Thermal Management for FPGAs

AN-358-4.0 Application Note

This application note provides guidance on thermal management of Altera® devices and helps you determine the thermal performance for your application. The factors you must consider in evaluating heat dissipation include evaluating the characteristics of the PCB used, determining the use for a heat sink, and selecting the type of thermal interface material (TIM).

This application note includes the following sections:

- "Thermal Management Overview"
- "PCB Considerations" on page 4
- "Determining Heat Sink Usage" on page 5
- "Thermal Interface Material" on page 8
- "Heat Sink Attachments" on page 10
- "Relevant Information" on page 14
- "Vendors List" on page 14

Thermal Management Overview

As IC process geometries shrink and FPGA densities increase, managing power becomes increasingly difficult. A 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 because the more power a device consumes, the more heat it generates. To maintain an optimal operating temperature, you must dissipate the heat.

Altera device packages are designed to minimize thermal resistance and maximize power dissipation. However, some applications dissipate more power and require external thermal solutions, including heat sinks.

Heat Dissipation

There are three ways to dissipate heat from a device—radiation, conduction, and convection. 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 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.

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A heat sink keeps a device at a temperature below the 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 or not a device requires a heat sink for thermal management, you can calculate their thermal resistance with 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 through the top of the package.

Figure 1. Thermal Circuit Model

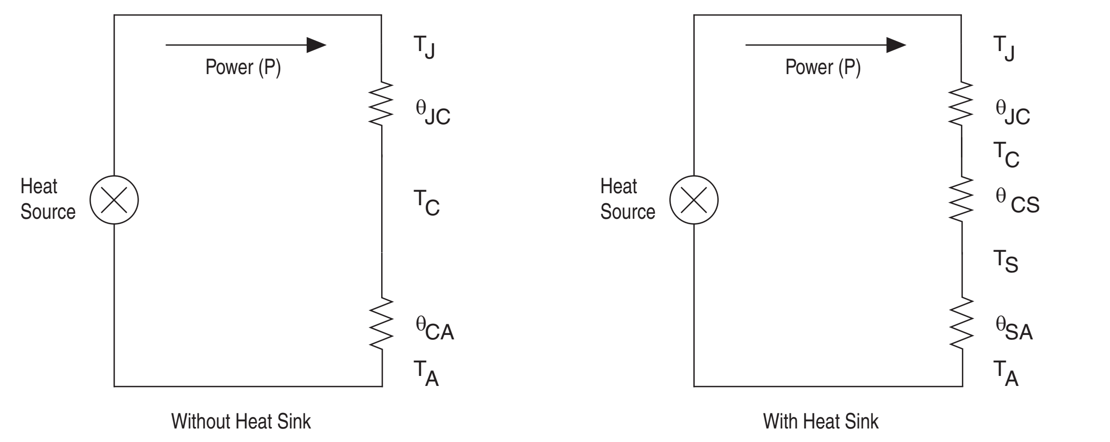


Table 1 lists the thermal circuit parameters. The thermal resistance of a device depends on the sum of thermal resistances from the thermal circuit model shown in Figure 1.

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

Parameter	Name	Unit	Description
θ_{JA}	Junction-to-ambient thermal resistance	°C/W	Specified in the datasheet
θ_{JC}	Junction-to-case thermal resistance	°C/W	Specified in the datasheet
θ_{CS}	Case-to-heat sink thermal resistance	°C/W	TIM thermal resistance
θ_{CA}	Case-to-ambient thermal resistance	°C/W	—
θ_{SA}	Heat sink-to-ambient thermal resistance	°C/W	Specified by the heat sink manufacturer
T_J	Junction temperature	°C	The junction temperature as specified in the “Recommended Operating Conditions” section in the respective device datasheet.
T_{JMAX}	Maximum junction temperature	°C	The junction temperature as specified in “Recommended Operating Conditions” section in the respective device datasheet.
T_A	Ambient temperature	°C	Temperature of the local ambient air near the component
T_S	Heat sink temperature	°C	—

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

Parameter	Name	Unit	Description
T_C	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 lists 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

You can use finite element models to calculate the thermal resistance for a device package or obtain the thermal resistance through actual measurement.

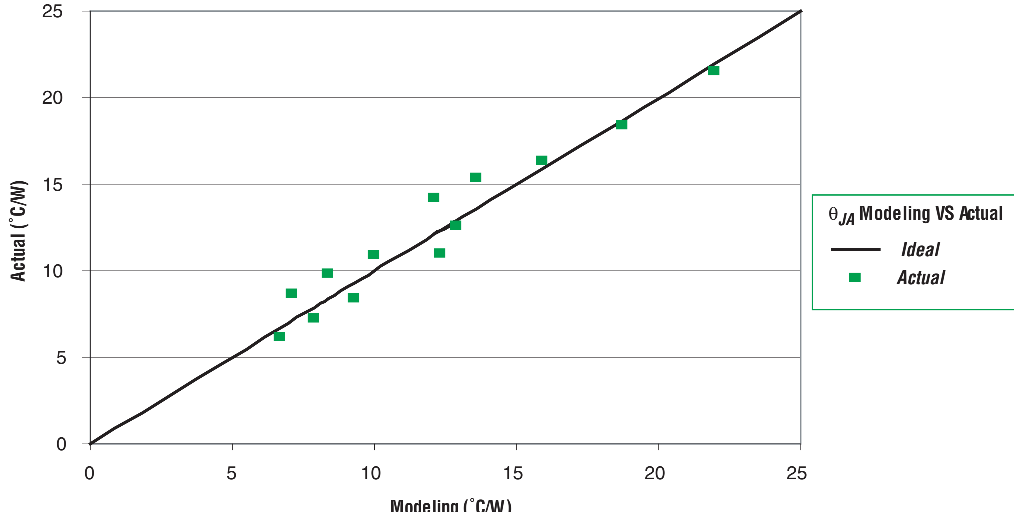
The following list briefly describes the finite element models:

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

The values produced by the models closely match the thermal resistance values measured, which are available on the Altera website.

Figure 2 shows the correlation of the models 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



PCB Considerations

Your application conditions (for example, board size and construction) are likely to differ from the JEDEC specifications; therefore, Altera recommends a customized evaluation of thermal resistances based on the actual conditions in thermally-challenged situations.

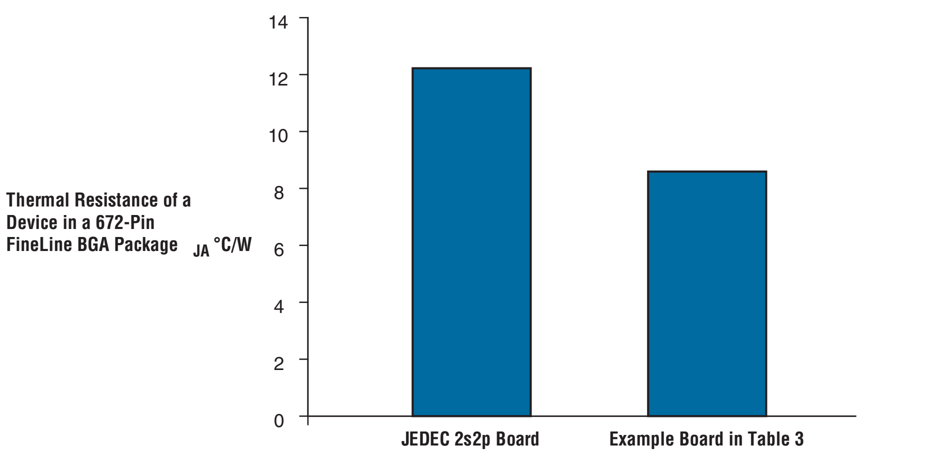
Table 3 lists an example board in an actual application with different characteristics than the JEDEC 2s2p test board specified in standard JESD51-9.

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 (FBGA) package has a θ_{JA} value of 12.2 °C/W in still air. With the example board listed in Table 3, the θ_{JA} value is 8.6 °C/W in still air. The larger board size and the increased layer count contribute to the smaller θ_{JA} value.

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 with the following equation:

Equation 1. Junction Temperature Calculation

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

You require a heat sink if the calculated junction temperature (T_J) is more than the specified maximum allowable junction temperature (T_{JMAX}). You can select an appropriate heat sink for your application with the following equations:

Equation 2. Junction-to-Ambient Thermal Resistance Calculation

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

Equation 3. Heat Sink-to-Ambient Thermal Resistance Calculation

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

For the terms used in these equations, refer to Table 1 on page 2.

The following example provides a method you can use to determine the necessity of using a heat sink and selecting the appropriate heat sink.

Table 4 lists the operational conditions in this example.

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

1. Using the junction temperature equation shown in Equation 1, calculate the junction temperature listed in Table 4:

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

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

2. Using the heat sink-to-ambient thermal resistance equation shown in Equation 3, and with a case-to-heat sink thermal resistance (θ_{CS}) of 0.1 °C/W (this is the rating for thermal resistance as stated in the datasheet of the chosen TIM), calculate the maximum heat sink-to-ambient thermal resistance with the following equation:

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

3. Select a heat sink that meets the thermal resistance requirement of 1.52 °C/W. The heat sink must also physically fit in 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 the Z40-12.7B heat sink at an air flow of 400 feet per minute is 1.35 °C/W. Therefore, you can use the Z40-12.7B heat sink because the thermal requirement is less than the required 1.52 °C/W.

Using the Z40-12.7B 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 °C, which is less than the specified maximum junction temperature of 85 °C.

Heat Sink Evaluation

The accuracy of the heat sink thermal resistance provided by heat sink suppliers is critical in selecting an appropriate heat sink. Both the finite element models and actual measurements verify that the data provided by the suppliers 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 with four Altera devices.

Table 5 shows that the thermal resistance calculated by the finite element models and the thermal resistance calculated from the supplier's datasheets are a close match.

Table 5. Junction-to-Ambient Thermal Resistance at 400 Feet per MInute Air Flow

Heat Sink	Package	θ_{JA} From Modeling (°C/W)	θ_{JA} From Datasheet (°C/W)
Z35-12.7B	Device in a 1020-pin FineLine BGA package	2.6	2.2
	Device in a 1020-pin FineLine BGA package	2.3	2.1
Z40-6.3B	Device in a 1020-pin BGA package	3.3	3.0
	Device in a 1020-pin BGA package	3.0	2.8

Actual Measurements

Thermal resistance is measured according to the JEDEC Standard JESD51-6. Altera measured the thermal resistance of the following heat sinks from Alpha Novatech:

- UB35-20B
- UB35-25B
- Z35-12.7B
- Z40-6.3B

These heat sinks contain pre-attached thermal tape (Chomerics T412). For a detailed description about TIM, refer to "Thermal Interface Material" on page 8.

For more information about these heat sinks, refer to the Alpha Novatech website.

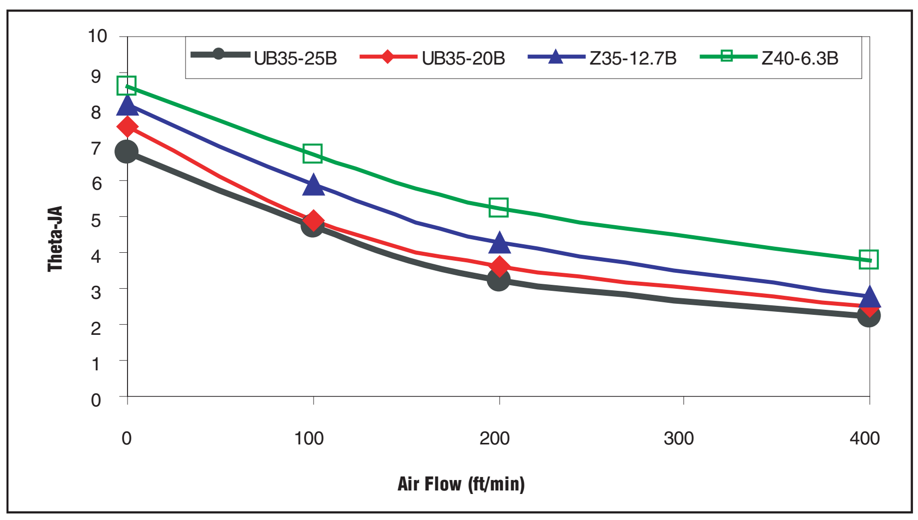
Four Altera devices were used to measure the heat sinks shown in Table 6. Table 6 shows a good correlation between the obtained measurements and the thermal resistance obtained from the supplier's datasheets.

Table 6. Junction-to-Ambient Thermal Resistance at 400 Feet per Minute Air Flow

Heat Sink	Actual θ_{JA} (°C/W)	Datasheet θ_{JA} (°C/W)
UB35-20B	2.5	2.4
UB35-25B	2.2	2.2
Z35-12.7B	2.8	2.6
Z40-6.3B	3.8	3.4

Figure 4 shows the effect of an airflow rate on junction-to-ambient thermal resistance.

Figure 4. Effect of the Airflow Rate on Junction-to-Ambient Thermal Resistance



Thermal Interface Material

After evaluating if you require a heat sink and which heat sink to use, you must decide on the TIM for your application. TIM is the medium used to attach a heat sink onto a package surface. TIM provides a minimum thermal resistance path from the package to the heat sink. Table 7 lists the types of TIM and their advantages and disadvantages.

Table 7. Types of TIM (Part 1 of 2)

TIM Type	Description	Advantage	Disadvantage
Grease	Silicone or hydrocarbon oil that contains various fillers used to bond heat sinks to packages. Grease is the oldest class of TIM and the most widely used material to attach heat sinks.	Low thermal resistance (0.2 to 1 C cm^2/W).	■ Messy and difficult to apply because of their high viscosity. ■ Require mechanical clamping (you must apply pressure within the 300 kPa range). ■ In applications with repeated power-on and power-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.	■ Low thermal resistance (0.4 to 0.8 C cm^2/W). ■ No pump-out issue.	Require mechanical clamping.

Table 7. Types of TIM (Part 2 of 2)

TIM Type	Description	Advantage	Disadvantage
Thermally conductive adhesives	Thermally conductive adhesives are usually epoxy- or silicone-based formulations that contain fillers, and they offer a superior mechanical bond.	■ Low thermal resistance (0.15 to 1 C cm^2/W). ■ Does not require mechanical clamping.	Not reworkable.
Thermal tape	Thermal tape is filled pressure sensitive adhesives (PSAs) coated on a support matrix such as polyimide film, fiberglass mat, or aluminum foil.	■ Simple assembly. ■ Does not require mechanical clamping.	■ High thermal resistance (1 to 4 C cm^2/W). ■ Not suitable for packages that do not 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 such as greases. They are supplied as die-cut preforms in the precise shape required for the application.	Simple assembly.	■ Require mechanical clamping. ■ Require high pressures (within the 700 kPa range) 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 within the 50 to 80 °C range. When operating above the melting point, they are not effective as an adhesive and require mechanical support, so they are always used with a clamp that applies pressure within the 300 kPa range.	Low thermal resistance (0.3 to 0.7 C cm^2/W).	■ Require mechanical clamping (applying pressure in the 300 kPa range). ■ Rework difficult.

Selecting a Thermal Interface Material for a Small Heat Source

TIM is applied between the heat source and heat sink. When the heat source is small, the performance of TIM becomes more significant.

The following example illustrates the importance of TIM performance. Table 8 lists the thermal resistance and temperature rise of two phase change materials: TPCM585 and TPCM905C.

Table 8. Thermal Resistance and Temperature Rise

Phase Change Material	Size	Input Power	Thermal Resistance	Temperature Rise
TPCM585	35 × 35 mm	10 W	0.01°C/W	0.10°C/W
	10 × 10 mm	10 W	0.13°C/W	1.30°C/W
TPCM905C	35 × 35 mm	10 W	0.03°C/W	0.30°C/W
	10 × 10 mm	10 W	0.32°C/W	3.20°C/W

Table 8 lists how a high performance TIM has a significant impact when the heat source is small. Also, phase change material or gap filler material requires a certain attachment pressure or load to perform properly.

Table 9 lists the impact of mounting pressure on phase change material performance.

Table 9. Load and Thermal Impedance *(Note)*

Phase Change Material	Load	Thermal Impedance
TPCM585	35 kPa (5 psi)	0.050°C (-in2)/W
	69 kPa (10 psi)	0.020°C(-in2)/W
TPCM905C	35 kPa (5 psi)	0.088°C(-in2)/W
	69 kPa (10 psi)	0.048°C(-in2)/W

Note to Table 9:

(1) (-in2)/W = Thermal resistance of one inch per square size.

The use of a Z-clip, push pin, or shoulder screw for attachment allows tight control over the attachment pressure or load, ensuring acceptable performance from the TIM.

Heat Sink Attachments

There are multiple methods to attach a heat sink to a heat source. For efficient heat dissipation, you must consider the advantages and disadvantages of each heat sink attachment method. The factors that influence your selection of the attachment method may include the package type, contact area of the heat source, and the heat sink type.

When attaching a heat sink to a heat source with a small contact area, consider the following factors:

- Possibility of the heat sink tipping or tilting
- Possibility of the exposed die being damaged during the heat sink installation
- Contact area can be too small to form a strong bond with adhesive or tape attachment

Heat Sink Attachment Methods

There are three basic types of heat sink attachments:

- Mechanical attachment—offers superior mechanical reliability and the ability to use a TIM such as grease or phase change material, enabling significantly lower thermal impedance.
- Thermal epoxy—a permanent attachment method as it creates a very reliable and secure bond, but one that is difficult to rework. Although it is possible to remove or rework a heat sink that is attached with epoxy, there is the risk of damaging the device.
- Thermal tape—inexpensive and easier to rework than thermal epoxy. However, tape offers a less reliable and weaker heat sink attachment (unless it is used with a mechanical attachment), especially if you work with larger heat sinks. Attachment strength is always a concern with tape-only solutions.

Table 10 lists the typical attachment methods for all package types.

Table 10. Advantage and Disadvantage for Each Attachment Method (Part 1 of 3)

Attachment Method	Advantage	Disadvantage	Examples *(Note 1)*
Plastic clip-on	Suitable for designs where space on the PCB is limited.	■ You must practice caution when installing or removing these clip-ons because the solder balls or chip substrate may be damaged during heat sink assembly due to localized stress. Refer to "Avoid Heat Sink Contact with the Chip Capacitors on the Substrate" on page 13. ■ Heat sink size is limited to the package substrate size.	
Z-clip	Provides stable attachment to heat source and transfers load to mounting anchors or the PCB.	Requires additional space on the PCB for anchor locations.	

Table 10. Advantage and Disadvantage for Each Attachment Method (Part 2 of 3)

Attachment Method	Advantage	Disadvantage	Examples *(Note 1)*
Push pin	■ Provides a stable attachment to a heat source and transfers load to the PCB. ■ Allows for tight control over mounting force and load placed on chip and solder balls.	Requires additional space on the PCB for push pin locations.	
Shoulder screw	■ Provides stable attachment to heat source and transfers load to the PCB, backing plate, or chassis. ■ Suitable for high mass heat sinks. ■ Allows for tight control over mounting force and load placed on chip and solder balls.	Requires additional space on the PCB for shoulder screws locations.	
Thermally conductive adhesive or glue	No additional space required on the PCB.	■ Adhesive application process is hard to control. ■ Rework is very difficult.	Epoxy or Thermally Conductive Adhesive

Table 10. Advantage and Disadvantage for Each Attachment Method (Part 3 of 3)

Attachment Method	Advantage	Disadvantage	Examples *(Note 1)*
Thermal tape	No additional spaces required on the PCB.	■ Relatively high impedance of tape significantly affects the thermal performance.	

Notes to Table 10:

(1) Images are courtesy of Alpha Novatech.

Avoid Heat Sink Contact with the Chip Capacitors on the Substrate

Heat sink must include methods to prevent the heat sink from forming an electrical short with the capacitors placed on the top side of the package. Several recommended methods are:

- Use of sponge pads—one preferred method is to use small compressible foam pads (sponge pads) on the heat sink. These pads prevent the heat sink from rocking or tilting on the die. While sponge pads prevent the heat sink from tipping and contacting the capacitors, they also cushion the heat sink during installation, which prevents the heat sink from possibly chipping or cracking the corner of the die. You must position these pads to make contact with the chip substrate in an area free of surface mount components.
- Use of an insulator—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 electromagnetic interface (EMI) or grounding reasons. In these cases, the use of the pads or an insulator is crucial.
- Use of rails or Z-stops—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.
- Use of an electrically-insulated gasket material—other suitable methods include using electrically-insulated gasket material at the base of the heat sink.
- Use of an insulator sheet—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.

To accomodate holes or slots on the PCB for a heat sink attachment, Altera recommends working with your heat sink suppliers and follow their instructions. For a list of heat sink vendors, refer to “Vendors List” on page 14.

Recommended Heat Sink Attachment Method

Altera recommends using the mechanical attachment for attaching heat sinks to Altera FPGAs. Because of the small contact area, the use of thermally-conductive tape or epoxy is no longer an effective option.

Mechanical attachment offers the following advantages:

- You can use higher performance TIMs such as grease or phase change materials
- Easier to rework

Common mechanical attachment methods include push pin, shoulder screw, Z-clip, and clip-on.

Clip-on heat sinks use a mechanical clip to hold the package edges. Altera recommends a clipping force ranging from 3.0 to 5.0 lb vertical force, per the heat sink vendor's recommendation.

Relevant Information

This section provides information related to thermal management for FPGAs.

Board Assembly

Table 11 lists the ball height (before and after board assembly) and the distance between the package edge and the first ball row.

Table 11. Ball Height and Distance Between the Package Edge and First Ball Row *(Note 1)*

Ball Height and Distance	Before Reflow	After Reflow
Ball Height	0.50 nom.	0.34 nom. *(2)*
Distance between the package edge and first ball rows center	1.0 mm = (40.00 - 38 × 1.0)/2	
Distance between the package edge and first ball rows	0.7 mm = 1.0 - 0.6/2	Not available

Notes to Table 11:

(1) The ball height value used is an example. For the actual ball height, refer to the *Altera Device Package Information Datasheet*.

(2) Assumed 33% reduction of height after reflow.

Vendors List

The following contains 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)

The following contains a list of TIM 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)

Document Revision History

Table 12 lists the revision history for this document.

Table 12. Document Revision History

Date	Version	Changes Made
March 2012	4.0	■ Removed lidless packages information.
August 2010	3.0	■ Added “Thermal Management Overview”, “Overcoming Heat Sink Tipping or Tilting for Small Heat Source and Lidless Packages”, “Selecting a Thermal Interface Material for a Small Heat Source”, “Selecting Heat Sink for Small Heat Source”, ■ Added Table 7 and Table 10. ■ Updated “Determining Heat Sink Usage” and “Vendors List”. ■ Removed “Conclusion”, and “Examples of Heat Sink Attachment Methods”. ■ Removed Figure 5 through Figure 7, Table 7 to Table 12.
December 2009	2.0	■ Converted to 8-1/2 x 11 page format. ■ Added “Heat Sink Attachments”, “Recommended Heat Sink Attachment Method”, “Examples of Mechanical Attachments”, “How to Avoid Heat Sink Contact with Chip Capacitors on the Substrate”, “Package Cross-Sectional View (Lidless Package)”, and “Lidless Package Loading Specifications”.
February 2007	1.1	■ Updated “Introduction”, “Thermal Resistances”, and “Heat Sink Evaluations”. ■ Added revision history.
September 2004	1.0	Initial release