ds becomes equal to V gs minus V T, but in other words when the channel potential at this location becomes equal to V ds V gs minus V T then the device current becomes constant it stalls it does not increase anymore with me. So, what we do is we take this equation, which is the linear equation and we substitute it in order to find out what this current is we just substitute we look at the last point on the linear region we substitute V ds is equal to vg minus V gs minus V T and we use that as the current for all values of V ds which are greater than V gs minus V T. So, we just say when V ds is V gs minus V T what happens the current becomes V gs minus V T square by 2.