Microelectronics
Circuit Analysis and Design

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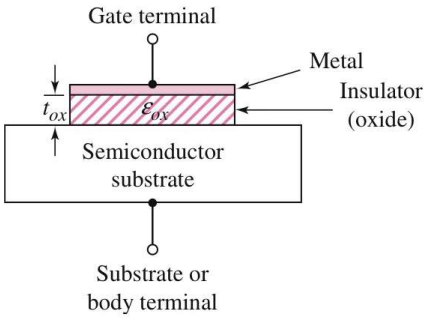
Chapter 3

The Field Effect Transistor

In this chapter, we will:

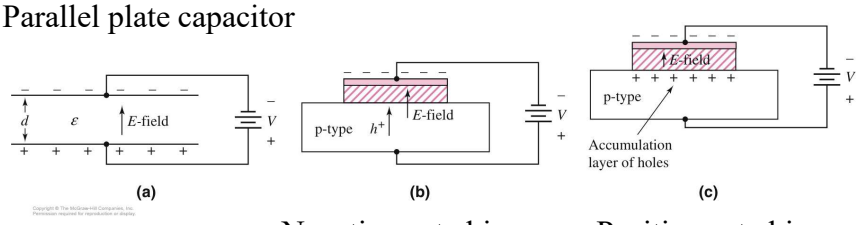
- Study and understand the operation and characteristics of the various types of MOSFETs.
- Understand and become familiar with the dc analysis and design techniques of MOSFET circuits.
- Examine three applications of MOSFET circuits.
- Investigate current source biasing of MOSFET circuits, such as those used in integrated circuits.
- Analyze the dc biasing of multistage or multitransistor circuits.
- Understand the operation and characteristics of the junction field-effect transistor, and analyze the dc response of JFET circuits.

Basic Structure of MOS Capacitor



MOS Capacitor Under Bias: Electric Field and Charge

Parallel plate capacitor



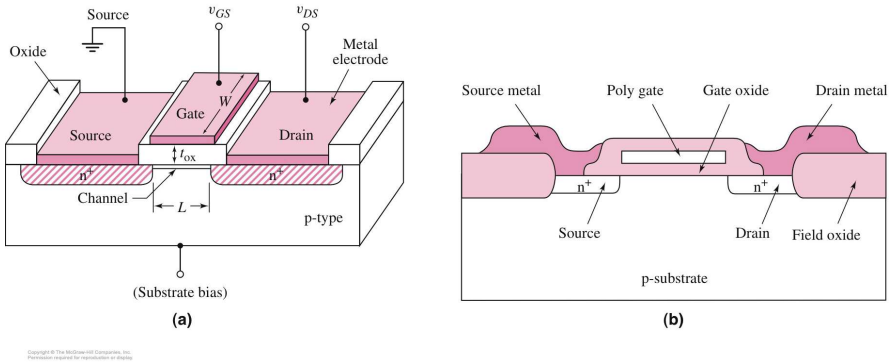
Negative gate bias:

Holes attracted to gate

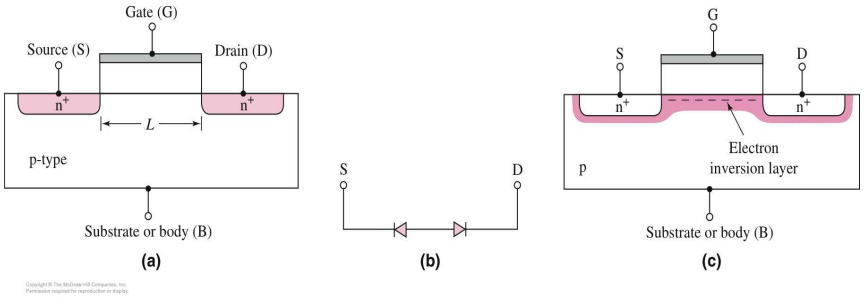
Positive gate bias:

Electrons attracted to gate

Schematic of n-Channel Enhancement Mode MOSFET



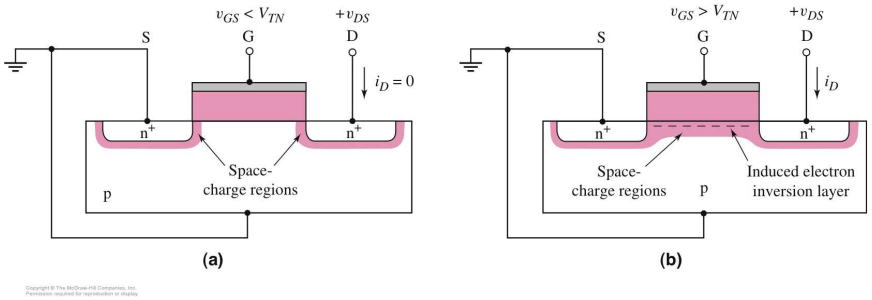
Basic Transistor Operation



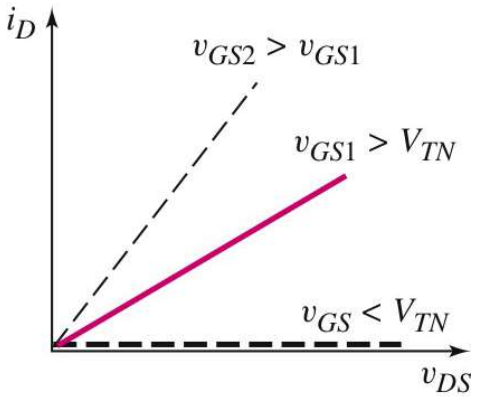
Before electron inversion layer is formed

After electron inversion layer is formed

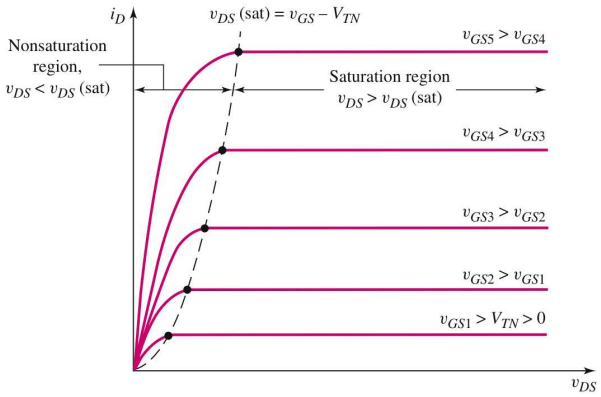
Basic Transistor Operation



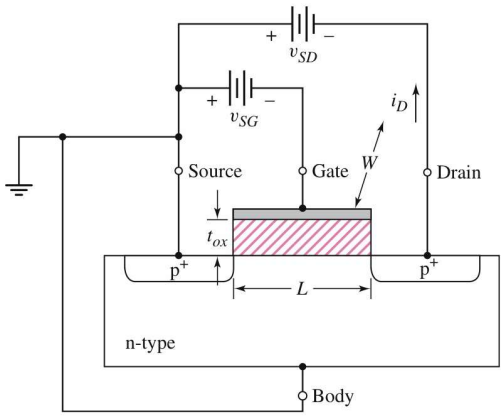
Current Versus Voltage Characteristics: Enhancement-Mode nMOSFET



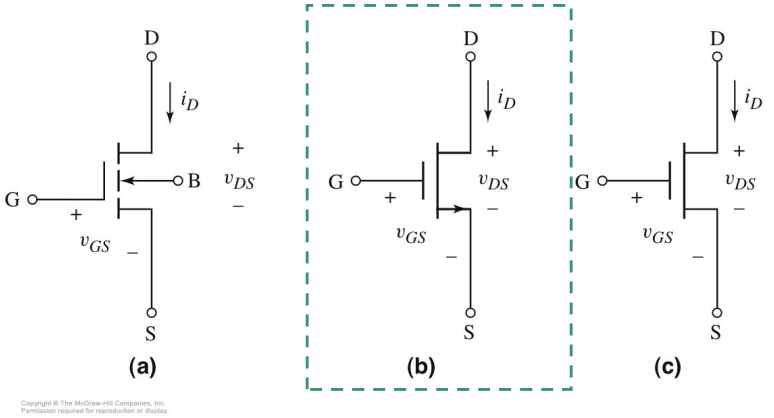
Family of i_D Versus v_{DS} Curves: Enhancement-Mode nMOSFET



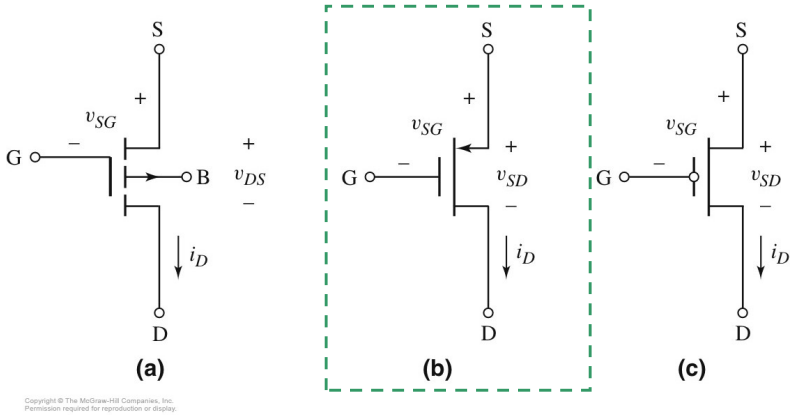
p-Channel Enhancement-Mode MOSFET



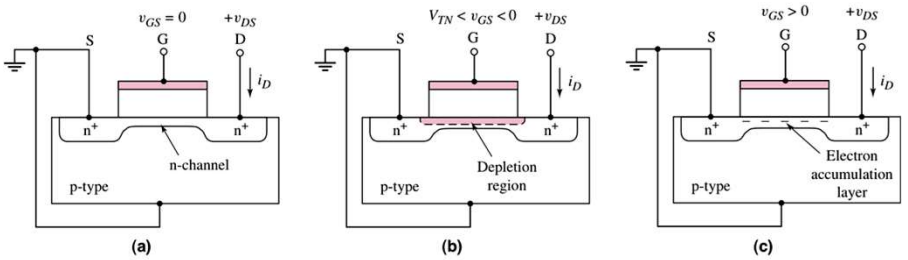
Symbols for n-Channel Enhancement-Mode MOSFET



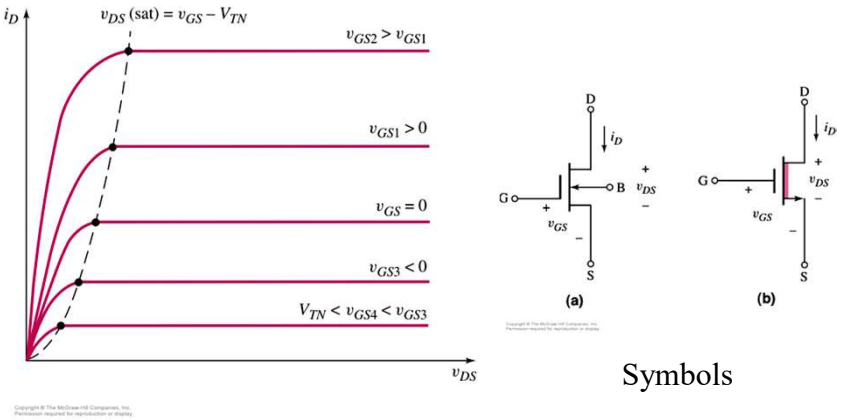
Symbols for p-Channel Enhancement-Mode MOSFET



n-Channel Depletion-Mode MOSFET

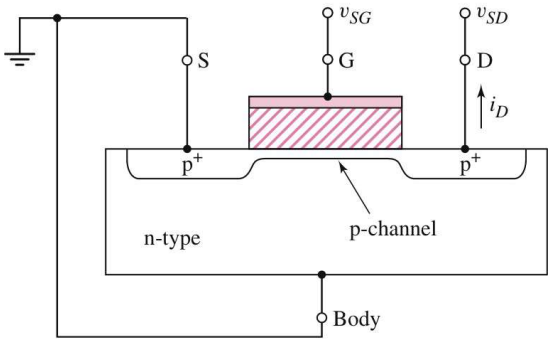


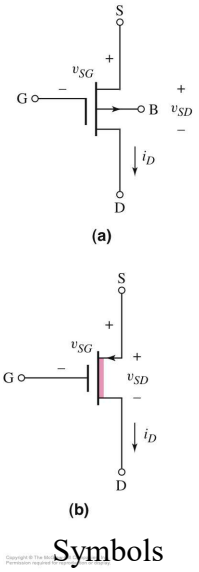
Family of i_D Versus v_{DS} Curves: Depletion-Mode nMOSFET



Symbols

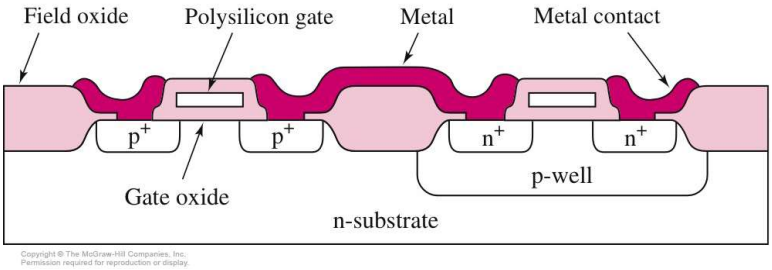
p-Channel Depletion-Mode MOSFET





Symbols

Cross-Section of nMOSFET and pMOSFET



Both transistors are used in the fabrication of CMOS circuitry.

Summary of I-V Relationships

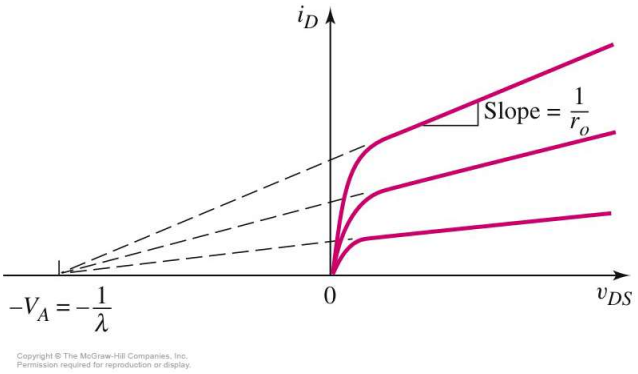
Region	NMOS	PMOS
Nonsaturation	$v_{DS}<v_{DS}(sat)$ $i_D=K_n[2(v_{GS}-V_{TN})v_{DS}-v_{DS}^2]$	$v_{SD}<v_{SD}(sat)$ $i_D=K_p[2(v_{SG}+V_{TP})v_{SD}-v_{SD}^2]$
Saturation	$v_{DS}>v_{DS}(sat)$ $i_D = K_n[v_{GS} - V_{TN}]^2$	$v_{SD}>v_{SD}(sat)$ $i_D = K_p[v_{SG} + V_{TP}]^2$
Transition Pt.	$v_{DS}(sat) = v_{GS} - V_{TN}$	$v_{SD}(sat) = v_{SG} + V_{TN}$
Enhancement Mode	$V_{TN} > 0V$	$V_{TP} < 0V$
Depletion Mode	$V_{TN} < 0V$	$V_{TP} > 0V$

Conduction Parameters

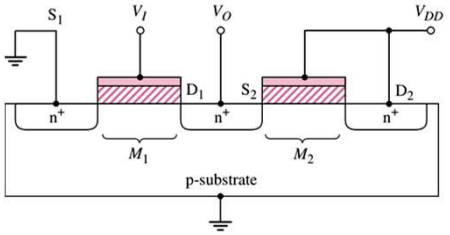
- NMOSFET $$K_n = \frac{W\mu_n C_{ox}}{L} = k_n' \frac{W}{L}$$
- PMOSFET $$K_p = \frac{W\mu_p C_{ox}}{L} = k_p' \frac{W}{L}$$

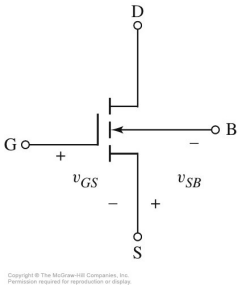
where: $$C_{ox} = \varepsilon_o / t_{ox}$$

Channel Length Modulation: Early Voltage

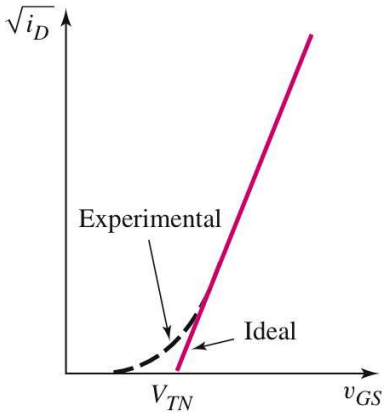


Body Effect

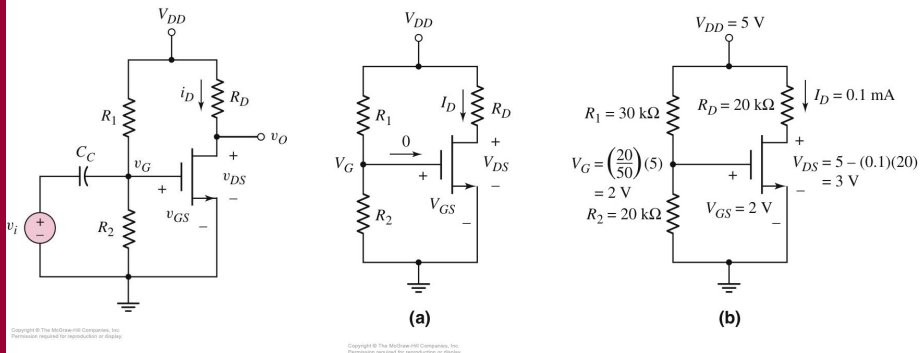




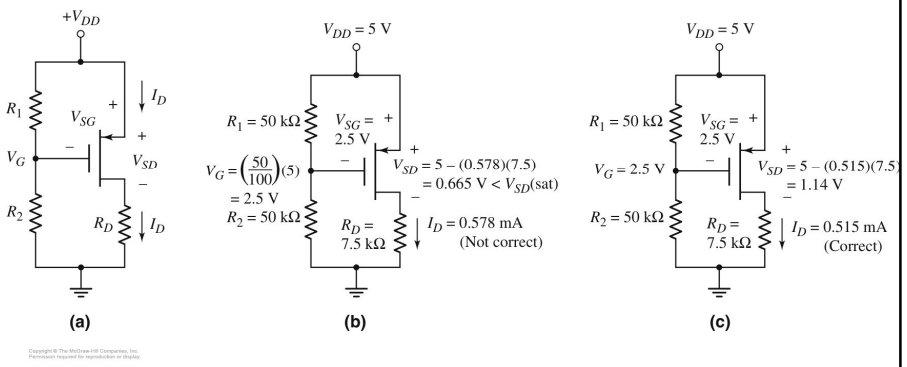
Subthreshold Condition



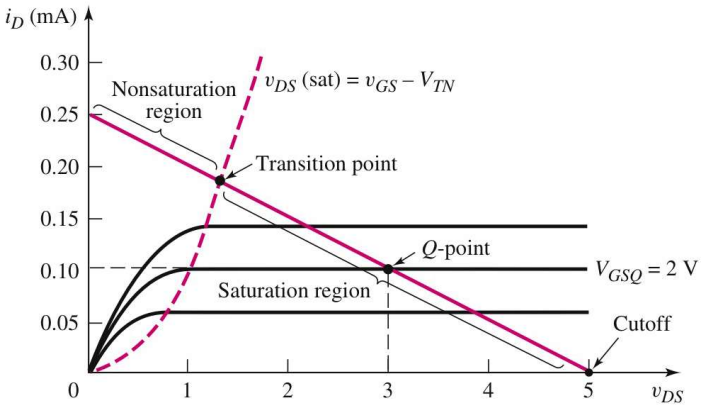
NMOS Common-Source Circuit



PMOS Common-Source Circuit



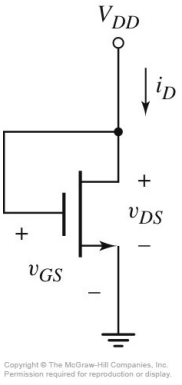
Load Line and Modes of Operation: NMOS Common-Source Circuit

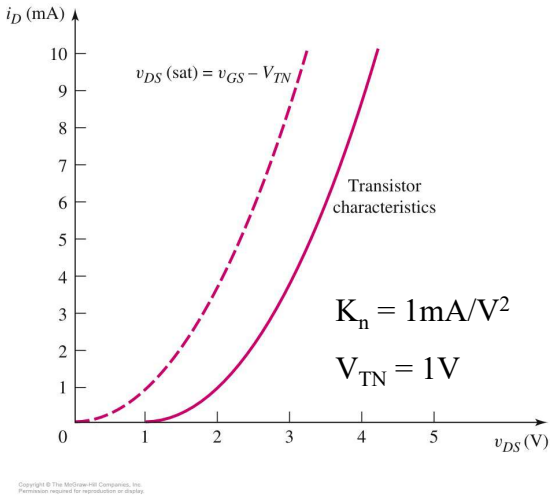


Problem-Solving Technique: NMOSFET DC Analysis

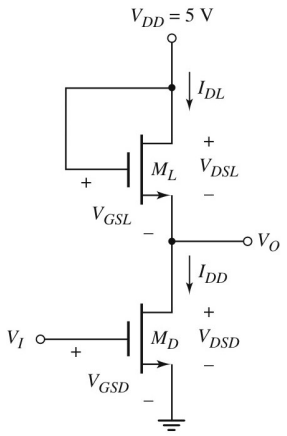
1. Assume the transistor is in saturation.
   a. $V_{GS} > V_{TN}$, $I_D > 0$, & $V_{DS} \geq V_{DS}(sat)$
2. Analyze circuit using saturation I-V relations.
3. Evaluate resulting bias condition of transistor.
   a. If $V_{GS} < V_{TN}$, transistor is likely in cutoff
   b. If $V_{DS} < V_{DS}(sat)$, transistor is likely in nonsaturation region
4. If initial assumption is proven incorrect, make new assumption and repeat Steps 2 and 3.

Enhancement Load Device





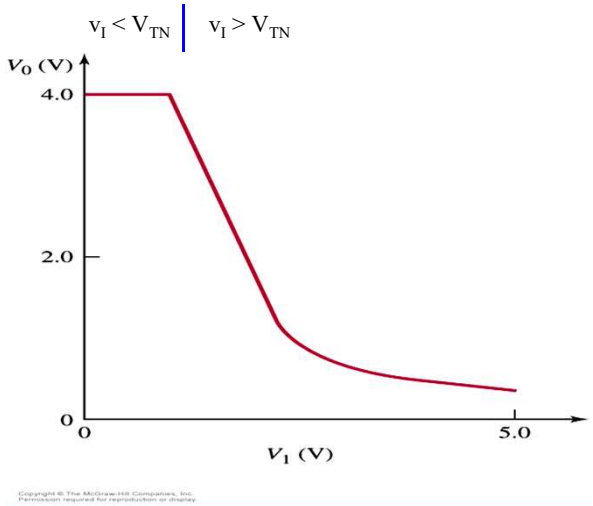
Circuit with Enhancement Load Device and NMOS Driver



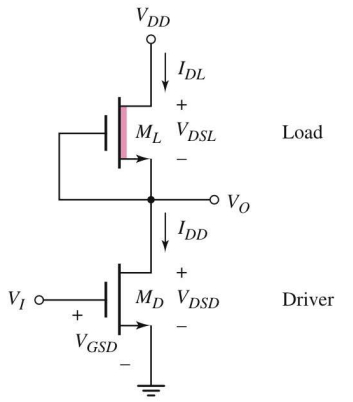
M_L is always in saturation.

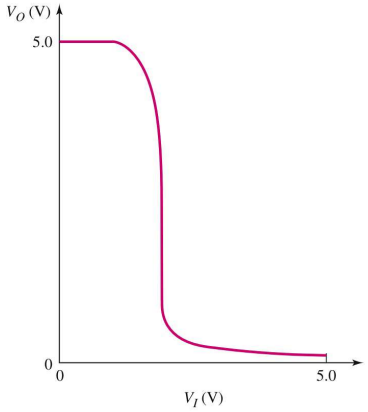
M_D can be biased either in saturation or nonsaturation region.

Voltage Transfer Characteristics:
NMOS Inverter with Enhancement Load Device

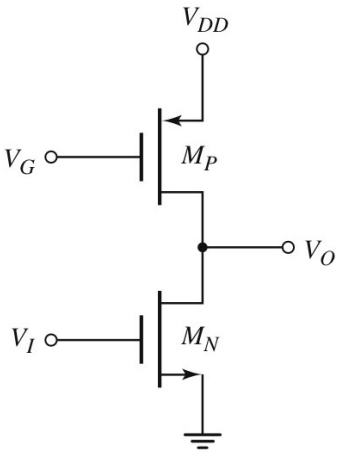


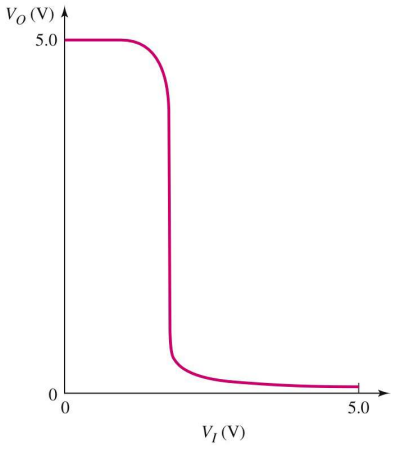
NMOS Inverter with Depletion Load Device



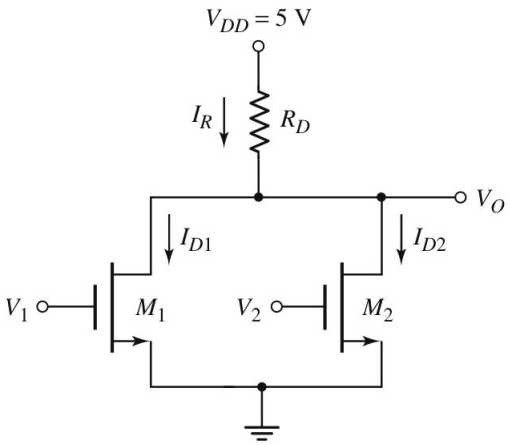


CMOS Inverter



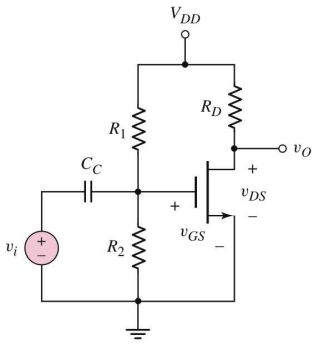


2-Input NMOS NOR Logic Gate

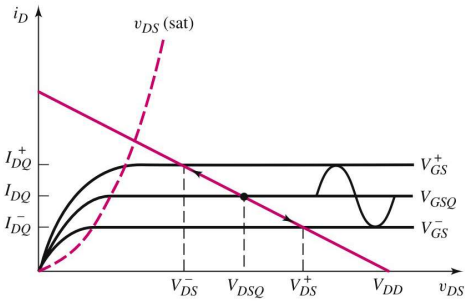


V_1 (V)	V_2 (V)	V_O (V)
0	0	High
5	0	Low
0	5	Low
5	5	Low

MOS Small-Signal Amplifier

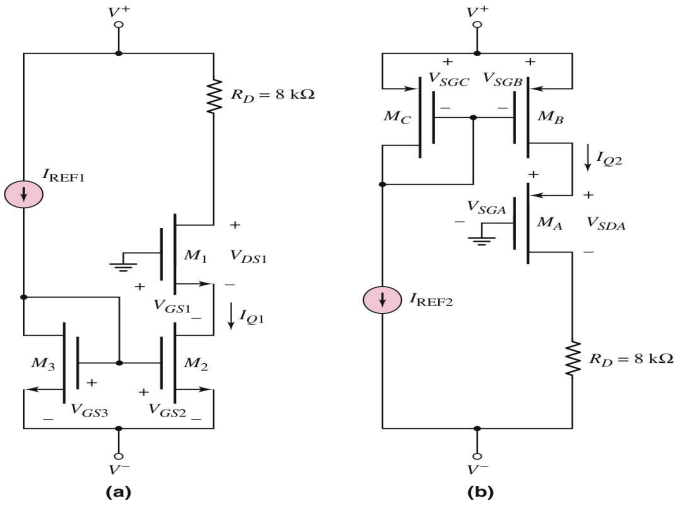


(a)

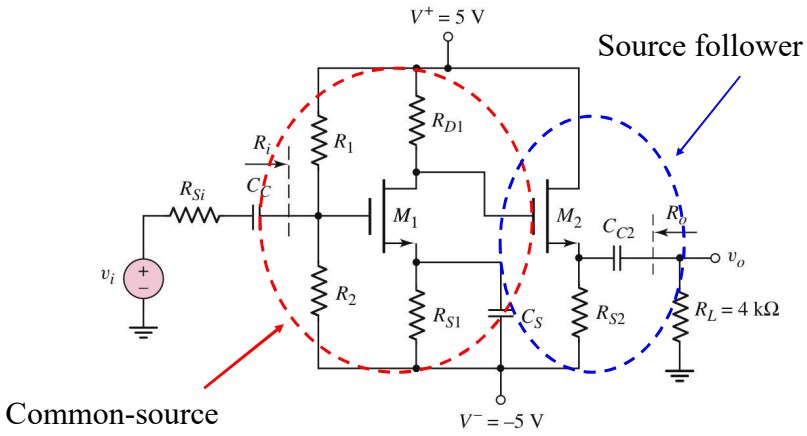


(b)

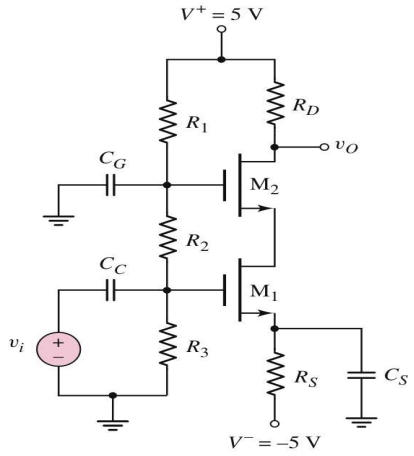
Current Mirrors



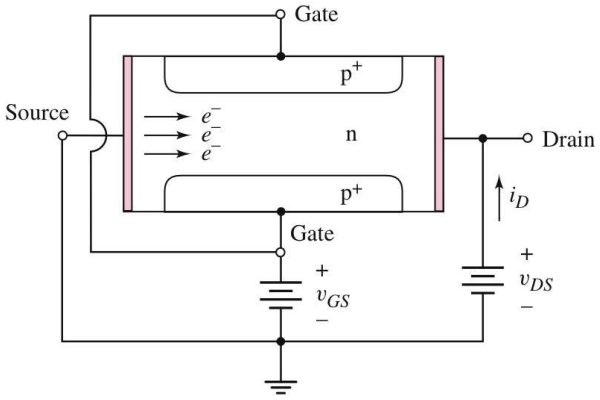
2-Stage Cascade Amplifier



NMOS Cascode Circuit



Cross Section of n-Channel Junction Field Effect Transistor (JFET)



Cross Section of n-Channel MESFET