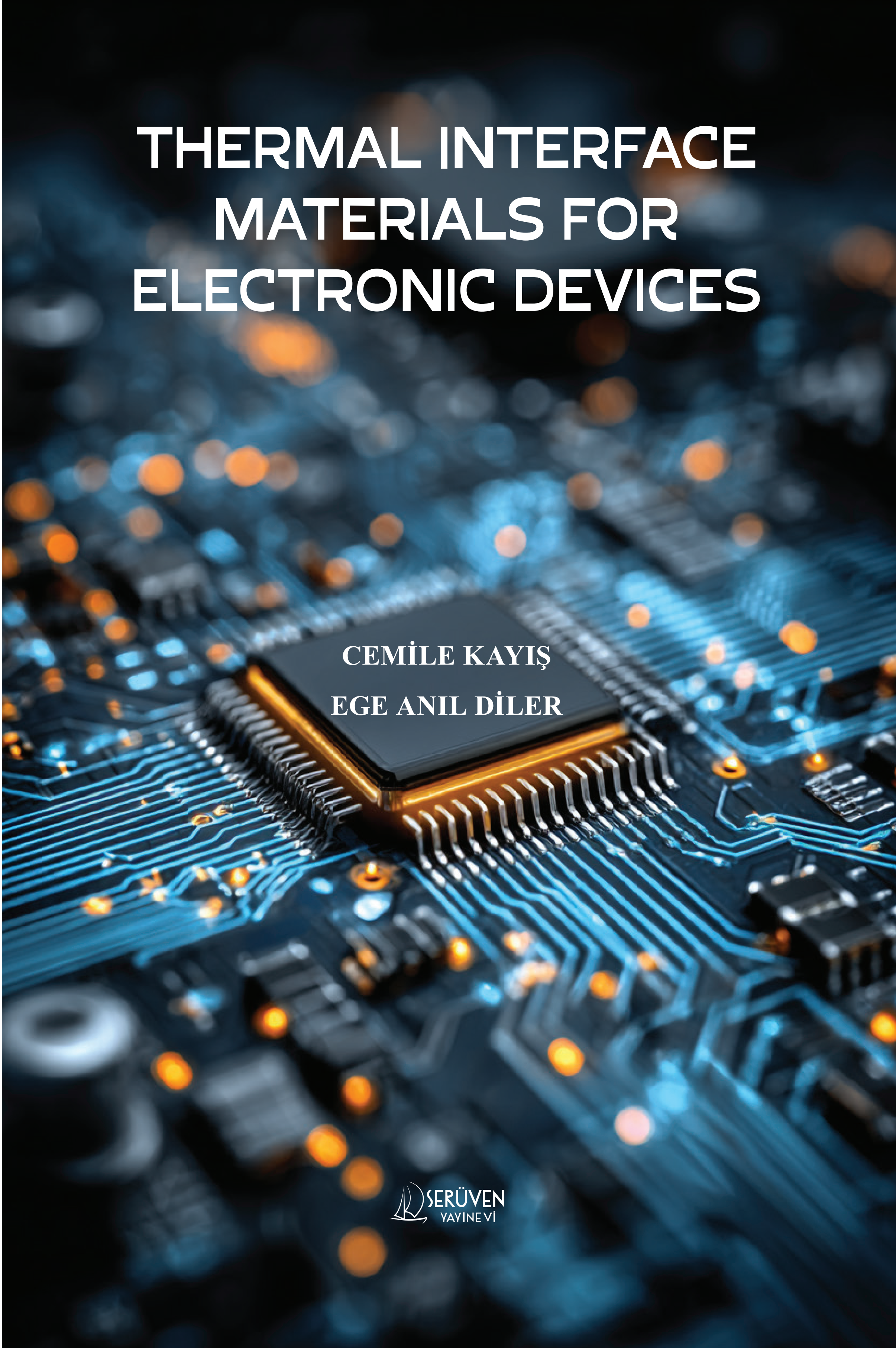

THERMAL INTERFACE MATERIALS FOR ELECTRONIC DEVICES

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PREFACE

The digital age, characterized by unprecedented connectivity and processing power, has integrated electronics into the very structure of daily existence. From the compact processors in portable devices to the colossal servers powering global data streams, reliance on high-performance electronic devices is absolute. Yet, this remarkable ascent brings with it an inherent, often understated, challenge: the efficient management of the heat these complicated systems inevitably generate. This book, "Thermal Interface Materials for Electronic Devices", stands as a testament to the critical importance of overcoming this thermal hurdle.

Engineers design chips, circuit boards, and cooling fins, only to find that the most stubborn limitation to heat dissipation often lies in the microscopic space between these perfectly designed components. It is in this imperceptible gap that air, a surprisingly potent insulator, traps heat, threatening to throttle performance or, worse, shorten the lifespan of vital electronics. The authors felt a compelling need to illuminate this often-overlooked yet critical interface, providing a resource that spans the fundamental science to the very forefront of material innovation.

This book is structured to offer a comprehensive explanation for anyone keen to master the complexities of thermal interface materials. It begins by unearthing the fundamental thermodynamic principles that govern heat flow and revealing the precise nature of thermal contact resistance, the adversary TIMs are designed to defeat. From there, a detailed examination of the diverse families of TIMs themselves is undertaken: the viscous efficiency of thermal pastes, the practical versatility of thermal pads, the compliant adaptability of gap fillers, the dual functionality of thermal adhesives, and the elegant thermal responsiveness of phase change materials. Each type is dissected, not just for its performance, but for the intricate material science behind its operation, delving deep into the impact of filler characteristics, matrix properties, and interfacial interactions.

Crucially, this is not merely an overview of existing solutions. A critical outlook is cast toward the horizon, examining the pioneering advancements shaping the future of TIMs. Readers will discover the promise of novel materials like advanced graphene and boron nitride nanostructures, alongside the intriguing possibilities of composites and complex hybrid architectures. Revolutionary manufacturing techniques are presented, including the precision of 3D printing, poised to redefine TIM application. The very concept of smart, adaptive, and self-healing TIMs suggests an exciting fundamental change, where materials dynamically respond to thermal stress. Finally, recognizing the widespread occurrence of thermal challenges, the scope broadens to illustrate the indispensable role of TIMs across a vast spectrum of industries. This ranges from the rapid cycles of consumer electronics to the extreme demands of automotive systems and the demanding requirements of industrial power applications.

This book is crafted for a wide audience: for students eager to grasp foundational concepts, for engineers seeking practical solutions to complex design problems, and for researchers extending the boundaries of material science.

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Introduction

The innovation in the sphere of modern electronics has led to a period of unprecedented computational power, reduced size, and increased complexity. From the common mobile devices that seamlessly connect our lives to the vast server farms that power the global digital infrastructure, electronic components are constantly challenged to their performance limits. This profound technological acceleration, however, introduces a formidable and often underestimated engineering imperative: the careful management of waste heat. As integrated circuits perform increasingly intricate operations at higher clock speeds and with greater energy density, they invariably generate substantial amounts of thermal energy. Without intelligently designed and highly efficient heat dissipation mechanisms, this accumulating heat can precipitate a cascade of detrimental effects, including accelerated material degradation, diminished operational performance through thermal throttling, and, in severe instances, irreversible component damage or outright system failure. Consequently, the development and deployment of durable, reliable, and advanced thermal solutions have transcended mere optimization goals, becoming an absolute prerequisite for the sustained progress and dependability of contemporary electronics. Anchoring these vital thermal strategies are Thermal Interface Materials (TIMs), specialized substances designed to bridge the microscopic gaps and inherent imperfections that inevitably impede the efficient transfer of heat between a heat-generating source and its critical heat-dissipating counterpart, such as a heat sink or cooling plate.

A comprehensive understanding of TIMs necessarily commences with a firm grasp of the fundamental scientific principles that govern heat transfer itself. Heat, at its essence, represents a form of kinetic energy that naturally migrates from regions of higher thermal energy to those of lower thermal energy, persistently seeking equilibrium. This thermodynamic imperative manifests predominantly through three core mechanisms: conduction, convection, and radiation. Within the intricate confines of modern electronic assemblies, where solid components are brought into direct, albeit imperfect, contact, conduction stands as the predominant mode of heat propagation. Yet, a deceptive simplicity masks the microscopic reality of these interfaces. What appears to the naked eye as a smooth, continuous surface on a silicon chip and a metallic heat sink is, under powerful magnification, revealed to be a complex topographical landscape of microscopic peaks and valleys, asperities and voids. When two such surfaces are mechanically pressed together, real physical contact, where solid-to-solid conduction can occur, is established over only a minuscule fraction of their apparent interface area. The vast majority of this interface remains separated by myriad microscopic pockets of trapped air. Crucially, air is an exceptionally poor conductor of heat, an effective insulator, in fact, and these isolated air gaps act as potent thermal barriers, severely impeding the flow of heat. This inherent impedance to efficient thermal flow is universally characterized as thermal contact resistance, a pervasive phenomenon that induces a significant and detrimental temperature drop across the interface, thereby critically compromising the overall effectiveness of heat dissipation from the heat-generating component.

The singular and primary function of a TIM is to decisively circumvent and mitigate this pervasive thermal contact resistance. By introducing a precisely formulated, conformable material into the minuscule interstice between the two mating surfaces, a TIM actively displaces these insulating air pockets, effectively replacing them with a medium that possesses significantly superior thermal conductivity. This strategic intervention establishes a continuous, uninterrupted, and highly efficient pathway for thermal energy to flow directly from the heat-generating source to the heat-dissipating element. While the intrinsic bulk thermal conductivity of the TIM material itself is undeniably a critical parameter, its ability to meticulously wet and conform to the microscopic surface irregularities, thereby establishing intimate, near-total contact across the entire interface, and concurrently minimizing the thickness of the applied material layer (the bond line thickness or BLT) are equally vital factors for achieving optimal real-world thermal performance. A well-chosen and correctly applied TIM effectively transforms a thermally resistive air gap into a thermally conductive bridge, dramatically enhancing the overall efficiency of the cooling solution.

This book offers a rigorous, comprehensive, and forward-looking exploration into the complex field of thermal interface materials for electronic components. It will commence with a thorough examination of the fundamental physics underpinning heat transfer and the inherent challenges posed by interfacial thermal resistance, thereby laying a foundational understanding for the indispensable role TIMs occupy in contemporary thermal management strategies. Subsequent discussions will then pivot to delve deeply into the diverse array of TIM types currently available, scrutinizing their unique chemical compositions, intricate operating mechanisms, and varying performance characteristics. Readers will gain granular insights into the distinct advantages and inherent limitations associated with each prominent category: from the highly fluid and exceptionally performing thermal pastes, prized for their ability to maximize microscopic contact and achieve ultra-thin bond lines, to the clean, user-friendly, and electrically insulating thermal pads, valued for their ease of application and gap-filling capabilities. This book will also present the highly versatile gap fillers, specifically designed to conform to larger and more irregular spaces, the dual-purpose thermal adhesives which uniquely combine efficient thermal transfer with strong structural bonding, and the innovative Phase Change Materials (PCMs), which ingeniously utilize a precise physical transformation from solid to liquid to achieve supreme post-melt wettability and long-term stability without material migration. A dedicated and in-depth analysis will be provided on the critical material properties that profoundly dictate the overall effectiveness of the TIM. This includes, but is not limited to, its intrinsic bulk thermal conductivity, its rheological behaviour essential for optimal surface wetting and the formation of a consistently thin bond line, and its long-term durability and stability under the demanding operational conditions prevalent in electronic devices.

As electronic device architectures continue to evolve, stretching the very boundaries of power density, integration complexity, and physical compression, the field of thermal interface materials is concurrently experiencing its own profound wave of pioneering innovation. This comprehensive work extends significantly beyond existing, commercially mature solutions to explore the emerging trends and future directions that are poised to redefine TIM technology. This book will delve into pioneering advancements in novel filler materials, examining the immense potential offered by advanced carbon allotropes such as high-purity graphene flakes and precisely designed carbon nanotubes, alongside specialized boron nitride nanostructures, which promise exceptional thermal conductivity while maintaining critical electrical insulation. The intriguing, yet inherently challenging, realm of liquid metal-based composites and intricate hybrid filler architectures will also be thoroughly discussed, highlighting the aim of these next-generation materials to synergistically combine disparate properties for enhanced performance. A rigorous and in-depth discussion will dissect the intricate parameters that profoundly influence thermal properties of these complex composite materials, ranging from the intrinsic characteristics of the constituent filler and matrix materials to their precise morphology, volumetric loading, and the crucial quality of their interfaces. Furthermore, this book will critically mention next-generation dispensing and manufacturing techniques, including the transformative potential of additive manufacturing (3D printing of TIMs) for creating highly customized and complex geometries in TIM application. The exciting and forward-looking prospect of smart and responsive TIMs, materials capable of dynamically adapting their thermal properties in real-time to varying operational conditions and even autonomously self-healing microscopic defects and delamination over prolonged periods, will also be discussed, pointing towards a future where thermal management solutions are truly intelligent and self-optimizing.

Finally, recognizing that the formidable challenges of thermal management are not confined to a singular domain and application, this book will extensively cover the diverse and pervasive applications of TIMs across a vast spectrum of industries. It will include their absolutely indispensable role in the high-volume landscape of consumer electronics, encompassing everything from powerful gaming consoles and high-performance laptops to compact smartphones and tablets, where striking a delicate balance between thermal efficiency, cost-effectiveness, and long-term reliability is crucial. This book will also delve into the uniquely stringent demands of automotive electronics, particularly in the rapidly expanding and safety-critical sector of electric vehicle battery packs and power electronics, where TIMs are vital for both optimal performance and uncompromising safety under harsh environmental conditions and prolonged operational cycles. The high-performance and unwavering reliability requirements intrinsic to telecommunications and data centres, which form the very foundation of the modern digital infrastructure, will be precisely detailed, showcasing how TIMs enable the continuous and efficient operation of mission-critical servers and networking equipment.

Ultimately, this comprehensive and rigorously book aims to provide readers, whether they are seasoned researchers, innovative product designers, dedicated engineers, or curious students, with a deep, practical, and forward-looking understanding of thermal interface materials, empowering them to make informed decisions, drive future innovation, and contribute meaningfully to enhanced thermal management in an ever-evolving and increasingly demanding electronic landscape.

1. Fundamental Principles of Heat Transfer and Thermal Contact Resistance

To genuinely grasp the significance of Thermal Interface Materials (TIMs), it is imperative to first acquire a thorough understanding of the foundational principles governing heat transfer and to delve into the intricate aspects of the ubiquitous challenge posed by thermal contact resistance at interfaces. Heat energy inherently exhibits a natural propensity to flow from regions of higher temperature to regions of lower temperature (Bejan, 2019). This fundamental flow is primarily facilitated by three distinct mechanisms: i) conduction, ii) convection, and iii) radiation. Within the specific context of solid interfaces, conduction emerges as the predominantly influential mechanism; wherein, thermal energy propagates through direct molecular contact and the movement of free electrons (Sidebotham, 2015; Viskanta, 1965).

The resistance encountered when transferring heat between two adjacent materials is known as interfacial thermal resistance (ITR). It indicates the degree to which the interface limits the heat flow in the process of heat transfer and can be defined through the following heat conduction formula (Wei et al., 2024):

$$R = \frac{\Delta T}{J} \tag{1}$$

where R is the ITR. ΔT is the temperature difference between the two adjacent materials at an interface. J is the density of heat flux through the interface. A lower ITR implies more efficient heat transfer, while a higher ITR indicates poorer heat transfer performance.

As depicted in the schematic diagram of heat dissipation in the components of the electronics (Figure 1), the interfacial thermal resistance of TIMs (R_{TIM}) is represented as follows.

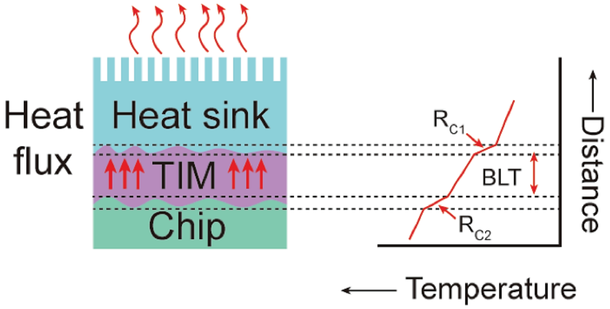


Figure 1. Heat dissipation and interfacial thermal resistance in high-power electronics (Xing et al., 2022)

The primary metric for evaluating TIMs is the impediment to heat flow across the interface. This impediment is characterized by the thermal resistance of the TIM (R_{TIM}), which can be expressed as (Shahil & Balandin, 2012):

$$R_{TIM} = \frac{BLT}{\kappa_{TIM}} + R_{c1} + R_{c2} \tag{2}$$

In this equation, κ_{TIM} signifies the thermal conductivity of the TIM, and BLT (bond line thickness) refers to the effective thickness of the

TIM. R_{c1} and R_{c2} denote the contact thermal resistances between the TIM and the device/heat sink, respectively.

To overcome the significant thermal resistance of a direct, rigid interface, a TIM is employed to achieve lower total thermal resistance (Tu et al., 2024). A substantial portion of current development focuses on improving the thermal conductivity of Thermal Interface Materials (TIMs), particularly κ_{TIM}. This primary objective aims to diminish the thermal resistance of the TIM (R_{TIM}), frequently underestimating the significant contributions of contact resistances, R_{c1} and R_{c2}.

When two seemingly flat solid surfaces are brought into contact, it is impossible to achieve a perfect, continuous surface of contact, even under significant applied force. The reality is that both surfaces, despite their apparent smoothness, possess a microstructure characterized by microscopic peaks (asperities) and valleys. Consequently, the actual physical contact occurs only over a minute fraction of the total apparent contact area, at the points where the highest asperities on opposing surfaces meet (Zhao et al., 2019). The vast majority of the apparent contact area is, inevitably, filled with an insulating medium, most commonly entrapped air. These diminutive air gaps, despite their size, act as extremely effective thermal barriers for heat flow. This situation leads to a significant temperature drop across the interface for a given heat flux, precisely defining the essence of thermal contact resistance (Dou et al., 2023; Due & Robinson, 2012).

The very purpose a TIM is to decisively obliterate this pervasive contact resistance. When a TIM, be it a compliant paste, a conformable pad, and a transformative phase change material, is carefully applied between the two surfaces and subjected to the requisite compression pressure, it performs a multifaceted thermal transformation.

- Air displacement and void filling: The TIM, owing to its inherently more compliant and fluid nature compared to rigid solid surfaces, actively deforms and flows into the microscopic valleys and irregularities of both contacting surfaces. This action systematically displaces the trapped, insulating air, replacing it with a material of significantly higher thermal conductivity.

- Creation of a continuous conduction path: By substituting the high-resistance air with a material whose thermal conductivity is typically much greater than that of air, the TIM establishes an uninterrupted, continuous, and efficient pathway for heat conduction across the interface. This ensures that heat is channelled directly from the hot spots of the component to the cold plate of the heat sink, bypassing the insulating air gaps. Figure 2 demonstrates the reduction in temperature difference between the heat source and the heat sink achieved by filling the air gaps with a high-thermal-conductivity TIM.

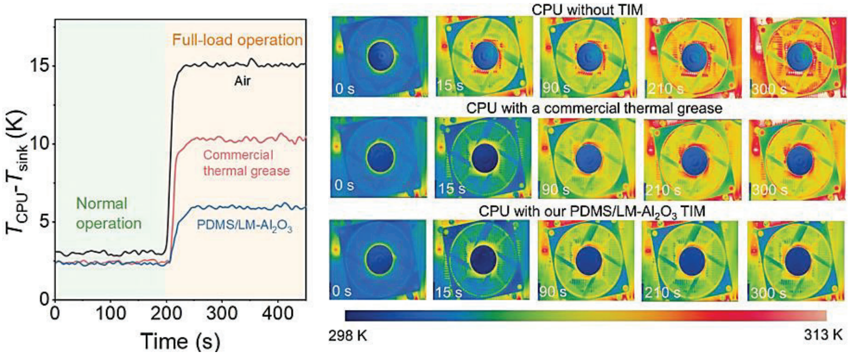


Figure 2. Temperature drop between CPU and heat sink depends on amount of air gaps and thermal conductivity of TIM (Xie, Z. et al., 2023)

- Optimization of Bond Line Thickness (BLT): While it is necessary for the TIM to be sufficient to fill all voids, the objective remains to achieve the thinnest possible TIM layer (BLT) that still ensures complete void filling and intimate, continuous contact. The governing principle of heat conduction dictates that thermal resistance is directly proportional to the thickness of the material ($R_{th} = t / (k \cdot A)$, where t is thickness, k is thermal conductivity, and A is the heat transfer area). Therefore, even with a highly thermally conductive TIM, an excessively thick bond line will inadvertently introduce additional thermal resistance (Abadi & Chung, 2011; Chung, 2022). The challenge of TIM application lies in finding this delicate balance: applying enough material to fill all voids, yet utilizing sufficient compression pressure to squeeze out excess material, thereby achieving the minimum effective BLT without creating dry spots (Figure 3).

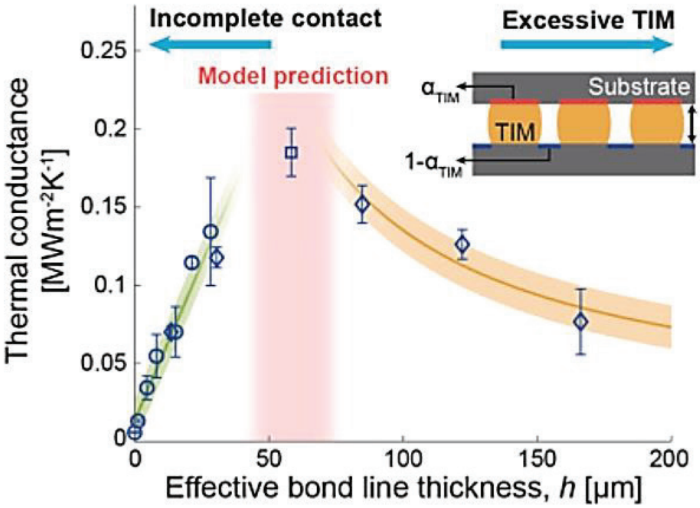


Figure 3. Relationship between thermal conductance and BLT (Lee & Park, 2025)

By fulfilling this critical function, bridging the microscopic thermal gap and establishing a direct, highly conductive thermal bridge, TIMs enable heat sinks to operate at their full potential. This, in turn, ensures that the heat-generating component remains within its safe operating temperature limits, thereby preserving its inherent performance capabilities, extending its operational lifespan, and preventing costly thermal failures.

2. Key Properties for Effective TIMs

Effectiveness of TIM comes from a combination of carefully designed material properties. An ideal TIM embodies an optimal balance of these characteristics, precisely calibrated to the demands of a specific application.

2.1. Thermal Conductivity

As the fundamental property of TIM performance, thermal conductivity quantifies the ability of the material to conduct heat. Its units, W/m·K, denote the power transferred per unit area for a given temperature gradient (Hu et al., 2006; Mahbubul, 2018; Wang & Kodur, 2019). Maximizing this property for TIMs is of crucial importance. This is achieved primarily by formulating TIMs as advanced composite materials, comprising a polymer matrix richly embedded with highly thermally conductive filler particles.

- Polymer matrix: This serves as the binder that holds the material together, endowing the TIM with its fundamental mechanical properties, structural integrity, and often its compliant nature. Common polymeric bases include silicones, acrylics, epoxies, polyurethanes, and various synthetic oils. While the polymer itself typically possesses low thermal conductivity, its role in holding the highly conductive filler particles in a stable, conformable medium is critically important (Ma et al., 2020;

Wang et al., 2017). The properties, such as viscosity, surface tension, and coefficient of thermal expansion, directly influence the final performance of the TIM. For instance, a lower viscosity polymer might allow for easier dispersion of fillers, but too low a viscosity could increase pump-out tendency (Gwinn & Webb, 2003; Wunderle et al., 2019).

- Thermally conductive filler particles: These constitute the true workhorse of the thermal performance of the TIM. They are meticulously dispersed within the polymer matrix at very high loading rates to create a continuous, dense network for phonon propagation. These high loadings are necessary to form a continuous thermal path that conducts heat effectively (Zhang et al., 2023b). The shape, size, and size distribution of the filler particles profoundly affect the final thermal conductivity. For example, spherical particles may be easier to process, while flake-like and fibrous particles can create more continuous thermal pathways, resulting in higher thermal conductivity (Rösel & Drummer, 2024; Zhao et al., 2018).

Metallic powder materials such as silver (Ag), aluminium (Al), and copper (Cu) possess inherently very high bulk thermal conductivities. Silver is highly valued for its exceptional thermal performance and is commonly used in the highest conductivity pastes (Mumtaz et al., 2024). A significant caveat, however, is their electrical conductivity; this necessitates extreme caution in electronic applications to prevent short-circuiting. Even a low amount can create undesired electrical bridges that damage sensitive circuits (Ji et al., 2024).

Ceramic powder materials include aluminium nitride (AlN)), boron nitride (BN), aluminium oxide (Al_2O_3), zinc oxide (ZnO), and silicon dioxide (SiO_2). These filler particles are preferred in many electronic applications due to their combination of high thermal conductivity and, crucially, their electrical insulating properties (Fang et al., 2022; Kume et al., 2008; Pornea et al., 2024). AlN and BN, especially, offer superior thermal performance among ceramic fillers and are increasingly employed in high-power electronics applications. Various particle shapes (spherical, flake, etc.) and sizes are tailored to ensure optimal packing density and efficient thermal pathways within the matrix (Du et al., 2017).

Carbon-based materials represent an exciting frontier in the development of thermal interface materials. Materials such as graphite, carbon nanotubes (CNTs), and graphene possess extraordinarily high thermal conductivities, potentially surpassing metals in certain directions. However, challenges persist in effectively dispersing these nanomaterials within polymer matrices and managing their potential electrical conductivity (especially with CNTs and graphene). Their anisotropic nature (different conductivities along different axes) can also be employed for directed heat flow, though this requires high precision in particle alignment (Chung, 2023; Khan et al., 2020).

The overall thermal conductivity of the composite TIM is not merely an average of its constituents. It is profoundly influenced by the type, size distribution, shape, and loading percentage of the filler particles, the quality of their dispersion (minimizing agglomeration), and, critically, the interfacial thermal resistance between the filler and the polymer matrix. Creating a continuous percolation network of filler particles is a key objective, as this network establishes direct, unimpeded pathways for heat flow. The percolation threshold refers to the filler concentration at which the thermally conductive network begins to form; above this threshold, thermal conductivity increases significantly.

2.2. Wettability

This property is absolutely foundational for the TIM to effectively displace air and establish intimate, uninterrupted contact at the microscopic interface. Without these, even a TIM with very high bulk conductivity would fail.

Wettability refers to the tendency of the TIM to spread evenly and spontaneously across a solid surface, exhibiting a low contact angle. Consider a droplet of water on a super hydrophobic leaf (high contact angle, poor wettability) versus a droplet of oil spreading effortlessly on a flat plate (low contact angle, good wettability) (Kim et al., 2022; Marmur et al., 2017). For TIMs, good wettability ensures that the material actively flows and coats all microscopic valleys and irregularities on the two mating surfaces, thereby effectively displacing trapped, insulating air. This maximizes the real physical contact area for heat transfer. The lower the contact angle, the better the wettability. Good wettability requires the TIM material to have a low surface tension; this must be lower than the surface energy of the solid surfaces it will contact. This allows the TIM to spread across the surface. Figure 4 shows representative images of low and high wettability.

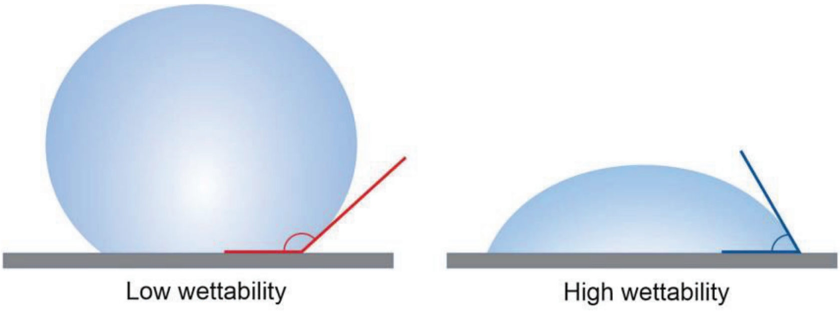


Figure 4. Contact angle and wettability characteristics (Mehralizadeh et al., 2019)

Compliance (flexibility) describes the ability of the TIM to deform under pressure and precisely conform its shape to both macroscopic irregularities and microscopic asperities. This is directly related to the viscosity of the material (for fluid TIMs) and its hardness and modulus (for solid and semi-solid TIMs).

For fluid-based TIMs (pastes, gels), low viscosity is the key enabler. Their inherent fluidity allows them to effortlessly hug the contours of the surfaces and fill even the smallest crevices. Viscosity is also related to how they respond to applied shear stress. This ensures that TIMs flow easily during dispensing yet retain their shape upon shear removal, thereby preventing sag (Zhao et al., 2019).

For solid and semi-solid TIMs (pads, phase change materials), high flexibility and compressibility are essential. When compressed, they must easily deform to conform to the surface contours, thereby minimizing the formation and persistence of air gaps. The mechanical properties of these materials, such as elasticity modulus or compressibility, determine their compliance (Li et al., 2021).

Superior wettability and excellent compliance directly translate into a dramatic reduction of interfacial thermal resistance. If a TIM does not wet well or is not sufficiently compliant, air gaps will persist. This compromises the thermal pathway and severely degrades overall performance, rendering the high bulk thermal conductivity of the material largely meaningless.

2.3. Bond Line Thickness (BLT)

Bond Line Thickness (BLT) refers to the precise remaining thickness of the TIM layer after the two components have been assembled and subjected to the recommended compression pressure. While a TIM is absolutely necessary to fill voids, a critical principle in thermal management is that a thicker TIM layer will inherently add more overall thermal resistance to the interface, even if it is made of a highly thermally conductive material. This is a direct consequence of the fundamental heat conduction equation, which states that thermal resistance is directly proportional to the thickness of the material. This clearly demonstrates that thermal resistance increases linearly with thickness (Dou et al., 2023b).

The overall design goal is to achieve the thinnest possible BLT that still ensures complete and effective void filling. This typically necessitates the application of significant and consistent compression pressure during assembly to effectively squeeze out excess TIM and bring the two main surfaces into as close contact as possible, leaving only a minimal TIM layer. However, this is a delicate balance. Too much pressure can potentially pump out too much TIM, leading to dry spots where no TIM remains, or even damage delicate components or the TIM itself. Excessive pressure can also compromise material integrity and permanently alter the mechanical properties of a pad. Insufficient pressure will leave a thicker, less effective TIM layer, or worse, allow air gaps to persist. A minimum compression pressure is often required for the TIM to achieve its fluidity and effectively fill surface asperities (Hu et al., 2004). Figure 5 presents the variation in thermal conductivity as a function of material thickness, which is obtained under different compression conditions.

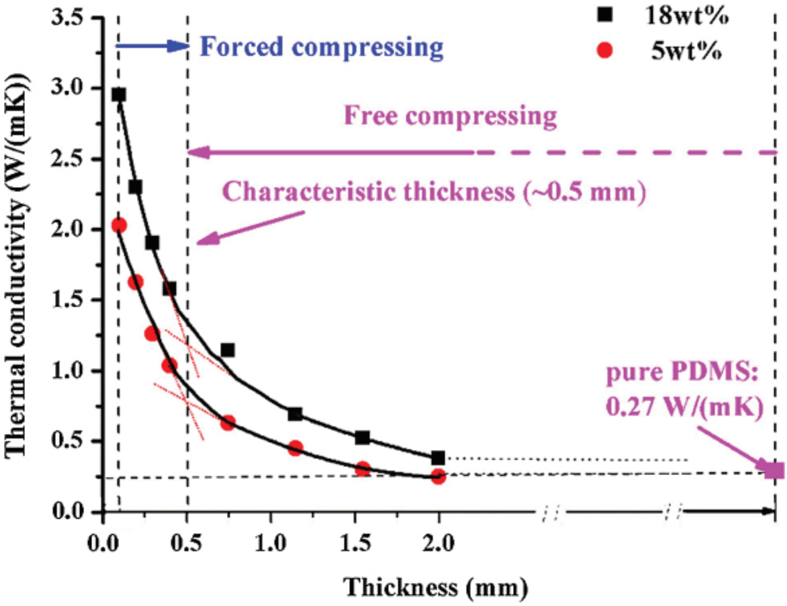


Figure 5. Effect of specimen thickness on the thermal conductivity of composites (He et al., 2018)

Therefore, optimizing BLT is a precise optimization task that requires careful consideration of the properties of the TIM, the quality of the contacting surfaces, and the available compression force. Achieving the ideal BLT is vital for extracting the maximum thermal performance from a given TIM. In modern manufacturing, controlling BLT with precise measurement techniques, such as laser sensors and ultrasonic techniques, is becoming increasingly important.

2.4. Durability and Reliability

The utility of a TIM extends far beyond its initial thermal performance. Its true value is realized in its ability to consistently maintain these critical properties throughout the entire projected operational lifespan of the device. This demands a strong resistance to various degradation mechanisms.

- Thermal cycling stability: Electronic devices are continuously subjected to dynamic thermal loads during operation, leading to frequent heating and cooling cycles (CPU powering on and off, fluctuations in load, etc.). These cycles induce differential thermal expansion and contraction among the various materials within the assembly (silicon, copper, aluminium, and the TIM itself). Differences in the coefficients of thermal expansion (CTEs) of dissimilar materials create stresses (Cai et al., 2021). A durable TIM must withstand these continuous mechanical stresses without cracking, delaminating (loss of adhesion), pumping out (fluid migration in liquid TIMs), and exhibiting significant changes in its physical and thermal properties. Reliability testing involves subjecting the TIM to thousands of cycles from low to high temperatures to assess if it maintains its performance over the long term.

- Pump-out resistance: This is a common concern primarily associated with paste-based TIMs (Zhao et al., 2019). Pump-out refers to the undesirable phenomenon where the liquid carrier fluid physically migrates away from the active thermal interface (e.g., towards the edges of the heat sink) over time, a process often exacerbated by the combined effects of thermal cycling and continuous compression pressure. With each thermal cycle, the differential expansion/contraction movements of the materials create a pumping action. As the fluid migrates, it leaves behind a less effective, often hardened, and less compliant filler material, leading to a detrimental increase in thermal resistance over time. High-quality pastes are formulated with advanced rheology (high thixotropy, low viscosity index, etc.) and more stable carrier fluids (low vapour pressure, high molecular weight, etc.) to significantly mitigate this phenomenon (Wunderle et al., 2019).

- Dry-out resistance: Similar to pump-out, dry-out occurs when the volatile components of the TIM (carrier fluids, solvents) evaporate over time, especially at elevated operating temperatures. This loss of volatile components leads to a reduction in the compliance of the material, potentially creating microscopic voids and even significant air gaps, thereby directly increasing thermal resistance. High-quality TIMs are formulated with non-volatile or highly stable components (high-boiling-point synthetic oils, cross-linked polymers, etc.) to resist dry-out (Due & Robinson, 2012; Nnebe & Feger, 2008).

- Chemical stability and compatibility: The TIM must be chemically inert and non-corrosive. It must not react with or degrade the contacting surfaces (copper, aluminium, gold, etc.); nor should it leach harmful chemicals that could damage or adversely affect other adjacent components within the electronic assembly over time. Liquid metal TIMs, in particular, can pose severe compatibility issues due to their potential to form intermetallic compounds with and brittle surfaces. Material compatibility must be rigorously tested over a wide range of temperatures.

- Mechanical stability (creep resistance): Under sustained compression pressure and elevated temperatures, some materials can exhibit a slow, time-dependent deformation known as creep. This can cause the TIM to slowly flow out to the sides and decrease in thickness, potentially affecting the contact area and bond line over time. A reliable TIM must possess sufficient mechanical stability and creep resistance to maintain consistent contact pressure and bond line integrity over prolonged periods, even under continuous mechanical load and vibration.

- Particle migration: In TIMs with high filler loadings, there is a potential for filler particles to migrate within the polymer matrix under thermal cycling and vibration. This can disrupt homogeneity and lead to a degradation of thermal performance over time. The formulation should ensure particle stability.

2.5. Electrical Insulation

For the vast majority of electronic applications, the TIM must simultaneously serve as a highly effective electrical insulator. This is critically important to prevent unintended short circuits between the heat-generating component (CPU die, power transistor, etc.) and the heat sink, which is often grounded and at a different electrical potential. While many high-performance TIMs utilize metallic fillers (such as silver) for their superior thermal conductivity, these fillers are inherently electrically conductive (Chung, 2023; Ji et al., 2024).

Therefore, TIMs designed for sensitive electronic applications typically rely on electrically insulating ceramic fillers (aluminium nitride, boron nitride, aluminium oxide) and are formulated with non-conductive polymer matrices. The dielectric strength of the TIM is a critical property for insulating TIMs, indicating the maximum electric field it can withstand before electrical breakdown occurs. The dielectric constant can also be important, given its influence on the capacitive behaviour of the TIM in high-frequency applications (Ma et al., 2020; Yuan et al., 2021). However, an electrically conductive TIM might be intentionally desired for its unique properties in certain specific applications.

2.6. Ease of Application and Reworkability

From a manufacturing and serviceability perspective, the practical aspects of TIM application are almost as important as their thermal performance.

While offering high performance, pastes can be messy and may require specialized dispensing equipment (automated syringes, robotic dispensers, screen printing, etc.) for precise and repeatable application in high-volume manufacturing. Rheological properties like viscosity and thixotropy directly influence dispensing ease.

Pads are generally the cleanest and easiest to apply, and they are typically placed manually or with automated pick-and-place machines. Most have inherent adhesiveness and an adhesive backing, which facilitates initial positioning.

Gels/Pasty dispensables can be automated with robotic dispensing systems, offering good control and coverage. They generally offer higher compliance than pads while being less disruptive than pastes.

Regarding TIM reworkability, it is crucial to ensure easy removal of the component from the heat sink, thorough cleaning of the old TIM, and reapplication of new TIM without causing damage to either component.

Thermal adhesives are generally form a permanent bond, making rework extremely difficult or impossible without damaging the components. Solvents and mechanical force are often required, typically with the risk of permanent damage to the component.

Thermal pastes, pads, non-curing gels, and PCMs generally offer good reworkability, making them preferred options for applications where service or upgrades are anticipated. Pastes may leave some residue that requires cleaning, but this is usually manageable with specialized cleaners.

2.7. Operating Temperature Range

A thermal interface material (TIM) must maintain its optimal performance characteristics and physical integrity across the entire projected operating temperature range of the device. Within the working temperature range, its viscosity, compliance, thermal conductivity, chemical stability, and mechanical properties should not degrade significantly. A TIM that becomes too stiff or brittle at low temperatures (leading to cracking and loss of contact), and degrades prematurely at high temperatures (leading to degradation, dry-out, and pump-out issues), will compromise the reliability of the device. The thermal stability and glass transition temperature (T_g) of the material are parameters that determine its usability across a wide operating temperature range. Prolonged exposure to extreme temperatures can cause irreversible changes in the molecular structure of the TIM, leading to permanent performance degradation.

3. Thermal Interface Materials

The TIM market is remarkably diverse, offering a rich spectrum of solutions optimized for varying performance levels, application methodologies, and cost considerations. Understanding this landscape necessitates a deep appreciation for the unique attributes of each category.

3.1. Thermal Pastes (Greases/Compounds)

Thermal pastes, also known interchangeably as thermal greases and thermal compounds, represent the most common and often highest-performing type of non-adhesive TIMs. They are meticulously engineered as semi-fluid, non-curing suspensions of highly thermally conductive solid particles homogeneously dispersed within a viscous liquid carrier (Skuriat et al., 2013).

Filler particles constitute the bulk of the thermal performance of the paste. Their volumetric loading percentage within the polymer matrix typically ranges from 60% to over 90%, and homogeneous dispersion is critically important to prevent agglomeration and to form a continuous thermal percolation network (Sarvar et al., 2006).

Metallic fillers, such as powders of silver (Ag), aluminium (Al), and copper (Cu) lead to very high-performance pastes due to their exceptional bulk thermal conductivities. However, their inherent electrical conductivity necessitates precise application and careful avoidance of electrical traces. Specifically, the risk of metallic pastes causing unintended short circuits is a significant concern for safety and reliability (Otiaba et al., 2011).

Ceramic fillers, including zinc oxide (ZnO), aluminium oxide (Al_2O_3), boron nitride (BN), and aluminium nitride (AlN), are widely employed. These are valued because they offer critical electrical insulating properties along with high thermal conductivity, making them safe for sensitive electronic components. BN and AlN, in particular, can exhibit high anisotropic thermal conductivity due to their crystal structure (hexagonal BN, etc.) and can be employed for directed heat transfer. Particle size distribution, ranging from nano to micro-scale, is carefully controlled to optimize packing density and create a low-thermal-resistance network. Particle surface modifications (coatings and surfactants) can also be utilized for better dispersion within the matrix and reduction of interfacial thermal resistance (Swamy & Satyanarayan, 2019).

Carbon-based fillers, including graphite flakes, carbon nanotubes (CNTs), and graphene nanoplatelets, are pushing the boundaries of thermal performance due to their extraordinarily high inherent thermal conductivities, potentially outperforming metals in certain directions. Challenges include ensuring stable dispersion (preventing agglomeration) and managing their potential electrical conductivity (especially with CNTs and graphene). Furthermore, the anisotropic nature of CNTs and graphene can be further exploited for enhanced thermal conductivity when used with appropriate alignment techniques (under magnetic and electrical fields) (Pathumudy & Prabhu, 2021).

Carrier fluid is the non-curing, viscous liquid that serves as the suspension medium for the filler particles. Common choices include silicone oils (known for their broad temperature stability, inertness, and dielectric properties), synthetic hydrocarbons, and other non-volatile organic liquids (Swamy et al., 2023). The choice of carrier fluid is crucial as it dictates the rheology (flow properties, viscosity index), pump-out resistance (low volatility and high molecular weight reduce fluid migration), long-term stability, and overall operating temperature range of the pastes. Advanced pastes utilize fluids with very low volatility and high stability to minimize evaporation and migration (Gwinn & Webb, 2003).

For optimal heat transfer, it is essential to achieve a bond line where the paste fills all microscopic voids on the contact surface while simultaneously providing the thinnest possible bond line. Specific application patterns such as a small central dot, a single line, an X pattern, and a series of dots are recommended to ensure even spreading under pressure and minimize entrapped air. Over-application can lead to excess material squeezing out, which can be messy or even lead to short circuits (for conductive pastes). Preventing the formation of air bubbles during application is also critical, as they can have a significant negative impact on thermal performance.

Thermal pastes offer distinct advantages, including low thermal resistance, superior void-filling capability, high performance versatility, and excellent reworkability. When properly applied with optimal compression pressure, high-quality thermal pastes can achieve an exceptionally thin bond line and excellent surface wettability. This results in the lowest thermal resistance among all non-liquid metal TIMs, making them the preferred choice for maximizing thermal efficiency. Theoretically, a super-thin bond line ensures the lowest interfacial thermal resistance for any TIM, regardless of its bulk thermal conductivity.

Their fluid nature allows them to conform almost perfectly to even the smallest microscopic surface irregularities and effectively displace all entrapped air. This maximizes the true physical contact area for heat transfer.

Their high performance makes them suitable for a wide range of applications, from consumer electronics (gaming CPUs, GPUs, etc.) to demanding industrial power modules, specialized LED lighting solutions, and servers. Different filler types and loadings offer a broad spectrum of performance levels. Figure 6 shows thermal paste applied to a microprocessor.

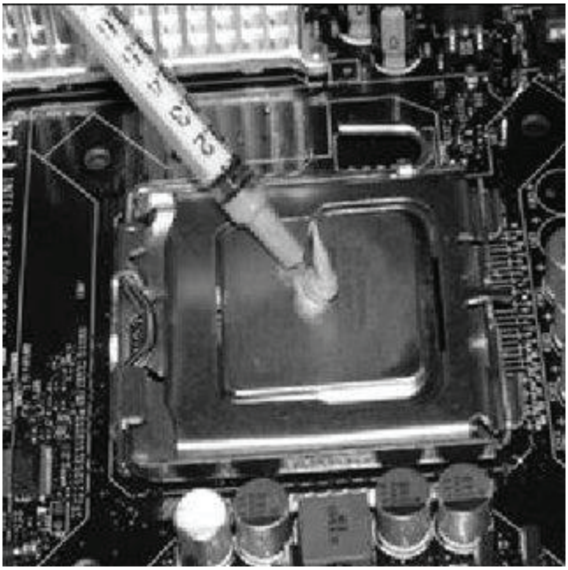


Figure 6. Application of thermal interface material (TIM) onto a computer microprocessor surface (Thang et al., 2009)

Since they do not cure or harden, components can be separated relatively easily, old paste residue cleaned off, and new paste reapplied for reassembly. This is highly valuable for testing, quality control, maintenance, and component upgrades. This feature is also beneficial, especially during development and prototyping phases.

Despite their advantages, thermal pastes exhibit certain drawbacks. Their application can be challenging, often requiring specialized equipment for neat and precise placement. This can lead to excess material that might contaminate surrounding components, subsequently introducing additional cleaning steps and costs within a production line.

Over prolonged periods or under aggressive thermal cycling, the liquid carrier fluid can physically migrate away from the hot interface (pump-out) or simply evaporate (dry-out), leaving behind a less effective, often hardened, filler material. This leads to a detrimental increase in thermal resistance over the lifespan of the device (Feng et al., 2020).

Pastes containing metallic fillers (such as silver) are electrically conductive. Their improper handling and accidental spread onto exposed electrical traces, component pins, and even within the integrated circuit package can cause catastrophic short circuits, necessitating meticulous application, careful component design, and necessary masking. For sensitive electronics, non-conductive options (with ceramic fillers) are vitally important and should always be preferred where no risk is acceptable.

Optimal performance is heavily reliant on achieving the correct compression pressure to ensure a thin, uniform bond line without dry spots. Insufficient pressure will lead to a thicker BLT and air gaps persisting, while excessive pressure can accelerate pump-out and damage delicate components (Zhou et al., 2020).

Some paste formulations may exhibit incompatibility with certain heat sink or component surfaces, which hinders optimal wettability and can lead to air gaps persisting.

Predominant in high-performance computing (laptops, servers for CPUs and GPUs, etc.), high-power semiconductor devices (IGBTs, MOSFETs in power converters, electric vehicle power modules, etc.), high-brightness LED arrays, and any scenario where achieving the absolute lowest thermal resistance is critical. They are generally the preferred solution for high-density power applications.

3.2. Thermal Pads

Thermal pads are pre-formed, solid or semi-solid sheets made from thermally conductive, compliant materials. They differ significantly from pastes in their application and form factor, prioritizing ease of use, electrical insulation, and gap-filling capabilities. They are typically made from silicone, acrylic, and other elastomer-based polymers, heavily loaded with thermally conductive fillers (Liao et al., 2011; Tuersun et al., 2025). They are available in a wide range of thicknesses and various hardness levels, often incorporating a reinforcing fiberglass mesh for improved handling and dimensional stability.

Thermal pads are primarily composed of silicone-based polymers, chosen for their exceptional flexibility, wide operating temperature range, and strong resistance to UV and ozone degradation. Acrylic and urethane elastomers are also used and can offer different mechanical properties and sometimes better adhesion to certain surfaces, though they may not possess the same high-temperature stability as silicones (Kim et al., 2015; Kim et al., 2017).

Filler particles, predominantly electrically insulating ceramic fillers such as aluminium oxide (Al_2O_3), boron nitride (BN), magnesium oxide

(MgO), zinc oxide (ZnO), and sometimes nitrides or silicates, are employed. These ensure thermal conductivity while preventing electrical short circuits. The filler loading directly impacts the thermal conductivity and mechanical properties of the pad (Idris & Subramani, 2021; Mun et al., 2025). Figure 7 shows the siloxane matrix Al_2O_3 reinforced composite thermal pad and the SEM image of this pad.

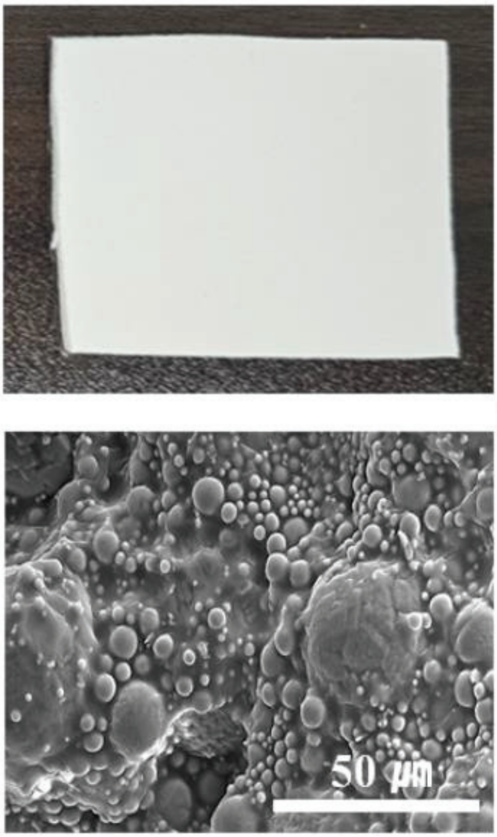


Figure 7. Al_2O_3–siloxane composite pad and its SEM image (Kim et al., 2024)

Some pads incorporate internal fiberglass reinforcement and mesh to enhance tear resistance and facilitate easier handling during assembly.

This reinforcement helps the pad maintain its integrity and prevents stretching and tearing during dispensing. Many features a layer of pressure-sensitive adhesive (PSA) on one or both sides, covered by a release liner, to facilitate precise placement and initial adhesion. The adhesive strength and thermal resistance of the PSA must be carefully considered (Mittal et al., 2020; Otiaba et al., 2011).

Thermal pads are straightforward to apply. They are supplied in pre-cut shapes or larger sheets and are simply placed between the component and the heat sink. Their inherent compliance allows them to fill the gap under compression. Application typically involves peeling off the PSA liner and placing the pad in the desired location.

Exceptional ease of application is their most significant advantage. They are clean, mess-free, and incredibly quick to apply. They require no curing time, no specialized dispensing equipment (other than cutting if needed), making them ideal for high-volume automated assembly lines with robotic pick-and-place machines, as well as for manual assembly. This significantly reduces labour costs and assembly time, especially in complex assemblies (Pathumudy & Prabhu, 2021).

The vast majority of thermal pads are carefully designed to be electrically insulating, providing a strong and safe dielectric barrier between electrically active components and grounded or biased heat sinks. This eliminates the risk of short circuits and obviates the need for additional insulating layers. Their dielectric strength is typically sufficient for high-voltage applications.

A key strength is their ability to effectively bridge larger, inconsistent, or irregular gaps that traditional thin pastes cannot reliably fill. They can accommodate significant variations in component height or surface irregularities (moulded heat sinks, etc.). This is particularly beneficial in applications where lower-cost cooling solutions are used that do not require precise machining.

The elastomeric nature of the pads provides inherent cushioning and damping against vibration and shock. This is highly beneficial in mechanically stressed applications (automotive, portable devices) and where differential thermal expansion between dissimilar materials might induce stress on solder joints or components (during thermal cycling). The pad acts as a buffer absorbing thermal stresses (Rao et al., 2024).

However, compared to thermal pastes, pads generally exhibit a higher overall thermal resistance due to some reasons. Even the thinnest pad is typically thicker than an optimal paste bond line. This thickness, even with a high thermal conductivity, contributes to the absolute thermal resistance. While compliant, they cannot achieve the same level of microscopic wettability and void filling as a low-viscosity fluid (like a paste and melted PCM), potentially leaving more residual air at the interface. Voids can be reduced to some extent by applying more pressure to the pad surface, but this can also deform the mechanical properties of the pad (Dai et al., 2019).

The need for mechanical integrity and handling often limits the maximum percentage of thermally conductive filler, which can slightly reduce the overall k value compared to pastes. Too high a filler loading can cause the pad to become brittle or difficult to process (Zhou et al., 2023).

The thermal performance of the pad is somewhat sensitive to the amount of compression applied; too little compression can leave microscopic air gaps, while too much compression can cause the material to flow excessively, potentially thinning the pad excessively and reducing overall thickness uniformity if not properly constrained. Also, some pads may exhibit compression set or creep under prolonged compression, leading to a reduction in contact pressure and thermal performance over time (He et al., 2018).

The need for ease of application and electrical insulation restricts the use of some higher thermal conductivity fillers (metallic powders, etc.).

These materials find widespread application in laptop components (including chipsets, Voltage Regulator Modules (VRMs), memory modules, etc.), solid-state drives (SSDs), LED lighting fixtures, and automotive electronics. They are also prevalent in consumer electronics such as gaming consoles, routers, and set-top boxes. Thermal pads are particularly favoured in scenarios where ease of assembly, electrical safety, and the ability to bridge larger, inconsistent gaps are prioritized over achieving the absolute lowest thermal resistance. They are often the preferred solution in high-volume applications due to their balance of cost-performance and manufacturing convenience.

3.3. Gap Fillers (Dispensable Gels/Pastes)

Gap fillers are a category of TIMs specifically designed to fill larger and often irregular gaps where traditional pastes would be too thin and pads might lack the ability to conform to complex geometries. They are typically supplied in a dispensable form, ranging from a soft, flowable gel to a thicker, formable paste. They can be formulated as either non-curing (remaining soft and compliant indefinitely) or curing (forming a soft, elastomer-like material after cross-linking) (Lee, 2010).

Gap fillers primarily consist of a polymer base, most commonly silicone and urethane, heavily loaded with thermally conductive filler particles. Their flow properties, specifically viscosity and thixotropy, are precisely controlled to ensure efficient dispensing and subsequent conformity to the application surface (Saums, 2013).

The polymer base plays a critical role in the performance of the material. Silicone-based gap fillers offer excellent temperature stability, flexibility, and chemical resistance. Platinum-cured silicones are often preferred for achieving higher thermal conductivity and lower compression set. Urethane-based options, while sometimes providing superior mechanical properties and better adhesion to specific surfaces, may not match the high-temperature stability of silicones (Park et al., 2010).

Similar to thermal pastes and pads, gap fillers incorporate electrically insulating ceramic fillers such as aluminium oxide, boron nitride, and zinc oxide. These fillers impart thermal conductivity while preserving dielectric strength. The size and shape of these particles are crucial for optimizing both dispensability, their flow through pumping equipment, and their ability to effectively fill gaps (Liu et al., 2024).

Various additives are incorporated to precisely control properties viscosity, thixotropy, adhesion, wettability, and long-term stability. For instance, surfactants can enhance wettability, while rheology modifiers allow for precise tailoring of dispensing characteristics.

Application methodology for gap fillers primarily involves automatic dispensing using specialized equipment, including pneumatic and volumetric pumps, and robotic systems. Their thixotropic nature is key to their functionality. They flow readily under shear during dispensing but quickly solidify once shear is removed, enabling precise placement without sagging. Curing mechanisms may involve oven heating or specific room temperature dwell times to achieve their final properties. The selection of dispensing equipment is contingent upon the viscosity of the material and filler content. Gap fillers are typically applied in beads, lines, or specific patterns to ensure optimal coverage.

Gap fillers offer exceptional utility for accommodating large and irregular gaps, which constitutes their primary strength. They are specifically designed to manage significant variations in component heights, ranging from hundreds of micrometres to several millimetres. Furthermore, they conform perfectly to complex, uneven 3D contours and multiple height differences on a single board. This capability is invaluable in manufacturing scenarios with looser tolerances and where components inherently possess irregular surfaces, such as GPU memory chips or Voltage Regulator Modules (VRMs).

Their high compliance and wettability, stemming from a gel-like and paste-like consistency, ensure excellent surface wetting. This allows them to intimately conform to irregular surfaces, effectively displacing trapped air and establishing intimate thermal contact under minimal to moderate pressure. Consequently, they can provide superior interfacial contact compared to thermal pads (Wei et al., 2024).

A significant advantage is their superior stress relief. Their compliant, soft nature effectively mitigates mechanical stresses induced by differential thermal expansion between dissimilar components (heat sink, etc.) and external vibrations. This reduces the risk of solder joint failure or brittle component damage. Notably, curing gap fillers often retain their elasticity even after the curing process.

Finally, some formulations provide versatile adhesion, exhibiting inherent adhesiveness and slight adhesion sufficient to hold components in place during assembly without requiring additional mechanical fasteners. Curing types generally form a stronger bond while maintaining enough flexibility to absorb thermal stresses.

Despite their advantages, gap fillers come with certain drawbacks. They typically exhibit higher thermal resistance compared to thermal pastes and phase change materials (PCMs). While significantly outperforming air, this is primarily due to the inherently thicker bond lines necessary to bridge larger gaps and, at times, lower maximum filler loading (by volume) required to maintain dispensability.

Material cost is another factor; gap fillers can be more expensive per unit volume than basic thermal pastes or pads. However, this cost is often offset by the gains in assembly efficiency and overall performance capabilities in specific applications.

There is also a potential for air entrapment. Although designed to minimize this, improper dispensing techniques (such as excessive dispensing speed or an incorrect pattern) or rapid compression can still lead to the entrapment of air bubbles. These bubbles act as insulating voids, significantly degrading thermal performance within the material layer.

Furthermore, non-curing types share a drawback with pastes in their potential for oil bleed and pump-out. Under prolonged operating conditions and thermal cycling, there is a risk of the liquid carrier separating and being expelled from the matrix, which can lead to performance degradation over time.

Gap fillers are becoming increasingly critical in various applications. They are widely used in automotive electronic control units (ECUs), where diverse components require cooling within compact, vibration-prone environments. Their utility extends to large battery packs for electric vehicles, where robust thermal management is crucial for both performance and safety, particularly given the varying gaps between cells and cooling plates. Other significant applications include industrial power supplies and medical devices. Essentially, gap fillers are vital in any application characterized by significant and varying component gaps where efficient, automated, and reliable material dispensing is paramount.

3.4. Thermal Adhesives (Epoxies/Tapes)

Thermal adhesives represent a class of TIMs that serve a dual purpose. They not only facilitate efficient heat transfer but also provide a strong, often permanent, mechanical bond between components. This unique capability can simplify assembly and save space by eliminating the need for traditional mechanical fasteners like screws, clips, and clamps. This category encompasses thermally conductive epoxies, acrylics, and pressure-sensitive adhesive (PSA) tapes.

Thermal adhesives fall into two primary categories based on their composition: thermally conductive epoxies/acrylics and thermally conductive tapes.

Epoxies and acrylics are typically supplied as two-part systems (resin and hardener) or as single-part formulations that cure with heat. These materials are heavily loaded with thermally conductive particles, predominantly electrically insulating ceramics like aluminium oxide and boron nitride, to prevent electrical short circuits. However, metallic fillers such as silver can be incorporated for maximum thermal conductivity in applications where electrical insulation is not a concern. Their adhesion strength and thermal stability are specifically formulated to meet the demands of a given application (Yue et al., 2021).

Thermally conductive tapes (PSAs) consist of a thin polymer film, commonly acrylic, silicone, and polyimide, which is either impregnated with or coated by a pressure-sensitive adhesive. These adhesives are also heavily filled with thermally conductive particles. Tapes often include protective release liners on one or both sides. The thermal performance of these tapes is determined by their overall thickness, the thickness of the adhesive layer, and the type of filler employed. Their typical thermal conductivity is generally lower than other TIM types (Cui et al., 2015).

The application methods for thermal adhesives vary significantly by type. Epoxies and acrylics are dispensed as a liquid or paste, either manually or using automated dispensing equipment. Two-part systems necessitate precise mixing before application and have a limited working time known as pot life. Single-part systems offer greater convenience but typically require heat curing. Most epoxy/acrylic thermal adhesives demand a specific curing process, involving heating to a defined temperature for a set duration (heat-cured) or simply dwelling at room temperature (room-temperature cured) (Alim et al., 2021).

The defining advantage of thermal adhesives is their combined thermal and mechanical functionality. They provide both efficient heat transfer and robust structural adhesion within a single material solution. This integration simplifies assembly, reduces part count, and can lower overall costs by eliminating the need for separate mechanical fasteners. This is particularly beneficial in applications where space is limited or where mechanical fasteners would detract from aesthetics.

Once fully cured (for epoxies) or optimally adhered (for tapes), these materials form a strong, permanent bond. This bond is highly durable and resistant to vibration, shock, thermal cycling, and long-term environmental degradation, including moisture and chemicals. This characteristic is particularly important in applications where high reliability is critical.

Furthermore, electrical insulation is a common and important feature. Most thermal adhesives designed for electronics incorporate electrically insulating fillers to prevent electrical short circuits, thereby providing a safe dielectric barrier and offering considerable design flexibility.

While offering benefits, thermal adhesives do pose some significant challenges. The most notable limitation is their permanent bond. The permanent nature of this bond makes it exceedingly difficult, if not impossible, to rework, remove, or replace components without causing damage to either the component or the heat sink. This renders them unsuitable for applications requiring field serviceability, upgrades, or extensive testing cycles. The risk of damage during repair attempts is inherently high.

For epoxy-based adhesives, curing time is another consideration. These materials demand a specific curing time and temperature profile, adding a step to the manufacturing process that can impact throughput and energy consumption. The final properties of the adhesive are profoundly influenced by its curing conditions (Zhang et al., 2024).

Once cured, epoxies exhibit limited compliance, becoming rigid or semi-rigid. This means their ability to fill very fine microscopic voids and conform to significant surface irregularities after curing is restricted. Optimal thermal performance relies on relatively flat and smooth contact surfaces prior to curing, and thorough surface preparation (cleaning, roughening) is critical to maximize bond strength. While tapes offer better initial compliance, they are limited by their inherent thickness and are generally not suitable for high heat flux applications.

There is also a potential for voids during application. Care must be taken, especially with liquid adhesives, to avoid entrapping air bubbles, as these will create insulating voids that significantly degrade thermal performance within the adhesive layer. Techniques such as vacuum curing and careful dispensing may be necessary to mitigate this risk (Zhang et al., 2019).

A further concern is thermal expansion mismatch. If the coefficient of thermal expansion (CTE) of the adhesive differs significantly from that of the components it is bonding, stresses can accumulate during thermal cycling. This can potentially lead to delamination and cracking. Adhesives generally have higher CTEs than most electronic components.

Thermal adhesives are ideally suited for applications where a strong, permanent structural bond combined with efficient thermal transfer is critical, and where rework or component replacement is not anticipated or practical. Key examples include:

- Attaching heat sinks to components without pre-drilled mounting holes, such as small chipsets in compact designs or voltage regulators.
- LED module assembly, where the LED package is directly bonded to a metal-core PCB for both maximum heat dissipation and robust structural integrity.
- Small form-factor devices like smartphones and tablets, where space and weight savings are paramount.
- Certain power electronics modules where a strong, integrated bond and long-term reliability are crucial.

3.5. Phase Change Materials (PCMs)

Phase Change Materials (PCMs) are a unique and highly intelligent category of TIMs that utilize a precise physical phase transition to achieve optimal thermal performance. Unlike traditional pastes that remain semi-fluid and pads that remain solid at room temperature, PCMs are specifically designed to be solid, clean, and easily handleable at room temperature.

PCMs are typically formulated from specialized polymer blends, paraffinic hydrocarbons, and waxes, heavily loaded with thermally conductive filler particles (aluminium oxide, boron nitride, zinc oxide, etc.) selected for their specific melting point and latent heat properties (Zhang et al., 2020).

PCMs feature a base material, typically a polymer and wax blend, specifically chosen for its precise melting point and latent heat characteristics. This base material is the primary component dictating the thermal behaviour and performance of the PCM.

Similar to other TIMs, PCMs incorporate electrically insulating ceramic fillers, such as aluminium oxide and boron nitride, which provide thermal conductivity while maintaining dielectric strength. The size, shape, and loading of these filler particles significantly influence both the fluidity of the material in the molten state and its thermal conductivity when solid (Bao et al., 2024; Liu et al., 2020).

Regarding their form factor, PCMs are often supplied as thin films, pre-cut pads, and in dispensable forms that solidify at room temperature. The inclusion of a carrier film or mesh is vital for maintaining the integrity of the material and preventing excessive flow once melted.

PCMs are applied as a solid film and pad at room temperature. The process typically involves peeling off a protective liner and carefully placing the PCM between the component and the heat sink. Upon the initial power-up cycle, as the device reaches its normal operating temperature, the PCM rapidly melts and significantly softens. This molten state enables the material to flow into every microscopic void and irregularity on the contacting surfaces, providing unparalleled wettability and effective air displacement. This dramatically reduces thermal resistance at the interface. When the device cools down, for instance during shut-off, the PCM re-solidifies. Crucially, it re-solidifies in situ, perfectly conforming to the intimately established contact geometry formed during its molten phase. This characteristic significantly enhances the long-term reliability of PCMs (Nurmawati et al., 2004; Zhao et al., 2025). Figure 8 illustrates the mechanism by which PCMs perform this function.

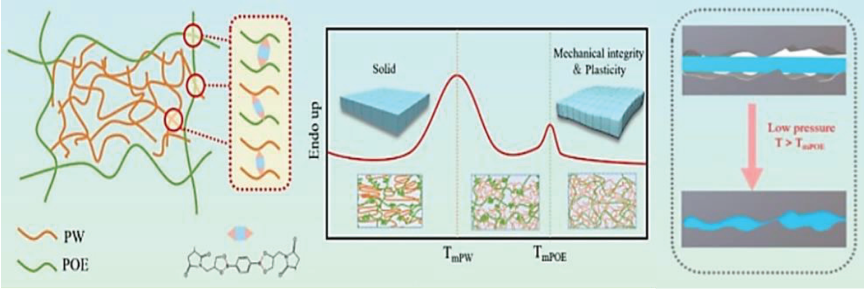


Figure 8. Schematic representation of the working mechanism of phase change thermal interface materials (PCMs) (Peng et al., 2022)

PCMs offer several notable advantages, with their optimal wettability and extremely low thermal resistance (post-melt) being the most prominent. Once the PCM melts, it behaves like a low-viscosity fluid, achieving near-perfect wettability and void filling that rivals and even surpasses the performance of the best traditional thermal pastes. This translates directly into extraordinarily low thermal resistance at the interface during active operation.

A significant benefit over traditional thermal pastes is the absence of pump-out and dry-out issues once the material has melted and re-solidified. Because the PCM re-solidifies in place after the initial melt/re-solidification cycles, there is no subsequent migration (pump-out) and evaporation (dry-out) of the carrier material. This ensures consistent and stable thermal performance over the long term, unlike the time-dependent degradation observed with some pastes. This makes PCMs particularly attractive for applications demanding critical reliability.

In their solid, pre-applied film and pad forms, PCMs are clean and easy to handle, being exceptionally mess-free and very straightforward to apply. This makes them highly suitable for automated assembly processes using pick-and-place robotics. Manual application is also simplified and less prone to error, with minimal risk of mess or misapplication (Ramaswamy et al., 2004).

PCMs deliver consistent long-term performance. Once the initial break-in and burn-in phase, where the material melts and flows for the first time, is complete, they provide highly stable and reliable thermal performance throughout the entire product lifespan. This capability allows them to meet product life expectancy without concerns of continuous performance degradation.

Furthermore, PCMs contribute to reduced application variability. Since the material flows and conforms optimally upon melting, minor variations in initial application pressure are often less critical than with thermal pastes, leading to more consistent overall performance. The material inherently tends to self-optimize its interface.

Lastly, most PCM formulations utilize electrically insulating ceramic fillers, rendering them safe for sensitive electronic applications.

Nevertheless, PCMs exhibit specific disadvantages that demand thorough consideration. Their superior thermal performance is only realized when the device consistently reaches and maintains a temperature above the phase change temperature of the PCM. Below this temperature, the PCM behaves more like a thermal pad, exhibiting higher resistance. This means they are not ideal for applications with very low or intermittent heat generation, as the material may not fully melt and achieve optimal contact. Therefore, the melting point must be precisely matched, set slightly below the typical operating temperature of the device.

The specific phase change temperature is a crucial design parameter. The melting point of the PCM must be carefully aligned with the normal operating temperature range of the device to ensure proper phase transition during operation. If the melting point is too high, the material may never fully melt, while a melting point that is too low could result in the product melting during storage or transit.

A potential concern for some very soft PCMs, prior to melting, is cold flow potential (pre-melt), where they might exhibit slight cold flow and creep under sustained pressure at room temperature. While modern formulations are designed to mitigate this, it can be critical during prolonged storage or assembly.

PCMs are increasingly becoming the preferred choice for high-performance CPUs and GPUs in gaming PCs, workstations, and servers, as well as in gaming consoles, high-power ASICs, and other advanced semiconductor devices. They are favoured in applications where consistent and optimal thermal performance over a long operational lifespan is critical, and where the device reliably reaches its operating temperature during normal use.

3.6. Liquid Metals

Liquid metal TIMs represent the apex of thermal conductivity among all TIM categories, offering performance that significantly surpasses even the best traditional thermal pastes. These are alloys that exist in a liquid state at or near room temperature.

Liquid metal TIMs are predominantly composed of alloys such as gallium-indium (Ga-In), gallium-indium-tin (Ga-In-Sn), and occasionally include traces of other elements like zinc and bismuth. Gallium, with its relatively low melting point, serves as an ideal base for liquid TIMs at room temperature. These alloys derive their exceptionally high thermal conductivity from their metallic constituents (Wang, X. et al., 2021).

Liquid metal TIMs are applied as an extremely thin layer between compatible surfaces. Due to their exceptionally low viscosity and often high surface tension (particularly on oxidized surfaces), precise application can be challenging. Achieving an even spread while preventing air voids is difficult. These materials tend to bead up or spread uncontrollably if an excessive amount is applied or if not handled with extreme care. Specialized applicators, brushes, and masking techniques are frequently employed to manage their flow. Pre-treatment of the surface, such as the removal of oxide layers, may be necessary to enhance wettability (Kong et al., 2019).

The singular and defining attribute of liquid metal TIMs is their extremely high thermal conductivity, which is unrivalled among all TIM categories. Liquid metals can exhibit thermal conductivities within certain range. This performance is often an order of greater than the best traditional thermal pastes, resulting in the absolute lowest thermal resistance at the interface. They provide significant thermal performance gains, particularly in applications with very high heat flux densities where even the slightest temperature drop is critical.

Their fluid, metallic nature also ensures superior wettability of compatible surfaces, allowing them to fill even the smallest imperfections and establish near-perfect contact. This characteristic largely eliminates the formation of insulating air gaps.

Although their thermal performance is supreme, liquid metal TIMs are associated with several severe limitations. Their most significant drawback is electrical conductivity. As excellent electrical conductors, any unintended spillage, overflow, or migration (even microscopic amounts) can lead to catastrophic electrical short circuits with exposed traces, component pins, or even within the integrated circuit package itself. This inherent risk renders them unsuitable for most general consumer and industrial electronic applications. Extreme caution, robust electrical insulation (encapsulation, protective barriers, etc.), and extensive masking around the component are mandatory during their use (Chen et al., 2020).

Corrosivity and material compatibility represent another major issue. Gallium, the primary component, readily alloys with and embrittles certain common metals over time, most notably aluminium. This renders liquid metals incompatible with the vast majority of aluminium heat sinks or components, which are prevalent in electronic devices, as they can cause significant structural degradation such as corroding holes and cracks. Consequently, their application is limited primarily to nickel-plated copper, bare copper, and gold-plated surfaces. This severely restricts their widespread adoption to specific hardware configurations. Prolonged exposure can also lead to the formation of an alloy layer on the contacting surfaces, potentially affecting long-term thermal conductivity and bond strength (Chen et al., 2024).

Application difficulty is another challenge. Their very low viscosity and high surface tension, which can cause beading, make precise and uniform application demanding. They are prone to spilling, and once spilled, they can be difficult to clean, often leaving stains and potentially permeating surfaces. There is also a risk of micro-droplets splattering during handling.

Furthermore, liquid metals are generally the most expensive TIM option per unit volume. Specialized alloys and stringent purity requirements contribute significantly to higher manufacturing costs.

Liquid metal TIMs are found almost exclusively in extreme performance computing environments, particularly by overclocking enthusiasts seeking to extract every last degree of cooling performance from high-performance CPUs and GPUs. They are also employed in highly specialized, niche high-power defence, aerospace, and industrial applications where maximum heat transfer is an absolute imperative, and the substantial risks associated with electrical conductivity and material compatibility can be rigorously managed, contained, and mitigated by expert engineers. They are not recommended for general consumer and commercial use without a deep understanding of their severe limitations and inherent risks. Notably, the use of liquid metal in mainstream manufacturing environments remains extremely limited due to its complexity and associated risks.

4. Innovations in Thermal Interface Materials

The intense pursuit of higher power densities and greater miniaturization in electronics continues to drive innovation in the field of thermal interface materials. As traditional TIMs approach their theoretical limits, new materials and application concepts are emerging, expending the limits of thermal management. Figure 9 shows the strategies for improving the thermal conductivity of polymer-based TIMS.

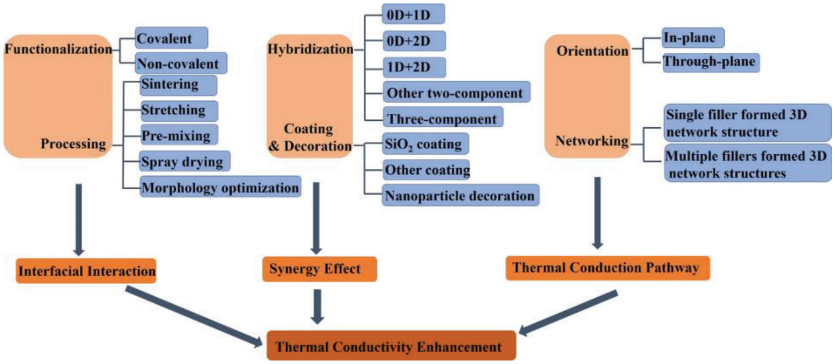


Figure 9. Strategies for for improving the thermal conductivity of polymer-based TIMS (Ma et al., 2020)

4.1. Advanced Filler Materials and Hybrid Composites

The quest for higher thermal conductivity in TIMs is largely dependent on the development and integration of novel, high-performance filler materials.

Graphene and Carbon Nanotubes (CNTs): As previously discussed, these carbon allotropes possess exceptionally high intrinsic thermal conductivities. The challenge lies in uniformly dispersing them within a polymer matrix at high loading levels without agglomeration and ensuring good interfacial wetting to realize their full potential. Efforts are focused on functionalizing their surfaces, developing sophisticated dispersion techniques (shear mixing, ultrasonication, etc.) (Jiang et al., 2023), and applying alignment methods (electric or magnetic fields) (Chung et al., 2024) to create highly anisotropic TIMs that can channel heat very efficiently in a specific direction.

Different techniques for the alignment of the fillers are depicted in Figure 10, encompassing mechanical force-based methods, template-assisted strategies, and 3D printing-based alignment.

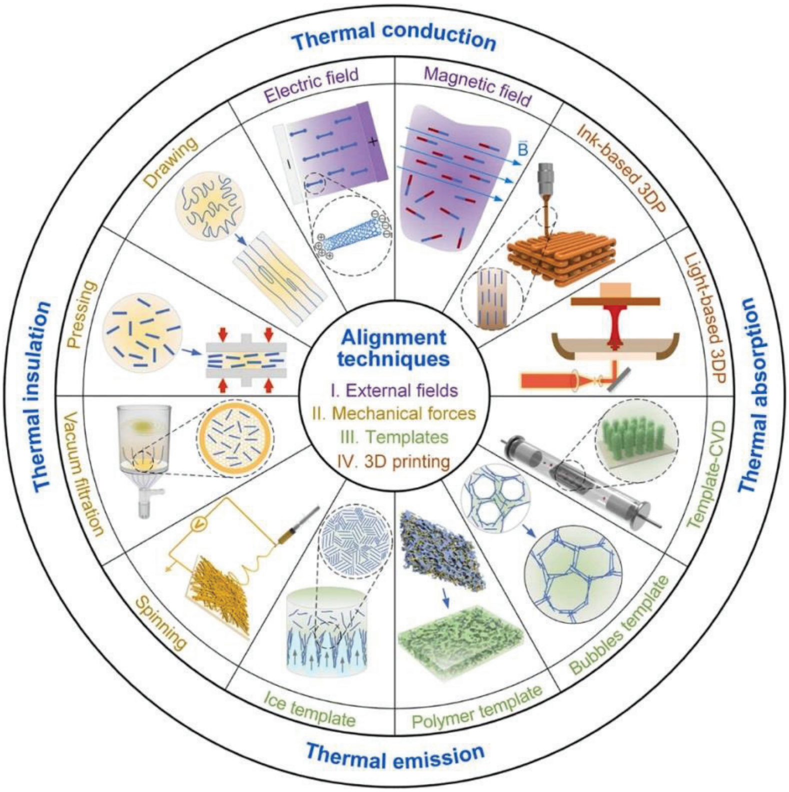


Figure 10. Alignment techniques for thermal material fillers (Xie, B. et al., 2023)

Figure 11 depicts the application of a rotating magnetic field, which enables a more compact and orderly orientation of graphene nano particles (GNPs) within polyvinyl alcohol (PVA). This leads to densified thermal conductive paths and, consequently, enhanced thermal conductivity in the composite (Cheng et al., 2023).

Hybrid composites, formed by combining carbon-based and ceramic fillers (such as BN and AlN), are being developed to balance performance and cost for TIMs (Akhtar, 2021).

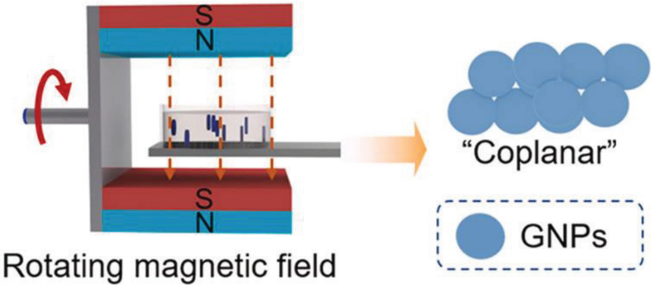


Figure 11. Schematic of GNPs orientation using a rotating magnetic field (adapted from (Cheng et al., 2023)

Boron Nitride Nanosheets (BNNS) and Nanotubes (BNNTs): Similar to their carbon counterparts, BN nanomaterials offer high thermal conductivity but with the critical advantage of being electrically insulating (An et al., 2023). This makes them highly attractive for sensitive electronic applications where electrical shorting is a concern.

Liquid Metal Based Composites: While pure liquid metals have compatibility issues, composite materials where liquid metal droplets are encapsulated within an electrically insulating polymer matrix (Kong et al., 2021). This approach aims to leverage the high thermal conductivity of liquid metals while mitigating their electrical conductivity and corrosive nature. The challenge lies in creating a stable emulsion and ensuring continuous thermal pathways through the encapsulated liquid metal.

Hybrid Filler Architectures: Future TIMs will increasingly feature complex, multi-modal filler systems. This includes using a combination of different particle sizes (macro, micro, nano) to maximize packing density and create a more continuous thermal network. Employing fillers with different geometries (spherical, flake, fibrous) in a synergistic manner is also being explored to optimize both thermal conduction pathways and mechanical properties.

4.2. Parameters Influencing Thermal Properties of Composite TIMs

When considering TIMs as composite materials, typically comprising a polymer matrix filled with conductive particles, their performance is not merely a function of their bulk thermal conductivity. A multitude of intricate parameters, inherent to the constituents and their interactions, critically influence their thermal conductivity. Given that TIMs often serve as electrical insulators while facilitating heat transfer, a comprehensive grasp of these intricate parameters is essential for effective design, optimization, and reliable deployment in modern electronic systems. The interplay among these factors is complex, often requiring complicated modelling and empirical validation to achieve desired performance metrics.

4.2.1. Thermal Conductivity

The effective thermal conductivity of a composite TIM is a complex and intricately determined property, not merely an average of its constituent parts. Instead, it is the intricate interplay between the intrinsic properties of the filler and matrix materials, their morphological arrangement, and the crucial quality of their interfaces that dictates the overall heat transfer efficiency. A comprehensive understanding of these factors is absolutely vital for the successful design and deployment of TIMs in the demanding landscape of modern electronics.

4.2.1.1. Filler Material Properties

- Intrinsic thermal conductivity: This fundamental property of the filler material itself forms the bedrock of the thermal capability of the composite. Highly thermally conductive materials are specifically chosen for their exceptional ability to facilitate phonon and, in the case of metals, electron transport (Mumtaz et al., 2024; Zhao et al., 2022). Advanced carbon allotropes, including graphene and carbon nanotubes, exhibit outstanding conductivities, particularly along their structural axes (in-plane for graphene, axial for nanotubes), enabling remarkably rapid phonon transport with minimal scattering (Stamper et al., 2024). Among traditional metallic fillers, silver remains a frequent choice due to its excellent inherent electrical and thermal conductivity. In the realm of ceramic fillers, aluminium nitride and especially hexagonal boron nitride are highly valued; the latter is particularly notable for its anisotropic high thermal conductivity in the basal plane (Yan et al., 2025), allowing for highly directional heat flow when properly oriented. The greater the intrinsic thermal conductivity of these individual filler particles, the more effective they are at creating efficient thermal pathways, drawing heat away from the heat-generating source, and channelling it expediently through the TIM layer to the cooling solution. Consequently, the initial selection of filler material often prioritizes those with the highest inherent capacity for thermal energy transfer, balancing performance with cost and process ability considerations.

- Filler (Volume Fraction): The proportion, or volume fraction, of these highly conductive filler materials suspended within the polymer matrix fundamentally dictates the overall ability of the composite to conduct heat. As the volume fraction of conductive particles increases, the probability of establishing continuous thermal pathways throughout the material rises significantly (Qi et al., 2022). This relationship is typically non-linear; initially, adding a small amount of filler might yield only a modest improvement in thermal conductivity, as the heat must still largely traverse the less conductive matrix. However, beyond a certain critical concentration, often referred to as the percolation threshold, the thermal conductivity can increase dramatically, which is particularly evident when, in addition to the increased filler volume fraction, the filler particles are also aligned in a specific direction, leading to significantly higher enhancements, as illustrated in Figure 12. At this point, filler particles begin to physically touch and form an interconnected, highly conductive network spanning the entire matrix. This phenomenon creates effective shortcuts for heat, enabling it to bypass the more resistive polymer.

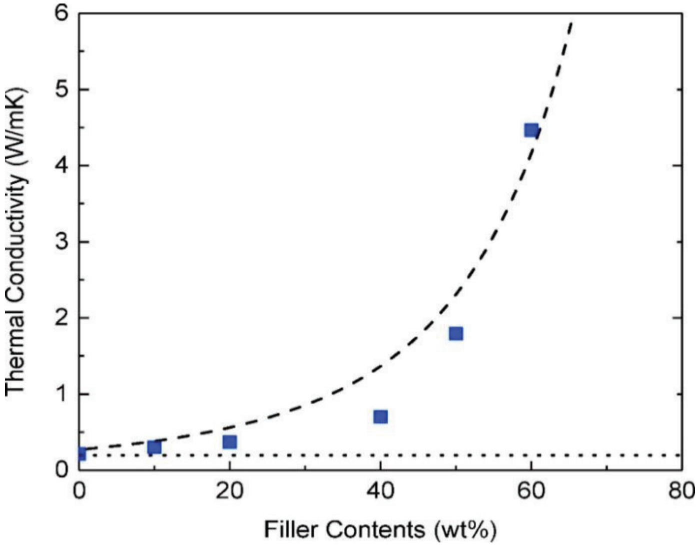
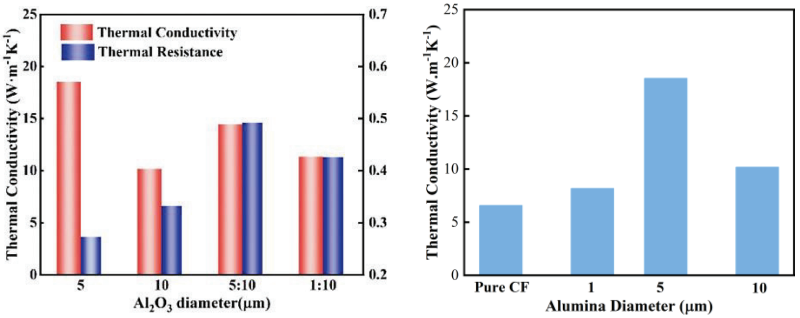


Figure 12. The influence of graphite filler content on the through-plane thermal conductivity of reference GP-TIMs (Chung et al., 2018)

While the pursuit of ever-higher thermal conductivity naturally pushes designers towards maximizing filler loading, this endeavour faces significant and often intractable practical manufacturing limitations. Incorporating too much solid material into the polymer matrix can lead to a substantial and often unmanageable increase in the viscosity of the composite. A highly viscous TIM may become exceedingly difficult to process, dispense precisely, and apply uniformly, risking the formation of detrimental air voids (Carlton et al., 2020). Such application challenges can ultimately compromise the thermal performance of the TIM, even if the fillers themselves possess exceptional intrinsic conductivity, because a poor interface will dominate the overall thermal resistance. Therefore, a careful and often painstakingly optimized balance must be struck between maximizing filler content for optimal thermal performance and maintaining a workable viscosity suitable for efficient manufacturing and reliable application.

- Particle size and size distribution: The physical dimensions of the individual filler particles exert a profound influence on the thermal properties of the composite, particularly at the numerous internal interfaces within the material.

The thermal conductivity and resistance of the composites are significantly influenced by the size of the embedded particles. As depicted in Figure 13(a), composites incorporating smaller, micron-sized particles, such as Al_2O_3, demonstrate superior thermal conductivity and reduced thermal resistance compared to those with larger particles. This enhancement is largely attributed to the increased specific surface area of the finer particles, which facilitates more extensive contact points among the filler particles.



(a) (b)

Figure 13. (a) and (b) Thermal conductivity and thermal resistance of the vertically oriented carbon fibre-silicone rubber composites with different alumina (Al_2O_3) particle sizes (adapted from (Fu et al., 2024)

Conversely, an excessively small particle size can hinder performance. Composites containing the smallest alumina particles show diminished thermal conductivity (Figure 13(b)). This decline primarily stems from the tendency of these minute particles to aggregate within the matrix, impeding uniform dispersion and consequently elevating interfacial thermal resistance during heat transfer. Further improvements in thermal conductivity can be achieved by employing a mixed-particle strategy. When larger alumina particles are combined with smaller particles, the thermal conductivity of the composite improves. This phenomenon aligns with established spherical particle density packing models, which suggest that smaller particles can effectively bridge the interstitial spaces between larger ones. This bridging action reduces the thermal resistance within these gaps, thereby enhancing the overall thermal conductivity of the composite (Fu et al., 2024).

While previous discussions have focused on the impact of filler size on thermal conductivity at a given volume fraction, a more comprehensive understanding emerges when filler size and volume fraction are considered concurrently. Specifically, as the filler volume fraction increases, larger-sized fillers are observed to significantly enhance thermal conductivity, as clearly demonstrated in Figure 14. Larger filler particle sizes can significantly influence the thermal conductivity of polymer composites. This phenomenon has been observed, where the incorporation of substantial boron nitride particles into an epoxy resin matrix resulted in a notable enhancement of thermal conductivity compared to composites utilizing smaller particle sizes. This improvement is primarily attributed to two factors: the reduced interfacial area between the filler and the polymer matrix, and critically, the increased contact area between the filler particles themselves. The use of larger filler dimensions facilitates more extensive direct contact among the particles, creating a more continuous pathway for heat transfer (Jasmee et al., 2021).

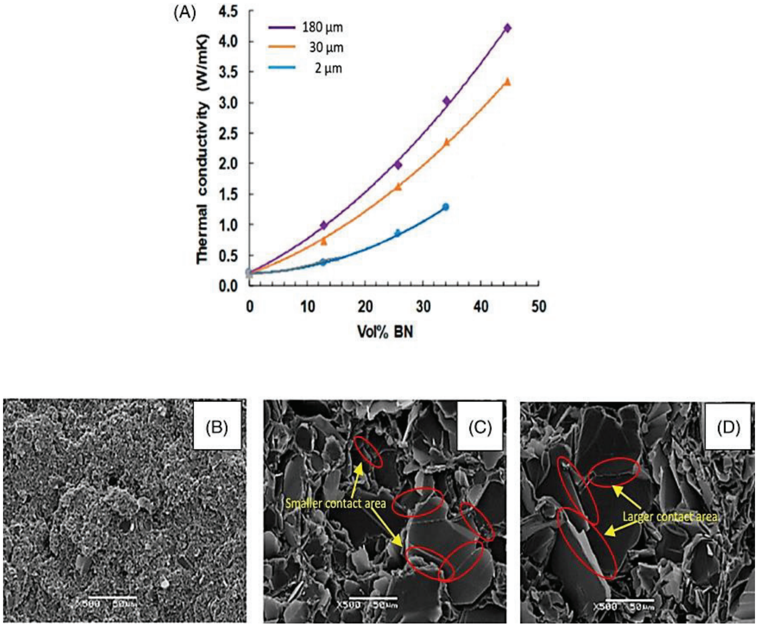


Figure 14. The impact of boron nitride (BN) filler size on thermal conductivity (A), alongside corresponding SEM images illustrating filler-filler contact areas for (B) 2 µm, (C) 30 µm, and (D) 180 µm particles (Jasmee et al., 2021 adapted this figure from the study of Moradi et al., 2019)

- Particle shape (morphology) and orientation:

The geometric form, or morphology, of the filler particles profoundly influences the thermal conductivity through the composite, impacting both the efficiency and directionality of heat flow (Chen et al., 2023). Isotropic shapes, such as perfect spheres, tend to offer consistent thermal pathways in all directions, leading to more uniform thermal conductivity throughout the material. While predictable, they may not offer the most optimized heat transfer. However, anisotropic shapes, such as thin flakes (hexagonal boron nitride, graphene nanoplates), elongated rods (multi-walled carbon nanotubes), and long fibres, can create far more efficient and directional heat transfer pathways.

Figure 15 demonstrates the relationship between filler shape and thermal conductivity. Flake-shaped particles possess a significantly higher aspect ratio, defined as their width relative to their thickness, compared to their spherical counterparts. This elongated geometry is crucial because it facilitates the establishment of more continuous and interconnected thermal pathways throughout the polymer matrix. These pathways essentially serve as efficient conduits for heat flow, unlike the often tortuous and discontinuous paths created by scattered spherical particles, which inherently increase thermal resistance. Given that heat preferentially follows the path of least resistance, the thermal bridges formed by flake particles prove far more effective at channelling heat. A significant hurdle to heat transfer in composites arises at the interface between the filler and the matrix, this is known as interfacial thermal resistance. It occurs due to phonon scattering at the boundary between materials with differing acoustic properties. At the same mass or volume fraction, spherical nanoparticles, with their higher surface area-to-volume ratio, present a larger total interfacial area than flakes. A greater interfacial area translates to more potential scattering sites for phonons, hindering smooth transition of heat. Flake filler, by offering a relatively lower total interfacial area, mitigates this resistance, facilitating a more seamless flow of heat across the filler-matrix boundary. As a result, the confluence of optimized morphology and reduced interfacial resistance positions flake filler as a demonstrably more effective filler for enhancing the thermal conductivity of composite materials when compared to its spherical counterpart (Huang et al., 2015).

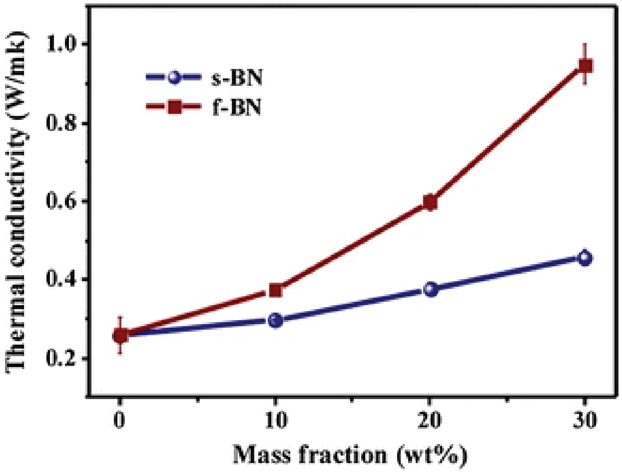


Figure 15. The effect of filler shape on the thermal conductivity of BN/epoxy composites at different mass fractions (adapted from Huang et al., 2015)

Fillers can be categorized by dimension: 0D (spherical), 1D (tubes, wires), and 2D (flakes). Figure 16 presents a schematic illustration of the 3D networks and associated contact areas that develop when fillers of varying dimensions are hybridized.

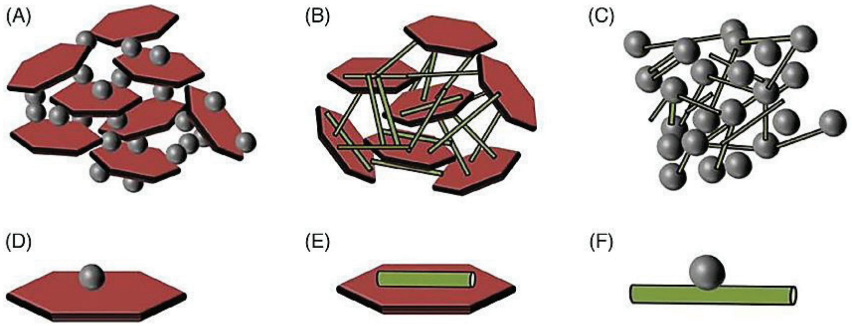


Figure 16. Schematic diagram of 3D network formed when hybridising: (a) 2D with 0D, (b) 2D with 1D, (c) 1D with 0D; contact area,(e) point-contact, (f) face-contact (g) point-contact (Jasmee et al., 2021)

2D-1D hybridization is particularly potent because the large surface area of 2D fillers (graphene, BN nanosheets, etc.) provides ample adsorption space for 1D fillers (carbon nanotubes, etc.). This interaction allows the 1D fillers to effectively bridge the gaps between the more rigid 2D fillers, preventing their undesirable stacking and agglomeration. This line-contact formation between 1D and 2D components creates an extensive and efficient three-dimensional (3D) thermal conductive network. The structural integrity of 2D fillers also ensures their aspect-ratio is maintained, maximizing contact area and reducing thermal boundary resistance and interfacial thermal resistance. For 2D-0D hybridization, while 0D fillers (Al_2O_3 nanoparticles, etc.) might form point contacts with 2D fillers, this configuration proves highly beneficial. The 0D nanoparticles act as spacers or intercalants between the larger 2D sheets, crucially preventing them from stacking upon one another. Stacking among 2D fillers significantly increases interfacial thermal resistance, so by mitigating this, 0D fillers help maintain a more dispersed and conductive network, even at lower loadings. This leads to a substantial synergistic enhancement in thermal conductivity. A major impediment to high thermal conductivity in single-filler composites is the tendency of fillers to aggregate or stack, creating discontinuities in the heat pathway. Hybrid systems, especially those combining different filler dimensions, can overcome this. Smaller fillers (0D or 1D) effectively fill the voids and gaps between larger particles, creating additional conductive paths and increasing packing density. This mechanism directly reduces thermal boundary resistance/interfacial thermal resistance by ensuring a more continuous thermal network (Jasmee et al., 2021).

The scientific reasoning emphasizes that carefully chosen hybrid combinations, particularly those involving 2D fillers with 1D or 0D counterparts, optimize the formation of efficient, continuous 3D thermal networks by minimizing detrimental filler-filler interactions (like stacking) and maximizing effective thermal contact points, all while maintaining desirable composite properties at lower filler concentrations.

4.2.1.2 Matrix Material Properties

- Intrinsic Thermal Conductivity: While significantly lower than that of the fillers, typically by one to three orders of magnitude, the intrinsic conductivity of the matrix still contributes to the overall effective thermal conductivity, particularly at lower filler loadings or if the filler network is discontinuous. The polymer matrix primarily serves to bind the filler particles together, ensuring mechanical integrity, adhesion, and conformability. Its role as a continuous phase for minor heat transfer should not be entirely overlooked, as it bridges the gaps between the highly conductive particles.

- Viscosity and rheology: These are arguably among the most critical parameters for the practical application of a TIM. The viscosity of the TIM dictates its ability to flow and conform under pressure, effectively displacing air from the microscopic asperities (roughness peaks and valleys) on the mating surfaces (heat sink). A lower viscosity at the application temperature, allows the TIM to spread easily, wet the surfaces thoroughly, and achieve a minimal, uniform BLT (Zhao et al., 2019). Since the thermal resistance of the bulk TIM layer is directly proportional to its thickness, minimizing BLT is paramount for optimal thermal performance. Ultimately, even a highly conductive TIM will perform poorly if it cannot achieve a thin and uniform interface due to high viscosity, leading to trapped air and non-ideal contact.

- Thermal stability and mechanical properties: The polymer matrix must remain stable and maintain its integrity across the entire operational temperature range of the electronic device, as well as over its intended lifespan, which can span many years. Degradation mechanisms can lead to pump-out (where the TIM migrates out from between the interfaces due to repeated thermal cycling and differential thermal expansion between dissimilar materials) and dry-out (Khuu et al., 2009). All of these phenomena can progressively increase the thermal resistance over time and significantly compromise the long-term reliability of the thermal management solution, potentially leading to device failure. Furthermore, the mechanical properties of the matrix, such as its elastic modulus, profoundly influence the ability of the TIM to maintain intimate contact with the mating surfaces, conform to surface irregularities under clamping pressure, and accommodate differential thermal expansion between components without delamination, cracking, and void formation. A compliant matrix that can absorb stress is often desirable to maintain consistent contact over time.

4.2.1.3. Interface Properties

The bottleneck at the boundaries between the filler particles and the polymer matrix, and crucially, between the TIM layer itself and the mating component surfaces, is often the most significant single contributor to the total thermal resistance of the entire thermal assembly. Interfacial thermal resistance arises primarily from phonon scattering. Phonons encounter resistance when transitioning from one material to another, leading to a temperature drop across the interface (Qiu et al., 2022). Applying specialized coupling agents, such as silanes, to the surfaces of filler particles can significantly improve their wettability by the polymer matrix. These agents facilitate stronger chemical bonding between the filler and the matrix (Mishra et al., 2025) and thereby enhance phonon coupling across the interface, ultimately reducing interfacial thermal resistance.

The micro-roughness of the surfaces where the TIM is applied directly impacts the actual contact area, which is typically much smaller than the apparent contact area. A rougher surface necessitates a greater amount of TIM material to effectively fill the microscopic gaps and valleys, leading to a thicker effective BLT and potentially increasing the overall contact resistance by introducing more resistive air pockets. Therefore, proper surface preparation, such as precision lapping and polishing of the components to achieve ultra-smooth finishes, can substantially improve the overall performance of the TIM by maximizing direct solid-to-solid contact and minimizing the resistive air gaps. The ideal scenario involves a TIM that completely fills all voids, creating a continuous and uninterrupted thermal path.

4.2. Next-Generation Dispensing and Manufacturing Techniques

Additive manufacturing methods, such as 3D printing and Direct Write Technologies, have emerged as instrumental methods for fabricating higher-performance TIMs (Fan et al., 2024; Hou et al., 2024; Zhang et al., 2023a). Figure 17 illustrates 3D printing technique for TIM.

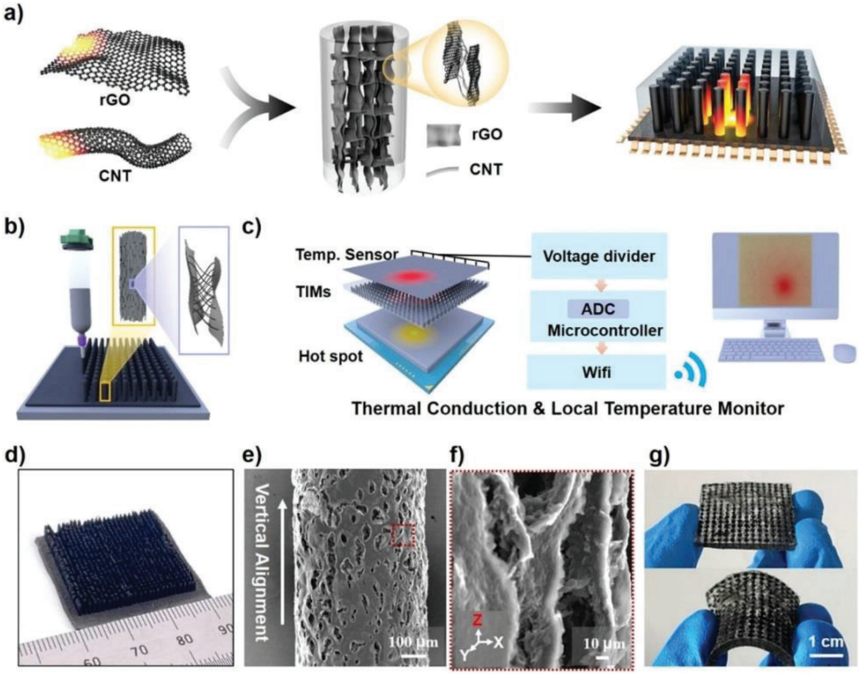


Figure 17. 3D printing of reduced graphene oxide (rGO)/carbon nanotubes (CNTs) arrays for developing flexible thermal interface materials (TIMs): (a) Schematic diagram of heat conduction and local temperature monitoring, (b) Schematical showing the vertical 3D printing of rGO/CNTs arrays and the amplification diagram of microscopic graphene layers connected to 1D CNTs (inset), (c) Schematic diagram of through-plane heat conduction in a TIM consisting of a vertical rGO/CNTs array and PDMS matrix, and their application in local temperature monitoring of electronic device, (d) Optical image of a

representative rGO/CNTs arrays with twenty-seven-by-twenty-seven vertical pillars, (e) and (f) SEM images of the surface morphology of a rGO/CNTs pillar, and (g) Photograph of a flexible rGO/CNTs-PDMS TIM specimen (Xia et al., 2024).

Additive manufacturing techniques, specifically 3D printing (Figure 17), hold immense promise for creating custom, complex TIM geometries tailored precisely to individual component interfaces. This could enable the fabrication of TIMs with integrated features like micro-channels for enhanced heat spreading or anisotropic structures for directional heat flow. This allows for highly customized thermal management solutions on demand, reducing waste and allowing for highly optimized designs for specific geometries.

Direct-Write technologies like Direct Ink Writing (DIW) allow for the precise deposition of highly viscous and even semi-solid TIMs in extremely fine patterns, potentially integrating the TIM application directly into the chip manufacturing and packaging process. This offers unmatched control over bond line thickness and material placement.

5. Applications of Thermal Interface Materials through Diverse Industries

The omnipresence of electronic devices across nearly every sector of modern life means that TIMS are not confined to a single industry; rather, they are critical enablers across a remarkably diverse range of applications. Figure 18 illustrates these applications. Their specific role, however, adapts to the unique demands of each industry, balancing performance with reliability, quality, and cost (Razeeb et al., 2017).

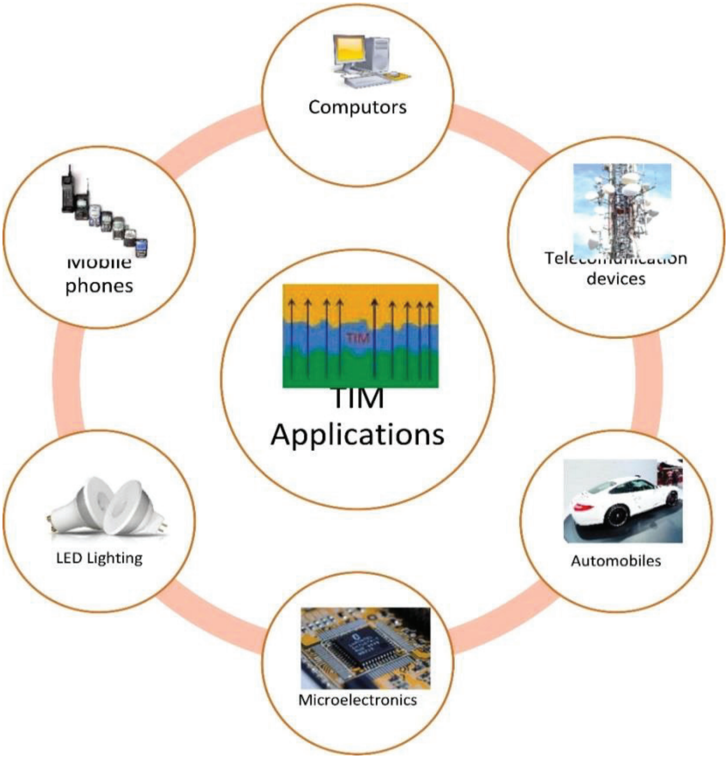


Figure 18. Applications of thermal interface materials (Rahman et al., 2025)

Among the various TIM applications, carbon-based TIMs are emerging as the most promising candidates for dissipating heat from electronic devices. Figure 19 illustrates these carbon-based TIMs and their diverse applications.

Figure 19. Applications of carbon-based thermal interface materials (Guo et al., 2021)

5.1. Consumer Electronics and Personal Computing

This sector, characterized by its rapid innovation cycles and immense production volumes, is a primary driver of TIM development, particularly in terms of cost-effectiveness and ease of assembly.

- Central processing Units (CPUs) and Graphics Processing Units (GPUs): In these applications, TIMs are crucial for accelerating heat transfer across the interfaces between heat-generating components and the heat sink (Wang, Z. et al., 2021). Thermal pads and pastes are commonly used due to their superior thermal conductivity and ability to achieve extremely thin bond lines between the CPU/GPU die and the heat sink (Chakarvarti et al., 2025; Gwinn & Webb, 2003). For extreme overclocking, liquid metal TIMs are sometimes employed by enthusiasts for their unmatched thermal conductivity, despite their inherent risks (electrical conductivity, corrosivity to aluminium, challenging application). For mass-produced laptops and pre-built desktops, phase change materials (PCMs) are gaining traction due as they offer clean, automated application and excellent long-term stability without pump-out issues.

- Memory Modules (RAM), Chipsets, and Voltage Regulator Modules (VRMs): These components also generate significant heat, particularly under heavy load. Most of the heat generated flows through the main substrate, encountering thermal resistances from the substrate itself, the thermal interface material (TIM), and the heat spreader; therefore, TIMs are crucial for these devices (Kaul et al., 2020). Thermal pads are appropriate materials in these applications due to their ease of application, ability to bridge variable gaps (between chips and a heat spreader, etc.), and excellent electrical insulation. For more demanding VRM cooling, softer gap fillers and thin thermal pads with higher thermal conductivity might be specified.

- Solid State Drives (SSDs): TIMs are frequently applied between the NAND flash controllers, DRAM chips, and a small heat spreader or directly to the laptop chassis to prevent thermal throttling and ensure sustained performance (Ye at al., 2018).

- Gaming Consoles: The custom System-on-Chips (SoCs) in modern consoles are very powerful and produce substantial heat. For effective heat removal from the SoC, TIMs like thermal pads, pastes, and liquid metals are typically employed (Kwok, 2021).

- Smartphones and Tablets: Figure 20 shows an application of a thermal pad on a smartphone CPU. Miniaturization and slim form factors pose immense thermal challenges in smartphones and tablets. Heat needs to be spread and dissipated away from the SoC. Thermal pads, particularly those increasingly made with carbon nanotube and graphene composites, are used to significantly dissipate heat (Sponagle et al., 2021; Wang et al., 2019). Figure 20 shows an application of a thermal pad on a smartphone CPU.

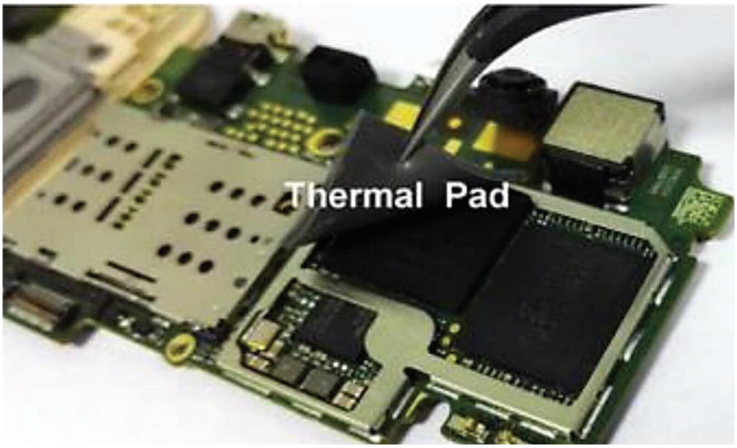


Figure 20. An application of a thermal pad on a smartphone CPU (Wang et al., 2019)

5.2. Automotive Electronics

The automotive industry places unique and stringent demands on TIMs, prioritizing long-term reliability under certain environmental conditions, resistance to vibration, and consistent performance across wide temperature ranges (Praveen & Rammohan, 2024).

- Electric Vehicle (EV) Battery Packs: Thermal management is critical for EV battery performance, safety, and longevity (Murugan et al., 2025). TIMs are used to transfer heat from individual battery cells and modules to cooling components (Stadler & Maurer, 2019). Dispensable gap fillers are ideal due to their ability to accommodate significant and varying gaps between cells and the cooling structure, their stress-relieving properties (absorbing vibration), and their automated application suitability. Their electrical insulation is also critical for safety.

- Power Inverters, Converters, and On-Board Chargers: For these applications, optimizing TIMs is a key area of focus. New, high-performance TIMs, including those enhanced with graphene composites, are being created to offer better thermal conductivity and mechanical stability (Dar et al., 2024).

- Engine Control Units (ECUs) and Advanced Driver-Assistance Systems (ADAS): TIMs in an ECU are located between the printed circuit board (PCB) and the housing base plate, as illustrated in Figure 21. ECUs operate in demanding under-hood environments. Robust thermal pads and phase-change materials are commonly used in these applications to ensure heat dissipation from microcontrollers and processors to the enclosure. Their compliance helps absorb shock and vibration (Otiaba et al., 2011).

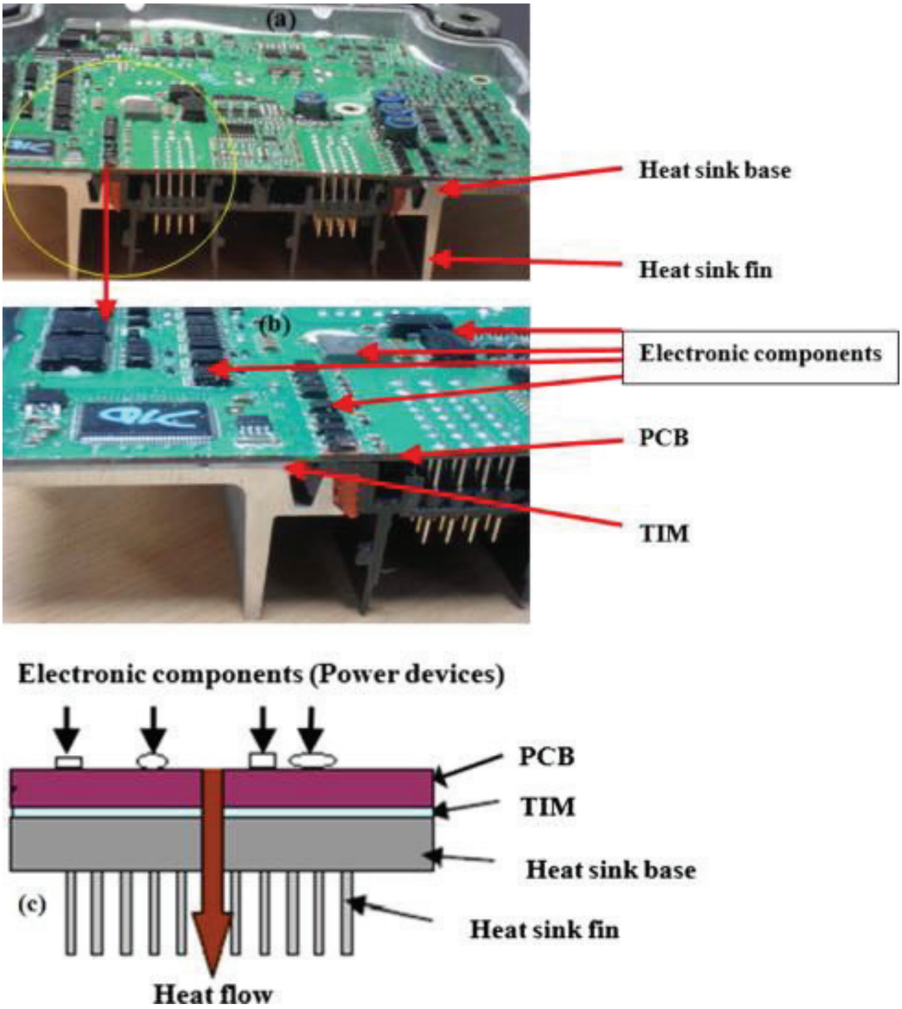


Figure 21. (a) Cross-section of an ECU with (b) details of the TIM, PCB, and electronic components, and (c) schematic diagram illustrating the heat flow within the ECU (Otiaba et al., 2011)

5.3. Telecommunications and Data Centres

The backbone of the digital age, these systems demand exceptionally high performance and unwavering reliability due to continuous operation and high power densities.

CPUs, GPUs, and specialized networking ASICs (Application-Specific Integrated Circuits) in data centres operate non-stop at high power, which makes heat dissipation an even more critical concern (Liang, 2025). High-density networking equipment also contains numerous heat-generating components (Razdan et al., 2022). High-performance thermal pastes, thermal pads, and advanced phase change materials can be an appropriate choice for these mission-critical components, aiming for the lowest possible thermal resistance to allow for maximum clock speeds and continuous operation.

In 5G and 6G base stations, the high-power amplifiers and processing units in 5G infrastructure require robust thermal management (Dbouk & Mourad, 2025). Thermal pads are crucial for dissipating heat from radio frequency components, processors, and power modules, often in outdoor environments that demand resilience to extreme temperatures and weather (Lewis, 2021; Tong, 2022).

5.4. Industrial and Power Electronics

This sector encompasses a wide array of demanding applications where high power, high temperatures, and long-term reliability are paramount.

IGBT Modules (Insulated Gate Bipolar Transistors) are found in motor drives, renewable energy inverters (solar, wind), uninterruptible power supplies (UPS), and industrial automation. Overheating significantly contributes to the high failure rate of IGBTs during operation; this is particularly true when they experience substantial transient currents upon startup. This makes effective thermal management of these power devices crucial for their safety and reliability. One way to address this is by using advanced thermal interface materials (TIMs). For example, a TIM that incorporates paraffin as a phase change material and graphene as a reinforced thermal conductive filler can be employed. Such a composite TIM can effectively slow down the heating rate and reduce the interfacial thermal resistance of IGBT modules, thereby enhancing heat dissipation and improving overall performance compared to traditional materials like commercial silicone grease (Zhang et al., 2025). These properties highlight the practical utility of such composite TIMs in real-world heat dissipation applications for IGBT modules.

Applications in aircraft, satellites, and military vehicles demand extreme reliability under severe conditions (vacuum, wide temperature fluctuations, high vibration, radiation, etc.). Thermal pads and phase change materials and are specifically designed for these demanding environments (Khan & Singh, 2024; Wu et al., 2021).

5.5. Renewable Energy Systems

The drive towards sustainable energy sources necessitates efficient and reliable thermal management in power conversion and storage.

Solar inverters convert DC power from solar panels to AC power. The power electronics within these inverters generate significant heat (Shaker et al., 2024). High-performance thermal pastes and electrically insulating gap fillers are critical for ensuring the longevity and efficiency of these outdoor-mounted systems. Similar to solar inverters, wind turbine converters manage the power output from wind turbines. The large power semiconductors require durable TIM solutions that can withstand harsh environmental conditions and operate reliably for decades.

Conclusion

The effective thermal management of electronic components is a critical imperative for the advancement of modern technology, with innovation in this field directly correlating to the increasing power densities and compaction trends of our devices. Thermal Interface Materials (TIMs) play an indispensable role in addressing this challenge by filling microscopic gaps between a heat-generating source and a heat sink, thereby eliminating the thermal contact resistance that impedes efficient heat transfer. This book has provided a comprehensive overview, commencing with the fundamental principles of heat transfer and progressing through the diverse types of TIMs, their critical material properties, and future developmental trajectories.

To comprehend heat transfer mechanisms and thermal contact resistance is foundational to grasping the functionality of TIMs. As demonstrated, even seemingly smooth surfaces possess microscopic irregularities that create significant air gaps, severely hindering heat flow. The primary purpose of TIMs is to decisively displace these insulating air pockets with a medium of significantly higher thermal conductivity, thereby establishing a continuous conduction path.

The efficacy of TIMs hinges on a delicate balance of critical properties such as thermal conductivity, wettability, compliance, and optimal bond line thickness (BLT). This book delves into various filler materials, such as metals, ceramics, and carbon-based nanomaterials, and their role in enhancing thermal performance.

The TIM market is remarkably diverse, offering a rich spectrum of solutions optimized for varying performance levels, application methodologies, and cost considerations. Grasping this landscape necessitates a deep appreciation for the unique attributes of each category discussed in this book. Thermal pastes (greases/compounds), for instance, are developed for maximum thermal performance and minimal thermal resistance, ideal for demanding applications like high-power CPUs and GPUs. However, they require precise application and careful consideration of electrical conductivity. Thermal pads, as pre-formed, solid sheets, prioritize ease of use, electrical insulation, and gap-filling capabilities, making them highly suitable for automated assembly in high-volume consumer electronics. While their thermal resistance is generally higher than optimal pastes, their convenience, electrical safety, and vibration damping properties are invaluable.

Gap fillers (dispensable gels/pastes) are designed to accommodate larger and often irregular gaps. Their unique thixotropic properties allow for precise automated dispensing, conforming perfectly to complex contours. They offer superior stress relief, crucial for automotive ECUs and EV battery packs. Thermal adhesives (epoxies/tapes), serving a dual purpose, provide both efficient heat transfer and a strong, often permanent, mechanical bond, simplifying assembly by eliminating fasteners. Their primary limitation is the irreversible nature of the bond, making rework difficult. Lastly, phase change materials (PCMs) are a highly intelligent category, solid at room temperature but melting at device operating temperatures to achieve exceptional wettability and extremely low thermal resistance. Their resistance to pump-out and dry-out ensures consistent long-term performance, making them attractive for critical reliability applications.

The intense pursuit of higher power densities and increased integration in electronics continues to drive innovation in the field of thermal interface materials. As traditional TIMs approach their theoretical limits, new materials and application concepts are emerging, extending the boundaries of thermal management. The quest for higher thermal conductivity relies on advanced filler materials and hybrid composites, including graphene and carbon nanotubes for their exceptional conductivity, and boron nitride nanosheets and nanotubes for similar benefits with electrical insulation. Liquid metal-based composites aim to utilize the high conductivity of liquid metals while mitigating their electrical and corrosive properties. Future TIMs will also feature complex, multi-modal filler systems, combining different particle sizes and geometries to maximize packing density.

The performance of composite TIMs is an intricate interplay of several parameters. The intrinsic thermal conductivity of filler materials, their volume fraction, particle size and distribution, and shape and orientation are all critical. The properties of the matrix material, including its thermal conductivity, viscosity, rheology, and thermal/mechanical stability, are equally vital for practical application. Most significantly, interfacial thermal resistance at filler-matrix and TIM-component boundaries often acts as the dominant constraint.

Advancements in TIM application are inseparable from their evolution. 3D printing of TIMs holds immense promise for creating custom, complex geometries, potentially integrating micro-channels for enhanced heat spreading. Direct-write technologies allow for precise deposition in fine patterns, integrating TIM application directly into chip manufacturing. The forward-looking prospect of smart and responsive TIMs, capable of dynamically adapting their thermal properties and even autonomously self-healing, suggests a future where thermal management solutions are truly intelligent and self-optimizing.

The presence of electronic devices across nearly every sector of modern life means that TIMs are not confined to a single industry; rather, they are critical enablers across a remarkably diverse range of applications. In consumer electronics and personal computing, thermal pastes dominate high-performance CPUs/GPUs, while thermal pads are common for memory modules. The automotive industry demands long-term reliability in harsh environments, making dispensable gap fillers ideal for EV battery packs and durable pads for ECUs. In telecommunications and data centres, high-performance pastes and phase change materials are crucial for server processors. Finally, in industrial and power electronics, high thermal conductivity pastes and insulating gap fillers are essential for components like modules, where high power and extreme temperatures are common.

In conclusion, this rigorous book aims to provide readers, whether seasoned researchers, innovative product designers, engineers, and curious students, with a practical and forward-looking understanding of thermal interface materials. By empowering them to make informed decisions and drive future innovation, a meaningful collective contribution can be made to enhanced thermal management in an ever-evolving and increasingly demanding electronic landscape.

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