

Diamond Heat Spreaders & GaN Phonon Transport Engineering Dossier

Acoustic Phonon Dispersion, Boundary Thermal Conductance, and 2,000 W/cm² AI Die Hotspot Mitigation

EXECUTIVE ABSTRACT: Next-generation 2,000W AI accelerators and high-voltage GaN power dies generate localized heat fluxes exceeding 2,000 W/cm² in microscopic hotspots. Chemical Vapor Deposition (CVD) polycrystalline diamond provides a thermal conductivity of 2,200 W/(m·K)—over 5x that of copper. Direct bonding of diamond to GaN and silicon eliminates acoustic phonon mismatch, slashing thermal resistance by 60%.

Thermal Spreading Material	Thermal Conductivity (W/m·K)	Debye Temperature (K)	Thermal Expansion (ppm/K)	Boundary Resistance (m²K/GW)
Oxygen-Free Copper (Cu)	390 - 400	343 K	16.5 ppm/K (High)	10.0 - 15.0 (High)
Silicon Carbide (SiC)	450 - 490	1,200 K	4.0 ppm/K (Matched)	5.0 - 8.0 (Moderate)
Pyrolytic Graphite Sheet	1,200 - 1,500 (In-plane)	950 K	1.0 ppm/K (Anisotropic)	20.0 - 35.0 (Interlayer)
CVD Diamond (Polycrystalline)	2,000 - 2,200 (Isotropic)	2,220 K (Extreme)	1.1 ppm/K (Matched)	2.5 - 4.5 (Low with ALD)

1. The Microscopic Heat Flux Crisis in AI Accelerators

Modern multi-die AI GPUs (such as Blackwell and MI300) draw upwards of 1,000W to 1,500W. While average die heat flux is ~100 W/cm², localized register files and SRAM crossbars produce extreme hotspots exceeding 2,000 W/cm² over areas smaller than 0.5 mm².

- Copper Spreading Limits: Copper heat sinks suffer from lateral thermal spreading resistance: heat cannot diffuse laterally fast enough through 400 W/(m·K) copper before localized silicon temperature exceeds 105°C.
- The CVD Diamond Revolution: Synthetic diamond features isotropic thermal conductivity of 2,200 W/(m·K), acting as an ultra-fast thermal conduit that flattens hotspot thermal gradients in sub-milliseconds.

2. Acoustic Phonon Transport & The Debye Temperature

In non-metallic crystals like diamond and silicon, heat is conducted not by free electrons, but by quantized lattice vibrational waves called **phonons**.

- Acoustic Phonon Velocity: The strong, rigid sp3 covalent carbon bonds in diamond produce an acoustic phonon sound velocity of ~18,000 m/s (4x faster than in copper).
- Debye Temperature (Theta_D): Diamond boasts a Debye temperature of 2,220 K. Because room temperature (300 K) is far below Theta_D, Umklapp phonon-phonon scattering is suppressed, resulting in unprecedentedly long phonon mean free paths (> 100 nm).

3. Thermal Boundary Resistance (TBR) & Surface Activated Bonding

The primary hurdle to integrating diamond with silicon or GaN is **Thermal Boundary Resistance (TBR)** across the hetero-interface:

- **Acoustic Mismatch:** Differences in phonon density of states between GaN and diamond reflect phonons at the boundary, creating an interfacial temperature drop.
- **Surface-Activated Bonding (SAB):** By treating diamond and GaN surfaces with argon beam irradiation in ultra-high vacuum and applying an ultra-thin 2nm silicon or titanium adhesion interlayer via Atomic Layer Deposition (ALD), interfacial TBR drops below 4.0 m²K/GW, cutting total junction-to-case thermal resistance by 60%.

4. Commercial Deployment in 1,000W+ AI Silicon

Foundries are integrating diamond heat spreaders into 2.5D/3D chiplet packaging (e.g. CoWoS and EMIB), allowing AI clusters to sustain 15% higher clock frequencies under continuous matrix compute without hitting thermal throttling ceilings.

STRATEGIC ARCHITECTURAL TAKEAWAYS

1. CVD polycrystalline diamond delivers 2,200 W/(m·K) thermal conductivity, 5x higher than copper.
2. Rigid sp³ carbon lattice and 2,220 K Debye temperature minimize acoustic phonon scattering at room temperature.
3. Surface-Activated Bonding (SAB) with ALD interlayers overcomes interfacial thermal resistance (TBR) for 2,000W AI dies.