ECE 327: Electronic Devices and Circuits Laboratory I

Bandgap Voltage Reference Example: LM317

Figure 1(a) is a highlighted version of the schematic in the datasheet of the LM317 from National Semiconductor. The highlighted portion, which is duplicated in Figure 1(b), provides the temperature-compensated 1.25 V voltage reference. The rest of the circuit implements the other features of the regulator.

![Schematic of LM317](Image)

Figure 1: National Semiconductor’s LM317 adjustable voltage regulator. Highlight in (a) is shown in (b).

1 National Semiconductor’s Choice: Matched Currents

Current Mirror: Q16 and Q18 are matched pnp transistors. Their bases are tied together and their emitters are tied together, and so they have the same base–emitter drop and thus identical collector currents.

Base–Emitter Difference: It is not shown in the schematic, but the base, collector, and emitter of the Q17 transistor each have ten times the area of the corresponding Q17 transistor regions. That is, Q19 can be redrawn as ten npn transistors with shared collector, base, and emitter nodes. Each of these ten transistors carries 1/10 of the current that the single Q17 transistor carries, and so the Q19 base–emitter drop will be smaller than the Q17 base–emitter drop. By the Ebers–Moll model of a bipolar transistor\(^1\), if two matched transistors have different currents, the difference in their base–emitter drops will be

\[
\Delta V_{BE} \approx v_{BE2} - v_{BE1} \approx \frac{kT}{q} \ln \left( \frac{i_{C2}}{i_{C1}} \right)
\]

where \( k \) is the Boltzmann constant \((1.38 \times 10^{-23} \text{J/K})\), \( T \) is the absolute temperature in Kelvin, \( q \) is the electric charge of an electron \((1.6 \times 10^{-19} \text{C})\), \( i_{C1} \) and \( i_{C2} \) are the collector currents for two bipolar transistors that are identified as 1 and 2, and \( v_{BE1} \) and \( v_{BE2} \) are the base–emitter drops for those two bipolar transistors. The quantity \( kT/q \) is \( \approx 25.3 \text{mV} \) at room temperature \((i.e., 21^\circ \text{C} \text{ or } 294.15 \text{ K})\). If \( i_{C2} \) is the current through Q17 and \( i_{C1} \) is the smaller current through “1/10” of Q19, then the ratio \( i_{C2}/i_{C1} = 10 \) and \( \Delta V_{BE} \approx 58.3 \text{mV} \) at room temperature. This \( \Delta V_{BE} \) is put across \( R_{15} = 2.4 \text{k}\Omega \) to set \( i_{C1} \approx 24 \mu\text{A} \) at room temperature. By the Q16-Q18 mirror, \( i_{C2} = i_{C1} \), and so \( i_{C2} \approx 24 \mu\text{A} \) at room temperature.

Temperature Compensation: The current into the top of the \( R_{14} = 12 \text{k}\Omega \) resistor is the sum \( i \approx i_{C1} + i_{C2} \). So at room temperature when \( v_{BE2} \approx 0.7 \text{V} \),

\[
V_{out} - \text{ADJ} = (i_{C2} + i_{C1})R_{14} + v_{BE2} \approx \frac{kT}{q} \ln(10)(1 + 1) \frac{R_{14}}{R_{15}} + v_{BE2} \approx 1.25 \text{V}
\]

which is suspiciously close to the silicon bandgap energy of \( \approx 1.22 \text{eV} \). In fact, by Equation (1), the current \( i \) will have a positive temperature coefficient — it will rise as temperature rises — and so the \( R_{14} \) voltage will also have a positive temperature coefficient. Additionally, the \( v_{BE2} \) diode drop will have a negative temperature coefficient proportional to \( T \). Hence, by setting \( R_{14} \) and \( R_{15} \) so that \( V_{out} - \text{ADJ} \) is equal to the silicon bandgap at one temperature, it will stay equal to the bandgap at all temperatures.

\(^1\)That is, \( i_{C1} = I_{D} \left( \exp(v_{BE1}/(kT/q)) - 1 \right) \) where \( I_{D} \) is a small proportionality constant, and so \( v_{BE1} \approx (kT/q) \ln(i_{C1}/I_{D}) \).
2 Another Choice: Current Ratio Through Matched Transistors

As discussed in section 1, National Semiconductor’s LM317 drives a matched current through two transistors with different emitter densities in order to generate the temperature-independent voltage reference. Alternatively, different currents can be pushed through matched transistors to get the same effect. Here, we examine how National Semiconductor could have used the same circuit in Figure 1 in this alternate way. In the previous circuit, we took $Q_{16}$ and $Q_{18}$ to be matched and made $Q_{17}$ and $Q_{19}$ have different emitter densities. In this circuit, we match $Q_{17}$ and $Q_{19}$ and let $Q_{16}$ and $Q_{18}$ differ.

**Ratio Mirror:** Because it is not explicitly shown in the schematic, we could make the base, collector, and emitter of the $Q_{16}$ transistor each take up three times as much area as the corresponding regions of the $Q_{18}$ transistor. That is, $Q_{16}$ can be redrawn as three $pnp$ transistors with shared collector, base, and emitter nodes. Because each base and each emitter is tied to the base and emitter of $Q_{16}$, respectively, the current through all “four” transistors is the same (i.e., they all have the same base–emitter drop, and so they must all have the same collector current). So the total current through $Q_{16}$ is always three times as much as the current through $Q_{18}$.

**Base–Emitter Difference:** By the Ebers–Moll model of a bipolar transistor, if two matched transistors have different currents, the difference in their base–emitter drops will be

$$\Delta V_{BE} \triangleq v_{BE2} - v_{BE1} \approx \frac{kT}{q} \ln \left( \frac{i_{C2}}{i_{C1}} \right)$$

(2)

where $k$ is the Boltzmann constant (1.38 $\times$ 10$^{-23}$ J/K), $T$ is the absolute temperature in Kelvin, $q$ is the electric charge of an electron (1.6 $\times$ 10$^{-19}$ C), $i_{C1}$ and $i_{C2}$ are the collector currents for two bipolar transistors that are identified as 1 and 2, and $v_{BE1}$ and $v_{BE2}$ are the base–emitter drops for those two bipolar transistors. The quantity $kT/q$ is $\sim 25.3$ mV at room temperature (i.e., 21°C or 294.15 K). If we let $i_{C2}$ be the current through $Q_{17}$ and $i_{C1}$ be the smaller current through $Q_{19}$ (i.e., a transistor matched to $Q_{17}$), then the ratio $i_{C2}/i_{C1} = 3$ and $\Delta V_{BE} \approx 27.8$ mV at room temperature. This $\Delta V_{BE}$ is put across $R_{15} = 2.4$ kΩ to set $i_{C1} \approx 12$ µA at room temperature. By the $Q_{16}$-$Q_{18}$ ratio mirror, $i_{C2} = 3i_{C1}$, and so $i_{C2} \approx 35$ µA at room temperature.

**Temperature Compensation:** The current into the top of the $R_{14} = 12$ kΩ resistor is the sum $i \triangleq i_{C1} + i_{C2}$. So at room temperature when $v_{BE2} \approx 0.7$ V,

$$V_{out} - \text{ADJ} = (i_{C2} + i_{C1})R_{14} + v_{BE2} \approx \frac{kT}{q} \ln(3)(3 + 1) \frac{R_{14}}{R_{15}} + v_{BE2} \approx 1.25 \text{ V}$$

which is suspiciously close to the silicon bandgap energy of $\sim 1.22$ eV. In fact, by Equation (2), the current $i$ will have a positive temperature coefficient — it will rise as temperature rises — and so the $R_{14}$ voltage will also have a positive temperature coefficient. Additionally, the $v_{BE2}$ diode drop will have a negative temperature coefficient proportional to $T$. Hence, by setting $R_{14}$ and $R_{15}$ so that $V_{out} - \text{ADJ}$ is equal to the silicon bandgap at one temperature, it will stay equal to the bandgap at all temperatures.

3 Comparison: Both Use Non-unity Current-Density Ratios

Because the base–emitter drop of a bipolar transistor has a negative temperature coefficient, the challenge to building a temperature-independent reference is generating a voltage with a positive temperature coefficient. In both designs, the positive temperature coefficient is built by driving two different current densities through matched transistors. In section 1, mirrored currents travel through transistors with unequal areas. In section 2, different currents travel through transistors with equal areas. In both cases, the difference in current density (i.e., current/area) sets up the voltage with the necessary positive temperature coefficient.

Links to more reading:

- [http://www.national.com/rap/Application/0,1570,24,00.html](http://www.national.com/rap/Application/0,1570,24,00.html)
- [http://anasp02.tamu.edu/~sanchez/889-bandgap-filret.pdf](http://anasp02.tamu.edu/~sanchez/889-bandgap-filret.pdf)