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EEE109: Electronic Circuits

Basic FET Amplifiers

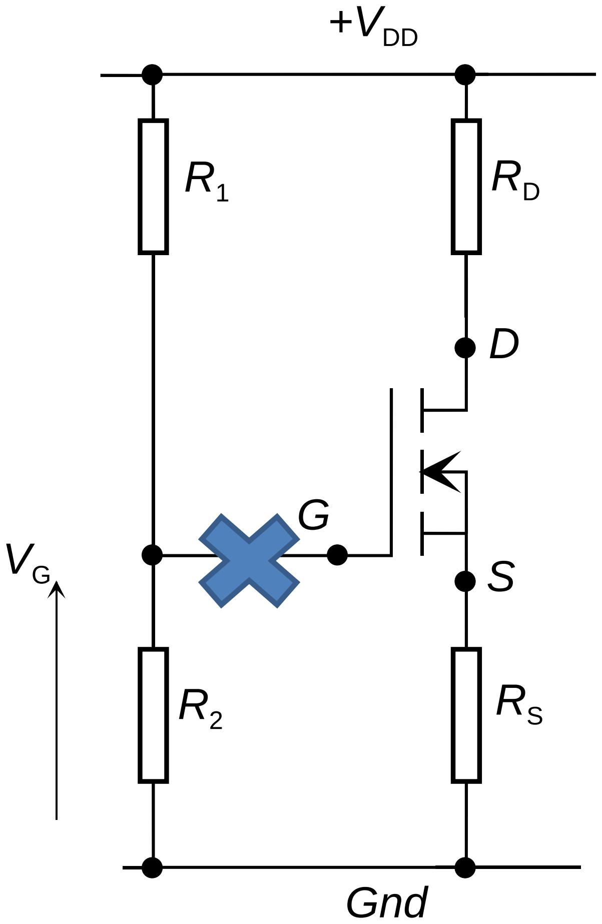
Contents of Chapter 4

- Investigate a single-transistor circuit that can amplify a small, time-varying input signal
  - Develop small-signal models that are used in the analysis of linear amplifiers.
- Discuss and compare the three basic transistor amplifier configurations.
  - Analyze the common-source amplifier.
  - Analyze the source-follower amplifier.
  - Analyze the common-gate amplifier.
- Analyze multitransistor or multistage amplifiers.
- Develop the small-signal model of JFET devices and analyze basic JFET amplifiers.
- Design a two-stage MOSFET amplifier circuit.

General Amplifier Characteristics

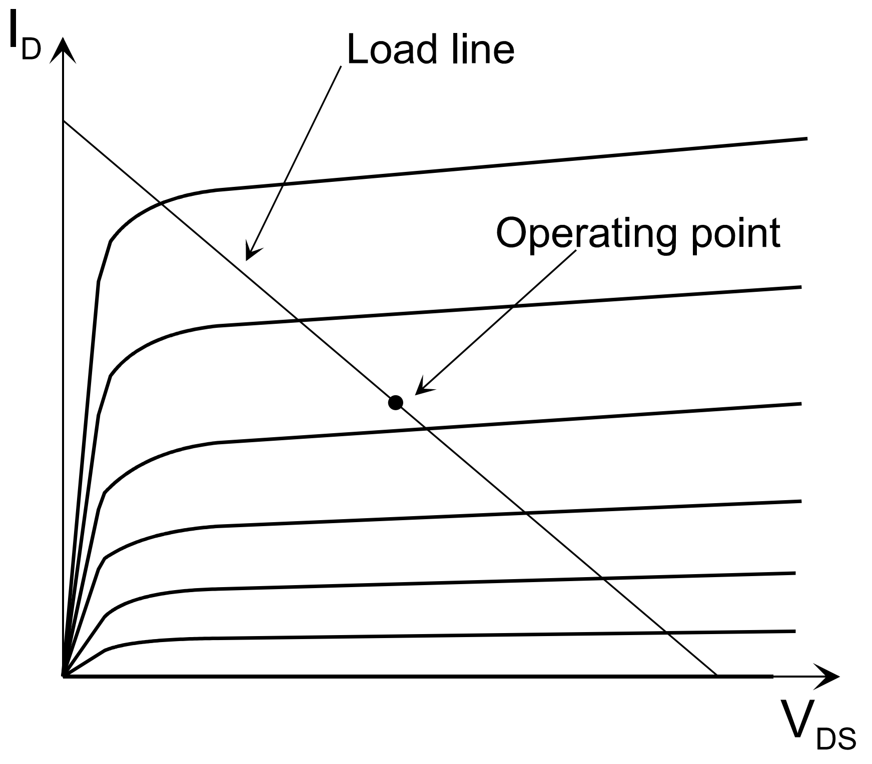
Amplifier Characteristics (1)

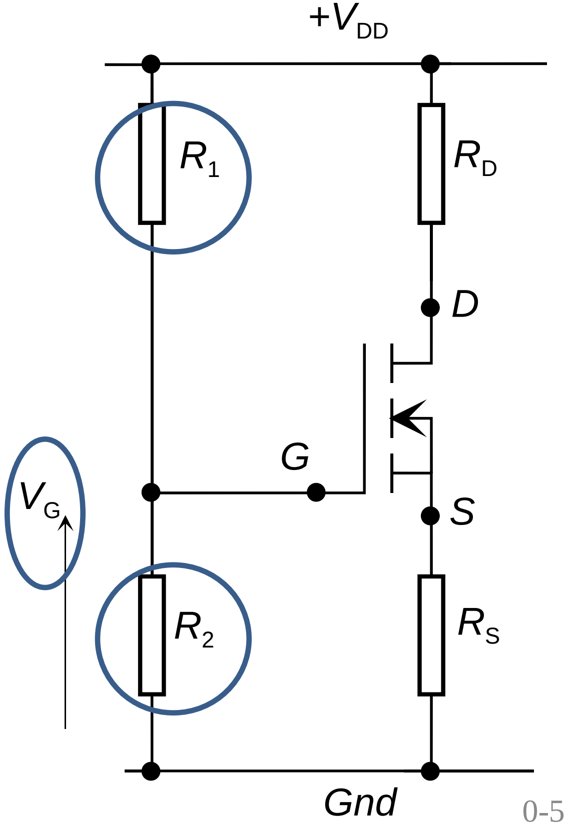
The MOSFET may be used as a **switch** or biased to operate as an **amplifier**; circuits are similar to those for the bipolar transistor **EXCEPT** **no current flows into the gate**. Using four resistor biasing a common source amplifier is formed.



Amplifier Characteristics (2)

The gate voltage V_G is set by the two resistors R_1 and R_2 and the voltage divider gives V_G. The MOSFET only conducts if $V_G > V_T$. The bias condition (operating point) gives the required values of V_{DS} and I_D.





Circuit Notation Conventions

Table 4.1 Summary of notation

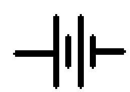
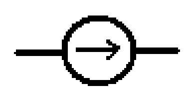
Variable	Meaning
i_D, v_{GS}	Total instantaneous values
I_D, V_{GS}	DC values
i_d, v_{gs}	Instantaneous ac values
I_d, V_{gs}	Phasor values

Small Signal Analysis Problem Solving Skills

Problem-Solving Technique: MOSFET AC Analysis

1. Analyze circuit with only the dc sources to find quiescent solution. Transistor must be biased in saturation region for linear amplifier.
2. Replace **elements** with small-signal model.
3. Analyze small-signal equivalent circuit, setting dc sources to zero, to produce the circuit to the time-varying input signals only.

Transformation of Elements

Element	DC Model	AC Model
Resistor	R	R
Capacitor	Open	C
Inductor	Short	L
Diode	$+V_\gamma$, r_f $-$ 	$r_d = V_T/I_D$
Independent Constant Voltage Source	+ V_S - 	Short
Independent Constant Current Source	I_S 	Open

Practical Skill: General DC & AC Analysis (General Procedure)

- **DC analysis:**
  - Find DC equivalent circuit by replacing all capacitors by open circuits and inductors by short circuits.
  - Find Q-point from DC equivalent circuit by using appropriate large-signal transistor model.
- **AC analysis:**
  - Find AC equivalent circuit by replacing all capacitors by short circuits, inductors by open circuits, DC voltage sources by ground connections and DC current sources by open circuits.
  - Replace transistor by small-signal model
  - Use small-signal AC equivalent to analyze AC characteristics of amplifier.
  - Combine end results of DC and AC analysis to yield total voltages and currents in the network.

Note: Since we are dealing with linear amplifiers (saturation mode), the principle of superposition holds

Practical Skill: General DC & AC Analysis (Equivalent Circuits)

- DC equivalent circuit:

1) replacing all capacitances with open circuits,
2) replacing inductances with short circuits,
3) reducing AC sources to zero:
    - ✓ Replacing AC voltage sources by short circuits and
    - ✓ Replacing AC current sources by open circuits.

- AC equivalent circuit:

1) reducing all DC sources to zero:
    - ✓ Replacing DC voltage sources with short circuits and
    - ✓ Replacing DC current sources with open circuits.
2) replacing all capacitances with short circuits,
3) replacing inductances with open circuits,
4) replacing transistor with small signal equivalent circuit.

NMOS Transistor Small-Signal Parameters

- Values depends on Q-point

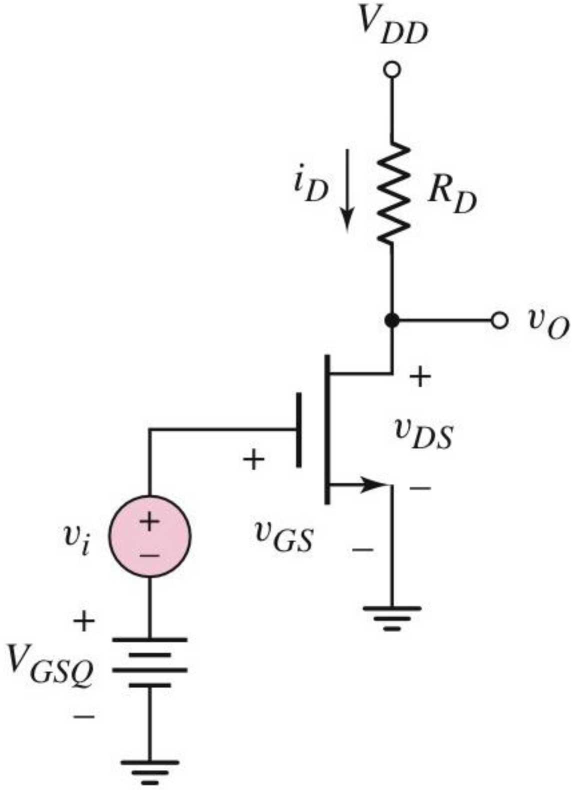
$$g_m = \frac{\partial i_D}{\partial v_{GS}} = \frac{i_d}{v_{gs}}$$

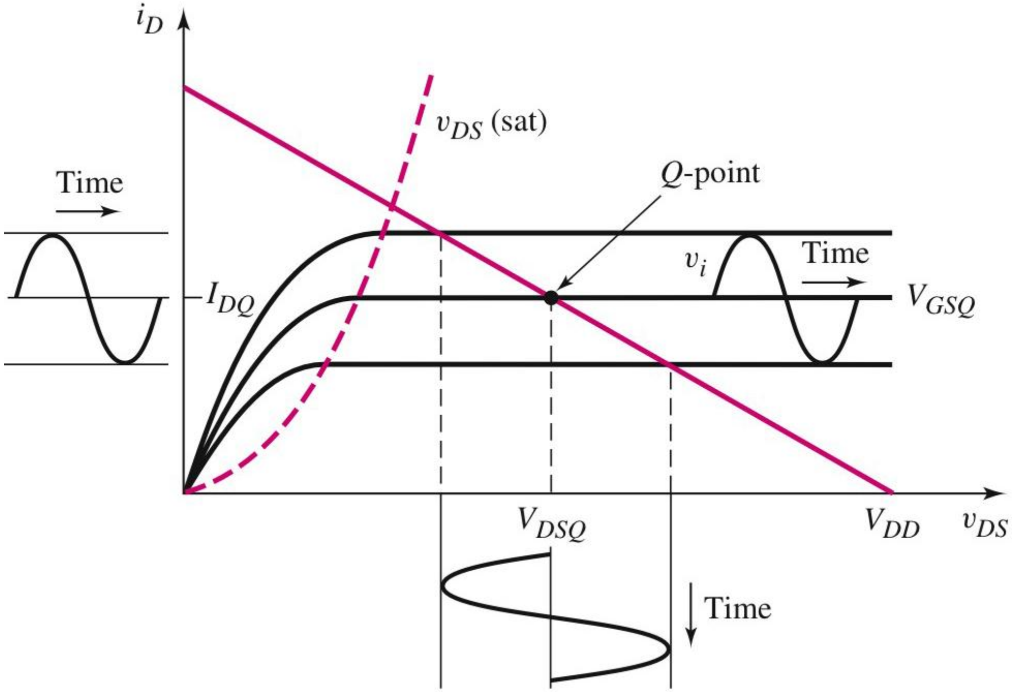
$$g_m = 2K_n(V_{GSQ} - V_{TN}) = \boxed{2\sqrt{K_n I_{DQ}}}$$

$$r_o = \left(\frac{\partial i_D}{\partial v_{DS}}\right)^{-1}$$

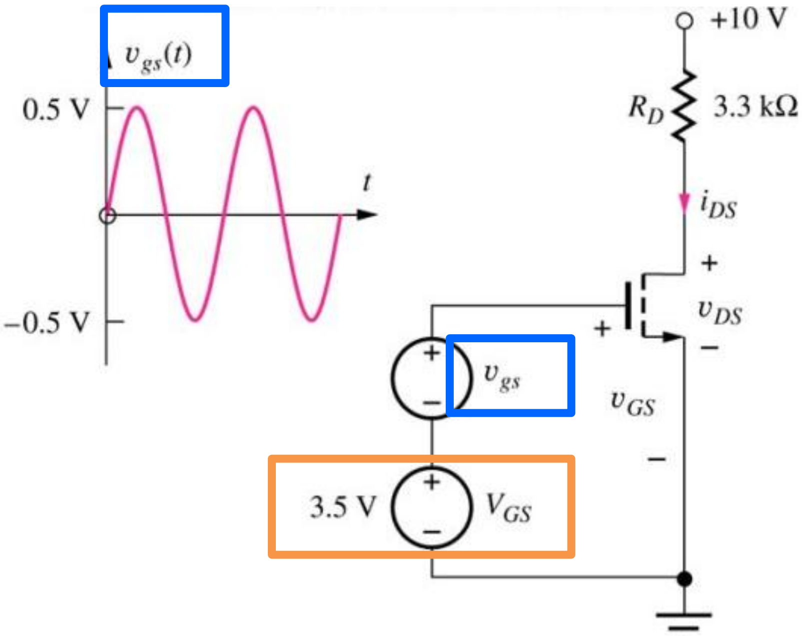
$$r_o = [\lambda K_n (V_{GSQ} - V_{TN})^2]^{-1} \cong \boxed{[\lambda I_{DQ}]^{-1}}$$

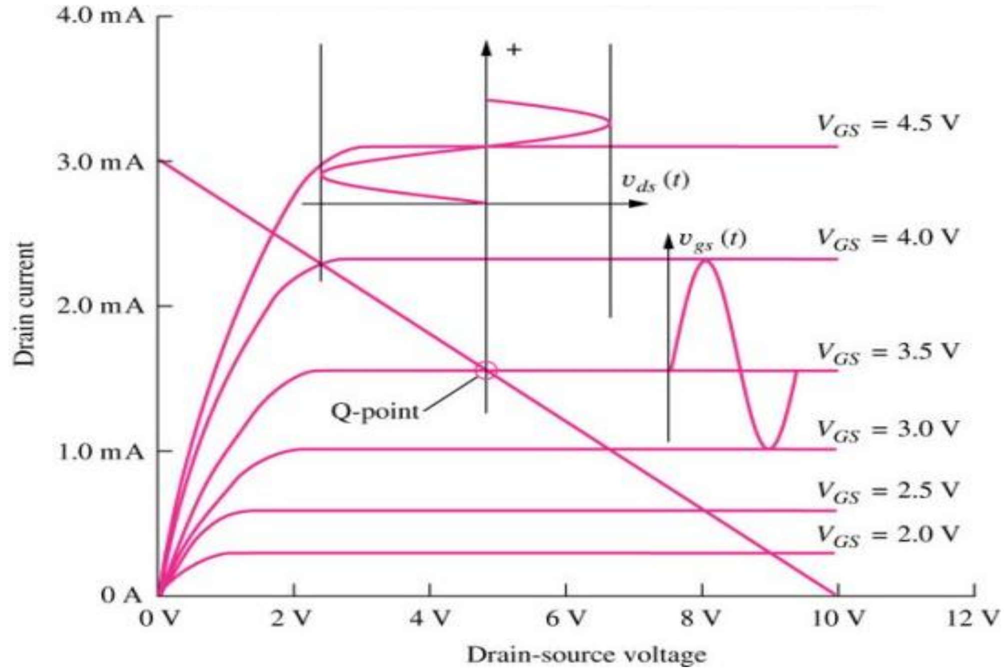
NMOS Common-Source Circuit





MOSFET Amplifier Example





MOSFET is biased in active region by DC voltage source V_{GS}.

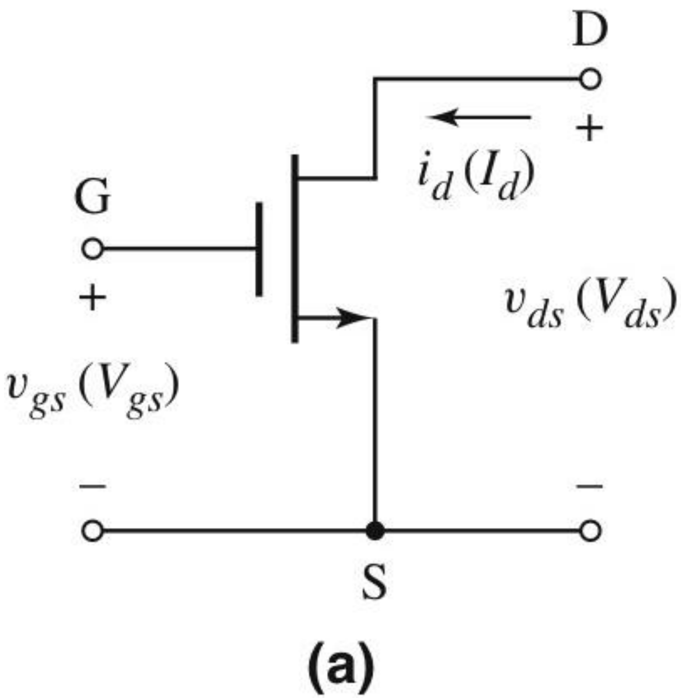
Q-point is set at (V_{DS}, I_D) = (4.8 V, 1.56 mA) @ V_{GS} = 3.5 V.

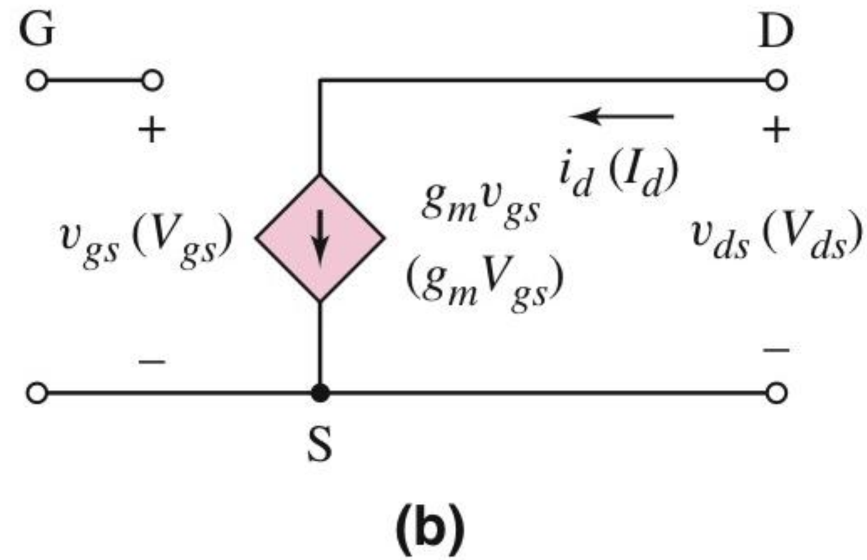
Total gate-source voltage is: $$v_{GS}(t) = V_{GS} + v_{gs}(t)$$

The input: 1 V *p-p* change in v_{GS}

The output: 1.25 mA *p-p* change in i_D and 4 V *p-p* change in v_{DS}.

Simple NMOS Small-Signal Transistor Equivalent Circuit (1)





Simple NMOS Small-Signal Transistor Equivalent Circuit (2)

$$v_{GS} = V_{GSQ} + v_i = V_{GSQ} + v_{gs} \tag{4.1}$$

where V_{GSQ} is the dc component and v_{gs} is the ac component. The instantaneous drain current is

$$i_D = K_n(v_{GS} - V_{TN})^2 \tag{4.2}$$

Substituting Equation (4.1) into (4.2) produces

$$i_D = K_n[V_{GSQ} + v_{gs} - V_{TN}]^2 = K_n[(V_{GSQ} - V_{TN}) + v_{gs}]^2 \tag{4.3(a)}$$

or

$$i_D = \boxed{K_n(V_{GSQ} - V_{TN})^2} + \boxed{2K_n(V_{GSQ} - V_{TN})v_{gs}} + \boxed{K_n v_{gs}^2} \tag{4.3(b)}$$

The first term in Equation (4.3(b)) is the dc or quiescent drain current I_{DQ}, the second term is the time-varying drain current component that is linearly related to the signal v_{gs}, and the third term is proportional to the square of the signal voltage. For a sinusoidal input signal, the squared term produces undesirable harmonics, or nonlinear distortion, in the output voltage. To minimize these harmonics, we require

$$v_{gs} \ll 2(V_{GSQ} - V_{TN}) \tag{4.4}$$

Simple NMOS Small-Signal Transistor Equivalent Circuit (3)

$$i_D = I_{DQ} + i_d \tag{4.5}$$

Again, small-signal implies linearity so that the total current can be separated into a dc component and an ac component. The ac component of the drain current is given by

$$i_d = 2K_n(V_{GSQ} - V_{TN})v_{gs} \tag{4.6}$$

The small-signal drain current is related to the small-signal gate-to-source voltage by the transconductance g_m. The relationship is

$$\boxed{g_m = \frac{i_d}{v_{gs}} = 2K_n(V_{GSQ} - V_{TN})} \tag{4.7}$$

The transconductance is a transfer coefficient relating output current to input voltage and can be thought of as representing the gain of the transistor.

The transconductance can also be obtained from the derivative

$$g_m = \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GSQ}=\text{const.}} = 2K_n(V_{GSQ} - V_{TN}) \tag{4.8(a)}$$

Common Source with Channel Modulation

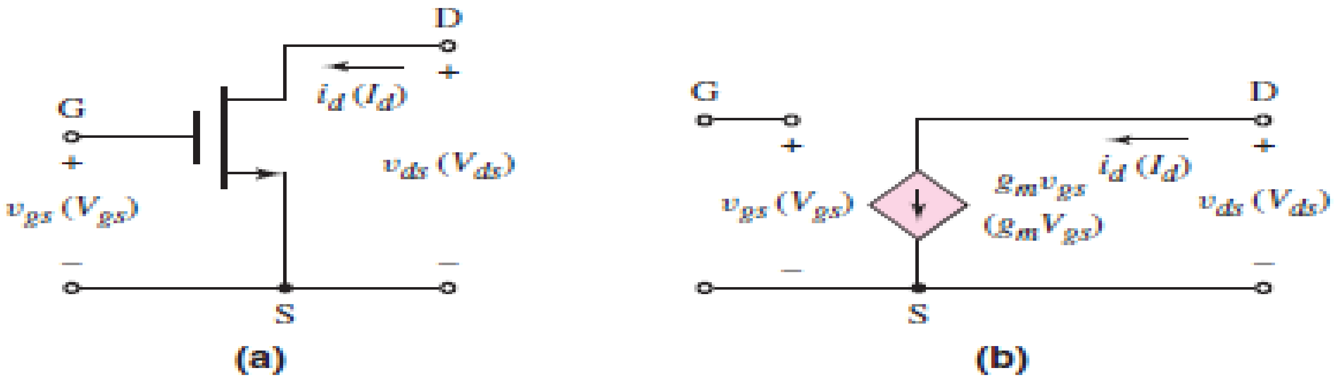


Figure 4.5 (a) Common-source NMOS transistor with small-signal parameters and (b) simplified small-signal equivalent circuit for NMOS transistor

$$i_D = K_n[(v_{GS} - V_{TN})^2(1 + \lambda v_{DS})] \tag{4.16}$$

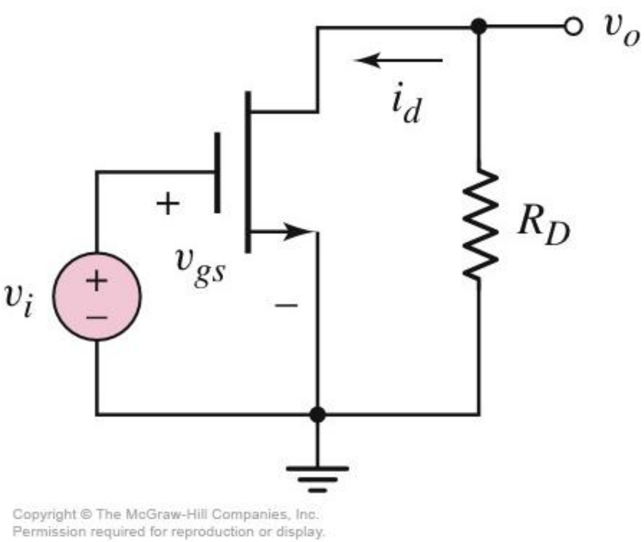
where λ is the channel-length modulation parameter and is a positive quantity. The small-signal output resistance, as previously defined, is

$$r_o = \left(\frac{\partial i_D}{\partial v_{DS}}\right)^{-1}\Bigg|_{v_{GS}=V_{GSQ}=\text{const.}} \tag{4.17}$$

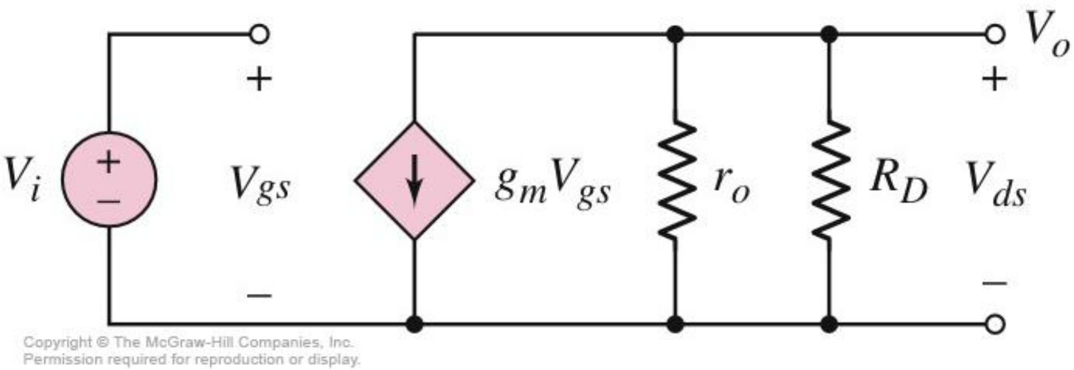
or

$$r_o = [\lambda K_n(V_{GSQ} - V_{TN})^2]^{-1} \cong [\lambda I_{DQ}]^{-1} \tag{4.18}$$

NMOS Common-Source Circuit



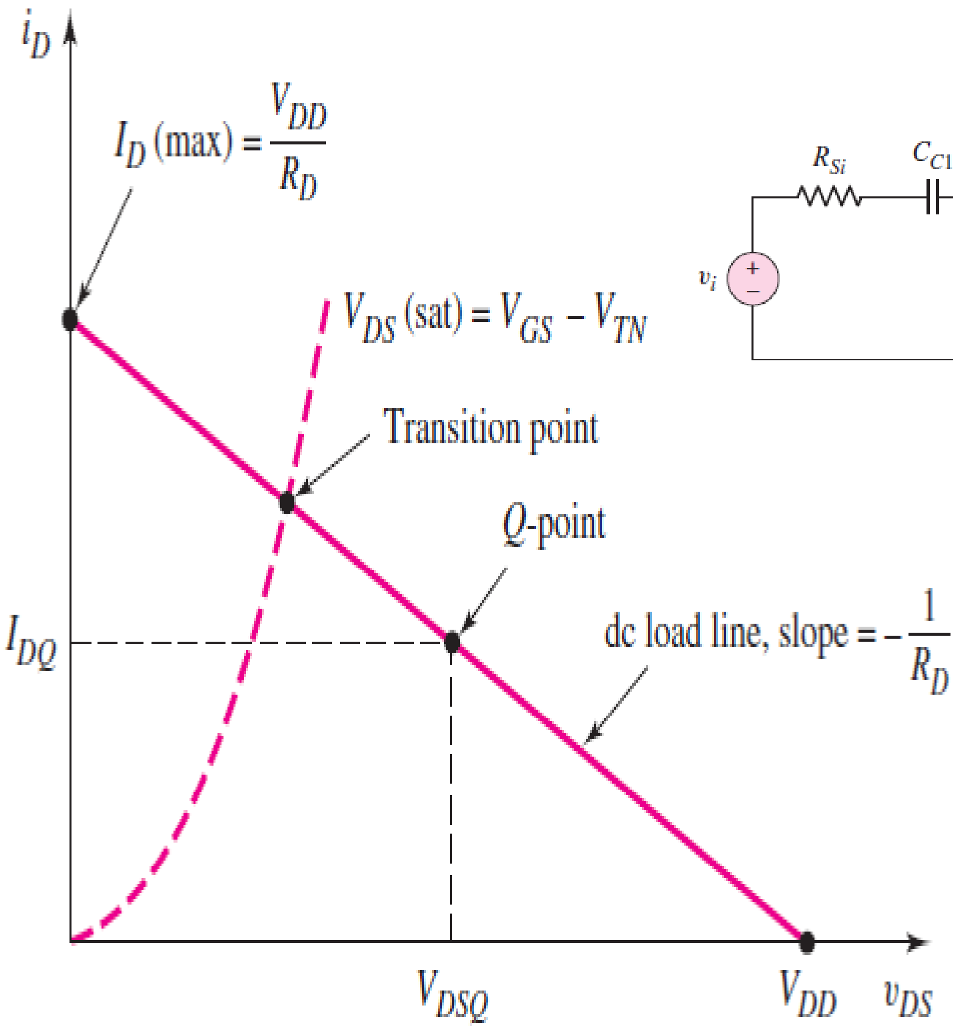
AC

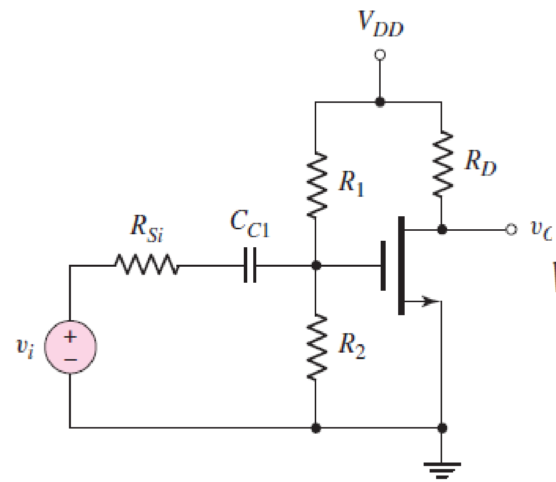


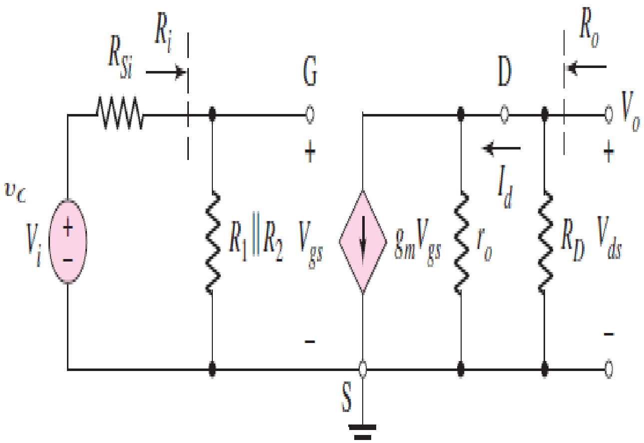
Small-signal

$$A_v = V_o / V_i = -g_m (r_o \| R_D)$$

NMOS Common-Source Circuit Analysis







$$V_o = -g_m V_{gs}(r_o \| R_D)$$

The input gate-to-source voltage is

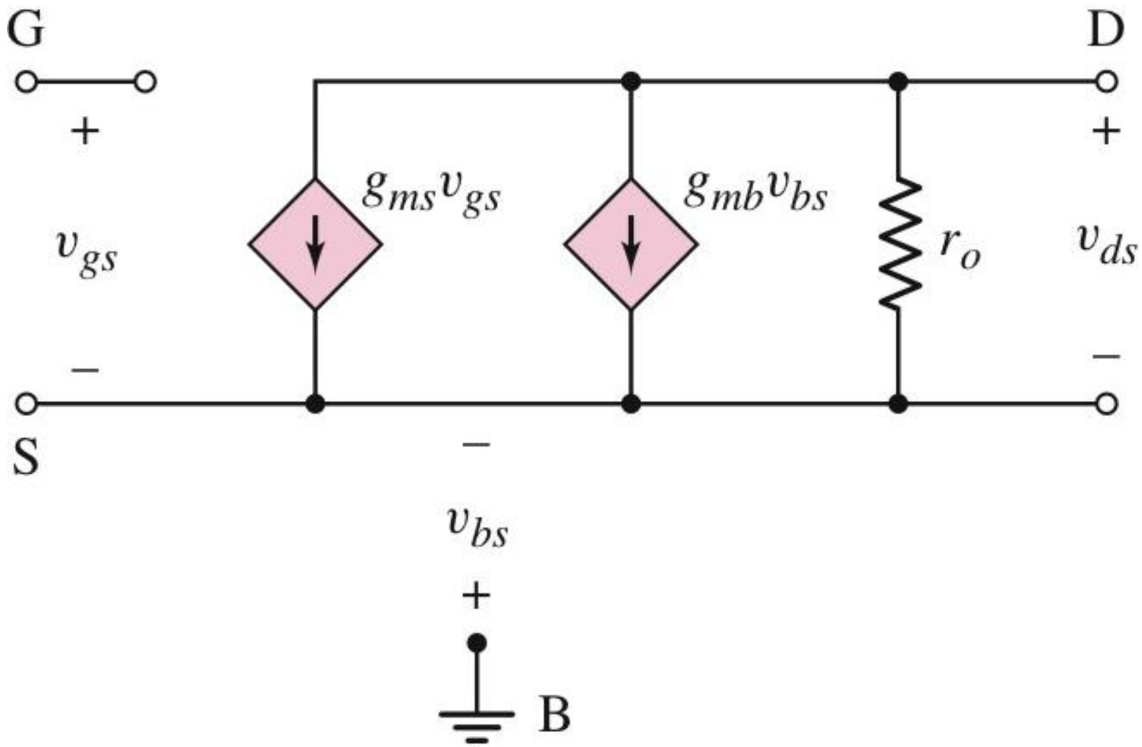
$$V_{gs} = \left(\frac{R_i}{R_i + R_{Si}}\right) \cdot V_i$$

so the small-signal voltage gain is

$$A_v = \frac{V_o}{V_i} = -g_m(r_o \| R_D) \cdot \left(\frac{R_i}{R_i + R_{Si}}\right)$$

Modeling the Body Effects

Modeling the Body Effects



Body Effect Consideration (1)

Modeling the Body Effect: As mentioned in Section 3.1.9, Chapter 3, the body effect occurs in a MOSFET in which the **substrate**, or **body**, is **not** directly connected to the **source**. For an NMOS device, the body is connected to the most negative potential in the circuit and will be at signal ground.

$$i_D = K_n(v_{GS} - V_{TN})^2$$

and the threshold voltage is given by

$$V_{TN} = V_{TNO} + \gamma\left[\sqrt{2\phi_f + v_{SB}} - \sqrt{2\phi_f}\right]$$

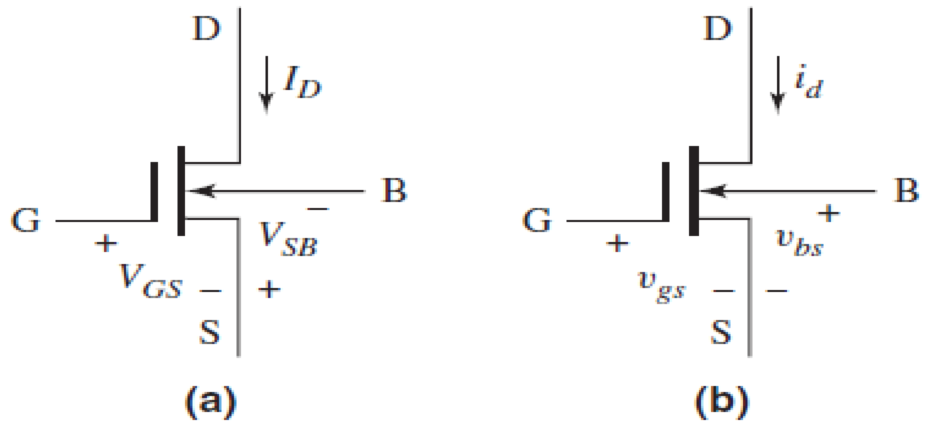


Figure 4.12 The four-terminal NMOS device with (a) dc voltages and (b) ac voltages

Body Effect Consideration (2)

$$g_{mb} = \left.\frac{\partial i_D}{\partial v_{BS}}\right|_{Q\text{-}pt} = \left.\frac{-\partial i_D}{\partial v_{SB}}\right|_{Q\text{-}pt} = -\left(\frac{\partial i_D}{\partial V_{TN}}\right)\cdot\left.\left(\frac{\partial V_{TN}}{\partial v_{SB}}\right)\right|_{Q\text{-}pt}$$

Using Equation (4.22), we find

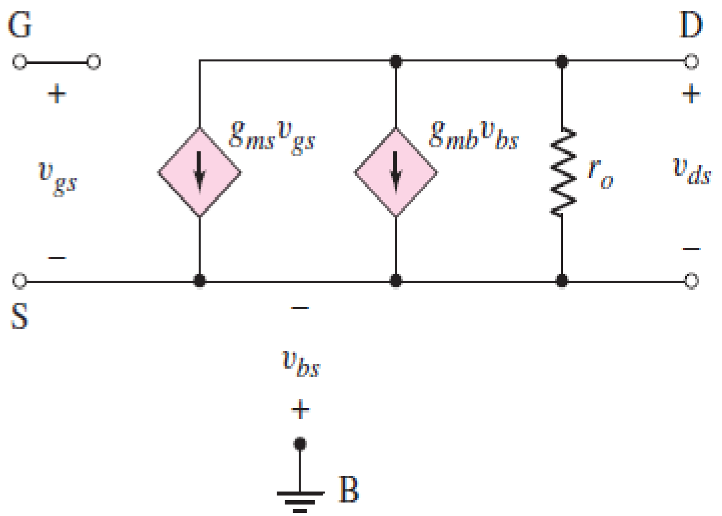
$$\frac{\partial i_D}{\partial V_{TN}} = -2K_n(v_{GS} - V_{TN}) = -g_m$$

and using Equation (4.23), we find

$$\frac{\partial V_{TN}}{\partial v_{SB}} = \frac{\gamma}{2\sqrt{2\phi_f + v_{SB}}} \equiv \eta$$

The back-gate transconductance is then

$$g_{mb} = -(-g_m)\cdot(\eta) = g_m\eta$$



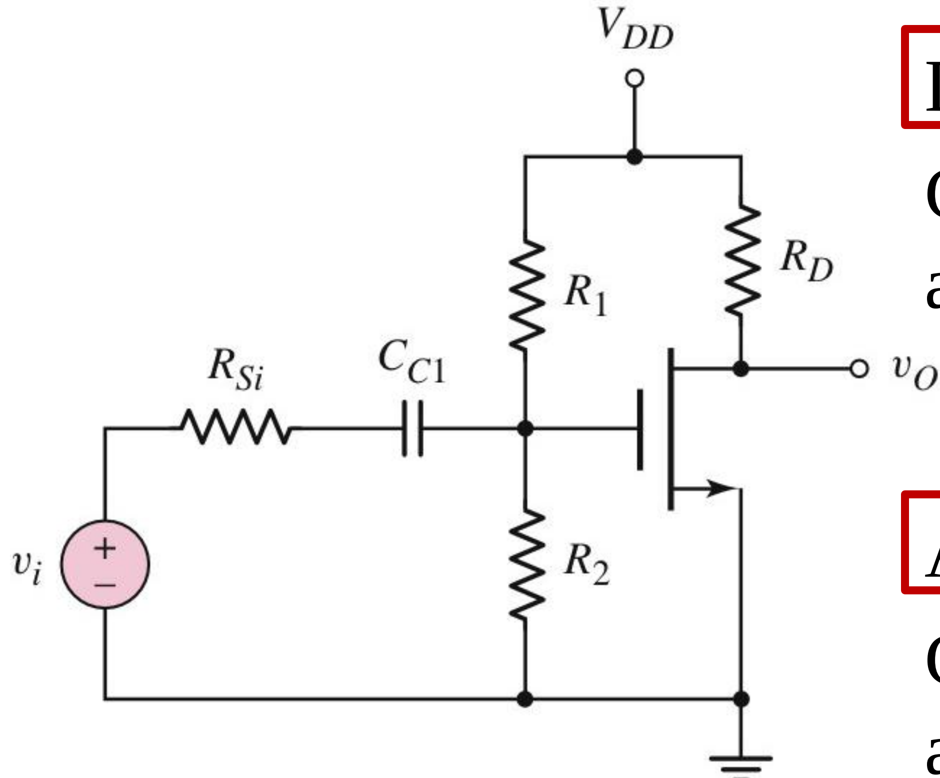
Small-signal equivalent circuit of NMOS device including body effect Test

Three Type of MOSFET Amplifier Circuit

- Common Source Amplifier
- Common Drain Amplifier
- Common Gate Amplifier

Common Source Amplifier Circuit

Common-Source Configuration



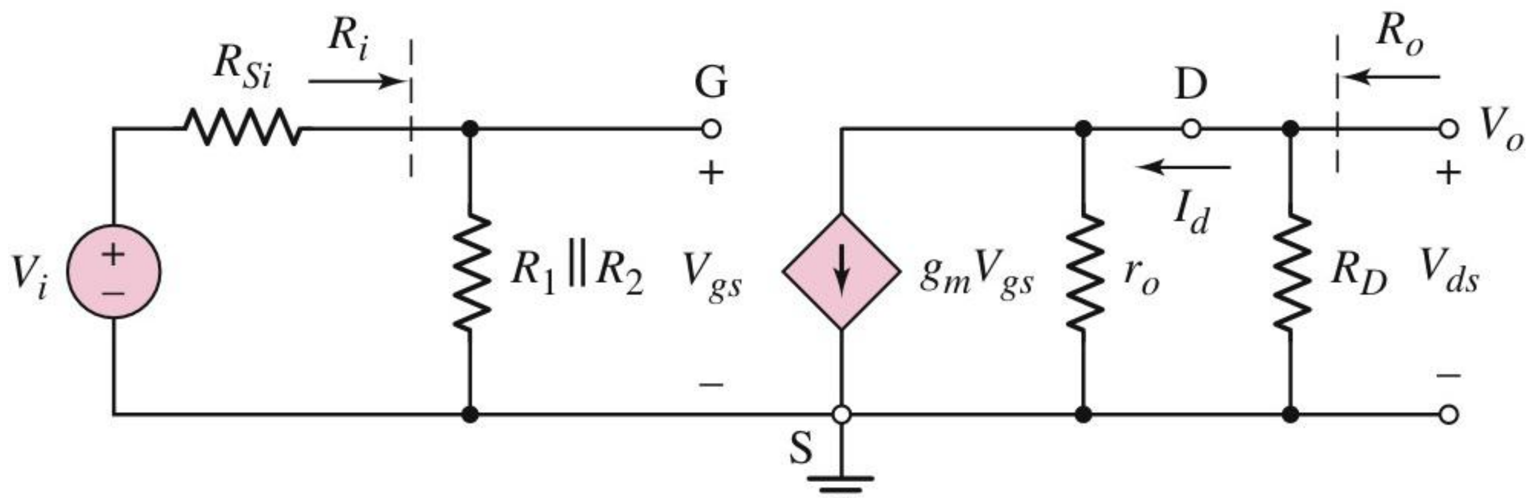
$\boxed{\text{DC}}$ analysis:

Coupling capacitor is assumed to be open.

$\boxed{\text{AC}}$ analysis:

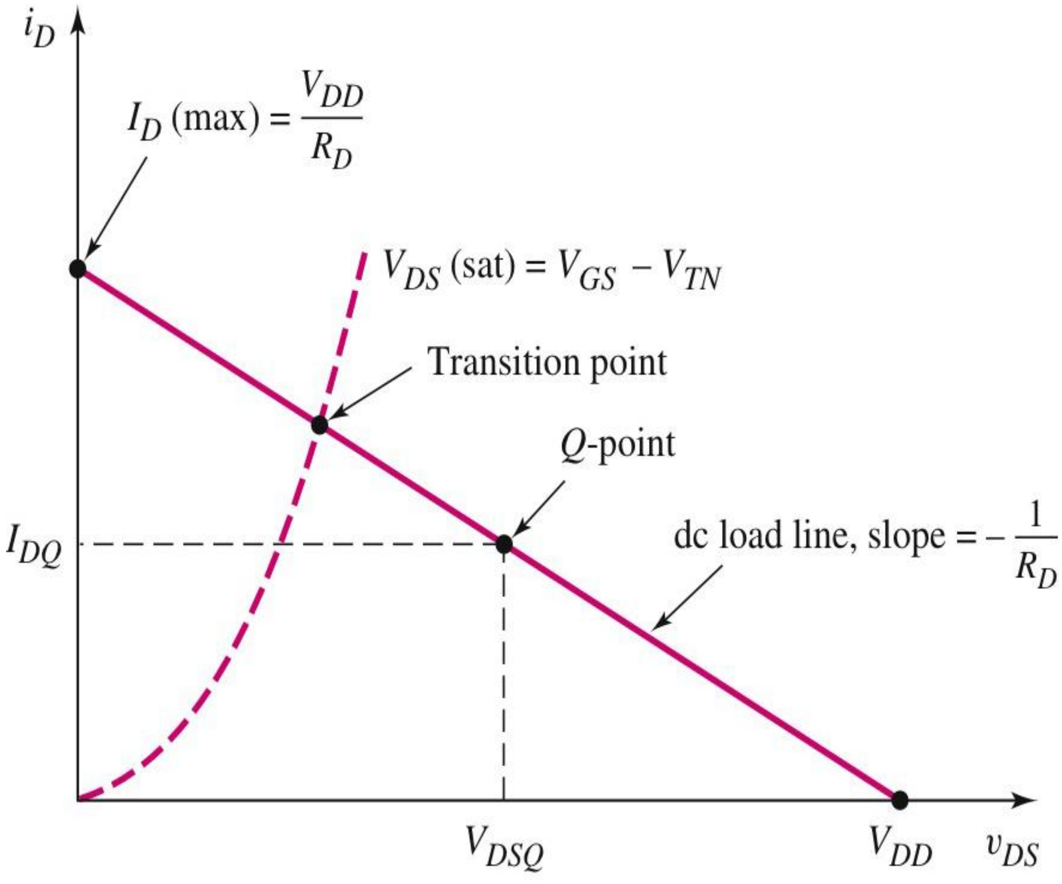
Coupling capacitor is assumed to be a short. DC voltage supply is set to zero volts.

Small-Signal Equivalent Circuit



$$A_v = V_o / V_i = -g_m (r_o \| R_D)\left(\frac{R_i}{R_i + R_{Si}}\right)$$

DC Load Line

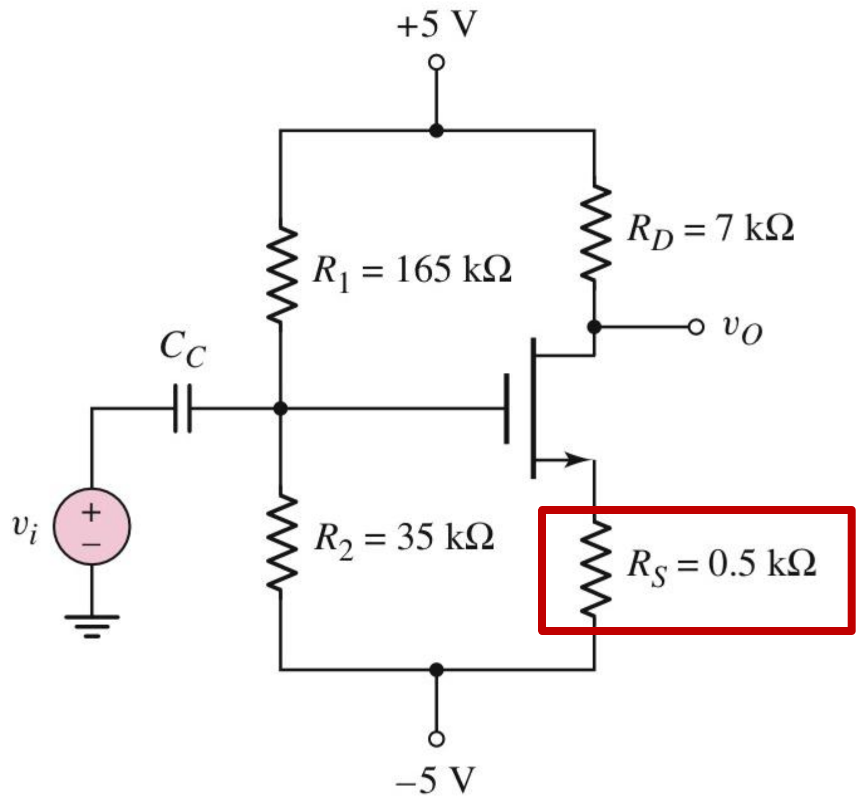


Q-point near the middle of the saturation region for maximum symmetrical output voltage swing,.

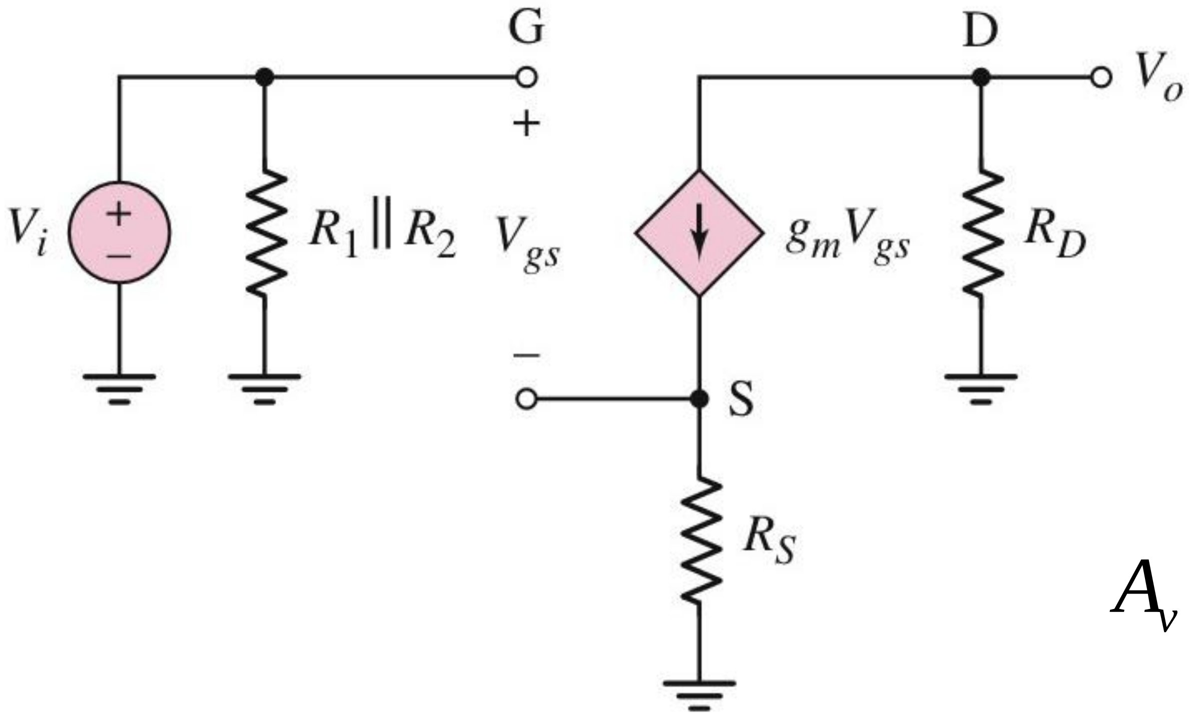
Small AC input signal for output response to be linear.

The Effect of Source Resistance

Common-Source Amplifier with Source Resistor



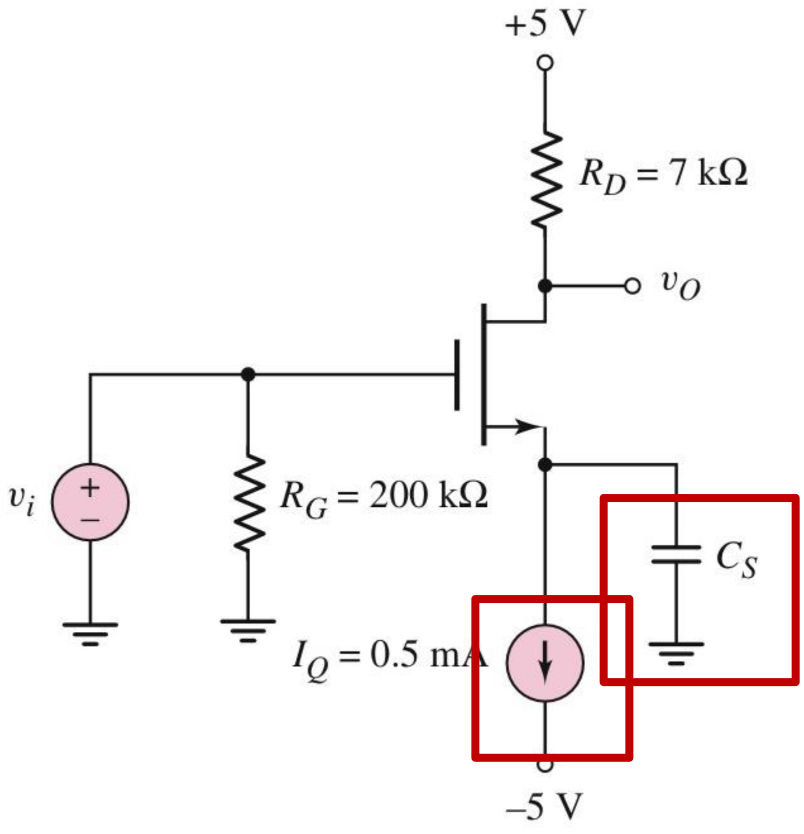
Small-Signal Equivalent Circuit for Common-Source with Source Resistor



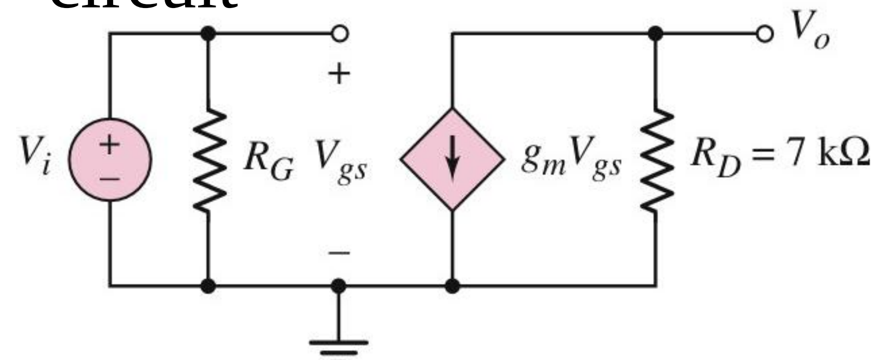
$$A_v = \frac{-\boxed{g_m} R_D}{1+\boxed{g_m} \boxed{R_S}}$$

- The source resistor is added to stabilize the Q-point.
- Voltage gain is reduced by an increase in the denominator.

Common-Source Amplifier with Bypass Capacitor



Small-signal equivalent circuit

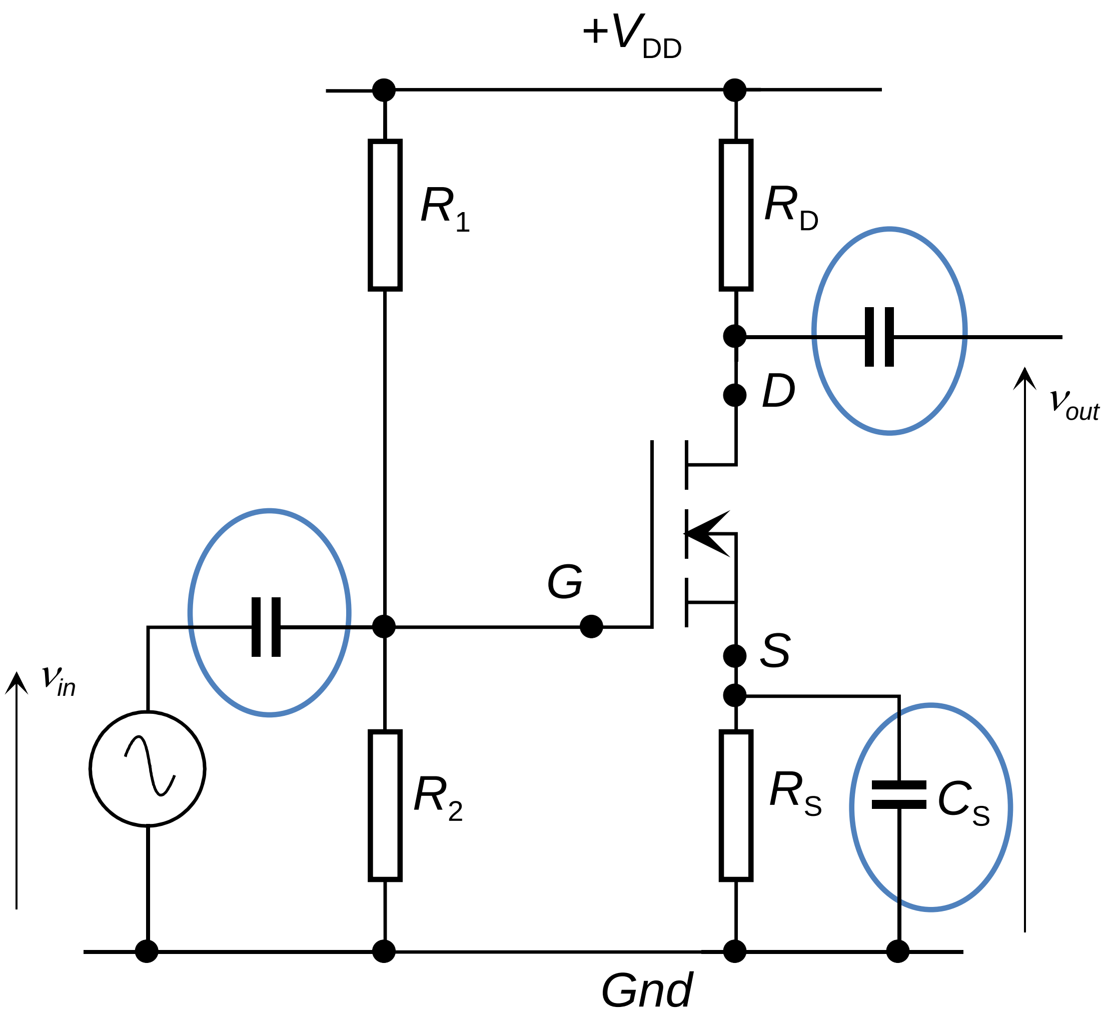


- Bypass capacitor is added to minimize the loss in the voltage gain.
- The source resistor is replaced by the current source to further stabilize the Q-poi

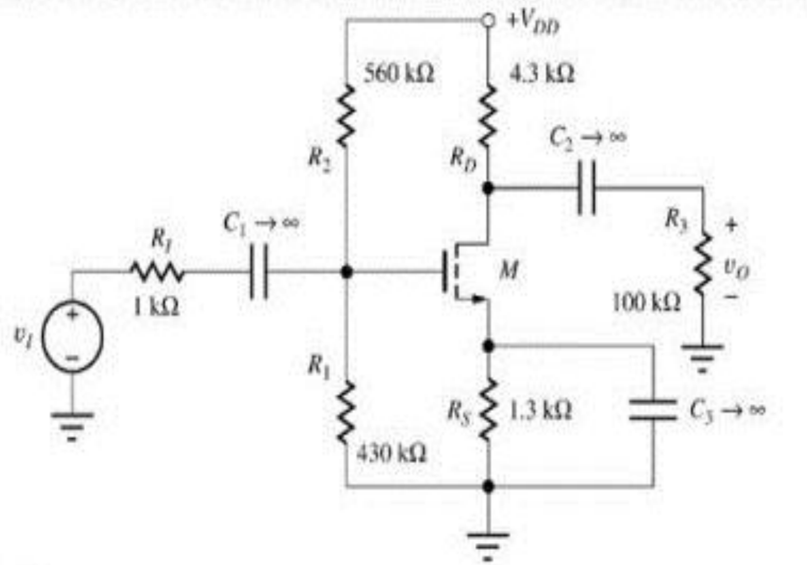
Common Source Small Signal Analysis Parameters

Small Signal Amplifier

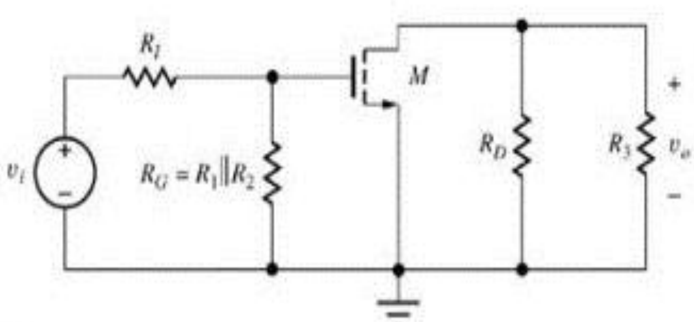
A small-signal amplifier is built by adding input and output coupling capacitors and a source bypass capacitor



Small-Signal Analysis of Complete C-S Amplifier: AC Equivalent



(a)



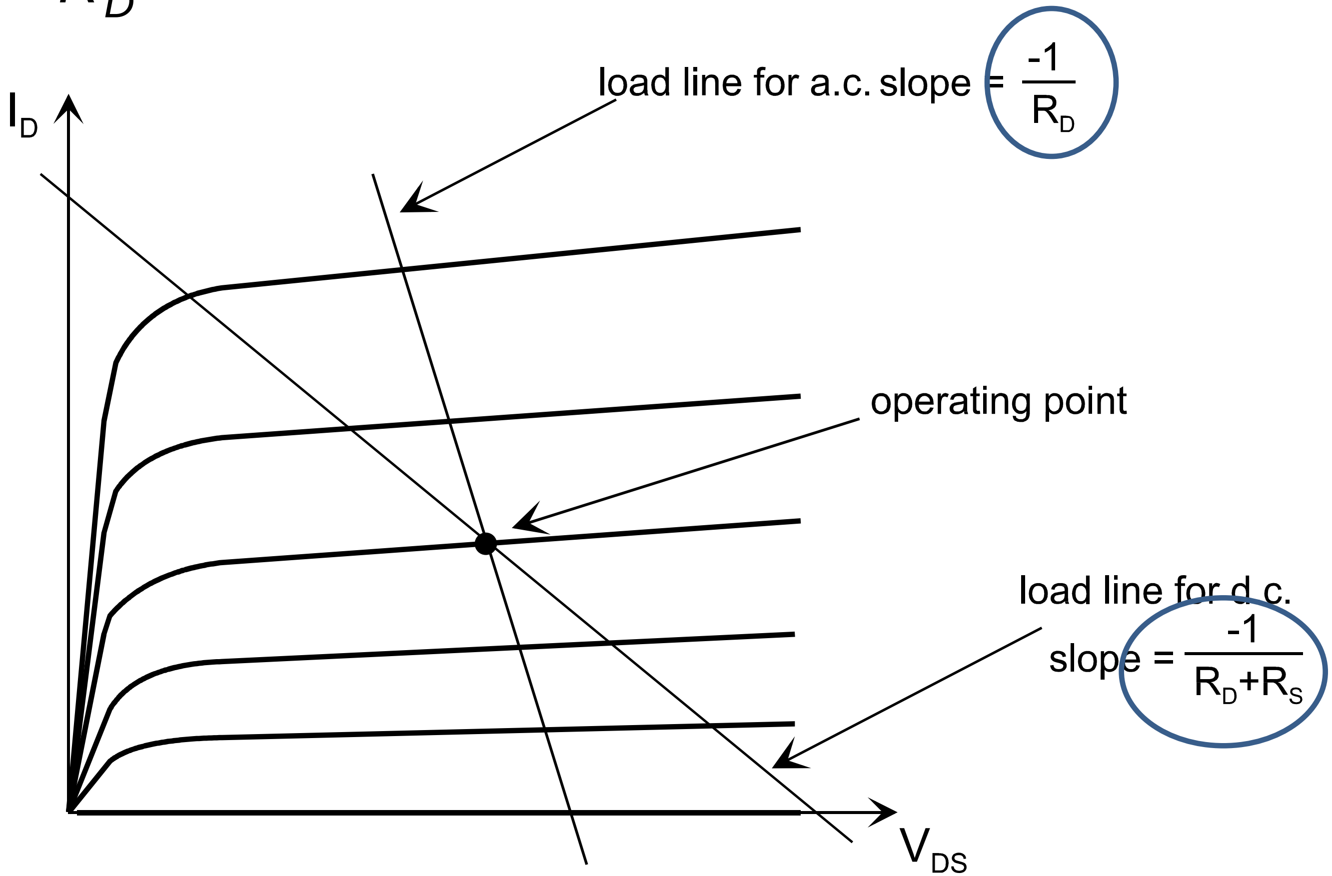
(b)

- AC equivalent circuit is constructed by assuming that all capacitances have zero impedance at signal frequency and dc voltage sources represent AC grounds.
- Assume that Q-point is already known.

$$R_G = R_1 \| R_2$$

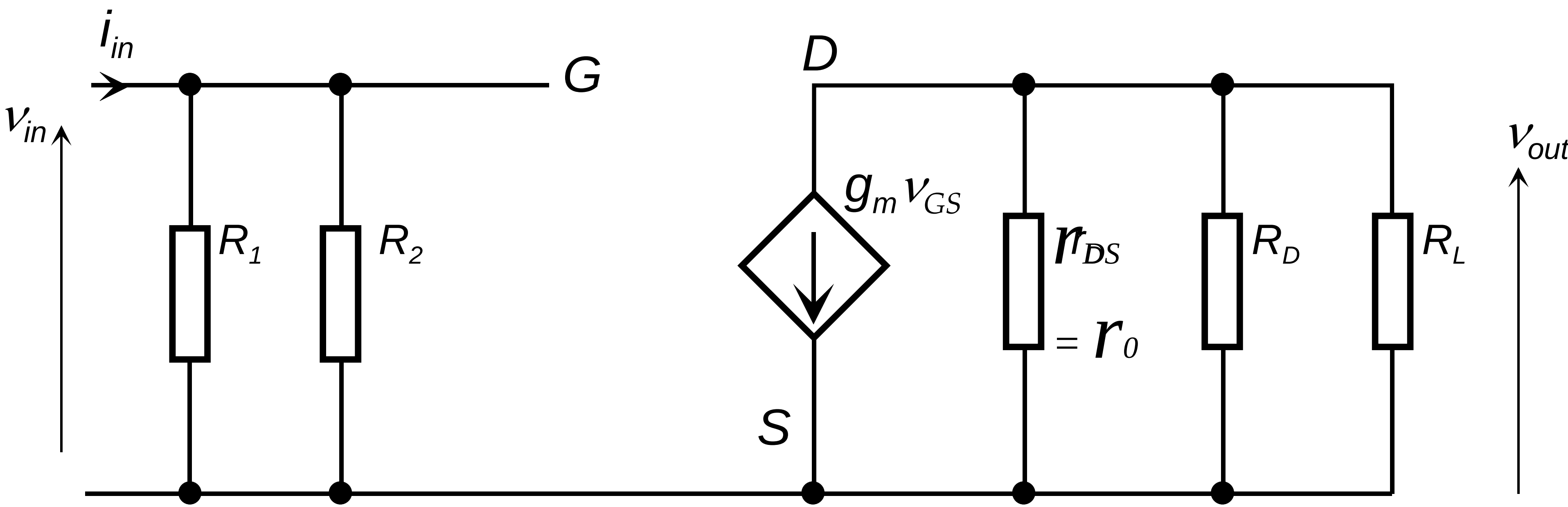
A.c. Load Line

Note that when the **source bypass capacitor** is used, only the **drain resist** R_D determines the a.c. response at the operating point, the a.c. load line slope is $-\dfrac{1}{R_D}$ at the operating point.



Small Signal Equivalent Circuit

The small signal equivalent circuit of the common-source amplifier is



Input Resistance and Voltage Gain

The **input resistance** is $R_{in} = \frac{v_{in}}{i_{in}}$ and $i_{in} = \frac{v_{in}}{R_G}$ where $R_G = \frac{R_1 R_2}{R_1 + R_2}$

Hence $$R_{in} = R_G = \frac{R_1 R_2}{R_1 + R_2}$$

Large values may be selected for R_1 and R_2 – the upper limit is set by high frequency requirements

The **open circuit voltage gain** is

$$A_v = \frac{v_{out}}{v_{in}}$$

$$v_{out} = -g_m v_{gs} R_D$$

$$v_{in} = v_{gs}$$

Hence $$A_v = \frac{v_{out}}{v_{in}} = -g_m R_D$$

Output Resistance

Note g_m has units of Siemens, Ω^{-1}, so A_V is dimensionless (has no units) as it should.

$$v_{oc} = -g_m v_{gs} R_D$$

$$i_{sc} = -g_m v_{gs}$$

Hence $$r_{out} = R_D$$

Summary - the generic (black box) amplifier properties of the common source amplifier are

$$R_{in} = R_G = \frac{R_1 R_2}{R_1 + R_2} \qquad A_v = \frac{v_{out}}{v_{in}} = -g_m R_D \qquad R_{out} = R_D$$

Common Source Circuit Examples

Example 1

Consider an n-channel enhancement-mode MOSFET with the following parameter: $V_{TN} = 0.75\text{V}$, $W = 40\mu\text{m}$, $L = 4\mu\text{m}$, $\mu_n = 650\,c\,\text{m}^2/\text{V}-\text{s}$, $t_{\text{ox}} = 450\,\overset{0}{\text{A}}$, and $\varepsilon_{\text{ox}} = (3.9)(8.85\,\text{x}\,10^{-14})\text{F/cm}$.

Determine the current when $V_{\text{GS}} = 2V_{TN}$, for the transistor biased on the saturation region.

Solution:

The conduction parameter is determine by equation R4. First, consider the units involved in this equation, as follows:

$$K_n = \frac{W(\text{cm}) \,.\, \mu_n\left(\dfrac{\text{cm}^2}{\text{V-s}}\right) .\, \varepsilon_{\text{ox}}\left(\dfrac{\text{F}}{\text{cm}}\right)}{2\text{L}(\text{cm}) \,.\, t_{\text{ox}}(\text{cm})} = \frac{\text{A}}{\text{V}^2}$$

Example 1 (Cont')

$$K_n = \frac{\left(40 \text{ x } 10^{-4}\right)\left(650\right)\left(3.9\right)\left(8.85 \text{ x } 10^{-14}\right)}{2\left(4 \text{ x } 10^{-4}\right)\left(450 \text{ x } 10^{-8}\right)} = 0.249 \text{ mA/V}^2$$

$$i_D = K_n\left(v_{GS} - V_{TN}\right)^2 = \left(0.249\right)\left(1.5 - 0.75\right)^2 = 0.140\text{mA}$$

Example 2

An n-channel enhancement-mode MOSFET with $V_{TN} = 1\text{V}$ has a drain Current $i_D = 0.8\text{mA}$ when $V_{\text{GS}} = 3\text{V}$ and $V_{\text{DS}} = 4.5\text{V}$.

Calculate the drain current when : .

a) $V_{\text{GS}} = 2\text{V}$; $V_{\text{DS}} = 4.5\text{V}$

b) $V_{\text{GS}} = 3\text{V}$; $V_{\text{DS}} = 1\text{V}$

Solution:

$$V_{TN} = 1\ V,\ V_{GS} = 3\ V,\ V_{DS} = 4.5\ V$$

$$V_{DS} = 4.5 > V_{DS}(sat) = V_{GS} - V_{TN} = 3 - 1 = 2\ V$$

Transistor biased in the saturation region

$$I_D = K_n (V_{GS} - V_{TN})^2 \Rightarrow 0.8 = K_n (3-1)^2 \Rightarrow K_n = 0.2\ mA/V^2$$

Example 2 (Cont')

(a) $V_{GS} = 2\ V,\ V_{DS} = 4.5\ V$

Saturation region:

$$I_D = (0.2)(2-1)^2 \Rightarrow \underline{I_D = 0.2\ mA}$$

(b) $V_{GS} = 3\ V,\ V_{DS} = 1\ V$

Nonsaturation region:

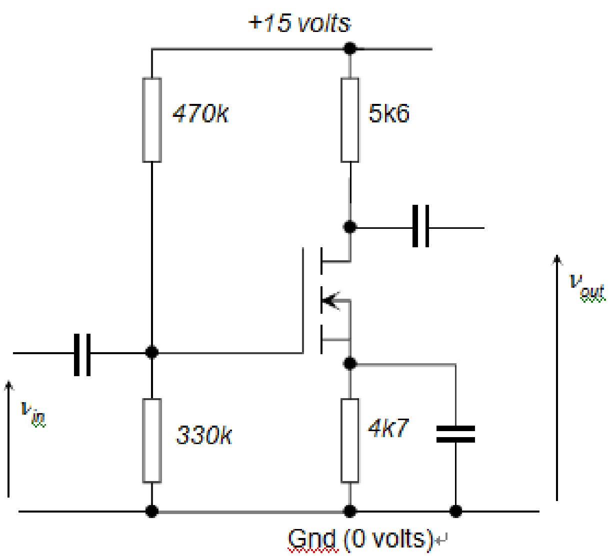
$$I_D = (0.2)\left[2(3-1)(1)-(1)^2\right] \Rightarrow \underline{I_D = 0.6\ mA}$$

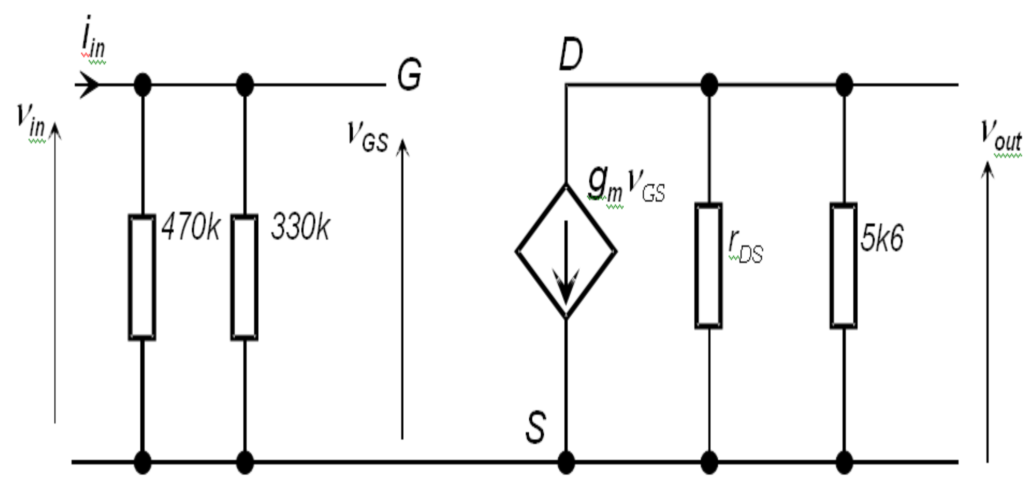
Example 3

A common source amplifier circuit based around a single n-channel MOSFET is shown in Figure Ex3.1. The equivalent hybrid pi model of the circuit is shown in the Figure Ex3.2.

a) Calculate the input resistance.
b) Calculate the output resistance.
c) Calculate the open circuit voltage gain .
d) Calculate the current gain when the amplifier has a load of 10k .

Assume the transconductance g_m = 30 mA/volts and assume that r_{DS} is so large it may be neglected.

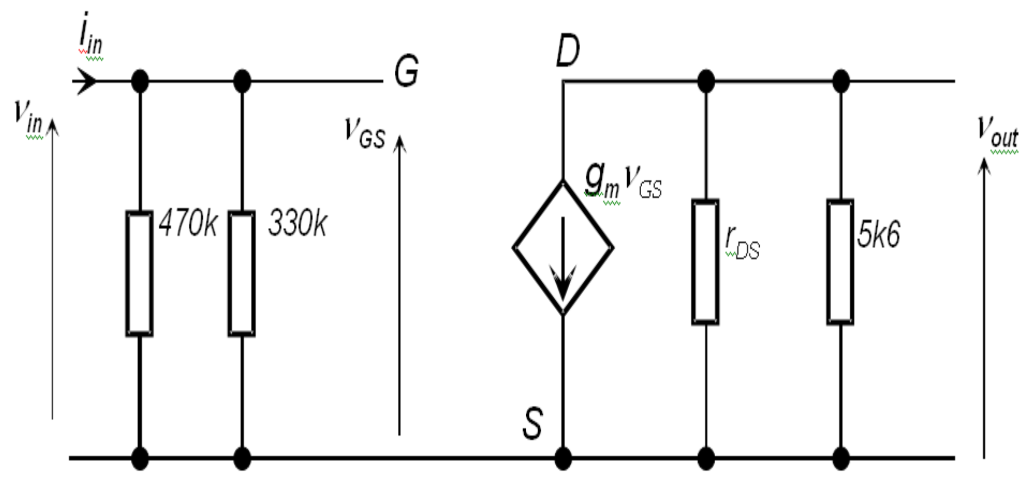




Example 3 (Cont')

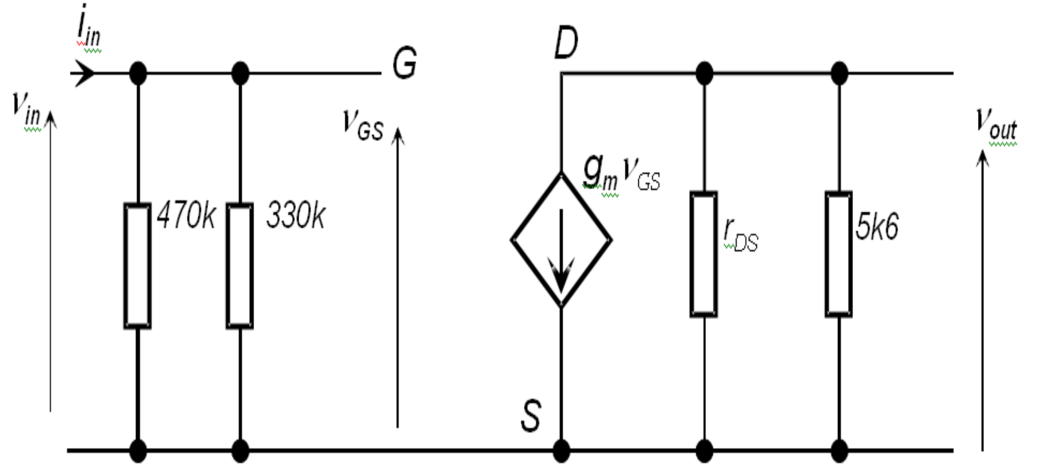
Solution:

a) Input resistance is 470k and 330k in parallel $R_{in} = \left(\frac{1}{470k} + \frac{1}{330k}\right)^{-1}$ = 194k

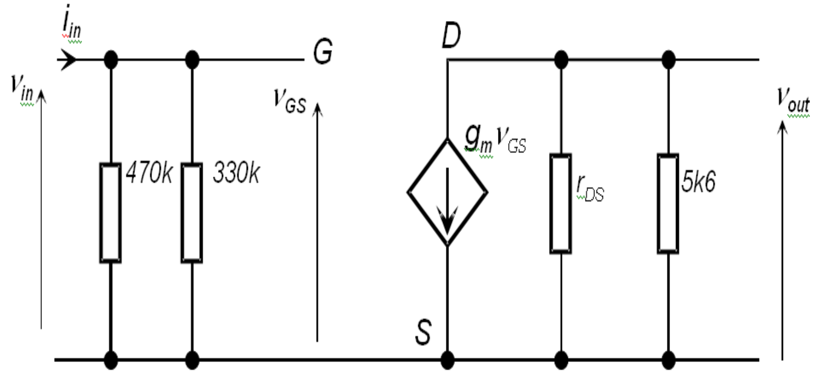


Example 3 (Cont')

b) Ignoring r_{DS}, output resistance is Rout = 5k6



Example 3 (Cont')



c) Open circuit voltage gain $A_v = \dfrac{v_{out}}{v_{in}}$

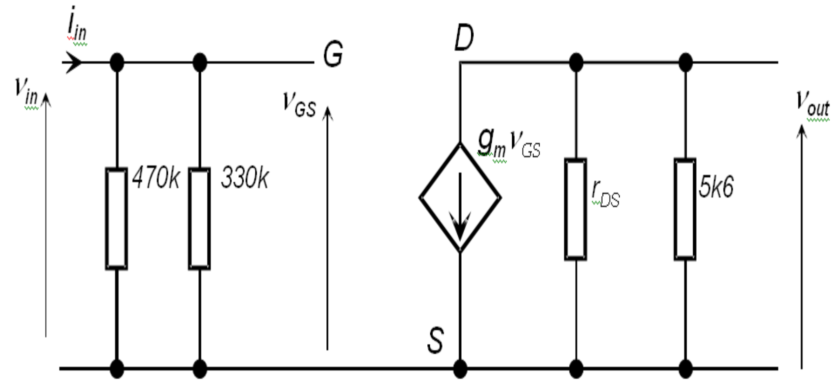
Since $v_{out} = -g_m v_{gs} R_D$ and $v_{in} = v_{gs}$

then

$$A_v = \frac{v_{out}}{v_{in}} = -g_m R_D$$

$$= -\ 30 \times 10^{-3} \times 5.6 \times 10^{+3} = -168$$

Example 3 (Cont')



d) Input current is $i_{in} = v_{in} / 194k$ mA

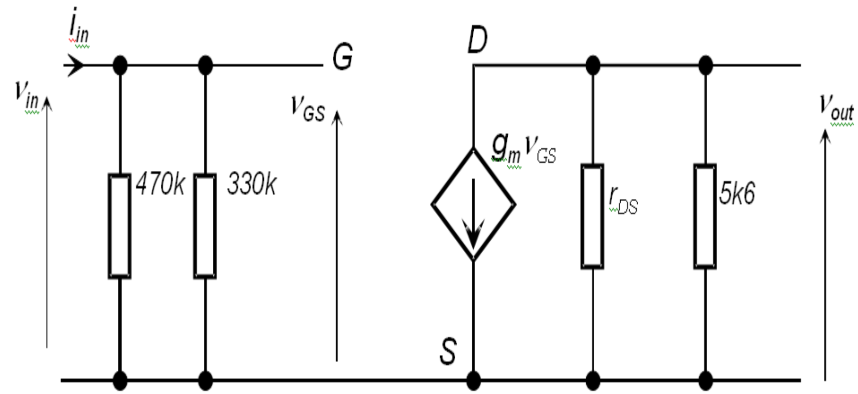
Combined output resistance with load is 5k6 and 10k in parallel is $R_C = \left(\frac{1}{5600} + \frac{1}{10000}\right)^{-1}$ = 3590Ω

Output voltage, $v_{out} = -g_m v_{gs} R_C$

$= - 30 \text{ x } 10^{-3} \times 3.59 \times 10^{+3} \times v_{in}$

$= - 107.7\, v_{in}$

Example 3 (Cont')



d) Output current

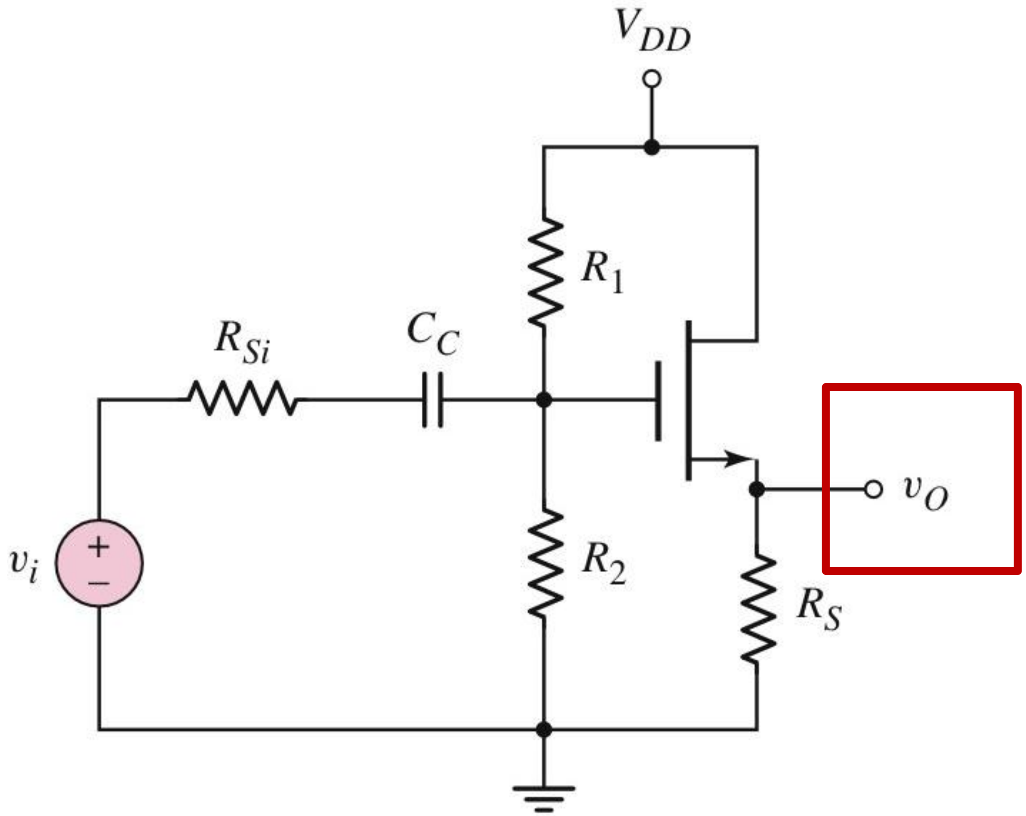
$$i_{out} = v_{out} / R_L = -107.7 v_{in} / 10^4 = \frac{-107.7 \times 194k \times i_{in}}{10k}$$

Hence current gain is

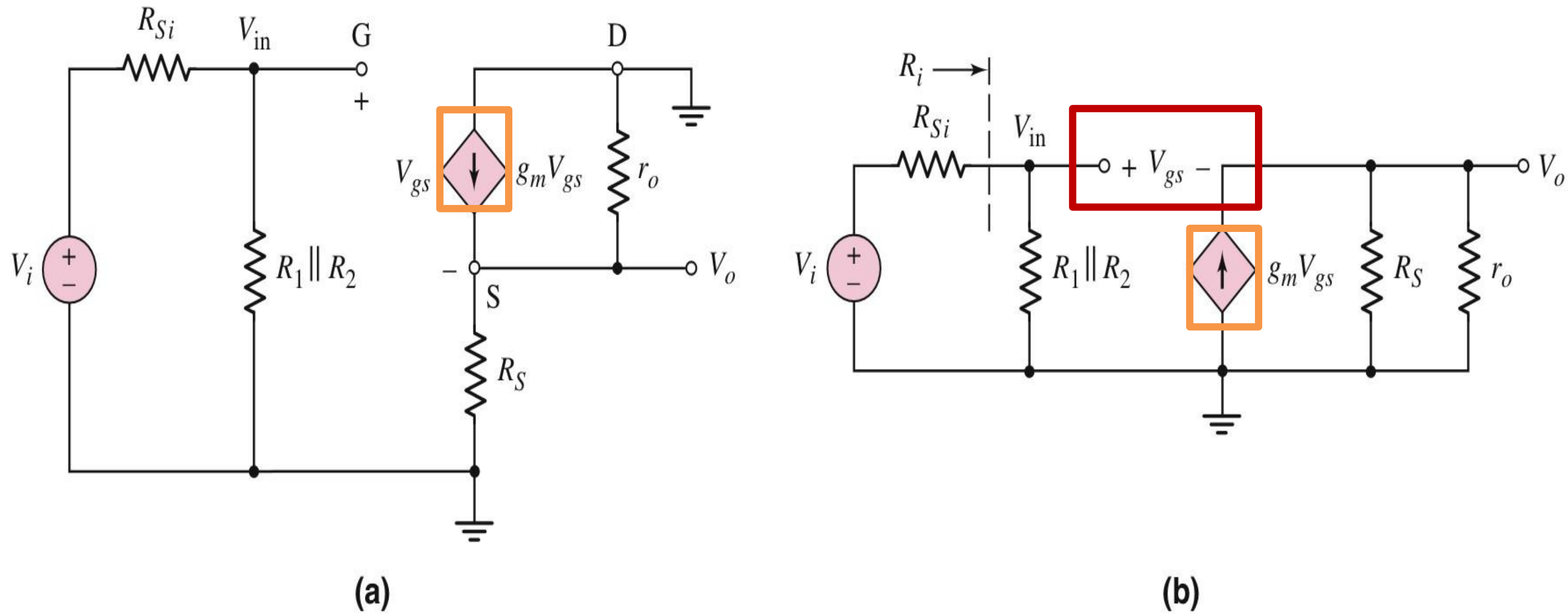
$$A_i = i_{out} / i_{in} = \text{-2089}$$

Common Drain or Source Follower Amplifier Circuit

NMOS Source-Follower or Common Drain Amplifier



Small-Signal Equivalent Circuit for Source Follower



Common Drain Amplifier

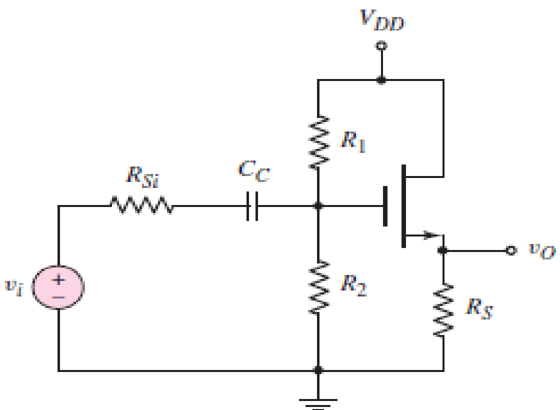
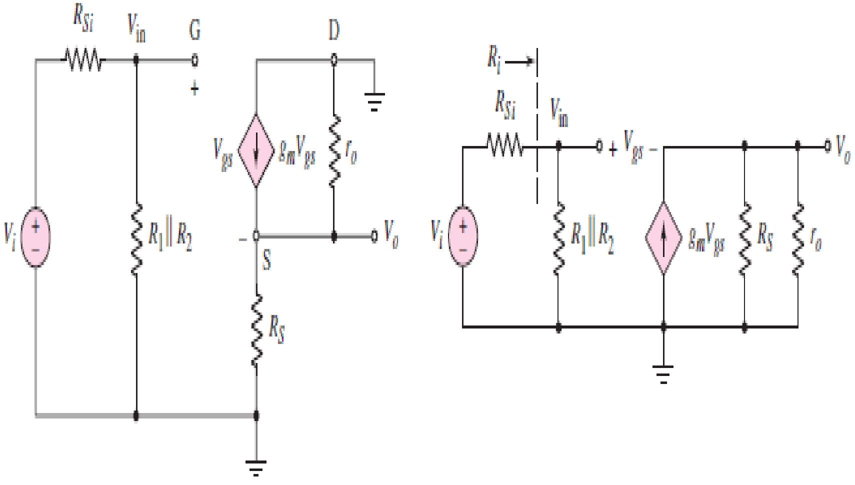


Figure 4.26 NMOS source-follower or common-drain amplifier



(a) (b)

Figure 4.27 (a) Small-signal equivalent circuit of NMOS source follower and (b) small-signal equivalent circuit of NMOS source follower with all signal grounds at a common point

$$V_o = (g_m V_{gs})(R_S \| r_o) \tag{4.30}$$

Writing a KVL equation from input to output results in the following:

$$V_{in} = V_{gs} + V_o = V_{gs} + g_m V_{gs}(R_S \| r_o) \tag{4.31(a)}$$

Therefore, the gate-to-source voltage is

$$V_{gs} = \frac{V_{in}}{1 + g_m(R_S \| r_o)} = \left[\frac{\frac{1}{g_m}}{\frac{1}{g_m} + (R_S \| r_o)}\right] \cdot V_{in} \tag{4.31(b)}$$

Equation (4.31(b)) is written in the form of a voltage-divider equation, in which the gate-to-source of the NMOS device looks like a resistance with a value of $1/g_m$. More accurately, the effective resistance looking into the source terminal (ignoring r_o) is $1/g_m$. The voltage V_{in} is related to the source input voltage V_i by

$$V_{in} = \left(\frac{R_i}{R_i + R_{Si}}\right) \cdot V_i \tag{4.32}$$

where $R_i = R_1 \| R_2$ is the input resistance to the amplifier.

Substituting Equations (4.31(b)) and (4.32) into (4.30), we have the small-signal voltage gain:

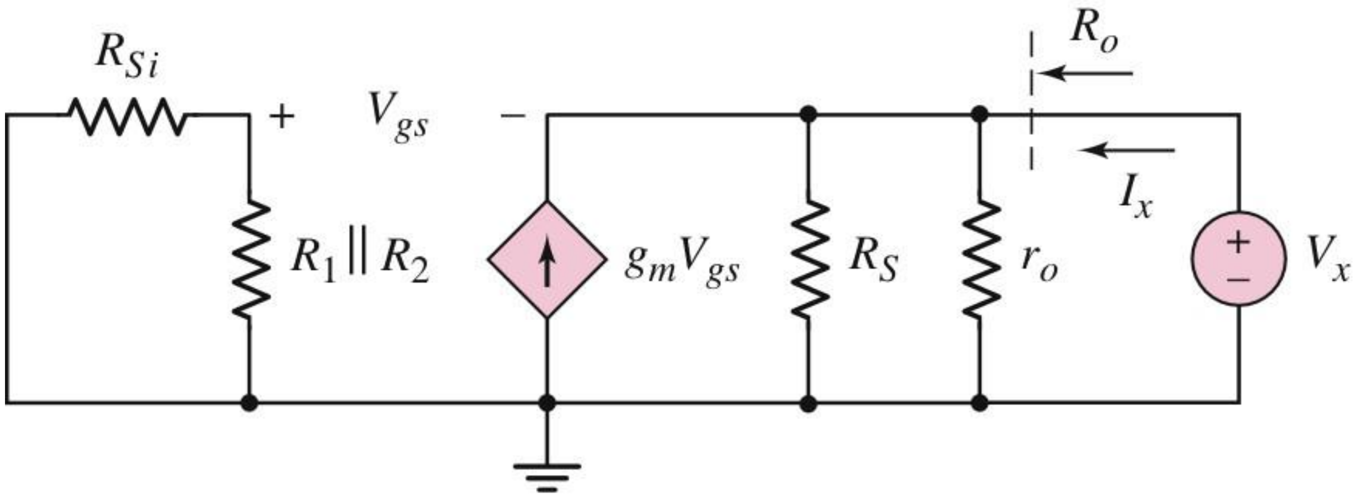
$$A_v = \frac{V_o}{V_i} = \frac{g_m(R_S \| r_o)}{1 + g_m(R_S \| r_o)} \cdot \left(\frac{R_i}{R_i + R_{Si}}\right) \tag{4.33(a)}$$

or

$$A_v = \frac{R_S \| r_o}{\frac{1}{g_m} + R_S \| r_o} \cdot \left(\frac{R_i}{R_i + R_{Si}}\right) \tag{4.33(b)}$$

which again is written in the form of a voltage-divider equation. An inspection of Equation 4.33(b) shows that the magnitude of the voltage gain is always less than unity.

Determining Output Impedance NMOS Source Follower



$$R_O = \frac{1}{g_m} \bigg\| R_S \| r_o$$

Input and Output Impedances

$$R_o = \frac{V_x}{I_x} \qquad (4.34)$$

Writing a KCL equation at the output source terminal produces

$$I_x + g_m V_{gs} = \frac{V_x}{R_S} + \frac{V_x}{r_o} \qquad (4.35)$$

Since there is no current in the input portion of the circuit, we see that $\boxed{V_{gs} = -V_x}$. Therefore, Equation (4.35) becomes

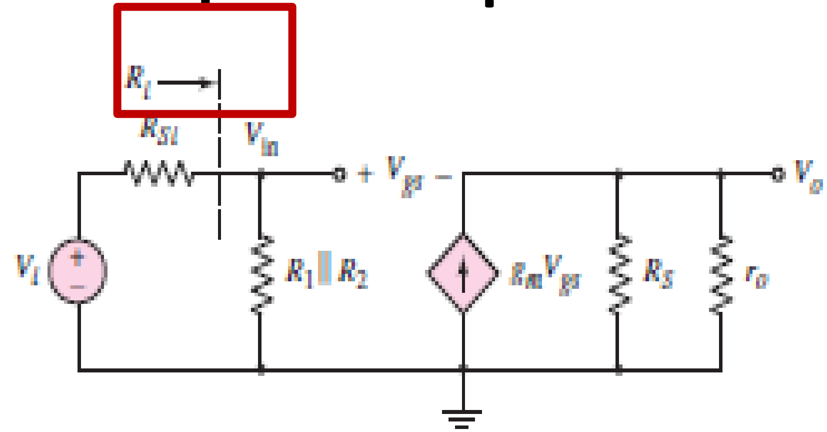
$$I_x = V_x\left(g_m + \frac{1}{R_S} + \frac{1}{r_o}\right) \qquad (4.36(a))$$

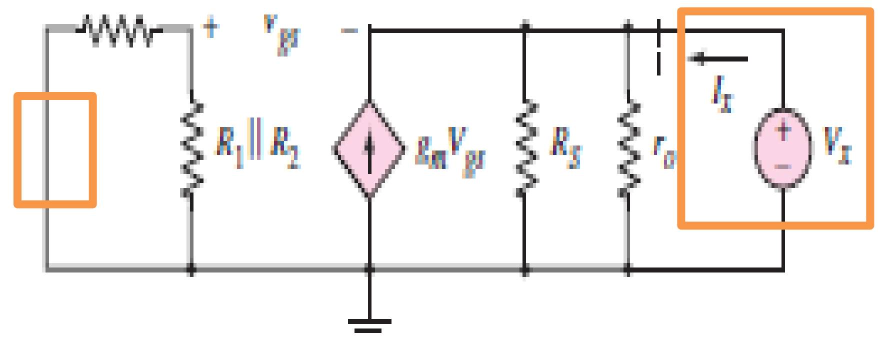
or

$$\frac{I_x}{V_x} = \frac{1}{R_o} = g_m + \frac{1}{R_S} + \frac{1}{r_o} \qquad (4.36(b))$$

The output resistance is then

$$\boxed{R_o = \frac{1}{g_m} \| R_S \| r_o} \qquad (4.37)$$



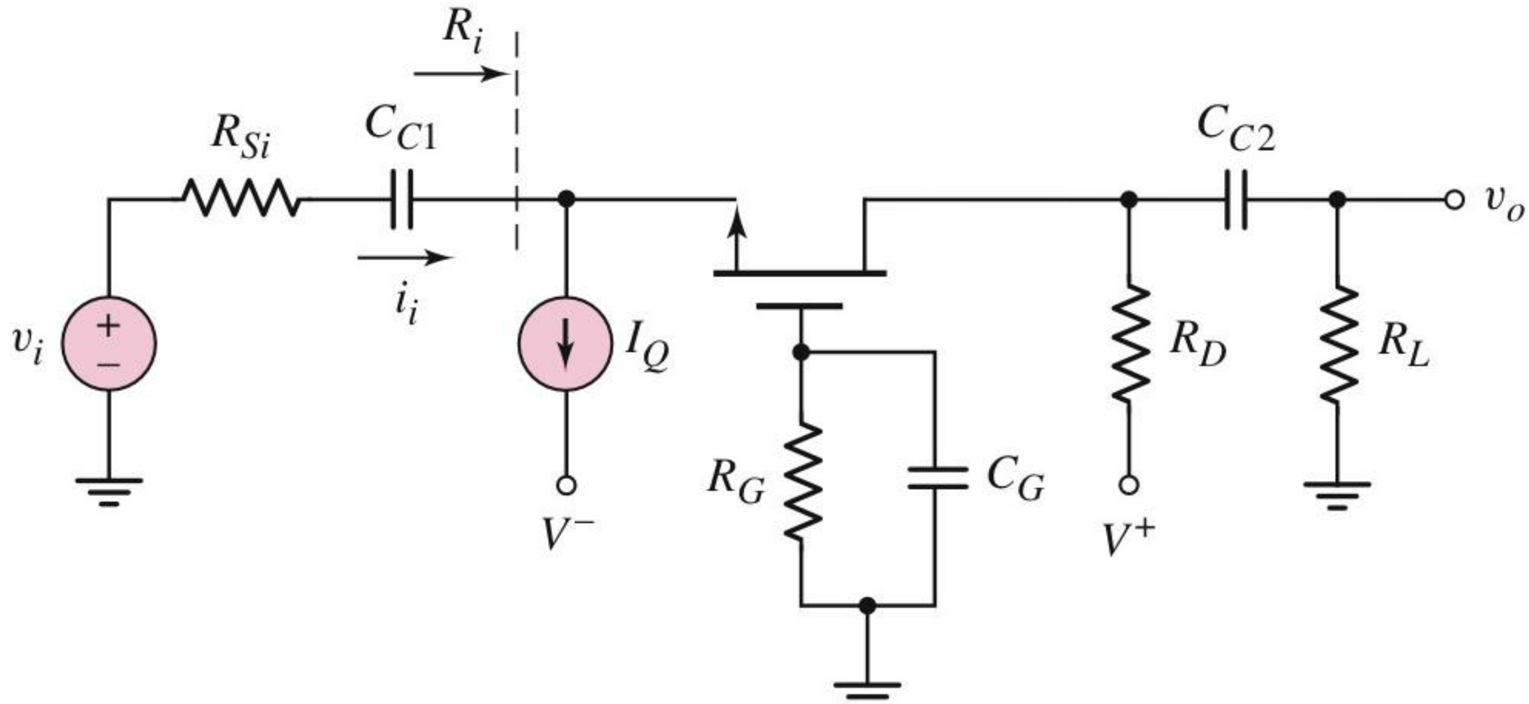


- The small-signal input resistance *Ri* as defined as the Thevenin equivalent resistance of the bias resistors (see figure above). So Ri = $R_1 \,||\, R_2$

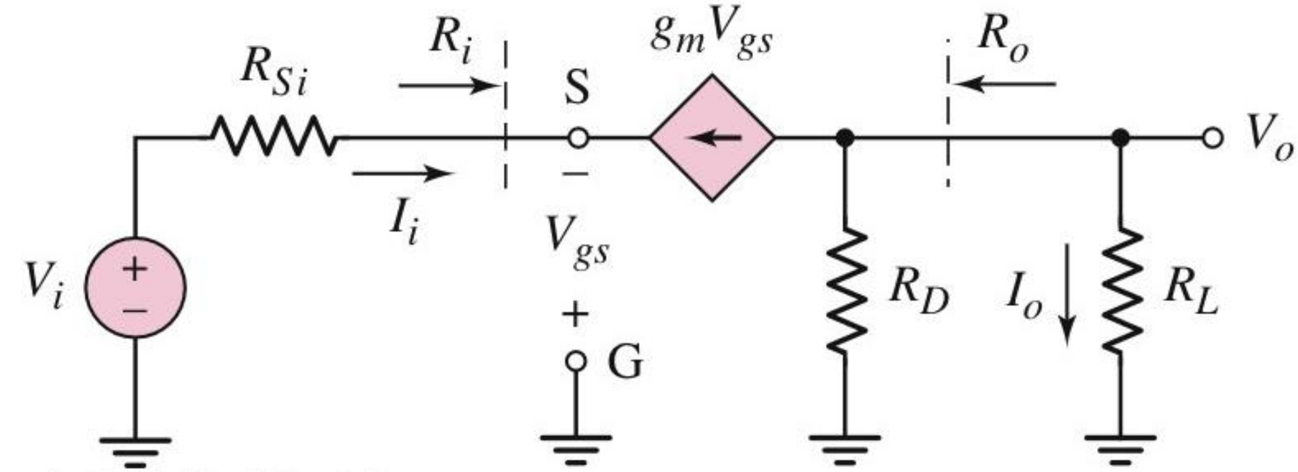
- To calculate the small-signal output resistance, we set all independent small signal sources equal to zero, apply a test voltage to the output terminals, and measure a test current.

Common Gate Amplifier Circuit

Common-Gate Circuit



Small-Signal Equivalent Circuit for Common Gate



$$A_v = \frac{g_m (R_D \| R_L)}{1 + g_m R_{Si}}$$

$$A_i = \frac{I_O}{I_i} = \left(\frac{R_D}{R_D + R_L}\right)\left(\frac{g_m R_{Si}}{1 + g_m R_{Si}}\right)$$

Common Gate Amplifier

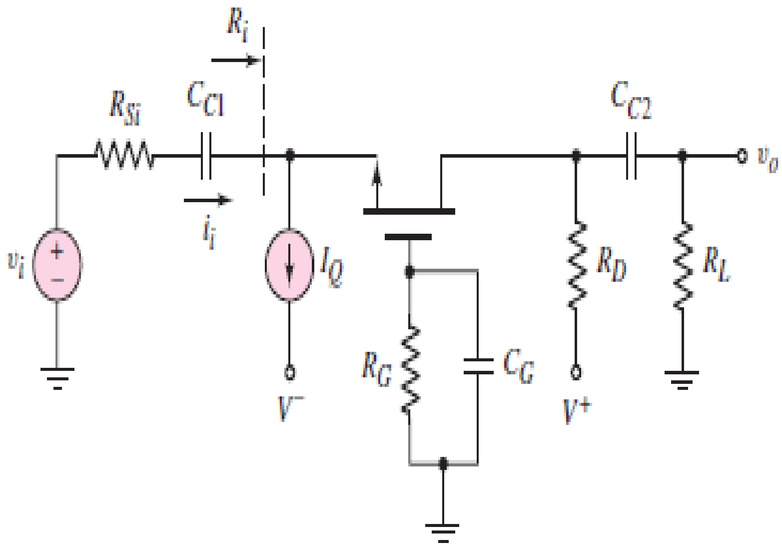


Figure 4.32 Common-gate circuit

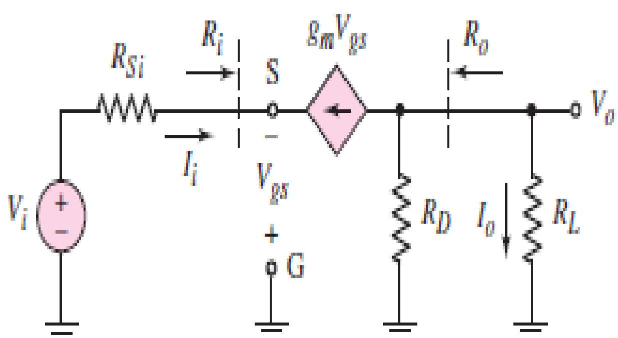


Figure 4.33 Small-signal equivalent circuit of common-gate amplifier

$$V_o = -(g_m V_{gs})(R_D \| R_L) \tag{4.38}$$

Writing the KVL equation around the input, we find

$$V_i = I_i R_{Si} - V_{gs} \tag{4.39}$$

where $I_i = -g_m V_{gs}$. The gate-to-source voltage can then be written as

$$V_{gs} = \frac{-V_i}{1 + g_m R_{Si}} \tag{4.40}$$

The small-signal voltage gain is found to be

$$\boxed{A_v = \frac{V_o}{V_i} = \frac{g_m(R_D \| R_L)}{1 + g_m R_{Si}}} \tag{4.41}$$

Also, since the voltage gain is positive, the output and input signals are in phase.

In many cases, the signal input to a common-gate circuit is a current. Figure 4.34 shows the small-signal equivalent common-gate circuit with a Norton equivalent circuit as the signal source. We can calculate a current gain. The output current I_o can be written

$$I_o = \left(\frac{R_D}{R_D + R_L}\right)(-g_m V_{gs}) \tag{4.42}$$

At the input we have

$$I_i + g_m V_{gs} + \frac{V_{gs}}{R_{Si}} = 0 \tag{4.43}$$

or

$$V_{gs} = -I_i\left(\frac{R_{Si}}{1 + g_m R_{Si}}\right) \tag{4.44}$$

The small-signal current gain is then

$$\boxed{A_i = \frac{I_o}{I_i} = \left(\frac{R_D}{R_D + R_L}\right) \cdot \left(\frac{g_m R_{Si}}{1 + g_m R_{Si}}\right)} \tag{4.45}$$

We may note that if $R_D \gg R_L$ and $g_m R_{Si} \gg 1$, then the current gain is essentially unity.

Input and Output Resistance

4.5.2 Input and Output Impedance

In contrast to the common-source and source-follower amplifiers, the common-gate circuit has a low input resistance because of the transistor. However, if the input signal is a current, a low input resistance is an advantage. The input resistance is defined, using Figure 4.33, as

$$R_i = \frac{-V_{gs}}{I_i} \tag{4.46}$$

Since $I_i = -g_m V_{gs}$, the input resistance is

$$\boxed{R_i = \frac{1}{g_m}} \tag{4.47}$$

This result has been obtained previously.

We can find the output resistance by setting the input signal voltage equal to zero. From Figure 4.33, we see that $V_{gs} = -g_m V_{gs} R_{Si}$, which means that $V_{gs} = 0$. Consequently, $g_m V_{gs} = 0$. The output resistance, looking back from the load resistance, is therefore

$$\boxed{R_o = R_D} \tag{4.48}$$

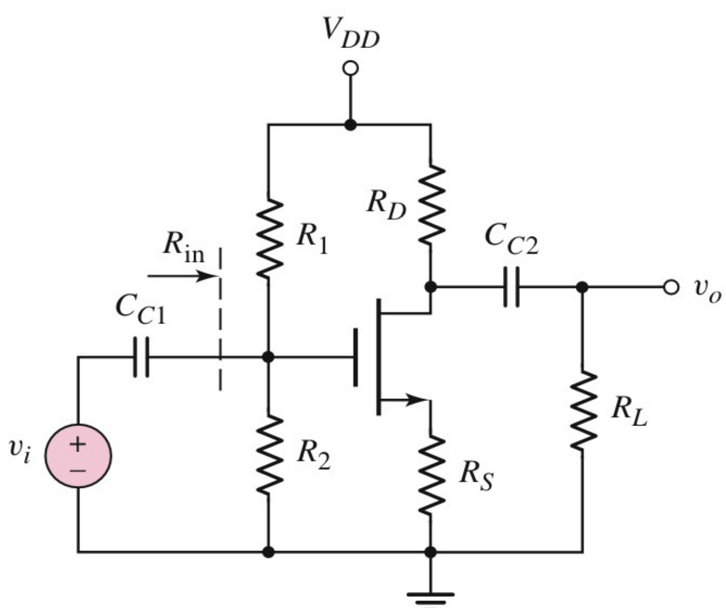
Comparison of Three Amplifier Circuits

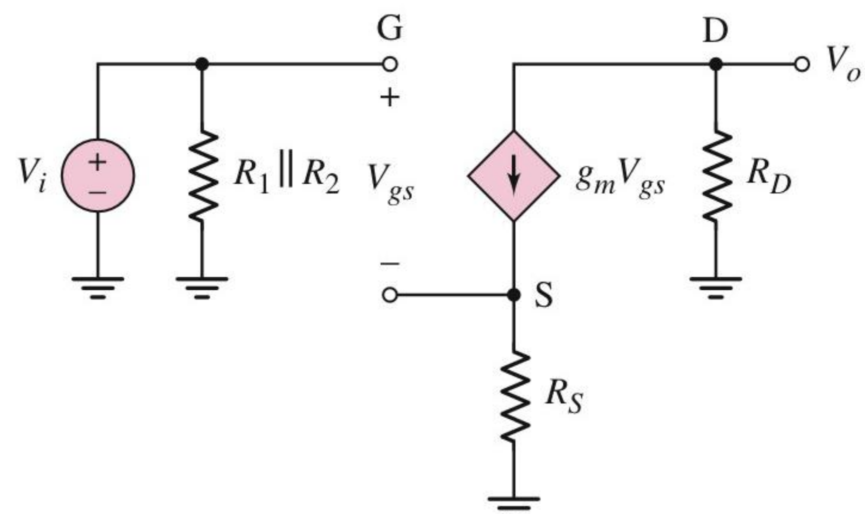
Comparison of 3 Basic Amplifiers

Configuration	Voltage Gain	Current Gain	Input Resistance	Output Resistance
Common Source	$A_v > 1$	—	R_{TH}	Moderate to high
Source Follower	$A_v \approx 1$	—	R_{TH}	Low
Common Gate	$A_v > 1$	$A_i \approx 1$	Low	Moderate to high

Example 4

The parameters of the circuit shown in Figure P4.15 are V_{DD} = 12 V, R_S = 0.5 kΩ, R_{in} = 250 kΩ, and R_L = 10 kΩ. The transistor parameters are V_{TN} = 1.2 V, K_n = 1.5 mA/V^2, are λ = 0. (a) Design the circuit such that I_{DQ} = 2 mA and V_{DSQ} = 5 V. (b) Determine the small signal voltage gain. (The small signal output resistance $r_O \cong \frac{1}{\lambda I_{DQ}}$. The transconductance $g_m = 2\sqrt{K_{n_{I_{DQ}}}}$.)





Solution

(a) $\boxed{V_{DSQ} = V_{DD} - I_{DQ}(R_S + R_D)}$

$5 = 12 - (2)(R_S + R_D) \Rightarrow \boxed{R_S + R_D = 3.5\ \text{k}\Omega}$

$R_S = 0.5\ \text{k}\Omega$, then $\boxed{R_D = 3\ \text{k}\Omega}$

$\boxed{I_{DQ} = K_n (V_{GSQ} - V_{TN})^2}$

$2 = 1.5(V_{GSQ} - 1.2)^2 \Rightarrow \boxed{V_{GSQ} = 2.355\ \text{V}}$

$\boxed{V_G = V_{GSQ} + I_{DQ} R_S} = 2.355 + (2)(0.5) = 3.355\ \text{V}$

$$\boxed{V_G = \left(\frac{R_2}{R_1 + R_2}\right) \cdot V_{DD}} = \frac{1}{R_1} \cdot R_{in} \cdot V_{DD}$$

$$3.355 = \frac{1}{R_1}(250)(12) \Rightarrow \boxed{R_1 = 894\ \text{k}\Omega}$$

$R_1 \| R_2 = 894 \| R_2 = 250 \Rightarrow \boxed{R_2 = 347\ \text{k}\Omega}$

(b) $g_m = 2\sqrt{(1.5)(2)} = 3.464\ \text{mA/V}$

$$A_v = \frac{-g_m (R_D \| R_L)}{1 + g_m R_S} = \frac{-(3.464)(3\|10)}{1 + (3.464)(0.5)} = -2.93$$

Chapter 4

- Investigate a single-transistor circuit that can amplify a small, time-varying input signal
  - Develop small-signal models that are used in the analysis of linear amplifiers.
- Discuss and compare the three basic transistor amplifier configurations.
  - Analyze the common-source amplifier.
  - Analyze the source-follower amplifier.
  - Analyze the common-gate amplifier.