Laser manufacturing for extreme chip cooling

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Dear Editor,

The rapid advancement of artificial intelligence, high-performance computing, and advanced power electronics has driven power densities in integrated systems to unprecedented levels, leading to severe thermal bottlenecks that threaten device performance and reliability. Although approaches such as ultra-high-thermal-conductivity materials, three-dimensional integration, and embedded microfluidic cooling are being explored, their practical implementation is hindered by the extreme hardness of these materials and the complexity of required geometries. Advanced laser manufacturing offers a promising solution, enabling high-precision, maskless fabrication within bulk materials and opening new pathways for realizing integrated three-dimensional thermal management architectures.

INTRODUCTION

The rapid expansion of artificial intelligence, high-performance computing, high-speed communications, and advanced power electronics is driving semiconductor systems toward unprecedented levels of integration and heterogeneous packaging. As device scaling approaches physical limits and three-dimensional integration becomes pervasive, on-chip power densities have escalated dramatically. State-of-the-art computing platforms now exceed thermal design powers (TDP) of 500 W, while localized hotspot heat fluxes can surpass 1000 W cm^{-2}. These extremes degrade carrier transport, induce threshold voltage shifts, and accelerate failure mechanisms, positioning near-junction thermal management as a defining bottleneck for post-Moore electronics.

In response, a growing body of research is turning to ultra-high thermal conductivity materials. Silicon (Si, $\kappa \approx 149$ W/(m·K)), long the backbone of the semiconductor industry, is increasingly showing its limitations in high-frequency and high-power applications. Wide-bandgap materials like silicon carbide (SiC, $\kappa \approx 300$–490 W/(m·K)) have gained a strong foothold in power electronics and RF devices, due to their high breakdown fields and superior thermal properties. However, for the extreme cooling demands of next-generation AI accelerators, advanced power electronics, and electronics for harsh environments, both industry and academia are converging on what is arguably the ultimate thermal substrate: diamond. With a theoretical thermal conductivity exceeding 2000 W/(m·K), diamond is widely regarded as an ideal medium for efficient near-junction heat extraction.

The same attributes that make ultra-wide-bandgap materials attractive for thermal management—chemical inertness, wide bandgaps, and extreme lattice rigidity—also render them fundamentally incompatible with conventional microfabrication. Techniques such as plasma etching and thin-film processing, developed for planar silicon platforms, exhibit low efficiency, limited selectivity, and restricted geometric control in materials like SiC and diamond.[1] Emerging cooling strategies require precise, three-dimensional structuring within bulk substrates, whereas existing processes remain inherently planar and assembly-intensive. Reliance on layer-by-layer fabrication and bonding introduces interfacial resistance, alignment complexity, and constrained design freedom. These limitations increasingly preclude scalable, monolithic integration of advanced thermal management architectures with next-generation electronic systems.

Laser manufacturing technology offers a compelling alternative. With its exceptional material versatility, ultrafast laser processing enables micrometer-scale ablation of even the most recalcitrant materials through nonlinear multiphoton absorption, effectively bypassing the limitations imposed by material hardness.[2] Leveraging multi-axis motion control and spatial light modulation, lasers enable direct 3D construction of complex microfluidic networks and bioinspired cooling geometries, as well as synthesis of novel carbon materials. Perhaps most importantly, direct laser writing is non-contact, maskless, and can be performed in situ, allowing localized micro-heat sinks to be integrated immediately adjacent to functional device layers. This letter showcases five key applications of laser manufacturing in chip cooling (Figure 1), aiming to reveal its vast potential in overcoming current thermal bottlenecks.

LASER APPLICATIONS IN CHIPS COOLING

Laser micromachining of microchannels

Embedded manifold microchannels[3] are generally acknowledged across academia and industry as one of the most effective and highly promising solutions for cooling high-performance and high-heat-flux chips. Conventional microfabrication technologies, such as reactive ion etching (RIE) and deep reactive ion etching (DRIE), are inherently limited to surface-level planar processing. Without relying on complex multi-layer stacking, they are unable to construct genuine three-dimensional architectures within bulk silicon, and they are largely ineffective for processing ultra-hard, wide-bandgap materials like diamond. In contrast, laser technology exhibits unparalleled material versatility and processing flexibility. For silicon, femtosecond laser-assisted wet etching enables direct internal modification, facilitating the monolithic integration of complex, non-linear 3D microfluidic networks seamlessly inside the wafer. For diamond, laser micromachining offers an efficient approach for fabricating high-aspect-ratio microchannels and other complex planar structures.

Recent work by *Wang et al.* has employed laser processing to fabricate microchannels and manifolds with high dimensional uniformity. By integrating Au–Sn bonding technology, they were the first to realize fully diamond-based embedded manifold microchannel heat sinks.[4] This laser-enabled architecture established record-breaking thermal limits: a 1 mm × 1 mm hotspot sustained an extreme heat flux of up to 10,000 W/cm^2, while over a larger area of 3.4 mm × 3.3 mm it handled a heat flux of 1000 W/cm^2 with a temperature rise of merely 42 K. However, the thermal performance in this study is to some extent constrained by the aspect ratio of the microchannels. The adoption of ultrafast laser processing techniques to further increase the aspect ratio is expected to enable even higher performance, without significantly increasing the existing bonding and fabrication costs.

Laser 3D integration

Through Glass Via (TGV) and Through Silicon Via (TSV) are core technologies for realizing three-dimensional (3D) vertical electrical interconnections in advanced semiconductor packaging. Although primarily designed for electrical routing, these microvias are typically filled with highly thermally conductive metals, most commonly copper. Consequently, they objectively function as critical thermal bridges within 3D packaging structures, thereby reducing internal thermal resistance and transporting heat from the interior to the surface.

A study on embedded microfluidic cooling for 2.5D packaging,[5] based on a silicon (TSV) interposer and numerical simulations, reported that the lowest peak temperature is observed at a heat flux of 145 W/cm², while the best temperature uniformity is achieved at 150 W/cm². In this work, silicon was processed using photolithography and deep reactive ion etching (DRIE), resulting in high process complexity and increased fabrication costs due to the low etching rate (~12 μm/min). In comparison, laser processing offers a lower technological barrier and shows strong potential for cost reduction.

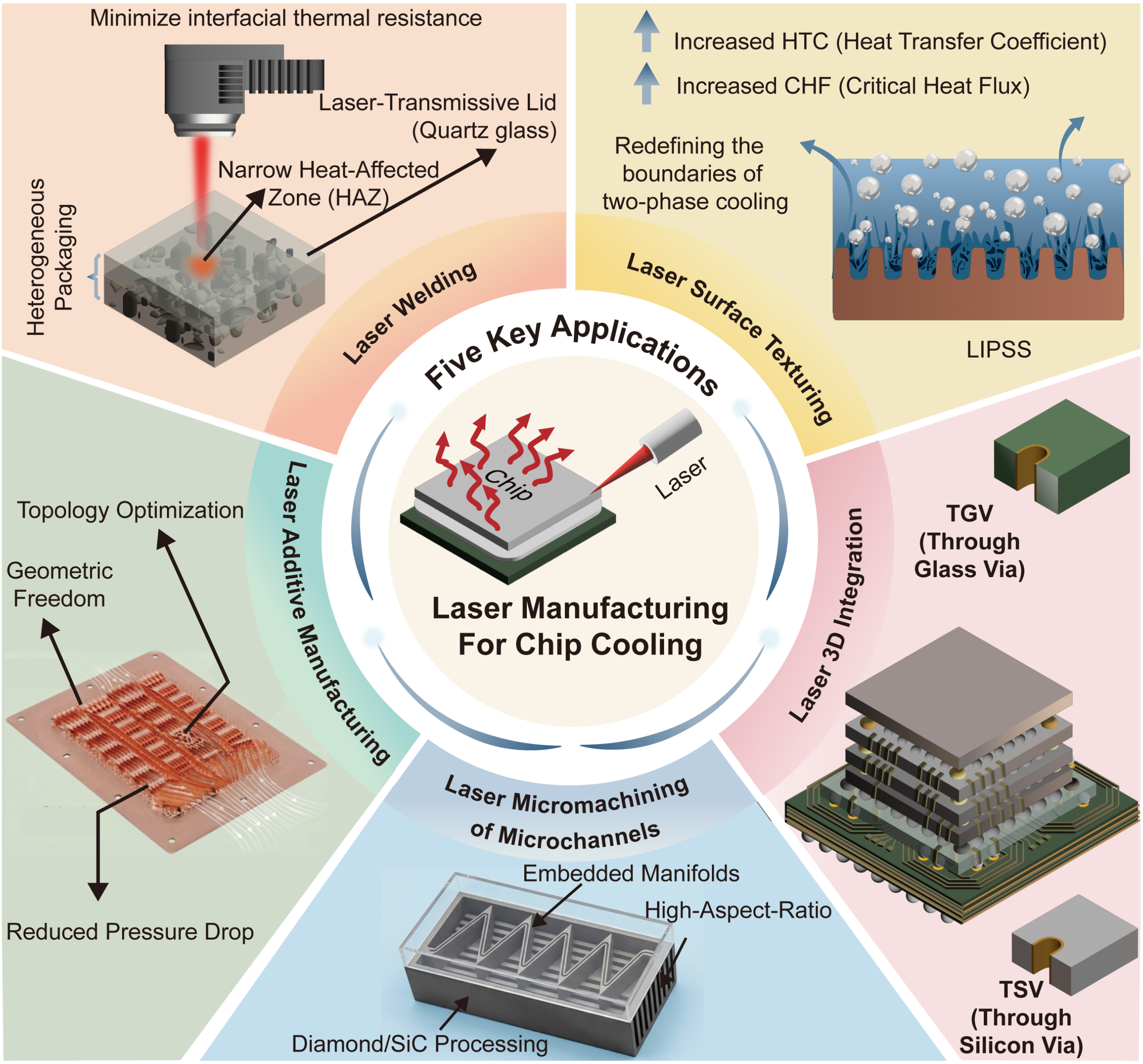

Figure 1. Applications of Laser Manufacturing for Chip Cooling.

Moreover, laser-based techniques enable the fabrication of high-thermal-conductivity materials such as silicon carbide, which can further enhance heat dissipation performance, whereas DRIE of SiC is significantly more complex and costly.

Laser welding

Laser manufacturing offers high-resolution, localized solutions to extreme heat dissipation bottlenecks in advanced packaging, replacing traditional bonding methods that often degrade temperature-sensitive components. Through laser transmission welding, localized photon energy enables rapid interfacial fusion with an extremely narrow heat-affected zone. This precision prevents global thermal stress and preserves the structural integrity of sub-micron cooling channels, even under high fluidic pressures. Unlike conventional thermocompression, this technique has expanded beyond quartz-to-silicon joining to include heterogeneous packaging of glass, metals, and ceramics, ensuring robust, hermetic seals for complex thermal management modules.

Beyond structural bonding, laser processing significantly modifies heat transfer pathways by optimizing thermal interface materials (TIMs) and surface contacts. The laser sintering of nanosilver pastes overcomes the low conductivity of traditional polymer greases, creating pure-metal conduction channels with thermal conductivities reaching 200–250 W/(m·K). Furthermore, ultrafast laser surface activation eliminates insulating oxides and microscopic contaminants at the wafer level without substrate ablation. By ensuring atomic-level contact and optimizing acoustic impedance matching, this pre-treatment minimizes phonon scattering and maximizes Kapitza conductance. Together, these laser-based strategies drastically reduce interfacial thermal resistance, fully unleashing the heat dissipation potential of next-generation electronic packaging.

Laser additive manufacturing

Additive manufacturing (AM) has become a major research focus in advanced manufacturing. Laser powder bed fusion (LPBF) is widely used for the direct fabrication of high-thermal-conductivity metal components. Owing to its layer-by-layer, bottom-up build principle, AM offers unprecedented geometric freedom. By integrating this intrinsic capability with advanced computational design methods, such as topology optimization and triply periodic minimal surfaces (TPMS), the limitations of conventional casting and machining—arising from tool accessibility and demolding constraints—can be overcome. This synergy enables the engineering design of spatially complex, interpenetrating three-dimensional microstructures.

A topology-optimized serpentine microchannel fabricated via LPBF has been reported to achieve up to a 91.57% reduction in pressure drop.[6] For micro-/nanoscale heat sinks operating under high heat flux, flow resistance and pressure drop are often the primary bottlenecks limiting coolant flow rate. Therefore, a design strategy that sacrifices a small margin in thermal performance (with the peak temperature increasing from 46.15 °C to 57.11 °C) in exchange for a significant improvement in hydraulic performance is highly valuable.

At present, such manufacturing approaches are mainly applied to package-level cooling structures. With the incorporation of stringent manufacturing constraints into optimization algorithms—particularly minimum feature size and 2.5D profile limitations—these advanced topological designs hold great potential for direct chip-level thermal management.

Laser surface texturing

Two-phase cooling leverages latent heat during vaporization to manage high heat fluxes, but it is physically limited by the Critical Heat Flux (CHF). At this threshold, coalescing bubbles form an insulating vapor film that triggers rapid temperature escalation. Femtosecond laser processing disrupts this bottleneck by sculpting "super-sponge" micro/nano-structures that induce potent capillary pumping. These architectures, including Laser-Induced Periodic Surface Structures (LIPSS) and microhole arrays, provide a "superwicking" effect that forcibly pulls fresh coolant back to the heated surface, delaying film formation and significantly elevating heat dissipation limits.

Recent experimental studies have validated the feasibility of this manufacturing approach. For example, on stainless steel,[7] LIPSS increased the critical heat flux (CHF) from 91 W/cm² to 142 W/cm² and doubled the heat transfer coefficient (HTC) to 67,400 W/(m²·K). These LIPSS determine the surface roughness characteristics of microchannels and influence the heat transfer coefficient by altering the flow regime of the coolant.

In principle, by tailoring laser processing parameters, it is possible to fabricate microchannels on ultra-high-thermal-conductivity materials such as diamond while simultaneously inducing controlled LIPSS, thereby further enhancing heat dissipation performance. This approach holds promise for pushing the performance limits of next-generation thermal management devices.

CONCLUSION

Against the backdrop of rapidly advancing computing power, extreme heat fluxes have triggered a severe semiconductor thermal management crisis. This letter introduces and evaluates five laser manufacturing technologies: laser micromachining of microchannels, laser 3D integration, laser welding, laser additive manufacturing, and laser surface texturing. Owing to their ultra-high spatiotemporal resolution and exceptional material versatility, these technologies exhibit strong potential to address key physical challenges, including the construction of complex three-dimensional cooling architectures, the reconfiguration of interfacial heat transfer pathways, and the overcoming of performance limits in two-phase cooling, thereby enabling record-high thermal performance. At the same time, laser manufacturing still faces challenges such as thermal damage, surface defects, and limited processing efficiency and scalability, which should be addressed in future work. Despite these challenges, with the escalating thermal demands of next-generation high-power electronic chips, laser manufacturing is expected to evolve from an optional approach into an indispensable enabling technology.

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DECLARATION OF INTERESTS

The authors declare no competing interests.