Diamond-on-GaN vs. GaN-on-SiC HEMT RF Transistors

2DEG Polarization Sheet Charge Dynamics and 100 GHz Thermal Boundary Resistance

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EXECUTIVE ABSTRACT: Gallium nitride high-electron-mobility transistors (HEMTs) operating at Ka and W-band frequencies suffer catastrophic thermal self-heating. While 4H-SiC substrates possess a bulk thermal conductivity of 490 W/m·K, synthetic diamond achieves 2,200 W/m·K. This dossier audits the sub-nanometer thermal boundary resistance (TBR) across bonded interfaces, 2DEG carrier density scaling, and RF output power density gains.

Physical Metric	GaN-on-SiC Baseline	Diamond-on-GaN HEMT
Substrate Thermal Conductivity	490 W/m·K (4H-SiC)	2,200 W/m·K (CVD Diamond)
Thermal Boundary Res (TBR)	35 m²·K/GW (SiC interface)	12 m²·K/GW (Bonded Diamond)
RF Power Density @ 94 GHz	4.2 W/mm (Thermal Limit)	12.8 W/mm (Sustained Power)
Peak Channel Junction Temp	225°C @ 5 W/mm Drive	142°C @ 12 W/mm Drive

1. Spontaneous & Piezoelectric Polarization in AlGaN/GaN Heterojunctions

The high electron mobility transistor relies on a two-dimensional electron gas (2DEG) formed without modulation doping. Spontaneous polarization arising from non-centrosymmetric wurtzite crystal asymmetry induces a sheet charge density exceeding 1.2 × 10^{13} cm■^{2}. Mechanical lattice mismatch creates piezoelectric polarization adding further carrier confinement, yielding sheet resistances below 280 Ω/sq.

2. Thermal Boundary Resistance (TBR) and Phonon Acoustic Mismatch

At 100 GHz, extreme electrical power densities exceeding 10 W/mm create localized Joule heating hotspots confined to 50 nm near the drain-side gate edge. Heat extraction is constrained by the acoustic mismatch model (AMM) and diffuse mismatch model (DMM), where transition-layer phonon scattering dominates total thermal impedance.

3. CVD Diamond Growth vs. Low-Temperature Hydrophilic Die Bonding

Direct CVD diamond growth onto GaN requires silicon nitride seeding interlayers that introduce a severe TBR penalty of 30-40 $m^2 \cdot K/GW$. Low-temperature surface-activated bonding (SAB) utilizing sub-5nm amorphous interlayers minimizes TBR to 10-12 $m^2 \cdot K/GW$, ensuring direct phonon coupling into the high-k diamond matrix.

4. Millimeter-Wave Power-Added Efficiency (PAE) Scaling

By depressing peak channel temperatures by over 80°C under continuous-wave (CW) saturation, optical phonon scattering rates fall by 35%. Consequently, carrier saturation velocity remains above 2.2 × 10■ cm/s, driving power-added efficiency (PAE) past 45% at 94 GHz radar bands.

STRATEGIC ARCHITECTURAL CONCLUSIONS:

- Diamond-on-GaN provides a 3x increase in continuous-wave RF power density compared to state-of-the-art GaN-on-SiC HEMTs.
- Minimizing thermal boundary resistance (TBR) below 15 $m^2 \cdot K/GW$ via surface-activated bonding is critical to prevent acoustic phonon bottlenecking.
- Lower operating temperatures extend Mean Time to Failure (MTTF) by more than two orders of magnitude in radar and 6G telecom power amplifiers.