Remote Thermal Sensing Diode Selection Guide

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INTRODUCTION

This application note is aimed at designers who build systems that use thermal sensors with remote diodes; specifically, remote diodes that are discrete bipolar junction transistors (BJTs).

Information presented here organizes important criteria for selecting the remote sensing diode to use with Microchip's high accuracy, low cost remote diode thermal sensors.

Microchip does produce temperature sensors that are designed to work specifically with CPU thermal diodes. So, these discussions are about selecting an appropriate BJT, as well as providing a list of acceptable BJTs, several are mentioned.

Throughout this application note, the phrase “remote diode-connected transistor” refers to a discrete, diode-connected (Base-Collector junction shorted) BJT.

This application note assumes that the reader has working knowledge of temperature sensing that uses diode-connected transistors.

OVERVIEW

This is a practical approach for selecting a remote diode-connected transistor to use with a thermal sensor, as illustrated in Figure 1.

Discussions of the semiconductor parameters of the transistor that affect the accuracy of temperature measurement are included here as the requisite feature of a remote thermal sensing diode.

A short table of qualified discrete 2N3904 NPN transistors is provided here. It lists devices from other manufacturers that have been tested and met established standards of accuracy.

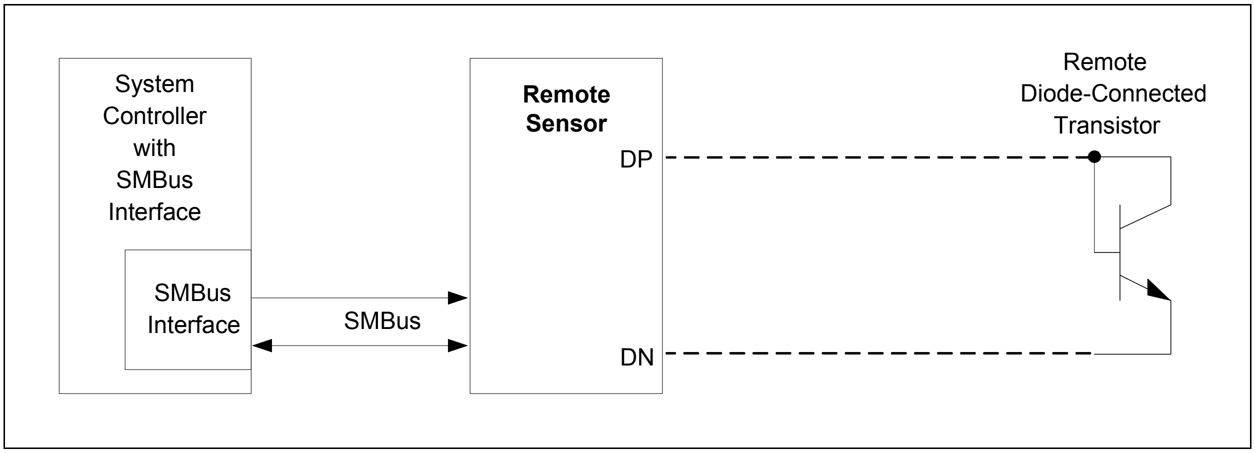

FIGURE 1: *Block Diagram of a Typical Temperature Sensing System.*

DIODE PARAMETERS

These three semiconductor parameters are the primary factors when considering diode-connected transistors in temperature sensing applications.

- Ideality Factor (η)
- Forward Current Gain (beta or hFE)
- Series Resistance (RS)

Ideality Factor (η)

The ideality factor is a parameter in the diode current-voltage relationship. It approaches a value of 1.0 when the carrier diffusion dominates the current flow, and approaches 2.0 when the recombination current dominates the current flow. This term is a constant on any particular device, though it can vary among individual devices.

Temperature sensors are calibrated during the final test to provide accurate readings with a diode that has a typical ideality factor. For the purposes of this document, the typical ideality factor value is expressed as $\eta_{ASSUMED}$ and the ideality factor value of the user's diode-connected transistor is expressed as η_{REAL}.

The temperature indicated by a temperature sensor will include an error from the real temperature, as defined by the equation in Equation 1. To use this equation, the temperature values must be converted to the Kelvin scale. The result will be incorrect if the values used reflect the Celsius or Fahrenheit scale.

EQUATION 1: TEMPERATURE ERROR DUE TO IDEALITY FACTOR MISMATCH

$$T_{MEASURED} = \frac{\eta_{REAL}}{\eta_{ASSUMED}} \times T_{REAL}$$

Generally, a 2N3904 transistor is the preferred remote diode. Several samples of each of the transistors listed in Table 1 were evaluated and their ideality factor was determined to be ~1.004. (Typically, the ideality factor is not be stated in the data sheet for a transistor.) While transistor devices other than the ones cited here could be used; to be confident of accurate operation, they should be qualified before use.

> **Note:** Qualification of these devices is ideally performed by obtaining data, on the parameters described in this application note, from the device manufacturer. Precision thermal equipment is required to measure the parameters. Contact your Microchip Field Applications Engineer for additional support.

TABLE 1: TYPICAL IDEALITY FACTOR VALUES FOR 2N3904 DIODE-CONNECTED TRANSISTORS

Manufacturer	Typical Ideality Factor
ROHM Semiconductor	1.0038
Diodes® Incorporated	1.0044
NXP®	1.0049
STMicroelectronics	1.0045
ON Semiconductor®	1.0046
Chenmko CO., LTD.	1.0040
Infineon® Technologies AG	1.0044
Fairchild Semiconductor®	1.0046
National Semiconductor	1.0037

In Equation 1, the ideality factor value that the temperature sensor is calibrated for is $\eta_{ASSUMED}$ and the actual ideality factor value of the diode-connected transistor is η_{REAL}. In this equation, the temperature measurement error is not a constant offset, but increases as T_{REAL}, the temperature of the remote diode-connected transistor, increases.

Figure 2 shows the temperature-measurement error that is induced solely from the differences between $\eta_{ASSUMED}$ and η_{REAL}. In this figure, $\eta_{ASSUMED}$ is 1.004, a typical ideality factor value for a 2N3904 NPN diode-connected transistor. Temperature sensors are typically calibrated in the range of the 2N3904 (1.004) because this is also very similar to the ideality factor of the majority of substrate diode-connected transistors that are found on CPUs and GPUs.

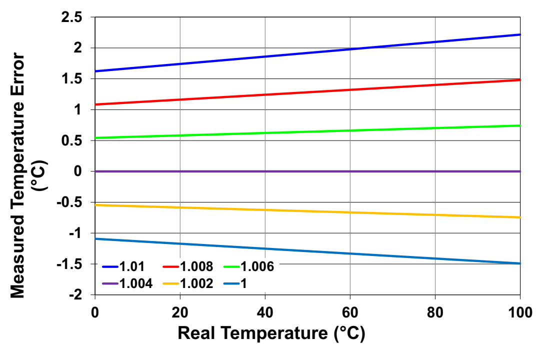

FIGURE 2: Temperature Error vs. Ideality Factor of Diode (with IC trimmed to 1.004).

Figure 2 also shows why true 2-terminal discrete diodes are not used in temperature sensing applications instead of 3-terminal devices such as the 2N3904. A discrete 2-terminal diode, ideally, would perform in temperature sensing applications as well as a thermal diode would. However, characterization in the labs determined that discrete 2-terminal diodes typically have an ideality factor much higher (1.2–1.5) than $\eta_{ASSUMED}$ of 1.004. This discrepancy (between $\eta_{ASSUMED}$ and η_{REAL}) would cause unacceptable temperature measurement errors at all temperatures.

Forward Current Gain (beta or h_{FE})

A typical temperature sensor forces two fixed currents (I_{F1} and I_{F2}) into the thermal diode to measure temperature, as shown in Figure 3.

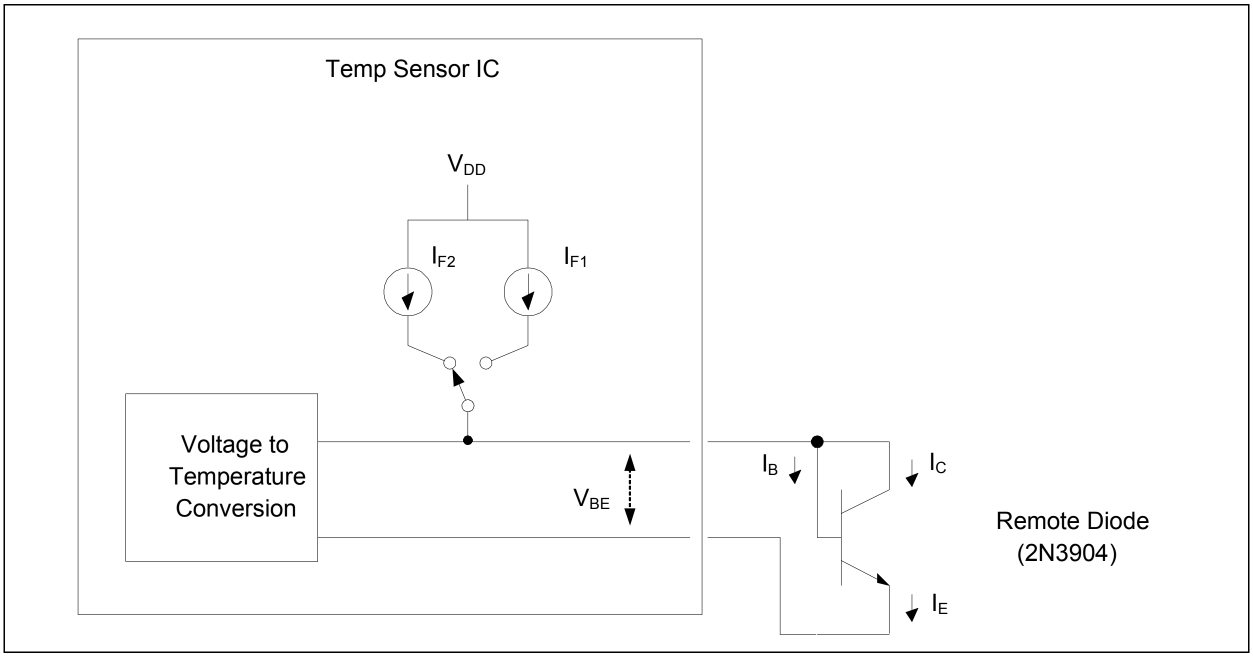

FIGURE 3: *Two Current Sources.*

The temperature sensor measures the voltage, V_{BE}, which is developed based on the collector current; not the emitter current.

EQUATION 2: IDEAL DIODE

$$T = \frac{(V_{BE2} - V_{BE1}) \times q}{\eta k \times \ln\left(\frac{I_{C2}}{I_{C1}}\right)}$$

The forward current gain (beta) of a transistor is not a constant over all operating conditions, but varies over temperature and as a function of I_C. The variation in beta over temperature does not induce temperature measurement error. However, if the transistor has a large variation in beta as a function of I_C, the temperature reading can be inaccurate, due to beta-induced error.

If the value of beta is relatively constant over the range of forced emitter currents, then the ratio of I_{C2}:I_{C1} remains equal to the ratio of the two forced emitter currents and induces no error. It only becomes a problem when the beta variation causes a mismatch between the I_{C2}:I_{C1} ratio and the I_{E2}:I_{E1} ratio.

Equation 3 shows the error induced from the non-constant value of beta at the two currents. β_{F1} represents the beta of the transistor at the current value I_{F1} while β_{F2} represents the beta at the current value I_{F2}. ‘N’ represents the fixed ratio of the two forced (I_{E1} and I_{E2}) currents. If beta is constant over the range of the two currents ($\beta_{F1} = \beta_{F2}$), then there is no temperature measurement error induced because of beta variation.

EQUATION 3: TEMPERATURE ERROR DUE TO BETA VARIATION

$$\Delta T_{ERROR} = T_{REAL} \times \left(\frac{\ln\left(\frac{\beta_{F2} \times (1 + \beta_{F1})}{\beta_{F1} \times (1 + \beta_{F2})}\right)}{\ln(N)} \right)$$

Figure 4 presents a plot of allowable beta variation over the sensor's sourced current range (10 – 400 µA) to be able to still maintain at least 1 degree accuracy at 70°C. The beta of the transistor must reside between the two lines in the plot, over the extremes of the current range of the temperature sensor, in order to maintain 1°C accuracy with the selected diode-connected transistor. The x-axis represents the beta of the diode-connected transistor at I_{F1}, while the y-axis is for the beta at I_{F2}. varies over the sensor's sourced current range.

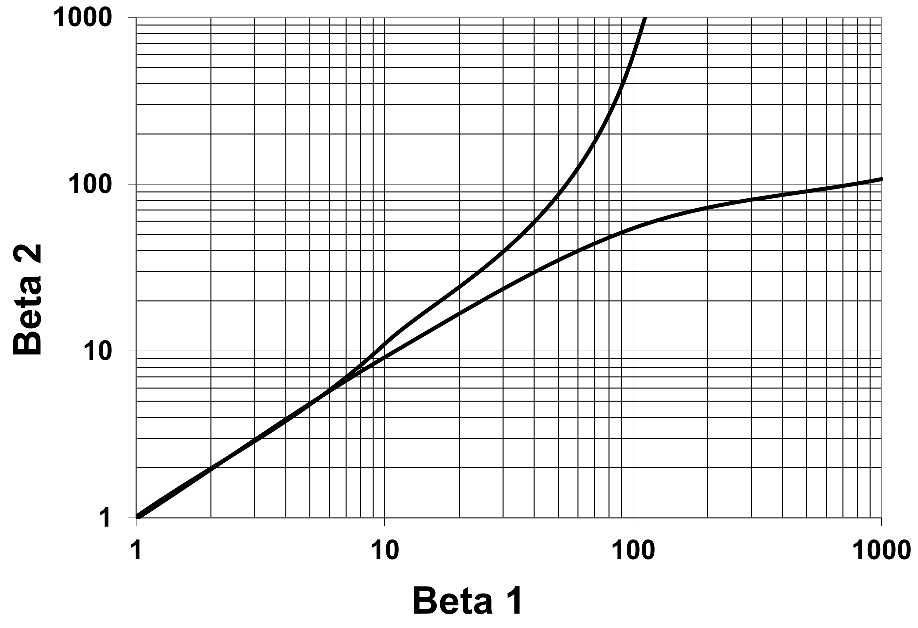

FIGURE 4: *Allowed Beta Variations for 1 Degree Accuracy at 70°C.*

Figure 5 shows typical values of transistor beta for a limited sample of these devices. These devices were characterized in Microchip characterization labs. This data should not to be used as a guaranteed value for the specific transistor, only a typical representation for the limited quantity tested by Microchip.

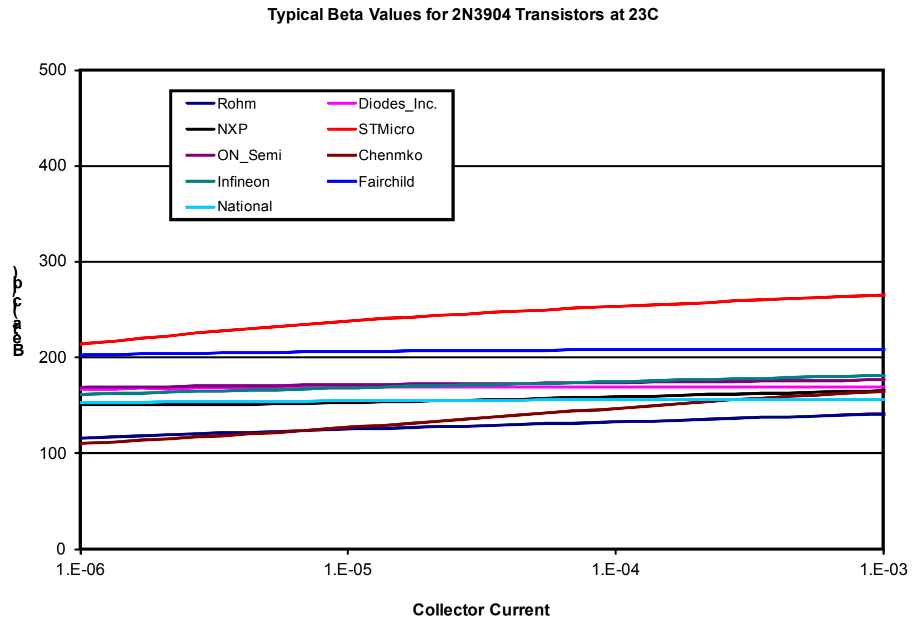

FIGURE 5: *Typical Beta Values for 2N3904 Transistors at 23°C.*

The conclusion to draw from Figure 4, Figure 5 and Table 2 is that for the set of 2N3904 transistors tested by Microchip, the beta was consistently high and flat. The measured value of beta easily resides inside the 2 lines of Figure 4, over the entire temperature sensor's sourced current range.

Table 2 quantifies the error induced from beta variation using the 2N3904s that were tested. As demonstrated through the tested devices, beta variation has a very small affect on temperature measurement accuracy.

TABLE 2: TEMPERATURE ERROR DUE TO 2N3904 BETA VARIATION AT 70°C

Manufacturer	Temperature Error (°C)
ROHM Semiconductor	+0.07
Diodes Incorporated	+0.00
NXP	+0.04
STMicroelectronics	+0.03
ON Semiconductor	+0.01
Chenmko CO., LTD.	+0.15
Infineon Technologies AG	+0.03
Fairchild Semiconductor	+0.00
National Semiconductor	+0.00

Series Resistance (R_S)

Series resistance is another parameter that affects temperature measurement accuracy. Series resistance causes the temperature sensor to report the temperature higher than the actual temperature of the thermal diode. The relationship between temperature offset and series resistance is displayed in the following equation.

EQUATION 4: TEMPERATURE OFFSET ERROR DUE TO SERIES RESISTANCE

$$T_{offset} = \left(\frac{q}{\eta k}\right)\frac{(I_{F2} - I_{F1})R_S}{\ln\left(\frac{I_{F2}}{I_{F1}}\right)}$$

The temperature error induced by series resistance is a constant offset for all temperatures. When using a typical Microchip temperature sensor, the magnitudes of I_{F2} and I_{F1} induce approximately +0.67°C error per Ohm of series resistance. For different 2N3904 devices characterized by Microchip, the R_S was found to be less than 1Ω. This does not include the series resistance due to PCB traces connecting the sensor and remote diode; this only represents the series resistance found in the characterized 2N3904 devices.

Table 3 quantifies some typical values of series resistance found for a sample of different 2N3904 devices. This value of series resistance for the set of 2N3904s tested was found to have a positive temperature coefficient and as a "rule-of-thumb", typically increased approximately 5% per +10°C increase.

> **Note:** Table 3 should not be used as a guideline for offsetting the temperature reported by an Microchip temperature sensor. Microchip temperature sensors are typically calibrated using a 2N3904 diode-connected transistor which already compensates for this series resistance error term.
>
> Table 3 is presented as a reference to help thermal designers understand the possible effects of non-idealities in temperature measurement

TABLE 3: TYPICAL VALUES OF SERIES RESISTANCE FOR 2N3904 DIODE CONNECTED TRANSISTORS

Manufacturer	Series Resistance (RS) @70°C
ROHM Semiconductor	0.68
Diodes Incorporated	0.65
NXP	0.72
STMicroelectronics	0.58
ON Semiconductor	0.90
Chenmko CO., LTD.	0.73
Infineon Technologies AG	0.57
Fairchild Semiconductor	0.60
National Semiconductor	0.51

TESTED DIODE LIST

This table lists a limited selection of 2N3904 NPN transistors that have been characterized found to meet the specifications to obtain 1°C accurate measurements.

TABLE 4: TESTED DIODES FOR TEMPERATURE SENSING APPLICATIONS

Manufacturer	Model Number
ROHM Semiconductor	UMT3904
Diodes Incorporated	MMBT3904-7
NXP	MMBT3904
STMicroelectronics	MMBT3904
ON Semiconductor	MMBT3904LT1
Chenmko CO., LTD.	MMBT3904
Infineon Technologies AG	SMBT3904E6327
Fairchild Semiconductor	MMBT3904FSCT
National Semiconductor	MMBT3904N623

CONCLUSION

In conclusion, while differences were seen between the various manufacturer’s versions of 2N3904 BJTs, the results, when using them with Microchip temperature sensors, were very consistent. For all typical 2N3904 devices tested, temperature never varied more than ±0.2 °C from the true temperature. The 2N3904 devices listed in Table 4 (or any BJT/diode with equivalent parameters) will yield accurate temperature measurement results when used with Microchip temperature sensors.

Microchip supplies a family of temperature sensors for many applications. Several special functions, such as resistance error correction and ideality configuration are available. In addition, some devices are designed to work specifically with CPU thermal diodes. Please consult your Microchip representative or visit the Microchip website for additional information at: www.microchip.com.

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