IIT ROORKEE

NPTEL ONLINE CERTIFICATION COURSE

CMOS DIGITAL VLSI DESIGN

MOS TRANSISTOR BASICS - I

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DEPARMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

Outline

- MOSFET as a Switch
- MOSFET Structure
- Types of MOSFET
- Threshold Voltage of MOSFET
- Current-Voltage Characteristics
- Transfer Characteristics and Sub-threshold Slope
- Basic Equations (to be remembered)
- Recapitulation

MOSFET as a Switch

- Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) can be considered as a switch which operates with proper biasing.

- This helps to give many answers itself-

1. **For what value of gate voltage device will turn ON (threshold voltage)?**
2. What is the resistance between source and drain when device is ON (OFF)?
3. What limits the speed of the device?

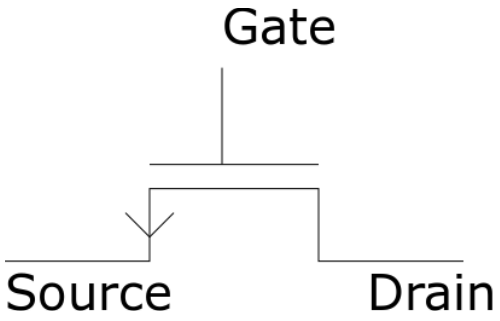
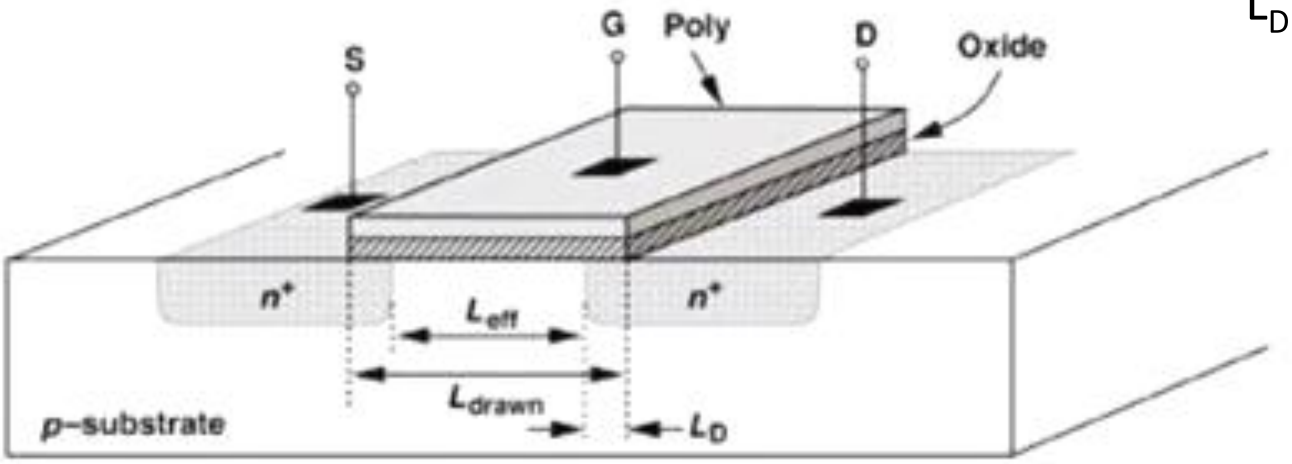


Figure : MOS device Schematic

MOSFET Structure



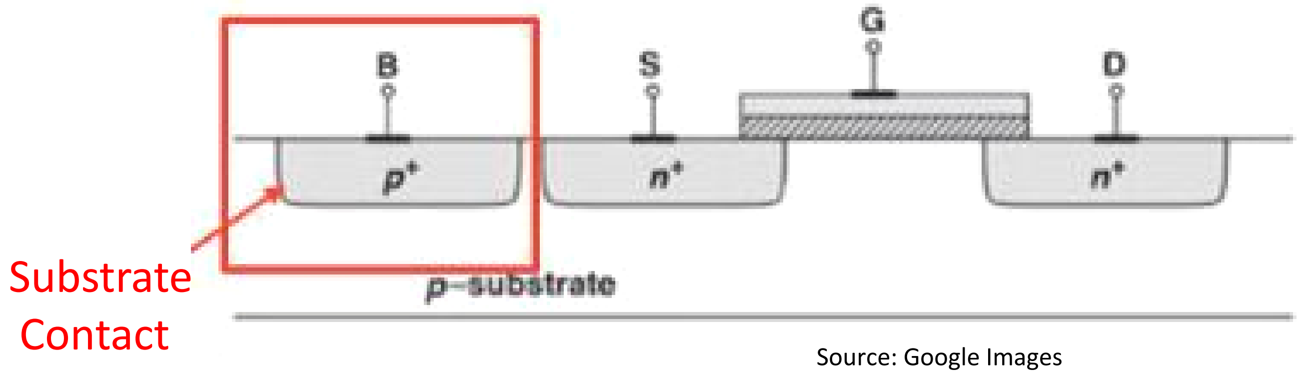
L_D: Side Diffusion Length

$L_{eff} = L_{drawn} - 2L_D$

- If MOS structure is symmetric then why one n-region is called source and another is drain?

Source: Google Images

Body Terminal and MOS symbols



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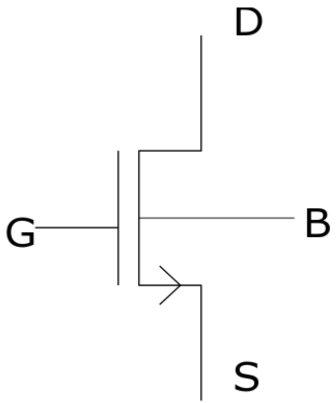
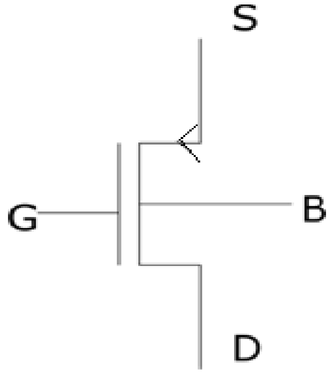


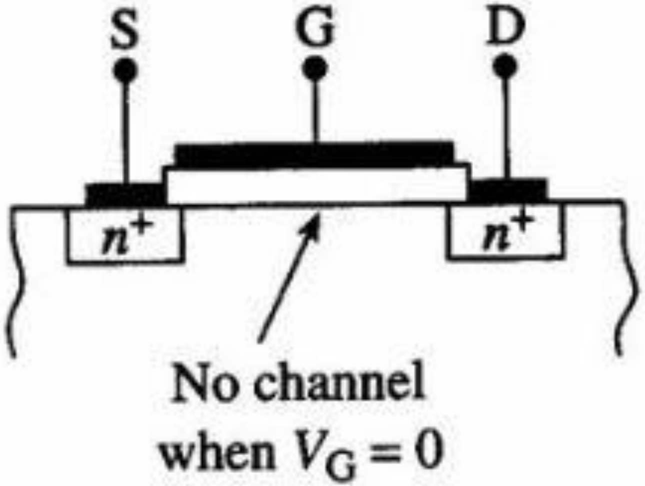
nMOS



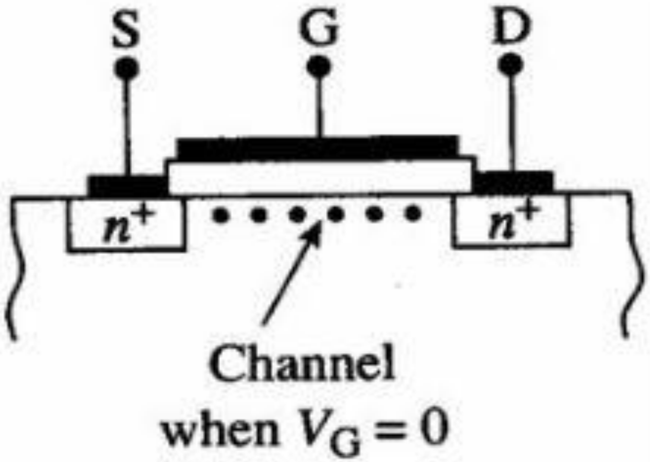
pMOS

- The substrate bias should be connected with the negative most supply of the system.
- nMOS and pMOS are in general made in same wafer, in which one device can placed in local substrate called as well.

Types of MOSFET



Enhancement MOSFET



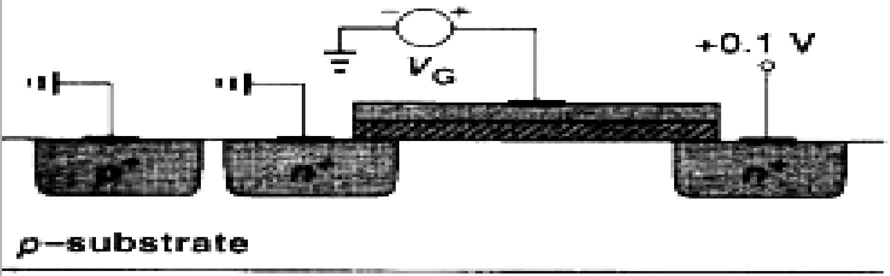
Depletion MOSFET

- Throughout the course we will discuss about Enhancement MOSFET.

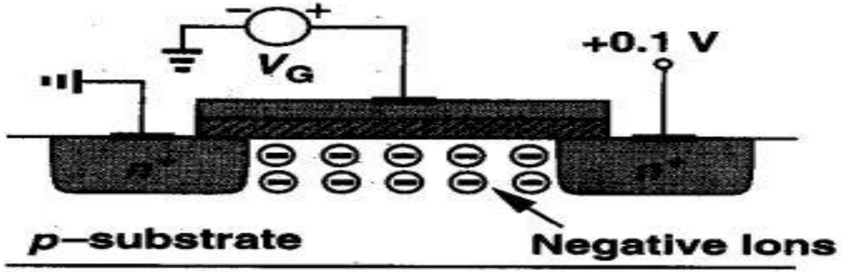
Source: R. F. Pierret, "Semiconductor Device Fundamental," Addison Wesley Longman.

Threshold Voltage of MOSFET

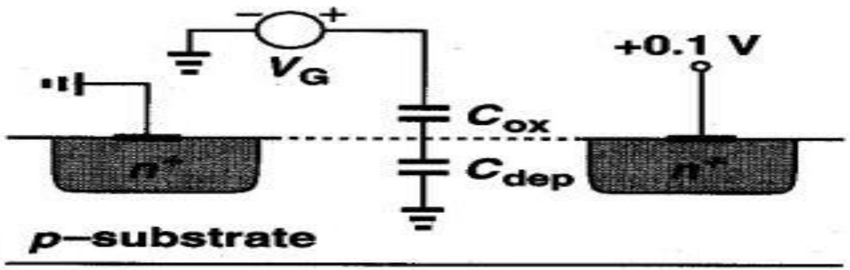
- With keeping constant drain bias, we'll analyze the different modes



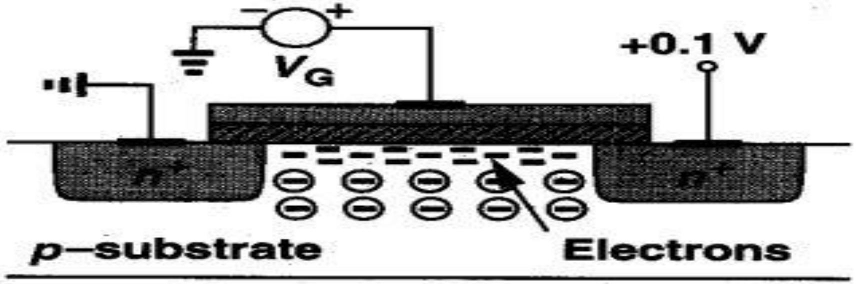
Device under consideration



Formation of Depletion Region



Onset of Inversion Layer



Formation of Inversion Layer

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

- As the gate and substrate forms a capacitor, the applied V_G images a opposite charge on the substrate.
- The increase in V_G increases the drop across gate-oxide and also the width of depletion region. Therefore, depletion capacitance (C_{dep}) and oxide capacitance (C_{ox}) are in series.
- Now, what would be the threshold value?

➢ The value of minimum gate voltage which inverts the surface, and hence an effective channels gets formed.

$$V_{TH} = \Phi_{MS} + 2\Phi_F + \frac{Q_{dep}}{C_{ox}}$$

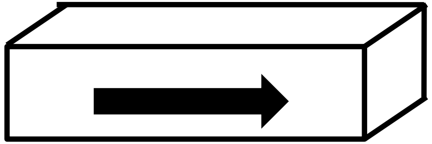
where $\Phi_{MS} = \Phi_M - \Phi_S$ is difference between metal and semiconductor work-functions

Current-Voltage Characteristics

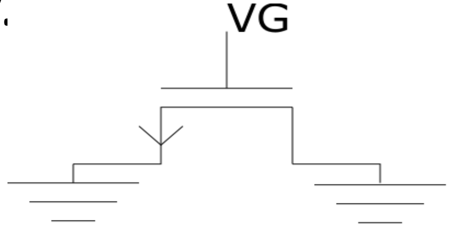
- To derive I-V characteristics, we make two observation-

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.

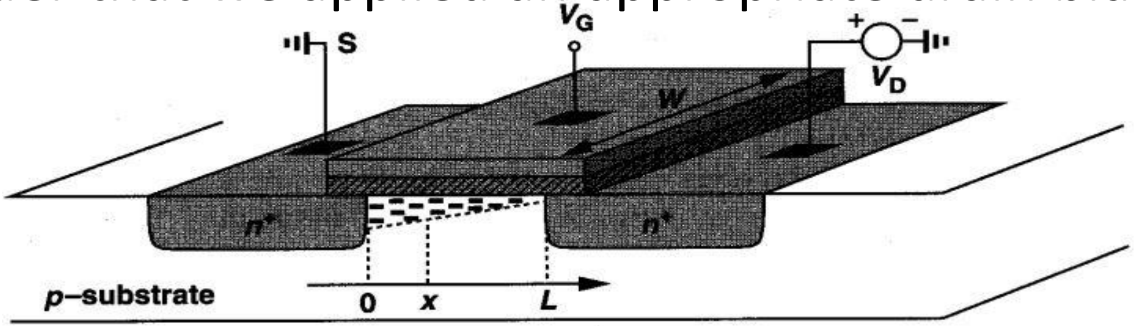


- We assume the ONSET of inversion takes place at $V_{GS}=V_{TH}$. So, the inversion charge density is proportional to $V_{GS}-V_{TH}$, *i.e.*

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

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.

Assumptions

-Gradual Channel Approximation

- Charge Sheet Model

- 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.

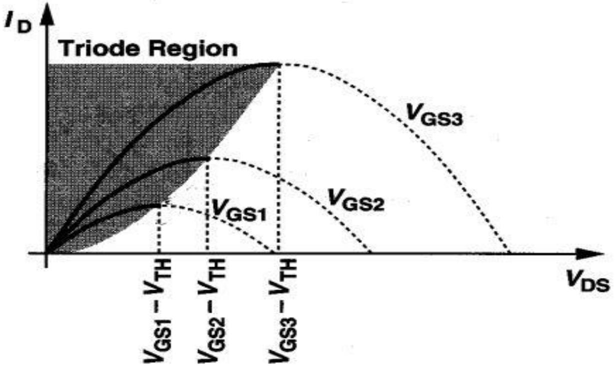
$$I_D = WC_{OX}[V_{GS} - V_{TH} - V(x)]\mu_n \frac{dV(x)}{dx}$$

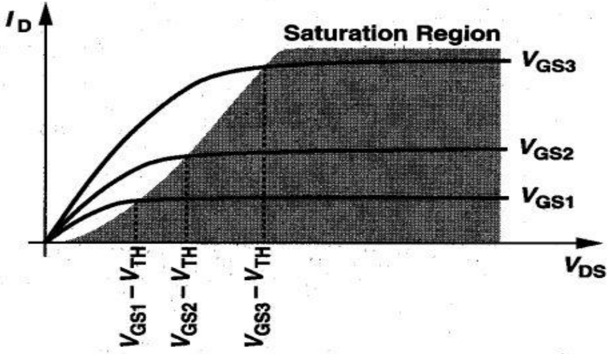
with applying the proper boundary conditions as V(0)=0 and V(L)=V_{DS}

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

Since the current is constant throughout the channel region.

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





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

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

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

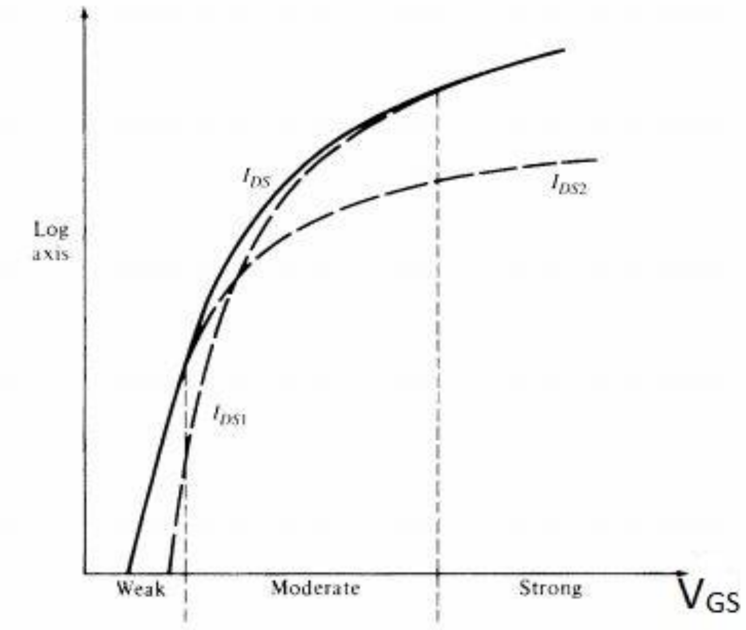
Source: B. Razavi, "Design of Analog CMOS Integrated Circuit," McGraw-Hill Education Pvt. Ltd., 2002.

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).



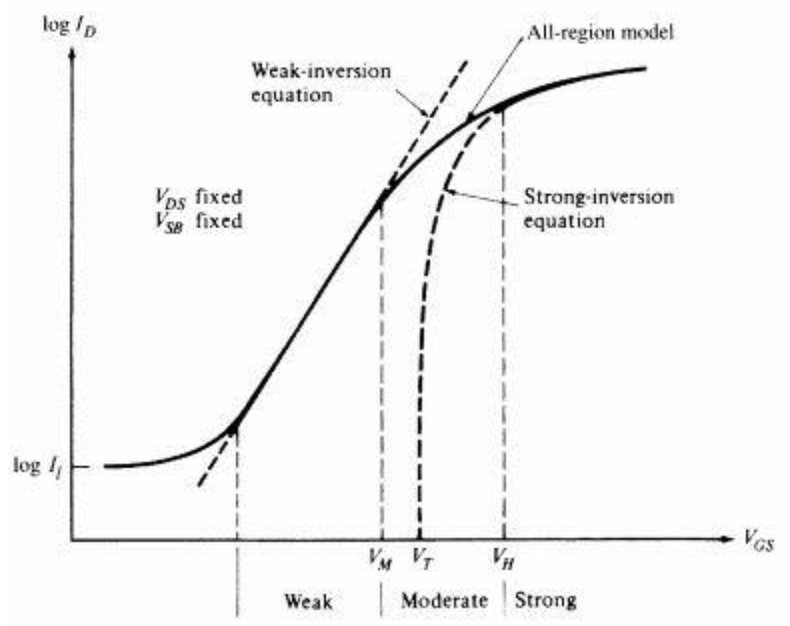
Source: Y. Tsividis and C. McAndrew, "The MOS Transistor," Oxford University Press, 2013.

Sub-threshold Slope

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

$$S = \frac{dV_{GS}}{d(\log I_D)}$$

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



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

Basic Equations to be remembered

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

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

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

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

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

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

Recapitulation

- 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.

Thank You