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Toward efficient high-heat-flux thermal management with diamond/Cu composites

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Increasing power density in electronic devices creates growing demands for high-heat-flux thermal management. Diamond/Cu composites offer high thermal conductivity, tunable thermal expansion, and compatibility with advanced cooling architectures, making them promising alternatives to conventional heat-spreading materials. However, thermal expansion mismatch between diamond and Cu can induce interfacial residual stresses and compromise thermal-cycle reliability. More importantly, high bulk thermal conductivity alone does not ensure efficient device-level cooling, which depends on coupled transport across materials, interfaces, and cooling structures. We argue that diamond exposure at coolant-facing surfaces should be treated as a key design variable linking near-surface heat conduction with liquid-side heat transfer, rather than merely as a consequence of material processing.

Multiscale thermal transport in diamond/Cu composite-based devices

Heat transport in diamond/Cu composite-based thermal management devices can be regarded as a continuous multiscale process involving bulk heat conduction, heterogeneous interfacial thermal transport, and solid–liquid interfacial heat transfer, as schematically illustrated in Figure 1A. Additional die-attach, metallization, and bonding layers may introduce extra thermal resistance but are omitted for clarity.

For diamond/Cu composites, the intrinsic thermal conductivity of diamond can exceed 2000 W m^{-1} K^{-1}, whereas that of Cu is approximately 400 W m^{-1} K^{-1}. However, the effective thermal conductivity of the composite depends not only on the intrinsic thermal conductivities of the two constituents but also on factors such as the di-amond volume fraction, particle size, and spatial distribution. During heat transport through the composite, heat must cross numerous diamond/Cu heterogeneous interfaces, where interfacial defects, pores, and differences in heat-transport mechanisms between the two phases introduce additional thermal boundary resistance. Recent time-domain thermoreflectance measurements showed that W (20 nm) and WC (15 nm) interlayers achieved diamond/Cu interfacial thermal conductances of 101.5 and 88 MW m^{-2} K^{-1}, respectively, corresponding to area-normalized interfacial thermal resistances on the order of 10^{-8} m^2KW^{-1}.[1] Therefore, establishing continuous low-resistance thermal transport pathways through the composite is essential for fully exploiting the intrinsically high thermal conductivity of diamond.

Efficient heat transport within the material does not necessarily ensure effective heat removal. At the coolant-facing surface, heat dissipation is governed not only by the thermal boundary between the solid and liquid phases but also by near-wall heat spreading, boundary-layer transport, surface morphology, and wettability. In flow-boiling conditions, surface characteristics can further influence bubble nucleation and critical heat flux. Therefore, diamond exposure should be considered as a surface-design variable that cou-ples heat conduction within the composite with liquid-side heat transfer rather than simply as a reduction of interfacial thermal resistance. At the device scale, microchannel architectures can further enhance heat dissipation by increasing coolant contact area and promoting convective heat transfer.

Wu et al. reported a diamond/Cu heat sink with a thermal conductivity of approxi-mately 790 W m^{-1} K^{-1}, and a thickness of 2 mm, yielding a one-dimensional, area-normalized conduction re-sistance of 2.53×10^{-6} m^2 KW^{-1}. The reported solder-layer resistance was 1.72×10^{-6} m^2KW^{-1}, while the maximum flow-boiling heat-transfer coefficient of 47.30 kW m^{-2} K^{-1} corresponds to a fluid-side resistance of 2.11×10^{-5} m^2KW^{-1}. This simplified comparison, excluding lateral spreading and additional packaging layers, highlights the importance of liquid-side heat transfer under the reported boiling conditions.[2]

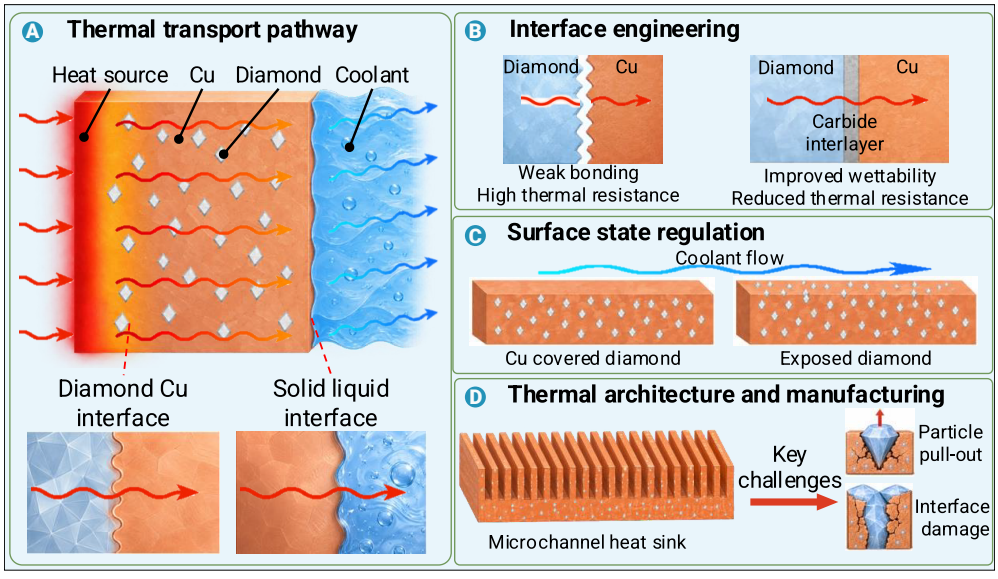


Figure 1. From high thermal conductivity to efficient heat dissipation in diamond/Cu composites (A) Multiscale thermal transport from the heat source to the coolant. (B) Diamond–Cu interface engineering for reduced interfacial thermal resistance. (C) Surface-state regulation for tailored solid–liquid heat transfer. (D) Thermal architecture design and manufacturing toward high-performance heat sinks.

FROM HIGH THERMAL CONDUCTIVITY TO EFFICIENT HEAT DISSIPATION

Addressing multiscale heat-transport challenges in diamond/Cu composite-based devices requires a shift from solely pursuing high bulk thermal conductivity toward coordinated optimization of interfacial transport, surface characteristics, and heat-dissipation structure design.

At the material scale, thermal transport in diamond/Cu composites is strongly influenced by the thermal resistance at heterogeneous diamond/Cu interfaces. Existing studies have mainly incorporated active elements such as Ti, Cr, W, Zr and B or introduced carbide interlayers to improve interfacial wettability and bonding strength, thereby enhancing heat transfer across the interface, as illustrated in Figure 1B. For example, Hao et al. achieved 1050 W m^{-1} K^{-1} using 80.47 vol% bimodal diamond particles (116 and 701 μm), gas-pressure infiltration, and an in situ B_4C inter layer.[3] Although carbide interlayers improve bonding, excessive thickness introduces additional thermal resistance. Fabrication routes, including infiltration, powder-based processing, and additive manufacturing, also influence porosity, diamond fraction, and interfacial integrity.

Beyond internal thermal transport, efficient device-level heat dissipation also depends critically on heat transfer across the solid–liquid interface. At this interface, diamond surface exposure, surface roughness, and wettability represent important surface-design variables, as illustrated in Figure 1C. Exposed diamond regions may enhance heat conduction toward the cooling surface but may suffer from unfavorable wettability for liquid cooling. In contrast, Cu-covered re-gions exhibit different surface chemistry and thermal conductivity, indicating a potential trade-off between near-surface heat conduction and liquid-side heat transfer. For exam-ple, Wu et al. demonstrated that tailoring the heterogeneous wettability and surface mi-crostructures of diamond/Cu composites enhanced the flow boiling heat transfer coeffi-cient by 38% compared with untreated surfaces.[2] However, the quantitative relationship between diamond exposure and solid–liquid inter-facial heat transfer in diamond/Cu composite thermal management devices remains insuf-ficiently established, and the underlying heat-transfer mechanisms require further investi-gation. In addition, the long-term stability of exposed diamond surfaces, including possi-ble particle detachment, surface degradation, and wettability evolution under coolant exposure, requires careful evaluation.

To further improve device-level heat dissipation, integrating diamond/Cu composites with functional cooling structures such as microchannel heat sinks has emerged as an im-portant strategy, as shown in Figure 1D. For example, Li et al. integrated diamond/Cu composite baseplates with Cu microchan-nels, achieving a 39% reduction in thermal resistance compared with conventional Cu heat sinks and a 12.3 °C decrease in the peak junction temperature of SiC power devices.[4] Depending on the cooling configuration, diamond/Cu composites can serve either as heat spreaders that redistribute localized heat before reaching the coolant, or as integrated heat sinks when directly coupled with coolant channels or boiling surfaces. Therefore, their contribution should be evaluated together with surrounding thermal interfaces and cool-ing architectures rather than by material conductivity alone.

However, the pronounced differences in hardness, brittleness, and material-removal behavior between the Cu matrix and diamond particles pose substantial challenges to conventional machining, often leading to severe tool wear, particle pullout, and interfacial damage. In recent years, laser processing has been explored as an alternative approach for fabricating microstructures in diamond/Cu composites. However, the effects of laser processing strongly depend on the laser regime. Nanosecond laser processing may induce pronounced thermal effects, graphitization, and interfacial damage due to heat accumulation,[5] whereas ultrafast laser approaches have shown potential for reducing the heat-affected zone and improving processing precision. Optimizing laser parameters and developing hybrid fabrication strategies are therefore important for controlling diamond exposure and fabricating complex cooling structures. Achieving these goals while preserving inter-facial integrity remains a key manufacturing challenge. Device-level optimization must therefore balance heat-transfer enhancement, pressure losses, and manufacturing constraints.

SUMMARY AND OUTLOOK

The device-level thermal management performance of diamond/Cu composites depends not only on bulk thermal conductivity but also on heterogeneous interfacial transport, solid–liquid heat transfer, and the architecture of functional heat-dissipation structures. However, the coupling mechanisms among these multiscale factors remain insufficiently understood. Future research should therefore focus on integrated optimization strategies that couple interface engineering, control of diamond surface exposure, and complex microchannel design and fabrication, thereby enabling more efficient device-level thermal management under high-heat-flux conditions.

Future research should prioritize three directions. First, interfacial thermal transport and stability should be characterized through advanced thermal metrology, such as time-domain thermoreflectance, under realistic operating conditions. Second, diamond expo-sure and cooling structures should be jointly optimized using multiphysics simulations and manufacturing-aware approaches. Third, standardized device-level evaluations should consider thermal resistance, pressure drop, and maximum temperature rather than relying solely on bulk thermal conductivity.

Key milestones include quantitative links between diamond exposure and heat-transfer performance, multiscale thermal-resistance prediction, and reliability validation under thermal cycling. These measurable outcomes would help establish practical design guidelines for integrating diamond/Cu composites into high-heat-flux cooling systems. These advances are particularly relevant to energy-intensive applications, including elec-tric vehicle power modules, renewable energy converters, and data-center thermal management, where efficient thermal management is essential for maintaining high perfor-mance and operational reliability.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.