StrataDNX/StrataXGS

Thermal Considerations for High-Power Switching Devices

Application Note

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Chapter 1: Introduction

This document provides critical thermal guidelines for high-power switching devices in the StrataDNX™ and StrataXGS® families. The intended audience is hardware engineers, thermal engineers, and system engineers.

Thermal solutions often require electrical, thermal, and mechanical integration in application system designs, which can be challenging for high-power devices. This document discusses various aspects of thermal design and testing to avoid and address thermal-related issues that may occur with application systems.

In general, the information in this document applies to all high-power StrataDNX and StrataXGS switch devices. To verify whether the information in this document applies to a specific device, or to check for device-specific recommendations that might be different than the information in this document, contact Broadcom support.

NOTE: Although this application note is intended to be used for designs with high-power devices, it contains good design guidance that can be applied to all devices.

1.1 General Guidelines

The device must be operated as defined in the device data sheet. Operation outside of the functional temperature range of the device will overstress the device. Overstressing the device could result in:

- Degraded system performance
- Logic errors
- Degraded device thermal performance
- Permanent changes in the operating characteristics
- Long-term device reliability issues that have an adverse effect

1.2 Device Documents with Thermal-Related Information

This section lists the documents that contain thermal-related information for the devices.

Refer to the Customer Support Portal (CSP) for device-specific documentation. The organization of information and file where the information is located might vary for different devices.

NOTE: This section, as well as the rest of the document, uses the BCM88680 (Jericho+) device as an example of where to find various information in related documentation.

The following documents contain thermal-related information:

- Device data sheet:
  - The BCM88680 data sheet (88680-DS1xx) includes:
    - Device maximum power in the “Device Power Consumption” section
    - Temperature sensors in the “Temperature Monitoring” section
    - Reflow details in the “Reflow Temperature” section
    - Heat sink assembly and package compressive load in the “Heat Sink Attachment Considerations” section
    - Package details in the “Packaging” section
    - 2R model parameters (θ_{JC}, θ_{JB}) in the “Package Thermal Specifications” section
- Hardware Design Guidelines
  - The BCM88680 *Hardware Design Guidelines* application note (DNX28NM-AN1xx) includes:
    - PVTMON supply and filtering in the “PLL and PVTMON 1.8V Supply” section
    - ROV and other power considerations in the “Power Aspects section”
- Delphi Thermal models
  - The BCM88680 Delphi model file is BCM88680_DELPHI.PDML
- SMT guidelines
  - The BCM88680 SMT guide file is Jericho+_BCM88680-SMT-Guide and includes:
    - Package warpage information
    - Guidelines for PCB PAD design
    - Reflow process recommendations

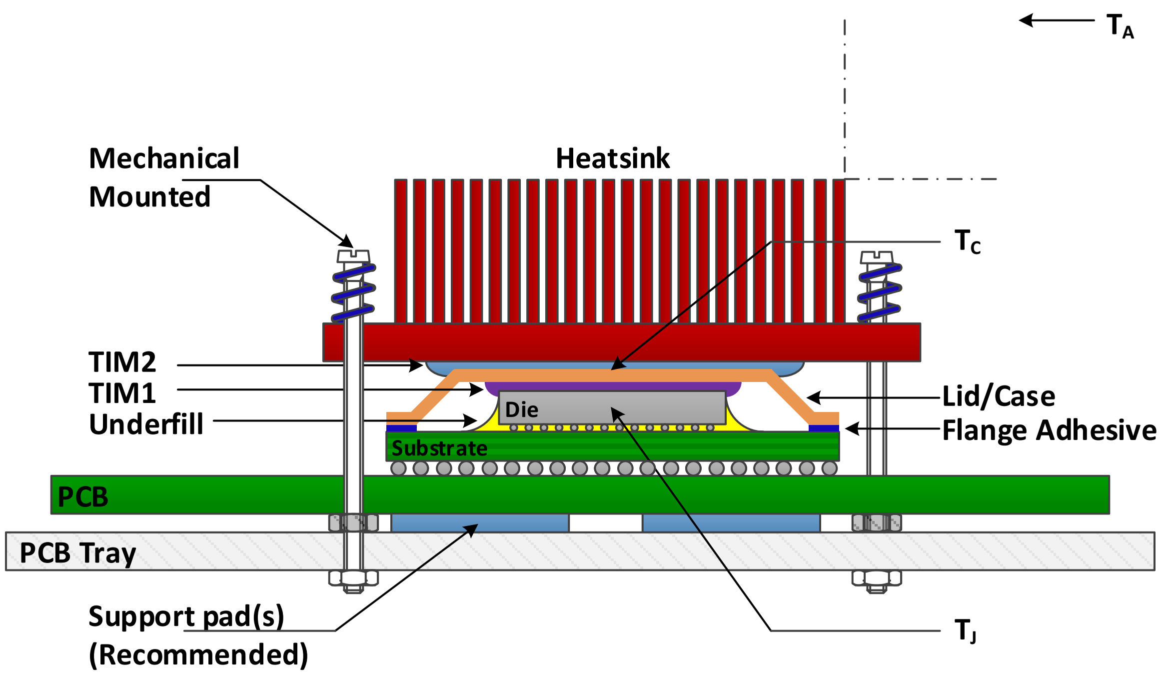
Chapter 2: Thermal Aspects

2.1 System Definitions

Figure 1 shows a Broadcom device soldered to a printed circuit board (PCB). The PCB is connected to the PCB tray, and the thermal pad is installed between the PCB tray and PCB board. Thermal Interface Material (TIM), identified as TIM2 in the figure, is placed between the Broadcom device lid and the device heat sink.

The Broadcom device shown in Figure 1 includes balls, substrate, bumps, underfill, die, TIM1, flange adhesive, and lid. The heat sink is placed on the device and spring-load mounted to the PCB.

Figure 1: System Thermal Definitions



Thermal measurement points:

- T_J—Device junction temperature, °C
- T_C—Package case top center surface temperature (sometimes referred to as T_T), °C
- T_A—Ambient temperature, °C

Thermal interface materials:

- TIM1—Thermal interface material between device die to device lid.
- TIM2—Thermal interface material between device lid to heat sink.
- Support pad(s)—Mechanical support between PCB and PCB tray. It is recommended to reduce device warpage during applications and testing.

2.2 Temperature Reference Points (T_J, T_C and T_A)

2.2.1 Junction Temperature—T_J

Junction temperature is the maximum temperature within the device die. In practice, junction temperature cannot be precisely measured but can only be estimated.

Maximum T_J is defined as the steady state maximum junction temperature at which the device operates for the majority of the time. The steady state maximum T_J is defined in the device data sheet. In all operating conditions, do not exceed max T_J.

For the BCM88680, max T_J is defined as 110°C.

2.2.1.1 T_J Excursions

The data sheets for some devices define the T_J excursion that is allowed for a specific time period, per year.

This excursion in junction temperature is typically the result of a rise in the system ambient temperature due to a temporary cooling failure, degradation, or system maintenance.

For example, the BCM88680 data sheet defines the T_J excursion as follows:

> A max excursion temperature of T_J = 125°C for 96 hours per year is allowed. During the excursion period, the device will continue to operate, but its performance may degrade.

2.2.1.2 T_J Measurement and Monitoring

T_J should be constantly monitored and estimated. Before T_J passes the recommended operating temperature, active actions should be taken by the system to reduce the temperature and not overstress the device.

The system should also consider the reaction time and avoid any situations in which the device is overstressed due to the way the system samples junction temperature—and act if needed.

While reading and estimating the real device junction temperature, the following should be considered:

- Max T_J sensor reading

  The T_J measurement is done by reading all device temperature sensors (PVTMON indication and thermal diode) and selecting the one with the highest temperature value.
- Sensor accuracy

  Each sensor, based on the sensor type, might have a different level of accuracy. The sensor accuracy should be considered when estimating the worst device junction temperature.

  For the BCM88680, for example, PVTMON accuracy is ±3°C, and the thermal diode accuracy is about ±2.5°C.
- Sensor locality and hot spot delta

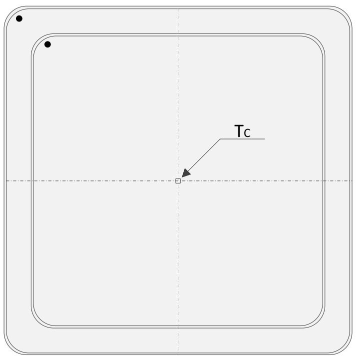
  Each sensor might indicate a different temperature based on its location in the die. The local sensor reading might not represent the current hottest junction point in the device, based on the device operation and environmental conditions.

  A safe system should consider the delta between the sensor temperature readings and the hottest spot in the device. When hot spot delta data is not available, customers should take a minimum of 5°C as a safeguard.

2.2.2 Case Temperature—T_C

T_C is the package case top center surface temperature (sometimes referred to as T_T). T_C is measured in steady-state device conditions.

Figure 2: T_C Sampled on the Center of Device Lid



NOTE: Broadcom does not expect customers to be able to accurately measure T_C since it is prone to measurement errors and often is not sufficiently reproducible. Measuring T_C on the application board usually produces erroneous results that do not help in investigating application system thermal issues.

When measuring device case temperature, follow standards that guide such measurements for high-power devices, for example MIL-STD-883J (METHOD 1012.1), JEP140, and JESD51-14. It is also possible to use commercial products for these measurements, such as T3Ster from Mentor Graphics. For information about non-Broadcom products, contact the product manufacturer or vendor.

Obtaining the T_C measurement might not be a trivial task due to the difficult execution and the special equipment required. Failure to follow the T_C measurements guidelines could result in an incorrect case temperature measurement that can lead to incorrect conclusions, incorrect θ_{JC} calculations, and an incorrect thermal understanding of the system.

NOTE: The T_C measurement may impact system thermal performance. When comparing a reference system with no T_C measurement to a system with where a T_C measurement has been taken, it is possible to see different results even if both systems are tested under the same conditions. For example, a lower junction temperature on a reference system can imply that the T_C measurement caused worse thermal conductivity due to the measurement.

For more information about T_C measurements, see Appendix A, TC Measurements Notes.

2.2.3 Ambient Temperature—T_A

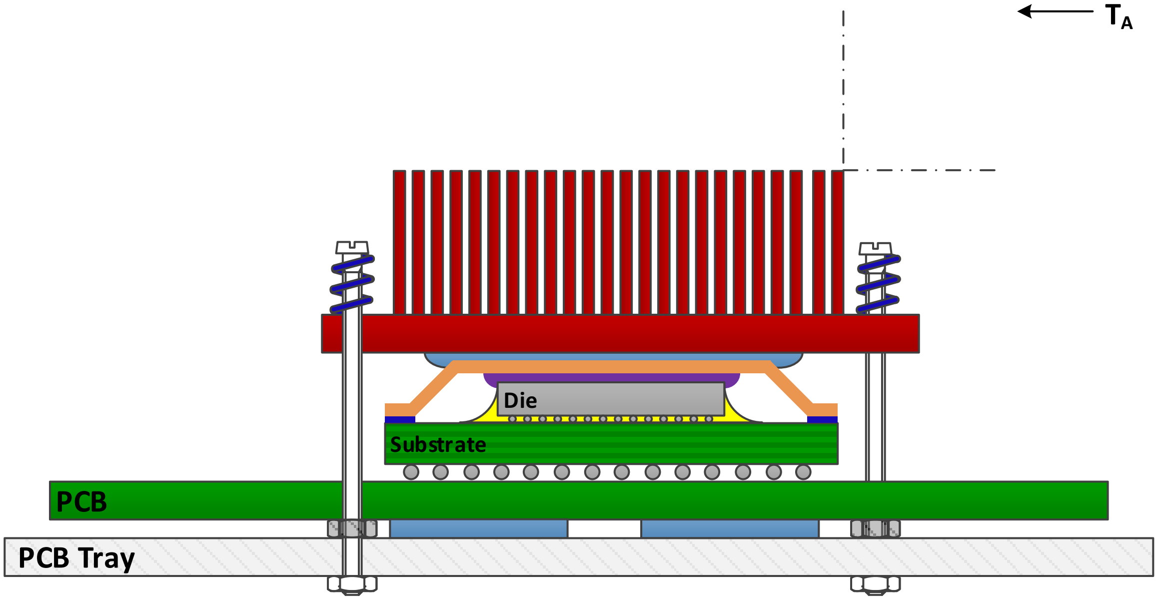
T_A represents the ambient temperature of the device. Working at ambient temperature (T_A) outside of the device requirements is considered overstress.

Unless the device data sheet specifies different values, the device ambient temperature requirements are:

- Commercial grade: 0°C to 70°C
- Industrial grade: –40°C to 85°C

The following figure is an example of a T_A measurement on a horizontal board. For the component, T_A should be defined within one inch upstream of the heat sink. For systems with forced-air cooling, the ambient air temperature of the system (not the device T_A) is defined as the air temperature at the system airflow inlet.

Figure 3: T_A Ambient Sensor



2.3 High-Power Device Thermal Design Considerations

2.3.1 Thermal Design Based Max Power and Deviation Between Devices

The system should be designed based on the maximum power specified in the data sheet. The following should be considered:

- Different devices may produce different current consumption and different power consumption, even under the same conditions.
- The maximum power specified in the device data sheet represents the power limit.
- For a flip-chip package, the primary heat dissipation path is through the top and bottom surfaces of the package (represented by θ_{JC} and θ_{JB}). For example, on the BCM88680, θ_{JC} = 0.12°C/W, and θ_{JB} = 0.32°C/W. Since θ_{JC} is much lower than θ_{JB}, it implies that most of the device power is dissipated through the package top.
- Different devices operating under different conditions will produce power deviations. Some devices will require more power, especially when temperature rise. For example, for the BCM88680, the max VDDC current delta between different devices and temperatures produced a maximum of ~24A, which translates to a ~24W difference.

NOTE: Large sampling and testing of devices is not considered to be a good representation for all possible device max power distribution during the device lifetime production. Only the max power specified in the device data sheet should be considered.

2.3.2 Junction Temperature System Design Target

Define the junction temperature design target, $T_{Jmax\_system\_target} = T_{J\_device} - \Delta T$, where:

- $T_{Jmax\_system\_target}$ is the customer target junction temperature, °C.
- T_{J_device} is the device junction max temperature, °C.
- ΔT is the customer target margin from junction, °C.

For example, on the BCM88680:

T_{J_device} is defined as 110°C, and ΔT is 10°C (assuming the customer wants a 10°C margin from the junction temperature). As a result, $T_{Jmax\_system\_target}$ is 100°C because 100°C = 110°C – 10°C.

2.3.3 Thermal Runaway

The current consumption of high-power devices increase exponentially with the device junction temperature.

It is important to note the following:

- For the system thermal design, be careful to avoid thermal runaway conditions by adding thermal safeguards and ensuring the device will not overheat for all ambient conditions.
- The system should continuously monitor the device junction temperature as well as current consumption, and if needed, cut off device power without delay to prevent the device from overheating or experiencing any other overstress conditions.
- The exponential change in current may be faster for some devices than others.
- An additional apparatus and method to monitor thermal runaway conditions for high-power devices may be necessary for some applications. Contact Broadcom if the application system has any thermal runaway issues that cannot be resolved.

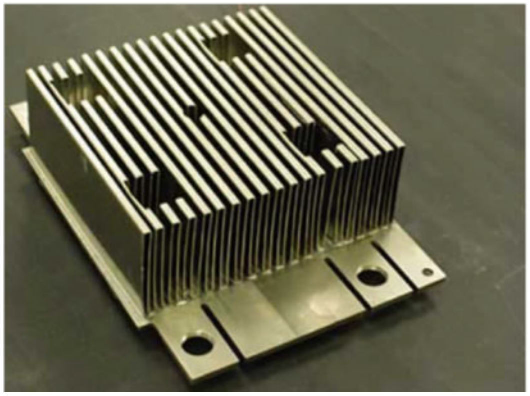
2.3.4 Heat Sink Selection Recommendations

Consider the following recommendations when selecting a heat sink:

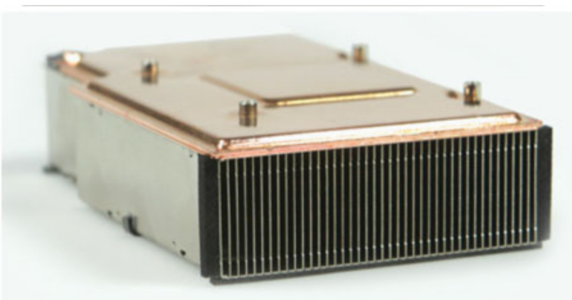
- To take advantage of low θ_{JC}, high efficiency heat sinks are recommended. Broadcom recommends a vapor chamber (VC) heat sink for its low thermal resistance.
- A separate heat sink is recommended for multiple devices on the same PCB. It enables better control of thermal interface (TIM2) thickness and coverage than sharing one heat sink.
- Using a spring-loaded screw-down heat sink is recommended for mechanically securing the attachment to the PCB tray.
- Using heat sink stand-off height control is recommended to prevent over tightening of the heat sink.
- For optimized force, perform a heat sink assembly evaluation test and reference the requirements of the heat sink and thermal interface supplier.
- Assuming most of the generated heat is dissipated through the package top, the heat sink can be designed based on application worst case total power, P, and thermal interface (TIM2) resistance between device and the heat sink. Example: BCM88680 total power P = 176W, ambient temperature is T_A =55°C, θ_{JC} = 0.12°C/W, and maximum allowed junction temperature is TJ = 110°C; therefore, the heat sink and TIM2 thermal resistance must be less than 0.19 °C/W.

The following figures show examples of a copper heat sink with a vapor chamber.

Figure 4: Copper Heat Sink with Vapor Chamber



Top View



Bottom View

Figure 5: General Heat Sink with Vapor Chamber

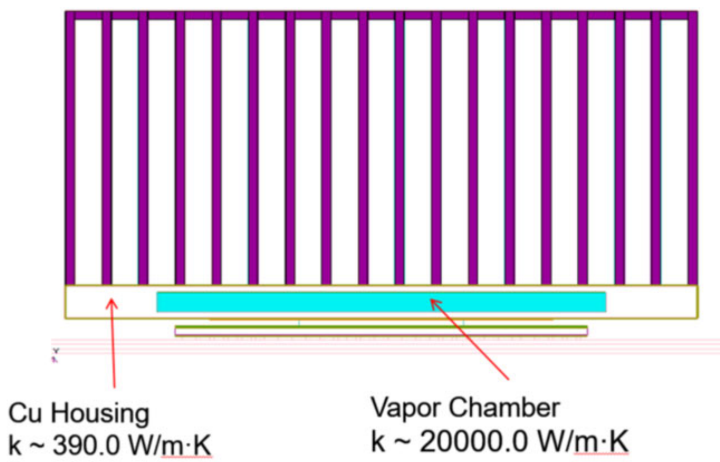
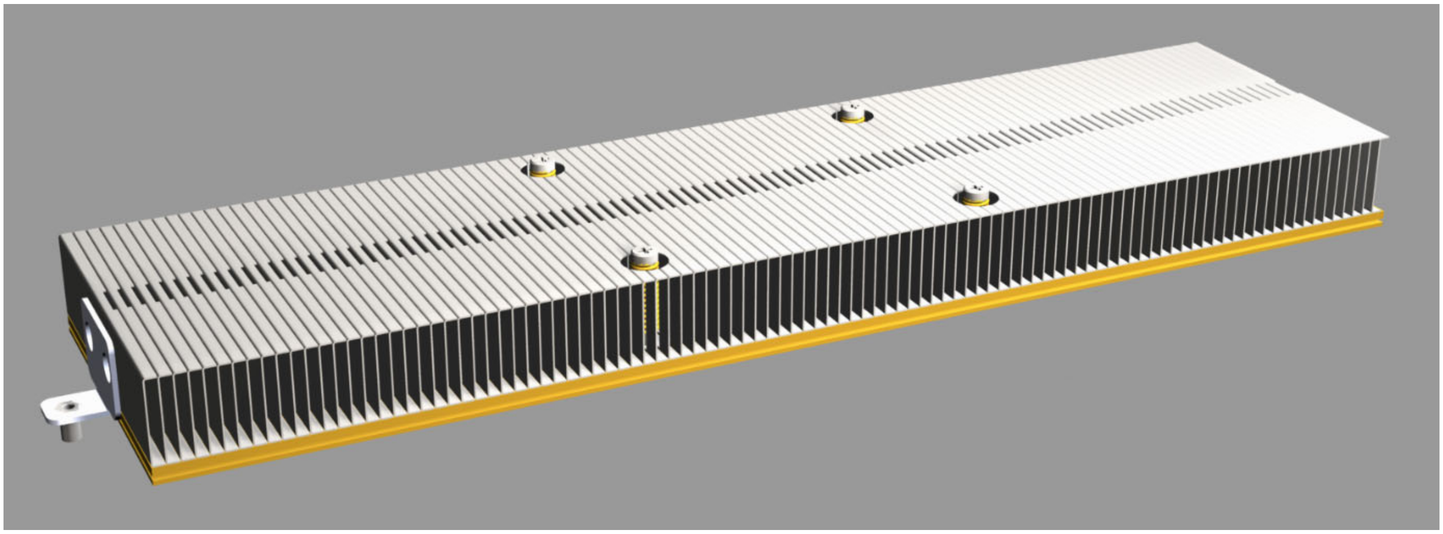


Figure 6: Folded Fin Heat Sink/VC Typical of the Size Used for > 275W Switch Devices



2.3.5 Airflow Design Recommendations

Use the following guidelines when designing the airflow for the system:

- The total airflow rate must meet the overall heat dissipation requirements for the system.
- Maximize the airflow through the heat sink. Heat dissipation should be modeled with CFD software to aid design.
- For designs with one device on the PCB:
  - Place the device heat sink at the airflow inlet or exit locations to maximize heat dissipation through the heat sink.
  - Consider using a ducted airflow design when placement of the device is not flexible.
  - If desired, use a heat pipe to place a condenser at the airflow inlet/exit.
- For designs with multiple devices on the PCB:
  - Ensure that the maximum junction temperature difference among the devices is less than 5°C.
  - Distribute incoming airflow evenly among device heat sinks for both air temperature and airflow rate.
  - Balance airflow resistances between the device heat sinks.
  - Minimize airflow bleeding above and from the side of the heat sink.

2.3.5.1 System Cooling Examples

The figures in this section show examples of techniques and methods for using:

- Air guides and ducting
- Plenums and remote pipes

Figure 7: Flexible Air Guide Example #1

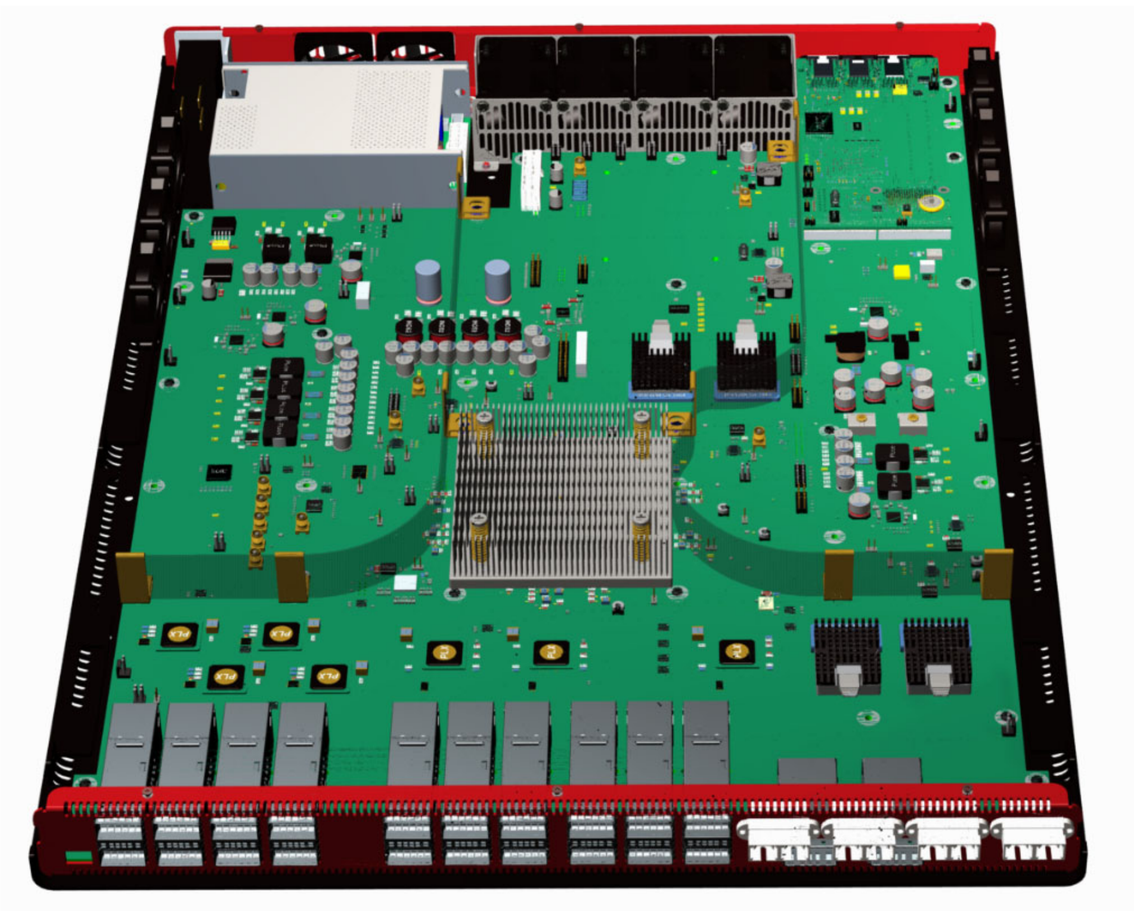


Figure 8: Flexible Air Guide Example #2

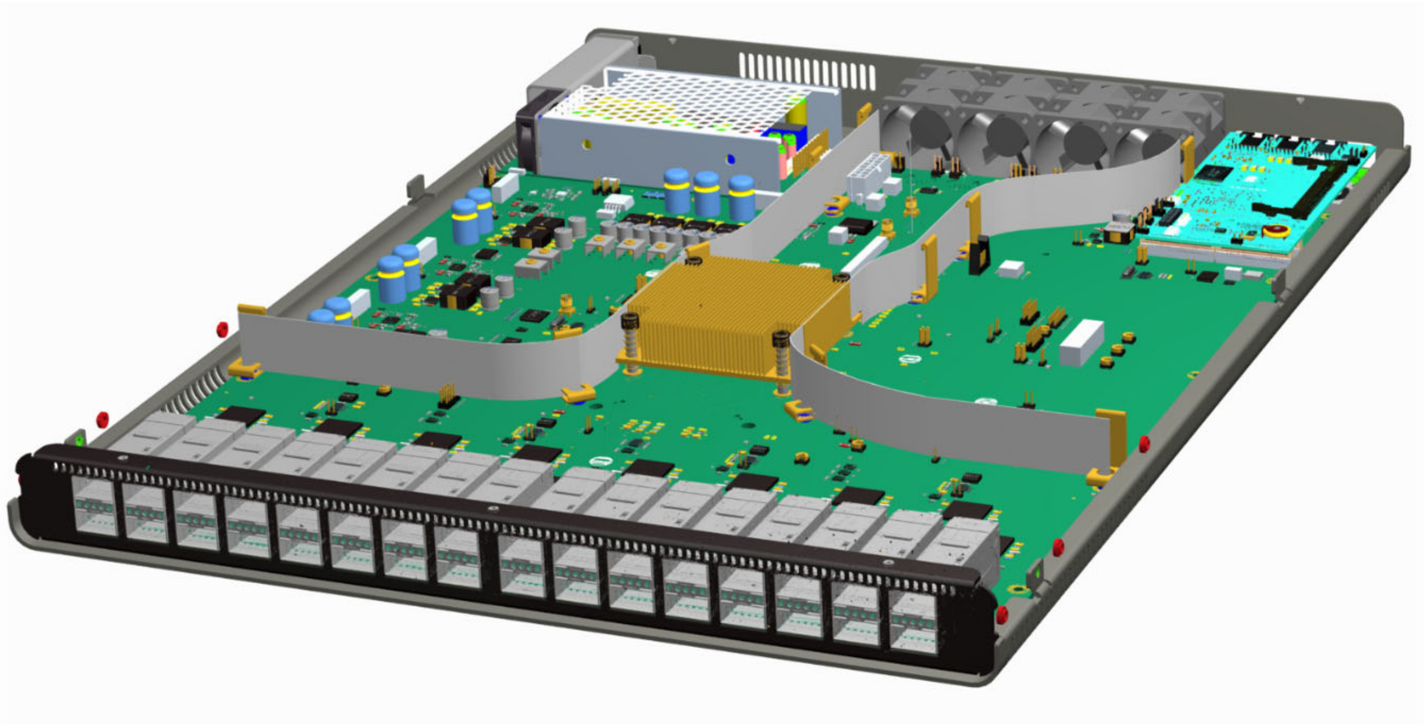


Figure 9: Remote Heat Pipe Example #1

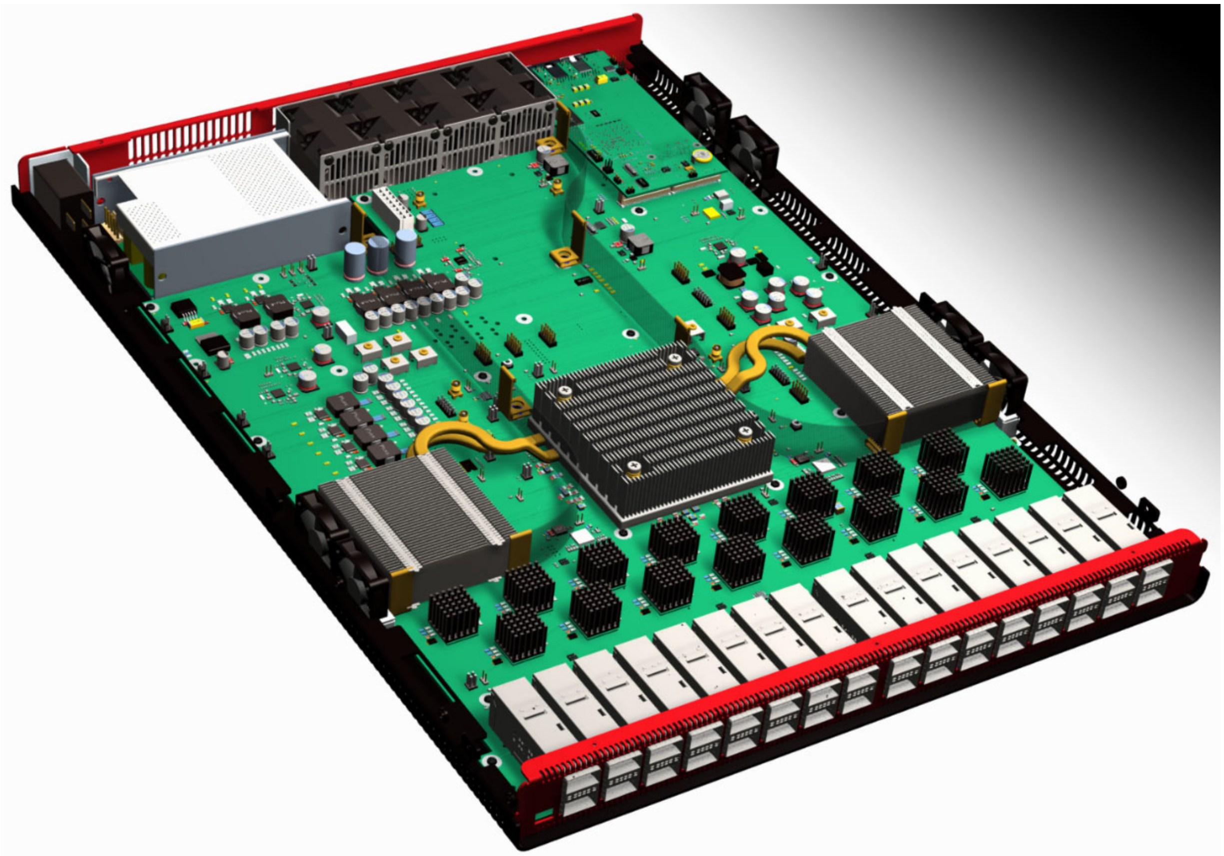


Figure 10: Remote Heat Pipe Example #2

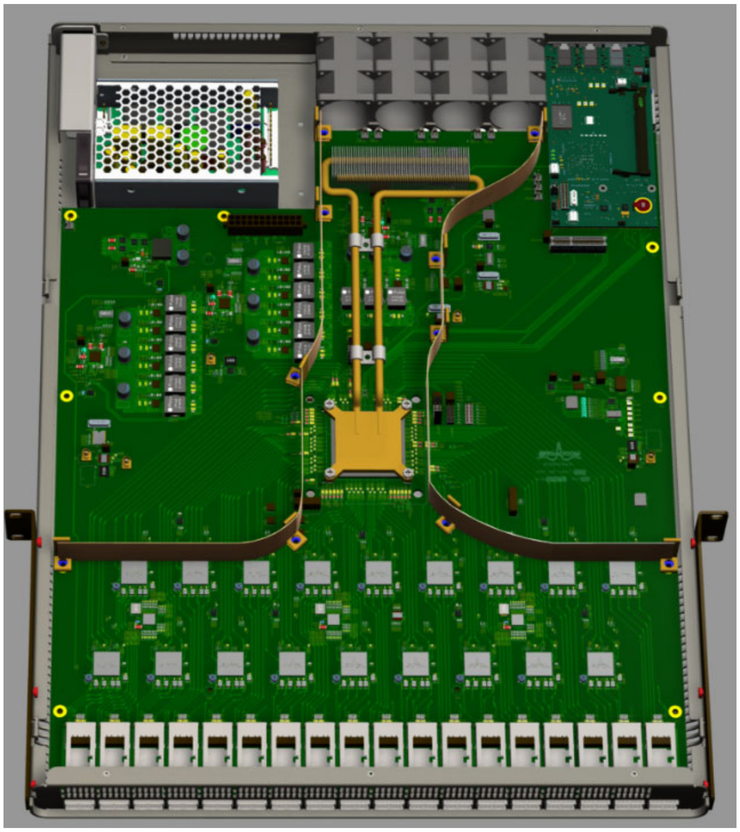
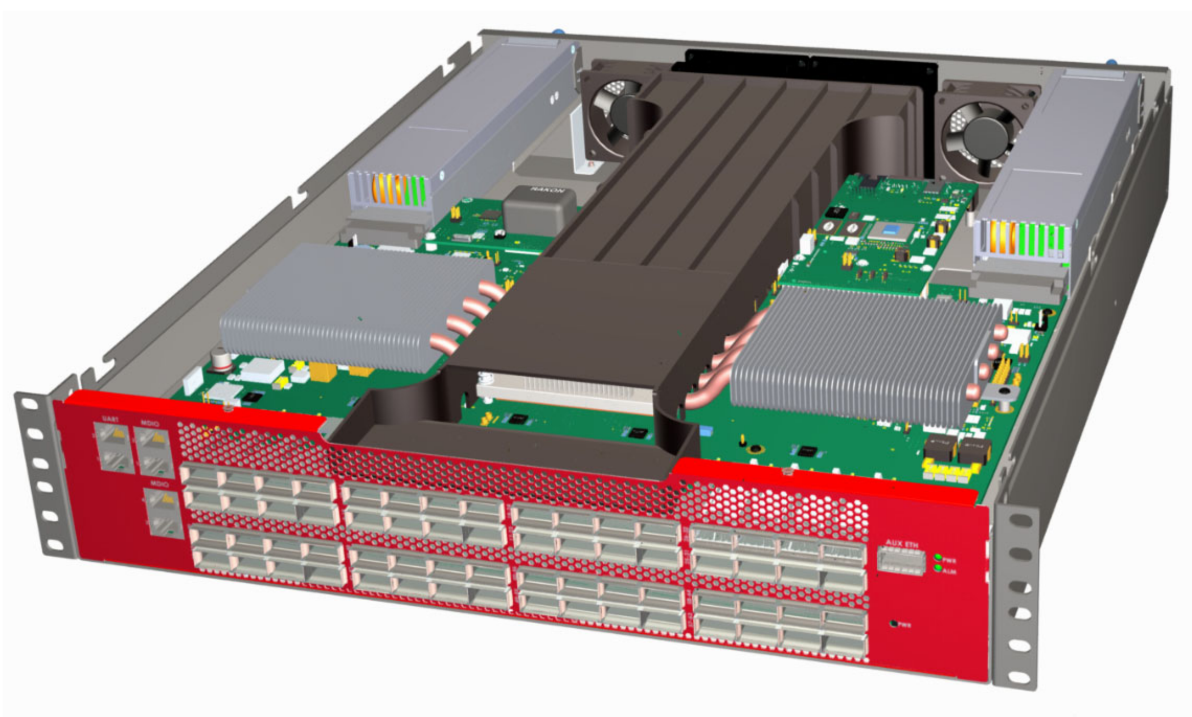


Figure 11: Remote Heat Pipe and High-Speed Air Plenum



2.3.6 TIM1 Thermal and Mechanical Overstress

The Broadcom TIM1 selection is a silicone-based material. The thermal performance of the material is expected to degrade gradually over the lifetime of the device. It is important to note that silicone-based materials degrade rapidly when exposed to temperatures in overstressed conditions. Over-temperature stress can increase the thermal resistance, and if the stress persists, it can result in further degradation and permanent failure. Also note that overstress has an accumulative effect on the material.

2.3.6.1 Assembly and Reflow TIM1 Effects

TIM1 temperature overstress can happen during device assembly on the PCB. The reflow profile and number of reflows can also have an impact on TIM1. To help avoid TIM1 and reflow issues, follow the device assembly guidelines and relevant standards.

2.3.6.2 Heat Sink Assembly TIM1 Effects

Thermal resistance of silicone-based TIMs are most sensitive to Bond Line Thickness (BLT) variations. As a result, the heat-sink assembly and loading can impact BLT. Follow the Broadcom heat sink recommendations to ensure optimum BLT and thermal performance in all device conditions. Guidelines and requirements for heat sink installation are in the device data sheet. For the BCM88680 device (for example), this information is in the “Heat Sink Attachment Considerations” section of the data sheet.

When attaching a heat sink, apply force uniformly on the device surface. Concentrated force on the device surface can cause die or package damage. For information about the maximum allowed sustained force and force during heat sink attachment, see the device data sheet.

Incorrect heat sink assembly may cause overstressing on TIM1 when there is excessive force on the device, which will permanently degrade the thermal performance.

NOTE: For a silicone-based TIM1, due to material density and BLT variation, CSAM (Confocal Scanning Acoustic Microscopy) anomalies are commonly observed—especially after component-level reliability testing. If such anomalies are observed after CSAM cross-section, it can often be verified that there are no major void/ delamination issues or issues with TIM1 or TIM1 BLT.

NOTE: If you suspect that a certain device does not meet specifications, Broadcom does not expect customers to perform CSAM, warpage measurements, or any other similar tests on the device package. Such devices should be returned to Broadcom for a failure analysis.

Make sure that the device returned for failure analysis is intact.

2.4 Temperature Cycles (T_C), Accelerated Testing, and Warpage

Temperature cycles are often used by the system vendor during production or reliability/accelerated tests and may happen during the device lifetime due to an ambient fluctuation.

NOTE: Performing an improper thermal cycle during the device lifetime may overstress the device.

2.4.1 Application Temperature Cycles

System vendors should be aware of industry standards such as JESD94 and IPC9701. When planning tests with thermal cycles, make sure the device is not overstressed per the application (server, telecom, networking, etc.) the device is targeted for.

For all applications, when performing temperature cycles, the device should meet the recommended operating condition specifications. For example, for high-end server applications, JESD94 specifies four cycles per year due to environmental conditions or power cycles, with an environmental temperature range between 10°C to 30°C and an operational temperature cycle range between 14°C to 55°C.

2.4.2 Temperature Cycles and Warpage

Temperature cycles cause warpage effects over the system, PCB, and devices. Temperature cycles can create accumulative stress effects on the system.

The Broadcom package should have compliance with:

- Room Temperature Coplanarity specification, JEP95
- High Temperature Warpage specification, SPP-024A

When temperature changes are applied on the device, control the warpage of the system as it undergoes changes to/from concave (smiling face) to/from convex (crying face).

Figure 12 shows the system at room temperature (7a) and high temperature (7b), changing from crying to smiling, respectively.

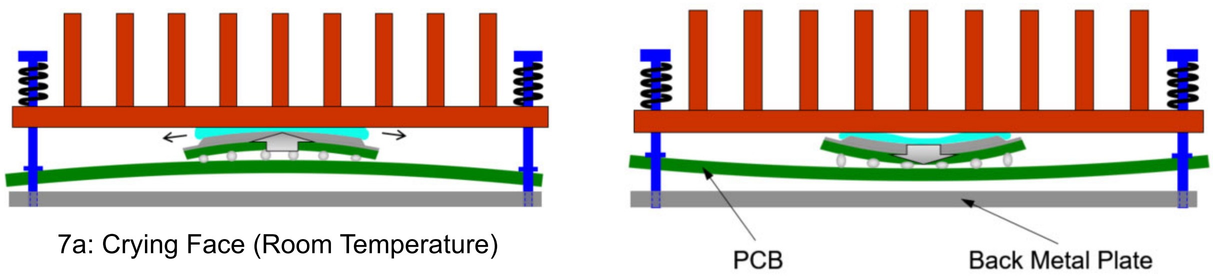
Room temperature:

- Crying face for both device and PCB.
- Device top surface squeezes the center area of TIM2 outward, which may lead to pump-out/loss of TIM2 from the contact interface.

High temperature:

- Smiling face for both device and PCB.
- May cause separation/cavity at the center area of TIM2, and may result increase of TIM2 thermal resistance.

Figure 12: Crying at Room Temperature (Left, 7a), Smiling at High Temperature (Right, 7b)



7a: Crying Face (Room Temperature)

7b: Smiling Face (High Temperature)

2.4.2.1 TIM2 Selection

Temperature cycles may affect TIM2 behavior and its characteristics due to PCB/component/heat sink CTE (Coefficient of Thermal Expansion) mismatch-induced warpage. As the temperature changes from low to high, the flip-chip device mounted on the PCB changes its shape from crying face (Figure 7a) to smiling face (Figure 7b). With each cycle of the temperature change, a small amount of TIM2 will be squeezed out of the heat sink contact footprint area. This phenomenon is called pump-out and it is typically irreversible. Over time, the TIM2 material at the contact interface center area will be lost at a level such that the TIM2 is not sufficient to bridge the gap between the device top surface and the bottom surface of the external heat sink.

Consider using TIM2 material pads designed to minimize pump-out at the device operating temperature range. Examples include: Laird TPCM 780, Laird TPCM AL52, and Chomerics T558.

Systems with a liquid TIM2 may be more exposed to pump-out of TIM2 material into the edges of device. This is due to warpage movements during temperature changes (see Figure 12). This movement is especially accumulated during accelerated test with temperature cycles. When TIM2 material migrates beyond the contact area, thermal performance will be degraded permanently, and thermal resistance will be increased. To fix the issue, TIM2 must be replaced.

2.4.2.2 Thermal Pad and Accelerated/Reliability Test

While performing an accelerated test with temperature cycles, it is recommended to reduce the warpage during the temperature changes by adding a thermal pad at the device footprint site between the back surface of the PCB (in the device area) and the stainless steel PCB tray. The thermal pad plays the roles of:

- Mechanical backing, to minimize PCB warpage during temperature change
- Improve thermal dissipation

2.4.2.3 Heat Sink Mounted on PCB Tray

If the heat sink is mounted on a PCB tray with screws (and not mounted to the PCB), the heat sink is able to have a little horizontal movement. In this case, the heat sink warpage does not follow PCB/device warpage.

2.4.3 Temperature Cycles for Accelerated Tests

Accelerated tests are used for stress and reliability tests and should be considered differently than production tests or normal operational conditions.

Accelerated test might reduce the device lifetime, might reduce long-term reliability, and might cause device performance degradation—even during the test.

When planning accelerated tests with thermal cycles, system vendors should be aware of industry standards such as JESD94, IPC9701, IPC-SM-785, and also JEDEC 150.01, JESD471-01, JESD22-A104D, and JESD22-A105D, and make sure the device is not overstressed per the application the device is targeted for.

For example, even if the device supports an industrial grade temperature range, simply cycling from –40°C to 85°C is not permitted by industry standards—even if monitoring the junction temperature during the test, and no T_J max violation occurred. As a further example, IPC-SM-785 for telecom applications specifies {ΔT = 35°C, T_D = 12 hours} during a normal test, while in an accelerated test {ΔT = 100°C, T_D = 15 min}.

2.5 Engineering-Sample Devices

Devices shipped before the Product Release Authorization (PRA) are not finalized and considered as engineering-samples.

Pre PRA:

- Devices may exceed max power as defined in the data sheet because the power screening tests are not yet defined or have not been finalized.
- The device package is subject to changes, such as a BOM change or dimension change. These changes may have an impact on the device thermal and mechanical behavior. Anyway, the thermal and mechanical properties of the device are not guaranteed before PRA.
- Devices may have a wide span in the current variance since mechanisms such as ROV/AVS are not implemented or finalized yet. Operation in suboptimal voltage can create a larger power variance between devices. For example, power measurements done on the BCM88680, pre PRA, showed a ~30A variance between devices when ROV was not implemented.
- Device assembly and SMT guidelines are not finalized (because the warpage study is not finalized).

All the above may affect the device thermal performance and behavior in different environmental conditions. It is likely that the data sheet will be updated during the pre-PRA period based on actual device measurement results and qualification test results.

Post PRA:

- Devices meet the max power value defined in the data sheet.
- ROV/AVS is finalized. Power deviation between devices is smaller. For example, BCM88680 showed about ~10A deviation between devices with the same ROV.
- The package is finalized and has completed qualification.
- Device assembly and SMT guidelines are finalized (because the warpage study is finalized).

Appendix A: T_C Measurements Notes

For customers who decide to perform T_C measurements, this appendix includes some guidelines for high-power device case temperature measurement.

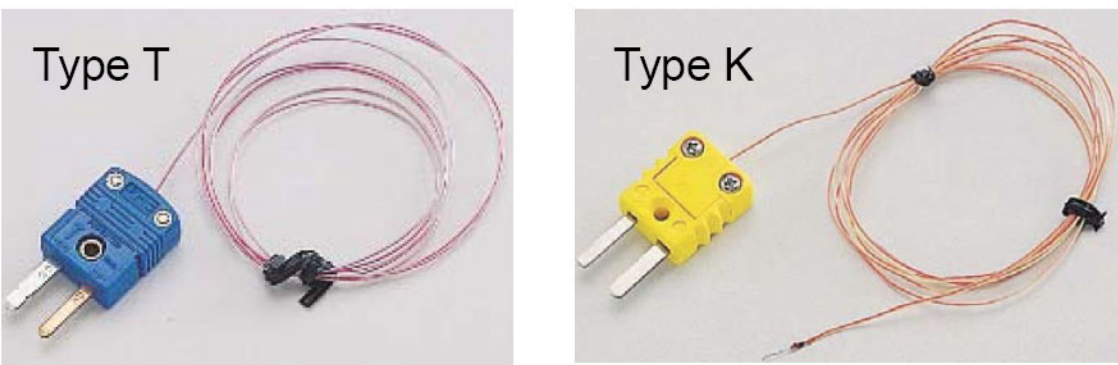
NOTE: Broadcom does not expect customers to be able to accurately measure T_C since it is prone to measurement errors and often is not sufficiently reproducible. Measuring T_C on an application board usually produces erroneous results that do not help in investigating application system thermal issues.

Thermocouple (T/C) requirements for component-case temperature measurement include:

- Type T (copper-constantan) or Type K (chromel-alumel). See Figure 13.
- ANSI color codes
  - Type T, blue connector
  - Type K, yellow connector
- 40 to 36 AWG

NOTE: The thermocouple can be ordered from Omega Engineering or THERM-X.

Figure 13: Thermocouple ANSI Type T and Type K Examples



Thermocouple (T/C) mounting location guidelines:

- Attach T/C at the package top center
- The T/C junction bead must be in contact with the package case surface.
  - Air temperature is measured when the T/C bead is not in contact with the part surface.
- Thermocouple wires should be laid along the top surface of the package case.

Guidelines for thermocouple (T/C) mounting for a heat sink attached with silicon or liquid TIM2 (no thermal tape):

- Machine a groove of 0.5 mm width and 0.5 mm depth on the heat sink bottom surface for the T/C wire route-out (see Figure 14).
- Fill the tip of the groove with a filler material (gap filler or thermal tape: thermal conductive materials) to press the T/C bead against part of the top surface (see Figure 15).
- Use the same TIM2 material placement as in production before reattaching the heat sink.
- Do not drill the heat sink (see Figure 16).
- Do not use Kapton tape to attach the thermocouple bead to the case (see Figure 17)

Figure 14: Heat Sink Machine Groove

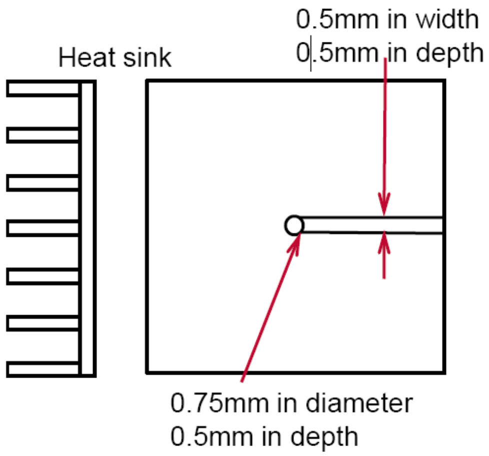


Figure 15: Thermocouple Bead Filler

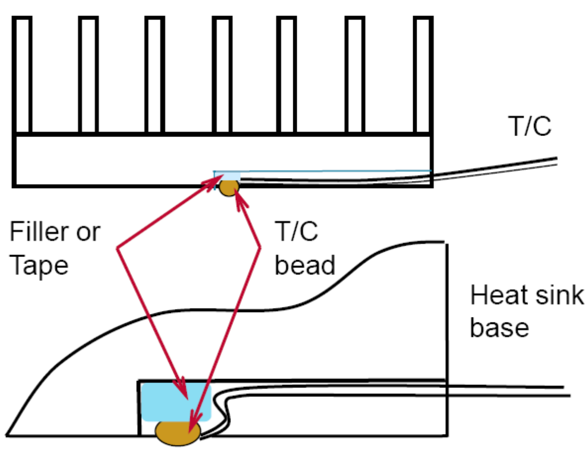


Figure 16: Do Not Drill the Heat Sink

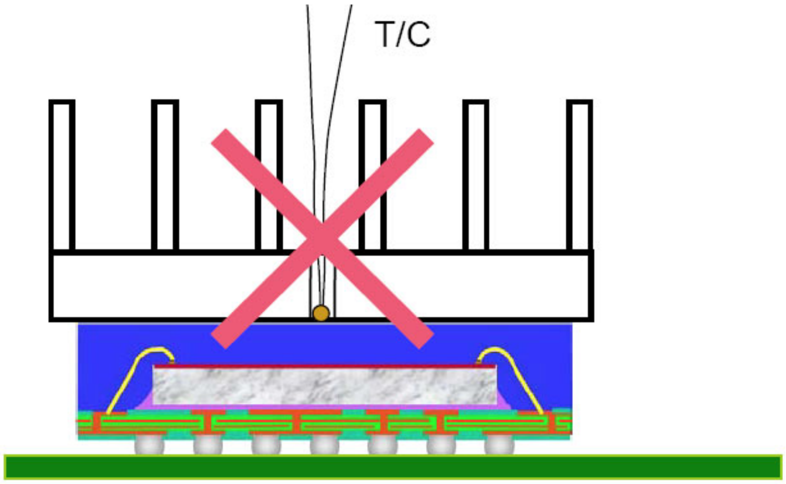


Figure 17: Do Not Use Kapton Tape

Thermocouple and thermometer measurement guidelines:

- Be sure to set the correct type of T/C in the thermometer.
  - Check the T/C type against the setting in the thermometer.
- Ensure the T/C and thermometer are calibrated.
- Perform a temperature probe check before testing.
  - Check all T/Cs against room air temperature (or skin, or ice water) to make sure the probe temperature readings make sense.
- Typical T/C temperature reading accuracy:
  - ±1°C for a T/C with a high-purity wire (recommended).
  - ±2°C for a T/C with a standard-grade wire.
- Keep good contact between the T/C junction bead and the package surface.
- The T/C junction bead must be pressed against the package surface.
- Make sure the test reaches a thermal steady state before taking temperature readings:
  - Typically, a test can take more than around 20 to 40 minutes to reach steady state.

Appendix B: Resources

The following JEDEC and IPC specifications may be used in conjunction with this document and other Broadcom documentation:

- JEDEC, *Temperature Cycling*, JESD22-A104
- JEDEC, *Stress-Test-Driven Qualification of Integrated Circuits*, JESD47
- JEDEC, *Application Specific Qualification Using Knowledge Based Test Methodology*, JESD94
- JEDEC, *High Temperature Storage Life*, JESD22-A103D
- JEDEC, *Two-Resistor Compact Thermal Model Guideline*, JESD15-3
- JEDEC, *Transient Dual Interface Test Method for the Measurement of the Thermal Resistance Junction-to-Case of Semiconductor Devices with Heat Flow Through a Single Path*, JESD51-14
- IPC, *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*, IPC9701
- JEDEC, *Reflow Flatness Requirements for Ball Grid Array Packages*, SPP-024A

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