Whitepaper

Effective Thermal Management for High-Power PCB Applications

Authors

Dan Miklovic (Third Eye Advisory)

Dr. Ambika Omprakash (Tech Mahindra)

Palani Elumalai (Tech Mahindra)

Executive Summary

Advances in semiconductor technology have led to the use of powerful electronic systems, placing greater thermal demands on high-power printed circuit boards (PCBs). Poor heat control can affect system reliability, performance, and operational lifespan.

In this paper, we examine the role of thermal planning and the temperature dependence of component reliability. We even evaluate active and passive cooling techniques, material selection, optimization techniques for PCB layout design, and various simulation approaches for heat dissipation. Basic calculations and thermal management hardware, including heatsink requirements, thermal interface materials (TIMs), and surrounding cooling structures, are also discussed. The whitepaper reviews methodologies to identify thermal considerations at the first stage of the design cycle to improve overall system effectiveness. [1.1]

When thermal considerations are addressed at the initial design stage, engineers can reduce failure risks, improve heat distribution, and enhance system endurance, especially in high-performance computing and industrial applications.

Introduction

With the continuous advancement of electronic systems, efficient thermal management in PCB design has become crucial. Due to the miniaturization of devices and the rise of power densities in compact spaces, traditional cooling techniques cannot keep up, especially for modern high-performance applications. Maintaining thermal reliability is especially important in systems operating under demanding conditions, like electric vehicles, 5G infrastructure, industrial automation, and IoT platforms, as they require robust heat control.

Technologies, such as AI, ML, and high-performance processing, depend on high-speed processors and RAM/flash memory that generate substantial heat. If heat dissipation is not properly planned and implemented, excessive temperatures can lead to component failure, signal degradation, reduced device lifespan, and potential safety hazards.

Several factors influence thermal management in PCBs, including heat generated by power-intensive components, such as microcontrollers, processors, and power MOSFETs. Copper trace resistance under high-current conditions affects board heating, while the thermal conductivity of the materials determines how effectively heat is transferred away from critical areas. Therefore, the PCB substrate material plays an important role.

Although FR-4 is widely used for its low cost and strong electrical properties, its relatively low thermal conductivity is insufficient for efficient heat dissipation in high-power or high-density designs.

The placement of high-power components and the routing of traces on a PCB layout also affect the overall performance. The components should be strategically placed to avoid localized heating and ensure uniform heat distribution across the PCB. Proper spacing improves airflow between components. Meanwhile, thermal relief pads with calculated spoke widths and copper pours in appropriate areas help spread heat more efficiently. Environmental conditions, ambient temperature, and airflow further influence PCB performance.

The enclosure design can either support or hinder effective heat dissipation. As a result, ventilation paths and airflow must be factored during the mechanical design phase.

Effective Thermal Management Approaches in PCBs

Selection of PCB Material

Effective thermal management begins with selecting the right PCB substrate material. Aluminum, copper, and ceramic substrates offer substantially better heat dissipation than the traditional FR-4 due to their higher conductivity.

To address the heat challenges in electronic systems, insulated metallic substrates (IMS) are widely used in high-power applications.It consists of a metallic base layer, typically aluminum or copper, with a thickness of 0.5-3.0 mm. Above this base is a dielectric layer, around 30-150 µm thick (as shown in Figure 1), with a higher thermal conductivity than FR-4. A copper design layer then tops the dielectric layer, forming a structure that allows efficient heat conduction.

applications such as LED drivers and power electronics, as it has a shorter thermal path through the dielectric, and the inherent conductivity of the metallic base offers strong heat dissipation

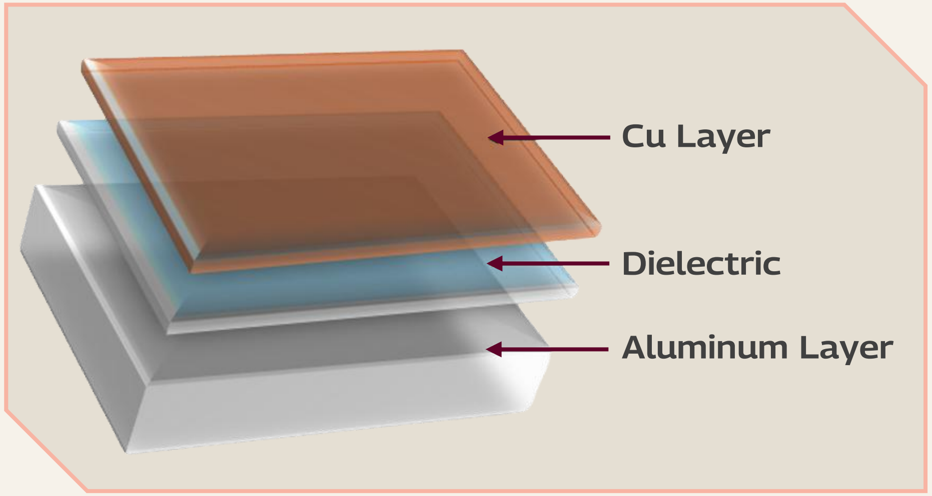


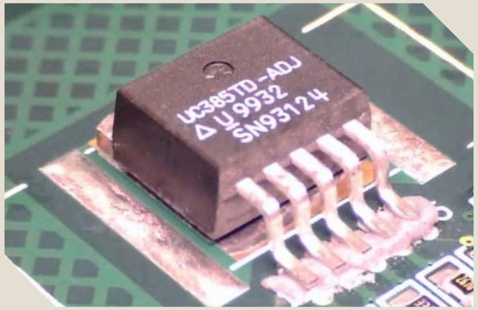
Figure 1: Aluminum-based PCBs

PCB Layout Optimization

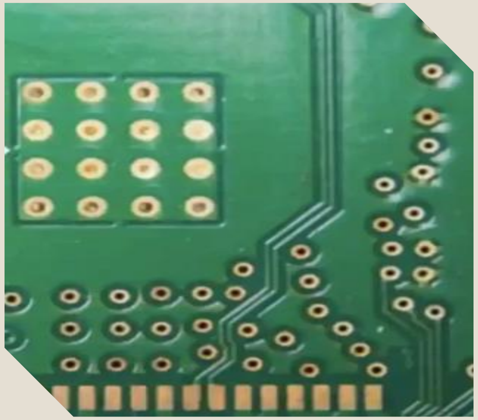
Given the temperature and heat challenges, the PCB layout must be carefully designed to enhance performance. Adhering to IPC standards is essential for effective heat dissipation. To support proper airflow, high-power components should be placed away from sensitive components, with adequate spacing between them.

Thermal relief pads (as shown in Figure 2a) help reduce thermal resistance between components and the PCB, while strategic copper pours in available areas act as heat spreaders. Thermal vias (as shown in Figure 2b) play an important role in transferring heat between PCB layers. The via size, quantity, and placement should be determined based on the actual heat load. For better conductivity, filled vias can be used, but they are costlier than standard through-hole vias.

Using vias with vertical conduction paths, via-extended thermal pads, or a combination of both reduces heat accumulation. Moreover, increasing the copper thickness across PCB layers improves heat dissipation and helps reduce localized hot spots.



(a)



(b)

Figure 2(a). Thermal Pads & 2(b). Thermal Vias

Cooling Systems and Heat Sinks on PCB

Heat sinks are commonly used to manage high thermal loads. To ensure proper heat dissipation into the surrounding air, heat sinks are connected to high-power components, such as power metal-oxide-semiconductor field-effect transistor (MOSFETs), regulators, and processors. Thermal interface materials (TIMs), including pastes and pads, improve heat transfer between heat sinks and high-power components. Cooling fans and blowers (shown in Figure 3) can further boost cooling performance.

The conditions to use heatsinks are based on the calculations below.

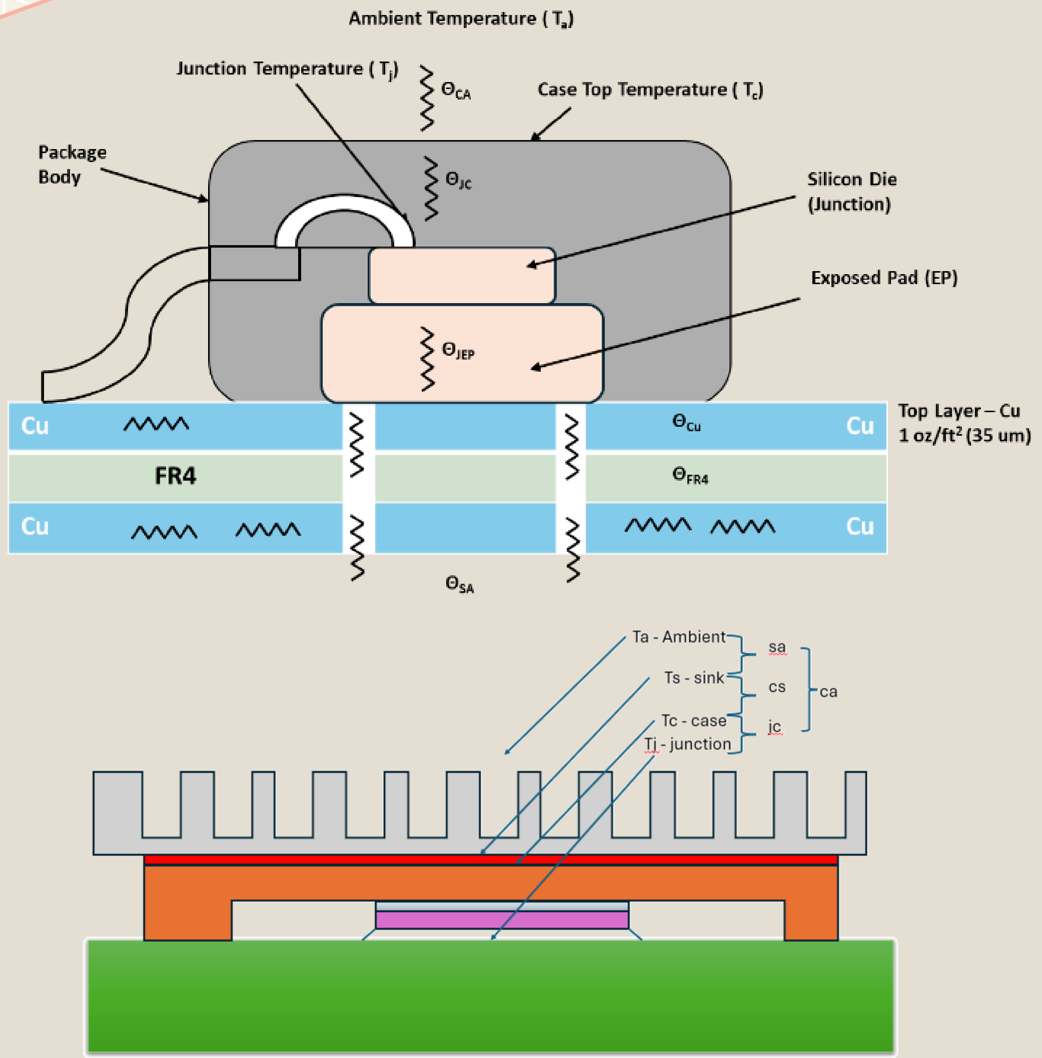
The junction temperature of a component without a heat sink is calculated based on the calculations below:

TJ = Ta +Pd x θJA ---(1)

If calculated TJ > specified max allowable TJ.max from the datasheet of the component, then need to place the heatsink.

θJA (with heatsink) : θJC + θCS + θSA = (Tj – Ta)/P -------------------------(2)

- θCS = case to heatsink resistance ; based on Thermal Interface material
- θSA = heatsink to ambient thermal resistance
- θSA = (Tj.max –Ta) /P - θCS - θJC



- θ = Thermal Resistance (°C/W)
- P = Total Device Power Dissipation (W)
- T = Temperature (°C)
- ΔT = Temperature Differential = $P \times \theta$
- θ_{JA} = Junction-Ambient Thermal Resistance
- θ_{JC} = Junction-Case Thermal Resistance
- θ_{CA} = Case-Ambient Thermal Resistance
- $\theta_{JA} = \theta_{JC} + \theta_{CA}$

Figure 3: Cooling Structure on the Case with the Heatsink and Cooling Fans

Cooling Systems and Heat Sinks on PCB

To predict and optimize PCB performance, simulations are performed using tools like SIwave, ICEPAK, and HyperLynx. The finite element analysis (FEA) technique is used to model heat transport within the board and identify possible hotspots. This helps designers make informed decisions early in the design process.

Computational fluid dynamics (CFD) models are used to evaluate cooling efficiency and airflow patterns. They optimize component placement, heat sinks, and cooling fans for better efficiency. These simulation tools can be applied at various design stages, including component placement, partially routed layouts, and fully routed PCBs.

Different heat-transfer modes, such as conduction, convection, and radiation, are modeled to generate temperature profiles and thermal gradients (as shown in Figure 4). These simulation-based evaluations give precise thermal validation during the PCB layout phase and reduce the number of iterations.

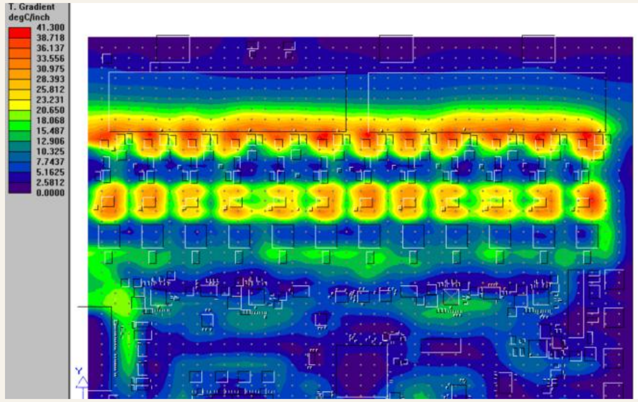
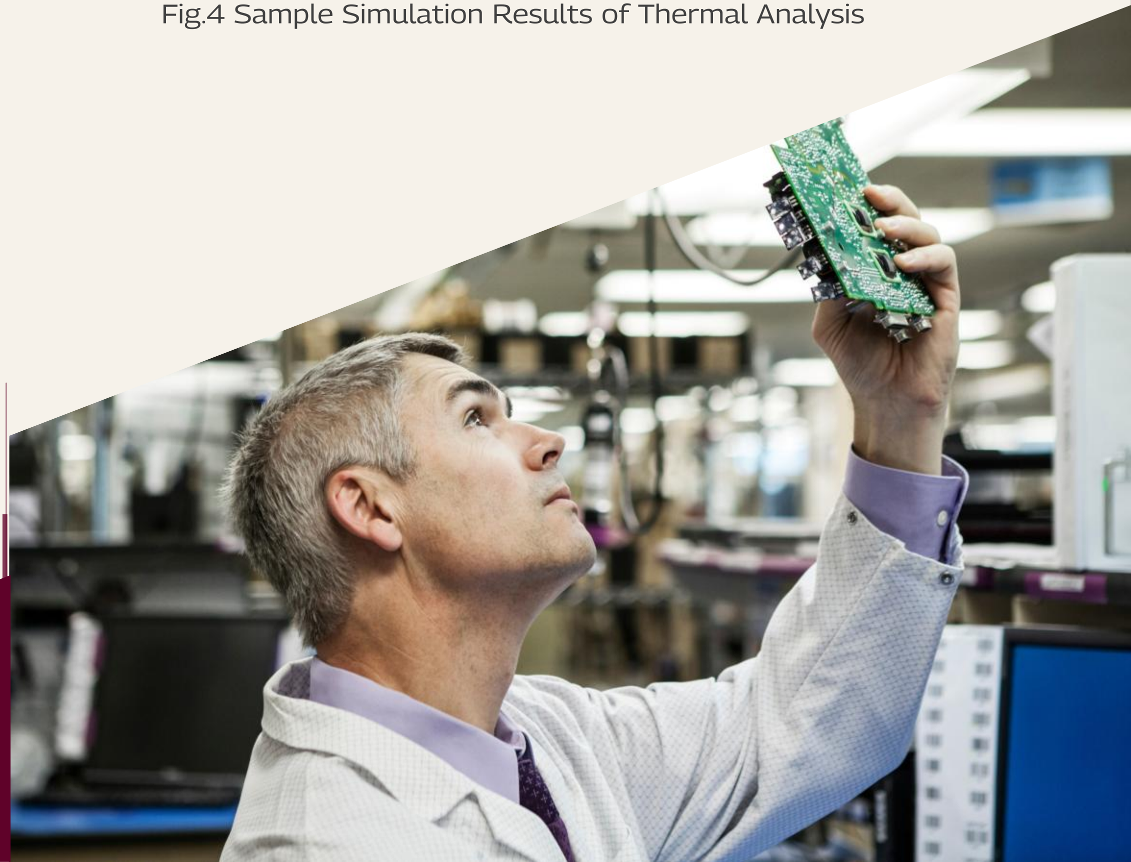


Fig.4 Sample Simulation Results of Thermal Analysis



Advanced Methods for Effective Thermal Reliability

Emerging technologies are advancing high-power thermal management in PCBs, proposing novel approaches to address the limitations of traditional cooling methods. One such technique is embedding high-power components directly within the PCB substrate to minimize thermal resistance. Overall heat dissipation improves by reducing the heat-conduction path. This technique also provides space savings and improved electrical characteristics.

Another emerging approach is additive manufacturing, which enables the fabrication of custom-designed heat sinks and cooling structures tailored to specific PCB dimensions. This allows designers to optimize solutions in the aerospace, automotive, and wearable consumer electronics industries, where conventional cooling methods may be less effective.

Phase change materials (PCMs) are increasingly used for their ability to absorb and release heat during phase transitions, providing passive cooling without the need for active systems. They are particularly effective in maintaining temperature stability and preventing thermal spikes.

Graphene and carbon nanotube materials are also being actively studied for their exceptional thermal conductivity, which is much higher than that of traditional materials. These drastically reduce thermal resistance and improve performance in compact, high-density applications.

Modern devices use advanced methods to improve performance and prevent overheating. For example, Apple's iPhone 17 Pro features an improved vapor chamber cooling system that works with the aluminum chassis to efficiently transfer heat away from critical components. It leverages phase-change cooling, where heat from the chip produces deionized water inside a sealed chamber to evaporate into vapor. Next, it moves to cooler regions, carrying the heat load. The vapor then condenses back into liquid and returns to the heat source through a taper-similar structure. This creates a continuous sequence of heat transport, absorption, and dissipation that prevents hot spots and thermal throttling during challenging tasks.

Conclusion

The demand for effective heat dissipation continues to increase as electronic devices become smaller and denser to achieve high performance. This makes thermal management in PCB design challenging, as it requires a comprehensive approach that spans material selection, layout optimization, heat sink integration, advanced cooling techniques, and the use of various thermal interface materials.

Both conventional and advanced management strategies have been examined, supported by analytical methods and simulation-based evaluation techniques. Advances in high-conductivity materials and innovative cooling solutions are expanding the design space for high-performance PCBs, while sustainable interface materials and recyclable substrates are enabling more environmentally responsible designs.

Meanwhile, eco-friendly interface materials and recyclable substrates are also introduced to support sustainable design practices. By applying the techniques discussed above, engineers can develop modern PCBs that meet the demands of modern electronics while maintaining high reliability and excellent performance.

Going forward, high-power PCB designs will depend on early thermal integration, supported by simulation-driven optimization and advanced materials.

About the Author

Dan is recognized as a thought leader and one of the top market place influencers in the Asset Performance Management and Manufacturing Operations sectors. His coverage spans across all forms of heavy industry from A&D to Utilities and covering topics such as MES, EAM, QMS, PLM, EH&S, and Al/ML as applied to industrial operations. Dan is involved in both professional and amateur auto sports as an emergency services official and race operations director. He is heavily involved In the start-uc community as a mentor and advisor for entrepreneurship programs at Lindenwood University, Washington University, University of Missouri - St. Louis and the eFactory program at Southwest Missouri University helping clients to validate product strategies and develop business plans to entice investors.

Dan Miklovic

Expert Advisor
Third Eye Advisory

About the Author

Dr. Ambika Omprakash is an Electronics Hardware Design Specialist with over 19 years of experience across industrial, research, and academic domains.
She brings deep expertise in end-to-end hardware development, system integration, and advanced technology implementation. Dr. Omprakash holds a Doctorate in Nanoelectronics and is known for her focus on innovation, precision engineering, and cross-disciplinary collaboration. She has published 10 international journal papers and presented 9 papers at international conferences, contributing significantly to advancements in nanoelectronic systems and applied hardware technologies.

Dr. Ambika Omprakash

Technical Manager,
Tech Mahindra

About the Author

Palani Elumalai serves as the Head of the Industry Business Unit (IBU) and Global Delivery Head for semiconductor and hi-tech at Tech Mahindra across India, North America, Europe, and Asia. With over 35 years of experience in global delivery excellence, he brings exceptional leadership and deep technical expertise in managing complex, large-scale engineering programs. Palani has an outstanding record in innovation, having co-developed more than 50 patents in collaboration with customers. He has also contributed over 230 technology papers submitted to leading engineering conferences in the semiconductor and hi-tech domains. His career reflects a strong commitment to advancing engineering capabilities, driving innovation-led transformation, and delivering high-value outcomes for global customers.

Palani Elumalai

IBU Head & Global Delivery Head,
Tech Mahindra

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*Figures as per Q3, FY 26.

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