FET Current-Mirror Examples

Common-Source Amplifier

Figure 1 shows a common-source amplifier. The active device is M_1. Its load consists of a current-mirror active load consisting of M_2 and M_3. The current source I_{REF} sets the drain current in M_3 which is mirrored into the drain of M_2. Because the source-to-drain voltage of M_2 is larger than that of M_3, the Early effect causes the dc drain current in M_2 to be slightly larger than I_{REF}.

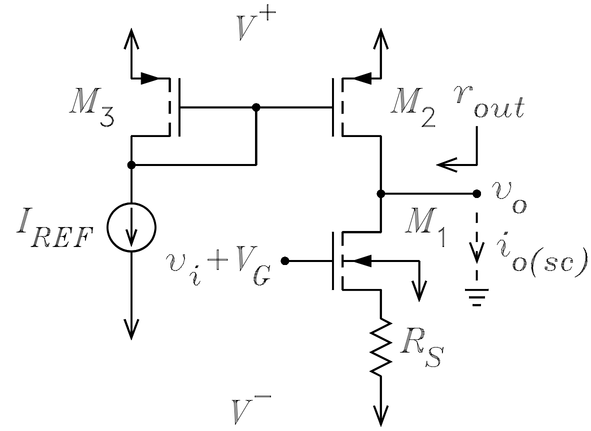

Figure 1: Common-source amplifier.

The voltage V_G is the dc component of the gate input to M_1. It is a dc bias voltage which sets the dc drain current in M_1. This current must be equal to the drain current in M_2 in order for the dc output voltage to be stable. In applications, V_G would usually be set by feedback. It will be assumed that $r_{01} = \infty$ in calculating $i_{o(sc)}$ but not in calculating r_{out}. Note that the body effect must be accounted for in M_1. Assume that $I_{D1} = I_{D2} = I_{D3} = I_{REF}$.

(a) Use the source equivalent circuit to calculate the short-circuit output current. Assume that $r_{01} = \infty$.

$$i_{o(sc)} = -i'_{d1} = -i'_{s1} = -\frac{\dfrac{v_i}{(1+\chi_1)}}{r_{is1} + R_S}$$

$$r_{is1} = \frac{r_{s1}}{1+\chi_1} = \frac{1}{g_{m1}(1+\chi_1)}$$

where

$$g_{m1} = 2\sqrt{K_1 I_{REF}}$$

(b) Calculate the output resistance. Assume that $r_{01} < \infty$.

$$r_{out} = r_{id1} \| r_{02}$$

where

$$r_{id1} = r_{01}\left(1 + \frac{R_S}{r_{is1}}\right) + R_S = r_{01}\left[1 + (1+\chi_1) g_{m1} R_S\right] + R_S$$

$$r_{01} = \frac{\lambda^{-1} + V_{DS1}}{I_{REF}}$$

$$r_{02} = \frac{\lambda^{-1} + V_{DS2}}{I_{REF}}$$

(c) Calculate the output voltage and the voltage gain.

$$v_o = i_{o(sc)} \times r_{out} = -\frac{\dfrac{v_i}{(1+\chi_1)}}{\dfrac{1}{g_{m1}(1+\chi_1)} + R_S} \times r_{id1} \| r_{02}$$

$$A_v = \frac{v_o}{v_i} = -\frac{1}{(1+\chi_1)} \times \frac{r_{id1} \| r_{02}}{\dfrac{1}{g_{m1}(1+\chi_1)} + R_S} = -\frac{r_{id1} \| r_{02}}{\dfrac{1}{g_{m1}} + (1+\chi_1) R_S}$$

Common-Gate Amplifier

Figure 2 shows a common-gate amplifier. The active device is M_1. Its load consists of a current-mirror active load consisting of M_2 and M_3. The current source I_{REF} sets the drain current in M_3. This current is mirrored into the drain of M_2. As with the common-source amplifier, the Early effect makes the drain current in M_2 slightly larger than that in M_3. The dc voltage V_G is a dc bias voltage which sets the drain current in M_1. This must be equal to the drain current in M_2 in order for the dc output voltage to be stable. In an applications, V_G would usually be set by feedback. It will be assumed that $r_{01} = \infty$ in calculating $i_{o(sc)}$ but not in calculating r_{out}. Note that the body effect must be accounted for in M_1. Assume that $I_{D1} = I_{D2} = I_{D3} = I_{REF}$.

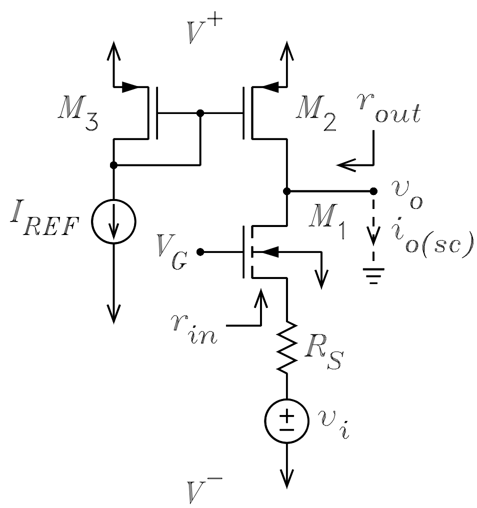

Figure 2: Common-gate amplifier.

(a) Use the source equivalent circuit for M_1 to calculate short-circuit output current. Assume that $r_{01} = \infty$.

$$i_{o(sc)} = -i'_{d1} = -i'_{s1} = \frac{v_i}{r_{is1} + R_S}$$

$$r_{is1} = \frac{r_{s1}}{1+\chi_1} = \frac{1}{g_{m1}(1+\chi_1)}$$

(b) Calculate the output resistance. Assume that $r_{01} < \infty$.

$$r_{out} = r_{id1} \| r_{02}$$

$$r_{id1} = r_{01}\left(1 + \frac{R_S}{r_{is1}}\right) + R_S = r_{01}\left[1 + (1+\chi_1) g_{m1} R_S\right] + R_S$$

$$r_{01} = \frac{\lambda^{-1} + V_{DS1}}{I_{REF}}$$

$$r_{02} = \frac{\lambda^{-1} + V_{DS2}}{I_{REF}}$$

(c) Calculate the output voltage and the voltage gain.

$$v_o = i_{o(sc)} r_{out} = \frac{v_i}{r_{s1} + R_S} r_{id1} \| r_{02}$$

$$A_v = \frac{v_o}{v_i} = \frac{r_{id1} \| r_{02}}{r_{is1} + R_S} = \frac{r_{id1} \| r_{02}}{\dfrac{1}{g_{m1}(1+\chi_1)} + R_S}$$

(d) Use the source equivalent circuit for M_1 to calculate the input resistance. Assume that $r_{01} = \infty$.

$$r_{in} = r_{is1} = \frac{r_{s1}}{1+\chi_1} = \frac{1}{g_{m1}(1+\chi_1)}$$

Common-Drain Amplifier

Figure 3 shows a common-drain amplifier. The active device is M_1. Its load consists of a current-mirror active load consisting of M_2 and M_3. The current source I_{REF} sets the drain current in M_3 which is mirrored into the drain of M_2. As with the common-source amplifier, the Early effect makes the drain current in M_2 slightly larger than that in M_3. The dc voltage V_G is a bias voltage which sets the dc output voltage. Note that the body effect must be accounted for in M_1. Assume that $I_{D1} = I_{D2} = I_{D3} = I_{REF}$.

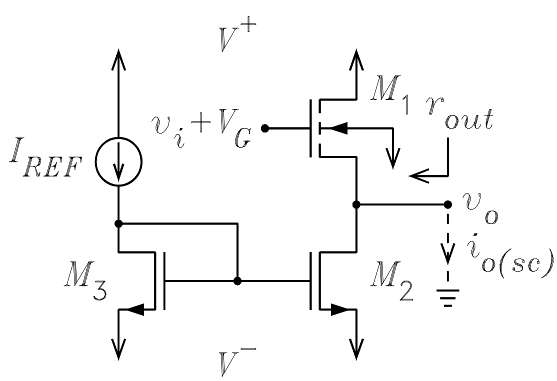

Figure 3: Common-drain amplifier.

(a) Use the pi model for M_1 to calculate $i_{o(sc)}$. Note that the body effect is not present because $v_{bs1} = 0$ when $v_o = 0$.

$$i_{o(sc)} = g_{m1} v_i$$

where

$$g_{m1} = 2\sqrt{KI_{REF}}$$

(b) Use the source equivalent circuit for M_1 to calculate the output resistance.

$$r_{out} = r_{is1} \| r_{01} \| r_{02}$$

$$r_{is1} = \frac{r_{s1}}{1+\chi_1} = \frac{1}{g_{m1}(1+\chi_1)}$$

$$r_{01} = \frac{\lambda^{-1} + V_{DS1}}{I_{REF}}$$

$$r_{02} = \frac{\lambda^{-1} + V_{DS2}}{I_{REF}}$$

(c) Calculate the output voltage and the voltage gain.

$$v_o = i_{o(sc)} r_{out} = g_{m1} v_i (r_{is1} r_{01} \| r_{02})$$

$$A_v = g_{m1} (r_{is1} \| r_{01} \| r_{02})$$

Differential Amplifier

A MOSFET differential amplifier with an active current-mirror load is shown in Fig. 4. The object is to determine the Norton equivalent circuit seen looking into the output. This consists of a current source $i_{o(sc)}$ in parallel with a resistance r_{out}. To do this, the output is connected to ac signal ground, which is indicated by the dashed line. It is assumed that $r_0 = \infty$ in all calculations except in calculating r_{id2} and r_{04}. Assume that $I_{D1} = I_{D2} = I_{D3} = I_{D4} = I_Q/2$.

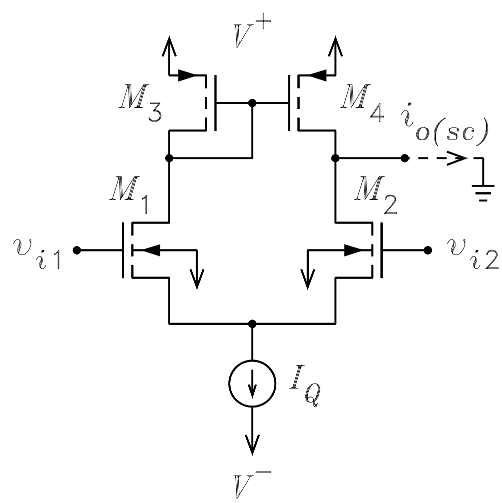

Figure 4: Diff amp.

(a) Use the current-mirror properties to solve for $i_{o(sc)}$ in terms of i'_{d1} and i'_{d2}.

$$i_{o(sc)} = i'_{d4} - i'_{d2} = i'_{d3} - i'_{d2} = i'_{d1} - i'_{d2}$$

(b) Because the tail supply is a current source, the common-mode currents are zero. Therefore, i'_{d1} and i'_{d2} can be calculated by replacing v_{i1} and v_{i2} with their differential components. In this case, the ac signal voltage at the sources of M_1 and M_2 is zero and the ac body-source voltages of M_1 and M_2 are zero. Thus the body effect is absent. Let $v_{i1} = v_{id}/2$ and $v_{i2} = -v_{id}/2$, where $v_{id} = v_{i1} - v_{i2}$. Use the pi model to solve for i'_{d1} and i'_{d2} in terms of v_{id}. Let g_m be the transconductance of M_1 and M_2.

$$i'_{d1} = g_m \frac{v_{id}}{2} \qquad i'_{d2} = -g_m \frac{v_{id}}{2}$$

where

$$g_m = 2\sqrt{K \frac{I_Q}{2}} = \sqrt{2KI_Q}$$

(c) Solve for $i_{o(sc)}$ in terms of $v_{id} = v_{i1} - v_{i2}$.

$$i_{o(sc)} = i'_{d1} - i'_{d2} = 2i'_{d1} = 2g_m \frac{v_{id}}{2} = g_m (v_{i1} - v_{i2})$$

(d) Calculate the output resistance.

$$r_{out} = r_{id2} \| r_{04}$$

$$r_{id2} = r_{02}\left(1 + \frac{r_{is1}}{r_{is2}}\right) + r_{is1} = 2r_{02} + r_{is} \simeq 2r_{02}$$

$$r_{02} = \frac{\lambda^{-1} + V_{DS2}}{I_{REF}}$$

$$r_{04} = \frac{\lambda^{-1} + V_{DS4}}{I_{REF}}$$

In the last equation for r_{id2}, the small-signal resistance R_{ts2} looking out of the source of M_2 is $R_{ts2} = r_{is1}$. Also, $r_{is1} = r_{is2} = r_{is} = 1/\left[(1+\chi)\, g_m\right]$.

(e) Calculate the output voltage and voltage gain.

$$v_o = i_{o(sc)} r_{out} = g_m (r_{id2} \| r_{04}) (v_{i1} - v_{i2})$$

$$A_v = \frac{v_o}{v_{id}} = g_m (r_{id2} \| r_{04})$$