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DIODE-BASED TEMPERATURE MEASUREMENT

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Diodes are frequently used as temperature sensors in a wide variety of moderate-precision temperature measurement applications. The relatively high temperature coefficient of about –2mV/°C is fairly linear. To make a temperature measurement system with a diode requires excitation, offsetting, and amplification. The circuitry can be quite simple. This Bulletin contains a collection of circuits to address a variety of applications.

THE DIODE

Just about any silicon diode can be used as a temperature measurement transducer. But the Motorola MTS102 Silicon Temperature Sensor is a diode specifically designed and optimized for this function. It is intended for temperature sensing applications in automotive, consumer and industrial products where low cost and high accuracy are important. Packaged in a TO-92 package it features precise temperature accuracy of ±2°C from –40°C to +150°C.

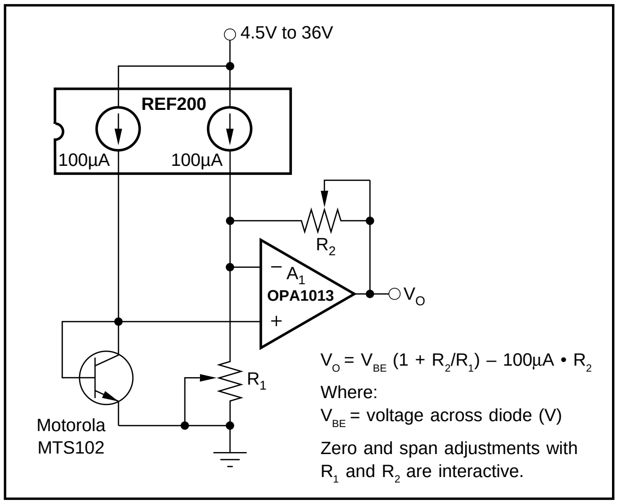
EXCITATION

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 5V single supply systems. Since the MTS102 is specified for 100µA operation, the Burr-Brown REF200 Dual 100µA Current Source/Sink makes the perfect match. One current source can be used for excitation and the other current source can be used for offsetting.

AMPLIFICATION

In most instances, any precision op amp can be used for diode signal conditioning. Speed is usually not a concern. When ±15V supplies are available, the low cost precision OPA177 is recommended. For 5V single-supply applications, the OPA1013 Dual Single-Supply op amp is recommended. Its inputs can common-mode to its negative power supply rail (ground in single-supply applications), and its output can swing to within about 15mV of the negative rail.

Figure 1 shows the simplest diode-based temperature measurement system. One of the 100µA current sources in the REF200 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 conversion is inverting. 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.



$V_O = V_{BE}\ (1 + R_2/R_1) - 100\mu A \cdot R_2$

Where:

V_{BE} = voltage across diode (V)

Zero and span adjustments with R_1 and R_2 are interactive.

Figure 1. Simple Diode-based Temperature Measurement Circuit.

The following relationships can be used to calculate nominal resistor values for the Figure 1 circuit.

BASIC TRANSFER FUNCTION

$$V_O = V_{BE}\ (1 + R_2/R_1) - 100\mu A \cdot R_2$$

CALCULATING RESISTOR VALUES

$$R_1 = \frac{(\delta V_O/\delta T) \cdot (V_{BE25} + T_C \cdot (T_{MIN} - 25°C)) - (T_C \cdot V1)}{100\mu A \cdot ((\delta V_O/\delta T) - T_C)}$$

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

Where:

R_1, R_2 = Resistor values (Ω)

V_{BE} = Voltage across diode (V)

V_{BE25} = Diode voltage at 25°C (V)

Three choices are available for the MTS102—See table on page 2.

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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_C value depends on V_{BE25}—See table below.

T_{MIN} = Minimum process temperature (°C)

$\delta V_O/\delta T$ = Desired output voltage change for given temperature change (V/°C)
(Note: Must be negative for Figure 1 circuit.)

AVAILABLE VBE_{25} AND T_C VALUES FOR MOTOROLA MTS102 TEMPERATURE SENSOR

V_{BE25} (V)	T_C (V/°C)
0.580	–0.002315
0.595	–0.002265
0.620	–0.002183

EXAMPLE

Design a temperature measurement system with a 0 to –1.0V output for a 0 to 100°C temperature.

T_{MIN} = 0°C

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

If V_{BE25} = 0.595V, T_C = –0.002265V/°C, and
R_1= 8.424kΩ
R_2= 28.77kΩ

For a 0 to –10V output with a 0 to 100°C temperature:
R_1= 6.667kΩ
R_2= 287.7kΩ

If independent adjustment of offset and span is required consider the circuit shown in Figure 2. 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. As with the Figure 1 circuit this circuit has the possible disadvantage that the temperature to voltage conversion is inverting.

The following relationships can be used to calculate nominal resistor values for the Figure 2 circuit.

BASIC TRANSFER FUNCTION

$$V_O = (V_{BE} + 100\mu A \cdot R_{ZERO}) \cdot (1 + R_2/R_1) - 100\mu A \cdot R_2$$

CALCULATING RESISTOR VALUES

Set R_{ZERO} = 1kΩ (or use a 2kΩ pot)

$$R_1 = \frac{(\delta V_O/\delta T)\cdot(V_{BE25} + (R_{ZERO}\cdot 100\mu A) + T_C\cdot(T_{MIN} - 25°C)) - (T_C \cdot V_1)}{100\mu A\cdot((\delta V_O/\delta T) - T_C)}$$

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

Where:

R_{ZERO} = Zero (offset) adjust resistor (Ω)

Others = as before

EXAMPLE

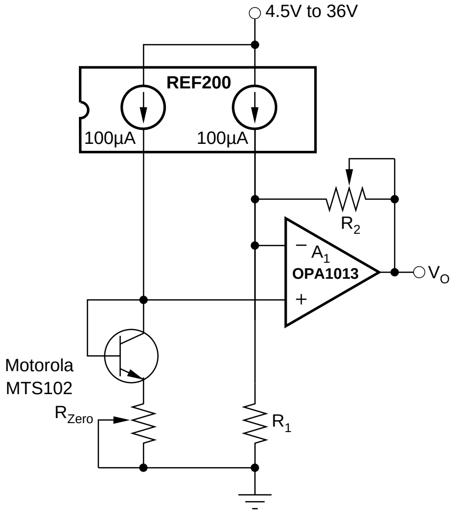
Design a temperature measurement system with a 0 to –1.0V output for a 0 to 100°C temperature.

T_{MIN} = 0°C

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

If V_{BE25} = 0.595V, T_C = –0.002265V/°C, and
R_{ZERO} = 1kΩ (use 2kΩ pot)
R_1 = 9.717kΩ
R_2 = 33.18kΩ

For a 0 to –10V output with a 0 to 100°C temperature:
R_{ZERO} = 1kΩ (use 2kΩ pot)
R_1 = 7.69kΩ
R_2 = 331.8kΩ



$V_O = (V_{BE} + 100\mu A \cdot R_{ZERO}) \cdot (1 + R_2/R_1) - 100\mu A \cdot R_2$

Where:

V_{BE} = voltage across diode (V)

Adjust span first with R_1 or R_2 then adjust zero with R_{ZERO} for noninteractive trim.

Figure 2. Diode-based Temperature Measurement Circuit with Independent Span (gain) and Zero (offset) Adjustment.

For a noninverting temperature to voltage conversion, consider the circuit shown in Figure 3. This circuit is basically the same as the Figure 2 circuit 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 the Figure 3 circuit is that it requires a negative power supply.

The following relationships can be used to calculate nominal resistor values for the Figure 3 circuit.

BASIC TRANSFER FUNCTION

$$V_O = (-V_{BE} - 100\mu A \bullet R_{ZERO}) \bullet (1 + R_2/R_1) + 100\mu A \bullet R_2$$

CALCULATING RESISTOR VALUES

R_1 = same as Figure 2
R_2 = same as Figure 2

Where:
Components = as before

EXAMPLE

Design a temperature measurement system with a 0 to 1.0V output for a 0 to 100°C temperature.

$T_{MIN} = 0°C$

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

If $V_{BE25} = 0.595V$, $T_C = -0.002265V/°C$, and

$R_{ZERO} = 1k\Omega$
$R_1 = 9.717k\Omega$

$R_2 = 33.18k\Omega$

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

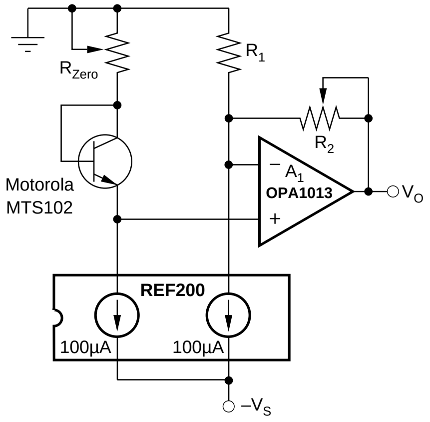
$R_{ZERO} = 1k\Omega$

$R_1 = 7.69k\Omega$

$R_2 = 331.8k\Omega$

For a single-supply noninverting temperature to voltage conversion, consider the Figure 4 circuit. This circuit is similar to the Figure 2 circuit, 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 4 circuit.



$V_O = (-V_{BE} - 100\mu A \bullet R_{ZERO}) \bullet (1 + R_2/R_1) + 100\mu A \bullet R_2$

Where:
V_{BE} = voltage across diode (V)

Adjust span first with R_1 or R_2 then adjust zero with R_{ZERO} for noninteractive trim.

Figure 3. Positive Transfer Function Temperature Measurement Circuit with Independent Span (gain) and Zero (offset) Adjustment.

BASIC TRANSFER FUNCTION

$$V_O = 100\mu A \bullet R_{ZERO} \bullet (1 + R_2/R_1) - V_{BE} \bullet R_2/R_1$$

CALCULATING RESISTOR VALUES

$$R_{ZERO} = \frac{(T_C \bullet V_1) - (\delta V_O/\delta T) \bullet (V_{BE25} + T_C \bullet (T_{MIN} - 25°C))}{100\mu A \bullet (T_C - (\delta V_O/\delta T))}$$

$R_1 = 10k\Omega$ (arbitrary)

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

Where:
Components = as before

EXAMPLE

Design a temperature measurement system with a 0 to 1.0V output for a 0 to 100°C temperature.

$T_{MIN} = 0°C$

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

If $V_{BE25} = 0.595V$, $T_C = -0.002265V/°C$, and

$R_{ZERO} = 5.313k\Omega$

$R_1 = 10.0k\Omega$

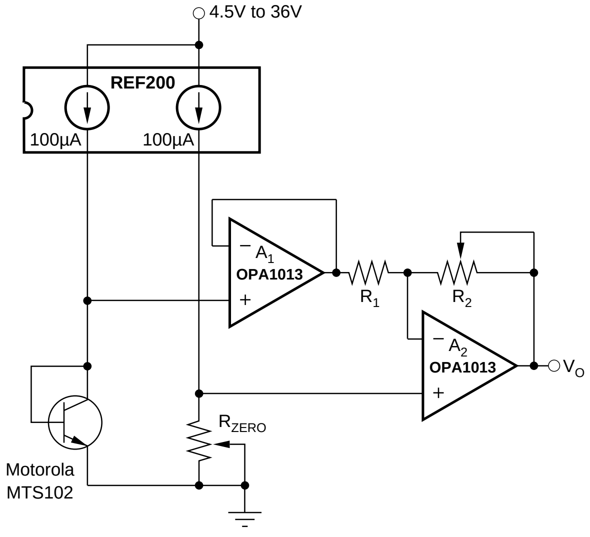
$R_2 = 44.15k\Omega$

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

$R_{ZERO} = 6.372k\Omega$

$R_1 = 10.0k\Omega$

$R_2 = 441.5k\Omega$



$V_O = 100\mu A \cdot R_{ZER\ O} \cdot (1 + R_2/R_1) - V_{BE} \cdot R_2/R_1$

Where:

V_{BE} = voltage across diode [V]

Adjust span first with R_1 or R_2 then adjust zero with R_{ZERO} for noninteractive trim.

Figure 4. Single-supply Positive Transfer Function Temperature Measurement Circuit with Independent Span (gain) and Zero (offset) Adjustment.

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% resistors are used, CMR will be greater than 70dB for gains over 50V/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 5 circuit.

BASIC TRANSFER FUNCTION

$$V_O = ((V_{BE2} + 100\mu A \cdot R_{ZERO2}) - (V_{BE1} + 100\mu A \cdot R_{ZERO1})) \cdot GAIN$$

Where:

$$GAIN = 2 + 2 \cdot R_1/R_{SPAN}$$

CALCULATING RESISTOR VALUES

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

$R_{ZERO1} = R_{ZERO2} = 500\Omega$ (use 1kΩ pot for R_{ZERO})

Where:

R_{SPAN} = Span (gain) adjust resistor [Ω]

Others = as before

EXAMPLE

Design a temperature measurement system with a 0 to 1.0V output for a 0 to 1°C temperature differential.

$T_{MIN} = 0°C$

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

If $V_{BE25} = 0.595V$, $T_C = -0.002265V/°C$, and

$R_{ZERO} = 1k\Omega$ pot

R_1, R_2, R_3, R_4 = 100kΩ, 1%

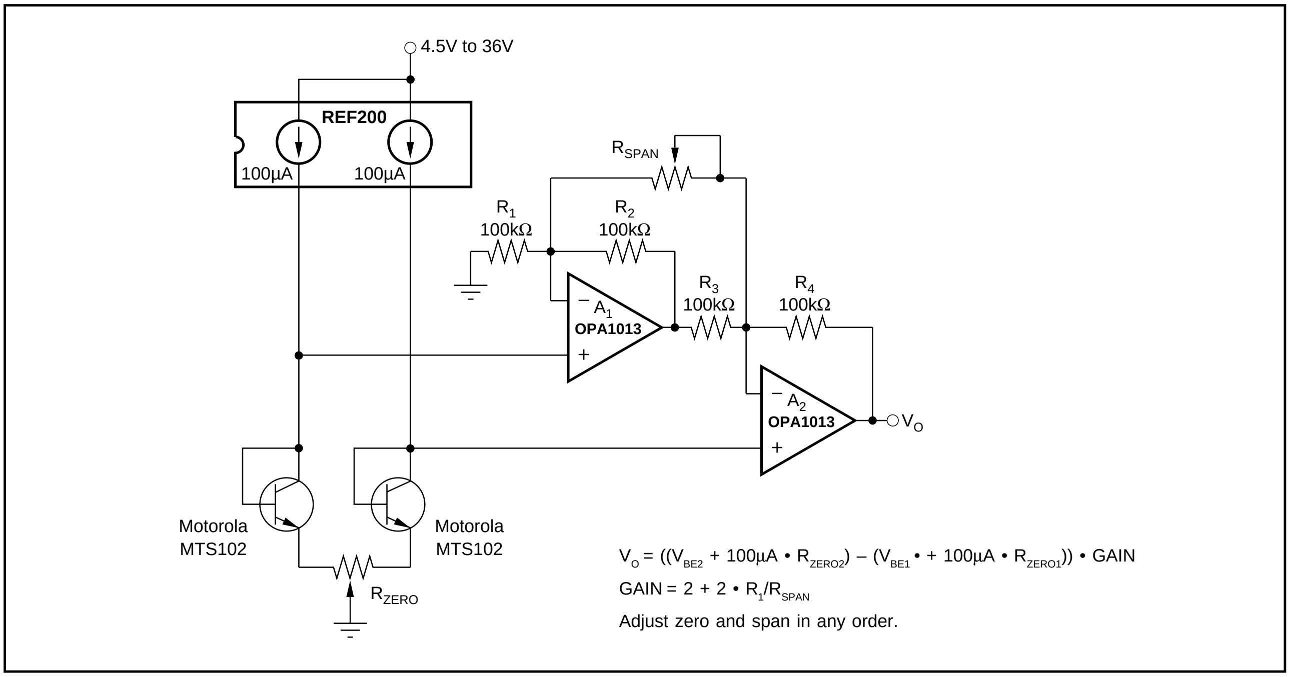
$R_{SPAN} = 455\Omega$

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

$R_{ZERO} = 1k\Omega$ pot

R_1, R_2, R_3, R_4 = 100kΩ, 1%

$R_{SPAN} = 45.3\Omega$



$V_O = ((V_{BE2} + 100\mu A \bullet R_{ZERO2}) - (V_{BE1} \bullet + 100\mu A \bullet R_{ZERO1})) \bullet GAIN$

$GAIN = 2 + 2 \bullet R_1/R_{SPAN}$

Adjust zero and span in any order.

Figure 5. Differential Temperature Measurement Circuit.