Load Switch Thermal Considerations

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ABSTRACT

Nearly every integrated circuit has layout considerations to ensure optimal performance. For example, high speed data paths should be the same length to minimize skew and DC/DC converters should have minimal parasitics to prevent instability. For devices that can often carry large amounts of current, such as load switches, the PCB can act like a heat sink. Layout is critical for the board's ability to dissipate heat away from the device. This application report will cover:

- Why, Where, and How Power is Dissipated in a Load Switch
- Managing Power Dissipation in a Load Switch
- Designing a PCB for Optimal Power Dissipation

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1 Power Dissipation in a Load Switch

Load switches are commonly used to deliver large amounts of power to downstream loads. Being resistive in nature, they will always dissipate a fraction of that power as heat. This section will discuss why and how load switches dissipate power.

1.1 Calculating Load Switch Power Dissipation

Even when a switch is fully on, there is still some minimal resistance. This “ON Resistance”, comprised of the pass-FET element as well as pin and packaging resistances, typically accounts for most of the power dissipated in a load switch. The Power Dissipated (P_D) across this ON Resistance (R_{ON}) is a function of the Load Current (I_{LOAD}) and can be found using Equation 1:

$$P_D = I_{LOAD}^2 \times R_{ON} \quad (1)$$

Figure 1 illustrates how a larger load current will exponentially increase the amount of power dissipated in a load switch in relation to the ON Resistance (R_{ON}).

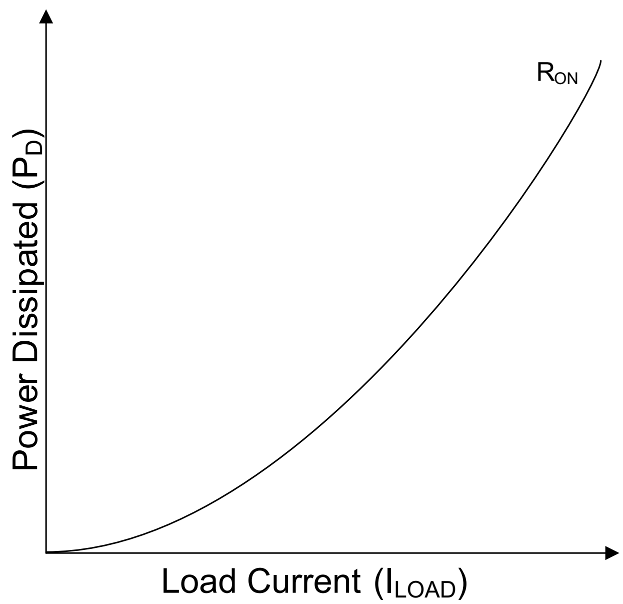


Figure 1. Power Dissipation in a Load Switch

1.2 Power is Dissipated as Heat

When power is dissipated in a load switch, it is transformed into heat energy which is then transferred from the silicon die (also known as the junction) to the device packaging, the printed circuit board, and into the air. Each of these materials will have a unique thermal resistance, which is a property that describes how a material will resist heat flow. The combined effectiveness of all materials to dissipate heat away from the junction is known as the Junction to Ambient Thermal Resistance or θ_{JA}.

As is the case with every integrated circuit, the junction inherently has a maximum temperature it can withstand without breaking down. This means the maximum power that can be dissipated in a load switch really becomes a question of how well heat can be transferred away from the junction. Equation 2 describes the total power ($P_{D,MAX}$) that can be dissipated in a load switch based upon the maximum operating Junction Temperature ($T_{J,MAX}$), the Ambient Air Temperature (T_A), and the Thermal Resistance from the junction to the ambient air (θ_{JA}).

$$P_{D,MAX} = \frac{T_{J,MAX} - T_A}{\theta_{JA}} \qquad (2)$$

Figure 2 shows the effect a larger thermal resistance has on the maximum allowable power dissipation in a load switch with a fixed ambient and maximum junction temperature. As thermal resistance increases, the maximum allowable power dissipation decereases.

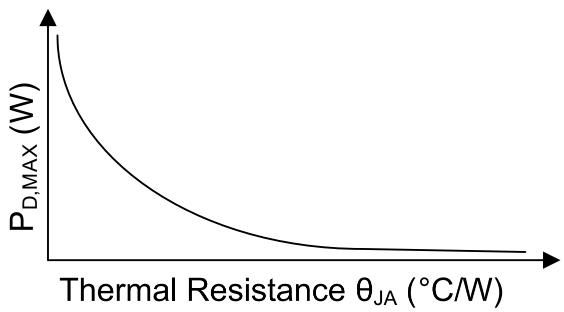


Figure 2. Effect of Thermal Resistance on Maximum Power Dissipation

2 Managing Load Switch Power Dissipation

When designing a load switch into a system, it is important to make sure the junction temperature does not exceed the device datasheet recommendations. This can be particularly challenging in situations where a large amount of power or heat is being dissipated inside the device. There are several methods that can be used to manage load switch power dissipation.

2.1 Use a Lower ON Resistance to Dissipate Less Power

The first method for managing power dissipation in a load switch is to simply dissipate less power. Going back to Equation 1, the power dissipated in a load switch is directly proportional to the ON Resistance. Figure 3 illustrates how a larger ON Resistance (R_{ON}) will increase the power dissipated for a given load current where $R_{ON,3} > R_{ON,2} > R_{ON,1}$.

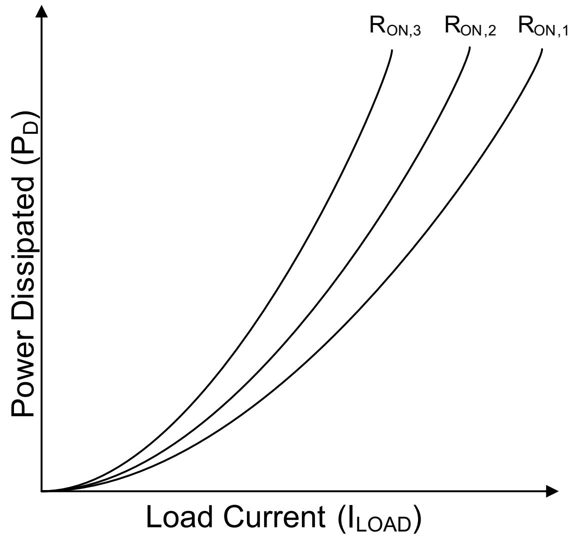


Figure 3. Effect of ON Resistance on Power Dissipation

This can be leveraged in situations with high ambient temperatures or where a large amount of current is passing through the load switch. In both cases, a lower ON Resistance will help ensure the device does not exceed the maximum junction temperature rating.

2.2 Select Packaging with Sufficient Thermal Resistance

Aside from reducing the amount of power that will be dissipated as heat inside the load switch, the next best option for managing load switch power dissipation is to lower the junction to ambient thermal resistance (θ_{JA}). This begins with the device packaging. There are several different types of packages available for load switches, and the thermal properties of the package type play a key role in how the device is able to dissipate heat.

While some of the heat is radiated from the package, the majority is dissipated through convection into the air or conduction to the PCB. For packages with a large area of direct contact with the PCB, conduction can drastically increase the amount of heat that can be transferred away from the load switch. For example, a Ball Grid Array (BGA) package only makes contact through solder balls so the heat transfer path from the package to the PCB is minimal whereas a package with an exposed thermal pad has a large thermally conductive surface through which heat can be transferred.

Selecting a device based upon the packaging thermal resistance will become even more important in applications where high power dissipation or high ambient temperature is present. In general, a larger package will allow more heat to be dissipated because there is more surface area; however, this is highly dependent upon the package material and the size of the silicon die.

2.3 Minimize the Thermal Resistance of the PCB

As mentioned in the previous section, for devices with a large area of direct contact with the PCB, heat conduction into the board can drastically reduce the overall thermal resistance. This is especially true for devices with an exposed thermal pad; however, due to the complexity of the Expanded Thermal Resistance Model for a Typical PCB it is difficult to exactly predict what the thermal resistance of the board will be without modeling software (see SNVA419 for more details). There are many factors that can affect the thermal resistance of a PCB including the board area, number and size of thermal vias, number of layers, copper thickness, breaks in the copper layers, and other heat sources that might be present.

Because PCB design can change drastically, a series of JEDEC standards were developed that specify the PCB size and layout. These board requirements are clearly defined, allowing for finding the overall junction to ambient thermal resistance (θ_{JA}) for packaged devices in a controlled way to provide a fair basis for comparison.

It is important to keep in mind that most boards will most likely have substantial differences compared to the JEDEC standardized board used to generate the thermal resistance values found in the device datasheet. In the next section, we will discuss some tips on how to optimize your PCB design for heat dissipation.

2.3.1 Optimizing PCB Design for Load Switch Power Dissipation

In order to design a PCB with low thermal resistance, it is important to understand how heat will travel from the silicon junction through the packaging into the PCB and finally to the air. Figure 4 shows a simplified model of heat flow for a device with an exposed thermal pad. They key thing to note here is that the direction of heat flow is normal to the bottom surface of the package.

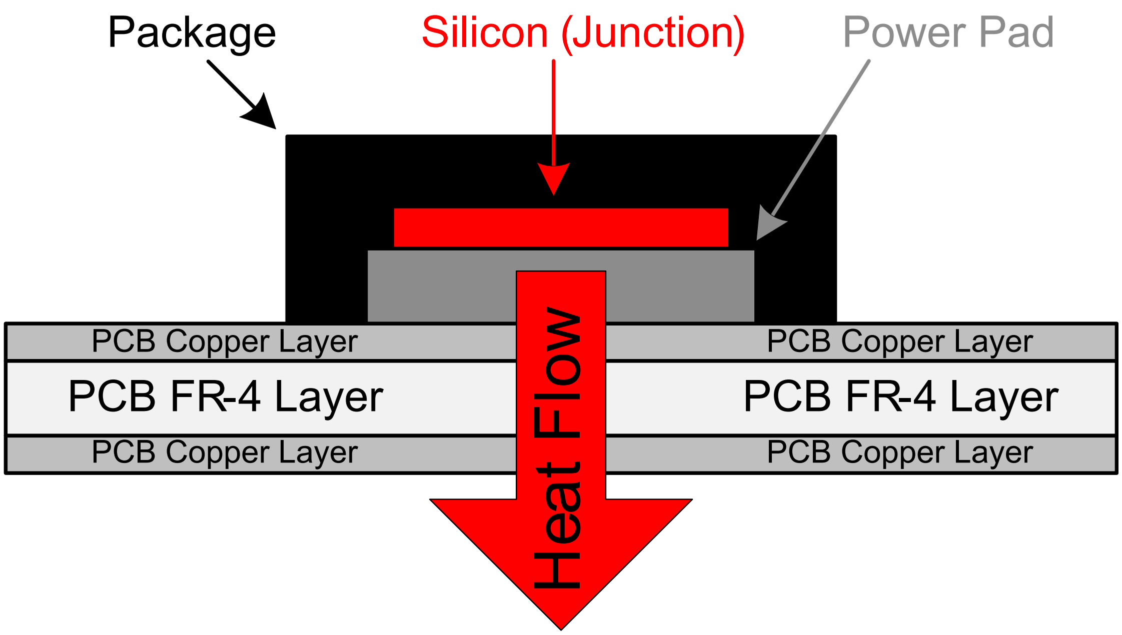


Figure 4. Simplified Model of Heat Flow for a Device with Exposed Thermal Pad

The most impactful characteristic of the PCB design is the cross-sectional area of heat flow. The cross-sectional area is linearly proportional to the PCBs ability to dissipate heat away from the device. This area is best illustrated by viewing the PCB from the bottom side as shown in Figure 5. The device position on the top side of the board is indicated with a dotted line, and the cross-sectional area with respect to direction of heat flow is colored red.

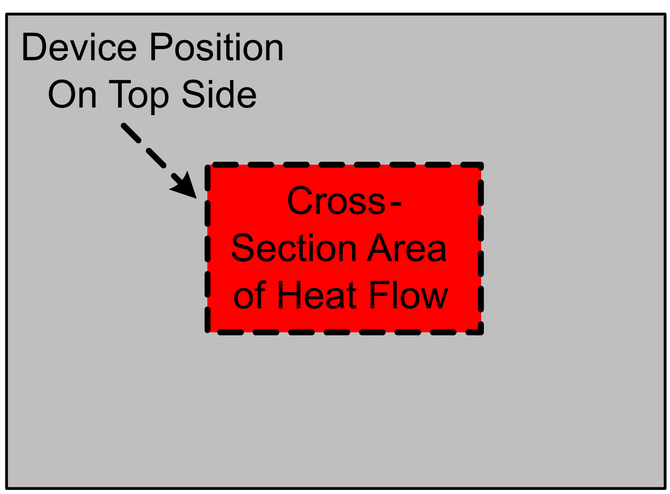


Figure 5. PCB Bottom View of Heat Flow Cross-Section Area

The next characteristic of PCB design that impacts the overall thermal resistance is the length in the direction of heat flow. The square root of the length is approximately proportional PCBs ability to dissipate heat away from the device. On a PCB, the length element would consist of the copper and FR-4 Layers as shown in Figure 6. Increasing the number of layers or the thickness of the layers will increase the overall length in the direction of heat flow and improve the board performance; however, this is generally limited by cost and manufacturing capabilities.

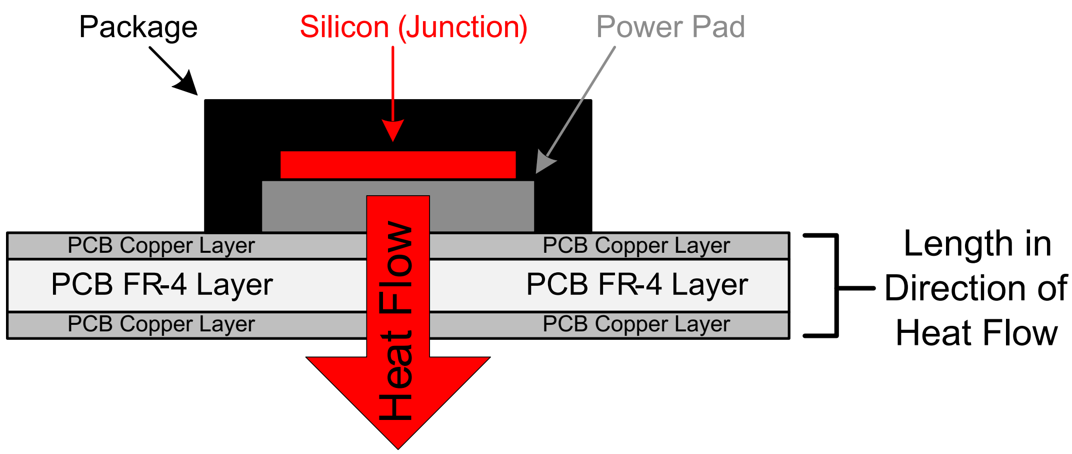


Figure 6. Simplified Model Showing the Length in Direction of Heat Flow

The next characteristic of the PCB that can be leveraged is the overall volume of the PCB. In general, a larger volume can dissipate more heat. This is often the easiest characteristic to improve because it includes the entire PCB. This could be from an increase in board area, number of copper layers, or the thickness of the copper layers. While these are also limited by manufacturing capabilities, the volumetric thermal resistance is directly related to the relative conductivity of the materials.

This leads to the fourth and final characteristic of a PCB that contributes to thermal performance which is the materials used to create the PCB. Within a certain volume, increasing the percentage of materials that conduct heat well will lower the average thermal resistance and allow the PCB to dissipate heat more effectively. Table 1 summarizes some common thermal resistance factors (R).

Table 1. Thermal Resistance Factors

Material	R (m°C/W)	R (in°C/W)
Copper	0.0028	0.11
Aluminum	0.0057	0.224
FR-4	4	157
Solder 63/67	0.026	1.02
Air	36.4	1430

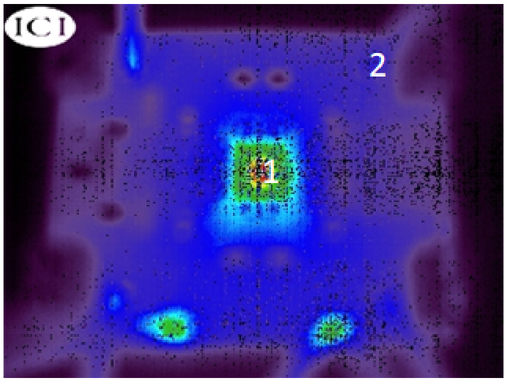
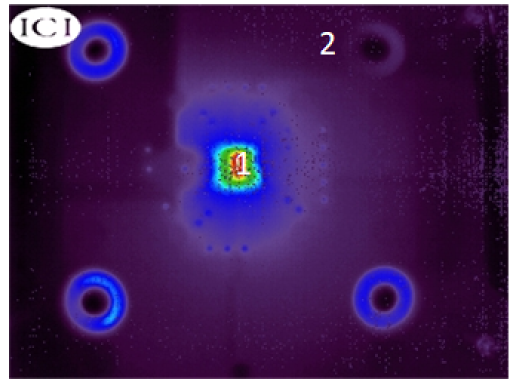
Since copper has a much lower thermal resistance than FR-4, increasing the percentage of copper in the heat flow path will lower the overall thermal resistance. Therefore it is a good idea to have a copper pad under the device for direct contact whenever possible, even if the packaging does not have an exposed thermal pad. Also, thermal vias should be added to the pad, and the combined area of the vias should be maximized.

2.3.2 Limited Effectiveness of Increasing the Board Area

The previous section discussed several different characteristics which can impact the thermal resistance of a PCB. It is important to understand there is some interdependency between these characteristics. This section will show how a particular method of improving the PCB thermal performance can be limited by other board characteristics. More specifically, how increasing the PCB area is limited by the cross-sectional area, the length, and the board materials.

Table 2 compares the thermal response of the TPS22976 both on the evaluation module (EVM) and a larger test board when 6A of current are passed through each of the two channels simultaneously. The same footprint and number of vias are used in both cases, and all measurements were taken at room temperature.

Table 2. TPS22976 PCB Thermal Comparison

	TPS22976EVM	TPS22976 Test Board
Supply Voltage	Vin = Von = Vbias = 5V	Vin = Von = Vbias = 5V
Inferred Image with 6A Through Each of the Two Channels		
Case Temp (Zone 1)	104°C	76°C
PCB Edge Temp (Zone 2)	47°C	24°C
PCB Area	2.25in. × 3.00in.	9.0in. × 9.0in.
Layers	2 Layers / 1oz Copper	8 Layers / 1oz Copper

Probably the first thing you notice is the difference in the case temperature between the two boards under the same conditions. This clearly demonstrates the impact of the PCB on the device operating temperature. Since the test board is much larger and has more layers, it can dissipate much more heat away from the device than the EVM.

Back to the main point of this section; take note of the Zone 2 temperature located near the edge of the PCBs. On the EVM, it is easy to distinguish the edge of the board because it has heated up to ~45°C. This means the entire area of the EVM board is being used to dissipate heat away from the TPS22976. The edges of the test board, on the other hand, are still at room temp ~26°C. This means only the center area of the board is actually being used to dissipate heat. This demonstrates the limited effectiveness of increasing only the board area. If more layers were added to the test board or if the copper thickness were increased, this would allow a larger area of the board to dissipate heat.

3 Example Power Dissipation Calculations

As mentioned previously, due to the fact that load switches are resistive in nature, they will always dissipate a fraction of power as heat. To determine the power dissipated in the TPS22976, there are a few calculations that can be followed, as shown below.

3.1 Calculating Power Dissipation for a Dual Channel Load Switch

Finding the power dissipated in a dual channel load switch is very similar to the method for finding the power dissipated in a single channel load switch as presented in Section 1.1. Basically, the total power dissipated in the device is the sum of power dissipated in each of the two channels as shown in Equation 3:

$$P_D = I_{LOAD,\ CH1}^2 \times R_{ON,CH1} + I_{LOAD,CH2}^2 \times R_{ON,CH2} \tag{3}$$

Based upon the datasheet typical characteristics graphs showing R_{ON} vs. Temperature, we can expect the ON Resistance for both channels to be approximately 15 mΩ. This can be used to find the total power dissipated in the device:

$$P_D = 6A^2 \times 15\ m\Omega + 6A^2 \times 15\ m\Omega = 1.08\ \text{Watts}$$

3.2 Converting Measured Case Temperature to Junction Temperature

The final step is to convert the case temperature found using the inferred camera to a junction temperature. Equation 4 can be used to perform this conversion using the Ψ_{JT} parameter from the device datasheet and the power dissipated found in the previous section:

$$T_{Junction} = T_{Case} + \left(\Psi_{JT} \times P_D\right) \tag{4}$$

$$T_{Junction} = 104^\circ C + \left(1.6^\circ C / W \times 1.08\ W\right)$$

$$T_{Junction} = 105.73^\circ C$$

4 References

1. *AN-2020 Thermal Design By Insight, Not Hindsight* (SNVA419)
2. *Understanding Thermal Dissipation and Design of a Heatsink* (SLVA462)
3. *Semiconductor and IC Package Thermal Metrics* application report (SPRA953)
4. *Using Thermal Calculation Tools for Analog Components* (SLUA566)
5. *Thermal Considerations for Surface Mount Layouts* (Charles Mauney, Texas Instruments)

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