

## Introduction

As IC process geometries shrink and FPGA densities increase, managing power becomes increasingly difficult. The dilemma for design groups is how to fit in all the functions the market demands without exceeding power budgets. Although power has been a third- or fourth-order concern for most FPGA designs, it is now an important concern for designs at 90 nm and below. The more power a device consumes, the more heat it generates. This heat must be dissipated to maintain an optimal operating temperature.

The design of Altera® device packages minimizes thermal resistance and maximizes power dissipation. However, some applications dissipate more power and require external thermal solutions, including heat sinks. This application note provides guidance on managing thermal performance.

## Heat Dissipation

Radiation, conduction, and convection are three ways to dissipate heat from a device. PCB designs use heat sinks to improve heat dissipation. The thermal energy transfer efficiency of heat sinks is due to the small thermal resistance between the heat sink and the air.

Thermal resistance is the measure of a substance's ability to dissipate heat, or the efficiency of heat transference across the boundary between different media. A heat sink with a large surface area and good air circulation gives the best heat dissipation.

A heat sink helps keep a device at a temperature below its specified recommended operating temperature. With a heat sink, heat from a device flows from the junction to the case, then from the case to the heat sink, and lastly from the heat sink to ambient air. The goal is to reduce thermal resistance. To determine whether a device requires a heat sink for thermal management, you can calculate its thermal resistance by using thermal circuit models and equations. These thermal circuit models are similar to resistor circuits, which follow Ohm's law.

Figure 1 shows a thermal circuit model for a device with and without a heat sink, reflecting the thermal transfer path via the top of the package.

Figure 1. Thermal Circuit Model

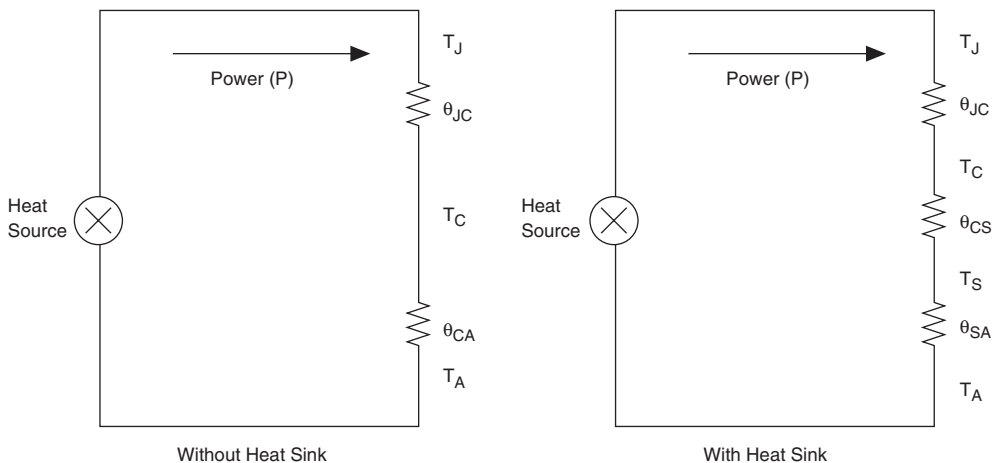


Table 1 defines thermal circuit parameters. The thermal resistance of a device depends on the sum of the thermal resistances from the thermal circuit model shown in Figure 1.

Parameter	Name	Units	Description
$\theta_{JA}$	Junction-to-ambient thermal resistance	$^{\circ}\text{C}/\text{W}$	Specified in the data sheet
$\theta_{JC}$	Junction-to-case thermal resistance	$^{\circ}\text{C}/\text{W}$	Specified in the data sheet
$\theta_{CS}$	Case-to-heat sink thermal resistance	$^{\circ}\text{C}/\text{W}$	Thermal interface material thermal resistance
$\theta_{CA}$	Case-to-ambient thermal resistance	$^{\circ}\text{C}/\text{W}$	
$\theta_{SA}$	Heat-sink-to-ambient thermal resistance	$^{\circ}\text{C}/\text{W}$	Specified by the heat sink manufacturer
$T_J$	Junction temperature	$^{\circ}\text{C}$	The junction temperature as specified under Recommended Operating Conditions for the device

Parameter	Name	Units	Description
T <sub>JMAX</sub>	Maximum junction temperature	°C	The maximum junction temperature as specified under Recommended Operating Conditions for the device
T <sub>A</sub>	Ambient temperature	°C	Temperature of the local ambient air near the component
T <sub>S</sub>	Heat sink temperature	°C	
T <sub>C</sub>	Device case temperature	°C	
P	Power	W	The total power from the operating device. Use the estimated value for selecting a heat sink

Table 2 shows the thermal resistance equations for a device with and without a heat sink.

Device	Equation
Without a heat sink	$\theta_{JA} = \theta_{JC} + \theta_{CA} = (T_J - T_A) / P$
With a heat sink	$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA} = (T_J - T_A) / P$

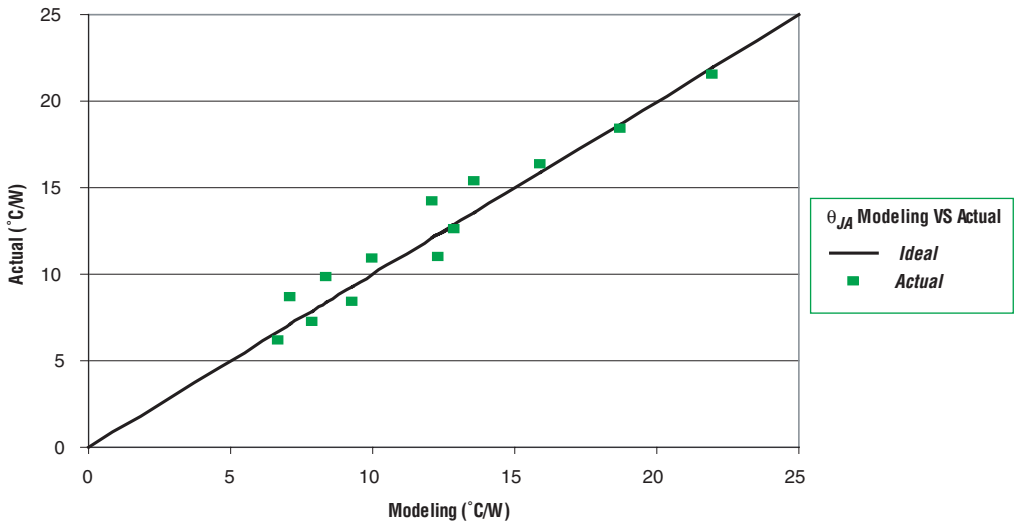
## Thermal Resistances

Finite element models were used to predict thermal resistance of packaged devices. The following list briefly describes the models:

- Three dimensional
- Model one quarter of the package due to symmetry
- Apply uniform heat flux to the active surface of die
- Use volume-averaged thermal conductivity for composite materials
- Assign heat transfer coefficients for exposed external surfaces using the empirical equations

The values produced by the modeling closely match the thermal resistance values, which are available on the Altera web site ([www.altera.com](http://www.altera.com)). Figure 2 shows the correlation of the modeling to the actual measurements. The average difference is less than 10%, which conforms to the JEDEC JESD51-X series Standards ([www.JEDEC.org](http://www.JEDEC.org)).

**Figure 2. Model Predictions Versus Actual Measurements**

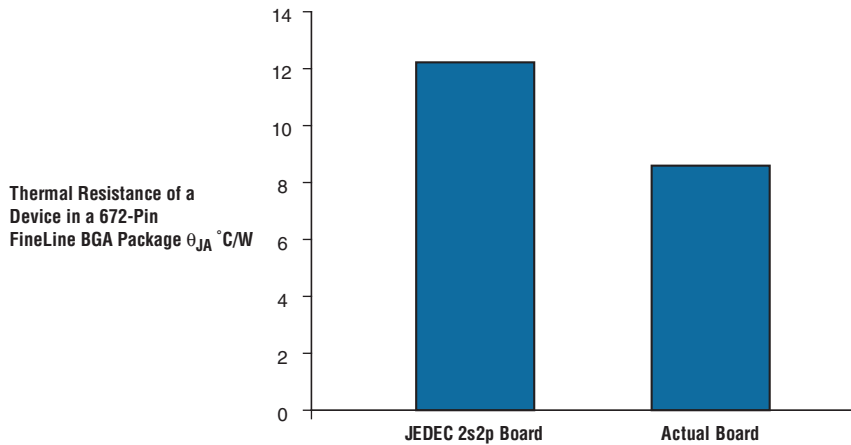


## Printed Circuit Board Considerations

Your application conditions (for example, board size and construction) will likely differ from the JEDEC specifications. Therefore, Altera recommends a customized evaluation of thermal resistances based on the actual conditions in thermally challenged situations. [Table 3](#) shows an example of a board in an actual application, with different characteristics than the JEDEC 2s2p test board specified in standard JESD51-9.

Dimensions (mm)	200 × 200 × 1.6
Number of layers	10
Layer thickness and copper (Cu) coverage	25 μm and 50%

[Figure 3](#) shows that board differences have a great effect on thermal resistance. Using the JEDEC 2s2P board, the EP2S15 device in a 672-pin FineLine BGA® package has a  $\theta_{JA}$  of 12.2 °C/W in still air. With the example board described in [Table 3](#),  $\theta_{JA}$  is 8.6 °C/W in still air. The larger board size and the increased layer count contribute to the smaller  $\theta_{JA}$ .

**Figure 3. Effect of Board Difference on Thermal Resistance**

## Determining Heat Sink Usage

To determine the necessity of a heat sink, calculate the junction temperature using the following equation:

$$T_J = T_A + P \times \theta_{JA}$$

If the calculated junction temperature ( $T_J$ ) is more than the specified maximum allowable junction temperature ( $T_{Jmax}$ ), a heat sink is required.

Select a heat sink using the following two equations:

$$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA} = (T_J - T_A) / P$$

$$\theta_{SA} = (T_{Jmax} - T_A) / P - \theta_{JC} - \theta_{CS}$$

Table 1 on page 2 defines the terms used in these equations.

## Example of Determining the Necessity of a Heat Sink

The following procedure provides a method you can use to determine the necessity of using a heat sink. Table 4 lists the operational conditions.

<b>Parameter</b>	<b>Value</b>
Power	20 W
Maximum $T_A$	50 °C
Maximum $T_J$	85 °C
Air flow rate	400 feet per minute
$\theta_{JA}$ under 400 feet per minute air flow	4.7 °C/W
$\theta_{JC}$	0.13 °C/W

- Using the junction temperature equation on page 5, calculate the junction temperature under the listed operational conditions:

$$T_J = T_A + P \times \theta_{JA} = 50 + 20 \times 4.7 = 144 \text{ °C}$$

The junction temperature of 144 °C is higher than the specified maximum junction temperature of 85 °C, so a heat sink is required.

- Using the heat-sink-to-ambient equation on page 5, and using a  $\theta_{CS}$  of 0.1 °C/W (this is the rating for thermal resistance as stated in the data sheet of the chosen thermal interface material), calculate the required heat-sink-to-ambient thermal resistance:

$$\theta_{SA} = (T_{Jmax} - T_A) / P - \theta_{JC} - \theta_{CS} = (85 - 50) / 20 - 0.13 - 0.1 = 1.52 \text{ °C/W}$$

- Select a heat sink that meets the thermal resistance requirement of 1.52 °C/W. The heat sink must also physically fit your application.

To select a heat sink, Altera reviewed heat sinks from several suppliers. A heat sink from Alpha Novatech (Z40-12.7B) is used in this example.

The thermal resistance of Z40-12.7B at air flow of 400 feet per minute is 1.35 °C/W. Therefore, this heat sink will work because the thermal requirement is less than the required 1.52 °C/W.

Using this heat sink:

$$T_J = T_A + P \times \theta_{JA} = T_A + P \times (\theta_{JC} + \theta_{CS} + \theta_{SA}) = 50 + 20 \times (0.13 + 0.1 + 1.35) = 81.6 \text{ }^\circ\text{C}$$

81.6 °C is less than the specified maximum junction temperature of 85 °C.

## Heat Sink Evaluations

The accuracy of heat sink thermal resistances provided by heat sink suppliers is critical in selecting an appropriate heat sink. Both finite element models and actual measurements verify that the supplier's data are accurate.

### Finite Element Models

The finite element models represent applications where a package contains a heat sink.

Altera tested thermal resistances on two heat sinks from Alpha Novatech using four Altera devices. Table 5 shows that the thermal resistances predicted by the models and the thermal resistances calculated from the supplier's datasheets are a close match.

Heat Sink	Package	$\theta_{JA}$ From Modeling (°C/W)	$\theta_{JA}$ From Datasheet (°C/W)
Z35-12.7B	Device in a 1,020-pin FineLine BGA package	2.6	2.2
Z35-12.7B	Device in a 1,020-pin FineLine BGA package	2.3	2.1
Z40-6.3B	Device in a 1,020-pin BGA package	3.3	3.0
Z40-6.3B	Device in a 1,020-pin BGA package	3.0	2.8

### Measurements

Thermal resistance is measured according to the JEDEC Standard JESD51-6. Altera measured the thermal resistances of the following heat sinks from Alpha Novatech: UB35-25B, UB35-20B, Z35-12.7B, and Z40-6.3B. Detailed information on these heat sinks is available at the Alpha Novatech website ([www.alphanovatech.com](http://www.alphanovatech.com)). These heat sinks

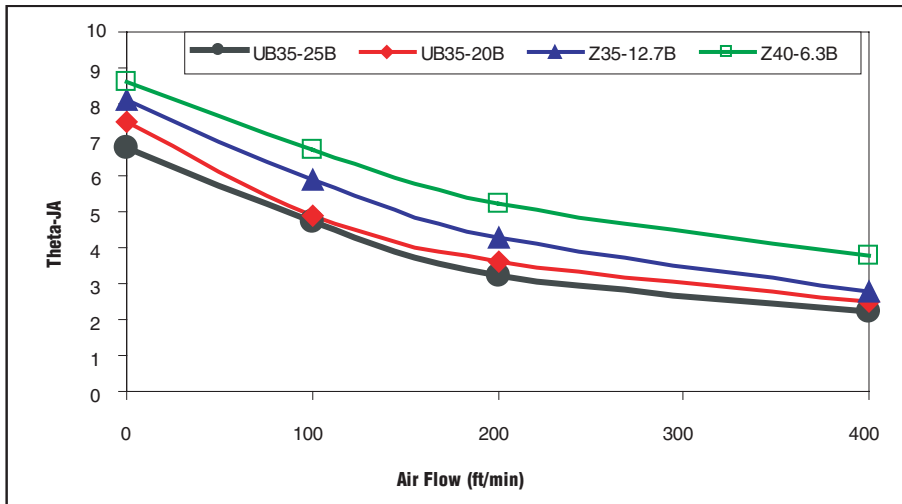
contain pre-attached thermal tape (Chomerics T412). An evaluation of thermal interface material is presented in [“Thermal Interface Material” on page 9](#).

Four Altera devices were used to measure the heat sinks shown in [Table 6](#). [Table 6](#) shows a good correlation between the obtained measurements and the thermal resistances obtained from the supplier's datasheets.

Heat Sink	Actual $\theta_{JA}$ ( $^{\circ}\text{C}/\text{W}$ )	Datasheet $\theta_{JA}$ ( $^{\circ}\text{C}/\text{W}$ )
UB35-25B	2.2	2.2
UB35-20B	2.5	2.4
Z35-12.7B	2.8	2.6
Z40-6.3B	3.8	3.4

The following graph shows the effect of airflow rate on  $\theta_{JA}$ .

**Figure 4. Effect of Airflow Rate on  $\theta_{JA}$**



# Thermal Interface Material

Thermal interface material (TIM) is the medium used to attach a heat sink onto a package surface. It functions to provide a minimum thermal resistance path from the package to the heat sink. The following sections describe the major categories of TIM.

## Grease

The grease used to bond heat sinks to packages is a silicone or hydrocarbon oil that contains various fillers. Grease is the oldest class of materials and the most widely used material used to attach heat sinks.

<i>Table 7. Greases</i>	
Pros	Cons
Low thermal resistance (0.2 to 1 C cm <sup>2</sup> /W).	Messy and difficult to apply because of their high viscosity.
	Require mechanical clamping (applying pressure in the 300 kPa range).
	In applications with repeated power on/off cycles, “pump-out” occurs, in which the grease is forced from between the silicon die and the heat sink each time the die is heated up and cooled down. This causes degradation in thermal performance over time and potentially contaminates neighboring components.

## Gel

Gels are a recently developed TIM. Gels are dispensed like grease and are then cured to a partially cross-linked structure, which eliminates the pump-out issue.

<i>Table 8. Gels</i>	
Pros	Cons
Low thermal resistance (0.4 to 0.8 C cm <sup>2</sup> /W).	Require mechanical clamping.

## Thermally Conductive Adhesives

Thermally conductive adhesives are usually epoxy or silicone based formulations containing fillers, and they offer a superior mechanical bond.

<i>Table 9. Thermally Conductive Adhesives</i>	
Pros	Cons
Low thermal resistance (0.15 to 1 C cm <sup>2</sup> /W).	Not reworkable.
No need for mechanical clamping.	

## Thermal Tapes

Thermal tapes are filled pressure sensitive adhesives (PSAs) coated on a support matrix such as polyimide film, fiberglass mat, or aluminum foil.

<i>Table 10. Thermal Tapes</i>	
Pros	Cons
Simple assembly.	High thermal resistance (1 to 4 C cm <sup>2</sup> /W).
No need for mechanical clamping.	Generally not suitable for packages that don't have flat surfaces.

## Elastomeric Pads

Elastomeric pads are polymerized silicone rubbers in the form of easy-to-handle solids. With a typical thickness of 0.25 mm, most pads incorporate a woven fiberglass carrier to improve handling and contain inorganic fillers as the greases do. They are supplied as die-cut preforms in the precise shape needed for the application.

<i>Table 11. Elastomeric Pads</i>	
Pros	Cons
Simple assembly.	Require mechanical clamping.
	Needs high pressures (~700 kPa) to achieve an adequate interface.
	High thermal resistance (1 to 3 C cm <sup>2</sup> /W).

## Phase Change Materials

Phase change materials are low temperature thermoplastic adhesives, predominantly waxes, that typically melt in the 50 to 80 °C range. When operating above the melting point they are not effective as an adhesive and need mechanical support, so they are always used with a clamp applying about 300 kPa of pressure.

<i>Table 12. Phase Change Materials</i>	
Pros	Cons
Thermal resistance (0.3 to 0.7 C cm <sup>2</sup> /W).	Require mechanical clamping (applying pressure in the 300 kPa range).
	Rework difficult.

## Heat Sink Vendors

The following is a list of heat sink vendors:

- Alpha Novatech ([www.alphanovatech.com](http://www.alphanovatech.com))
- Malico Inc. ([www.malico.com.tw](http://www.malico.com.tw))
- Aavid Thermalloy ([www.aavidthermalloy.com](http://www.aavidthermalloy.com))
- Wakefield Thermal Solutions ([www.wakefield.com](http://www.wakefield.com))
- Radian Heatsinks ([www.radianheatsinks.com](http://www.radianheatsinks.com))
- Cool Innovations ([www.coolinnovations.com](http://www.coolinnovations.com))
- Heat Technology, Inc. ([www.heattechnology.com](http://www.heattechnology.com))

## Thermal Interface Material Vendors

The following is a list of interface material vendors:

- Shin-Etsu MicroSi ([www.microsi.com](http://www.microsi.com))
- Lord Corporation ([www.lord.com](http://www.lord.com))
- Thermagon Inc. ([www.thermagon.com](http://www.thermagon.com))
- Chomerics ([www.chomerics.com](http://www.chomerics.com))
- The Bergquist Company ([www.bergquistcompany.com](http://www.bergquistcompany.com))

## Conclusion

90-nm devices are designed to minimize thermal resistance and to maximize power distribution, however, your application may require an external thermal solution, such as a heat sink. This application note provides the information you need to determine the thermal requirements for your application. The factors you must consider include evaluating the characteristics of the printed circuit board being used, determining the need for a heat sink, determining which heat sink to use, and selecting an appropriate thermal interface material.

## Document Revision History


Table 13 shows the revision history for this document.

<b>Date and Document Version</b>	<b>Changes Made</b>	<b>Summary of Changes</b>
February 2007, v1.1	<ul style="list-style-type: none"> <li>• Updated “Introduction”, “Thermal Resistances”, and “Heat Sink Evaluations” sections.</li> <li>• Added revision history.</li> </ul>	
September 2004, v1.0	Initial Release	



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