Current Sources

The approach we have used with resistor network biasing and decoupling capacitors is not desirable when using monolithic integrated-circuit techniques. The rules of thumb in monolithic IC design are: (a) use transistors whenever possible, (b) use a minimum number of the smallest possible resistors, (c) avoid capacitors if possible, and (d) forget inductors until frequencies approach a few tens of MHz. One major drawback is the large amount of real estate consumed by the components of (b), (c), (d).

Transistors can be implemented in a very compact (efficient) way. In addition, for several transistors on the same die, close matching between transistor parameters is possible. Hence, our emphasis will be to use transistors wherever possible for IC implementations.

Let's consider components needed for such biasing schemes.
Simple Current Source

\[ V_{cc} \]

\[ I_{ref} \]

\[ I_C \]

\[ I_B \]

\[ V_{BE} \]

For this circuit, \( I_C \) is independent of \( \beta \) and almost independent of \( V_{BE} \) and \( I_{CBO} \). The device operates barely into the forward-active region.

This circuit is a special case of the bias circuit shown:

\[ V_{cc} \]

\[ R_s \]

\[ R_e \]

\[ C_e \]

\[ \text{A sensitivity analysis similar to the one performed earlier in class leads to} \]

\[ \frac{\Delta I_C}{I_C} = \Delta \beta \left( \frac{R_b}{\beta} \right) + \frac{\Delta V_{BE}}{(V_{cc} - V_{BE})} + \frac{\Delta I_{CBO}(R_bR_e)}{(V_{cc} - V_{BE})} \]
When \( R_b \to 0 \)

\[
\frac{\Delta I_c}{I_{c1}} = \frac{\Delta V_{be}}{V_{cc} - V_{be}} + \frac{\Delta I_{cbo} (R_c)}{V_{cc} - V_{be}}
\]

To make this a more versatile constant-current source, we add a second transistor in a back-to-back configuration as shown:

![Diagram with two transistors](image)

Temporarily neglecting \( r_o \),

we have \( V_{be1} = \frac{kT}{q} \ln \frac{I_{c1}}{I_s} \)

and \( V_{be2} = \frac{kT}{q} \ln \frac{I_{c2}}{I_s} \).

Since \( T_1 \) and \( T_2 \) are closely matched \( I_{c1} = I_{c2} = I_c \).

\[ I_{ref} = I_{c1} + I_{c1} / \beta_1 + I_{c2} / \beta_2 = I_c \left( 1 + \% \right) \]
If $\beta \gg 1$, then $I_{REF} \approx I_c \approx 0.7$.

But $I_{REF} = \frac{V_{CC} - (-V_{EE}) - V_{BE}}{R_1} = \frac{V_{CC} + V_{EE} - kT/2e}{R_1}$.

**Example**

Design a current source using matched 2N2222 transistors to deliver 500 mA from a $\pm$ 15 V supply. Neglect $r_o$.

$$\frac{500 \text{ mA}}{I_{REF}} = \frac{15 + 15 - 0.7}{R_1} \Rightarrow R_1 = 58.6 \text{ k}\Omega$$

![Graph](image)

$VA$ (early voltage)

$$r_o = \frac{V_{EE} - VA}{I_c}$$

If $VA = -100$ V and $V_{EE} = 1$ V, to obtain $I_c = 500 \text{ mA}$,

$$r_o = \frac{101}{500 \times 10^{-6}} \approx 2 \text{ M}\Omega$$

Then,

$$I_c = I_s e^{\frac{V_{CC}}{kT}} \left(1 + \frac{V_{EE}}{VA}\right)$$
Finally, \[ \frac{I_{C2}}{I_{C1}} = \frac{I_{S2} e^{\frac{V_{CE2}}{V_{A1}}}}{I_{S1} e^{\frac{V_{BE1}}{V_{A1}}}} \left(1 + \frac{V_{CE2}}{V_{A1}}\right) \]

or \[ I_{C2} = I_{C1} \left(1 + \frac{V_{CE2}}{V_{A}^\prime}\right) \left(1 + \frac{0.7}{V_{A}}\right) \]

for well matched devices \[ \approx I_{C1} \left(1 + \frac{V_{CE2}}{V_{A}}\right) \]

Example of the effect of \( r_o \)

Using the 2N3904 as an example with \( I_C = 1 \text{mA}, \ h_{oee} = 5 \mu \text{s (min)} \to 35 \mu \text{s (max)} \Rightarrow r_o = 200 \text{k}\Omega (\text{min}) \to 28.5 \text{k}\Omega (\text{min}) \).

This \( \Rightarrow \) \( V_{A} = I_C r_o = 200V (\text{max}) \)

\( \to \) \( V_{A} = I_C r_o = 28.5V (\text{min}) \)

Our value for \( I_C \), however, is \( I_C = 500 \mu \text{A} \). Hence, using the min. value \( r_o = \frac{200 \sqrt{5}}{500 \mu \text{A}} = 400 \text{k}\Omega \)

In this case \( I_o \) changes from 500\( \mu \text{A} \) to 525\( \mu \text{A} \) if \( V_{CE2} \) changes from 0V to 10V. This change of 5\( \% \) is generally acceptable. However, if \( r_o = \frac{28.5V}{500 \mu \text{A}} = 57 \text{k}\Omega \)
In this case a change in $V_{ee2}$ from 0 V to 10 V results in a change in $I_o$ from 500 mA to 675 mA, a 35% change. This change is generally too large.

**Approach:**

1. **Hand select transistors**
2. **Select different transistor with higher standard**
3. **Look at alternatives**

Notice that this approach can be used to establish multiple current sources.
Wilcar current source

To obtain smaller currents using reasonable resistor values and to obtain a lower power supply stability factor, feedback is incorporated into the circuit as shown below:

\[
\begin{align*}
    & \text{Vcc} \\
    & I_{\text{REF}} \downarrow R_1 \\
    & T_1 \quad \text{VBE}_1 \downarrow V_{\text{BE}_2} \downarrow R_2 \\
    & T_2 \quad I_{C_2} = I_0 \\
    & \text{Generally, } R_2 \ll R_1 \\
    & \text{Initially we assume } r_o \rightarrow \infty \text{ and } \beta_r \text{ is large:} \\
    & V_{\text{BE}_1} = V_{\text{BE}_2} + I_{C_2} R_2 \\
    & \text{or } \frac{kT}{q} \ln \frac{I_{C_1}}{I_{S_1}} = \frac{kT}{q} \ln \frac{I_{C_2}}{I_{S_2}} + I_{C_2} R_2 \\
    & \Rightarrow \frac{kT}{q} \ln \frac{I_{C_1} \cdot I_{S_2}}{I_{S_1} \cdot I_{C_2}} = I_{C_2} R_2
\end{align*}
\]
But \( I_{S1} = I_{S2} \) and so
\[
I_{c2} R_2 = \frac{kT}{q} \ln \frac{I_{c1}}{I_{c2}} = \frac{kT}{q} \ln \frac{I_{REF}}{I_{c2}}
\]

We also still have
\[
I_{REF} = \frac{V_{CC} + V_{EE} - \frac{kT}{q} \ln \frac{I_{c1}}{I_{S1}}}{R_1}
\]

Combining the above 2 expressions leads to
\[
I_o = I_{c2} = \frac{kT}{R_2 q} \ln \left[ \frac{V_{CC} + V_{EE} - 0.7}{R_1 I_{c2}} \right]
\]

**Example**

Design a Widlar current source using matched 2N2222A transistors to deliver 500μA from a ±15V power supply. Assume \( T = 25^\circ C \) and select values compatible with modern IC technology.

Select \( R_1 = 10k\Omega \) and so
\[
I_{REF} = \frac{29.3}{10k\Omega} = 2.9\, mA
\]
To obtain $I_0 = 500 \mu A$ we select

$$R_2 = \frac{26 \text{ mV}}{500 \mu A} \ln\left(\frac{2.9 \text{ mA}}{500 \mu A}\right) = 92 R$$

Assess the stability or occurring as a result of $r_0$.

Use to find impedance of current source.
\[ R_0 = \frac{V}{I} \quad , \quad R' = \left( \frac{R_m + R_0}{R_m} \right) R_1 + g_m \]

Assume \( R' \) is small compared to \( r_m \) so \( R'' = r_m // R_2 \)
and
\[ R_0 = r_{o2} \left( 1 + g_m R'' \right) + R'' = r_{o2} \left( 1 + g_m R'' \right) \approx r_{o2} \left( 1 + g_m R_2 \right) \]

Example
\[ \beta = 100 \quad r_m = \frac{\beta}{g_m} \]
\[ g_m = 19 \text{ mS} \quad R'' = r_m // R_2 \approx 5.2 \text{kΩ} // 19 \Omega = 92 \Omega \]
\[ r_{o2} = 400 \text{kΩ} \]
so \( R_0 = 400 \text{kΩ} \left[ 1 + (19 \text{ mS})(92) \right] = 1.14 \text{MΩ} \)

\[ \Delta I_C = \frac{\Delta V_{CC}}{R_0} = \frac{10 \text{ V}}{1.14 \text{MΩ}} = 9 \text{ mA} \]

or 500 mA would increase to 509 mA. Assuming \( r_{o2} = 58 \text{kΩ} \), \( R_0 = 160 \text{kΩ} \) and 500 mA increases to 562 mA. That is much better than before. Also, improved sensitivity to \( V_{CC} \).
Wilson Current Source

Although the Widlar current source offers higher output impedance than the simple current source, its output impedance may still not be sufficiently high for some applications.

Consider a Wilson current source:

\[
I_{REF} = \frac{V_{CC} + V_{EE} - 2V_{f}}{R_i} = I_0
\]

For matched transistors it is apparent that

Consider the small-signal circuit model:
Due to matched components, assuming most of the current through $r_m$ goes through the voltage-controlled current source $(g_{m1}v_{m1})$, and assuming $g_{m3}$ dominates the total impedance from node O to ground, the circuit can be simplified to

We can then write 3 equations with 3 unknowns. At node O:

$$-g_{m1}v_{m1} + \frac{v_i - v_x}{r_o} + 2g_{m1}v_i = 0$$

Eqn 2:

$$v_{m1} = -g_{m1}r_o v_i$$

Eqn 3:

$$i_x = g_{m1}v_{m1} + \frac{v_x - v_i}{r_o}$$

We can then combine these equations so as to eliminate $v_i$ and $v_{m1}$, we then obtain

$$R_o = \frac{v_x}{i_x} = r_o \left(1 + \frac{g_{m1}r_o}{2} + \frac{1}{2g_{m1}r_o}\right)$$

$$\approx r_o \left(1 + \frac{r_o}{2}\right)$$
With the same ZN2222 as used before, and the same current level it is now possible to obtain an \( R_0 \) of over 2M\( \Omega \) (worst case).

General comments on current sources:
- One reference arm can be used to obtain multiple current sources.

> This can be done by varying device area from reference arm to current source arm.

> For the Widlar current source this can be done by varying the feedback resistor in each current source arm.

- Current sources can act as true sources or sinks depending on the type of device.
- The same basic ideas hold for FET current source except the \( i-v \) characteristics are different.