Lecture 4

of

EEE307

Electronics for Communications

Department of Electrical & Electronic Engineering

Xi'an Jiaotong-Liverpool University (XJTLU)

Friday, 27th September 2019

- ❑ LNA in Wireless Receiver
- ❑ Transistor Amplifiers
  - ➢ fundamental configurations
- ❑ Equivalent Circuit at RF
  - ➢ transistor parasitic circuit elements

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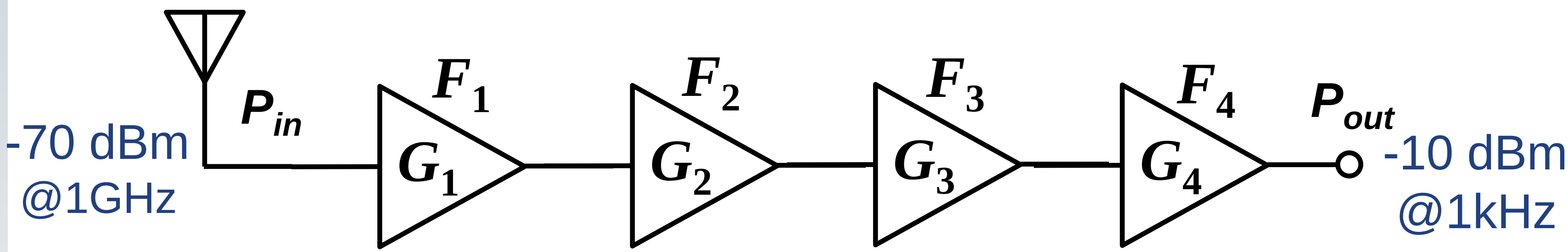
Receiver in Communication

(amplification of weak RF signals)

- In the receiver of a wireless communication system, very weak RF signals are received from the antenna and then amplified and filtered subsequently.



  - F_1 is the **noise factor** of the first-stage amplification with a signal gain G_1 so on and so forth.
  - The RF signals are typically down-converted from the **carrier frequency** to the **baseband**.

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Amplifying Received RF Signals

(noise factor & noise figure)

- The front-end amplification has a dominant impact on the receiver's performance, especially in terms of the sensitivity.

$$F_{overall} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} \cdots$$

$$F_{noise} = \frac{SNR_{in}}{SNR_{out}} \qquad SNR = \frac{P_{signal}}{P_{noise}} \qquad NF = 10\log_{10}\left(\frac{SNR_{in}}{SNR_{out}}\right)$$

  - Since an amplification circuit always adds noise to the input signal, the input **signal-to-noise ratio** (**SNR**) is always larger than the output SNR. $\Rightarrow$ ***F*** > 1 & ***NF*** > 0 dB
  - NF: noise figure (noise factor in dB)

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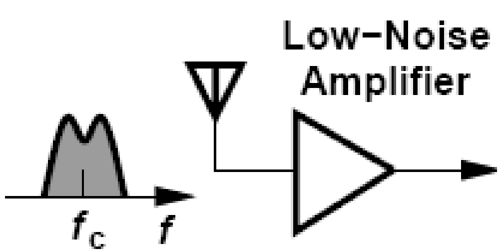
Low-Noise Amplifier

(first stage amplification in receiver)

- With its dominant impact on the overall noise performance (hence the sensitivity) of the whole receiver circuit, the first-stage amplification therefore needs to have a very low **noise factor** F_1 and also preferably a high signal gain G_1.
- Such an amplifier in a radio receiver is called the **low-noise amplifier (LNA)**.
  - A typical LNA has a **noise figure** of less than 2 dB and a signal gain of about 15-20 dB.



From: Behzad Razavi, *RF Microelectronics*, © 2012 Pearson , USA.

Low-Noise Amplifier

(design consideration)

- To design and construct an LNA, there are other considerations apart from the **noise factor** and **signal gain**.
  - input matching, output matching, gain stability, non-linearity (measured by the input or output **IP3**)
- In this module, only basic analysis of LNA circuits will be taught for essential understanding.
  - Interested students can refer to the recommended textbooks and papers for detailed theoretical analysis and design considerations.

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Low-Noise Amplifier
(from basic transistor amplifiers)

- Regardless of the apparent variety of circuit configurations for the LNA, they can be viewed as just different combinations of the fundamental transistor amplifiers:
  - Using the MOS transistors, the three fundamental transistor amplifiers are the common-source (CS), common-gate (CG) and common-drain (CD) configurations.
  - In the bipolar junction transistor (BJT) case, the counterparts are the common-emitter (CE), common-base (CB) and common-collector (CC) configurations.

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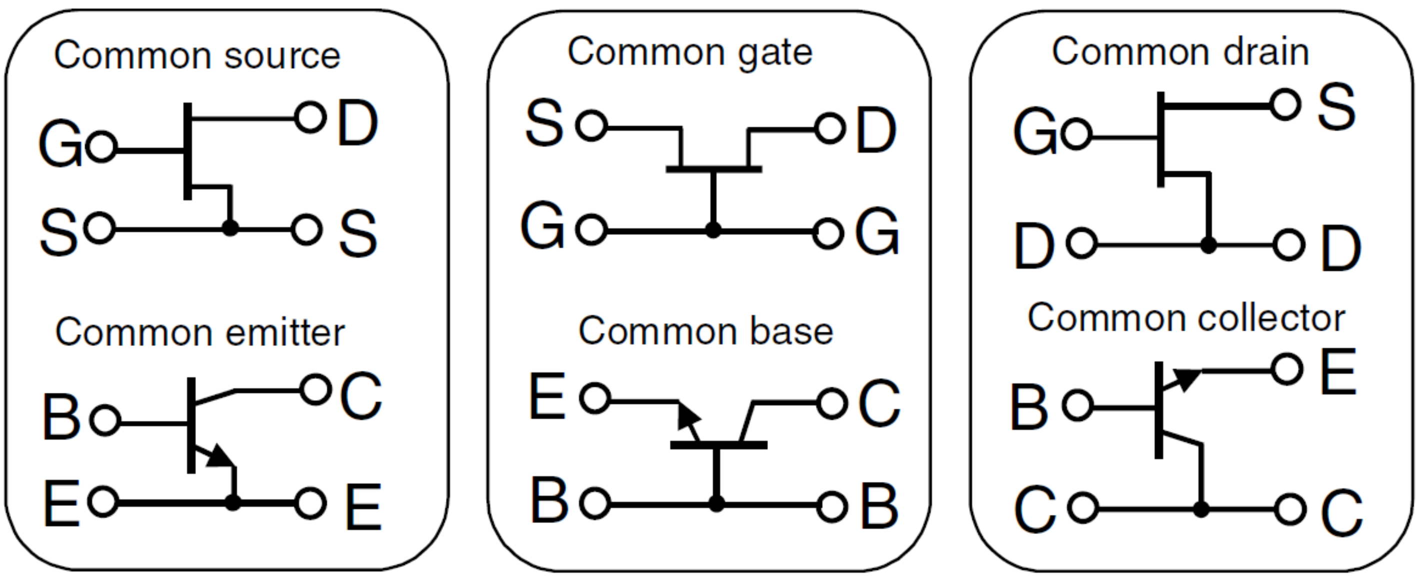
Transistor Amplifiers

(fundamental configurations)

- An LNA is a key building block of an electronic communication system. An LNA circuit itself is constructed from building-block transistor circuits.

From: Frank Ellinger, *Radio Frequency Integrated Circuits and Technologies*, © 2007 Springer, Germany.



- Starts from basics in engineering.

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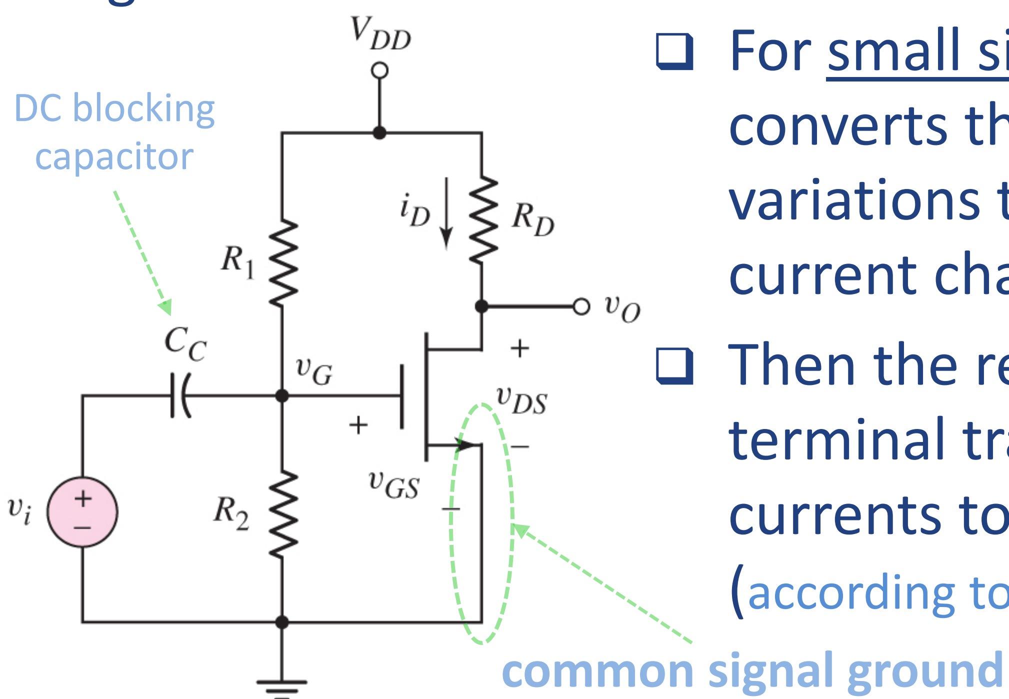
Transistor Amplifiers

(common-source configuration)

- A basic **common-source (CS) amplifier** can be formed by configuring a single MOSFET with the source terminal as the common signal ground for both the input and output signals.

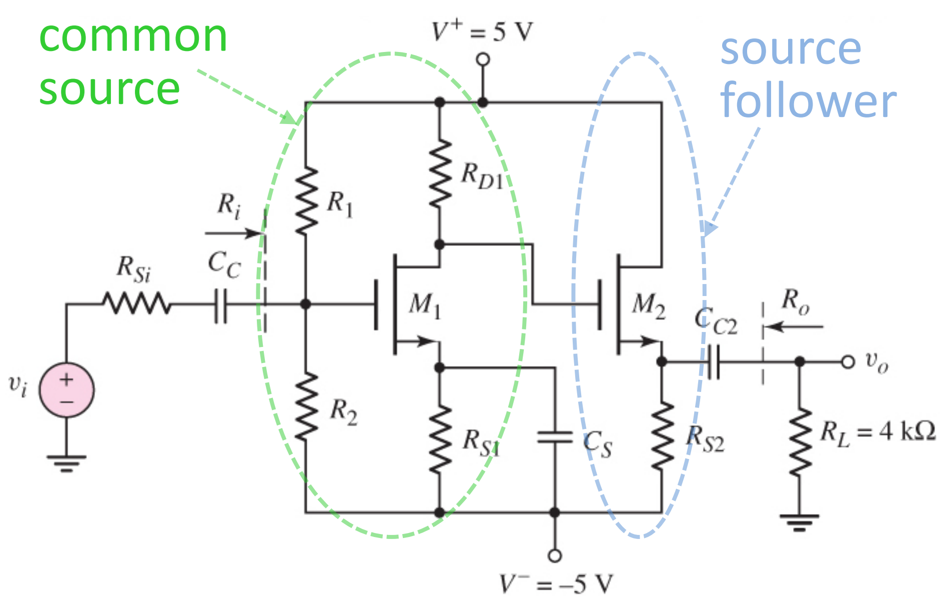


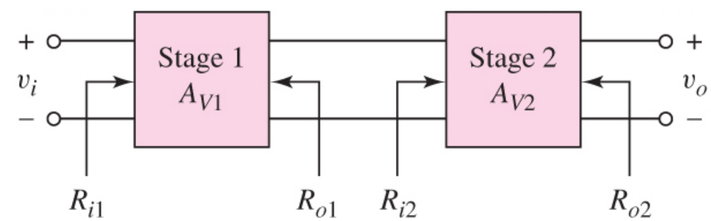
- For small signals, the MOSFET converts the input voltage variations to proportional drain current changes.
- Then the resistor R_D at the drain terminal transforms the drain currents to the output voltage (according to Ohm's law).

Transistor Amplifiers

(multi-stage amplifiers)

- In most applications, a single-transistor amplifier will not be able to meet the combined specifications of e.g. a given signal gain and output impedance.
- Multiple single-transistor amplifiers can be connected together to obtain the desirable circuit performance.





- The amplifier circuit on the left is called a **cascade** configuration.

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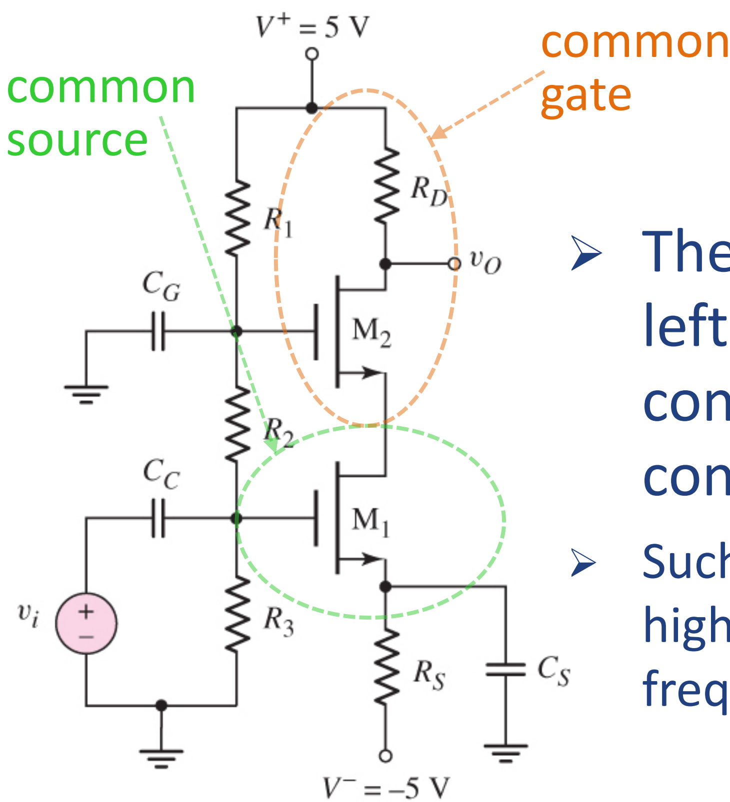
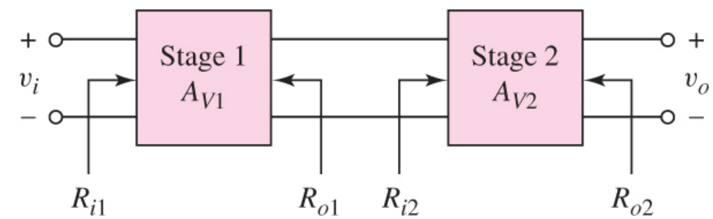
Transistor Amplifiers

(cascode configuration)

- Another common design for multi-stage amplifier circuits is the use of the **cascode** configuration.





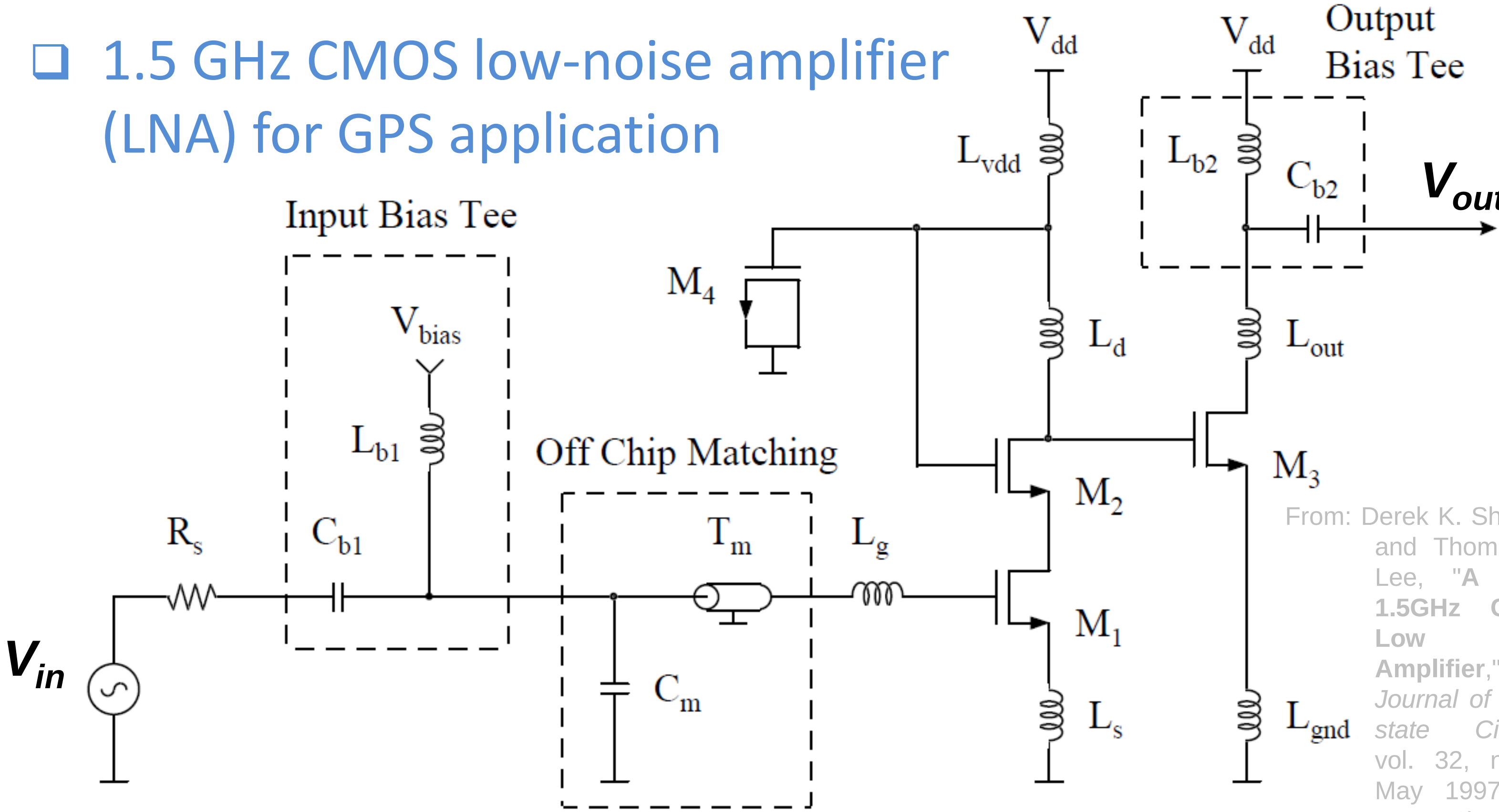
- The amplifier circuit shown on the left is essentially a **common-source** configuration and a **common-gate** configuration combined together.
- Such a **cascode** configuration allows very high output resistance and better high frequency response.

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition,

LNA Example

(3-stage transistor amplifier)

- 1.5 GHz CMOS low-noise amplifier (LNA) for GPS application



From: Derek K. Shaeffer and Thomas H. Lee, "**A 1.5V, 1.5GHz CMOS Low Noise Amplifier**," *IEEE Journal of Solid-state Circuits*, vol. 32, no. 5, May 1997 (pp. 745-759).

- CS, CG and CS amplifiers connected together
  - Note the source-degeneration CS configuration.

Analysis of Transistor Amplifiers

(analysis of DC biasing)

- To understand the LNA circuits, the constituent transistor circuits in DC operation need to be analysed using the basic transistor characteristics and properties.
- **DC circuit analysis** is the first step both in hand calculation and computer simulation.
  - In particular, analysis of the DC biasing of transistor circuits is important for analogue circuit design.
- Note that the MOSFET has three regions of operation: cut-off, **triode** and **saturation**.
- For circuit applications, we need to set a well-defined biasing condition or called **quiescent operating point** (or ***Q*-point** for short) for the MOSFET in a particular region of operation.

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AC Analysis of Amplifier Circuits

(guidelines applicable to transistor circuits)

- In carrying out **AC analysis** of transistor circuits, the following guidelines are suggested.
  1. Analyze the circuit with only the DC sources to find the **quiescent** solution. Transistors must be biased in **saturation region** for linear amplifiers.
  2. Replace the transistors (or other electronic devices e.g. diodes) with small-signal models.
  3. Analyse the small-signal equivalent circuit, setting DC sources to zero (i.e. short-circuited), to produce the circuit to the time-varying input signals only.
     - $r_{AC} = (\Delta V_{DC})/(\Delta I_{DC}) = 0/(\Delta I_{DC}) = 0 \Rightarrow$ a DC voltage source becomes short-circuited in the small signal equivalent circuit.
     - How about the case for a DC current source?

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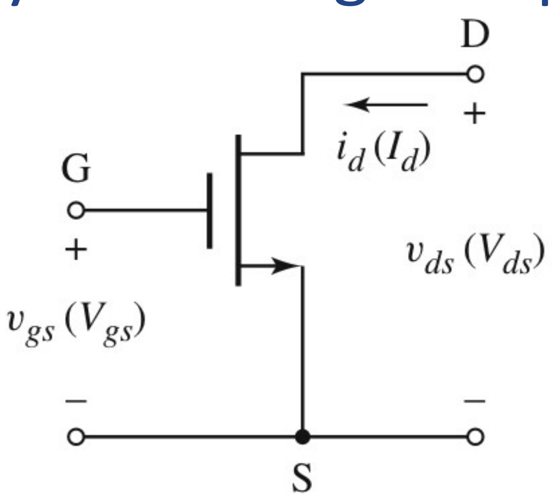
Common-Source Amplifier

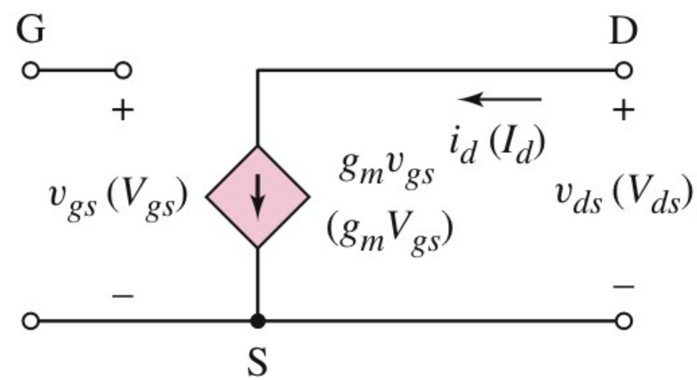
(small-signal equivalent circuit)

- In the AC analysis of transistor circuits, the MOSFET (or in general any transistors) can be represented by a small-signal equivalent circuit (Fig. (b)):

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.



(a)



(b)

- Initially, we assume that the signal frequency is sufficiently low so that the capacitance at the gate terminal can be neglected $\Rightarrow$ *open circuit* for the gate terminal.

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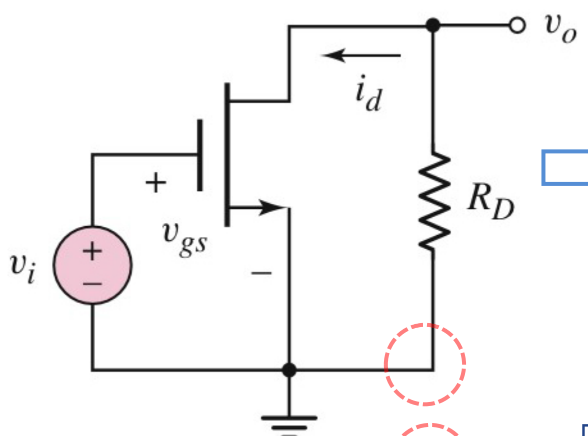
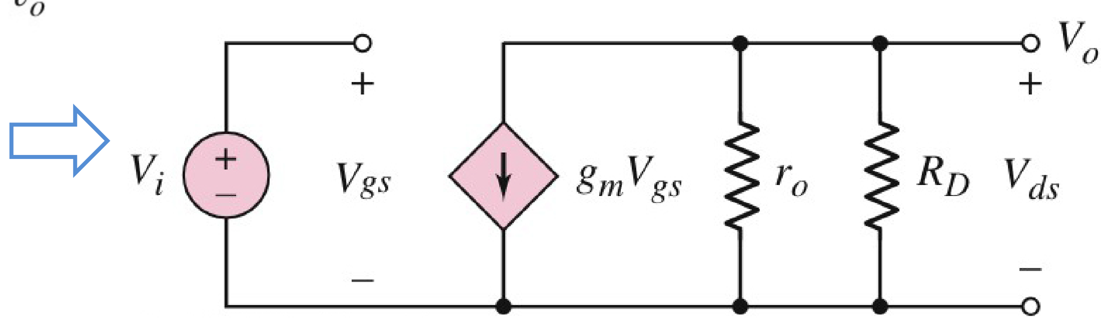
Common-Source Amplifier

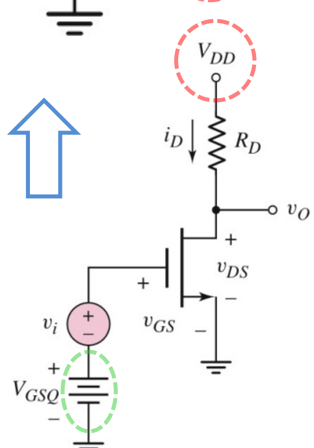
(AC analysis using the equivalent circuit)

- By representing the common-source amplifier using the small-signal equivalent circuit, the **voltage gain** can be determined easily.

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.







- Note that the DC sources are set to zero in the small-signal equivalent circuit $\Rightarrow$ the V_{DD} node becomes AC grounded!

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Common-Source Circuit

(voltage gain)

- The small-signal equivalent circuit can be analysed using circuit theorems and laws.

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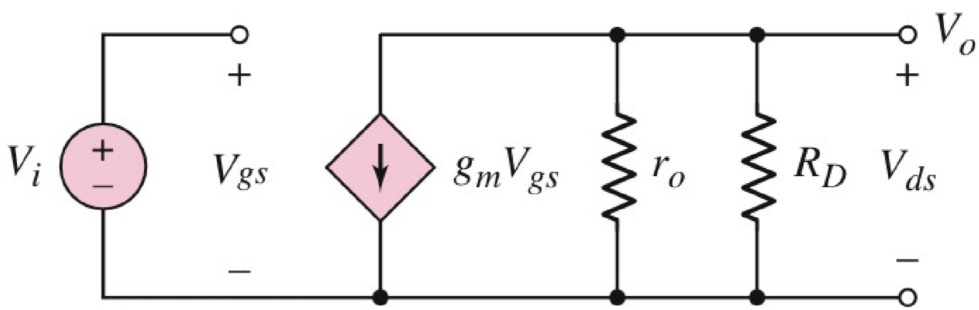

$$g_m = 2K_n(V_{GSQ} - V_{TN}) = 2\sqrt{K_n I_{DSQ}}$$

$$r_o = \left[\lambda K_n (V_{GSQ} - V_{TN})^2\right]^{-1} \approx (\lambda I_{DSQ})^{-1}$$

- At the output, $\boldsymbol{v_o = -i_{ds}(r_o \| R_D)}$ (according to **Ohm's law**).
- But $\boldsymbol{i_{ds} = g_m v_{gs}}$ (according to **Kirchhoff's current law**)
- So $\boldsymbol{v_o = -(g_m v_{gs})(r_o \| R_D) = -(g_m v_i)(r_o \| R_D)}$
- the <u>small-signal</u> **voltage gain** for the CS circuit is

$$A_v = \frac{v_o}{v_i} = -g_m (r_o \| R_D)$$

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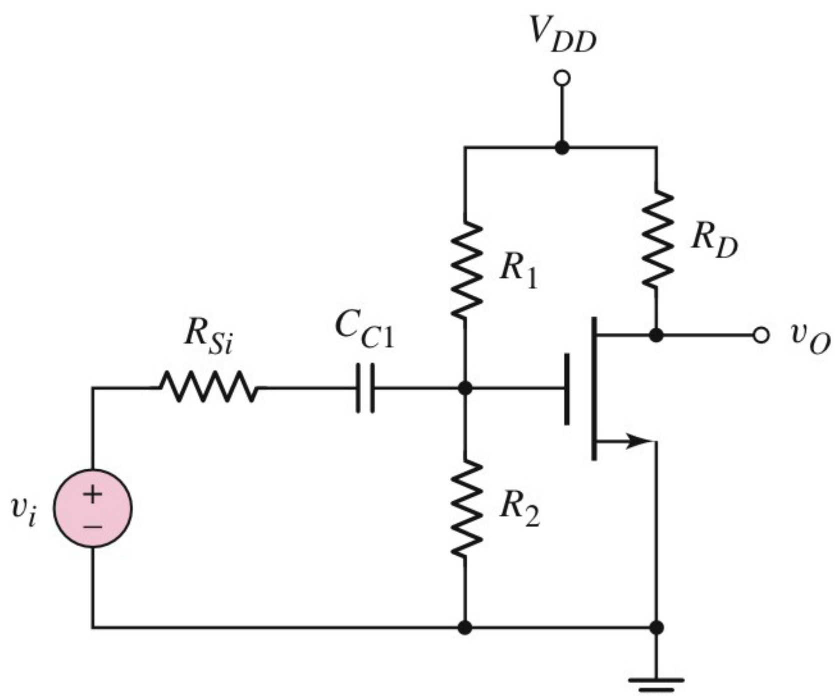
Common-Source Amplifier

(with voltage divider biasing)

- Consider a practical common-source amplifier in which the MOSFET is biased at a certain quiescent point with voltage divider biasing and there is a coupling capacitor to provide DC isolation between the amplifier and the signal source.



- The coupling capacitor usually has a high enough capacitance $\boldsymbol{C_C}$ so that the magnitude of the capacitor impedance is negligible (short-circuited) at the signal frequency (e.g. 20 kHz $\Rightarrow$ $|\boldsymbol{Z_C}| \approx 0.8\ \Omega$ with $\boldsymbol{C_C}$ = 10 μF):

$$|Z_C| = \frac{1}{2\pi f C_C}$$

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Common-Source Amplifier

(AC circuit analysis)

- Representing the practical CS amplifier by a small-signal equivalent circuit, the voltage gain can be determined straightforwardly, especially by "breaking" the whole circuit into two amplification stages.

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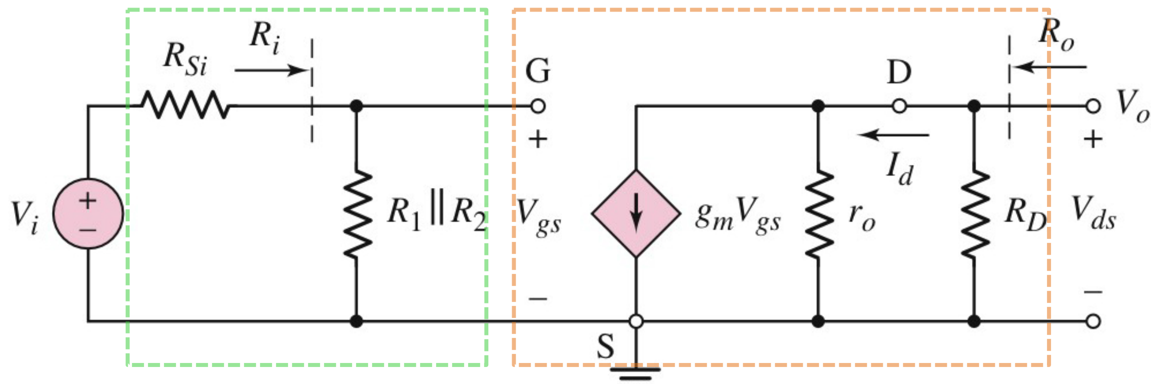
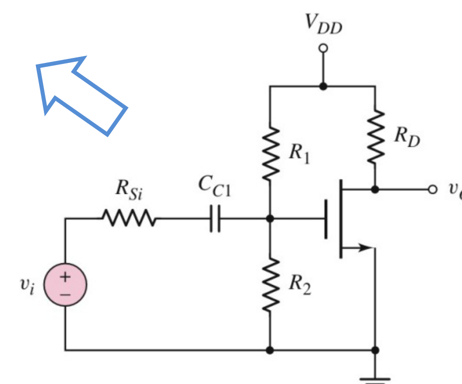


$$A_{v1} = v_{gs}/v_i = \frac{R_i}{R_i + R_{Si}}$$

$$A_{v2} = v_o/v_{gs} = -g_m(r_o \| R_D)$$

$$R_i = R_1 \| R_2$$

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



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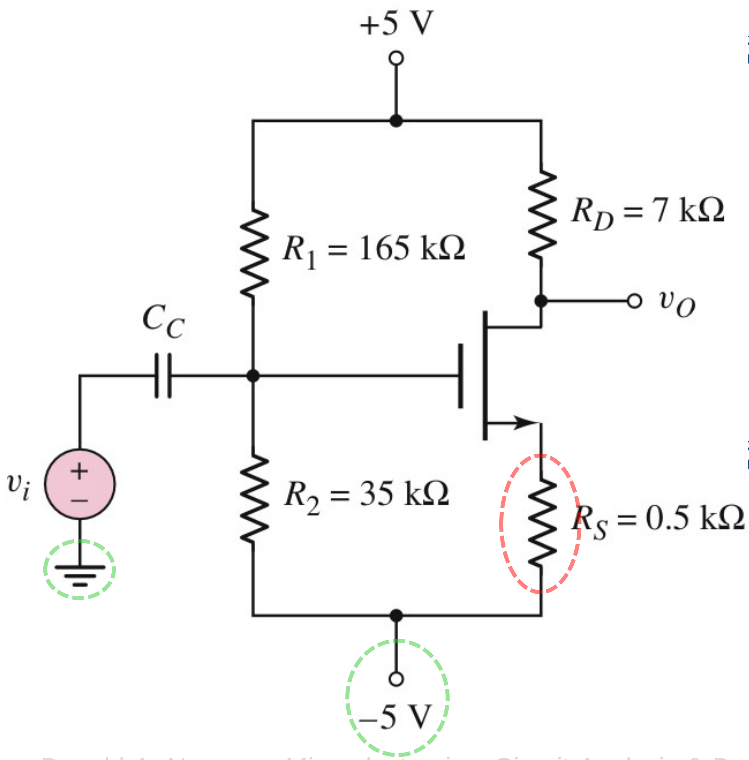
CS Amplifier with Source Resistor

(source degeneration)

- In the CS amplifier, a source resistor (or an inductor) is sometimes added achieve certain purposes e.g. to stabilise the *Q*-point against transistor variations.



- In the circuit shown on the left, it has positive and <u>negative supply voltages</u>.

  $\Rightarrow$ different **DC biasing** from the previous CS amplifier

- The negative supply voltage node however becomes <u>grounded</u> in the **AC analysis**.

  Why?

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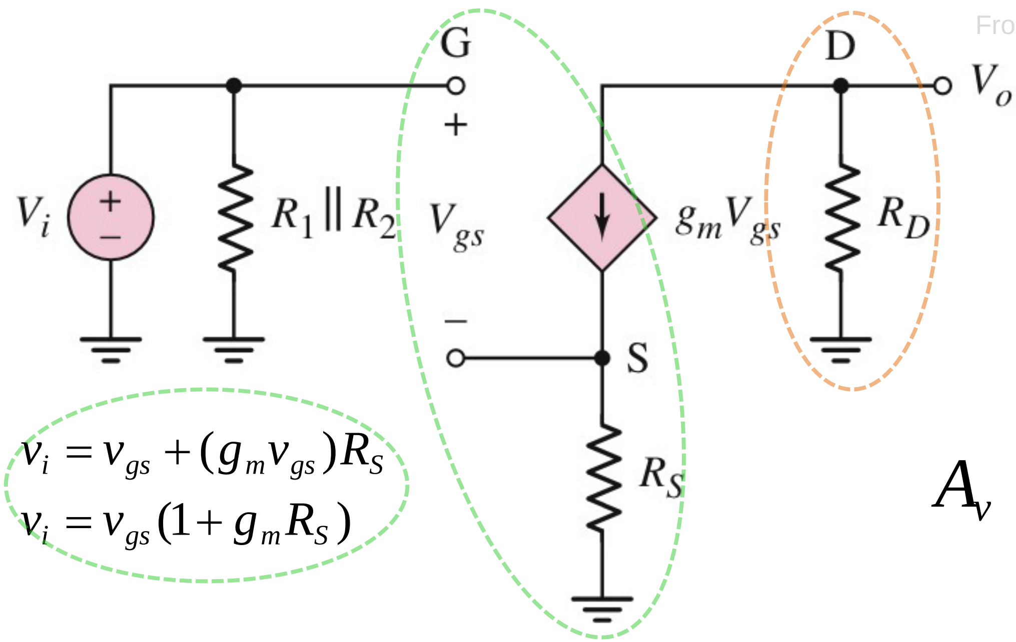
CS Amplifier with Source Resistor

(AC analysis)

- After the DC analysis (to calculate V_{GSQ} and I_{DSQ}) to obtain the small-signal parameters (g_m and r_o), the circuit can be represented by a small-signal equivalent circuit.



From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.

$$v_i = v_{gs} + (g_m v_{gs})R_S$$
$$v_i = v_{gs}(1 + g_m R_S)$$

$$v_o = -(g_m v_{gs})R_D$$

- The small-signal voltage gain is v_o/v_i

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

- $G_m = g_m/(1+g_m R_S)$ is the effective transconductance.

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Source Bypass Capacitor

(minimise the loss in the CS signal gain)

- Instead of using a resistor in the source-degeneration CS amplifier, a source bypass capacitor can be added to minimise the loss in the small-signal voltage gain while maintaining the *Q*-point stability.

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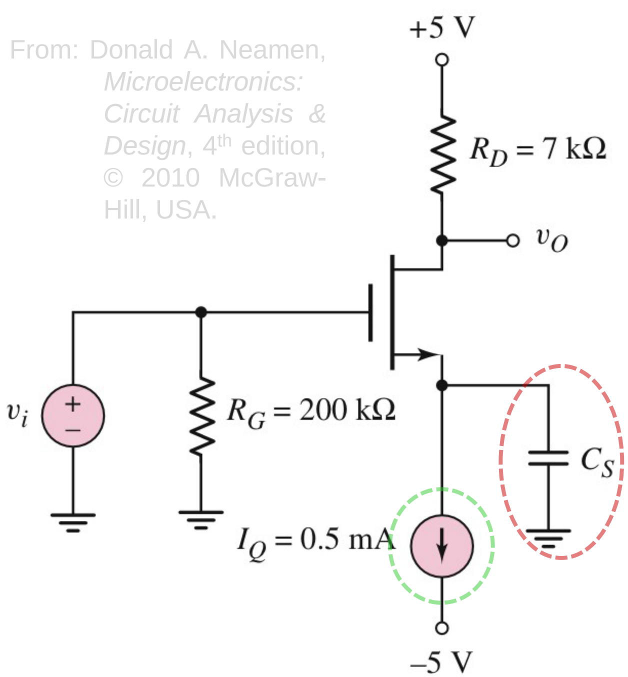

- The source bypass capacitor needs to have a high enough capacitance C_S so that it can be regarded as an AC short-circuit.
- The *Q*-point stability can be further increased by replacing the source-degeneration resistor with a constant current source.

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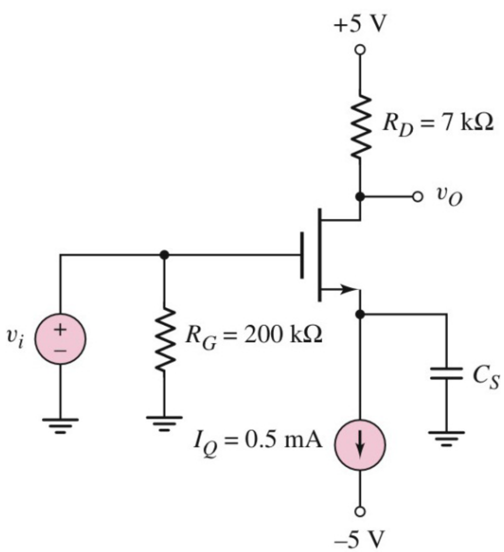
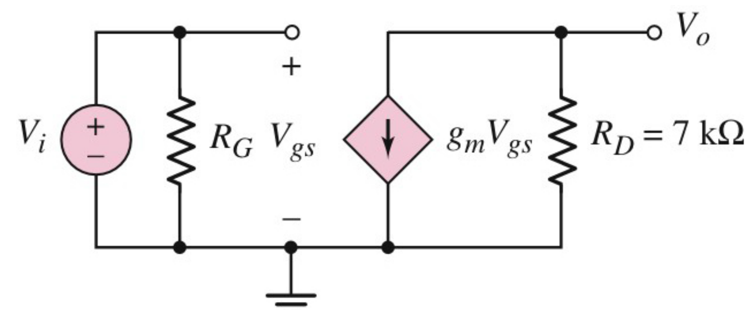
Source Bypass Capacitor

(minimise the loss in the CS signal gain)

- The same as before, the DC analysis needs to be carried out first (to calculate V_{GSQ} and I_{DSQ}) to determine the small-signal parameters (g_m and r_o).
- The circuit can then be represented by a small-signal equivalent circuit for AC analysis:
  - The source is held at the AC signal ground with the bypass capacitor.
  - The constant DC current source becomes an AC open-circuit.





From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.

Common-Gate Configuration

(gate at signal ground)

- The third topology of basic FET amplifiers is the common-gate configuration: the input signal is applied to the source and <u>the gate is at signal ground</u>.

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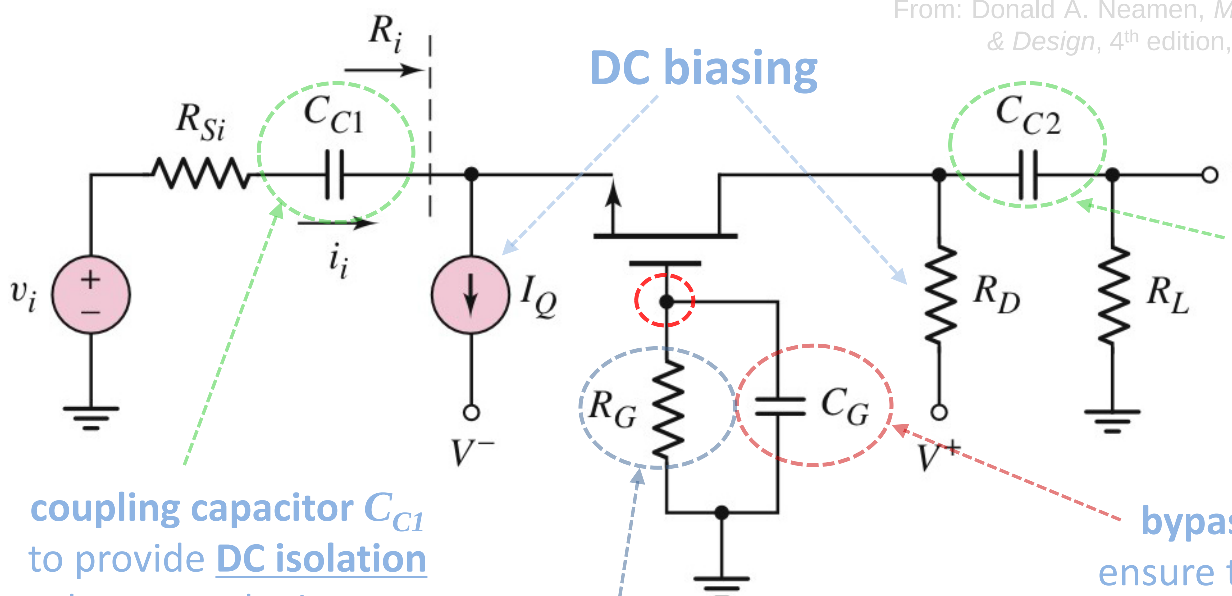

coupling capacitor C_{C2} to provide **<u>DC isolation</u>** between the load and the drain terminal

coupling capacitor C_{C1} to provide **<u>DC isolation</u>** between the input signal source and the amplifier circuit

gate resistor to prevent the build-up of static charge on the gate terminal

bypass capacitor to ensure the gate terminal is at signal ground

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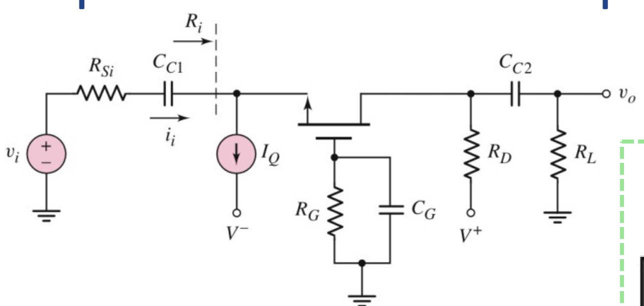
Common-Gate Configuration

(small-signal equivalent circuit & voltage gain)

- Same as before, representing the common-gate circuit by a **small-signal equivalent circuit, AC analysis** can be performed after simplifying the equivalent circuit further.



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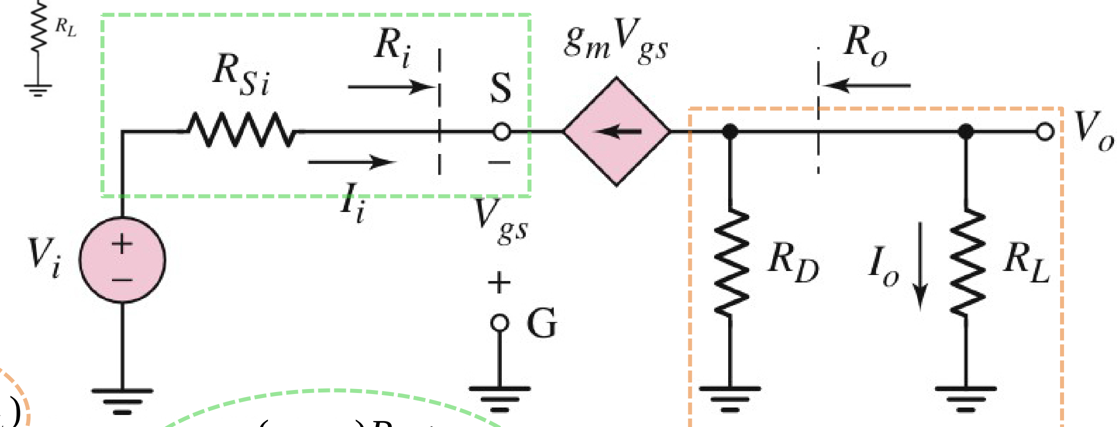

$$\frac{v_{gs}}{v_i} = -\frac{1}{1+g_m R_{Si}}$$

$$\frac{v_o}{v_{gs}} = -g_m (R_D \| R_L)$$

$$v_i = -(g_m v_{gs}) R_{Si} + v_{sg}$$
$$v_i = -(g_m v_{gs}) R_{Si} - v_{gs}$$
$$v_i = -v_{gs}(g_m R_{Si} + 1)$$

$$v_o = -(g_m v_{gs})(R_D \| R_L)$$

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

Note: **As A_v is <u>positive</u>, the output and input signals are <u>*in phase*</u>.**

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Common-Gate Configuration

(small-signal current gain)

- In some cases, the signal input to a common-gate circuit is a current. Then we need to calculate the current gain also using the **small-signal equivalent circuit**, but with a **Norton equivalent circuit** as the signal source.

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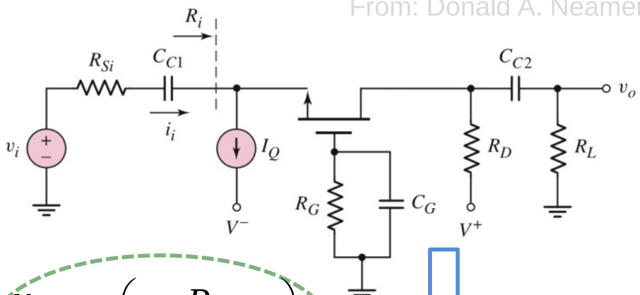

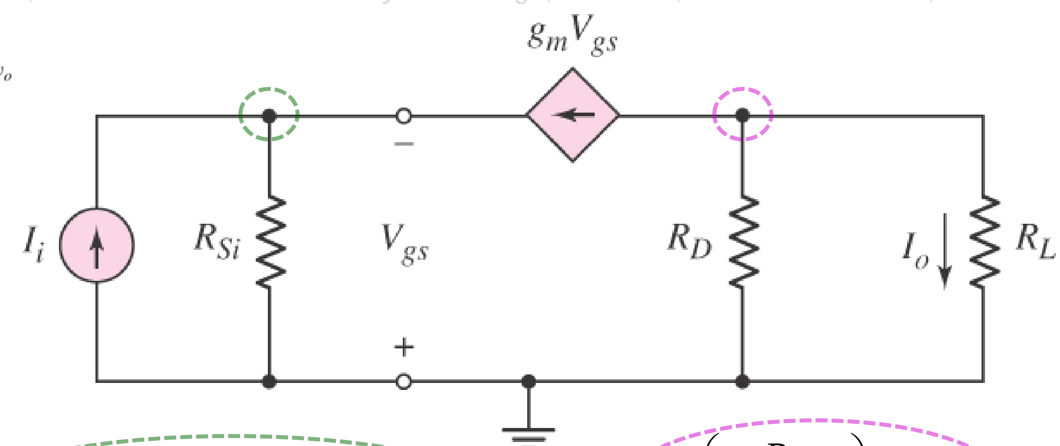

$$\frac{v_{gs}}{i_i} = -\left(\frac{R_{Si}}{1+g_m R_{Si}}\right)$$

$$\frac{i_o}{v_{gs}} = -g_m\left(\frac{R_D}{R_D+R_L}\right)$$

$$i_i = \frac{v_{sg}}{R_{Si}} + (-g_m v_{gs}) = -\frac{v_{gs}}{R_{Si}} - g_m v_{gs}$$

$$i_o = \left(\frac{R_D}{R_D+R_L}\right)(-g_m v_{gs})$$

$$i_i = -v_{gs}\left(\frac{1+g_m R_{Si}}{R_{Si}}\right)$$

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

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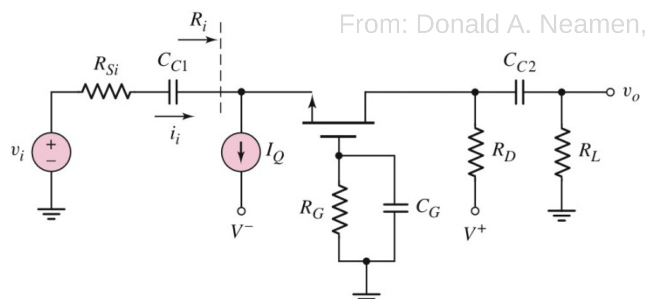
Common-Gate Configuration

(current gain & summary notes)

- In the common-gate amplifier circuit, the current gain is close to unity if $R_D >> R_L$ and $g_m R_{Si} >> 1$:

$$A_i = \frac{i_o}{i_i} = \left(\frac{R_D}{R_D + R_L}\right)\left(\frac{g_m R_{Si}}{1 + g_m R_{Si}}\right) \approx 1 \qquad \text{if } R_D >> R_L \text{ and } g_m R_{Si} >> 1$$



- Advanced notes: the common-gate amplifier suffers from the ***trade-off*** between the **voltage headroom** and the **signal gain**.
  - To achieve a high gain, it is necessary to have a high biasing drain current I_D or a high R_D.
  - However, the drain voltage, $V_{DS} = V_{DD} - I_D R_D$, must remain above ($V_{GSQ} - V_{TN}$) to ensure that the MOSFET is in the saturation region (i.e. $V_{DS} > V_{DSsat}$).

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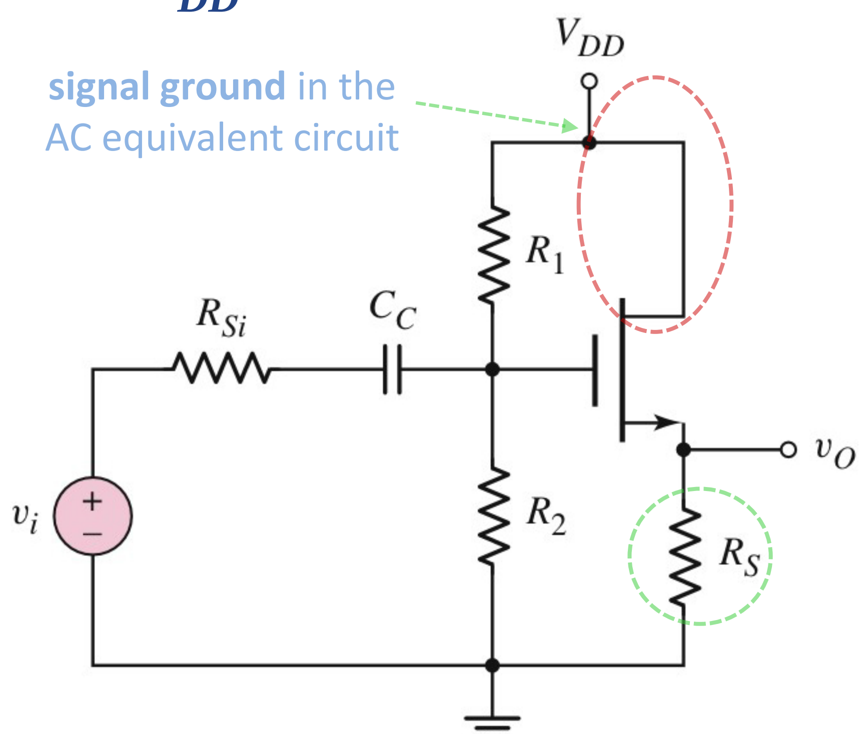
Common-Drain Amplifier

(output taken off at the source)

- The second topology of basic FET amplifiers is the common-drain configuration: the output signal is taken off the source with respect to ground and the drain is connected directly to V_{DD}.

signal ground in the AC equivalent circuit



- Since the node becomes signal ground in the small-signal equivalent circuit, the <u>drain</u> terminal of the MOSFET is the <u>common signal ground</u> for both the input and output signals.

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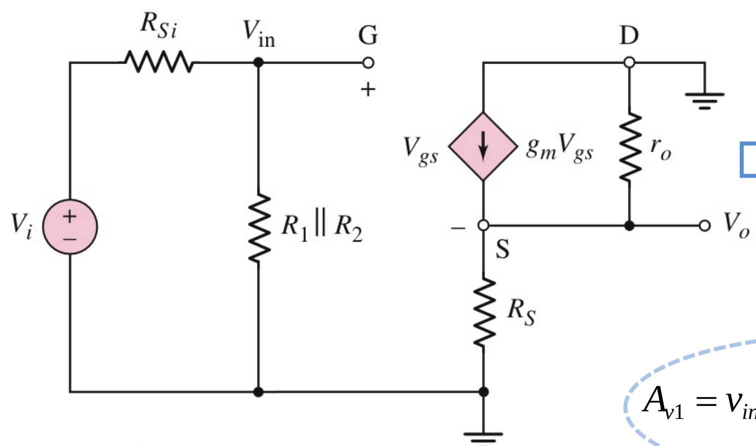
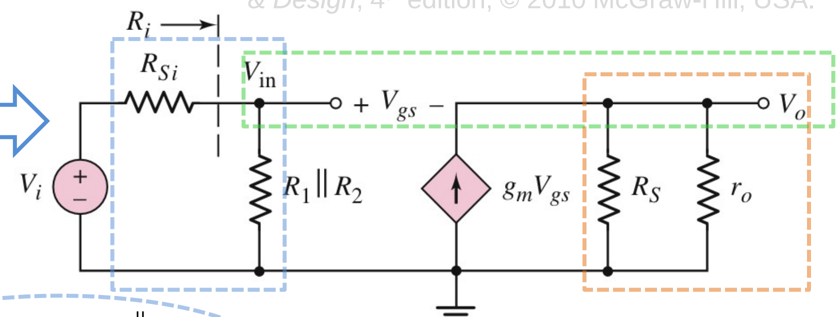
Common-Drain Amplifier

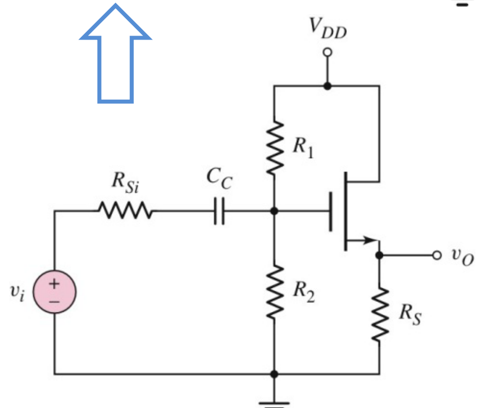
(AC analysis)

- Representing the common-drain circuit by a **small-signal equivalent circuit, AC analysis** can be performed as usual after simplifying the equivalent circuit further.

From: Donald A. Neamen, *Microelectronics: Circuit Analysis & Design*, 4th edition, © 2010 McGraw-Hill, USA.







$$A_{v1} = v_{in}/v_i = \frac{R_1 \| R_2}{R_1 \| R_2 + R_{Si}}$$

$$v_o = (g_m v_{gs})(R_S \| r_o)$$

$$v_{in} = v_{gs} + v_o = v_{gs} + (g_m v_{gs})(R_S \| r_o)$$

$$v_{in} = v_{gs}\left[1 + g_m(R_S \| r_o)\right]$$

$$R_i = R_1 \| R_2$$

$$A_v = \overbrace{\frac{g_m(R_S \| r_o)}{1 + g_m(R_S \| r_o)}}^{\text{source follower}} \left(\frac{R_i}{R_i + R_{Si}}\right)$$

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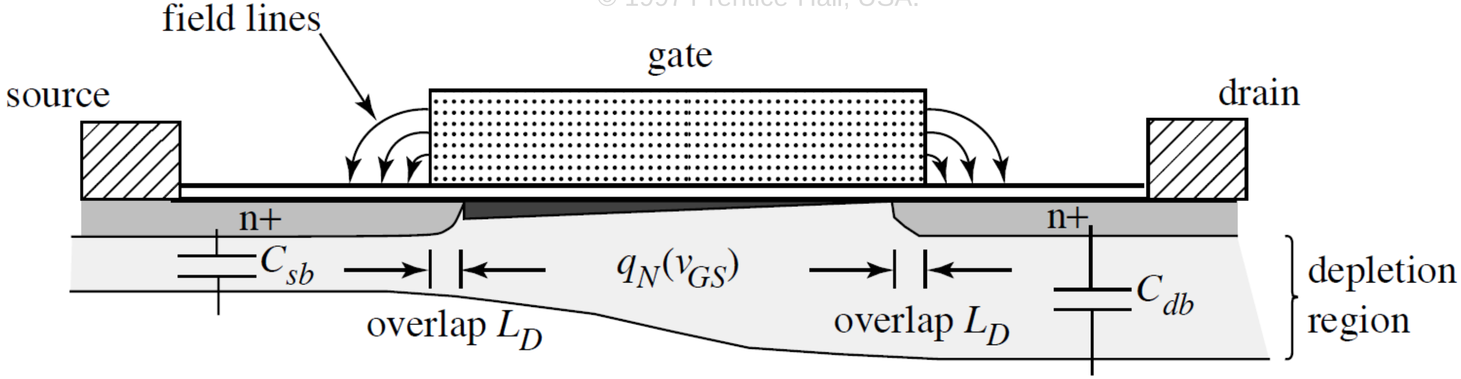
Transistor at Radio Frequencies

(parasitic circuit elements)

- To analyse LNA circuits which operate well beyond the multi-hundred kHz range, the low-frequency transistor circuit analysis need to be modified.
- In the radio frequency range, the parasitic circuit elements (especially capacitors) cannot be ignored.

From: Roger T. Howe & Charles G. Sodini, *Microelectronics: An Integrated Approach*, © 1997 Prentice-Hall, USA.

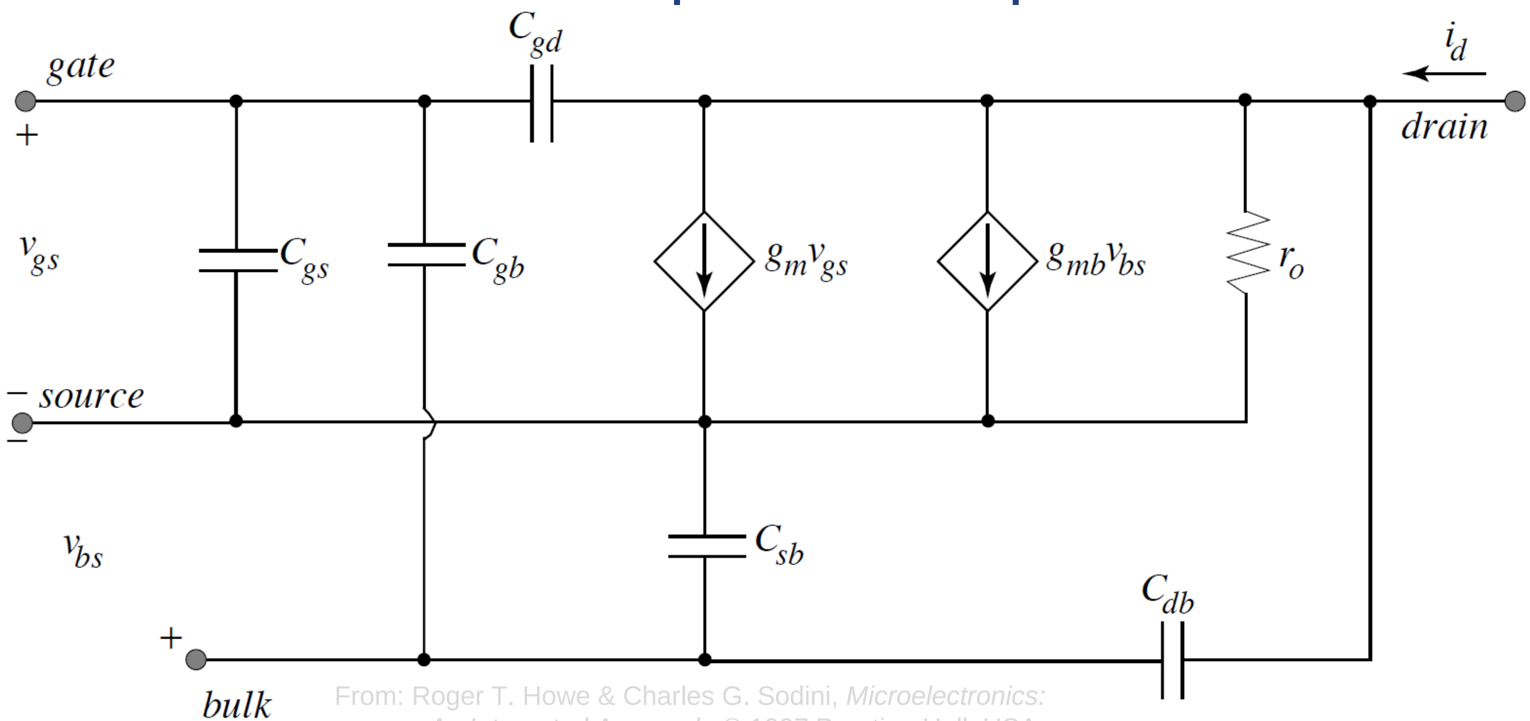


  - The transistor's equivalent circuit needs to be modified.

Transistor at Radio Frequencies

(small-signal equivalent circuit)

- The small-signal equivalent circuit for the transistor needs to include the parasitic capacitance.



From: Roger T. Howe & Charles G. Sodini, *Microelectronics: An Integrated Approach*, © 1997 Prentice-Hall, USA.

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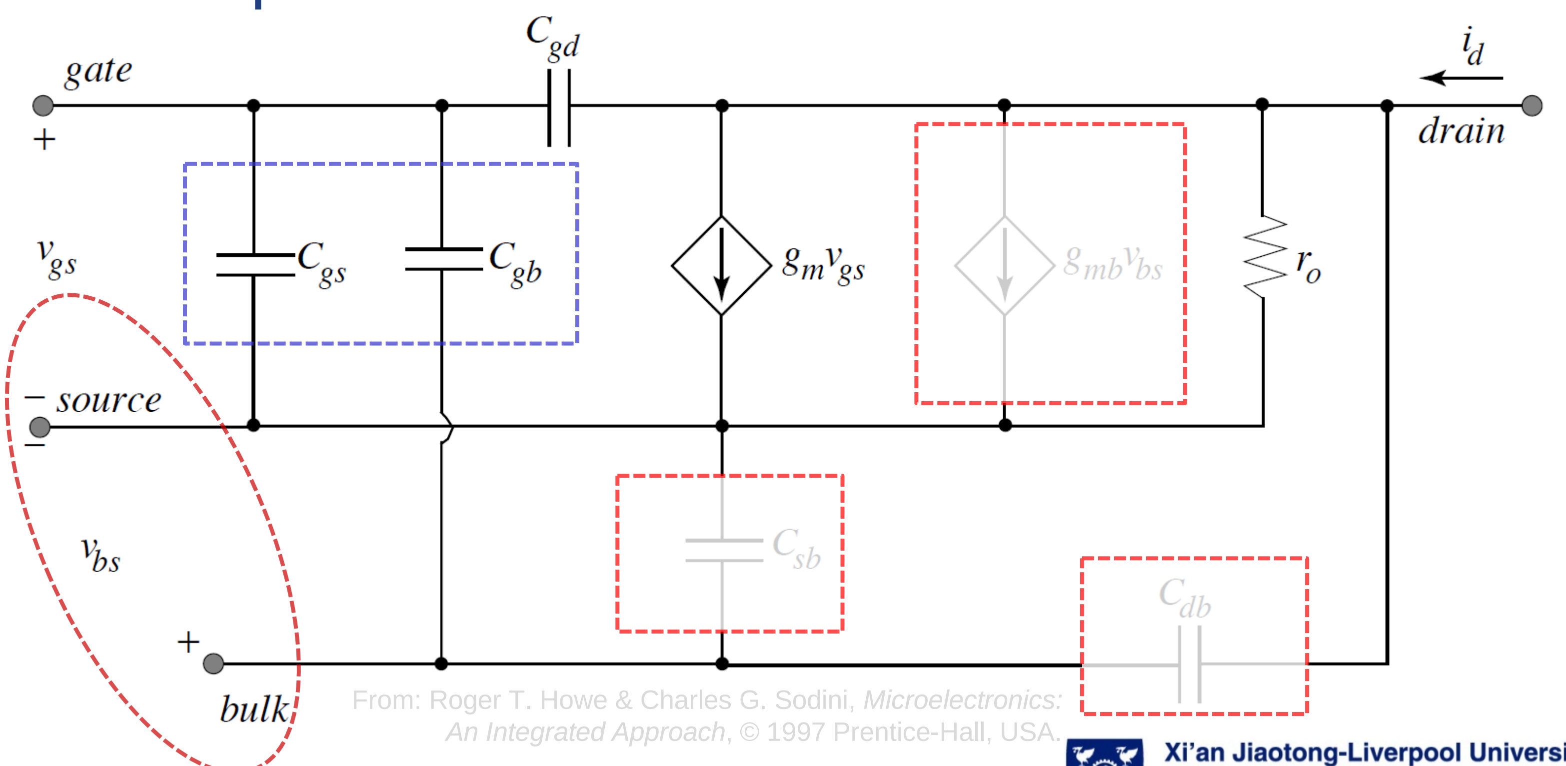
Transistor at Radio Frequencies

(small-signal equivalent circuit)

- In the CS configuration, the equivalent circuit can be simplified.



From: Roger T. Howe & Charles G. Sodini, *Microelectronics: An Integrated Approach*, © 1997 Prentice-Hall, USA.

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RF Transistor Amplifiers

(AC analysis & circuit construction)

- With the small-signal equivalent circuits including the capacitors and inductors, similar AC analysis of the LNA circuit can be performed.
- In the circuit construction (using discrete components in this EEE307 module), suitable transistors need to be selected first.
  - The transistors can operate at high enough frequency of interest.
  - One parameter of interest is f_T, called the unity gain frequency. f_T is the frequency at which the current gain is one (i.e. 0 dB).
  - Refer to the transistor's data sheet

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