Texas Instruments

Application Report

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Wearable Temperature Sensing Layout Considerations Optimized for Thermal Response

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ABSTRACT

This application note discusses thermal response considerations for IC temperature sensors in measuring skin temperature for wearable applications such as fitness bands and medical devices. It will specifically focus on two devices—the LMT70 and the TMP117 temperature sensors—over the human body temperature range. This information can be applied, however, to other temperature sensors that come in similar packages. Contact temperature sensors, such as the LMT70 and the TMP117, need to be placed in close contact with the surface that must be measured. This can be quite challenging for both DSBGA (LMT70 and TMP117) and WSON (TMP117) packages if fast thermal response is also necessary. Experimental results of different PCB layouts for measuring axillary (armpit) temperature and oral temperature will be presented.

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1 Introduction

The two major concerns for measuring body temperature in wearables are accuracy and speed. The temperature sensor response speed is determined by the amount of thermal mass surrounding the sensor. The accuracy can be addressed by picking a temperature sensor with high measurement accuracy such as the TMP117 and the LMT70 which are 0.1°C and 0.13°C, respectively. The thermal response of the temperature sensor is how fast the device responds to a sudden change in temperature. This application note will discuss PCB layout options to achieve good thermal conductivity, as well as quick thermal response for the LMT70 and TMP117 as PCB layout can dramatically affect these parameters. In addition to correct layout, good mechanical and thermal contact are also critical. The LMT70 and TMP117 are contact sensors, thus making good contact with the surface that is measured is of primary importance. To achieve the fast thermal response of a temperature sensor, there are a number of layout technique considerations. There are three methods of heat transfer: conduction, convection, and radiation. For more detailed information, refer to the *Design Considerations for Measuring Ambient Air Temperature* (SNOA966) and *Temperature Sensors: PCB Guidelines for Surface Mount Devices* (SNOA967) application notes.

1.1 LMT70

The LMT70 is a 4-pin analog temperature sensor that comes in a DSBGA package measuring 0.88 mm × 0.88 mm. The small size of the package yields small thermal mass and thus fast thermal response. The LMT70 also includes internal calibration making it one of the most accurate analog IC temperature sensors in the market. The LMT70's typical accuracy of 0.05°C from 25°C to 45°C makes it ideal for measuring body temperature. The LMT70 temperature-sensing circuitry is based on the transistor base emitter diode junction thermal properties. The diode voltage is then amplified and buffered as shown in Figure 1. The sensing element of the LMT70 consists of stacked BJT base emitter junctions that are biased by a current source. The output of the sensing element is buffered by a precision amplifier whose class AB push-pull output stage can easily source and sink currents of up to 3 mA. The amplifier output connects to an output switch that is turned on and off by the digital control input T_ON (see Figure 1). This switch allows for the multiplexing of multiple sensors on one signal line.

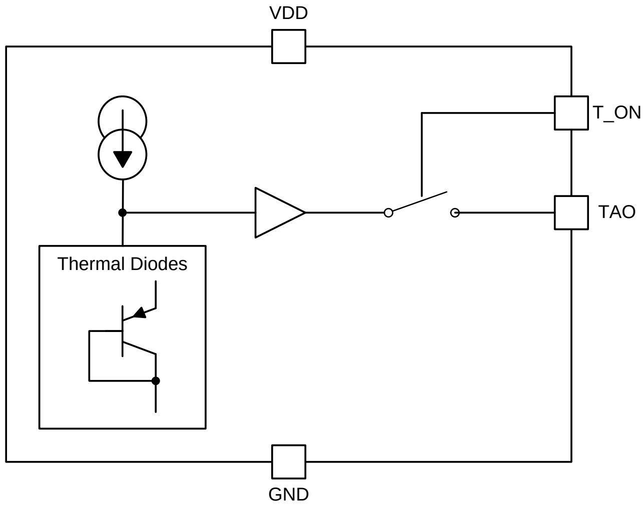

Figure 1. LMT70 Block Diagram

1.2 TMP117

The TMP117 devices are a family of high-precision digital temperature sensors with integrated EEPROM. The TMP117 is I2C and SMBus interface-compatible, has programmable alert functionality, and can support up to four devices on a single bus. These sensors provide an accuracy of ±0.1°C over the -20°C to 50°C range, and 0.2°C accuracy over the -40°C to 100°C range with 16-bit resolution. The TMP117 comes in a small 2.00-mm × 2.00-mm 6-pin WSON package, operates from 1.8 V to 5.5 V, and typically consumes around 3.5 µA.

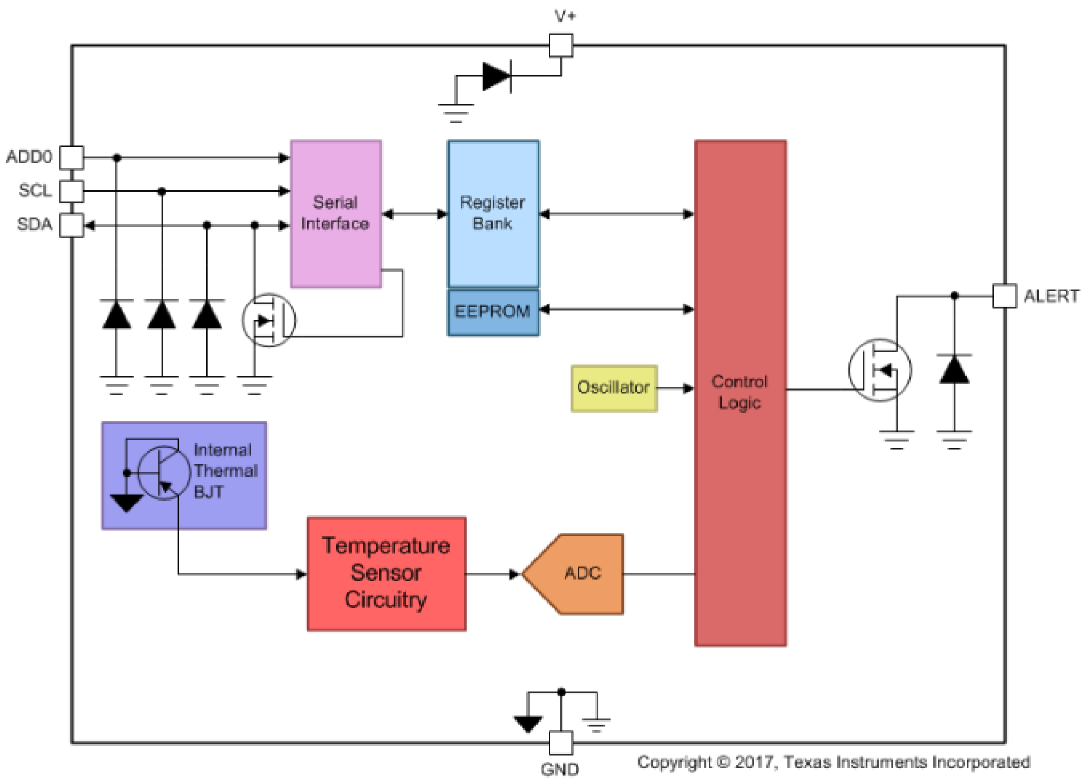

Figure 2. TMP117 Block Diagram

1.3 Thermal Conductivity

When measuring temperature, thermal conductivity is a key material property that must be considered. Thermal conductivity (W/(mK)) of several materials that may be used in the production of a PCB are listed in Table 1.

Table 1. Thermal Conductivity of Different Materials

MATERIAL	THERMAL CONDUCTIVITY k [W/(m×K)]
Air	0.023 to 0.045
Wood	0.04 to 0.3
Epoxy coating on top of LMT70 die	0.2 to 0.3
FR4	0.4
Polyimide	0.5
Mold Compound	1
Thermally Conductive Epoxy	1 to 7
LMT70 Solder Ball	7 to 8
Stainless Steel	16 to 24
Solder (63/67)	39
Nickle	91
Silicon	100 to 120
Aluminum	204 to 250
Gold	320
Copper	400
Silver	425
Diamond	900<

The higher the k factor, the better the thermal conductivity and thus the faster the response time. Maintaining a small thermal mass will improve the thermal response time of the circuit. This is where good thermal modeling software becomes a necessity. Shown in Figure 3 is a cross section of an LMT70 mounted on a PCB. As can be seen in the Thermal Conductivity of Different Thermal Materials table copper is a very good thermal conductor when soldered. The red arrow shows the heat flow path from the back side of the PCB to the LMT70 active circuitry (cross hatched area) through metal portions of the PCB (the traces, pads, and solder balls). There is air surrounding the part and the solder balls in this example, so the thermal conductivity is compromised. Better results can be obtained if underfill material is added surrounding the LMT70 die (package) as shown in Figure 4. This can improve the conductivity to the actual silicon which has very high thermal conductivity. FR4 and Polyimide insulators do not have very good thermal conductivity, thus their thickness should be minimized.

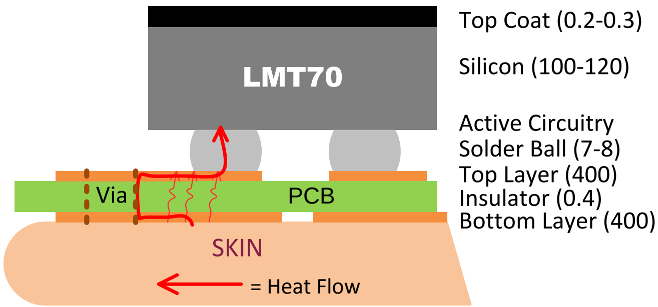

Figure 3. LMT70 PCB Path of Heat Flow (Thermal Conductivity of Materials, k [W/(m×K)], Given in Parenthesis)

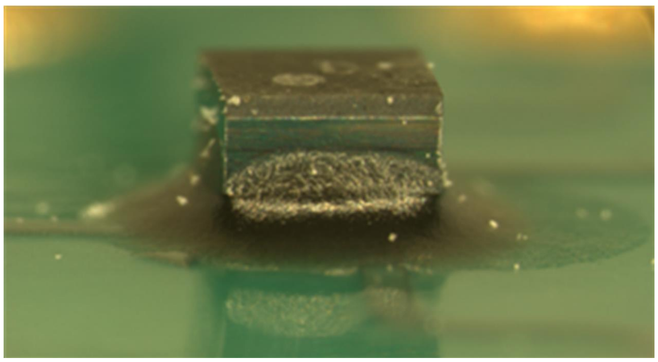

Figure 4. Closeup of LMT70 Mounted on a PCB With Underfill Material

Figure 5 depicts the cross section of a typical PCB stack up using several common materials, with the TMP117 mounted on top. TI recommends two vias per landing pattern for this particular package. The construction of the landing pattern helps to improve the thermal performance. The die contacts the large area of the exposed pad which provides the most the dominant heat flow path. The heat flows from the skin directly to the stacked materials and into the exposed pad through the two vias thermal and to the die. This allows the die to respond quickly to any skin temperature changes.

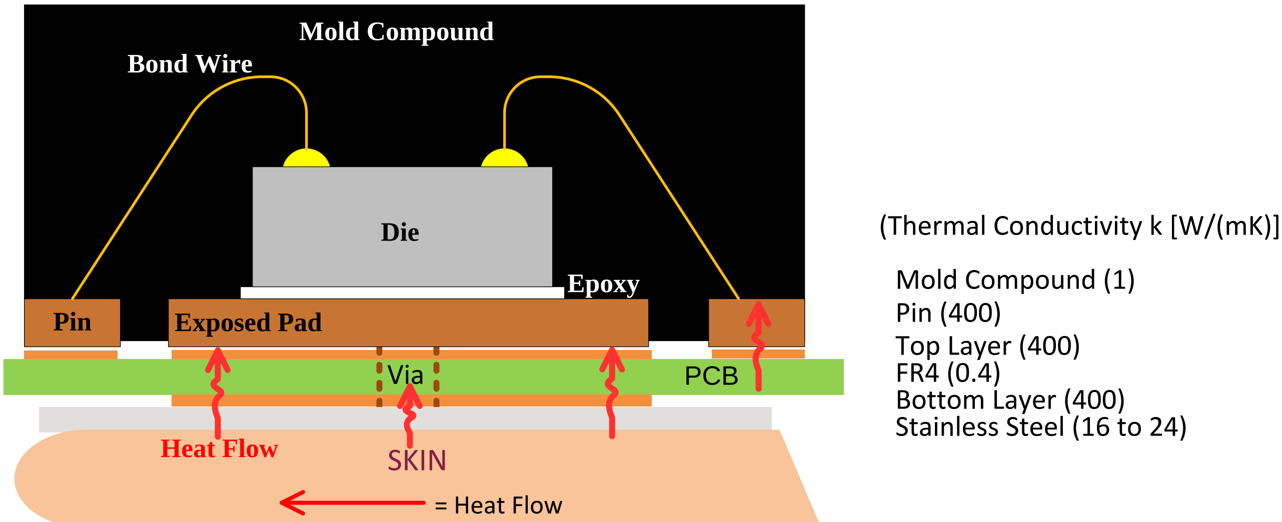

Figure 5. TMP117 Heat Flow Path

2 Small Board Probe Board Description

As mentioned previously, both the size and the choice of material impacts total thermal mass. The following board was designed to optimize the thermal response time of the LMT70 and TMP117. The board described in this section was made very small and approaches the minimum sizes for PCB manufacturing. The back side of the board has a large surface area with vias to the top side as shown in Figure 6 to Figure 9.

2.1 *LMT70 Mini Board*

All boards are assembled with LMT70 first with the panel intact. The LMT70s are then epoxied to the board. Forty gauge nickel wire was soldered to the PCB connecting holes for connection purposes as shown in Figure 16. Nickel was chosen for the wire material as it has lower thermal conductivity than copper. The small diameter wire was chosen because of its small mass. This type of wire was used in order to minimize the thermal effects of the wires to the PCB response time. The wires attached to the PCB can act as a heat sink thus lower thermal mass and lower thermal conductivity would minimize the heat sink affect. Holes were used rather than pads in order to provide more mechanical strength to the wire assembly. 4-mil copper traces and 40 AWG copper wire should affect the response time by a very small amount as the main benefits of this layout are the exposed copper bottom side pads and vias.

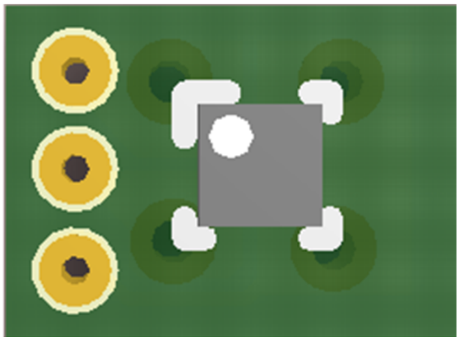

Figure 6. Small LMT70 Probe Board Top Side

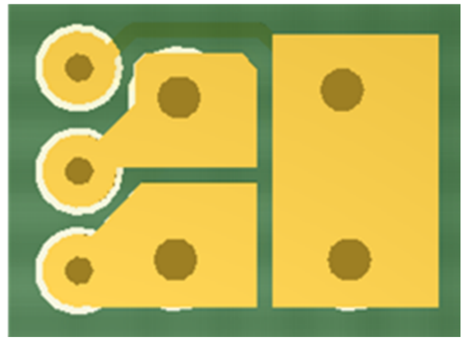

Figure 7. Small LMT70 Probe Board Bottom Side

Probe Board Dimensions

- Width: 115 mil (2.9 mm)
- Height: 85 mil (2.16 mm)
- Thickness: 20 mil with 1-oz copper
- Via size: 12-mil hole, 24-mil diameter
- Wire pad: 8-mil hole, 20-mil diameter
- No bottom side solder mask

2.2 TMP117 Mini Board

To measure the thermal response and the temperature accurately, TMP117 is assembled on a tiny board based on the layout technique in Figure 10 to Figure 14. The mini board is glued with highly thermally conductive adhesive to the walls of the stainless steel tube. The thin, thermal epoxy sometimes creates a bubble of air which will form an insulator and increases the thermal response time. Four insulated nickel wires are soldered to the through hole for provision of power and I^2C communication at the end of the probe. The mini board is inserted into a fitted stainless steel probe. The bottom side of the mini board is filled up with highly thermal conductive epoxy to keep the board contact with the probe casing. This allows the external heat to transfer more quickly to the TMP117.

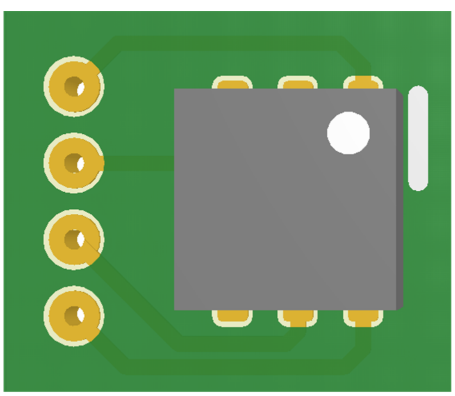

Figure 8. TMP117 Mini Probe Board Top Side L3

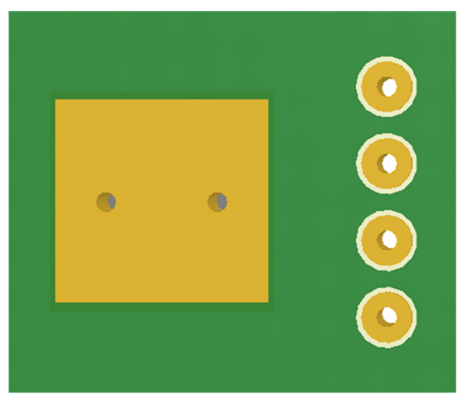

Figure 9. TMP117 Mini Probe Board Bottom Side L3

Probe Board Dimensions

- Width: 150 mil (3.81 mm)
- Height: 170 mil (4.31 mm)
- Thickness: 20 mil with 1-oz copper
- Via size: 8-mil hole, 20-mil diameter
- Wire pad: 8-mil hole, 20-mil diameter
- No bottom side solder mask

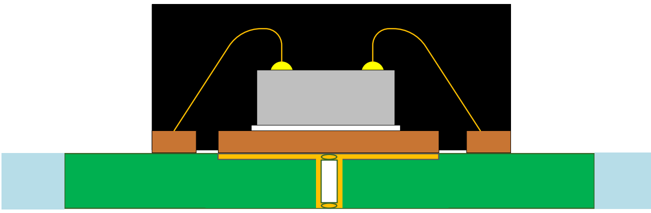

Figure 10. TMP117 Mini Board Cross Section L1

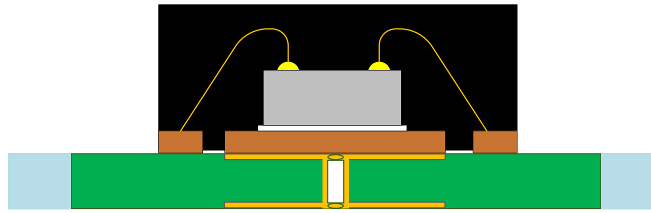

Figure 11. TMP117 Mini Board Cross Section L2

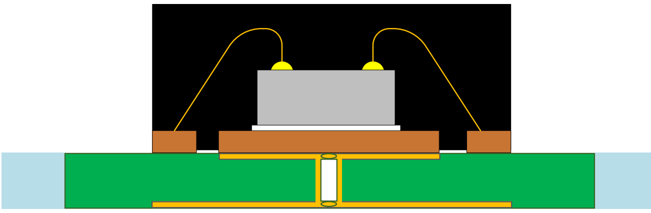

Figure 12. TMP117 Mini Board Cross Section L3

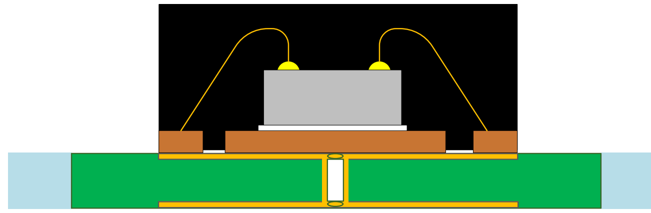

Figure 13. TMP117 Mini Board Cross Section L4

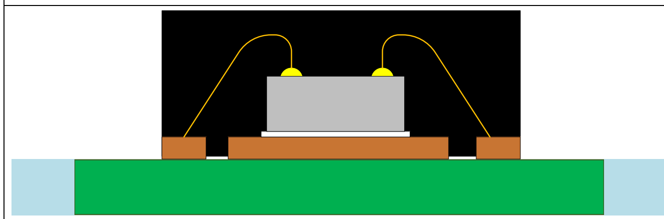

Figure 14. TMP117 Mini Board Cross Section L5

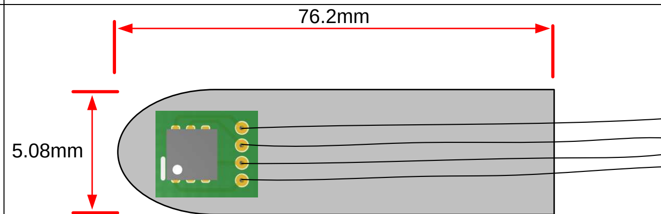

Figure 15. TMP117 Finished Temperature Probe

All the materials used on the finished probe are constructed to sense any temperature change and can detect the temperature instantly. Placing the IC temperature sensors into a closed-ended stainless steel protective probe may help prevent contamination or potential damage. The board layout and construction for wearable applications is similar to the design procedure for the temperature probe in Figure 15. The same techniques can be applied to make wearable applications such as watches by placing the bottom mini PCB between the thermal-sensing contact and the skin.

3 The Measurement System

3.1 LMT70 Setup

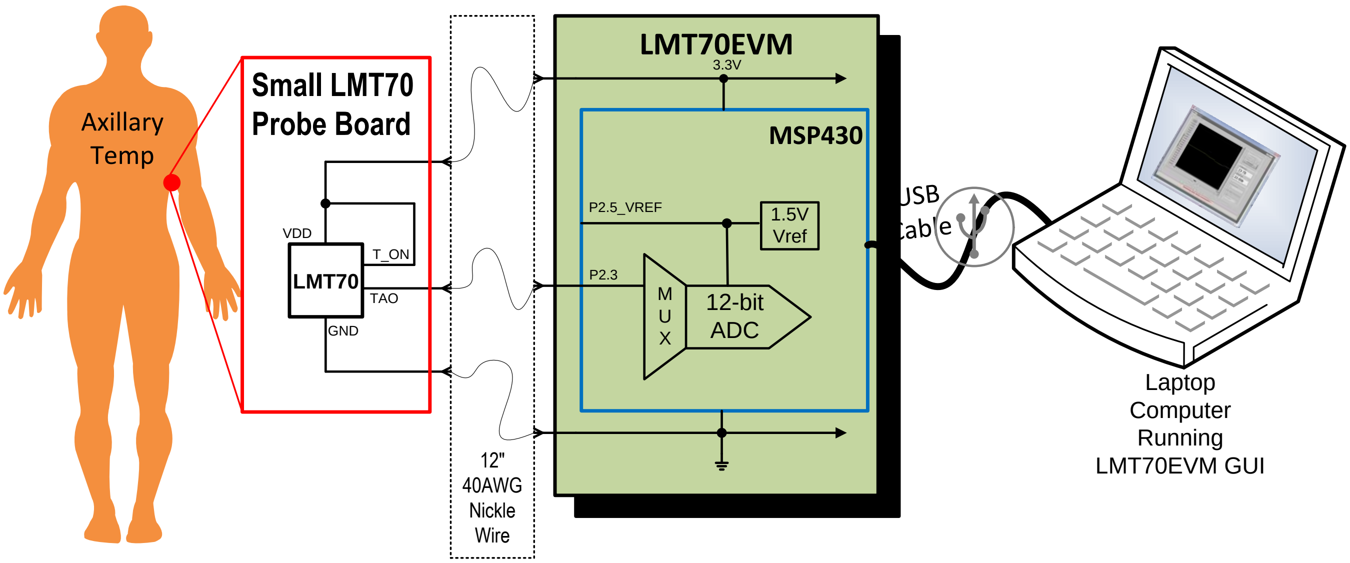

Figure 16. LMT70 Probe Board Thermal Response Measurement System

The LMT70 Probe board is connected to the LMT70EVM through 40AWG wires as shown in Figure 16. The LMT70 output temperature is recorded using the LMT70EVM GUI. The LMT70EVM is USB powered. See the *Temperature Sensor for Wearable Devices Reference Design* (TIDA-00452) and *LMT70EVM User's Guide* (SNIU024) for more information on the GUI and firmware source code and performance of the system.

3.2 TMP117 Setup

The purpose of these experiments is to investigate how long it takes for the TMP117 to respond to a sudden change when the temperature is set to 70°C or human body temperature. Speed and accuracy are very important when measuring human body temperature. The speed of the thermal response is dependent on the materials used and the thermal mass of the probe that the TMP117 have been assembled into. Any thermal mass such as stainless steel metal, PCB materials, and thermal compound will slow the response time. The thermal response time for the probe result may differ, perhaps due to the different types of systems used for each probe.

There are five types of tests for thermal response performed: oral, underarm, stirred oil, still air, and moving air. The setup for the first method, human body temperature thermal response, is shown in Figure 17. The second method uses the oven chamber for still air and moving air. River rocks are placed inside the oven chamber in order to increase thermal mass to help maintain temperature stability and uniformity, although these are not depicted in Figure 18 and Figure 19. Finally, the stirred oil, which has the most thermal conductivity and therefore the fastest thermal response time, is shown in Figure 20.

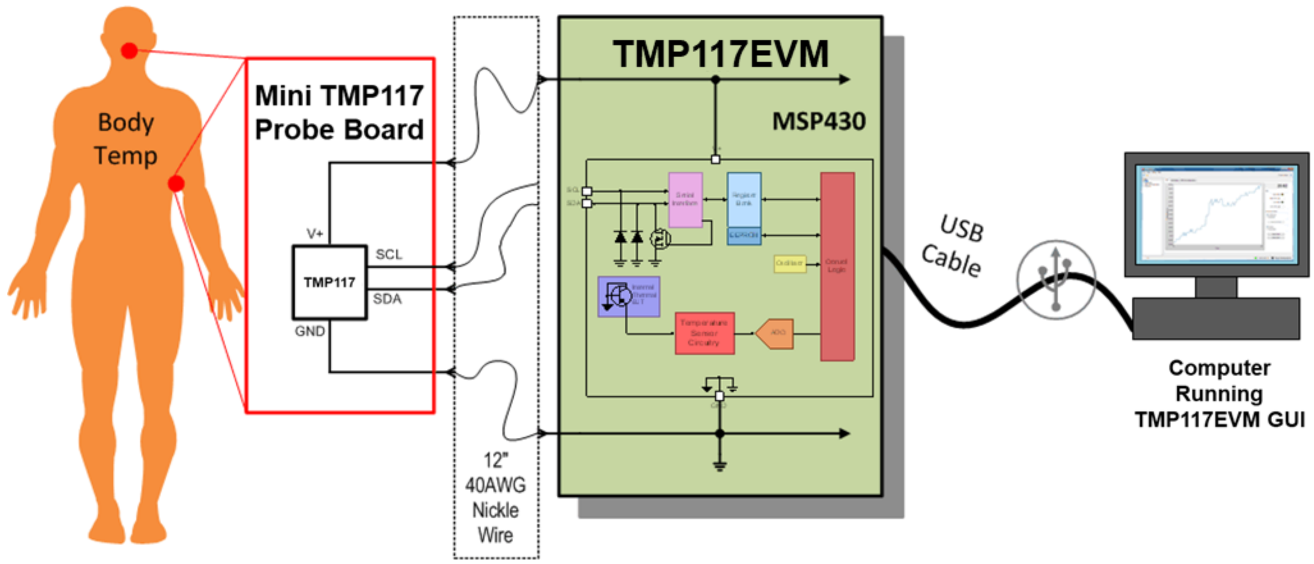

Figure 17. Body Temperature Measurement System

The TMP117EVM comes in a USB stick form factor with an onboard MSP430F5528 microcontroller, which interfaces with both the host computer and the TMP117. TMP117EVM uses the +5-V input power supply of the USB connector to power the EVM. The TMP117EVM is designed with a perforated breakaway portion on the board, which was removed for these experiments. The finished temperature probe is connected to the EVM headers for remote temperature measurements. The simplest way to take a temperature measurement from the human body is in the mouth or under the arm.

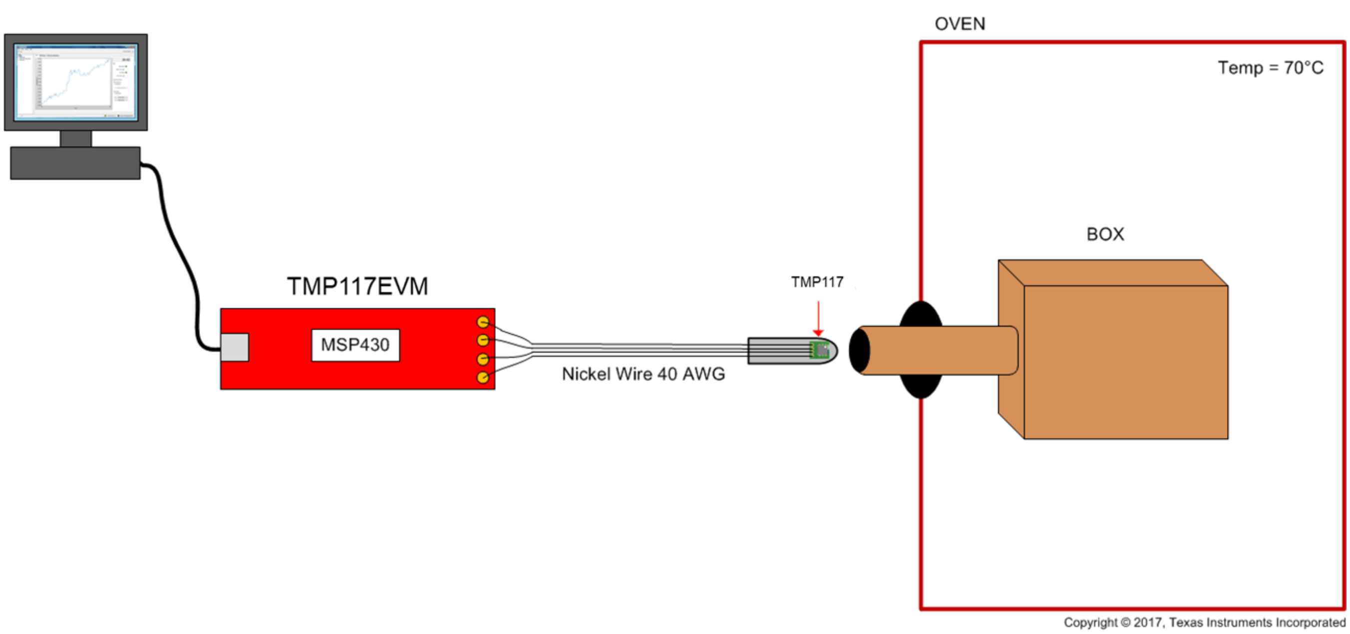

Figure 18. Still Air Thermal Response Measurement System

In this test, the box is completely sealed, and the only opening is an insert with a diameter of about 0.75 inches. River rocks are placed inside the box, creating a high thermal mass that helps the temperature remain uniform across the chamber. The TMP117 probe is connected via the TMP117EVM USB connector to the computer, and the TMP117 probe is powered by the +5-V input power supply of the USB connector. After several hours, when the oven chamber reaches the set point temperature (70°C), the probe is quickly inserted into the cavity opening, and the TMP117EVM GUI logs the temperature data.

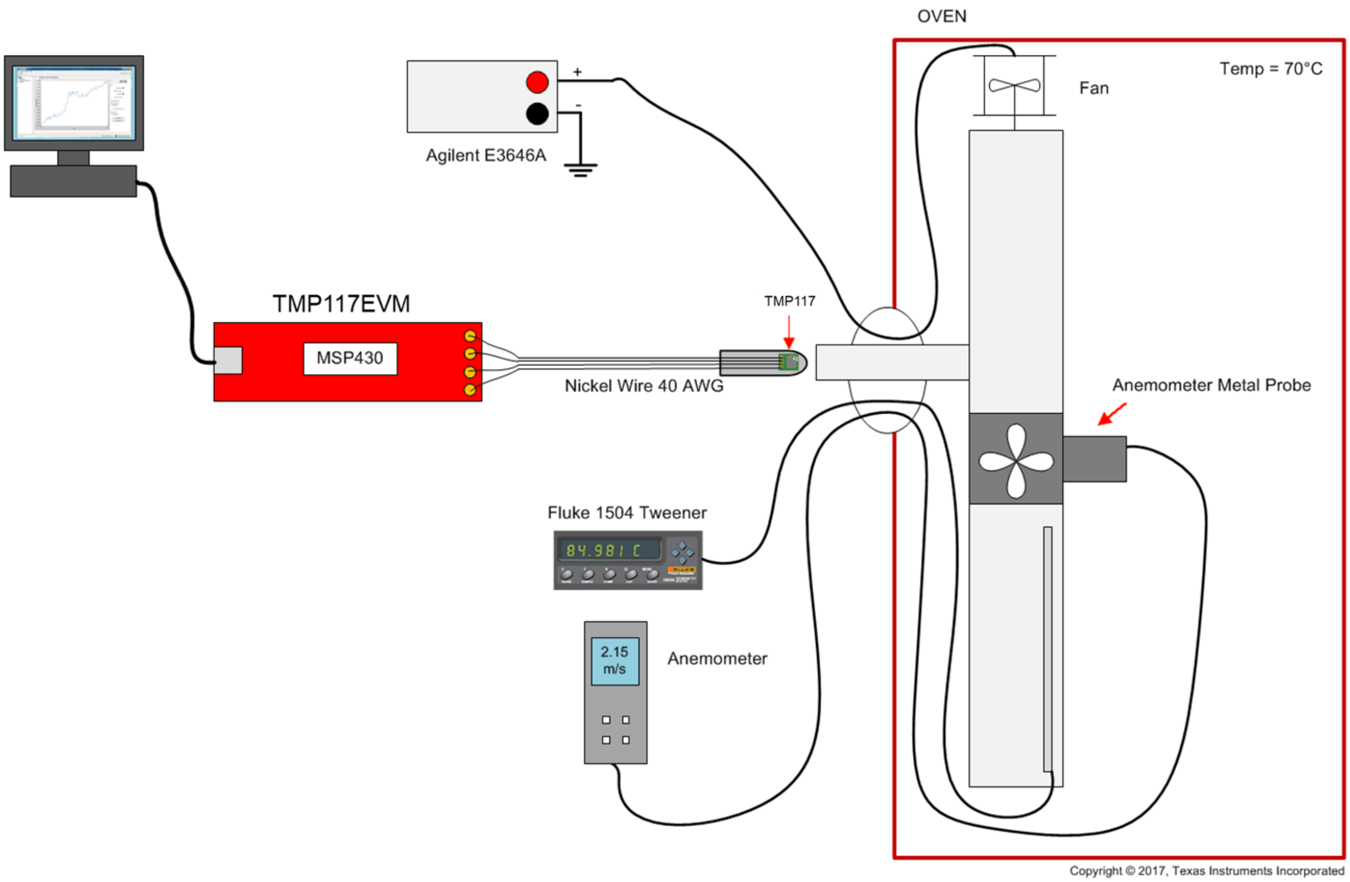

Figure 19. Moving Air Thermal Response Measurement System

The next method is the moving air thermal response shown in Figure 19. In this experiment, river rocks are placed inside the box, creating a thermal mass that helps the temperature remain uniform across the chamber. The tunnel is assembled with an anemometer metal probe and a fan. The anemometer metal probe measures the air velocity, and the fan pumps a constant air temperature into the tunnel. The fan's speed can be controlled, and the designer can choose various velocities using a signal generator. The test in this example, however, is using a constant velocity of 2.15 m/s with the TACH pin left floating.

The oven temperature is set to 70°C, and after several hours, the fan's power supply (12 V) and anemometer meter are turned ON. Once the fan and anemometer meter are stabilized, the TMP117 probe is quickly inserted into the tube until the TMP117 probe reaches the set point temperature.

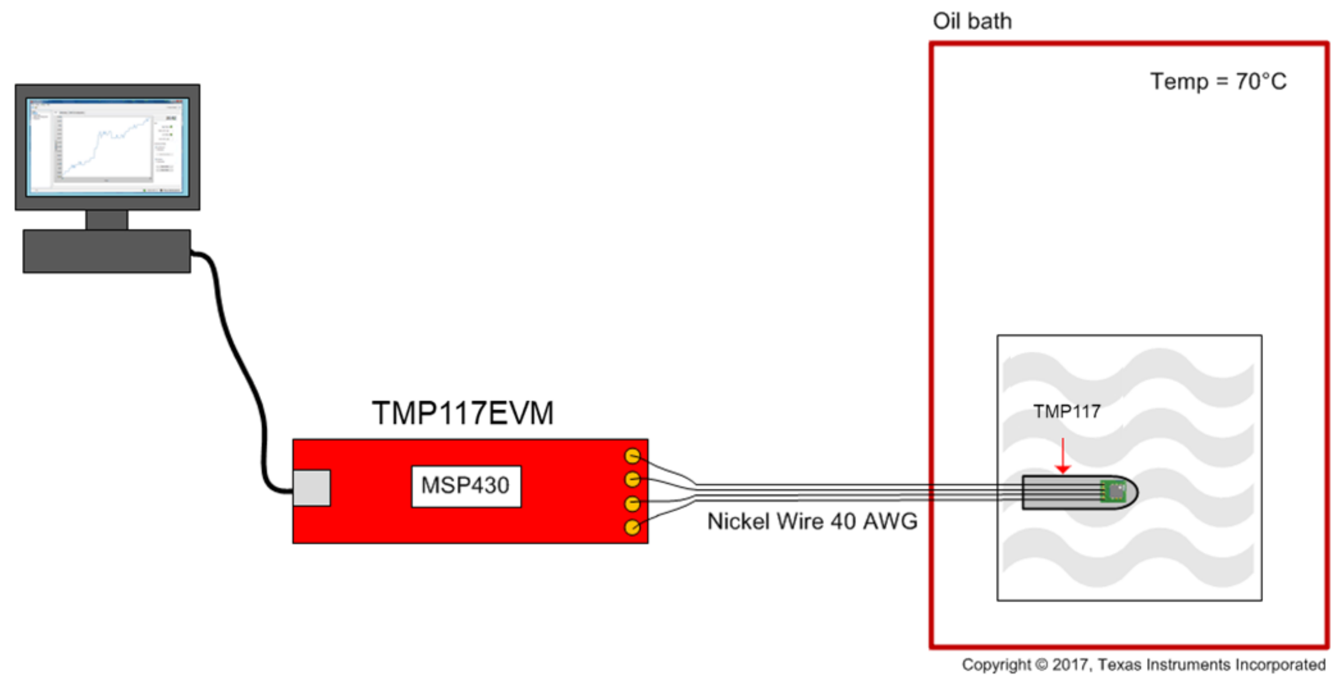

Figure 20. Stirred Oil Thermal Response Measurement System

The final method is the stirred oil thermal response, as shown in Figure 20. Among the three experiments, this method has the fastest thermal response time. The oil bath's temperature is set to 70°C, similar to the still air and moving air setup. Once the temperature is stabilized, the TMP117 probe is dipped into the oil bath's well while the TMP117EVM GUI logs the temperature. The oil bath is a compact chamber that contains a special fluid that helps obtain stability and uniform temperature; the oil bath also uses the precision tweener as a reference temperature.

4 Probe Board Test Results

The curve in Figure 21 shows the percent of final value on the Y axis and time in seconds on the X axis. An initial temperature of about 22°C is the 0% level as shown in the curve. The 100% level is the axillary skin temperature. It is common to normalize the thermal response time of a temperature sensor in this manner. Usually thermal time constant is given to the 63% level, similar to RC time constant. This is a good way to compare the response times of different boards as it normalizes the starting temperature of the test and allows for easy comparison.

4.1 LMT70 Thermal Response Result

As seen in Figure 21, the **Small LMT70 Probe Board** (purple trace) improves the thermal response time performance at 99% of the final value when compared to several other types of PCBs by about 100 seconds. The next best performing PCB is the flex PCB shown in green. More information on the Thin PCB (red), Flex PCB (green), and Regular PCB (blue) can be found in the *Temperature Sensor for Wearable Devices Reference Design* - LMT70 TI Design (TIDA-00452) and Section 6.

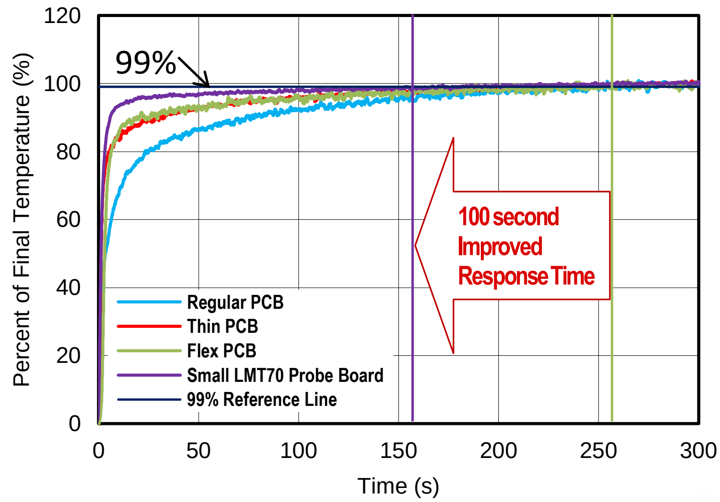

Figure 21. Comparison of the Small PCB to Other Types of Substrates When Measuring Axillary Body Temperature

4.2 TMP117 Thermal Response Result

The approximation for step response in 1τ is about 63.2%. The plots from Figure 22 to Figure 26 show how quickly different probe types respond to changes in temperature in different mediums—oral, underarm, still air, moving air, and stirred oil. The TMP117 has an exposed thermal pad for better heat transfer through the package. Figure 22 to Figure 26 show the performance with and without the thermal pad soldered to the PCB. These results shows that the TMP117 with exposed pad soldered responds more quickly compared to without the thermal pad soldered. Table 2 shows the numeric value for all test setup at 63.2%.

Figure 24 and Figure 25 illustrate the major difference in response time from different PCB thicknesses. Figure 26 shows that the oral, underarm, and stirred oil experiments yield faster thermal response time compared to moving air and still air measurement. The response curve of the stirred oil setup has the fastest thermal response time, because the heat transfer through the fluid is more efficient than heat transfer through air.

Table 2. One-time Constant Thermal Response Results

PROBE NO.	ONE-TIME CONSTANT (τ)					LAYOUT	BOARD THICKNESS	THERMAL PAD SOLDERED?
	STIRRED OIL (s)	ORAL (s)	ARMPIT (s)	MOVING AIR (s)	STILL AIR (s)			
P1	16	18.6	32.4	74.2	256.8	L1	20 mil	No
P2	14.8	16.8	22.2	62.2	208	L1	20 mil	Yes
P3	15	16.8	23.6	82.2	252.6	L2	20 mil	No
P4	15.2	18.8	23.2	84.8	265.2	L2	20 mil	Yes
P5	13.2	15.2	23.2	82	253.2	L3	20 mil	No
P6	13.2	15.2	19.6	82.2	257.8	L3	20 mil	Yes
P7	13	14.8	24.8	75.8	267	L4	20 mil	No
P8	9.4	15	26.6	80.6	252	L4	20 mil	Yes
P9	12.4	14.4	16.6	73.4	261.6	L5	20 mil	n/a
P10	16.6	19.2	26.4	80	267.6	L1	40 mil	No
P11	14.8	19	26.8	80.6	268	L1	40 mil	Yes
P12	15.8	20	24	87	267.2	L2	40 mil	No
P13	18.6	22.6	27.8	91.4	256.6	L2	40 mil	Yes
P14	19	20	30	91.8	270.6	L3	40 mil	No
P15	16.4	20.4	28.2	82	258.2	L3	40 mil	Yes
P16	16	20.4	31.4	84	271.2	L4	40 mil	No

Table 2. One-time Constant Thermal Response Results (continued)

PROBE NO.	ONE-TIME CONSTANT (τ) STIRRED OIL (s)	ORAL (s)	ARMPIT (s)	MOVING AIR (s)	STILL AIR (s)	LAYOUT	BOARD THICKNESS	THERMAL PAD SOLDERED?
P17	18.4	19	26.8	83.2	265	L4	40 mil	Yes
P18	15.8	19.6	28.2	81.8	273.8	L5	40 mil	n/a
P19	22	30.6	37.6	90.8	280	L3	62 mil	No
P20	20.6	26.4	33.2	87.6	275	L3	62 mil	Yes

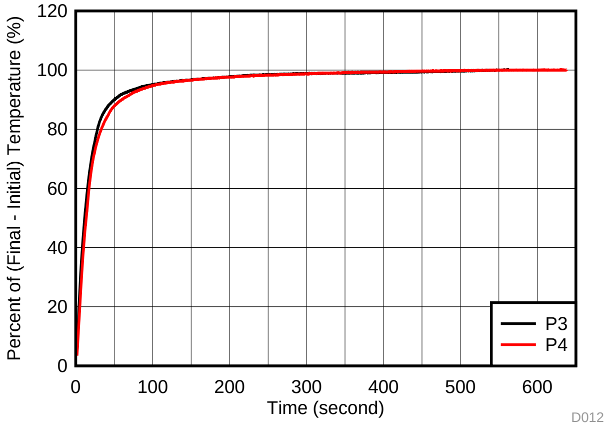

Figure 22. Oral Thermal Response With (P4) And Without (P3) Thermal Pad Soldered

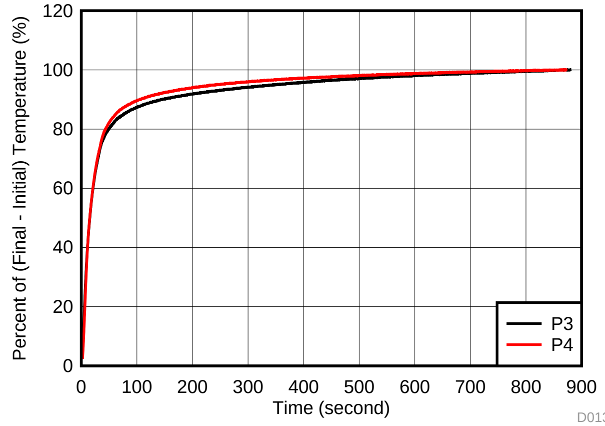

Figure 23. Underarm Thermal Response With (P4) and Without (P3) Thermal Pad Soldered

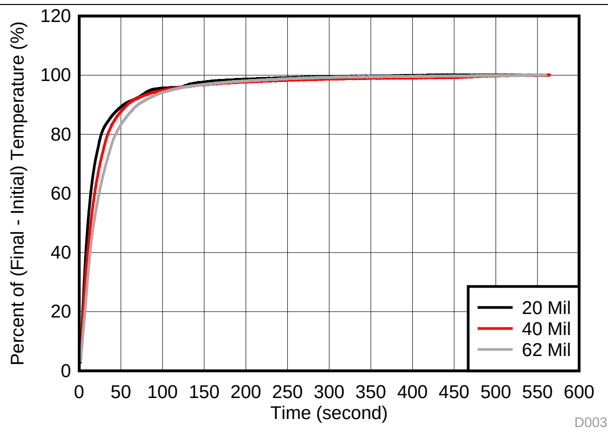

Figure 24. Oral Thermal Response With Different Board Thickness

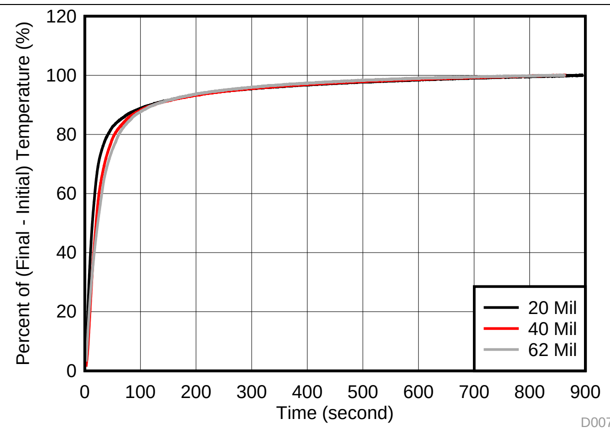

Figure 25. Armpit Thermal Response With Different Board Thickness

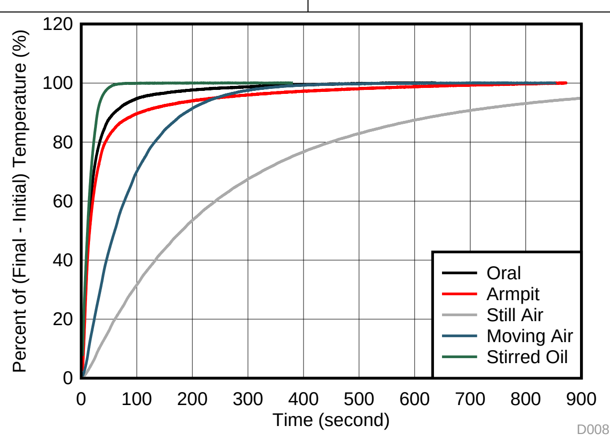

Figure 26. Thermal Response Comparison All Tests

5 Conclusion

The purpose of the thermal response study was to demonstrate how various layout methods could improve IC temperature sensor thermal response time. Among all sensor layout techniques, the temperature response data shows that the thickness of the board made the most significant improvement in response time. However, whether the thermal pad is soldered or not, the temperature response is nearly identical when the device is immersed into temperature environment where the bottom side design with copper plane is placed underneath the IC. Overall, stirred oil and oral tests provide the fastest thermal response because these tests contain fluid that has the ability to transmit temperature quickly.

6 Appendix

6.1 Other Board Descriptions

A quick review of the additional LMT70 boards are briefly described in this section. These boards have a color-coded boarder to match the traces shown in Figure 21 for easy reference purposes. Figure 27 is 2 mm wide at the right, (8 mm wide at left), and 0.5 mm thick with 0.102-mm (4-mil) traces. The LMT70 mounts at the far right. No thermal vias or pads are on the back side of the board.

Figure 27. Thin PCB

Figure 28 has the LMT70 mounted in the middle. It has a stiffener on the back side of the LMT70 to provide mechanical stability to the LMT70 mounting.

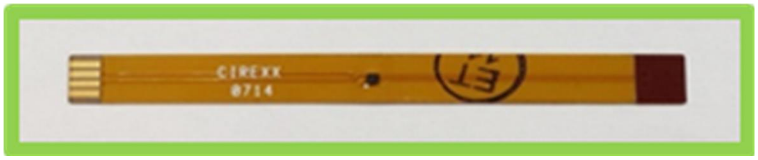

Figure 28. Flex PCB

Figure 29 is the LMT70EVM which is standard 12-mil thickness but has very small 4-mil traces. The LMT70 is mounted on the far right. The size of the PCB is 850 mils or 21 mm by 600 mils or 15 mm with thickness of 1.5 mm.

Figure 29. Regular PCB (From LMT70 Evaluation Module)

Figure 30 shows a wearable patch design using the TMP117, which communicates via BLE to an Android or IOS app. The design is flexible, with a total board thickness of less than 7 mils, meaning the expected thermal response should be very fast. The TMP117 layout is consistent with L4, and the patch is designed for use in Axillary (underarm) measurements. The TMP117 extends away from the rest of the board in a thin flex-cable, which allows the TMP117 to sit under the arm of the wearer while the rest of the board is exposed to open air. The TMP117 thermal pad is not soldered down in this design.

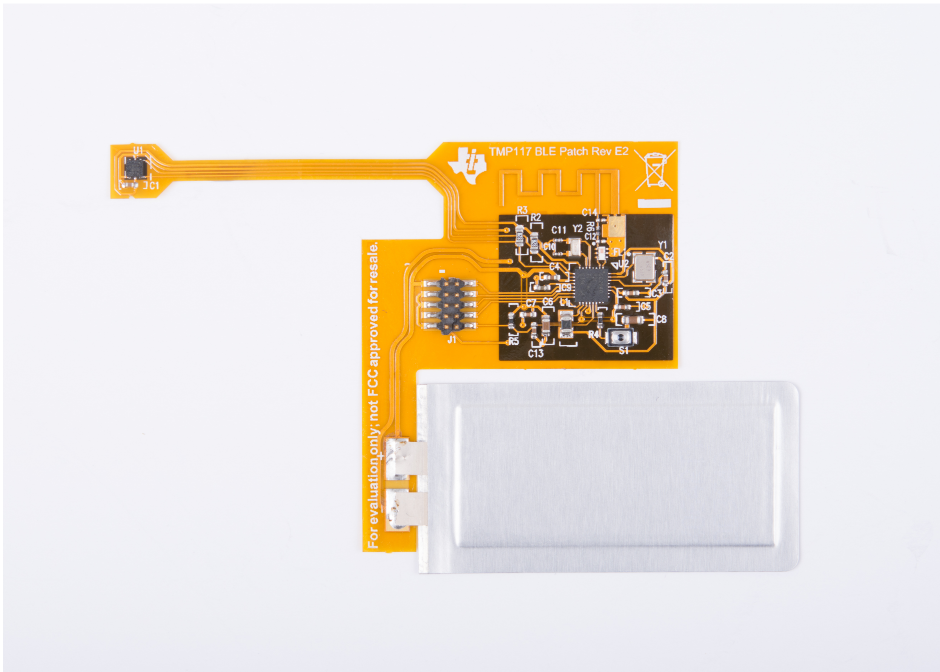

Figure 30. TMP117 BLE Patch Design

7 References

- *TMP117x High-Accuracy, Low-Power, Digital Temperature Sensor With SMBus- and I2C-Compatible Interface* (SBOS740)
- *Design Considerations for Measuring Ambient Air Temperature* (SNOA966)
- *Temperature Sensors: PCB Guidelines For Surface Mount Devices* (SNOA967)
- *LMT70, LMT70A ±0.1°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC Data Sheet* (SNIS187)
- *LMT70 Evaluation Module Precise Analog Output Temperature Sensor with Output Enable* (SNIU024)
- *Temperature Sensor for Wearable Devices Reference Design* (TIDA-00452)

Revision History

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

Changes from A Revision (December 2017) to B Revision	Page
• Added references to the TMP117 in the document	1

Changes from Original (August 2015) to A Revision	Page
• Added new content and subsections to Section 1	2
• Added Section 2.1	5
• Added Section 2.2	6
• Split Section 3 into *LMT70 Setup* and *TMP117 Setup*	8
• Split Section 4 into *LMT70 Thermal Response Result* and *TMP116 Thermal Response Result*	11
• Added Section 5	14
• Added new references to Section 7	16

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