Inclusive Innovations in Thermal Management: Advancing High-Power Electronics Through Diverse Material and Cooling Technologies

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Abstract
With the trend towards miniaturization in electronics to meet modern demand for better performance and portability, power densities have risen sharply, creating major challenges in heat management. Conventional cooling methods such as passive heat sinks, forced convention and legal thermal interface materials (TIMs) are falling short of managing the thermal loads generated by compact, high-power components. This paper provides an overview of advanced and emerging thermal management strategies that enable more equitable access to high performance computing and sustainable electronics design. It encompasses a diversity of tactics such as liquid cooling with micro-channel cold plates, two-phase and immersion cooling and the integration of nanomaterial-enhanced TIMs. New materials like boron arsenide, synthetic diamond and 2D hexagonal boron nitride (h-BN) coatings are explored for their ability to enhance heat dissipation and improve device performance. Additionally, cutting-edge designs like through-chip microchannels, direct-bonded heat sinks and dielectric coatings for water cooling highlight how design diversity can cater to different applications, device shapes and resource constraints. Leveraging on the knowledge from thermofluid dynamics, material science and electrical engineering, this study supports fair and inclusive technology progress, as a result enhancing thermal performance and device reliability. It also elaborates on the democratization of high-density power electronics.

Keywords: *Heat Dissipation, Nanomaterials, Thermal Interface Materials, Thermal Management.*

1.Introduction

The continued demand for device miniaturization – the process of making electronic and electrical devices smaller in physical size to increase their performances, has led to the generation of more heat in limited spaces by the devices referred to as high power density in electrical systems (Zhang, 2021; Dhumal, Kulkami, & Ambhore 2023). This has exacerbated thermal management challenges. This increase in power density often surpasses the heat dissipation capacity of traditional cooling methods, such as passive heat sinks, natural and forced convection, and thermal interface materials (TIMs) have been extensively utilized to mediate heat dissipation (Zhang, 2021; Dhumal et al., 2023; Tu et al., 2024; Wei et al., 2024). However, as power densities continue to rise, the thermal resistance of these methods becomes a bottleneck, necessitating the adoption of advanced thermal solutions (Ao & Ramiere, 2023).

Ongoing developments in thermal management has focused on enhancing the thermal conductivity by employing novel nanomaterials and ultrahigh-thermal- conductivity crystals such as boron arsenide (BAs) and boron phosphide (BP), which exceed the performance of conventional materials like graphene and copper (Li et al., 2018; Liu & Zhang, 2022). Incorporation of these materials into thermal interface layers dramatically reduces thermal contact resistance, facilitating more effective heat transfer between semiconductor junctions and heat spreaders (Chen et al., 2021; Lee et al., 2023).

Furthermore, hybrid thermal management systems that combine phase-change materials (PCMs) with structured surfaces and dynamic cooling elements provide new pathways to buffer heat spikes and maintain thermal stability under transient working conditions (Dhumal et al., 2023; Karimi et al., 2022; Wang et al., 2022). This study explores and provides an overview of a wide spectrum of innovative techniques, including liquid cooling with micro-channel cold plates, two-phase and immersion cooling systems, and the incorporation of nanomaterial-enhanced thermal interface materials (TIMs) in thermal management.

2. Methodology

This study adopted a narrative literature review approach based primarily on previously published research articles. The review process was conducted through the following steps and as shown in Fig.1. First, the research topic was clearly defined to establish the scope of the study and to guide the overall and direction of the review. Based on this understanding, an outline was drawn to organize the paper into five main sections:

1) The Introduction
2) Methodology
3) Convectional methods for managing heat dissipation in high-power components
4) Recent advancements in thermal management, and
5) The Conclusion

Subsequently, relevant literature was searched for and collected for each section of the paper. The search was conducted using reputable academic databases and search platforms, including Science Direct, Willey Online Library, and Google scholar. The literature search focused primarily on peer-reviewed research papers published within 2018-2025, ensuring the inclusion of current and relevant studies. Key search terms used during the literature retrieval process include: thermal management research papers between 2018 and 2025, cooling techniques, heat dissipation in high-power electrical components. After retrieval, the selected articles were carefully reviewed, and pertinent findings, methodologies and conclusions were synthesized to support the discussion presented in this paper.

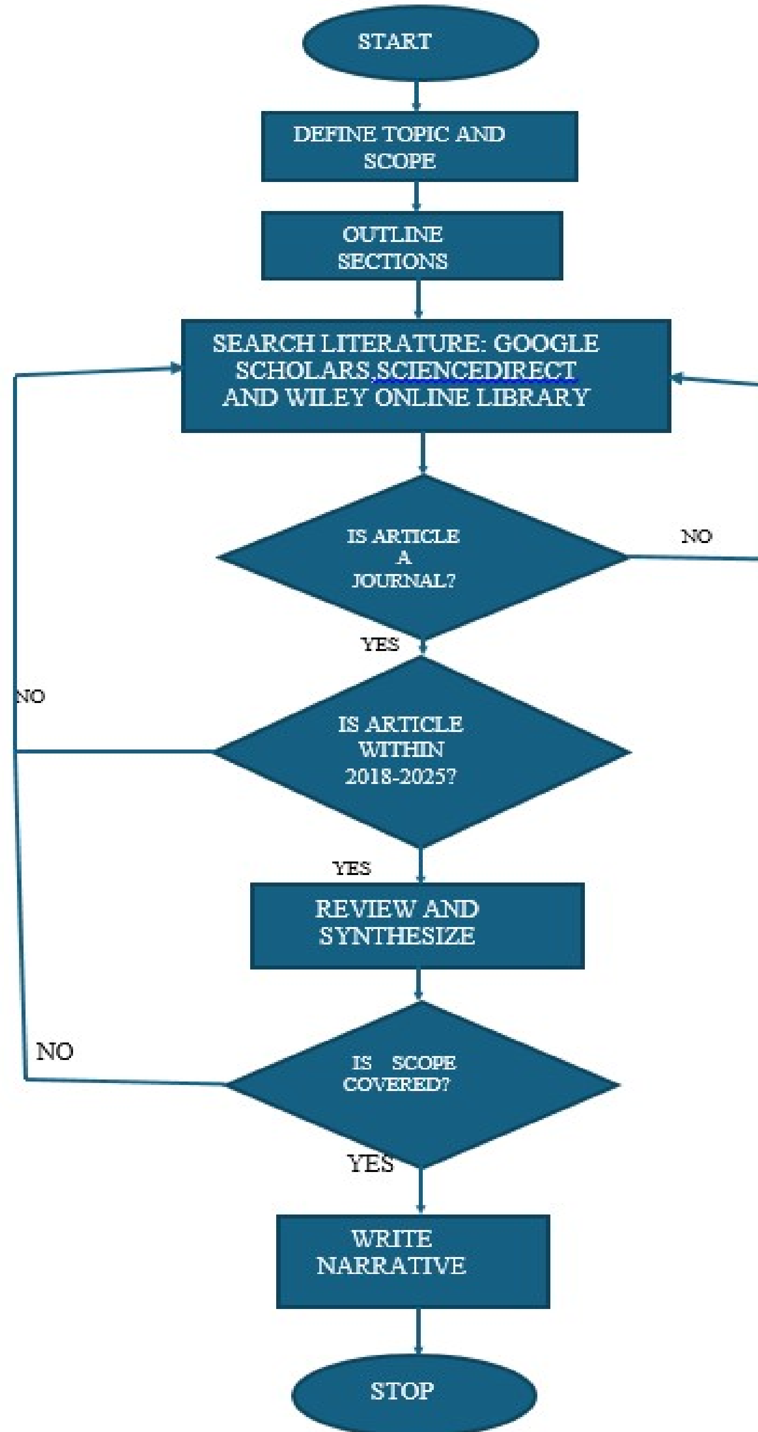

Fig.1: Methodology flowchart

3. Conventional methods for managing heat dissipation in high-power components

The following are the various strategies that have been developed and refined to dissipate heat in high-power electrical components. Each of these methods has its unique strengths and limitations depending on the power density, component geometry, and system integration level.

3.1 Conduction and convection techniques

Traditional methods like air-cooled heat sinks and heat pipes leverage conduction and forced convection to move heat away from the source as shown in Fig. 2. Although widely used, they are limited by the thermal resistance of interface materials and air cooling inefficiency at high power densities. Conduction involves heat transfer through direct contact, like a component transferring heat to a heat sink. Convection involves heat transfer through the movement of fluids (like air or liquid), which can be natural or forced e.g., with a fan (Yeh et al., 2021; Van et al., 2020; Tuma, 2020). Forced convection is characterized by a higher convective heat transfer coefficient and is essential for high-power or high heat flux applications (Li & Yang 2023). Spacecraft and avionics systems often use heat pipes due to their high effective conductivity and no reliance on gravity for circulation especially, in some designs (Lv et al., 2024).

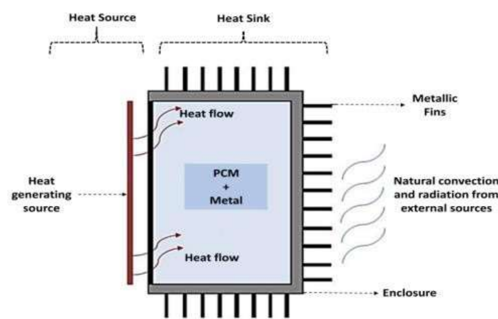

Fig.2: Thermal management in an electronic device segment through a fixed Phase Change Materials module (PCM) (Source: Dhumal et al., 2023)

3.2 Liquid cooling solutions

Liquid cooling systems for electronics use a liquid coolant (often water or a waterglycol mixture) to absorb heat from components and transfer it away from the device, typically via a heat exchanger to the surrounding environment (Zang et al., 2025; Tuma, 2020). The key components of typical cooling system are: coolant, cold plate or channels, pump, heat exchanger and tubing (Kumar & Kumar 2024). These systems often incorporate a pump to circulate the coolant. It can be used in various applications like in power semiconductor modules where heat loads exceed the capacity of air cooling, majorly found in industrial power systems e.g. wind power converter, where forced liquid cooling plates reduce operating temperature and improve reliability so also in computers and even spacesuits (Zhu et al., 2024). Liquid cooling via micro-channel cold plates, embedded microfluidics, and jet impingement significantly increases heat transfer efficiency. For example, cold plates with micro-channels can reduce thermal resistance to as low as 0.07 K/W. Flow boiling in such channels has demonstrated heat transfer coefficients exceeding 300 $kW/m^2{\cdot}K$ under high heat fluxes (Park & Mukherjee, 2021; Singh et al., 2022).

3.3 Two-phase and immersion cooling

The relentless increase in power density of modern electronics—from data center servers to high-performance computing and electric power modules—demands innovative cooling strategies beyond conventional air and single-phase liquid cooling methods. Two-phase and immersion cooling systems leverage latent heat from phase change processes to drastically improve thermal control, efficiency, and compactness (Zhang et al., 2025).

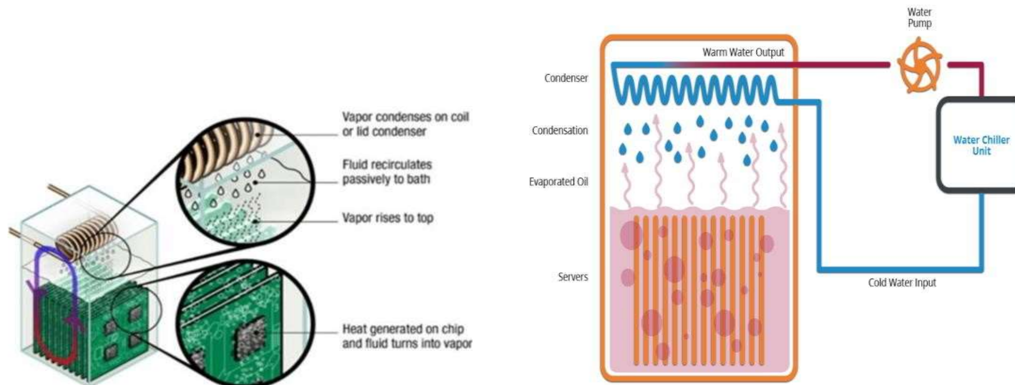

Fig.3: Diagrams showing two phase and immersion cooling method (Source: Zhang et al., 2025).

3.4 Advanced thermal interface materials (TIMs)

The development of high thermal conductivity TIMs—including those based on vertically aligned graphite nano-platelets and graphene-lamellae structures—has improved thermal coupling between devices and heat sinks as shown in Fig. 4. These materials can reach conductivities above 150 W/m·K and drastically reduce contact resistance, allowing for more effective heat transfer (Wang et al., 2021; Chen et al., 2021). Advanced thermal interface materials (TIMs) play a crucial role in maintaining high-power density in electrical systems by efficiently transferring heat away from heat-generating components to heat sinks (Wang et al., 2021, Birbarah et al., 2020). These materials fill microscopic air gaps between surfaces, improving thermal contact and reducing thermal resistance. Common types include thermal pastes, gels, pads, and phase-change materials, each with varying properties like thermal conductivity and conformability (Wang et al., 2021; Chen et al., 2021).

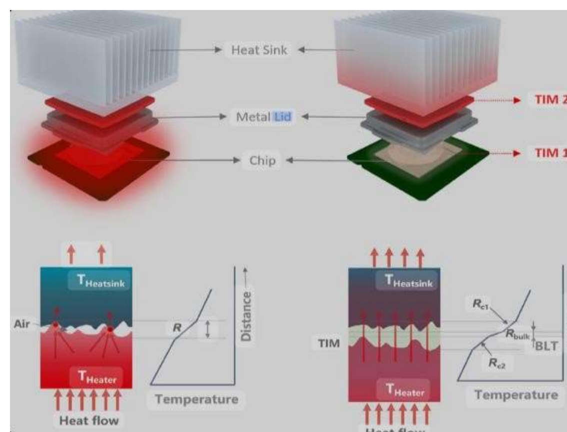

Fig.3: Diagram Showing How Advanced Thermal Interface Materials (TIMs) help in Power Electronics (Source: Karimi et al., 2022).

3.5 Emerging composite materials

The emerging composite materials are at the fore-front of modern energy storage, electronics and thermal management technologies, they are approaches within the emerging technologies for super-capacitors due to their role in heat dissipation. The blend of various elements like polymers, ceramics, metals and nano-materials at the micro-scale or nano-scale is to ensure superior and tailored performance over the conventional options (Adedoja et al., 2023). The composites; graphene, carbon nanotubes or boron nitride give thermal conductivities above 150W/m.K while still maintaining mechanical flexibility, reducing thermal contact resistance and filling microscopic surface gaps (Chen et al., 2021).

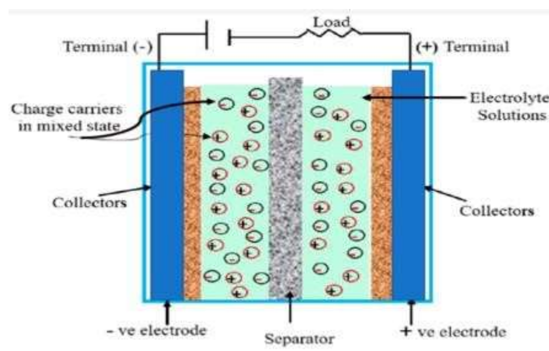

Fig.5: Construction of a typical supercapacitor (Source: Adedoja et al., 2023)

4. Recent advancements in thermal management techniques

The recent advancements in thermal management techniques have become increasingly necessary as a result of power densities, device miniaturization and growing energy efficiency demands across sectors and sustainability (Wang et al., 2022). Within this context, this section presents the key development that are shaping the future of thermal management.

4.1 2D Hexagonal boron nitride (hBn) surface coatings

Two-Dimensional hexagonal boron nitride (h-BN) has emerged a promising surface coating materials for thermal management and electrical insulation in high-density electronic systems. Its surface coating offer a promising solution for managing high power density in electronics by enhancing heat dissipation and electrical insulation (Wang et al., 2021). These coatings, often referred to as "white graphene" are characterized by their wide band-gap, thermal stability, high thermal conductivity, chemical inertness, and excellent dielectric properties. Due to its excellent thermal conductivity, electrical insulating properties, chemical stability and mechanical robustness, h-BN coatings can enhance device performance, reliability and longetivity when integrated into power electronics and microelectronics packaging (Zhang et al., 2021). Karthik et al. (2023) demonstrated scalable hBN coatings (via spray/drop-casting)

on ICs, boosting surface thermal conductivity from ~0.3 W/m·K to ~260 W/m·K. Result: over 2 times heat flux and a ~17% drop in operating temperature in an audio amplifier PCB.

4.2 Through-chip microchannels for 3D IC cooling

Through-chip microchannels (TCMCs) are used in 3D integrated circuit (3D IC) cooling to remove heat from stacked layers and maintain high power densities. They involve creating a network of micro-scale channels within the chip itself, allowing for direct cooling of each layer with a coolant like water. This approach offers more effective heat dissipation compared to traditional methods, especially in high-power, high-density 3D ICs. Ao & Ramiere (2023) proposed embedding micro-scale water channels through silicon dies (chips). CFD simulations indicated handling >10,000 W/cm² heat flux while keeping ΔT < 60 K, independent of layer count. Three-dimensional integrated circuits (3D ICs) offer a revolutionary way to increase system performance, functionality, and density by stacking multiple layers of active components.

However, stacking generates significant thermal challenges due to limited heat dissipation paths. An emerging solution is the integration of through-chip micro-channels**,** which enable direct liquid cooling inside the chip stack**,** significantly enhancing thermal performance. (Zhang et al., 2025).Through-chip micro-channels, fabricated vertically through the silicon die, allow coolant to pass directly through each chip layer. This drastically reduces the thermal path length and enables localized heat removal, keeping junction temperatures low even under high workloads (Lee et al., 2023). As compared to traditional heat spreaders or heat sinks, these microchannels offer over 2–5 times improvement in thermal resistance reduction (Imran et al., 2020). This capability is critical in preventing thermal hotspots that degrade device performance and reliability in 3D ICs (Yeh et al., 2021).

4.3 Two-phase immersion cooling (active and passive)

Two-phase immersion cooling, both active and passive, explains a method for maintaining high-power density in electrical systems by submerging components in a dielectric fluid that undergoes a phase change (liquid to vapor) to dissipate heat numerically showed methanol-based two-phase immersion reduced average component temperature to ~80 °C with ΔT ≈8 °C and a CHF heat flux coefficient of 2740 W/(m²·°C).The method adopted here involves two-phase immersion cooling in which electronic components are submerged in a dielectric liquid that boils on contact with hot surfaces. The resulting vapor is condensed on a heat exchanger and returned to the bath—either passively via gravity or actively using pumps (Ao & Ramiere 2023).The latent heat of vaporization enables efficient heat removal even at low temperature differences (Tuma, 2020).The benefits are exceptional heat transfer capability, energy efficiency and reduced cooling overhead, improved reliability and noise reduction and, compactness and scalability. The key applications are power electronics, data centres, electric vehicles and batteries. Power modules in electrified propulsion systems achieve 12KW cooling through integrated condensers and low-boiling fluids so also Lithium battery packs maintain temperatures below 30°C at 5C discharge (Wu et al., 2025)

4.4 Water immersion with electrically insulating coatings

Water immersion cooling is emerging as a highly effective thermal management technique for high-density electronics due to water's superior thermal properties. However, water is naturally electrically conductive, which restricts its direct use for submerging active electronic

components. To overcome this, researchers and engineers have developed electrically insulating coatings that allow components to be safely submerged in water**,** unlocking its full thermal potential without electrical hazards. Birbarah et al. (2020) developed Parylene-C insulated PCBs enabling immersion in water. They measured up to 562 W/cm^2 heat flux and successfully cooled a 2 kW converter at ~97% efficiency. To utilize water safely in immersion cooling, devices are coated with thin dielectric films such as parylene-C, silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), or polymer-based nanocoatings as shown in fig.6**.** These materials provide high dielectric strength**,** low thermal resistance**,** and chemical stability**,** allowing for direct water contact while maintaining electrical isolation (Tuma, 2020).

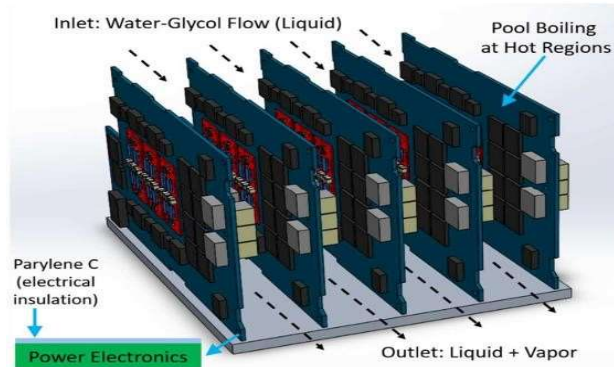

Fig.6: Schematic rendering of the conceptual integration of electronics immersion cooling with current state-of-the-art vehicle cooling systems. (Source: Birbarah et al., 2020)

Water-ethylene glycol mixture (WEG) from the conventional cooling system is leveraged as an immersion fluid and boils at the hotspots of the interleaved printed circuit boards (PCBs) which make up the power converter. The components are coated with a thin (< 100 µm) dielectric layer of Parylene C, which acts to electrically isolate active components from the WEG.

4.5 Nanomaterial-enhanced phase-change materials (PCMs)

Nanomaterial additives like graphene and carbon nanotubes also improve the mechanical integrity of PCM composites, minimizing issues like leakage, cracking, or delamination during repeated melting and solidification cycles (Dincer & Rosen, 2021). Nanomaterial-enhanced Phase Change Materials (PCMs) improve thermal management in electronic devices by increasing heat capacity and thermal conductivity, allowing for higher power densities and preventing overheating. Fig.7 shows a diagram of this system in which a PCM (like paraffin wax) embedded with nanoparticles (like alumina or copper oxide). Dincer & Rosen. (2021) highlighted NEPCMs (with graphene, nanoparticles) that boost thermal conductivity and latent heat, reducing hotspots by ~6–10% in electronics. Additional reviews echo that nano-infused PCMs yield smoother thermal transient response but still grapple with long-term stability.

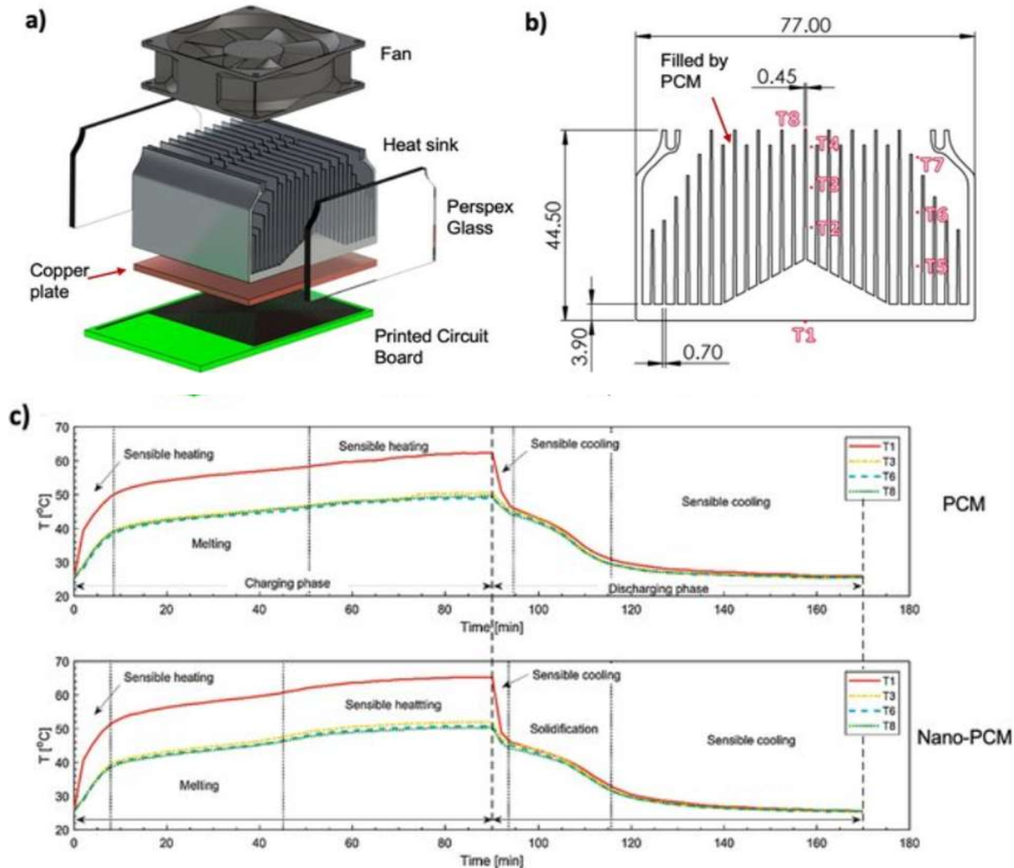

Fig.7: Experimental set up of a nanotube/para n based heat sink for the thermal management of an electronic device developed by (a) Heat sink assembly. (b) Thermocouples positions and dimensions in mm. (c) Temperature response of the PCM and nano-PCM thermal module under 6.000 W/m^2 power density (Source: Dincer & Rosen, 2021).

4.6 Ultra-high conductivity bulk materials: Boron Arsenide & Synthetic Diamond

Boron arsenide (BAs) and synthetic diamond are both excellent materials for maintaining high power density in electronic devices due to their exceptionally high thermal conductivity (Liu & Zhang 2022). Diamond is a well-known thermal conductor, while BAs has recently emerged as another material with ultrahigh thermal conductivity, comparable to or even exceeding that of diamond in some cases. The thermal conductivity of Boron Arsenide, Diamond and Boron Nitrate against the temperature is shown in Fig.8 with Diamond having highest thermal conductivity followed by Boron Arsenide (Li et al., 2018). These materials are crucial for efficient heat dissipation in high-power devices, preventing overheating and ensuring optimal performance. Both Boron Arsenide and Synthetic Diamond use phonons (i.e quantized lattice vibrations) rather than free electrons to carry heat efficiently which is crucial for thermal management in high-power electronics and opto-electronics (Li S., et al 2018). This enables ultra-high thermal conductivity essential for dissipating heat. Boron arsenide and synthetic diamond are used as heat sink layers in high power devices to significantly reduce peak operating temperatures (Li et al., 2025).

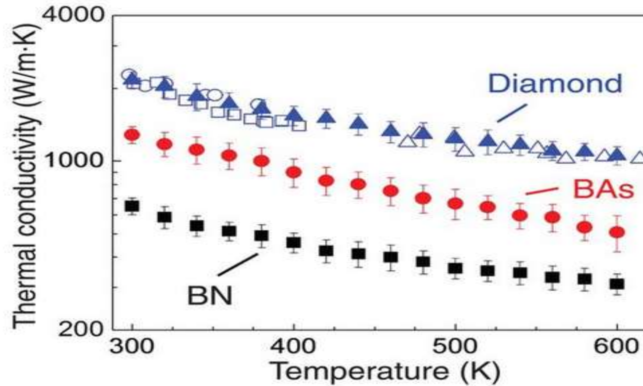

Fig.8: Temperature-dependent thermal transport measurement (Source: Li et al., 2018).

3.7 Integrated direct-bonded heat-sinks with manifold microchannels (sic modules)

SiC (Silicon Carbide) power modules are widely used in high-power and high-frequency electronics because of their superior electrical and thermal properties compared to silicon-based devices. However, efficient heat dissipation remains a critical challenge due to the high heat flux generated by these devices (Fan *et al*., 2025). High-power SiC power electronic vehicles and aerospace benefit from integrated cooling, handling fluxes up to $1KW/cm^3$ while enduring vibrations and temperature greater than 200°C. Data Center Processors and RF amplifiers use these for intra-chip cooling, integrating directly with GaN/SiC dies to minimize conduction losses. Emerging uses include hypersonic vehicle electronics and concentrated photovoltaics, where SiC's oxidation resistance supports extreme environments (Yang et al., 2025, Tang et al., 2025).

5. Conclusion

Traditional cooling methods are increasingly insufficient to meet the demands of rising power densities, calling for the integration of advanced solutions. This paper has explored a broad spectrum of innovative thermal management methods that are important for addressing the increasing heat dissipation challenges in high-power, miniaturized electronic devices. The development and application of cutting-edge materials like boron arsenide, synthetic diamond, and 2D hexagonal boron nitride coatings demonstrate significant potential in improving thermal conductivity and device reliability. Novel designs including through-chip microchannels and direct bonded heat sinks demonstrate how interdisciplinary and inclusive research can lead to tailored cooling solutions that suit varying device architectures and usage contexts. These advancements collectively contribute to enhancing device performance, longevity and energy efficiency while supporting sustainable electronics design.

Authors' Contributions

All authors contributed to the conception, writing, and critical revision of this narrative review. Specific contributions are detailed below:

Aderonke Adekemi Dare: Conceptualization; identification of key themes and sources; co-writing of sections; critical revision for intellectual content; final approval of the version to be published.

Samuel Oghenenyerovwo Enochoghene: Conceptualization; critical revision for intellectual content; final approval of the version to be published.

Oluseye David Dare: Methodological framing; validation of source relevance and quality; editing and integration of sections; critical revision; final approval of the version to be published.

Oladimeji Leshi Kazeem: Methodological framing; validation of source relevance and quality; editing and integration of sections; critical revision; final approval of the version to be published.

All authors agree to be accountable for all aspects of the work and affirm the integrity and accuracy of the review.

References

Adedoja, O. S., Sadiku, E. R., & Hamam, Y. (2023). An overview of the emerging technologies and composite materials for supercapacitors in energy storage applications. *Polymers, 15*(10), Article 2272. https://doi.org/10.3390/polym15102272

Ao, L., & Ramiere, A. (2023). Through-chip microchannels for three-dimensional integrated circuits cooling. *arXiv*. https://doi.org/10.48550/arXiv.2307.16495

Birbarah, P., Gebrael, T., Foulkes, T., Stillwell, A., Moore, A., Pilawa-Podgurski, R. C. N., & Miljkovic, N. (2020). Water immersion cooling of high power density electronics. *International Journal of Heat and Mass Transfer, 147*, Article 118918. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118918

Chen, L., Yong, Z., & Robert, S. (2021). Advanced direct bonding of wide bandgap devices with integrated cooling for reduced thermal resistance. *Applied Thermal Engineering, 191*, 116862. https://doi.org/10.1016/j.applthermaleng.2021.116862

Dhumal, S. S., Deshpande, S. S., & Pakle, P. V. (2023). Thermal management in an electronic device segment through a fixed phase change materials module (PCM). *Journal of Thermal Analysis and Calorimetry, 149*(2), 1079–1091. https://doi.org/10.1007/s10973-020-10796-8

Dincer, I., & Rosen, M. A. (2021). *Thermal energy storage: Systems and applications* (3rd ed., pp. 223–227). Wiley.

Fan, K., Guo, J., Huang, Z., Xu, Y., Huang, Z., Xu, W., Wang, Q., Lin, Q., Li, X., Liu, H., & Liu, X. (2025). GaN-on-diamond technology for next-generation power devices. *Journal of Electronic Materials, 2*(8). https://doi.org/10.1007/s44275-024-00022-z

Imran, A. N., Farahmand, F., Ghannam, S., Bondre, R., Viovy, J.-L., Roose, T., Mailley, P., Vincent, G. P., Tarsoly, M. S., Cesbron, T., & Castaing, J.F.(2020). .High-performance cooling of 3D ICs using through-chip microfluidic channels. *Microsystems & Nanoengineering, 6*, Article 71. https://doi.org/10.1038/s41378-020-0161-5

Karimi Danial, D., Berecibar, M., & Van Mierlo, J. (2022). Modular methodology for developing comprehensive active and passive thermal management systems for electric vehicles. *General*. https://www.researchgate.net/publication/359893616

Karthik, R., Srivastava, A., Midya, S., Shanu, A., Slathia, S., Vandana, S., Sreeram, P. R., Kar, S., Glavin, N. R., Roy, A. K., Singh, A. K., & Tiwary, C. S. (2023). Enhanced heat dissipation and lowered power consumption in electronics using two-dimensional hexagnal boron nitride coatings. *arXiv preprint*. https://doi.org/10.48550/arXiv.2311.10030

Kim, J., & Kwon, B. (2020). High-dielectric strength coatings for immersion cooling of electronic devices. *IEEE Access, 8*, 143562–143570. https://doi.org/10.1109/ACCESS.2020.3015097

Lee, D., Park, J., & Kim, H. (2023). Transient liquid phase bonding of copper to SiC substrates for direct-bonded heat sinks. *Materials Science and Engineering: B, 287*, Article 115867. https://doi.org/10.1016/j.mseb.2023.115867

Park, J., & Mukherjee, S. (2021). Design of through-silicon microchannels for 3D ICs: Thermal performance and flow uniformity. *Applied Thermal Engineering, 185*, Article 116327. https://doi.org/10.1016/j.applthermaleng.2020.116327

Singh, M., Kumar, A., & Patel, D. (2022). Compact microchannel heat sinks integrated with power electronics for automotive powertrain systems. *IEEE Transactions on Components, Packaging and Manufacturing Technology, 12*(4), 652–660. https://doi.org/10.1109/TCPMT.2022.3150861

Sun, Y., Zhang, L., Huang, Q., Chen, Z., Wang, D., Seyfouri, M. M., Chang, S. L. Y., Wang, Y., Zhang, Q., Liao, X., Li, S., Zhang, S., & Wang, D. (2022). Ultrahigh energy storage density in glassy ferroelectric thin films under low electric field. *Advanced Science, 9*, Article 2203926. https://doi.org/10.1002/advs.202203926

Tuma, P. E. (2020). Overview of two-phase immersion cooling for data centers. *Electronics Cooling Magazine, 25*(1), 14–21.

Van, R., Kampitsis, G., & Matioli, E. (2020). Co-designing electronics with microfluidics for more sustainable cooling. *Nature, 585*, 325–330. https://doi.org/10.1038/s41586-020-2477-2

Wang, C., Xiong, C., Song, L., Ding, R., Han, P., & Li, W. (2021). Recent advances in hexagonal boron nitride coatings for thermal management in electronics. *Applied Materials Today, 24*, Article 101073. https://doi.org/10.1016/j.apmt.2021.101073

Wang, H., Yang, L., & Thomas, S. (2022). Impact of microchannel cooling on thermal cycling and hotspot suppression in high-power SiC modules. *Microelectronics Reliability, 133*, 114604. https://doi.org/10.1016/j.microrel.2021.114604

Wikipedia contributors. (2025, June 17). Ultra-high conductivity bulk material. *Wikipedia: The Free Encyclopedia.*

Xu, H., Huang, J., Tian, W., & Li, Z. (2023). Thermal performance optimization of integrated microchannel cooling plate for IGBT power module. *Micromachines, 14*(8), 1605. https://doi.org/10.3390/mi14081605

Yeh, L. T., Lee J., Lee W., Oropallo R. S., & Narayanaswamy, S. R. (2021). Thermal challenges in 3D integrated circuits and the role of microchannel cooling. *IEEE Transactions on Device and Materials Reliability, 21*(3), 512–519. https://doi.org/10.1109/TDMR.2021.3065612

Zhang, C., Wang, H., Huang, Y., Zhang, L., & Chen, Y. (2025). Immersion liquid cooling for electronics: Materials, systems, applications and prospects. *Renewable and Sustainable Energy Reviews, 208*, Article 114989.

Zhang, K., Feng, Y., Wang, F., Yang, Z., & Wang, J. (n.d.). (2025).Two dimensional hexagonal boron nitride (2D-hBN): Synthesis, properties and applications. *Journal of Materials Chemistry C*.
https://doi.org/10.1039/C7TC04300G

Zhang, N., Ruiwen, L., & Kong, Y. (2022). Experimental investigation of embedded micro-channel manifold cooling for power chips. *Thermal Science, 26*(5), 4151–4164. https://doi.org/10.2298/TSCI210908328Z

Zhang, Y., Ma, H., Song, S., Kaynak, M., & Miljkovic, N. (2020). Thermal management of 3D ICs with integrated through-silicon microchannel cooling. *IEEE Transactions on Components, Packaging and Manufacturing Technology, 10*(6), 987–996. https://doi.org/10.1109/TCPMT.2020.2984501

Zhang,W., Zhao,Z., Wu,H., Zhou,N., Gardner,D. S., Xie,Z., & Miljkovic,N. (2021). Water immersion cooling enabled by dielectric thin-film coatings for high-density electronics. *IEEE Transactions on Components, Packaging and Manufacturing Technology, 11*(5), 871–880. https://doi.org/10.1109/TCPMT.2021.3063451