Application Report

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Optimizing Placement and Routing for Humidity Sensors

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ABSTRACT

Texas Instruments' family of Humidity-to-digital converters (HDCs) provide excellent measurement accuracy at industry's leading power consumption levels. In addition to AC powered applications like smart home assistants or washer/dryers, the HDC family's low power consumption also facilitates use in battery powered IoT applications such as wearables or smart thermostats. Humidity-to-digital converter (HDC) ICs are available in small packages (WSON or DSBGA) that simplify board design, and are factory calibrated for ease of use.

In order to determine relative humidity, HDCs measure absolute humidity and ambient temperature. For other calculations, such as calculating the dew point, determining temperature in addition to relative humidity is also required. It is therefore necessary to consider component placement and PCB routing of the sensor IC for both temperature and humidity measurements, even if only relative humidity is of interest.

This application note describes techniques for accurate measurement of both temperature and humidity levels using the HDC1010, HDC1080, and HDC2010.

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1 Background

1.1 Humidity Parameters

Humidity is the presence of water vapor in air (or any other gas). It is expressed in several different ways:

[1]1.1.1 Absolute Humidity

Absolute is the measure of water vapor in air. Absolute humidity is expressed as:

$$AH = \frac{m_{H20}}{V_{net}}$$

where

- AH = absolute humidity [kg/l]
- m_{H2O} = mass of water vapor [kg]
- V_{net} = volume of air + water vapor mixture [l] (1)

Since absolute humidity does not take temperature into consideration, which greatly affects the saturation moisture level, it has limited practical use.

1.1.2 Relative Humidity

Relative Humidity is the amount of moisture in the air compared to the saturation moisture level at that temperature. This is the most commonly used measure of humidity and is usually expressed as a percentage with the symbol RH% (for example, the humidity is 51 RH%). The term *relative humidity* is commonly abbreviated to RH. Note this is different from the unit symbol RH%.

$$RH\,\% = \frac{P_{\text{water vapor}}}{P_{\text{saturation water vapor}}} \times 100$$

where

- $P_{\text{water vapor}}$ is the pressure of the water vapor in the air at a given temperature
- $P_{\text{saturation water vapor}}$ is the saturation pressure of water vapor in the air at a given temperature. (2)

1.1.3 Dew Point (or Dew Point Temperature)

Dew Point (or Dew Point Temperature) is the temperature at which condensation (dew) would occur if a gas was cooled at constant pressure. Dew point is a useful measure for two reasons:

- The dew point tells the minimum system temperature to prevent condensation.
- Dew point is an absolute measure of the gas humidity (at any temperature) and relates directly to the amount of water vapor present (partial pressure of water vapor).

The dew point can be calculated by using the relative humidity and temperature as inputs.

$$Dp = \frac{\lambda \times \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta \times T}{\lambda + T} \right)}{\beta - \left(\ln\left(\frac{RH}{100}\right) + \frac{\beta \times T}{\lambda + T} \right)}$$

where

- Dp = Dew point [°C]
- λ and β are Magnus parameters. For the range from –45°C to 60°C, the Magnus parameters are β =17.62 and λ=243.12°C. (3)

[1] http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-86-2-225

1.2 What Is Heat Conduction?

There are three methods of heat transfer: heat conduction through solids, heat convection through fluids and gases, and heat generated by radiation. This report focuses on heat conduction as it dominates the heat transfer in PCBs and is therefore most relevant to temperature measurements.

Heat conduction is defined as the transfer of heat through a volume or a body. Heat is transferred through microscopic collisions of particles; the more collisions, the hotter the object is. Heat transfer occurs when there is a temperature difference between two objects or between different areas of an object, and its rate depends on the geometry, thickness, and material of the object. Due to the law of equilibrium, heat transfers from a hotter body to a colder body until the whole system reaches final equilibrium, as shown in Figure 1. There is no net heat transfer between two objects that are equilibrium temperature. The equation for heat transfer through conduction is shown in Equation 4

$$\frac{Q}{t} = kA\frac{\left(T_2 - T_1\right)}{d} \tag{4}$$

where

- Q/t: The rate of heat transfer [J/s]
- k: the thermal conductivity of the material [W/m×K]
- A: Surface of the contact area [m^2]
- ∆T: The temperature difference of T1 temperature of one object and T2 temperature of the other [K]
- d: The thickness of the material [m]

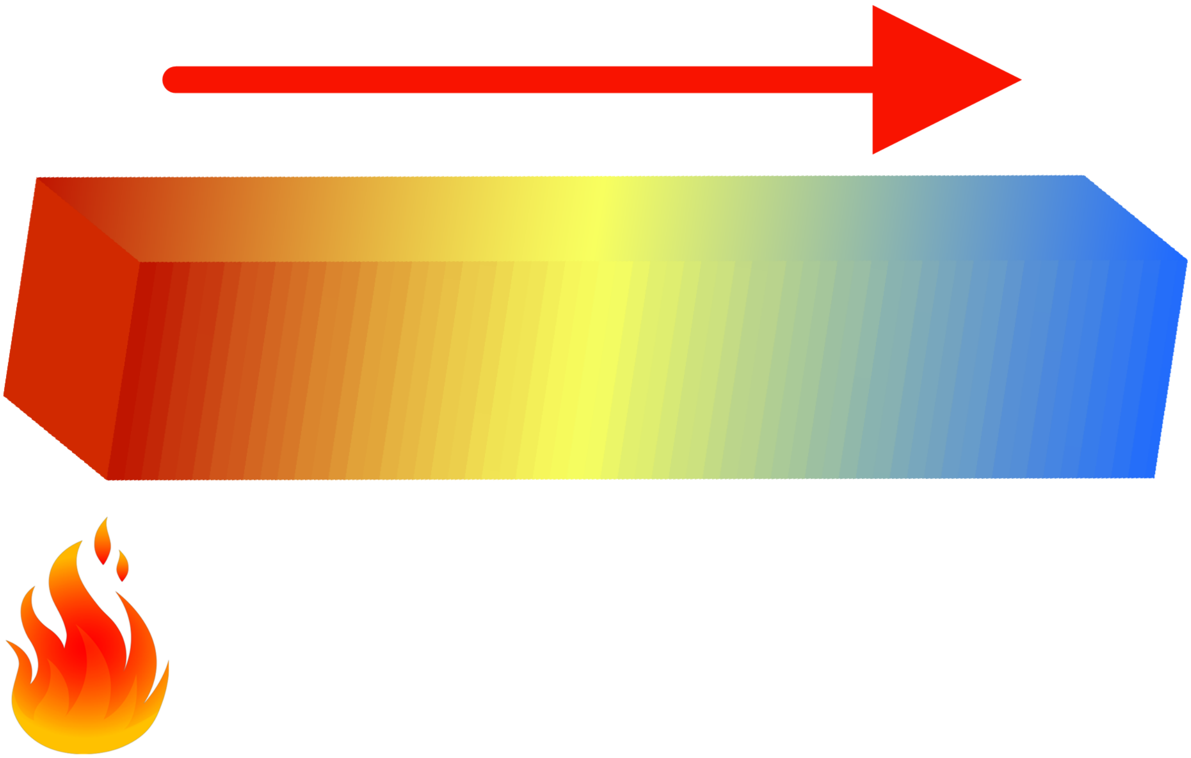

Figure 1. Thermal Conduction Model

Thermal conductivity (k) is the measure of a material's capability to conduct heat. It is used to describe how heat conducts through a material. Metals are highly thermally conductive whereas materials like air, wool, paper, or plastic are poor conductors of heat. Materials with a very low thermal conductivity, such as polystyrene foam, act like a thermal insulator.

The materials that are most relevant to thermal analysis of PCBs are copper, FR4, and solder mask. Copper is an excellent conductor of heat; it conducts heat significantly faster than FR4. Table 1 lists the thermal conductivities found in PCBs. The higher the value, the more efficient the material is in transferring heat, which results in a shorter thermal response time. For low k values, the temperature gradient between the source and the sensor can be significantly large and must be considered carefully during layout.

Table 1. Material Thermal Conductivity Coefficients Of Selected Materials

Material	Thermal Conductivity k [W/(m×K)]
Air	0.0275
Solder Mask	0.245
FR4	0.25
Gold	314
Copper	385
Silver	406

2 Design Guide

The accuracy of RH and temperature measurements depends on the sensor accuracy and the design of the sensing system. The HDC sensors sample relative humidity and temperature of their local environment. Therefore it is important that the local conditions of the sensor correspond to the conditions under the test.

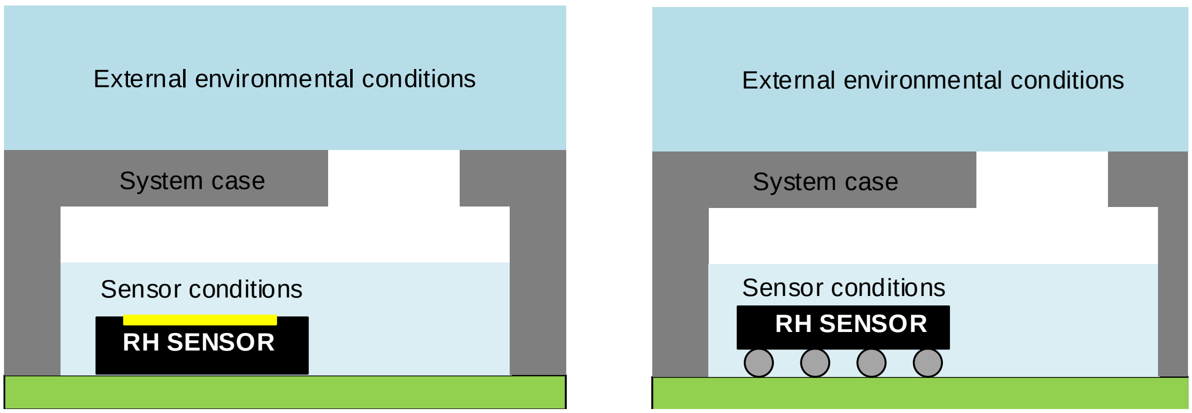

Figure 2. Same Sensor Conditions and External Environmental Conditions Ensure Accurate RH Measurements

More generally, correct sampling requires that the measurement is representative of the desired environmental condition. Avoid temperature and relative humidity (RH) deviations between the sensor and the environment. A common root causes for temperature deviations are nearby heat sources, while RH deviations are mostly caused by temperature deviations as well as slow response times caused by dead air pockets near the sensor.

For any temperature or humidity change of the environment, the sensor requires a certain amount of time to equilibrate with the new environmental conditions. To get accurate data, TI recommends designing for a fast response time of the sensor system.

To optimize the measurement of the relative humidity, consider the following design constraints:

- Air flow (Section 2.1)
- Heating
  - Self-heating (Section 2.2)
  - Conducted Heat (Section 2.3)

PCB Layout examples are drawn in Section 2.4

2.1 Optimizing Air Flow

To monitor outside humidity using the sensor mounted in the device, a design with air flow around the sensor is favorable in terms of response times. Even if there is no defined flow (no active air circulation in a room) a design with multiple openings and a possible flow is preferred. Placing the sensor close to the sampling aperture and making the cavity around the sensor small helps improve the sensor's response time.

Devices in a WSON package (HDC1080) have the sensing element exposed on the top surface. It is recommended that HDCs in WSON packages are not placed in a direct line of sight between the top surface of the package and the ambient. This reduces the possibility of ambient light, water droplets, cleaning agents, dust or other airborne contaminates falling directly on the sensor surface during operation. Long exposures to UV light, visible light or high concentration chemical vapors for prolonged periods may shift the RH output and should be avoided.

Figure 3 to Figure 9 list recommended component placement which optimize the air flow to measure the outside humidity.

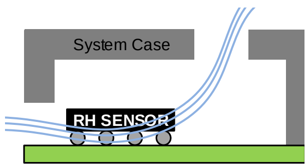

Figure 3. Multiple Windows (Openings Not Aligned)

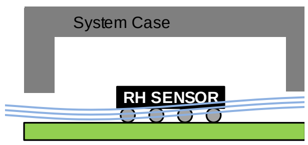

Figure 4. Multiple Windows (Openings Aligned)

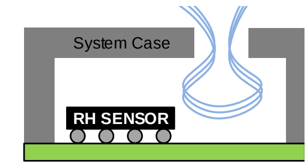

Figure 5. Single Window

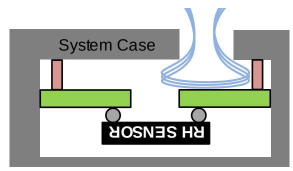

Figure 6. Single Window (Flipped Device)

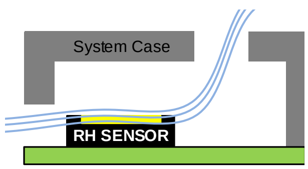

Figure 7. Multiple Windows (Openings Not Aligned)

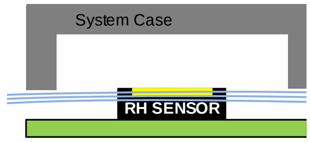

Figure 8. Multiple Windows (Openings Aligned)

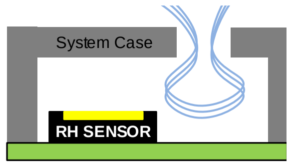

Figure 9. Single Window

2.2 Minimizing Self-Heating

The humidity sensors have very low power consumption in sleep mode so their self-heating is very limited. The power consumption during the measurement increases and it might cause self-heating. To mitigate this effect, TI suggests limiting the read cycles to no more than two measurements per second at high resolution (one temperature measurement and one relative humidity measurement). The length of the active state depends on the acquisition time: the higher the resolution, the longer is the active state.

2.3 Minimizing Conducted Heat

Heat sources on the PCB on the same PCB as the Humidity Sensor can result in an inaccurate ambient temperature reading. Common heat sources include a nearby processor or power management IC, which transfer heat to the HDC primarily through conduction through the copper in the PCB. Temperature changes cause relative humidity changes, so isolating the sensor from the heat source is important. Guidelines for thermal isolation are given in sections Section 2.3.1 to Section 2.3.6.

2.3.1 Ground Plane Considerations

Due to the higher thermal conductivity of copper, running solid ground planes between other ICs and the sensor will cause undesired heat transfer. It is best to avoid copper planes near the sensor that are connected to the copper planes of other ICs, as shown in Figure 10. Hatched GND planes in the main section of the PCB further reduce heat flow from other ICs to the sensor. If applicable, add a physical gap between the plane around the sensor and the planes of the rest of the PCB.

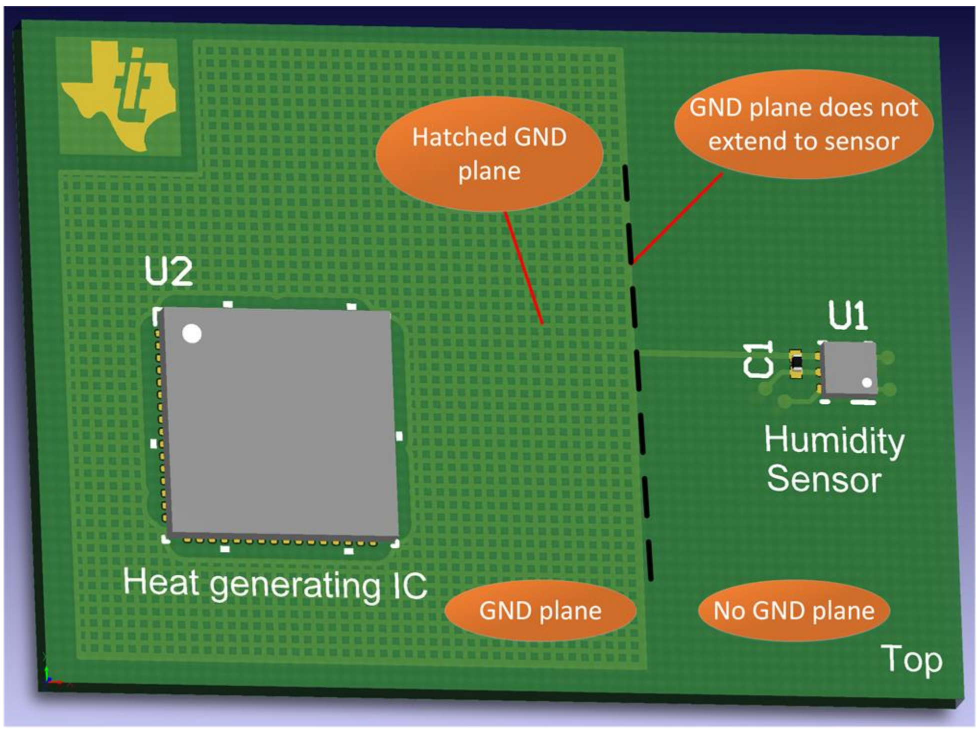

Figure 10. GND Plane Does Not Extend To Sensor

2.3.2 Partitioning the PCB

The humidity sensor should be in an area of the PCB that is as far away from the main heat generating ICs, as shown in Figure 11. This can be achieved by placing the sensor in a corner of the PCB, away from other components. Doing so will minimize the effect that other components on the board have on the temperature reading.

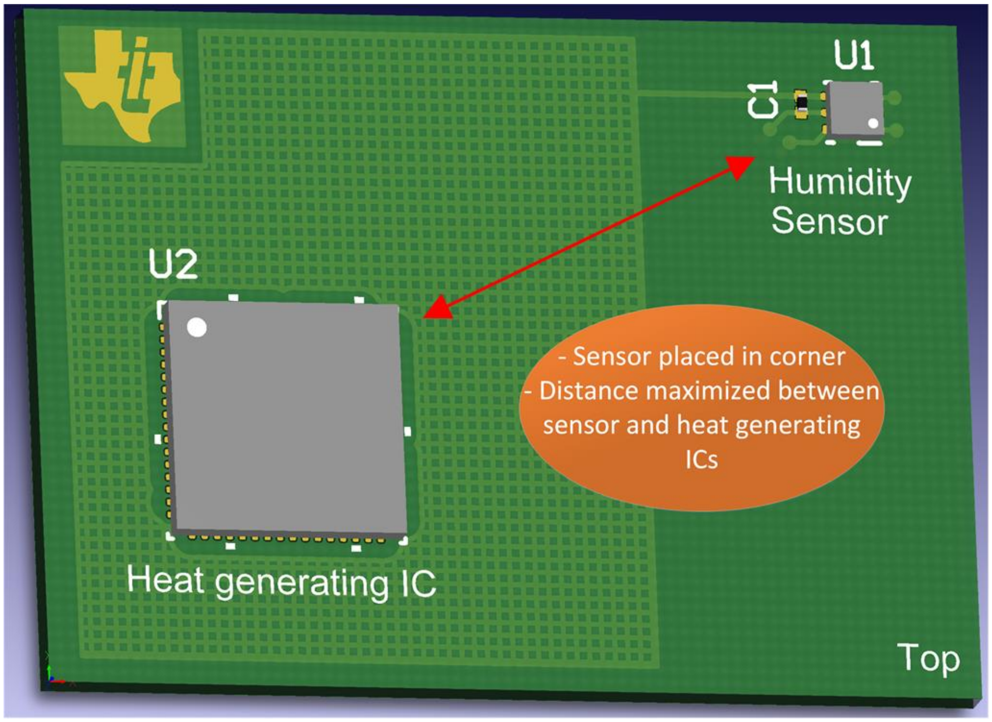

Figure 11. Sensor Placed In PCB Corner

2.3.3 Isolation Island

If feasible, a partial router trace around the humidity sensor creates an isolation island which greatly reduces heat transfer from the main heat source to the sensor. Heat transfer is reduced because the thermal conductivity of air compared is significantly lower than the thermal conductivity of FR4. An example of an isolation island is shown in Figure 12.

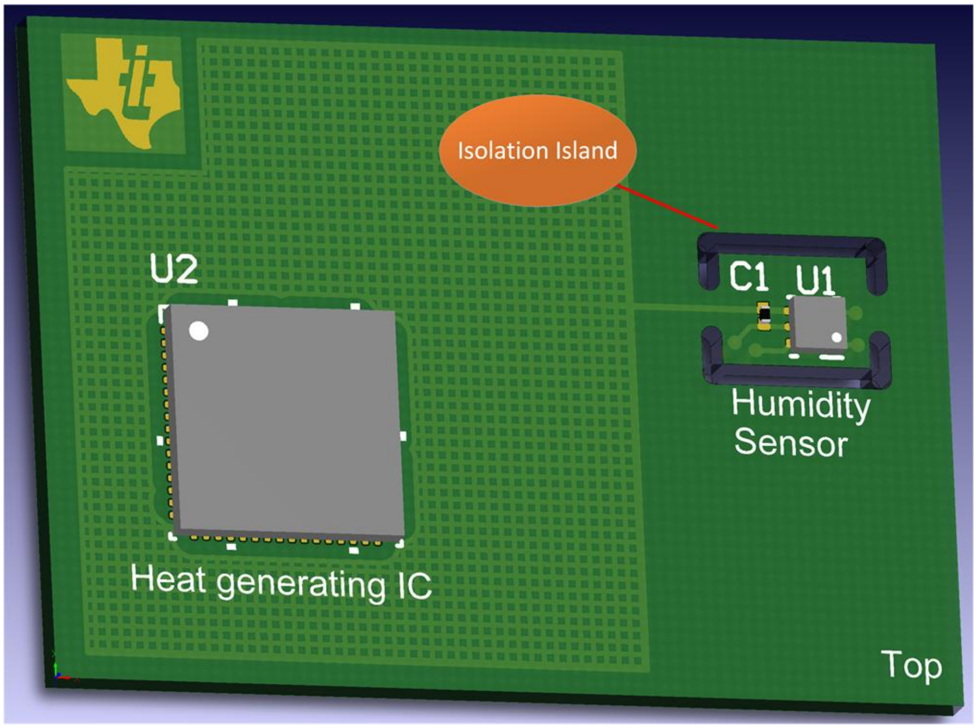

Figure 12. Isolation Island Significantly Reduces Heat Transfer From Main Heat Source To Humidity Sensor

2.3.4 Perforation

As an alternative to the isolation island discussed in Section 2.3.3, it is possible to add a perforation around the section with the humidity sensor, as shown in Figure 13. Doing so greatly minimizes the amount heat transfer through the FR4 material. An example of a perforated PCB is the TMP116 Evaluation module.

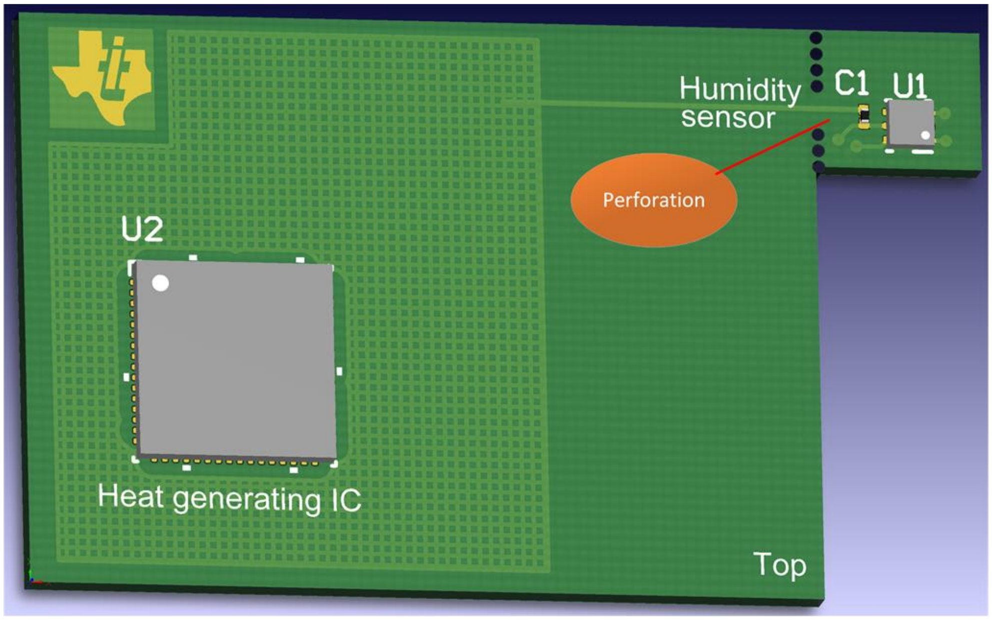

Figure 13. Perforation Reduces Heat Transfer From Heat Source To Sensor

2.3.5 Edge Connector

A miniature PCB that contains only the humidity sensor and is mounted using an edge connector to the main PCB is a highly effective method for avoiding significant heat transfer from the main PCB to the sensor. The edge connector should ideally be mounted at a location away from major heat sources on the main PCB so that radiated heat from ICs does not interfere with the temperature reading. This technique is illustrated in Figure 14

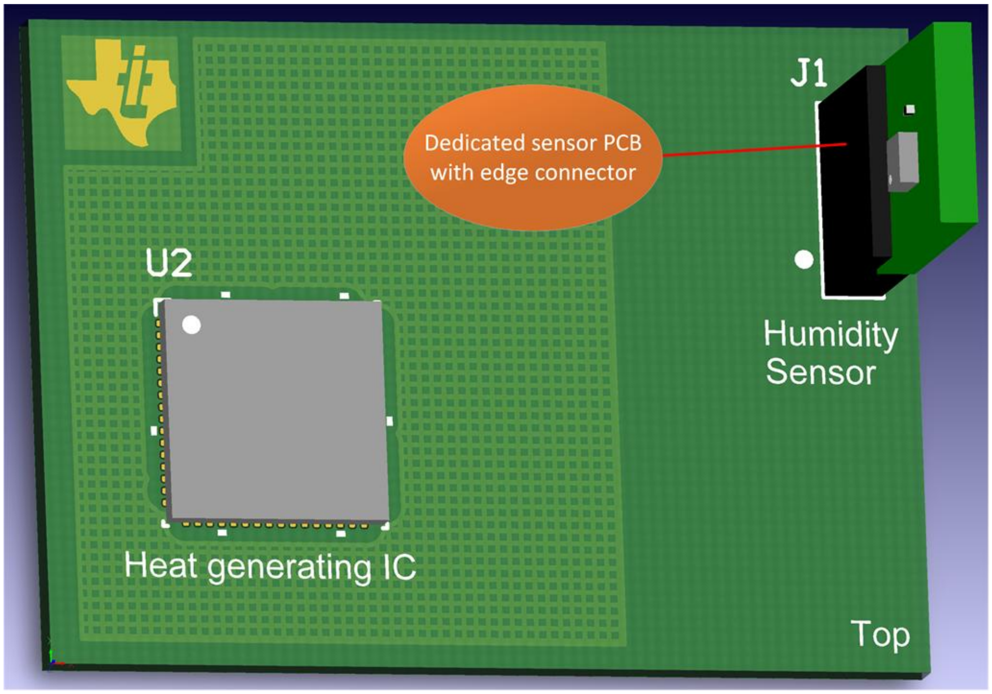

Figure 14. Dedicated Sensor PCB With Edge Connector

2.3.6 Controlling the Thermal Mass of the PCB

The thermal mass is a material's ability to store heat energy. A material with a high thermal mass will respond to temperature fluctuations more slowly than one with a lower thermal mass. To keep the thermal mass of the PCB as small as possible, it is advised to use a thin PCB (e.g. 0.8mm rather than the standard 1.6mm FR4 thickness), or even place the sensor on a flex PCB as shown in Figure 15. When combined with either one of the techniques for reducing PCB surface area (see Section 2.3.3 and Section 2.3.4), a thin PCB can correspond to changes in air temperature much more rapidly than a large, thick PCB with a high thermal mass.

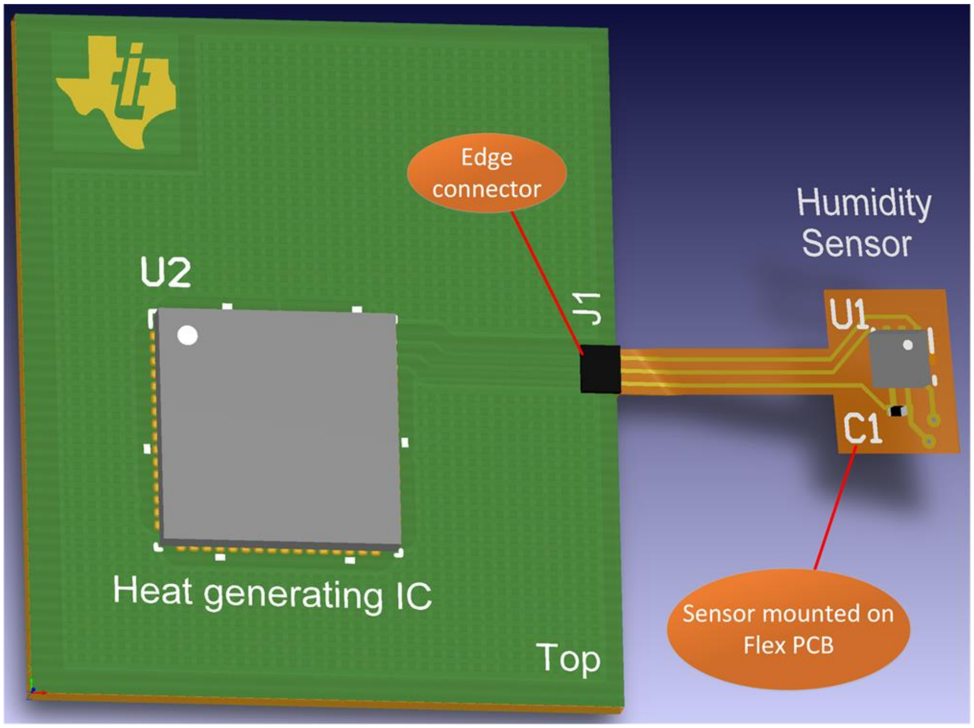

Figure 15. Dedicated Sensor Flex PCB with Edge Connector

2.4 Recommended PCB Layout

In addition to common PCB design rules and industrial practices, some additional layout and process guidelines should be applied for humidity sensor soldering:

- WSON package only: to reduce the thermal mass and minimize the heat conductance, the die attach pad (DAP) must be soldered to a floating pad on the board, but the board pad must NOT be connected to GND. The pad should not contain any vias..
- The area covered by the HDC must be defined as a “keep out" area. It is strongly recommended not to place any metal patterns (e.g., traces, pours) or vias underneath the HDC or place components on the opposite reverse side of the PCB.
- It is recommended to design a PCB land pattern as non-solder-mask defined (NSMD).
- It is strongly recommended not to place large insertion components (e.g., shields, buttons, cover insertions, screws) at a distance of less than 5mm from the sensor package.
- To obtain the best package self-alignment on the designed PCB footprint during solder reflow, care must be taken for symmetry on pad traces (e.g., use dummy traces even on pads not internally connected).
- Due to the low power consumption of the HDC, large traces on VDD or GND nets are not required. Thin traces are preferred to minimize heat transfer from the rest of the PCB to the HDC.
- A bypass capacitor must be placed as close to the IC as feasible. TI recommends a multilayer ceramic bypass X7R capacitor of 0.1µF between the VDD and GND pins.

Figure 16 and Figure 17 show layout examples for the WSON and DSBGA packages, respectively.

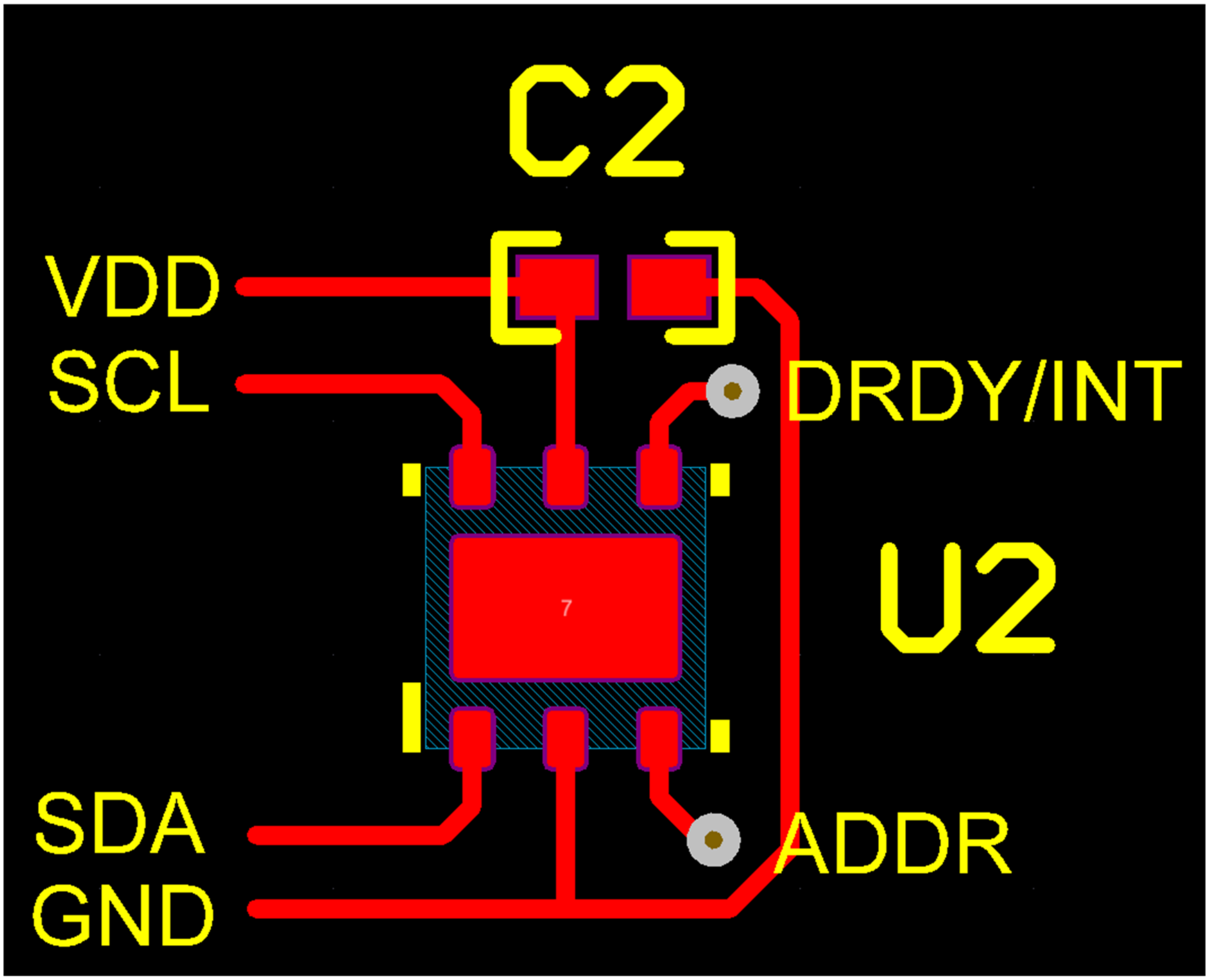

Figure 16. PCB Layout Example HDC1080 [WSON Package]

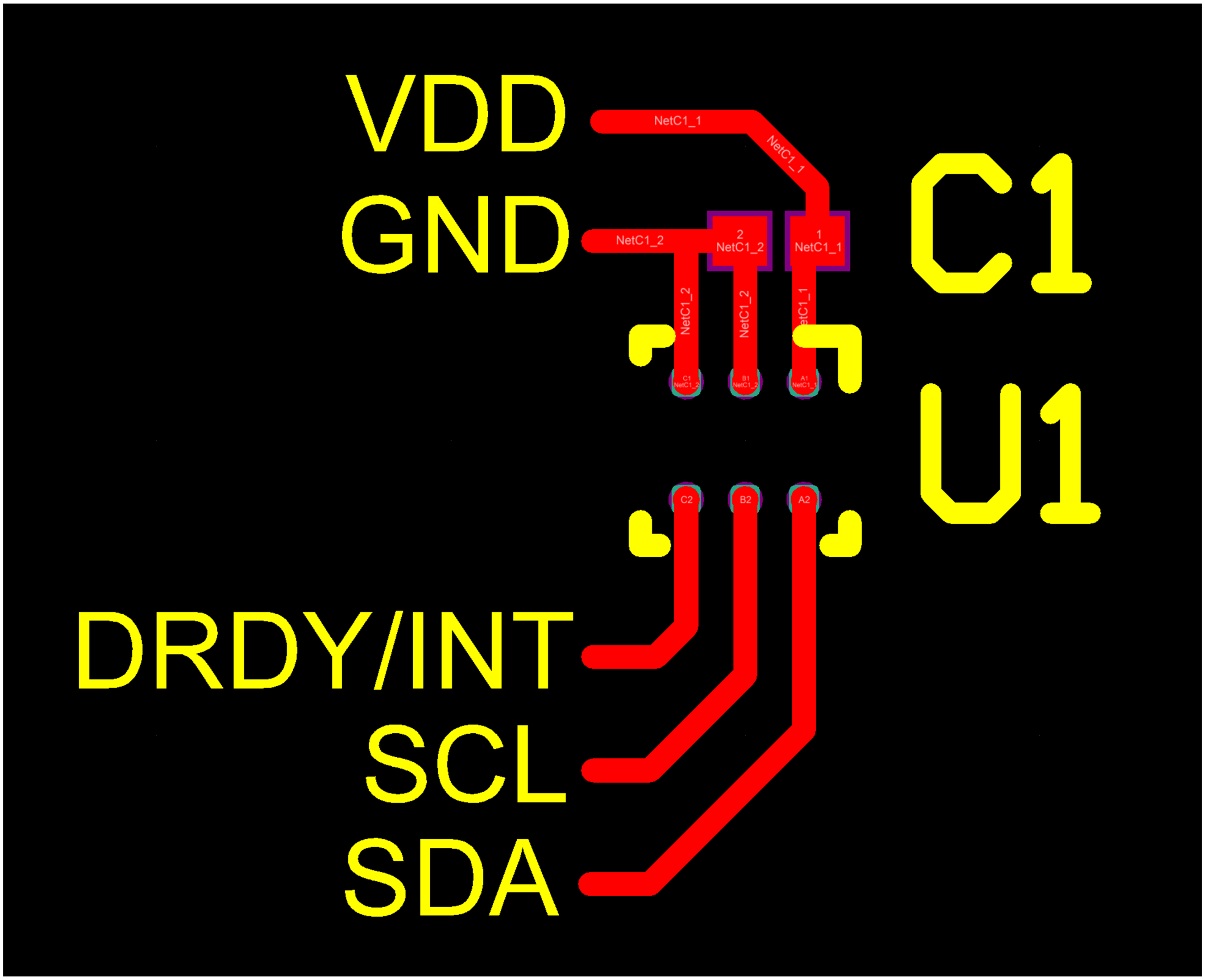

Figure 17. PCB Layout Example HDC1010, HDC2010 [DSBGA Package]

3 Appendix: Determining The Dominant Thermal Conduction Path Of Selected Package Types

Surface mount humidity sensors offer several advantages over sensors with through-hole packages. Advantages include a smaller package size with a low profile, convenient PCB placement, and ease of assembly. However, SMT sensors can be difficult to isolate because they have the tendency to measure the PCB temperature rather than ambient air temperature. Therefore, special layout techniques need to be employed if the objective of the sensor is to measure the ambient temperature rather than the PCB temperature. The HDC devices determine temperature by measuring their own die temperature. Therefore, it is important to understand the dominant temperature conduction paths between the die of the sensor and the object or environment whose temperature is to be determined.

Heat is conducted primarily through the following paths:

1. The Die-attach pad (DAP), if present, provides the most dominant thermal path between the PCB and the die
2. The leads provide the most significant thermal path if the package type does not include a DAP
3. The mold compound provides an additional thermal path, but due to its low thermal conductivity, any heat transfer through the mold compound itself is slower than heat transfer through the leads or DAP.

The package type choice determines how quickly the HDC can respond to changes in temperature. Figure 18 shows the relative thermal response rates of different classes of selected SMT package types that are used for temperature measurements.

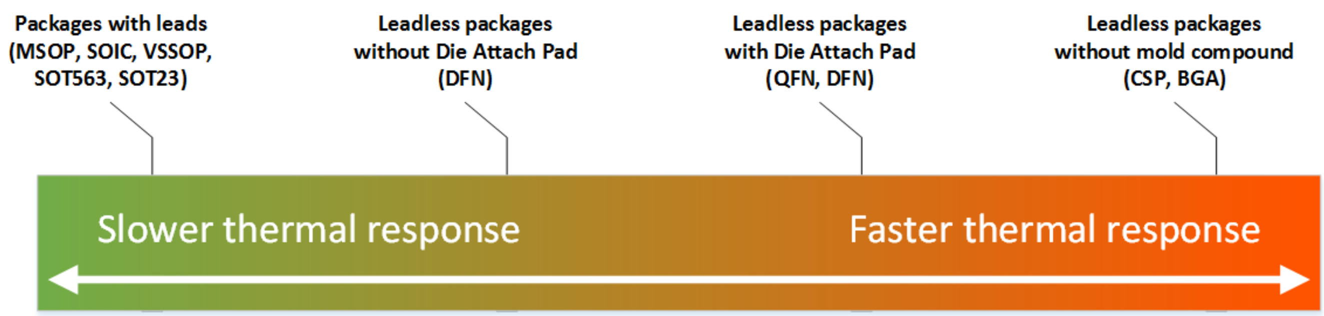

Figure 18. Relative Thermal Response Rate (Typical)

Sections Section 3.1 and Section 3.2show cross sections of SMT package types for Texas Instruments' humidity sensors.

3.1 Leadless Packages Without Mold Compound (WLCSP)

Wafer Level Chip Scale Package (WLCSP) leads are Ball Grid Array (BGA) balls processed directly onto the die. Heat from the BGA balls are directly transferred to the die instead of transferring over the pins or through a die attach pad, as shown in Figure 19. Generally, this is the package type with the fastest thermal response because there is no mold compound to heat up.

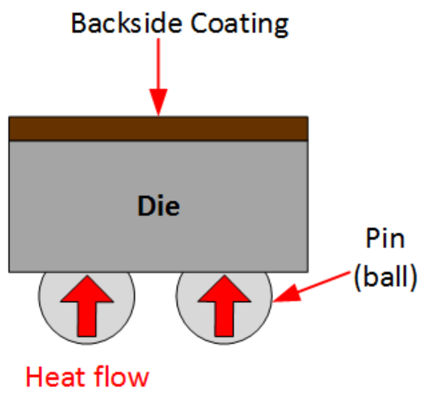

Figure 19. Heat Transfer WLCSP (HDC1010[YPA], HDC2010[YPA]) Package Cross Section

3.2 Leadless Packages With Die Attach Pad (DFN)

Packages with a DAP, such as DFN packages, have a large exposed surface area through which heat can transfer quickly. These package types will respond quickly to temperature changes of the copper plane which the DAP is soldered onto. Because the die sits directly on top of the thermal pad, heat can transfer rapidly from the thermal pad to the die.

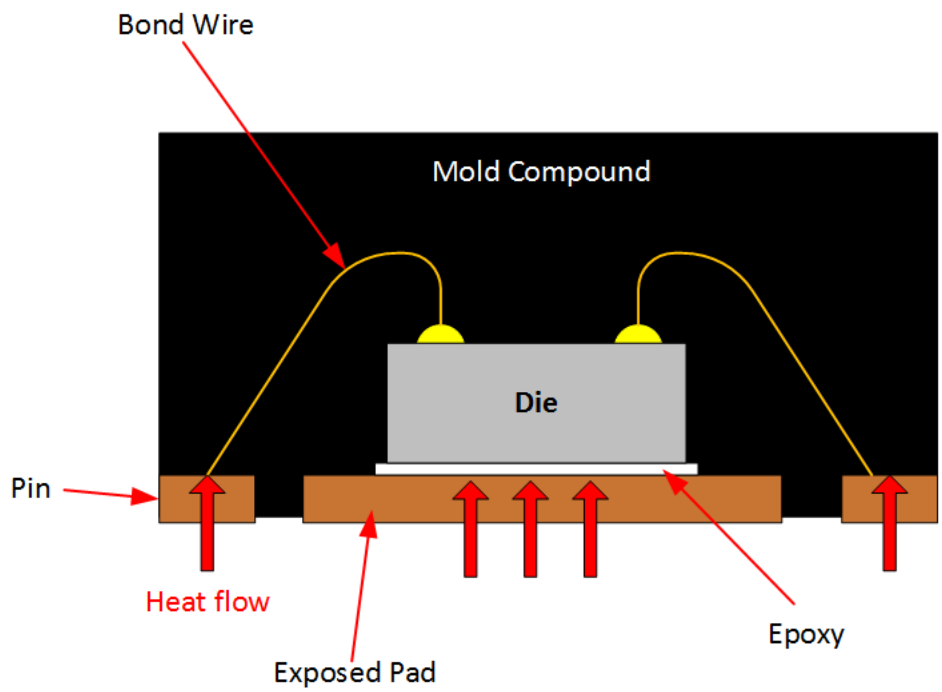

Figure 20. Heat Transfer WSON (HDC1080[DMB]) Package Cross Section

4 Appendix: Determining Thermal Conduction Through The PCB

Power hungry components can generate a significant amount of heat during operation, and a PCB designer needs to have an understanding of how heat is conducted by the PCB. The layout of the PCB affects the thermal conductivity and thus the temperature measurement. Understanding the total thermal resistance of the PCB will help the PCB designer to determine whether it is necessary to use filled or plated vias, use thicker copper plating or add additional copper layers to disperse heat quicker.

4.1 General Thermal Conduction Equation

Thermal resistance can be expressed by the following equation:

$$\theta = \frac{L}{k \times A_{CS}}$$

where

- θ is the thermal resistance [K/W]
- k is the thermal conductivity factor [W/(m*K)]
- L is the thermal path length [m]
- A_{CS} is the cross sectional area in which heat is applied [m^2] (5)

To calculate the thermal conduction through the PCB, the individual paths can be broken down and analyzed separately. The main components are the thermal conduction through the PCB (see Section 4.4 and Section 4.2), and the conduction through the via (see Section 4.5). The most common materials in many PCB applications are FR4, copper, and soldermask materials. By applying] Equation 5 to the perpendicular path for the appropriate PCB materials, the longitudinal path, and the thermal flow through the vias individually, thermal conduction through the PCB can be modeled accurately.

4.2 Longitudinal Thermal Conduction

Figure 21 shows the longitudinal conduction path of a PCB with the direction of the heat flow from the heat source along the FR4.

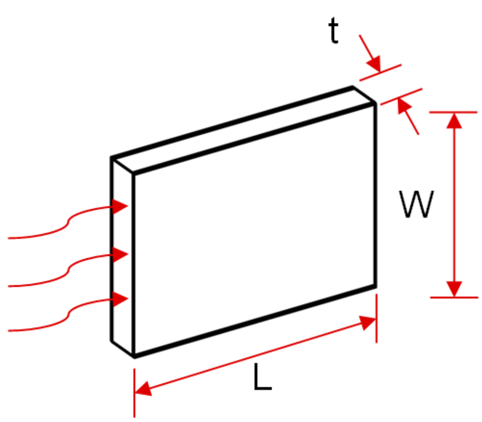

Figure 21. Longitudinal Conduction Heat Flow

Figure 21 applies the general thermal conduction equation to a cuboid.

$$\theta = \frac{L}{k \times A_{CS}} = \frac{L}{k \times W \times t}$$

where

- L is the path length of heat flow
- W is the width and t is the thickness
- W x t = A_{CS} is the cross sectional area where the heat is being applied
- L = W for square (6)

4.3 Example: Determining The Dominant Longitudinal Thermal Conduction Path

Applying Equation 6 to a 1.6mm thick layer of FR4 of square dimensions (1m × 1m) results in a thermal resistance of 2,500°C/W, as shown in Equation 7

$$\theta_{FR4} = \frac{L}{k \times W \times t} = \frac{1m}{0.25 \frac{W}{m \times °C} \times 1m \times 2 \times 1.6^{-3} m} = 2500°C / W \tag{7}$$

Two 1oz (35µm) copper planes of the same PCB would have the thermal resistance of 3,710°C/W, as calculated in Equation 8

$$\theta_{Cu} = \frac{L}{k \times W \times t} = \frac{1m}{385 \frac{W}{m \times °C} \times 1m \times 2 \times 35^{-6} m} = 3710°C / W \tag{8}$$

While thickness of the copper plane is significantly thinner than the thickness of the FR4 layer, the ability to transfer heat is in the same order of magnitude. This is because the thermal conductivity of copper is approximately 1,500 times larger than the thermal conductivity of FR4. It can be seen that the copper planes of the above example PCB transfer heat slightly slower than the significantly thicker FR4 layer.

In the longitudinal direction, several layers of the PCB need to be considered in parallel. Compared to a PCB without copper floods, it is possible to almost double the heat transfer rate along the plane by adding two 1oz layers of copper floods.

Because the different layers transfer heat in parallel, the effective total thermal resistance of the cross-section is 1,494°C/W, as calculated in Equation 9

$$\theta_{total} = \theta_{Cu} \,||\, \theta_{FR4} = \frac{\theta_{Cu} \times \theta_{FR4}}{\theta_{Cu} + \theta_{FR4}} = \frac{3710 \times 2500}{3710 + 2500} = 1494°C / W \tag{9}$$

4.4 Perpendicular Thermal Conduction

Figure 22 shows the perpendicular conduction heat flow of a PCB.

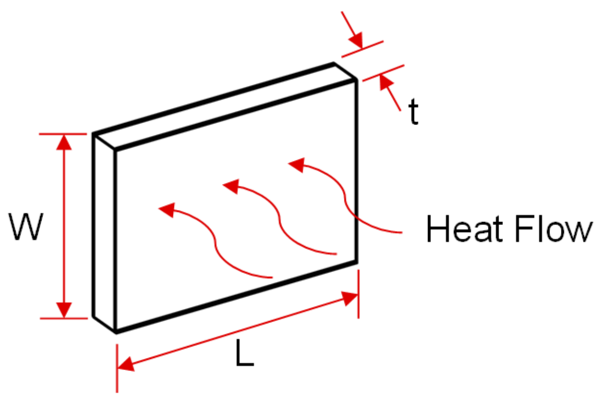

Figure 22. Perpendicular Conduction Heat Flow

Equation 10 is the perpendicular conduction heat flow equation to determine the thermal resistance of a material, as specified in Table 1.

$$\theta = \frac{t}{k \times A_{CS}} = \frac{t}{k \times W \times L}$$

where

- t is the path of heat flow (the heat flows through the thickness of the material) [m]
- W x L = A_{CS} is the cross sectional area where the heat is being applied [m^2] (10)

4.5 Thermal Conduction Through A Via

Calculating the thermal conduction path of a via (as shown in Figure 23) can be useful to determine if a regular via suffices, a larger size or quantity of vias is required, or if vias need to be filled with a conductive fill. A conductive fill transfers heat faster to the opposite side of the board, but also increases PCB manufacturing cost.

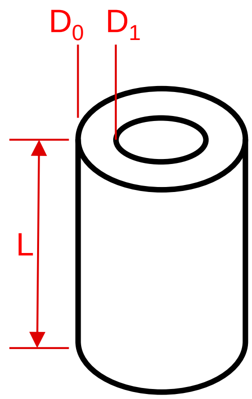

Figure 23. Conduction Through Via

Equation 11 applies the general thermal conduction equation to a via.

$$\theta = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left(\left(\frac{D_0}{2} \right)^2 - \left(\frac{D_1}{2} \right)^2 \right)}$$

where

- L is the length of the via (the heat flows through the length of the cylinder) [m]
- D_0 is the outer via diameter [m]
- D_1 is the inner via diameter [m] (11)

4.6 Example: Determining The Dominant Perpendicular Thermal Conduction Path

In the perpendicular direction, a PCB designer may want to compare the thermal resistance of a via with the equivalent thermal resistance of FR4 to determine if placing additional vias is a useful technique in transferring heat quickly from one side of the PCB to the other.

The sidewalls of a non-tented, non-filled via with a 0.5mm drill hole size, a sidewall copper thickness of 35µm, and a length of 1.6mm have the thermal resistance of 81℃/W, as shown in Equation 12. Note that the sidewall thickness of a via is often different from the copper plating thickness and depends on via dimensions and the manufacturing process of the PCB manufacturer.

$$\theta_{Cu} = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left(\left(\frac{D_0}{2} \right)^2 - \left(\frac{D_1}{2} \right)^2 \right)} = \frac{1.6^{-3}}{385 \frac{W}{m \times °C} \times \pi \times \left(\left(\frac{0.5^{-3}}{2} \right)^2 - \left(\frac{0.43^{-3}}{2} \right)^2 \right)} = 81°C / W \quad (12)$$

In order to obtain an accurate result, the thermal resistance of the air cylinder inside the via also needs to be calculated and considered in parallel with the thermal resistance of the via sidewalls.

$$\theta_{air} = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left(\left(\frac{D_0}{2} \right)^2 - \left(\frac{D_1}{2} \right)^2 \right)} = \frac{1.6^{-3}}{0.0275 \frac{W}{m \times °C} \times \pi \times \left(\left(\frac{0.3^{-3}}{2} \right)^2 - \left(\frac{0}{2} \right)^2 \right)} = 400646°C / W \quad (13)$$

Equation 13 shows that the thermal resistance of the air cylinder is greater than 400,000℃/W. Because it is approximately 5,000 times as large as the thermal resistance of the via sidewalls, the thermal conduction contribution of the air has a negligible effect and can be ignored, as is proven by Equation 14.

$$\theta_{via} = \theta_{Cu} \parallel \theta_{air} = \frac{\theta_{Cu} \times \theta_{air}}{\theta_{Cu} + \theta_{air}} = \frac{81 \times 400646}{81 + 400646} = 81°C / W \tag{14}$$

The air filled drill hole of a via does not contribute much to the heat transfer rate, so almost all of the heat transfer of a standard via occurs through its sidewalls. However, vias in which the hole is filled with a different material may benefit from the heat transfer contribution of that material. Some designs require vias to be filled in order to transfer heat even faster than a normal via. Filled vias should be considered if even multiple parallel standard vias do not provide a sufficiently fast heat transfer rate to meet system specifications.

The thermal resistance of 81℃/W for the non-filled via from this example can be compared to the thermal resistance of a solid FR4 cylinder of equal outer diameter to determine how much more effective a copper via is in transferring heat from one side of the PCB to the other. Equation 15 shows that the thermal resistance of an equivalently sized cylinder of FR4 is 32,595℃/W, which is approximately 400 times more resistive than the thermal resistance of the via.

$$\theta_{FR4} = \frac{L}{k \times A_{CS}} = \frac{L}{k \times \pi \times \left(\left(\frac{D_0}{2} \right)^2 - \left(\frac{D_1}{2} \right)^2 \right)} = \frac{1.6^{-3}}{0.25 \frac{W}{m \times °C} \times \pi \times \left(\left(\frac{0.5^{-3}}{2} \right)^2 - \left(\frac{0}{2} \right)^2 \right)} = 32595°C / W \tag{15}$$

An air filled drill hole contributes negligible thermal transfer. However, because the thermal conductivity of copper is approximately 1,500 higher than FR4, the via of above dimensions is able to transfer heat to the opposite side of the PCB through the via sidewalls approximately 400 times faster than an FR4 cylinder of the same outer diameter. Therefore, placing multiple parallel non-filled vias can be a very effective method to transfer heat quickly from one side of the PCB to the other within a localized area.

Revision History

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