Thermal Management Using Heat Sinks

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Introduction

Thermal management is an important design consideration with complex devices running at high speeds and power levels as these devices can generate significant heat. Proper thermal management can increase product performance and life expectancy. The thermal management requirements for a programmable device depend on its application. Altera® packages are designed to minimize thermal resistance characteristics and maximize heat dissipation. However, in some cases, complex designs require heat dissipation greater than packages provide.

This application note discusses ways to dissipate heat, how to calculate the heat dissipation of a device, and how to determine if a device requires a heat sink in an application.

Heat Dissipation Theory

Radiation (device), conduction (heat sink), and convection (fan) are three ways to dissipate heat from a device. In printed circuit board (PCB) designs, heat sinks are used to increase the heat dissipation from hot devices because the heat dissipation between the heat sink and the surrounding air is more efficient than between the device and the surrounding air. 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 the heat dissipation capability of a surface or, in other words, how efficiently heat is transferred across the boundary between different mediums. A heat sink with a large surface area and good air circulation gives the best heat dissipation. Limited vertical space between PCBs in a system constrains airflow and heat sink dimensions.

A heat sink helps keep a device at a temperature below its specified maximum operating temperature. To determine whether a device requires a heat sink for thermal management, calculate its thermal resistance through the use of thermal circuit models and equations. These thermal circuit models are similar to resistor circuits, which follow Ohm's law. With a heat sink, heat from a device flows from the junction to the case, then from the case to the heat sink, and finally from heat sink to ambient air.

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Figure 1 shows a thermal circuit for a device with and without a heat sink. Table 1 defines the thermal circuit parameters.

The thermal resistance of a device depends on the sum of the thermal resistances from the circuit model. See Table 2 for the thermal resistance equations for a device with and without a heat sink. Basic thermal equations are simple. However, the challenge can be finding the required data to substitute into the equations.

Figure 1. Thermal Circuit

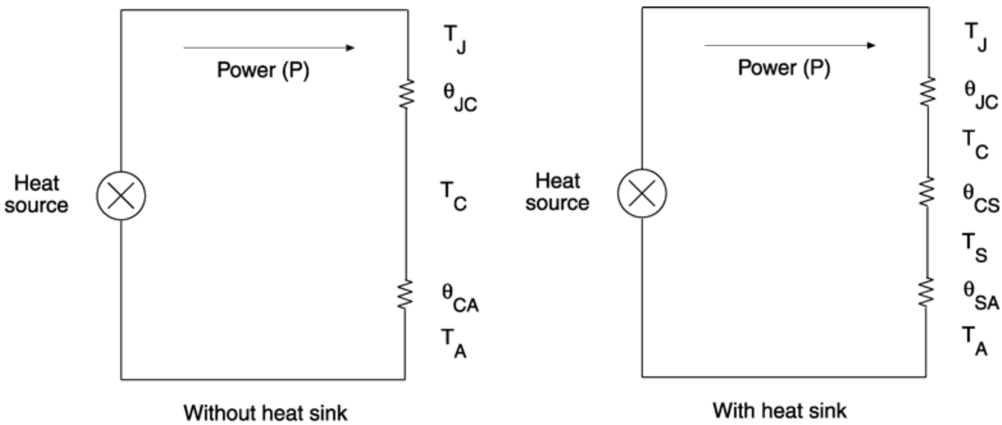


Table 1. Thermal Circuit Parameters

Parameter	Name	Units	Description
θ_{JA}	Junction-to-ambient thermal resistance	°C/W	Specified in the data sheet
θ_{JC}	Junction-to-case thermal resistance	°C/W	Specified in the data sheet
θ_{CS}	Case-to-heat sink thermal resistance	°C/W	Adhesive compound thermal resistance specified by manufacturer
θ_{CA}	Case-to-ambient thermal resistance	°C/W	Solved for by equation
θ_{SA}	Heat sink-to-ambient thermal resistance	°C/W	Solved for by equation and specified by the heat sink manufacturer
T_J	Junction temperature	°C	The maximum junction temperature as specified for the device
T_A	Ambient temperature	°C	Usually the maximum ambient air temperature specified for the device on the device's data sheet
T_S	Heat sink temperature	°C	The heat sink's maximum measured temperature near the device
Tc	Device case temperature	°C	The device package's maximum measured temperature
P	Power	W	Total rate of heat dissipation from the device while operating. Use the maximum value for selecting a heat sink

Table 2. Device Thermal Resistance Equations

Device	Equation
Without a heat sink	$\theta_{JATotal} = \theta_{JC} + \theta_{CA} = \frac{T_J - T_A}{P}$
With a heat sink	$\theta_{JATotal} = \theta_{JC} + \theta_{CS} + \theta_{SA} = \frac{T_J - T_A}{P}$

Thermal Equation Parameters

Many parameters contribute to a design's thermal circuit, including the device's maximum power consumption for the design, the maximum environment temperature, package characteristics, and airflow at the device.

Maximum Power Consumption (P)

Use the power calculator values from design simulations in the Altera Quartus® II software (or the device's power calculator at http://www.altera.com) to estimate the maximum power consumption of the device. Once a prototype design is available, measure the actual power consumption and use this value for thermal calculations.

Maximum Temperature (T_J & T_A)

The maximum ambient and junction temperatures are found in the data sheet for the device under **Device Absolute Maximum Rating** and the operating junction temperature is found under **Device Recommended Operating Conditions**. The temperature must be kept within the maximum conditions or damage could occur. The junction temperature should be kept within the recommended operating conditions to ensure the device achieves the performance reported by the Quartus II software.

Package Characteristics (θ_{JC} & θ_{JA})

Table 3 is an example of package thermal characteristics as found on the Altera device data sheets.

Table 3. Example Package Characteristics

Device	Pin Count	Package	θ_{JC} (°C/W)	θ_{JA} (°C/W) Still Air	θ_{JA} (°C/W) 100 ft./min.	θ_{JA} (°C/W) 200 ft./min.	θ_{JA} (°C/W) 400 ft./min.
EP20K400E	652	BGA	0.5	9.0	8.0	7.0	6.0
	672	FineLine BGA	0.2	11.7	9.7	8.0	6.7

Example Applications

An Example Application Not Requiring a Heat Sink

First, use the operational conditions shown in Table 4 in the device's power calculator on the web page to get the maximum power consumption. If the design is complete and simulation vectors are available, you can also use the Quartus II software's Power Gauge feature.

Table 4. Operational Conditions for Example Application

Parameter	Value
Device	EP20K400EBC652
V_{CCINT}	1.8 V
V_{CCIO}	3.3 V
f_{max}	50 MHz
Flip flops	8000
Carry chain logic elements (LE)	4000
Non-carry chain LE	3500
Number of I/O pins	300
Toggle rate	20%
Air flow rate	100 ft./min.
Maximum T_J	85° C
Maximum ambient temperature (T_A)	50° C

From the power calculator, these values give a maximum power consumption of P= 1.32 W. Then substitute the parameter values in Table 3 and Table 4 into the equation in Table 2 to determine the P allowable without a heat sink.

$$\theta_{JA\ Max\ Commercial} = \frac{T_J - T_A}{P}$$

$$P \le \frac{T_J - T_A}{\theta_{JA\ Max\ Commercial}}$$

$$P \le \frac{85°C - 50°C}{8°C/W}$$

$$P \le 4.375\ \ W$$

The 1.32 W consumed is less than the 4.375 W this device can accommodate. Therefore, this design does not require a heat sink.

Example Application Requiring a Heat Sink

First, use the operational conditions shown in Table 5 in the device's power calculator on the web page to get the maximum power consumption. If the design is complete and simulation vectors are available, you can also use the Quartus II software's Power Gauge feature.

Table 5. Operational Conditions for Example Application

Parameter	Value
Device	EP20K400EBC672
V_{CCINT}	1.8 V
V_{CCIO}	3.3 V
f_{max}	70 MHz
Flip flops	6500
Carry chain logic elements (LE)	3000
Non-carry chain LE	3000
Number of I/O pins	300
Toggle rate	25%
Air flow rate	200 ft./min.
Maximum T_J	85° C
Maximum ambient temperature (T_A)	70° C

Therefore, P=2.00 W.

Next, use the equation for thermal resistance without a heat sink:

$$P \le \frac{T_J - T_A}{\theta_{JA\ Max\ Commercial}}$$

$$P \le \frac{85°C - 70°C}{8°C/W}$$

$$P \le 1.85\ W$$

The 2.0 W consumed is greater than the 1.85 W this device can accommodate. Therefore, this design requires a heat sink. An alternative to a heat sink would be to increase the air flow across the device.

Finally, for this example, calculate the appropriate thermal resistance for a heat sink. θ_{CS} is typically extremely small. As such, the number to use is the adhesive compound thermal resistance that runs between 0.15 and 0.8 °C/W. For this example, use θ_{CS}= 0.5 °C/W.

$$\theta_{JA} = \frac{T_J - T_A}{P}$$

$$\theta_{JA} = \frac{85°C - 70°C}{2W}$$

$$\theta_{JA} = 7.5°C/W$$

Use the θ_{CS} just calculated to solve for the required heat sink.

$$\theta_{JATotal} = \theta_{JC} + \theta_{SA} + \theta_{CS}$$

$$7.5°C/W > 0.2°C/W + \theta_{SA} + \theta_{CS}$$

$$\theta_{SA} < 7.3°C/W - 0.5°C/W$$

$$\theta_{SA} < 6.8°C/W$$

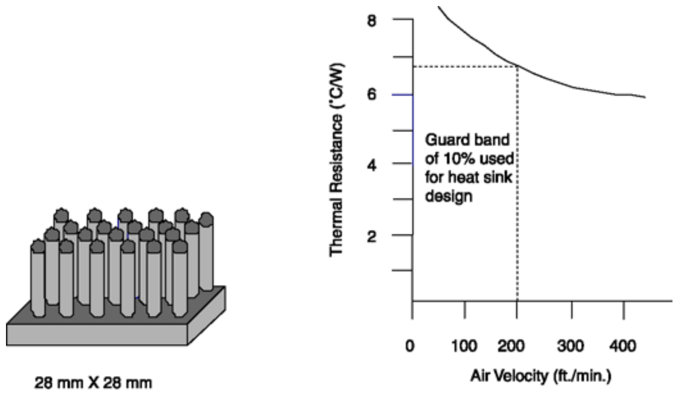
Selecting a Heat Sink

Selection of a heat sink manufacturer is typically straightforward. Once the maximum thermal resistance has been calculated, locate available heat sinks with that characteristic for the size of package. A few iterations may be required to get the final design. Altera also recommends a guard band of 10 to 15% less thermal resistance than calculated rather than only matching the maximum thermal resistance value.

The heat sink to choose is one that meets a design's thermal, packaging, power, and cost requirements. A few heat sinks types include stampings, extrusions, folded fin, or active heat sinks with fans. Figure 2 apply to the application in the "Example Application Requiring a Heat Sink" section.

☞ Guard band was added for the 6.8 °C/W heat sink required at the 200 ft./min. in the example application.

Figure 2. Heat Sink & Thermal Resistance Curve for Example Application Requiring a Heat Sink



Conclusion

The equations in this application note help determine the heat dissipation requirements for a design. The easiest ways to improve a system's thermal characteristics are to increase the airflow, lower the power consumed, or reduce the maximum ambient temperature. When the environmental conditions cannot be modified enough to remove the need for a heat sink, then these equations can be used to find the heat sink required.

References

For a power consumption calculator worksheet and more information about thermal management, refer to *AN 74: Evaluating Power for Altera Devices*.

Please evaluate any vendor's products for compatibility with Altera devices. The vendors listed at the time of the writing of this paper had heat sink characteristics in the range of the application in the "Example Application Requiring a Heat Sink" section. For more information on heat sinks visit the following heat sink vendor web sites:

- Malico Inc. (http://www.malico.com.tw)
- Cool Innovations (http://www.coolinnovations.com)
- Aavid Thermalloy (http://www.aavidthermalloy.com)
- Dynatron Corp (http://www.dynatron-corp.com)
- Alpha (http://www.micforg.co.jp)
- Heat Technology (http://www.heattechnology.com)

Revision History

The information contained in *AN 185: Thermal Management Using Heat Sinks* version 2.1 supersedes information published in previous versions. *AN 185: Thermal Management Using Heat Sinks* version 2.1 contains the following change:

- Updated text in the paragraph below Table 4 from "typical power" to "maximum power."

101 Innovation Drive
San Jose, CA 95134
(408) 544-7000
http://www.altera.com
Applications Hotline:
(800) 800-EPLD
Literature Services:
lit_req@altera.com