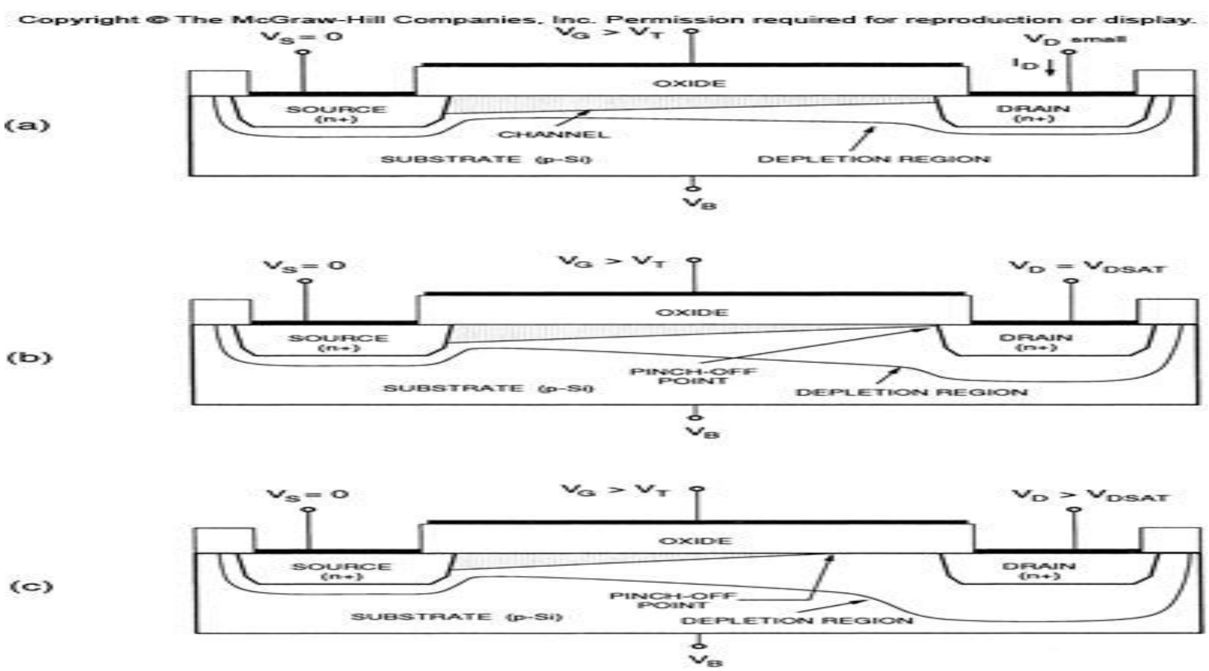
UNIT - 1 **(16 hours)**

MOS transistors: Structures, MOS system under external bias, operation of MOS transistor (MOSFET),
MOS transistors: Threshold voltage MOSFET current-voltage characteristics (GCA), channel length modulation, substrate bias effect.
Measurements of parameters – KN, VTP & γ. Short channel effects, Narrow channel effects. Latch up and its prevention. MOSFET capacitances.

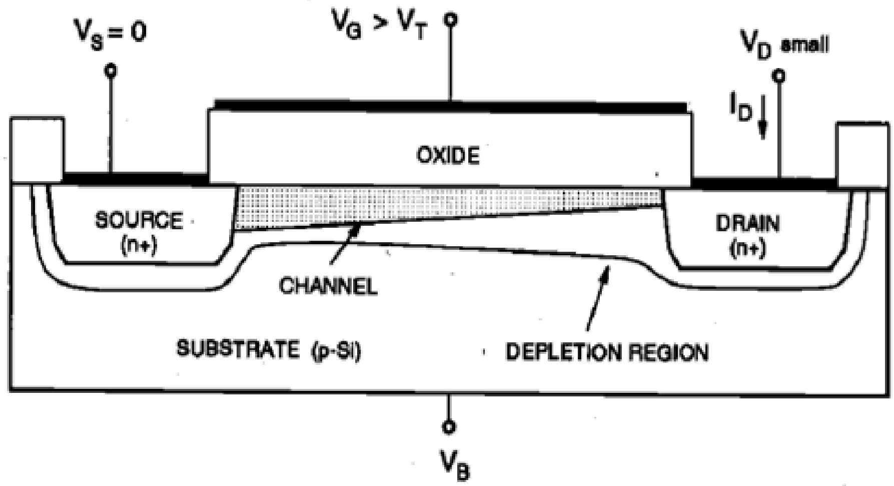
MOSFET Operation: A Qualitative View



Cross-sectional view of an n-channel (nMOS) transistor, (a) operating in the linear region, (b) operating at the edge of saturation, and (c) operating beyond saturation

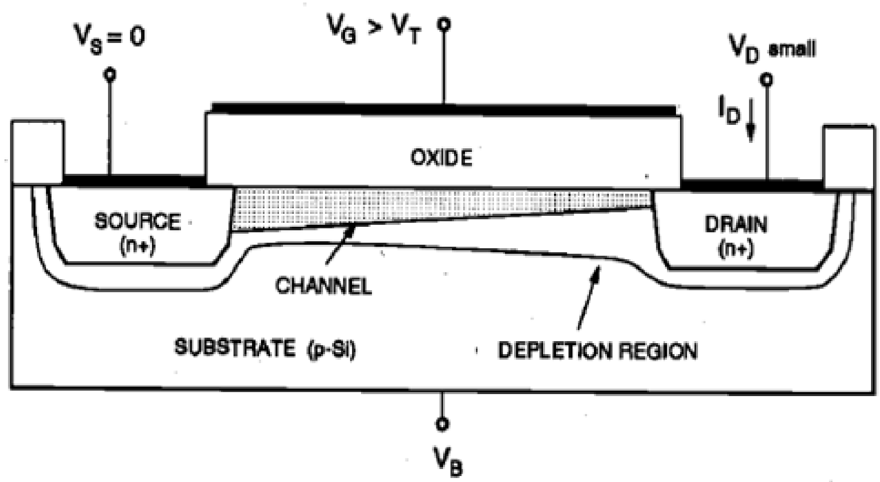
Operating in the linear region

(a)



Cross-sectional view of an n-channel (nMOS) transistor operating in the linear region

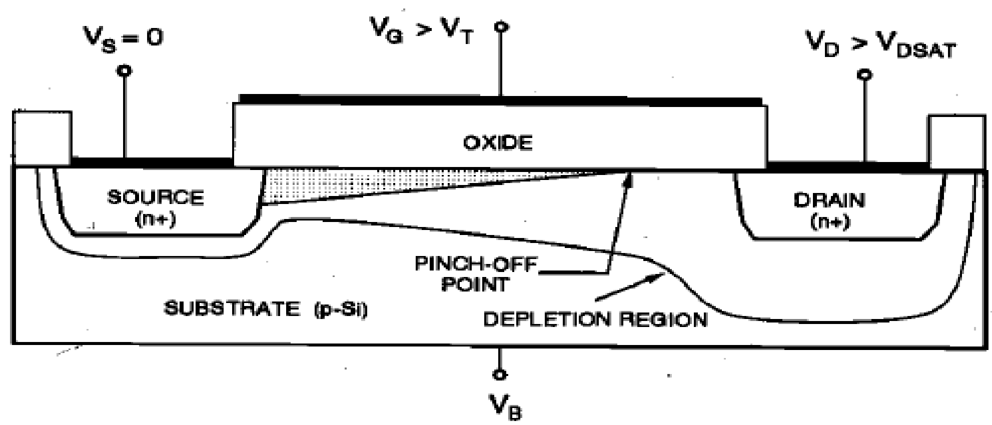
(a)



Cross-sectional view of an n-channel (nMOS) transistor operating in the linear region

N-channel (nMOS) transistor operating beyond saturation

(c)



MOSFET Current-Voltage Characteristics

- The analytical derivation of the MOSFET current-voltage relationships for various bias conditions requires that several approximations be made to simplify the problem.
- Without these simplifying assumptions, analysis of the actual three-dimensional MOS system would become a very complex task and would prevent the derivation of closed form current-voltage equations.
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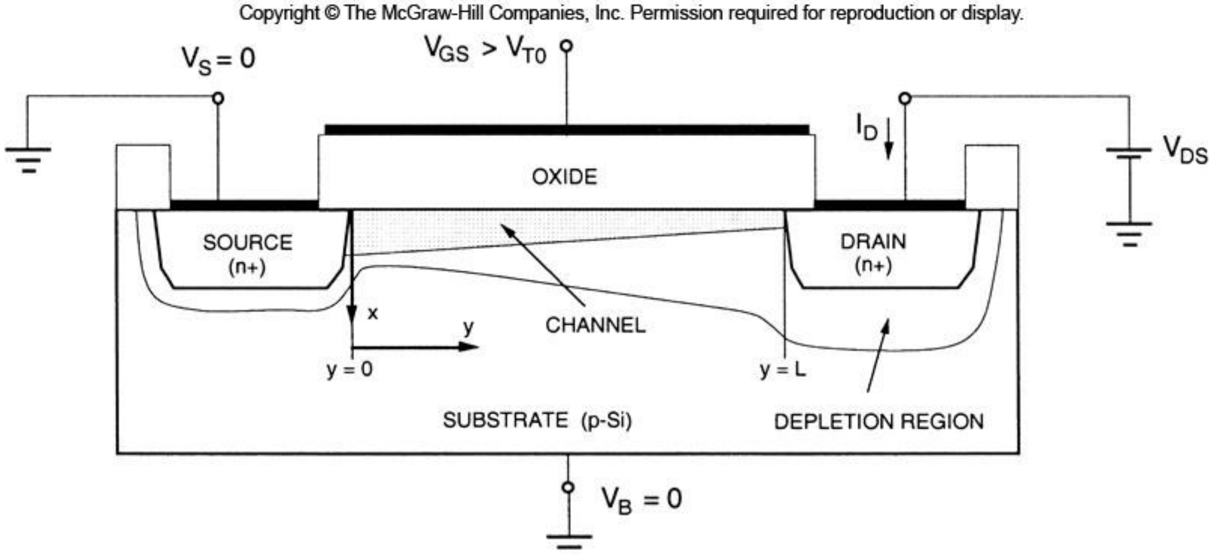


Gradual Channel Approximation(GCA)

- The *gradual channel approximation (GCA) for establishing the MOSFET current-voltage relationships,*effectively reduces the analysis to a one-dimensional current-flow problem.

- As in every approximate approach, however, the GCA also has its

limitations, especially for small-geometry MOSFETs.

1. Consider the cross-sectional view of the n-channel MOSFET operating in the linear mode, as shown in the figure. Here, the source and the substrate terminals are connected to ground, i.e., Vs = *VB = 0.*
2. *The gate-to-source* voltage *(VGS) and the drain-to-source voltage (VDS) are the external parameters controlling* the drain (channel) current *ID.*
3. *The gate-to-source voltage is set to be larger than the* threshold voltage VT0 to create a conducting inversion layer between the source and the drain.
4. The *channel voltage with respect to the source is denoted by Vc(y).*
5. *Assumption: T*he threshold voltage VT0 is constant along the entire channel region, between y = 0 and *y = L.*
6. *(In reality, the threshold voltage changes along the channel since the channel voltage* is not constant)
7. Assumption: The electric field component *Ey along the y-coordinate is dominant compared to the electric field component Ex along the x-coordinate.*
8. *(This* assumption will allow us to reduce the current-flow problem in the channel to the y dimension only)

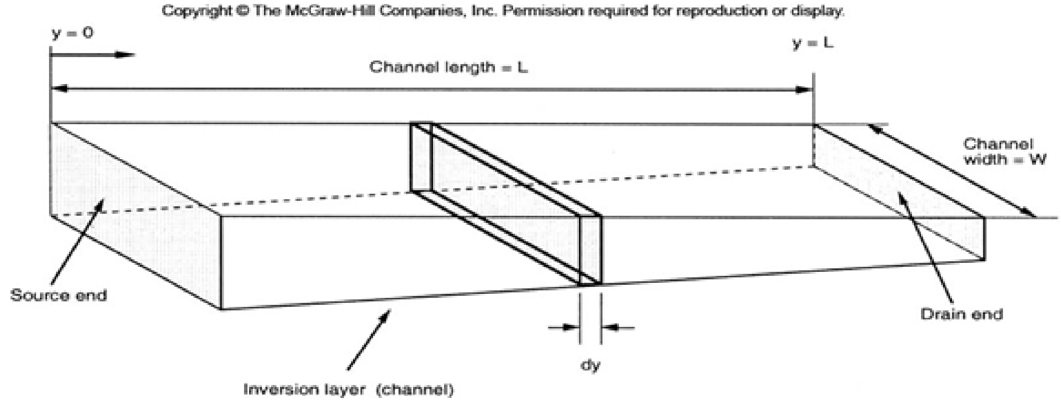
The boundary conditions for the channel voltage Vc are:

$$V_c(y=0) = V_S = 0$$
$$V_c(y=L) = V_{DS}$$

Assumption: The entire channel region between the source and the drain is inverted, i.e.,

$$V_{GS} \geq V_{T0}$$
$$V_{GD} = V_{GS} - V_{DS} \geq V_{T0}$$

➢The thickness of the inversion layer tapers off as we move from the source to the drain, since the gate-to-channel voltage causing surface inversion is smaller at the drain end.



Simplified geometry of the surface inversion layer (channel region)

➢Let $Q_I(y)$ be the total mobile electron charge in the surface inversion layer. This charge can be expressed as a function of the gate-to-source voltage V_{GS} *and of the channel* voltage Vc(y) as follows

$$Q_I(y) = -C_{ox} \cdot \left[V_{GS} - V_c(y) - V_{T0}\right] \qquad (15)$$

The boundary conditions for the channel voltage Vc are:

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$$V_{GS}\geq V_{T0}$$
$$V_{GD}=V_{GS}-V_{DS}\geq V_{T0}$$

The incremental resistance *dR of the differential channel segment can be expressed as*
*(*assuming constant *surface mobility* μ_n *of* all mobile electrons in the inversion layer)

$$dR=-\frac{dy}{W\cdot\mu_n\cdot Q_I(y)} \qquad (16)$$

The minus sign is due to the negative polarity of the inversion layer charge Q_I

$Q_I(y)=qnx_c(y)$ [per unit W - y area; x_c = channel depth at y]

$$\rho=\frac{1}{\sigma}=\frac{1}{q\mu_n n}$$

Applying Ohm's law for this segment yields the voltage drop along the incremental segment *dy, in the y direction.*

$$dV_c=I_D\cdot dR=-\frac{I_D}{W\cdot\mu_n\cdot Q_I(y)}\cdot dy \qquad (17)$$

MOSFET Drain Current Equation(GCA)

The incremental resistance *dR of the differential channel segment can be expressed as*

*(*assuming constant *surface mobility* μ_n *of* all mobile electrons in the inversion layer)

$$dR = -\frac{dy}{W \cdot \mu_n \cdot Q_I(y)} \qquad (16)$$

The minus sign is due to the negative polarity of the inversion layer charge Q_I

$Q_I(y) = qnx_c(y)$ [per unit W - y area; x_c = channel depth at y]

$$\rho = \frac{1}{\sigma} = \frac{1}{q\mu_n n}$$

Applying Ohm's law for this segment yields the voltage drop along the incremental segment *dy, in the y direction.*

$$dV_c = I_D \cdot dR = -\frac{I_D}{W \cdot \mu_n \cdot Q_I(y)} \cdot dy \qquad (17)$$

Integrating along the Channel

$$\int_0^L I_D \cdot dy = -W \cdot \mu_n \int_0^{V_{DS}} Q_I(y) \cdot dV_c \qquad (18)$$

$$I_D \cdot L = W \cdot \mu_n \cdot C_{ox} \int_0^{V_{DS}} \left(V_{GS} - V_c - V_{T0}\right) \cdot dV_c \qquad (19)$$

$$I_D = \frac{\mu_n \cdot C_{ox}}{2} \cdot \frac{W}{L} \cdot \left[2 \cdot \left(V_{GS} - V_{T0}\right) V_{DS} - V_{DS}^2\right] \qquad (20)$$

Integrating along the Channel

$$\int_0^L I_D \cdot dy = -W \cdot \mu_n \int_0^{V_{DS}} Q_I(y) \cdot dV_c \qquad (18)$$

$$I_D \cdot L = W \cdot \mu_n \cdot C_{ox} \int_0^{V_{DS}} \left(V_{GS} - V_c - V_{T0}\right) \cdot dV_c \qquad (19)$$

$$I_D = \frac{\mu_n \cdot C_{ox}}{2} \cdot \frac{W}{L} \cdot \left[2 \cdot \left(V_{GS} - V_{T0}\right) V_{DS} - V_{DS}^2\right] \qquad (20)$$

Equation (20) represents the drain current I_D *as a simple second-order function of the* two external voltages, V_{GS} *and* V_{DS}.

This current equation can also be rewritten as

$$I_D = \frac{k'}{2} \cdot \frac{W}{L} \cdot \left[2 \cdot \left(V_{GS} - V_{T0}\right) V_{DS} - V_{DS}^2\right] \qquad (21)$$

or

$$I_D = \frac{k}{2} \cdot \left[2 \cdot \left(V_{GS} - V_{T0}\right) V_{DS} - V_{DS}^2\right] \qquad (22)$$

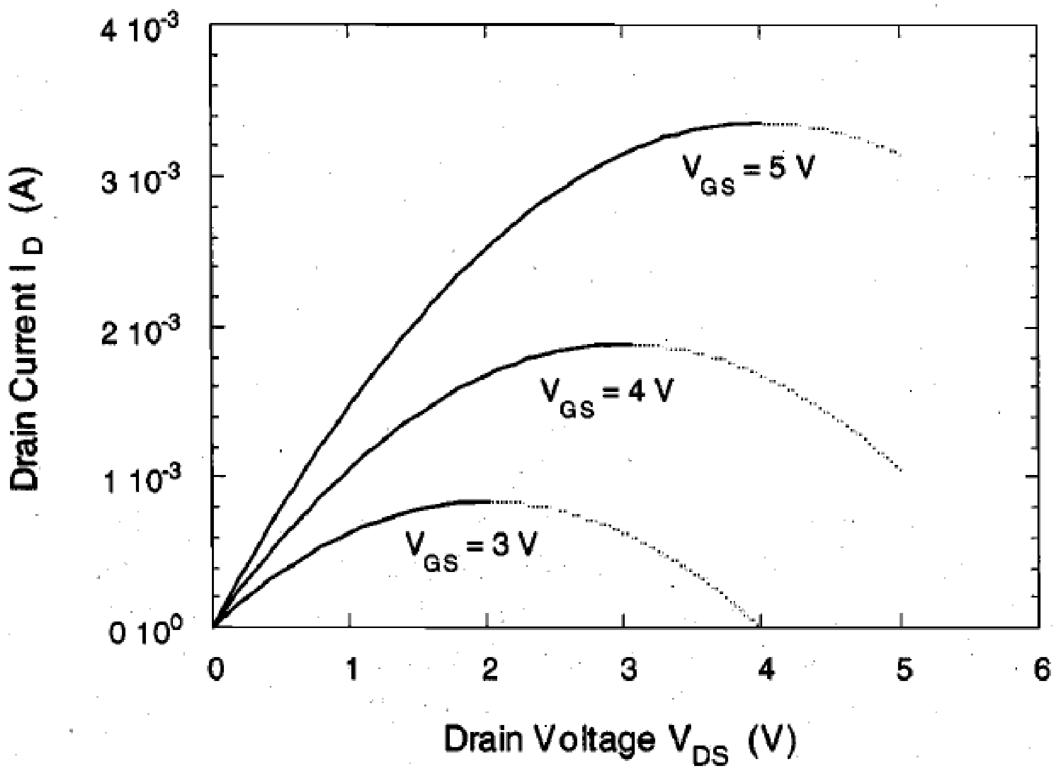
where the parameters *k and k' are defined as*

$k' = \mu_n \cdot C_{ox}$ **process transconductance parameter**

$k = k' \cdot \frac{W}{L}$ gain factor

Current-voltage relationship is affected by to the process dependent constants *k'*, V_{T0}*, and is also affected by the* device dimensions, W and *L*.

Region of Validity of the Equation



The second-order current-voltage equation given above produces a set of inverted parabolas for each constant *VGS value.*

The drain current-drain voltage curves shown above reach their peak value for *VDS = VGS – VT0*

Beyond this maximum, each curve exhibits a negative differential conductance, which is not observed in actual MOSFET current-voltage measurements (section shown by the dashed lines)

Validity of the Equation (Linear Region)

We must remember now that the drain current equation (20) has been derived under the following voltage assumptions,

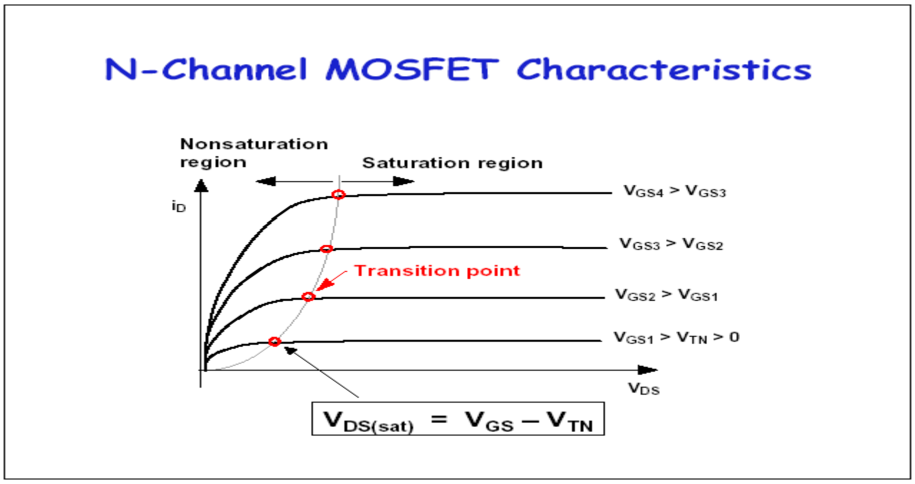
$$V_{GS} \geq V_{T0}$$

$$V_{GD} = V_{GS} - V_{DS} \geq V_{T0}$$

which guarantee that the entire channel region between the source and the drain is inverted.

This condition corresponds to the *linear operating mode for the MOSFET*

Hence, the current equation (20) is valid only for the linear mode operation.



Current Equation for Saturation Region

Beyond the linear region boundary, i.e., for V_{DS} values *larger than V_{GS} - V_{T0}, the MOS transistor is assumed to be in saturation.*

$$Q_I(y=L) = -C_{ox}(V_{GS} - V_{T0} - V_{DSAT}) = 0$$

$$\Rightarrow V_{DSAT} = V_{GS} - V_{T0} \qquad \text{Definition}$$

$$V_{DS} \geq V_{DSAT} = V_{GS} - V_{T0} \qquad \text{Condition for Saturation}$$

When $V_{DS} = V_{DSAT}$

$$I_D(sat) = \frac{\mu_n \cdot C_{ox}}{2} \cdot \frac{W}{L} \cdot \left[2 \cdot (V_{GS} - V_{T0}) \cdot (V_{GS} - V_{T0}) - (V_{GS} - V_{T0})^2\right]$$

$$= \frac{\mu_n \cdot C_{ox}}{2} \cdot \frac{W}{L} \cdot (V_{GS} - V_{T0})^2 \qquad (23)$$

This expression indicates that the saturation drain current has no dependence on V_{DS}