Design Considerations for Measuring Ambient Air Temperature

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ABSTRACT

Power-hungry electronic components such as processor chips, field programmable gate arrays (FPGAs), application-specific integrated circuits (ASICs), as well as power ICs heat up during operation. When the system is turned on, the heat generated by these ICs transfers to lower temperature objects nearby. Measuring ambient air temperature with a surface mount device can be challenging because heat transfer from components on the same PCB can influence and interfere with the ambient air temperature reading of the sensor. To maintain accuracy in applications that require ambient air temperature measurement, it is important to follow good layout techniques such as understanding the dominant thermal path, isolating the island surrounded by the package, and keeping the device as far away from interfering heat sources as possible. This application note will focus on layout strategies to overcome off-board (ambient air) temperature sensing challenges encompassing many applications. It details recommended layout techniques for accurate measurement of ambient air temperature with a temperature sensor in a plastic package, such as the TMP116 or TMP117. The application note includes measurement data of the TMP116 ambient air temperature measurement, and the LMT70 which is used as a reference to the temperature sensor to distinguish between air temperature measurement and the interference from a nearby heat source.

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1 Introduction

There are three methods of heat transfer: heat conduction through solids, heat convection through fluids, 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 is transferred from nearby components of the PCB to the die of the sensor through the PCB itself and through the sensor package. For details on heat conduction and how it applies to heat transfer through a PCB and through selected surface mount packages, refer to the application note, *Temperature Sensors: PCB Guidelines for Surface Mount Devices* (SNOA967).

1.1 Temperature Sensor Location

The most accurate method for measuring the temperature of a local analog or digital temperature sensor is to physically measure its own die temperature. Section 1.1.1 and Section 1.1.2 show the cross section drawings of the TMP116 and the LMT70, respectively, including their dominant conduction transfer paths.

1.1.1 Dominant Thermal Conduction Path of a DFN (TMP116)

For sensors in plastic packages without leads such as TMP116 WSON, the DAP (Die Attach Pad) provides the most dominant thermal path from its environment to the die, as shown in Figure 1. Because of the large contact area of the DAP, a temperature sensor can respond quickly to changes in PCB temperature and create a thermal equilibrium between the surrounding PCB temperature and the temperature of the sensor die. The cross section figure shows that the die is mounted on top of the metal plate leadframe with a non-conductive die adhesive, allowing for a fast thermal response transferring through the pins.

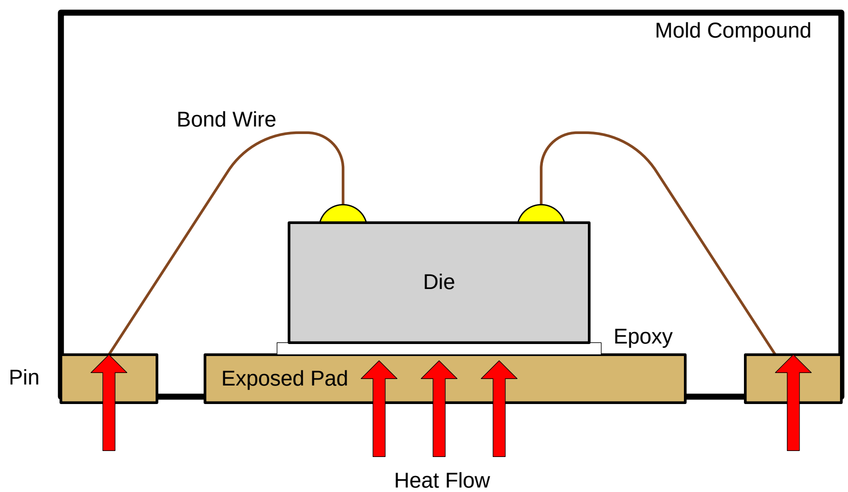


Figure 1. Heat Transfer WSON (TMP116) Package Cross Section

1.1.2 Dominant Thermal Conduction Path of a WCSP (LMT70)

Wafer Chip Scale Package (WCSP) leads are actually Ball Grid Array (BGA) balls processed directly onto the die; they are different than a regular surface-mount package. Heat from the PCB is directly transferred to the die through the balls instead of transferring through the pins or the DAP, as shown in Figure 2.

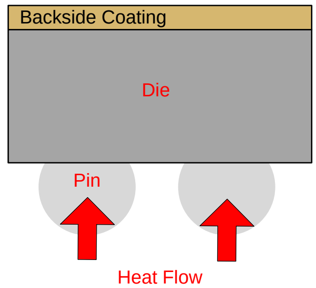


Figure 2. Heat Transfer WCSP (LMT70) Package Cross Section

1.2 Surface Mount IC

Most applications use the IC surface mount to measure the temperature of the PCB hot spots. Using the surface-mount IC benefits low profile and small packages, and allows measuring PCB temperature in any position and placement. The temperature sensors can be placed close to the heat source as possible. The board-mounted IC sensor can measure the temperature of the circuit board accurately due to the leads of the package soldered down to the PCB. To measure the temperature of the ambient air temperature that is close to the heat generators and not the circuit board requires proper design layout techniques. For more information, refer to the application note, *Temperature Sensors: PCB Guidelines for Surface Mount Devices* (SNOA967).

2 Method and Procedure

2.1 General Overview

The system block diagram is shown in Figure 3. The three LMT70YFQT analog sensors are positioned as close as possible and mounted on top of the copper plane hot spot (TDH35H power resistor). The LMT70 analog output temperature sensor is connected to a 16-bit resolution ADC (ADS1115IDGST). The three TMP116AIDRVT devices are placed away from the heat generators of the power resistor in Figure 4 to simulate the best layout scenario of keeping the temperature sensors as far away as possible from the heat source. Heat is generated when power is applied to the power resistor and a temperature gradient is created on the PCB. There are a total of six layout techniques investigated in this report.

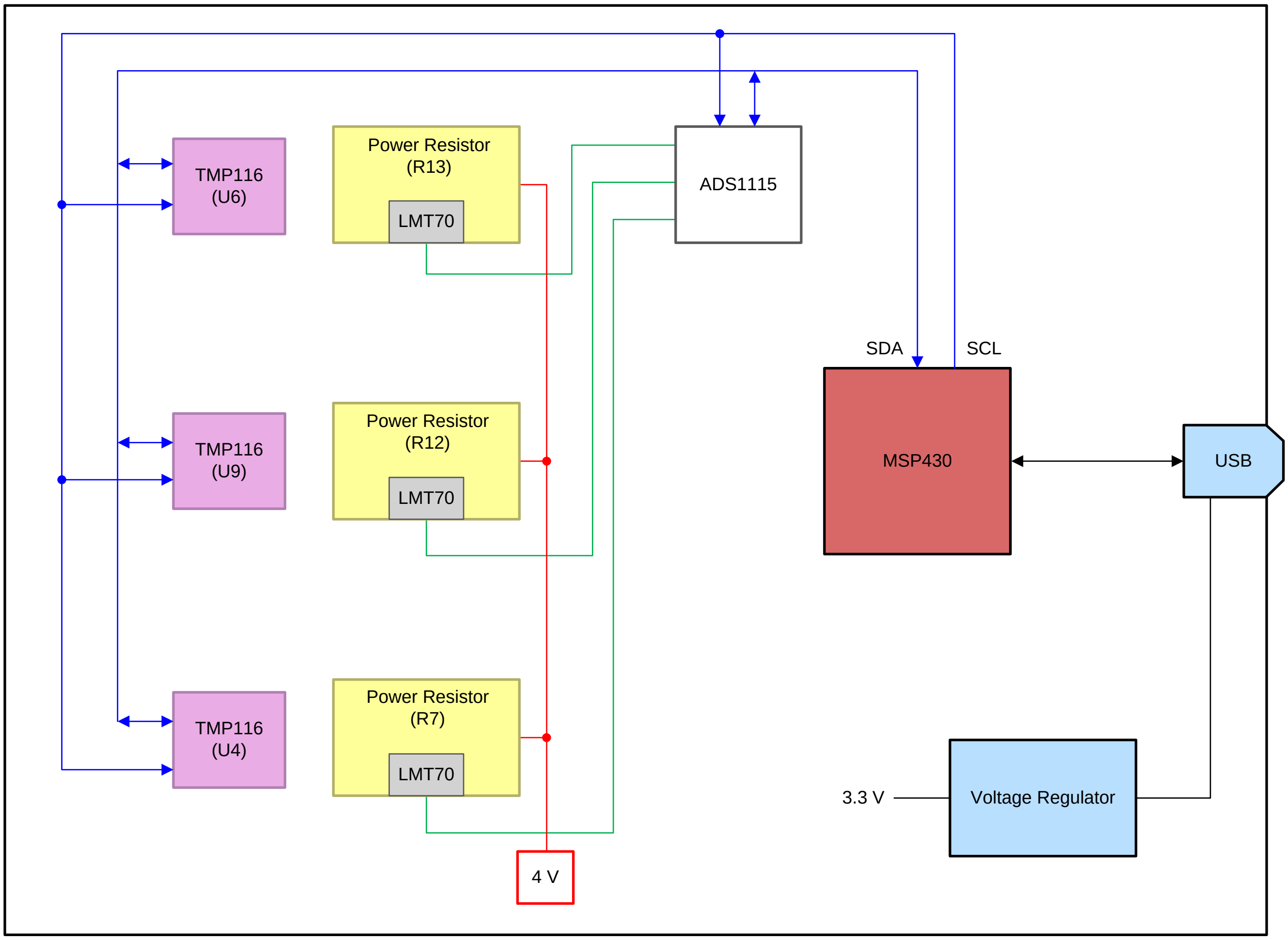


Figure 3. Ambient Air Temperature Measurement System Block Diagram

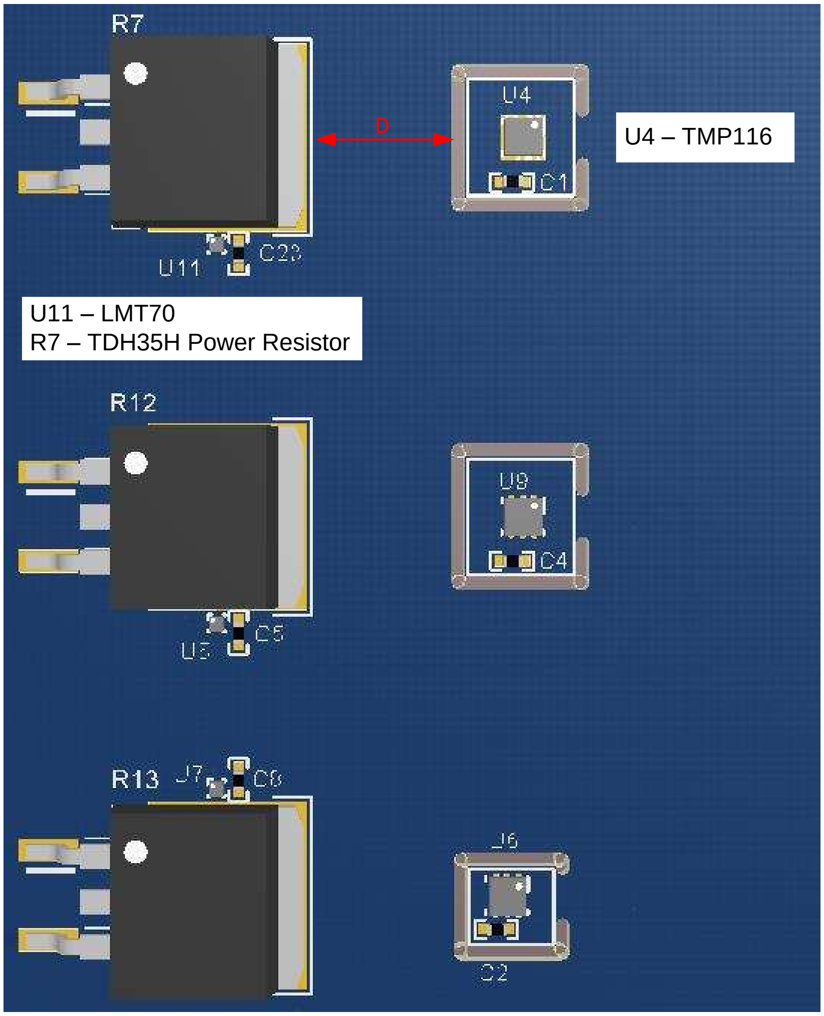


Figure 4. General Physical Layout for Test Board

2.2 Key System Components

2.2.1 TMP116 and TMP117

The TMP116 and TMP117 devices are pin-compatible, high-precision digital temperature sensors with integrated EEPROM. Both devices are I^2C- and SMBus-interface compatible, have programmable alert functionality, and can support up to four devices on a single bus. The TMP116 provides up to ±0.1°C accuracy over the +20°C to +42°C range, and ±0.2°C accuracy over the –10°C to +85°C range with 16-bit resolution. The TMP117 provides up to ±0.1°C accuracy over +20°C to +50°C range, and ±0.2°C accuracy over the –55°C to +150°C range with 16-bit resolution. Both devices come in a small 2.00-mm × 2.00-mm 6-pin WSON package. The TMP117 is also offered in a 1.00-mm × 1.60-mm 6-pin DSBGA package. The operational voltage range of the TMP116 operates from 1.9 V to 5.5 V, and the TMP117 operates from 1.8 V to 5.5 V. Both devices typically consume 3.5 μA.

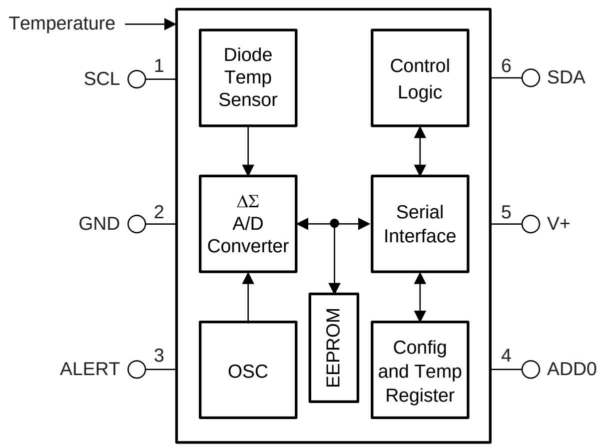


Figure 5. TMP116 Block Diagram

2.2.2 LMT70

The LMT70 is a high-accuracy analog output temperature sensor with an output enable pin, as shown in Figure 6. This temperature sensor has a very linear output with a slope of –5.19 mV/°C. It has an accuracy of 0.36°C over its full operating temperature range of –55°C to 150°C. The part comes in a small chip scale package (WCSP) measuring only 0.88 mm × 0.88 mm, which makes it ideal for applications where space is critical. There are two methods to interface the LMT70. First method is to interface with an external, standalone ADC, which interfaces with a microcontroller such as a MSP430. The second method is to use the integrated ADC inside a microcontroller to digitize the analog signal from the LMT70.

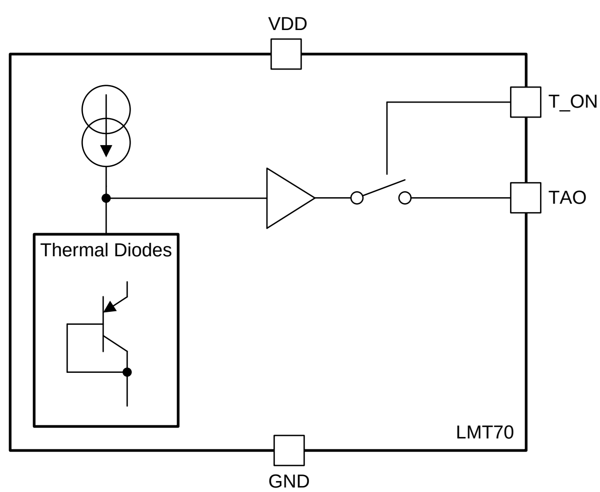


Figure 6. LMT70 Block Diagram

2.2.3 ADS1115

The ADS1115 is a 16-bit sigma-delta analog-to-digital converter (ADC) with an integrated voltage reference and oscillator, as shown in Figure 7. The power supply of the ADS1115 ranges from 2.0 V to 5.5 V and draws 150 µA in continuous mode and 500 nA in power-down mode. The ADS1115 communicates with a host through an I^{2}C interface and features four hard programmable addresses. The precision ADC samples at a maximum of 860 samples per second and can either operate in continuous or single-shot modes.

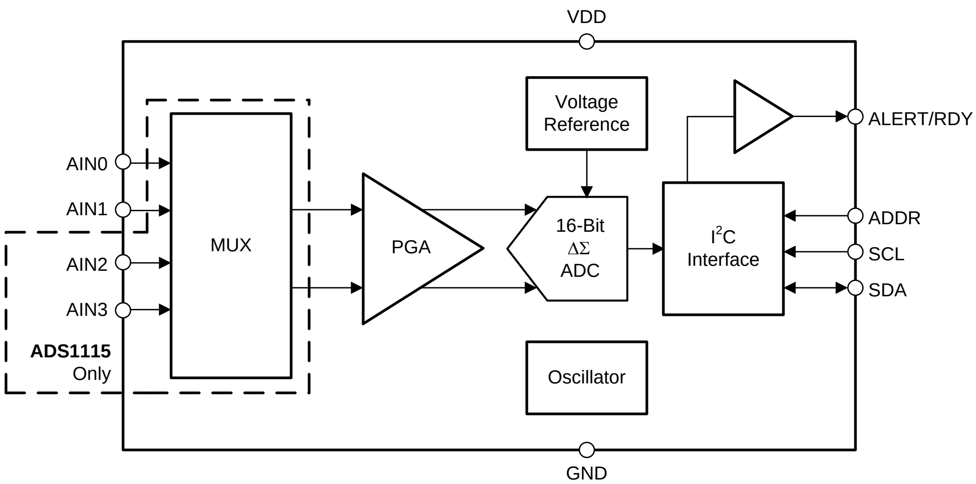


Figure 7. ADS1115 Block Diagram

2.2.4 TDH35H

The TDH35H is a surface-mount power resistor with a nominal resistance value of 10 Ω. The thermal resistance of the resistor is 4.28°C/W. The tolerance of the resistance ranges from 1% to 10% and has a temperature coefficient of ±50 ppm/°C.

2.3 Layout Techniques

2.3.1 Overview

To accurately measure the ambient temperature using a sensor that is in a plastic package, the sensor can be isolated from the heat source using isolation island techniques and distance. For this particular package, TI recommends two vias per TMP116 dimension of the thermal pad. The construction of the DAP and two vias help improve the thermal characteristics. To take advantage of this feature, the TMP116 needs to be mounted onboard as shown in the cross section with two copper planes top and bottom of equal length as the exposed die attach dimension. The bottom plane consist of the sensing elements of the temperature through all directions. To achieve the fast response of the temperature, the dimension of the mini board should enough to allocate for TMP116 and the bypass capacitor; in addition to using the isolation air gap to prevent the heat source dissipation to the mini sub-board.

Thermal response is used to determine how fast the TMP116 reacts to the change of the temperature environment. Two elements should be considered when conducting the thermal responses experiment: the thermal conductivity and thermal mass. Table 1 compares the different layout techniques with or without isolation islands, polygon cooper planes, and solder mask options users can choose, and lists the dimensions of each board so the user can monitor ambient air temperature with high accuracy, linearity, and faster thermal responses using TI IC temperature sensors. To get the speedy temperature response, a good layout technique is to maintain the thermal mass of the isolation island as small as possible. The smaller the thermal mass is the better thermal response. Layout A shows the TMP116 placed next to the power resistor without isolation. In this layout, the TMP116 measures onboard temperature that increases due to power dissipation from the power resistor. Layout B is similar to Layout A, but the TMP116 temperature sensor more accurately tracks and measures ambient temperature in Layout B because it has contour routing to create an isolation island, preventing an ambient temperature reading error associated with heat dissipating directly to the TMP116. In Layout C, two polygon copper planes are created on both top and bottom layers extending beyond the TMP116 package. This helps absorb the ambient temperature to reach equilibrium temperature at steady-state, but it has a slow thermal response due to thermal mass. Layout D also has two copper planes on the top and bottom layers with equal size to the package's dimension, but the thermal response is very similar to Layout C. Layout E and F have a similar design to Layout D, but the two polygon copper planes are of equal size to the thermal pad. Layout F shows a significantly faster thermal response and accurately measures the ambient air temperature.

Table 1. Cross Section Layout

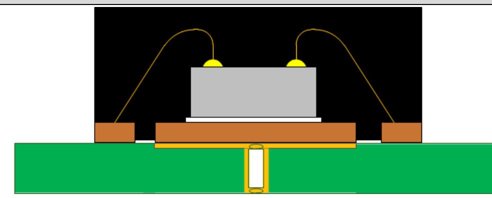
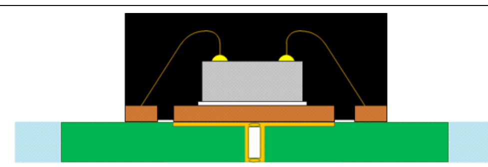
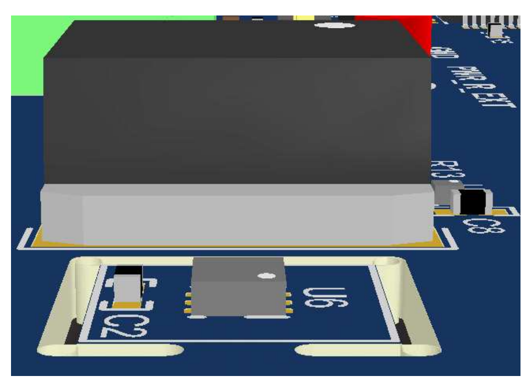
LAYOUT NAME	DESCRIPTION	LAYOUT TECHNIQUES
Layout A	• No perforation isolation island • No bottom copper plane • No top and bottom solder mask removed • TMP116 senses PCB temperature	 
Layout B	• Thermal isolation • Board dimension 240 × 260 mils • No bottom copper plane • No top and bottom soldermask removed • Air gap 40 mils	 

Table 1. Cross Section Layout (continued)

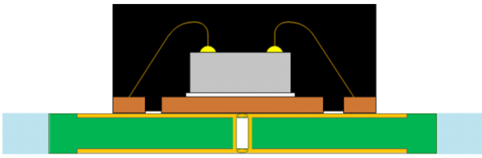
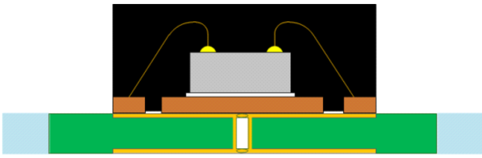
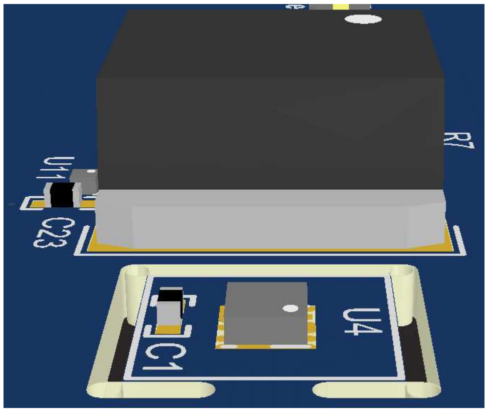
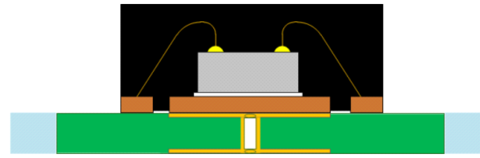
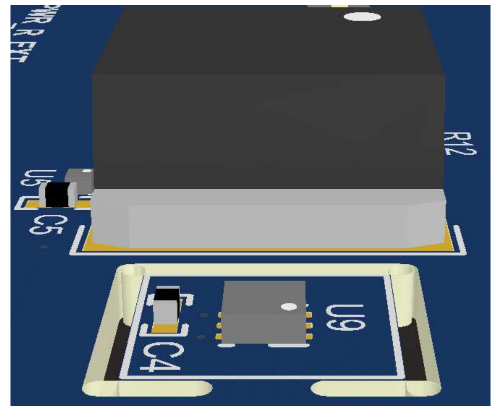
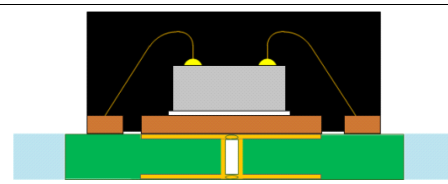
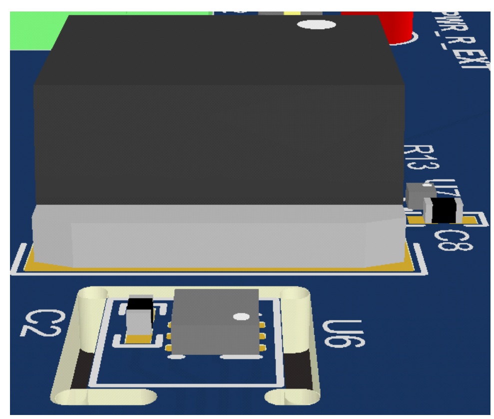
LAYOUT NAME	DESCRIPTION	LAYOUT TECHNIQUES
Layout C	• Thermal isolation • Board dimension 240 × 260 mils • Top and bottom copper plane 130 × 140 mils exposed pad • Top and bottom solder mask removed • Air gap 40 mils	 
Layout D	• Thermal isolation • Board dimension 240 × 260 mils • Top and bottom copper plane 100 × 100 mils exposed pad equal size to the package • Top and bottom solder mask removed • Air gap 40 mils	 

Table 1. Cross Section Layout (continued)

LAYOUT NAME	DESCRIPTION	LAYOUT TECHNIQUES
Layout E	• Thermal isolation • Board dimension 240 × 260 mils • Top and bottom copper plane 64 × 40 mils exposed pad equal size to the center pad • Top and bottom solder mask removed • Air gap 40 mils	 
Layout F	• Thermal isolation • Board dimension 190 × 170 mils • Top and bottom copper plane 64 × 40 mils exposed pad equal size to the center pad • Top and bottom solder mask removed • Air gap 40 mils	 

2.4 Test Setup

The system diagram of the test setup for simulating enclosed chassis environment for off-board temperature sensing is shown in Figure 8. This shows the test setup used to determine an effective way to measure air temperature using a PCB. Each test board is placed inside an 11-in.' × 10-in. × 7-in. clear plastic box to simulate a still-air condition. The red line rectangular box is the cardboard box that helps to create another layer of insulation. This will prevent any disturbance of the air flow. The board has an integrated MSP430 microcontroller that provides I^2C communication protocol between the sensors and a microcontroller to a computer.

The temperature of the power resistor is monitored by contact with the LMT70 at the edge of the power resistor mounted pad. The resistor temperature is also measured with a very fine-type T thermocouple tip into a hole on the backside of the resistor through bottom side. This thermocouple is connected to an Omega DPi8-C24 readout. The LMT70 is used as a reference temperature for the TMP116. A high-precision RTD is connected to a Fluke 1502A with an excellent reference probe model 5615-9. It has an accuracy of 12m°C, and is placed inside the clear plastic box just right above the TMP116 to measure the ambient air temperature. The power resistor generates heat when voltage and current is applied 4 V and 0.4 A, respectively, from an external power supply. The controlled temperature of the power resistor is within 90°C. The hot spot is controlled to have temperature ranging from 40°C to 100°C. The temperature values from the system is gathered with I^2C interface board and sent over USB as well as GPIB to a LabView program.

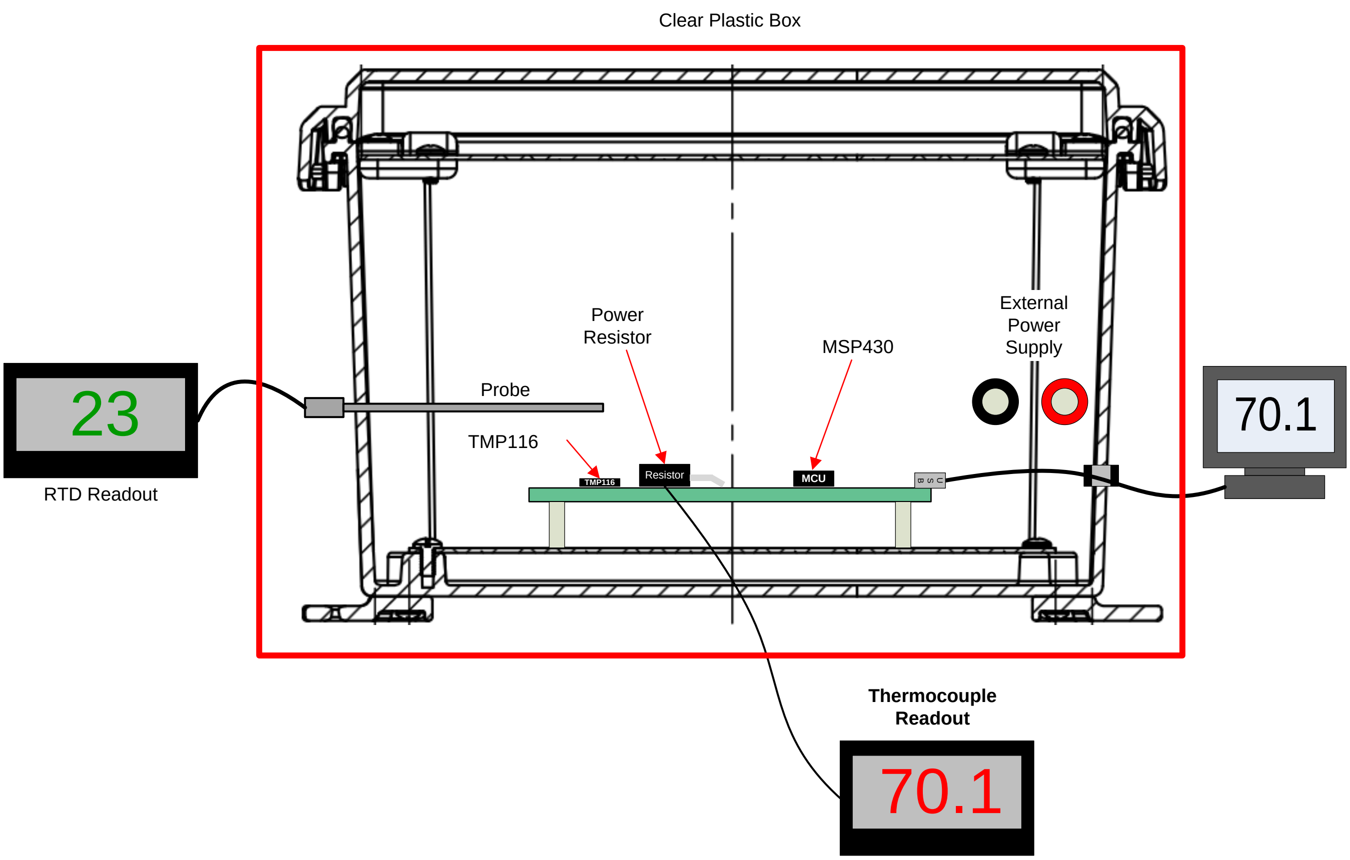


Figure 8. Test Setup System Diagram

3 Result

3.1 Temperature Response

In Table 1 is an example of PCB layouts to prevent heat source affecting the ambient temperature measurement of the TMP116. The thermal isolation is required to avoid thermal coupling from the heat source component through the PCB, because heat can radiate through air and transfer the heat to surrounding components. To accurately monitor ambient temperature, maximize the air gap between the temperature sensors and heat source by creating a contour routing around the desired hot spot (anti-etching) with a wider cutout when it is close to the source. Another method is to move the sensor away from the heater source as far as possible; however, the wider cutout is not required when the distance is away from the heat source. Figure 9 is example of an ambient temperature measurement without heat source.

In Figure 11 through Figure 15, power is applied to the power resistor to generate heat approximately 90°C. The results for TMP116 ambient air temperature measurement is shown in Figure 9 through Figure 15. The measurement result shows the temperature gradient decreasing when the TMP116 is placed farther away from the heat source and the hot spot temperature increases logarithmically for all layouts.

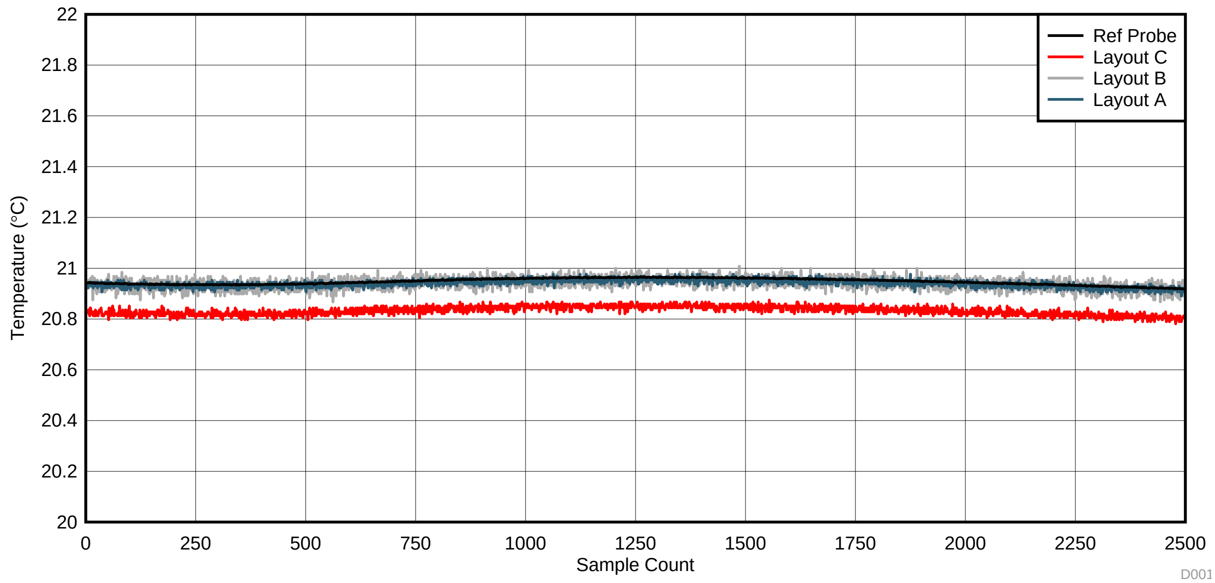


Figure 9. Layout A, B, C Ambient Air Temperature Measurement

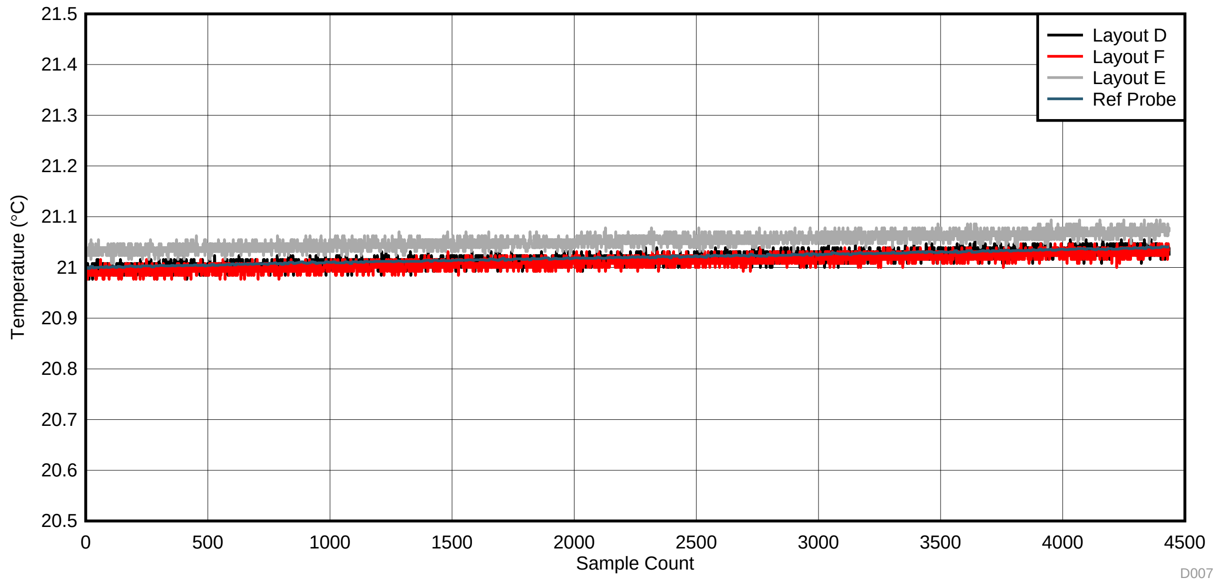


Figure 10. Layout D, E, F Ambient Air Temperature Measurement

In Figure 11 and Figure 13, the TMP116 mini-sub board was placed a close distance of 0.508 mm away from the power resistor. Creating a PCB contour routing around the sensor and other circuits, and leaving a narrow channel away from heat source components as a routing bridge into the island, minimizes the main heat source dissipation into the TMP116. Layout A (TMP116_U9) without the cutout island isolation shows that the TMP116 temperature reading is influenced by the power resistor temperature; therefore affecting the reading the ambient temperature. However, Layout C with contour routing, via and two copper planes shows the TMP116 temperature reading is much closer to the reference temperature. The two exposed copper planes that are bolted the top to the bottom layer with two recommended vias have very high thermal conductivity. At a distance of 15.24 mm away from the heat source, there is no significant temperature gradient difference between contour routing and no contour routing.

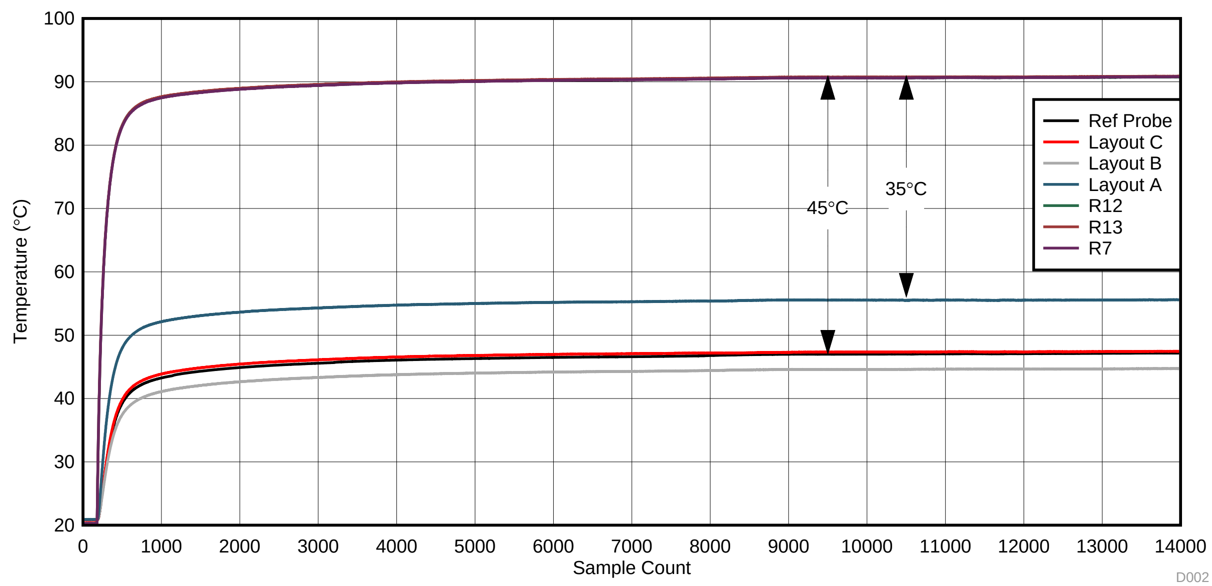


Figure 11. Layout A, B, C — 0.508-mm Distance

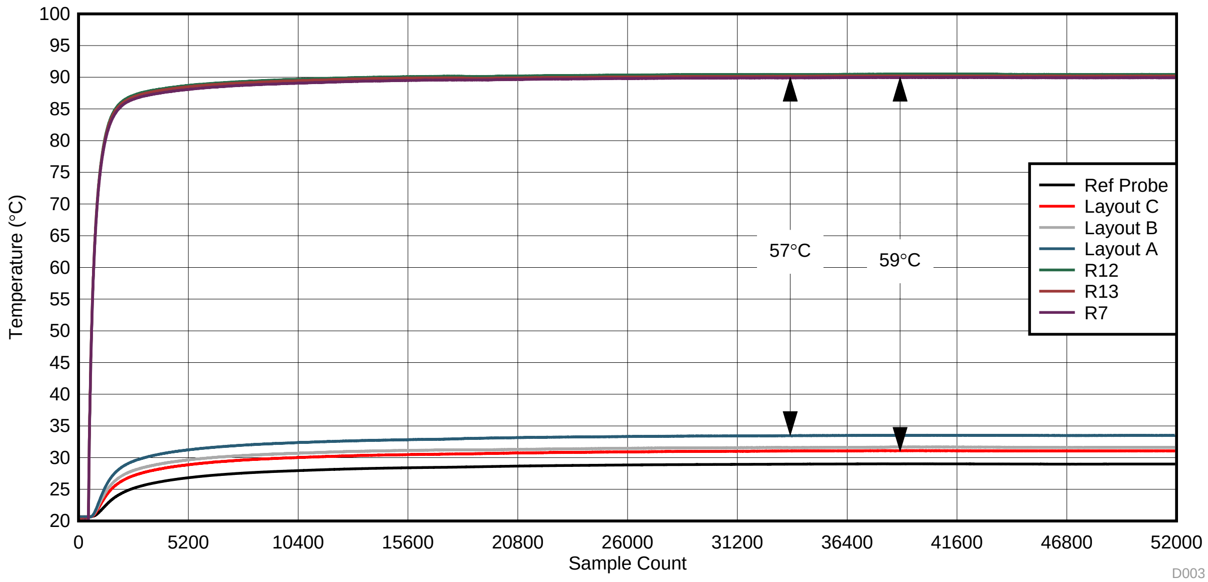


Figure 12. Layout A, B, C — 15.24-mm Distance

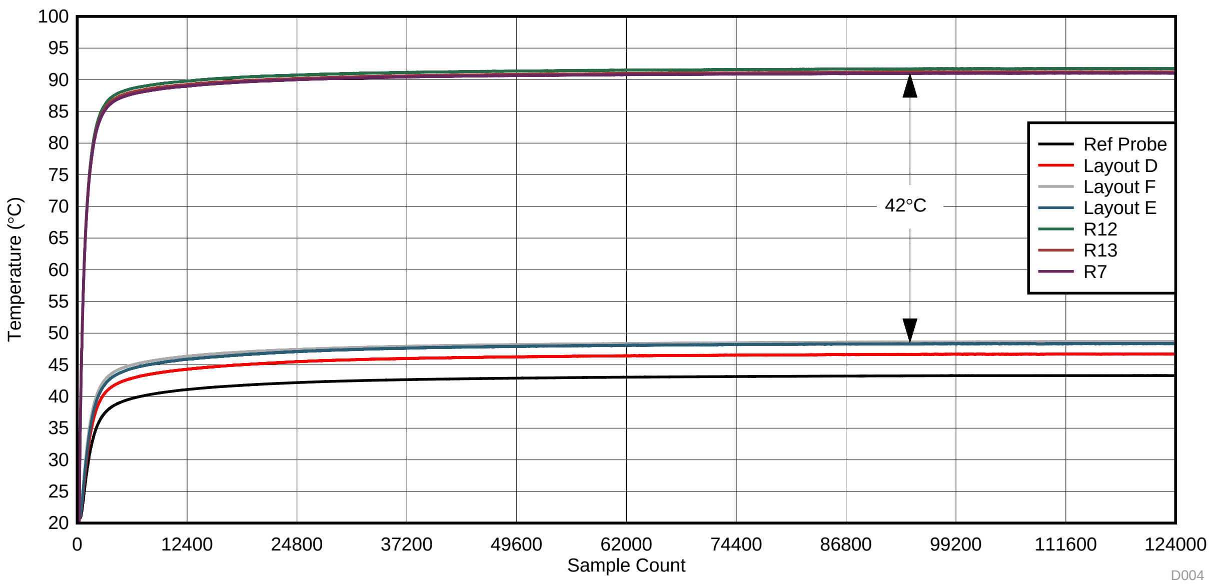


Figure 13. Layout D, E, F — 0.508-mm Distance

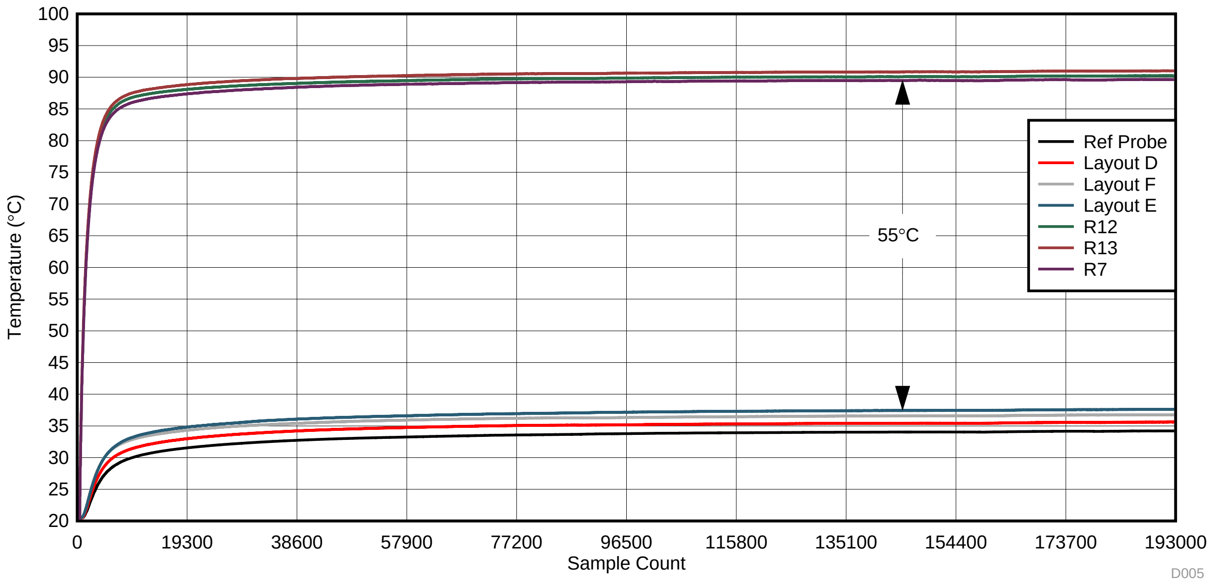


Figure 14. Layout D, E, F — 7.62-mm Distance

In comparison between Figure 14 and Figure 15, opening a wider air gap on the contour routing from 1.52 mm to 2.54 mm does not show much temperature difference when measuring the ambient temperature away from the heat source components.

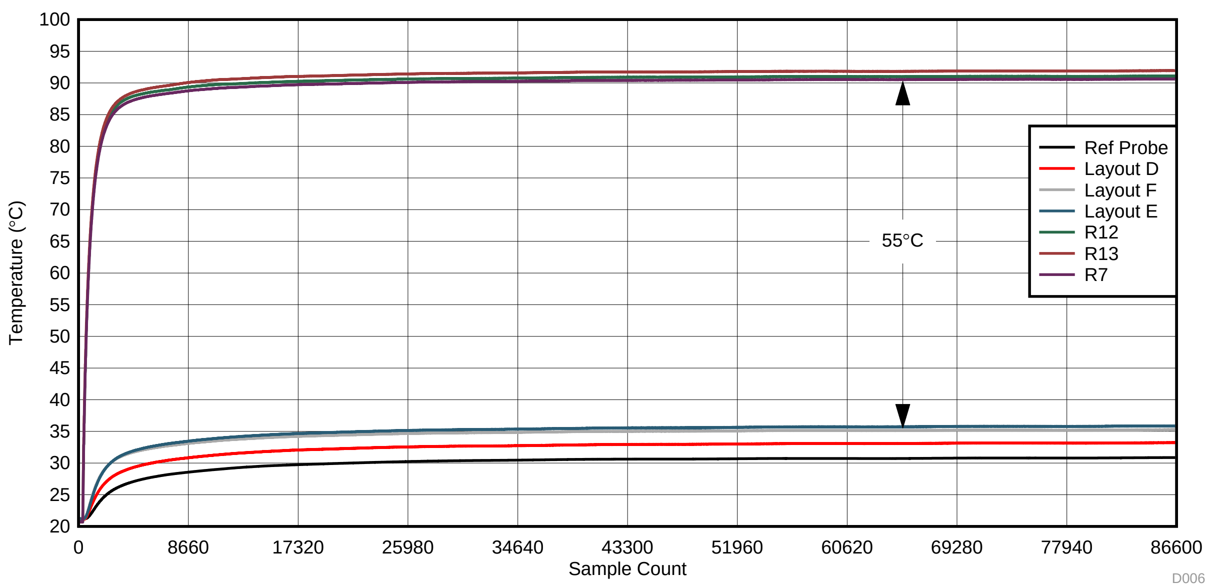


Figure 15. Layout D, E, F — 2.54-mm Isolation Air Gap

Distance is very important when measuring the ambient temperature. Table 2 lists the recommended distances for the heat source temperature.

Table 2. Recommended Distance Away From Heat Source

HEAT SOURCE TEMPERATURE	AMBIENT TEMPERATURE	RECOMMENDED DISTANCE
40°C	20°C	7.62 mm
60°C	20°C	15.24 mm
100°C	20°C	38.1 mm

3.2 IR Thermal Image

All simulations were done with PCB inside a 254-mm × 175-mm × 172-mm plastic box with a 3-mm thick wall. The air temperature surrounding the box is 20°C, where the power resistor heater pads are set at 40°C, 60°C and 100°C. The temperature boundary condition was used instead of applying power to the heater. Thermal images were captured with FloTHERM thermal analysis tool to show the temperature distribution of the hot spot across the board. In Figure 16 heat radiated through air from the heat source. The temperature of the hotspot varies depending on where the reference probe is placed. The thermal map shows a significant temperature concentration near the resistor hot spot due to low thermal conductivity between the TMP116 sensors and hot spot. The thermal image Figure 17 provides a top down view of the PCB. So, it is important to know where the heat source is so that routing traces near the heat source can be avoided.

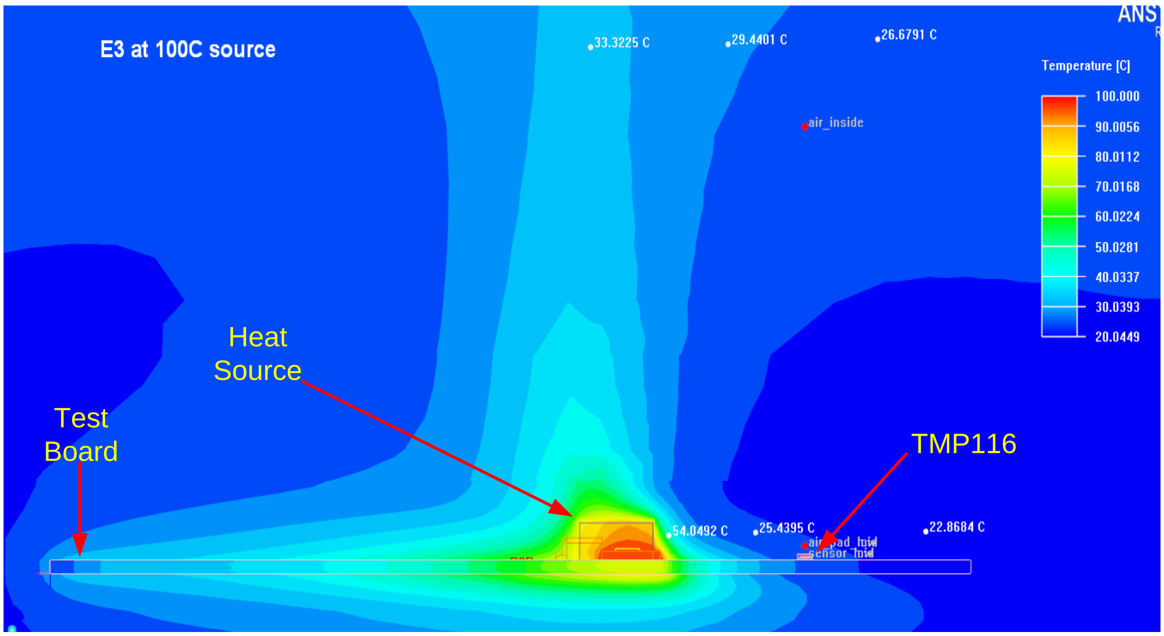


Figure 16. Heat Radiated Across Test Board

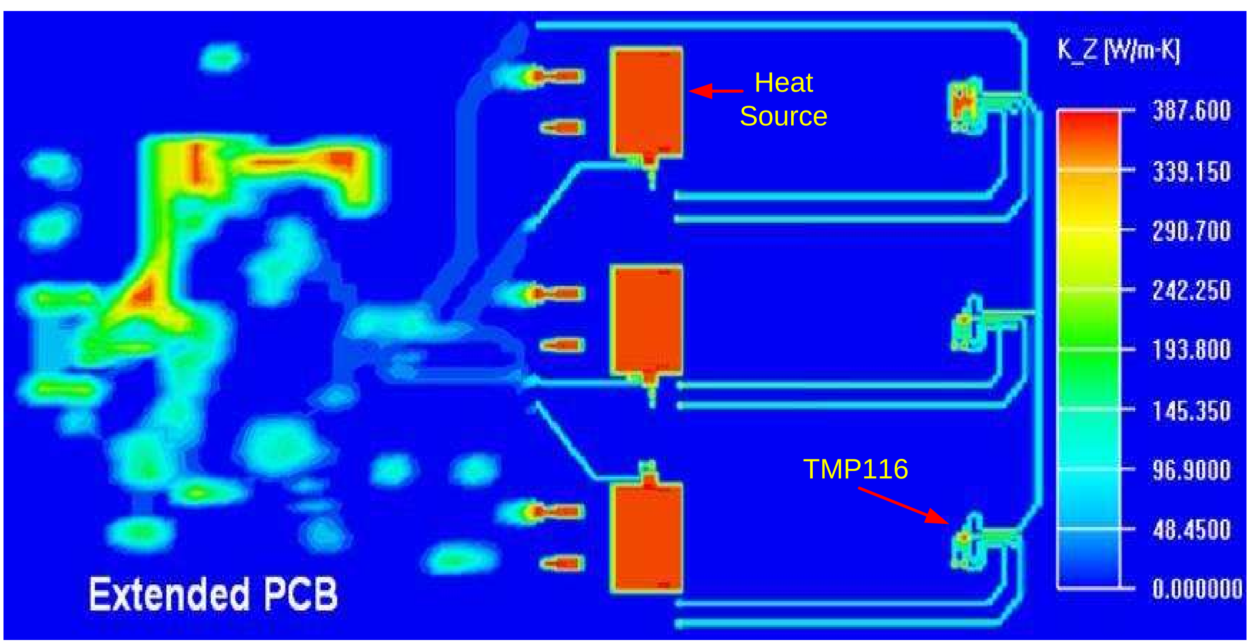


Figure 17. Layout D, E, F Extended Distance

In Figure 18 the isolation air gap is about 0.8 mm. The bigger the air gap the better the ambient air measurement when the temperature sensors are close to the heat source. However, the gap does not make any difference when the temperature sensor is placed far away.

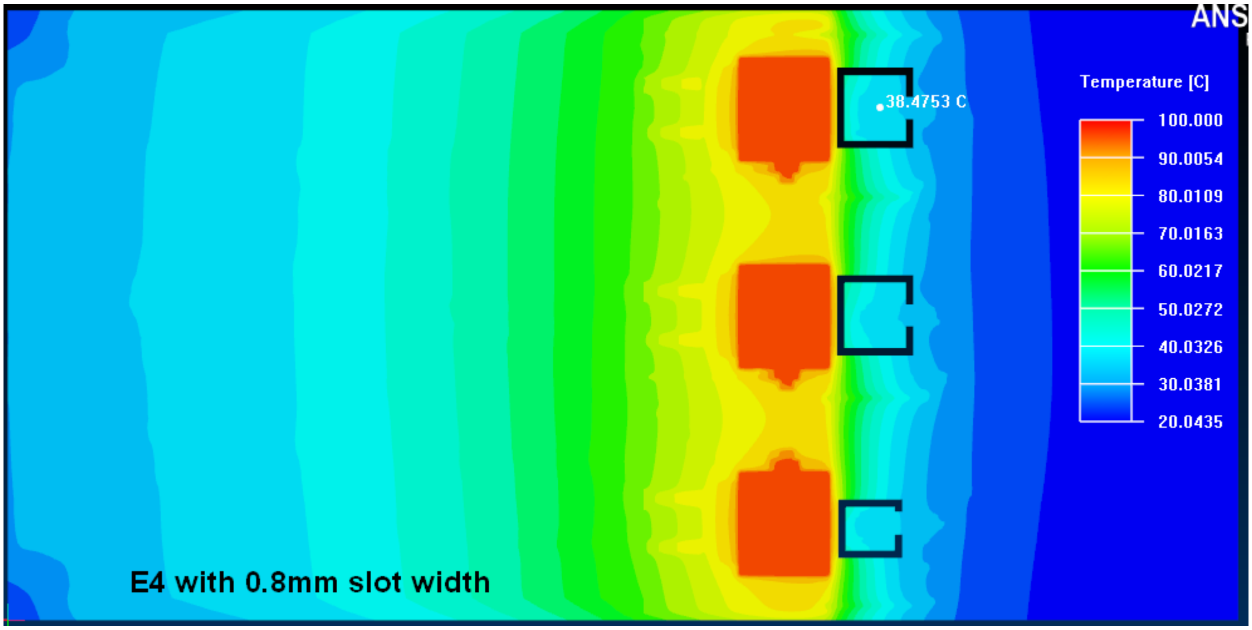


Figure 18. Layout D, E, F Thermal Air Gap 0.8-mm Slot Width

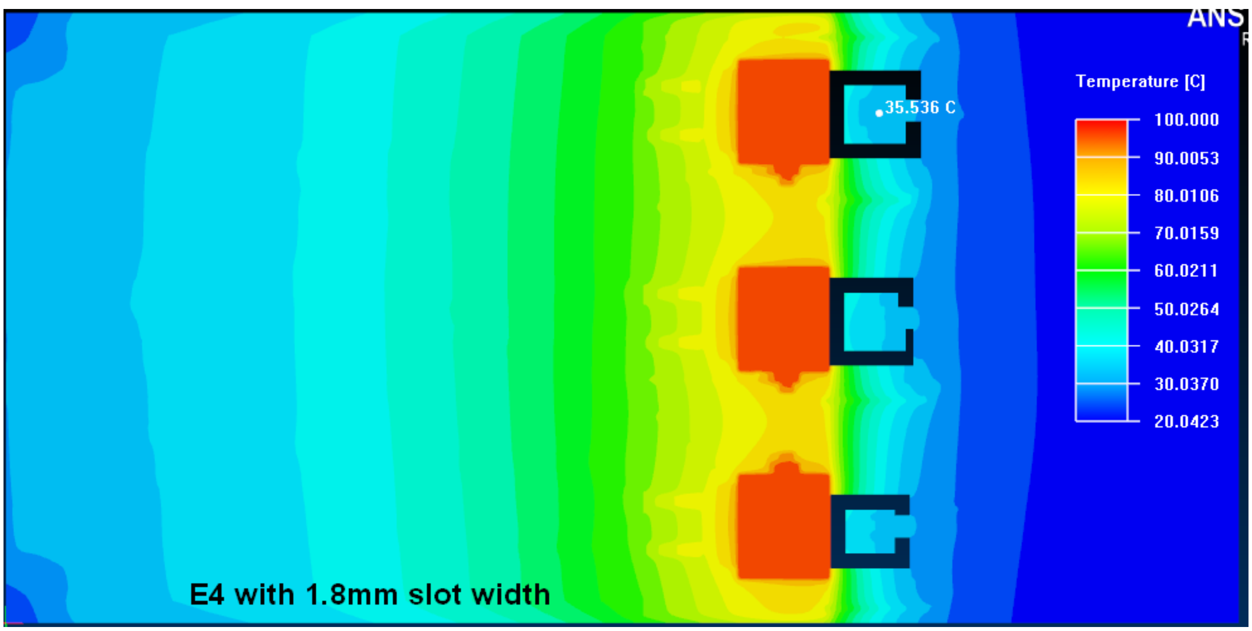


Figure 19. Layout D, E, F Thermal Air Gap 1.8-mm Slot Width

4 Conclusion

PCB physical design can have a significant effect on temperature sensing. In this investigation, layout F showed the best result because it has a small dimension with fast temperature response. TI recommends that the designer consider the following design guidelines:

- Copper planes and vias should be used to enhance thermal conduction and allow a better ambient air temperature measurement
- Miniaturize the board to reduce thermal mass to provide improved thermal response, if needed
- Place two copper planes of equal size to the top and bottom of the exposed pad so that the ambient air temperature can be transferred directly to the device.
- Remove the top solder mask if possible because it helps absorb a better air temperature.
- Cover exposed copper with solder paste to prevent oxidation.
- Thermal isolation is required to avoid thermal coupling from heat source components through the PCB.
- Avoid running copper plane underneath the temperature sensor.
- Maximize the air gap between the sensor and the surrounding copper areas (anti-etch), especially when close to the heat source.
- Create a PCB cutout between sensor and other circuits. Leave a narrow channel away from heat source components as a routing bridge into the island.
- Route all signals on the bottom side, avoid traces on top if heat source is coming from the top side.
- Place the board vertically to improve air flow and to reduce dust collection.
- Do not solder thermal pad for improved accuracy.

Revision History

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

Changes from A Revision (August 2018) to B Revision	**Page**
• Changed application report title from: *Ambient Air Temperature Measurement Strategies* to: *Design Considerations for Measuring Ambient Air Temperature*	1

Changes from Original (August 2017) to A Revision	**Page**
• Changed application report title from: *TMP116 Ambient Air Temperature Measurement* to: *Ambient Air Temperature Measurement Strategies*	1
• Added references to the TMP117	1
• Added the *TMP116 and TMP117* subsection to the *Key System Components* section	7

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