Application Report
SNOA986A–April 2018–Revised August 2019

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.

Contents

1 Introduction 2
2 TMP116 and TMP117 Device Differences 2
3 PCB Considerations 3
4 Measuring Solid Surface Temperature 3
5 Measuring Human Body Temperature 5
6 Measuring Still Air Temperature 6
7 Measuring Moving Air Temperature 6
8 Measuring Thermal Resistance in Different Environments 8
9 Soldering to PCB 9
10 Self-Heating 11
11 Self-Heating Estimation Example 12
12 Supply Voltage Change 14
13 Data Averaging 14
14 Summary 15

List of Figures

1 Simplified Schematic of Temperature Flow During Solid Surface Measurement 3
2 PCB Layout Example for Rigid Surface Temperature Measuring 5
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. 7
4 PCB Layout Example for Air Temperature Measuring 8
5 Printed-Circuit Boards Used 9
6 Soldering Shift at +25ºC and Supply 3.3 V With Thermal Pad Soldered on a Rigid PCB. 10
7 Soldering Shift for TMP116/117 Without the Thermal Pad Soldered to the PCB. +25ºC, V = +3.3 V 10
8 Device Consumption Power vs Temperature and Part Supply Voltage in Continuous Conversion Mode. No Pauses Between Conversions, No I2C Bus Activity. 11
9 Supply Current vs. Pin Input Voltage and Device Supply Voltage for Any Digital Pin Input Cell. 12
10 Device Supply Current vs. I2C Bus Clocking Frequency and Supply Voltage. Part is in Shutdown Mode, but SCL, SDA, and ADD0 Pins are Under Constant I2C Data Flow. 12
11 TMP116/117 Coupon Board Self-Heating Effect vs. Time and Supply Voltage in Still +25ºC Air. 13
12 The TMP116/117 Sampling Distribution for 3 Different Oil Bath Temperatures and 3.3-V Supply Voltage. No Data Averaging. 14
13 The TMP116/117 Sampling Distribution for 3 Different Supply Voltages at +25ºC. No Data Averaging. 15
14 Temperature Sampling Noise With 8, 32, and 64 Internal Averages. Temperature +25ºC and V = +3.3 V. 15

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 I2C 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 +25ºC (+125ºC) (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-µF 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.

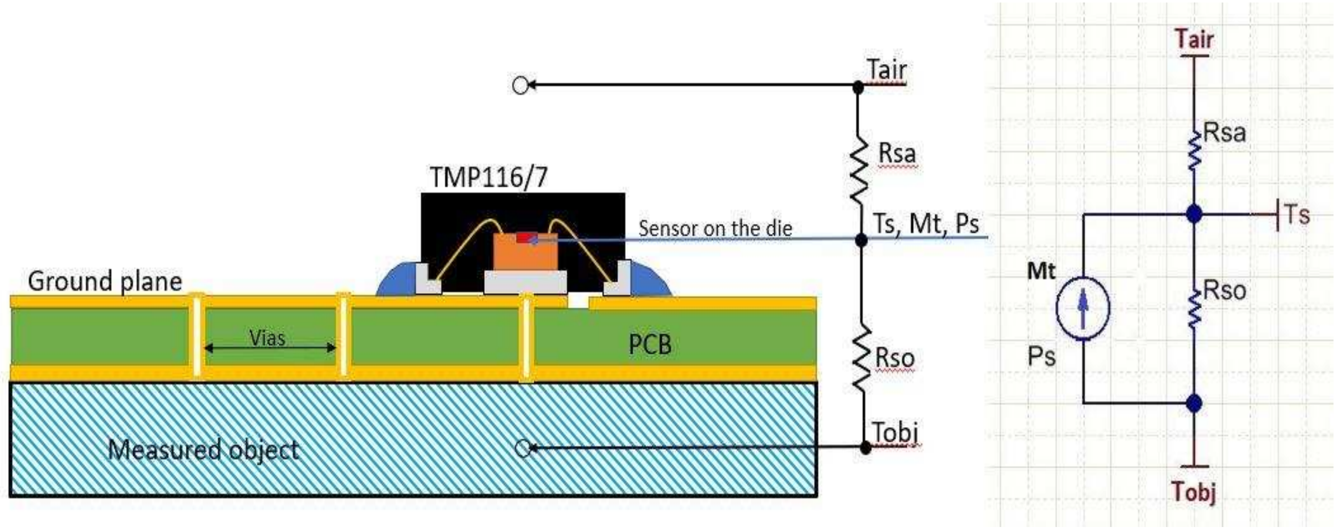


Figure 1. Simplified Schematic of Temperature Flow During Solid Surface Measurement

On this schematic:

- T_{obj} is the measured object temperature.
- T_{air} is the environment temperature (typically air).
- T_s is the sensor temperature.
- R_{so} is the thermal resistance between the sensor and the object.
- R_{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:

$$T_{ofs} = \left(\frac{T_{obj} - T_{air}}{R_{so} + R_{sa}} \right) \times R_{so}$$ (1)

$$T_s = T_{obj} - T_{ofs}$$

where

- T_{ofs} is a temperature offset between the measured object and sensor. (2)

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

Let's calculate temperature offsets for two metallic object temperatures (+50°C and +100°C) where still air temperature stays the same +25°C and the temperature resistance from sensor to object surface assumed from line 6 of Table 2 (140m°C/mWt). Let's also assume that the temperature resistance between sensor and air is equal to line 1 of Table 2 (300m°C/Wt). For object temperatures +50°C and +100°C, the measurement offset, according to Equation 1, will be 7.9°C and 23.8°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_{obj} and T_{air}. This happens because R_{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_{sa} value estimation very difficult to find. However, by making R_{so} as small as possible and R_{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_{obj1} to T_{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.

$$T_s = T_{obj1} + \left(T_{obj2} - T_{obj1}\right) \times e^{-t/tr}$$

where

- t is a time passing from beginning object temperature change.
- t_r is a response time. (3)

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

Here we can assume that R_{sa} >> R_{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_{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_{sh} is calculate by Equation 5.

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

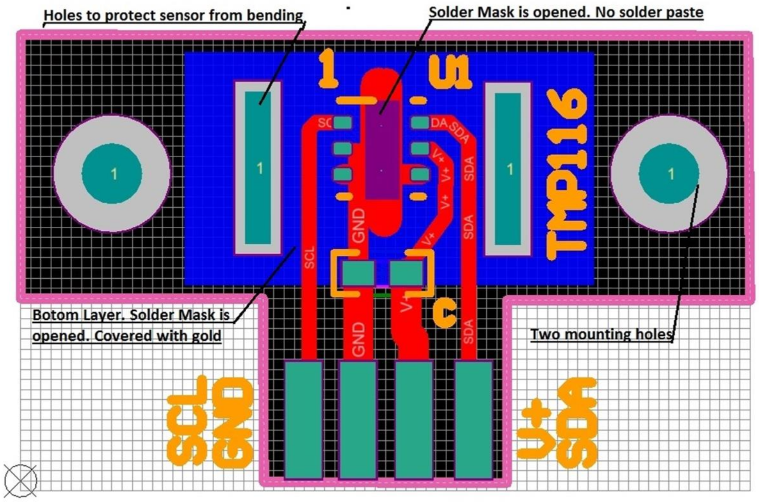
The influence of self-heating on measurement precision is discussed in Section 10.

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.



(1) Alert pin is not used and grounded. I2C bus pullup resistors are located on master board.

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.

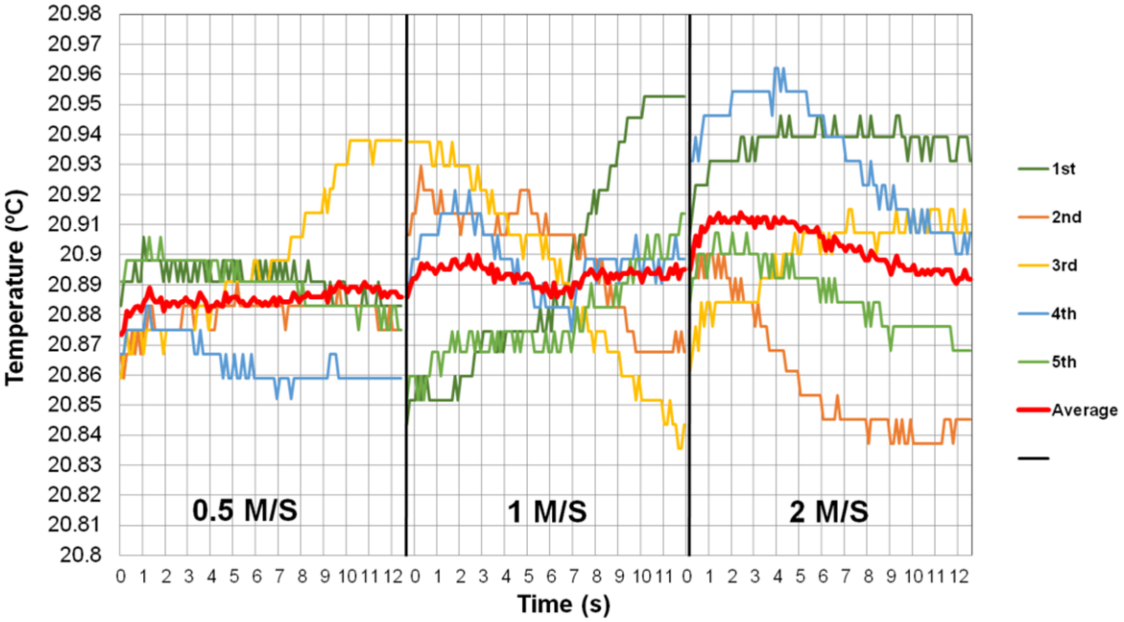


Figure 3. Moving Air Temperature Measurements Noise. Air Speed 0.5, 1 and 2 Meter/Sec. Averaging 8 Samples Per Reading. 5 Consecutive Measurements at Room Temperature.

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, $Fc=1/t_r$. 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. I2C 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}:

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

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-µF 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 (1)
Moving Air along CB. 0.5 M/Sec	190	6 mill (0.15 mm) flex CB (1)
Moving Air along CB. 2 M/Sec	200	64 mill (1.62 mm) rigid CB (1)
Moving Air along CB. 2 M/Sec	156	6 mill (0.15 mm) flex CB (1)
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 (1).
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

(1) 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.

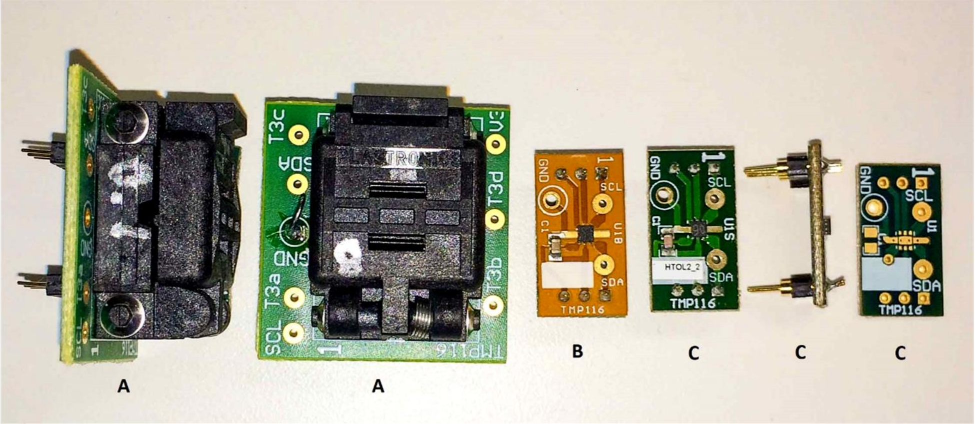


Figure 5. Printed-Circuit Boards Used

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 +25ºC 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 20mºC, but for device #4456, it reaches 50mºC. According to our research, the soldering shift is not predictable, can be positive or negative, and, in the worst case, can reach ±100mºC.

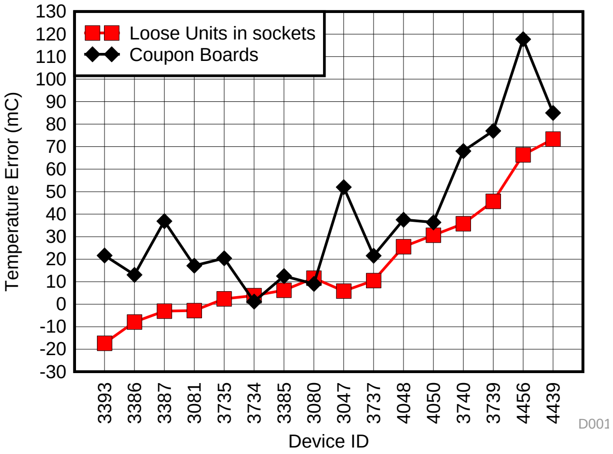


Figure 6. Soldering Shift at +25ºC and Supply 3.3 V With Thermal Pad Soldered on a Rigid PCB.

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.

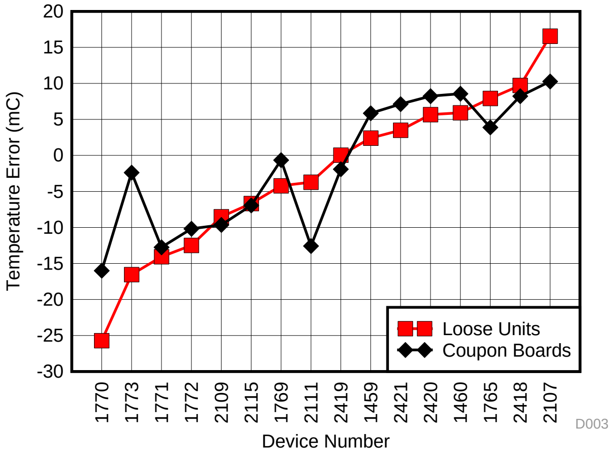


Figure 7. Soldering Shift for TMP116/117 Without the Thermal Pad Soldered to the PCB. +25ºC, V = +3.3 V

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 140ºC/W_t. By knowing the thermal resistance and device thermal mass M_t = 5.1 mJ/ºC, 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 +250ºC for one minute.
- Manual soldering is not acceptable because it creates additional stress on the device package, resulting in soldering shift as large as ±150mºC.
- 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 uWt at +25°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.

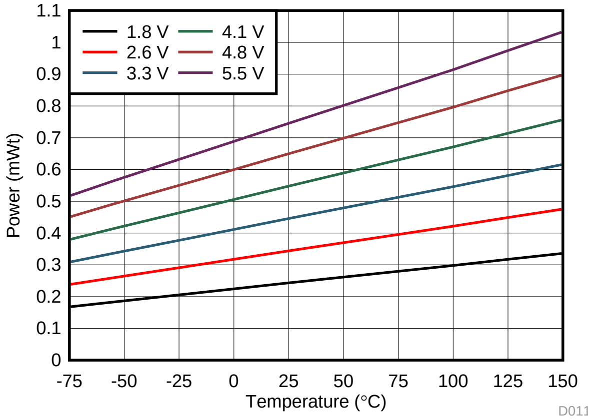


Figure 8. Device Consumption Power vs Temperature and Part Supply Voltage in Continuous Conversion Mode. No Pauses Between Conversions, No I2C Bus Activity.

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 kΩ 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 I2C 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.

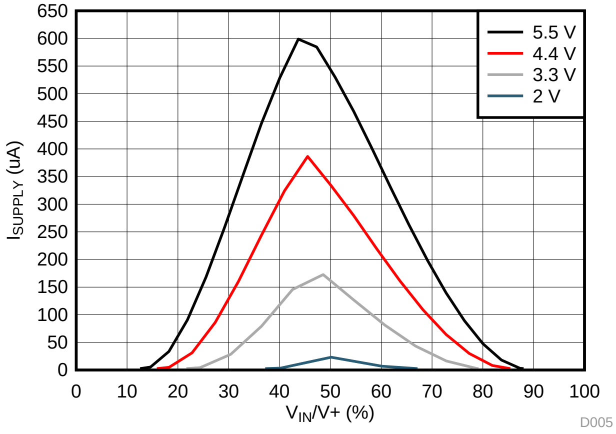


Figure 9. Supply Current vs. Pin Input Voltage and Device Supply Voltage for Any Digital Pin Input Cell.

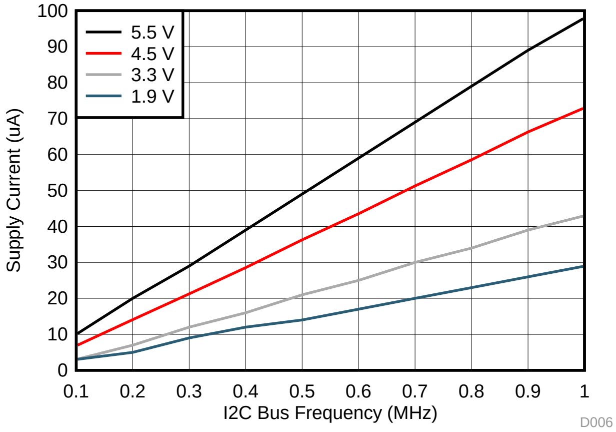


Figure 10. Device Supply Current vs. I2C Bus Clocking Frequency and Supply Voltage. Part is in Shutdown Mode, but SCL, SDA, and ADD0 Pins are Under Constant I2C Data Flow.

11 Self-Heating Estimation Example

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

$$\text{Tsh} = \text{P} \times \text{Rt}$$

where

- Tsh is a temperature offset due to sensor self-heating.
- P is an averaged power dissipated by the sensor.
- Rt 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 listened cases when the self-heating effect can be ignored:

- The desired measurement precision is worse than ±0.2ºC.

- 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 I2C 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.

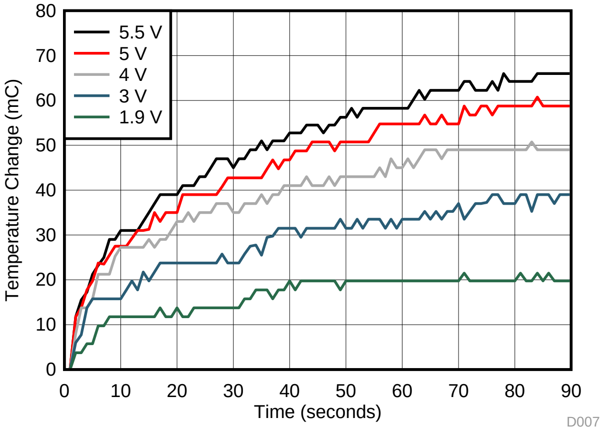


Figure 11. TMP116/117 Coupon Board Self-Heating Effect vs. Time and Supply Voltage in Still +25ºC Air.

For example, assume the customer test was done with a 3-V supply and air temperature +25ºC. We see the device temperature stabilized after 90 seconds with 40mºC 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 Rt = 40mºC/ 0.36 mWt = 111C/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 +125ºC 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 Tsh = 111C/Wt x 0.65mWt = 72m°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 10mºC/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 ±3 sigma rule. This leads to the important conclusion that sensor internal noise is the same for whole temperature range –55ºC to +150ºC, 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 ±25m°C.

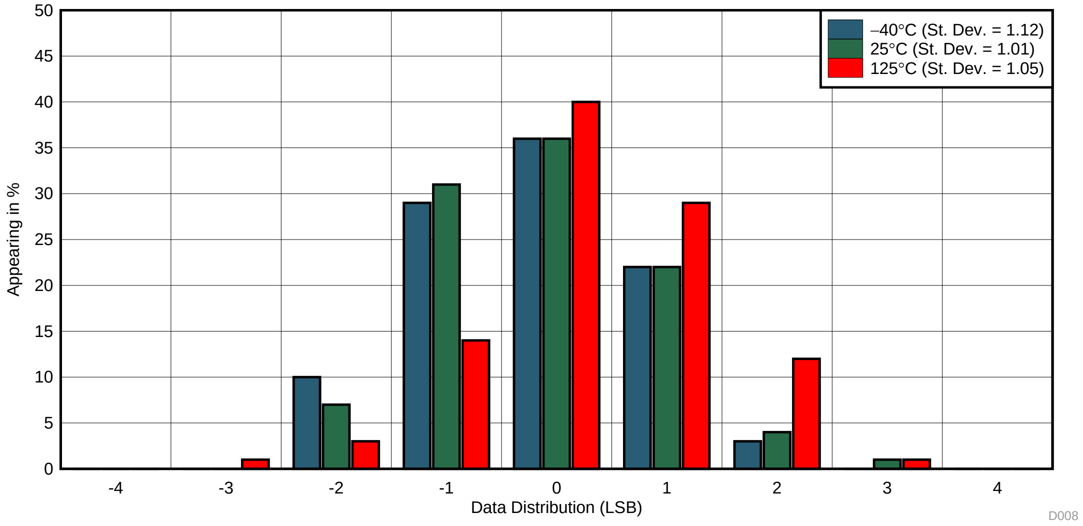


Figure 12. The TMP116/117 Sampling Distribution for 3 Different Oil Bath Temperatures and 3.3-V Supply Voltage. No Data Averaging.

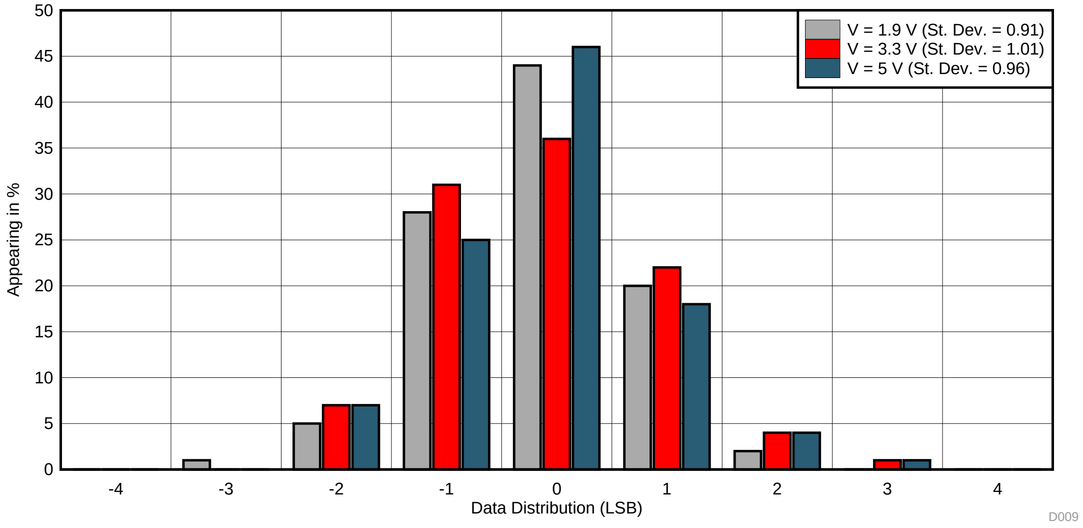


Figure 13. The TMP116/117 Sampling Distribution for 3 Different Supply Voltages at +25ºC. No Data Averaging.

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 I2C 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.

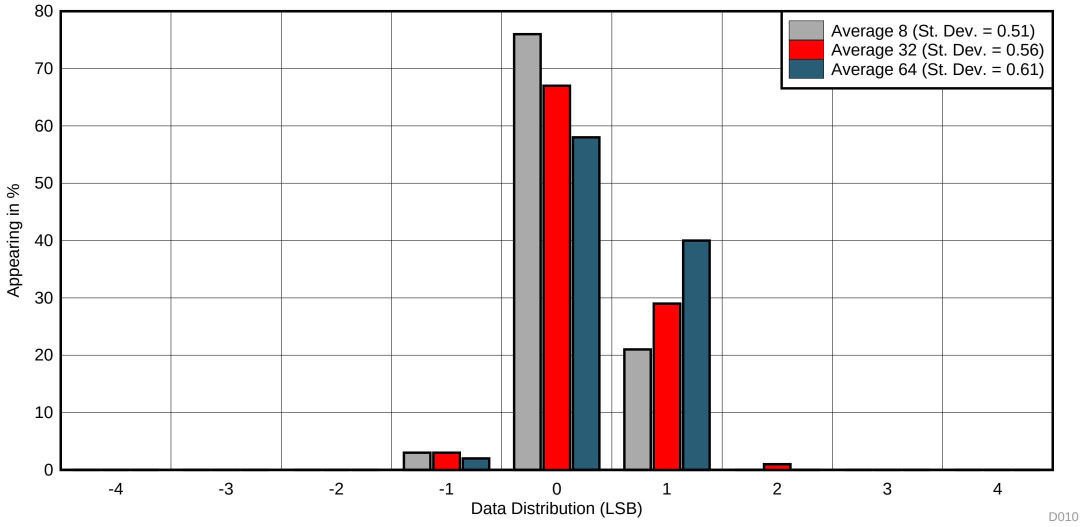


Figure 14. Temperature Sampling Noise With 8, 32, and 64 Internal Averages. Temperature +25ºC and V = +3.3 V.

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 *Measuring Solid Surface Temperature* section	3
• Added *Measuring Human Body Temperature* section	5
• Added *Measuring Still Air Temperature* section	6
• Added *Measuring Human Body Temperature* section	6
• Added *Measuring Thermal Resistance in Different Environments* section	8
• Removed *Devices Temperature Error Change Due to Device Soldering for 6 Different Temperatures. V = +3.3 V* graph	10
• Added recommendations on how to minimize the soldering shift in the TMP116/117 parts	10
• Changed *Device Consumption Power vs Temperature and Part Supply Voltage in Continuous Conversion Mode* graph	11
• Added *Supply Voltage Change* section	14

IMPORTANT NOTICE AND DISCLAIMER

TI PROVIDES TECHNICAL AND RELIABILITY DATA (INCLUDING DATASHEETS), DESIGN RESOURCES (INCLUDING REFERENCE DESIGNS), APPLICATION OR OTHER DESIGN ADVICE, WEB TOOLS, SAFETY INFORMATION, AND OTHER RESOURCES “AS IS” AND WITH ALL FAULTS, AND DISCLAIMS ALL WARRANTIES, EXPRESS AND IMPLIED, INCLUDING WITHOUT LIMITATION ANY IMPLIED WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE OR NON-INFRINGEMENT OF THIRD PARTY INTELLECTUAL PROPERTY RIGHTS.

These resources are intended for skilled developers designing with TI products. You are solely responsible for (1) selecting the appropriate TI products for your application, (2) designing, validating and testing your application, and (3) ensuring your application meets applicable standards, and any other safety, security, or other requirements. These resources are subject to change without notice. TI grants you permission to use these resources only for development of an application that uses the TI products described in the resource. Other reproduction and display of these resources is prohibited. No license is granted to any other TI intellectual property right or to any third party intellectual property right. TI disclaims responsibility for, and you will fully indemnify TI and its representatives against, any claims, damages, costs, losses, and liabilities arising out of your use of these resources.

TI’s products are provided subject to TI’s Terms of Sale (www.ti.com/legal/termsofsale.html) or other applicable terms available either on ti.com or provided in conjunction with such TI products. TI’s provision of these resources does not expand or otherwise alter TI’s applicable warranties or warranty disclaimers for TI products.

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265

Copyright © 2019, Texas Instruments Incorporated