Chapter 4

Single-stage MOS amplifiers

Single-stage MOS amplifiers

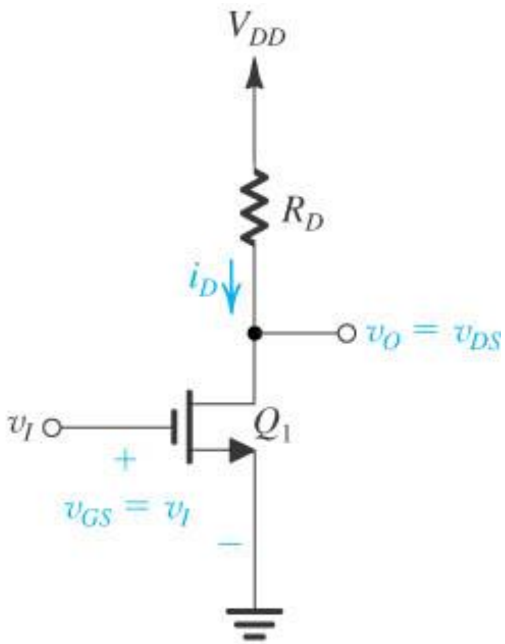
Outline

- NMOS as an amplifier: example of common-source circuit
  - NMOS amplifier example
  - Introduction to biasing and small-signal operation
- Biasing in MOS amplifier circuits
  - Fixing VGS
  - Fixing VG and adding a source resistance
  - Using RDG
  - Using a constant-current source
- Small-signal operation and models
  - Introduction to small-signal operation: common-source circuit
  - Small-signal models for NMOS transistors
- Other common single-stage MOS amplifiers
  - Common-source circuit
  - Common-source with source resistance
  - Common-drain circuit
  - Common-gate circuit
- Frequency response of MOSFET
  - HF response of NMOS transistor
  - HF response of common-source amplifier
  - LF response of common-source amplifier

NMOS amplifier example

Common-source amplifier

- common = grounded
- i_D can be defined in two ways
  - Kirchhoff's voltage law in V_{DD}-R_D-v_o loop: $v_o = V_{DD} - R_D i_D$
  - Output of transistor:

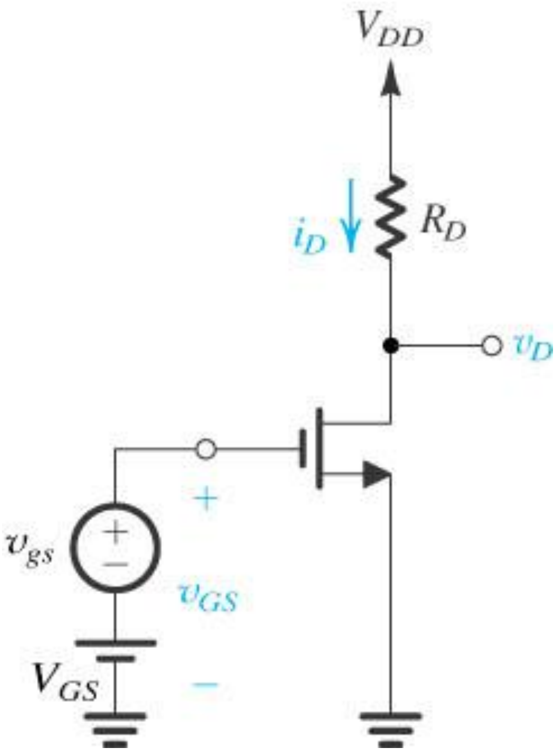


$$\begin{cases} i_D = k_n' \dfrac{W}{L}\left[(v_{GS} - V_T)v_o - \dfrac{1}{2}v_o^2\right] & \text{if } v_{DS} \le v_{GS} - V_T \\ i_D = \dfrac{1}{2}k_n' \dfrac{W}{L}(v_{GS} - V_T)^2 & \text{otherwise} \end{cases}$$

Small-signal operation

Common-source amplifier

- V_{GS} is the constant voltage used to bias the transistor
- v_{gs} is the AC signal to be amplified



$$v_{GS} = V_{GS} + v_{gs}$$

$$\Rightarrow i_D = \frac{1}{2} k_n' \frac{W}{L} \left(V_{GS} + v_{gs} - V_t\right)^2$$

$$\Rightarrow i_D = \frac{1}{2} k_n' \frac{W}{L} \left(V_{GS} - V_t\right)^2 + k_n' \frac{W}{L} \left(V_{GS} - V_t\right) v_{gs} + \frac{1}{2} k_n' \frac{W}{L} v_{gs}^2$$

$$v_{gs} << V_{GS}$$

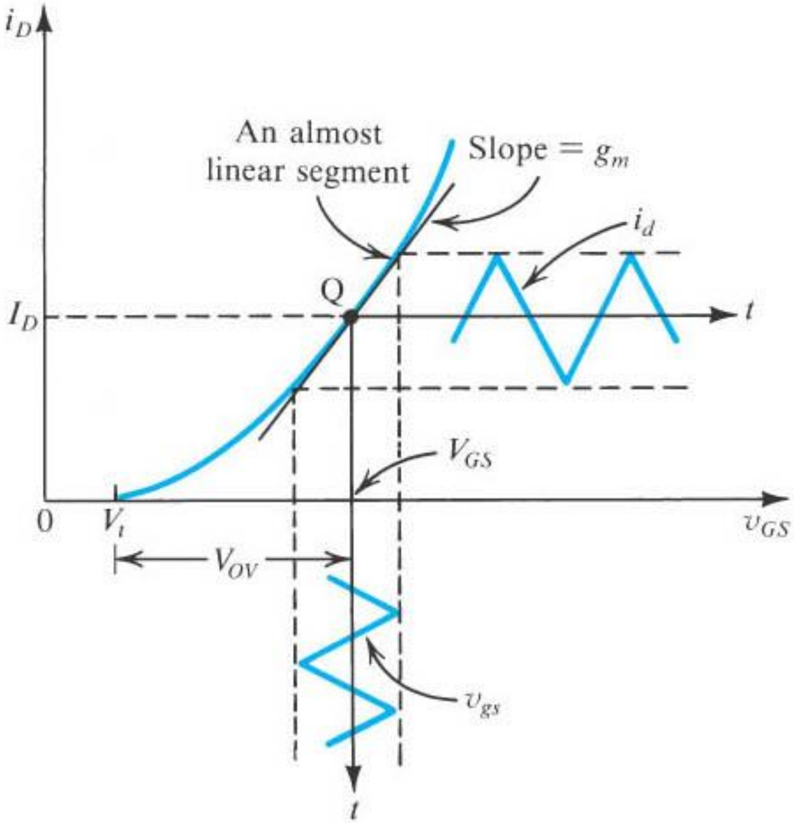
$$\Rightarrow i_D = I_D + i_d \quad \text{with} \quad i_d = k_n' \frac{W}{L} \left(V_{GS} - V_t\right) v_{gs}$$

Small-signal operation

Common-source amplifier

- MOSFET transconductance: $g_m = \frac{i_d}{v_{gs}} = k_n' \frac{W}{L}(V_{GS} - V_t)$

$\Rightarrow$ Equal to slope of iD-vGS characteristic at bias point: $g_m = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$



Biasing: setting the bias point Q

Small-signal operation: signal variations around the point Q

Small-signal operation

Common-source amplifier

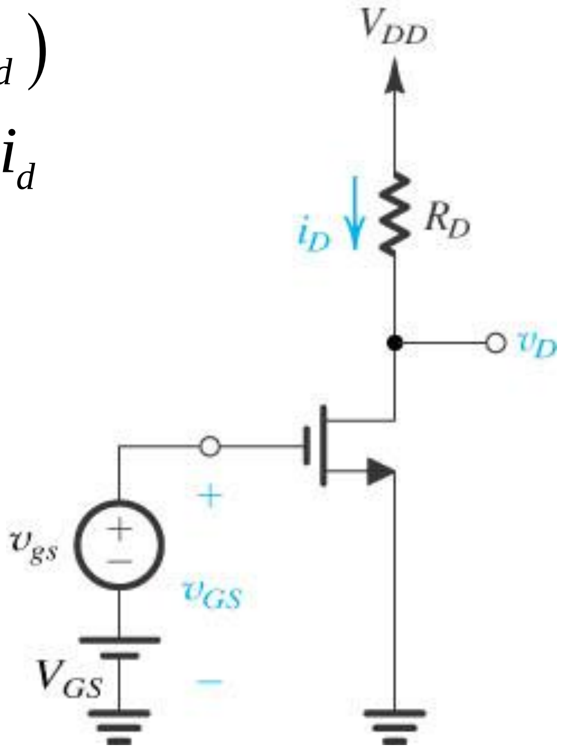
- Output voltage: $v_D = V_{DD} - R_D i_D$

$$= V_{DD} - R_D \left(I_D + i_d \right)$$

$$= \underbrace{V_{DD} - R_D I_D}_{V_D} \underbrace{- R_D i_d}_{= v_d}$$

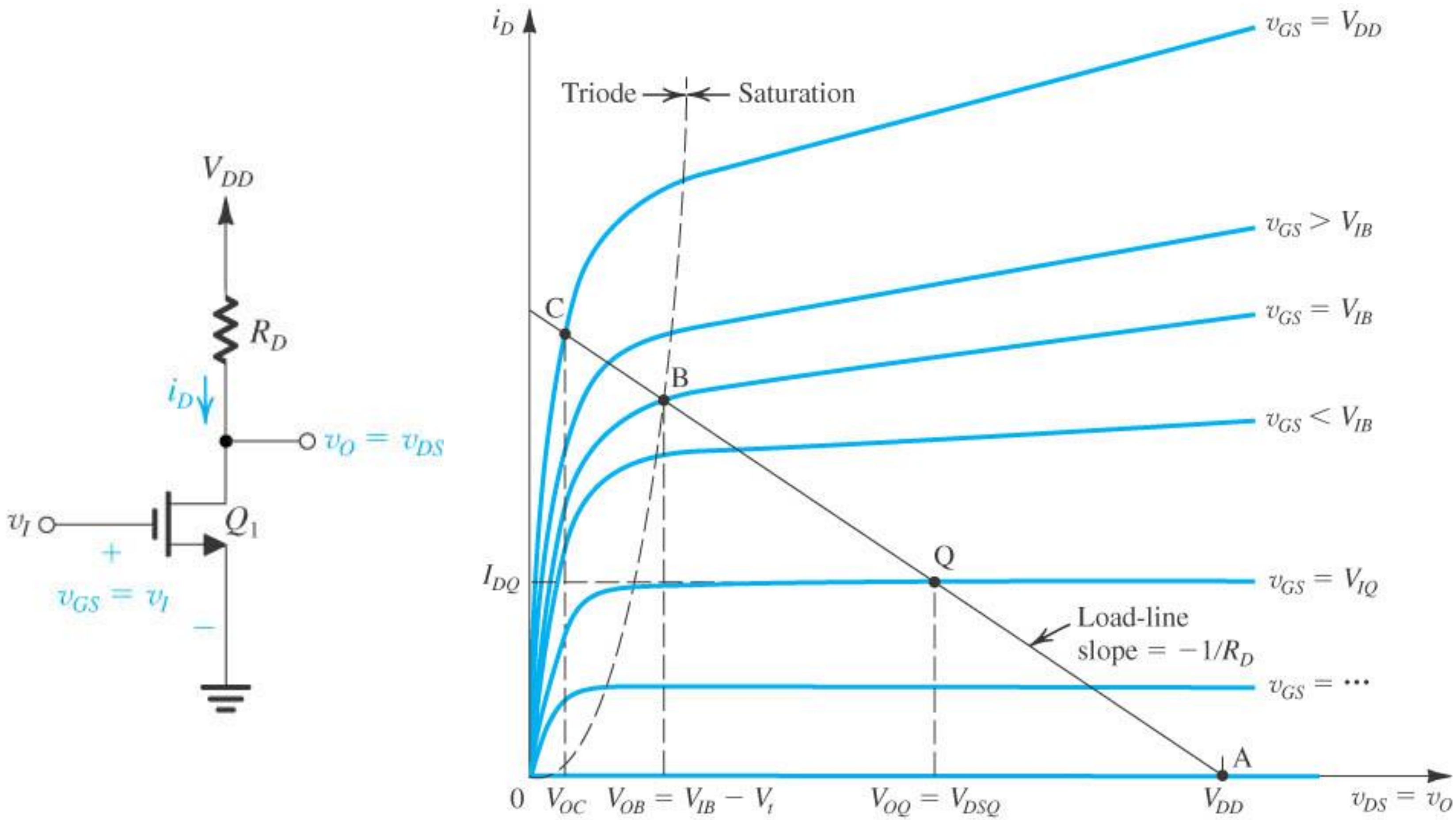
$$\Rightarrow v_d = -R_D i_d = -g_m R_D v_{gs}$$

$$\Rightarrow A_v = \frac{v_d}{v_{gs}} = -g_m R_D$$



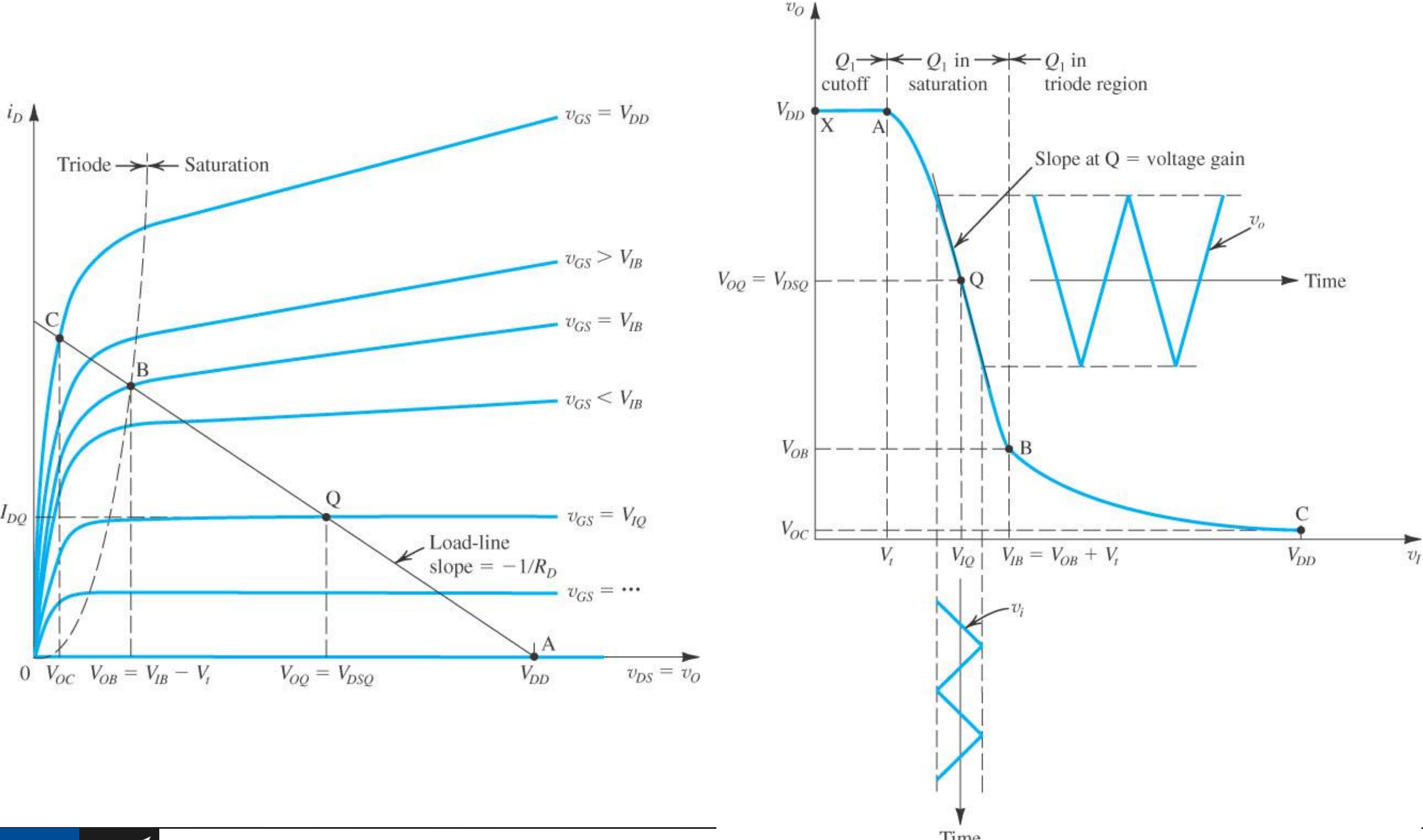
NMOS amplifier example

Common-source amplifier



NMOS amplifier example

Common-source amplifier



NMOS amplifier example

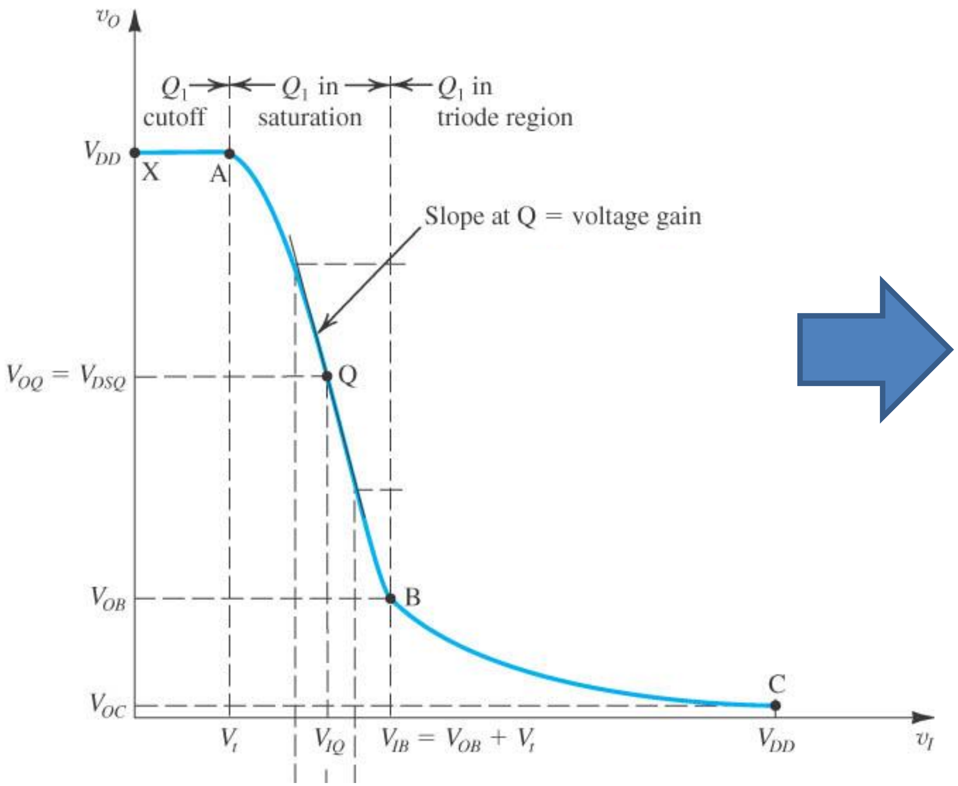
Biasing and small scale signals

- If input: small AC signal v_I (no DC component)

  => Add a DC component so that $v_{GS} = V_{IQ} + v_I$

  $\Rightarrow$ if v_I small, transfer characteristic +/- linear and $v_o = V_{oQ} + Av_I$

  gain of circuit



Biasing => setting the DC signals such that the transistor circuit operates in a linear region for small AC input

Note: choosing the bias point Q appropriately allows for larger AC input signals

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Biasing MOS amplifier circuits

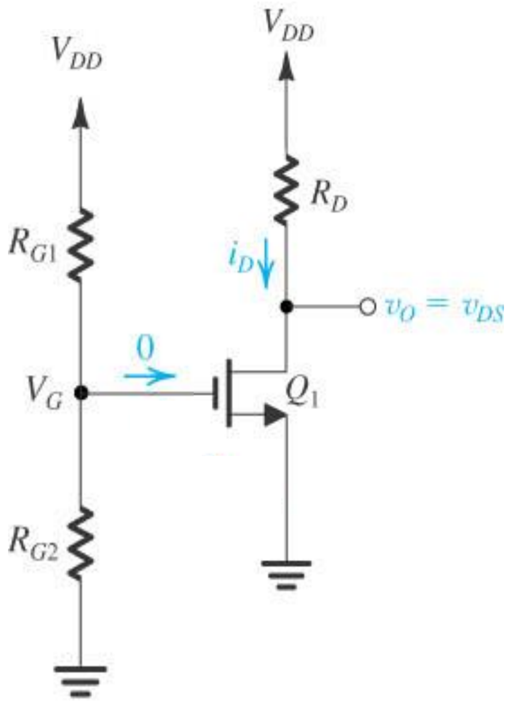
About notations…

- Real voltages and currents in the transistor are noted with lowercase letters and uppercase indices
  - E.g. v_{GS}, i_D, v_{DS}
- DC voltages and currents for biasing a transistor are usually noted with uppercase letters and uppercase indices
  - E.g. V_{GS}, I_D, V_{DS}, …
- Voltage and current variations (AC signals) are noted with lowercase letters and lowercase indices
  - E.g. v_{gs}, i_d, v_{ds}
- In the frequency analysis (LF and HF), AC signals are noted with uppercase letters and lowercase indices
  - E.g. V_{gs}, I_d, V_{ds}

Biasing MOS amplifier circuits

Biasing by fixing V_{GS}

- V_{GS} fixed (e.g. by voltage divider with power supply V_{DD})



$$V_{GS} = V_G - V_S = \frac{R_{G2}}{R_{G1} + R_{G2}} V_{DD}$$

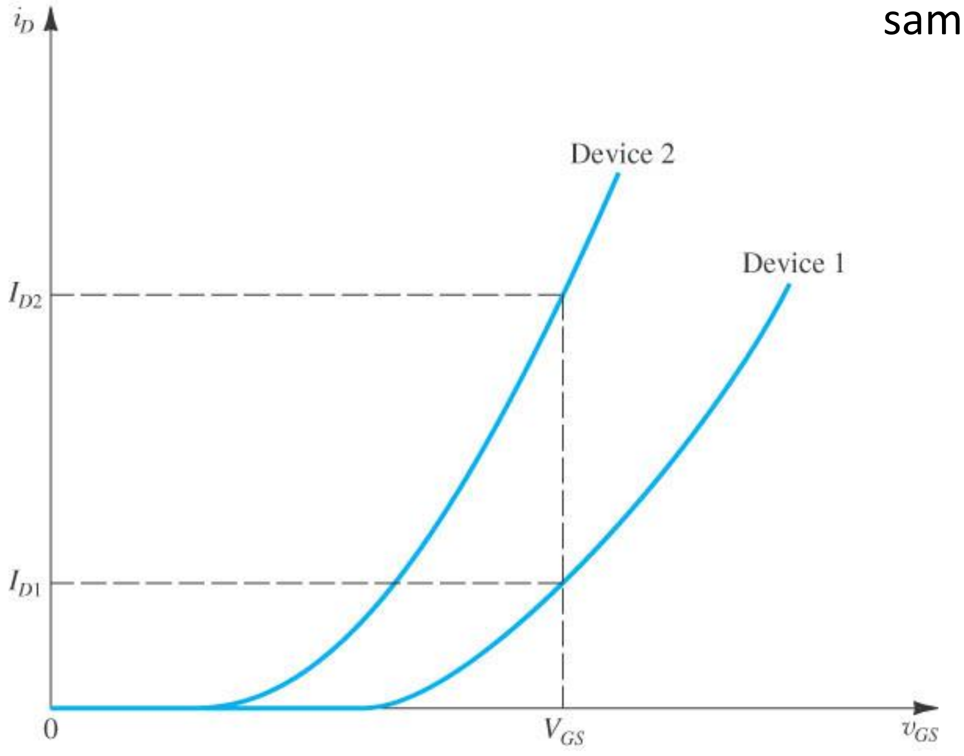
$\Rightarrow$ I_D is fixed through transistor equation $\Rightarrow I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_t)^2$

Biasing MOS amplifier circuits

Biasing by fixing V_{GS}

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{L}(V_{GS} - V_t)^2$$

can vary a lot between transistors, even for devices supposedly of the same size !

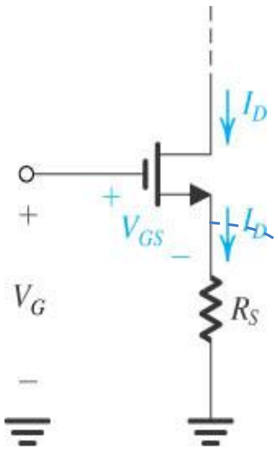


For the same value of V_{GS}, I_D varies a lot between different transistors

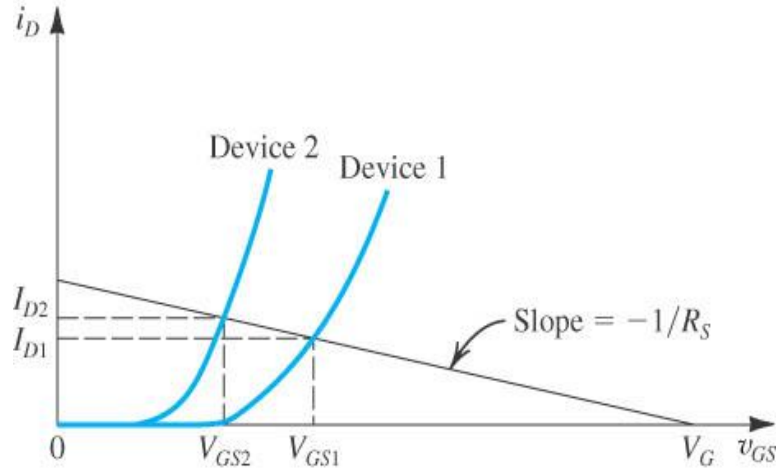
Fixing V_{GS} not a good way to set I_D!

Biasing MOS amplifier circuits

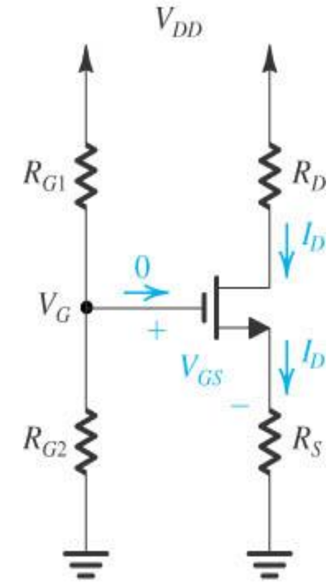
Fixing V_G and adding a source resistance



(a)



(b)



(c)

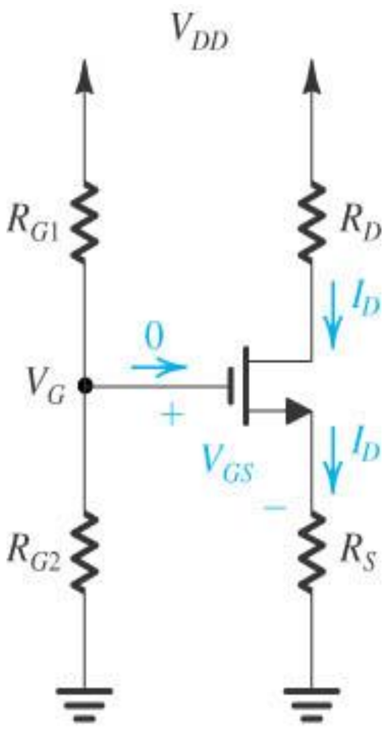
$$V_S = R_s I_D$$

$$\Rightarrow I_D = \frac{V_G - V_{GS}}{R_s}$$

- If R_S is chosen large enough, I_D becomes much more stable w.r.t. manufacturing tolerance
- V_G again set with voltage divider

Biasing MOS amplifier circuits

Fixing V_G and adding a source resistance



⇒ Adding a source resistance makes the transistor biasing much more stable against transistor manufacturing tolerance

- ⇒ I_D does not change so much between transistors

⇒ Key idea: set I_D (and let V_{GS} vary depending on transistor)

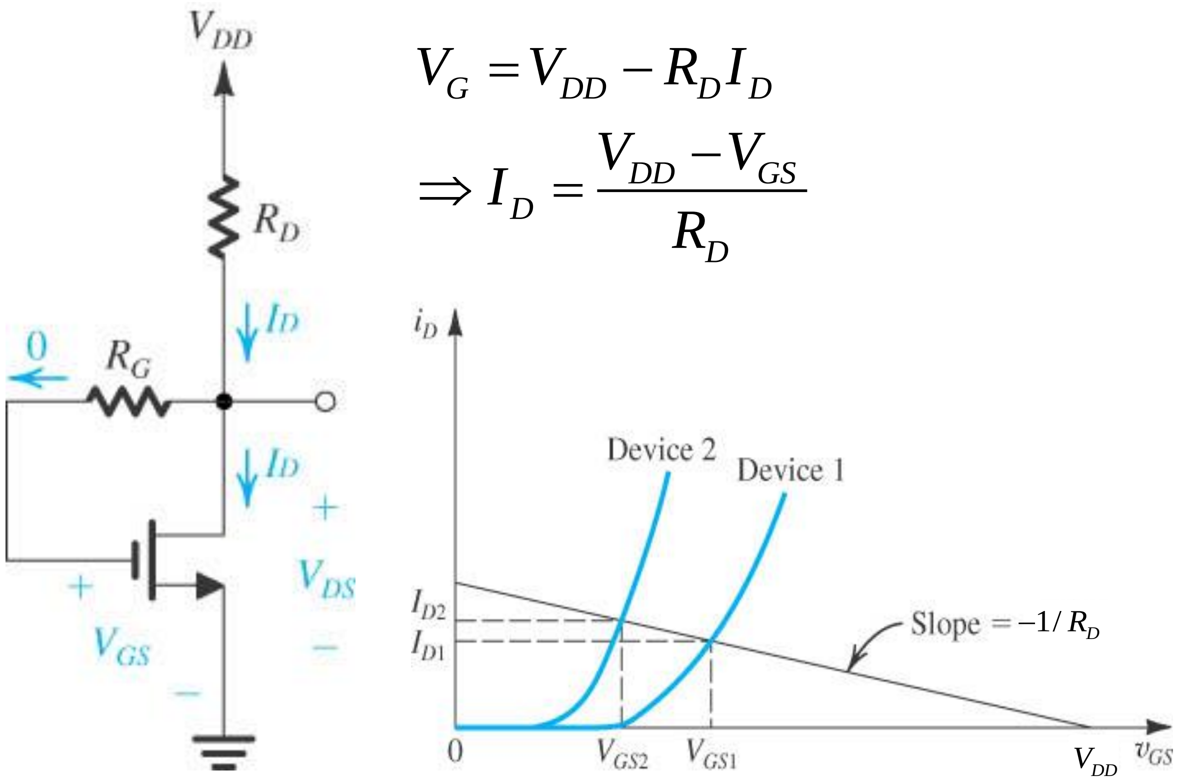
⇒ Choosing large values for R_{G1} and R_{G2} ensures that the circuit has large input impedance

Biasing MOS amplifier circuits

Using a drain-to-gate feedback resistor

$$V_G = V_{DD} - R_D I_D$$

$$\Rightarrow I_D = \frac{V_{DD} - V_{GS}}{R_D}$$



- Similar to previous biasing scheme
- R_G chosen large (usually MΩ range) to force I_G=0

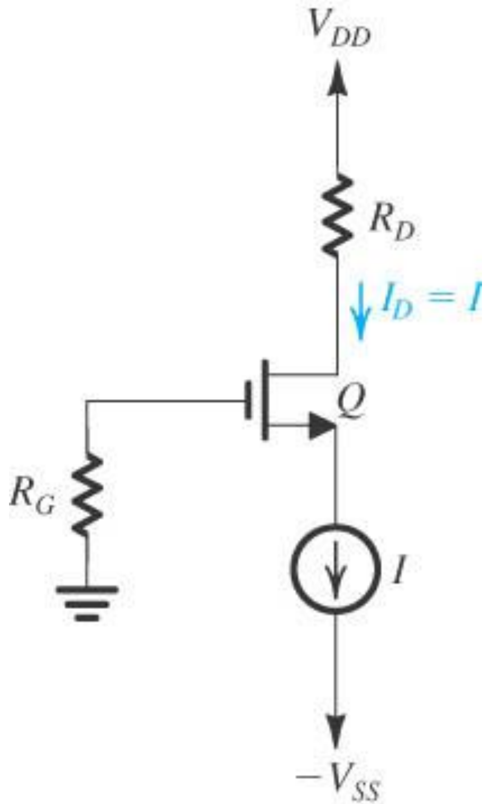
Biasing MOS amplifier circuits

Using a constant-current source

- Set I_D with a constant-current source

  ⇒ V_G = 0 in this circuit

  ⇒ V_S is such that V_{GS} matches I_D



I_D fixed

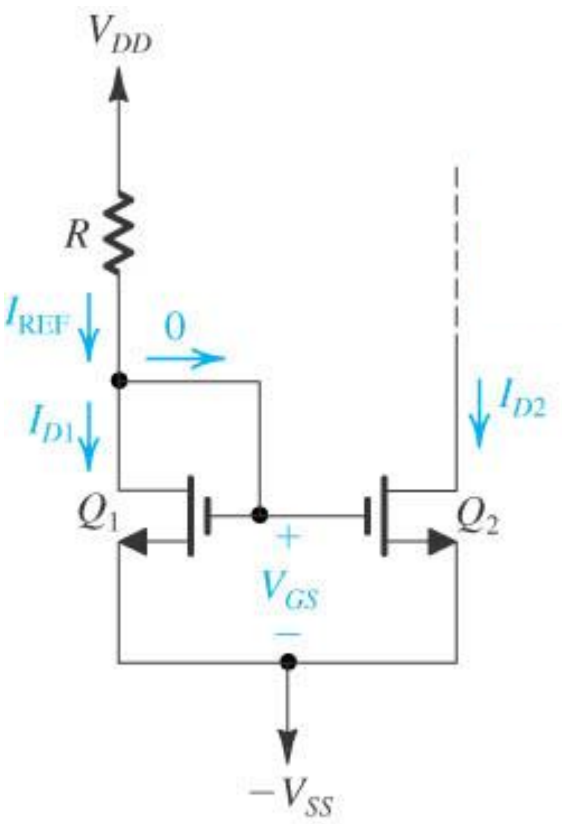
$V_{GS} = V_t + \sqrt{2I_D/(k_n' W/L)}$

Saturation region iif $V_{DS} \geq V_{GS} - V_t$
iif $V_D \geq -V_t$

Biasing MOS amplifier circuits

… making a current source with 2 NMOS transistors

Current mirror



- Drain Q1 connected to gate Q1:

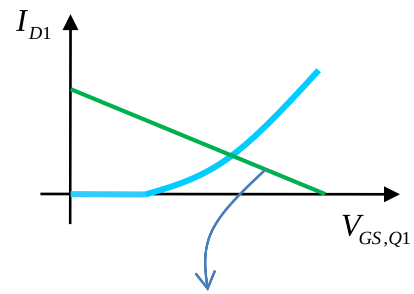
$$V_{D,Q1} = V_{G,Q1}$$

$$\Rightarrow V_{DS,Q1} > V_{GS,Q1} - V_t$$

$$\Rightarrow \text{saturation region}$$

- I_{REF} fixed by R, V_{DD}, V_{SS} and NMOS:

$$\begin{cases} I_{\mathrm{REF}} = \dfrac{V_{DD} + V_{SS} + V_{GS,Q1}}{R} \\ I_{\mathrm{REF}} = \dfrac{1}{2} k_n' \dfrac{W_{Q1}}{L_{Q1}} \left(V_{GS,Q1} - V_t\right)^2 \end{cases}$$



$$I_{D1} = \frac{V_{DD} + V_{SS} + V_{GS,Q1}}{R}$$

- $$V_{GS,Q1} = V_{GS,Q2}$$

$$\Rightarrow I_{D2} = \frac{1}{2} k_n' \frac{W_{Q2}}{L_{Q2}} \left(V_{GS,Q2} - V_t\right)^2$$

$$\Rightarrow I_{D2} = I_{REF} \frac{W_{Q2} / L_{Q2}}{W_{Q1} / L_{Q1}}$$

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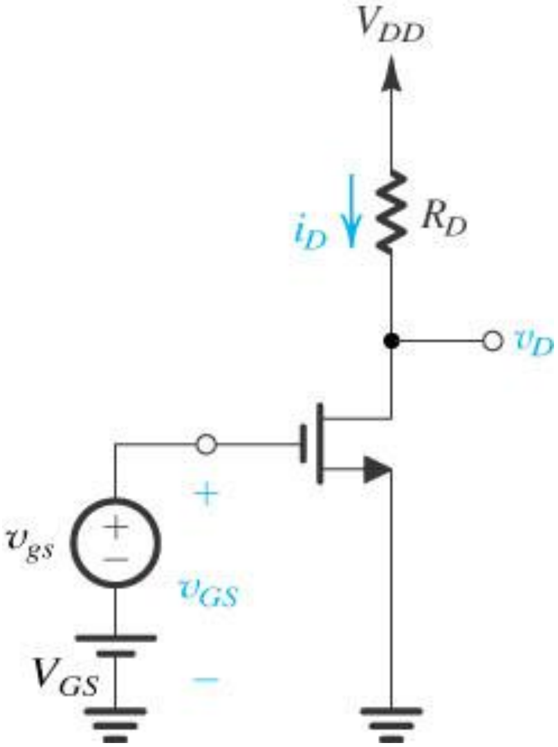
Small-signal operation

Example of the common-source circuit

- V_{GS} is the constant voltage used to bias the transistor
- v_{gs} is the AC signal to be amplified



$$v_{GS} = V_{GS} + v_{gs}$$

$$\Rightarrow i_D = \frac{1}{2} k_n' \frac{W}{L} \left(V_{GS} + v_{gs} - V_t\right)^2$$

$$\Rightarrow i_D = \frac{1}{2} k_n' \frac{W}{L} \left(V_{GS} - V_t\right)^2 + k_n' \frac{W}{L} \left(V_{GS} - V_t\right) v_{gs} + \frac{1}{2} k_n' \frac{W}{L} v_{gs}^2$$

$$v_{gs} << V_{GS}$$

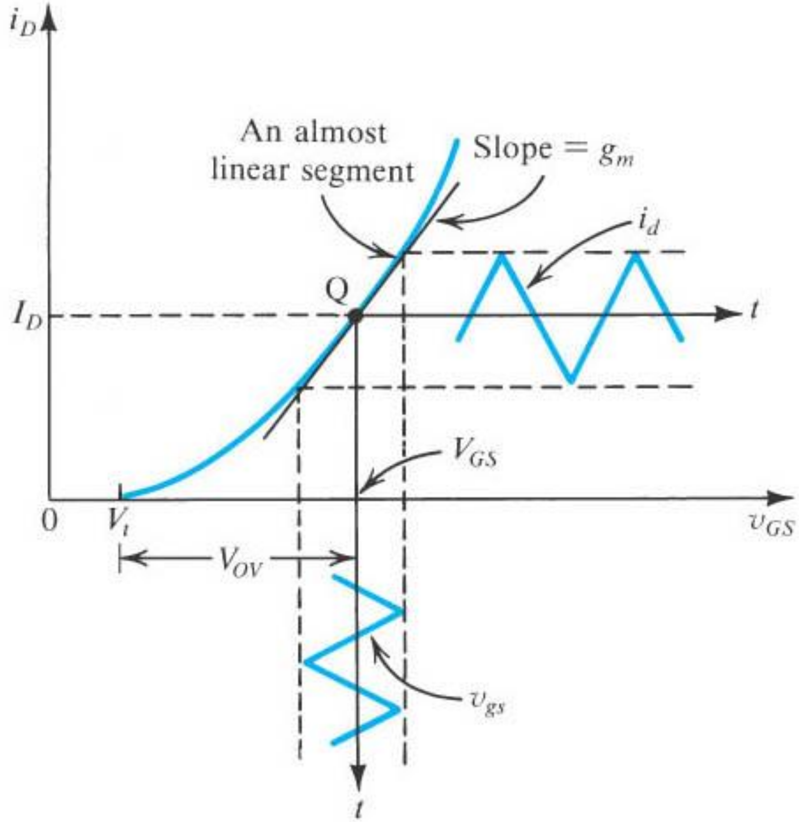
$$\Rightarrow i_D = I_D + i_d \quad \text{with} \quad i_d = k_n' \frac{W}{L} \left(V_{GS} - V_t\right) v_{gs}$$

Small-signal operation

Example of the common-source circuit

- MOSFET transconductance: $g_m = \dfrac{i_d}{v_{gs}} = k_n' \dfrac{W}{L}(V_{GS} - V_t)$

$\Rightarrow$ Equal to slope of iD-vGS characteristic at bias point: $g_m = \left.\dfrac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$



Biasing: setting the bias point Q

Small-signal operation: signal variations around the point Q

Small-signal operation

Example of the common-source circuit

- Output voltage: $v_D = V_{DD} - R_D i_D$

$$= V_{DD} - R_D \left(I_D + i_d \right)$$

$$= \underbrace{V_{DD} - R_D I_D}_{V_D} \underbrace{- R_D i_d}_{= v_d}$$

$$\Rightarrow v_d = -R_D i_d = -g_m R_D v_{gs}$$

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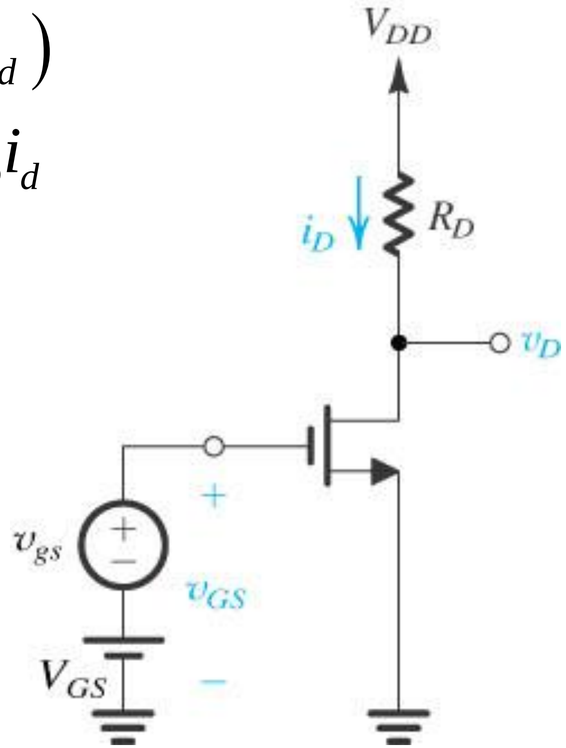


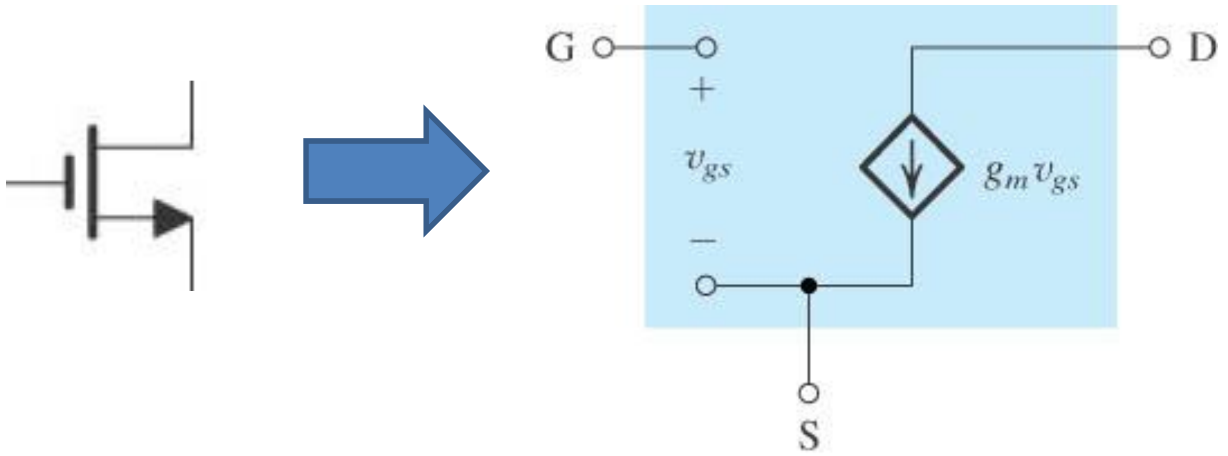
Small signal equivalent-circuit models

For small- signal operation, MOSFET transistor…

… behaves like a voltage-controlled current source

- ⇒ Input voltage v_{gs} between gate and source
- ⇒ Input resistance is very high (+/- infinite)
- ⇒ Ouptut current $g_m v_{gs}$ at drain terminal

⇒ when analyzing (small) AC signal component, NMOS can be replaced with small-signal equivalent



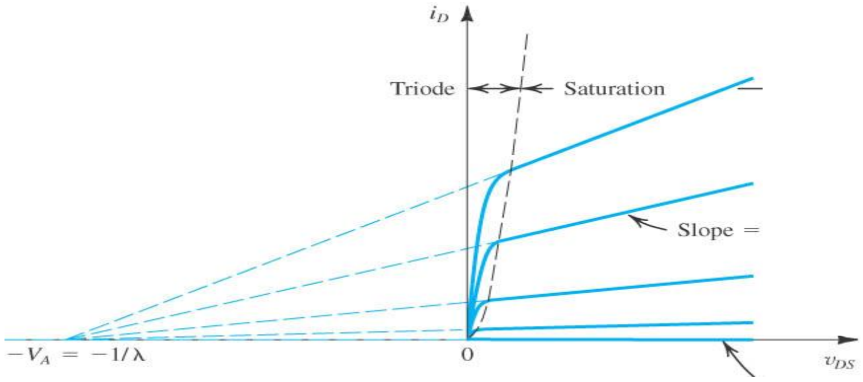
NMOS small-signal model

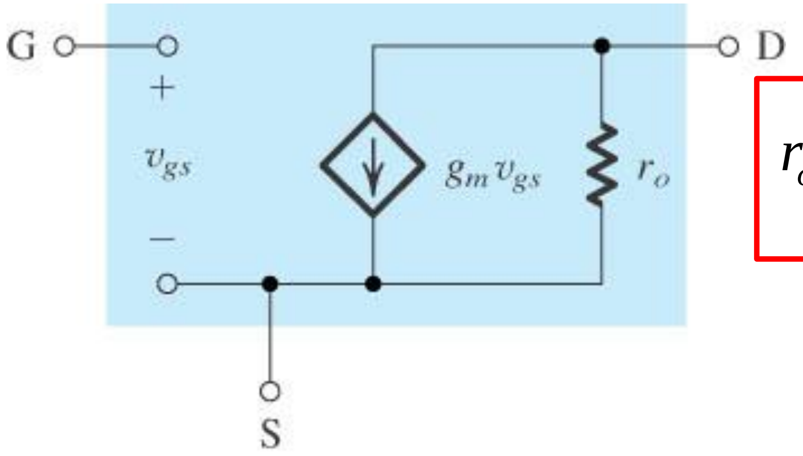
… taking into account output resistance

… due to channel pinching

⇒ Variations in v_{DS} result in different i_D

⇒ Imperfect current source





$$r_o = \frac{V_A}{I_D} \qquad g_m = k_n'(W/L)(V_{GS} - V_t)$$

g_m and r_o depend on biasing point !!!

NMOS small-signal model

g_m can be expressed several ways

$$g_m = \frac{i_d}{v_{gs}} = k_n' \frac{W}{L}(V_{GS} - V_t)$$

$$I_D = \frac{1}{2} k_n' \frac{W}{L}(V_{GS} - V_t)^2 \quad \Rightarrow \quad (V_{GS} - V_t) = \sqrt{2 \frac{L}{W} \frac{1}{k_n'} I_D}$$

$$\Rightarrow g_m = \sqrt{2 k_n' \frac{W}{L} I_D}$$

$$I_D = \frac{1}{2} k_n' \frac{W}{L}(V_{GS} - V_t)^2 \quad \Rightarrow \quad k_n' \frac{W}{L} = \frac{2 I_D}{(V_{GS} - V_t)^2}$$

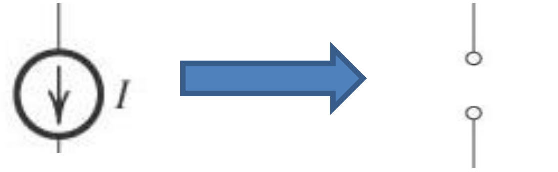
$$\Rightarrow g_m = \frac{2 I_D}{V_{GS} - V_t}$$

Small-signal models

Converting a circuit to its small-signal equivalent

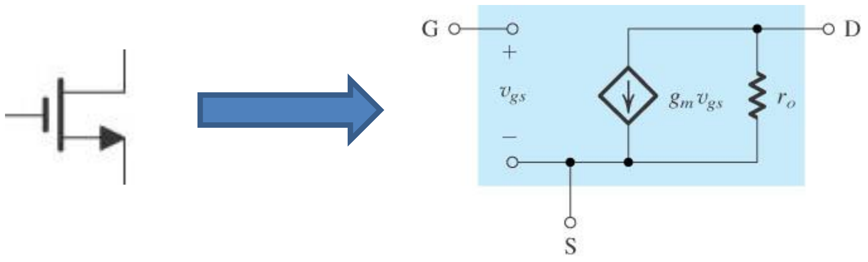
- DC voltage sources => short-circuits

- DC current sources => open-circuits



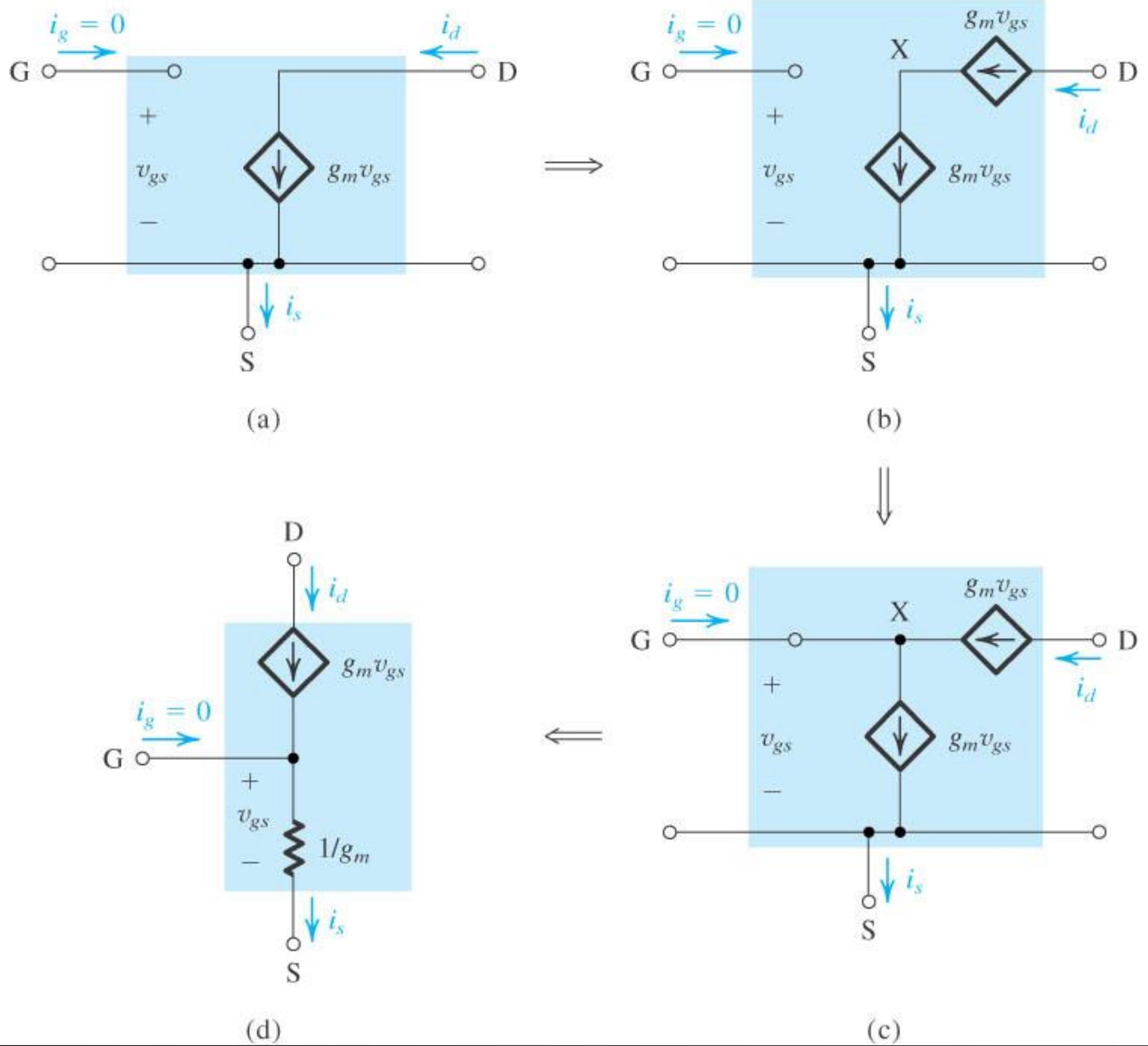
- Capacitors => short-circuits

- Transistors => equivalent mode



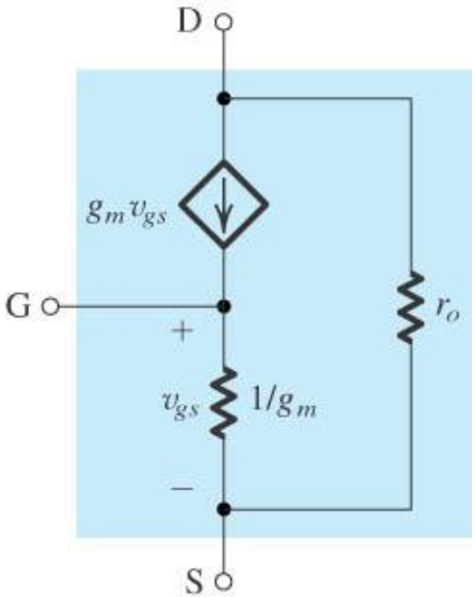
Small-signal models

T equivalent-circuit model for NMOS transistor



Small-signal models

T model with output resistance



$$i_g = 0 \quad \Rightarrow \quad r_{in} = \infty$$

$$g_m = k_n'\left(W/L\right)\left(V_{GS} - V_t\right)$$

$$r_o = \frac{V_A}{I_D}$$

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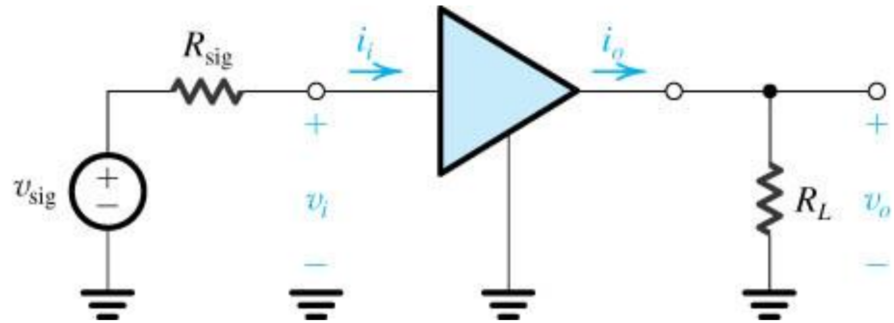
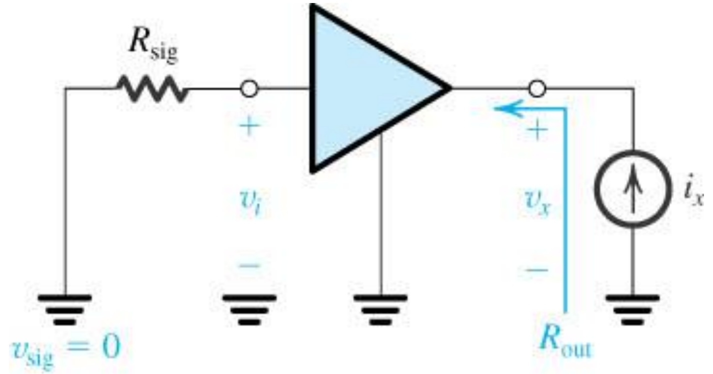
Amplifiers

Definitions and general characteristics

- Open-circuit voltage gain: $A_{vo} = \left. \frac{v_o}{v_i} \right|_{R_L = \infty}$
- Voltage gain: $A_v = \frac{v_o}{v_i}$
- Input resistance: $R_i = \frac{v_i}{i_i}$



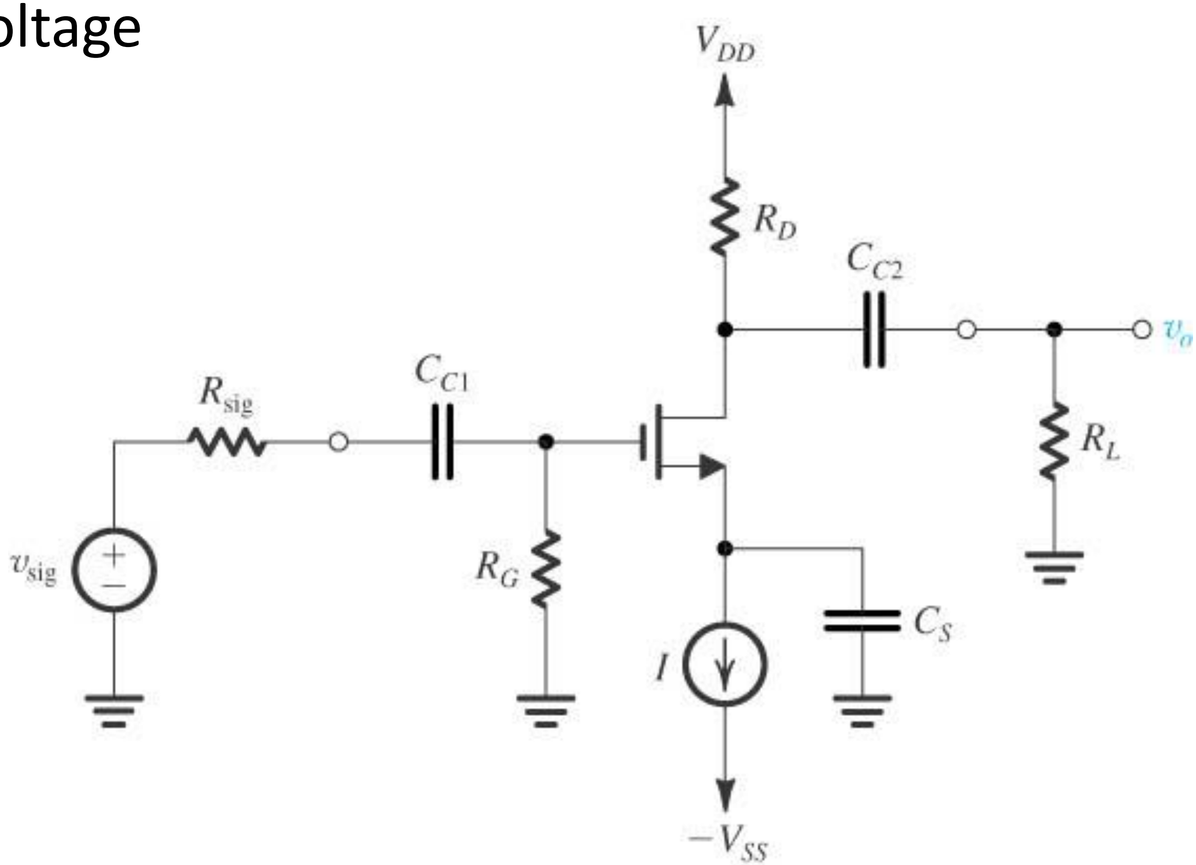
- Output resistance: $R_o = \left. \frac{v_x}{i_x} \right|_{v_{sig} = 0}$



Common-source amplifier

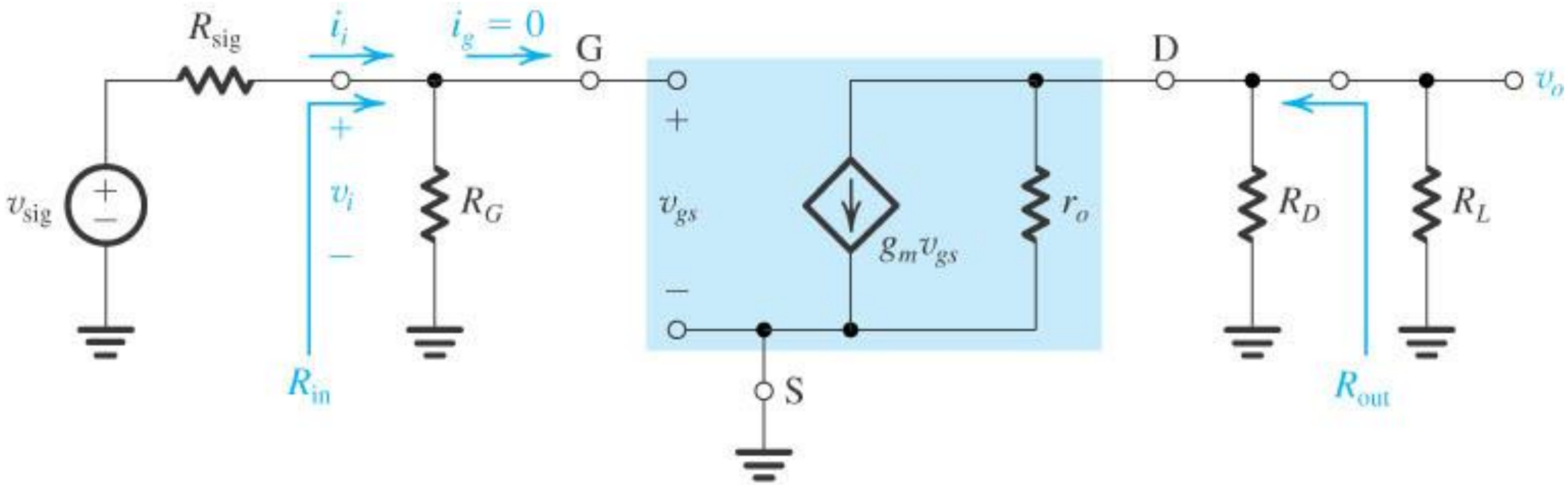
Biased with constant-current source

- Bypass capacitor C_S for connecting source to ground (in AC)
- Coupling capacitors C_{C1} and C_{C2} in order not to disturb the DC bias voltage



Common-source amplifier

Replace circuit with small-signal equivalent



$$i_g = 0 \;\Rightarrow\; v_i = \frac{R_G}{R_G + R_{sig}} v_{sig}$$

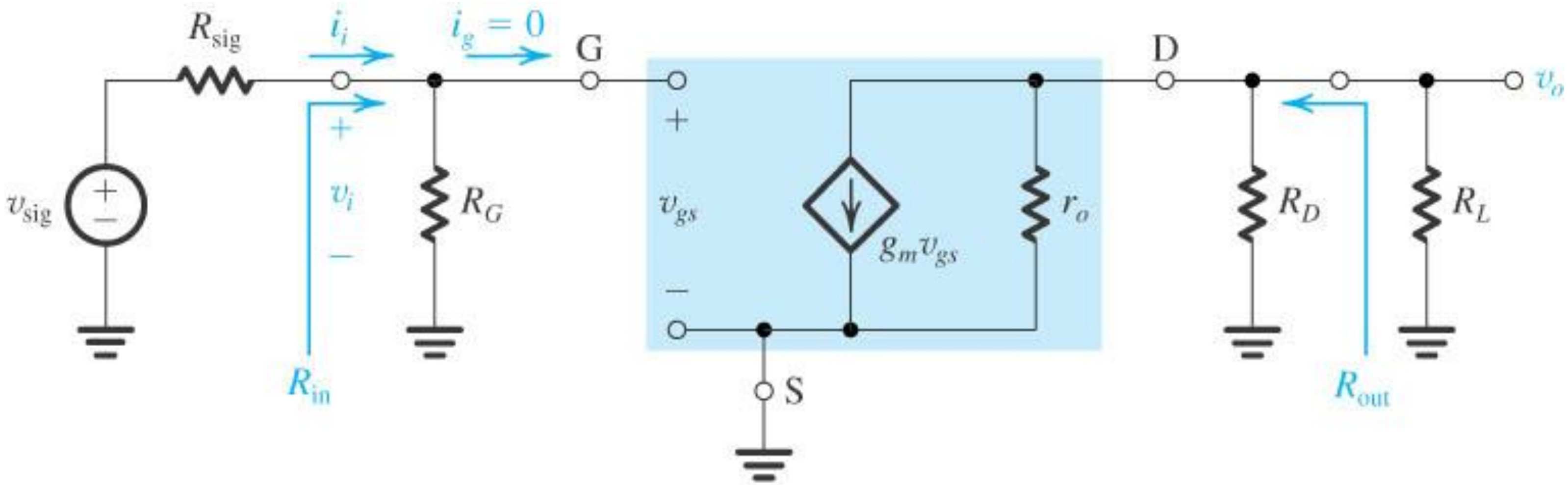
$$v_{gs} = v_i \;\Rightarrow\; v_o\big|_{R_L=\infty} = -\left(r_o \,\|\, R_D\right) g_m v_i$$

$$\Rightarrow\; A_{vo} = -\left(r_o \,\|\, R_D\right) g_m$$

$$\Rightarrow\; A_v = -\left(r_o \,\|\, R_D \,\|\, R_L\right) g_m$$

Common-source amplifier

Replace circuit with small-signal equivalent



$$R_i = \frac{v_i}{i_i}$$

$$\Rightarrow \quad R_i = R_G$$

$$R_o = \left.\frac{v_x}{i_x}\right|_{v_{sig}=0}$$

$$\Rightarrow \quad R_o = \left(r_o \parallel R_D\right)$$

Common-source amplifier

Summary

$$\Rightarrow \quad A_{vo} = -\left(r_o \parallel R_D\right) g_m$$

$$\Rightarrow \quad A_v = -\left(r_o \parallel R_D \parallel R_L\right) g_m$$

$$\Rightarrow \quad R_i = R_G$$

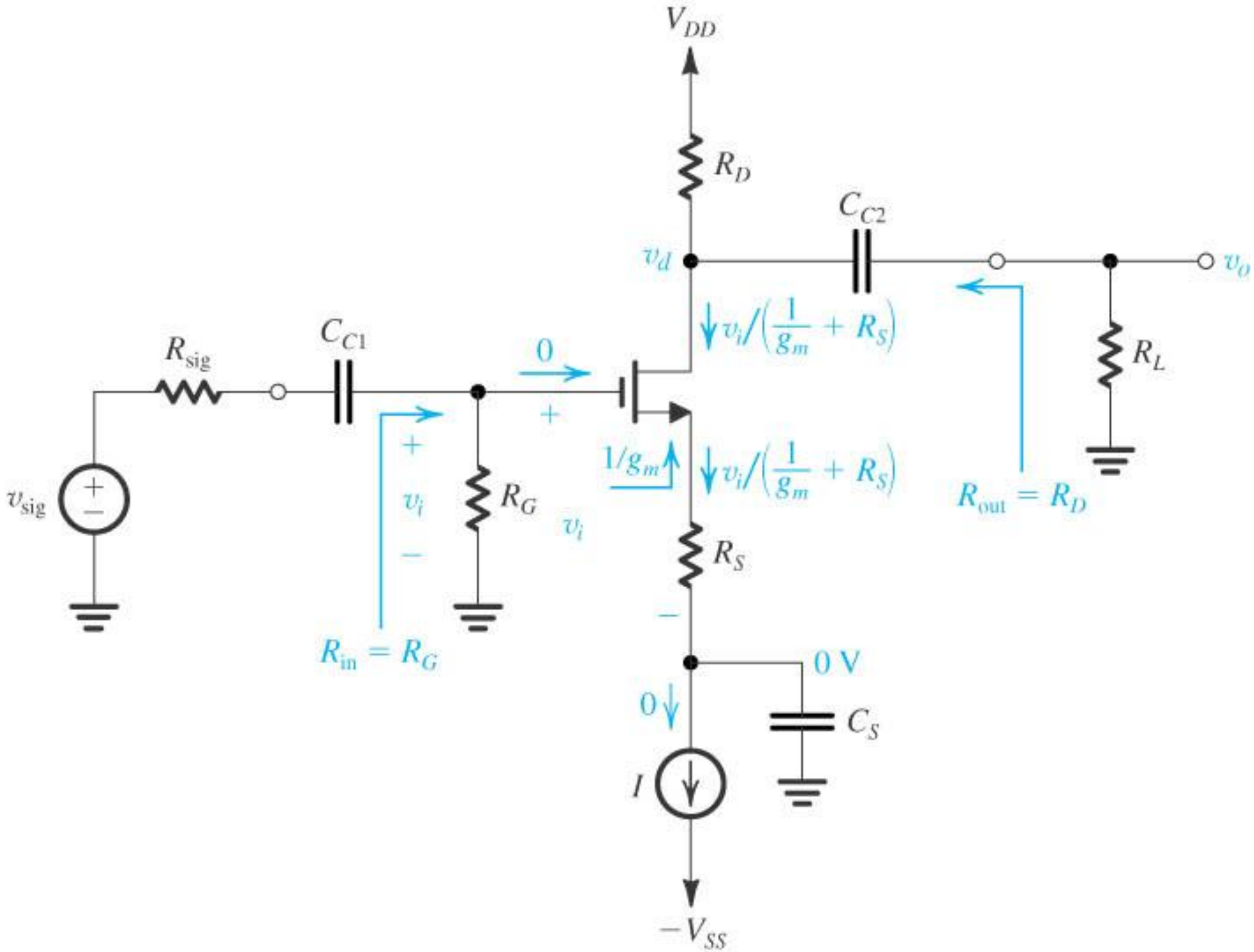
$$\Rightarrow \quad R_o = \left(r_o \parallel R_D\right)$$

R_D large or small ??

- Moderately high voltage gain
- High input resistance
- Relatively high output resistance

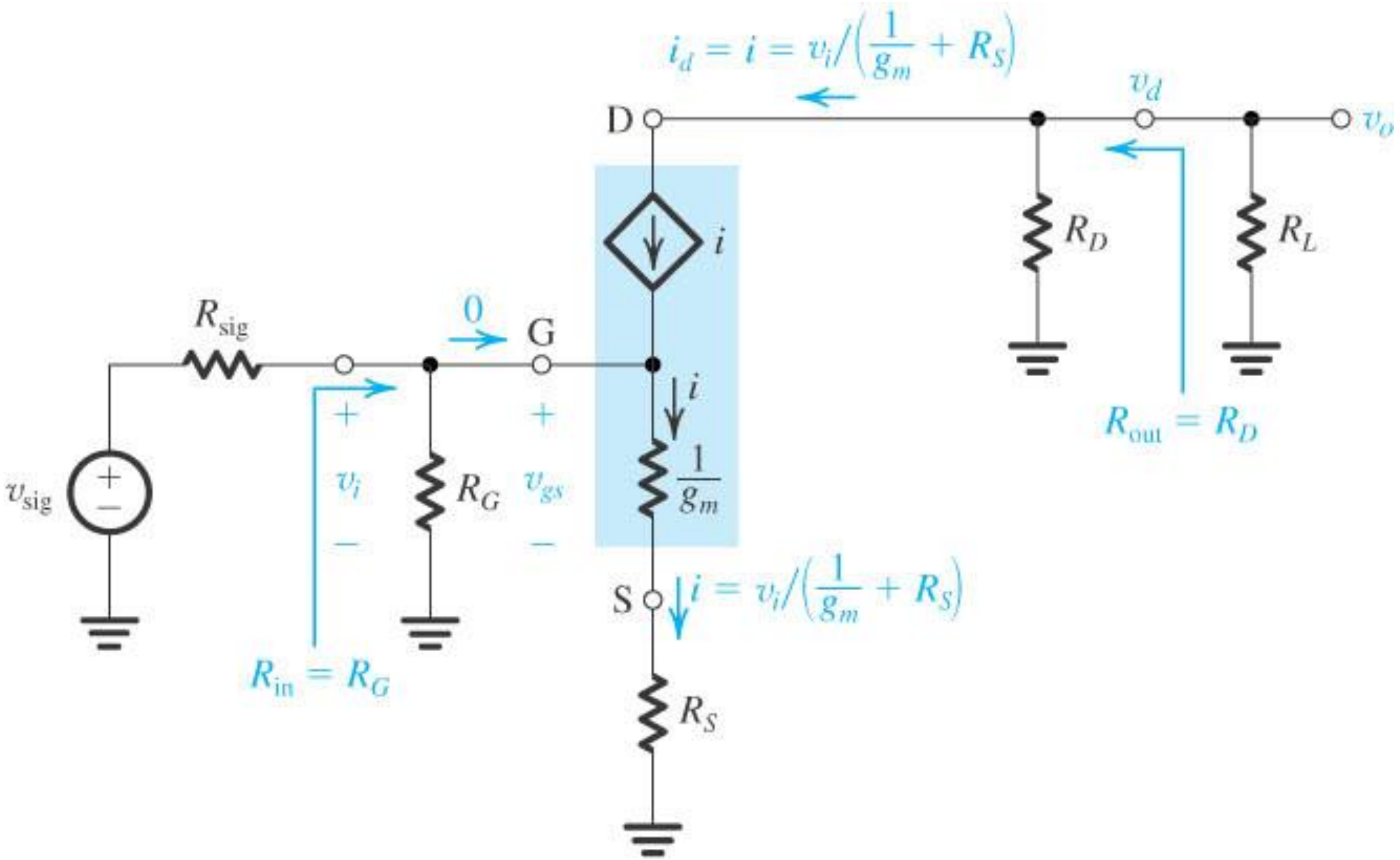
CS amplifier with source resistance

R_S at source terminal, biased with current source



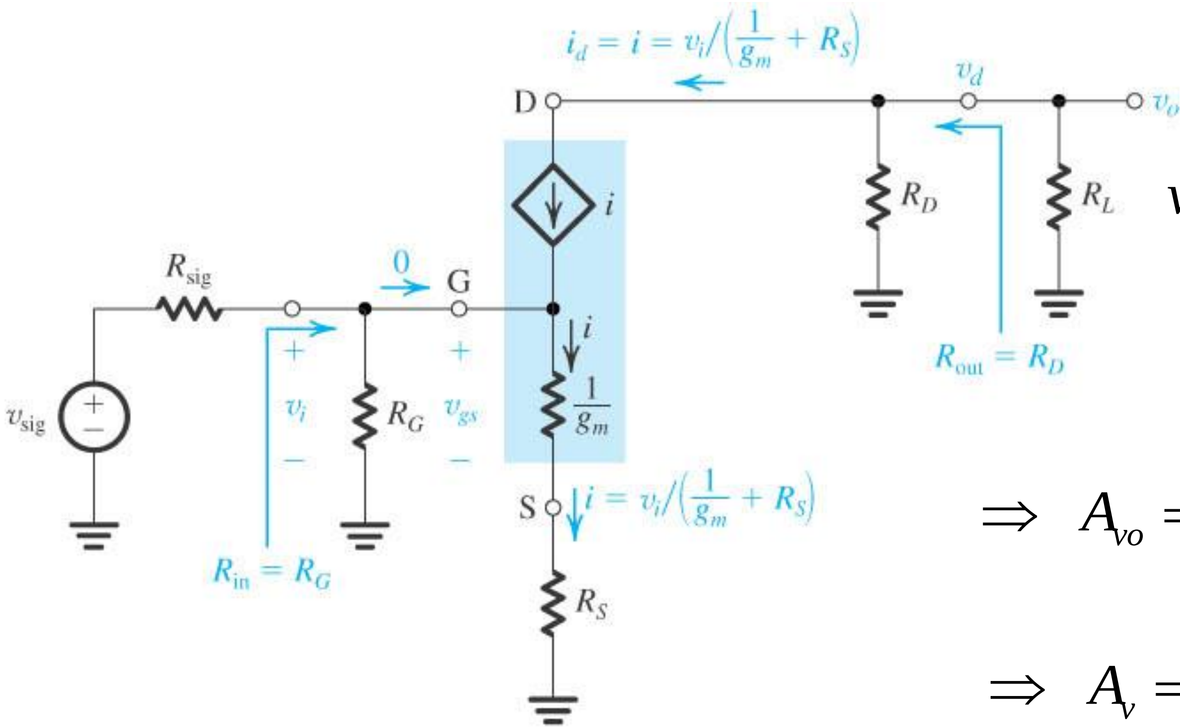
CS amplifier with source resistance

Use T model for small-signal equivalent (neglect r_o)



CS amplifier with source resistance

Use T model for small-signal equivalent



$$v_{gs} = \frac{1/g_m}{1/g_m + R_S} v_i$$

$$\Rightarrow i = g_m v_{gs} = \frac{1}{1/g_m + R_S} v_i$$

$$\Rightarrow A_{vo} = -\frac{g_m R_D}{1 + g_m R_S}$$

$$\Rightarrow A_v = -\frac{g_m (R_D \parallel R_L)}{1 + g_m R_S}$$

$$\Rightarrow R_i = R_G$$

$$R_o = \left.\frac{v_x}{i_x}\right|_{v_{sig}=0} \Rightarrow R_o = R_D$$

CS amplifier with source resistance

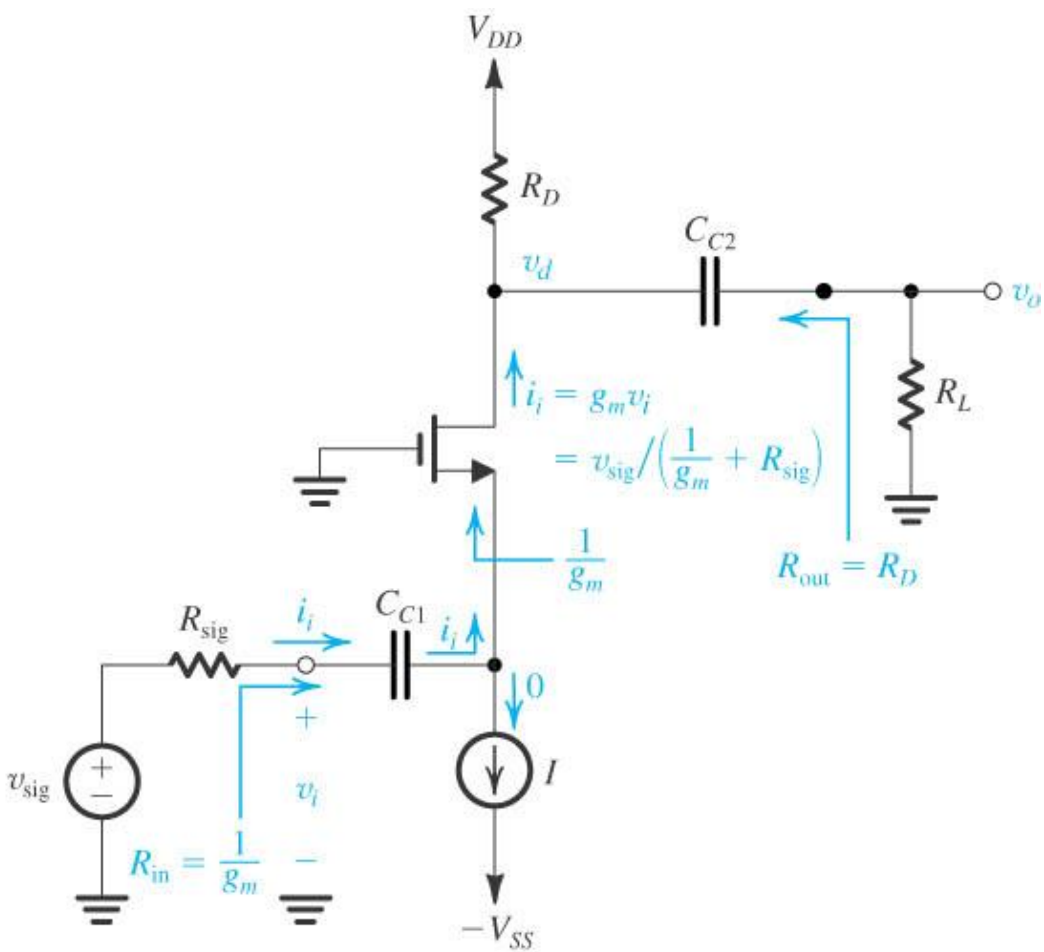
Summary

Compared to CS amplifier

- Decreases gain by factor $1+g_m R_S$
- But remember … adding a resistance at the source makes the biasing much more stable w.r.t. transistor variations
- Input and output resistance identical to CS amplifier

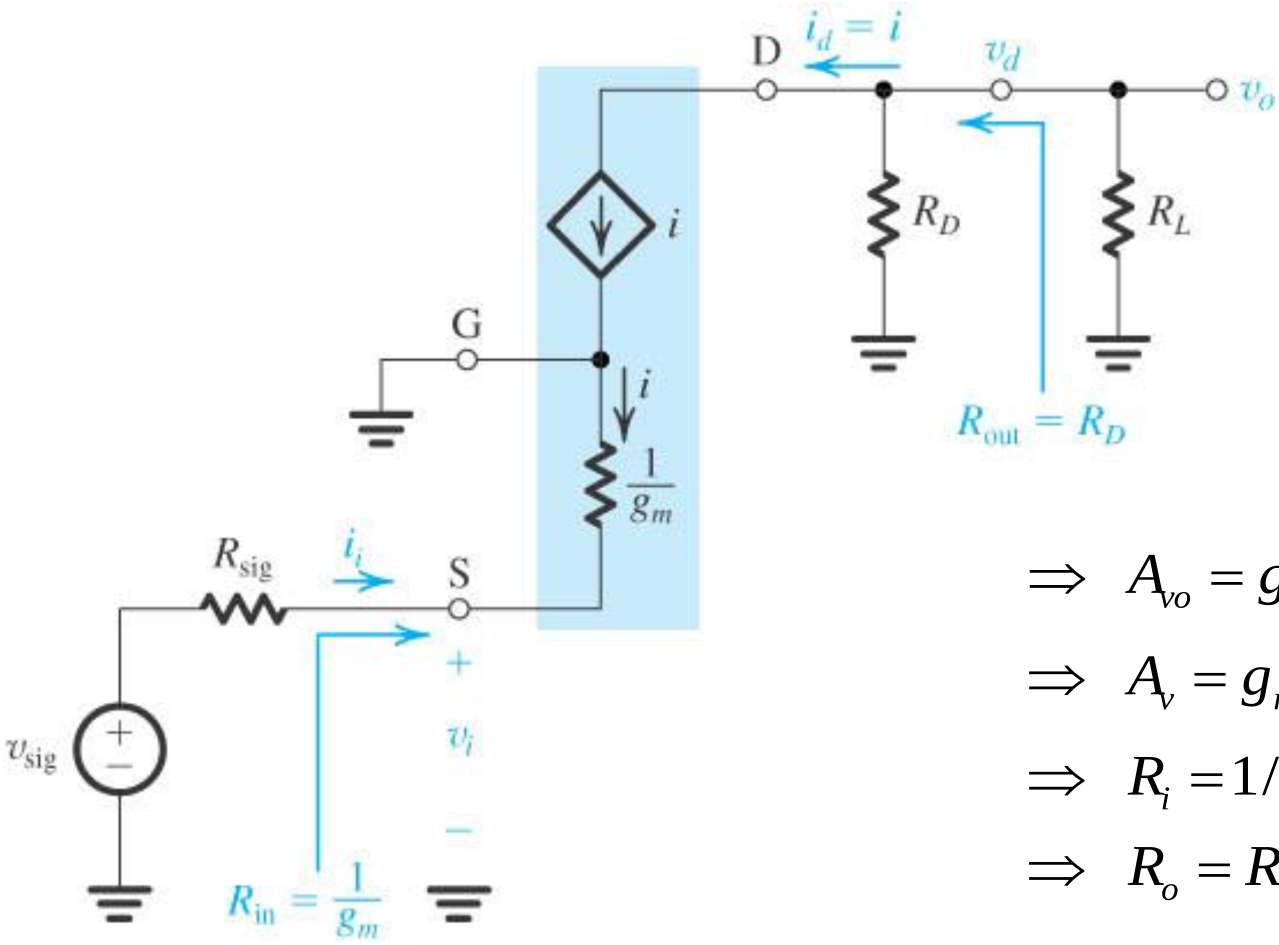
Common-gate amplifier

Input signal applied to source terminal



CG amplifier

Small-signal equivalent (neglecting r_o)



$$v_{gs} = -v_i$$

$$\Rightarrow i = -g_m v_i$$

$$\Rightarrow v_o = \left(R_D \parallel R_L\right) g_m v_i$$

$$\Rightarrow \quad A_{vo} = g_m R_D$$

$$\Rightarrow \quad A_v = g_m \left(R_D \parallel R_L\right)$$

$$\Rightarrow \quad R_i = 1/g_m$$

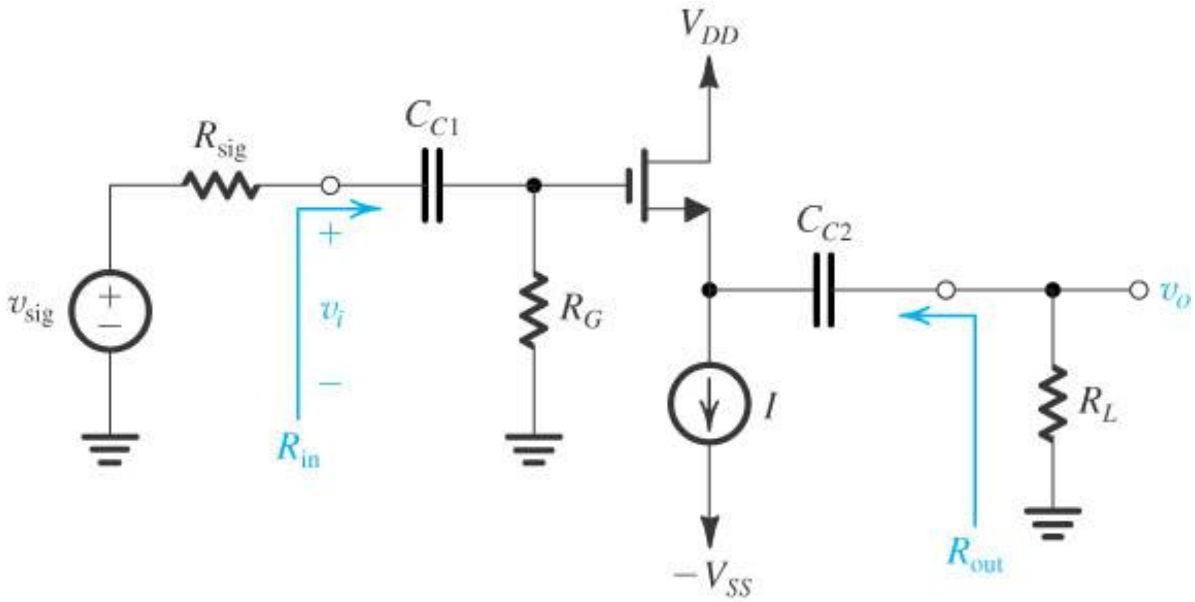
$$\Rightarrow \quad R_o = R_D$$

Common-drain amplifier

… also called source-follower amplifier

- Drain is not connected to ground, but to VDD

  $\Rightarrow$ Small-signal equivalent is connected to ground



CD amplifier

Small-signal equivalent

- Use either small-signal model for transistor (do not neglect r_o)

CD amplifier

CD circuit characteristics

- Open-circuit gain = ?
- Gain = ?
- Input resistance = ?
- Output resistance = ?
- Why is it called source-follower amplifier? What is it used for?

Single-stage MOS amplifiers

Outline

- NMOS as an amplifier: example of common-source circuit
  - NMOS amplifier example
  - Introduction to biasing and small-signal operation

- Biasing in MOS amplifier circuits
  - Fixing VGS
  - Fixing VG and adding a source resistance
  - Using RDG
  - Using a constant-current source

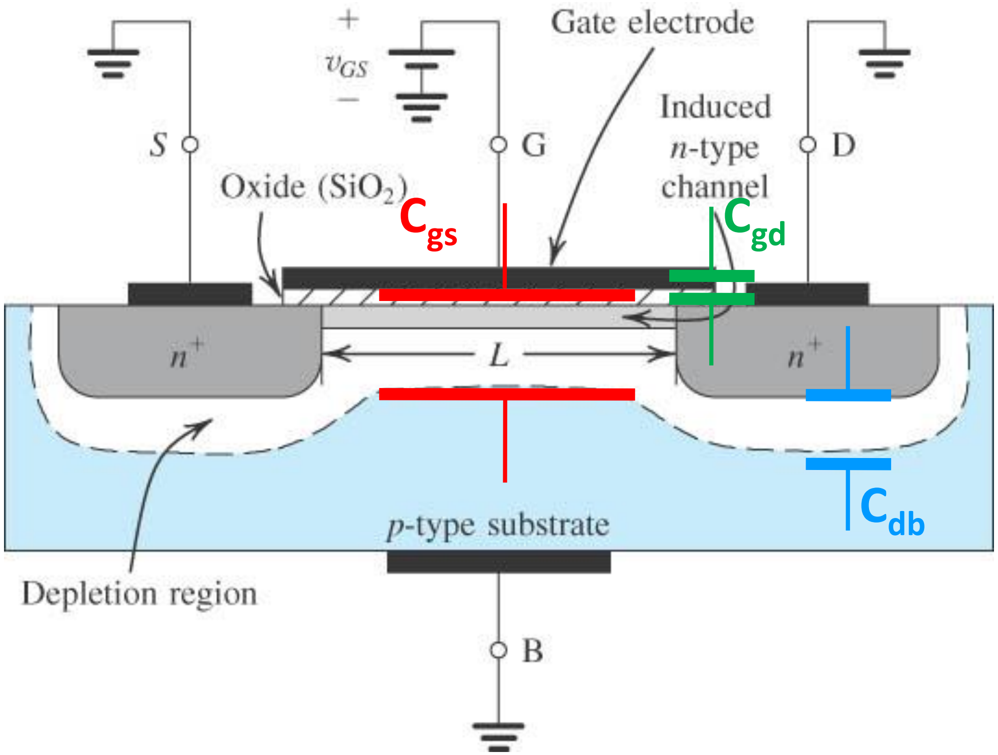
- Small-signal operation and models
  - Introduction to small-signal operation: common-source circuit
  - Small-signal models for NMOS transistors

- Other common single-stage MOS amplifiers
  - Common-source circuit
  - Common-source with source resistance
  - Common-drain circuit
  - Common-gate circuit

- Frequency response of MOSFET
  - HF response of NMOS transistor
  - HF response of common-source amplifier
  - LF response of common-source amplifier

High-frequency models for MOSFET

Several internal capacitances



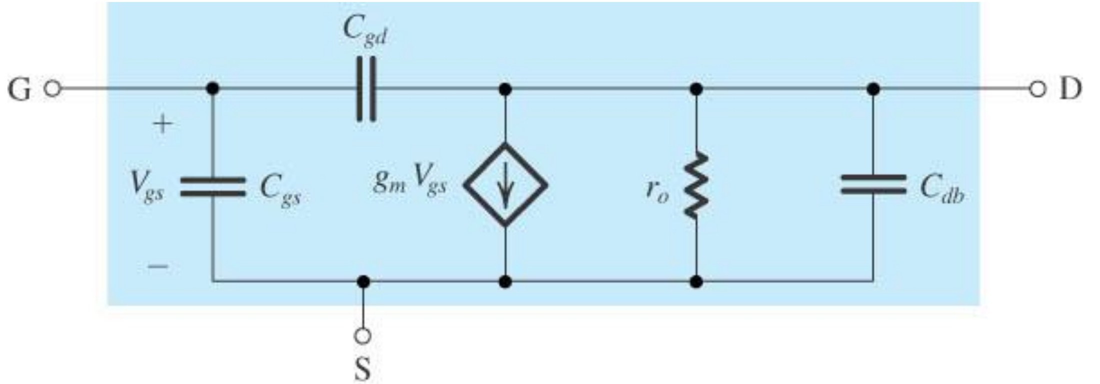
$$C_{gs} \approx (2/3) W L C_{ox}$$

$$C_{db} \propto v_{DB}^{-1/2}$$

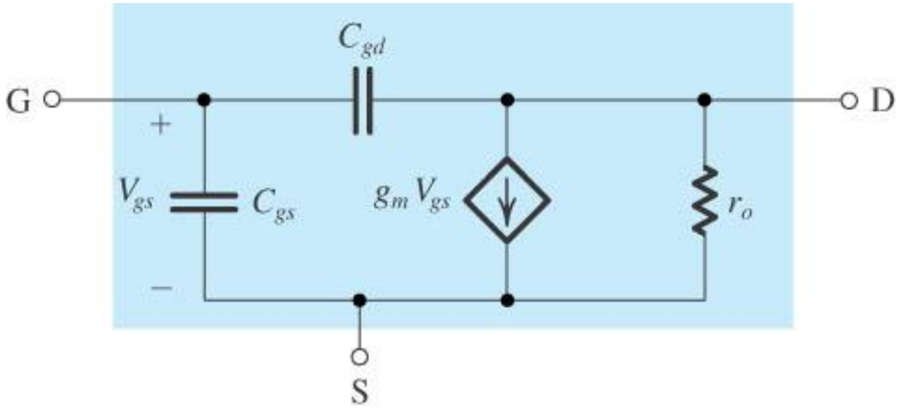
These parasitic capacitances will affect the high-frequency response of the transistor (and transistor circuit) !

High-frequency models for MOSFET

Small-signal HF model

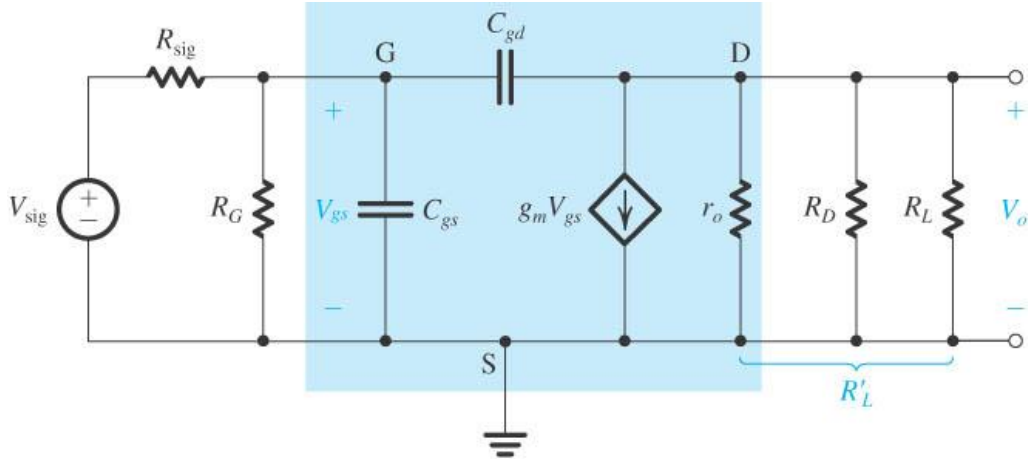


- C_{gd} small but plays significant role
- C_{db} often neglected to simplify analysis

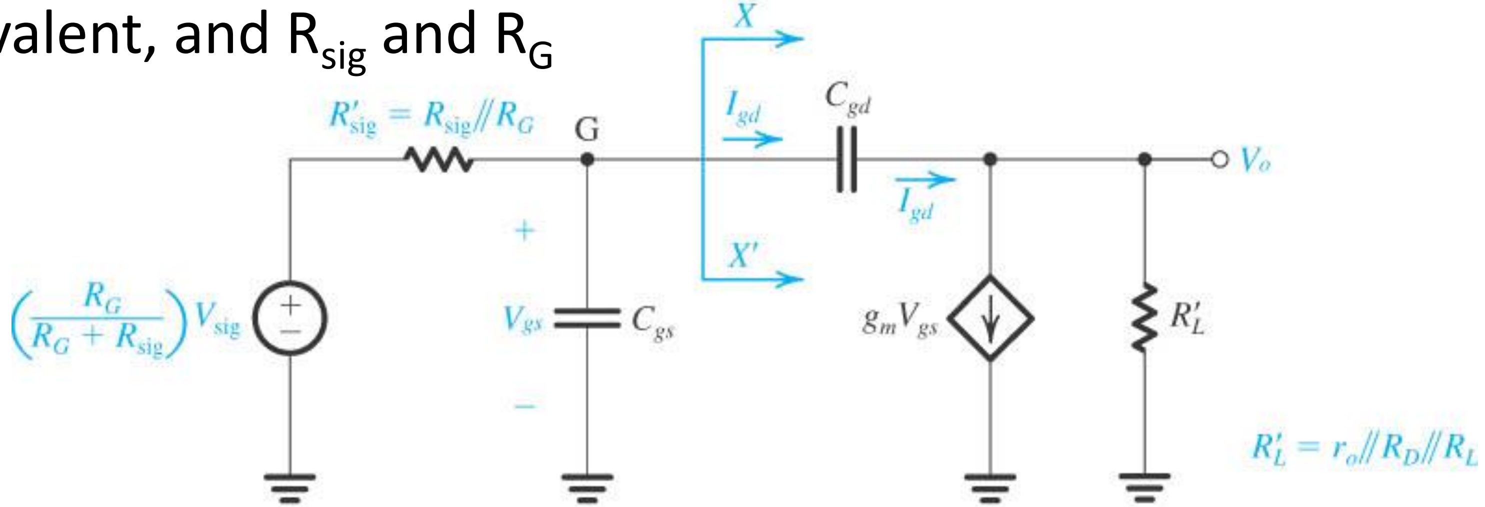


HF response of common-source amplifier

Replace NMOS with HF small-signal model

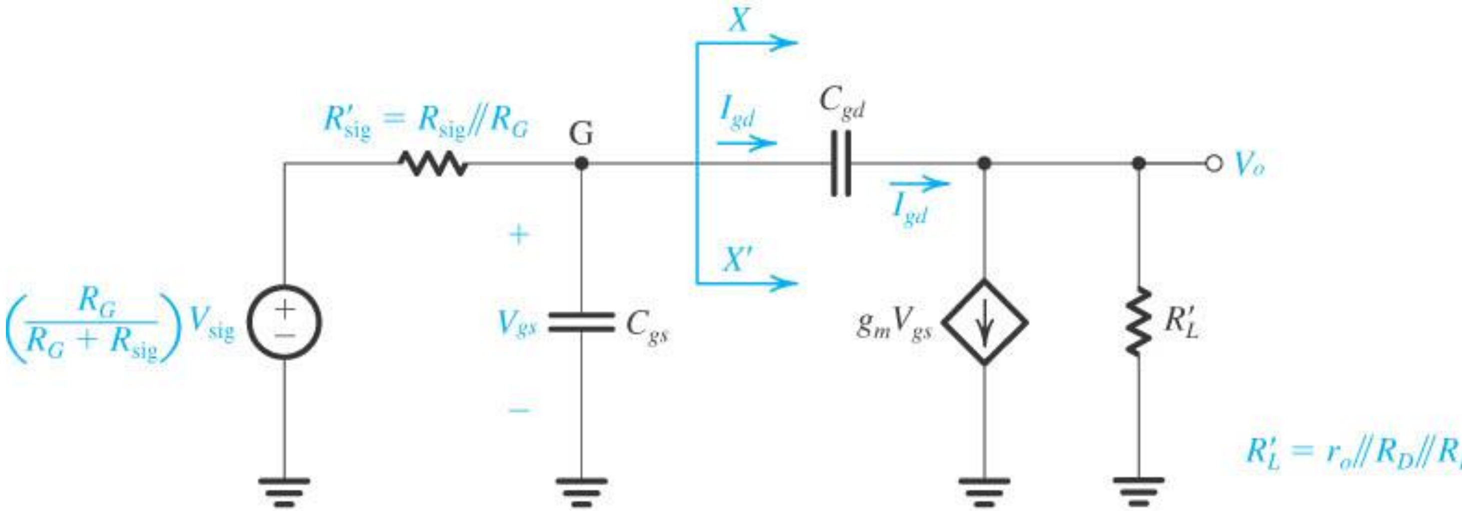


- Group r_o, R_D and R_L, and replace source and R_G with Thevenin equivalent, and R_{sig} and R_G



HF response of common-source amplifier

HF analysis



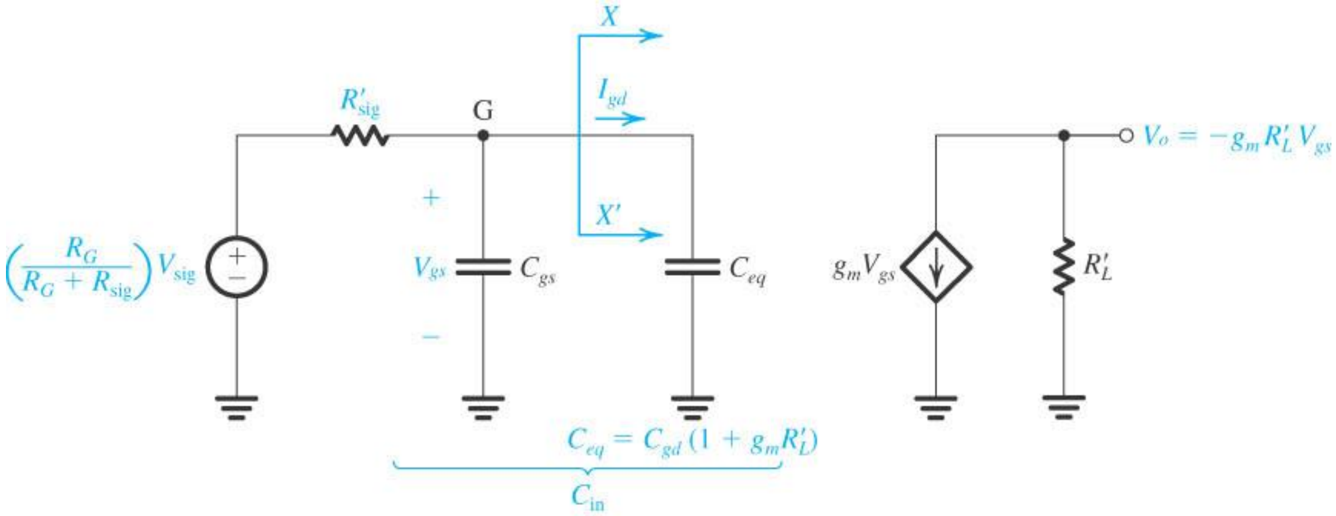
- Consider I_{gd} small w.r.t. $g_m V_{gs}$

$$\Rightarrow V_o \approx -g_m R'_L V_{gs}$$

- $$\begin{aligned} I_{gd} &= j\omega C_{gd}\left(V_{gs} - V_o\right) \\ &= j\omega C_{gd}\left(V_{gs} + g_m R'_L V_{gs}\right) \\ &= j\omega C_{gd}\left(1 + g_m R'_L\right)V_{gs} \end{aligned}$$

HF response of common-source amplifier

HF analysis (cont'd)



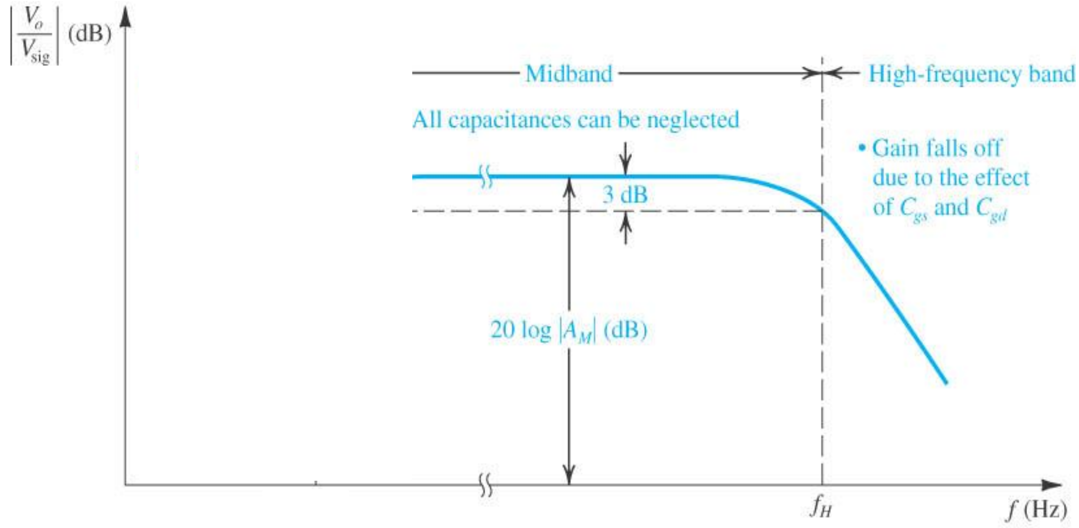
- $\Rightarrow C_{eq} = C_{gd}\left(1 + g_m R'_L\right)$
- $\Rightarrow C_{in} = C_{gs} + C_{eq} = C_{gs} + C_{gd}\left(1 + g_m R'_L\right)$
- $V_{gs} = \dfrac{1/\left(j\omega C_{in}\right)}{1/\left(j\omega C_{in}\right) + R'_{sig}} V'_{sig}$

$$= \frac{1}{1 + j\omega C_{in} R'_{sig}} \left(\frac{R_G}{R_G + R_{sig}} \right) V_{sig} \qquad \omega_0 = 1/\left(C_{in} R'_{sig}\right)$$

HF response of common-source amplifier

HF analysis (cont'd)

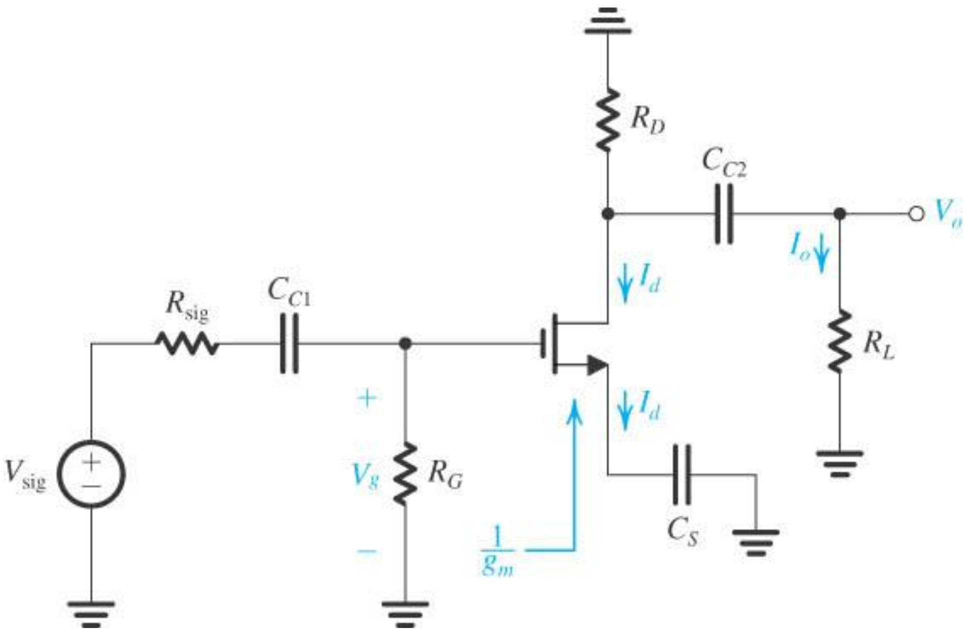
- $$\frac{V_o}{V_{sig}} = -\left(\frac{R_G}{R_G + R_{sig}}\right)(g_m R'_L)\frac{1}{1 + j\frac{\omega}{\omega_0}}$$
- At high frequencies, gain tends to zero
- Cut-off frequency: $f_H = \frac{\omega_0}{2\pi} = \frac{1}{2\pi C_{in} R'_{sig}}$



LF response of common-source amplifier

each coupling capacitor creates a high-pass filter

- Effect of C_{C1}



$$V_g = \frac{R_G}{R_G + R_{sig} + \frac{1}{j\omega C_{C1}}} V_{sig}$$

$$= \frac{R_G}{R_G + R_{sig}} \frac{1}{1 + \frac{1}{j\omega C_{C1}\left(R_G + R_{sig}\right)}} V_{sig}$$

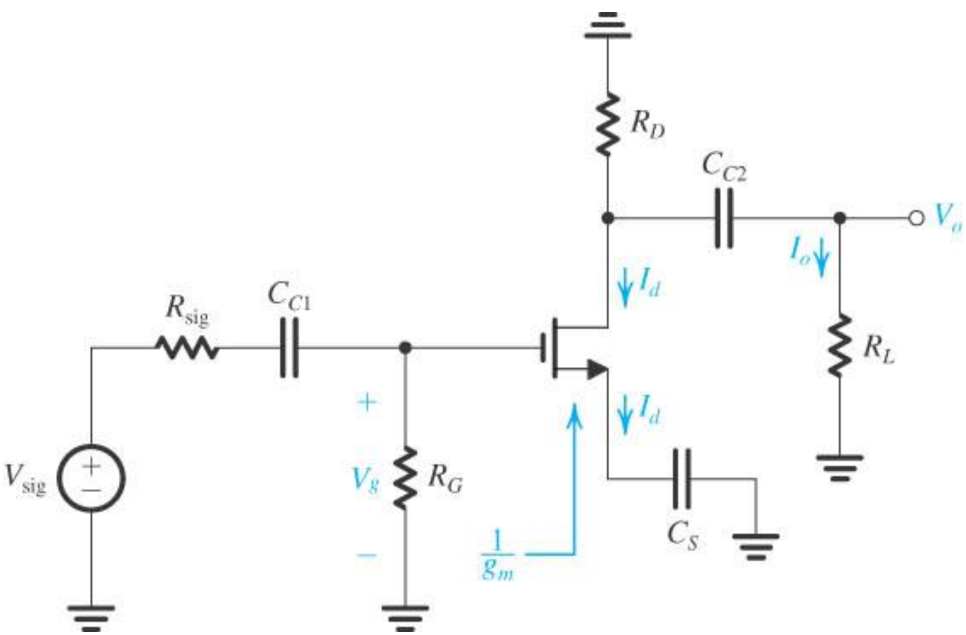
High-pass with cut-off frequency:

$$f_{P1} = \frac{1}{2\pi C_{C1}\left(R_G + R_{sig}\right)}$$

LF response of common-source amplifier

each coupling capacitor creates a high-pass filter

- Effect of C_S (use T-model)



$$I_d = \frac{V_g}{\frac{1}{g_m} + \frac{1}{j\omega C_S}} = \frac{1}{1 + \frac{1}{j\omega \frac{1}{g_m} C_S}} g_m V_g$$

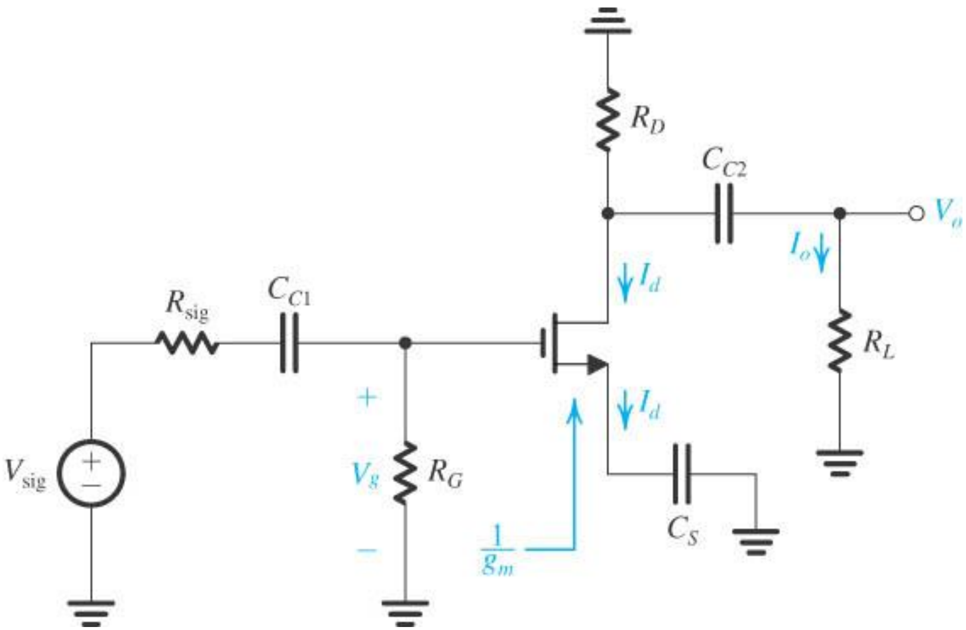
High-pass with cut-off frequency:

$$f_{P2} = \frac{1}{2\pi C_S (1/g_m)}$$

LF response of common-source amplifier

each coupling capacitor creates a high-pass filter

- Effect of C_{C2} (current divider)



$$I_o = -I_d \frac{R_D}{R_D + \frac{1}{j\omega C_{C2}} + R_L}$$

$$= -I_d \frac{R_D}{R_D + R_L} \frac{1}{1 + \frac{1}{j\omega C_{C2}\left(R_D + R_L\right)}}$$

High-pass with cut-off frequency:

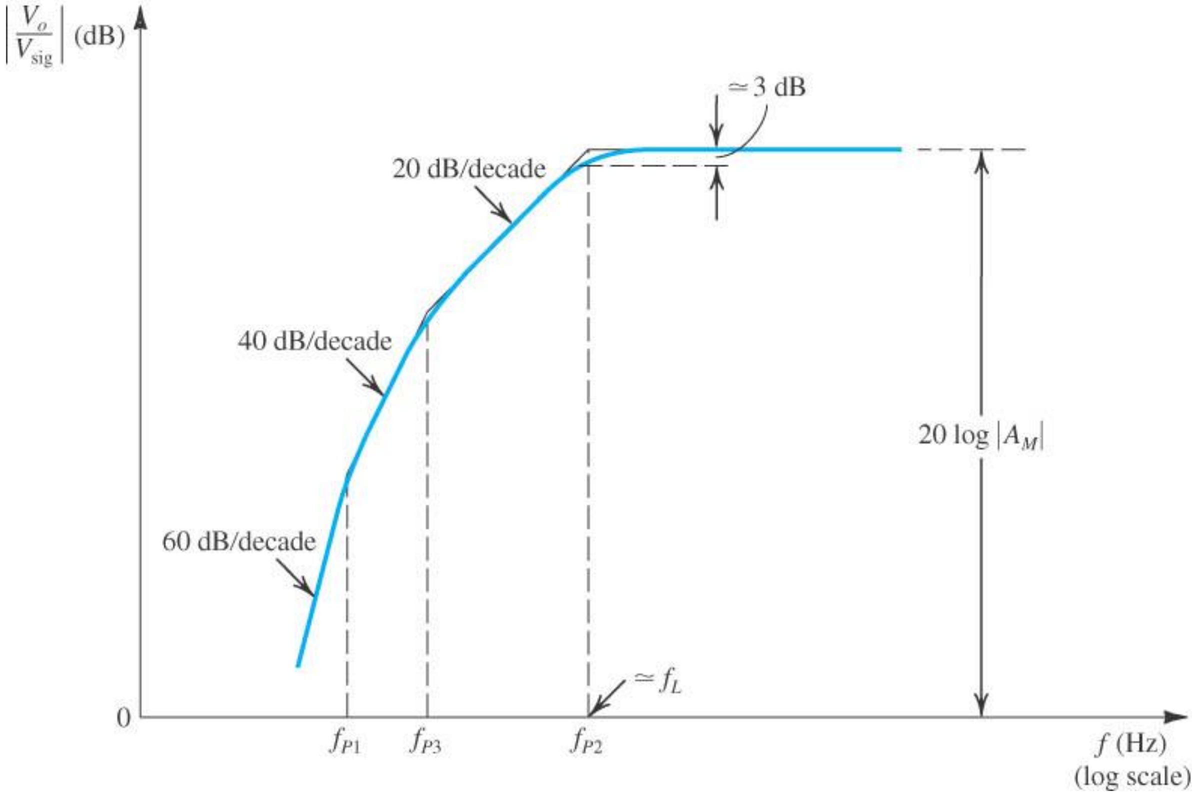
$$f_{P2} = \frac{1}{2\pi C_{C2}\left(R_D + R_L\right)}$$

LF response of common-source amplifier

Total low-frequency response

$$V_o = R_L I_o$$

$$\Rightarrow \frac{V_o}{V_{sig}} = -R_L \left(\frac{R_D}{R_D + R_L} \right) g_m \left(\frac{R_G}{R_G + R_{sig}} \right) \left(\frac{j\omega}{j\omega + \omega_{P1}} \right) \left(\frac{j\omega}{j\omega + \omega_{P2}} \right) \left(\frac{j\omega}{j\omega + \omega_{P3}} \right)$$



Usually, one cut-off frequency is higher than the two others

Frequency response of common-source amplifier

Total LF and HF response