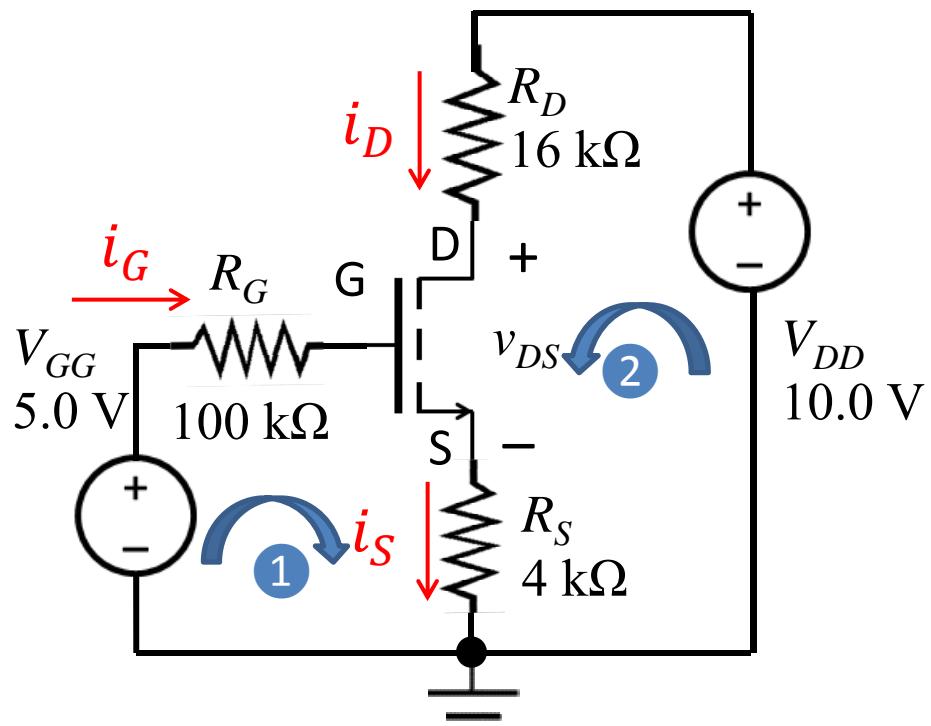


Announcements

- HW 5 due Friday.
- Emily Allstot will give Friday's lecture.
- Exam 1 regrade requests to me by 2pm today
(grades may go up or down upon regrade).

MOSFET Circuit Analysis (e.g. 2')

Now R_D changes to $16 \text{ k}\Omega$



Known: NMOS, $V_{TO} = 1.0 \text{ V}$, $\lambda = 0$, $K'_n = 25 \mu\text{A}/\text{V}^2$, $\frac{W}{L} = 10$

Solve: Q-point (i_D , v_{DS})

- Everything would be the same until the last check for saturation:

$$v_{DS} = V_{DD} - i_D(R_D + R_S) \\ = 10\text{V} - 500\mu\text{A} \cdot 20\text{k}\Omega = 0\text{V}$$

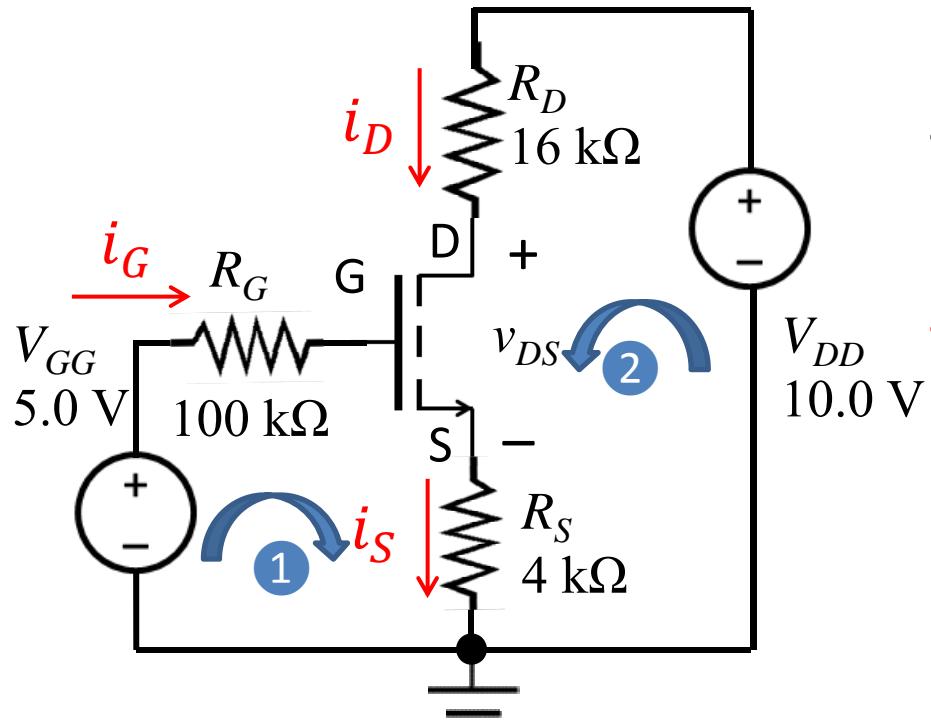
$v_{DS} = 0 \text{ V} < V_{GS} - V_{TN} = 2 \text{ V}$. Not in saturation.

- Guess in triode:

$$i_D = K'_n \frac{W}{L} \left(v_{GS} - V_{TN} - \frac{v_{DS}}{2} \right) v_{DS} \quad (1)$$

MOSFET Circuit Analysis (e.g. 2')

Now R_D changes to $16 \text{ k}\Omega$



Q-point: (447 μA, 1.06 V)

- **KVL:**

$$v_{DS} = V_{DD} - i_D(R_D + R_S) \quad (2)$$

$$v_{GS} = V_{GG} - i_D R_S \quad (3)$$

- Substituting (2) (3) into (1), we get a quadratic equation of i_D . Solution is:

$$i_D = 186 \mu\text{A} \text{ or } 447 \mu\text{A}$$

- **Check:**

- First root:

$$v_{GS} = V_{GG} - i_D R_S = 4.25 \text{ V} > V_T \quad \text{V}$$

$$\begin{aligned} v_{DS} &= V_{DD} - i_D(R_D + R_S) \\ &= 6.27 \text{ V} > v_{GS} - V_{TN} \end{aligned} \quad \text{X}$$

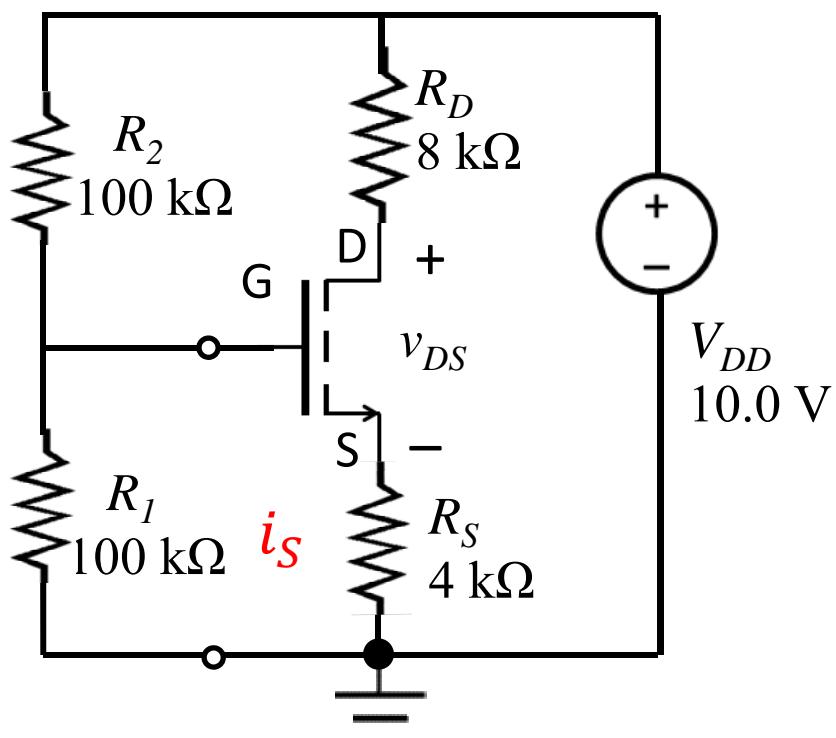
- Second root:

$$v_{GS} = V_{GG} - i_D R_S = 3.21 \text{ V} > V_T \quad \text{V}$$

$$v_{DS} = 1.06 \text{ V} < v_{GS} - V_{TN} \quad \text{V}$$

MOSFET Circuit Analysis (e.g. 3)

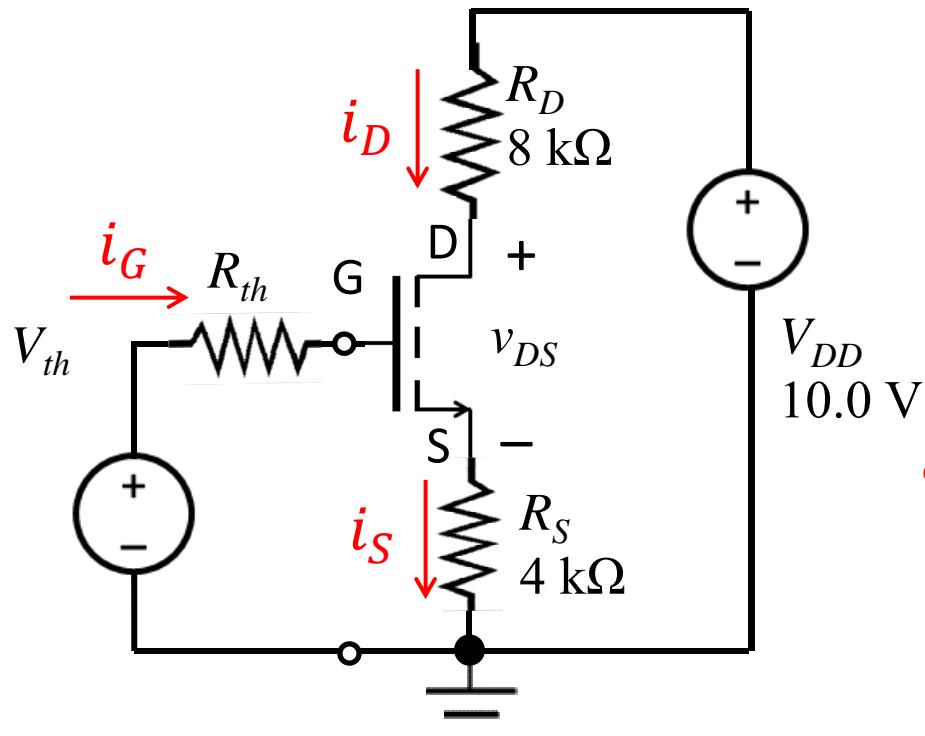
Four-resistor circuit



Known: NMOS, $V_{TO} = 1.0\text{ V}$, $\lambda = 0$, $K_n = 25\mu\text{A/V}^2$, $\frac{W}{L} = 10$
Solve: Q-point (i_D , v_{DS})

- Simplification: Find the Thevenin equivalent circuit of the left side.

MOSFET Circuit Analysis (e.g. 3)



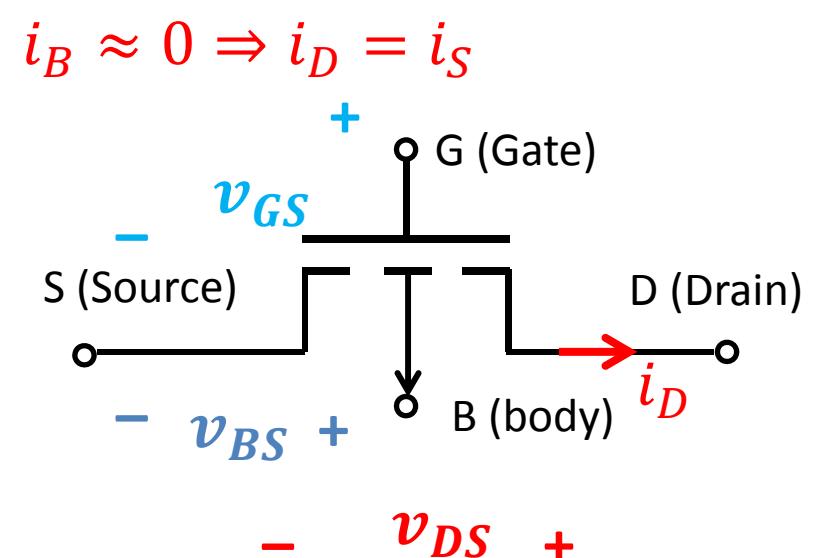
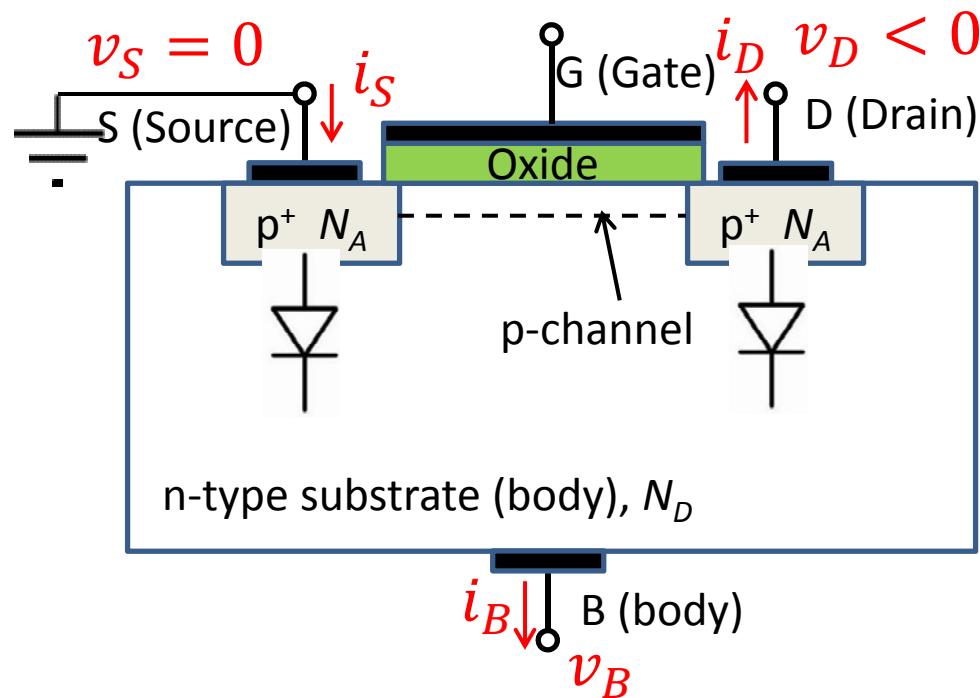
- Same circuit as in e.g. 2, with

$$V_{th} = V_{DD} \frac{R_1}{R_1 + R_2} = 5 \text{ V}$$

$$R_{th} = R_1 || R_2 = 50 \text{ k}\Omega$$

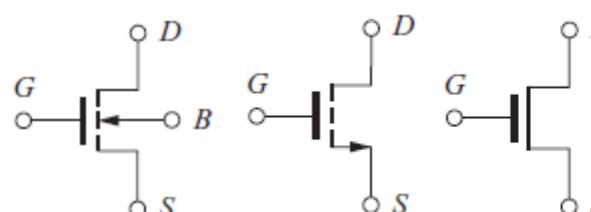
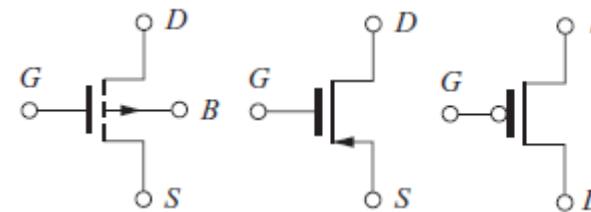
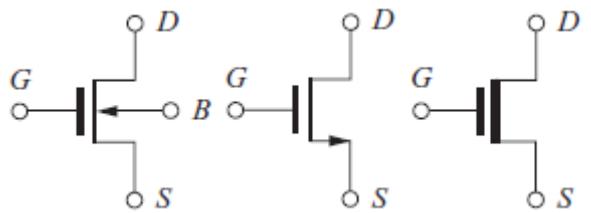
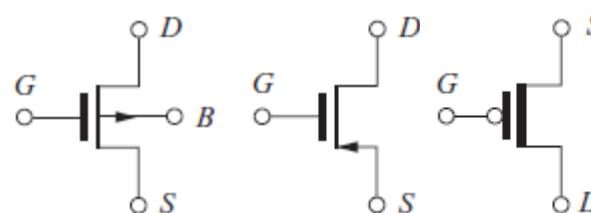
- Read Example 4.3 in the textbook
 - Circuit analysis
 - Advantage of 4-resistor circuits

PMOS Transistors

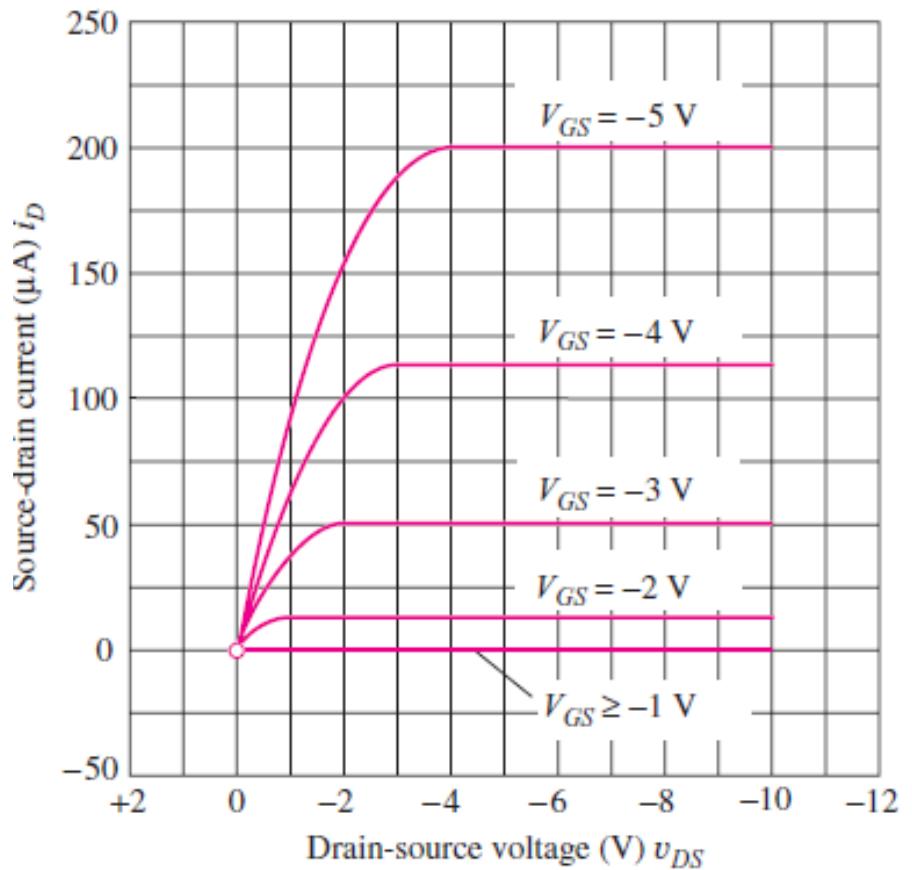
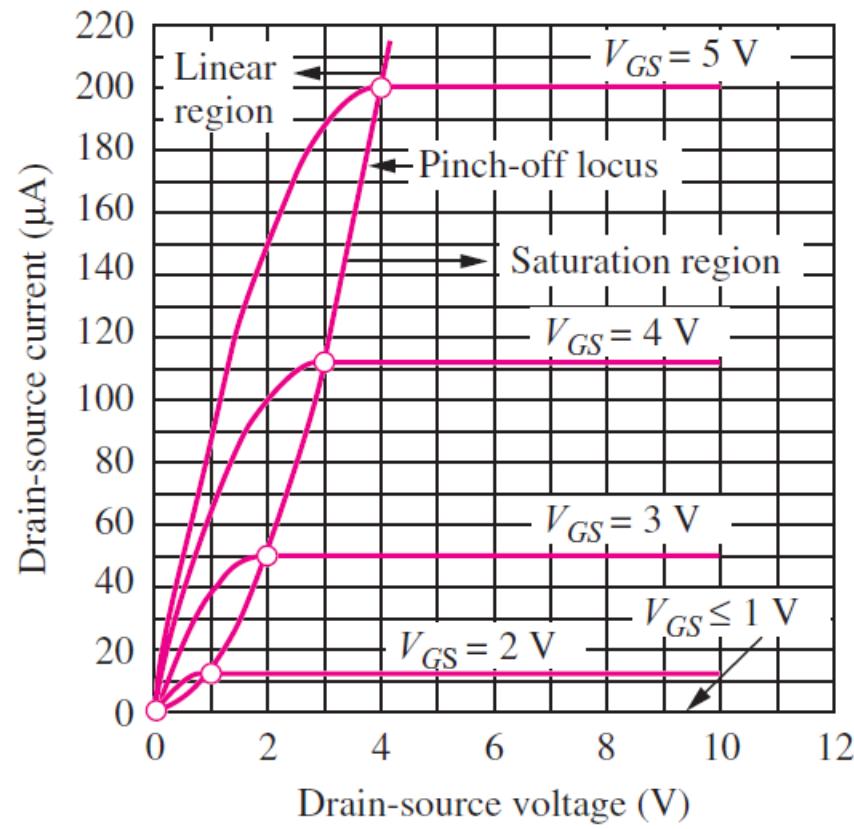


PMOS Physics

MOSFET Circuit Symbols

	NMOS	PMOS
E-Mode	 Three NMOS transistors in E-mode. The first two have their drain terminals (D) connected to ground. The third has its drain terminal (D) connected to its source terminal (S). All three have their gate terminals (G) connected to a common signal line. The body terminals (B) are connected to the source terminals (S).	 Three PMOS transistors in E-mode. The first two have their drain terminals (D) connected to a power supply. The third has its drain terminal (D) connected to its source terminal (S). All three have their gate terminals (G) connected to a common signal line. The body terminals (B) are connected to the source terminals (S).
D-Mode	 Three NMOS transistors in D-mode. The first two have their drain terminals (D) connected to a power supply. The third has its drain terminal (D) connected to its source terminal (S). All three have their gate terminals (G) connected to a common signal line. The body terminals (B) are connected to the source terminals (S).	 Three PMOS transistors in D-mode. The first two have their drain terminals (D) connected to ground. The third has its drain terminal (D) connected to its source terminal (S). All three have their gate terminals (G) connected to a common signal line. The body terminals (B) are connected to the source terminals (S).

N/P-MOS Output Characteristics



NMOS Operation Region

Operation Region	Current Equation	Condition
Cutoff	$i_D = 0$	$v_{GS} \leq V_{TN}$
Triode	$i_D = K'_n \frac{W}{L} \left(v_{GS} - V_{TN} - \frac{v_{DS}}{2} \right) v_{DS}$	$v_{GS} > V_{TN}$ $v_{GS} - V_{TN} > v_{DS}$
Saturation	$i_D = \frac{K'_n}{2} \frac{W}{L} (v_{GS} - V_{TN})^2 (1 + \lambda(v_{DS} - v_{DSat}))$	$v_{GS} > V_{TN}$ $v_{GS} - V_{TN} \leq v_{DS}$

Channel Length Modulation

Body Effect:

$$V_{TN} = V_{TO} + \gamma (\sqrt{v_{SB} + 2\phi_F} - \sqrt{2\phi_F})$$

PMOS Operation Region

Operation Region	Current Equation	Condition
Cutoff	$i_D = 0$	$v_{GS} \geq V_{TP}$
Triode	$i_D = K'_p \frac{W}{L} \left(v_{GS} - V_{TP} - \frac{v_{DS}}{2} \right) v_{DS}$	$v_{GS} < V_{TP}$ $ v_{GS} - V_{TP} \geq v_{DS} $
Saturation	$i_D = \frac{K'_p}{2} \frac{W}{L} (v_{GS} - V_{TP})^2 (1 + \lambda v_{DS} - v_{DSat})$	$v_{GS} < V_{TP}$ $ v_{GS} - V_{TP} < v_{DS} $

Body Effect:

$$V_{TP} = V_{TO} - \gamma (\sqrt{v_{BS} + 2\phi_F} - \sqrt{2\phi_F})$$

Enhancement mode PMOS: $V_{TP} < 0$

Depletion mode PMOS: $V_{TP} > 0$