Application Report
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Diode-Based Temperature Measurement

Ethan Than

ABSTRACT

Diodes are frequently used as temperature sensors in a wide variety of moderate-precision temperature measurement applications. Linear temperature coefficient such as –2mV/C° across operating temperatures makes diodes a great solution for flexible and low-cost applications. The circuitry can be quite simple, but making a temperature measurement system with a diode will require excitation, offsetting, and amplification. This application report contains a collection of circuits to address a variety of applications.

Contents

List of Figures

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1 The Diode

Just about any silicon diode can be used as a temperature measurement transducer. A diode connected bipolar transistor (BJT) rather than a standard true diode is recommended. This is because BJTs have consistent temperature coefficient which results in smaller errors over temperature. Low cost and high accuracy are important in temperature-sensing applications such as automotive, consumer, and industrial products. Make sure the diode is in the correct package to the specified application and features a specified accuracy over the system operating temperature. This report will be using an NPN BJT, such as the MMBT3904 or MMBT2222.

2 Temperature Coefficient

The base-emitter voltage (V_{BE}) of a BJT is the voltage drop across the base and emitter of the transistor. Since the transistor is diode connected, the collector-emitter voltage (V_{CE}) is also the same as base-emitter voltage. This voltage is considered the forward voltage of the diode. The forward voltage is present when there is enough current source for diode excitation.

Across temperature, the forward voltage is negatively proportional to increasing temperature. This results in a negative temperature coefficient (–mV/C°). This linear relationship between forward voltage and temperature is the reason why diodes can be used as temperature measurement devices. A diode's data sheet will have a typical graph of forward voltage across forward current and temperature. A BJT's data sheet will have a graph of base-emitter saturation voltage $V_{BE(SAT)}$ across collector current (I_C) and temperature. Calculations can be made to find the temperature coefficient of the diode.

Figure 1 shows a typical graph of temperature coefficient of a BJT.

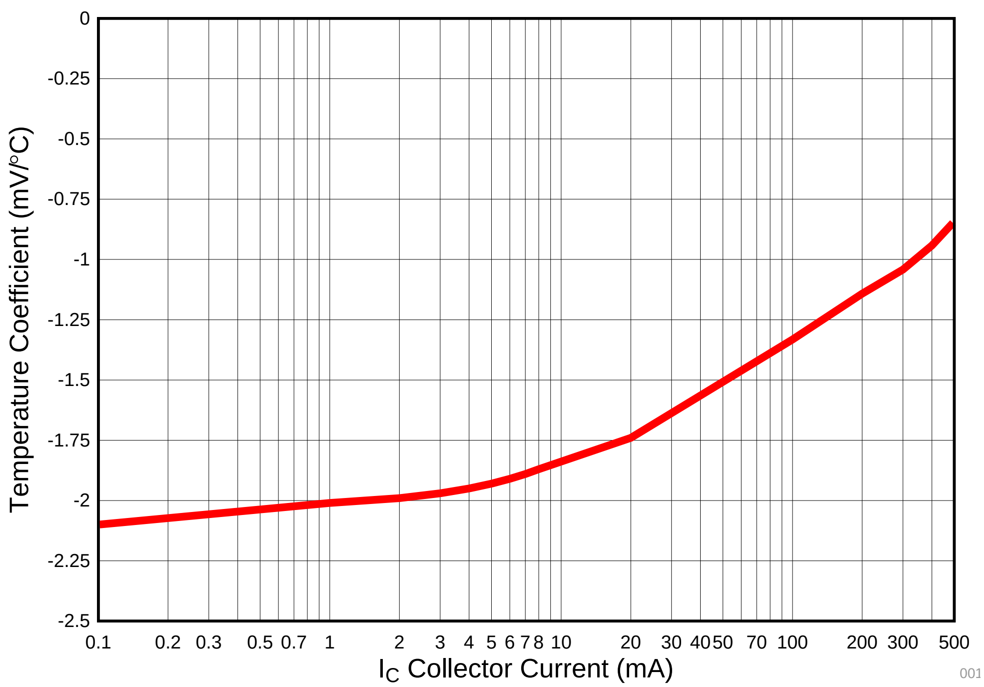


Figure 1. Temperature Coefficient of a BJT

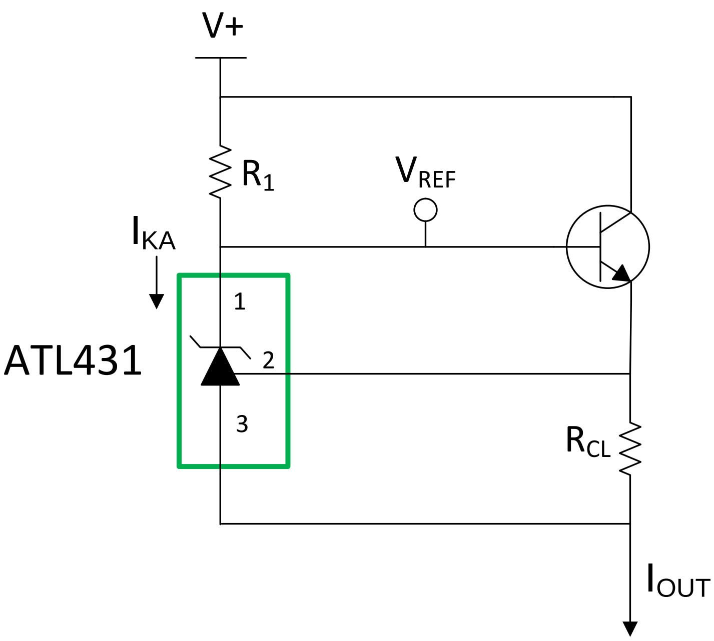
3 Excitation

A current source is the best means for diode excitation. In some instances, resistor biasing can provide an adequate approximation, but power supply variations and ripple can cause significant errors with this approach. These problems are exacerbated in applications with low power supply voltages such as 5-V, single-supply systems. Depending on the specifications of the BJT, choose a constant-current source that provides the desired temperature coefficient.

4 Constant-Current Sources

Constant-current sources can be created in many different circuits and configurations. This application requires precision low-current sources across temperature which can only be done a handful of ways. One way is to use an adjustable shunt voltage reference like the ATL431. With initial accuracy as low as 0.5%, and 20-µA minimum cathode current, the ATL431 can be configured to provide a low-cost precision constant-current source.

Figure 2 shows an example of a constant-current source circuit using the ATL431.



$$R_1 = \frac{V+}{\frac{I_{OUT}}{h_{FE}} + I_{KA}}$$

$$I_{OUT} = \frac{V_{REF}}{R_{CL}} + I_{KA}$$

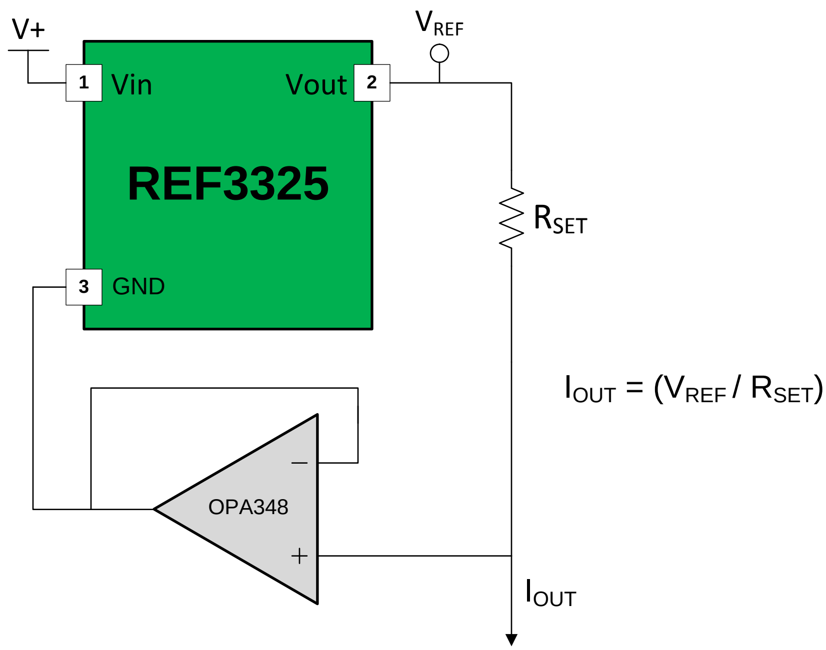
Where:

I_{KA} = Operating cathode current (A)
V_{REF} = Cathode reference voltage (V)
R_1, R_{CL} = Resistor values (Ω)
h_{FE} = Forward current gain

Figure 2. Constant-Current Source Using ATL431

For even higher precision, a series voltage reference with ultra-low drift and high initial accuracy can be used to build a current source. The REF33XX is a family of series voltage references. With an initial accuracy of 0.15% and a maximum temperature coefficient of 30 ppm/C°, the REF33XX can create an extremely high precision low constant-current source. The REF33XX has a variety of voltage options, but the source current can be programmed regardless of any voltage.

Figure 3 shows a constant-current source circuit using the REF3325. The GND pin of the REF3325 is made equal to the voltage of the load. The op-amp buffer is used stop GND leakage current, creating a more accurate current source. The output voltage across the resistor R_{SET} determines the value of the output current.



Where:

V_{REF} = Output reference voltage (V)

R_{SET} = Resistor value (Ω)

Figure 3. Constant-Current Source Using REF3325

It is good to note that the two current source circuits shown above rely on the precision of the resistors, R_{CL} or R_{SET}. Make sure to choose resistors with accuracy and temperature coefficients that fit your application.

An option to avoid these resistors errors is to use a built in current source device. The REF200 is a dual-output, 100-µA current source and sink. This matches perfectly with our temperature measurements circuits because two current sources are required. The REF200 has a fixed current source value, so it does not have the flexibility of changing the current values like the previous devices.

5 Amplification

In most instances, any precision op amp can be used for diode signal conditioning. Speed is usually not a concern. For most V_{IN} supplies, the OPA197 is recommended. The OPA2197 is the dual single-supply op-amp counterpart. These devices offer outstanding DC precision, including rail-to-rail input/output, low offset, low drift, and a 10-MHz bandwidth.

Figure 4 shows the simplest diode-based temperature measurement system. One of the current sources is used for diode excitation. The other current source is used for offsetting. One disadvantage of this circuit is that the span (GAIN) and zero (OFFSET) adjustments are interactive. You must either accept the initial errors or use an interactive adjustment technique. Another possible disadvantage is that the temperature to voltage are inversely proportional. In other words, a positive change in temperature results in a negative change in output voltage. If the output is to be processed in a digital system, neither of these limitations may be a disadvantage.

The relationships found in Equation 2 and Equation 3 can be used to calculate nominal resistor values for the circuit.

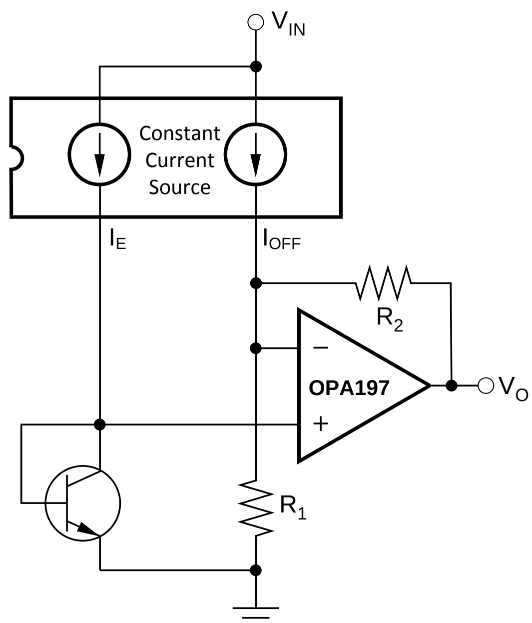


Figure 4. Simple Diode-Based Temperature Measurement Circuit

BASIC TRANSFER FUNCTION:

$$V_O = V_{BE}(1 + R_2 / R_1) - I_{OFF} \times R_2$$

where

- R_1, R_2 = Resistor values (Ω)
- V_{BE} = Voltage across diode (V)
- I_{OFF} = Resistor offset current (A) (1)

CALCULATING RESISTOR VALUES:

$$R_1 = \frac{(\delta V_O / \delta T) \times (V_{BE25} + T_C \times (T_{MIN} - 25°C) - (T_C \times V_1))}{I_{OFF} \times ((\delta V_O / \delta T) - T_C)}$$

where

- V_{BE25} = Diode voltage at 25°C (V)
- V_1 = Output voltage of circuit at T_{MIN} (V),
- V_O = Output voltage of circuit (V),
- T_C = Diode temperature coefficient (V/°C).
- T_{MIN} = Minimum operating temperature (°C)
- $\delta V_O/\delta T$ = Desired output voltage change for given temperature change (V/°C) (Note: Must be negative for the Figure 4 circuit.) (2)

$$R_2 = R_1 \times \left(\frac{\delta V_O / \delta T}{T_C} - 1 \right)$$

where

- V_O = Output voltage of circuit (V),
- T_C = Diode temperature coefficient (V/°C).
- $\delta V_O/\delta T$ = Desired output voltage change for given temperature change (V/°C) (Note: Must be negative for the Figure 4 circuit.) (3)

5.1 Example 1

Design a temperature measurement system with a 0-V to –1-V output for a 0 to 100°C temperature.

Assume:

- V_{BE25} = 0.6 V
- T_C = –0.0021 V/°C

T_{MIN} = 0°C

$\delta V_O/\delta T$ = (–1V – 0V)/(100°C – 0°C) = –0.01V/°C

R_1 = 8.259 kΩ

R_2 = 31.071 kΩ

For a 0-V to –10-V output with a 0 to 100°C temperature:

R_1 = 6.665 kΩ

R_2 = 310.71 kΩ

6 Independent Offset and Span

If independent adjustment of offset and span is required consider the circuit shown in Figure 5. In this circuit, a third resistor, R_{ZERO} is added in series with the temperature-sensing diode. System zero (offset) can be adjusted with R_{ZERO} without affecting span (gain). To trim the circuit adjust span first. Either R_1 or R_2 (or both) can be used to adjust span. Similar to the circuit in Figure 4, this circuit has the disadvantage that the temperature to voltage conversion is also inverting.

The following relationships can be used to calculate nominal resistor values for the Figure 5 circuit.

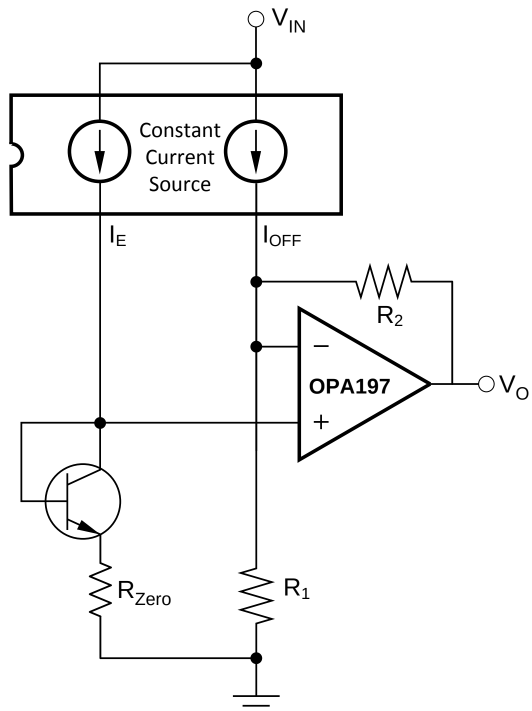


Figure 5. Temperature Measurement Circuit With Independent Gain and Offset Adjustment

BASIC TRANSFER FUNCTION:

$$V_O = (V_{BE} + I_E \times R_{ZERO}) \times (1 + R_2 / R_1) - I_{OFF} \times R_2$$

where

- R_{ZERO} = Zero (offset) adjust resistor (Ω)
- Others = as before (4)

CALCULATING RESISTOR VALUES:

$$R_1 = \frac{(\delta V_O / \delta T) \times (V_{BE\,25} + (R_{ZERO} \times I_E) + T_C \times (T_{MIN} - 25°C) - (T_C \times V_1))}{I_{OFF} \times ((\delta V_O / \delta T) - T_C)} \quad (5)$$

$$R_2 = R_1 \times \left(\frac{\delta V_O / \delta T}{T_C} - 1 \right) \quad (6)$$

6.1 Example 2

Design a temperature measurement system with a 0-V to –1-V output for a 0 to 100°C temperature.

Assume:

- V_{BE25} = 0.6 V
- T_C = –0.0021 V/°C
- R_{ZERO} = 1 kΩ

T_{MIN} = 0°C

$\delta V_O/\delta T$ = (–1V – 0V)/(100°C – 0°C) = –0.01V/°C

R_1 = 9.525 kΩ

R_2 = 35.833 kΩ

For a 0-V to –10-V output with a 0 to 100°C temperature:

R_1 = 7.686 kΩ

R_2 = 358.33 kΩ

7 Noninverting Temperature Measurements

For a noninverting temperature to voltage conversion, consider the circuit shown in Figure 6. This circuit is similar to the circuit in Figure 5, except that the amplifier is connected to the low side of the diode. With this connection, the temperature to voltage conversion is noninverting. As before, if adjustment is required, adjust span with R_1 or R_2 first, then adjust zero with R_{ZERO}. A disadvantage of this circuit is that it requires a negative power supply.

The following relationships can be used to calculate nominal resistor values for the Figure 6 circuit.

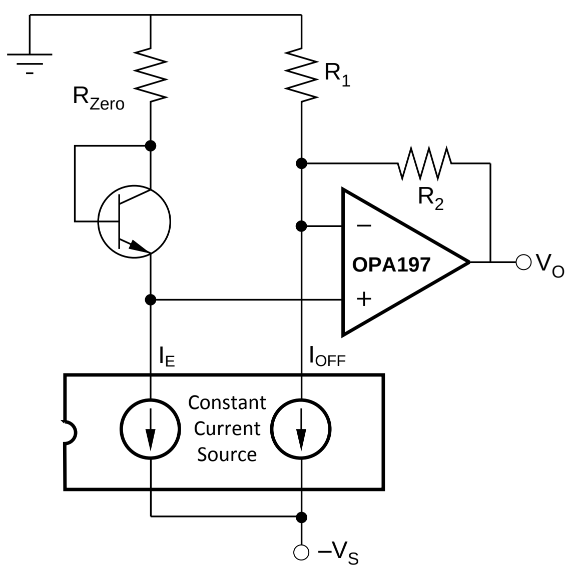


Figure 6. Positive Temperature Measurement Circuit with Negative Supply

BASIC TRANSFER FUNCTION:

$$V_O = (-V_{BE} - I_E \times R_{ZERO}) \times (1 + R_2 / R_1) + I_{OFF} \times R_2 \quad (7)$$

CALCULATING RESISTOR VALUES:

R_1= the same as Equation 5

R_2 = the same as Equation 6

7.1 Example 3

Design a temperature measurement system with a 0-V to 1-V output for a 0°C to 100°C temperature.

Assume:

- V_{BE25} = 0.6 V
- T_C = –0.0021 V/°C
- R_{ZERO} = 1 kΩ

T_{MIN} = 0°C

$\delta V_O/\delta T$ = (1V – 0V)/(100°C – 0°C) = 0.01V/°C

R_1 = 9.525 kΩ

R_2 = 35.833 kΩ

For a 0-V to –10-V output with a 0 to 100°C temperature:

R_1 = 7.686 kΩ

R_2 = 358.33 kΩ

8 Positive Supply Noninverting Temperature Measurements

For a single-supply noninverting temperature to voltage conversion, consider the Figure 7 circuit. This circuit is similar to the circuit in Figure 5, except that the temperature-sensing diode is connected to the inverting input of the amplifier and the offsetting network is connected to the noninverting input. To prevent sensor loading, a second amplifier is connected as a buffer between the temp sensor and the amplifier. If adjustment is required, adjust span with R_1 or R_2 first, then adjust zero with R_{ZERO}.

The following relationships can be used to calculate nominal resistor values for the Figure 7 circuit.

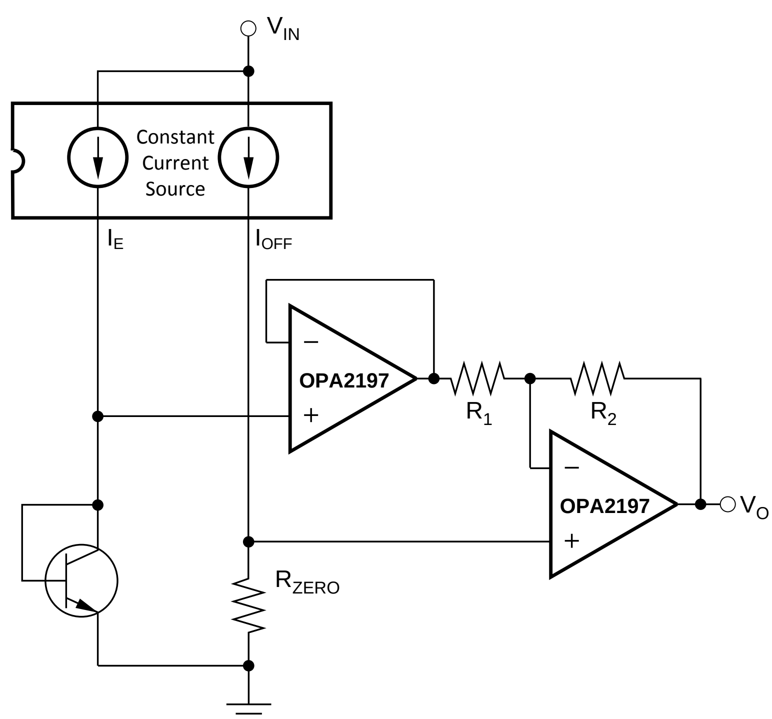


Figure 7. Positive Transfer Function Temperature Measurement Circuit With Positive Supply

BASIC TRANSFER FUNCTION:

$$V_O = I_{OFF} \times R_{ZERO} \times (1 + R_2 / R_1) - V_{BE} \times R_2 / R_1 \tag{8}$$

CALCULATING RESISTOR VALUES:

$$R_{ZERO} = \frac{(T_C \times V_1) - (\delta V_O / \delta T) \times (V_{BE25} + T_C \times (T_{MIN} - 25°C))}{I_{OFF} \times (T_C - (\delta V_O / \delta T))} \tag{9}$$

$$R_2 = -R_1 \times \left(\frac{\sigma V_O / \sigma T}{T_C} \right) \tag{10}$$

R_1 = 10 kΩ (arbitrary)

8.1 *Example 4*

Design a temperature measurement system with a 0-V to 1-V output for a 0°C to 100°C temperature

Assume:

- V_{BE25} = 0.6 V
- T_C = –0.0021 V/°C
- R_1 = 10.0 kΩ

T_{MIN} = 0°C

$\delta V_O / \delta T$ = (1 V – 0 V)/(100°C – 0°C) = 0.01V/°C

R_{ZERO} = 5.393 kΩ

R_2 = 47.619 kΩ

For a 0-V to 10-V output with a 0°C to 100°C temperature:

R_{ZERO} = 6.391 kΩ

R_2 = 476.2 kΩ

9 Differential Temperature Measurements

For differential temperature measurement, use the circuit shown in Figure 5. In this circuit, the differential output between two temperature-sensing diodes is amplified by a two-op-amp instrumentation amplifier (IA). The IA is formed from the two op amps in a dual OPA1013 and resistors R_1, R_2, R_3, R_4, and R_{SPAN}. R_{SPAN} sets the gain of the IA. For good common-mode rejection, R_1, R_2, R_3, and R_4 must be matched. If 1% of resistors are used, CMR will be greater than 70 dB for gains over 50 V/V. Span and zero can be adjusted in any order in this circuit.

The following relationships can be used to calculate nominal resistor values for the Figure 8 circuit.

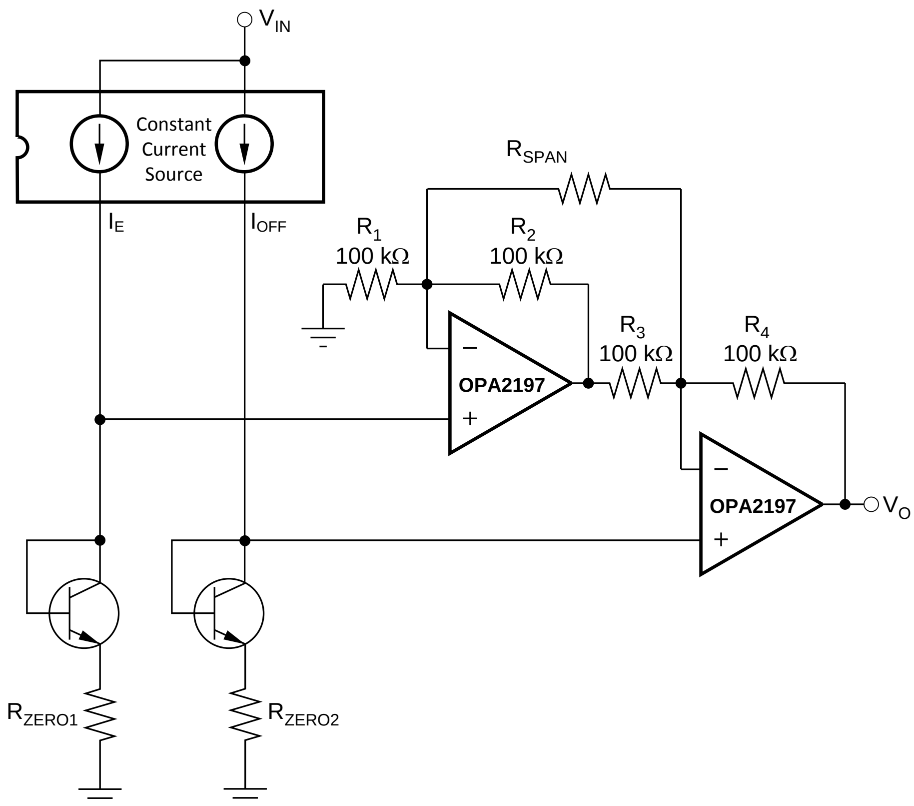


Figure 8. Differential Temperature Measurement Circuit

BASIC TRANSFER FUNCTION:

$$V_O = ((V_{BE2} + I_{OFF} \times R_{ZERO2}) - (V_{BE1} + I_E \times R_{ZERO1})) \times GAIN$$

where

- GAIN = 2 + 2 × R_1 /R_{SPAN} (11)

CALCULATING RESISTOR VALUES:

$$R_{SPAN} = \frac{-2 \times R_1 \times T_C}{(\delta V_O / \delta T) + 2 \times T_C}$$

where

- R_{SPAN} = Span (gain) adjust resistor (Ω)
- Others = as before (12)

R_{ZERO1} = R_{ZERO2} = 500 Ω (arbitrary)

9.1 Example 5

Design a temperature measurement system with a 0-V to 1-V output for a 0°C to 1°C temperature differential.

Assume:

- V_{BE25} = 0.6 V
- T_C = –0.0021 V/°C
- $R_{ZERO1,}$ R_{ZERO2} = 500 Ω
- R_1, R_2, R_3, R_4 = 100 kΩ

T_{MIN} = 0°C

$\delta V_O/\delta T$ = (1 V – 0 V)/(1°C – 0°C) = 1.0V/°C

R_{SPAN} = 422 Ω

For a 0-V to 10-V output with a 0°C to 1°C temperature differential:

R_{SPAN} = 42.0 Ω

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