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Thermal Relief Design for ADSP-TS201S TigerSHARC® Processors

Contributed by Greg F.

Rev 1 – February 3, 2004

Introduction

This EE-Note discusses thermal relief design considerations for Analog Devices ADSP-TS201S TigerSHARC® processors. This document assists PCB and system designers by providing thermal data as well as heat sink recommendations to allow for proper design of their thermal relief system.

The ADSP-TS201S processor is an ultra-high-performance, static superscalar, 32-bit processor from the TigerSHARC family of Analog Devices Inc. The processor core operates at a clock frequency of 500 MHz, and is available in a flip-chip ball grid array (BGA_ED) package.

Overview

This EE-Note discusses the following topics:

- Thermal overview
- Thermal calculations
- Heat sink basics
- Heat sinks: pin fins vs. rectangular-fins
- Heat sink recommendations
- Specification recommendations
- Heat sink attachment recommendations
- PCB design for thermal dissipation
- Thermal simulations
- Alternate thermal relief solutions
- Terminology

Thermal Overview

Proper thermal management is required to ensure that the processor operates within the temperature specifications provided in the ADSP-TS201S data sheet [1]. Operating within the specified temperature range ensures proper processor operation and reliability.

The overall power estimation can also be used to estimate a thermal relief budget for the processor. Equation 1 gives a value for the total average estimated power. Note that this equation yields the total estimated average power consumption for a single ADSP-TS201S in a given system. Guard-banding this value is recommended for a thermal relief design that will allow the system to operate within specified thermal parameters, even under worst-case conditions.

$$P_{THERMAL} = P_{DD}\,(avg.) + P_{DD\_IO}\,(avg.) + P_{DD\_DRAM}\,(avg.)$$

Equation 1. Total Estimated Average Power

For more information on power consumption for the ADSP-TS201, refer to the Engineer-to-Engineer note EE-170, titled “Estimating Power for ADSP-TS201S TigerSHARC Processors” [2], which can be found on the Analog Devices Web site, at www.analog.com/tigersharc.)

Figure 1 shows the top and side views of the ADSP-TS201S processor package. This TigerSHARC processor is available in a 25mm x 25mm BGA_ED package.

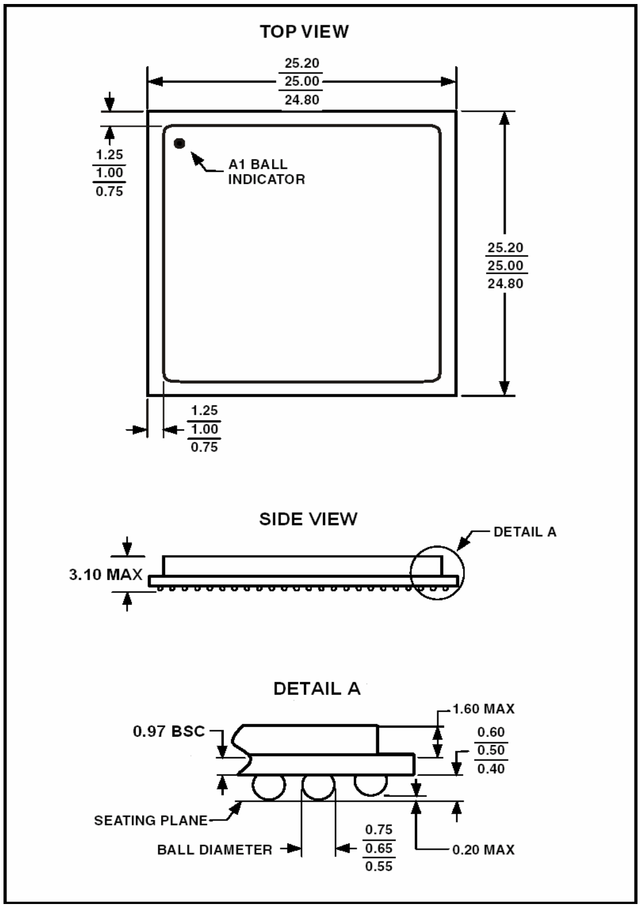

Figure 1. ADSP-TS201S Outline Diagram

The BGA_ED package consists of the laminate (with the attached ball-grid array on its bottom surface), and a heat spreader, which is bonded to the processor die via a thermally conductive adhesive. The heat spreader aids in thermal dissipation, since it attaches directly to the processor die and provides a much larger surface area than the die. (Increasing the surface area decreases the overall thermal resistance for a given surface.)

After thermal calculations have been completed, if it is determined that a heat sink is necessary in the system, use a heat sink with a minimum size of 25mm square for thermal relief of the processor.

Figure 2 is a simple model of a thermal system, showings the components of the processor package. This model shows all of the associated components present in a thermal system. Note that there are two possible avenues for thermal heat dissipation: the primary heat dissipation path (i.e., the path with the least thermal resistance) is via the “top” of the processor package (through the thermal path denoted by θ_{JC}), and the secondary heat dissipation path is through the “bottom” of the processor package, via the package balls (through the thermal path denoted by θ_{JB}) to the PCB.

The maximal thermal energy of the processor can be transferred when the thermal resistance from each component in the system is minimized. Thus, the thermal energy generated by the processor can be dissipated to the cooler ambient air of the system (or through the PCB by the use of thermal vias and an internal or external heat sinking plane).

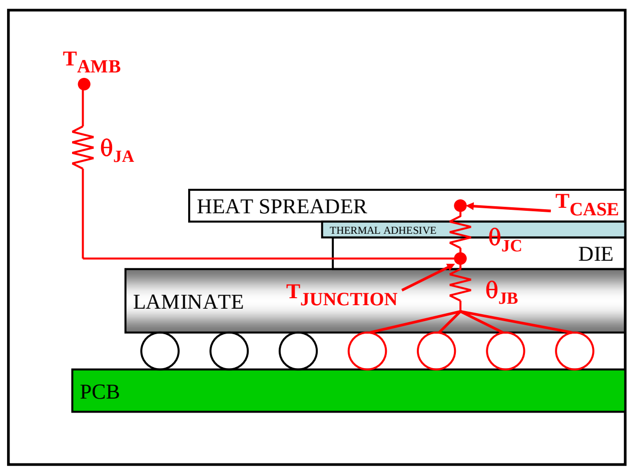

Figure 2. Thermal System Model Example

Note that θ_{JA} is a composite parameter that encompasses all possible paths to the system’s ambient air temperature based on the JEDEC X-Y-Z spec. (The values for θ_{JA}, θ_{JB}, and θ_{JC} are provided in the “Thermal Characteristics” section of the ADSP-TS201S data sheet.)

Thermal Calculations

To calculate the thermal performance of a system, the first parameter that should be known at the time of performing thermal calculations is the maximum ambient air temperature, $T_{AMBIENT}$, of the system. The second parameter that should be known is the value of the processor's thermal power consumption ($P_{THERMAL}$). The third parameter is the junction-to-ambient thermal resistance, θ_{JA}. These three system parameters are required to calculate the maximum junction temperature, as shown in Equation 2.

$$T_{JUNCTION} = (P_{THERMAL} \times \theta_{JA}) + T_{AMBIENT}$$

Equation 2. Processor Junction Temperature Calculation

From the result of Equation 2, we can then use the calculated value for $T_{JUNCTION}$ to solve for the calculated value for the processor's case temperature, T_{CASE}, using Equation 3. The result of Equation 3 determines whether a heat sink is required to allow the ADSP-TS201 to operate within the thermal operating conditions specified in the ADSP-TS201S data sheet. If the calculated value for T_{CASE} exceeds the maximum specified case temperature for the device (from the ADSP-TS201S data sheet), a heat sink will be required.

$$T_{CASE}\ (max) = T_{JUNCTION} - (P_{THERMAL} \times \theta_{JC})$$

Equation 3. Heat Sink Requirement Equation

If a heat sink is required for the processor, an appropriate heat sink with the proper thermal performance characteristics must be chosen. The following two parameters for the heat sink must be known: the sink-to-ambient (θ_{SA}) thermal resistance, and the thermal resistance of the thermal interface material (θ_{CS}), which resides between the processor's case and the bottom surface of the heat sink.

Knowing these two thermal resistance parameters of the desired heat sink, we can now calculate the case temperature (T_{CASE}) of the processor with the heat sink attached by using Equation 4.

$$T_{CASE\ (MAX)} \leq T_{AMBIENT} + (P_{THERMAL} \times \theta_{SA}) + (P_{THERMAL} \times \theta_{CS})$$

Equation 4. Derived Heat Sink Requirement Equation

If the resultant value from Equation 4 exceeds the maximum value for $T_{CASE\ (MAX)}$ (from the ADSP-TS201S data sheet), a heat sink with *better* thermal characteristics will be required.

Equation 4 yields a conservative estimate for the value for T_{CASE}. This is because there are other paths in the system to sink the thermal energy (for example, through the PCB). A more comprehensive model of the system to include these additional paths can be used when performing the thermal calculations for the processor. (The value for θ_{JB} is provided in the data sheet of the ADSP-TS201S.)

Table 2 shows the thermal resistance parameters of the BGA_ED package of the processor based on preliminary thermal parameters.

Air Velocity (m/s)	θ_{JA} Without Heat Sink (°C/W)	θ_{JB} Nominal (°C/W)	θ_{JC} Nominal (°C/W)
0	19.6	8.3	0.7
1	15.4	8.3	0.7
2	13.7	8.3	0.7

Table 2. BGA_ED Thermal Resistance Parameters

Table 3 shows thermal resistance values for an AAVID 374224B00032 heat sink. The values shown in Table 3 are provided as an example.

Air Velocity (m/s)	θ_{SA} Heat Sink Resistance (°C/W)	θ_{JA} With Heat Sink (°C/W)
0	19.7	10.7
1	6.4	5.5
2	4.8	4.5

Table 3. Heat Sink Thermal Resistance Example

For a specific application, the heat sink's thermal resistance values can be obtained from the particular heat sink vendor.

Using Equation 4 and the data from Table 3, the required minimal airflow over the heat sink can be determined to allow for operating the ADSP-TS201S within the maximum case temperature specified in the processor's data sheet. If this value is still insufficient, an active thermal relief solution is required. See "Alternate Thermal Relief Designs" later in this document.

Heat Sink Basics

A heat sink is characterized by its thermal resistance, which describes the flow of heat from the heat sink to the ambient air for a given rise in the heat sink temperature.

Thermal resistance is measured in units of °C/W. Heat sink to local ambient thermal resistance (θ_{SA}) is a measure of the thermal resistance from the bottom of the heat sink to the local ambient air.

Thermal resistance is dependent upon the following four parameters:

- Heat sink material
- Thermal conductivity of the heat sink
- Geometry of the heat sink
- Air velocity through the fins of the heat sink

Lowering the thermal resistance between the processor and the ambient air increases the thermal solution's efficiency.

Copper heat sinks are less thermally resistive than aluminum, however, they are more expensive typically. For copper, the value of thermal resistivity (R) is 0.11; for aluminum the thermal resistivity value is 0.23. The units for R are given as °C-inches per Watt.

When performing processor case temperature measurements, measure the case temperature, T_{CASE}, at the center of the heat spreader using a thermocouple.

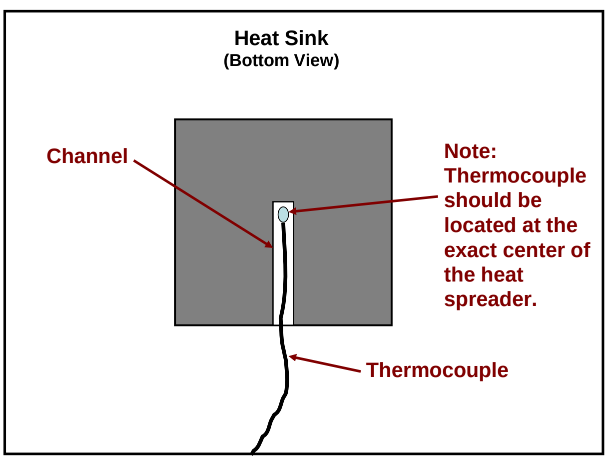

Figure 3. Thermocouple Placement and Heat Sink Channel

If a heat sink is to be used during the thermal measurements, mill a channel in the heat sink to facilitate the placement of the thermocouple. (See Figure 3.) The channel should be deep enough and long enough to allow for the thermocouple to sit at the center of the heat spreader of the processor.

Place the thermocouple at the center of the heat spreader. Secure it with a small, single bead of thermally conductive epoxy. Clean the heat sink and the heat spreader surfaces with isopropyl alcohol (100%), and a lint-free cloth or swab prior to attachment.

Pin Fins versus Rectangular Fins

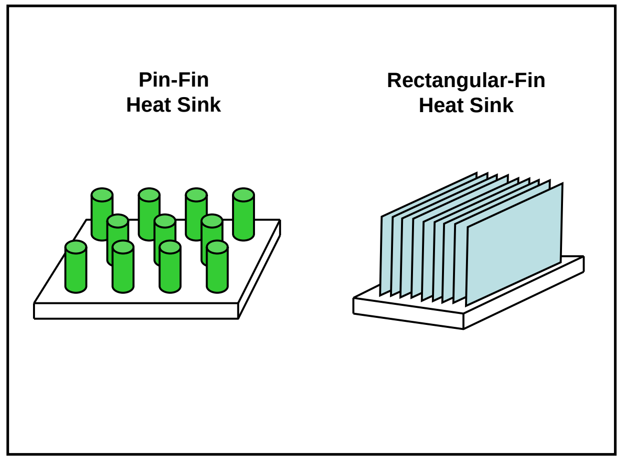

Figure 4. Pin-Fin vs. Rectangular-Fin Heat Sink Example

Although rectangular-fin heat sinks have been around longer, pin-fin heat sinks perform better than rectangular-fin heat sinks, especially in environments that provide little or no airflow in the system. Due to the omni-directional structure of pin-fin heat sinks, air can penetrate and exit the heat sink at every possible angle, providing more efficiency. The round shape of the “pin-fins” creates turbulence within the heat sink; this turbulence breaks the stagnant air boundary layers around the pins, enhancing the heat sink’s thermal performance. In addition, the round pin structure exposes a large percentage of the surface area to incoming airflow without presenting an extreme pressure resistance to the incoming airflow.

Heat sinks of many different sizes are available from the listed manufacturers. Following is a list of recommended heat sink manufacturers and specific heat sinks that exhibit required thermal relief performance. Visit the Web sites listed below for more information.

Cool Shield Inc., *www.coolshieldinc.com*:

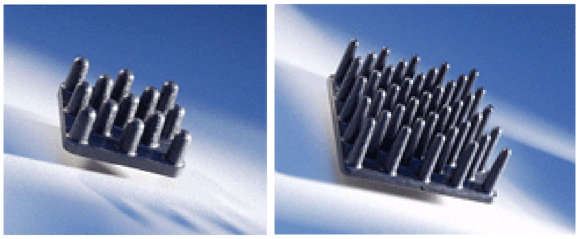

Figure 5. CSH0xx012 and CSH0xx021 Polymer Heat Sinks

Cool Innovations, *www.coolinnovations.com*:

4-101005U (pin-fin, copper)
4-101003U (pin-fin, copper)
3-101003U (pin-fin, aluminum)
3-101005M (pin-fin, aluminum)

Figure 6. Cool Innovations "M" Series Pin-Fin Heat Sinks

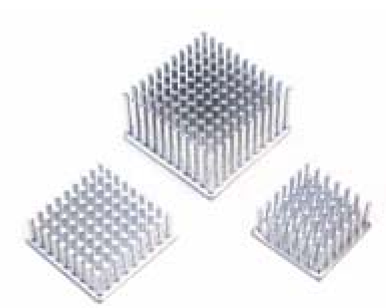

Figure 7. Cool Innovations "U" Series Pin-Fin Heat Sinks

AAVID Thermalloy, *www.aavidthermalloy.com*:

Figure 8. AAVID Thermalloy 374224B00032 Heat Sink

Figure 9. AAVID Thermalloy 374224B60023 Heat Sink

Specification Recommendations

The heat sink used to cool the ADSP-TS201S is recommended to not exceed the weight and dimension guidelines shown in Table 4. A horizontal position for the assembled heat sink and processor package is recommended.

Maximum Heat Sink Dimension (mm)	Maximum Weight (grams)	Minimum Lateral (X-Y) Shear Strength (psi)	Maximum Vertical (Z) Force (Kg)
53 x 53 x 16.5	54	200	5

Table 4. Heat Sink Weight and Dimension Guidelines

Do not exceed the maximum lateral and vertical forces when installing or removing the heat sink.

Analog Devices, Inc. recommends a heat sink with length and width dimensions of 25mm. This allows proper coverage of the heat spreader of the processor package. If a larger heat sink (> 25mm square) is to be used, mechanical support is necessary to avoid cantilevering of the heat spreader.

Ensure that the heat sink is centered on the heat spreader. When using a heat sink of 23mm x 23mm (which are the dimensions of the heat spreader), used to ensure that the heat sink is centered on the heat spreader to within 0.06”.

Heat Sink Attachment Recommendations

The thermal heat spreader is designed to increase the thermal performance of the processor, and is also the physical interface for attaching a heat sink. Clear the thermal heat spreader and bottom surface of the heat sink cleaned with Isopropyl alcohol (100%) and a clean, lint-free swab before mating the surfaces. Allow the isopropyl alcohol to fully evaporate before dispensing the heat sink adhesive.

Special care should be used when physically handling the nickel-plated copper BGA_ED package, since oil in the skin of the fingers can contaminate the top surface of the thermal heat spreader. Remove any finger oil, which contaminates the thermal heat spreader, with isopropyl alcohol before applying a heat sink or thermal interface material to the processor.

For ADSP-TS201S processors, Analog Devices, Inc. recommends three types of heat sink attachment methods: tape anchor, solder anchor, and adhesive.

The tape attachment method requires the use of a thermally conductive adhesive tape that mates the surfaces of the processor and the heat sink. The tape serves a dual-purpose since it is also used to compensate for any small surface imperfections in either the processor or the heat sink, which would work as an insulating air barrier and would therefore increase the thermal resistance in the system.

A solder anchor attachment method also requires thermally conductive interface material between the processor and the heat sink. This interface material does not aid in attaching the heat sink to the processor. The advantage to this method is that a smaller amount of thermal interface material is required; therefore, less thermal resistance is introduced into the system. The disadvantage is that additional board real estate is required in order to facilitate the use of the solder anchors on the top of the PCB.

GE Silicones “TSE 3281G” can be used to attach a heat sink to the heat spreader of the ADSP-TS201S package. (This material may be purchased from General Electric Company, 960 Hudson River Road, Waterford, NY 12188 USA. General Electric’s phone number is (800) 332-5390.

Consider the adhesive's shelf life when selecting the adhesive used to attach the heat sink to the processor’s package. Dispense the adhesive in an “X” pattern in the center of the nickel-plated heat spreader; the adhesive is not allowed on the bottom surface of the package laminate. A small amount of adhesive is allowed to flow out to the edge at the heat spreader and heat sink interface. It is desired that no adhesive flows out of the interface.

It is recommended that there is 0.45” clearance on two opposite sides between the BGA_ED body and the nearest component for heat sink tool removal access.

The following information is presented for reference purposes only. Verify any specific applications needs.

- The adhesive thickness on the bonded surface is nominally 0.004” (0.10mm) and must not exceed 0.010” (0.25mm).
- The percentage of covered area of the bonded surface shall not be less than 80% and must not exceed 90% of the heat sink surface. The adhesive must be centered about the heat spreader’s surface within 0.06” (1.5mm).

- The surfaces to be bonded must be flat to within 0.004” (0.10mm).

PCB Design for Thermal Dissipation

Figure 10, a thermal model of the BGA_ED package, shows that more thermal energy will be dissipated through the top of the package since the die is upside-down in the package. Due to design constraints, there may be situations where sufficient clearance to install a heat sink on the device may not be available (or there may be enough room only for a smaller heat sink that may not have sufficient heat dissipation characteristics) to allow for thermal power dissipation to escape through this interface.

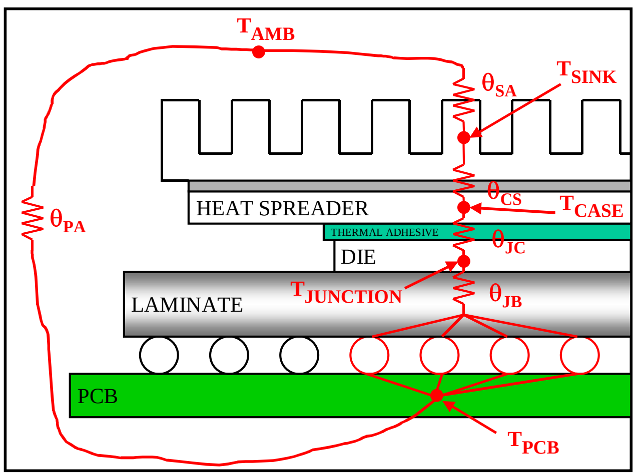

Figure 10. ADSP-TS201S BGA-ED Thermal Model

In this situation, thermal energy can be dissipated from the solder balls of the BGA_ED package to a heat sinking plane of the PCB. Thermal vias in the PCB can be used in conjunction with a heat sinking plane (i.e., a copper layer or some other type of thermally conductive material) of sufficient area to allow thermal transfer to a heat sink or some other means of thermal relief.

Thermal Simulations

Due to the high-performance of modern DSP-based systems, proper thermal management is critical for desired performance and operation. Performing thermal simulations on a given system is one method of ensuring proper system performance.

Correct processor performance is not guaranteed if T_{CASE} is exceeded; ensure that the operating value for T_{CASE} is within the range specified in the ADSP-TS201S data sheet.

Below is a listing of vendors that provide thermal simulation software. These companies can also provide thermal simulation assistance.

- Maya (*http://www.mayahtt.com/home.asp*)
- Flotherm (*http://www.flowtherm.com*)
- ThermoAnalytics, Inc. (*http://www.thermoanalytics.com*)
- Harvard Thermal Inc. (*http://www.harvardthermal.com*)

Alternate Thermal Relief Designs

In some specific cases, a passive thermal relief solution may not be sufficient for cooling the processor to within its specified operating temperature range. Alternate thermal relief solutions that may be applicable to specific system application include:

- Heat sink fans
- Heat pipes
- Forced airflow (ducting)

Heat Sink Fans

A heat sink and fan combination is probably the simplest method in achieving better thermal relief performance over a passive system. The heat sink fan increases the flow of air across the heat sink, which aids in decreasing the overall thermal resistance of the heat sink.

Pros: Better thermal relief performance is achieved with the same heat sink.

Cons: A fan requires additional system power. It also consumes additional space in the system, regardless whether the fan is located on top of or next to the heat sink.

Heat Pipe

A heat pipe can be used as a thermal relief solution when there is insufficient height in a system to allow placement of a heat sink, or the height requirements limit the use of specific heat sinks that exhibit insufficient thermal characteristics. In this case, a heat pipe can conduct thermal energy away from the processor (via a cooling plate and a thermally conductive pipe filled with a pressurized coolant) to a remote heat sink and system fan to dissipate the thermal energy to cooler air outside of the system.

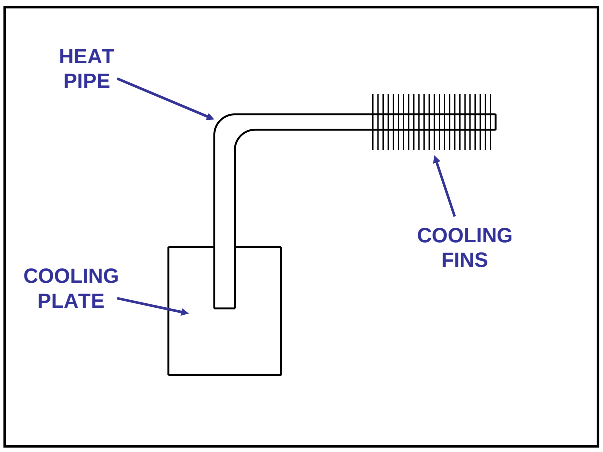

Figure 11. Heat Pipe Example

Pros: Heat pipes can be advantageous in systems where a heat sink may be physically too large to install.

Cons: Compared to a heat sink or fan sink design, heat pipes are typically custom designed and can be expensive.

Forced Airflow and Air Ducts

Forced airflow or ducting is another means to achieve better cooling performance over a passive design. Forced airflow is advantageous in system designs with small enclosures that may be so small that a fan of sufficient airflow characteristics and size may not fit. A fan external to the enclosure draws in or expels air through an air duct, forcing air across the processor heat sink.

Pros: The air duct (and fan combination) draw cooler outside air into the enclosure and across the processor's heat sink. The air duct can be designed to increase the speed of the air that flows through it, increasing the cooling characteristics of the system; a smaller fan can be used in this case, decreasing overall system noise. Lastly, air ducts can also isolate the processor from the effects of system heating (caused by other system components, such as a linear regulator.)

Cons: Since air ducts are custom designed, they can be expensive when compared to a heat sink.

Terminology

P_{DD}: The total power consumed on the V_{DD} voltage domain by the TigerSHARC core. This is an average value.

P_{DD_IO}: The total power consumed on the V_{DD_IO} voltage domain by the Link Ports and Cluster Bus of the TigerSHARC processor. This value is system dependent, and is an average value.

P_{DD_DRAM}: The total power consumed by the internal DRAM of the processor. This is an average value.

$P_{THERMAL}$: Total power consumed by the processor. This is an average value.

Heat transfer coefficient: theta (θ), given in °C/W.

Thermal resistance: A measure of the flow of heat from one medium to another.

Thermal equilibrium: System state when the electrical power dissipated in the device is equal to the heat flow out of the device.

$T_{AMBIENT}$: The temperature of the local air surrounding the processor in the system.

T_{CASE}: The case temperature of the processor.

$T_{JUNCTION}$: The processor junction temperature.

T_{SINK}: The temperature of the heat sink.

θ_{CA}: The thermal resistance between the case of the processor and the ambient air.

θ_{JA}: The thermal resistance between the junction of the processor and the ambient air.

θ_{JB}: The thermal resistance between the junction and the balls of the package.

θ_{JC}: The thermal resistance between the junction and the case of the processor.

θ_{SA}: The thermal resistance between the heat sink and the ambient air. This is also sometimes known as the thermal resistance of the thermal interface material (applied between the heat sink and the processor package), or θ_{TIM}.

References

[1] *ADSP-TS201S TigerSHARC Embedded Processor Preliminary Data Sheet.* Rev PrH, January 2004. Analog Devices, Inc.

[2] *Estimating Power for ADSP-TS201S TigerSHARC Processors (EE-170)*. In preparation. Analog Devices, Inc.

Document History

Version	Description
Rev 1 – February 3, 2004 by Greg F.	Public Release