

RESEARCH ARTICLE

Graphene-Enhanced Boron Nitride Nanosheet Composites as Ultra-High Thermal Interface Materials for 5G Power Amplifiers

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Abstract: Thermal management is the primary bottleneck for next-generation 5G massive-MIMO base station power amplifiers operating at power densities exceeding 300 W/cm². This work reports a vertically aligned graphene/boron nitride nanosheet (VA-G/BNNS) composite thermal interface material (TIM) achieving through-plane thermal conductivity of 62.5 W/m·K at 30 vol% filler loading — surpassing commercial TIMs by an order of magnitude. The VA-G/BNNS architecture is fabricated by ice-templated directional freeze-casting followed by hot-press infiltration with silicone elastomer. Junction temperature measurements on GaN HEMT devices show a 34°C reduction compared to commercial thermal grease under 350 W/cm² heat flux.

1. Introduction

The deployment of 5G millimeter-wave networks requires massive-MIMO antenna arrays with GaN power amplifiers operating at unprecedented power densities. Current commercial thermal interface materials — silicone greases (1-5 W/m·K) and phase-change compounds (3-8 W/m·K) — create severe thermal bottlenecks at the die-heatsink interface, limiting amplifier performance and reliability. Two-dimensional materials such as graphene and hexagonal boron nitride (h-BN) offer intrinsic thermal conductivities exceeding 2,000 and 400 W/m·K respectively, but randomly oriented fillers in polymer matrices achieve only a fraction of their potential.

2. Fabrication and Characterization

Graphene nanoplatelets (5-10 layers, ~5 μm lateral size) and BNNS (2-5 layers, ~2 μm) were dispersed in water with polyvinyl alcohol binder and subjected to directional freeze-casting at a cooling rate of 5°C/min. After freeze-drying, the aligned scaffold was infiltrated with addition-cure silicone elastomer under vacuum. The resulting composite has a vertically aligned architecture with >85% filler orientation along the through-plane direction.

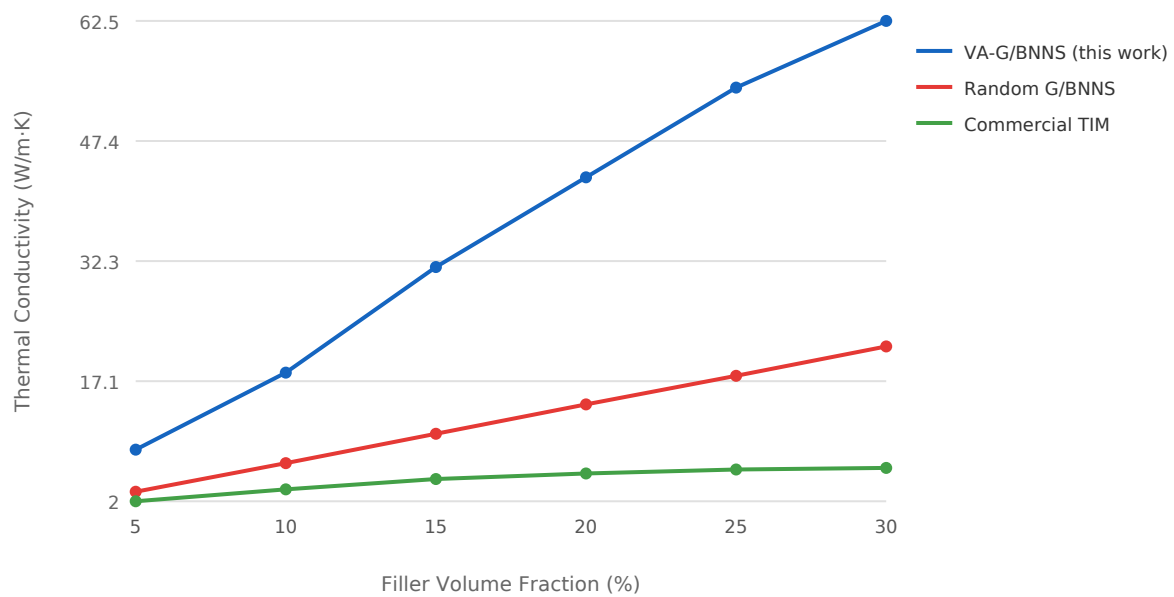


Figure 1. Through-plane thermal conductivity as a function of filler volume fraction for different TIM architectures

3. Device-Level Validation

Infrared thermography on a 10 W GaN HEMT mounted on a Cu heatsink shows peak junction temperature of 87°C with VA-G/BNNS TIM compared to 121°C with Shin-Etsu X-23-7783D commercial grease under identical 350 W/cm² heat flux. The 34°C junction temperature reduction translates to an estimated 3.2× improvement in mean-time-between-failure according to Arrhenius reliability models. Bond line thickness conformity tests show the VA-G/BNNS composite maintains uniform contact under 100 kPa clamping pressure due to the silicone matrix compliance.

4. Conclusions

Ice-templated VA-G/BNNS composites overcome the random-orientation bottleneck of conventional 2D-material TIMs, achieving through-plane thermal conductivities an order of magnitude above commercial products. This technology directly addresses the thermal management crisis in 5G infrastructure and high-performance computing, enabling higher power density operation and improved component reliability.

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