

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 $-2\text{mV}/^\circ\text{C}$ 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

1	The Diode	2
2	Temperature Coefficient	2
3	Excitation.....	2
4	Constant-Current Sources	3
5	Amplification	5
6	Independent Offset and Span	7
7	Noninverting Temperature Measurements	8
8	Positive Supply Noninverting Temperature Measurements	9
9	Differential Temperature Measurements	11

List of Figures

1	Temperature Coefficient of a BJT	2
2	Constant-Current Source Using ATL431	3
3	Constant-Current Source Using REF3325	4
4	Simple Diode-Based Temperature Measurement Circuit.....	5
5	Temperature Measurement Circuit With Independent Gain and Offset Adjustment.....	7
6	Positive Temperature Measurement Circuit with Negative Supply.....	8
7	Positive Transfer Function Temperature Measurement Circuit With Positive Supply	9
8	Differential Temperature Measurement Circuit	11

Trademarks

All trademarks are the property of their respective owners.

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 ($-mV/^\circ C$). 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.

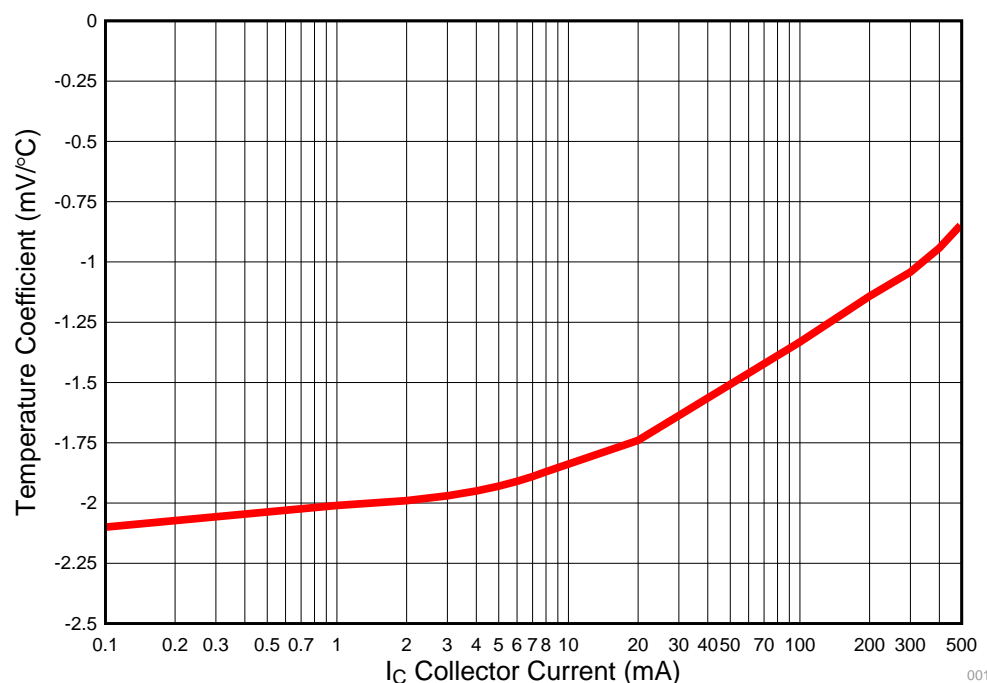


Figure 1. Temperature Coefficient of a BJT

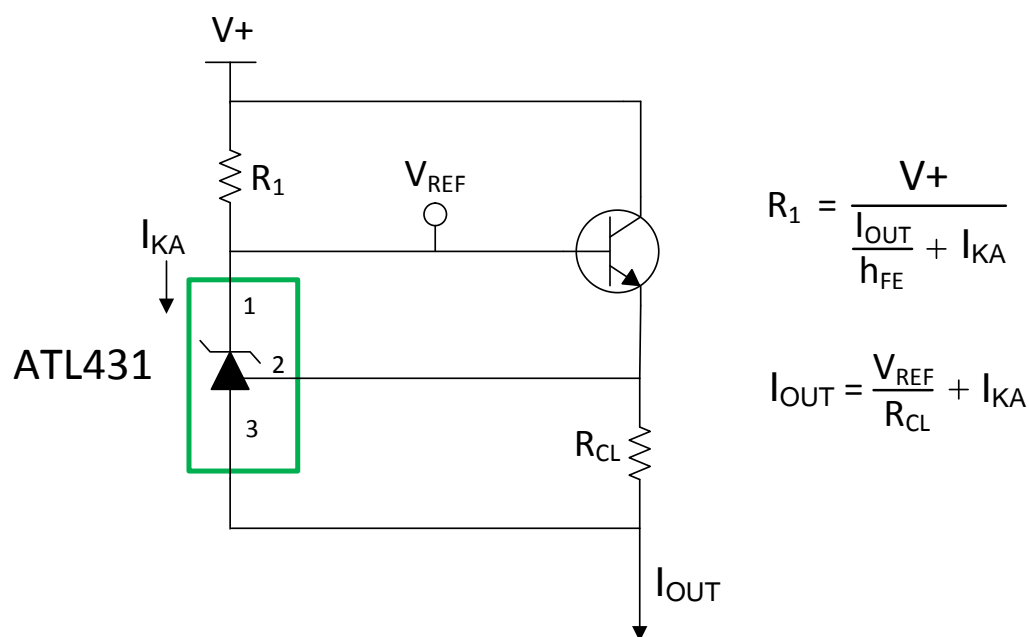
3 Excitation

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- μ A 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.



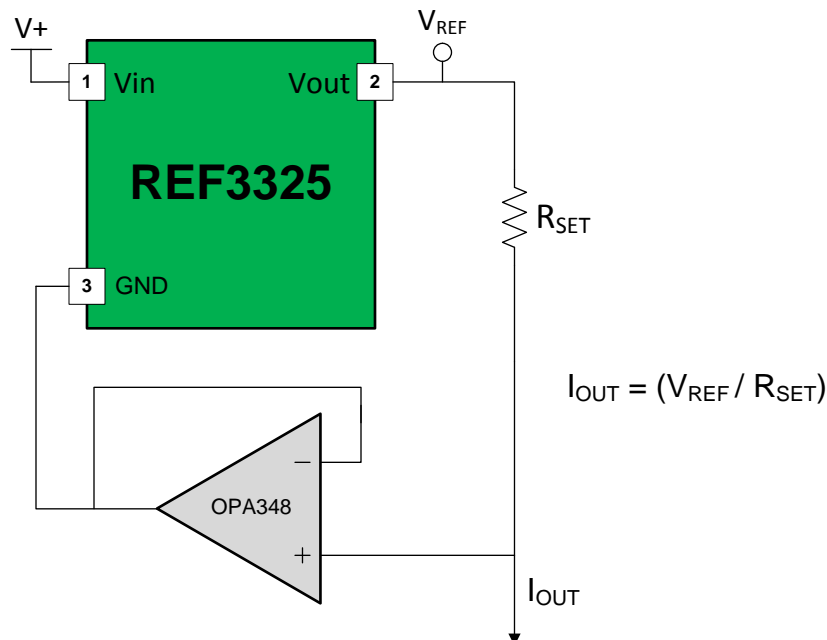
Where:

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 to 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- μ A 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.

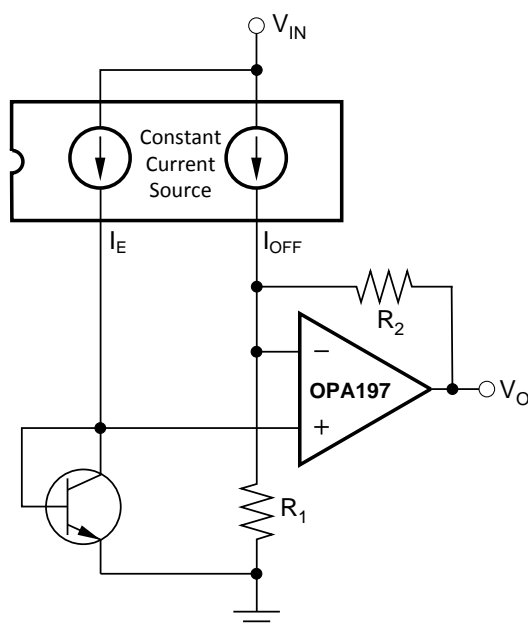


Figure 4. Simple Diode-Based Temperature Measurement Circuit

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:

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

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:

- $V_{BE25} = 0.6 \text{ V}$
- $T_C = -0.0021 \text{ V/°C}$

$$T_{MIN} = 0^\circ C$$

$$\delta V_O / \delta T = (-1V - 0V) / (100^\circ C - 0^\circ C) = -0.01V/^\circ C$$

$$R_1 = 8.259 \text{ k}\Omega$$

$$R_2 = 31.071 \text{ k}\Omega$$

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

$$R_1 = 6.665 \text{ k}\Omega$$

$$R_2 = 310.71 \text{ k}\Omega$$

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.

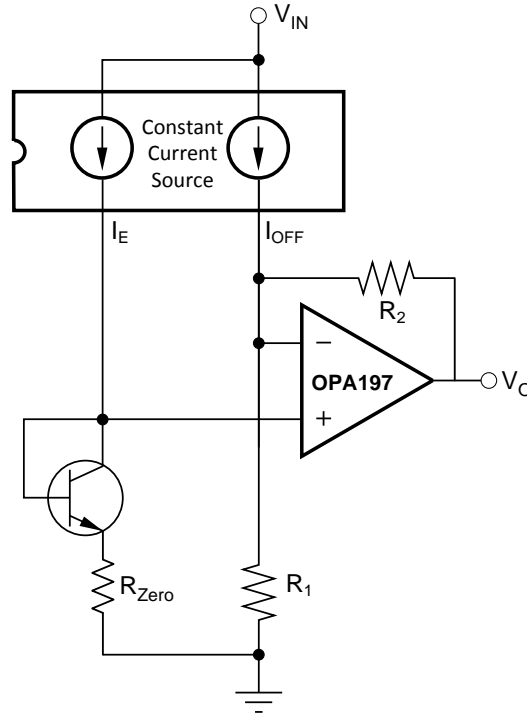


Figure 5. Temperature Measurement Circuit With Independent Gain and Offset Adjustment

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:

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

(5)

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

(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:

- $V_{BE25} = 0.6 \text{ V}$
- $T_C = -0.0021 \text{ V/}^\circ\text{C}$
- $R_{ZERO} = 1 \text{ k}\Omega$

$$T_{MIN} = 0^\circ\text{C}$$

$$\delta V_O / \delta T = (-1\text{V} - 0\text{V}) / (100^\circ\text{C} - 0^\circ\text{C}) = -0.01\text{V/}^\circ\text{C}$$

$$R_1 = 9.525 \text{ k}\Omega$$

$$R_2 = 35.833 \text{ k}\Omega$$

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

$$R_1 = 7.686 \text{ k}\Omega$$

$$R_2 = 358.33 \text{ k}\Omega$$

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.

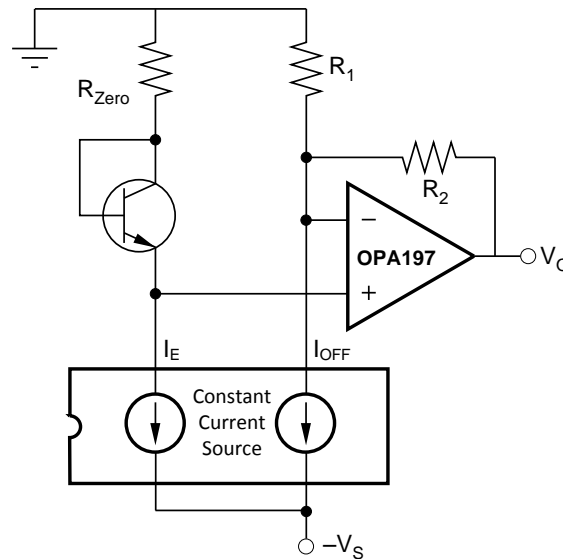


Figure 6. Positive Temperature Measurement Circuit with Negative Supply

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:

- $V_{BE25} = 0.6 \text{ V}$
- $T_C = -0.0021 \text{ V/}^\circ\text{C}$
- $R_{ZERO} = 1 \text{ k}\Omega$

$$T_{MIN} = 0^\circ\text{C}$$

$$\delta V_O / \delta T = (1\text{V} - 0\text{V}) / (100^\circ\text{C} - 0^\circ\text{C}) = 0.01\text{V/}^\circ\text{C}$$

$$R_1 = 9.525 \text{ k}\Omega$$

$$R_2 = 35.833 \text{ k}\Omega$$

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

$$R_1 = 7.686 \text{ k}\Omega$$

$$R_2 = 358.33 \text{ k}\Omega$$

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.

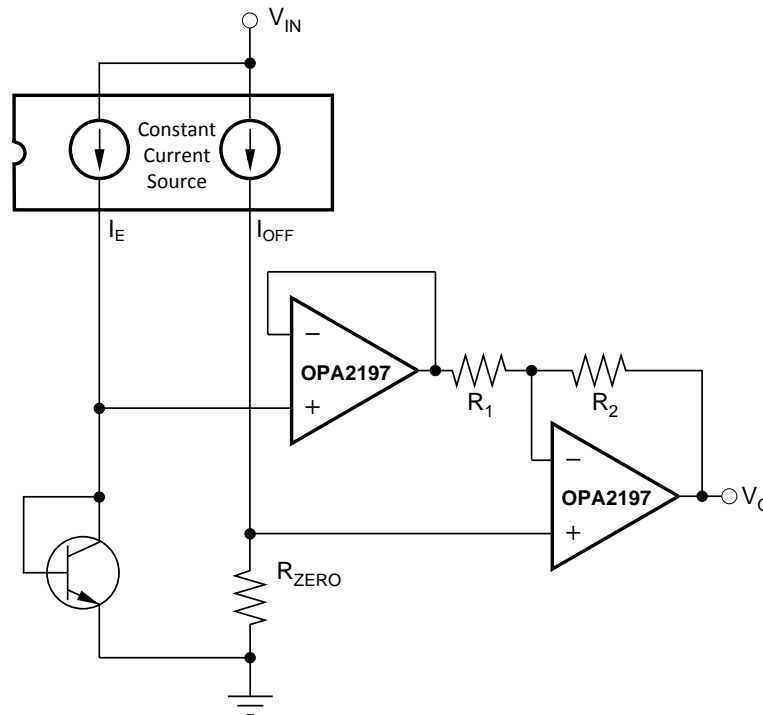


Figure 7. Positive Transfer Function Temperature Measurement Circuit With Positive Supply

BASIC TRANSFER FUNCTION:

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

CALCULATING RESISTOR VALUES:

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

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

$$R_1 = 10 \text{ k}\Omega \text{ (arbitrary)}$$

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:

- $V_{BE25} = 0.6 \text{ V}$
- $T_C = -0.0021 \text{ V}/^\circ\text{C}$
- $R_1 = 10.0 \text{ k}\Omega$

$$T_{MIN} = 0^\circ\text{C}$$

$$\delta V_O / \delta T = (1 \text{ V} - 0 \text{ V}) / (100^\circ\text{C} - 0^\circ\text{C}) = 0.01 \text{ V}/^\circ\text{C}$$

$$R_{ZERO} = 5.393 \text{ k}\Omega$$

$$R_2 = 47.619 \text{ k}\Omega$$

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

$$R_{ZERO} = 6.391 \text{ k}\Omega$$

$$R_2 = 476.2 \text{ k}\Omega$$

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.

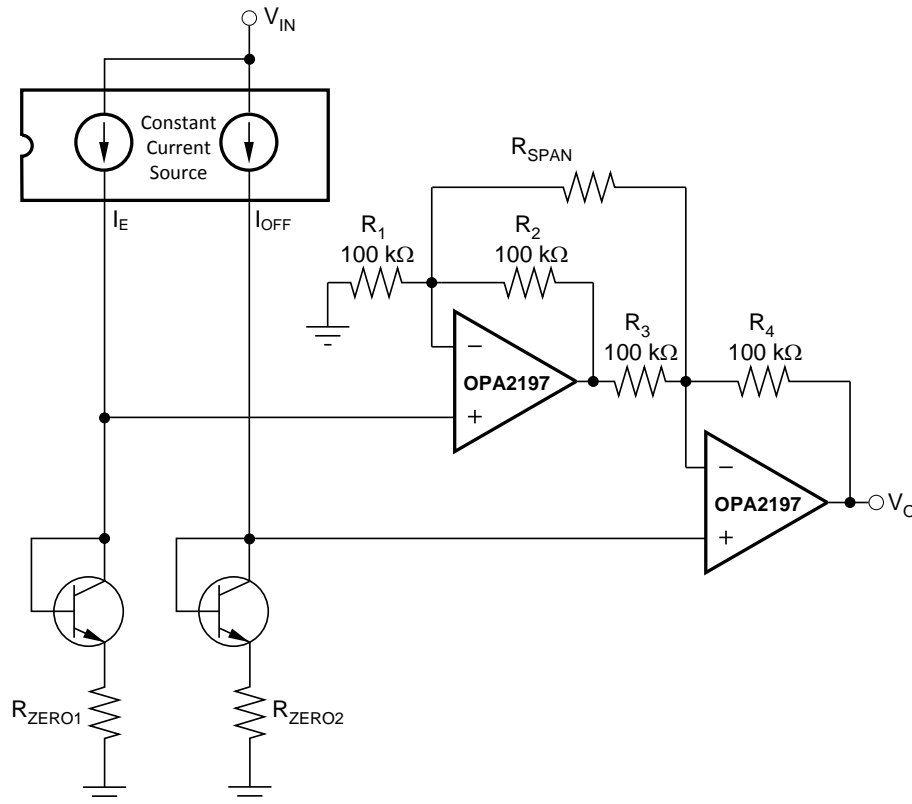


Figure 8. Differential Temperature Measurement Circuit

BASIC TRANSFER FUNCTION:

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

where

- $\text{GAIN} = 2 + 2 \times R_1 / R_{SPAN}$ (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)

$$R_{ZERO1} = R_{ZERO2} = 500 \, \Omega \text{ (arbitrary)}$$

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:

- $V_{BE25} = 0.6 \text{ V}$
- $T_C = -0.0021 \text{ V/}^\circ\text{C}$
- $R_{ZERO1}, R_{ZERO2} = 500 \text{ } \Omega$
- $R_1, R_2, R_3, R_4 = 100 \text{ k}\Omega$

$$T_{MIN} = 0^\circ\text{C}$$

$$\delta V_O / \delta T = (1 \text{ V} - 0 \text{ V}) / (1^\circ\text{C} - 0^\circ\text{C}) = 1.0 \text{ V/}^\circ\text{C}$$

$$R_{SPAN} = 422 \text{ } \Omega$$

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

$$R_{SPAN} = 42.0 \text{ } \Omega$$

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Texas Instruments Incorporated ("TI") technical, application or other design advice, services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, "TI Resources") are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using any particular TI Resource in any way, you (individually or, if you are acting on behalf of a company, your company) agree to use it solely for this purpose and subject to the terms of this Notice.

TI's provision of TI Resources does not expand or otherwise alter TI's applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources.

You understand and agree that you remain responsible for using your independent analysis, evaluation and judgment in designing your applications and that you have full and exclusive responsibility to assure the safety of your applications and compliance of your applications (and of all TI products used in or for your applications) with all applicable regulations, laws and other applicable requirements. You represent that, with respect to your applications, you have all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. You agree that prior to using or distributing any applications that include TI products, you will thoroughly test such applications and the functionality of such TI products as used in such applications. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

You are authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED "AS IS" AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING TI RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY YOU AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

You agree to fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of your non-compliance with the terms and provisions of this Notice.

This Notice applies to TI Resources. Additional terms apply to the use and purchase of certain types of materials, TI products and services. These include; without limitation, TI's standard terms for semiconductor products (<http://www.ti.com/sc/docs/stdterms.htm>), [evaluation modules](#), and [samples](http://www.ti.com/sc/docs/sampterm.htm) (<http://www.ti.com/sc/docs/sampterm.htm>).

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2018, Texas Instruments Incorporated