Texas Instruments

Application Report
SNIA021–August 2015

Wearable Temperature Sensing Layout Considerations Optimized for Thermal Response

Aaron Heng

ABSTRACT

This application note covers thermal response considerations for IC temperature sensors measuring skin temperature for wearable applications such as fitness bands and medical devices. It will specifically focus on two devices, the LMT70 and the TMP116 temperature sensors, over the human body temperature range, but learning can be applied to other temperature sensors that come in similar packages. Contact temperature sensors, such as the LMT70 and the TMP116, need to be placed in close contact with the surface that needs to be measured. This can be quite challenging for both DSBGA (LMT70) and WSON (TMP116) packages if fast thermal response is also necessary. Experimental results of different PCB layouts will be presented from measuring axillary (human armpit) and oral temperature.

Contents

List of Figures

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 TMP116 and the LMT70 which are 0.2°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 the PCB layout considerations required to achieve good thermal conductivity as well as fast thermal response for the LMT70 and TMP116 as PCB layout can dramatically affect these parameters. In addition to PCB layout, good mechanical and thermal contact are also critical. The LMT70 and TMP116 are contact sensors, thus making good contact with the surface that is measured is of primary importance. In order to achieve the fast thermal response of a temperature sensor, there are a number of layout techniques considerations. There are three methods of heat transfer conduction, convection and radiation. For more detailed information, please refer to SNOA966 and SNOA967 apps note.

1.1 LMT70

The LMT70 is a 4-pin analog temperature sensor that comes in a DSBGA package measuring 0.88 mm x 0.88 mm. Its small size 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.

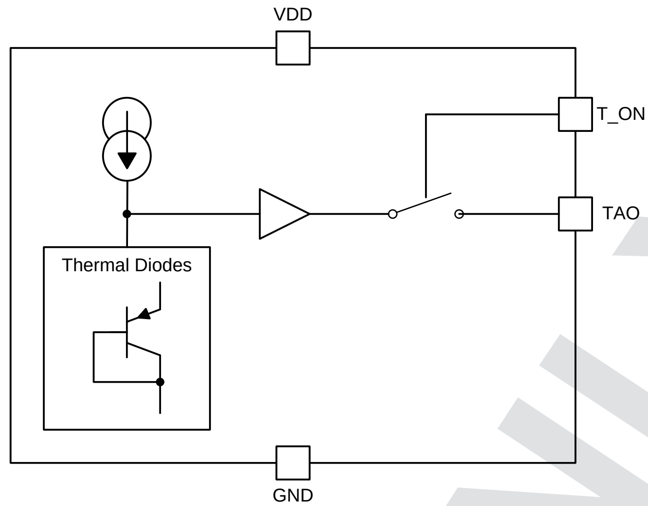

Figure 1. LMT70 Block Diagram

1.2 TMP116

The TMP116 devices are a family of high-precision digital temperature sensors with integrated EEPROM. The TMP116 is I2C- and SMBus-interface compatible, has programmable alert functionality, and can support up to four devices on a single bus. The TMP116 family provides an accuracy of ±0.1°C accuracy over the 20°C to 42°C range, and 0.2°C accuracy over the 0°C to 85°C range with 16-bit resolution. The TMP116 comes in a small 2.00-mm × 2.00-mm 6-pin WSON package. The operational voltage range of the TMP116 operates from 1.9 V to 5.5 V and typically consumes 3.5 µA.

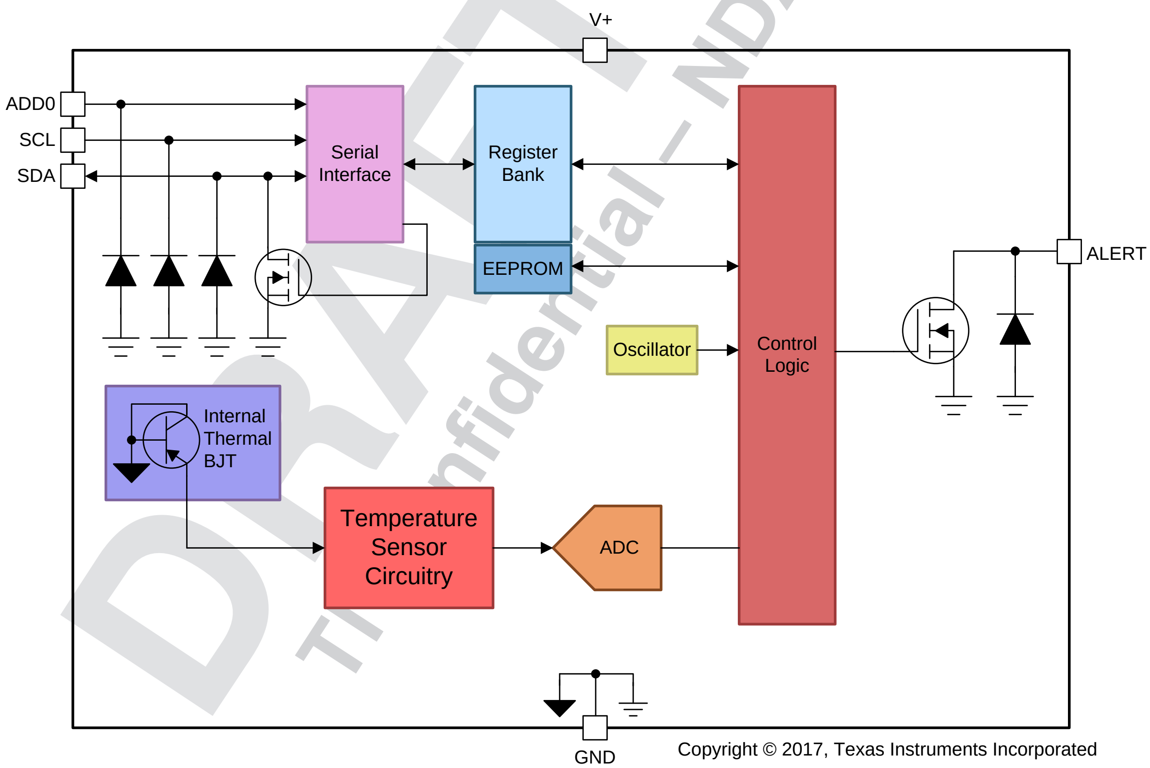

Figure 2. TMP116 Block Diagram

Thermal conductivity is the main parameter of a material that needs to be considered. Thermal conductivity (W/(mK)) of several materials that may be used in the production of a PCB are given in the table shown 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). Since there is air surrounding the part and the solder balls in this example 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, thus improving 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.

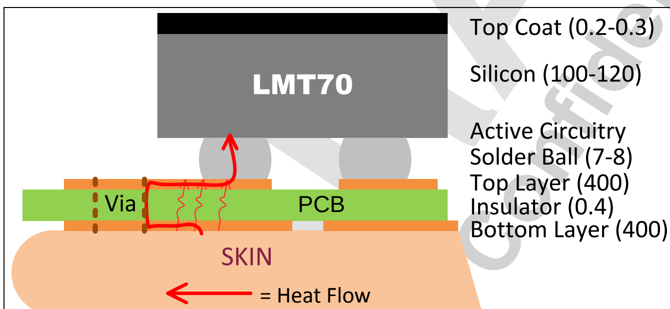

Figure 3. LMT70 PCB path of heat flow (thermal conductivity of materials, k [W/(m×K)], given in parenthesis)

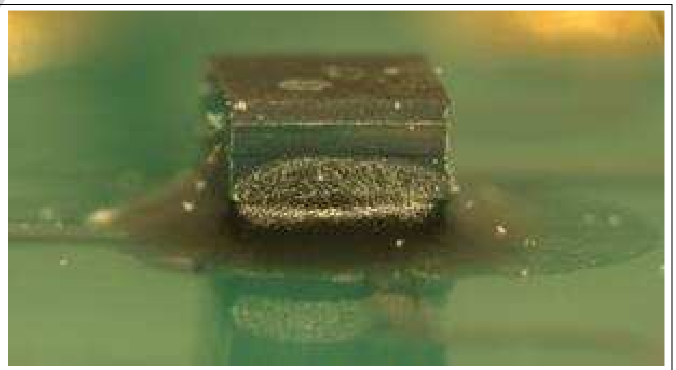

Figure 4. Close up of LMT70 mounted on a PCB with underfill material

Figure 5 depicts the cross section of a TMP116 mounted on a PCB stacked with different materials. 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.

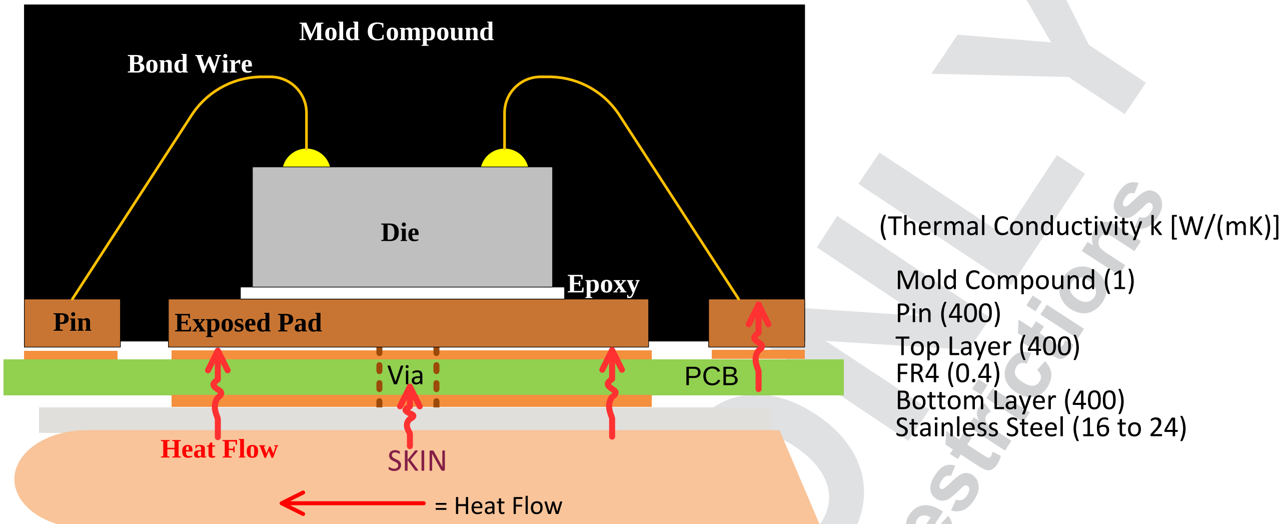

Figure 5. TMP116 Heat Flow Path

2 Small Board Probe Board Description

As mentioned previously, both the size and the material impacts thermal mass. The following board was designed to optimize the thermal response time of the LMT70 and TMP116. 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

Boards are all assembled with LMT70 first with the panel intact. Then the LMT70s are 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. Four 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.

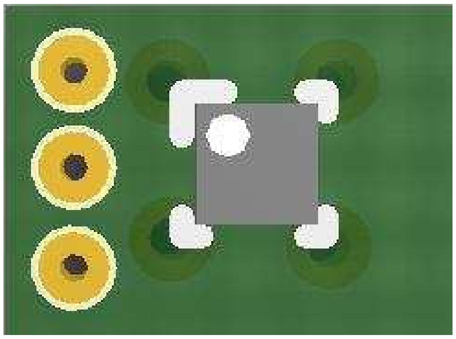

Figure 6. Small LMT70 Probe Board Top Side

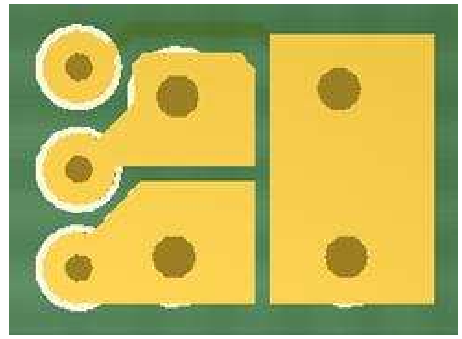

Figure 7. Small LMT70 Probe Board Bottom Side

Probe Board Dimensions

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

2.2 TMP116 Mini Board

In order to measure the thermal response and the temperature accurately, TMP116 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 adhesion to the walls of the stainless steel tube. The thin, thermal epoxy sometimes creates a bubble of air which will form an insulator and reduce 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 fitly 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's wall. This allows the heat to transfer quickly to the TMP116.

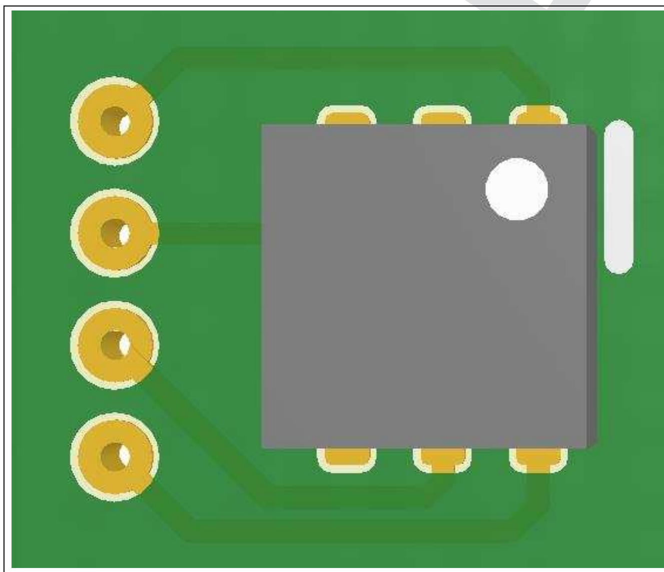

Figure 8. TMP116 Mini Probe Board Top Side L3

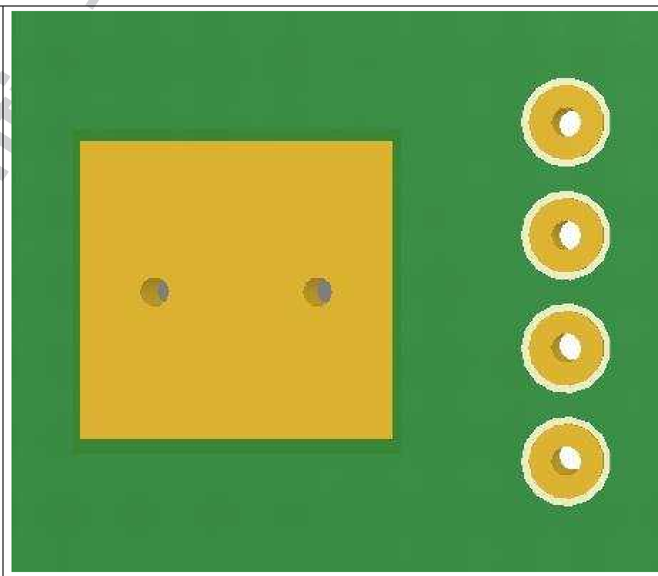

Figure 9. TMP116 Mini Probe Board Bottom Side L3

Probe Board Dimensions

- Width: 150mil (3.81mm)
- Height: 170mil (4.31mm)

- Thickness: 20mil with 1oz copper
- Via size: 8mil hole, 20mil diameter
- Wire pad: 8mil hole, 20mil diameter
- No bottom side solder mask

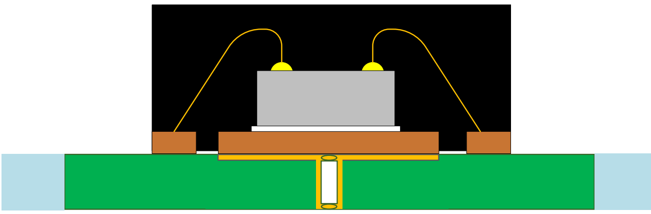

Figure 10. TMP116 Mini Board Cross Section L1

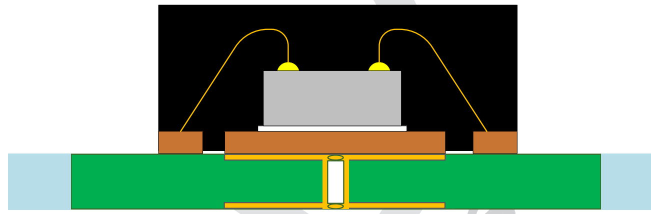

Figure 11. TMP116 Mini Board Cross Section L2

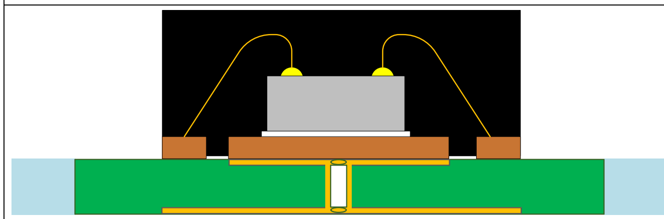

Figure 12. TMP116 Mini Board Cross Section L3

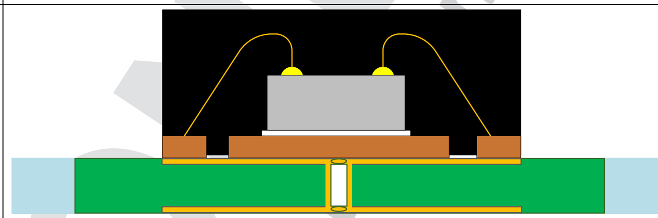

Figure 13. TMP116 Mini Board Cross Section L4

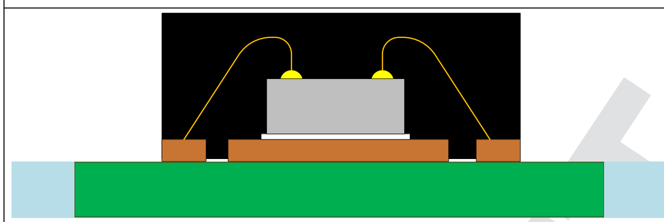

Figure 14. TMP116 Mini Board Cross Section L5

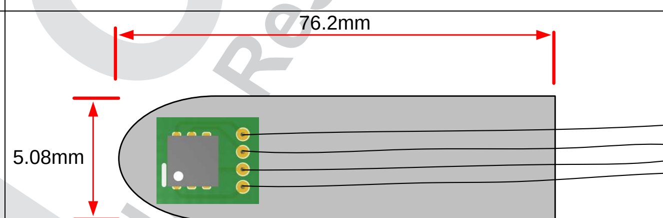

Figure 15. TMP116 Finished Temperature Probe

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 a wearable applications such as watches when the bottom mini PCB is sandwiched between the sensing thermal contact to the skin.

3 The Measurement System

3.1 LMT70 Setup

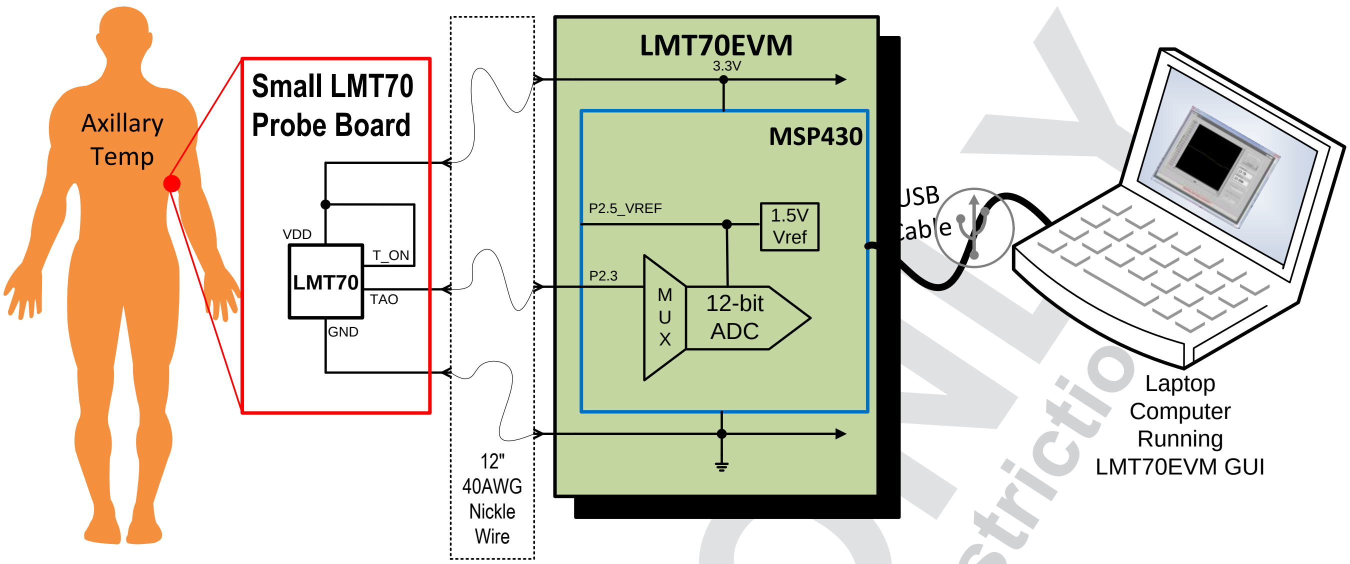

Figure 16. LMT70 Probe Board Thermal Response Measurement System

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 TI Design "Temperature Sensor for Wearable Devices Reference Design" (TDA-00452) and the LMT70EVM for more information on the GUI and firmware source code and performance of the system.

3.2 TMP116 Setup

As mentioned earlier in this report, the TMP116 device is assembled into a stainless steel probe. The purpose of these experiments is to investigate how long it takes for the TMP116 to respond to a sudden change in temperature when the temperature is set to 70°C or human body temperature. Speed and accuracy is very important when measuring human body temperature. The speed of the thermal response is dependent on the materials used and thermal mass of the probe. Any thermal mass such as stainless steel metal, PCB materials, thermal compound will slow the response time. The thermal response time for the probe result may differ, perhaps due to the different types of system used for each probe.

There are five types of tests for the thermal response: oral, underarm, stirred oil, still air, and moving air. The setup for the first method, human body temperature thermal response, is shown in the diagram below Figure 17. The second method used the oven chamber for still air and moving air. River rocks are placed inside the oven chamber in order to create a thermal mass to maintain the 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 is shown in Figure 20.

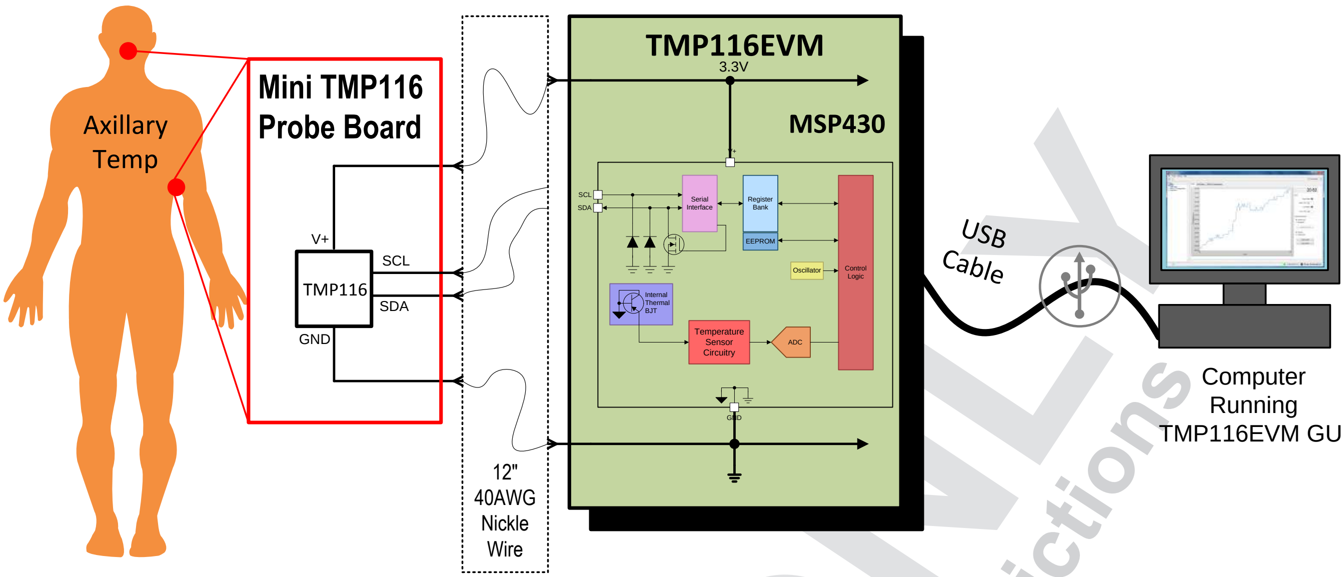

Figure 17. Body Temperature Measurement System

All setups using the EVM comes in a USB stick form factor with an onboard MSP430F5529 microcontroller that interfaces with both the host computer and the TMP116. TMP116EVM utilizes the +5V input power supply of the USB connector to power the EVM. The EVM is designed with the perforation location on the EVM board. The finished temperature probe is connected to the header for remote temperature measurements. The simplest way to take a temperature measurement from the human body is in the mouth or under the arm.

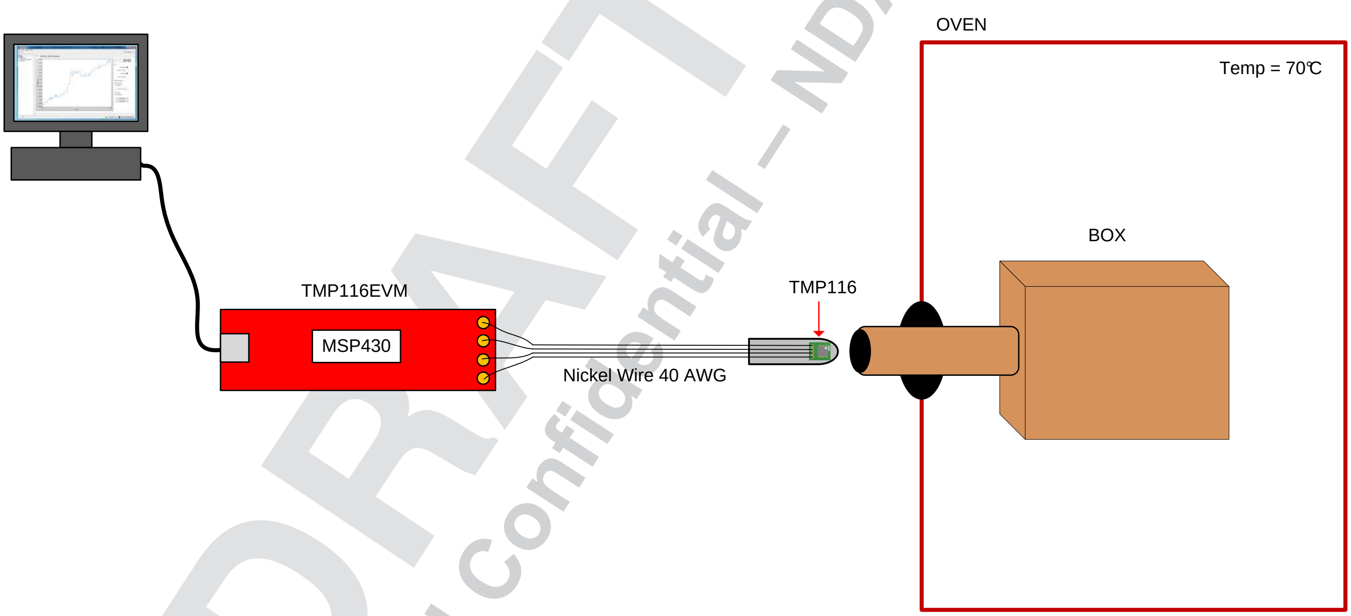

Figure 18. Still Air Thermal Response Measurement System

In this test, the box is completely sealed, the only opening being an insert with a diameter of about 0.75 inches. River rocks are placed inside the box, creating a thermal mass that helps the temperature remain uniform across the chamber. The TMP116 probe is connected to the TMP116EVM via USB connector to the computer, and the TMP116 probe is powered by the +5V 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 opening cavity tube insert, and the TMP116EVM GUI logs the temperature data.

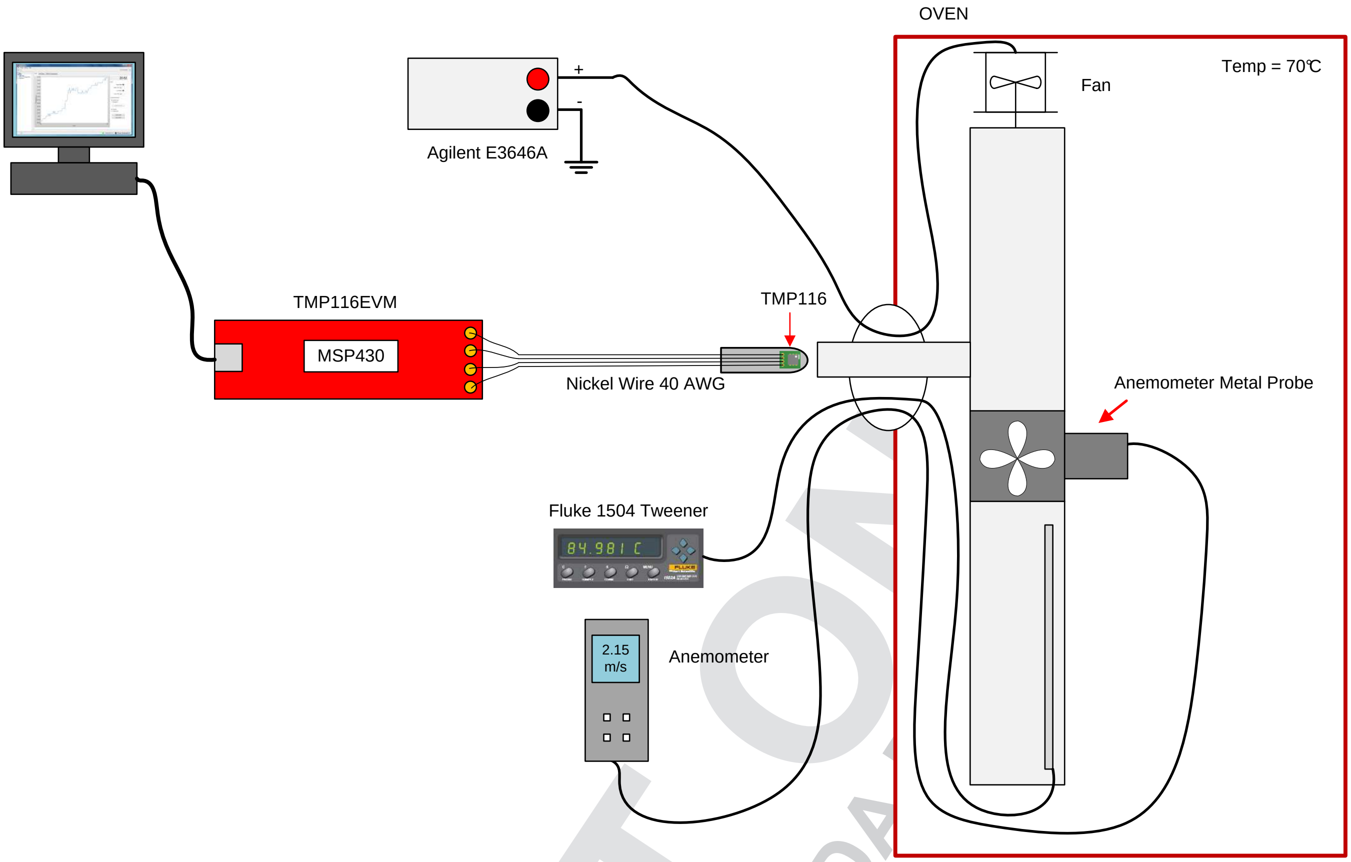

Figure 19. Moving Air Thermal Response Measurement System

The next method is the moving air thermal response as shown in the above diagram, Figure 19. In this experiment, river rocks are also 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 - various velocities can be chosen using a signal generator; however, in this test, we are using a constant velocity of 2.15 m/s, with the TACH pin left floating.

The oven's temperature is set to 70°C, and after several hours, the fan's power supply (12V) and anemometer meter are turned ON. Once the fan and anemometer meter are stabilized, the TMP116 probe is quickly inserted into the tube until the TMP116 probe reaches the set point temperature.

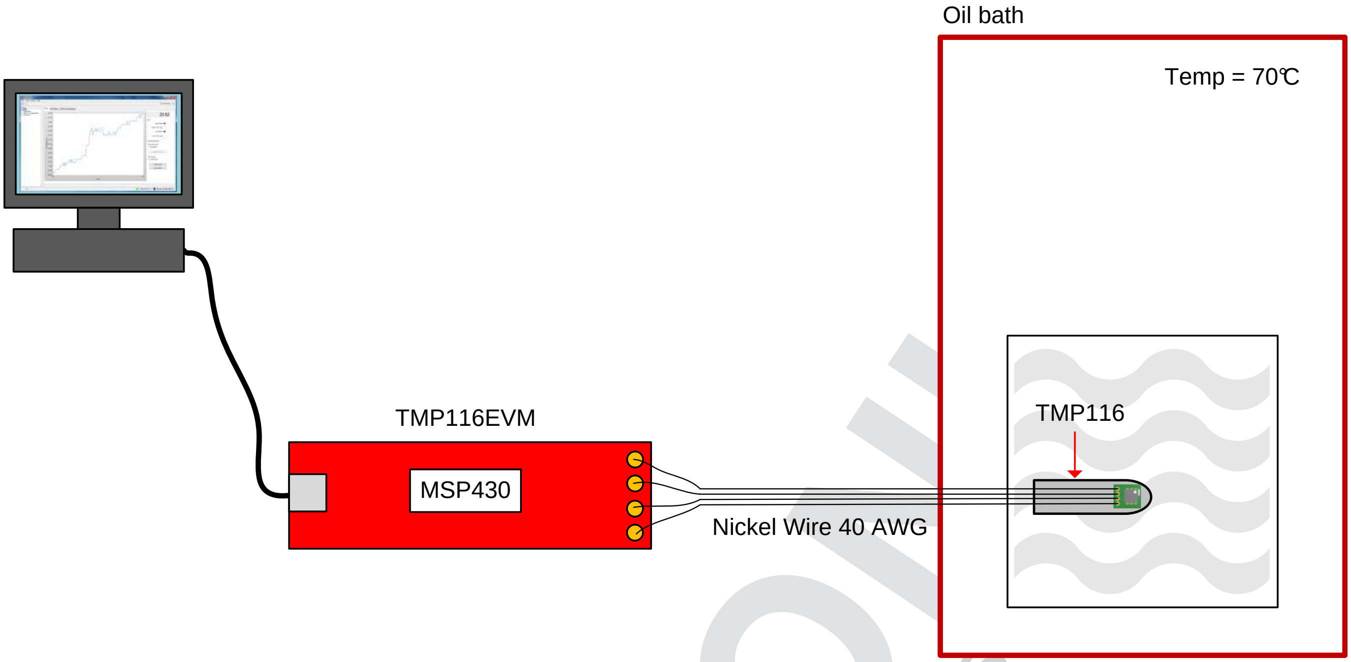

Figure 20. Stirred Oil Thermal Response Measurement System

The final method is the stirred oil thermal response, as shown in the above diagram 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 still air and moving air setup. Once the temperature is stabilized, the TMP116 probe is dipped into the oil bath's well while the TMP116EVM GUI logs the temperature. The oilbath is a compact chamber contained a special fluid that allows obtaining a stability and uniformity temperature, and used 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. Initial temperature of about 22°C is the initial 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 can be 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 TI Design "Temperature Sensor for Wearable Devices Reference Design" (TIDA-00452) and Section 5.

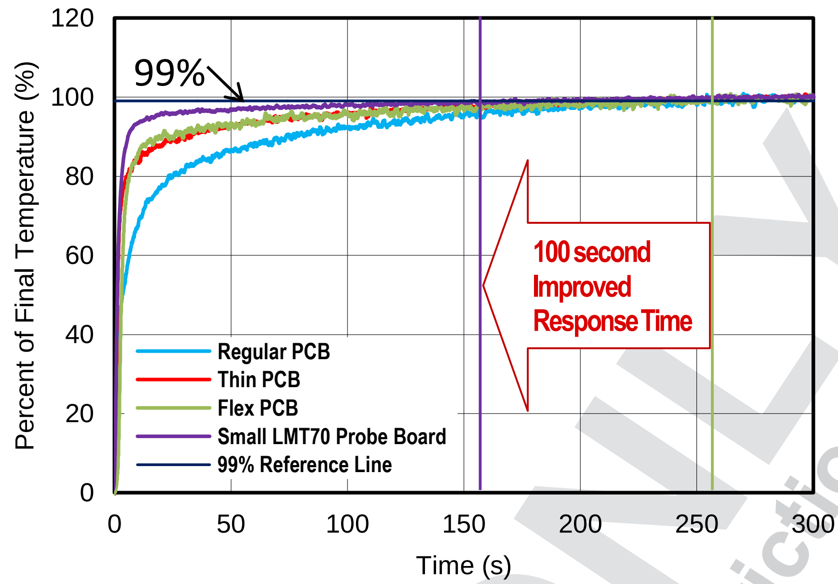

Figure 21. Comparison of the Small PCB to other types of substrates when measuring axillary body temperature.

4.2 TMP116 Thermal Response Result

The approximation for step response in 1τ is about 63%. The plots from Figure 22 to Figure 28 show how quickly different probe types respond to changes in temperature in different mediums – oral, underarm, still air, moving air, and stirred oil. The TMP116 has an exposed thermal pad for better heat transfer through the package. Figure 22 to Figure 25 show the performance with and without the thermal pad soldered to the PCB. These results shows that the TMP116 with exposed pad soldered responds much more quickly compared to without soldered the thermal pad. Table 2 shows the numeric value for all test setup at 63.2%.

Figure 26 and Figure 27 illustrate the major difference in response time from different PCB thicknesses. Figure 28 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 since heat transfer from fluid is more efficient than heat transfer through air.

Table 2. One-time Constant Thermal Response Results

Probe #	One-time Constant (τ)					Layout	Board Thickness	Thermal Pad Soldered?
	Stirred Oil (sec)	Oral (sec)	Armpit (sec)	Moving Air (sec)	Still Air (sec)			
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

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

Probe #	One-time Constant (τ)					Layout	Board Thickness	Thermal Pad Soldered?
	Stirred Oil (sec)	Oral (sec)	Armpit (sec)	Moving Air (sec)	Still Air (sec)			
P16	16	20.4	31.4	84	271.2	L4	40 mil	No
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

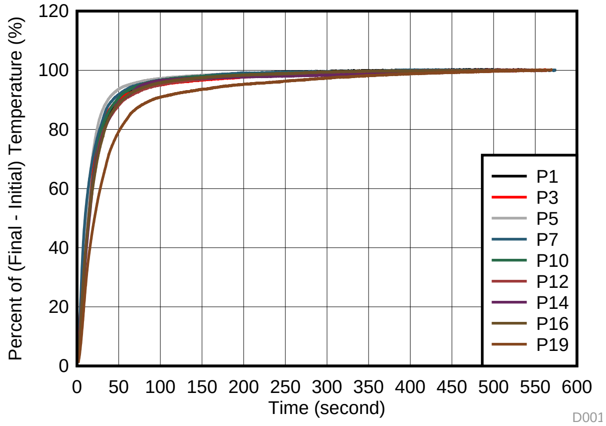

Figure 22. Oral Thermal Response with Thermal Pad Soldered

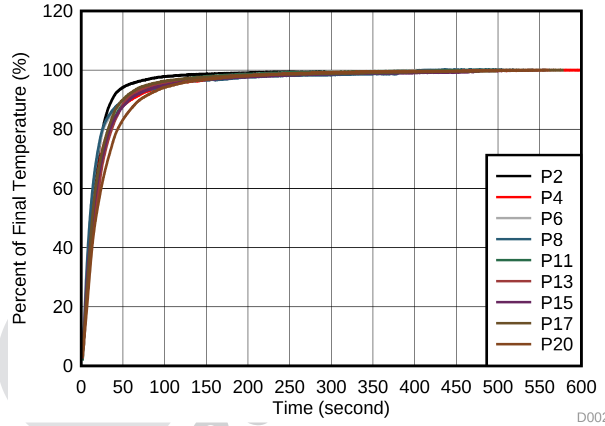

Figure 23. Oral Thermal Response without Thermal Pad Soldered

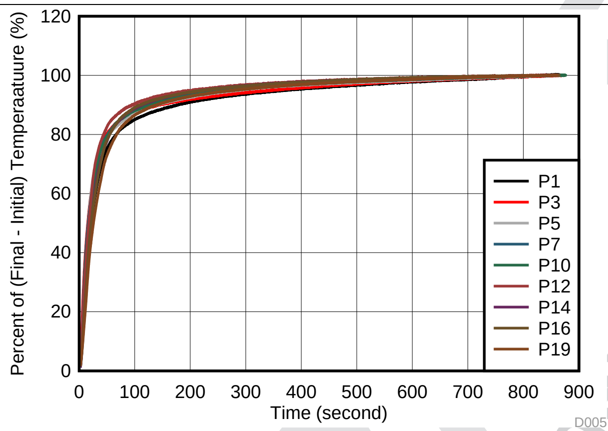

Figure 24. Underarm Thermal Response with Thermal Pad Soldered

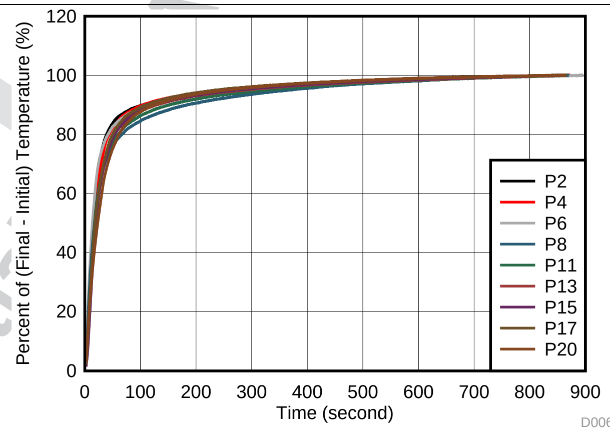

Figure 25. Underarm Thermal Response without Thermal Pad Soldered

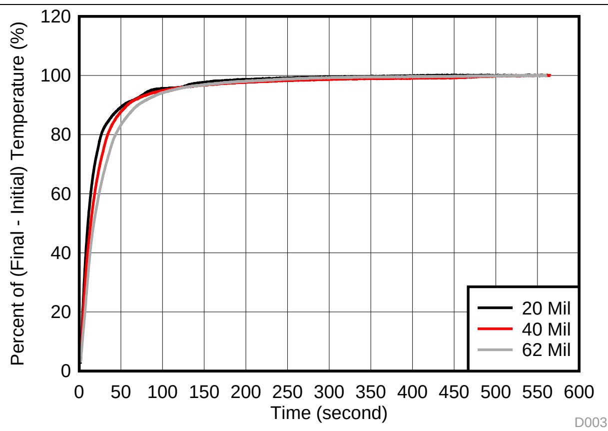

Figure 26. Oral Thermal Response with Different Board Thickness

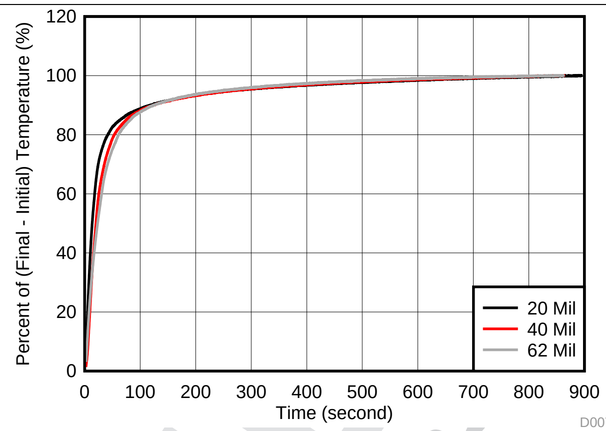

Figure 27. Armpit Thermal Response with Different Board Thickness

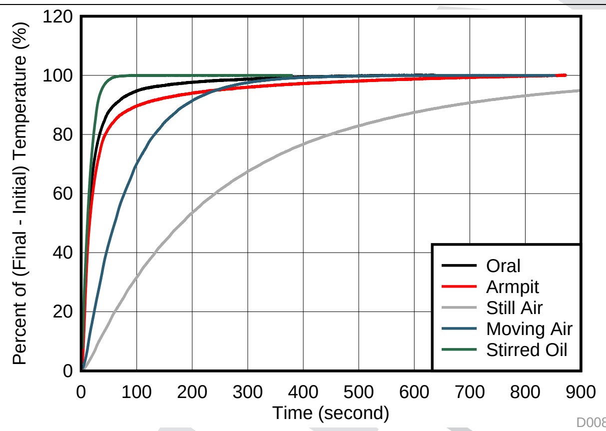

Figure 28. Thermal Response Comparison All Tests

5 Appendix

5.1 Other Board Descriptions

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

Figure 29. Thin PCB

The green trace Flex PCB has the LMT70 mounted in the middle. It has a stiffener on the back side of the LMT70 in order to provide mechanical stability to the LMT70 mounting.

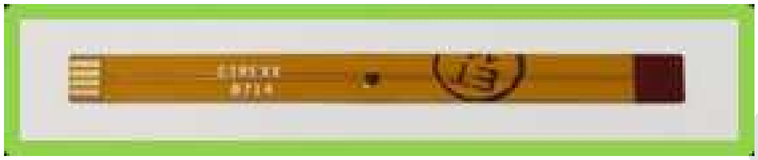

Figure 30. Flex PCB

The blue trace Regular PCB 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 21mm by 600 mils or 15mm with thickness of 1.5mm.

Figure 31. Regular PCB (from LMT70 Evaluation Module)

6 References

- *LMT70, LMT70A ±0.1°C Precision Analog Temperature Sensor, RTD and Precision NTC Thermistor IC Data Sheet* (LMT70 Datasheet.)
- *LMT70 Evaluation Module Precise Analog Output Temperature Sensor with Output Enable* (LMT70 EVM)
- TI Design: *Temperature Sensor for Wearable Devices Reference Design* (LMT70 TI Design)

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES

Texas Instruments Incorporated (‘TI”) technical, application or other design advice, services or information, including, but not limited to, reference designs and materials relating to evaluation modules, (collectively, “TI Resources”) are intended to assist designers who are developing applications that incorporate TI products; by downloading, accessing or using any particular TI Resource in any way, you (individually or, if you are acting on behalf of a company, your company) agree to use it solely for this purpose and subject to the terms of this Notice.

TI’s provision of TI Resources does not expand or otherwise alter TI’s applicable published warranties or warranty disclaimers for TI products, and no additional obligations or liabilities arise from TI providing such TI Resources. TI reserves the right to make corrections, enhancements, improvements and other changes to its TI Resources.

You understand and agree that you remain responsible for using your independent analysis, evaluation and judgment in designing your applications and that you have full and exclusive responsibility to assure the safety of your applications and compliance of your applications (and of all TI products used in or for your applications) with all applicable regulations, laws and other applicable requirements. You represent that, with respect to your applications, you have all the necessary expertise to create and implement safeguards that (1) anticipate dangerous consequences of failures, (2) monitor failures and their consequences, and (3) lessen the likelihood of failures that might cause harm and take appropriate actions. You agree that prior to using or distributing any applications that include TI products, you will thoroughly test such applications and the functionality of such TI products as used in such applications. TI has not conducted any testing other than that specifically described in the published documentation for a particular TI Resource.

You are authorized to use, copy and modify any individual TI Resource only in connection with the development of applications that include the TI product(s) identified in such TI Resource. NO OTHER LICENSE, EXPRESS OR IMPLIED, BY ESTOPPEL OR OTHERWISE TO ANY OTHER TI INTELLECTUAL PROPERTY RIGHT, AND NO LICENSE TO ANY TECHNOLOGY OR INTELLECTUAL PROPERTY RIGHT OF TI OR ANY THIRD PARTY IS GRANTED HEREIN, including but not limited to any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information regarding or referencing third-party products or services does not constitute a license to use such products or services, or a warranty or endorsement thereof. Use of TI Resources may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

TI RESOURCES ARE PROVIDED “AS IS” AND WITH ALL FAULTS. TI DISCLAIMS ALL OTHER WARRANTIES OR REPRESENTATIONS, EXPRESS OR IMPLIED, REGARDING TI RESOURCES OR USE THEREOF, INCLUDING BUT NOT LIMITED TO ACCURACY OR COMPLETENESS, TITLE, ANY EPIDEMIC FAILURE WARRANTY AND ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE, AND NON-INFRINGEMENT OF ANY THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

TI SHALL NOT BE LIABLE FOR AND SHALL NOT DEFEND OR INDEMNIFY YOU AGAINST ANY CLAIM, INCLUDING BUT NOT LIMITED TO ANY INFRINGEMENT CLAIM THAT RELATES TO OR IS BASED ON ANY COMBINATION OF PRODUCTS EVEN IF DESCRIBED IN TI RESOURCES OR OTHERWISE. IN NO EVENT SHALL TI BE LIABLE FOR ANY ACTUAL, DIRECT, SPECIAL, COLLATERAL, INDIRECT, PUNITIVE, INCIDENTAL, CONSEQUENTIAL OR EXEMPLARY DAMAGES IN CONNECTION WITH OR ARISING OUT OF TI RESOURCES OR USE THEREOF, AND REGARDLESS OF WHETHER TI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

You agree to fully indemnify TI and its representatives against any damages, costs, losses, and/or liabilities arising out of your non-compliance with the terms and provisions of this Notice.

This Notice applies to TI Resources. Additional terms apply to the use and purchase of certain types of materials, TI products and services. These include; without limitation, TI’s standard terms for semiconductor products http://www.ti.com/sc/docs/stdterms.htm), evaluation modules, and samples (http://www.ti.com/sc/docs/sampterms.htm).