



# An Engineer's Guide to Temperature Sensing

Temperature sensor design challenges and solutions

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 **TEXAS INSTRUMENTS**

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# Introduction

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Whether you are designing personal electronics, industrial or automotive systems, you must address some of the same challenges: how to increase performance, add features and shrink form factors. Along with these considerations, it's imperative to carefully monitor temperature in order to ensure safety and protect systems and consumers from harm.

Another trend across numerous industries is increased data processing from more sensors, further emphasizing the importance of temperature measurement – not just to measure system or environmental conditions but to compensate for other temperature-sensitive components and maintain both sensor and system accuracy. As an added benefit, accurate temperature monitoring can increase system performance and reduce costs by removing the need to overdesign systems to compensate for inaccurate temperature measurements.

This e-book's chapters describe significant temperature challenges, focus on design considerations for applications, and assess trade-offs between temperature accuracy and application size while considering sensor placement. If you have feedback about the topics covered here or any other temperature monitoring and protection questions, please submit them to the [\*\*Sensors forum on the TI E2E™ design support forums\*\*](#).

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# Chapter 1: Temperature sensor technologies

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## Overview

The demand for temperature sensing in today's advanced manufacturing environments has grown to encompass nearly every application in the automotive, industrial, personal electronics, communications and enterprise sectors. Given the diverse array of applications that require temperature monitoring, there are many considerations when choosing the most efficient type of sensor, including sensor accuracy, size, placement, drift and calibration.

In order to help you select the best sensor for your application, Chapter 1 compares the four most popular temperature sensors:

- **Integrated circuit (IC) sensors.** Made from silicon and able to leverage the highly predictable thermal characteristics of the silicon p-n junction, IC sensors provide high accuracy, low power consumption, fast response time and a compact form factor.
- **Thermistors.** There are two main categories of thermistors: negative temperature coefficients (NTCs) and positive temperature coefficients (PTCs). As temperature rises, the resistance of an NTC will decrease, while the resistance of a PTC will increase. NTCs usually require calibration for greater accuracy, but silicon-based PTC thermistors have a linear relationship between temperature and resistance and thus do not require calibration, saving resources and time in your design process.

- **Resistive temperature detectors (RTDs).** Because

RTDs are made of pure metal, such as platinum, they can operate with high accuracy in extremely high-temperature environments; the downside is that they are one of the most expensive types of temperature sensors. RTDs operate on the known correlation between a pure metal's increase in resistance and an increase in temperature.

- **Thermocouples.** A thermocouple fuses together two different metals, such as copper and iron, to form a junction. This junction produces a small voltage when the temperature changes, which is convertible into a corresponding temperature value. Although thermocouples can measure the widest temperature range among the four sensor types, they are often larger in size and cost more than IC sensors or thermistors.

# Temperature sensing fundamentals



## Introduction to Temperature Sensing

In embedded systems, there is a constant need for higher performance and more features in a smaller form factor. This requires system designers to **monitor** the overall temperature to ensure safety and **protect** the systems. The trend of sensor data-logging further drives the need for temperature measurement to not only measure system or environmental conditions, but to **compensate** for temperature-sensitive components and maintain accuracy of the total system.

## Thermal Design Considerations

Considerations for efficient thermal monitoring and protection include:

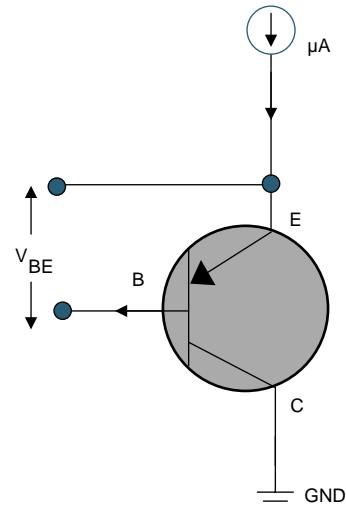
- i. **Accuracy:** Sensor accuracy represents how close the temperature is to the true value. Applications should consider factors such as linearity and acquisition circuits across the operating temperature range.
- ii. **Size:** While the size of the sensor makes an impact on the design, analyzing the overall circuit can yield a more optimized design.
- iii. **Sensor Placement:** Package and placement can impact the response time and conduction path. Both are critical for effective thermal design.

**Table 1. Temperature Sensing Technology Comparison**

	IC Sensor	Thermistor	RTD	Thermo couple
Range	-55°C to +200°C	-100°C to +500°C	-240°C to 600°C	-260°C to +2300°C
Accuracy	Good / Best	Calibration dependant	Best	Better
Footprint / Size	Smallest	Small	Moderate	Large
Complexity	Easy	Moderate	Complex	Complex
Linearity	Best	Low	Best	Better
Topology	Point-to-point, Multi-drop, Daisy Chain	Point-to-point	Point-to-point	Point-to-point
Price	Low to Moderate	Low to Moderate	Expensive	Expensive

## IC Sensors

IC temperature sensors rely on the predictive temperature dependence of a Silicon bandgap. The precision current sources the internal forward biased p-n junction with the resulting  $\Delta V_{BE}$  that corresponds to the device temperature.



**Figure 1. Temperature Dependence of Silicon Bandgap**

$$\Delta V_{BE} = \frac{KT}{q} \times \ln\left(\frac{I_{C1}}{I_{C2}}\right) \quad (1)$$

Given the predictable behavior, ICs offer high linearity and accuracy across a wide temperature range (up to  $\pm 0.1^\circ\text{C}$ ). IC sensors can integrate system functionality that offers a small footprint and low power consumption. These sensors do operate in a limited temperature range and offer fewer packaging options that can measure off-board temperature when compared to thermistors.

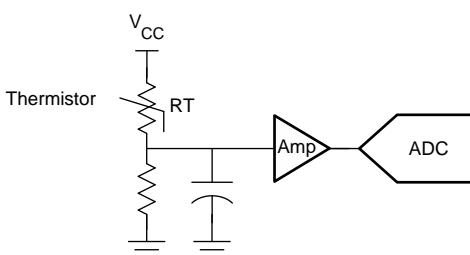
These sensors are typically fully-integrated, and monolithic sensors and accuracy are designed for the entire system instead of for one element.

## Thermistors

Thermistors are passive components that change resistance with temperature. Thermistors fall into two categories, negative temperature coefficient (NTC) and positive temperature coefficient (PTC).

While thermistors offer a variety of package options for onboard and off-board temperature sensing, typical implementation requires more system components. NTC thermistors are non-linear and often bear increased calibration cost and software overhead. An exception to this are Silicon-based PTC thermistors.

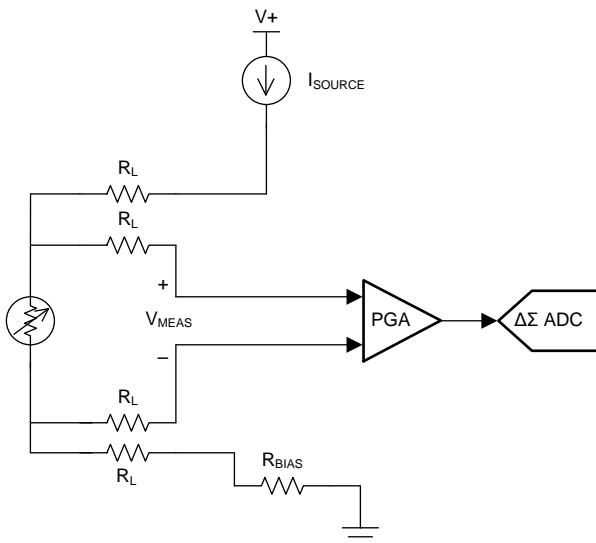
The true system accuracy for Thermistors are often difficult to determine. NTC system error contributors include NTC tolerance, bias resistor (Tolerance, Temperature Drift), ADC (quantization error), linearization error, reference voltage (Accuracy, Temperature Drift).



**Figure 2. Typical Thermistor Implementation**

### Resistive Temperature Detectors (RTD)

RTDs are temperature sensors made of pure material, typically in platinum, nickel, or copper, with a highly predictable resistance-temperature relationship.



**Figure 3. Complex 4-Wire RTD Circuit**

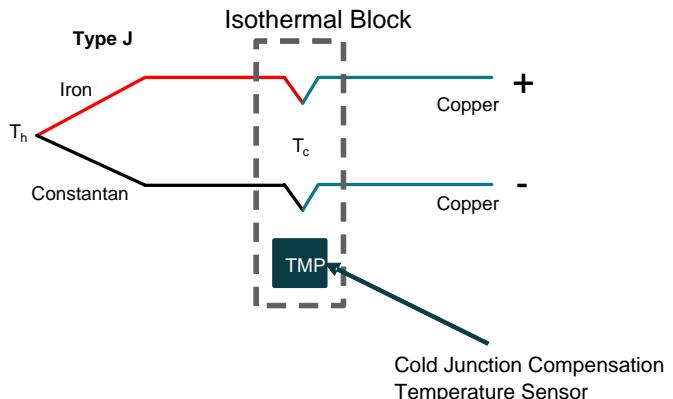
Platinum RTDs can be highly accurate and very linear across a very wide temperature range up to 600°C. Implementation with these analog sensors involve complex circuitry and design challenges. Ultimately, the accurate systems involve complex error analysis due to a higher number of contributing components that also impact the overall system size. RTDs also require calibration during manufacturing followed by an annual calibration process in the field.

Contributors to the RTD system error include RTD Tolerance, self-heating, ADC (quantization error) and references used in the system.

### Thermocouples

Thermocouples are made of two dissimilar electrical conductors that form electrical junctions at different temperatures. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric seebeck effect. This voltage translates to the difference of temperature between the hot junction ( $T_h$ ) and the cold junction ( $T_c$ ).

The temperature of the cold junction must be known to derive the hot junction temperature. Here, accuracy is limited by the fact that there are two systems that have separate tolerances and capabilities interacting with each other.



**Figure 4. Thermocouple With CJC Temperature Sensor**

Thermocouples do not require external excitation, and hence are not impacted by self-heating issues. They can also support extreme temperatures (>2000°C). While they are rugged and inexpensive, thermocouples do require an additional temperature sensor for cold-junction-compensation (CJC). They tend to be non-linear and are highly sensitive to parasitic junctions where the thermocouple is attached to the board.

Finally, digitizing a thermocouple would be susceptible to previously discussed ADC errors.

### Device Recommendations

For 40 years, Texas Instruments has manufactured several IC-based temperature sensors, including:

- [Digital temperature sensors](#):
  - Highest accuracy temperature sensors
  - Lowest power with the smallest footprint
  - LM75 / TMP75 temperature sensors
  - Multi-channel remote diode temperature sensors
- [High-accuracy analog temperature sensors](#)
- [Linear thermistors](#)
- [Temperature switches or thermostats](#) that offer integrated hysteresis for enhanced noise immunity

**Table 2. Related Documentation**

COLLATERAL	DESCRIPTION
Application Report - Accuracy	<a href="#">Layout Considerations for Accurately Measuring Ambient Temperature</a>
Application Report - Temperature Calibration	<a href="#">Methods to Calibrate Temperature Monitoring Systems</a>

# Chapter 2: Ambient and board temperature monitoring

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## Overview

Power-hungry electronic components such as central processing units, graphics processing units, field-programmable gate arrays or voltage regulators heat up during regular operation. This is because all electrical components have at least a small natural resistivity to current, which causes some of the electrical energy to be lost as heat. The heat generated from these components can interfere with accurate temperature measuring.

Some applications require ambient air temperature measurements, while others need to measure the temperature of a nearby component on the printed circuit board (PCB). But instantaneous temperature measuring is not possible in real-world processes for several reasons. Factors such as the position of the sensor relative to the heat-generating element(s) and the physical characteristics of the sensor itself can cause the recorded temperature value to lag behind the actual temperature value. When integrating a temperature sensor, you'll need to minimize the trade-off between meeting system requirements and obtaining the optimal thermal response time at the lowest possible cost.

Perhaps the most important design decision is layout technique. A poor PCB layout can lead to inaccurate temperature readings and eventually system damage and a shortened board lifetime. Board layout considerations include the maximum allowable temperature, the operating environment and how much power (as heat) the board components will dissipate.

Chapter 2 explains methods for improving accuracy while reducing thermal response time and offers recommendations regarding:

- **Ambient temperature monitoring.** Maintaining tight control of environmental conditions or ensuring safe operating conditions requires high-accuracy ambient temperature monitoring. High ambient temperatures can cause overheating that leads to hardware damage or reduced system efficiency. Selecting the correct layout technique for your process helps minimize the impact of heat generated from components on the PCB.
- **PCB component temperature monitoring.** For PCBs, temperature monitoring helps maintain component safety, reliability and performance. High temperatures can cause hardware damage and electrical hazards and decrease system efficiency and life spans. High temperatures can also come from multiple sources, including heat-generating components mounted directly on the PCB or inadequate system ventilation. Because it's possible to place TI's small-form-factor temperature sensors in proximity to heat sources, measurement accuracy improves.

# **Temperature sensors: PCB guidelines for surface mount devices**

Ben Kasemsadeh, Aaron Heng, and Amit Ashara

## **ABSTRACT**

Power hungry electronic components such as CPUs, GPUs, or FPGAs, as well as voltage regulators heat up during operation. Some applications require ambient air temperature measurements while others need to measure the temperature of a nearby component on the PCB. Measuring ambient air temperature with a surface mount technology (SMT) device is challenging due to the thermal influence of other components within the system. In other systems, in which the temperature of a component needs to be measured, ambient air temperature can influence and degrade the measurement accuracy.

The system designer needs to make certain design decisions regarding both package type and PCB layout when integrating a temperature sensor. This application note provides recommendations to system designers and explains methods for improving the accuracy of the temperature point being measured. The Recommendations are provided both for air temperature measurements and for component temperature measurement. The report details layout techniques, device orientation, and best practices for mounting.

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1 Introduction

## **1.1 What Is Heat Conduction?**

There are three methods of heat transfer: heat conduction through solids, heat convection through fluids and gases, and heat generated by radiation. This report focuses on heat conduction as it dominates the heat transfer in PCBs and is therefore most relevant to temperature measurements.

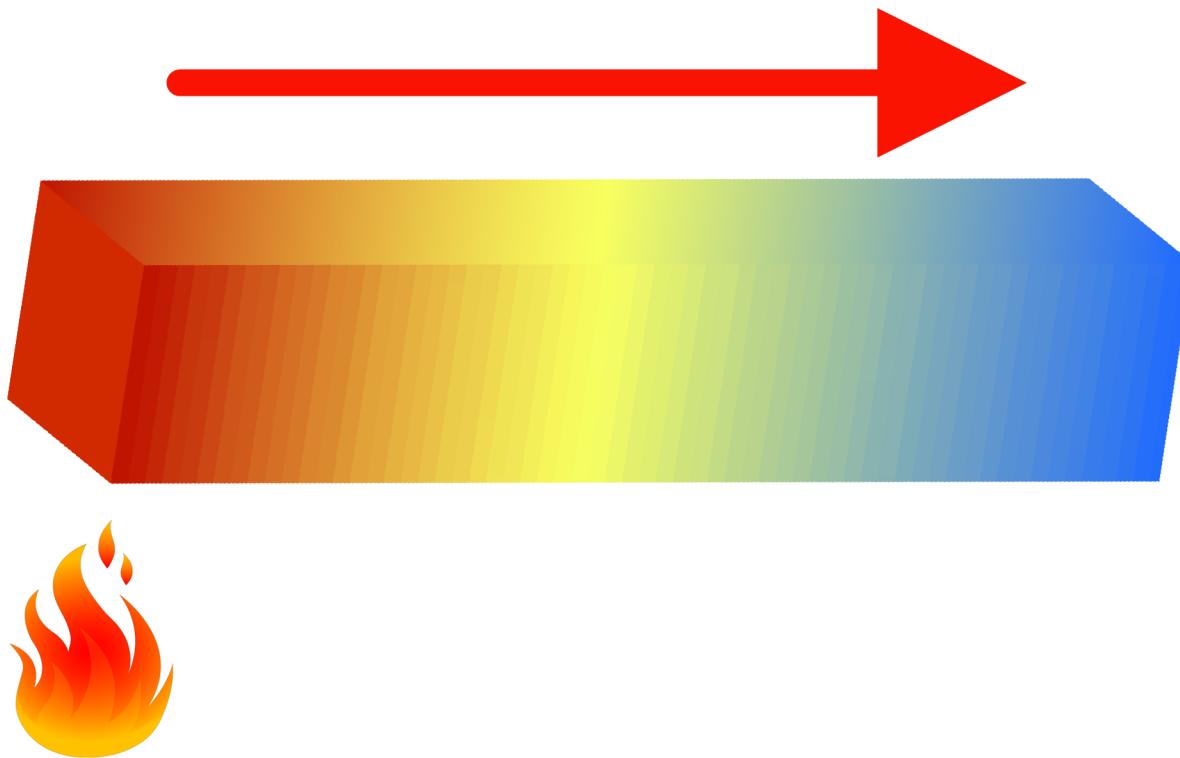
Heat conduction is defined as the transfer of heat through a volume or a body. Heat is transferred through microscopic collisions of particles; the more collisions, the hotter the object is. Heat transfer occurs when there is a temperature difference between two objects or between different areas of an object, and its rate depends on the geometry, thickness, and material of the object. Due to the law of equilibrium, heat transfers from a hotter body to a colder body until the whole system reaches final equilibrium, as shown in [Figure 1](#). There is no net heat transfer between two objects that are equilibrium temperature. The equation for heat transfer through conduction is shown in [Equation 1](#)

$$\frac{Q}{t} = kA \frac{(T_2 - T_1)}{d}$$

where

- Q/t: The rate of heat transfer [J/s]
  - k: the thermal conductivity of the material [W/mxK]
  - A: Surface of the contact area [m<sup>2</sup>]
  - $\Delta T$ : The temperature difference of T1 temperature of one object and T2 temperature of the other [K]
  - d: The thickness of the material [m]

(1)



**Figure 1. Thermal Conduction Model**

Thermal conductivity ( $k$ ) is the measure of a material's capability to conduct heat. It is used to describe how heat conducts through a material. Metals are highly thermally conductive whereas materials like air, wool, paper, or plastic are poor conductors of heat. Materials with a very low thermal conductivity, such as polystyrene foam, act like a thermal insulator.

The materials that are most relevant to thermal analysis of PCBs are copper, FR4, and solder mask. Copper is an excellent conductor of heat; it conducts heat significantly faster than FR4. [Table 1](#) lists the thermal conductivities found in PCBs. The higher the value, the more efficient the material is in transferring heat, which results in a shorter thermal response time. For low k values, the temperature gradient between the source and the sensor can be significantly large and must be considered carefully during layout.

**Table 1. Material Thermal Conductivity Coefficients Of Selected Materials**

Material	Thermal Conductivity $k$ [W/(m×K)]
Air	0.0275
Solder Mask	0.245
FR4	0.25
Gold	314
Copper	385
Silver	406

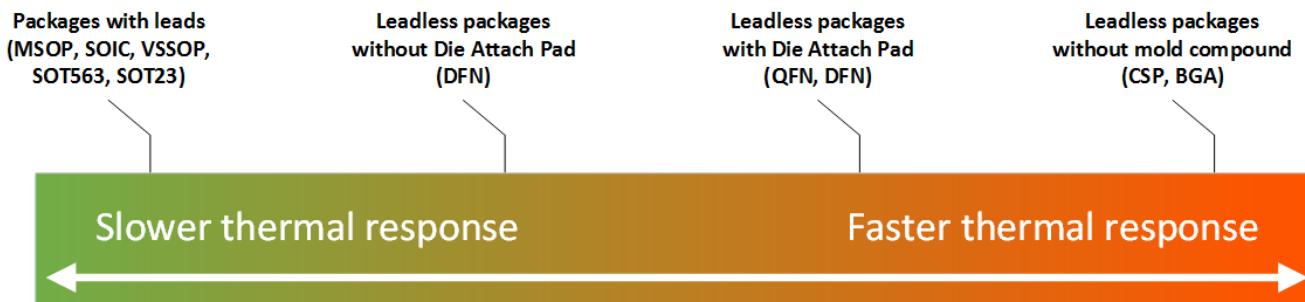
## 1.2 Determining The Dominant Thermal Conduction Path Of Selected Package Types

Surface mount temperature sensors offer several advantages over sensors with through-hole packages. Advantages include a smaller package size with a low profile, convenient PCB placement, and ease of assembly. However, SMT temperature sensors can be difficult to isolate because they have the tendency to measure the PCB temperature rather than ambient air temperature. Therefore, special layout techniques need to be employed if the objective of the temperature sensor is to measure the ambient temperature rather than the PCB temperature. Local analog or digital temperature sensors determine temperature by measuring their own die temperature. Therefore, it is important to understand the dominant temperature conduction paths between the die of the temperature sensor and the object or environment whose temperature is to be determined.

Heat is conducted primarily through the following paths:

1. The Die-attach pad (DAP), if present, provides the most dominant thermal path between the PCB and the die
2. The leads provide the most significant thermal path if the package type does not include a DAP
3. The mold compound provides an additional thermal path, but due to its low thermal conductivity, any heat transfer through the mold compound itself is slower than heat transfer through the leads or DAP.

The package type choice determines how quickly the temperature sensor can respond to changes in temperature. [Figure 2](#) shows the relative thermal response rates of different classes of selected SMT package types that are used for temperature measurements.



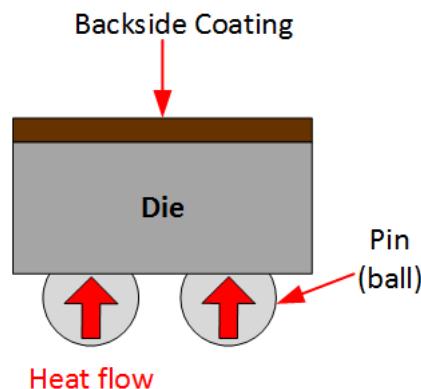
**Figure 2. Relative Thermal Response Rate (Typical)**

Package types without a mold compound (CSP, DSBGA) and packages with a DAP (QFN, DFN) are well suited if a fast thermal heat transfer from the PCB is desired, while package types without DAP are better in applications in which slower response rates are desired. A fast thermal response rate allows the temperature sensor to respond to any temperature changes quickly and therefore provide an accurate reading.

Sections [Section 1.2.2](#) to [Section 1.2.1](#) show cross sections of commonly used SMT package types for Texas Instruments' temperature sensors.

### 1.2.1 Leadless Packages Without Mold Compound (CSP, DSBGA)

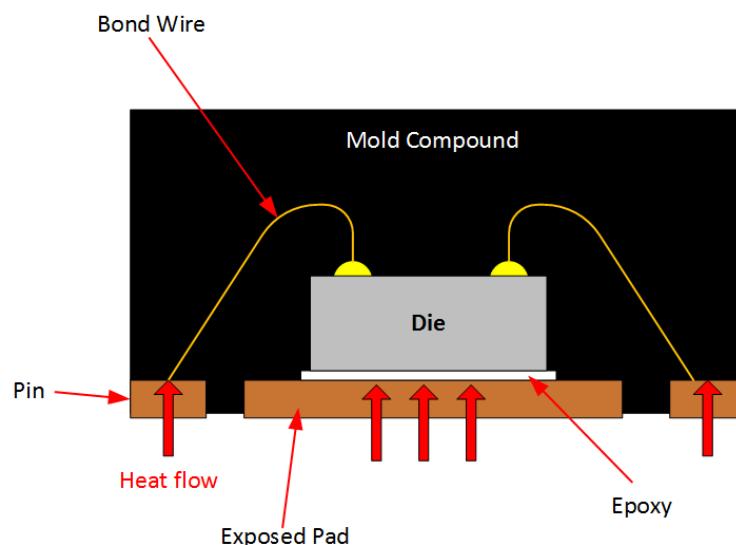
Wafer Chip Scale Package (WCSP) leads are Ball Grid Array (BGA) balls processed directly onto the die. Heat from the BGA balls are directly transferred to the die instead of transferring over the pins or through a die attach pad, as shown in [Figure 3](#). Generally, this is the package type with the fastest thermal response because there is no mold to heat up.



**Figure 3. Heat Transfer WCSP (LMT70[YFQ], TMP103[YFF], TMP108[YFF]) Package Cross Section**

### 1.2.2 Leadless Packages With Die Attach Pad (QFN, DFN)

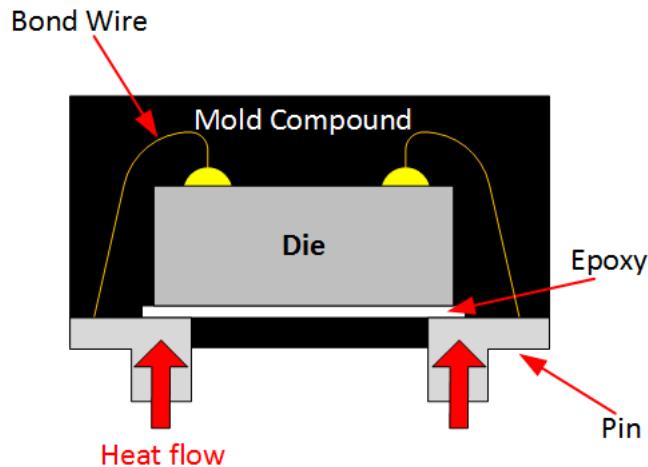
Packages with a DAP, such as QFN and DFN packages, have a large exposed surface area through which heat can transfer quickly. These package types will respond quickly to temperature changes of the copper plane which the DAP is soldered onto. Because the die sits directly on top of the thermal pad, heat can transfer rapidly from the thermal pad to the die.



**Figure 4. Heat Transfer WSON (TMP116[DRV]) Package Cross Section**

### 1.2.3 Leadless Packages Without Die Attach Pad (DFN)

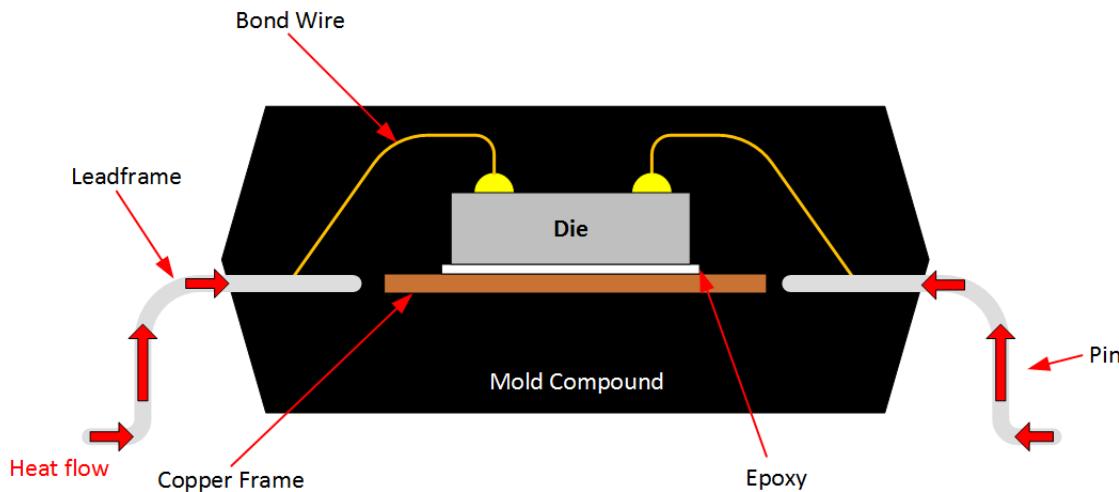
Leadless packages without a DAP, such as the 2-pin DFN package of the LMT01 shown in [Figure 5](#), transfer most heat through the pins itself. A small package of this type can still respond to temperature change quickly because of its small thermal mass of the mold compound.



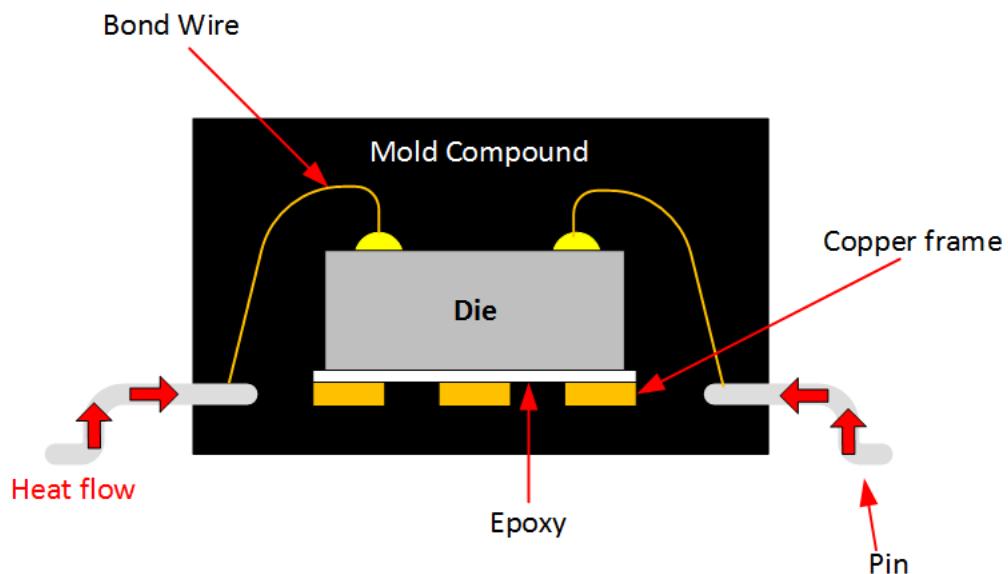
**Figure 5. Heat Transfer WSON (LMT01[DQX]) Package Cross Section**

### 1.2.4 Packages With Leads (MSOP, SOIC, VSSOP, SOT563, SOT23)

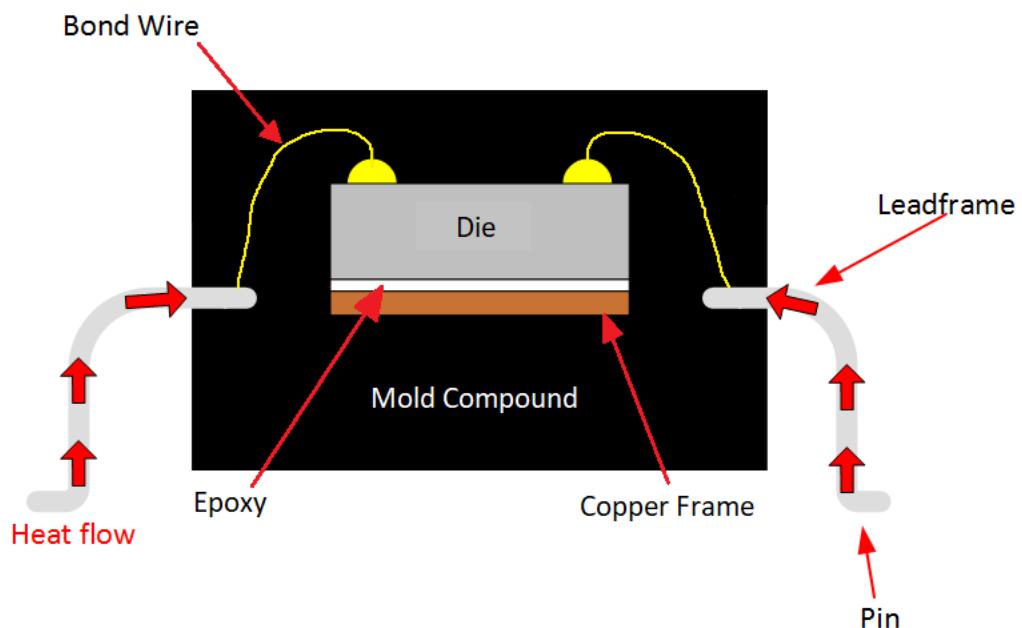
Other packages such as SOIC8, MSOP8, SOT563, and SOT23 transfer most heat through their leads. The leads transfer 60% to 70% heat to the die thermal sensor.



**Figure 6. Heat Transfer MSOP8, SOIC8 (LM75[D], TMP75[D]) Package Cross Section**



**Figure 7. Heat Transfer SOT563 (TMP102[DRL]) Package Cross Section**



**Figure 8. Heat Transfer SOT23 (LM71A[DBV]) Package Cross Section**

### 1.3 Determining Thermal Conduction Through The PCB

Power hungry components can generate a significant amount of heat during operation, and a PCB designer needs to have an understanding of how heat is conducted by the PCB. The layout of the PCB affects the thermal conductivity and thus the temperature measurement. Understanding the total thermal resistance of the PCB will help the PCB designer to determine whether it is necessary to use filled or plated vias, use thicker copper plating or add additional copper layers to disperse heat quicker.

#### 1.3.1 General Thermal Conduction Equation

Thermal resistance can be expressed by the following equation:

$$\theta = \frac{L}{k \times A_{CS}}$$

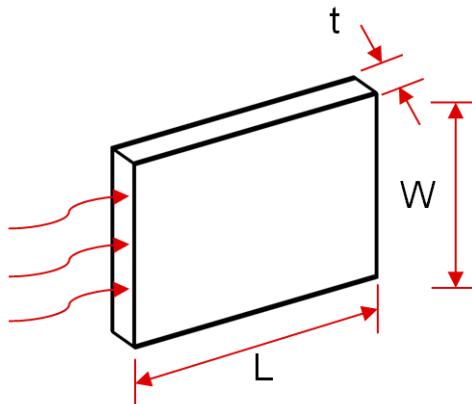
where

- $\theta$  is the thermal resistance [K/W]
  - $k$  is the thermal conductivity factor [W/(m\*K)]
  - $L$  is the thermal path length [m]
  - $A_{CS}$  is the cross sectional area in which heat is applied [ $m^2$ ]
- (2)

To calculate the thermal conduction through the PCB, the individual paths can be broken down and analyzed separately. The main components are the thermal conduction through the PCB (see [Section 1.3.4](#) and [Section 1.3.2](#)), and the conduction through the via (see [Section 1.3.5](#)). The most common materials in many PCB applications are FR4, copper, and soldermask materials. By applying [Equation 2](#) to the perpendicular path for the appropriate PCB materials, the longitudinal path, and the thermal flow through the vias individually, thermal conduction through the PCB can be modeled accurately.

#### 1.3.2 Longitudinal Thermal Conduction

[Figure 9](#) shows the longitudinal conduction path of a PCB with the direction of the heat flow from the heat source along the FR4.



**Figure 9. Longitudinal Conduction Heat Flow**

[Figure 9](#) applies the general thermal conduction equation to a cuboid.

$$\theta = \frac{L}{k \times A_{CS}} + \frac{L}{k \times W \times t}$$

where

- $L$  is the path length of heat flow
  - $W$  is the width and  $t$  is the thickness
  - $W \times t = A_{CS}$  is the cross sectional area where the heat is being applied
  - $L = W$  for square
- (3)

### 1.3.3 Example: Determining The Dominant Longitudinal Thermal Conduction Path

Applying [Equation 3](#) to a 1.6mm thick layer of FR4 of square dimensions ( $1\text{m} \times 1\text{m}$ ) results in a thermal resistance of  $2,500^\circ\text{C/W}$ , as shown in [Equation 4](#)

$$\theta_{\text{FR4}} = \frac{L}{k \times W \times t} = \frac{1\text{m}}{0.25 \frac{W}{\text{m} \times {}^\circ\text{C}} \times 1\text{m} \times 2 \times 1.6 \times 10^{-3}\text{m}} = 2500^\circ\text{C/W} \quad (4)$$

Two 1oz (35 $\mu\text{m}$ ) copper planes of the same PCB would have the thermal resistance of  $3,710^\circ\text{C/W}$ , as calculated in [Equation 5](#)

$$\theta_{\text{Cu}} = \frac{L}{k \times W \times t} = \frac{1\text{m}}{385 \frac{W}{\text{m} \times {}^\circ\text{C}} \times 1\text{m} \times 2 \times 35 \times 10^{-6}\text{m}} = 3710^\circ\text{C/W} \quad (5)$$

While thickness of the copper plane is significantly thinner than the thickness of the FR4 layer, the ability to transfer heat is in the same order of magnitude. This is because the thermal conductivity of copper is approximately 1,500 times larger than the thermal conductivity of FR4. It can be seen that the copper planes of the above example PCB transfer heat slightly slower than the significantly thicker FR4 layer.

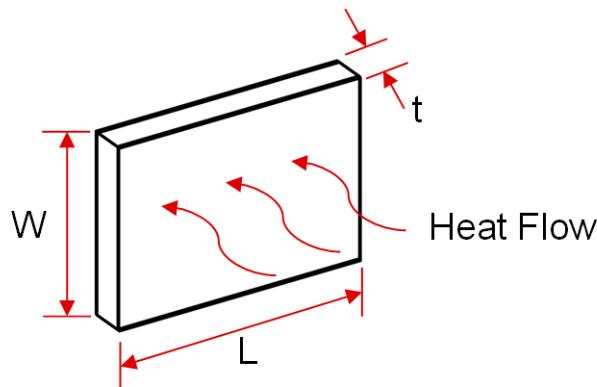
In the longitudinal direction, several layers of the PCB need to be considered in parallel. Compared to a PCB without copper floods, it is possible to almost double the heat transfer rate along the plane by adding two 1oz layers of copper floods.

Because the different layers transfer heat in parallel, the effective total thermal resistance of the cross-section is  $1,494^\circ\text{C/W}$ , as calculated in [Equation 6](#)

$$\theta_{\text{total}} = \theta_{\text{Cu}} \parallel \theta_{\text{FR4}} = \frac{\theta_{\text{Cu}} \times \theta_{\text{FR4}}}{\theta_{\text{Cu}} + \theta_{\text{FR4}}} = \frac{3710 \times 2500}{3710 + 2500} = 1494^\circ\text{C / W} \quad (6)$$

### 1.3.4 Perpendicular Thermal Conduction

[Figure 10](#) shows the perpendicular conduction heat flow of a PCB.



**Figure 10. Perpendicular Conduction Heat Flow**

[Equation 7](#) is the perpendicular conduction heat flow equation to determine the thermal resistance of a material, as specified in [Table 1](#).

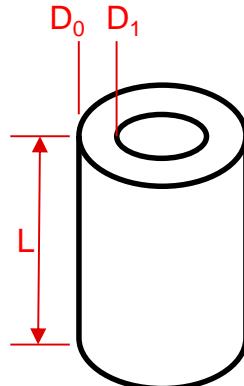
$$\theta = \frac{t}{k \times A_{\text{CS}}} = \frac{t}{k \times W \times L}$$

where

- $t$  is the path of heat flow (the heat flows through the thickness of the material) [m]
  - $W \times L = A_{\text{CS}}$  is the cross sectional area where the heat is being applied [ $\text{m}^2$ ]
- (7)

### 1.3.5 Thermal Conduction Through A Via

Calculating the thermal conduction path of a via (as shown in [Figure 11](#)) can be useful to determine if a regular via suffices, a larger size or quantity of vias is required, or if vias need to be filled with a conductive fill. A conductive fill transfers heat faster to the opposite side of the board, but also increases PCB manufacturing cost.



**Figure 11. Conduction Through Via**

[Equation 8](#) applies the general thermal conduction equation to a via.

$$\theta = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left( \left( \frac{D_0}{2} \right)^2 - \left( \frac{D_1}{2} \right)^2 \right)}$$

where

- $L$  is the length of the via (the heat flows through the length of the cylinder) [m]
  - $D_0$  is the outer via diameter [m]
  - $D_1$  is the inner via diameter [m]
- (8)

### 1.3.6 Example: Determining The Dominant Perpendicular Thermal Conduction Path

In the perpendicular direction, a PCB designer may want to compare the thermal resistance of a via with the equivalent thermal resistance of FR4 to determine if placing additional vias is a useful technique in transferring heat quickly from one side of the PCB to the other.

The sidewalls of a non-tented, non-filled via with a 0.5mm drill hole size, a sidewall copper thickness of 35µm, and a length of 1.6mm have the thermal resistance of 81°C/W, as shown in [Equation 9](#). Note that the sidewall thickness of a via is often different from the copper plating thickness and depends on via dimensions and the manufacturing process of the PCB manufacturer.

$$\theta_{Cu} = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left( \left( \frac{D_0}{2} \right)^2 - \left( \frac{D_1}{2} \right)^2 \right)} = \frac{1.6 \times 10^{-3}}{385 \frac{W}{m \times ^\circ C} \times \pi \times \left( \left( \frac{0.5 \times 10^{-3}}{2} \right)^2 - \left( \frac{0.43 \times 10^{-3}}{2} \right)^2 \right)} = 81^\circ C/W$$
(9)

In order to obtain an accurate result, the thermal resistance of the air cylinder inside the via also needs to be calculated and considered in parallel with the thermal resistance of the via sidewalls.

$$\theta_{Cu} = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left( \left( \frac{D_0}{2} \right)^2 - \left( \frac{D_1}{2} \right)^2 \right)} = \frac{1.6 \times 10^{-3}}{385 \frac{W}{m \times ^\circ C} \times \pi \times \left( \left( \frac{0.43 \times 10^{-3}}{2} \right)^2 - \left( \frac{0}{2} \right)^2 \right)} = 400646^\circ C/W$$
(10)

[Equation 10](#) shows that the thermal resistance of the air cylinder is greater than 400,000°C/W. Because it is approximately 5,000 times as large as the thermal resistance of the via sidewalls, the thermal conduction contribution of the air has a negligible effect and can be ignored, as is proven by [Equation 11](#).

$$\theta_{\text{via}} = \theta_{\text{Cu}} \parallel \theta_{\text{air}} = \frac{\theta_{\text{Cu}} \times \theta_{\text{air}}}{\theta_{\text{Cu}} + \theta_{\text{air}}} = \frac{81 \times 400646}{81 + 400646} = 81^\circ\text{C / W} \quad (11)$$

The air filled drill hole of a via does not contribute much to the heat transfer rate, so almost all of the heat transfer of a standard via occurs through its sidewalls. However, vias in which the hole is filled with a different material may benefit from the heat transfer contribution of that material. Some designs require vias to be filled in order to transfer heat even faster than a normal via. Filled vias should be considered if even multiple parallel standard vias do not provide a sufficiently fast heat transfer rate to meet system specifications.

The thermal resistance of 81°C/W for the non-filled via from this example can be compared to the thermal resistance of a solid FR4 cylinder of equal outer diameter to determine how much more effective a copper via is in transferring heat from one side of the PCB to the other. [Equation 12](#) shows that the thermal resistance of an equivalently sized cylinder of FR4 is 32,595°C/W, which is approximately 400 times more resistive than the thermal resistance of the via.

$$\theta_{\text{FR4}} = \frac{L}{k \times A_{\text{CS}}} = \frac{L}{k \times \pi \times \left( \left( \frac{D_0}{2} \right)^2 - \left( \frac{D_1}{2} \right)^2 \right)} = \frac{1.6 \times 10^{-3}}{0.25 \frac{W}{m \times ^\circ\text{C}} \times \pi \times \left( \left( \frac{0.5 \times 10^{-3}}{2} \right)^2 - \left( \frac{0}{2} \right)^2 \right)} = 32595^\circ\text{C/W} \quad (12)$$

An air filled drill hole contributes negligible thermal transfer. However, because the thermal conductivity of copper is approximately 1,500 higher than FR4, the via of above dimensions is able to transfer heat to the opposite side of the PCB through the via sidewalls approximately 400 times faster than an FR4 cylinder of the same outer diameter. Therefore, placing multiple parallel non-filled vias can be a very effective method to transfer heat quickly from one side of the PCB to the other within a localized area.

## 2 Design Guidelines For Air Temperature Measurement

For some applications, it is desirable to design for a low thermal conductivity between the PCB and the temperature sensors. This is desired when the ambient air temperature is to be measured, rather than the temperature of the PCB or nearby components.

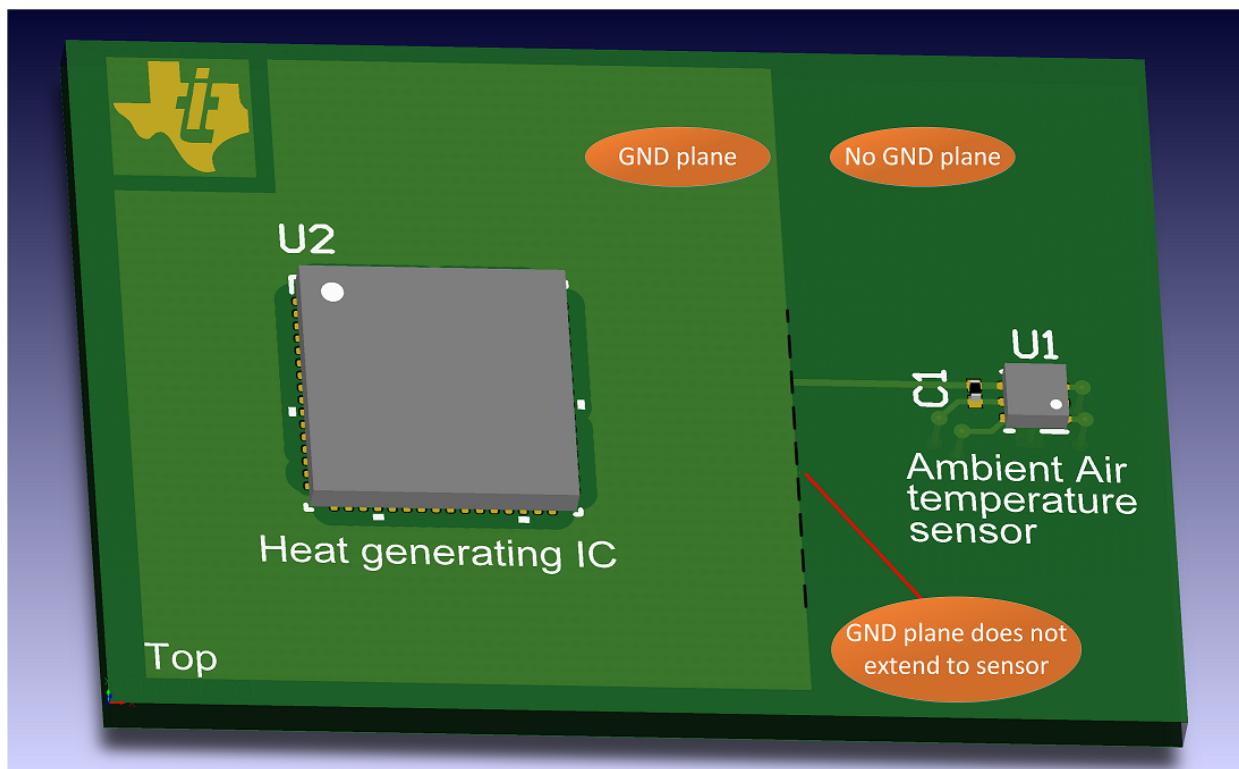
Examples of such applications include

- Thermostat ambient air temperature measurement
- Indoor and outdoor weather stations
- Wireless sensor node

In such systems, slow changes in air temperature are of interest, while heat sources such as a the heat of a nearby processor would result in an inaccurate reading. The guidelines in sections [Section 2.1](#) to [Section 2.6](#) docato-extra-info-title Edge connector [Section 2.5](#).

### 2.1 Ground Plane Considerations

Due to the higher thermal conductivity of copper, running solid ground planes between other ICs and the sensor will cause undesired heat transfer which should be avoided. It is best to avoid copper planes near the temperature sensor that are connected to the copper planes of other ICs, as shown in [Figure 12](#)



**Figure 12. GND Plane Does Not Extend To Temperature Sensor (Top View)**

For even better results, create a separate a small copper plane on both sides of the sensor as shown in [Figure 13](#) and [Figure 14](#), and add several vias to thermally link the top and bottom planes together.

Because of the low thermal conductivity of the solder mask compared to copper (see [Table 1](#)), it is advised to create a solder mask cut-out around the copper plane. This will allow the sensor to respond to ambient air temperature measurements significantly faster than in systems in which the copper plane is coated by solder mask. Add a physical gap between the plane around the sensor and the planes of the rest of the PCB. Hatched GND planes in the main section of the PCB further reduce heat flow from other ICs to the sensor.

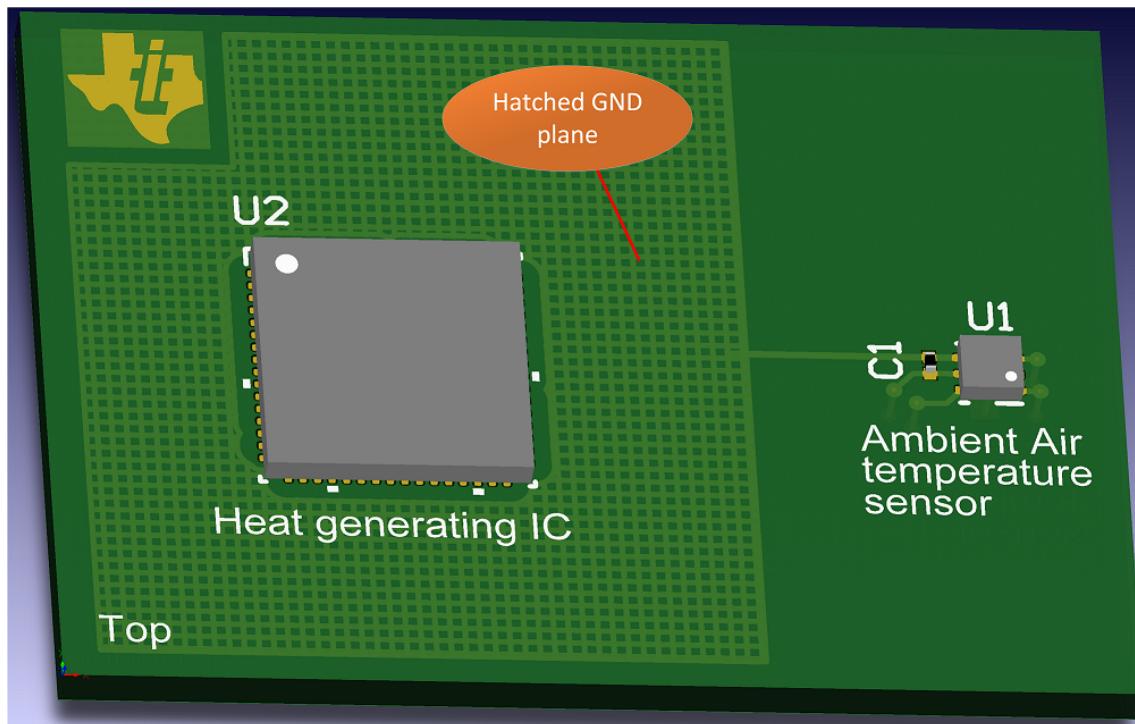


Figure 13. Hatched GND Plane (Top View)

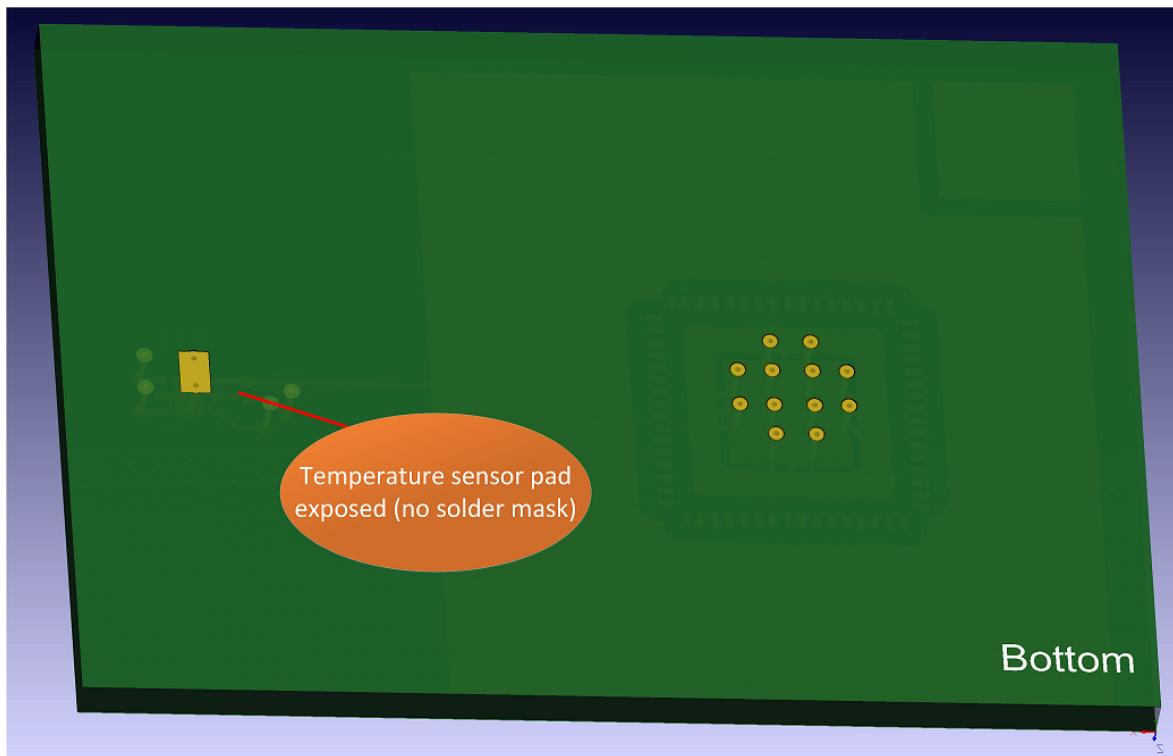
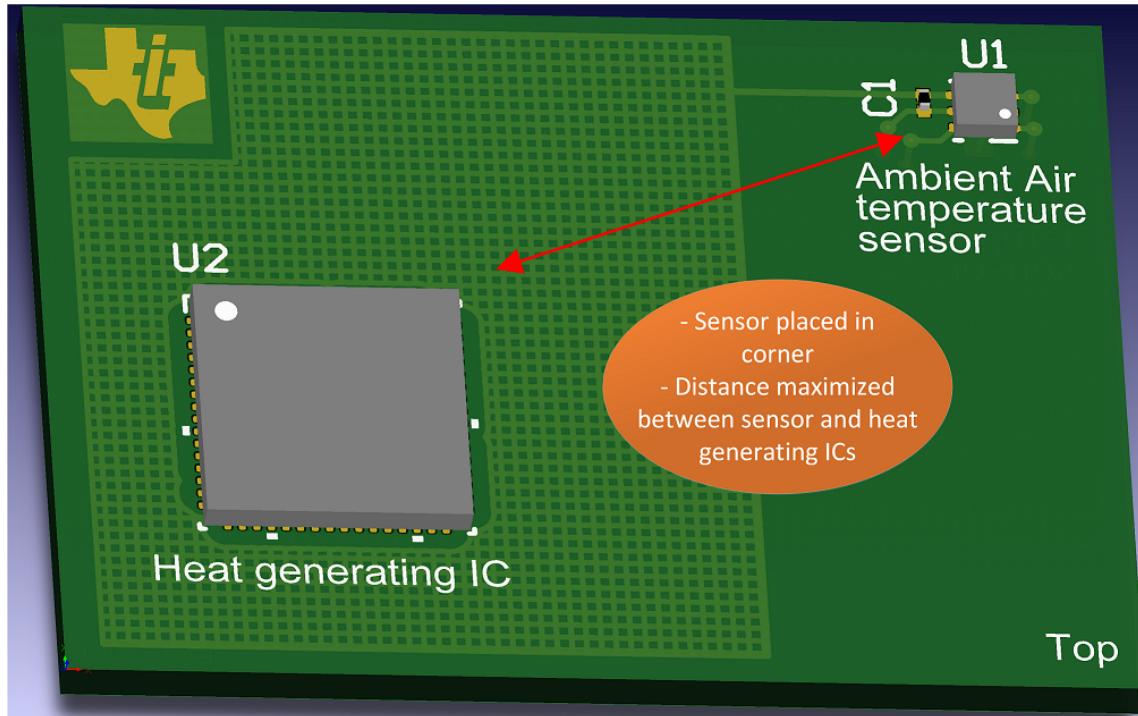


Figure 14. Exposed Sensor GND Pad (Bottom View)

## 2.2 Partitioning the PCB

The temperature sensor should be in an area of the PCB that is as far away from the main heat generating ICs, as shown in [Figure 15](#). This can be achieved by placing the sensor in a corner of the PCB, away from other components. Doing so will minimize the effect that other components on the board have on the temperature reading.



**Figure 15. Sensor Placed In PCB Corner**

## 2.3 Isolation Island

If feasible, a partial router trace around the temperature sensor creates an isolation island which greatly reduces heat transfer from the main heat source to the sensor. Heat transfer is reduced because the thermal conductivity of air compared is significantly lower than the thermal conductivity of FR4. An example of an isolation island is shown in Figure 16.

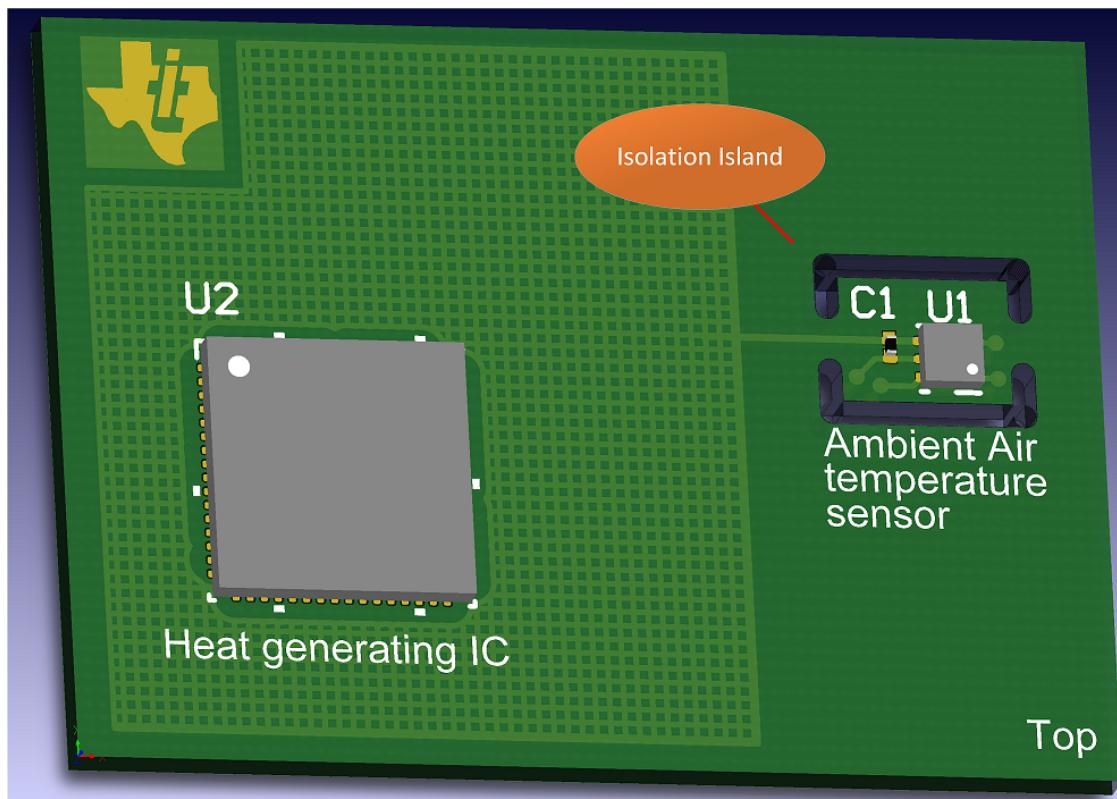
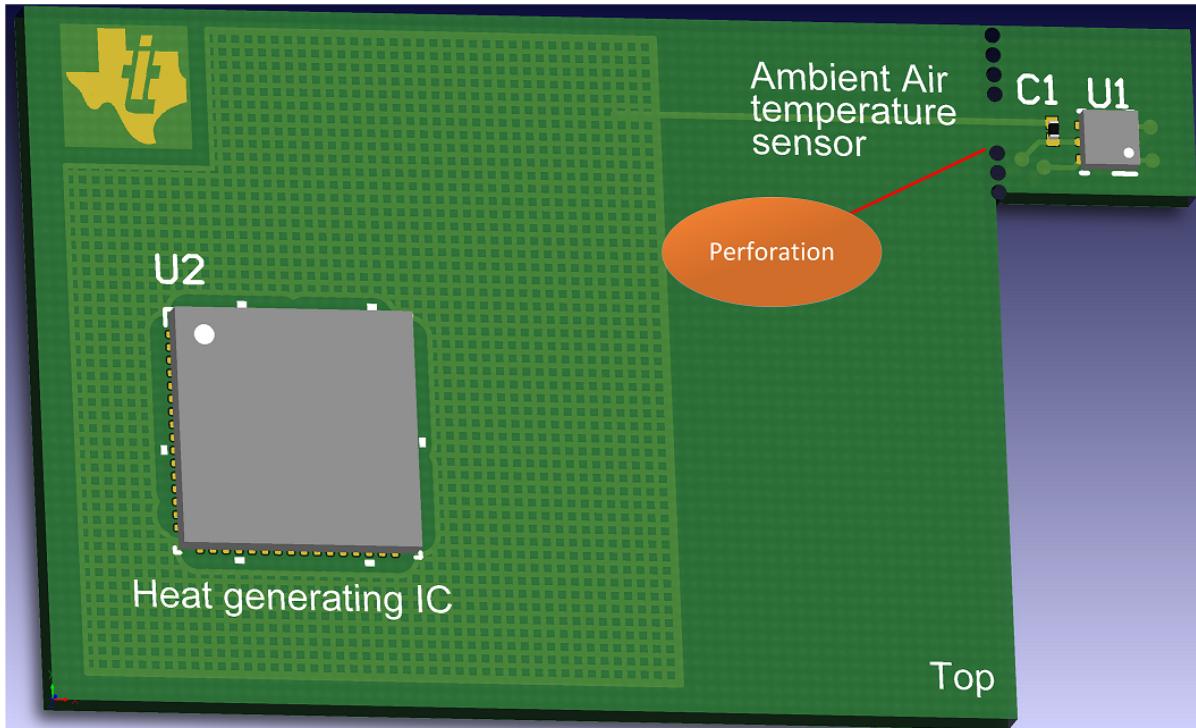


Figure 16. Isolation Island Significantly Reduces Heat Transfer From Main Heat Source To Temperature Sensor

## 2.4 Perforation

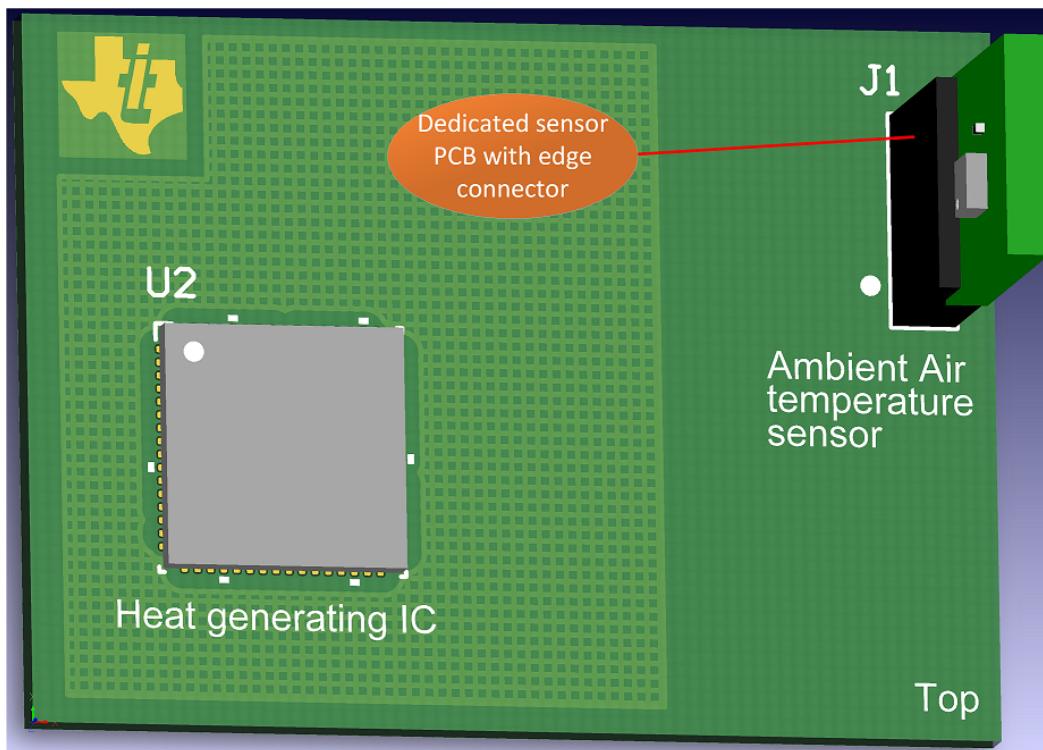
As an alternative to the isolation island discussed in [Section 2.3](#), it is possible to add a perforation around the section with the temperature sensor, as shown in [Figure 17](#). Doing so greatly minimizes the amount heat transfer through the FR4 material. An example of a perforated PCB is the TMP116 Evaluation module.



**Figure 17. Perforation Reduces Heat Transfer From Heat Source To Temperature Sensor**

## 2.5 Edge Connector

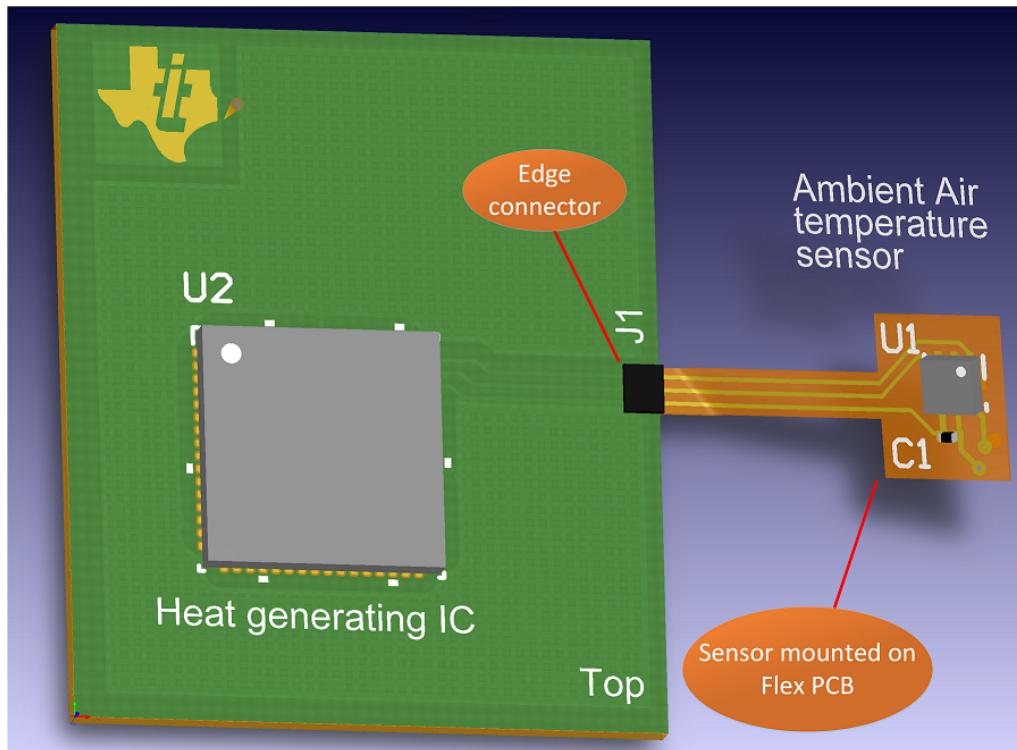
A miniature PCB that contains only the temperature sensor and is mounted using an edge connector to the main PCB is a highly effective method for avoiding significant heat transfer from the main PCB to the temperature sensor. The edge connector should ideally be mounted at a location away from major heat sources on the main PCB so that radiated heat from ICs does not interfere with the temperature reading. This technique is illustrated in [Figure 18](#)



**Figure 18. Dedicated Sensor PCB With Edge Connector**

## 2.6 Controlling the Thermal Mass of the PCB

The thermal mass is a material's ability to store heat energy. A material with a high thermal mass will respond to temperature fluctuations more slowly than one with a lower thermal mass. To keep the thermal mass of the PCB as small as possible, it is advised to use a thin PCB (e.g. 0.8mm rather than the standard 1.6mm FR4 thickness), or even place the temperature sensor on a flex PCB as shown in [Figure 19](#). When combined with either one of the techniques for reducing PCB surface area (see [Section 2.3](#) and [Section 2.4](#)), a thin PCB can correspond to changes in air temperature much more rapidly than a large, thick PCB with a high thermal mass.



**Figure 19. Dedicated Sensor Flex PCB With Edge Connector**

### 3 Design Guidelines For Component Temperature Measurement

In many scenarios, system designers want to monitor the die temperature of a power hungry IC such as a MCU, GPU, ASIC, FPGA, DSP, or CPU in order to dynamically adjust its performance, control fan speed in the system, or initiate a safe system shutdown. Using a remote temperature sensor such as TMP46x, TMP43x or TMP411 is the preferred method for monitoring temperature of ICs as long as they have a suitable integrated temperature diode. Guidance on product selection for remote temperature sensors is available [here](#). Application note [Optimizing Remote Diode Temperature Sensor Design](#) contains details on compensation techniques and layout practices for remote temperature sensors.

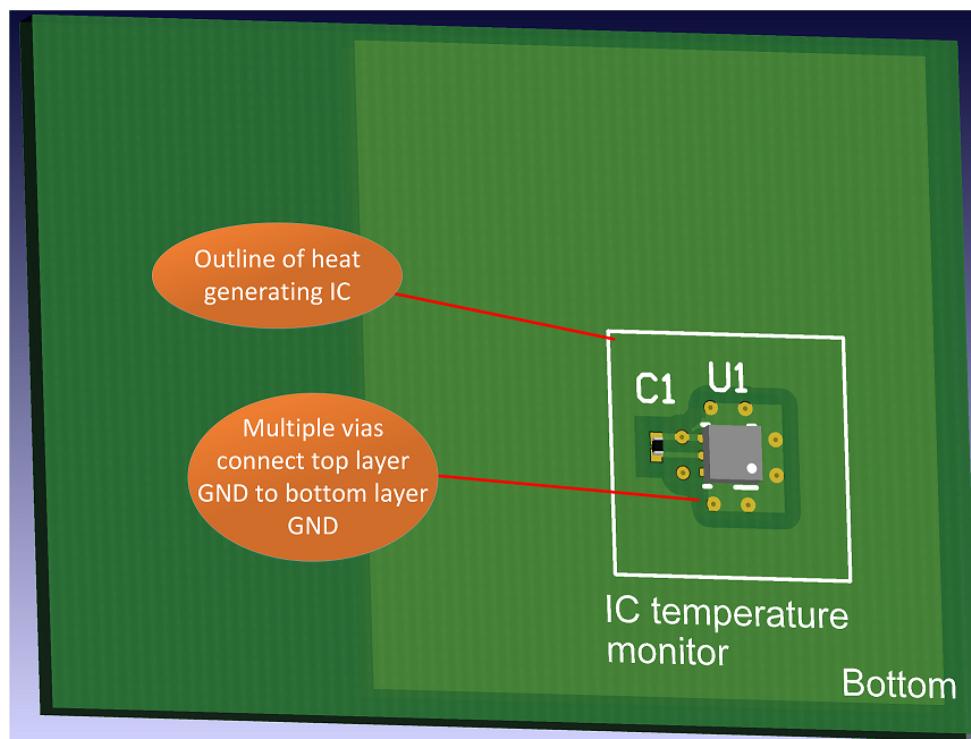
If the IC does not contain a suitable temperature sense diode or if a remote sensor cannot be used for any other reason, then a local sensor or an external diode can be used instead. The following sections provide guidelines on obtaining the most accurate measurement and fastest response of a local sensor that monitors the temperature of another IC.

#### 3.1 Location

The sensor location should be chosen to be as close as possible to the heat source that is to be monitored. Avoid any perforations or slits in the PCB between the IC and the temperature sensor, as they will reduce the thermal response.

##### 3.1.1 Bottom-Side Mounting

If possible, mount the temperature monitor on the bottom side of the PCB, directly below the heat source, as shown in [Figure 20](#). As explained in section [Section 1.3.5](#), vias are a highly effective method for transferring heat quickly from one side of the PCB to the other because of the superior thermal conductivity of copper compared to FR4. Therefore, using as many parallel vias as feasible or using filled conductive vias to transfer heat from the heat source to the temperature monitor creates a fast thermal equilibrium between the two ICs. A QFN or DFN package with a DAP further helps to decrease the thermal resistance path between the vias and the sensor die.



**Figure 20. Sensor Mounted On Opposite Side Of Heat Source; Multiple Vias Ensure Fast Heat Transfer**

### 3.1.2 Ground Plane Considerations

If it is not practical or cost effective to place the temperature sensor on the opposite side of the heat source, place it on the same side as close as possible to it, as shown in [Figure 21](#). The most effective way of creating a thermal equilibrium between the heat source and the temperature monitor is through the ground plane. Use a solid ground plane that extends from the heat source to the temperature sensor.

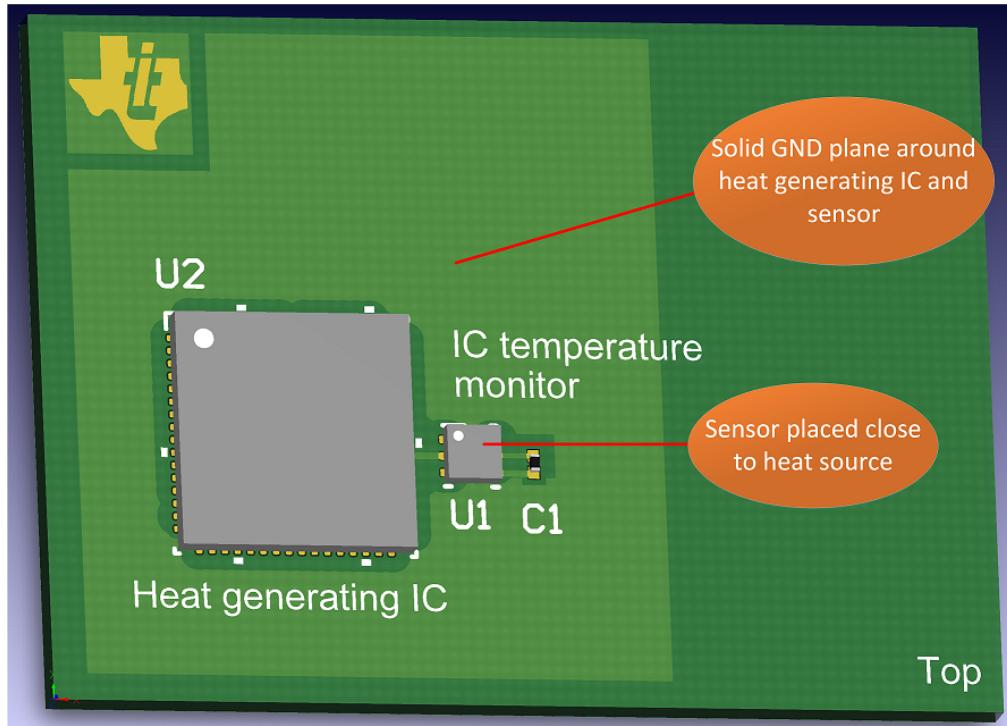


Figure 21. Shared GND Plane Helps With Thermal Equilibrium

## 4 Summary

When designing a PCB with a temperature sensor, the system designer needs to consider if the objective is to measure ambient air temperature or to monitor the temperature of a nearby power hungry IC. This application note discusses the background and layout techniques for both objectives. For ambient air temperature measurements, physical isolation between the sensor and heat generating components on the same PCB is critical. Additionally, consideration of thermally conductive paths such as GND planes play an important role to ensure that nearby components do not cause false ambient temperature readings. In contrast, measuring the die temperature of ICs requires careful consideration of sensor location and a path with high thermal conductivity to create a fast thermal equilibrium between the sensor and the heat generating IC.

## Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

<b>Changes from Original (July 2017) to A Revision</b>	<b>Page</b>
• Corrected <a href="#">Figure 8</a> .....	6
• Changed <a href="#">Equation 4</a> .....	8
• Changed <a href="#">Equation 5</a> .....	8
• Changed <a href="#">Equation 9</a> .....	9
• Changed <a href="#">Equation 10</a> .....	9
• Changed <a href="#">Equation 12</a> .....	10

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# Chapter 3: Temperature sensing application examples

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## Overview

Temperature sensing is crucial in a wide variety of applications for:

- Protection: instant notifications when a system crosses a thermal limit in order to prevent damage or maintain safety.
- Monitoring and controlling system temperature: to take appropriate corrective actions.
- Calibration: to compensate for temperature-sensitive sensors and applications while maintaining high accuracy and functionality.

Chapter 3 discusses several temperature sensing application examples and the implementation of TI's temperature sensor portfolio in these applications:

• **Multipoint temperature monitoring.** It might be necessary to place temperature sensors in multiple locations to monitor systems and subsystems. For example, temperature sensors are primarily placed on PCBs next to components that need measuring, or mounted to heat sinks, in the cavity beneath a socketed processor, or daisy-chained together in a cable. Designers can also use remote temperature sensors to monitor the temperature across a P-channel N-channel P-channel bipolar junction transistor and collect measurements from several PCB locations simultaneously.

• **Body temperature sensing.** Understanding a patient's temperature is a critical first step in clinical diagnosis and an important concern for athletes. Wearable temperature monitors have design trade-offs between power usage, size, system performance (radio frequency, accuracy), and comfort. Beyond ultra-high accuracy, industry trends favor compact, wearable form factors. TI's temperature sensors (up to 0.1°C accuracy) meet American Society for Testing and Materials E1112 standards for medical thermometers and can help keep battery-powered wearables compact and comfortable.

• **Fluid temperature measurement.** Many metering and industrial processes must have either a direct measure of a fluid's temperature or use temperature data for compensation to more accurately calculate the volumetric rate of flow. Fluid temperature monitoring requires small sensors (to reduce resistance in the flow) that consume low power (for cases with flammable fluids). TI's low-power analog and digital solutions have an accuracy comparable to Class-AA resistive temperature detectors, draw as little as 6.3 µW and reduce the amount of cabling compared to a four-wire resistive-temperature detector configuration.

• **Simple temperature limit alerts.** In some applications, continuous temperature collection is unnecessary. However, it's critical for systems to stay above or below a temperature threshold to prevent thermal damage. TI's temperature switches and digital temperature sensors enable simple temperature monitoring to detect when a temperature crosses a limit with hysteresis. An external resistor (either pin-programmable, factory-programmed or software-configurable over I2C) can select threshold trip points.

• **Cold junction compensation.** Temperature drift factors into correcting temperature shifts in a system. Temperature affects everything from passive components (resistors, capacitors) to active components (amplifiers, data converters, references, clocks) to optical components (intensity changes, spectral shifts, sensitivity, noise). Cold junction compensation increases the temperature accuracy of a thermocouple. TI's highly linear, high-accuracy integrated circuit (IC) temperature sensors provide feedback to correct temperature shifts in precision systems and condense the number of additional components.

• **Processor die temperature monitoring.** The effective monitoring of processor die temperature requires high-temperature accuracy and optimal sensor placement. Integrated thermal diodes or external temperature sensors are more accurate alternatives to built-in low-accuracy internal sensors. Remote temperature sensors have inputs for direct connections to the processor's integrated diodes. If there are no integrated diodes, it is possible to set high-accuracy IC sensors external to the processor. These alternatives maximize temperature accuracy and maintain high reliability over time.

• **Ultra-high accuracy temperature sensing.** Temperature monitoring is perhaps one of the most important parameters to know for a system, yet it can be difficult to measure accurately. These challenges are due to factors that can influence the accuracy of a temperature sensor like sensor self-heating, calibration drifts and distance from heat sources. TI's temperature sensors were designed to overcome these challenges and provide accurate temperature readings. Engineers can leverage these devices to more easily incorporate temperature sensing into existing system designs.

# Efficient Cold Chain Management With Scalable High-Accuracy Temperature Sensors



From producers to consumers, it is important that perishable items, especially food and medicines, reach the end consumer in fresh and viable condition, so as to maintain their nutrients and efficacy. To ensure quality and product safety, manufacturers specify the temperatures at which the items must be transported and stored.

Before reaching the consumer at their local grocery, perishable produces like fruits, vegetables or frozen meals, spend a significant time in transportation and on the shelves of large refrigeration units as shown in [Figure 1](#). The same is true of pharmaceuticals such as vaccines. Thus it becomes crucial that these items be maintained at the correct temperature.

Cold chain management and Good Distribution Practices (GDP) ensure that the right conditions are met during every phase of the life cycle of packaged and perishable items. At the same time it ensures that anytime a possible excursion outside the storage temperature is about to occur, an appropriate action can be taken by the operator either during transportation or during storage to ensure that there is as little wastage as possible.



Figure 1. Typical Grocery Aisle

## Cold Chain Topology

Use of temperature sensors with gauges and simple analog sensors, have been quite common for a long time. However, with advances in semiconductor technology and the fact that most cold chain management is done in the temperature range of  $-40^{\circ}\text{C}$  to  $+10^{\circ}\text{C}$ , integrated temperature sensors are the best option for cold chain management in these

temperature ranges. Based on the application, there are different topologies that may be deployed. In the point to point topology like that represented in [Figure 2](#), a single microcontroller (MCU) is connected to a temperature sensor that may be an analog output or a digital output sensor. This is useful when managing a pallet of goods or a temperature controlled container during shipping.

The TMP116 temperature sensor operates from  $-55^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$  with  $0.2^{\circ}\text{C}$  accuracy from  $-10^{\circ}\text{C}$  to  $+85^{\circ}\text{C}$ . It contains I<sup>2</sup>C and SMBus-interface communication, as well as an integrated EEPROM memory. There is no calibration required for the TMP116, and minimal current is consumed which minimizes self-heating. The TMP116 is typically found in applications with a heavy focus on high accuracy.

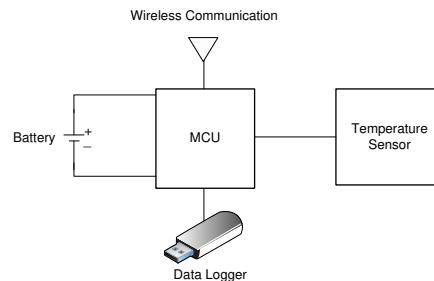


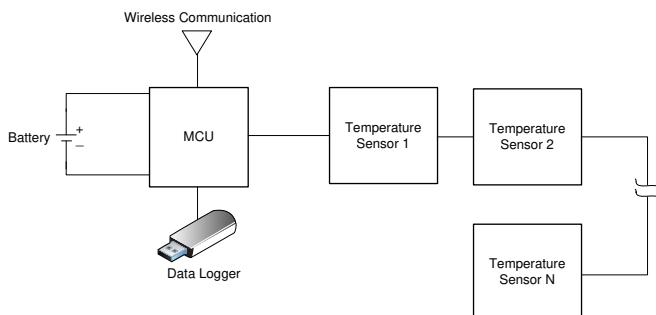
Figure 2. Point-to-Point Topology

When sensing multiple locations like display in refrigerators or in reefer containers, the cost of a single MCU is too high to be implemented multiple times in the entire system. In such cases, the most common topologies that are used are the star, daisy chain ([Figure 3](#)) or shared bus, with one MCU being the host controller for multiple sensors. A star topology allows easy fault isolation if one branch fails and may use both analog and digital output temperature sensors, but has a higher cost of implementation as the controller peripheral count is higher because of which the system cannot scale very well and the cost of assembly and cable itself.

On the other hand, with shared bus, the scalability can easily be addressed with digital temperature sensor that share the line and may be individually addressed using in band addressing like the case of

I<sup>2</sup>C bus or out of band signaling using chip select which is the case with SPI. However, reliable power delivery and signal integrity over a long chain may be a concern.

The daisy chain does not require out of band signaling and rather uses in band addressing scheme. As each stage of the chain acts as a buffer for the next chain, signal integrity may be maintained over longer distances.



**Figure 3. Daisy Chain of Temperature Sensors**

Irrespective of which stage of cold chain management is being monitored, electronic systems provide a unique advantage of not only logging the temperature of the pallet or refrigeration unit, but also providing thresholds that generate alert above a certain threshold. Such events can be visually communicated through audio or visual alerts like a buzzer or flashing LED, but also can be integrated into cloud services using either wired or wireless MCUs, allowing round the clock monitoring and data logging.

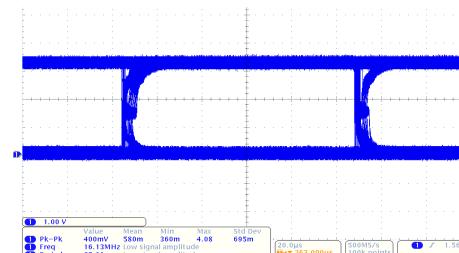
#### Daisy chain topology in cold chain management

The TMP107 is a digital output temperature sensor that supports a total of 32 daisy-chained devices and is ideal for replacing NTC thermistors in cold chain management, because of its high accuracy and ease of system wide scalability without the need to add additional MCUs. The TMP107 has a maximum accuracy specification of  $\pm 0.4^{\circ}\text{C}$  in the range of  $-20^{\circ}\text{C}$  to  $+70^{\circ}\text{C}$  and  $\pm 0.55^{\circ}\text{C}$  in the range of  $-40^{\circ}\text{C}$  to  $+100^{\circ}\text{C}$  with a temperature resolution of 0.015625°C.

With an automated address assignment, the TMP107 allows system developers to write software without the need to assign the address at each sensor node as the system is scaled by adding additional sensor node. At the same time, with the use of a push-pull communication IO, the system is made more resilient against the noise affecting the temperature value over long cables. This allows for data transfers over span lengths of 1000 feet between adjacent devices in the chain.

Figure 4 shows the signal integrity of the communication interface at 9600 bps. The

communication interface of SMAART Wire™ uses UART bus which is a standard peripheral on almost all MCU, making it easier develop software, than using bit-banged approach. At the same time, with a daisy chain implementation, it makes it easier to identify the location of a cable break, which enables easy maintenance and overall system reliability.



**Figure 4. Eye Diagram for TMP107**

The current consumption of the TMP107 when performing temperature conversions with an active bus communication is typically 300  $\mu\text{A}$ . It has a shutdown current of 3.8  $\mu\text{A}$  in low power mode. With a wide operating voltage of 1.7 to 5.5 V, the low current consumption makes it ideal for battery operated systems during transport phase of cold chain management. At the same time the baud rate can be increased for more real time update as may be the case when storing frozen food items.

Additionally, TMP107 allows the configuration and temperature limits to be stored to its internal non-volatile memory. This enables the device to be automatically configured on power up, eliminating the need for individual device configuration to be performed making the system operational faster. It also has 8 EEPROM locations providing up to 128 bits of EEPROM to store user information or calibration information.

In conclusion, different types of temperature measurement solutions can be used to efficiently track temperature in cold chain applications. The TMP116 could be ideal for monitoring a single location and has accuracy suitable for both produce and pharmaceuticals, while the TMP107 has the right combination of accuracy, power consumption and features to support a battery-based cold chain management system where multi-point monitoring is needed.

**Table 1. Device Recommendations**

Device	Optimized Parameters	Performance Trade-Off
TMP107	0.4°C accuracy and 32 devices in daisy chain	0.4°C accuracy may not be enough for pharmaceuticals
TMP144	Small form factor	16 devices in daisy chain and 1°C accuracy
TMP116	0.2°C accuracy across temperature	No daisy chain capability

# Design Challenges of Wireless Patient Temperature Monitors



## Introduction

Monitoring patient vitals in a clinical environment has traditionally been a job for expensive and heavily calibrated systems requiring patients to be tethered to bedside monitors. Wireless patient monitoring systems provide for both patient comfort and clinical convenience, provided they can still be made to operate within strict medical standards.

In the case of wearable temperature monitors, there are many design tradeoffs that must be considered for power consumption, size, system performance (in terms of both RF and accuracy), and patient comfort. Thinner flexible batteries provide greater comfort but may require more careful power management. Smaller, lower cost, designs suffer in terms of thermal isolation and RF performance. Optimal solutions for long term monitoring must make good use of board area to improve accuracy and signal integrity, while trying to keep current consumption as low as possible. System designers will have to balance these requirements alongside the comfort and experience of the patient.

## Standard Compliance for Thermometers

The governing standards for intermittent electrical patient thermometers are given in ASTM E1112 and ISO-80601-2-56. For standard compliant clinical temperature measurement applications under ASTM E1112, human body temperature monitors must produce readings within  $\pm 0.1^{\circ}\text{C}$  accuracy, and must read and display temperature from a minimum of  $35.8^{\circ}\text{C}$  to  $41.0^{\circ}\text{C}$ . At a bare minimum, any temperature monitoring design should include a sensing element able to meet these requirements after calibration.

TI recommends using the TMP117 ultra-high-accuracy digital temperature sensor for this purpose. The device itself has better than  $0.1^{\circ}\text{C}$  accuracy from 25 to  $50^{\circ}\text{C}$  and requires no calibration to exceed the requirements of both ASTM E1112, and ISO-80601. Additionally, the TMP117's low overall current draw and one-shot mode are ideal for battery operated applications. The digital I<sub>2</sub>C output of this device also greatly simplifies system design when compared with RTD or thermistor based solutions.

## Layout Considerations

Even with an appropriate sensing element, ensuring total system accuracy will still require care in terms of layout. For monitoring skin temperature an ideal layout will do all of the following:

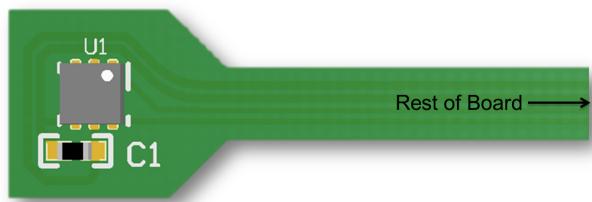
1. Maximize thermal isolation between the sensing

element and the other devices.

2. Minimize thermal mass surrounding the temperature sensing element for faster response.
3. Provide good thermal contact between the patient and the sensing element to minimize the temperature gradient between the sensor and the target.

## Optimizing Thermal Isolation & Mass

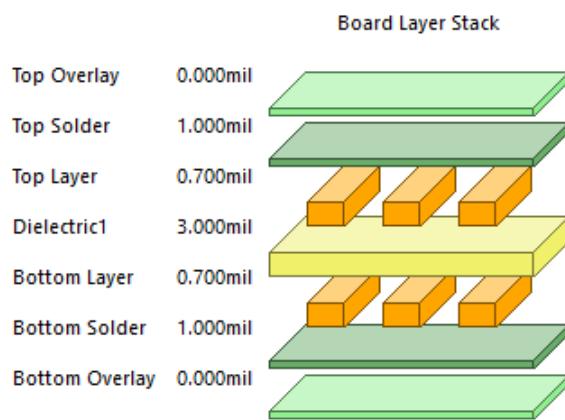
For optimal thermal mass and isolation, the recommendations in [Layout Considerations for Wearable Temperature Sensing](#) should be followed. Figure 1 shows an example of this for a skin temperature monitoring system. The TMP117 measuring temperature is extended from the rest of the PCB using a narrow arm to minimize thermal conductance from the rest of the board. Figure 2 shows the stack up for the same 2-layer flex PCB. Using a flex-board also helps to reduce total thermal mass, which improves thermal response time of the patient monitor. Copper fills between the top and bottom side of the board should be omitted to avoid drawing heat away from the TMP117, and increasing the thermal mass.



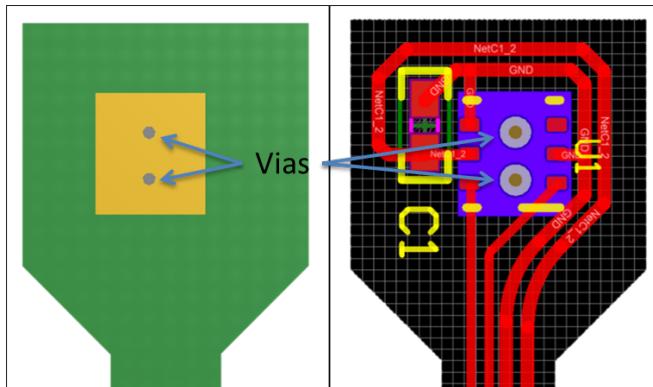
**Figure 1. TMP117 (U1) on Flex PCB, using an extended arm isolates the IC from being influenced by heat from other devices.**

## Thermal Contact

Reliable measurement of the patient's skin temperature requires good thermal contact between the patient to be monitored and the sensing device. This works in conjunction with the thermal isolation from the rest of the board to ensure that the temperature being reported is as close as possible to the actual skin temperature of the patient. With the TMP117, a solid copper pour and contact vias can be used to provide a thermal path from the underside of the board as shown in Figure 3. The pad contacts the wearer's skin directly, and ensures the primary heat source for the device is from the person to be monitored.



**Figure 2. Example flex layer Stack, thickness should be minimized to reduce thermal mass.**



**Figure 3. Copper pour underneath TMP117 (Left), topside layout for TMP117 (U1, Right). The vias underneath the TMP117 and the copper pour provide a thermal path between the patient's skin and the device.**

### Self-Heating

Regardless of the choice of sensing element and proper layout, the stringent accuracy requirements for medical thermometers will require that device self-heating be taken into consideration. Some self-heating will always be present from the resistive losses of the chosen sensing element. The TMP117, may be configured for one-shot mode conversion and be kept in shutdown mode between successive reads, to minimize self-heating. Individual temperature readings (using a configurable number of averaged readings) can be triggered using the one-shot feature of the device. Human body temperature will not conventionally exhibit change on the order of seconds, so taking these readings at 10 to 60 second intervals is sufficient to monitor patient temperature over long periods. This method has the added benefit of extending the active-battery life of the system.

### System Power

Power requirements will vary based on overall system design, but most wireless patient monitors will need to have enough energy storage for several years of shelf life, and at least 48-72 hours of active life. Coin-cell batteries can easily exceed these requirements for energy capacity, but they are entirely rigid and may be uncomfortable to device wearers. In the case of patches which are not intended to be reused, a coin-cell based solution can also be extremely wasteful.

An alternative option for energy storage is to use thin-film, flexible batteries. Due to small storage capacities, using these batteries will require that total system power consumption be minimal. For only intermittent temperature monitoring, systems powered with flexible batteries can exceed the requirements for multiple years of shelf-life and 48-72 hours active time. The design trade off between current consumption and additional features must be made by the system designer.

### Making System Tradeoffs

If the system is required to meet the requirements of ASTM E1112 and ISO ISO-80601-2-56 following the recommendations on layout is essential, but there are other system design considerations to be made. For patient comfort, non-temperature-sensing devices and the RF region should be kept in as small an area as possible. Keeping the populated region of the board compact will reduce the portion of the monitor which feels rigid to the wearer.

For RF communication, any wireless protocol that can be made to work on a flex PCB is acceptable. Since most wearable patient monitors will want to keep power consumption low, a BLE wireless communication link is recommended. If the information being transmitted from the monitor is only temperature, the monitor can be configured to broadcast the temperature reading alongside its pairing ID. Sending the information in this manner removes the requirement for an actual connection to be made and maintained, and will reduce system power consumption even further.

To get more information on these topics, or for general tips when measuring temperature, please see the additional resources linked to in [Table 1](#).

**Table 1. Related Materials**

Document Type	Description
Application Report	<a href="#">Wearable Temp-Sensing Layout Consideration Optimized for Thermal Response</a>
Tech Note	<a href="#">Layout Considerations for Wearable Temperature Sensing</a>
Tech Note	<a href="#">Precise Temperature Measurements with TMP116</a>

# RTD replacement in heat meters using digital temperature sensors



A heat meter is a device which measures thermal energy by measuring the flow rate and the change of temperature between the inlet and outlet of the system. These devices are very commonly found in both industrial plants to measure boiler outputs and in residential heating and cooling systems to measure the heat delivery.

Since the measurement of thermal energy requires both flow rate and temperature, it is imperative that they be measured accurately. Accuracy is important because an inaccurate measurement can result in under billing or over billing.

To avoid measurement errors, a resistance temperature detector (RTD) is commonly used. An RTD is a passive component whose resistance changes with temperature. RTDs are made using metals—such as platinum, copper, or nickel—and support a wide temperature range (approximately  $-200^{\circ}\text{C}$  to  $+850^{\circ}\text{C}$ ). The accuracy of a Platinum RTD is defined by its class. The IEC/EN60751 standard defines four RTD classes—Class C, B, A, and AA—where Class C is the least accurate and Class AA is the most accurate. The lower accuracy classes will have a larger temperature range. For example, a Class C thin-film RTD covers the temperature range of  $-50^{\circ}\text{C}$  to  $+600^{\circ}\text{C}$ , while a Class AA thin-film RTD covers the temperature range of  $0^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$ .

Most RTD applications use a current source to excite the RTD element and create a voltage difference across the RTD, as shown in Figure 1. This voltage is proportional to the resistance of the RTD and the excitation current. The voltage potential is amplified, converted to a digital output by an ADC, and then fed into an MCU where a lookup table is used to convert the digital output to temperature.

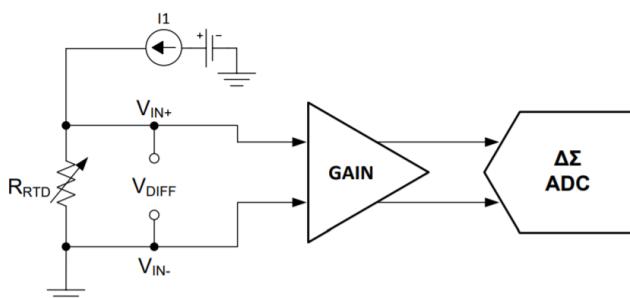


Figure 1. Basic RTD Circuit

## RTDs in Heat Meters

Solid-state heat meters are gaining popularity in heat energy billing for residential and industrial users. These meters come with both flow measurement on either the inlet or outlet pipe and a pair of matched RTD temperature probes on both inlet and outlet pipes. Figure 2 shows a block diagram of a heat meter system using RTDs.

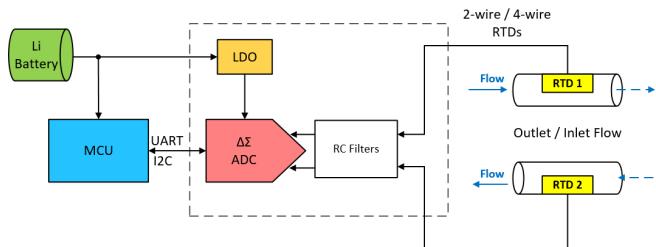


Figure 2. Fluid Temperature Measurement With RTD

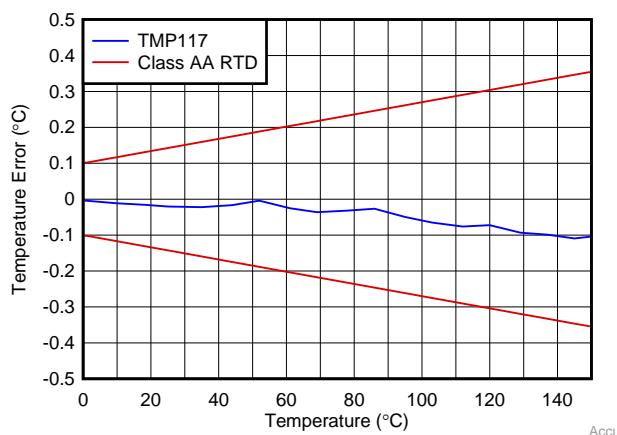
Low-power and high-accuracy RTDs in heat meters are desired because heat meters are standalone, battery-powered systems in most residential units. The system's ability to quickly wake from power-off mode, sample the RTD temperature, and return to power-off mode extends battery life and minimized energy consumption.

However, these system require that the RTDs are well-matched and have matched traces to read the differential measurement correctly. At the same time, the system cost and complexity requires careful design consideration and costly calibration. High-accuracy digital temperature sensors like the TMP117 can provide a cost-optimized, yet equally accurate replacement for RTDs.

## Replacing RTD With TMP117 Digital Temp Sensors

The TMP117 is a digital temperature sensor designed for low-power, high-accuracy applications. The device provides a 16-bit temperature result with a resolution of  $0.0078^{\circ}\text{C}$ , along with a typical factory-calibrated accuracy of  $\pm 0.1^{\circ}\text{C}$  across  $-20^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$  with a maximum accuracy specification of  $\pm 0.3^{\circ}\text{C}$  over the temperature range of  $-55^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$ , which exceeds the accuracy of a Class AA RTD in the same range.

Figure 3 illustrates the accuracy specification of the TMP117 vs an RTD. The graph clearly shows that accuracy specification for the TMP117 can easily outperform that of a Class AA RTD.



**Figure 3. TMP117 vs. RTD Class-AA Accuracy**

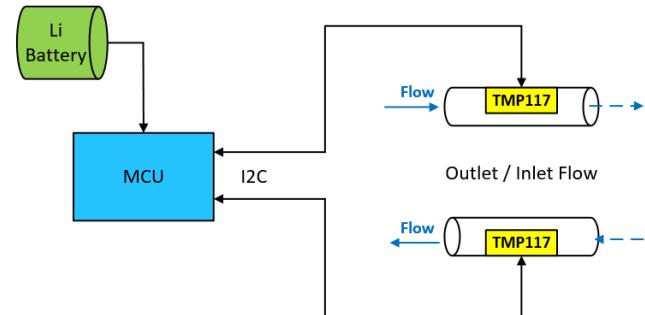
The TMP117 features a shutdown mode where the device aborts the active running conversion and enters a low-power shutdown mode where it typically consumes 250 nA of current. It can perform quick, 15.5-ms temperature conversions using the one-shot conversion mode at an active current as low as 3.5  $\mu$ A for a duty cycle of 1 Hz. After completing a one-shot conversion, the device returns to low-power shutdown mode.

Also, the device features an offset register that automatically applies a user-defined offset to the measurement results prior to an MCU read. As the TMP117 provides additional simplicity over an RTD, it eliminates the need for costly calibration, external circuitry, matched traces, and Kelvin connections easing the system designers task for accurate measurement.

Finally the TMP117 features a fast mode (400 kHz) I<sub>C</sub> communication. These specs make the TMP117 excellent for low-power consumption requirements, as well as quick power on-off cycling necessary in Heat Meter systems.

The TMP117, with a comparable accuracy as the Class AA thin-film RTD while consuming only a fraction of the power required for temperature measurement, is designed for a variety Heat Meter applications.

**Figure 4** shows the same block diagram of Heat Meter system using the TMP117 to replace the RTDs. By using the TMP117 instead of an RTD, designers can simplify both their software and system architecture to save time, board space, and costs.



**Figure 4. Fluid Temperature Measurement With TMP117**

Overall, the high-accuracy TMP117 temperature sensor with digital interface, fast conversion, and extremely low-power shutdown mode eliminates the need for multiple narrow-tolerance discrete components and integrated devices, which can save PCB space, complexity, and cost in Heat Meters.

COLLATERAL	DESCRIPTION
TMP117	<i><a href="#">±0.1°C Accurate Digital Temperature Sensor with Integrated NV Memory</a></i>
TMP116	<i><a href="#">±0.2°C Accurate Digital Temperature Sensor with Integrated NV Memory</a></i>
Application Report	<i><a href="#">RTD Class-AA Replacement With High-Accuracy Digital Temperature Sensors in Field Transmitters</a></i>
Application Report	<i><a href="#">Replacing Resistance Temperature Detectors With the TMP116 Temp Sensor</a></i>
Application Report	<i><a href="#">Precise Temperature Measurements with TMP116</a></i>

# How to protect battery power management systems from thermal damage



## Introduction

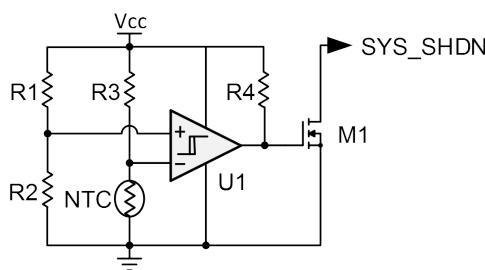
With a growing demand for portable personal electronics, battery power management systems are becoming increasingly important for stringent design, reliability, and safety requirements. Nowadays, customers expect their personal electronics to have a longer battery life, a shorter charge time, and a smaller form factor. The increased charge and discharge currents, as well as the smaller form factor, make the battery packs vulnerable to thermal damage. In addition, different battery technologies have different charging and discharging requirements that are sensitive to temperature as shown in [Table 1](#).

Typically, batteries can be discharged over a wider temperature range, but the charge temperature is limited. Note: fast charging can be done safely if the cell temperature is kept between 10°C and 40°C. These temperature limits are tied to the battery cell chemistry due to its temperature dependent chemical reaction. If charged too quickly, the cell pressure can build up and may lead to venting and reduced battery life. If the operating temperature is too high, cell degradation can occur and may result in thermal runaway and explosion. On the other hand, if the temperature is too low, irreversible cell chemical reactions can occur and shorten battery life. Thus, battery temperature monitoring is very critical for battery management systems.

**Table 1. Common Charge and Discharge Temperature Limits for Various Batteries**

Battery Type	Charge Temperature	Discharge Temperature
Lead Acid	-20°C to 50°C	-20°C to 50°C
NiCd, NiMH	0°C to 45°C	-20°C to 65°C
Li-ion	0°C to 45°C	-20°C to 60°C

## Thermal Protection Solutions

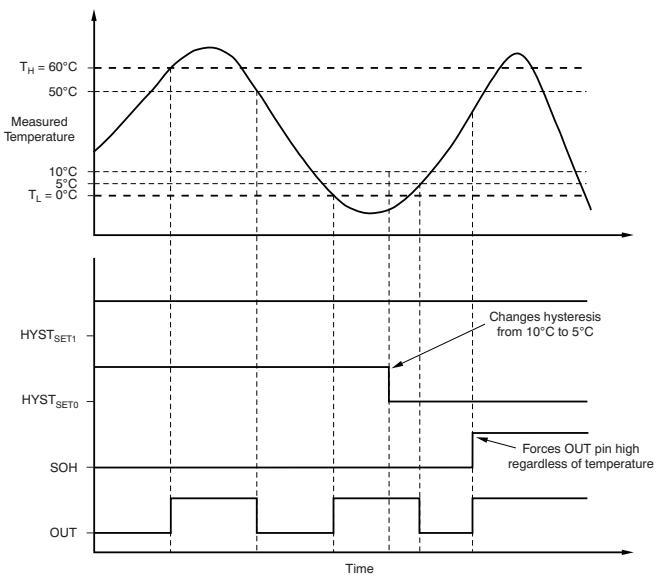


**Figure 1. Example Discrete Implementation of a Temperature Switch**

To protect battery management systems (BMS) from thermal damage, either discrete or integrated temperature-sensing solutions are used. A discrete solution consists of a thermistor, a comparator, and a voltage reference as shown in [Figure 1](#). This approach provides real-time thermal protection without interrupting the control processing system. Since battery applications require protection at both hot and cold temperatures, a temperature window comparator is better solution. An example of this output is displayed in [Figure 2](#). In this example, the trip points are set to 60°C and 0°C with a 10°C hysteresis. Note that the Set Output High (SOH) is a system diagnostic test feature that allows the user to force the output high independent of the temperature. The specific implementation depends on the application requirements:

- Features
- Cost
- Footprint
- Power
- Accuracy

Some of the key features that customers typically look for are hysteresis, trip point programmability, trip test, qualifications (like automotive and UL, for example), output type, channel count, and supply voltage range.



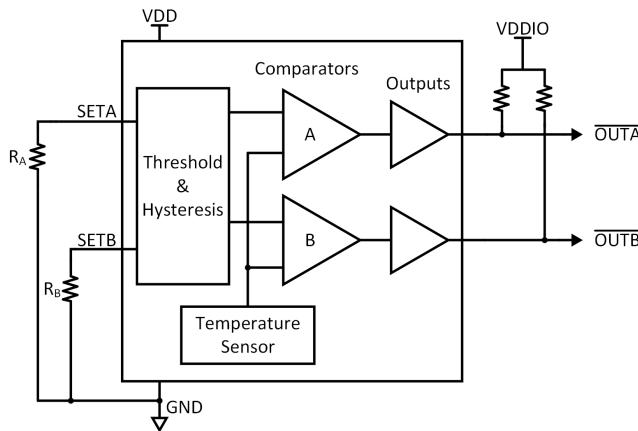
**Figure 2. Example Temperature Window Comparator Output Behavior**

## Discrete Solutions

It is quite common to see discrete implementations of a temperature switch using a Negative Temperature Coefficient (NTC) thermistor since the use of these devices are well established. Furthermore, thermistor solutions are often considered low-cost. However, due to the demanding requirements of thermal protection like guaranteed performance, discrete solutions often prove to be challenging and costly. Some of the key challenges when designing a discrete thermal protection solution are accuracy, reliability, and efficiency.

Due to the non-linear nature of NTC thermistors, maintaining an accurate trip point at high or low temperatures is difficult without using precision components that can increase system cost. Calibration is also not practical in these hardware-based switching applications. In addition, discrete implementations require multiple components to work together, which can decrease system reliability. Lastly, NTC discrete solutions dissipate a significant amount of power at hot temperatures because the NTC resistance decreases significantly.

## IC Solutions: Temperature Switch/Termostats



**Figure 3. TMP390 Block Diagram**

Integrated temperature switches, like the TMP303 and TMP390, are becoming more popular with battery power management systems. These devices typically have a temperature sensor, comparator, and voltage reference fully integrated in a single chip. These reduce design complexity by autonomously making decisions providing real-time thermal protection without interrupting the control processing system. The key advantages of these sensors are as follows:

- Autonomously enable thermal protection independent of control unit
- Zero software
- Guaranteed temperature accuracy for trip point with hysteresis
- Simple & cost effective over / under temperature

detection

- Various threshold programming options (resistor, pin programmable, factory preset)
- Some parts also offer analog output

The highly integrated sensor lowers the solution cost, which enables redundancy in safety applications.

TI provides a broad portfolio of temperature switch/thermostats like the TMP303 and TMP390. The TMP303 uses a window comparator and offers design flexibility through an extra small footprint (SOT-563), low power (5  $\mu$ A maximum) and low supply voltage capability (as low as 1.4 V). No additional components are required for operation and can function independent of microprocessors or microcontrollers. Seven trip points are available through different device options which can be programmed at the factory to any desired temperature. For applications that require different values, contact your local TI representative.

The TMP390, as shown in [Figure 3](#), is a resistor-programmable dual-output temperature switch with two internal comparators and two outputs. The TMP390 is offered in the same small package, has ultra-low power (1  $\mu$ A maximum) and low supply voltage capability (1.62 V). Both the hot and cold trip points can be configured at any desired temperature window with hysteresis options between 5°C and 30°C, using just two resistors. The separate hot and cold trip outputs generate independent warning signals to be interpreted by the microprocessor.

For alternative device recommendations, refer to [Table 2](#). To learn more about batteries, PCB guidelines, and protection, refer to the reference material in [Table 3](#).

**Table 2. Alternative Device Recommendations**

Device	Optimized Parameters	Performance Trade-Off
<a href="#">TMP708</a>	Resistor Programmable	Reduced Accuracy
<a href="#">TMP302</a>	Pin-programmable temperature switch	Increased power consumption
<a href="#">LM56</a>	Two internal comparators. Two overtemp outputs and one analog output	Increased power consumption

**Table 3. Related Documentation**

Literature Number	Title
<a href="#">Web Link</a>	BU-410: Charging at High and Low Temperatures
<a href="#">SNOA967</a>	Temperature Sensors: PCB Guidelines for Surface Mount Devices
<a href="#">SNOA996</a>	Protecting Control Systems From Thermal Damage

# Temperature compensation using high-accuracy temperature sensors

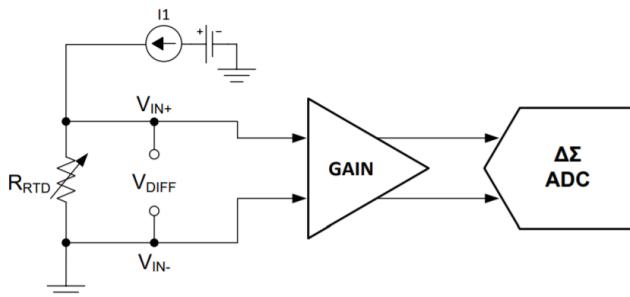


Field transmitters are used extensively in factory automation and control-to-sense process parameters like temperature, pressure, and flow rate, to name a few. The sensors used in the field transmitters are mostly analog sensors that must be sampled accurately using an analog front-end (AFE).

Due to the operational conditions that arise from the placement of the field transmitters, it may be subjected to wide varying temperature conditions and hence, require some form of temperature compensation. Traditionally, accurate temperature sensors like Platinum resistance temperature detector (RTD) are used in such temperature compensation systems.

RTDs are most commonly used temperature-sensing components in industrial applications where high accuracy and longevity is desired.

Most RTD applications use a current source to excite the RTD element and create a voltage difference across the RTD, as shown in [Figure 1](#). This voltage is proportional to the resistance of the RTD and the excitation current. The voltage potential is amplified, converted to a digital output by an ADC, and then fed into an MCU where a lookup table is used to convert the digital output to temperature.



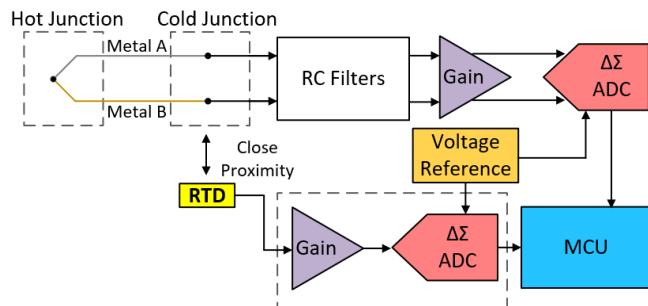
**Figure 1. Basic RTD Circuit**

## RTDs in Cold Junction Compensation Systems

Thermocouples are temperature-sensing devices that cover a large temperature range and are made by joining wires of two different metals. Due to seebeck effect, the output voltage is approximately proportional to the difference in temperature between the hot junction and cold junction.

Because the thermocouple measures a differential temperature, the temperature at the cold junction must be known to determine the temperature at the hot junction—this process is known as cold junction compensation (CJC).

Platinum RTDs are popularly used to measure the temperature of the cold junction due to their high accuracy. [Figure 2](#) shows a block diagram of a cold junction-compensated thermocouple system using an RTD reference.



**Figure 2. CJC Using RTD System Block Diagram**

However, while the system block diagram looks quite simple, there are a lot of considerations like noise, self-heating, and placement considerations that must be carefully analyzed. Also, RTDs are sensitive to trace routing and the trace lengths must be matched. A lot of these considerations may be optimized to reduce complexity and cost by replacing RTDs with temperature-sensing ICs like the TMP117 digital temperature sensor.

## Replacing RTD With TMP117 Digital Temp Sensors

The TMP117 is a digital temperature sensor designed for low-power, high-accuracy applications. The device provides a 16-bit temperature result with a resolution of  $0.0078^{\circ}\text{C}$ , along with a factory-calibrated performance of  $\pm 0.1^{\circ}\text{C}$  across  $-25^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$  or  $\pm 0.3^{\circ}\text{C}$  across the full operating range of  $-55^{\circ}\text{C}$  to  $+150^{\circ}\text{C}$ , which exceeds the accuracy of a Class-AA RTD. [Figure 3](#) depicts the results of an oil bath experiment conducted on the TMP117. The graph shows that TMP117 can meet the accuracy of a thin film Class AA RTD for a CJC application.

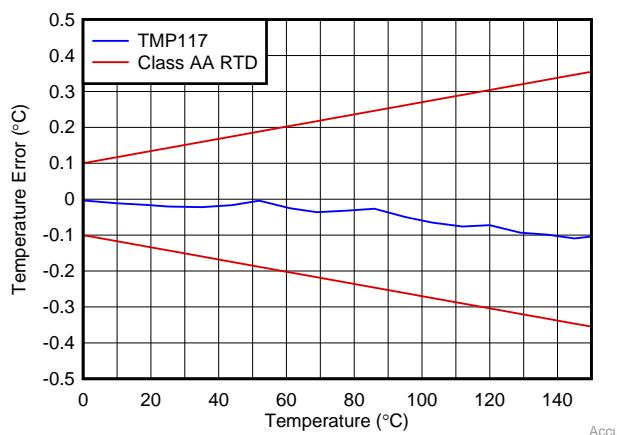


Figure 3. TMP117 vs. RTD Accuracy

The TMP117 features a shutdown mode where the device aborts the active running conversion and enters a low-power shutdown mode where it typically consumes 250 nA of current mitigating the effects of self-heating. When triggered by an MCU, the TMP117 can perform quick, 15.5-ms temperature conversions using the one-shot conversion mode with active current as low as 3.5  $\mu$ A for a duty cycle of 1 Hz. The output is a direct temperature read which does not require any linearization. After completing a one-shot conversion, the device automatically returns to low-power shutdown mode. This simplifies the software implementation versus an RTD, eliminating the need for calibration, external circuitry, matched traces, and Kelvin connections.

The TMP117 also features a fast mode (400 kHz) I<sub>C</sub> communication and an offset register that automatically applies a user-defined offset to the measurement results prior to an MCU read. These specs make the TMP117 excellent for low-power consumption requirements in CJC applications for field transmitters.

As described earlier, the TMP117 is comparable in accuracy to the Class AA thin-film RTD and consumes a fraction of the power of a PT100 RTD, when used in CJC applications. Figure 4 shows the block diagram for CJC systems using the TMP117 to replace the RTDs. The systems using the TMP117 eliminates the need for additional components, such as delta-sigma ADCs, programmable gain amplifiers, and RC filters, than the systems using RTD elements reducing the overall system cost. At the same time it reduces complex layout considerations because of a digital read out.

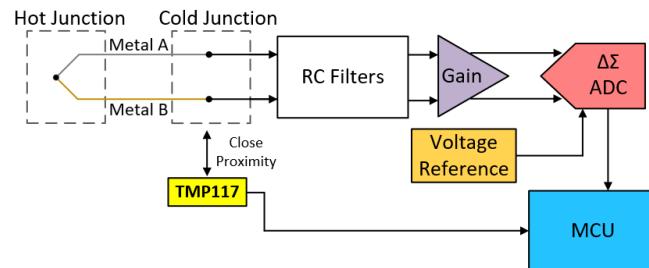


Figure 4. CJC Using TMP117 System Block Diagram

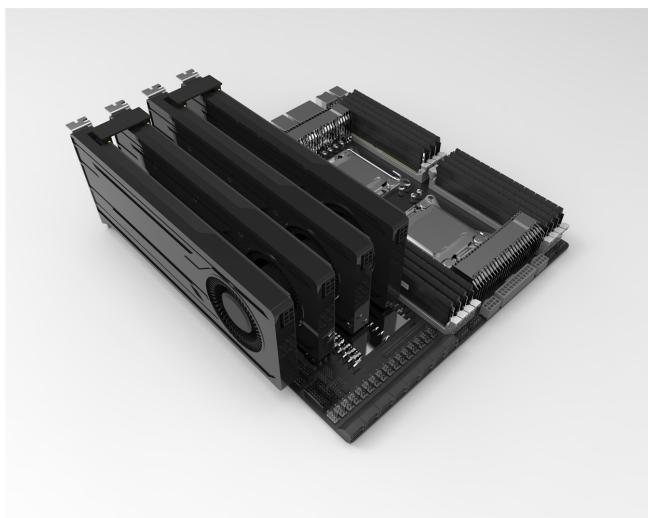
COLLATERAL	DESCRIPTION
TMP117	<i><math>\pm 0.1^\circ\text{C}</math> Accurate Digital Temperature Sensor with Integrated NV Memory</i>
TMP116	<i><math>\pm 0.2^\circ\text{C}</math> Accurate Digital Temperature Sensor with Integrated NV Memory</i>
Application Report	<i>RTD Class-AA Replacement With High-Accuracy Digital Temperature Sensors in Field Transmitters</i>
Application Report	<i>Replacing Resistance Temperature Detectors With the TMP116 Temp Sensor</i>
Application Report	<i>Precise Temperature Measurements with TMP116</i>

# High-Performance Processor Die Temperature Monitoring



## Introduction

Power management in high-performance processors, such as CPUs, GPUs, ASICs, and FPGAs, is typically complex. With thermal monitoring, these systems can not only initiate a safe system shutdown, but also leverage temperature to dynamically adjust performance. To enhance system reliability and maximize performance, it is often desirable to monitor processor temperature. Higher temperatures can activate a cooling fan, modify a system clock, or, should the thermal threshold of the processor be exceeded, quickly shut down the system completely. Applications such as infotainment, ADAS, servers, notebooks, and aerospace and defense systems can take advantage of these thermal monitoring techniques.



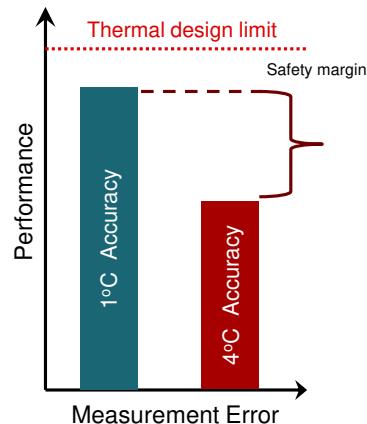
**Figure 1. Motherboards With High Performance Processors Typically Need Heat Sinks**

## Design Considerations in Die Temperature Monitoring

For effective temperature monitoring, there are two design considerations for high-performance processors: (i) Temperature accuracy (ii) Sensor Placement. The temperature accuracy of the processor has a direct correlation to the sensor location.

Processor performance can be maximized to drive the overall system to its thermal design limit through high-accuracy temperature monitoring. While most ICs have built-in temperature sensors due to variations across wafers and other various lots, the accuracy is not consistent. High-performance processors include

complex circuitry that impact the accuracy of the integrated sensor. In such systems, the accuracy is at  $\pm 5^\circ\text{C}$ . Systems designed with such lower accuracy are not able to maximize their performance their thermal design limit.



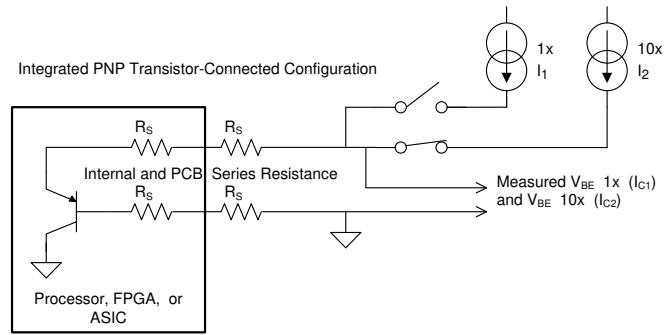
**Figure 2. Performance of a System Can be Enhanced Through High-Accuracy Thermal Monitoring**

## Sensor Placement & Accuracy

The thermal behavior of processors is monitored either through an integrated temperature sensor or thermal diode, or alternatively through an external temperature sensor. In some cases, both are used to maximize performance and boost reliability of the system.

### Integrated Temperature Sensor: BJT

Some high-performance processors include a bipolar transistor (BJT) for temperature sensing. This has a very predictable transfer function that is dependent on temperature. Remote temperature sensors use this principle to measure the die temperature. The most common BJT found in CMOS processes is a PNP.



**Figure 3.  $\Delta V_{BE}$  Measurement With Two Currents**

The design of such systems can be challenging due to the noise and error caused by BJT process variations. Thermal diode error sources can be from Ideality Factor variation, series resistance, noise injection, and Beta Compensation.

**Ideality Factor Variation**— BJT-thermal-diode characteristics are dependent on process geometry and other process variables. If the Ideality Factor  $n$  is known, the  $n$ -factor register can be used to correct the  $n$ -factor error. Alternatively, software calibration methods can be used to correct this in the desired temperature range.

**Series Resistance**— Due to the current source, any resistance in the signal path appears as a voltage offset. Modern remote temperature sensors employ a series resistance cancellation algorithm that removes temperature error due to resistance up to  $1\text{--}2\text{ k}\Omega$ . This enables robust, accurate measurements, even when coupled with RC Filters.

**Noise Injection**— EMI or inductive coupling into the remote junction PCB traces can cause error when diode traces run in parallel with high-frequency signal lines carrying high currents. Tracing remote temperature sensors need to consider this during board design.

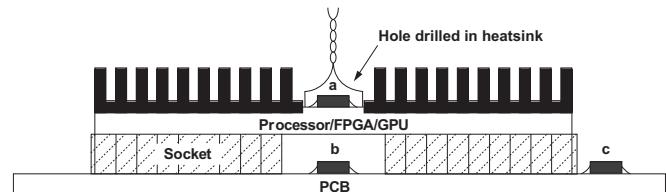
**Beta Compensation**— Thermal Transistors integrated into an FPGA or processor may have  $\text{Beta} < 1$ . A remote temperature sensor with Beta Compensation is specifically designed to work with these transistors, and to correct temperature measurement errors associated with them. The Beta Compensation feature provides no benefit when used with a typical discrete transistor.

### Device Recommendation

TMP46x devices offer high-accuracy temperature measurements to monitor up to eight remote BJTs, as well as the local temperature. Many commercial applications can benefit from such multi-channel remote sensors. The TMP451-Q1 offers an automotive qualified high-accuracy remote and local temperature sensor for automotive applications.

### External Temperature Sensor

Some processors have built-in temperature sensor. While the location is ideal, the built-in sensors make them less accurate due to variations across the wafers and different lots. Additionally, it is essential to trim the processor based on a reference; this reference is compared with die temperature to adjust the coefficients. Given the complex circuitry, the processors incur self-heating that builds an error. This error increases with increases in temperature.



**Figure 4. Sensor Placement for High-Performance Processor Temperature Monitoring**

- i. **Location a:** Sensor located in a hole drilled into the center of the heat sink of the microprocessor provides close proximity. The heat sink can be clipped to the processor or attached with epoxy, and generally sits on top of the processor. These typically require long leads, and as the heat sink-to-microprocessor thermal connection degrades, the sensor data becomes incorrect.
- ii. **Location b:** Another potential location is in the cavity beneath a socketed processor, with which assembly is straightforward. Given the sensor is isolated from the airflow, ambient temperature has minimal impact on the sensor reading. Additionally, if the heat sink gets detached from the processor, the sensor indicates an increase in processor temperature. That said, given the sensor placement, the temperature differences between the sensor and the processor case are  $5^\circ\text{C}$  to  $10^\circ\text{C}$ .
- iii. **Location c:** The sensor can be mounted on the circuit board next to the MPU. While this is simple to implement, the correlation between sensor temperature and MPU temperature is much weaker.

### Device Recommendation

Footprint size is a factor in selecting a local temperature sensor. The TMP112 with a  $1.6 \times 1.6\text{ mm}$  can be used in close proximity of the processor and gain a good accuracy of  $0.5^\circ\text{C}$ . This can maximize performance when compared to a  $5^\circ\text{C}$  to  $20^\circ\text{C}$  that is typically observed in temperature sensors integrated within processors.

**Table 1. Key Collaterals**

COLLATERAL	DESCRIPTION
Remote Temperature Sensor	<a href="#">Optimizing Remote Diode Temperature Sensor Design</a>
Local Temperature Sensor	<a href="#">Temperature Sensors: PCB Guidelines for Surface Mount Devices</a>
Board Temperature Monitoring	<a href="#">Monitoring Board Temperature</a>

# Precise Temperature Measurements With the TMP116 and TMP117

Mihail Gurevitch

## ABSTRACT

Engineers must carefully consider the overall system design when designing high-precision temperature measurement applications. This application note provides recommendations on how to design a precise temperature measuring system based on the TMP116 and TMP117 temperature sensors. By following this application note, the user should be able to design a precise measuring system which adheres to the performance specifications of the TMP116/117.

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## Trademarks

All trademarks are the property of their respective owners.

## 1 Introduction

There are many system factors which can negatively affect the precision of temperature measurements, and these must be addressed to achieve a high accuracy. The main parameters that affect measurement precision with the corresponding source of their control are:

- The accuracy of the temperature sensor itself as its accuracy, stability, and repeatability, are set by the manufacturer and out of the designer's control.
- The system engineer controls the supply voltage range and noise, the sensor conversion mode, the system power consumption, the data sampling rate, the communication bus voltage, the I<sub>2</sub>C bus frequency, and data flow over it.
- The PCB designer controls the mounting and position of the sensor on the PCB, the temperature resistance between the sensor and the measured object, and the temperature "leakage" from the sensor to surrounding air.

These parameters are important for precise temperature measurements and must be analyzed during the system design. The purpose of this article is to provide recommendations to the system designer, based on experience obtained in part characterization and device use in real applications.

When using the TMP116/117 for precise temperature measurements, there are a few critical considerations that must be accounted for by the system designer:

- Proper PCB sensor location and orientation in the system. The proper location must provide the precise temperature measurement with minimal offset and minimal time delay.
- Proper device electrical and communication interface mode, which can minimize measurement noise, minimize part self-heating and ensure measurements stability.
- Proper PCB material and thickness, PCB mounting, and PCB layout. All these should provide a minimal temperature difference between the sensor and the measured object, and should minimize sensor response time when an object temperature is changing.

## 2 TMP116 and TMP117 Device Differences

The TMP116 and TMP117 have a similar internal schematic, register map, and electrical characteristics. The main differences between two devices are shown in [Table 1](#).

**Table 1. Parameter Differences Between the TMP116 and TMP117**

PARAMETER	TMP116	TMP117
Ensured precision at room temperature (°C)	±0.2	±0.1
Temperature range (°C)	-40 to +125	-55 to +150
Supply voltage range (V)	1.9 to 5.5	1.8 to 5.5
Shut down current at +25°C (+125°C) (µA)	0.25 (3)	0.15 (0.8)
Typical PSRR (m°C/V)	10	6
Package	DRV-6	DRV-6 and WCSP
Thermal mass (mJ/°C)	5.1	5.1 and 0.8 (WCSP)
Price on Jun 2019 (1 Ku) (\$)	0.99	1.6

Additionally, the TMP117 has a register to compensate the temperature offset and a reset bit in the configuration register. Both parts are in the same 6-pin DRV package, but the TMP117 also has a smaller WCSP-6 package version with a 1.5-mm × 1.0-mm × 0.5-mm die size. All conclusions found for either device listed in this application note will apply to both the TMP116 and TMP117.

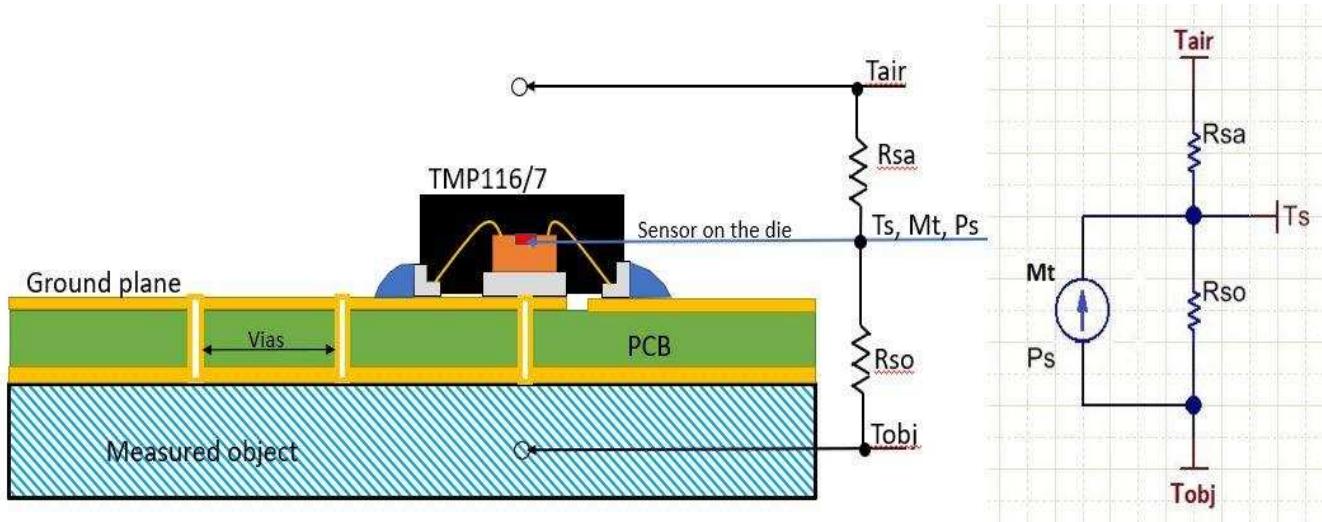
### 3 PCB Considerations

There are two main tasks in temperature measurements: measuring air (gas) temperature and measuring temperature of a solid surface. A liquid temperature measurement usually falls in one of the above, because the sensor is often placed inside a metallic probe for liquid measurements. These two different tasks dictate two different approaches to device mounting. However, in all cases, these common rules must be applied:

- To get the manufacturer ensured measurement precision, the  $0.1\text{-}\mu\text{F}$  bypass capacitor must be placed no more than 5 mm (200 mils) away from the device
- To avoid possible heat influence coming from the pullup resistor on the SDA pin and the pullup resistor on the SCL and ALERT pins (if present), the pins must be placed at least 10 mm (400 mils) away from the device.
- If there is a risk that the board may bend during PCB mounting, all efforts to prevent the mechanical tension on the device package must be taken. Guard holes in the PCB around the part can help in this case.

### 4 Measuring Solid Surface Temperature

Measuring the temperature of a solid surface is the most common type of temperature measurement, and the standard approach is to make a tiny rigid PCB, solder the device on one side of the PCB, and attach the opposite side of the PCB to object surface. **Figure 1** shows a cross-sectional view on how to mount the TMP116/117 sensor to a PCB, along with a simplified schematic of the thermal processes required for surface temperature measurement.



**Figure 1. Simplified Schematic of Temperature Flow During Solid Surface Measurement**

On this schematic:

- $T_{\text{obj}}$  is the measured object temperature.
- $T_{\text{air}}$  is the environment temperature (typically air).
- $T_s$  is the sensor temperature.
- $R_{\text{so}}$  is the thermal resistance between the sensor and the object.
- $R_{\text{sa}}$  is the thermal resistance between the sensor and the air (environment).
- $P_s$  is the averaged power dissipated by the sensor during the measurement.
- $M_t$  is the combined thermal mass of device, plus the surrounding PCB area.

The most important formula for the precise temperature measurement is:

$$\begin{aligned} T_{\text{ofs}} &= \left( \frac{T_{\text{obj}} - T_{\text{air}}}{R_{\text{so}} + R_{\text{sa}}} \right) \times R_{\text{so}} \\ T_s &= T_{\text{obj}} - T_{\text{ofs}} \end{aligned} \quad (1)$$

where

- $T_{\text{ofs}}$  is a temperature offset between the measured object and sensor.

[Equation 1](#) shows that the sensor temperature offset is zero only in two cases: if  $R_{\text{so}}$  is zero or  $R_{\text{sa}}$  is infinite. If there is a difference between  $T_{\text{obj}}$  and  $T_{\text{air}}$  (and despite all efforts to make  $R_{\text{sa}} >> R_{\text{so}}$ ), however, there will always be some offset between sensor and object temperature. This shift will increase when the difference between  $T_{\text{obj}}$  and  $T_{\text{air}}$  is larger, or when  $R_{\text{sa}}$  becomes smaller and approaches to  $R_{\text{so}}$  value.

Let's calculate temperature offsets for two metallic object temperatures ( $+50^{\circ}\text{C}$  and  $+100^{\circ}\text{C}$ ) where still air temperature stays the same  $+25^{\circ}\text{C}$  and the temperature resistance from sensor to object surface assumed from line 6 of [Table 2](#) ( $140\text{m}^{\circ}\text{C/mWt}$ ). Let's also assume that the temperature resistance between sensor and air is equal to line 1 of [Table 2](#) ( $300\text{m}^{\circ}\text{C/Wt}$ ). For object temperatures  $+50^{\circ}\text{C}$  and  $+100^{\circ}\text{C}$ , the measurement offset, according to [Equation 1](#), will be  $7.9^{\circ}\text{C}$  and  $23.8^{\circ}\text{C}$  accordingly, which is not acceptable for precise measurements. TI recommends to use a thinner PCB with a better layout, and cover the top surface of PCB with thermal isolating foam. The best solution to avoid temperature leakage to the surrounding air may be to make a cave-kind cavern in the object body and put the PCB of the sensor inside it, but this kind solution is not always available.

If the sensor temperature shift from the object temperature is too big and cannot be ignored, a system calibration is needed. In some cases, it should be done for different combinations of  $T_{\text{obj}}$  and  $T_{\text{air}}$ . This happens because  $R_{\text{sa}}$  is not a linear parameter, and instead depends on the air speed, air moisture, air temperature, PCB orientation, and so on. All this makes the  $R_{\text{sa}}$  value estimation very difficult to find. However, by making  $R_{\text{so}}$  as small as possible and  $R_{\text{sa}}$  as big as possible, it would be much easier to minimize the temperature shift.

Another important aspect is when designers can trust the sensor readings, like when the object temperature changes from  $T_{\text{obj1}}$  to  $T_{\text{obj2}}$ . To estimate or understand the process of this temperature change, we can use a Gaussian formula for an ideal case. In reality, the object temperature rarely changes instantly, and therefore the sensor follows the object temperature slower than [Equation 3](#) shows.

$$T_s = T_{\text{obj1}} + (T_{\text{obj2}} - T_{\text{obj1}}) \times e^{-t/t_r}$$

where

- $t$  is a time passing from beginning object temperature change.
- $t_r$  is a response time.

$$t_r = R_{\text{so}} \times M_t \quad (4)$$

Here we can assume that  $R_{\text{sa}} >> R_{\text{so}}$  and ignore the temperature leakage to environment. According to formula, to have minimal measurement delay, it is important to have a small response time ( $t_r$ ), which means the  $R_{\text{so}}$  and  $M_t$  should be kept at minimal value, especially if the object temperature changes fast.

Because the device is dissipating some power during the measurements, the sensor is heating itself. The self-heating temperature shift  $T_{\text{sh}}$  is calculated by [Equation 5](#).

$$T_{\text{sh}} = P_s \times R_{\text{so}} \quad (5)$$

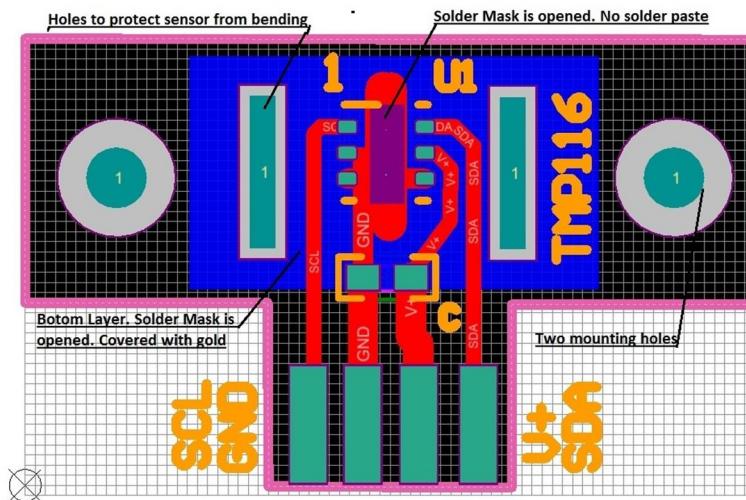
The influence of self-heating on measurement precision is discussed in [Section 10](#).

The following are the recommendations for systems measuring rigid surface temperature:

- Use a PCB with minimal thickness.
- The side of the PCB that makes contact with the surface to be measured should be covered with an exposed copper layer (and not covered with a solder mask). To prevent copper oxidation, a gold or melted solder paste cover should be used.
- To improve thermal contact to the surface, consider adding a thermal conducting paste or sticky thermal film between the surface and the PCB.

- Place additional vias to connect copper layers on both sides of the PCB. Generally, a via has 400 times less thermal-resistance than the same area of regular PCB material. Using a filled via further decreases the thermal resistance.
- If the PCB internal layers are not used under the device, it is recommended to create internal copper polygons under the sensors to reduce the PCB side-to-side thermal resistance.
- To increase the temperature resistance to surrounding air, minimize the amount of copper wires on top of the board.
- To increase thermal resistance to surrounding air, the sensor and the PCB surface exposed to the air must be covered with thermal-isolating foam, film, or at least with some stain. This protection is especially important for precise measurements when air around the sensor is moving.
- To minimize the convection air influence, the PCB should be located horizontally and out of any air flow.
- Soldering the device's thermal pad (TP) to the PCB may be a good choice only for systems which undergo calibration. The negative aspects of TP soldering are described in [Section 9](#). If the TP is soldered, it should be connected to ground or left floating. Connecting the package TP to a voltage other than system ground can lead to permanent device damage.

[Figure 2](#) shows an example of a PCB layout for surface temperature measuring.



**Figure 2. PCB Layout Example for Rigid Surface Temperature Measuring**

## 5 Measuring Human Body Temperature

When making human body temperature measurements, it is important to understand the two cases that may affect the performance of the system.

The first case is when the thermometer is exposed to the surrounding air temperature before it is pressed to the body. The goal is to make precise body temperature measurements in the shortest amount of time when the sensor temperature is changing rapidly at the beginning of measurement. In this case, the minimal combined thermal mass will allow the sensor to reach a body temperature in the shortest amount of time. Take care to avoid temperature "leakage" from the sensor to surrounding air. TI recommends to have a temperature stabilization check before a measurement report is done. As an example, the stabilization check can be to verify that the temperature didn't change more than 0.2°C during the last 5 seconds. It is easy to achieve a good thermal contact to the object in this case, and therefore there is less need to worry about the sensor self-heating. The conversion mode with a small standby time is recommended.

- Use rigid PCB with minimal thickness to minimize the sensor-to-body thermal resistance.
- Cover the PCB side that makes direct contact with the body with a copper plane. Remove the solder

masks above the planes. To avoid oxidation, cover the exposed copper plane with gold or a melted soldering material.

- Use a bypass capacitor with minimal dimensions to reduce thermal mass.
- Place pullup resistors away from the sensor.
- Depending on the design, cover the sensor and top side of PCB with a thermal-isolating compound.

The second case is a monitoring case where sensor attached to the body for a long period of time. In this scenario, the temperature is changing very slowly and samples are taken less frequently (like once every 16 sec). It is easy to make a good thermal contact to a body and minimize temperature leakage. Bigger sensor thermal mass may be useful as a low-frequency filter working to reduce temperature fluctuation (noise). This can reduce the averaging number down to 1 during sampling, which lowers the power consumption and extends the battery life. Bigger sensor thermal mass also reduces device self-heating during conversions.

- Use a flexible PCB to make better temperature contact to the body.
- Cover the PCB side that makes direct contact with the human body with a copper plane. Remove the solder masks above the planes. To avoid oxidation, cover the exposed copper plane with gold or a melted soldering material.
- To make PCB maximal flexible and to increase PCB reliability, use the smallest size capacitor and place the pullup resistors away from the sensor.
- To prevent temperature leakage and protect device contacts from oxidation, cover the top side of the board with a thermal-isolating protection compound.

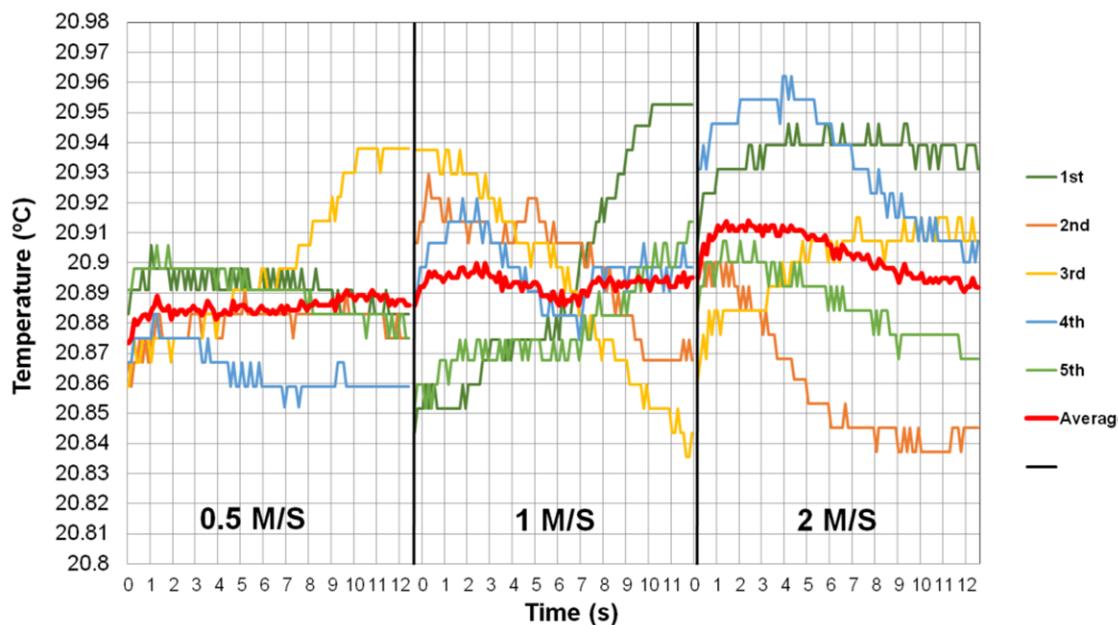
## 6 Measuring Still Air Temperature

The main feature of still air measurement is that the temperature changes slowly (usually less than a degree per minute), and this is primarily due to air convection. When temperature change is slow, it is not critical to have minimal thermal mass for sensor and surrounding PCB. Even with increased thermal mass, the sensor will be able to follow the air temperature with minimal lag. The thermal resistance between slow moving or still air and the PCB (including mounted sensor) is very high. Therefore, the designer should try to improve the thermal contact with the air while simultaneously excluding any heat transfer from other heat sources located on the same PCB. Due to the slow temperature change, there is no need to keep the device running continuously. The update rate of one sample per second or less may be sufficient for most use cases. When the device spends most of the time in standby or in shutdown mode, the power consumption is minimal and self-heating is negligible.

- Place the PCB vertically. This will improve convection air flow and reduce dust collection over time. The layer of accumulated dust works as a thermal-isolating barrier between the air and the PCB.
- To make a better PCB thermal contact with the air, place copper planes on both sides of PCB.
- Remove the solder masks above the planes. To prevent oxidation, cover the exposed copper plane with melted soldering material or gold.
- Thermal isolation is required to avoid thermal coupling from the heat sources through the PCB. Use air gaps between the sensor and PCB heat sources, if needed.

## 7 Measuring Moving Air Temperature

The main feature of moving air temperature measurement is high thermal noise, which is coming from the temperature fluctuation inside air stream. [Figure 3](#) shows the measurement noise of the room air flow, which is moving along the rigid coupon board with a mounted TMP117 sensor at different speeds. As seen in the graph, the measurements are still noisy even with an internal averaging of 8 temperature samples.



**Figure 3. Moving Air Temperature Measurements Noise. Air Speed 0.5, 1 and 2 Meter/Sec. Averaging 8 Samples Per Reading. 5 Consecutive Measurements at Room Temperature.**

The standard approach to reduce the noise is to increase the sample average number, but an alternate method is to increase the sensor thermal response time in [Equation 4](#).

Increased response time works as a low-pass filter, and it reduces the measurements noise. Knowing response time  $t_r$ , the designer can calculate the filter 3db cut-off frequency,  $F_c=1/t_r$ . However, it is difficult to estimate the effective combined thermal mass and effective thermal resistance between the sensor and moving air, due to its dependents of many non-linear factors.

Moving air provides a good thermal contact to the sensor, and there can be a rare case where the sensor can have the same temperature as a measured object. Low thermal resistance to moving air also minimizes the device self-heating effect.

- Because moving air temperature usually has a lot of fluctuations, the PCB increased thermal mass can reduce measurement noise. Therefore, it is acceptable in these cases to use a PCB with increased thickness.
- Place the PCB vertically along air flow. This makes air flow smooth and prevent air "shades".
- Design PCB soldering pads bigger than usual, especially the package corner pads. This will improve the thermal contact from package to air.
- Cover both side of unused board space with a copper layer,
- Use a PCB with thicker copper layers, if possible. This improves thermal conductivity along the PCB, and it allows better "average" temperature fluctuations from different parts of the board.
- If air (or gas) is expected to contain moisture or includes some corrosive components, the device pins must be protected by a stain to avoid corrosion or moisture accumulation on the pins.

Figure 4 is an example of a PCB layout for air temperature measuring.



- (1) Alert pin is not used and grounded. I<sub>2</sub>C pullup resistors are located on master board.

**Figure 4. PCB Layout Example for Air Temperature Measuring**

## 8 Measuring Thermal Resistance in Different Environments

As mentioned earlier, the thermal resistance between the sensor and measured object is a parameter sensitive to PCB layout, board mounting, and environment condition. This parameter is not easily calculable upfront. A more practical way is to measure the thermal resistance between the sensor and object, and the sensor and environment, in already designed system. Knowing  $P_s$ ,  $R_{so}$ ,  $R_{sa}$  and using Equations 1-5, it is possible to estimate the measurement error and sensor response time for different temperatures and apply a necessary system correction. To measure  $R_{so}$  or  $R_{sa}$ , the system designer may do the following:

- The environment or object temperature is fixed and well controlled.
- When TMP116/117 temperature is stabilized the device temperature  $T_1$  is read using minimal conversion power. Single shot mode, which makes  $P_1$  power almost zero, is the best choice.
- The TMP116/117 an average consumption power is increased in any possible way. The simplest way is to increase the supply voltage from min to max and switch to conversion mode without the standby time. This will be the device power  $P_2$ .
- When the device internal temperature is stabilized after power increase, the temperature reading  $T_2$  is taken.

Now the designer can calculate the thermal resistance  $R_{sx}$ , which is  $R_{so}$  or  $R_{sa}$ :

$$R_{sx} = \frac{(T_2 - T_1)}{(P_2 - P_1)} \quad (6)$$

In this measurement, it is assumed that the object (environment) temperature is stable during the test and is not changed due to sensor self-heating.

Using this method, data about thermal resistance between part mounted on a coupon board (CB) to a different kind of environment has been collected. The 2-layer coupon boards used in the experiments have board size of 21 mm × 11 mm, a board thickness from 6 to 64 mil (0.15 to 1.62 mm), and an identical layout. See Figure 5. Each CB has surface mounted 0.1- $\mu$ F bypass capacitor and 6 contact pins. Table 2 shows the thermal resistance from the TMP116/117 to a different environment.

**Table 2. Thermal Resistance Between TMP116/117 to Differentiate Environment. The CB is 21 mm × 11 mm.**

ENVIRONMENT	THERMAL RESISTANCE (m°C/mWt)	COMMENTS
Still Air.	260-320	For all CB thickness and all CB orientation

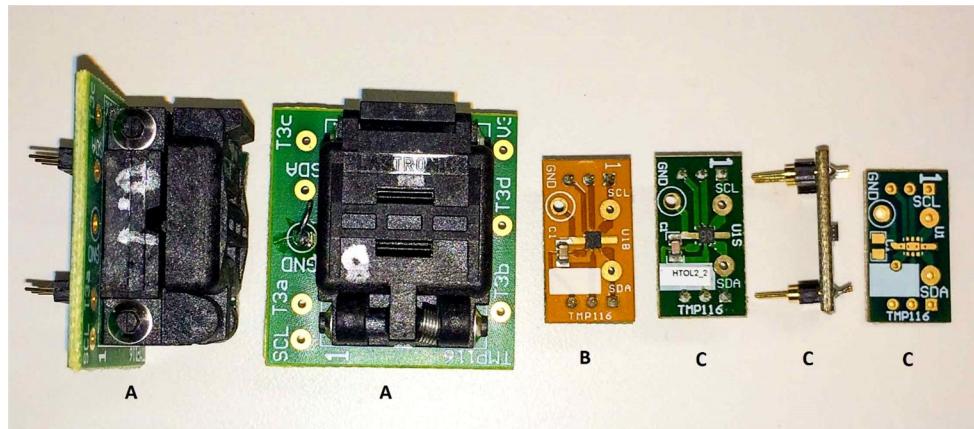
**Table 2. Thermal Resistance Between TMP116/117 to Differentiate Environment. The CB is 21 mm × 11 mm. (continued)**

ENVIRONMENT	THERMAL RESISTANCE (m°C/mWt)	COMMENTS
Moving Air along CB. 0.5 M/Sec	236	64 mill (1.62 mm) rigid CB <sup>(1)</sup>
Moving Air along CB. 0.5 M/Sec	190	6 mill (0.15 mm) flex CB <sup>(1)</sup>
Moving Air along CB. 2 M/Sec	200	64 mill (1.62 mm) rigid CB <sup>(1)</sup>
Moving Air along CB. 2 M/Sec	156	6 mill (0.15 mm) flex CB <sup>(1)</sup>
CB pressed to flat copper surface. Device thermal pad is not soldered.	140	64 mill (1.62 mm) rigid CB. Thermal conductive paste between PCB and copper is used.
CB pressed to flat copper surface. Device thermal pad is soldered.	75	64 mill (1.62 mm) rigid CB. Thermal conductive paste between PCB and copper is used.
Oil bath.	40	64 mill (1.62 mm) rigid CB. Oil is under intensive circulation <sup>(1)</sup> .
WCSP die. CB pressed to flat copper surface.	160	32 mill (0.81 mm) rigid CB
WCSP die. CB pressed to flat copper surface.	160	6 mill (0.18 mm) flexible CB

<sup>(1)</sup> The decision to solder or not solder the thermal pad does not make a significant difference.

## 9 Soldering to PCB

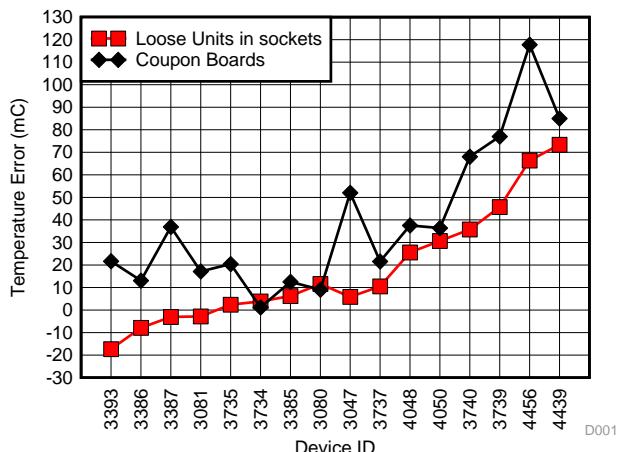
Soldering the TMP116/117 to a PCB can create significant package stress and degrade the absolute accuracy. The measuring error of a TMP116/117 device in an oil bath before and after soldering often shows an increase in the error, especially on rigid PCBs with the thermal pad soldered. This soldering shift can be significant for precise measurements. [Figure 5](#) shows the boards used in soldering shift tests. All measurements were made in an oil bath.



**Figure 5. Printed-Circuit Boards Used**

In [Figure 5](#), Board A is the socketed board used for testing loose devices prior to soldering. Board B is a flexible PCB, and board C is a rigid PCB. Both used for testing devices after soldering.

[Figure 7](#) shows the impact of soldering for 16 devices soldered to a rigid coupon boards. In [Figure 7](#), parts were measured in an oil bath at +25°C with a 3.3-V supply before and after soldering. In this case, the package thermal pad was also soldered to the coupon board. The average soldering shift in the example is around 20m°C, but for device #4456, it reaches 50m°C. According to our research, the soldering shift is not predictable, can be positive or negative, and, in the worst case, can reach ±100m°C.

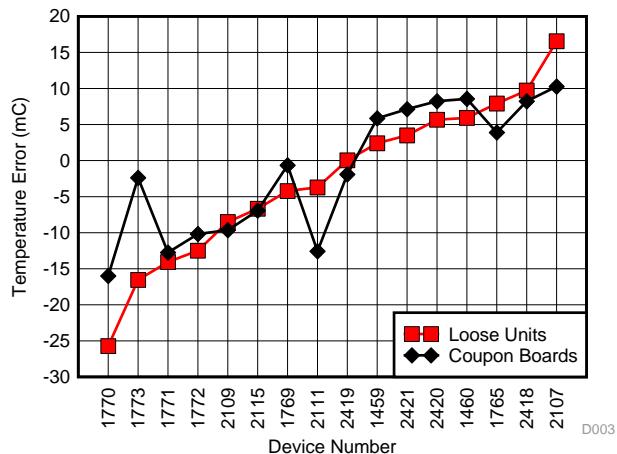


**Figure 6. Soldering Shift at +25°C and Supply 3.3 V With Thermal Pad Soldered on a Rigid PCB.**

Furthermore, the soldering shift can be different for different temperatures, which makes it even less predictable.

The main reason for the soldering shift is mechanical tension coming to the silicon die through the package from the PCB and the hardened solder. When the temperature drops in the reflow oven, the solder hardens and fixes the thermal pad and package pin locations. But package material continues to contract, and because the solder and the rigid PCB have different contraction coefficients than device package, it creates the mechanical tension which leads to package bending and therefore creates tensions in the silicon die. However, when the package thermal pad is not soldered, the bending forces are applied only to the package pins, which have much less mechanical contact to the silicon die.

Figure 7 shows the effects of soldering when the thermal pad is not soldered to the PCB. In this case, the accuracy shift is much less and the worst-case offset is only 15 mC.



**Figure 7. Soldering Shift for TMP116/117 Without the Thermal Pad Soldered to the PCB. +25°C, V = +3.3 V**

The reasonable question is: when the thermal pad is not soldered, by how much will the thermal resistance between the sensor and the PCB going to increase? In conducted experiments, the device was soldered to a rigid coupon board 11-mm × 22-mm × 1.1-mm size with no vias under the part and a copper radiator was attached to the opposite side of PCB. (The silicon thermo conductive paste between copper radiator and PCB back side was applied). The measurements showed that not soldering the package thermo pad increased the thermal resistance from 75 to 140°C/W. By knowing the thermal resistance and device thermal mass  $M_t = 5.1 \text{ mJ}/\text{°C}$ , it is possible to calculate the sensor thermal response time with Equation 4.

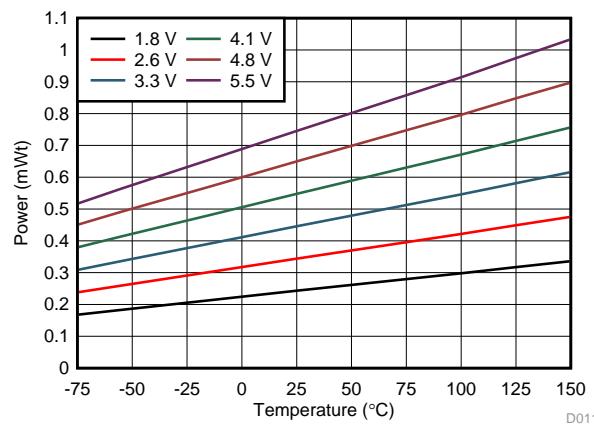
The calculated response time values are 0.39 and 0.72 seconds and measured response time matched the calculated values. Because the device package thermal mass is extremely small, the thermal response time is also very small and even the 0.72 second value, when the thermal pad is not soldered, satisfies most users applications.

Here are the recommendations on how to minimize the soldering shift in the TMP116/117 parts:

- To maintain device manufacturer precision, in case the system calibration is not planned, TI highly recommends not to solder the package thermal pad to avoid a soldering shift.
- Use the standard reflow oven soldering process with a maximum temperature to +250°C for one minute.
- Manual soldering is not acceptable because it creates additional stress on the device package, resulting in soldering shift as large as  $\pm 150\text{m}^{\circ}\text{C}$ .
- Using a flexible PCB with thickness less than 6 mil (0.15 mm) creates minimal mechanical tensions and minimal soldering shift even in the case when the thermal pad is soldered.
- When using a flexible PCB with thickness more than 6 mil (0.15 mm), the thermal pad must not be soldered. The flexible PCB minimizes the thermal mass and thermal resistance, which may improve measurement precision.

## 10 Self-Heating

To achieve the best measurement accuracy, the TMP116/117 part is specially designed to dissipate minimal power and minimize the part temperature change due to self-heating. In typical conditions (supply voltage is 3.3 V, 8 samples average, one data collection per second), the TMP116/117 dissipates 53  $\mu\text{Wt}$  at  $+25^{\circ}\text{C}$ . However, when operating with a higher supply voltage and taking more frequent measurements, the power dissipation can increase to almost 1 mWt. [Figure 8](#) shows the power dissipation as a function of the device temperature at different voltage supplies.



**Figure 8. Device Consumption Power vs Temperature and Part Supply Voltage in Continuous Conversion Mode. No Pauses Between Conversions, No I2C Bus Activity.**

The power consumption in user measurements is usually significantly less than 1 mWt, but to make the most accurate measurement and reduce any influence of self-heating, all efforts to reduce the dissipation power must be taken. Here are recommendations on how to reduce the device power consumption:

- Use the minimal supply voltage acceptable for the system. This is especially important when the device is in continuous conversion mode without the pauses.
- Use one-shot conversion mode or use a conversion cycle mode where the device goes into standby after a conversion.
- Use pullup resistors larger than 5 k $\Omega$  on the SDA, SCL, and ALERT pins. Place resistors at least 10 mm from the TMP116/117 to reduce any influence from the resistor's heat dissipation.
- Ensure that the SCL and SDA signal levels are below 10% and above 90% of the device supply voltage. If the SCL, SDA, and ADD0 pin input voltages are close to ground or device supply level, the current going through the digital pin input cell is low, which minimizes the sensor heating (see [Figure 9](#)). Remember that the I2C bus voltage can go up to 6 V and is not limited by the applied supply

voltage.

- Avoid heavy bypass traffic on the I<sub>2</sub>C bus. Remember that the intensive communication to other devices on the same bus increases the TMP116/117 supply current, even if the device is in shutdown mode (see Figure 10).
- Use the highest available communication speed. To increase the SCL and SDA rising edge speeds, use a bus pullup voltage higher than the device supply voltage.

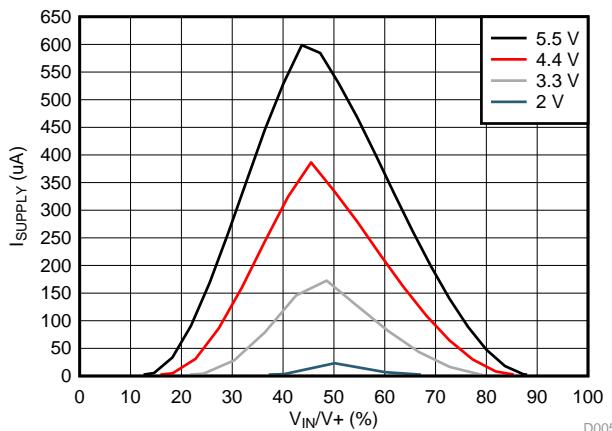


Figure 9. Supply Current vs. Pin Input Voltage and Device Supply Voltage for Any Digital Pin Input Cell.

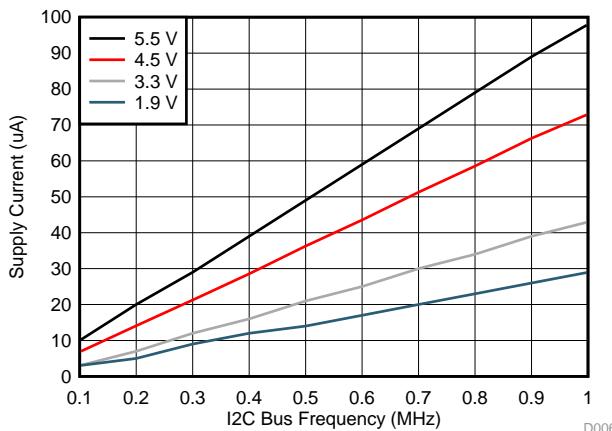


Figure 10. Device Supply Current vs. I<sub>2</sub>C Bus Clocking Frequency and Supply Voltage. Part is in Shutdown Mode, but SCL, SDA, and ADD0 Pins are Under Constant I<sub>2</sub>C Data Flow.

## 11 Self-Heating Estimation Example

The self-heating impact can be calculated by the simple formula below:

$$T_{sh} = P \times R_t$$

where

- $T_{sh}$  is a temperature offset due to sensor self-heating.
- $P$  is an averaged power dissipated by the sensor.
- $R_t$  is a combined temperature resistance to the environment. (7)

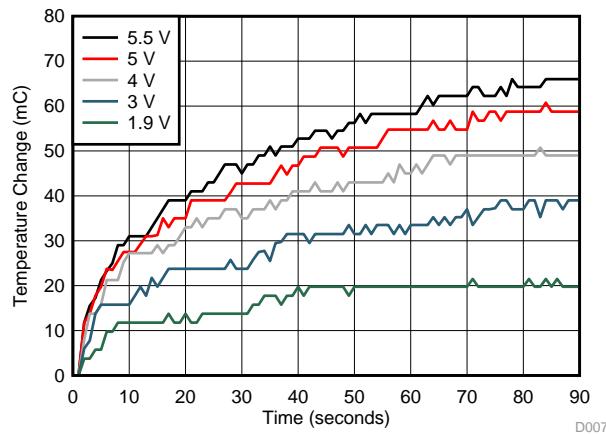
This implies that another way to reduce the self-heating is to reduce the thermal resistance to the measured object. On the contrary, the larger the thermal resistance between the sensor and measured object, the larger the self-heating influence on measurement precision. Below are listed cases when the self-heating effect can be ignored:

- The desired measurement precision is worse than  $\pm 0.2^\circ\text{C}$ .

- The system calibration takes care of self-heating and all other effects.
- The device average consumption power is less than 0.1 mWt.
- The thermal resistance between the sensor and measured object is small.

In this list, the most difficult parameter to estimate is the thermal resistance between the sensor and the environment. The estimation is difficult because it depends on many poorly controlled factors. Here is a recommendation on how to estimate the device object thermal resistance in a real application environment and then calculate a possible self-heating temperature rise for a worst case scenario. The idea is to measure the self-heating for some fixed supply voltage and fixed environment temperature, and then extrapolate results over an entire voltage and temperature range.

[Figure 11](#) shows an example of the self-heating effect on positioning the coupon boards horizontally in a "still air box", with a TMP116/117 placed on top of the board. At time zero, the device is switched from shutdown mode to continuous conversion mode with a 64 sampling averaging and no pauses between conversions. There is no heating from the I<sup>2</sup>C bus activity because the data reading happens only once per second. The temperature change on [Figure 11](#) happens only due to device dissipated power and following self-heating. Let's calculate the thermal resistance between the part and its environment.



**Figure 11. TMP116/117 Coupon Board Self-Heating Effect vs. Time and Supply Voltage in Still +25°C Air.**

For example, assume the customer test was done with a 3-V supply and air temperature +25°C. We see the device temperature stabilized after 90 seconds with 40m°C self-heating value. According to [Figure 8](#), the consumption power for this mode is 0.36 mWt for a 3-V supply. So, the thermal-resistance between the device and surrounding air is  $R_t = 40\text{m}^\circ\text{C} / 0.36 \text{ mWt} = 111\text{C/Wt}$ . Now, knowing the thermal resistance, it is possible to calculate the self-heating offset for other situations. For example, if the air temperature is +125°C and the supply voltage is 4 V according to [Figure 8](#), the dissipated power would be 0.65mWt and self-heating temperature offset would be  $T_{sh} = 111\text{C/Wt} \times 0.65\text{mWt} = 72\text{m}^\circ\text{C}$ . The 80-second long settling time here is associated with stabilization time of air convection process in the "still air box". If the box size changes, the self-heating and stabilization time will also change.

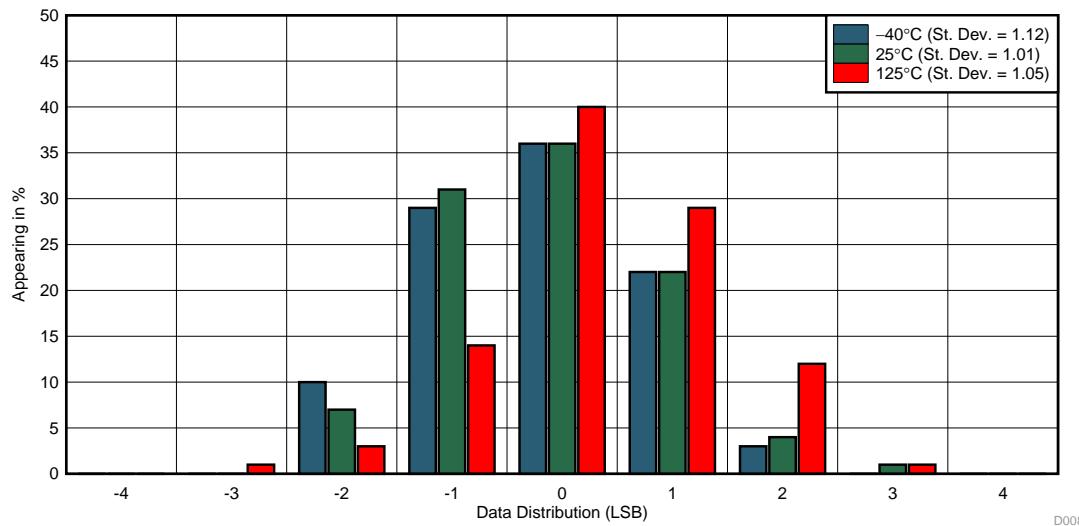
As a reminder, this example above is a worst-case scenario where the thermal resistance between the device and environment is high and device is continuously converting. It does demonstrate, however, that self-heating can occur and must be considered when trying to achieve the best precision. If the experiment is repeated with moving air, the self-heating offset will be much smaller and could become negligible. But in all cases, the recommendation is the same: **minimize the device dissipated power**. The easiest way to minimize the dissipated power is to limit the rate at which the temperature is sampled. If we used device default mode (8 sample averaging with sampling rate 1 Hz) in the example above, the average supply current would be 16 µA, the dissipated power would be only 48 µWt, and the self-heating would only be 5.3m°C, which is less than sensor resolution and is negligible.

## 12 Supply Voltage Change

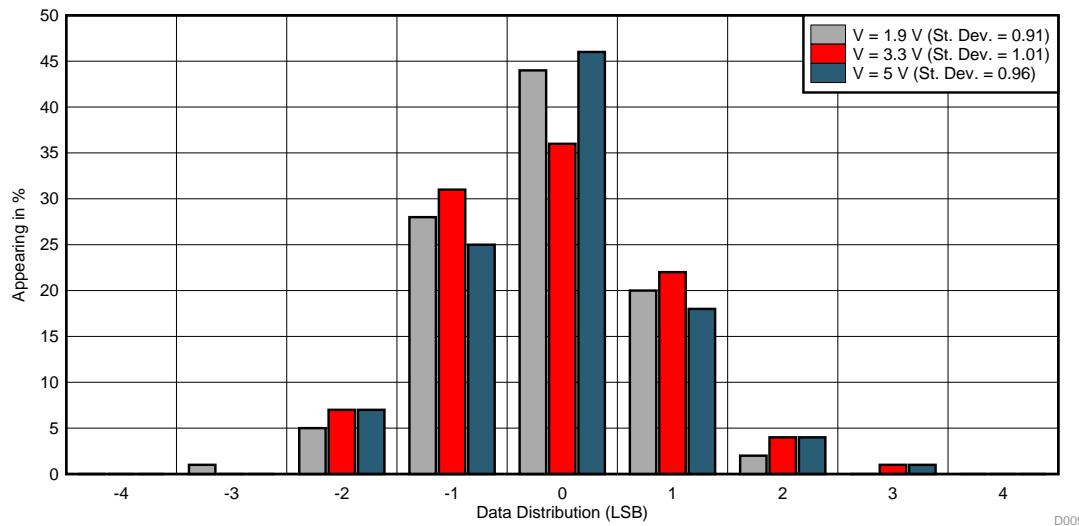
Precise measurements usually mean that supply voltage has minimal noise that does not change during the measurements. In some battery systems, however, the voltage can change significantly with battery aging. The TMP117 has excellent (almost zero) electrical PSRR, and the supply voltage change has no effect on the precision of the readings. The only case where a system designer must take precautions is when the device dissipates some heat in continues conversion mode without the standby. If the thermal resistance to the object is significant, the supply voltage change from the maximum to minimum can create sensor self-heating offset change (so named self-heating PSRR). Standard recommendations of minimizing device average dissipated power and minimizing thermal resistance to the object applies in this case. For the TMP116, the typical electrical PSRR is around  $10\text{m}^\circ\text{C/V}$ , and should be considered if the supply voltage changes. The best recommendation for precise temperature measurements is simple: stabilize the supply voltage at minimum system acceptable level.

## 13 Data Averaging

The TMP116/117 can be configured to take multiple measurements and provide the resultant average as the result. [Figure 12](#) and [Figure 13](#) show the output temperature distribution with no averaging for 3 temperatures, and no averaging for different supply voltages. In all these cases, the standard deviation of the readings is about 1 LSB, and data distribution covers an area approximately of six neighboring codes, which match the  $\pm 3$  sigma rule. This leads to the important conclusion that sensor internal noise is the same for whole temperature range  $-55^\circ\text{C}$  to  $+150^\circ\text{C}$ , and the whole supply voltage range 1.9 V (1.8 V) to 5.5 V. Based on this data, the sensor internal noise without averaging in ideal bath condition can be estimated as  $\pm 25\text{m}^\circ\text{C}$ .

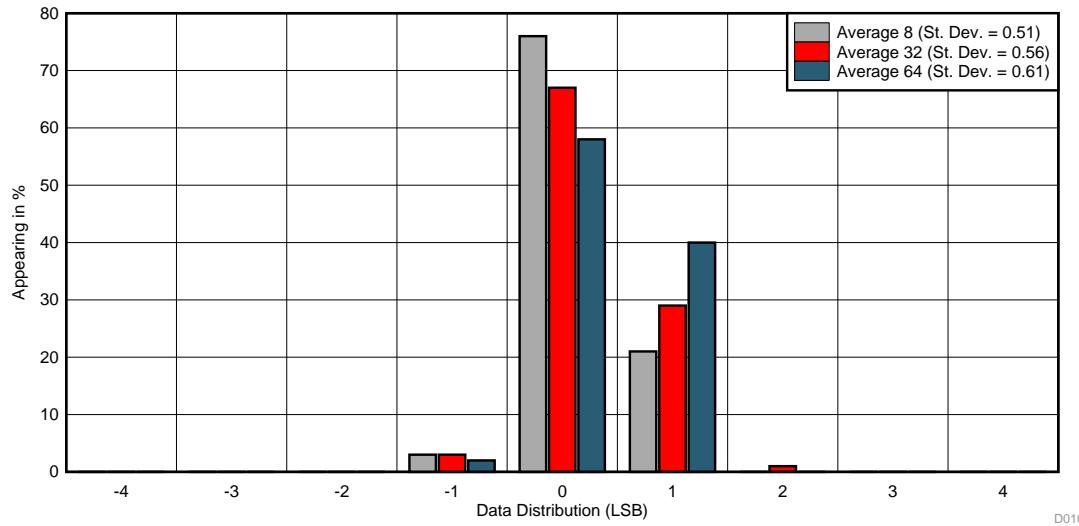


**Figure 12. The TMP116/117 Sampling Distribution for 3 Different Oil Bath Temperatures and 3.3-V Supply Voltage. No Data Averaging.**



**Figure 13. The TMP116/117 Sampling Distribution for 3 Different Supply Voltages at +25°C.  
No Data Averaging.**

The TMP116/117 provides an internal mechanism for averaging 8, 32, and 64 consequent samples controlled by the configuration register. As shown in Figure 14, even the 8 samples averaging reduces the internal noise distribution to a theoretical minimum of 2 LSB. This means that if the measured temperature changes slowly and has no temperature fluctuations, the supply voltage is stable and has no glitches, and there is no heavy bypassing traffic on I<sub>2</sub>C bus, the 8 samples averaging is enough to neutralize the internal sensor noise and provide stable temperature readings. However, if the measured conditions are far from ideal, higher averaging numbers are recommended.



**Figure 14. Temperature Sampling Noise With 8, 32, and 64 Internal Averages.  
Temperature +25°C and V = +3.3 V.**

## 14 Summary

The TMP116/117 provides excellent precision, small power consumption, extremely small thermal mass, and averaging tools with wide temperature and supply range. To achieve best performance, system designers must follow the recommendations in this application note and product data sheets.

## Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Original (April 2018) to A Revision	Page
• Added references to the TMP117 device .....	1
• Added <i>Measuring Solid Surface Temperature</i> section .....	3
• Added <i>Measuring Human Body Temperature</i> section .....	5
• Added <i>Measuring Still Air Temperature</i> section.....	6
• Added <i>Measuring Human Body Temperature</i> section .....	6
• Added <i>Measuring Thermal Resistance in Different Environments</i> section .....	8
• Removed <i>Devices Temperature Error Change Due to Device Soldering for 6 Different Temperatures. V = +3.3 V graph</i> .....	10
• Added recommendations on how to minimize the soldering shift in the TMP116/117 parts.....	10
• Changed <i>Device Consumption Power vs Temperature and Part Supply Voltage in Continuous Conversion Mode</i> graph .....	11
• Added <i>Supply Voltage Change</i> section .....	14

# Additional Resources

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## [Temperature sensors overview](#)

Explore TI's portfolio of temperature sensors for any need.

## [Temperature sensors parametric quick search tool](#)

Filter TI's selection of temperature sensors to find the right solution for your design.

## [TI Precision Labs – temperature sensors](#)

Learn the basics of temperature sensors, terminology, key specifications and design tips in TI's video training curriculum, with on-demand courses and tutorials.

## [Remote temperature sensor calibration tool](#)

Use this calibration tool to optimize performance across a selection of temperature sensors.

## [Thermistor design tool](#)

TMP6 thermistor design tool with look-up tables, performance comparisons and code examples.

## [SysConfig system configuration tool](#)

An intuitive and comprehensive collection of graphical utilities for configuring pins, peripherals, radios, subsystems and other components.

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