Application Note

Component Temperature Monitoring Using Differential Temperature Measurements

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Temperature and Humidity Sensing

ABSTRACT

Accurate component temperature monitoring is essential in applications that require temperature compensation or operation around the system temperature limits (for example, radar sensors, processors, and power ICs). Higher temperature-sensing accuracy in these designs impacts either the quality, the uptime, or both the quality and uptime in the system. The technique of differential temperature measurements provides another option for high-accuracy component temperature monitoring to improve system performance, and can be implemented using any temperature sensors. This application note details the technique using two of TI's low-cost TMP6 thermistors due to their high temperature sensitivity and low thermal mass compared to traditional NTCs. This report introduces the technique of differential temperature measurements for temperature monitoring and briefly compares it to other potential temperature sensing layouts.

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1 Introduction

When monitoring the temperature of critical components in a system, better accuracy leads to better information feedback to temperature control loops used for compensation or safety shutdown purposes. In some ICs, designers include a thermal diode pin, which connects to an external temperature sensor to monitor the internal temperature of the die. This method is viable when the internal diode-connected transistor used for temperature sensing is well-constructed and has an overtemperature behavior which closely follows that of a standard BJT.

Some ICs may not have an internal thermal transistor designed in, or its overtemperature characteristics may provide poor quality for temperature detection. Instead, the designer may choose to use the internal temperature sensor of the device if one is available. One main disadvantage of the included temperature sensing element in most ICs is that they have extremely low accuracy—typically on the order of ± 5°C to 10°C—because process deviation in silicon can be 15% or more, which leads to high temperature errors in the die.

There are several options for measuring the temperature of the desired component. Option 1 is to use the internal diode or temperature sensor, if available. Option 2 is to place an external integrated temperature sensor or thermistor on the PCB as close as possible to the heat source. Finally, option 3 is to calculate the temperature of the component by taking differential temperature measurements. Option 3 enables highly-accurate temperature monitoring using a dedicated thermal layout (for example, a ground plane, heat sink, or dedicated thermal trace) and two temperature sensors, such as TI's TMP6 thermistors.

2 Component Temperature Monitoring With Adjacent PCB Placement

The most common method of monitoring the temperature of a critical component is to place a temperature sensor directly next to the component. Heat conducts to the sensor via the PCB and traces. This method is cheap and simple, but thermal interference from ambient temperature and heat from other components on the board affect the temperature sensor. The heat radiated from the critical component can also decay very quickly, especially when the temperature differential between the component and ambient is very high. Figure 2-1 shows a thermal capture of the AWR2243BOOST evaluation module (EVM) mounted onto the DCA1000EVM for data capture. The *HI* temperature reading shows that the AWR2243, operating at a moderate load, has reached a temperature of 51.5°C. The *LO* value is the ambient temperature of 22.9°C, and the board temperature as measured by the thermal camera is 41.9°C.

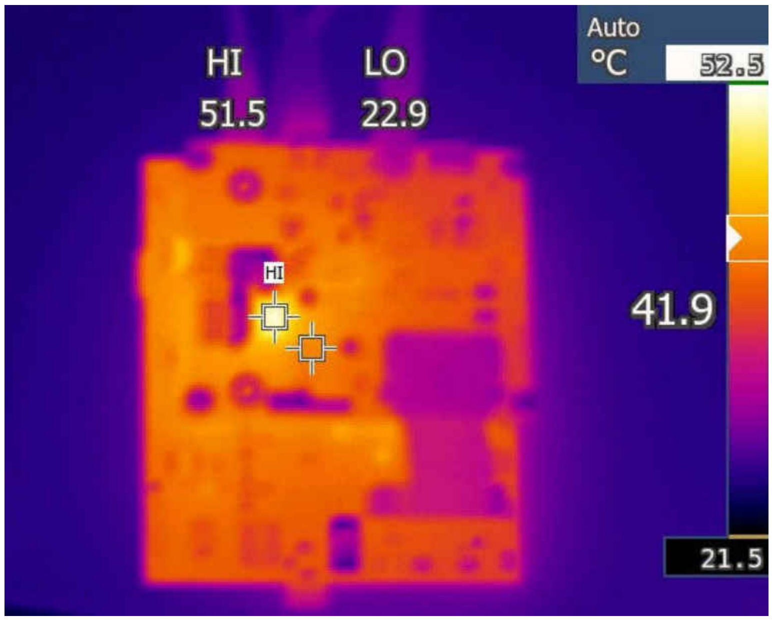

Figure 2-1. Thermal Capture of AWR2243BOOST Under Moderate Load

As shown, the quality of temperature data declines as distance from the radar chip on the PCB increases. By placing a temperature sensor adjacent to the AWR2243, the measured temperature even a few centimeters away from the heat source will be several degrees Celsius less than the actual die temperature of the device. This is due to the various thermal resistances between the component and the location of the temperature sensor.

Furthermore, there are often temperature gradients on the die blocks of the chips themselves. When monitoring critical components, it is important to accurately monitor the temperature of the precise hot spot of the device, which can be difficult if using only one adjacent external temperature sensor.

Finally, Figure 2-2 shows a thermal simulation of a test board with a temperature sensor near a 100°C heat source. The temperature at the temperature sensor is significantly lower than the temperature of the heat source due to the thermal resistances between the two. There are techniques to compensate for these thermal resistances and estimate the die temperature from one external temperature measurement, but the exact thermal resistances are difficult or even impossible to determine, making it difficult to accurately measure the die temperature of the device across a wide temperature range.

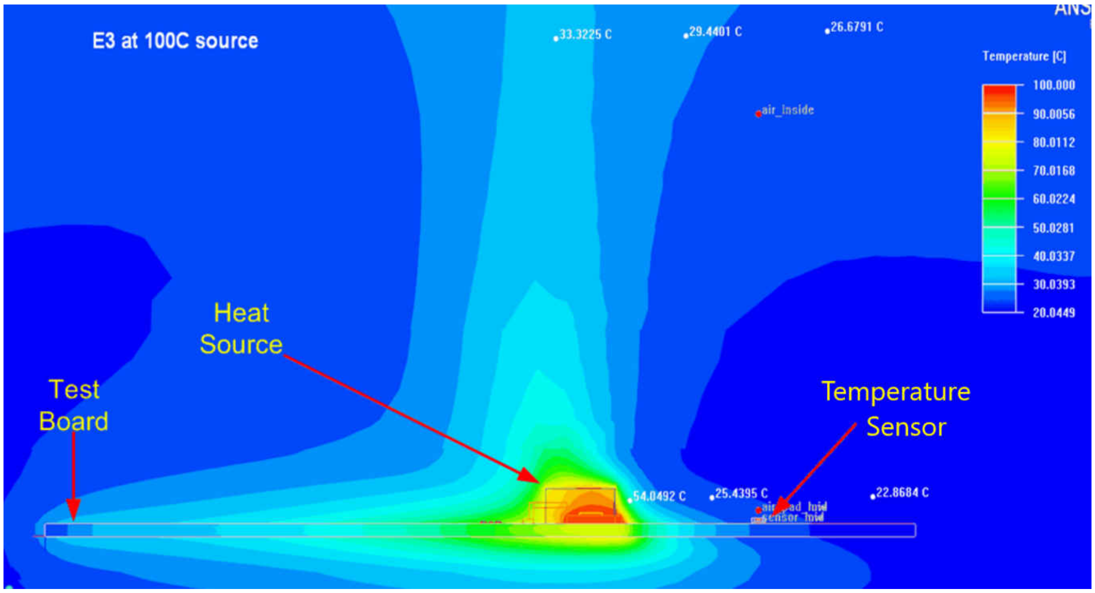

Figure 2-2. Thermal Simulation of Temperature Sensor Near 100°C Heat Source

From the examples provided, it is evident that a different technique is necessary to accurately monitor the temperature of certain components using external sensors. One effective technique is to use differential temperature measurements.

3 Component Temperature Monitoring Using Differential Techniques

This section discusses the physics of differential temperature measurements and explains how to use the technique to accurately monitor the temperature of a critical component.

3.1 Physics of Differential Temperature Measurements

The heat transfer process, known as thermal conduction, can be quantified in terms of appropriate rate equations. The rate equation in this heat transfer mode is based on Fourier's law of thermal conduction. This law states that the time rate of heat transfer through a material is proportional to the negative gradient of temperature and the area, at right angles to that gradient, through which the heat flows. Equation 1 can be derived, and is valid as long as all the parameters are constant throughout the sample.

$$\vec{q} = -k\,\Delta T \quad (1)$$

where:

- q is the vector of local heat flux density [W/m^2]
- k is the conductivity of the material [W/mK]
- ΔT is the temperature gradient [K/m^2]

From Equation 1, heat flow can be modeled using a thermal circuit as shown in Figure 3-1, where heat sources are represented by current or voltage sources, heat flow is represented by current, temperature is represented by voltage, and absolute thermal resistances are represented by resistors.

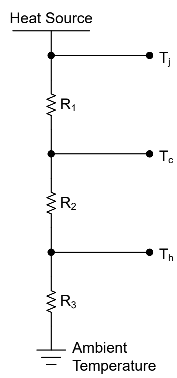

Figure 3-1. Equivalent Thermal Circuit for Heat Source and Two Reference Measurements

where:

- T_j is the junction temperature of the device
- T_c is the temperature at its case
- T_h is the differential temperature along its path
- R_1 is the thermal resistance along the path to the die
- R_2 is the thermal resistance between the two reference measurements
- R_3 is the unknown resistance along the path to the ambient temperature

Again, it is difficult to account for the thermal resistances and external influences to determine T_j. Although the exact thermal resistances may not be known, the thermal equivalent model of a voltage divider circuit and the consistent ratio of temperature drops between measurements can be used to accurately calculate the die temperature. To understand this ratio, consider the voltage divider circuit in Figure 3-2, with known voltage measurements and unknown resistances.

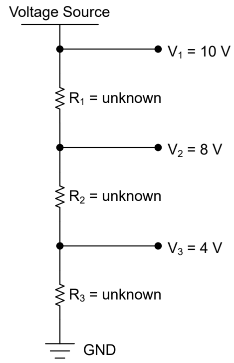

Figure 3-2. Voltage Divider Circuit With Unknown Resistances

The voltage across R_1 is 2 V and the voltage across R_2 is 4 V, and the ratio of these voltage drops is 1/2. This voltage drop ratio remains constant even if the source voltage changes, because the current through R1 equals the current through R2. Equation 2 and Equation 3 can be applied to this circuit according to Ohm's law.

$$V_{1-2} = I \times R_1 \tag{2}$$

$$V_{2-3} = I \times R_2 \tag{3}$$

Solving for *I* in Equation 2 and Equation 3, setting them equal to each other, and manipulating the resulting equation gives Equation 4:

$$\frac{V_{1-2}}{V_{2-3}} = \frac{R_1}{R_2} \tag{4}$$

From Equation 2 through Equation 4, the exact resistance values in the circuit are no longer needed because a ratio of the resistance values has been established using the voltage drops across the two resistors instead. As long as the resistances remain constant, the ratio of the voltage drops remains constant. This ratio can be used to calculate a missing voltage drop, and therefore a missing voltage, when just one voltage drop is known. Consider the circuit in Figure 3-3 with the same unknown resistances but a different, unknown voltage source and new voltage measurements.

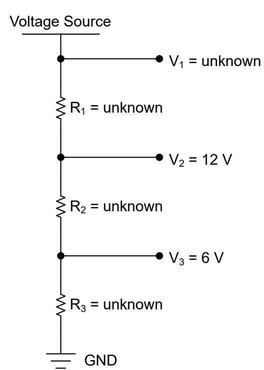

Figure 3-3. Voltage Divider Circuit With Unknown Resistances and Unknown Voltage Source

The voltage drop ratio calculated from the initial circuit can now be used to find the new, unknown voltage source. The voltage drop across R_2 is 6 V. The voltage drop across R_1 is found by multiplying 6 V by the previously calculated ratio of ½, which results in 3 V. Adding 3 V to the 12 V measured at V_2 reveals the new voltage source, V_1, is 15 V. This example of using differential voltage measurements to find the value of the unknown voltage source is the same concept used to determine the unknown temperature of a heat source using differential temperature measurements.

3.2 Three-Point Differential Temperature Measurement

In this example of differential temperature measurements, a TIDA-00982 2S1P Drone BMS Board is used. The ground plane on layer 2 functions as the heatsink on a 4-layer PCB. The thermal power pad of the IC is soldered to the PCB copper pad on layer 1 and 12 vias are used to connect to the ground plane on layer 2 of the PCB. The thermal conduction of the ground plane on layer 2 results in good thermal flow to measure the temperature differentially external to the IC. The thermal flow across the PCB is shown in the thermal image in Figure 3-4.

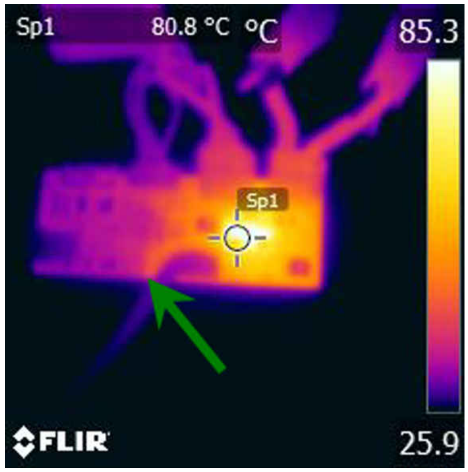

Figure 3-4. Thermal Flow Across TIDA-00982 Ground Plane

Three points on the PCB are used in the differential measurements: the die hot spot (Sp1) and two reference points (Sp2 and Sp3). In Figure 3-5, a thermal image of the PCB is shown at nominal operation with the 3 temperature measurements, along with an equivalent thermal circuit.

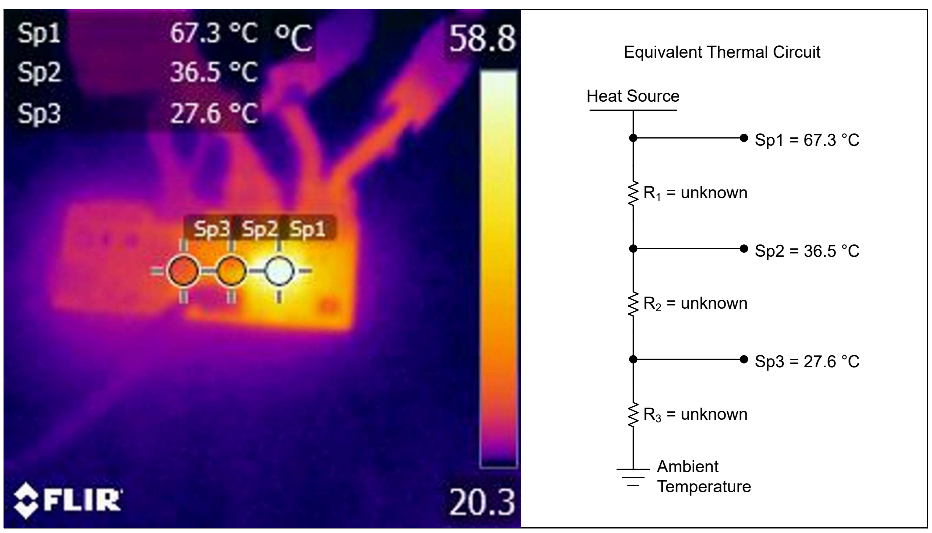

Figure 3-5. Thermal Capture of TIDA-00982 Under Moderate Load With Three Reference Points

Using these measurements, the temperature drops (DT1 and DT2) between the test points are calculated, which are then used to determine the ratio of the two temperature drops. The measurements and calculations are summarized in Table 3-1.

Table 3-1. Calculating Ratio of Temperature Drops From Three Reference Points

Reference Point	Temperature	Calculation	Value	Description
Sp3	27.6°C	DT2	8.9°C	Sp2 – Sp3
Sp2	36.5°C	DT1	30.8°C	Sp1 – Sp2
Sp1 (Die)	67.3°C	Ratio	3.46	DT1 / DT2

Using the ratio of the temperature drops, the die temperature (Sp1) can now be calculated from only the temperature measurements at the two reference points, Sp2 and Sp3. For example, consider another thermal IR image of the same PCB under heavy operation in Figure 3-6, along with the equivalent thermal circuit. Assume that initially Sp1 is unknown.

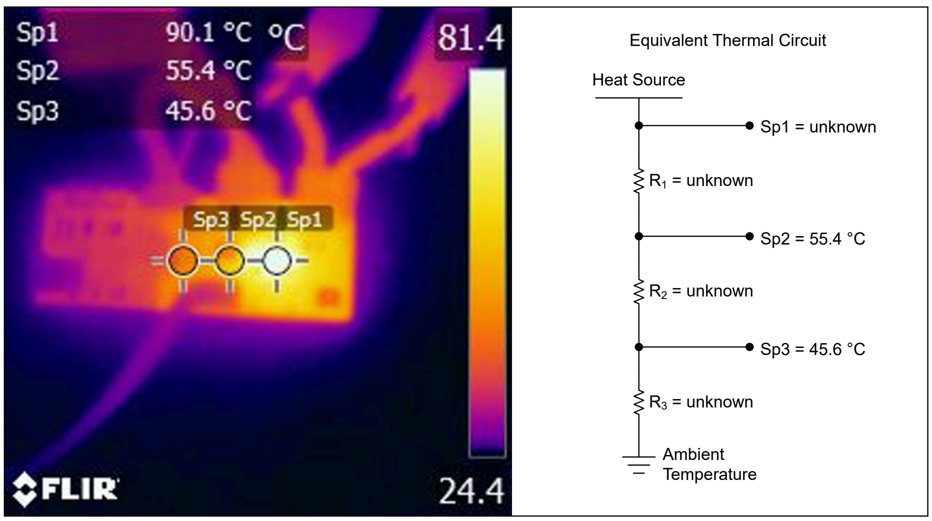

Figure 3-6. Thermal Capture of TIDA-00982 Under Heavy Load With Three Reference Points

To determine the die temperature, the temperature drop from Sp2 to Sp3 (DT2) is found. Then, the temperature drop (DT1) from Sp1 to Sp2 is calculated by multiplying DT2 by the previously determined ratio of 3.46. Adding DT1 to Sp2 gives the calculated die temperature (Sp1). These calculations are summarized in Table 3-2. As Figure 3-6 shows, the actual measured die temperature (Sp1) is 90.1°C, and the calculated die temperature from the differential measurements is 89.3°C. The differential temperature error in this test case is –0.8°C.

Table 3-2. Calculating Die Temperature From Two Reference Points

Reference Point	Measured Temperature	Calculation	Temperature	Description
Sp3	45.6°C	DT2	9.8°C	Sp2 – Sp3
Sp2	55.4°C	DT1	33.9°C	DT2 × Ratio
Sp1	90.1°C	Die Temperature	89.3°C	Sp2 + DT1

Therefore, using this differential temperature measuring technique and a thermal camera, the die temperature of an IC can be calculated within ±1°C. Using two of TI's TMP6 thermistors and a dedicated thermal layout, measuring the die temperature can be performed accurately.

3.3 Differential Temperature Measurement Design Guidelines

The technique of differential temperature measurements may seem simple, but there are several factors that to consider to accurately monitor the critical component.

Most importantly, use an infrared thermal camera to measure the hot spot on the IC to represent the die temperature, then calculate the temperature delta ratio based on the die temperature and the two external temperature measurements. The thermal camera is effective because of its ability to detect the emitted thermal radiation (ETR) that is reflected off the top of the encapsulated material above the IC die area, as shown in Figure 3-7. Much like the image of a person or light is seen in the reflection on a window pane; the ETR is visible on the top of the IC package and can be measured by the thermal camera. This is similar to how a thermal camera can measure through walls. A thermal camera cannot really identify objects through walls, but, if it is sensitive enough, it can detect the ETR of a human body on the walls. The thermal measurement through the IC package can be as accurate as ±0.2°C. The losses are minimal at this distance, but the accuracy is diminished by the emissions that spread in all directions, much like a light would shine in an outward spreading pattern.

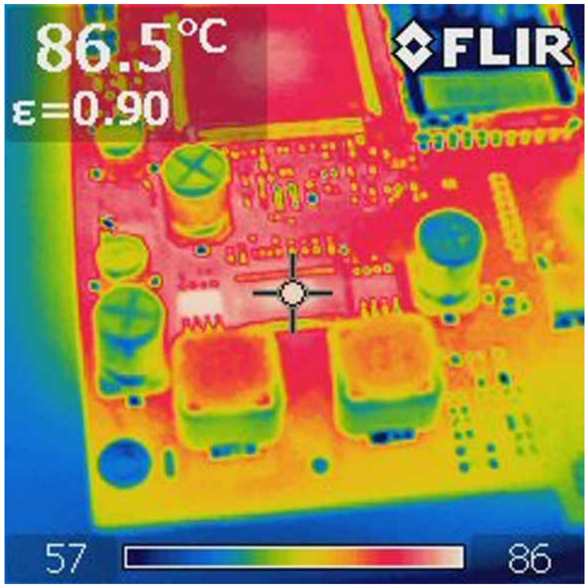

Figure 3-7. Thermal Capture of Emitted Thermal Radiation Above and IC

The board must also have a designated thermal layout. There are several options to consider when designing the thermal layout of a PCB using the differential temperature measurement technique. Option 1 is to use the ground plane to achieve good thermal flow across the PCB and use vias to the ground plane to take the temperature measurements. Option 2 involves using the thermal flow across a heatsink and two temperature sensors at different locations along the heatsink to take the differential measurements. Option 3 is to use a dedicated thermal trace. Options 1 and 2 tend to provide the best low-impedance heat path, but option 3 can be used to create a thermal path if one does not exist. If a dedicated thermal trace is needed, the concept of squares can be used to estimate the ratio of the thermal resistances, which should later be verified using a thermal camera.

The concept of squares is based on thermal resistance and heat-conduction physics but is applied using Ohm's law. The thermal trace is made up of squares, where the width of the trace defines the length of one thermal square. In Figure 3-8, the distance between thermistors R_1 and R_2 is two squares of thermal trace. The distance between the source and R_1 is five squares.

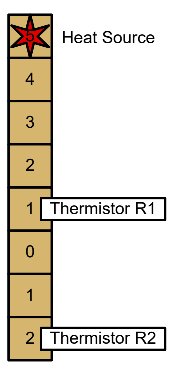

Figure 3-8. Concept of Squares Using a Thermal Trace

In this example, the estimated ratio of the thermal resistances based on the concept of squares is 5 / 2 or 2.5. This concept can help simplify the technique of differential measurements, but using a thermal camera to calculate the ratio of the die temperature and the two external temperature measurements provides the best results because there is a high potential for error if all factors are not considered.

Use the following additional guidelines to maintain the accuracy of the differential thermal calculation:

- Extend the length of the thermal trace beyond the two differential measurement points to help prevent thermal saturation of the trace
- Keep the thermal trace as far away from outside heat sources as possible
- Ensure the thermal trace has consistent width and consistent spacing from the ground plane
- Keep the thermal trace as straight as possible
- If a via is used in one thermal location, use vias for the other two as well
- Routing the thermal trace on an internal layer results in less interference from outside air movement or ambient temperatures than a thermal trace routed on an external layer

3.3.1 Example: Differential Temperature Layout for a Power IC

Sometimes it may not be possible to route on the top layer because the IC is soldered to the pad. Instead, as Figure 3-9 shows, a dedicated thermal trace can be routed on the ground plane layer. Isolation protects the thermal trace from being connected to the plane, except at the vias used for thermal measurement. The thermal trace begins at a specific location on the ground plane layer underneath the power IC.

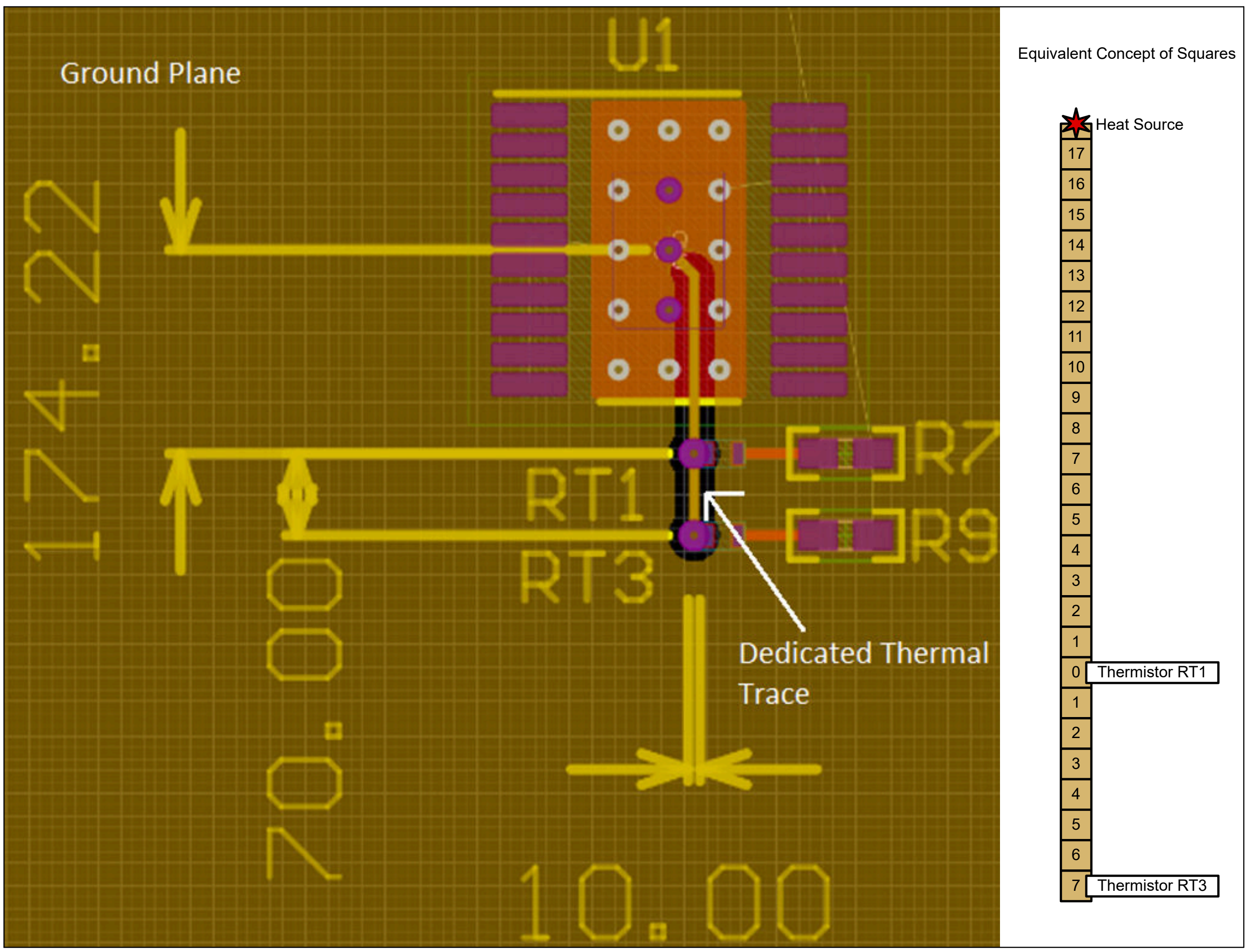

Figure 3-9. Differential Temperature Measurement Layout With Dedicated Thermal Trace and Concept of Squares Diagram

RT1 is the first TMP6 thermistor and RT3 is the second thermistor. R7 and R9 are the bias resistors for the two thermistors. The trace is 10 mil wide, which means there are 7 squares between RT1 and RT3 and 17.5 squares from the internal via to RT1. The ratio of the thermal resistances is calculated as 17.5 / 7 or 2.5. This ratio is an estimate and should be verified using a thermal camera. Once the ratio is verified, the temperature between RT1 and RT3 can be multiplied by the ratio and added to the temperature at RT1 to calculate the temperature at the center of the IC.

4 Summary

High-accuracy component temperature monitoring is essential in applications where temperature compensation is needed, or where a system requires safety shutoff limits. This type of temperature monitoring, especially when components have die hot spots, can be done very well and at low cost by taking differential temperature measurements using two of TI's TMP6 thermistors.

This style of design returns more accurate results than using the internal temperature sensor of the device or using a sensor placed adjacent to the device on the PCB. Differential temperature measurements can be considered when an intentional thermal layout for the two temperature sensors can be included in the design, and when other temperature-sensing techniques are not compatible with system design requirements.

5 References

For related documentation, see the following:

- Texas Instruments, *TMP61-Q1 Automotive Grade, ±1% 10-kΩ Linear Thermistor With 0402 and 0603 Package Options Data Sheet*
- Texas Instruments, *AWR2243 Evaluation Module (AWR2243BOOST) mmWave Sensing Solution User's Guide*
- Texas Instruments, *DCA1000EVM Data Capture Card User's Guide*