上海科技大学
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EE115 Analog Circuits
Transistor Amplifier 2

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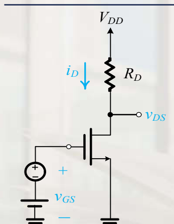
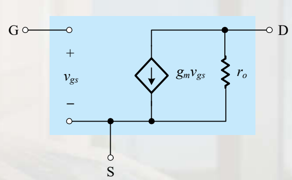
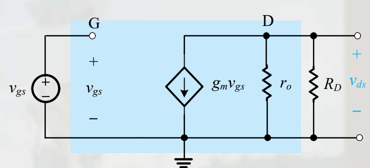
Outline

MOSFET Small Signal Model







■ In small signal AC analysis, **DC voltage source = short circuit**

$$A_v = \frac{v_{ds}}{v_{gs}} = -g_m(R_D||r_o)$$

■ The equivalent circuit is valid for both NMOS and PMOS

■ In **PMOS**, use **absolute sign** for all parameters: $|V_{GS}|$, $|V_t|$, $|V_{OV}|$, $|V_A|$, and replace k_n with k_p

Output Resistance and Transconductance

Output resistance at drain:

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

Transconductance:

$$i_D = I_D + i_d = \frac{1}{2}k_n\left(V_{GS} + v_{gs} - V_{tn}\right)^2$$
$$= \frac{1}{2}k_n(V_{GS} - V_{tn})^2 + \boldsymbol{k_n\,(V_{GS} - V_{tn})v_{gs}} + \frac{1}{2}k_n v_{gs}^2$$

$$i_d = k_n\,(V_{GS} - V_{tn})v_{gs}$$

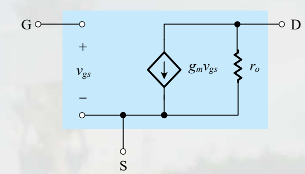
Or

$$g_m \equiv \left.\frac{\partial i_D}{\partial v_{GS}}\right|_{v_{GS}=V_{GS}}$$

$$g_m = \frac{i_d}{v_{gs}} = k_n(V_{GS} - V_{tn}) = k_n\,V_{OV}$$

$$V_{OV} = \sqrt{2I_D/k_n} = \sqrt{2I_D/(k_n'\,W/L)}$$

$$\boldsymbol{g_m = \sqrt{2k_n'}\sqrt{W/L}\,\sqrt{I_D}}$$



Or

$$g_m = k_n V_{OV} = k_n'(W/L)V_{OV}$$

Or

$$g_m = \frac{2I_D}{V_{GS} - V_{tn}} = \frac{2I_D}{V_{OV}} = \frac{I_D}{V_{OV}/2}$$

Three **design parameters**: W/L, V_{OV}, and I_D.

Systematic Procedure for Transistor Amp Analysis

- 1. Perform **DC analysis** (ignore small signal source)
- 2. Calculate small-signal parameters (g_m, r_o, etc)
- 3. Generate AC small-signal equivalent circuit
  - Replace **DC voltage source** by **short** circuit
  - Replace **DC current source** by **open** circuit
  - Replace transistor by **hybrid-π model (or T model)**
- 4. Perform **circuit analysis** to determine voltage gain or other amplifier performance parameters

MOSFET Amplifier Example

- Given: The MOSFET has V_t = 1.5V, k_n = 0.25 mA/V and V_A = 50V. Find voltage gain for the amplifier.
  (1) Solve DC Bias Point

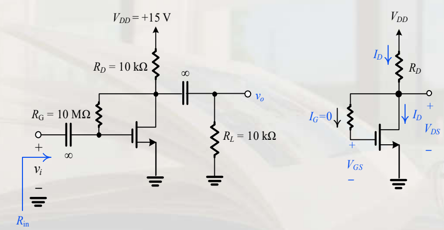


Fig. (a) amplifier circuit; **(b)** circuit for determining the dc operating point;

Solution:

$$V_{GS} = V_{DS} = V_{DD} - R_D I_D$$

$$I_D = \frac{1}{2} k_n (V_{GS} - V_t)^2$$

$$I_D = 1.06\ mA$$

$$V_{GS} = V_{DS} = 4.4\text{ V}$$

$$V_{OV} = 4.4 - 1.5 = 2.9\text{ V}$$

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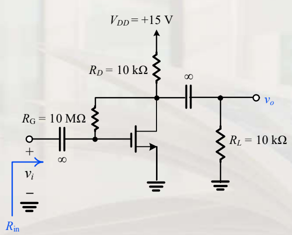
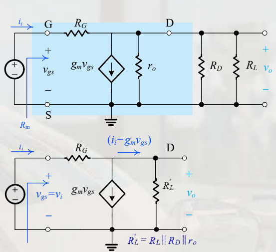
(2) Solve AC Small Signal Circuit





Solution:

$$g_m = k_n V_{OV} = 0.25 \times 2.9 = 0.725\text{mA/V}$$

$$r_o = \frac{V_A}{I_D} = \frac{50}{1.06} = 47\text{ k}\Omega$$

$$R_L' = R_L || R_D || r_o = 10||10||47 = 4.52\text{ k}\Omega$$

$$v_o = (i_i - g_m v_{gs})\, R_L'$$

$$i_i = \frac{v_{gs} - v_o}{R_G}$$

$$A_v = -g_m\ R_L' \frac{1 - (1/g_m/R_G)}{1 + (\,R_L'/R_G)}$$

$$A_v \cong -g_m\ R_L'$$

$$A_v \cong -3.3\text{V/V}$$

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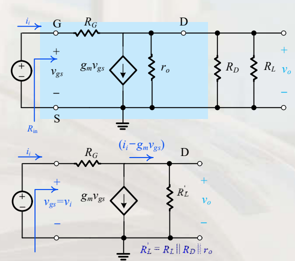
(3) Additional Parameters of Interest



Solution:

$$R_{in} = \frac{R_G}{1 + g_m\ R_L'}$$

$$R_{in} = \frac{10\text{M}\Omega}{1 + 3.3} = 2.33\text{M}\Omega$$

$$v_{DS} \geq v_{GS} - V_t$$

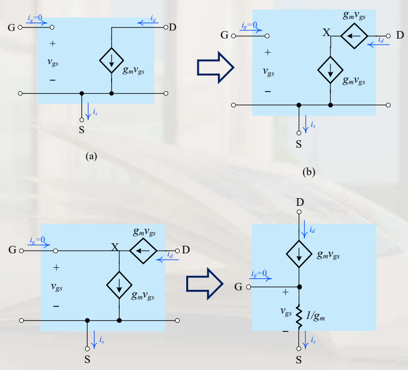
$$v_{DSmin} \geq v_{GSmax} - V_t$$

$$V_{DS} - |A_v|\hat{v}_i = V_{GS} + \hat{v}_i - V_t$$

$$\hat{v}_i \leq \frac{V_t}{|A_v|+1}$$

$$\hat{v}_i \leq \frac{1.5}{3.3 + 1} = 0.35\text{ V}$$

From π Model to T Model

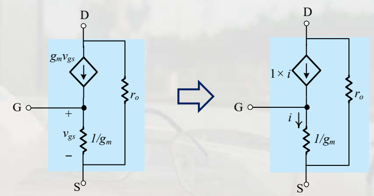


(a) (b) (c) (without r_o) (d)

(b) No change in circuit: **the additional dependent current source** has the same current.

(c) No change in circuit: no current flows through the **new connected path**

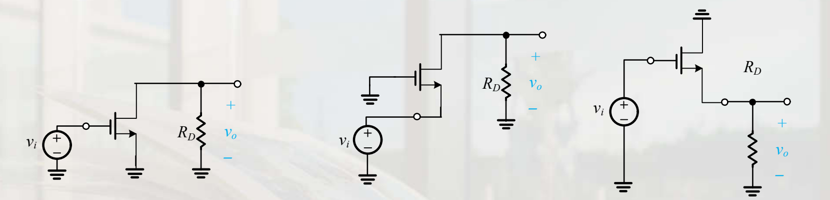
(d) Same current with the dependent current source replaced by equivalent **resistance**



(a) (b)

(with r_o)

Basic Single-Transistor Amp. Configurations



(a) Common source (CS)

(b) Common Gate (CG)

(c) Common Drain (CD) or Source Follower

Two-Port Model of Amplifiers

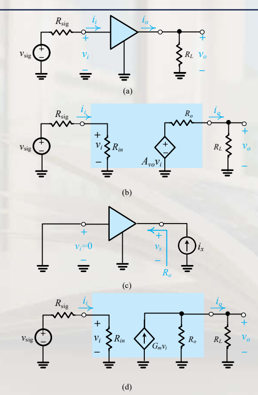


Fig. Characterization of the amplifier as a functional block

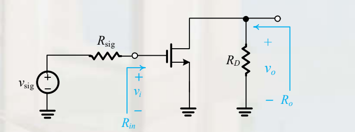
$$G_v = \frac{R_{in}}{R_{sig} + R_{in}} A_{v0} \frac{R_L}{R_o + R_L}$$

- In addition to **gain**, it's important to have proper **input and output resistances**.
- e.g. Procedure to find R_o:
  - Ground input, remove R_{sig}
  - Apply a test current source at output (conceptually, not experimentally),
  - Find voltage at output terminal.

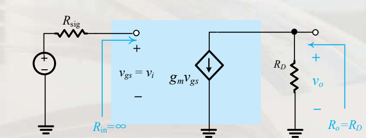
$$R_o = \frac{v_x}{i_x}$$

Question: How to find R_{in}?

Common-Source (CS) Amplifier



(a)



(b)

Figure 7.36

- Previously, using MOSFET equation, we derived analytically :

$$A_V = -k_n V_{OV} R_D$$

- Using hybrid-π model, it is almost **trivial** to solve: $A_V = -g_m R_D$
- With load resistance, R_L:

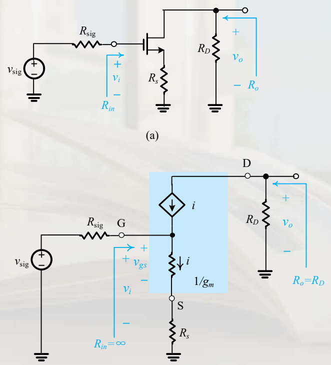
Since R_L is in parallel with R_D

$$G_V = -g_m(R_D||R_L)$$

$$R_{in} = \infty$$

$$R_o = R_D$$

CS with Source Resistance (Source Degeneration)



- You can analyze the circuit using hybrid-π model. (Try it !)
- However, whenever **there is a resistor connected to source**, it is much easier to use the **T-model**

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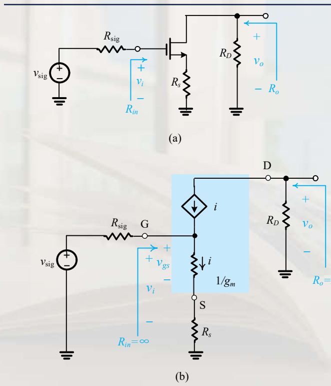


Fig. CS amplifier with a source resistance R_s

- Note

$$A_v = -\frac{R_D}{\frac{1}{g_m} + R_s} = -\frac{Total\ resistance\ in\ Drain}{Total\ resistance\ in\ Source}$$

- R_S provides **negative feedback**, which
  - Stabilize drain current
  - Increase linearity by keeping v_{gs} small

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

  - Increase usable bandwidth
- R_S: **source-degeneration** resistance

Common-Gate (CG) Amplifier

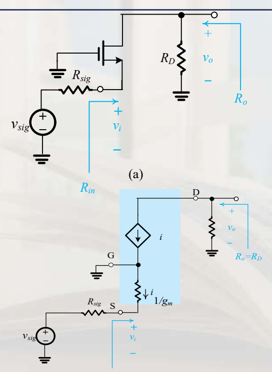


Fig. (a) CG amplifier with bias arrangement omitted. (b) Equivalent circuit of the CG amplifier with the MOSFET replaced with its T model.

- R_{sig} connected to source
  → Use **T-model**

$$R_{in} = \frac{1}{g_m}$$

$$A_{vo} \equiv \frac{v_o}{v_i} = g_m R_D$$

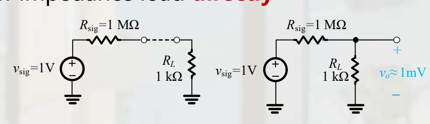
$$R_o = R_D$$

$$G_V = \frac{1/g_m}{R_{sig} + 1/g_m}[g_m(R_D||R_L)]$$

$$G_V = \frac{R_D||R_L}{R_{sig} + 1/g_m}$$

Need for Voltage Buffers

- Driving low impedance load **directly**



- Driving low impedance load with **unit-gain buffer**

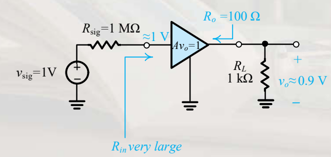


Fig. Illustrating the need for a unity-gain voltage buffer amplifier

Source Follower (Common-Drain Amplifier)

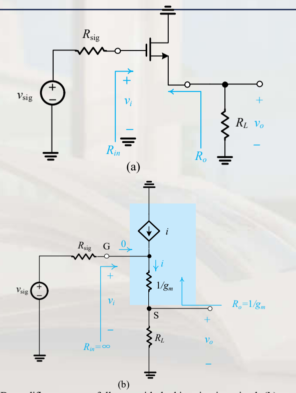


Fig. (a) CD amplifier or source follower with the bias circuit omitted. **(b)** Equivalent circuit of the source follower obtained by replacing the MOSFET with its T model.

- R_L connected to source → Use **T-model**

$$R_{in} = \infty$$

$$A_v \equiv \frac{v_o}{v_i} = \frac{R_L}{R_L + 1/g_m}$$

If $R_L \gg 1/g_m$, $A_{vo} \approx 1$

$$R_o = 1/g_m$$

$$G_v = A_v = \frac{R_L}{R_L + 1/g_m}$$

Comparison of Different Amp. Configurations

- **CS** provides the **bulk** of the gain
- **CD** used as **voltage buffer** in output stage