

Temperature Measurement Theory and Practical Techniques

By Donal McNamara

HEAT TRANSFER THEORY

The transfer of heat is normally from a high temperature object to a lower temperature object. Heat transfer from a cold region to a hot region can be done by forcing the system (refrigerators, for example) to perform the energy transfer.

Heat transfer is accomplished by three basic methods.

- Conduction
- Convection
- Radiation

Conduction

Conduction is the most common means of heat transfer in a solid. On a microscopic scale, conduction occurs as hot, rapidly moving or vibrating atoms and molecules interacting with neighboring atoms and molecules, transferring some of their energy (heat) to these neighboring atoms.

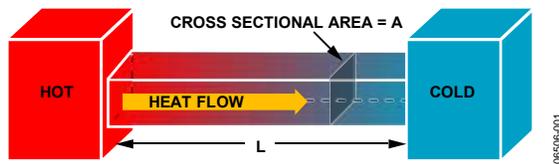


Figure 1. Conduction

Convection

Convection is usually the dominant form of heat transfer in liquids and gases. This is a term used to characterize the combined effects of conduction and fluid flow. In convection, heat content transfer occurs by the movement of hot or cold portions of the fluid together with heat transfer by conduction.

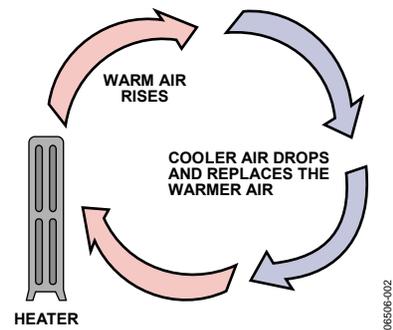


Figure 2. Convection

Radiation

Radiation is the only form of heat transfer that can occur in the absence of any form of medium and as such, is the only means of heat transfer through a vacuum. Thermal radiation is a direct result of the movements of atoms and molecules in a material. Because the amount of emitted radiation increases with increasing temperature, a net transfer of energy from higher temperatures to lower temperatures results.

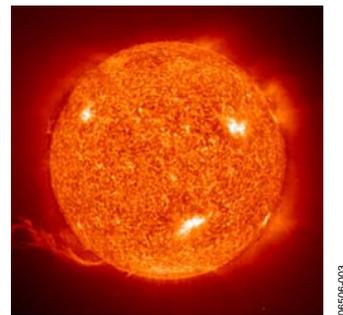


Figure 3. Radiation

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Fact: Conduction is the Most Prevalent Heat Transfer Method in PCBs

If one end of a PCB is at a higher temperature, energy is transferred down the PCB towards the colder end. The higher speed particles collide with the slower ones with a net transfer of energy to the slower ones. The rate of conduction heat transfer is

$$H = \frac{(K \times A(T_{HOT} - T_{COLD}))}{L}$$

where:

H = energy conducted in time (J/sec)

K = thermal conductivity of the copper (385 W/(m•K) @ room temperature)

A = area of copper on PCB

T = temperature

L = distance between hot and cold bodies.

Figure 4 shows that heat travels faster from a hot body to a cold body if the area of the medium it is conducting through (copper, for example) is increased. Likewise, if the area of the copper is reduced, the heat transfer rate is reduced. Common sense deduces that the further away the two bodies are from each other, the longer it takes for the cold body to heat up.

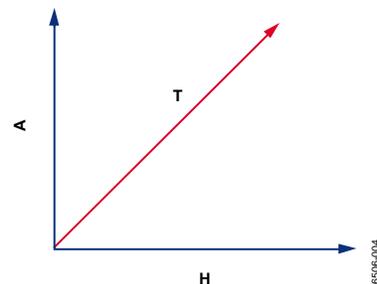


Figure 4. Conduction Heat Transfer Rate

Copper is an excellent conductor of heat and is subsequently used in many PCB designs to dissipate heat from a heat source. Silver and diamond are the only other materials to have better thermal conductivity (see Table 1).

Table 1. Material Thermal Conductivity Table

Material	Thermal Conductivity (W/m•K)
Diamond	1000 to 2600
Silver	406
Copper	385
Gold	320

CORRECT PCB LAYOUT FOR MEASURING PCB TEMPERATURE

The pins transfer 60% to 65% of the PCB heat to the die thermal sensor. The GND pin is connected to the substrate, therefore, the GND pin has the least thermal resistance between the temperature sensor and heat source (see Figure 5).

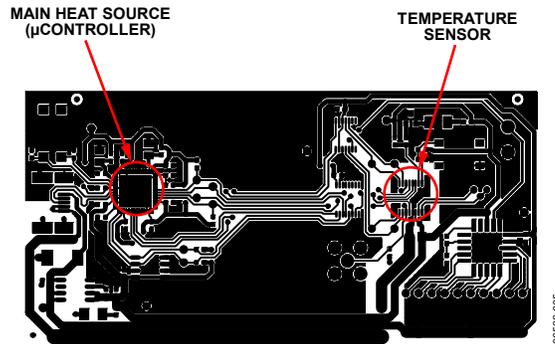


Figure 5. Correct Layout for Measuring Temperature of PCB

Tips for Efficient PCB Temperature Measurement

Apply the following tips to ensure that the temperature sensor tracks and accurately measures the PCB temperature and subsequently, the main heat source, as shown in Figure 6.

- Use a common GND plane between the temperature sensor and heat source.
- Ensure that all GND pins of the temperature sensor are connected to the heat source GND plan.
- Keep the temperature sensor and heat source as close as possible to each other on the PCB.

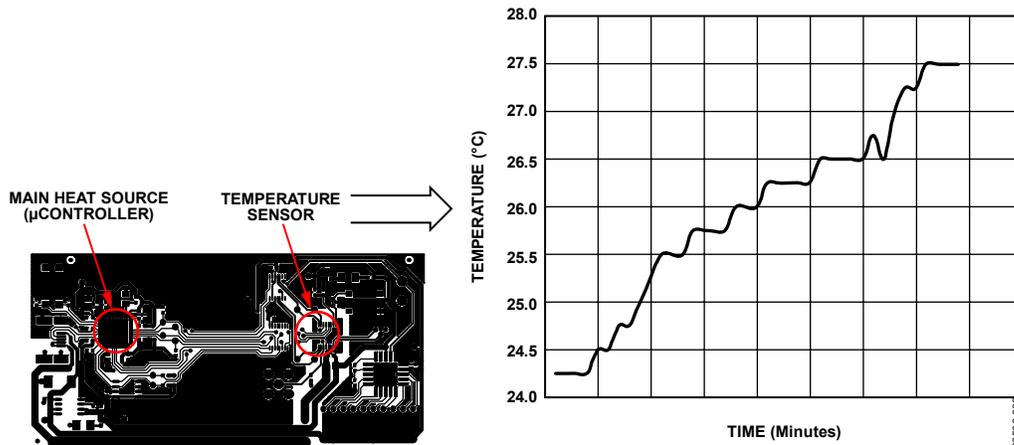


Figure 6. Digital Temperature Sensor Accurately Tracks the Temperature of the Heat Source

Most customers want to use IC temperature sensors to measure the temperature of the PCB or a component. Therefore, it is better to use the PCB layout technique shown in Figure 5 and Figure 6.

CORRECT PCB LAYOUT FOR MEASURING AMBIENT TEMPERATURE

Many designers don't want to measure the PCB temperature. They just want to measure the ambient air temperature. The problem is, how do designers prevent the PCB heat sources from affecting the ambient temperature measurement of the temperature sensor? The answer is to use the PCB layout design shown in Figure 7.

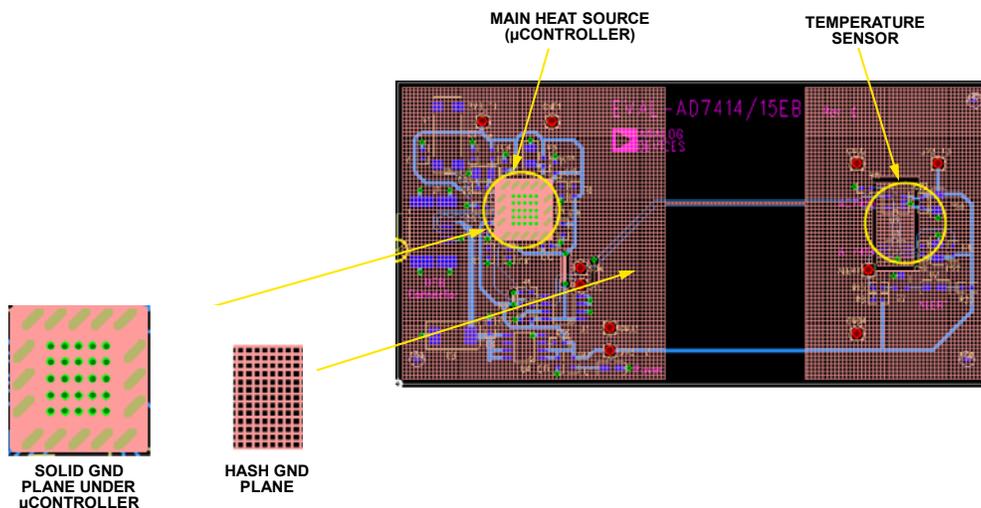


Figure 7. Correct Layout for Measuring Ambient Temperature

Tips for Efficient Ambient Temperature Measurement

Use the following tips to prevent the heat dissipated by the main heat source from affecting the temperature sensor and to accurately monitor ambient temperature:

- Use a hash GND plane. Reduce the GND plane area to increase thermal resistance.
- Keep the temperature sensor as far away from heat sources as possible.
- Use a separate GND plane for the temperature sensor and keep connections to the main GND plane as low as possible.
- Use narrow GND connections to increase thermal resistance.
- Use a solid GND plane under the main heat source and expose the green solder mask. This gives the minimum thermal resistance for the main heat source to dissipate heat.

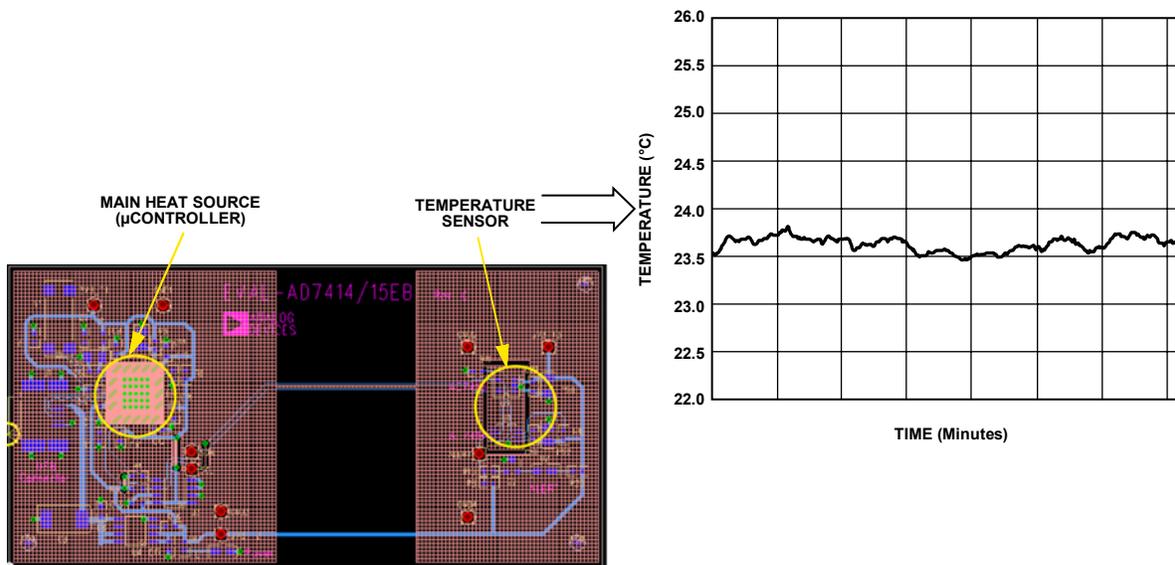


Figure 8. Digital Temperature Sensor Accurately Tracks the Ambient Temperature

Some customers want to monitor air temperature and also use the accuracy, linearity, speedy response, and convenience of an IC temperature sensor. It is best for them to use the PCB layout technique shown in Figure 7 and Figure 8.

PACKAGES

Apart from size and pin count, there are a number of other package considerations.

- Package thermal resistance
- Power dissipated in the device
- Soldering temperatures
- Response to thermal shock

Package Thermal Resistance

Two package performance metrics are usually indicated in data sheets, junction-to-air (θ_{JA}) thermal resistance and junction-to-case (θ_{JC}) thermal resistance.

Junction-to-Air (θ_{JA}) Thermal Resistance

This measures ease of heat flow between the die surface and air. It also reflects how heat flows from junction-to-ambient temperature via all paths. The primary path is leads to board.

θ_{JA} thermal resistance is relevant for packages used without external heat sinks, and it is measured in $^{\circ}\text{C}/\text{W}$. The lower the value, the better. For example,

- 8-Lead MSOP = $205.9^{\circ}\text{C}/\text{W}$
- 8-Lead SOIC = $157^{\circ}\text{C}/\text{W}$

Junction-to-Case (θ_{JC}) Thermal Resistance

This measures ease of heat flow between the chip surface and the package surface. It also reflects how heat flows into the external heat sink, making it relevant for packages used with external heat sinks. θ_{JC} thermal resistance is measured in $^{\circ}\text{C}/\text{W}$. The lower the value, the more easily the heat flows into a heat sink. For example,

- 8-Lead MSOP = $43.74^{\circ}\text{C}/\text{W}$
- 8-Lead SOIC = $56^{\circ}\text{C}/\text{W}$

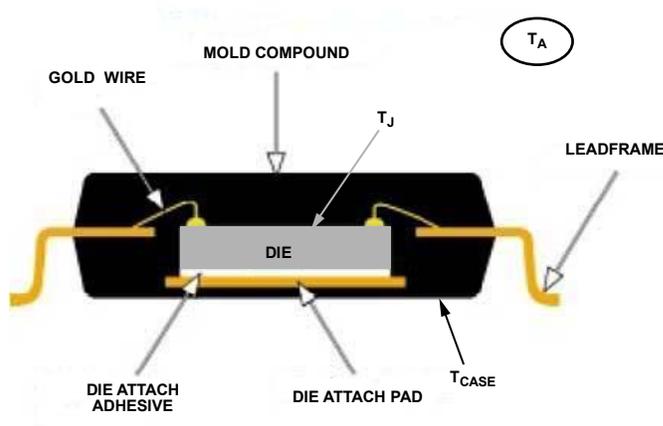


Figure 9. TSSOP Package Cross Section

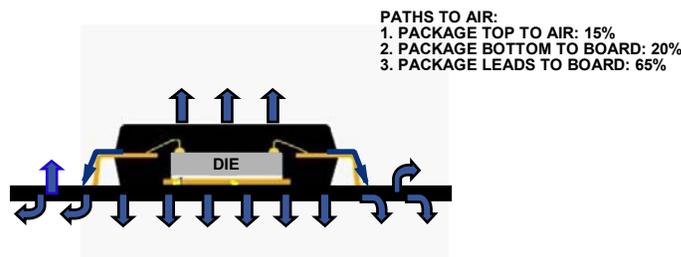


Figure 10. Major Paths to Air

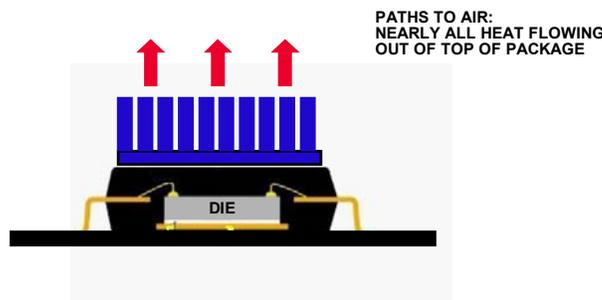


Figure 11. Paths to Air

Power Dissipated in the Device

This following equation is available in the absolute maximum ratings section of data sheets. It is defined as a maximum power rating.

$$W_{MAX} = \frac{(T_{AMBmax} - T_A)}{\theta_{JA}}$$

where:

W_{MAX} = maximum power dissipated in the device.

T_{AMBmax} = maximum ambient temperature specified in the data sheet.

T_A = junction temperature.

θ_{JA} = junction-to-ambient thermal resistance in °C/W.

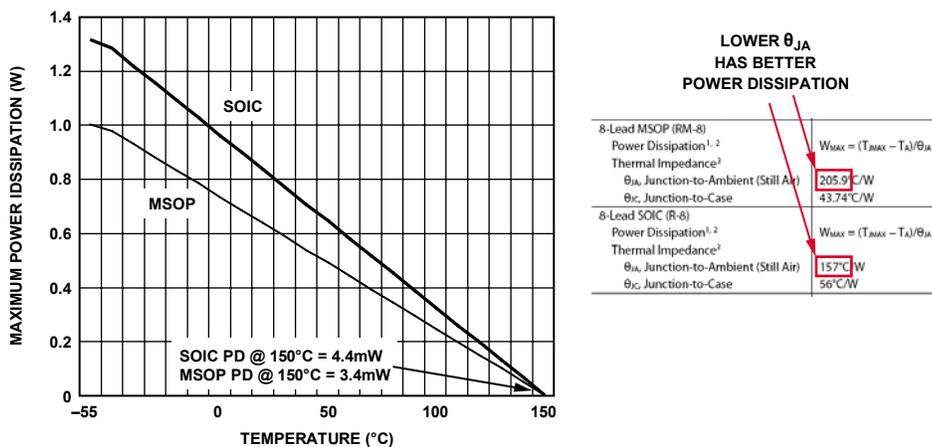


Figure 12. Power Dissipation in SOIC and MSOP Packages

06506-012

Package Soldering Information

Analog Devices, Inc. produces two types of package leads, Sn-Pb leaded leads and Pb-free unleaded leads (as of 2006, all new parts released from Analog Devices only contain Pb-free materials). There are different time and temperature parameters when soldering both types of leads. The most important difference between leaded and unleaded leads is the peak soldering temperature. This difference is shaded in gray in Table 2.

Table 2. Data Table for Soldering Sn-Pb and Pb-free Packages

Average Ramp-Up Rate	Sn-Pb Assembly (3°C/sec max)	Pb-Free Assembly (3°C/sec max)
Preheat		
Temperature Minimum (T_{SMIN})	100°C	100°C
Temperature Maximum (T_{SMAX})	150°C	150°C
Time (T_{SMIN} to T_{SMAX})	60 sec to 120 sec	60 sec to 120 sec
Time Maintained Above		
Temperature	183°C	217°C
Time	60 sec to 150 sec	60 sec to 150 sec
Peak Soldering Temperature	220°C	260°C
Time Within 5°C of Actual Peak Temperature	10 sec to 30 sec	20 sec to 40 sec
Ramp-Down Rate	6°C/sec max	6°C/sec max
Time from 25°C to Peak Temperature	6 min max	6 min max

Response to Thermal Shock

Reducing the thermal resistance between the die and the heat source reduces the thermal time constant and improves the thermal response of the die. One thermal time constant is the time it takes for a temperature Δ to change to 63.2% of its final value. In Figure 13, the ADT7301 experiences a thermal shock from 25°C to 125°C; it takes typically 2 sec for the ADT7301 to reach 88.2°C.

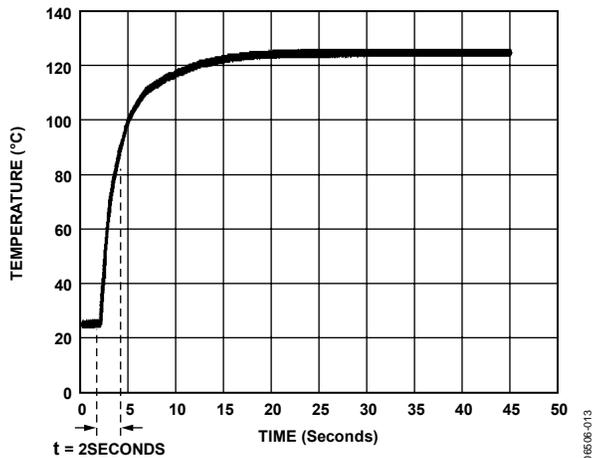


Figure 13. ADT7301 Thermal Time Constant

Figure 13 also shows that the same thermal time constant is used for both ADT7301 packages, SOT-23 and MSOP. Evaluation data has shown that package type has only a small effect on thermal time constant value. This indicates that most of the heat flows through the package leads. θ_{JA} (junction-to-air thermal resistance) and θ_{JC} (junction-to-case thermal resistance) have little effect on the thermal response of surface mount digital temperature sensors.

In general, effective GND pin contact to the ground plane of the heat source is far more important than the package type. Most modern temperature sensors draw very little current (μA). As a result, power dissipation and consequently, self heating, are not factors to be overly concerned about.

In the case of current output temperature sensors (for example, the AD590, AD592, and TMP17), package types TO-52, T0-92 (see Figure 14), CQFP, and SOIC rely on a low $\theta_{JC} + \theta_{JA}$ for fast thermal response. Note that there are no GND pins on these parts.



Figure 14. TO-92

The LFCSP (see Figure 15) has a metal stub at the base that is directly connected to the GND of the die. Connecting this stub to the PCB GND plane gives the LFCSP a lower thermal resistance than most packages.

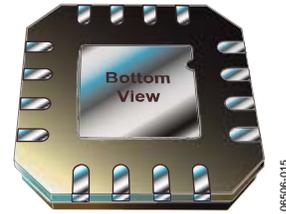


Figure 15. LFCSP