

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.

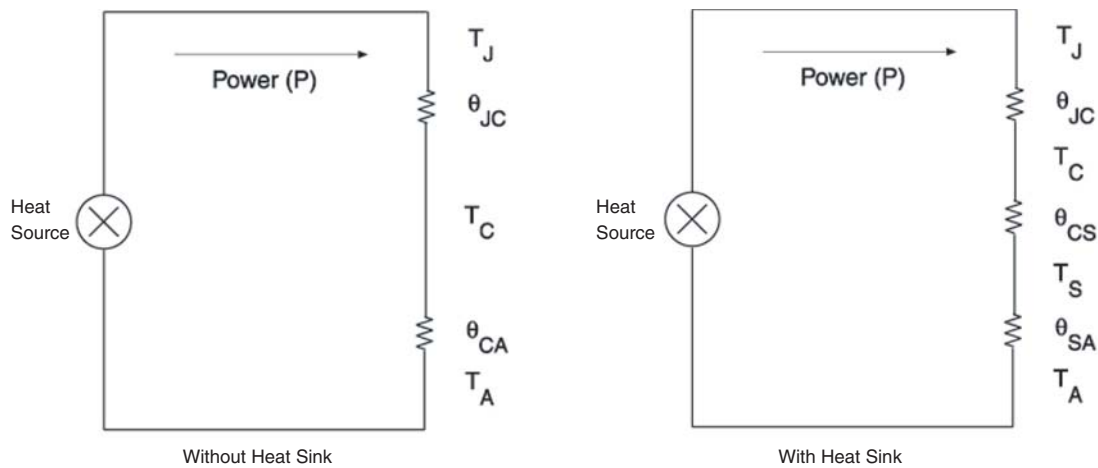
Figure 1. Thermal Circuit Model

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**.

Table 1. Thermal Circuit Parameters (Part 1 of 2)

Parameter	Name	Units	Description
θ_{JA}	Junction-to-ambient thermal resistance	$^{\circ}\text{C}/\text{W}$	Specified in the data sheet
θ_{JC}	Junction-to-case thermal resistance	$^{\circ}\text{C}/\text{W}$	Specified in the data sheet
θ_{CS}	Case-to-heat sink thermal resistance	$^{\circ}\text{C}/\text{W}$	Thermal interface material thermal resistance
θ_{CA}	Case-to-ambient thermal resistance	$^{\circ}\text{C}/\text{W}$	
θ_{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
T_{JMAX}	Maximum junction temperature	$^{\circ}\text{C}$	The maximum junction temperature as specified under Recommended Operating Conditions for the device
T_A	Ambient temperature	$^{\circ}\text{C}$	Temperature of the local ambient air near the component
T_S	Heat sink temperature	$^{\circ}\text{C}$	

Table 1. Thermal Circuit Parameters (Part 2 of 2)

Parameter	Name	Units	Description
T_C	Device case temperature	$^{\circ}\text{C}$	
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.

Table 2. Device Thermal Equations

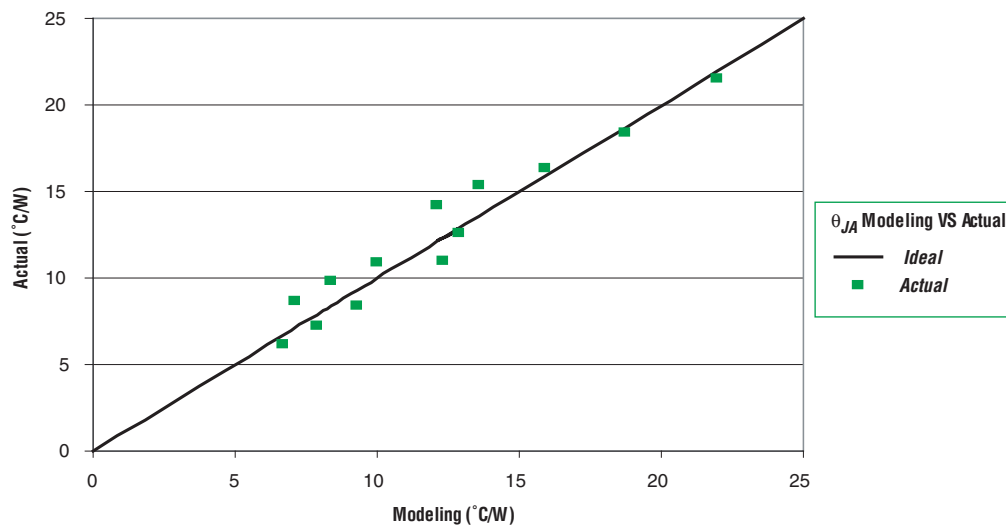
Device	Equation
Without a heat sink	$\theta_{JA} = \theta_{JC} + \theta_{CA} = (T_J - T_A) / P$
With a heat sink	$\theta_{JA} = \theta_{JC} + \theta_{CS} + \theta_{SA} = (T_J - T_A) / P$

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 website (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).

Figure 2. Model Predictions Versus Actual Measurements

Printed Circuit Board Considerations

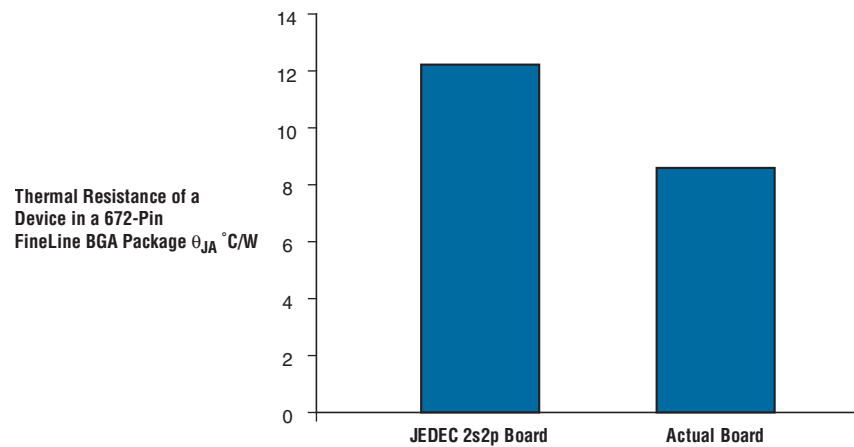
Your application conditions (for example, board size and construction) will likely differ from the JEDEC specifications. Therefore, Altera recommends a customized evaluation of thermal resistances based on the actual conditions in thermally challenged situations. Table 3 shows an example of a board in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

Table 3. Board Parameters in an Actual Application

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 θ_{JA} of 12.2 $^{\circ}\text{C}/\text{W}$ in still air. With the example board described in Table 3, θ_{JA} is 8.6 $^{\circ}\text{C}/\text{W}$ in still air. The larger board size and the increased layer count contribute to the smaller θ_{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.

Table 4. Operational Conditions

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

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

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

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 θ_{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:

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

- 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 data sheets are a close match.

Table 5. θ_{JA} at 400 Feet per Minute Air Flow (Part 1 of 2)

Heat Sink	Package	θ_{JA} From Modeling (°C/W)	θ_{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

Table 5. θ_{JA} at 400 Feet per Minute Air Flow (Part 2 of 2)

Heat Sink	Package	θ_{JA} From Modeling (°C/W)	θ_{JA} From Datasheet (°C/W)
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

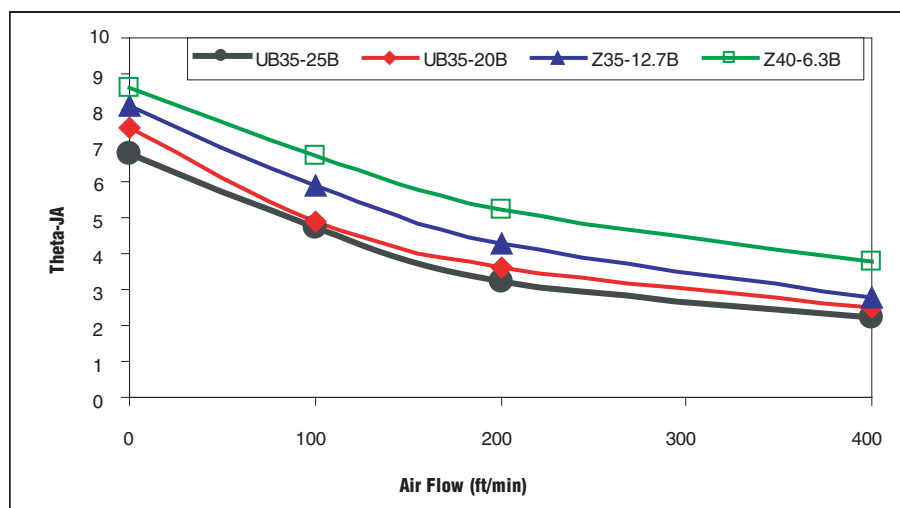
Thermal resistance is measured according to the JEDEC Standard JESD51-6. Altera measured the thermal resistances of the following heat sinks from Alpha Novatech: UB35-25B, UB35-20B, Z35-12.7B, and Z40-6.3B. Detailed information about these heat sinks is available at the Alpha Novatech website (www.alphanovatech.com). These heat sinks contain pre-attached thermal tape (Chomerics T412). An evaluation of thermal interface material is presented in “[Thermal Interface Material](#)” on page 8.

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

Table 6. θ_{JA} at 400 Feet per Minute Air Flow

Heat Sink	Actual θ_{JA} (°C/W)	Datasheet θ_{JA} (°C/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

[Figure 4](#) shows the effect of airflow rate on θ_{JA} .

Figure 4. Effect of Airflow Rate on θ_{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. [Table 7](#) lists the pros and cons of using greases.

Table 7. Greases

Pros	Cons
Low thermal resistance (0.2 to 1 C cm ² /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.

Gels

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. [Table 8](#) lists the pros and cons of using gels.

Table 8. Gels

Pros	Cons
Low thermal resistance (0.4 to 0.8 C cm ² /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. [Table 9](#) lists the pros and cons of using thermally conductive adhesives.

Table 9. Thermally Conductive Adhesives

Pros	Cons
Low thermal resistance (0.15 to 1 C cm ² /W).	Not reworkable.
No need for mechanical clamping.	

Thermal Tape

Thermal tape is filled pressure sensitive adhesives (PSAs) coated on a support matrix such as polyimide film, fiberglass mat, or aluminum foil. [Table 10](#) lists the pros and cons of using thermal tape.

Table 10. Thermal Tape

Pros	Cons
Simple assembly.	High thermal resistance (1 to 4 C cm ² /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. [Table 11](#) lists the pros and cons of using elastomeric pads.

Table 11. Elastomeric Pads

Pros	Cons
Simple assembly.	Require mechanical clamping.
	Need high pressures (~700 kPa) to achieve an adequate interface.
	High thermal resistance (1 to 3 C cm ² /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. [Table 12](#) lists the pros and cons of using phase change materials.

Table 12. Phase Change Materials

Pros	Cons
Thermal resistance (0.3 to 0.7 C cm ² /W).	Require mechanical clamping (applying pressure in the 300 kPa range).
	Rework difficult.

Heat Sink Attachments

There are three basic types of heat sink attachments:

- Mechanical attachment
- Thermal epoxy
- Thermal tape
 - Mechanical attachment offers superior mechanical reliability as well as the ability to use a thermal interface material such as grease or phase change material, enabling significantly lower thermal impedance.
 - Thermal epoxy is considered a permanent attachment method, as it creates a very reliable and secure bond, but one that is difficult to rework. Although it's possible to remove/rework a heat sink that has been attached with epoxy, there is risk of damage to the device.
 - Thermal tape is relatively inexpensive and easier to rework than epoxy. However, tape offers a less reliable and weaker heat sink attachment (unless it is used in conjunction with mechanical attachment), especially when working with larger heat sinks. Attachment strength is always a concern with tape-only solutions.

Recommended Heat Sink Attachment Methods

Mechanical attachment is strongly recommended for attaching heat sinks to Altera FPGAs. The use of thermally conductive tape or epoxy is no longer an effective option due to the small contact area. This is especially true for Altera lidless packages.

Mechanical attachment offers the following advantages:

- Higher performance thermal interface materials such as grease or phase change material can be used.
- Rework is easier.

Common mechanical attachment methods include Push Pin, Z-Clip, and Clip-On.

Examples of Mechanical Attachments

The following figures show examples of mechanical attachment methods.

[Figure 5](#) shows an example of the Push Pin attachment method.

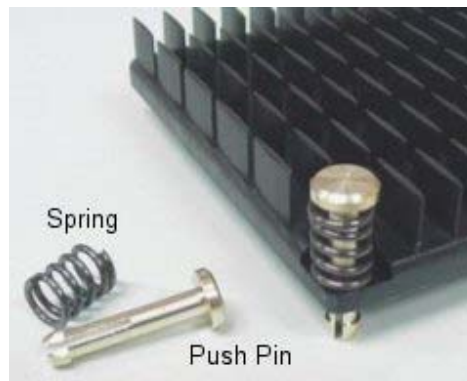
Figure 5. Push Pin Attachment

Figure 6 shows an example of the Z-Clip attachment method.

Figure 6. Z-Clip Attachment

Figure 7 shows an example of the Clip-On attachment method.

Figure 7. Clip-On Attachment

For lidless package application, vendors use compressible foam pads to prevent die chipping.

How to Avoid Heat Sink Contact with Chip Capacitors on the Substrate

The heat sink should include a means to prevent the heat sink from forming an electrical short with the capacitors placed on the top side of the package:

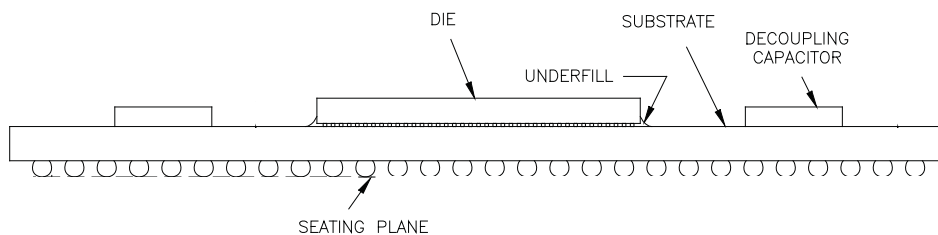
- One preferred method is to use small compressible foam pads on the heat sink. These pads prevent the heat sink from rocking or tilting on the die. They not only prevent the heat sink from tipping and contacting the capacitors, they also cushion the heat sink during installation, preventing the heat sink from possibly chipping or cracking the corner of the die. These pads should be positioned to make contact with the chip substrate in an area free of surface mount components.
- Heat sinks are often anodized, which is a non-conductive surface. In some cases, customers request a bare finish or an electrically conductive finish for EMI/grounding reasons. In these cases, the use of the pads or an insulator is crucial.
- Heat sinks with rails or Z-stops machined into the base of the heat sink to make contact with the chip substrate. The rails minimize tipping and ensure that the heat sink contacts the substrate instead of the capacitors.
- Other methods that are suitable include using electrically insulated gasket material at the base of the heat sink. Another method is to use an insulator sheet on the base of the heat sink, with a center cutout to allow contact with the die.

It is strongly advised to work with your heat sink suppliers and follow their instructions for accommodating holes or slots on the PCB for heat sink attachment. Refer to [“Heat Sink Vendors”](#) on page 13 for a list of heat sink vendors.

Package Cross-Sectional View (Lidless Package)

When designing heat sink attachments for a lidless package, you must consider the height of the die above the substrate and also the height of Decoupling Capacitors (in some devices). [Figure 8](#) is a cross-sectional view of the lidless package. For detailed package information, refer to the [Altera Device Package Information Data Sheet](#).

Figure 8. Cross-Sectional View of Lidless Package



Package Loading Specifications

Table 13 provides static load specifications for the lidless package. This mechanical maximum load limit should not be exceeded during heat sink assembly, shipping conditions, or standard use conditions. Any mechanical system or component testing should not exceed the maximum limit.

The package substrate should not be used as a mechanical reference or load-bearing surface for the thermal and mechanical solution. The post-reflow package height should be utilized for heat sink clip preload calculation.

Table 13. Package Loading Specifications

Parameter	Maximum	Notes
Static	700 Kpa	(1), (2), (3)

Notes to Table 13:

- (1) These specifications apply to uniform compressive loading in a direction normal to the package.
- (2) Maximum allowed load from the heat sink retention clip. Minimum load must also be achieved to ensure adequate force from the heat sink to the package for heat transfer.
- (3) This information is based on limited testing for design characterization. Loading Limits are for the package only.

Heat Sink Vendors

The following is a list of heat sink vendors:

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

Thermal Interface Material Vendors

The following is a list of interface material vendors:

- Shin-Etsu MicroSi (www.microsi.com)
- Lord Corporation (www.lord.com)
- Laird Technologies (www.lairdtech.com)
- Chomerics (www.chomerics.com)
- The Bergquist Company (www.bergquistcompany.com)

Conclusion

90-nm and below 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.

Table 14 shows the revision history for this document.

Document Revision History

Table 14. Document Revision History

Date	Version	Changes Made
December 2009	v2.0	<ul style="list-style-type: none"> ■ Converted to 8-1/2 x 11 page format. ■ Added “Heat Sink Attachments”, “Recommended Heat Sink Attachment Methods”, “Examples of Mechanical Attachments”, “How to Avoid Heat Sink Contact with Chip Capacitors on the Substrate”, “Package Cross-Sectional View (Lidless Package)”, and “Package Loading Specifications”.
February 2007	v1.1	Updated “Introduction”, “Thermal Resistances”, and “Heat Sink Evaluations”. Added revision history.
September 2004	v1.0	Initial Release



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