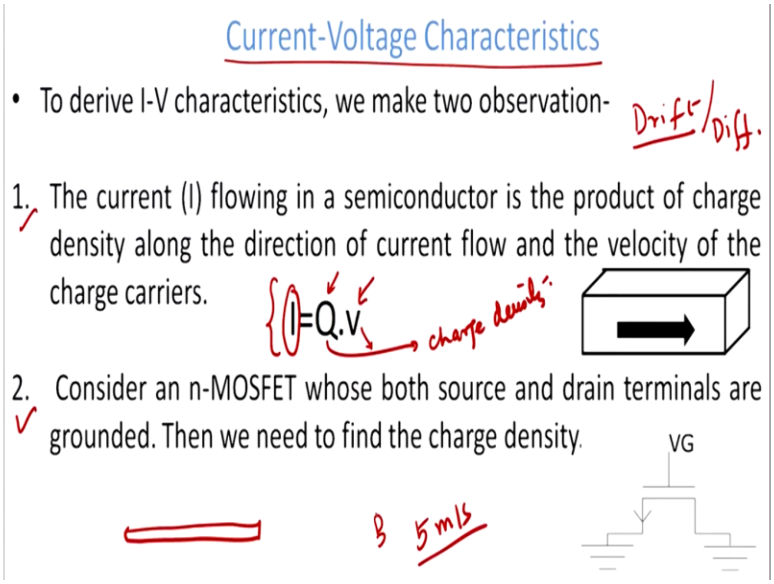
CMOS Digital VLSI Design
Prof. Sudeb Dasgupta
Department of Electronics and Communication Engineering
Indian Institute of Technology – Roorkee

Module No # 01
Lecture-02
MOS TRANSISTER BASICS – II

Okay welcome back we had in our previous session seen the basic building block of the device which is MOSFET this session we will be concentrating on how to find out current versus the voltage characteristics of a devices.

(Refer Slide Time: 00:41)



Current-Voltage Characteristics

- To derive I-V characteristics, we make two observation- Drift/Diff.

1. The current (I) flowing in a semiconductor is the product of charge density along the direction of current flow and the velocity of the charge carriers. $I=Q.V$ charge density

2. Consider an n-MOSFET whose both source and drain terminals are grounded. Then we need to find the charge density.

B 5 m/s

Which is basically current versus voltage that means if you apply a gate voltage source and a drain voltage how can you predict how much of current is flowing through the devices. That is the main motivation for this part of the lecture. We primarily two important derivation or observation and this are observation are underline as 1 and 2 here if you look at the current here which is basically current as I define with you that the current value we have two types of current we has drift as well as diffusion we will be concentrating here on the drift current which is primarily due to the presence of electric field.

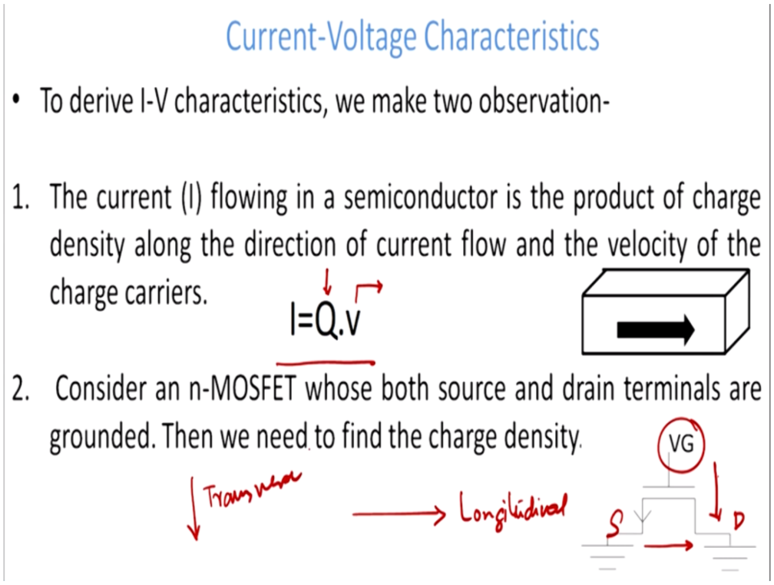
So when you have a electric field electrons and are holes in the electric field they will be having a force attached to it because of which they will be moving a point A to point B then we define the current to be charging flowing per unit area per unit time. With that basic knowledge we derived that current flowing I equal to Q into V where V is the velocity of charge carrier and Q is the charge density.

$$I=Q.v$$

So this is the charge per unit area right this is charge density right which means that if you assume say group of charges which is electrons moving at the rate of 5 meters per second let us suppose 5 meters per second right 5 meter per second then in 1 second if I assume it to be as a block of 5 meter dimension I can safely assume that in 1 second you electrons flowing by 5 meters right.

If you that is the V that is multiplied by Q that is the charge per unit area then you get charge per unit area per unit time and that gives you the value of current. So current gives you the value which therefore all the practical purposes we say current to be equals to Q into velocity V right so that is what we are referring to this case.

(Refer Slide Time: 02:34)



Current-Voltage Characteristics

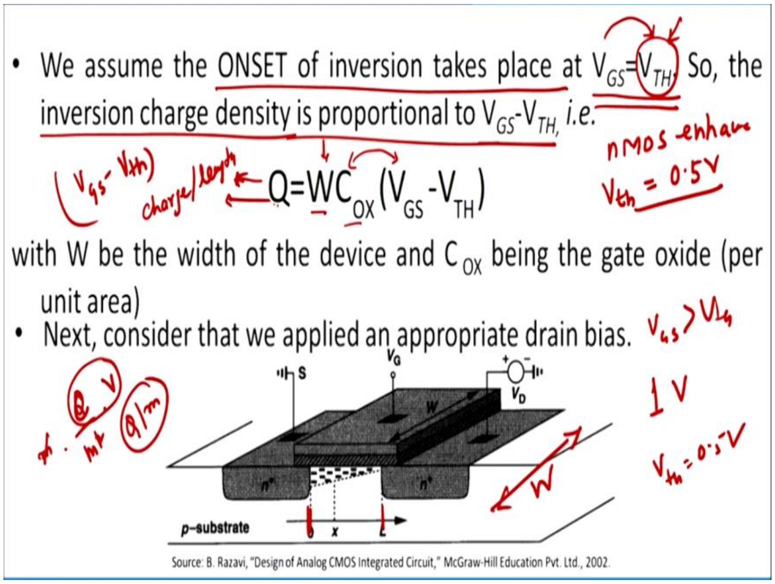
- To derive I-V characteristics, we make two observation-

1. The current (I) flowing in a semiconductor is the product of charge density along the direction of current flow and the velocity of the charge carriers. $I=Q.v$
2. Consider an n-MOSFET whose both source and drain terminals are grounded. Then we need to find the charge density.

So my job is to do what to find out the current charge per unit area and also to find out the velocity of charge carriers. Now what we will do here is we will ground both my source which we generally do ground or source we also ground our drain right. So both the source and drain are grounded so there is no electric field in the longitudinal devices so I will define this to be as longitudinal direction so there is no electric filed in this direction.

But we go on the applied voltage which is VG so there will be a electric filed in transverse direction transverse is this direction so this is my longitude direction and this will be referring to as longitudinal direction. And this is referred to as transverse direction right.

(Refer Slide Time: 03:26)



- We assume the ONSET of inversion takes place at $V_{GS}=V_{TH}$. So, the inversion charge density is proportional to $V_{GS}-V_{TH}$, i.e.

$$\text{charge/length} \leftarrow Q=WC_{OX}(V_{GS}-V_{TH})$$

$(V_{gs}-V_{th})$

with W be the width of the device and C_{OX} being the gate oxide (per unit area)

- Next, consider that we applied an appropriate drain bias.

nMOS enhanc

$V_{th} = 0.5V$

$V_{gs} > V_{th}$

1 V

$V_{th} = 0.5V$

Source: B. Razavi, "Design of Analog CMOS Integrated Circuit," McGraw-Hill Education Pvt. Ltd., 2002.

With this let me see how it works out we just now saw or we just now had a look that the gate voltage at which the channel is formed is defined as my threshold voltage. So if you look at the underline path in this presentation that gate voltage at with the channel is just formed is referred to as threshold voltage right. So we say that the onset of inversion is taking place at which place at that value of gate voltage when it is equal to the threshold voltage of the device.

So typically let us suppose I have a NMOS enhancement mode MOSFET, enhancement mode then I will have a threshold voltage VTH of approximately at equal to 0.5 volts which means that after 0.5 volts only a channel will be formed between source and drain right the problem we have ovhoweverer here is that you will not only give a gate voltage just equals to threshold voltage but you will like to give a gate voltage slightly larger than that right.

And why and how we will see in subsequent slide but if you give gate voltage greater than threshold voltage right out of that extra voltage which is available to you some of it falls on the gate voltage I give some of the example let us suppose the gate value of 1 volt and your threshold voltage gives the 0.5 volt and out of the 1 volt given by the gate 0.5 volt is just utilized to form the the channel right.

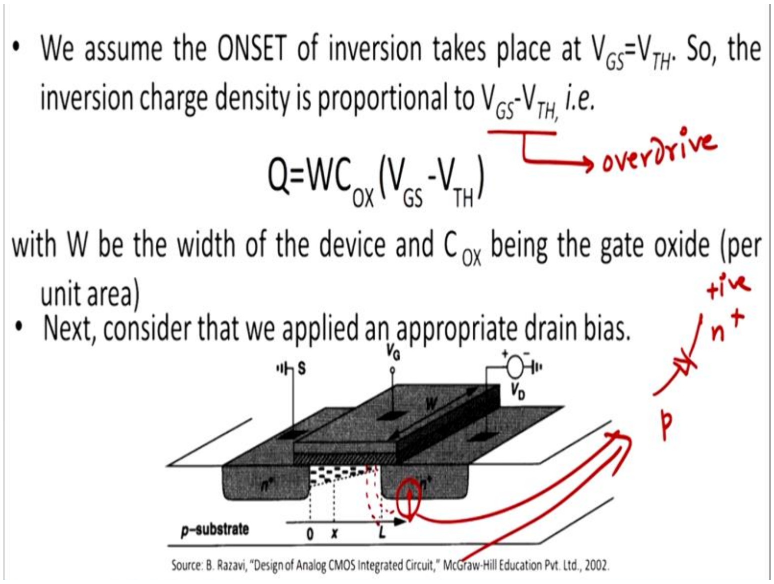
So how much extra voltage is available at the silicon-silicon dioxide as interface it is approximately equals to 0.5. So we define the VGS-VTH right which is this one as the available gate voltage to the channel that means a charge carrier or once the inversion has been formed electrons assuming it to be an N channel enhancement mode MOSFET electrons will actually see a voltage of VGS-VTH and therefore the inversion charge will be actually proportional to this potential right.

Just like in a simple parallel plate capacitor therefore we can define Q that is the charge per unit area right is equal to the charge this is actually charge per unit length this is charge per unit length right is equal to width, width of the device is along this direction. So this is W this is your L between this point and this point so W into Cox C into V Q is equal to CV so this is basically C into V this is charge per unit area so this is charge per unit area right into voltage. What is the W value?

W value is in meters so this meters cancels with meters Q into V equal to Q sorry C into V. C into V is equal to your charge and therefore charge per unit meter is basically the amount of charge which is available to you. So Q equal to this value is basically VGS - VTH.

$$Q=WC_{OX}(V_{GS}-V_{TH})$$

(Refer Slide Time: 06:16)



- We assume the ONSET of inversion takes place at $V_{GS}=V_{TH}$. So, the inversion charge density is proportional to $V_{GS}-V_{TH}$, *i.e.*

$$Q=WC_{OX}(\underbrace{V_{GS}-V_{TH}}_{\text{overdrive}})$$

with W be the width of the device and C_{OX} being the gate oxide (per unit area)

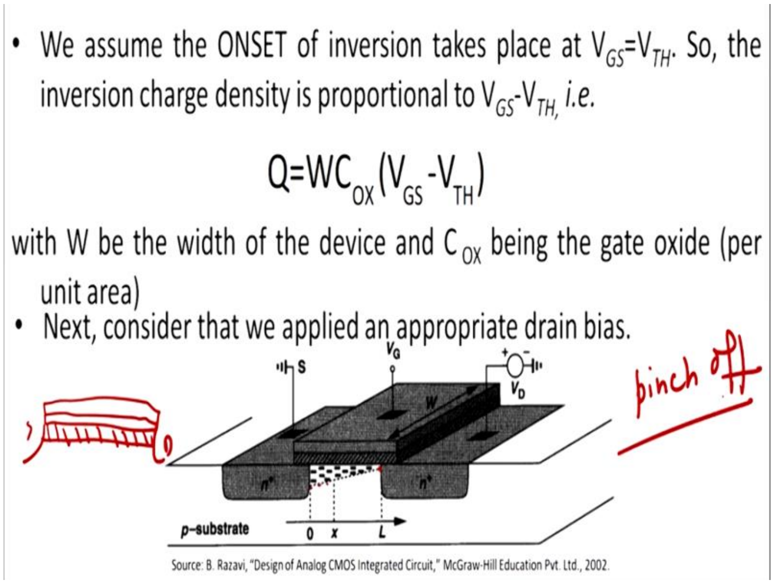
- Next, consider that we applied an appropriate drain bias.

Source: B. Razavi, "Design of Analog CMOS Integrated Circuit," McGraw-Hill Education Pvt. Ltd., 2002.

VGS-VTH is also refer to as over drive right it is also refer to over drive now let us consider that I have a applied voltage now. Now till this much time there is no drain voltage now I apply a drain voltage keeping my source to be equal to grounded and gate voltage of the threshold. So above threshold my channel is already formed. Now when I apply a drain voltage a positive drain voltage.

Please understand this n+p region right can be replaced by a diode which is something like this this is n n+p region this is p region right I can replace this by a diode. So if I apply a positive voltage here I am basically reverse biasing in the diode which effectively means that there will be depletion region on this side which was initially like this for you did not apply a bias now because something like this. So when you applied the gate voltage when you apply a drain voltage which is very high the depletion region starts to eat away into to the channel.

(Refer Slide Time: 07:22)



- We assume the ONSET of inversion takes place at $V_{GS}=V_{TH}$. So, the inversion charge density is proportional to $V_{GS}-V_{TH}$, *i.e.*

$$Q=WC_{OX}(V_{GS}-V_{TH})$$

with W be the width of the device and C_{OX} being the gate oxide (per unit area)

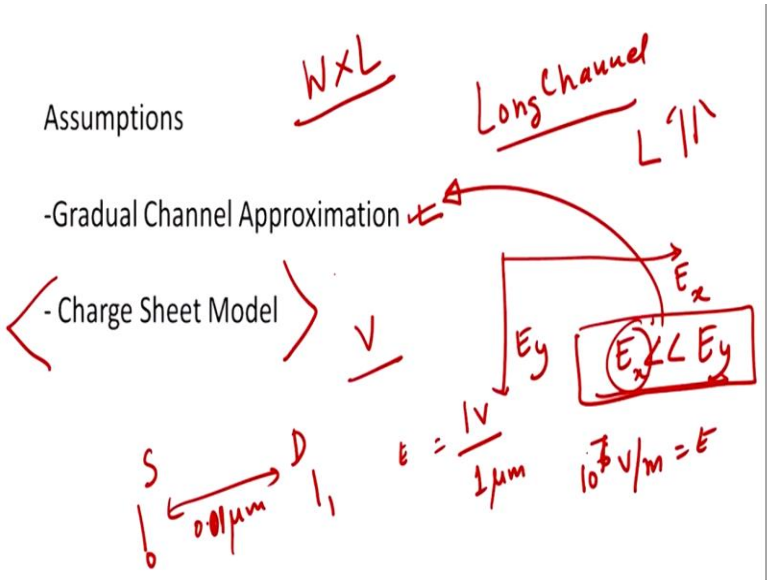
- Next, consider that we applied an appropriate drain bias.

Source: B. Razavi, "Design of Analog CMOS Integrated Circuit," McGraw-Hill Education Pvt. Ltd., 2002.

And therefore so initially what was happening? Initially if you had this as your oxide thickness here and this was your metal layer here and this was source and this was drain right the layer of the inversion layer was perfectly like this it was exactly equal to as you move from source to drain exactly the same because source is grounded drain is grounded this is no potential in this direction and therefore nothing is happening.

Now what has happened since your reverse bias drain to the channel you have actually added a large amount of depletion region near as a drain end and therefore the depletion region eats up the channel this phenomena is referred to as pinch off right. So this the pinch off channel taking place here right.

(Refer Slide Time: 08:08)



Assumptions

-Gradual Channel Approximation

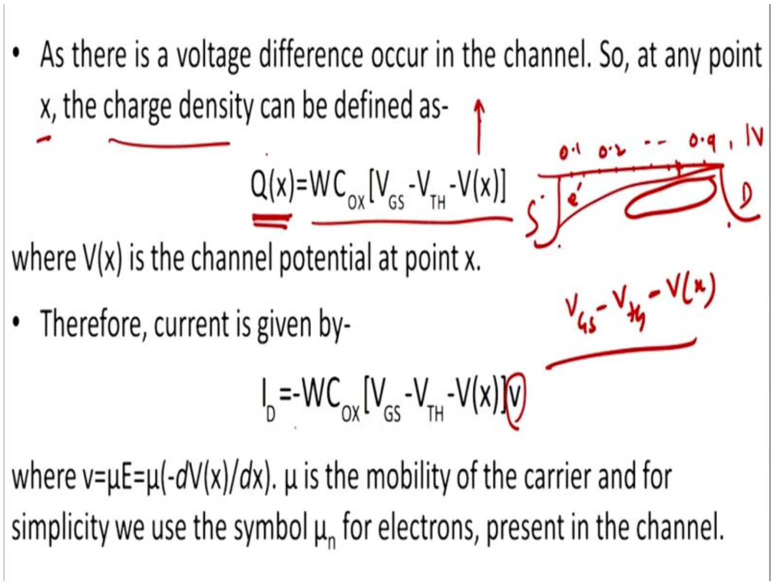
- Charge Sheet Model

What approximation we are taking we will not going into the details of this one. One is the gradual channel approximation which we assume that the longitutal direction electric field. Electric field this is Ex and this Ey, Ex is much smaller as compare to Ey this Ex is much compare to Ey this is known as gradual channel approximation right. Please understand this idea is only will hold for long channel devices when your why long channel devices?

Why because when you L is large right voltage so if this is source and drain and this is grounded and if you apply 1 volt here and say this is 1 micron and then what is electric field? Electric field will be 1 volt divided by 1 micron which is basically 10 to the power 6 volts per meter will be the electric filed. But if you reduce the dimensions and say make it 0.1 microns then this becomes 10 to the power 7 volts per meter which means electric fields start to increase which means this electric fields starts to increase then this gradual channel approximation will not hold good.

So gradual channel approximation are only available or only important for long channel devices. We also assume that this thickness of the charge is almost 0 and this is known as charge sheet approximation or charge sheet model. That means the thickness of the inversion layer is so small as I can consider it to be a single layer or a single thickness, the thickness is very very small right so you will have how many dimensions? one L and you will have one W in this direction right so the area under the gate will be W into L width into length right. All this area will be filled by a thin sheet of electron.

(Refer Slide Time: 09:56)



- As there is a voltage difference occur in the channel. So, at any point x, the charge density can be defined as-

$$Q(x)=WC_{OX}[V_{GS}-V_{TH}-V(x)]$$

where V(x) is the channel potential at point x.

- Therefore, current is given by-

$$I_D=-WC_{OX}[V_{GS}-V_{TH}-V(x)]v$$

where $v=\mu E=\mu(-dV(x)/dx)$. μ is the mobility of the carrier and for simplicity we use the symbol μ_n for electrons, present in the channel.

Now, at any point in the channel now what was my assumption that I have applied a drain voltage here VD right I have applied a source voltage is grounded so I had my pinch of direction right which means that as I move from source to drain in X direction there will be change in potential because this is at the 0 say this is at 0.5 volts and 1 volt let us suppose right. Let us suppose let us suppose I have a drain here I have a source here and this is at 1 volt right and this is what happening here.

Now as I move from source to drain I actually see the voltage going on increasing almost like a potential divider right. So this will have 0.1, this will have 0.2 so on so forth till I reach 0.9 and then 1 volt which means that an electron line here will see 0.7 or 0.8 volts whereas electrons line here will only see only 0.1 volts available to me. And therefore electron at this place will be shifted more in the up and this will be more depletion here will be shifted more towards the bottom.

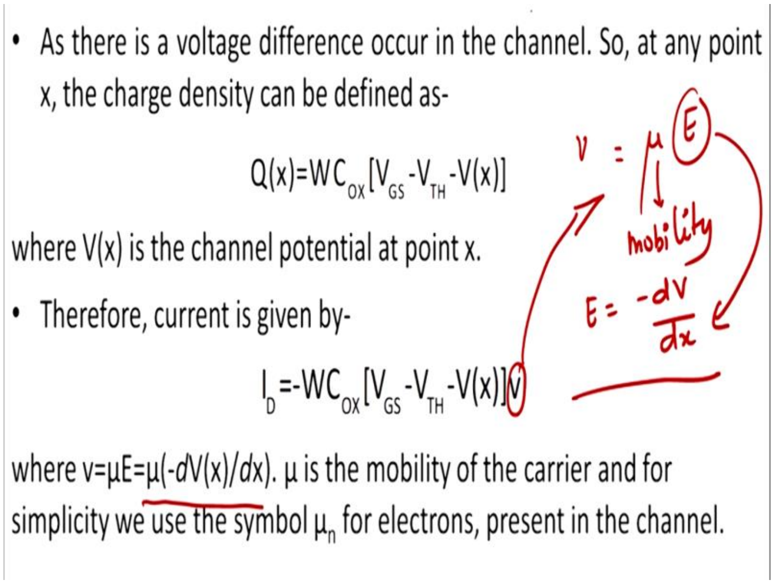
Therefore what we do we say that therefore effective value of charge density at any point X, the charge density will be VGS-VTH is always be there at a substrate how much VX which is nothing but the approximate value of voltage at the particular point Y virtue of the channel potential that will also get subtracted from the VGS-VTH. Here is it okay? Which effectively means that as you move from source to drain this VX will go on increasing which effectively means that QX will go on decreasing.

Which means that as you move from source to drain there will be reduction in the charge density and therefore there will be thinning of the charge sheet inversion layer and then thinning will be taking place from X to Y. Now it is very simple current was equal to this into velocity so what I do? I just multiply the velocity V here and I get the current.

$$I_D=-WC_{OX}[V_{GS}-V_{TH}-V(x)]v$$

Why is the negative sign why because very simple electrons moving in the one direction conventional electrons the conventional current will be flowing in the opposite direction therefore I have the negative sign available with me . Now V by you basic fundamental principal of the semi conductor we know that V which is the velocity of charge carrier.

(Refer Slide Time: 12:12)



- As there is a voltage difference occur in the channel. So, at any point x, the charge density can be defined as-

$$Q(x)=WC_{OX}[V_{GS}-V_{TH}-V(x)]$$

where V(x) is the channel potential at point x.

- Therefore, current is given by-

$$I_D=-WC_{OX}[V_{GS}-V_{TH}-V(x)]v$$

where v=μE=μ(-dV(x)/dx). μ is the mobility of the carrier and for simplicity we use the symbol μ_n for electrons, present in the channel.

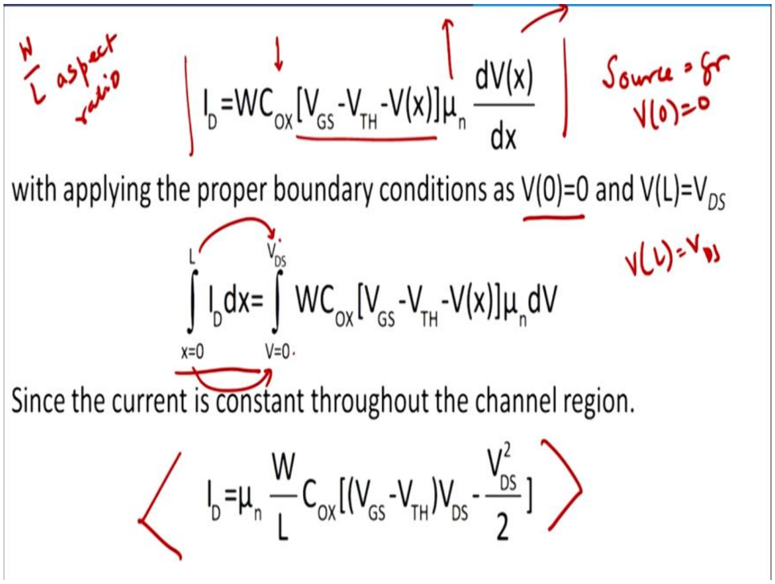
$$v = \underset{\text{mobility}}{\mu} E$$

$$E = \frac{-dV}{dx}$$

V will be given as Miu into E when Miu is defined as a mobility of the charge carrier right mobility of the charge carrier from basic device equations. E is given as – DV by DX right why -DVDX because you see very well that if the voltage is increasing in this direction right is increasing in this direction which means that I have a low voltage on this side and high voltage on this side electrons will be actually moving in the opposite direction why because electrons has been negative sign to it.

Voltage is increasing in this direction but the electrons will be moving in the opposite direction as electric field therefore equals to -DV time DX which is- of DVDX right it is for electrons. Therefore if I therefore this multiple this so if I put this is what I am saying Miu into - DVDX so that minus and minus sign will get cancel out each other I do what I do replace this velocity by what this velocity by Miu into E and this E by-DVDX.

(Refer Slide Time: 13:11)



$\frac{W}{L}$ aspect ratio

$$I_D = WC_{OX}[V_{GS}-V_{TH}-V(x)]\mu_n \frac{dV(x)}{dx}$$

Source = gr
$V(0)=0$

with applying the proper boundary conditions as $V(0)=0$ and $V(L)=V_{DS}$

$V(L)=V_{DS}$

$$\int_{x=0}^{L} I_D dx = \int_{V=0}^{V_{DS}} WC_{OX}[V_{GS}-V_{TH}-V(x)]\mu_n dV$$

Since the current is constant throughout the channel region.

$$I_D = \mu_n \frac{W}{L} C_{OX}\left[(V_{GS}-V_{TH})V_{DS} - \frac{V_{DS}^2}{2}\right]$$

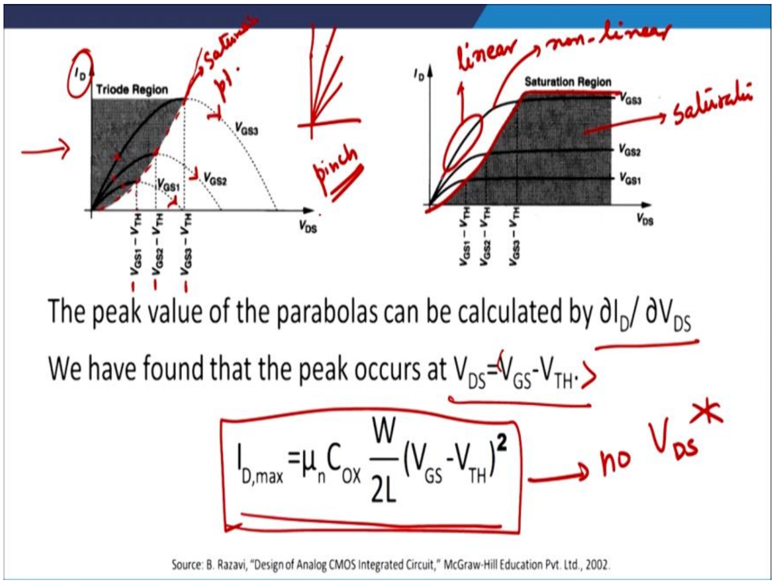
Once I do that I get this final expression for ID with W is width Coxide Cox is the oxide capacitance per unit area this is the effective potential energy this the mobility of charge carrier in this case electronic and this DVDX which is this is nothing but the electric field. Now as you very know you have apply a boundary condition because this is primarily as a differential equation which I need to be solved what are the boundary conditions?

That at that X = 0 as I can assume that source is grounded it is a very valid assumption at this stage but since source is grounded right is grounded I will have obviously V (0) = 0 and my V(L) will be equals to VDS why VL = VDS because of that is the amount of voltage upon the drain side. Just put those values here that means you will have X = 0 to L X = when you integrate from 0 to L you also integrate from 0 to VDS.

So at L the voltage was equals to VDS at X = 0 source side Voltage = 0. Integrate this point assuming that the current is constant obviously the current continuity has to be maintained I get an expression which is something like this quite interesting expression in front of you which is ID = Miu NW / L Cox VG – VTH which is the over drive multiplied by (VDS – VDS square / 2) right. Also please refer to this point that W /L is also referred to as to as aspect ratio of a device right.

$$I_D = \mu_n \frac{W}{L} C_{OX} [(V_{GS} - V_{TH}) V_{DS} - \frac{V_{DS}^2}{2}]$$

(Refer Slide Time: 14:35)



The peak value of the parabolas can be calculated by $\partial I_D / \partial V_{DS}$

We have found that the peak occurs at $V_{DS} = V_{GS} - V_{TH}$.

$$\boxed{I_{D,max} = \mu_n C_{OX} \frac{W}{2L} (V_{GS} - V_{TH})^2}$$

Source: B. Razavi, "Design of Analog CMOS Integrated Circuit," McGraw-Hill Education Pvt. Ltd., 2002.

So I get this expression if I get this expression if I want to plot it what should I plot it if I plot ID versus VD this is this is parabolic equation because it is VDS square and it you plot it this if you see this graph and if you plot between VDS and ID the drain current versus drain to source voltage then I will get a parabolic profile here parabolic because it is VDS square so VDS square will across VDS in parabolic but quite interestingly higher the value of VGS right higher will be value of ID.

So higher the value this is quite interesting higher the value of this VGS higher will be value of ID and that you can see in the next slide but as you increase the this so this is (VGS -VTH1) this VGS 2 – VTH 2 and this is VGS3 – VTH3 which means that threshold voltage is constant of course but I am changing the gate to source voltage from VGS1, VGS2 and VGS 3 once you are doing that your effectively increasing the over drive and therefore the current is also increasing.

So you see for the same value right higher the gate voltage higher will be the current higher voltage higher will be the current higher gate voltage higher will be the current right so on and so forth. This is this is what I get from this expression now if you want to calculate the peak value of parabola then in define I del ID del VDS so what we do this you just differentiate this equation just differentiate this equation and what you get out of it is basically that the peak will occur where at VDS = VGS – VTH.

So please understand very very important property that the peak is the point at which the drain current or the drain to source voltage loses control over the charge carrier flow. I give a explain to you what do I mean by that so the peak occurs where at that values of drain to source voltage at which VGS-VTH that means higher the value of overdrive the higher value will be the pinch off. This point is also referred to a saturation point or even a pinch of point so I got few names that this is the value of voltage at a pinch of voltage will take this saturation will take this and this is basically.

A parabolic profile which you get in front of you right. We discuss that later on but let us see at VDS=VGS - VTH if you replace therefore in this equation in this which equation? In this equation what will you replace? You replace VDS/ VGS -VTH then I end up having this equation available to me and this is the quite interesting that the maximum value of drain current ID max is MiuN Coxide W/L VGS – VTH whole square.

$$I_{D,max}=\mu_n C_{OX}\frac{W}{2L}(V_{GS}-V_{TH})^2$$

Now you can see that if you would have followed this equation even after pinch of point your VDS square / 2 could have exceeded and the value of current would have dropped that is what I showing here the value of current would had dropped why? Because VDS is increasing beyond the particular point VDS square / 2 will increasing will be increasing much faster rate and there will be larger and therefore ID will starts to fall down.

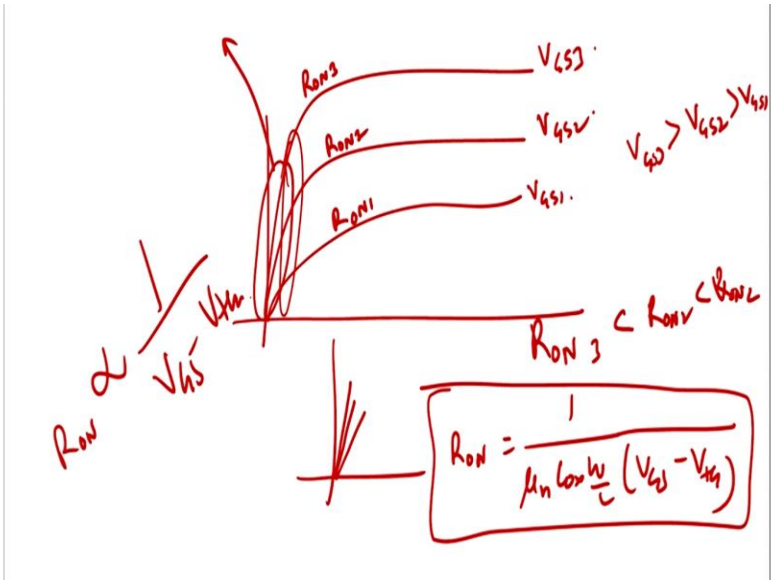
Whereas what actually happens is beyond pinch of there is no VDS term here there is no VDS which means that the drain current is independent of the drain to source voltage and therefore the drain current is constant. So I get a constant drain current available to me and its given by this expression MiuN Coxide W/2L VGS – VTH whole square ok.

$$\mu_n C_{OX} \frac{W}{2L}(V_{GS}-V_{TH})^2$$

This region beyond which your saturation takes place is defined as my saturation region right this is known as saturation region and we will define this to be as the where I versus V voltage is a linear graph we define this to be as linear region right. This is the non-linear will not name it as this stage this is non-linear and this is basically deep triode I will explain this points as we move along right.

I just give a brief insight into two important properties of two important properties here we will discuss on this point later on in much more detail but let me give you a brief idea here before we move forward and see the so this is basically drain voltage versus drain current right. So this is drain voltage versus drain current and this IV characteristics.

(Refer Slide Time: 19:10)



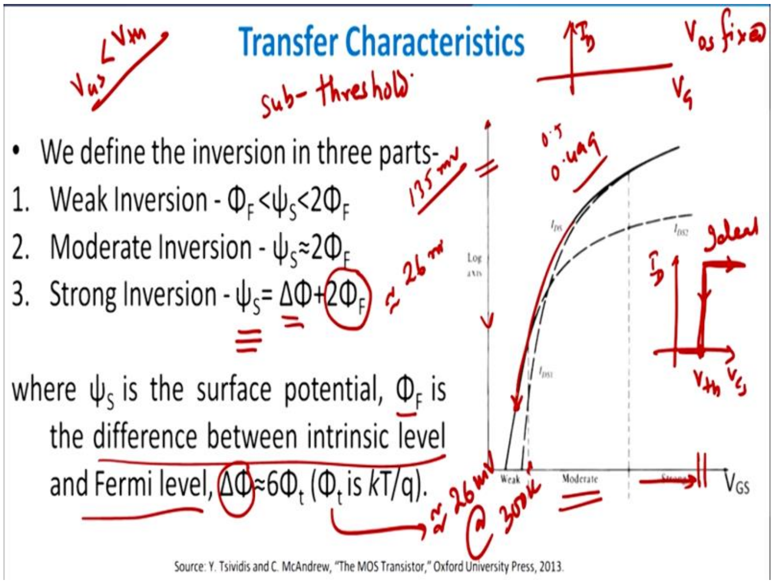
if you go back if as I discuss with you if you look at the slide here and you will see this is how it looks like right how its look like. So this is VGS1, VGS2, VGS3 and VGS3 is greater than VGS2 is greater than VGS1 as can see here so if you just concentrate here then you see VGS3is much more steeper as compared to VGS2 as compare to VGS1 VGS3 will be much more steeper. Steeper means with the small change in VDS, I get a large change in ID which means on resistance offered in much much smaller incase of VD VGS3 as compared to VDS Ron3 will be smaller than Ron2 smaller than Ron1 where at this region.

Where this the linear region of operation so if I bias my devices here by applying proper VDS I can use it as voltage variable resister. I go on changing the voltage of gate to source voltage and I get various Ron values available to me so you can see I can just simply changing the voltage to VGS1, VG2, VG3 by Ron will change right. My Ron will therefore be defined as will be defined **in** in all practical prepossess Ron will be defined as is 1 upon MuN Coxide W /L into VGS – VTH right this is my on resistance.

$$R_{ON}=1/\mu_n \frac{W}{L} C_{OX}(V_{GS}-V_{TH})$$

So you see Ron is therefore inversely proportional to VGS – VTH higher the value of the over drive lower the value of on resistance right. So this is quite interesting observation which you see.

(Refer Slide Time: 20:50)



Transfer Characteristics

- We define the inversion in three parts-

1. Weak Inversion - $\Phi_F < \psi_S < 2\Phi_F$
2. Moderate Inversion - $\psi_S \approx 2\Phi_F$
3. Strong Inversion - $\psi_S = \Delta\Phi + 2\Phi_F$

where ψ_S is the surface potential, Φ_F is the difference between intrinsic level and Fermi level, $\Delta\Phi \approx 6\Phi_t$ (Φ_t is kT/q).

Source: Y. Tsividis and C. McAndrew, "The MOS Transistor," Oxford University Press, 2013.

Let us come to the transfer characteristics just give the brief inside what this is it basically between drain voltage ID verse gate voltage VG keeping fixed VDS. VDS is fixed let us suppose. Then if you plot this is basically a log axis and this is your linear axis you will see that unlike the requirement which I have got which means that at threshold voltage the current should fall to 0.

So if you plot ideally if you plot it I should something like drain current if I plot versus gate voltage then at threshold ideally I should get something like this at threshold the current should go down to 0 and above threshold the current above 0 which is an quite interesting idea that this is the ideal case which I am trying to follow but in reality it will not like that there will be a smooth transition at the threshold voltage.

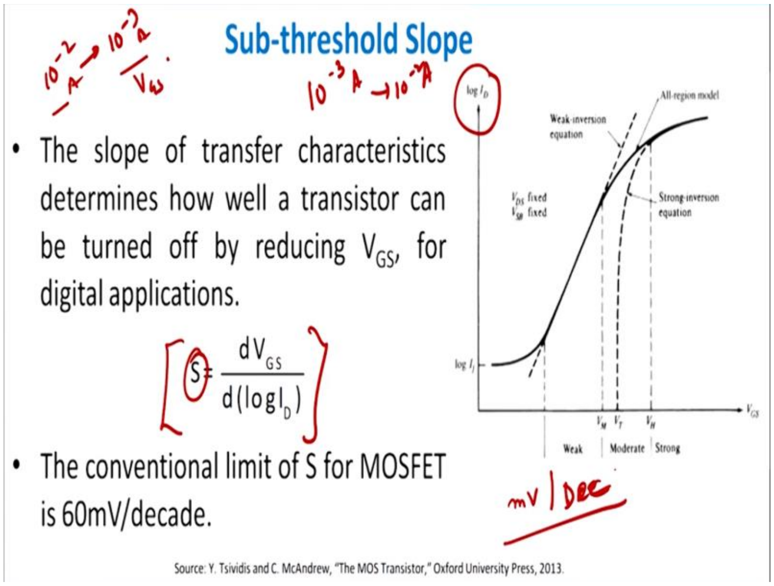
And therefore the devices is said to be ON even when your VGS is less than VTH threshold voltage my understanding till now if you want to switch on the device make VGS less than VTH absolutely true but if you keep it less than VTH suppose your VTH is 0.5 and keep it 0.499 then also as per my previous discussion is should be off. But now what we see is no there is some continuity in the drain current and therefore there will be some flow of charge carrier even at that particular point of time fine and that is known as sub threshold region of operation sub-threshold region of a operation.

And it is given by under the fact that when you strong inversion which is this is surface potential. Surface potential is nothing but at this stage assume it to be channel potential. Whenever channel potential is larger than twice the Fermi potential + the applied voltage we defined as a strong inversion case right and we defined that to be as onset of strong inversion. So you see Sie S is the surface potential Phi MS is the difference between the intrinsic level of the Fermi level.

And we assume that del Phi to be approximately = 6 Phi T Phi T is thermal equivalent voltage available to me so this is the approximately equals to 26 milli volt at 300 Kelvin for all practical purposes. So 6 times of Phi T is approximately 130 to 135 milli volts available. So if you are able to make your device by 135 milli volts higher than the twice Fermi potential 2 Phi F, I will get a strong inversion available to me right at that stage we do it.

So if I move to sub-threshold I will have a very very low current if I move because you can see this is log axis so just so if this is this is your strong inversion this is your moderate inversion and therefore suddenly there is a fall in the current and the current the fall on drastically. So if you want a operate it as switch you have to switch your voltage from above threshold to below threshold but then you have to ensure that it goes well below threshold to actually go into cut off is it okay.

(Refer Slide Time: 23:53)



$10^{-2}A \rightarrow 10^{-3}A$ / Vω.

Sub-threshold Slope

$10^{-3}A \rightarrow 10^{-2}A$

- The slope of transfer characteristics determines how well a transistor can be turned off by reducing V_{GS}, for digital applications.

$$\left[\boxed{S} = \frac{dV_{GS}}{d(\log I_D)} \right]$$

- The conventional limit of S for MOSFET is 60mV/decade.

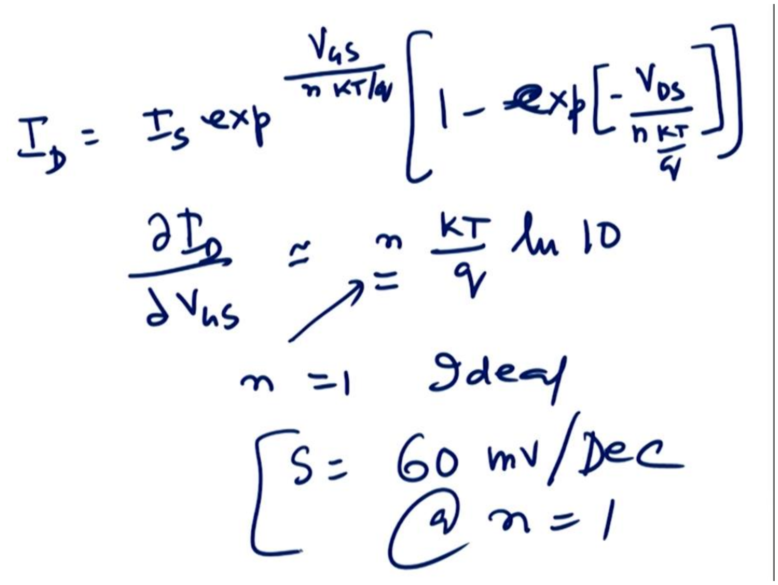
mV | DEC

Source: Y. Tsividis and C. McAndrew, "The MOS Transistor," Oxford University Press, 2013.

We define another important term known as sub-threshold slope and it is defined as the definition is something like this that for the amount of gate voltage required for one a decade drop in the current is defined as a sub-threshold slope. Which means that it is a logscale please understand so this is the one decade drop in the current the amount of gate voltage require to do that so you to what you have to do the voltage is gone below threshold as it just goes to threshold you go just below threshold you lower it to gate voltage and the see as it drops say 10 to the power -3 ampere 2 10 the power -2 ampere.

Let us suppose 10 the power – 2amphre it drops to 10 to the power -3 amperes right as it drops into 2 to the -2 to the power – 3 the amount of gate voltage is require to do such a change is defined as sub-threshold slope and it is referred as to as milli volts per decade dec milli volt per decade. Ideally as I discussed with you the value of the voltage which is given is.

(Refer Slide Time: 24:57)



$$I_D = I_s \exp^{\frac{V_{GS}}{n KT/q}}\left[1 - \exp\left[-\frac{V_{DS}}{n\frac{KT}{q}}\right]\right]$$

$$\frac{\partial I_D}{\partial V_{GS}} \simeq \; \nearrow = \; n\frac{KT}{q}\ln 10$$

$n = 1$ Ideal

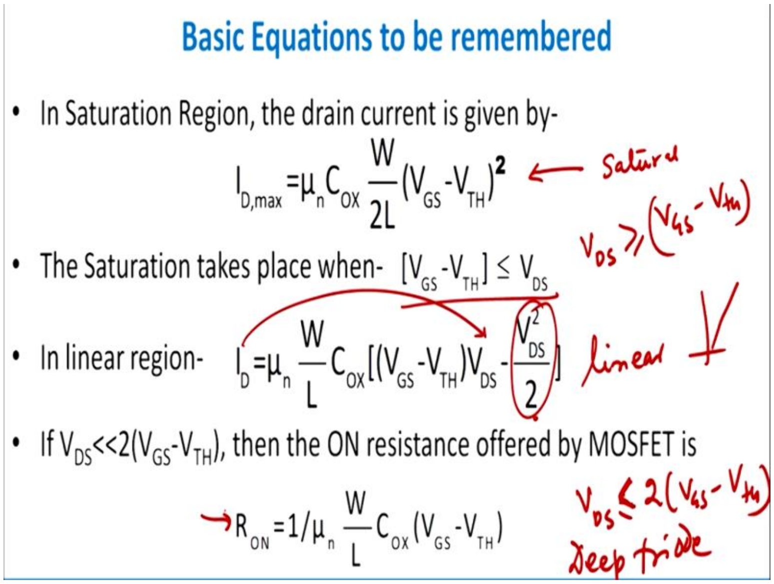
$$\left[\begin{array}{l} S = 60\ mV/Dec \\ @\ n = 1 \end{array}\right.$$

In subs threshold I will go into detail of it but I will I just write down for you I get exponential VGS / N KT / Q right I get 1 – 1 – exponential right exponential – VDS / N KT / Q right and then we close it saying that is 1+ lambda times VDS right you can even remove this point no issues you can what you can do is just remove this point and we will have just the VDS value available here so what you do here is I define IDS = VDS so if you look at the whole issue here or the whole point here the whole point which I have wanted to mention in front of you is that with this idea if you find out del ID/del VGS then approximately you get this a expression.

$$I_D=I_s \exp^{V_{GS}/\eta V_T}\left(1-\exp^{\left(-V_{DS}/\eta V_T\right)}\right)\left(1+\lambda V_{DS}\right)$$

You get N KT / LN of 10 this N varies from 1 to higher value for ideal case N equal to 1 right for ideal case N = 1 when N = 1 I get S to be equals to 60 Milli volt per decade at N= 1 which means that I will require 60 milli volt of gate voltage swing in order to change by current into 1 decade right. So this the whole explanation idea of a sub-threshold design or sub-threshold slope right.

(Refer Slide Time: 26:33)



Basic Equations to be remembered

- In Saturation Region, the drain current is given by-

$$I_{D,max} = \mu_n C_{OX} \frac{W}{2L}(V_{GS}-V_{TH})^2 \leftarrow \text{Saturd}$$

- The Saturation takes place when- $[V_{GS}-V_{TH}] \le V_{DS}$

$V_{DS} \geqslant (V_{GS}-V_{TH})$

- In linear region- $I_D = \mu_n \frac{W}{L} C_{OX}[(V_{GS}-V_{TH})V_{DS} - \boxed{\frac{V_{DS}^2}{2}}]$ linear

- If $V_{DS} << 2(V_{GS}-V_{TH})$, then the ON resistance offered by MOSFET is

$$\rightarrow R_{ON} = 1/\mu_n \frac{W}{L} C_{OX}(V_{GS}-V_{TH})$$

$V_{DS} \leqslant 2(V_{GS}-V_{TH})$

Deep triode

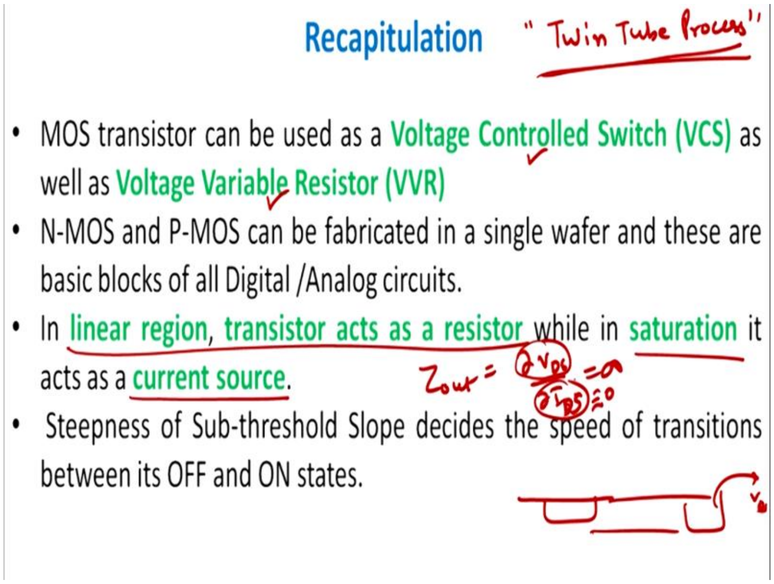
With this we therefore just remembrance for your case we have got ID equation this the ID equation as saturation right we will at the saturation will takes places at this region when VDS is greater than or equal to VGS – VTH. We define it to be as on set of saturation before that it is a linear region where current is a strong function of VDS. So if you see when VDS is small this is very small.

So therefore when this is very small ID is directly proportional to VDS and therefore I have a Omic law so it is straight line which you see when VDS becomes still smaller in fact it is much smaller that this thing it is the equation is VDS is should be less than equals to 2VGS- VTH when this is the quotation the what we define as to be a deep triode region right deep triode region and you will have certain issues available there right.

We will not discuss that at this stage to just to recapitulate and this was Ron value which we discussed in our previous slides to recapitulate let us see what you have seen at least for this one. We have seen that the devices can be working in saturation in linear region the can also in operate in deep triode region for saturation region gate to drain to source should be greater than VGS – VTH at this stage the drain loses control over the charge carrier only the gate voltage place a role.

So if you want to change the ON resistance of a devices just change a over drive voltage automatically get a variable values of a on resistances. We also look it into the linear region that it will following the Ohm’s law and there will be a direct dependency of ID with respect to VDS and the ON resistance will be as I discuss with you inversely proportional to the over drive voltage.

(Refer Slide Time: 28:23)



Recapitulation

" Twin Tube Process"

- MOS transistor can be used as a Voltage Controlled Switch (VCS) as well as Voltage Variable Resistor (VVR)
- N-MOS and P-MOS can be fabricated in a single wafer and these are basic blocks of all Digital /Analog circuits.
- In linear region, transistor acts as a resistor while in saturation it acts as a current source.
- Steepness of Sub-threshold Slope decides the speed of transitions between its OFF and ON states.

$Z_{out} = \frac{\partial V_{DS}}{\partial I_{DS}} = \infty$ $\simeq 0$

With this knowledge let me recapitulate the whole slide show we just now seen basic structure of MOS how a MOSFET work types of MOSFET we also looked into the fact how it works as the voltage control switch. We also look at the voltage variable as a resistor and since they are fabricated in the same chip PMOS and NMOS I require N well process or the twin tub process.

We can actually look into this twin tub process from any of the twin tub process from any other previous NPTEL courses or your books or your standard books and this also methodology by which you can fabricate PMOS and NMOS as i discuss with you linear region, transistor acts as a resistor. While in saturation it works as current source what is the current source?

Fixed current with varying value of VDS so what do I mean to say that mean if I have a MOSFET here I have a MOSFET here right if I go on varying the value of VDS nothing happens current remains constant. So current is the independent of the external applied voltage so ideal current source will have output impedance infinite large which basically means the del VDS del IDS will be infinite will be equals to infinity right and true also right because if you change this VDS value large I will not get no change in the value of ID.

So del ID will be approximately equal to 0 and this will be close to infinity so therefore MOSFET behaves as current source in saturation as a resister in a known in the non-linear region so you also seen what you mean by sub-threshold slope and what you mean by the steepness in sub-threshold slope how you define the sub-threshold slope right then how it is department on the value of threshold voltage with these few words I will just conclude this lecture for you understanding thank you.