MOSFET Device Structure and Physical Operation

Unit 5: Field-Effect Transistors

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Lecture Overview

What is a MOSFET?

- **M**etal-**O**xide-**S**emiconductor **F**ield-**E**ffect **T**ransistor
- Three-terminal voltage-controlled device
- Current controlled by electric field
- Foundation of modern integrated circuits

Why MOSFETs?

- Low power consumption
- High input impedance
- Scalable to nanometer dimensions
- Digital logic (billions per chip)
- Analog circuits (amplifiers)

Lecture Objectives

- Understand MOSFET device structure
- Analyze physical operation principles
- Study operating regions (cutoff, linear, saturation)
- Derive I-V characteristics
- Understand field effect and channel modulation

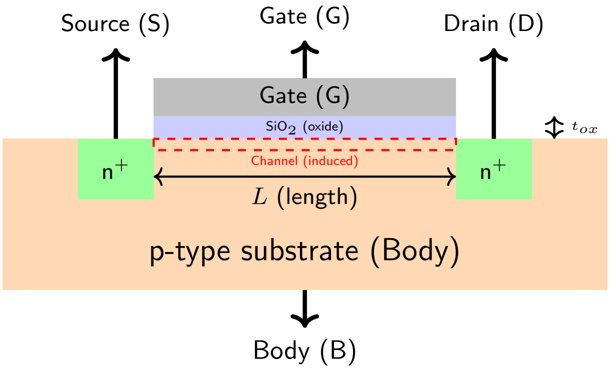
MOSFET Device Structure: n-Channel (NMOS)

Key Components:

- **Gate**: Controls channel
- **Source/Drain**: n^+ regions in p-substrate
- **Oxide**: Insulator (SiO_2)
- **Channel**: Conducting path (induced)

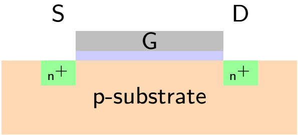
Parameters:

- L: Channel length
- W: Channel width (into page)
- t_{ox}: Oxide thickness
- $C_{ox} = \epsilon_{ox}/t_{ox}$: Oxide capacitance



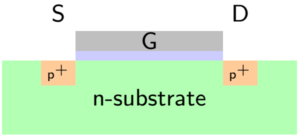
n-Channel vs p-Channel MOSFET

n-Channel (NMOS)



- p-type substrate
- n^+ source and drain
- Electrons are carriers
- Positive V_{GS} creates channel

p-Channel (PMOS)



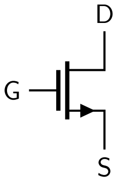
- n-type substrate
- p^+ source and drain
- Holes are carriers
- Negative V_{GS} creates channel

Focus of This Lecture

We will focus on **n-channel enhancement-mode MOSFETs**. Concepts apply to PMOS with appropriate sign changes.

MOSFET Symbol

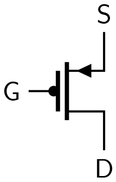
n-Channel MOSFET



Conventions:

- Arrow points **out of** channel (n-type)
- Source: lower potential terminal
- Drain: higher potential terminal

p-Channel MOSFET



Conventions:

- Arrow points **into** channel (p-type)
- Source: higher potential terminal
- Drain: lower potential terminal

Operating Principle: The Field Effect

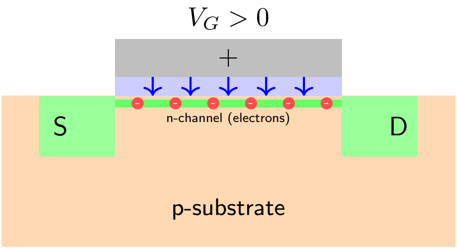
Key Concept:

- Gate - oxide - substrate form capacitor
- Electric field attracts carriers to oxide interface
- Forms conducting **inversion layer**
- Channel connects source to drain
- Current flows when $V_{GS} > V_{th}$

Threshold Voltage (V_{th}):

- Minimum V_{GS} to create channel
- Typically 0.3V to 1.0V for NMOS

Channel Formation (NMOS)



Field Effect

Positive gate voltage attracts electrons to the surface, forming a conducting channel of mobile carriers (electrons in inversion layer).

MOSFET Operating Regions

Region	Condition	Current	Description
Cutoff	$V_{GS} < V_{th}$	$I_{DS} = 0$	No channel formed, transistor OFF
Linear (Triode)	$V_{GS} > V_{th}$ and $V_{DS} < V_{GS} - V_{th}$	$I_{DS} \propto V_{DS}$	Channel exists throughout, acts like resistor
Saturation	$V_{GS} > V_{th}$ and $V_{DS} \geq V_{GS} - V_{th}$	I_{DS} constant	Channel pinched off at drain, current saturates

Key Voltages:

- V_{GS}: Gate-to-Source voltage
- V_{DS}: Drain-to-Source voltage
- V_{th}: Threshold voltage
- $V_{OV} = V_{GS} - V_{th}$: Overdrive voltage

Operating Region Selection:

- **Digital**: Cutoff (Off), Saturation (On)
- **Analog amplifiers**: Saturation region
- **Switches**: Linear region (low $R_{DS,on}$)

Cutoff Region: $V_{GS} < V_{th}$

MOSFET Structure

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Introduction

MOSFET Structure

Operating Principles

Operating Regions

I-V Characteristics

Summary

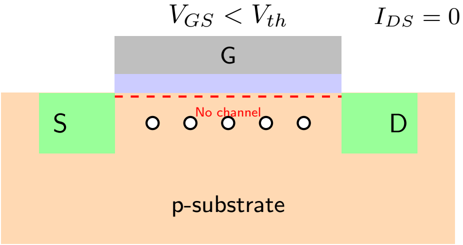
Conditions:

- $V_{GS} < V_{th}$
- Gate voltage too low to invert substrate surface
- No inversion layer or channel

Characteristics:

- $I_{DS} \approx 0$
- Transistor is off
- Source and drain electronically isolated
- Only leakage current flows (nA range)

Device Cross-Section



Equation:

$$I_{DS} \approx 0 \quad \text{for } V_{GS} < V_{th}$$

Linear (Triode) Region

Conditions:

- $V_{GS} > V_{th}$ (channel exists)
- $V_{DS} < V_{GS} - V_{th}$ (channel continuous)

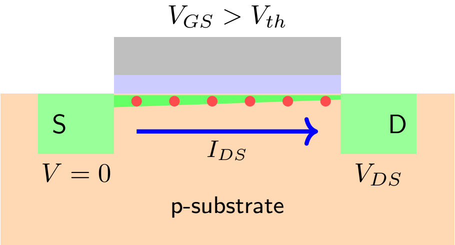
Characteristics:

- Channel depth varies along length
- Current proportional to V_{DS} (for small V_{DS})
- Acts like voltage-controlled resistor
- Used in analog switches

Equation:

$$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{th}) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

Device Cross-Section



Saturation Region

Conditions:

- $V_{GS} > V_{th}$ (channel exists)
- $V_{DS} \geq V_{GS} - V_{th}$ (pinch-off)

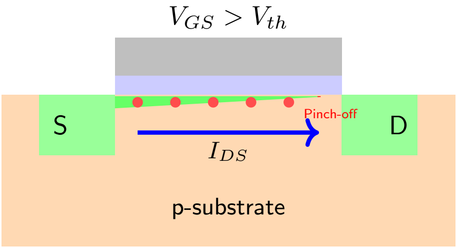
Characteristics:

- Channel pinched off near drain
- Used in amplifiers (constant current source)
- Output resistance r_o is high

Equation With channel-length modulation λ:

$$I_{DS} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{th})^2(1 + \lambda V_{DS})$$

Device Cross-Section



Channel Length Modulation Effect

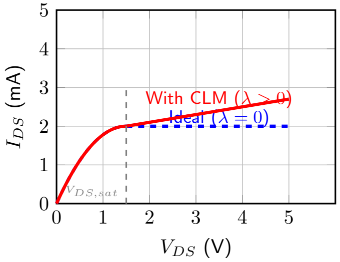
Physical Mechanism:

- In saturation, pinch-off point moves toward source
- Effective channel length decreases: $L_{eff} = L - \Delta L$
- ΔL increases with V_{DS}
- Current increases slightly with V_{DS}
- Finite output resistance

Channel-Length Modulation Param. (λ):

- Units: V^{-1}
- Typically 0.01 to 0.1 V^{-1}
- Smaller for longer channels
- Decreases with technology scaling

Effect on I-V Characteristics:



Output Resistance:

$$r_o = \frac{\partial V_{DS}}{\partial I_{DS}} \approx \frac{1}{\lambda I_{DS}}$$

I_{DS} vs V_{GS} Characteristics (Transfer Curve)

Saturation Region (V_{DS} constant, large):

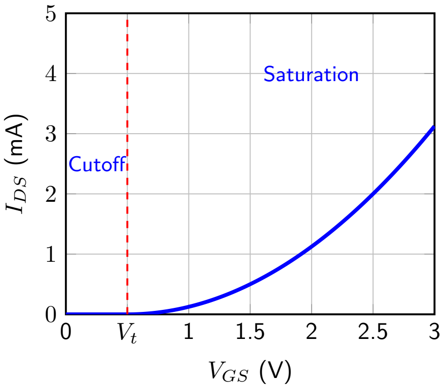
$$I_{DS} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{th})^2$$

- Quadratic relationship
- Threshold at $V_{GS} = V_{th}$
- Steeper for larger W/L
- Transconductance: $g_m = \frac{\partial I_{DS}}{\partial V_{GS}}$

Transconductance:

$$g_m = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{th})$$

$$g_m = \sqrt{2\mu_n C_{ox}\frac{W}{L} I_{DS}}$$



I_{DS} vs V_{DS} Characteristics (Channel Length Modulation)

Observations:

- Each curve: constant V_{GS}
- Linear region: I_{DS} increases with V_{DS}
- Saturation: I_{DS} increases slightly due to CLM
- Higher V_{GS} $\rightarrow$ higher I_{DS}

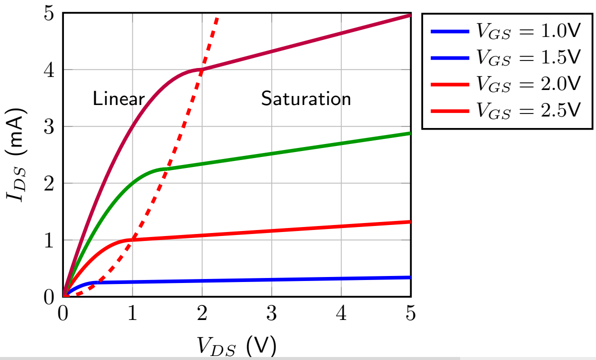
Boundary (dashed line):

$$V_{DS} = V_{GS} - V_{th}$$

- Left: Linear/Triode region
- Right: Saturation region

Saturation Region with CLM

$$I_{DS} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS} - V_{th})^2(1 + \lambda V_{DS})$$



Summary: MOSFET Structure and Operation

Device Structure:

- Four-terminal device (G, D, S, B)
- Gate controls channel via field effect
- n-channel: electrons, p-channel: holes
- V_{th} (threshold voltage)

Operating Regions:

1. **Cutoff**: $V_{GS} < V_{th}$, $I_{DS} = 0$
2. **Linear**: $V_{DS} < V_{GS} - V_{th}$, resistor-like
3. **Saturation**: $V_{DS} \geq V_{GS} - V_{th}$, current source

I-V Characteristics:

- **Linear region**:

$$I_{DS} = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{th}) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

- **Saturation region**:

$$I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2 (1 + \lambda V_{DS})$$

Channel Length Modulation:

- Finite output resistance in saturation
- $r_o \approx \frac{1}{\lambda I_{DS}}$

Key Parameters and Definitions

Parameter	Description
V_{th}	Threshold voltage
V_{GS}	Gate-source voltage
V_{DS}	Drain-source voltage
V_{OV}	Overdrive: $V_{GS} - V_{th}$
W/L	Aspect ratio

Parameter	Description
μ_n	Electron mobility
C_{ox}	Oxide capacitance per unit area
λ	Channel-length modulation
g_m	Transconductance
r_o	Output resistance