A Review on Thermal Interface Materials For CPU Cooling Applications

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Abstract- *The CPU thermal paste is a kind of material that we put between the processor and the heat spreader or heat sink. This helps to reduce the resistance to heat flow between these two parts. The CPU thermal paste is not meant to be better than copper or aluminum at conducting heat. It helps to fill in the tiny gaps between the surfaces with a material that can spread the heat easily.The CPU thermal paste works by replacing the air in these gaps with a material that can wet the surface and create a thin path for the heat to flow. Many people have studied the CPU paste, like Prasher in 2006 and Razeeb and others in 2018 and Wei and others in 2024. They found that the performance of the CPU paste depends on many things, such as how well the filler material conducts heat and the thickness of the paste. the pressure on the paste and how well it wets the surface.It is not about how well the CPU thermal paste conducts heat, but also about its long-term stability. Some other people, like Goel and others in 2008 and Prasher and Shipley and others in 2003 have also studied this. This article will talk about how the CPU thermal paste's made, what materials are used, strengths, weaknesses and how it has changed over time from old grease-based systems to new nanostructured and hybrid systems. We will also talk about alternatives to the CPU thermal paste, such as phase-change materials, graphite sheets, liquid metals and metal-based bonded interfaces, which have been studied by people like S Chen and others in 2020 Hoffmeyer and others in 2017 Lee and Kim in 2024 and Razeeb and others, in 2018.*

I. INTRODUCTION

The Central Processing Units get really hot. This causes problems with the connection between the CPU package and the cooler. Even when you have smooth metal surfaces they touch at a few points, which leaves some space in between. This space can trap air which is not very good at transferring heat. This is where the thermal paste comes in. The thermal paste fills-in these spaces, helps the surfaces fit together better when you press them together and reduces the difference in temperature between the CPU package and the cooler.

For the Central Processing Units the best thermal paste is not the one that can transfer heat efficiently. Research has shown that the best thermal paste for the Central Processing Units is one that has a combination of things. It needs to have a lot of filler which is the material that helps transfer heat, it needs to be easy to spread, be able to fill in the spaces between the

Central Processing Unit package and the cooler and it needs to be stable when it gets hot or cooled. The Central Processing Units need a paste that can do all of these things, so people are always looking for new and better thermal pastes for the CPUs.

What CPU Thermal paste is made of

When we talk about CPU thermal paste it is made up of two main things: a continuous matrix and conductive fillers.

Component	Typical role	Common examples from the literature
Base matrix	Provides compliance, wetting, spreadability, and adhesion to rough surfaces	Silicone oils, siloxane systems, curable silicone grease, polymeric carriers (Dal, 2004; Miyoshi et al., 2008; Q. Wang et al., 2003)
Thermally conductive filler	Creates heat-conduction pathways through the paste	Alumina, zinc oxide, aluminum nitride, boron nitride, silver, diamond, graphite, graphene, carbon nanotubes (H. Chen et al., 2013; Chou et al., 2010; Circle et al., 2005; Shishkin et al., 2018; Yu et al., 2015)
Additives	Tune dispersion, viscosity, bleeding, curing, and stability	Surface treatments, functionalization agents, rheology modifiers, hybrid filler systems (Kumaresan et al., 2020; Lin & Chung, 2009b; Zeng et al., 2023)

The trend with materials is really clear. For a time people used greases that had a lot of ceramic and metal particles mixed with silicone. Then people started looking into using types of fillers that are shaped like long thin sticks. They also tried using combinations of materials like boron nitride and graphite and graphene and carbon nanotubes and even diamond. The idea was to create a network of these materials that would work well together and make the grease spread easily. The materials trend is about finding the right balance with these materials (He & Wang, 2019; Prasher, 2006; Razeeb et al., 2018; Y. Wang et al., 2023; Yu et al., 2015).

How Thermal Paste is made

The main challenge in manufacturing is adding enough heat conducting material into a soft base material so that heat can flow properly, while still keeping the paste smooth, stable, and easy to use. Studies on highly filled pastes mainly focus on four connected steps: choosing the right materials, mixing the filler evenly, controlling the flow of the paste and forming a good bonding layer during assembly (Feger et al., 2005; Lin & Chung, 2009b; Prasher et al., 2002).

Convectional production route

1. Select a base fluid or polymer matrix, most often silicone based for thermal stability (Miyoshi et al., 2008; Q. Wang et al., 2003).
2. Choose filler chemistry, particle size, and particle loading based on the needed balance of conductivity, viscosity, cost, and electrical behavior (Circle et al., 2005; Kumaresan et al., 2020; Shishkin et al., 2018).
3. Mix and disperse the filler into the matrix using highshear or other intensive mixing so clumps are reduced and the filler is distributed evenly (Feger et al., 2005).
4. Tune the rheology so the paste can be dispensed, spread under mounting pressure and hold a thin bond line without excessive pumpout or oil bleed (Feger et al., 2005; Lin & Chung, 2009b).
5. Apply the paste between CPU package surfaces, where pressure drives the material into voids and creates the final bondline thickness that governs much of the thermal resistance (Goel et al., 2008; Prasher, Shipley, et al., 2003).

Old and newer production approaches

Era or approach	Main idea	Main limitation
Early particle-filled greases	Use ceramic or metal particles in a soft polymer carrier	Limited conductivity and strong sensitivity to bond-line thickness (Prasher, 2006; Sarvar et al., 2006)
Improved high-fill greases	Raise filler content and optimize particle packing	High viscosity and poorer conformity at very high loadings (Feger et al., 2005; Prasher, Koning, et al., 2003)
Engineered filler shape and size	Use spherical, plate-like, nano, or hybrid particles to improve packing and percolation	More complex processing and dispersion control (Circle et al., 2005; Kumaresan et al., 2020; Zeng et al., 2023)
Carbon-enhanced greases	Add graphite, graphene, or CNT-based fillers for higher intrinsic conductivity	Contact resistance, agglomeration, and cost remain issues (H. Chen et al., 2013; Lin & Chung, 2009a; Yu et al., 2015)
Hybrid nanocomposite greases	Combine multiple fillers to gain synergistic thermal paths	Gains in bulk conductivity may be offset by stiffness and interface losses (He & Wang, 2019; Razeeb et al., 2018)

A key lesson from the literature is that better bulk conductivity does not guarantee better CPU cooling. If filler loading makes the paste too stiff, the bond line can thicken and contact resistance can rise, erasing the theoretical gain (Prasher, Shipley, et al., 2003; Razeeb et al., 2018).

Advantages of thermal paste

Thermal paste remains widely used because it solves a difficult contact problem with a lowcost, lowpressureand serviceable material (Prasher, 2006; Razeeb et al., 2018; Stern et al., 2005).

It fits well into tiny surface roughness and uneven areas (Prasher, 2006; Razeeb et al., 2018).

It can achieve low interface resistance without the high bonding temperatures of solders or sintered metals (Razeeb et al., 2018; Sarvar et al., 2006).

It is easy to dispense and compatible with mass CPU assembly (Miyoshi et al., 2008; Stern et al., 2005).

It is reworkable and replaceable during maintenance, unlike many bonded metallic TIMs (Razeeb et al., 2018).

It allows wide formulation freedom through changes in matrix, filler and additive chemistry (Feger et al., 2005; Kumaresan et al., 2020; Yu et al., 2015).

Disadvantages of thermal paste

The same softness that makes the thermal paste useful also drives its main weaknesses (Due & Robinson, 2013).

Limitation	Why it matters for CPUs	Representative literature
Pump-out	Thermal cycling can drive grease out of the interface, raising resistance over time	(Chiu et al., 2001; Nagrani et al., 2023; Wunderle et al., 2019)
Dry-out or bleed	Loss or migration of fluid phase changes rheology and worsens contact	(Dal, 2004; DeVoto et al., 2017; Nnebe& Feger, 2008)
Thickness sensitivity	Performance depends strongly on bond-line thickness and mounting pressure	(Goel et al., 2008; Prasher, Shipley, et al., 2003; J.-W. Zhao et al., 2019)
Bulk versus interface tradeoff	More filler may improve conductivity but worsen wetting and compliance	(Prasher, Koning, et al., 2003; Razeeb et al., 2018)
Aging and reliability limits	High temperature, humidity, and power cycling can degrade performance	(Carlton et al., 2020; Gowda et al., 2005; Khuu et al., 2009)

This is why many papers treat thermal grease not as a static material property problem, but as a coupled problem in rheology, mechanics and heat transfer (Carlton et al., 2020; Due & Robinson, 2013).

Reliability and degradation

For CPU applications the paste you use might work well at first but it can lose its performance over time. The main things that can go wrong with this paste are things like pump-out, oil bleed, void growth and when some of the materials inside the paste or around it start to oxidize. Also the way the paste is put together can change because of stress. That can be a problem too. The paste can even fail because of these things. CPU applications need a paste that will keep working so these problems are important to think about when you are choosing a paste, for CPU applications (Chiu et al., 2001; Dal, 2004; Due & Robinson, 2013; Nnebe& Feger, 2008).Accelerated testing has therefore become a major part of TIM research. Studies use thermal cycling, elevated temperature, humidity exposureand custom pumpout rigs to predict longterm behavior and compare grease designs (Chiu et al., 2001; González et al., 2024; Gowda et al., 2005; Wunderle et al., 2017; Wunderle et al., 2022). Recent studies also use real-time optical and infrared techniques to observe degradation as it happens, instead of depending only on measurements taken before and after testing (Kulkarni et al., 2023; McClure &Davoodabadi, 2024).

Replacements for thermal paste

The literature does not suggest one single replacement for all cases. Instead, it describes different types of alternatives, where each one is more suitable depending on factors like performance, ease of maintenance, reliability and manufacturing cost (Razeeb et al., 2018; Wei et al., 2024).

Phase-change materials

Phase-change TIMs are solid or semi-solid while being handled, but they soften or melt at operating temperature to spread more effectively across the surface. They are less messy to use and usually provide more consistent performance than grease-based TIMs, while still remaining softer than metal-bonded materials (Lee & Kim, 2024; Ramaswamy et al., 2004; 赵 et al., 2025). CPU-focused work also exists for high-power server processors (Shia & Yang, 2020). Their main limits are activation behavior, leakage control and applicationdependent stability (Allen, 2012; Chacon, 2024).

Graphite sheets and pads

Graphite-based TIMs provide a dry and reusable alternative with good heat conduction along the surface and useful flexibility in specially designed forms. Research on natural graphite, flexible graphite, and aligned graphite structures shows that they are promising for high performance computing and reusable thermal interfaces (Fältström, 2014; Hoffmeyer et al., 2017; Smalc et al., 2003; Y. Zhao et al., 2012). Their weakness is that thermal performance depends strongly on through-thickness transport and contact quality, so they are not a drop-in replacement in every CPU geometry (Fältström, 2014; Hoffmeyer et al., 2017).

Liquid metals and low-melting metal TIMs

Galliumbased liquid metals and low-melting alloys can deliver far higher intrinsic thermal conductivity than polymer greases. This makes them attractive where maximum heat flux removal matters (S. Chen et al., 2020; Martin & Kessel, 2007; Zhang & Deng, 2023). Indium and indium-based TIMs also appear often in microprocessor packaging work (Deppisch et al., 2006; Too et al., 2009). The main drawbacks are cost, oxidation, wetting control, possible leakage, corrosion compatibility, and lower ease of rework than paste (S. Chen et al., 2020; Razeeb et al., 2018; Stagon et al., 2020).

Solder and sintered-metal interfaces

Bonded metallic TIMs, including indium solder systems and sintered silver, can achieve very low thermal resistance and good long-term structural stability in some packages (Deppisch et al., 2006; Wereszczak et al., 2014). They are better viewed as packaging-level interfaces than as user-applied CPU paste replacements. Their limits are process temperature, stiffness, rework difficulty, and manufacturing complexity (Razeeb et al., 2018; Wereszczak et al., 2014).

Carbon nanostructured replacements

CNT arrays and related nanostructured solid TIMs are appealing because they may combine thin bond lines with strong intrinsic axial conductivity (Tong et al., 2007; Xu & Fisher, 2006). Yet the literature repeatedly shows that contact resistance at the ends of the structure remains a hard problem, and large-scale reliable manufacturing is still challenging (Hansson et al., 2018; McNamara et al., 2012; Razeeb et al., 2018).

II. DISCUSSION

The literature suggests that CPU thermal paste should be understood as a systems material rather than a simple compound. The best design is not the one with the most conductive filler in isolation. It is the one that creates the lowest total interface resistance after assembly and keeps that performance through thermal and mechanical aging (Due & Robinson, 2013; Goel et al., 2008; Prasher, Shipley, et al., 2003).

This helps explain the historical path of the field. Older work focused on replacing air gaps with compliant greases and improving filler loading. Newer work pushes toward engineered particle packing, hybrid fillers, nanostructures, and metallic alternatives. At the same time, the most mature literature keeps returning to the same practical limits: viscosity, bond-line thickness, wetting, pump-out, dry-out, and contact resistance (Feger et al., 2005; Prasher, 2006; Razeeb et al., 2018; Wei et al., 2024).

III. CONCLUSION

CPU thermal paste is typically made by dispersing thermally conductive fillers into a compliant polymer or silicone matrix and tuning the mixture so it can spread well, form a thin bond line, and remain stable during service (Feger et al., 2005; Lin & Chung, 2009b; Miyoshi et al., 2008). Its main advantage is that it conforms to rough surfaces and provides low-cost, reworkable thermal coupling. Its main weakness is that the same softness that enables conformity also makes it vulnerable to pump-out, dry-out, and other aging effects (Chiu et al., 2001; Due & Robinson, 2013; Nnebe& Feger, 2008).

The field has moved from conventional ceramic and metal particle greases toward hybrid and nanostructured composites, but no single approach solves all tradeoffs. For the highest performance, phase-change TIMs, graphite sheets, liquid metals, and metal-bonded interfaces are the main replacement paths discussed in the literature (S. Chen et al., 2020; Deppisch et al., 2006; Hoffmeyer et al., 2017; Lee & Kim, 2024). The central message across decades of research is that future CPU TIM development will depend less on headline conductivity and more on achieving a stable, thin, low-resistance interface under real operating conditions (Prasher, 2006; Razeeb et al., 2018; Wei et al., 2024).

REFERENCES

[1] Allen, S. T. (2012). Evaluation of Phase Change Thermal Interface Materials by In-Situ Methods and Their Application Dependent Performance Parameters. *SMTA International*. https://doi.org/10.37665/smvfhsn96713

[2] Carlton, H., Pense, D., & Huitink, D. (2020). Thermomechanical Degradation of Thermal Interface Materials: Accelerated Test Development and Reliability Analysis. In *Journal of Electronic Packaging* (Vol. 142). https://doi.org/10.1115/1.4047099

[3] Chacon, A. J. R. (2024). Characterization of Phase Change Thermal Interface Material Pre-conditioning by Enabling High-Temperature Pressure Mapping Capabilities. *2024 23rd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 1–6. https://doi.org/10.1109/ITherm55375.2024.10709526

[4] Chen, H., Wei, H., Chen, M., Meng, F., Li, H., & Li, Q. (2013). Enhancing the effectiveness of silicone thermal grease by the addition of functionalized carbon nanotubes. In *Applied Surface Science* (Vol. 283, pp. 525–531). https://doi.org/10.1016/J.APSUSC.2013.06.139

[5] Chen, S., Deng, Z., & Liu, J. (2020). High performance liquid metal thermal interface materials. *Nanotechnology*, *32*. https://doi.org/10.1088/1361-6528/abcbc2

[6] Chiu, C., Chandran, B., Mello, M., & Kelley, K. (2001). An accelerated reliability test method to predict thermal grease pump-out in flip-chip applications. *2001 Proceedings. 51st Electronic Components and Technology Conference (Cat. No.01CH37220)*, 91–97. https://doi.org/10.1109/ECTC.2001.927696

[7] Chou, H., Yang, S., Wang, S.-F., & Sung, J. (2010). Thermal Conductivity of Diamond-Containing Grease. In *Journal of Electronic Packaging* (Vol. 132, p. 041015). https://doi.org/10.1115/1.4003002

[8] Circle, O., Meneghetti, P., Hans, P., & Nagarkar, K. (2005). *Spherical BoronNitride Fillers ForHighPerformanceThermalGreases*.

[9] Dal, S. (2004). Degradation mechanisms of siloxane-based thermal interface materials under reliability stress conditions. In *2004 IEEE International Reliability Physics Symposium. Proceedings* (pp. 537–542). https://doi.org/10.1109/RELPHY.2004.1315386

[10] Deppisch, C., Fitzgerald, T., Raman, A., Hua, F., Zhang, C., Liu, P., & Miller, M. R. (2006). The material optimization and reliability characterization of an indium-solder thermal interface material for CPU packaging. In *JOM* (Vol. 58, pp. 67–74). https://doi.org/10.1007/S11837-006-0186-6

[11] DeVoto, D., Major, J., Paret, P., Blackman, G., Wong, A., & Meth, J. (2017). Degradation characterization of thermal interface greases. *2017 16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 394–399. https://doi.org/10.1109/ITHERM.2017.7992501

[12] Due, J., & Robinson, A. (2013). Reliability of thermal interface materials: A review. *Applied Thermal Engineering*, *50*, 455–463. https://doi.org/10.1016/J.APPLTHERMALENG.2012.06.013

[13] Fältström, L. (2014). *Graphite sheets and graphite gap pads used as thermal interface materials : A thermal and mechanical evaluation*.

[14] Feger, C., Gelorme, J., McGlashan-Powell, M., &Kalyon, D. (2005). Mixing, rheology, and stability of highly filled thermal pastes. *IBM J. Res. Dev.*, *49*, 699–708. https://doi.org/10.1147/rd.494.0699

[15] Goel, N., Anoop, T. K., Bhattacharya, A., Cervantes, J. A., Mongia, R., Machiroutu, S. V., Lin, H.-L., Huang, Y.-C., Fan, K.-C., Denq, B.-L., Liu, C.-H., Lin, C.-H., Tien, C., & Pan, J.-H. (2008). Technical review of characterization methods for thermal interface Materials (TIM). *2008 11th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*, 248–258. https://doi.org/10.1109/ITHERM.2008.4544277

[16] González, E., Li, P., Bhagwagar, D., & Ewers, T. D. (2024). Accelerated Test For Thermal Grease Pump-out. *2024 23rd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 1–4. https://doi.org/10.1109/ITherm55375.2024.10709469

[17] Gowda, A., Esler, D., Paisner, S. N., Tonapi, S., Nagarkar, K., & Srihari, K. (2005). Reliability testing of silicone-based thermal greases [IC cooling applications]. In *Semiconductor Thermal Measurement and Management IEEE Twenty First Annual IEEE Symposium, 2005.* (pp. 64–71). https://doi.org/10.1109/STHERM.2005.1412160

[18] Hansson, J., Nilsson, T., Ye, L., & Liu, J. (2018). Novel nanostructured thermal interface materials: a review. *International Materials Reviews*, *63*, 22–45. https://doi.org/10.1080/09506608.2017.1301014

[19] He, X., & Wang, Y. (2019). Synergistic effects on the enhancement of thermal conductive properties of thermal greases. In *Journal of Applied Polymer Science*. https://doi.org/10.1002/APP.47726

[20] Hoffmeyer, M., Subramanian, P., Beyerle, R., & Mann, P. (2017). Novel graphite-based TIM for high performance computing. *2017 16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 243–250. https://doi.org/10.1109/ITHERM.2017.7992478

[21] Khuu, V., Osterman, M., Bar-Cohen, A., & Pecht, M. (2009). Effects of Temperature Cycling and Elevated Temperature/Humidity on the Thermal Performance of Thermal Interface Materials. In *IEEE Transactions on Device and Materials Reliability* (Vol. 9, pp. 379–391). https://doi.org/10.1109/TDMR.2009.2025367

[22] Kulkarni, R., Nagrani, P. P., &Marconnet, A. (2023). In situ Optical Observations of Degradation of Thermal Greases with Thermal Cycling. *2023 22nd IEEE*

Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), 1–8. https://doi.org/10.1109/ITherm55368.2023.10177650

[23] Kumaresan, V., Sreekantan, S., Devarajan, M., & Mohamed, K. (2020). Effect of hybrid filler ratio and filler particle size on thermal conductivity and oil bleed of polydimethylsiloxane/Al2O3/ZnO liquid thermal filler for microelectronics packaging applications. In *Journal of Materials Science: Materials in Electronics* (Vol. 32, pp. 861–874). https://doi.org/10.1007/s10854-020-04864-9

[24] Lee, W., & Kim, J. (2024). A comprehensive review of research on organic-based phase-change thermal interface materials for thermal management of electric devices: Methods, performance, and applications. *Polymer Testing*. https://doi.org/10.1016/j.polymertesting.2024.108677

[25] Lin, C., & Chung, D. (2009a). Graphite nanoplatelet pastes vs. carbon black pastes as thermal interface materials. In *Carbon* (Vol. 47, pp. 295–305). https://doi.org/10.1016/J.CARBON.2008.10.011

[26] Lin, C., & Chung, D. (2009b). Rheological Behavior of Thermal Interface Pastes. In *Journal of Electronic Materials* (Vol. 38, pp. 2069–2084). https://doi.org/10.1007/S11664-009-0883-3

[27] Martin, Y., & Kessel, T. (2007). *High Performance Liquid Metal Thermal Interface for Large Volume Production*.

[28] McClure, P., &Davoodabadi, A. (2024). IR and Optical Imaging Technique for Stability Analysis of Thermal Interface Materials Under Accelerated Power Cycling. *2024 23rd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 1–9. https://doi.org/10.1109/ITherm55375.2024.10709431

[29] McNamara, A., Joshi, Y., & Zhang, Z. M. (2012). Characterization of nanostructured thermal interface materials – A review. *International Journal of Thermal Sciences*, *62*, 2–11. https://doi.org/10.1016/J.IJTHERMALSCI.2011.10.014

[30] Miyoshi, K., Yamada, K., & Isobe, K. (2008). Highly reliable silicone TIM for CPU package - Silicone curable grease -. In *2008 IEEE 9th VLSI Packaging Workshop of Japan* (pp. 117–119). https://doi.org/10.1109/VPWJ.2008.4762226

[31] Nagrani, P. P., Kulkarni, R., &Marconnet, A. (2023). Influence of Thermal Cycling on Degradation Behavior of Thermal Greases. *2023 22nd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 01–10. https://doi.org/10.1109/ITherm55368.2023.10177495

[32] Nnebe, I., & Feger, C. (2008). Drainage-Induced Dry-Out of Thermal Greases. In *IEEE Transactions on Advanced Packaging* (Vol. 31, pp. 512–518). https://doi.org/10.1109/TADVP.2008.924231

[33] Prasher, R. (2006). Thermal Interface Materials: Historical Perspective, Status, and Future Directions. *Proceedings of the IEEE*, *94*, 1571–1586. https://doi.org/10.1109/JPROC.2006.879796

[34] Prasher, R., Koning, P., Shipley, J., &Devpura, A. (2003). Dependence of Thermal Conductivity and Mechanical Rigidity of Particle-Laden Polymeric Thermal Interface Material on Particle Volume Fraction. In *Journal of Electronic Packaging* (Vol. 125, pp. 386–391). https://doi.org/10.1115/1.1602703

[35] Prasher, R., Shipley, J., Prstic, S., Koning, P., & Wang, J. (2002). *Rheological Study of Micro Particle Laden Polymeric Thermal Interface Materials: Part 2 — Modeling* (pp. 53–59). https://doi.org/10.1115/IMECE2002-32118

[36] Prasher, R., Shipley, J., Prstic, S., Koning, P., & Wang, J. (2003). Thermal Resistance of Particle Laden Polymeric Thermal Interface Materials. In *Journal of Heat Transfer-transactions of The Asme* (Vol. 125, pp. 1170–1177). https://doi.org/10.1115/1.1621893

[37] Ramaswamy, C., Shinde, S., Pompeo, F., Sahlinski, W., Bradley, S., Boron, &Parafii. (2004). Phase change materials as a viable thermal interface material for high-power electronic applications. *The Ninth Intersociety Conference on Thermal and Thermomechanical Phenomena In Electronic Systems (IEEE Cat. No.04CH37543)*, *2*, 687–691 Vol.2. https://doi.org/10.1109/ITHERM.2004.1318354

[38] Razeeb, K., Dalton, E., Cross, G., & Robinson, A. (2018). Present and future thermal interface materials for electronic devices. *International Materials Reviews*, *63*, 1–21. https://doi.org/10.1080/09506608.2017.1296605

[39] Sarvar, F., Whalley, D. C., & Conway, P. P. (2006). Thermal Interface Materials - A Review of the State of the Art. *2006 1st Electronic Systemintegration Technology Conference*, *2*, 1292–1302. https://doi.org/10.1109/ESTC.2006.280178

[40] Shia, D., & Yang, J. (2020). Analytical, Numerical and Experimental Study of Phase Change Material in TIM2 Application for High-Power Server CPUs. *2020 19th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 158–165. https://doi.org/10.1109/ITherm45881.2020.9190178

[41] Shishkin, R., Zemlyanskaya, A., &Beketov, A. R. (2018). High Performance Thermal Grease with Aluminum Nitride Filler and an Installation for Thermal Conductivity Investigation. In *Solid State Phenomena*

(Vol. 284, pp. 48–53). https://doi.org/10.4028/www.scientific.net/SSP.284.48

[42] Smalc, M., Norley, J., Reynolds, R., Pachuta, R., &Krassowski, D. (2003). *Advanced Thermal Interface Materials Using Natural Graphite*. 253–261. https://doi.org/10.1115/IPACK2003-35113

[43] Stagon, S., Blaser, N., Bevill, G., & Nuszkowski, J. (2020). Nanoscale Barrier Layers to Enable the Use of Gallium-Based Thermal Interface Materials with Aluminum. In *Journal of Materials Engineering and Performance* (Vol. 29, pp. 5132–5138). https://doi.org/10.1007/s11665-020-05007-1

[44] Stern, M., Gektin, V., Pecavar, S., Kearns, D., & Chen, T. (2005). Evaluation of high performance thermal greases for CPU package cooling applications. In *Semiconductor Thermal Measurement and Management IEEE Twenty First Annual IEEE Symposium, 2005.* (pp. 39–43). https://doi.org/10.1109/STHERM.2005.1412157

[45] Tong, T., Zhao, Y., Delzeit, L., Kashani, A., Meyyappan, M., & Majumdar, A. (2007). Dense Vertically Aligned Multiwalled Carbon Nanotube Arrays as Thermal Interface Materials. In *IEEE Transactions on Components and Packaging Technologies* (Vol. 30, pp. 92–100). https://doi.org/10.1109/TCAPT.2007.892079

[46] Too, S., Touzelbaev, M., Khan, M., Master, R., Diep, J., &Keok, K. (2009). Indium thermal interface material development for microprocessors. In *2009 25th Annual IEEE Semiconductor Thermal Measurement and Management Symposium* (pp. 186–192). https://doi.org/10.1109/STHERM.2009.4810762

[47] Wang, Q., Gao, W., & Xie, Z. (2003). Highly thermally conductive room-temperature-vulcanized silicone rubber and silicone grease. In *Journal of Applied Polymer Science* (Vol. 89, pp. 2397–2399). https://doi.org/10.1002/APP.12363

[48] Wang, Y., Shi, N., Liu, M., Han, S., & Yan, J. (2023). Enhanced Thermally Conductive Silicone Grease by Modified Boron Nitride. *Lubricants*. https://doi.org/10.3390/lubricants11050198

[49] Wei, B., Luo, W., Du, J., Ding, Y., Guo, Y., Zhu, G., Zhu, Y., & Li, B. (2024). Thermal interface materials: From fundamental research to applications. *SusMat*, *4*. https://doi.org/10.1002/sus2.239

[50] Wereszczak, A., Liang, Z., Ferber, M., &Marlino, L. (2014). Uniqueness and Challenges of Sintered Silver as a Bonded Interface Material. *Journal of Microelectronics and Electronic Packaging*, *2014*, 000178–000187. https://doi.org/10.4071/HITEC-WA23

[51] Wunderle, B., Heilmann, J., May, D., Arnold, J., Hirscheider, J., Bauer, J., Schacht, R., Vogel, J., & Ras, M. A. (2017). Modelling and characterisation of a grease pump-out test stand and its use for accelerated stress testing of thermal greases. In *2017 23rd International Workshop on Thermal Investigations of ICs and Systems (THERMINIC)* (pp. 1–6). https://doi.org/10.1109/THERMINIC.2017.8233806

[52] Wunderle, B., May, D., Heilmann, J., Arnold, J., Hirscheider, J., Li, Y., Bauer, J., Schacht, R., & Ras, M. A. (2019). Accelerated Pump Out Testing for Thermal Greases. *2019 20th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, 1–11. https://doi.org/10.1109/EUROSIME.2019.8724540

[53] Wunderle, B., May, D., Li, Y., Arnold, J., & Ras, M. A. (2022). Accelerated Stress Testing and Failure Analysis of Thermal Greases. In *2022 28th International Workshop on Thermal Investigations of ICs and Systems (THERMINIC)* (pp. 1–8). https://doi.org/10.1109/THERMINIC57263.2022.9950680

[54] Xu, J., & Fisher, T. (2006). Enhancement of thermal interface materials with carbon nanotube arrays. In *International Journal of Heat and Mass Transfer* (Vol. 49, pp. 1658–1666). https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2005.09.039

[55] Yu, W., Xie, H., Yin, L., Zhao, J., Xia, L., & Chen, L. (2015). Exceptionally high thermal conductivity of thermal grease: Synergistic effects of graphene and alumina. In *International Journal of Thermal Sciences* (Vol. 91, pp. 76–82). https://doi.org/10.1016/J.IJTHERMALSCI.2015.01.006

[56] Zeng, X., Fan, J.-F., Rao, S., Ren, L., Zeng, X., & Sun, R. (2023). Effect of Filler Particle Size and Surface Functionalization on the Properties of Thermal Grease. *2023 24th International Conference on Electronic Packaging Technology (ICEPT)*, 1–3. https://doi.org/10.1109/ICEPT59018.2023.10491958

[57] Zhang, X., & Deng, Z. (2023). Roadmap towards new generation liquid metal thermal interface materials. *Science China Technological Sciences*, *66*, 1530–1550. https://doi.org/10.1007/s11431-023-2379-6

[58] Zhao, J.-W., Zhao, R., Huo, Y.-K., & Cheng, W. (2019). Effects of surface roughness, temperature and pressure on interface thermal resistance of thermal interface materials. In *International Journal of Heat and Mass Transfer*. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2019.06.045

[59] Zhao, Y., Strauss, D., Chen, Y., Liao, T., & Chen, C.-L. (2012). *Experimental Study of a High Performance Aligned Graphite Thermal Interface Material* (pp. 283–290). https://doi.org/10.1115/MNHMT2012-75049

[60] 赵C. 成功. Z., 李Y. L., 蒋C. 晨. J., 唐Y. 元政. T., 何Y. 燕. H., 于W. Y., &曹B. 炳阳. C. (2025). Phase change thermal interface materials: From principles to applications and beyond. *Chinese Physics B, 34*. https://doi.org/10.1088/1674-1056/ade59f