Basic Current Mirrors and Single-Stage Amplifiers

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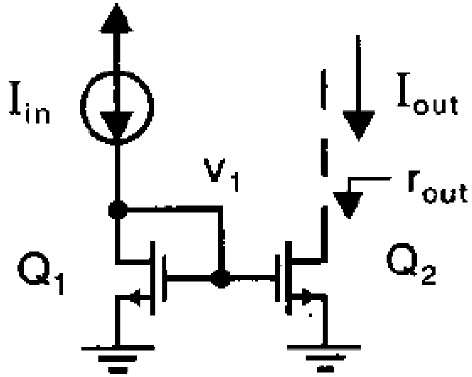
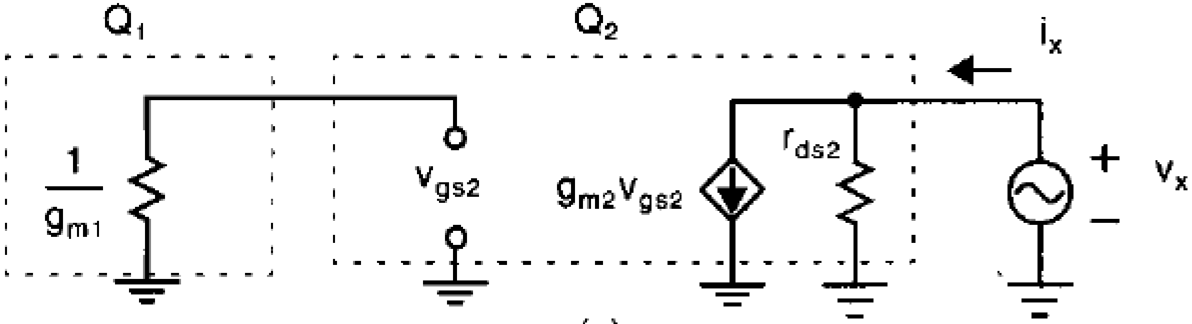
Simple Current Mirror

$$r_{out} = r_{ds2}$$

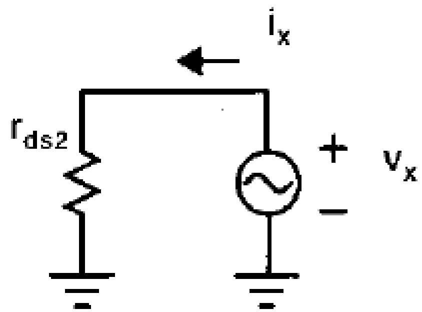
$$I_{out} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1} I_{in}$$

$$V_{out} \geq V_{eff}$$



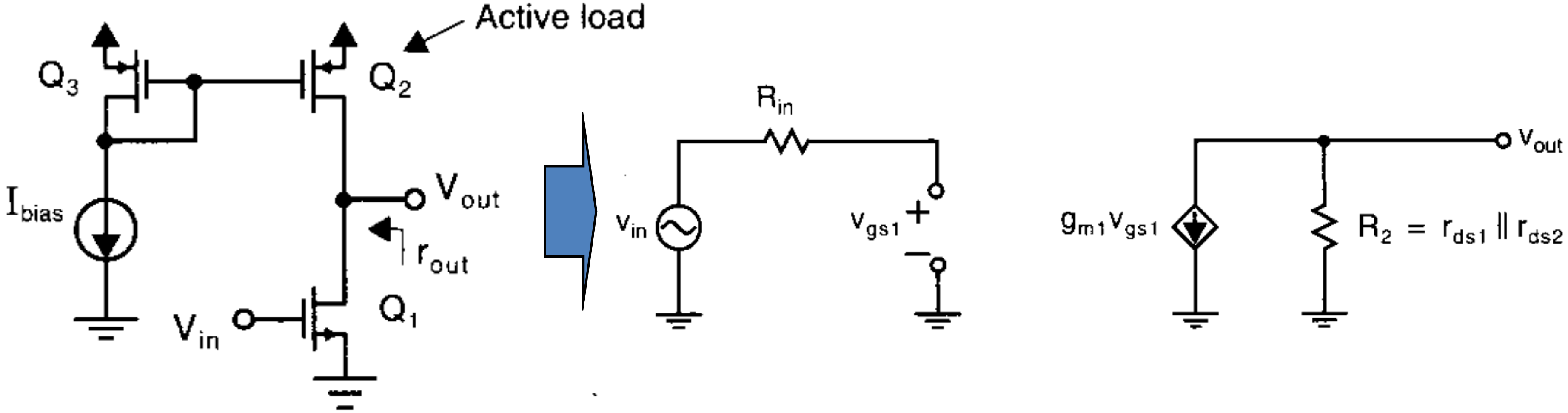


(a)



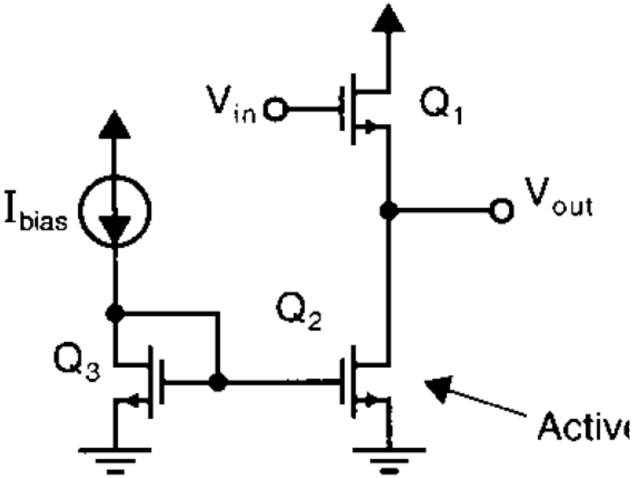
(b)

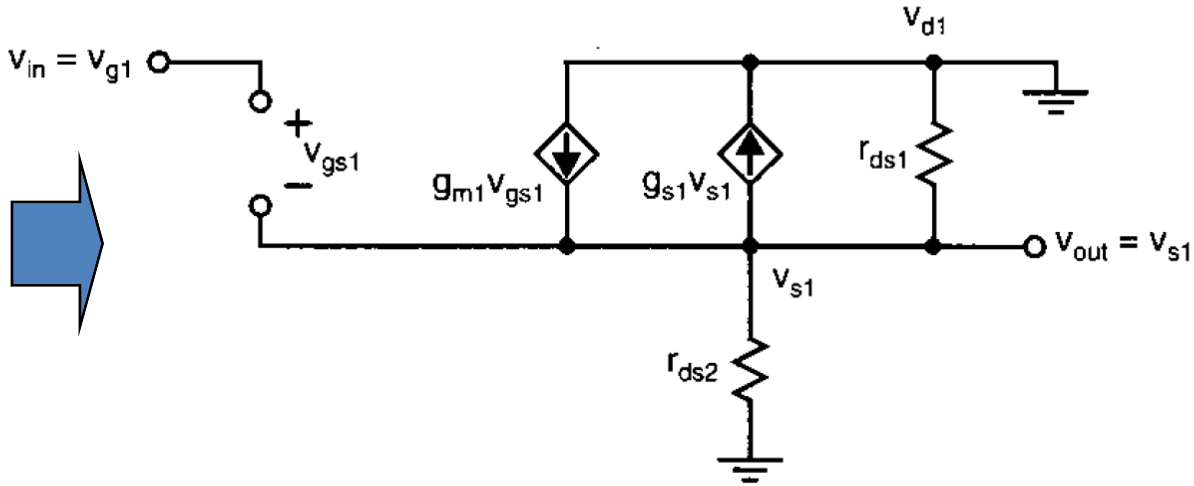
Common-Source Amplifier

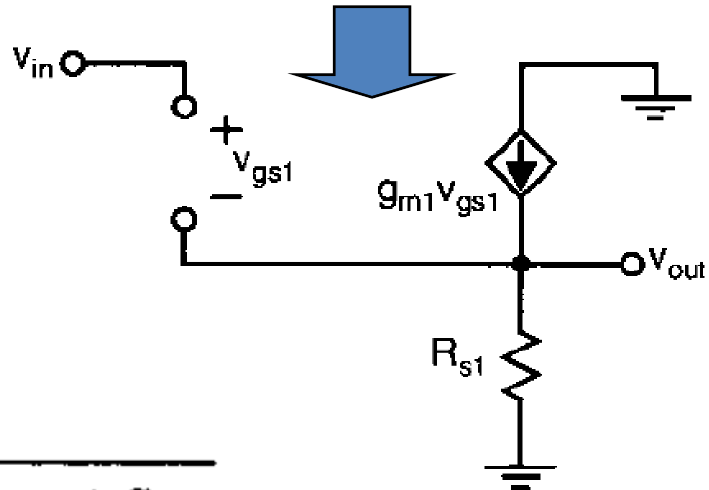


$$A_V = \frac{v_{out}}{v_{in}} = -g_{m1}R_2 = -g_{m1}(r_{ds1} \| r_{ds2})$$

Source-Follower or Common-Drain Amplifier





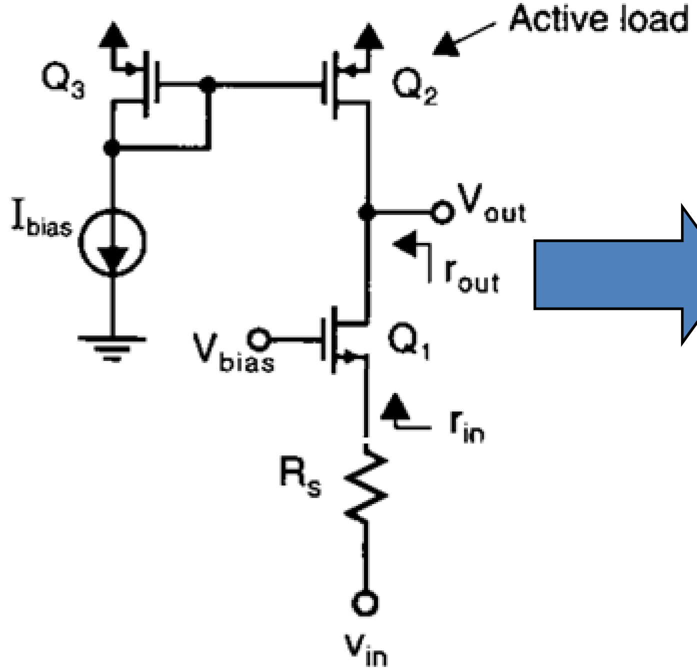


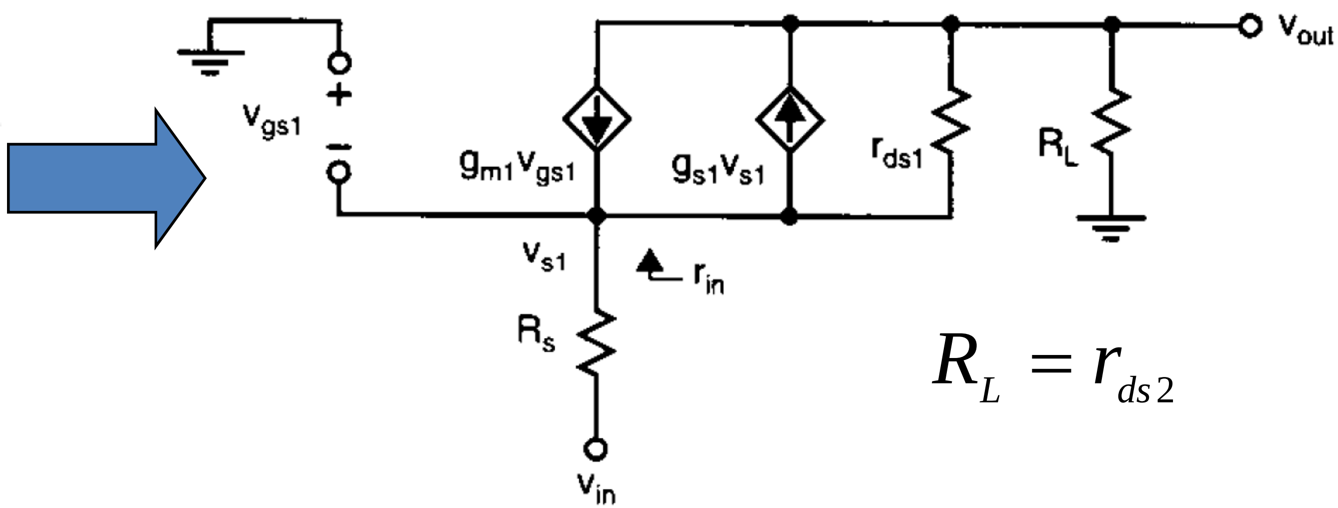
g_{s1} denotes the body effect. ($g_{s1} = g_{mb1}$)

$$R_{s1} = r_{ds1} \parallel r_{ds2} \parallel 1/g_{s1} \qquad G_{s1} = 1/R_{s1}$$

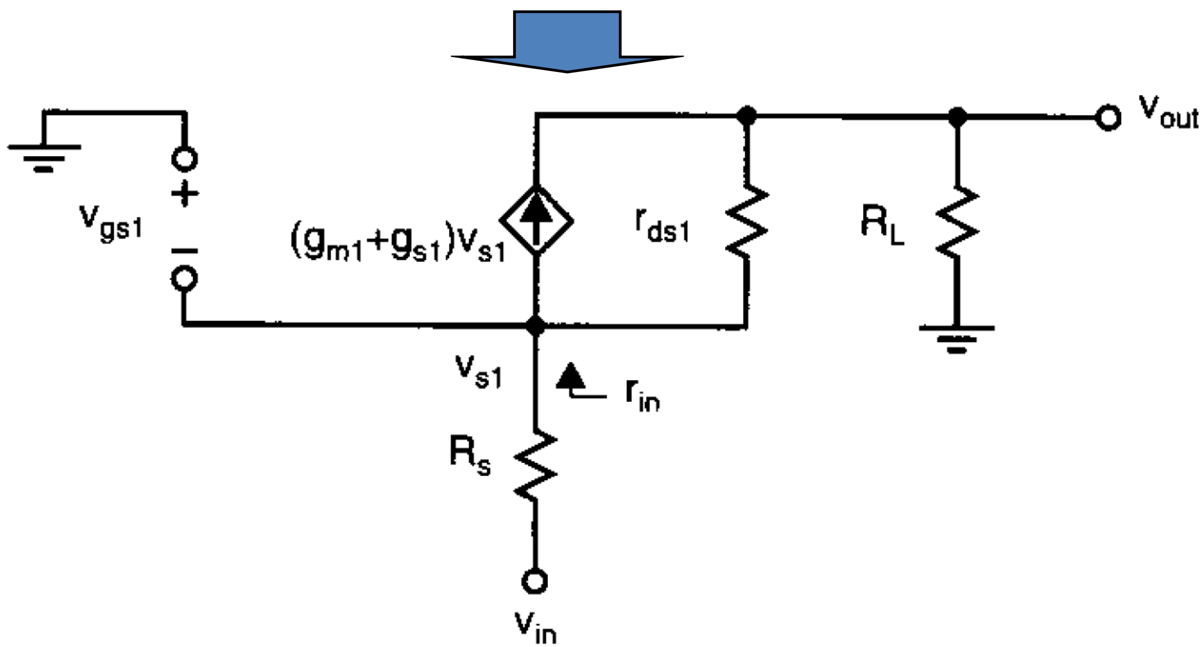
$$A_v = \frac{v_{out}}{v_{in}} = \frac{g_{m1}}{g_{m1} + G_{s1}} = \frac{g_{m1}}{g_{m1} + g_{s1} + g_{ds1} + g_{ds2}}$$

Common-Gate Amplifier

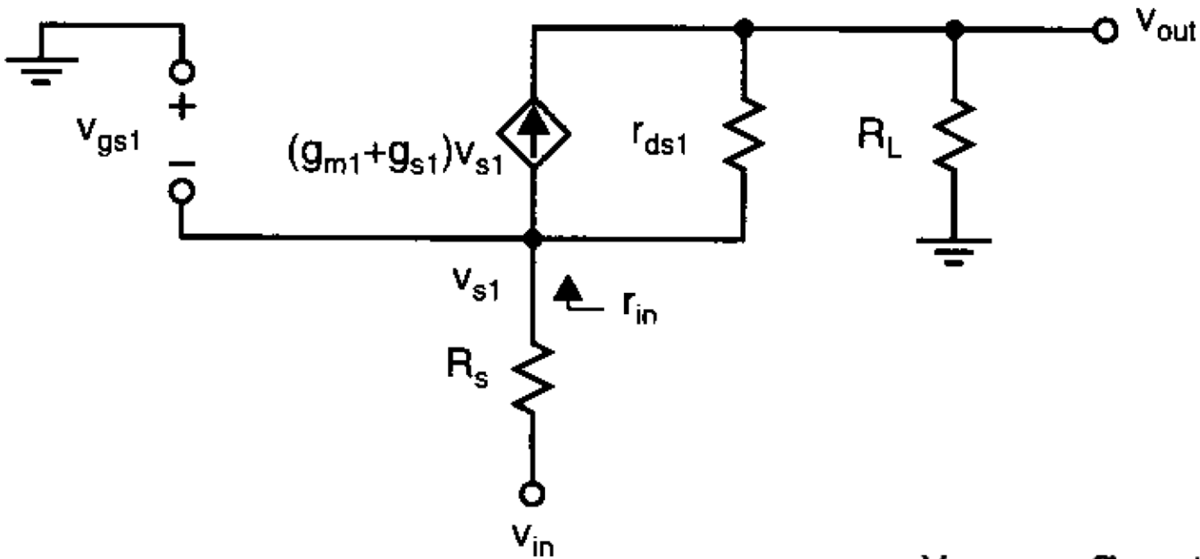




$$R_L = r_{ds2}$$



Common-Gate Amplifier

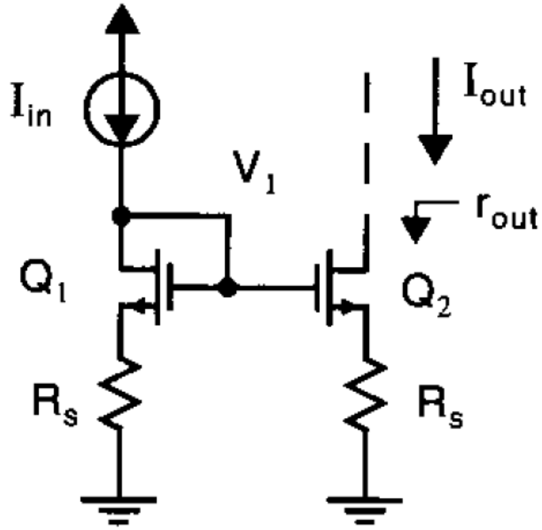


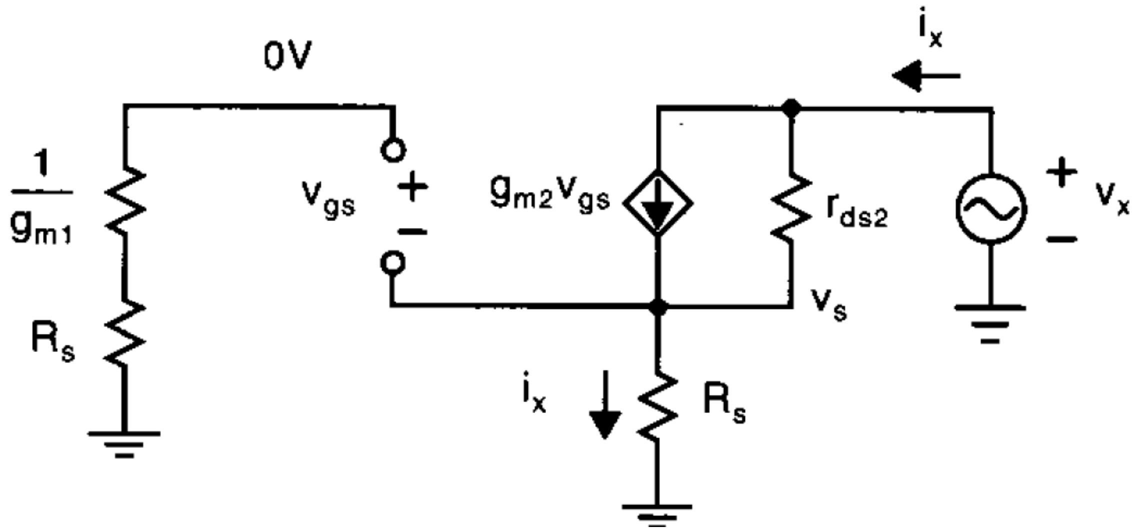
$$v_{out}(G_L + g_{ds1}) - v_{s1}g_{ds1} - (g_{m1} + g_{s1})v_{s1} = 0 \Rightarrow \frac{v_{out}}{v_{s1}} = \frac{g_{m1} + g_{s1} + g_{ds1}}{G_L + g_{ds1}}$$

$$\frac{v_{s1}}{v_{in}} = \frac{G_s}{G_s + \dfrac{g_{m1} + g_{s1} + g_{ds1}}{1 + g_{ds1}/G_L}}$$

$$A_V = \frac{v_{out}}{v_{in}} = \left[\frac{G_s}{\left(G_s + \dfrac{g_{m1} + g_{s1} + g_{ds1}}{1 + g_{ds1}/G_L}\right)}\right]\frac{g_{m1} + g_{s1} + g_{ds1}}{G_L + g_{ds1}}$$

Source-Degenerated Current Mirrors





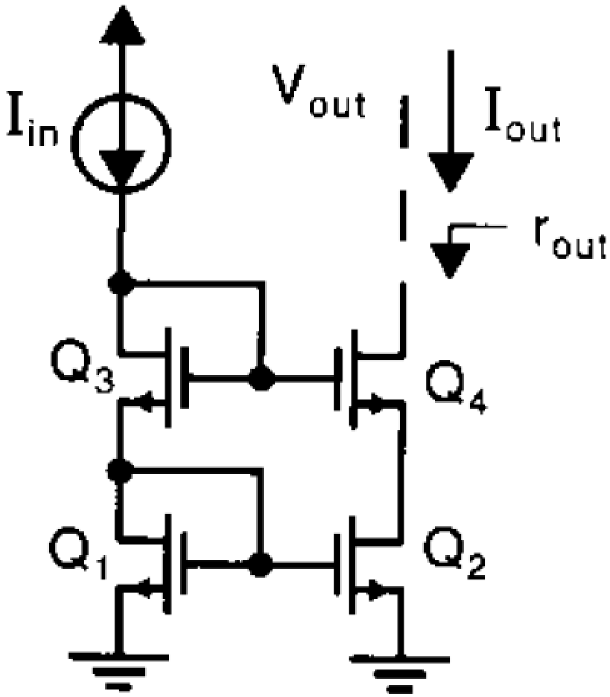
$$r_{out} = \frac{v_x}{i_x} = r_{ds2}[1 + R_s(g_{m2} + g_{ds2})] \cong r_{ds2}(1 + R_s g_{m2})$$

$$if \left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 \Rightarrow \quad I_{out} = I_{in}$$

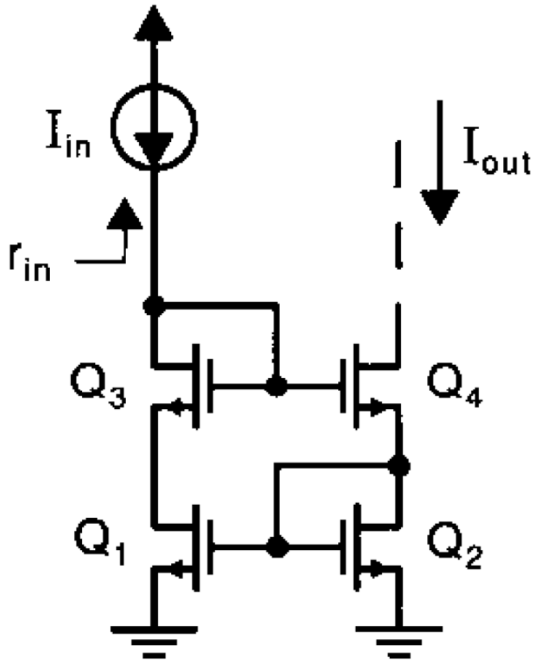
$$V_{out} \geq R_s I_{out} + V_{eff}$$

High-Output-Impedance Current Mirrors

Cascode Current Mirror



Wilson Current Mirror

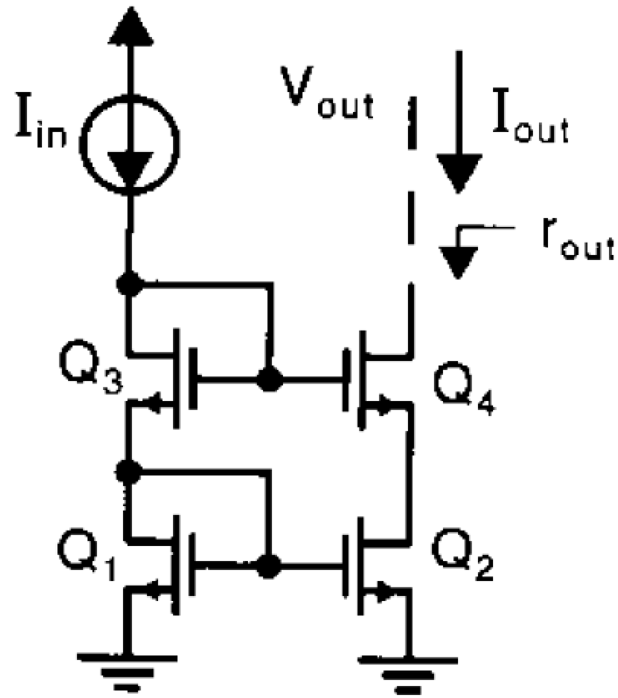


Cascode Current Mirror

$$r_{out} = r_{ds4}[1 + r_{ds2}(g_{m4} + g_{s4} + g_{ds4})]$$

$$\cong r_{ds4}[1 + r_{ds2}(g_{m4} + g_{s4})]$$

$$\cong r_{ds4}(r_{ds2} g_{m4})$$



$$V_{out} > V_{DS2} + V_{eff} = 2V_{eff1} + V_{tn}$$

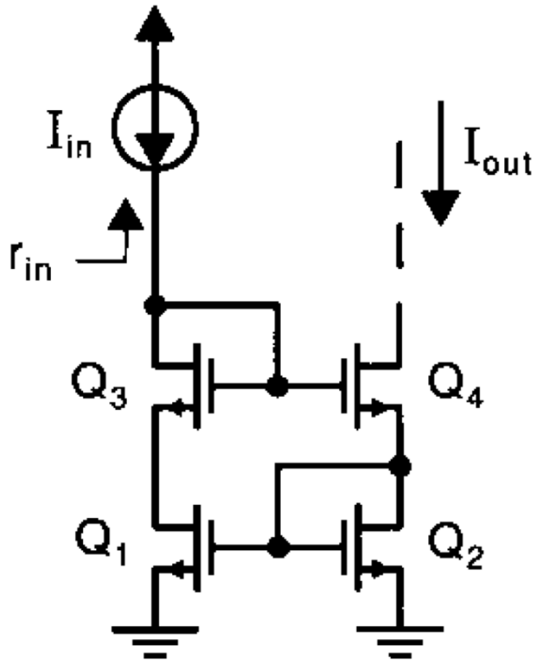
$$I_{out} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1} I_{in}$$

Wilson Current Mirror

$$r_{out} \cong 2r_{ds4}\frac{g_{m1}(r_{ds1} \parallel r_{in})}{2} \cong r_{ds4}\left(\frac{g_{m1}r_{ds1}}{2}\right)$$

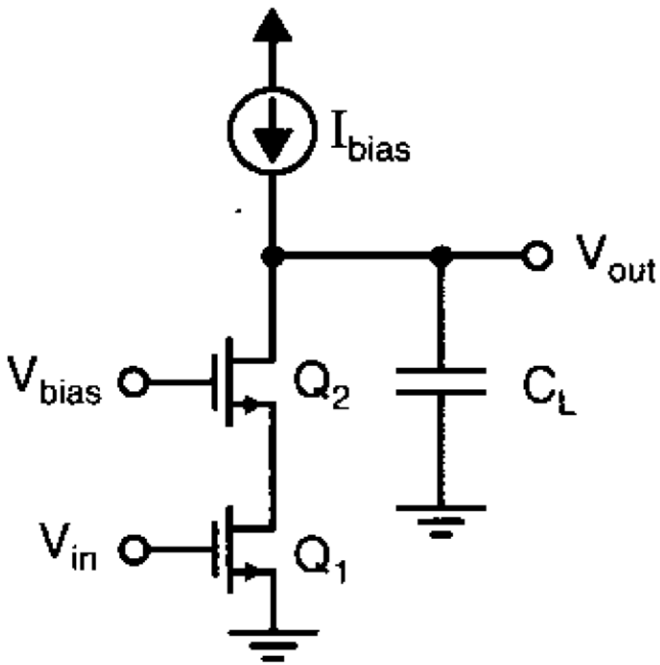
$$V_{out} > V_{DS2} + V_{eff} = 2V_{eff1} + V_{tn}$$

$$I_{out} = \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1} I_{in}$$

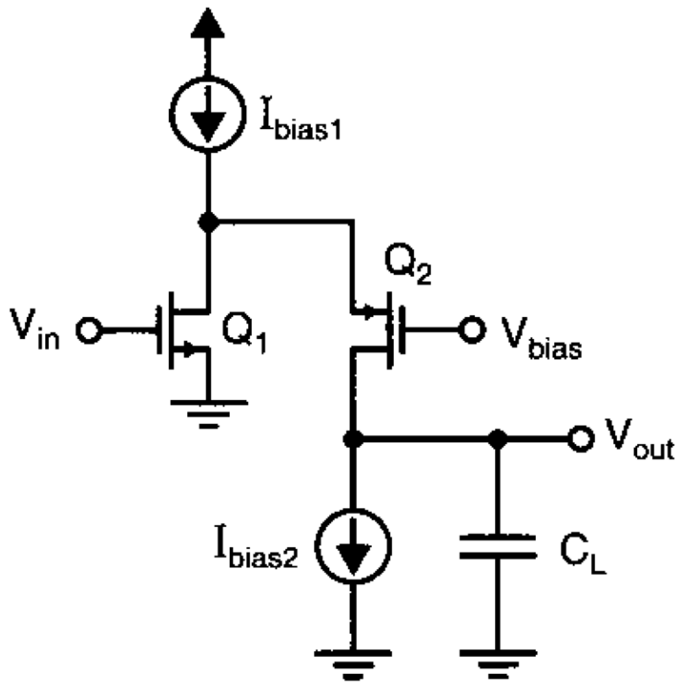


CASCODE Gain Stage

telescopic-cascode amplifier



folded-cascode amplifier



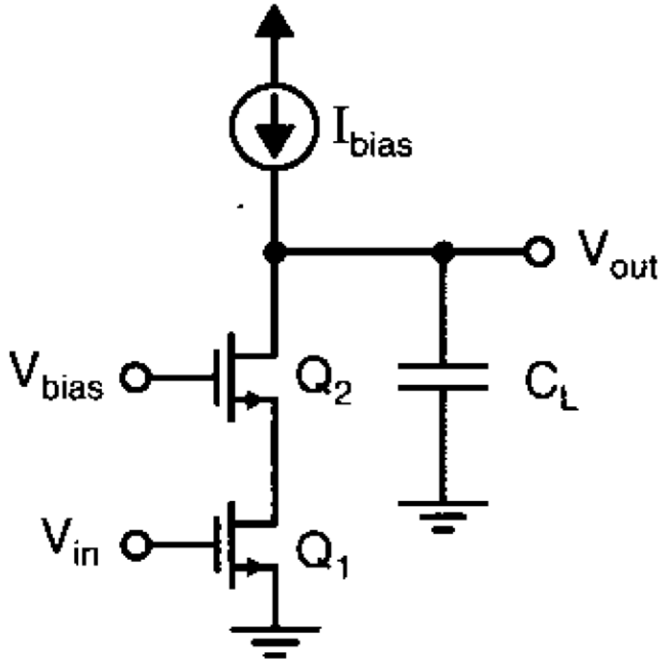
Telescopic-Cascode Amplifier

$$r_{d2} \cong g_{m2} r_{ds1} r_{ds2}$$

$$R_L \cong g_{m\text{-}p} r_{ds\text{-}p}^2$$

$$R_{out} = r_{d2} \parallel R_L$$

$$A_V \cong -g_{m1} \times R_{out}$$



The folded-cascode amplifier is analyzed similarly.

Differential Pair

After a few manipulation, it is proven that:

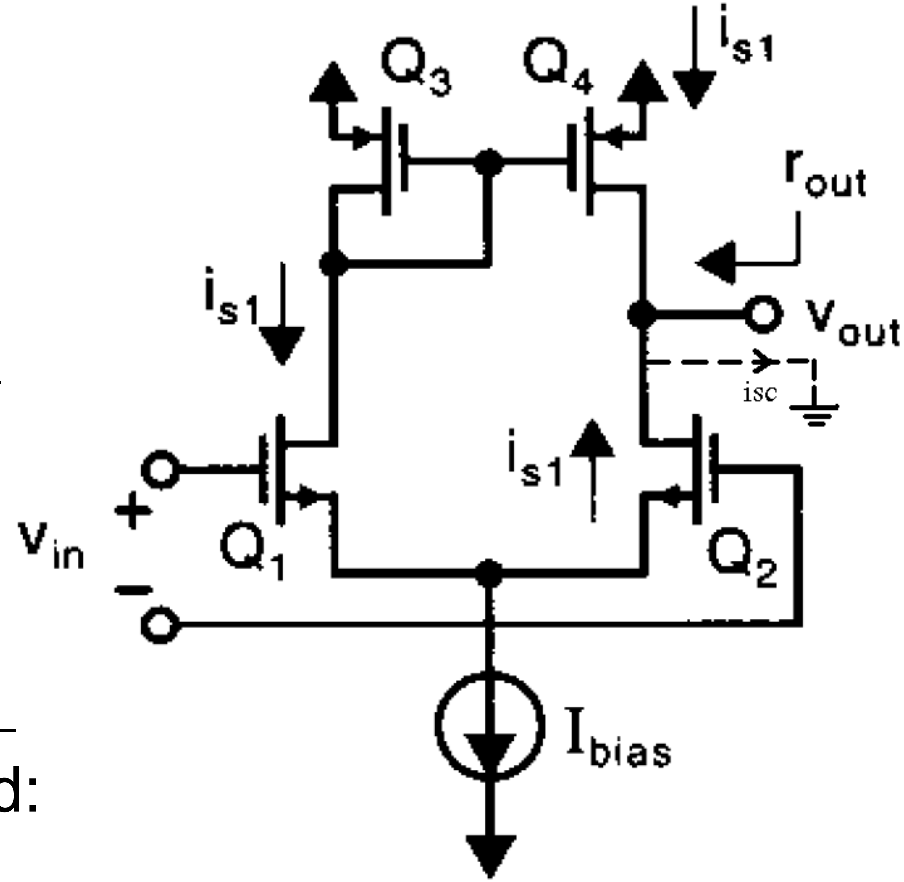
$$r_{out} \cong r_{ds4} \| r_{ds2}$$

Besides, we have:

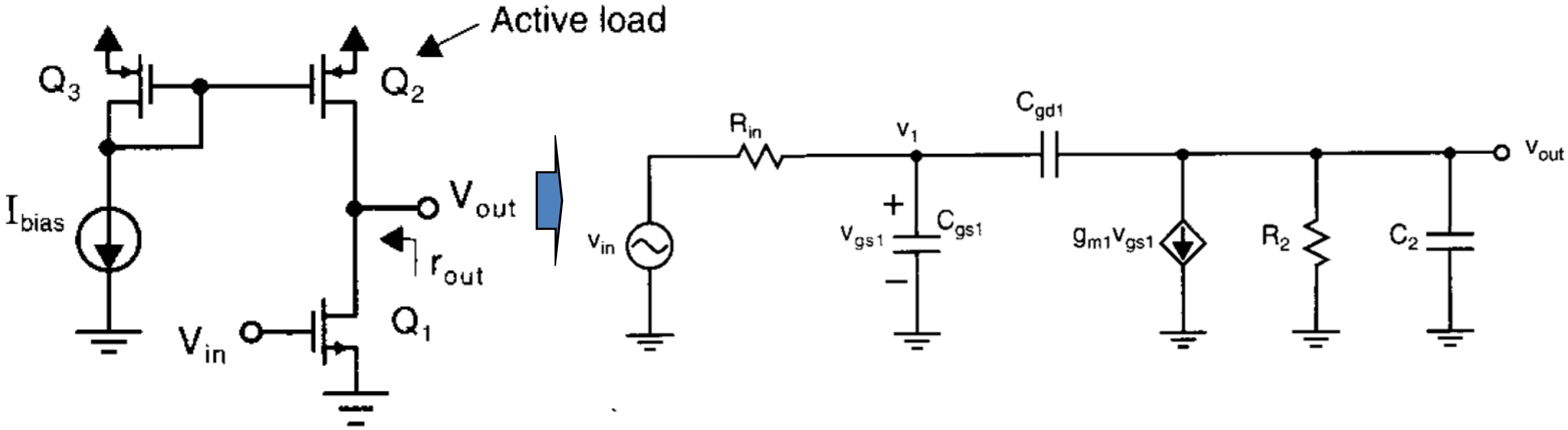
$$i_{sc} \cong 2i_{s1} = 2g_{m1}\frac{v_i}{2} = g_{m1}v_i$$

So, the voltage-gain is obtained:

$$A_V = g_m r_{out}$$



Frequency Response
Common-Source Amplifier



$$v_1(G_{in} + sC_{gs1} + sC_{gd1}) - v_{in}G_{in} - v_{out}sC_{gd1} = 0$$

$$v_{out}(G_2 + sC_{gd1} + sC_2) - v_1 sC_{gd1} + g_{m1}v_1 = 0$$

$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}R_2\left(1 - s\frac{C_{gd1}}{g_{m1}}\right)}{1 + sa + s^2b}$$

Frequency Response
Common-Source Amplifier

$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}R_2\left(1 - s\frac{C_{gd1}}{g_{m1}}\right)}{1 + sa + s^2b}$$

$$a = R_{in}[C_{gs1} + C_{gd1}(1 + g_{m1}R_2)] + R_2(C_{gd1} + C_2)$$

$$b = R_{in}R_2(C_{gd1}C_{gs1} + C_{gs1}C_2 + C_{gd1}C_2)$$

Assuming that poles are real numbers and $\omega_{p1} << \omega_{p2}$, we have:

$$D(s) = \left(1 + \frac{s}{\omega_{p1}}\right)\left(1 + \frac{s}{\omega_{p2}}\right) \cong 1 + \frac{s}{\omega_{p1}} + \frac{s^2}{\omega_{p1}\omega_{p2}}$$

$$\omega_{-3\ dB} \cong \frac{1}{R_{in}[C_{gs1} + C_{gd1}(1 + g_{m1}R_2)] + R_2(C_{gd1} + C_2)}$$

$$\omega_{p2} \cong \frac{g_{m1}C_{gd1}}{C_{gs1}C_{gd1} + C_{gs1}C_2 + C_{gd1}C_2}$$

Frequency Response
Common-Source Amplifier

$$\frac{v_{out}}{v_{in}} = \frac{-g_{m1}R_2\left(1 - s\frac{C_{gd1}}{g_{m1}}\right)}{1 + sa + s^2b}$$

$$a = R_{in}[C_{gs1} + C_{gd1}(1 + g_{m1}R_2)] + R_2(C_{gd1} + C_2)$$
$$b = R_{in}R_2(C_{gd1}C_{gs1} + C_{gs1}C_2 + C_{gd1}C_2)$$

If the poles are complex conjugate, we will write the above transfer function as follows:

$$A(s) = A(0)\frac{N(s)}{1 + \frac{s}{\omega_0 Q} + \frac{s^2}{\omega_0^2}}$$

$$A(0) = -g_{m1}R_2$$

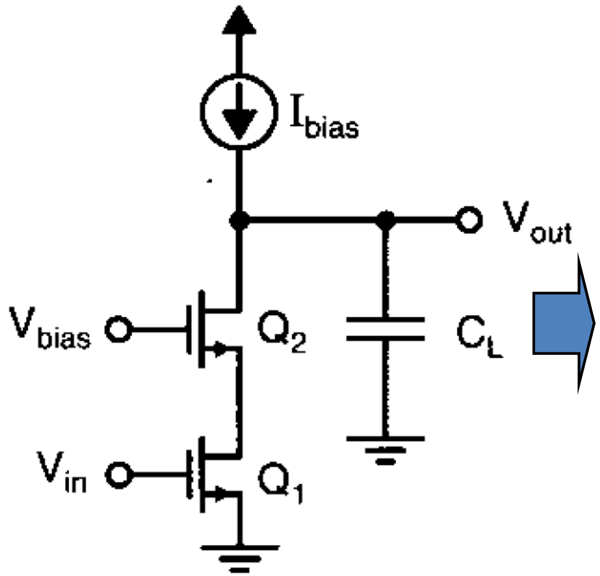
$$\omega_0 = \frac{1}{\sqrt{b}}$$

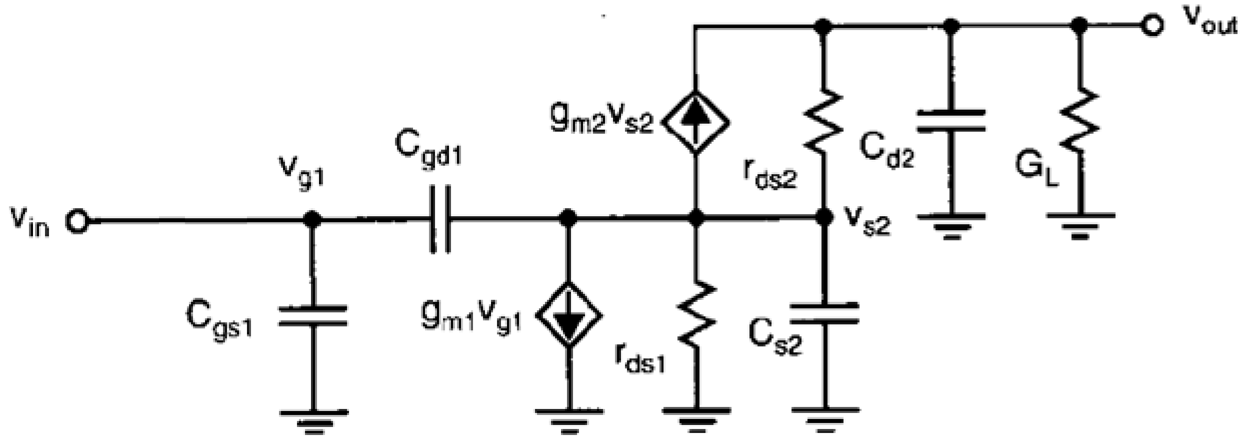
$$Q = \frac{\sqrt{b}}{a}$$

$$\%\ \text{overshoot} = 100e^{-\pi/\sqrt{4Q^2 - 1}}$$

Similarly, we can analyze the C.D and C.G amplifiers.

Frequency Response
CASCODE Amplifier





$$\omega_{p1} \cong \frac{1}{R_{out} C_{d2}} \cong \frac{1}{R_{out} C_L}$$

$$\omega_{p2} \cong \frac{g_{m2}}{C_{s2}}$$