
# Lecture 16: Analog Circuits

VE311 Electronic Circuits

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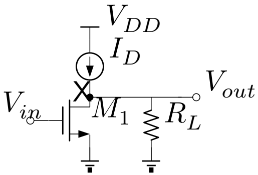
# Recap of Last Lecture

- Source Follower

# Topic to be covered

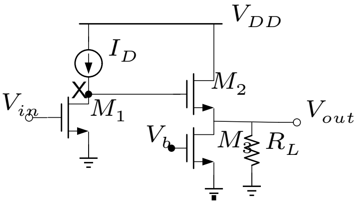
- Source Follower
- Emitter Follower
- Common Gate

# CS + Source Follower




$$A_v = -gm_1 \left( r_{o1} \parallel R_L \right)$$

- Voltage gain severely reduced when $R_L$ very small

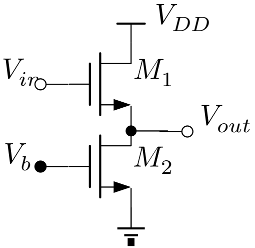



$$A_v = -gm_1 r_{o1} \times gm_2 \left( r_{o2} \parallel \frac{1}{gm_2 + g_{mb2}} \parallel r_{o3} \parallel R_L \right) \quad (1)$$

- Voltage gain maintained when $R_L$ very small

# Source Follower Example

$$(W/L)_1 = 20/0.5, I_D = 0.2\ mA,\ V_{\text{THO}} = 0.6\ V, 2\Phi_F = 0.7\ V, \mu_n C_{ox} = 50\mu A/V^2, \gamma = 0.4\ V^{1/2} \text{ and } \lambda = 0$$




(a) Calculate $V_{out}$ for $V_{in} = 1.2V$.

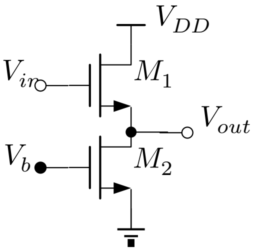
$$I_D = \frac{1}{2}\mu_n C_{\text{ox}} \frac{W}{L} \left(V_{\text{in}} - V_{\text{out}} - V_{THO}\right)^2 \quad (2)$$

$$\rightarrow V_{\text{out}} = 0.153\ V \quad (3)$$

# Source Follower Example

$$V_{TH1} = V_{THO} + \gamma\left(\sqrt{2\Phi_F + V_{\text{out}}} - \sqrt{2\Phi_F}\right) = 0.635\ V \quad (4)$$

$$\rightarrow V_{\text{out}} \approx 0.118\ V \quad (5)$$

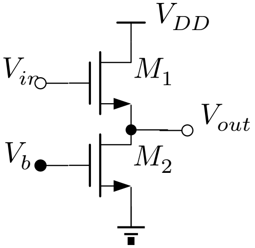


# Source Follower Example

(b) Minimum $(W/L)_2$ for which $M_2$ remains saturated.

$$V_{\text{out}} = 0.118\ V \geq V_{GS2} - V_{TH2} \tag{6}$$

$$I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GS2} - V_{TH2}\right)^2 \rightarrow \left(\frac{W}{L}\right)_2 \geq \frac{283}{0.5} \tag{7}$$



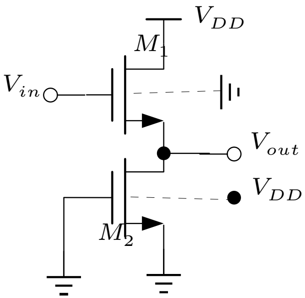
# Source Follower Example

Calculate the small signal voltage gain of the circuit below.

$$G_m = g_{m1} \tag{8}$$

$$R_{out} = \frac{1}{gm_1 + gmb_1} \parallel r_{o1} \parallel \frac{1}{gm_2 + gmb_2} \parallel r_{o2} \tag{9}$$

$$A_v = G_m R_{out} \tag{10}$$

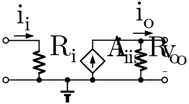


# Emitter Follower

Common Collector

Reading: Sedra & Smith, 8th Ed.: 7.3 (BJT CC )

Current Amplifier



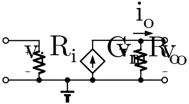
Short-Circuit Current Gain

$$A_{ix} \equiv \frac{i_o}{i_i}|_{v_o=0}(\ A/A)$$

$R_i = 0$

$R_o = \infty$

Transconductance Amplifier



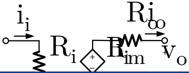
Short-Circuit Transconductance

$$G_m \equiv \frac{i_o}{v_i}|_{v_o=0}(\ A/V)$$

$R_i = \infty$

$R_o = \infty$

Transresistance Amplifier

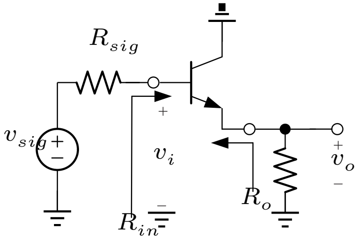


Short-Circuit

$R_i = 0$

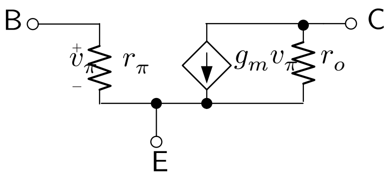
$R_o = 0$

# Emitter Follower

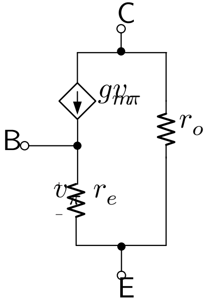



- Transistor is biased to be in the FAR using the same biasing technique for CE amplifier.

# Emitter Follower impedance



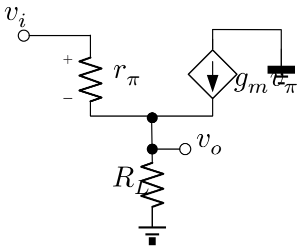

Textbook Pi-model




Textbook T-model

$$g_m = \frac{\alpha}{r_e} r_\pi = (\beta + 1) r_e$$

# Emitter Follower impedance




$$R_{\text{in}} = r_\pi + (\beta + 1) R_L \tag{11}$$

$$R_{\text{out}} = r_\pi \parallel (1/gm) \tag{12}$$

# Emitter Follower gain

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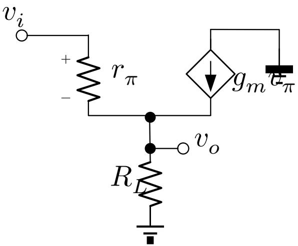



$$\frac{v_o}{v_i} = \frac{R_L}{\frac{1}{g_m + 1/r_\pi} + R_L} \tag{13}$$

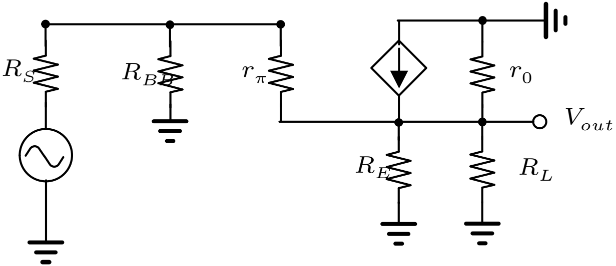
# CC Amplifier with Biasing Circuit

- No collector resistor
- no bypass capacitor
- Biasing scheme remains the same.
- Output taken out at the emitter.

# CC Amplifier with Biasing Circuit

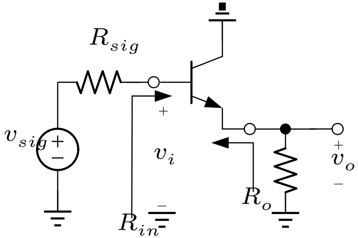
# CC Amplifier with Biasing Circuit

Use the current relationship of $i_b$ and $i_c$



# CC Amplifier with Biasing Circuit






$$\frac{v_i}{v_{\text{sig}}} = \frac{R_{in}}{R_{in} + R_{sig}} = \frac{(\beta + 1)\,(r_e + R_L)}{(\beta + 1)\,(r_e + R_L) + R_{sig}} \tag{14}$$

$$G_v \equiv \frac{v_o}{v_{\text{sig}}} = \frac{v_i}{v_{\text{sig}}} \times A_v \tag{15}$$

$$G_v = \frac{(\beta + 1)R_L}{(\beta + 1)R_L + (\beta + 1)r_e + R_{sig}} \tag{16}$$

# CC Amplifier Swing

- Assume output is a sinusoid with peak voltage of $V_P$

# CC Amplifier Swing

- Emitter voltage can get to within $V_{CESAT}$ of the supply voltage before transistor enters saturation, therefore the maximum output voltage is $V_{CC} - V_{CESAT} - V_{EQ}$.

# CC Amplifier Swing

Total emitter current is given by:

$$i_E = \frac{V_{EQ}}{R_E} + \frac{v_p}{R_E} + \frac{v_p}{R_L}$$

$$i_E = \frac{V_{EQ}}{R_E} - \frac{V_P}{R_E} - \frac{V_P}{R_L} = 0$$

$$\frac{V_{EQ}}{R_E} - \frac{V_P\,(R_L + R_E)}{R_L R_E} = 0$$

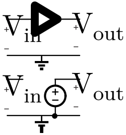
$$V_P = \frac{V_{EQ}\,(R_L)}{R_L + R_E}$$

$$= V_{EQ} / \left(1 + \frac{R_E}{R_L}\right)$$

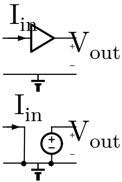
$$V_{E\min} = V_{EQ} - V_P = \frac{V_{EQ}\,(R_E)}{R_L + R_E} = V_{EQ} / \left(1 + \frac{R_L}{R_E}\right)$$

# Ideal Amplifier

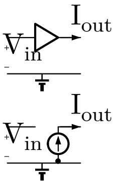
Voltage Amp.



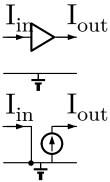

Transimpedance Amp.




Transconductance Amp.

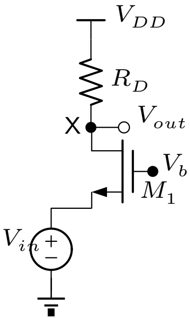



Current Amp.




- For converting and amplifying small-signal current to voltages, common-gate provides low input impedance and moderate gain, but relatively large output impedance.

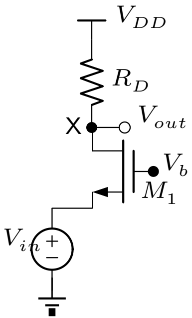
# Common-Gate ($\lambda = 0, \gamma \neq 0$)




- $V_{\text{in}} > V_b - V_{TH} \rightarrow M_1$ Off
- $V_{\text{out}} = V_{DD}$
- $V_b - V_{TH} > V_{\text{in}} > V_{\text{in}\ 1} \rightarrow M_1$ in Saturation

$$V_{\text{out}} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{w}{L} (V_b - V_{\text{in}} - V_{TH})^2 \tag{17}$$

# Common-Gate




At the boundary of triode/saturation:

$$V_{\text{out}} = V_b - V_{TH} \tag{18}$$

$$= V_{DD} - R_D \frac{1}{2}\mu_n C_{ox} \frac{W}{L} \left(V_b - V_{in1} - V_{TH}\right)^2 \tag{19}$$

$$V_{\text{in}} < V_{\text{in }1} \rightarrow M_1 \text{ in Triode} \tag{20}$$

Triode region equation as follows:

$$V_{\text{out}} = V_{DD} - R_D \mu_n C_{ox} \frac{W}{L} \left[ \left(V_b - V_{in} - V_{TH}\right)\left(V_{\text{out}} - V_{in}\right) - \frac{1}{2}\left(V_{\text{out}} - V_{in}\right)^2 \right] \tag{21}$$

# Common-Gate $(\lambda = 0, \gamma \neq 0)$

$$V_b - V_{TH} > V_{in} > V_{in1} \rightarrow M_1 \text{ in Saturation} \tag{22}$$

$$V_{\text{out}} = V_{DD} - R_D \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_b - V_{\text{in}} - V_{TH}\right)^2 \tag{23}$$

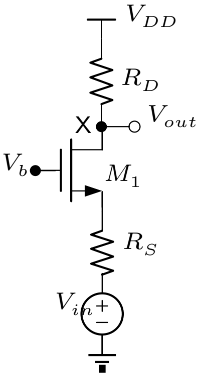
$$\frac{\partial V_{\text{out}}}{\partial V_{\text{in}}} = -R_D \frac{1}{2}\mu_n C_{ox}\frac{W}{L} 2\left(V_b - V_{in} - V_{TH}\right)\left(-1 - \frac{\partial V_{TH}}{\partial V_{in}}\right) \tag{24}$$

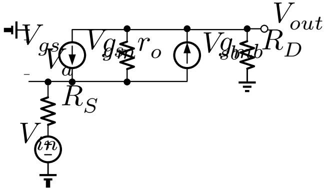
$$= R_D \mu_n C_{ox}\frac{W}{L}\left(V_b - V_{in} - V_{TH}\right)\left(1 + \frac{\partial V_{TH}}{\partial V_{\text{in}}}\right) \tag{25}$$

$$A_v = \frac{\partial V_{\text{out}}}{\partial V_{\text{in}}} = R_D g\ m(1+\eta) \tag{26}$$

- $g_m$ is a function of $I_D$ and $\eta$ is a function of $V_{SB}$.
- $A_v$ is not quite linear.

# Common-Gate ($\lambda = 0, \gamma \neq 0$ Small-signal)




$$G_m = \frac{(gm + gmb)r_o + 1}{r_o + R_S + (gm + gmb)r_o R_S}$$

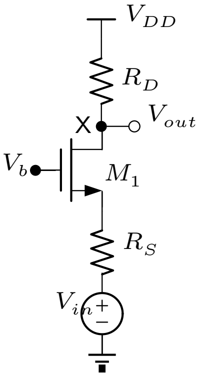
$$R_{\text{out}} = R_D \parallel [r_o + R_S + (gm + gmb)r_o R_S]$$

$$A_v = \frac{(g_m + g_{mb})r_o + 1}{r_o + R_S + (g_m + g_{mb})r_o R_S + R_D} R_D \approx R_D g_m (1 + \eta)$$

# Common-Gate ($\lambda = 0, \gamma \neq 0$ Small-signal)

# Common-Gate SS gain

Transconductance gain: use Norton equivalent



# Common-Gate SS gain



Output Impedance: SS model