MOSFET

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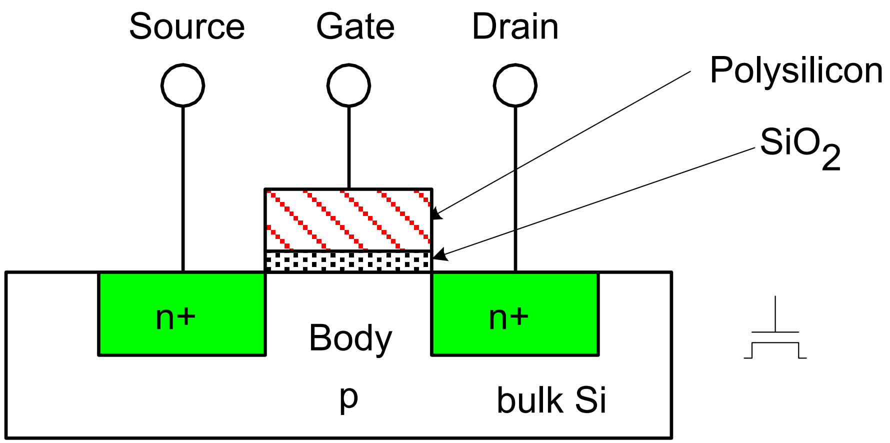
Outline

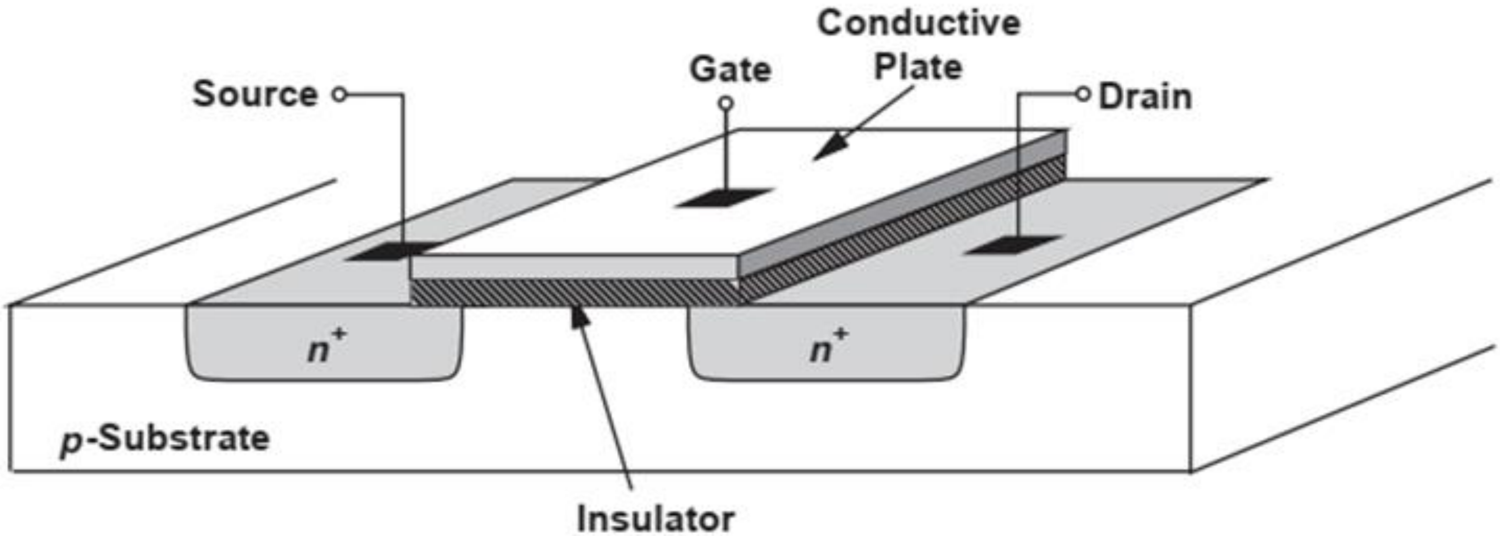
- MOSFET Basics
- MOSFET Operations
- MOSFET Characteristics
- Types of MOSFETs

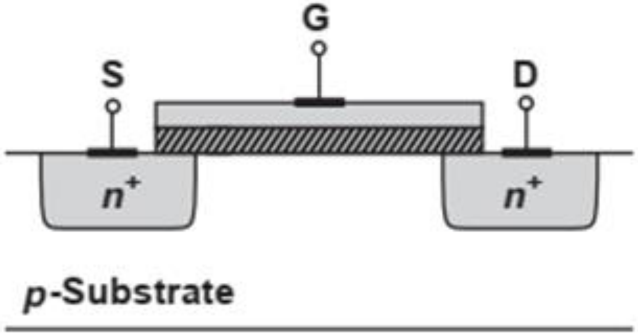
nMOS Transistor

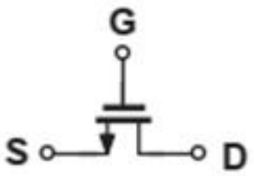
- Four terminals: gate, source, drain, body
- Gate – oxide – body stack looks like a capacitor
  - Gate and body are conductors
  - SiO2 (oxide) is a very good insulator
  - Called metal – oxide – semiconductor (MOS) capacitor
  - Even though gate is no longer made of metal



MOSFET Structure

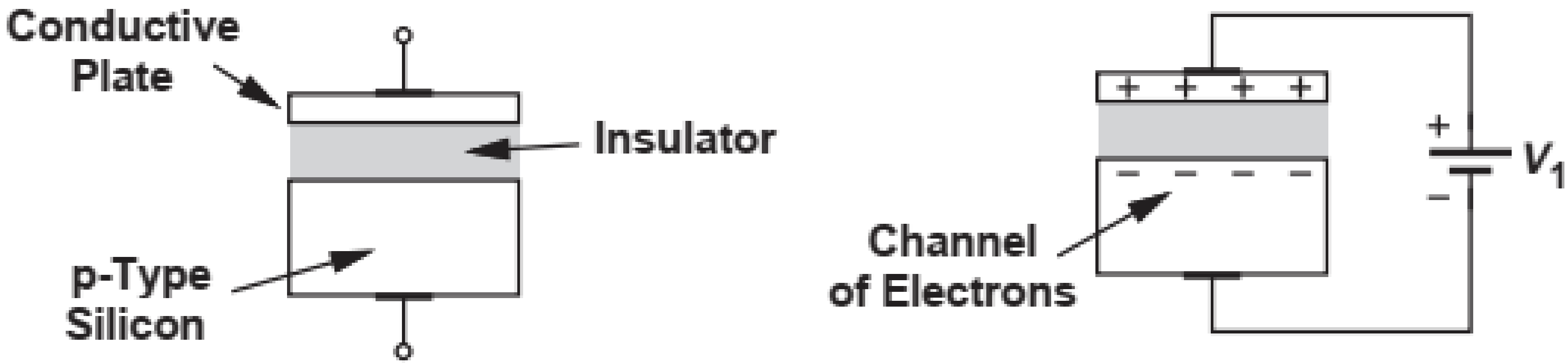






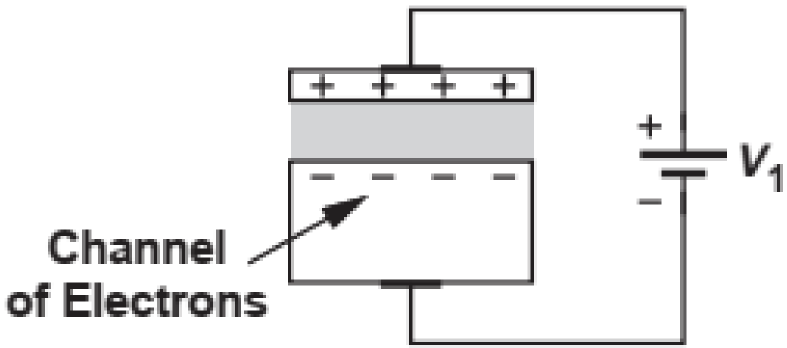
Side view and circuit symbol

MOSFET Working

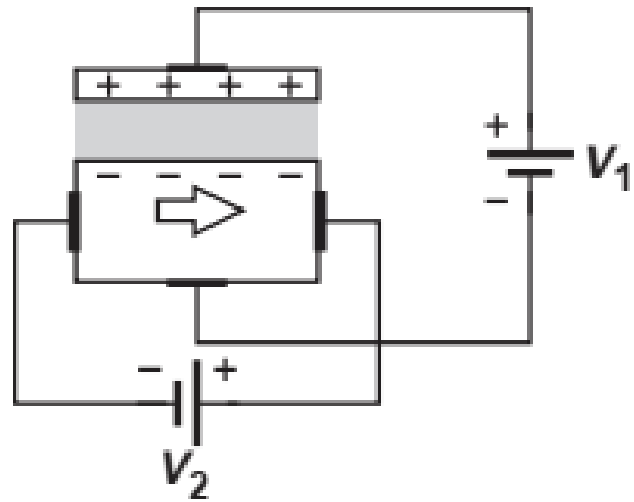


Current flow as a result of potential difference

MOSFET Working



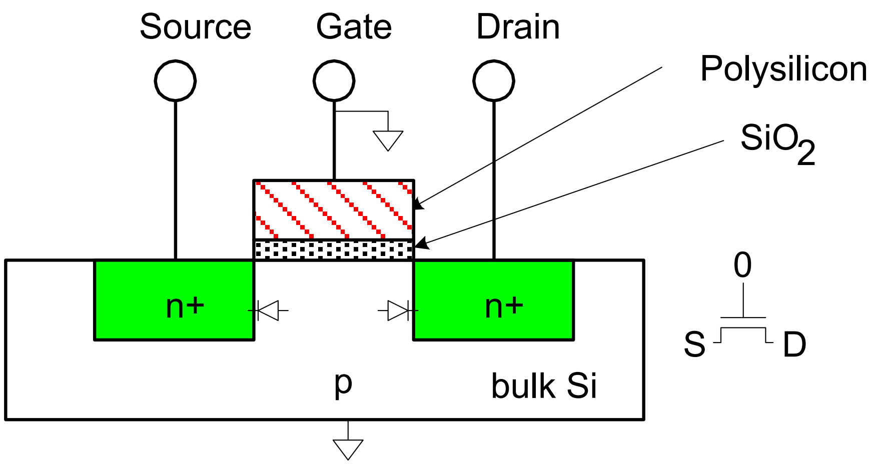
Semiconductor Device



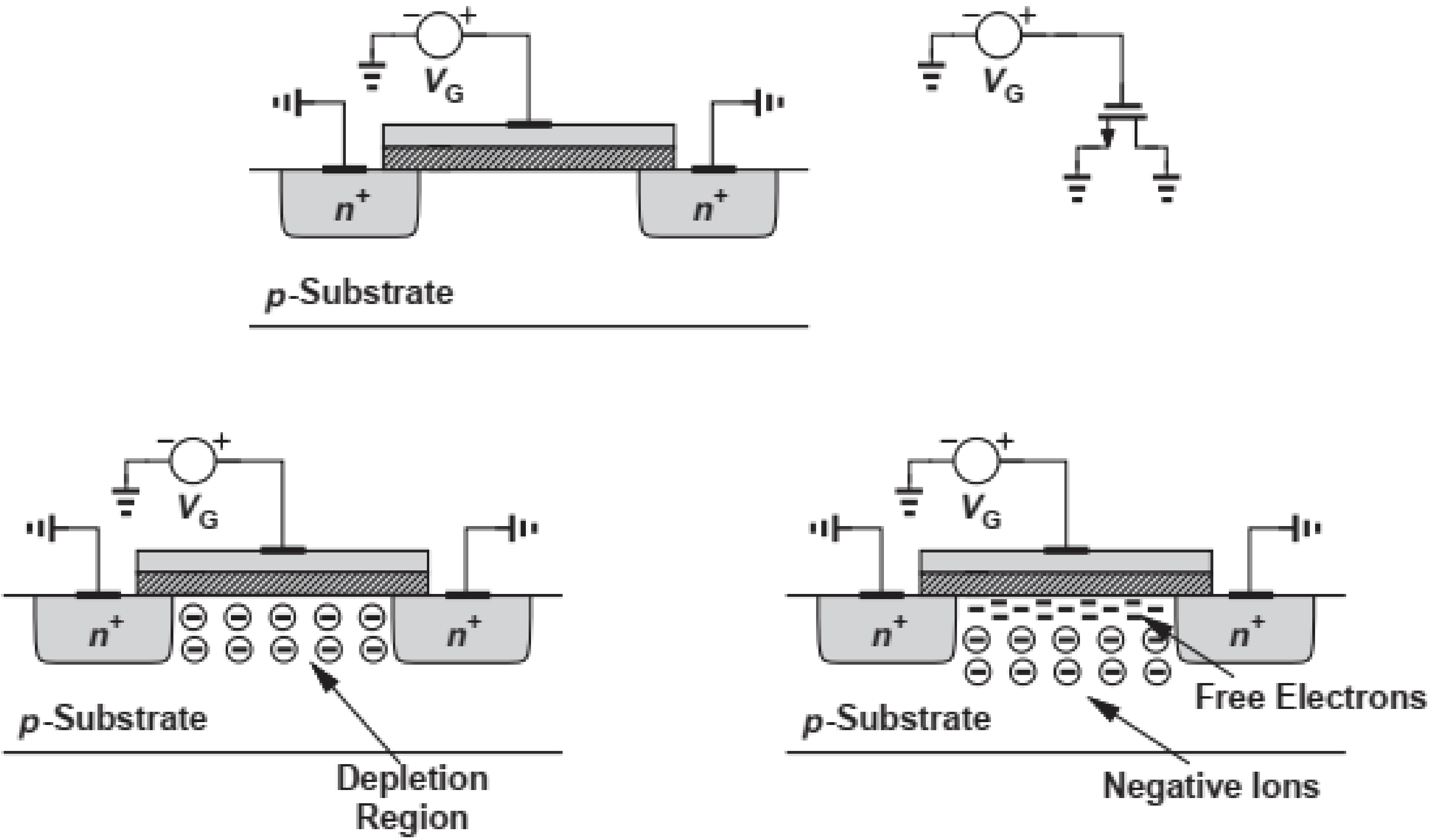
operation as a capacitor

nMOS Transistor Operation

- Body is usually tied to ground (0 V)
- When the gate is at a low voltage:
  - P-type body is at low voltage
  - Source-body and drain-body diodes are OFF
  - No current flows, transistor is OFF

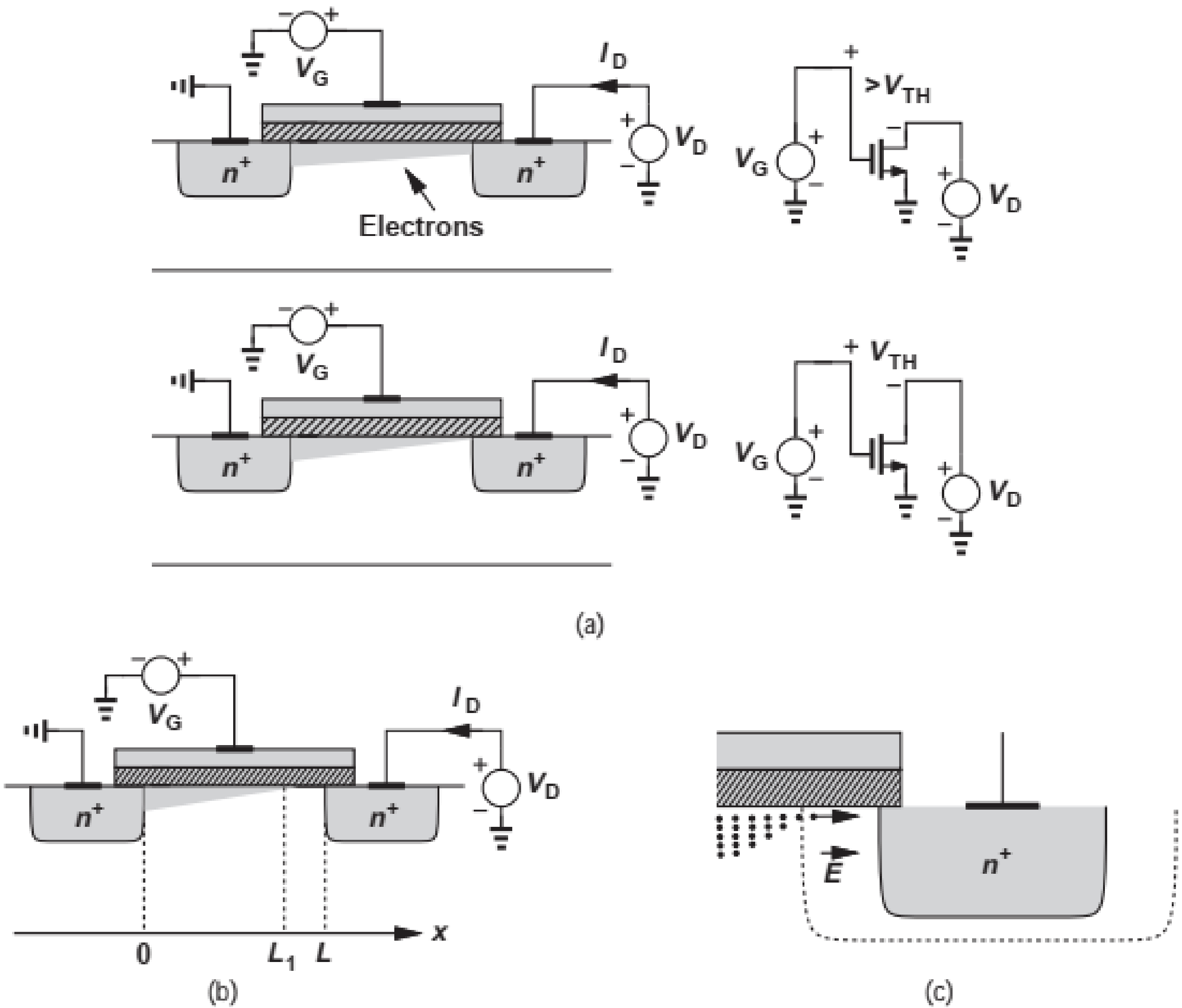


MOSFET Operation



Side view and circuit symbol

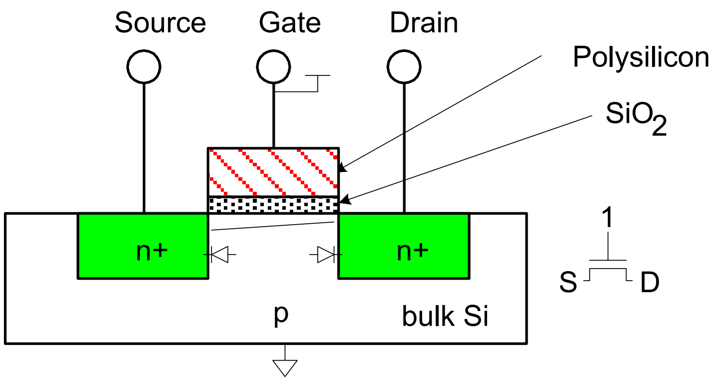
MOSFET Operation (Pinch-off)



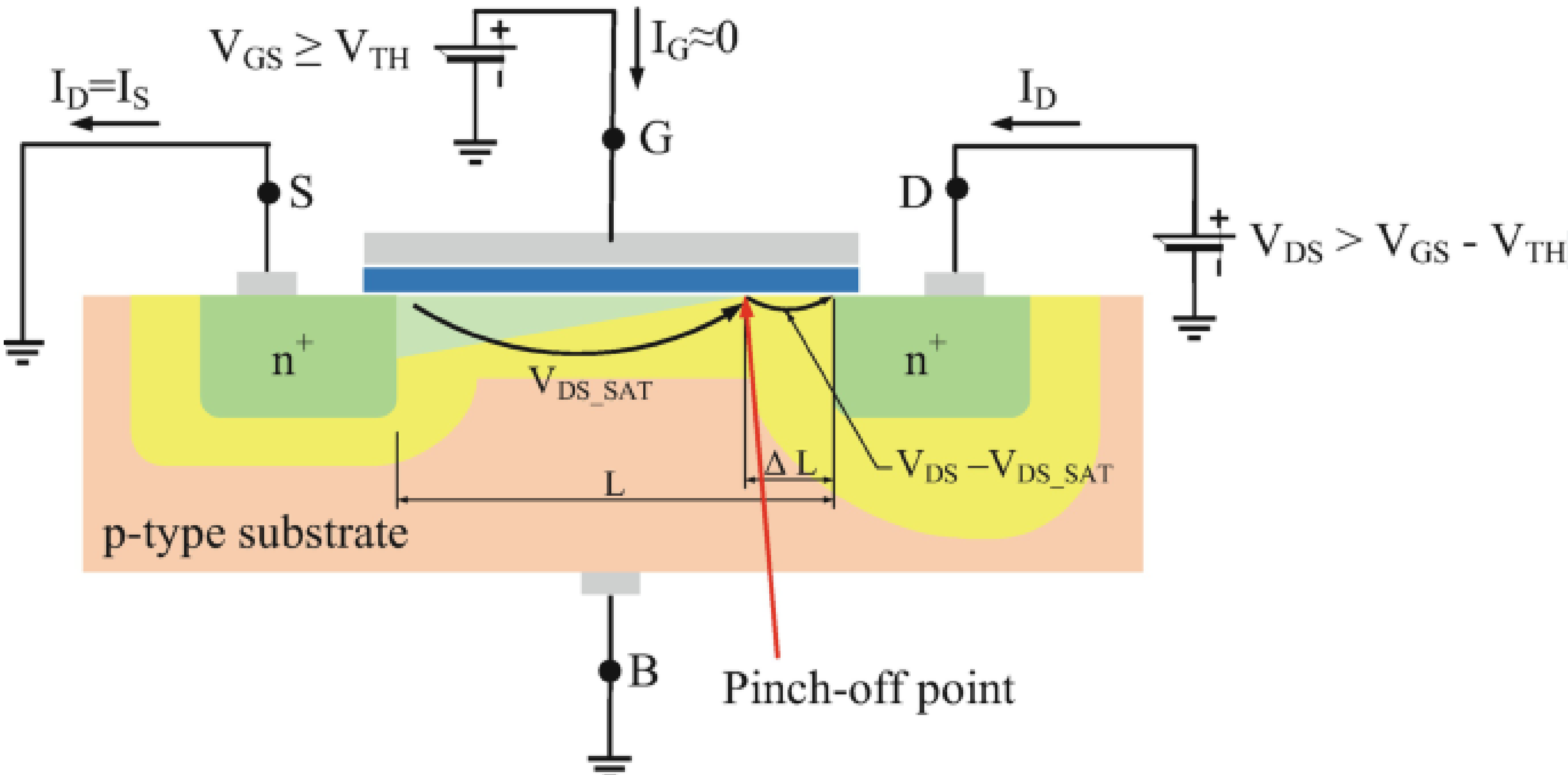
Pinch-off ,variation of length with drain voltage

nMOS Transistor Operation Contd..

- When the gate is at a high voltage:
  - Positive charge on gate of MOS capacitor
  - Negative charge attracted to body
  - Inverts a channel under gate to n-type
  - Now current can flow through n-type silicon from source through channel to drain, transistor is ON

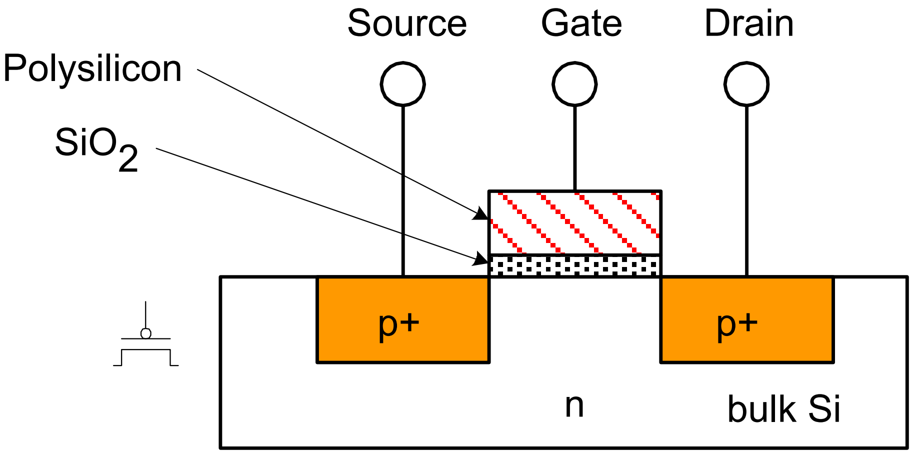


nMOS Transistor Operation Contd..



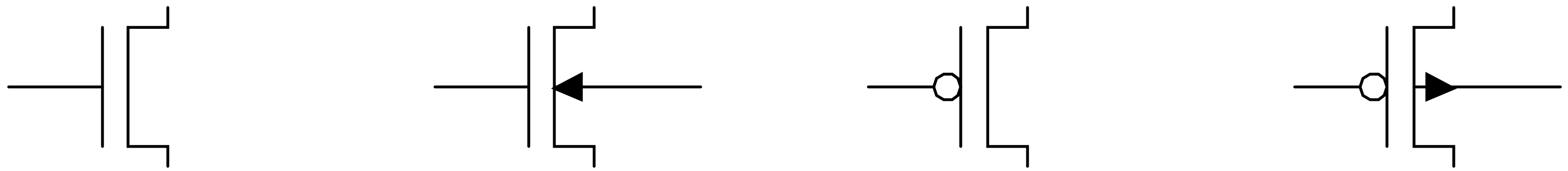
pMOS Transistor Operation

- Similar, but doping and voltages reversed
  - Body tied to high voltage (VDD)
  - Gate low: transistor ON
  - Gate high: transistor OFF
  - Bubble indicates inverted behavior



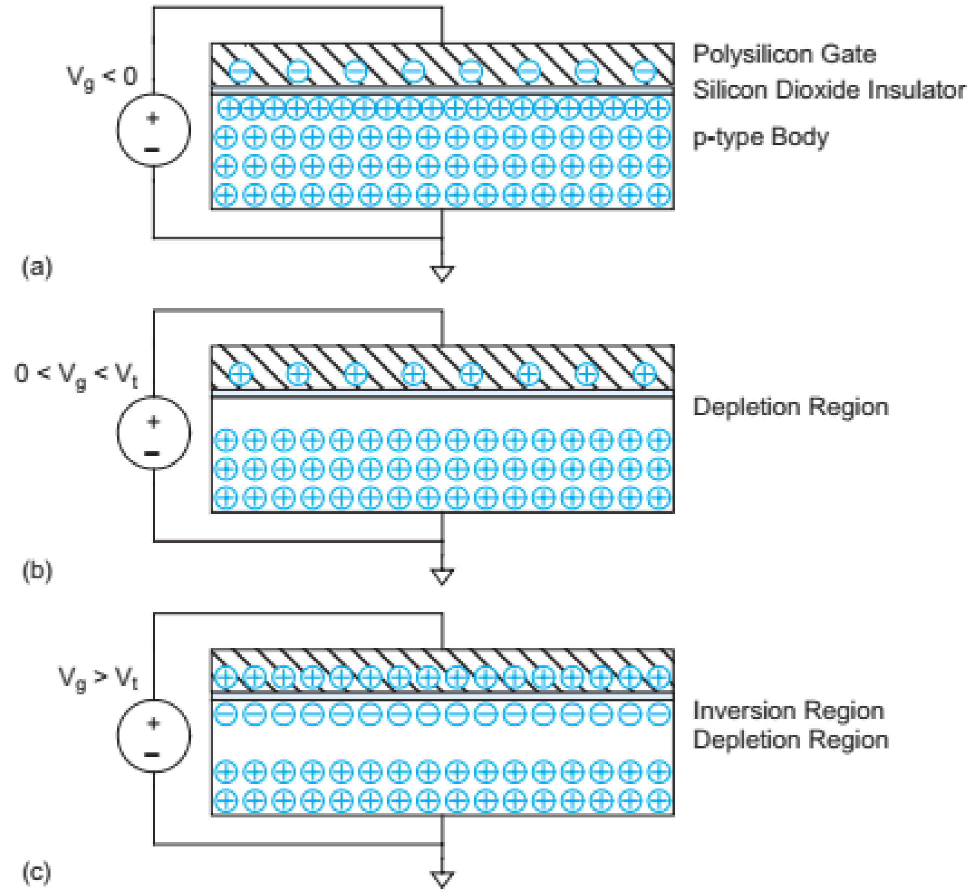
Speed of Operation

- So far, we have treated transistors as ideal switches
- An ON transistor passes a finite amount of current
  - Depends on terminal voltages
  - Derive current-voltage (I-V) relationships
- Transistor gate, source, drain all have capacitance
  - I = C (dV/dt) -> dt = (C/I) dV
  - Capacitance and current determine speed



MOS Capacitor

- Gate and body form MOS capacitor
- Operating modes
  - Accumulation
  - Depletion
  - Inversion

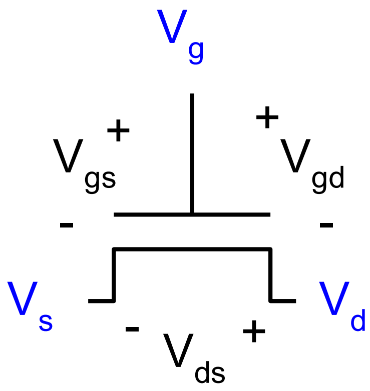


Modes

- **Accumulation:** Positive charges (holes) accumulate near the oxide when a negative voltage is applied, but no current flows.
- **Depletion:** A small positive voltage creates a region where the charges are depleted, but still no current flows.
- **Inversion:** A larger positive voltage attracts electrons to form a conductive channel, allowing current to flow between the source and drain.

Terminal Voltages

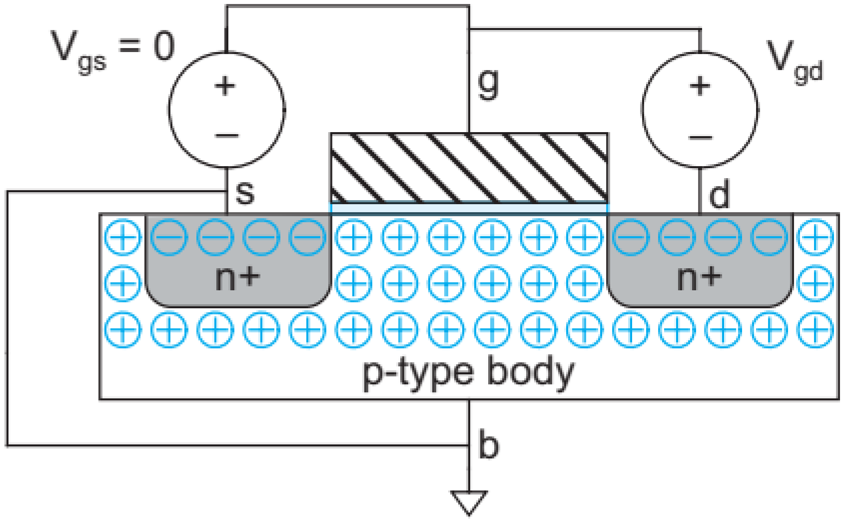
- Mode of operation depends on Vg, Vd, Vs
  - Vgs = Vg – Vs
  - Vgd = Vg – Vd
  - Vds = Vd – Vs = Vgs - Vgd



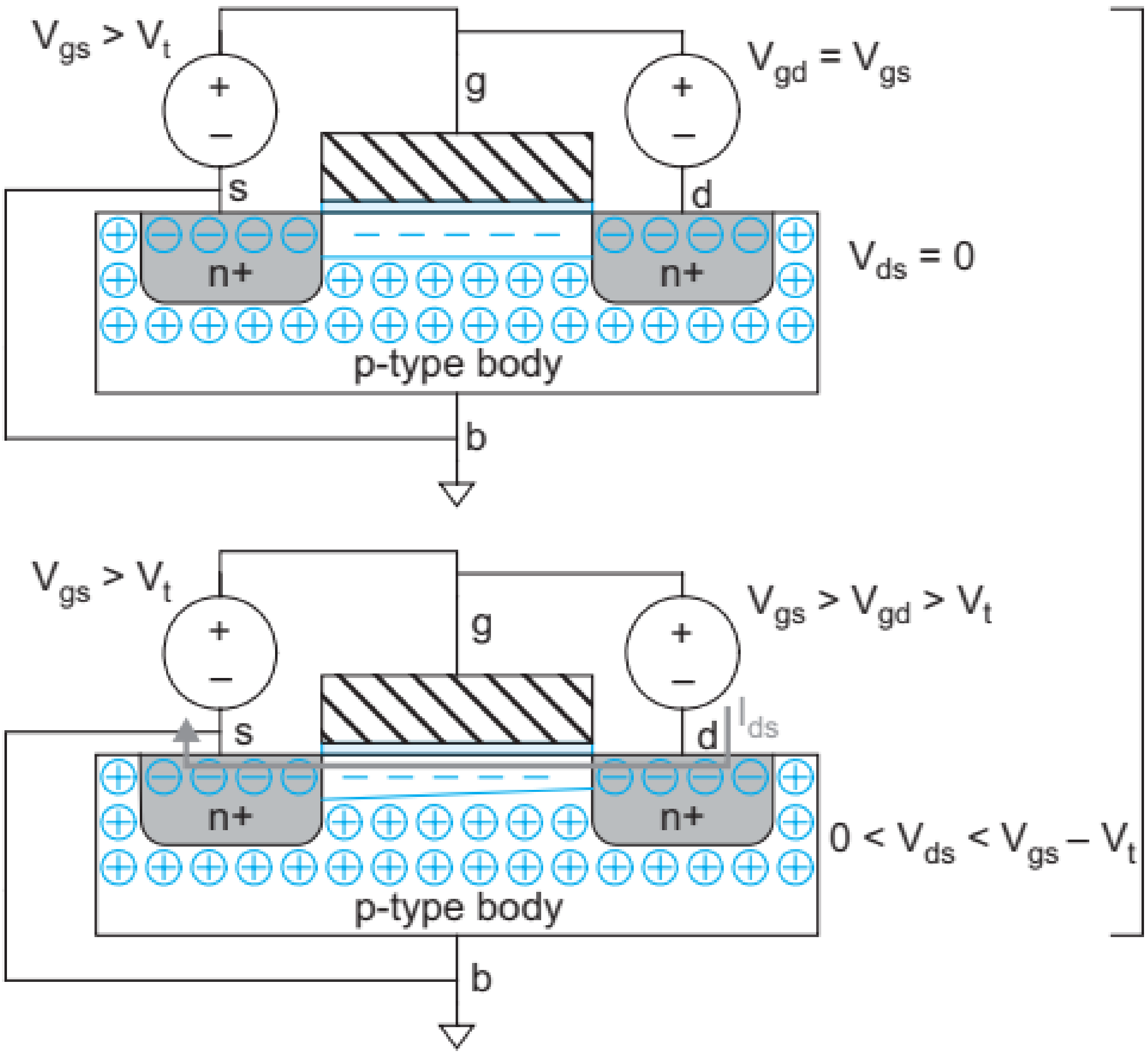
- Source and drain are symmetric diffusion terminals
- By convention, source is terminal at lower voltage Hence Vds $\geq$ 0
- nMOS body is grounded. First assume source is 0 too.
- Three regions of operation
  - Cutoff
  - Linear
  - Saturation

nMOS Cutoff Region

- No channel
- Ids ≈ 0



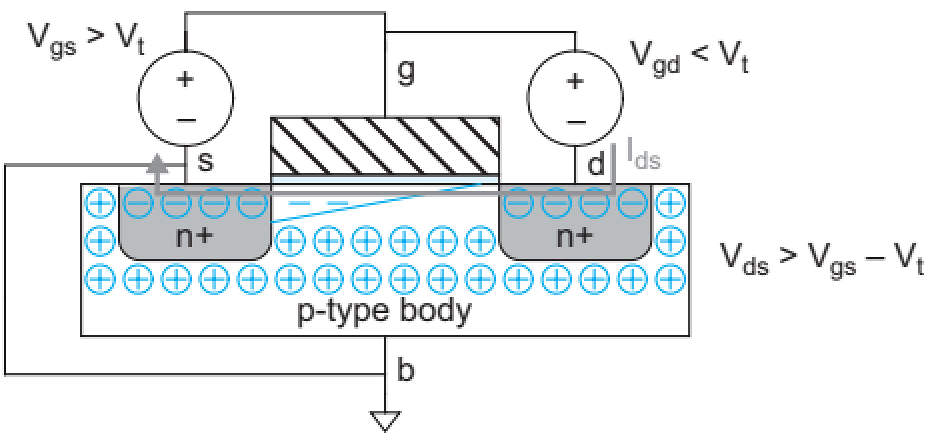
nMOS Linear Region



Linear:
Channel Formed
I_{ds} Increases with V_{ds}

nMOS Saturation Region

- Channel pinches off
- Ids independent of Vds
- We say current saturates
- Similar to current source

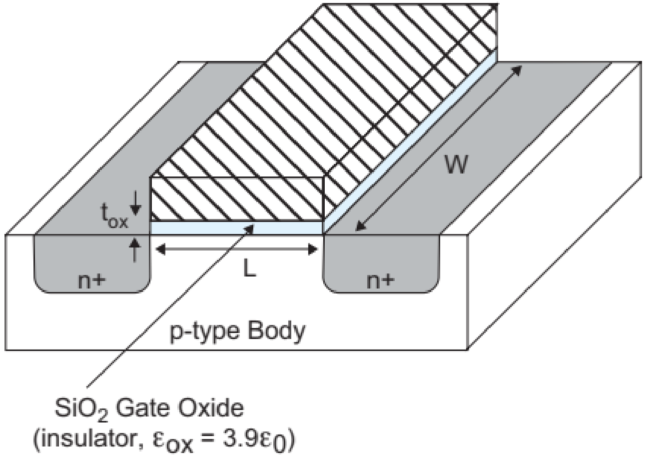


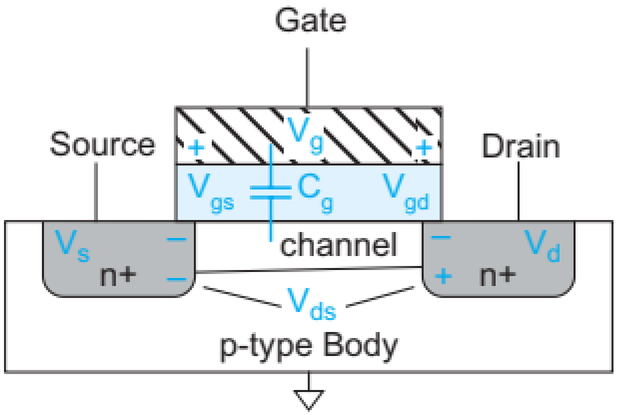
Saturation:
Channel Pinched Off
I_{ds} Independent of V_{ds}

Channel Charge

- MOS structure looks like parallel plate capacitor while operating in inversions
  - Gate – oxide – channel
- $Q_{channel} = CV$
- $C = C_g = \varepsilon_{ox}WL/t_{ox} = C_{ox}WL$
- $V = V_{gc} - V_t = (V_{gs} - V_{ds}/2) - V_t$

$$C_{ox} = \varepsilon_{ox} / t_{ox}$$





Carrier velocity

- Charge is carried by e-
- Electrons are propelled by the lateral electric field between source and drain
  - $E = V_{ds}/L$
- Carrier velocity v proportional to lateral E-field
  - $v = \mu E$ μ called mobility
- Time for carrier to cross channel:
  - $t = L / v$

Drain Current (Linear Region)

$$I_{ds} = \frac{Q_{\text{channel}}}{t}$$

$$= \mu C_{\text{ox}} \frac{W}{L} \left(V_{gs} - V_t - {V_{ds}}/{2} \right) V_{ds}$$

$$= \beta \left(V_{gs} - V_t - {V_{ds}}/{2} \right) V_{ds}$$

$$\beta = \mu C_{\text{ox}} \frac{W}{L}$$

Drain Current (Saturation Region)

If $V_{gd} < V_t$, channel pinches off near drain

- When $V_{ds} > V_{dsat} = V_{gs} - V_t$

Now drain voltage no longer increases current

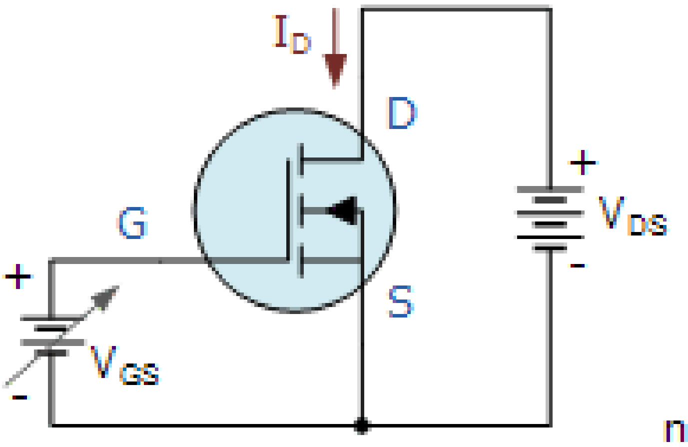
$$I_{ds} = \beta\left(V_{gs} - V_t - \frac{V_{dsat}}{2}\right)V_{dsat}$$

$$= \frac{\beta}{2}\left(V_{gs} - V_t\right)^2$$

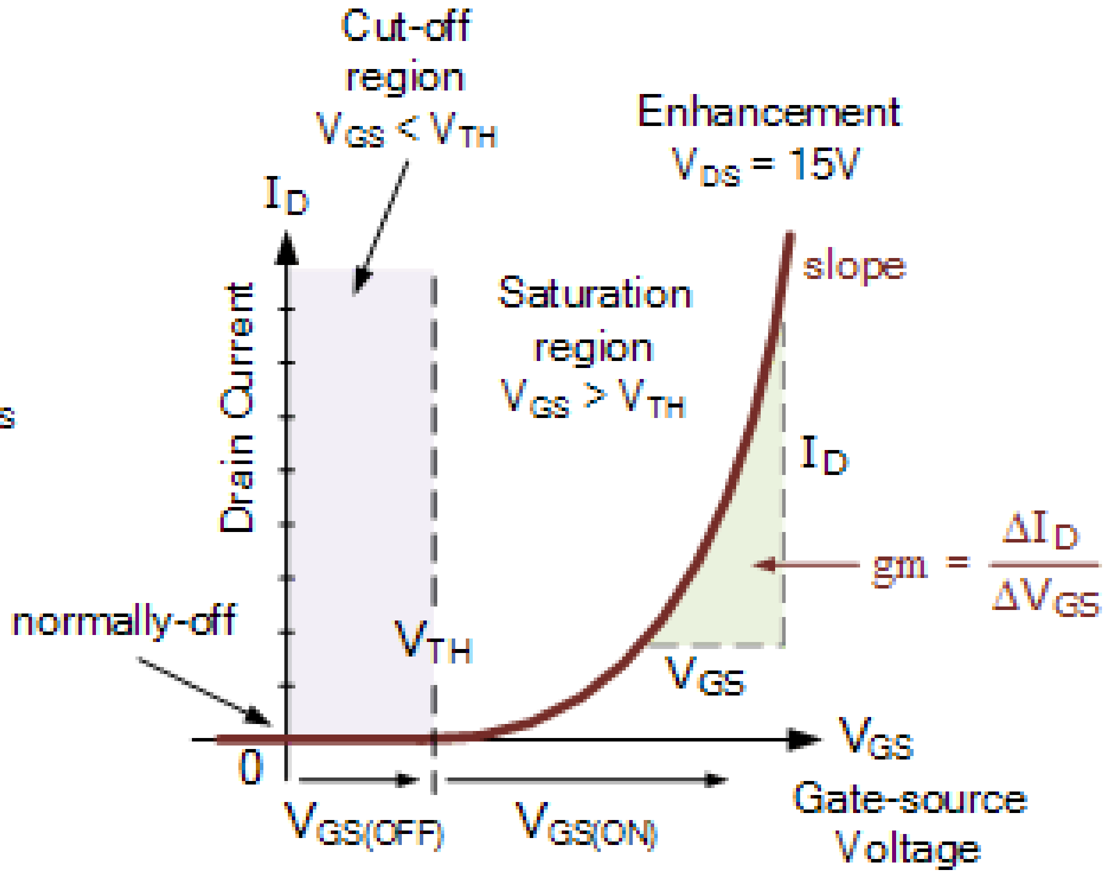
Summary

$$I_{ds} = \begin{cases} 0 & V_{gs} < V_t & \text{cutoff} \\ \beta\left(V_{gs} - V_t - \frac{V_{ds}}{2}\right)V_{ds} & V_{ds} < V_{dsat} & \text{linear} \\ \frac{\beta}{2}\left(V_{gs} - V_t\right)^2 & V_{ds} > V_{dsat} & \text{saturation} \end{cases}$$

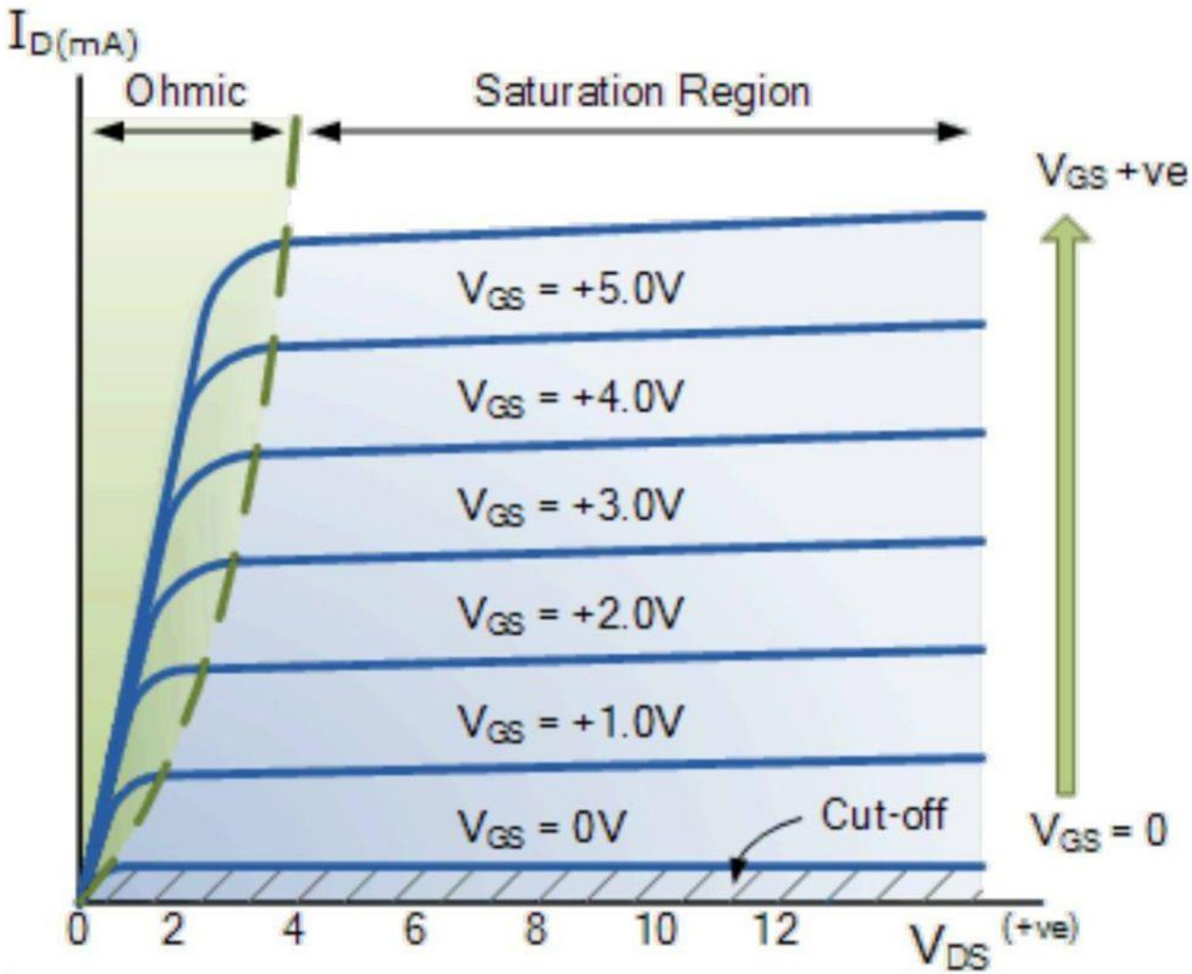
Transfer Characteristics



eMOSFET test circuit



Drain Characteristics



Id vs Vds Graph for MOSFET

Capacitance

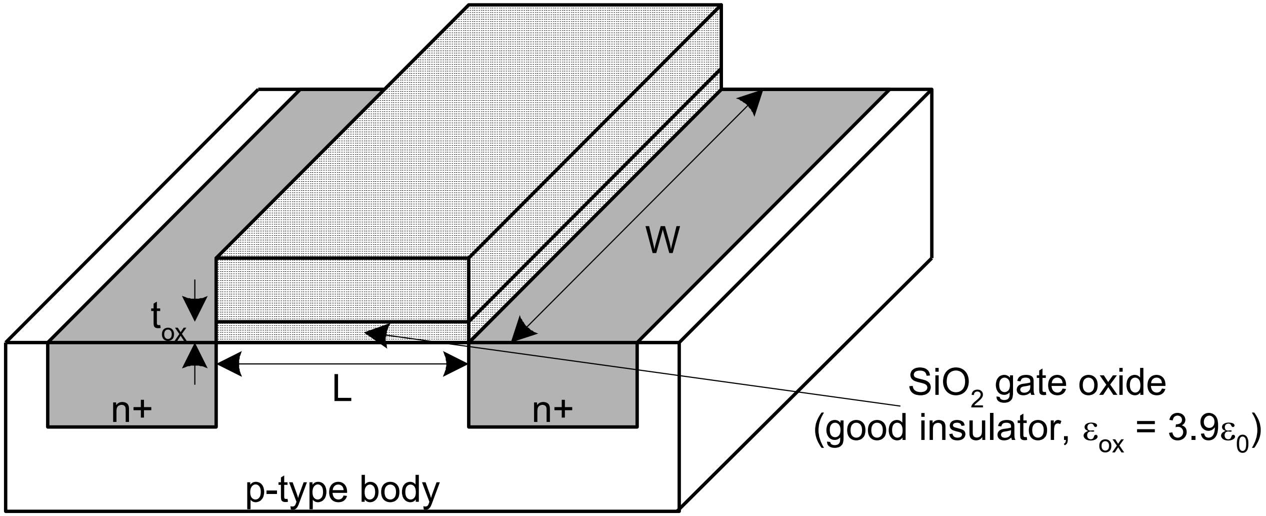
- Any two conductors separated by an insulator have capacitance
- Gate to channel capacitor is very important
  - Creates channel charge necessary for operation
- Source and drain have capacitance to body
  - Across reverse-biased diodes
  - Called **diffusion capacitance** because it is associated with source/drain diffusion

Gate Capacitance

$$C_g = C_{ox}WL$$

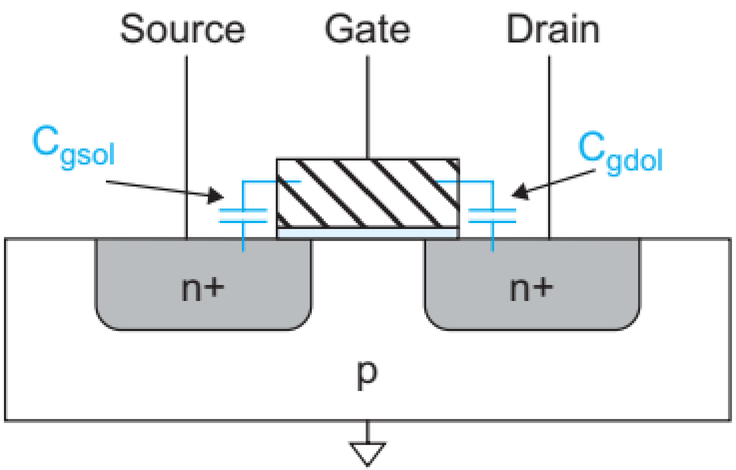
$$C_g = C_{\text{permicron}} \times W$$

$$C_{\text{permicron}} = C_{ox}L = \frac{\varepsilon_{ox}}{t_{ox}}L$$



Detailed MOS Capacitance

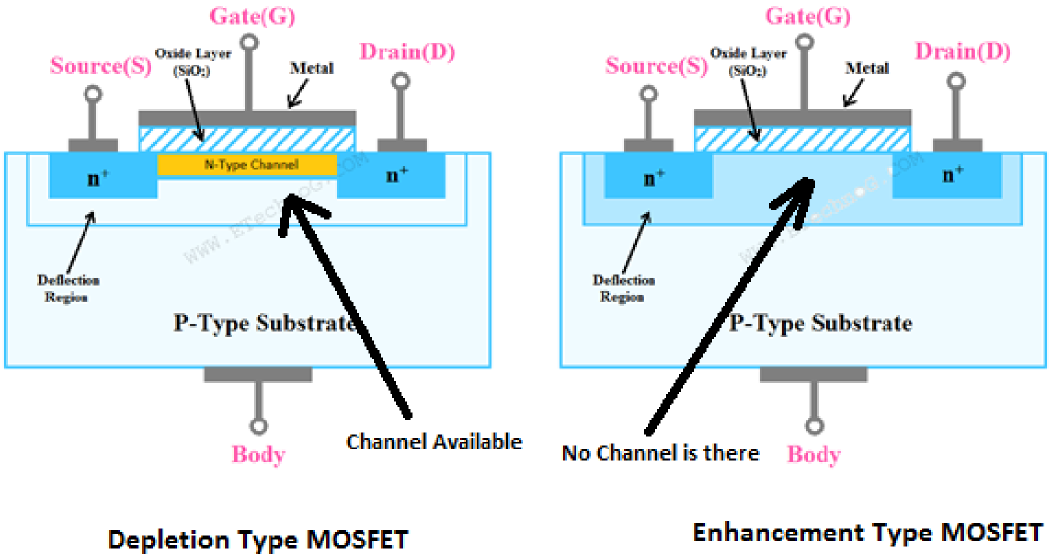
- Total gate capacitance (Cg) of a MOSFET can be modeled as a combination of capacitances
  - Gate-to-source capacitance (Cgs)
  - Gate-to-drain capacitance (Cgd)
  - Gate-to-bulk capacitance (Cgb)



- Gate capacitance depends on the operating region
  - Cut-off Region
  - Linear (Triode) Region
  - Saturation Region

MOSFET Types

- There are two types of MOSFET based on Channel
  - Enhancement type : No conducting channel region at zero bias voltage
  - Depletion type : Conducting channel region at zero bias voltage

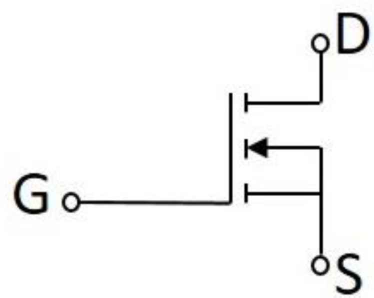


MOSFET Types

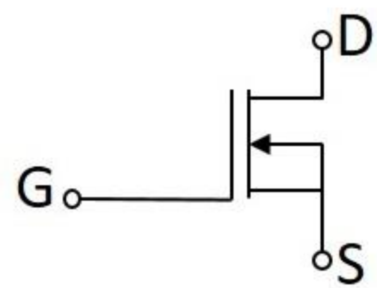
- Enhancement Type –
  - requires a Gate-Source voltage, (VGS) to switch the device “ON”. It is equivalent to a “Normally Open” switch.
- Depletion Type –
  - requires the Gate-Source voltage, (VGS) to switch the device “OFF”. It is equivalent to a “Normally Closed” switch.

MOSFET Types

Symbols of N-Channel MOSFET

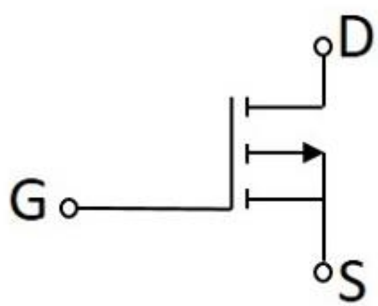


Enhancement Mode

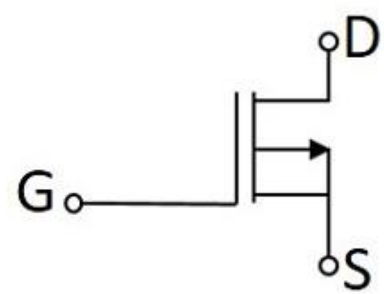


Depletion Mode

Symbols of P-Channel MOSFET



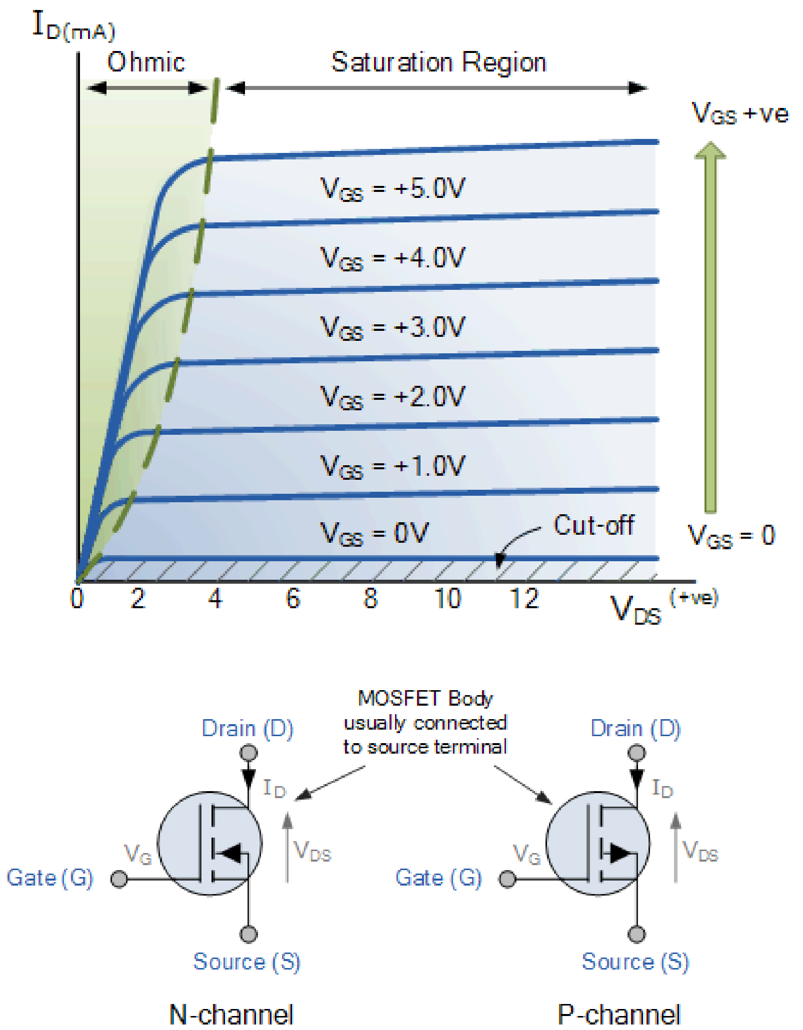
Enhancement Mode



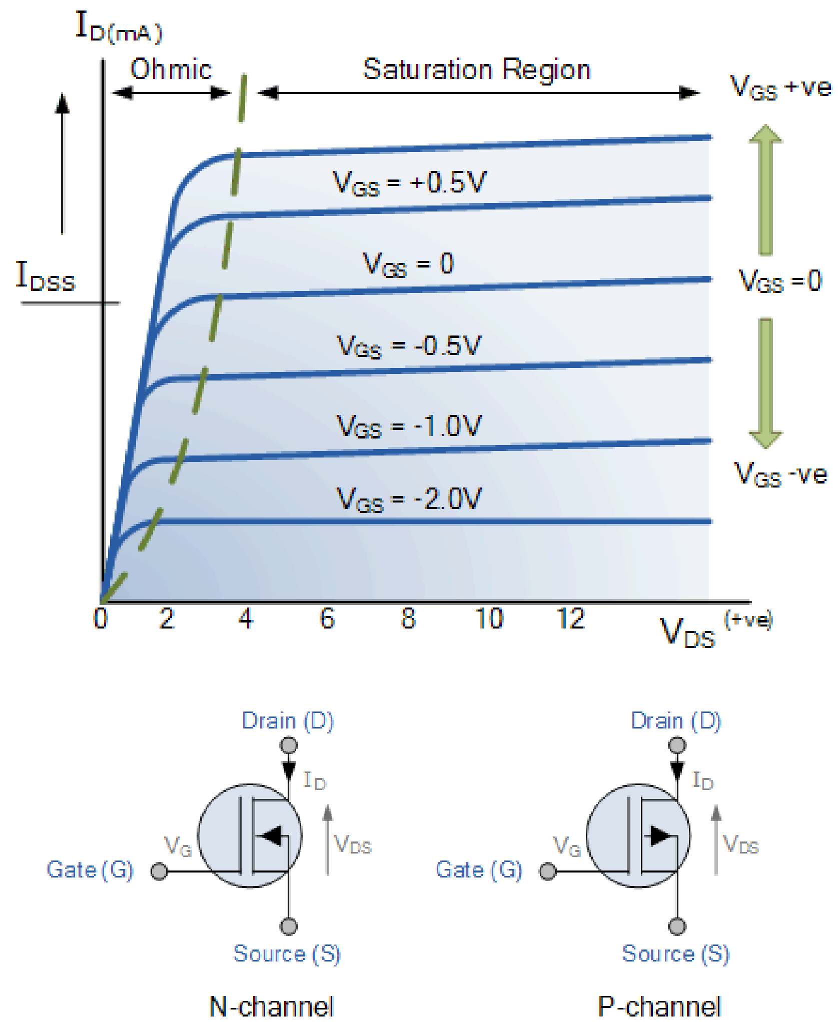
Depletion Mode

MOSFET Types

Enhancement-mode N-Channel



Depletion-mode N-Channel

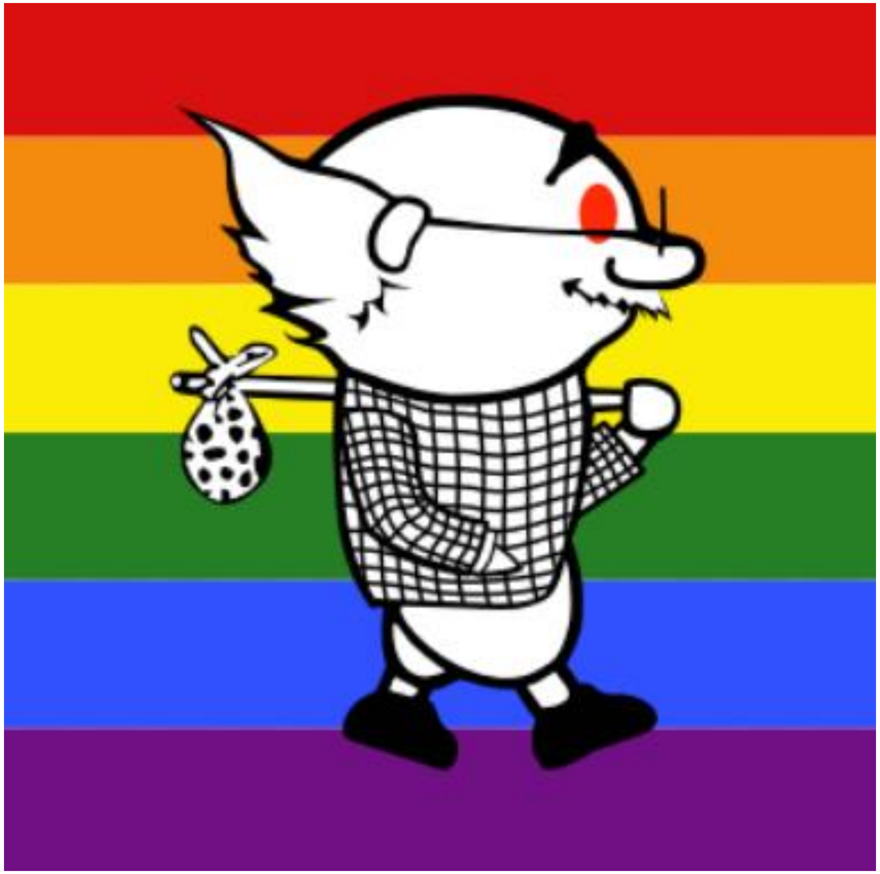


MOSFET Types

Feature	Enhancement-Type MOSFET	Depletion-Type MOSFET
Channel at VGS=0	Absent (device is OFF)	Present (device is ON)
Type of Device	Normally OFF	Normally ON
Turn ON Condition (NMOS)	VGS>Vth	Already ON at VGS=0; VGS<0 to reduce ID
Application Area	Digital circuits (CMOS, logic gates)	Analog circuits, depletion load logic
Symbol (channel line)	Continuous line	Dashed line (indicating default channel)
Power Consumption at Idle	Low (no conduction)	Some conduction (unless turned off)
Fabrication Complexity	Standard in CMOS processes	Requires special doping to pre-form channel
Output Current at VGS=0	Zero	Maximum (for NMOS)

Summary

- MOSFET is a voltage-controlled semiconductor device used to amplify or switch electronic signals
- There are two main types:
  - Enhancement-mode MOSFETs (normally OFF)
  - Depletion-mode MOSFETs (normally ON)
- The operation of a MOSFET is based on controlling the flow of charge carriers in a semiconductor channel using an electric field applied through the gate terminal.



Thank you !
Happy Learning