Current Sources

Current mirrors are commonly used for current sources in integrated circuit design. This section covers other current sources that are often seen.

FET Current Sources

Figure 1(a) shows two FET current sources, one which uses an n-channel depletion mode MOSFET and the other which uses an n-channel JFET. The equivalent p-channel sources are shown in Fig. 1(b). Remember that the JFET is a depletion mode device. The analysis for the two sources is the same with the exception that the transconductance parameter is denoted by K for the MOSFET and by β for the JFET.

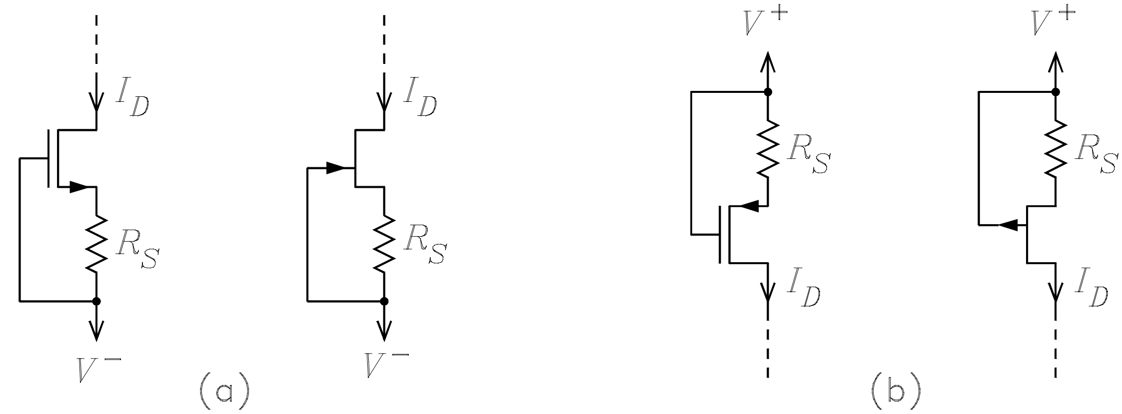

Figure 1: MOSFET (depletion mode) and JFET current sources. (a) n-channel. (b) p-channel.

For the n-channel device, the MOSFET drain current and gate-source voltage are given by

$$I_D = K\left(V_{GS} - V_{TO}\right)^2$$

$$V_{GS} = -I_S R_S = -I_D R_S$$

The object is to solve for R_S for a desired drain current. When the equation for V_{GS} is substituted into the equation for I_D, we obtain

$$I_D = K\left(-I_D R_S - V_{TO}\right)^2 = K\left(I_D R_S + V_{TO}\right)^2$$

This can be solved for R_S to obtain

$$R_S = \frac{\sqrt{I_D/K} - V_{TO}}{I_D}$$

where $V_{TO} < 0$. Note that $K = K_0\left(1 + \lambda V_{DS}\right)$. If V_{DS} is not specified, an often used approximation is $K \simeq K_0$.

For the n-channel JFET, the drain current is given by

$$I_D = \beta\left(V_{GS} - V_{TO}\right)^2$$

It follows that the MOSFET solution for R_S can be used with the substitution of β for K to obtain

$$R_S = \frac{\sqrt{I_D/\beta} - V_{TO}}{I_D}$$

The output resistance is a figure of merit for a current source. Ideally, it should be infinite. The output resistance is the resistance seen looking into the drain of each source. It is given by

$$r_{out} = r_{id} = r_0\left(1 + \frac{R_S}{r_s}\right) + R_S \qquad r_s = \frac{1}{g_m}$$

$$r_0 = \frac{\lambda^{-1} + V_{DS}}{I_D}$$

where $g_m = 2\sqrt{KI_D}$ for the MOSFET and $g_m = 2\sqrt{\beta I_D}$ for the JFET.

For the p-channel devices, the subscripts for the voltages are reversed, e.g. V_{GS} become V_{SG} and V_{DS} becomes V_{SD}.

Example 1 *A depletion mode MOSFET has the parameters $K_0 = 5 \times 10^{-4}\,\mathrm{A/V^2}$, $\lambda = 10^{-4}\,\mathrm{V^{-1}}$, and $V_{TO} = -2\,\mathrm{V}$. Calculate the value of R_S and r_{out} if the transistor is to be used as a current source with a current $I_D = 1.5\,\mathrm{mA}$. Assume $V_{DS} = 8\,\mathrm{V}$.*

Solution.

$$K = K_0\left(1 + \lambda V_{DS}\right) = 5.2 \times 10^{-4}\,\mathrm{A/V^2}$$

$$R_S = \frac{\sqrt{I_D/K} - V_{TO}}{I_D} = 2.47\,\mathrm{k\Omega}$$

$$r_0 = \frac{\lambda^{-1} + V_{DS}}{I_D} = 13.87\,\mathrm{k\Omega}$$

$$g_m = 2\sqrt{KI_D} = 1.766 \times 10^{-3}\,\mathrm{S} \qquad r_s = \frac{1}{g_m} = 566.1\,\Omega$$

$$r_{out} = r_{id} = r_0\left(1 + \frac{R_S}{r_s}\right) + R_S = 745\,\mathrm{k\Omega}$$

Resistor R_S causes r_{out} to be greater than r_0 by more than a factor of 5.

One-BJT Current Source

Figure 2 shows npn and pnp BJT current sources. The object is to select the resistors in the circuit for a desired collector current I_C.

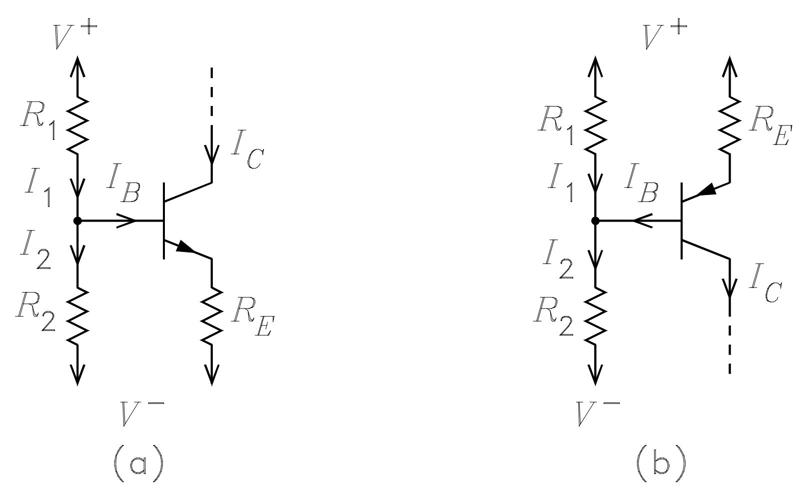

Figure 2: BJT current sources.

For the npn device, the steps can be summarized as follows:

(a) Choose a value for R_E . It should be small but large enough for good bias stability. It is common to choose R_E so that the voltage across it is some multiple n of the base-emitter junction voltage V_{BE}, where typically $1 \le n \le 4$. The larger n, the better the current stability. It follows that

$$I_E R_E = \frac{I_C}{\alpha} R_E = n V_{BE} \Longrightarrow R_E = \frac{\alpha n V_{BE}}{I_C}$$

(b) Choose a value for R_2. It is usually chosen so that the current I_2 is some multiple m of I_B, where typically $m \ge 9$. It follows that

$$I_2 R_2 = m I_B R_2 = m \frac{I_C}{\beta} R_2 = (n+1) V_{BE} \Longrightarrow R_2 = \frac{\beta (n+1) V_{BE}}{m I_C}$$

If m is too small, the uncertainty in I_B can cause errors if β is not known precisely or if β drifts with temperature.

(c) Solve for R_1.

$$\begin{aligned} I_1 R_1 &= (m+1) I_B R_1 = (m+1) \frac{I_C}{\beta} R_1 = V^+ - \left[V^- + (n+1) V_{BE}\right] \\ \Longrightarrow &\quad R_1 = \beta \frac{V^+ - V^- - (n+1) V_{BE}}{(m+1) I_C} \end{aligned}$$

(d) Solve for r_{out}.

$$r_{out} = r_{ic} = \frac{r_0 + r_e' \| R_E}{1 - \dfrac{\alpha R_E}{r_e' + R_E}}$$

$$r_0 = \frac{V_A + V_{CE}}{I_C} \qquad r_e' = \frac{R_1 \| R_2 + r_x}{1+\beta} + r_e$$

For the pnp device, the subscripts for the voltages are reversed, e.g. V_{BE} become V_{EB} and V_{CE} becomes V_{EC}.

Example 2 *A BJT has the parameters $\beta = 100$, $V_A = 75\,\text{V}$, and $r_x = 40\,\Omega$. The transistor is to be used as a current source with a current $I_C = 1.5\,\text{mA}$, $V^+ = 15\,\text{V}$, and $V^- = -15\,\text{V}$. Calculate the values of R_1, ,R_2, and r_{out} if $I_1 = 10 I_B$ $(n = 10)$ and $I_E R_E = 2 V_{BE}$ $(m = 2)$. Assume $V_{BE} = 0.65\,\text{V}$ and $V_{CE} = 8\,\text{V}$.*

Solution.

$$R_E = \frac{\alpha n V_{BE}}{I_C} = \frac{\beta n V_{BE}}{(1+\beta) I_C} = 858\,\Omega$$

$$R_1 = \beta \frac{V^+ - V^- - (n+1) V_{BE}}{(m+1) I_C} = 170\,\text{k}\Omega$$

$$R_2 = \frac{\beta (n+1) V_{BE}}{m I_C} = 13\,\text{k}\Omega$$

$$r_0 = \frac{V_A + V_{CE}}{I_C} = 55.33\,\text{k}\Omega$$

$$r_e' = \frac{R_1 \| R_2 + r_x}{1+\beta} + r_e = \frac{R_1 \| R_2 + r_x}{1+\beta} + \frac{\alpha V_T}{I_C} = 136.5\,\Omega$$

$$r_{out} = r_{ic} = \frac{r_0 + r_e' \| R_E}{1 - \dfrac{\alpha R_E}{r_e' + R_E}} = 380.4\,\text{k}\Omega$$

Resistor R_E causes rout to be greater than r_0 by almost a factor of 7.

Two-BJT Current Source

Figure 3 shows npn and pnp two-transistor BJT current sources that are simpler to design. The output current in each is the collector current I_O. For the circuit of Fig. 3(a), the following equations can be written

$$V^+ - V^- = I_1 R_1 + V_{BE2} + V_{BE1} + \frac{I_{C1}}{\alpha_1} R_{E1} \qquad I_{C1} = I_1 - \frac{I_O}{\beta_2}$$

$$\left(\frac{I_O}{\alpha_2} - \frac{I_{C1}}{\beta_1}\right) R_{E2} = V_{BE1} + \frac{I_{C1}}{\alpha_1} R_{E1}$$

For the pnp circuit, the subscripts for the voltages are reversed, e.g. V_{BE} become V_{EB}.

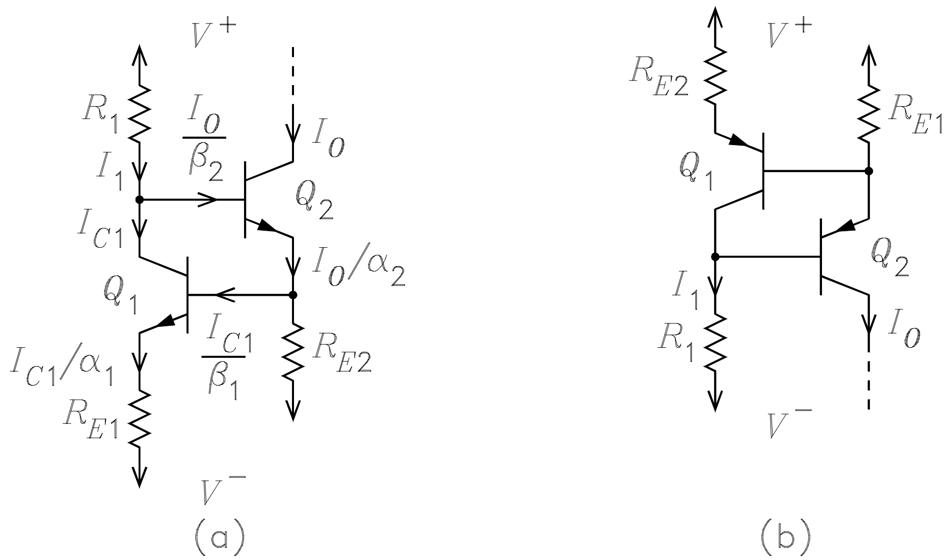

Figure 3: Two-BJT current sources.

There is a positive feedback effect in these circuits which increases the output resistance seen looking into the collector of Q_1. To see this, consider the small-signal circuit with $V^+ = V^- = 0$ and the collector of Q_1 driven by a small-signal test current source i_t. If i_t is positive, it causes a current to flow through r_{01} from its collector to its emitter. This forces the base voltage of Q_2 to increase. This is amplified by Q_2 to cause its collector voltage to decrease. This decrease is applied to the base of Q_1 to cause its collector voltage to increase. This feedback effect causes the collector voltage of Q_1 to be larger than it would be without the feedback. Because resistance is voltage divided by current, it follows that the resistance seen looking into the collector of Q_1 is increased.

The circuit can be designed by specifying the currents I_1 and I_{C1} and the resistor R_{E2}. The current I_1 must be chosen so that it is much larger than the anticipated base current in Q_1. R_{E2} can be omitted, but it aids in preventing temperature drift of the currents. If it is too large, however, it reduces the gain around the positive feedback loop, thus reducing the output resistance. Typically, R_{E2} might be chosen to have a value such that $V_{BE1} \leq I_{E1} R_{E1} \leq 4V_{BE1}$. Resistors R_1 and R_{E1} are then given by

$$R_1 = \frac{V^+ - V^- - (V_{BE1} + V_{BE2}) - \left(I_1 - \dfrac{I_O}{\beta_2}\right) \dfrac{R_{E1}}{\alpha_1}}{I_1}$$

$$R_{E2} = \frac{V_{BE1} + \dfrac{I_{C1}}{\alpha_1} R_{E1}}{\dfrac{I_O}{\alpha_2} - \dfrac{I_{C1}}{\beta_1}}$$

Example 3 *For $V^+ = 15\,\text{V}$ and $V^- = -15\,\text{V}$, design the circuit in Fig. 3(a) for an output current $I_{C1} = 1.5\,\text{mA}$.*

Solution. If we estimate $\beta = 100$, the base current in Q_1 is $0.015\,\text{mA}$. Let us choose $I_1 = 20 I_{B2} = 0.3\,\text{mA}$. We estimate $V_{BE1} = V_{BE2} = 0.65\,\text{V}$. The current I_{C1} is given by $I_{C1} = I_1 - I_O/\beta = 0.285\,\text{mA}$. The current through R_{E1} is $I_{E1} = I_{C1}/\alpha = 0.288\,\text{mA}$. If we choose $I_{E1}R_{E1} = V_{BE1}$, it follows that R_{E1}, R_1, and R_{E2} are given by

$$R_{E1} = \frac{0.65}{0.288\,\text{mA}} = 2.26\,\text{k}\Omega$$

$$R_1 = \frac{30 - 2 \times 0.65 - 0.285\,\text{mA} \times 2.26\,\text{k}\Omega}{0.3\,\text{mA}} = 91.2\,\text{k}\Omega$$

$$R_{E2} = \frac{2 \times 0.65}{1.5\,\text{mA}} = 867\,\Omega$$

Current Sources Using an Op Amp

Figure 4 shows two current sources that use an op amp as an error amplifier. The emitter current in each transistor is

$$I_E = \frac{I_O}{\alpha}$$

This current divides between R_F and R_E go cause the voltage at the negative op-amp input to be

$$V_N = \frac{I_C}{\alpha} \frac{R_1}{R_E + R_F + R_1} R_E$$

Because the op amp forces $V_N = V_I$, it follows that I_O is given by

$$I_O = \alpha \left(1 + \frac{R_E + R_F}{R_1}\right) \frac{V_I}{R_E}$$

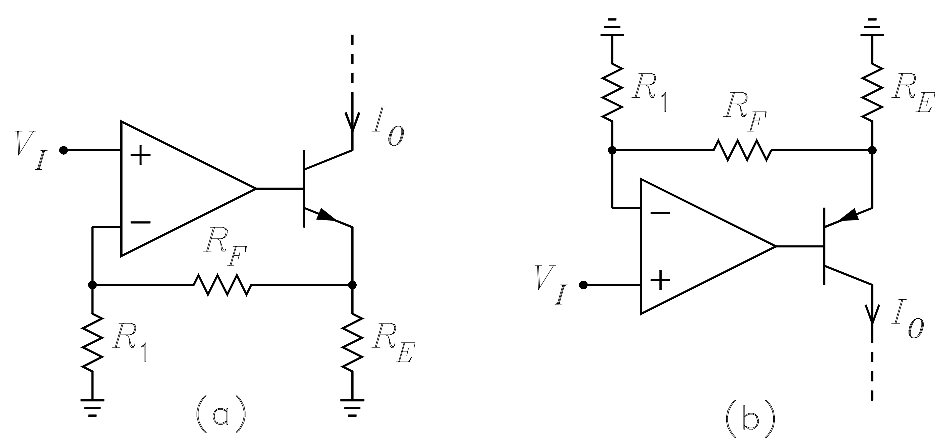

Figure 4: Current sources using an op amp.