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EE115 Analog Circuits Transistor Amplifier 2

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Outline

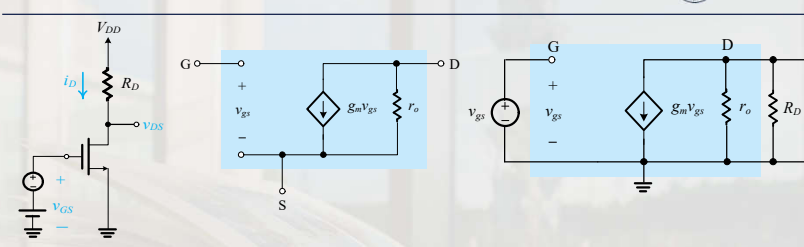
- Transistor amplifier 2
 - Review: Small Signal Model
 - Basic Configurations
- Reading: SEDTRA/SMITH book pages 422-447

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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

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Output Resistance and Transconductance

Output resistance at drain:

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

Transconductance:

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

$$= \frac{1}{2} k_n (V_{GS} - V_{tn})^2 + k_n (V_{GS} - V_{tn}) v_{gs} + \frac{1}{2} k_n v_{gs}^2$$

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

Or

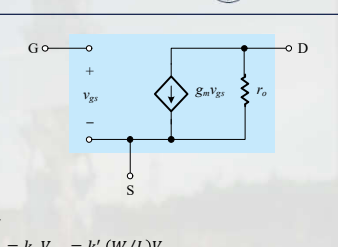
$$g_m = k_n V_{OV} = k'_n (W/L) V_{OV}$$

Or

$$g_m = \frac{\partial i_D}{\partial v_{GS}} \bigg|_{v_{GS}=V_{GS}}$$

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

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

$$g_m = \sqrt{2k'_n W/L} \sqrt{I_D}$$


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

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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



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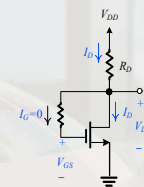
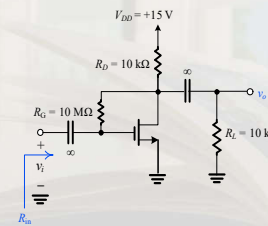
MOSFET Amplifier Example



- Given: The MOSFET has $V_t = 1.5\text{V}$, $k_n = 0.25\text{ mA/V}$ and $V_A = 50\text{V}$. Find voltage gain for the amplifier.

(1) Solve DC Bias Point

Solution:



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

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

$$I_D = 1.06\text{ mA}$$

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

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

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



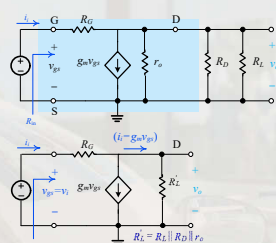
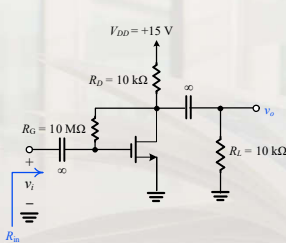
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(2) Solve AC Small Signal Circuit

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



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

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

$$v_o = (i_i - g_m v_{gs}) R'_L$$

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

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

$$A_v \approx -g_m R'_L$$

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



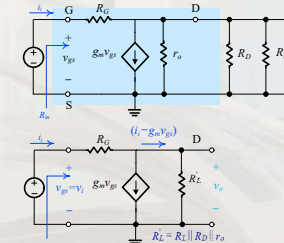
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(3) Additional Parameters of Interest

Solution:



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

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

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

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

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

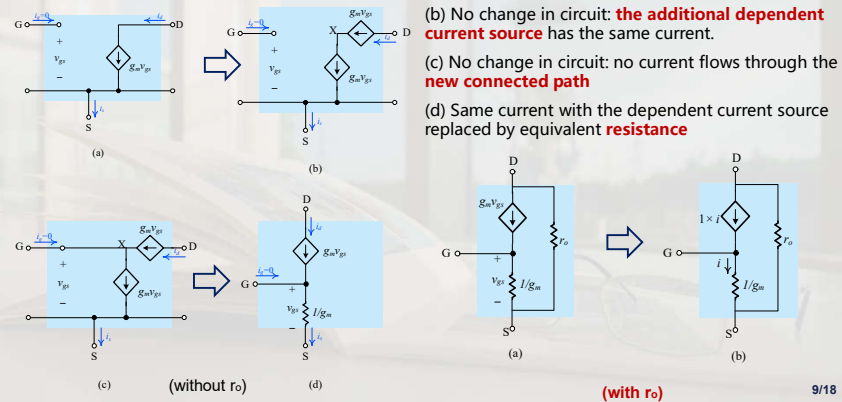
$$\hat{v}_i \leq \frac{V_t}{|A_v| + 1}$$

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



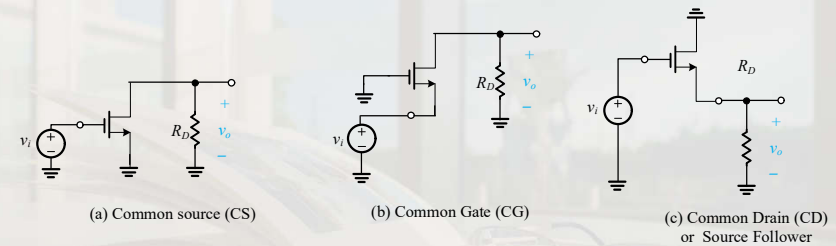
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From π Model to T Model



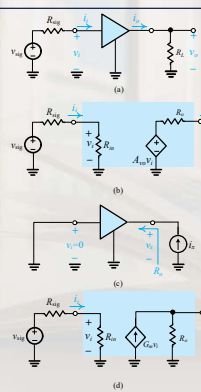
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Basic Single-Transistor Amp. Configurations



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Two-Port Model of Amplifiers



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

- 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_o ?

Fig. Characterization of the amplifier as a functional block

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Common-Source (CS) Amplifier

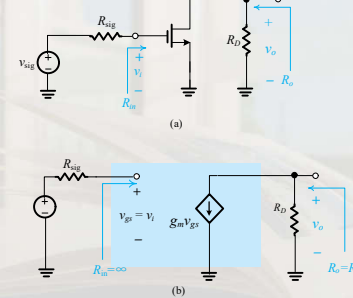


Figure 7.36

- Previously, using MOSFET equation, we derived analytically:

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

- Using hybrid- π model, it is almost

$$\text{trivial to solve: } A_v = -g_m R_D$$

- With load resistance, R_L :

$$\text{Since } R_L \text{ is in parallel with } R_D$$

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

$$R_{in} = \infty$$

$$R_o = R_D$$

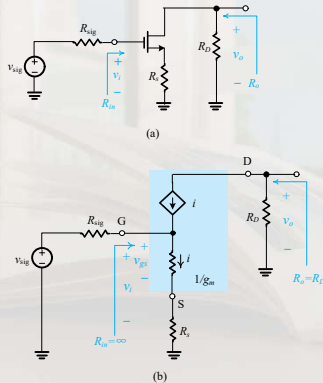


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CS with Source Resistance (Source Degeneration)



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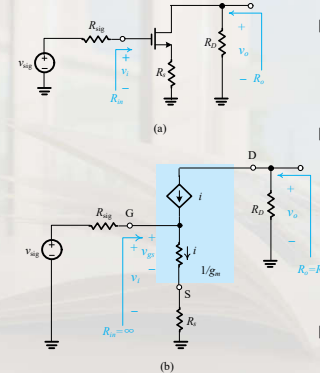
- You can analyze the circuit using hybrid- π model. (Try it !)
- However, whenever **there is a resistor connected to source**, it is much easier to use the **T-model**

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Note

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

- 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

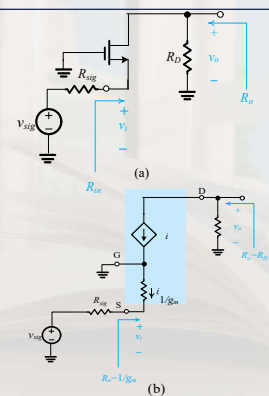
Fig. CS amplifier with a source resistance R_S

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Common-Gate (CG) Amplifier



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

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

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

$$R_o = R_D$$

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

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

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

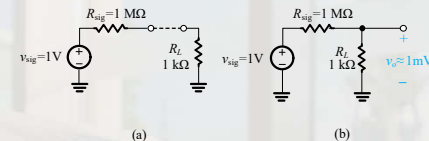
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Need for Voltage Buffers



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- Driving low impedance load **directly**



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

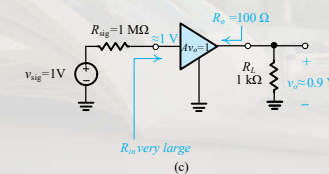


Fig. Illustrating the need for a unity-gain voltage buffer amplifier

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Source Follower (Common-Drain Amplifier)

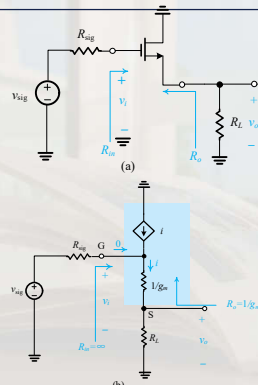


Fig. (a) CD amplifier or source follower with the bias circuit omitted. (b) Equivalent circuit of the source follower obtained by replacing the MOSFET with its T model.

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

$$R_{in} = \infty$$

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

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

$$R_o = 1/g_m$$

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

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Comparison of Different Amp. Configurations



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



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