

Developing a New Thermal Paradigm for Gallium Nitride (GaN) Device Technology

J.D. Blevins¹, G.D. Via¹, A. Bar-Cohen², A. Sivananthan³

¹Air Force Research Laboratory (AFRL), Wright-Patterson AFB, OH

²Defense Advanced Research Projects Agency (DARPA), Arlington, VA

³Booz-Allen-Hamilton, Arlington, VA

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Abstract

Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) are rapidly becoming the technology of choice for high power RF applications. The intrinsic properties of GaN make it an ideal semiconductor material for microwave/millimeter wave power amplifiers [1]. Cree previously demonstrated AlGaN/GaN HEMTs with power densities exceeding 40 W/mm [2]. Use of GaN is leading to revolutionary performance enhancements for both military and commercial RF components. However, exploiting the true operational capability of GaN remains problematic due to the inability to effectively manage device self-heating. Current remote cooling solutions rely on thermal conduction across multiple material interfaces and cannot effectively manage the device junction temperature. Continued application of this “remote cooling” paradigm has resulted in thermal management hardware accounting for a large fraction of the size, weight, power consumption and cost (SWaPC) of RF components [3]. Thermal impediments are presently limiting GaN device technology from realization of its true capability. Control of the junction temperature requires integration of thermal transport solutions near the heat source to ensure optimal performance and reliable operation [4]. Development of improved thermal transport solutions within microns of the GaN HEMT device channel have been the subject of DARPA investment for the past several years. This paper will examine the motivation for the DARPA Intra/Interchip Embedded Cooling (ICECool) Program, review performer technical approaches and highlight key results to date.

INTRODUCTION

GaN power amplifiers are rapidly becoming the technology of choice for high power and high frequency RF components. During the past 10 years GaN devices have rapidly matured enabling insertion

into a variety of military radar, electronic warfare and communication systems as well as commercial wireless infrastructure components. Significant advances in epitaxial growth, device fabrication and design have enhanced the electrical performance to a point where thermal management is now a primary limiting factor in device and circuit operation [5]. Even though small periphery GaN devices have exceeded 30W/mm of RF output power density, devices are typically de-rated to 5-6 W/mm to ensure reliable operation. Continued use of conventional thermal conduction and spreading techniques is limiting the realization of GaN’s intrinsic electronic capabilities. Improved thermal management solutions are necessary to exploit the true operational capability of GaN [3]. Military electronics continue to rely on existing closed-loop single phase “remote” cooling systems utilizing fluids such as ethylene glycol and water (EGW) or propylene glycol and water (PGW). Dependence on these “macro” remote-cooling techniques remains limited by the need for progressively larger heat spreaders and interface layers that separate the heat source from the cold plate [6]. Continued application of this “remote cooling” paradigm has resulted in thermal management hardware accounting for a large fraction of the SWaPC of RF components [3]. Overcoming the remote cooling paradigm requires reducing the thermal resistance of the near-junction region and heat sink without producing deleterious effects in electrical performance [3]. Approaches under consideration involve the use high thermal conductivity polycrystalline diamond and/or micro-channel cooling in close proximity to device hot spots. Future military electronics will continue to pursue higher levels of integration and miniaturization only exacerbating the need for improved thermal transport solutions.

The self-heating effects for GaN/SiC HEMTs are well known to limit power density and have been thoroughly documented [6]. Recent demonstrations of diamond integrated within microns of the GaN

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transistor junction has proven to be effective at reducing intra-device thermal resistance enabling significant increases in HEMT areal power density (W/mm^2) without commensurate increases in operating temperature [7]. The introduction of micro-channel coolant flow adjacent to the device die reduces the number of thermal interfaces thus decreasing the overall thermal resistance from the junction to the coolant [8]. The decreased thermal resistance between the heat sources and cooling medium reduces the thermal constraints providing the device designer additional options to exploit the inherent characteristics of GaN [6]. Since the device operates cooler, it is possible to reduce the device gate pitch to achieve higher areal output power while maintaining an acceptable junction temperature. As shown in Figure 1, the gate pitch of a GaN-on-Diamond HEMT can be reduced from $49\mu\text{m}$ to $10\mu\text{m}$, enabling a $>5\text{X}$ improvement in power over GaN-on-SiC HEMT [4]. The application of near junction embedded cooling could expand the operational envelope of thermally limited GaN Monolithic Microwave Integrated Circuits (MMICs).

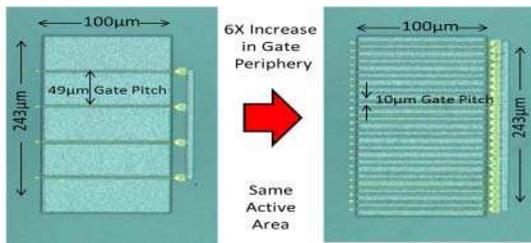


Figure 1: Standard $4\text{X}100\mu\text{m}$ and reduce gate pitch $24\text{X}100\mu\text{m}$ GaN HEMTs having the same device area. The use of polycrystalline diamond within microns of device junction can enable a 6X increase in gate periphery leading to a $>5\text{X}$ increase in RF power than the standard GaN-on-SiC HEMT.

DARPA ICECool PROGRAM

In partnership with industry performers BAE, Boeing, Lockheed Martin, Northrop-Grumman (NGAS), Nuvotronics and Raytheon, DARPA kicked off the ICECool Applications Program in December 2013. The ICECool Program follows the Near Junction Thermal Transport (NJTT) Program that demonstrated the feasibility of increasing the GaN transistor output power by $>3\text{X}$ through the integration of polycrystalline diamond in close proximity to the device junction (Figure 2) [5]. DARPA is aiming to further exploit the performance promise of GaN MMICs with embedded microfluidic cooling to address ever-increasing power density requirements. The overarching vision for the ICECool Program is to adopt a “co-design” philosophy that places an equal emphasis on thermal management with that of RF performance [3]. This

co-design approach required extensive use of fluid, thermal, electromagnetic and mechanical simulations to optimize the GaN MMIC layout and microchannel cooling structures [6].

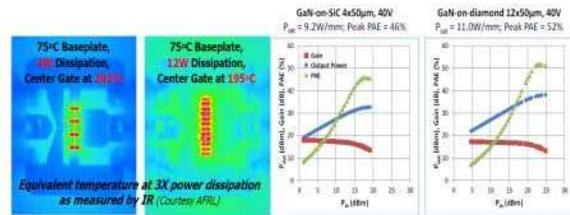


Figure 2: Comparison of thermal and 10GHz CW output power characteristics of GaN-on-SiC HEMT and GaN-on-Diamond HEMT with 3X larger gate periphery.

The ICECool Applications Program is well into a 36-month design, development and demonstration of single phase, embedded microfluidic cooling of thermally limited GaN MMICs. During Phase I, industry performers in the GaN MMIC track were required to demonstrate a Thermal Demonstration Vehicle (TDV) that typically consisted of DC biased transistors and resistors on a representative GaN substrate and were capable of managing GaN die-level heat fluxes of $1\text{kW}/\text{cm}^2$ and HEMT (sub-millimeter “hot spot”) heat fluxes of $30\text{kW}/\text{cm}^2$ [3]. The fluid coefficient of performance (CoP) goal was >20 while being capable of operating at an inlet temperature up to 70°C without exceeding the allowable junction temperature. These goals, as outlined in Table 1, represent a major increase in heat flux density compared to current SOA GaN MMICs. A total of four teams in the GaN MMIC track, including BAE, Lockheed Martin, Northrop-Grumman and Raytheon, were down selected to continue development of their respective ICECool GaN MMIC designs in an operational Electrical Demonstration Vehicle (EDV) module. Each EDV will be measured against the thermal metrics as well as the RF performance of the baseline (conventionally-cooled) GaN MMIC.

TABLE I
ICECool APPLICATION PROGRAM GaN METRICS

	Phase 1 Metric	Phase 2 Metric	Units
Thermal Metrics	TDV Demonstrated	EDV Demonstrated	
MMIC (die-level) heat flux	> 1	> 1	kW/cm^2
Heat density	> 2	> 2	kW/cm^2
Total heat	Proposer defined	Proposer defined	kW
HEMT “hot spot” flux	> 30	> 30	kW/cm^2
Thermal resistivity	Proposer defined	Proposer defined	$\text{cm}^2\text{K}/\text{kW}$
Thermofluid CoP	> 20	> 20	N/A
Electrical Performance Metrics	Simulated	EDV Demonstrated	
Output power	$> 3\text{x}$ baseline	$> 3\text{x}$ baseline	W
Reliability Metrics			
Design for MTF	10^6	10^6	Hours
Demonstrated cycles	10^3	10^3	Cycles
Demonstrated lifetime	10^2	10^2	Hours
Hermetic connector leakage	$< 1\%$	$< 1\%$	% per year

ICECool TECHNOLOGY

Performer approaches being developed under ICECool leverage the use of existing military cooling fluids to reduce the thermal resistance of the GaN MMIC thermal stack. These embedded cooling approaches are being designed to be compatible with existing GaN MMIC fabrication processes. The majority of performers are integrating CVD polycrystalline diamond into their design in combination with fluids to maximize heat removal capability. Central to this strategy is the use of jet impingement, of varying velocities and pressures, strategically located under critical HEMT hot spots to maximize solid to liquid heat transfer. The use of jet impingement replenishes coolant enabling efficient heat transfer. However, use of high velocity fluids does increase the risk of erosion and corrosion effects within the micro-channels and introduces potential electromagnetic effects [6].

BAE is pursuing a “device first” process that leverages their existing GaN-on-SiC MMIC process by removing the active GaN device layers and bonding them to a CVD polycrystalline diamond substrate. A single-phase, CTE matched metal microcooler is attached to the ground plane located just below the diamond substrate [5]. The close proximity (~1um) of the high thermal conductivity diamond to the active junction provides for optimal thermal spreading to the microcooler. BAE’s ICECool design is shown in Figure 3 [10]. Co-design simulations predicted the TDV and EDV to meet all thermal flux requirements. BAE’s EDV is targeting a >3X increase in RF output power compared to their GaN-on-SiC MMIC baseline. The application of ICECool technology is ideally suited for wideband power amplifiers due to their continuous wave operation and need to improve power-added efficiency.

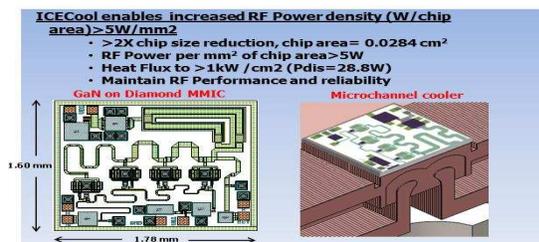


Figure 3: BAE microchannel cooled, high power GaN-on-Diamond MMIC.

NGAS is developing an impingement cooled embedded diamond (ICED) heat spreader approach that integrates diamond-lined microfluidic channels embedded in the SiC substrate directly under the GaN MMIC (Figure 4) [9]. A micro-machined silicon

manifold, solder bonded to the GaN MMIC backside, routes high flow rate fluid to submerged microfluidic impingement jets. The diamond provides efficient thermal spreading to the microfluidic channel where heat can be removed by the impingement jet fluid. Co-design simulations predicted both the TDV and EDV to meet all thermal flux requirements. NGAS is targeting >4X RF output power with their EDV compared to their baseline GaN-on-SiC MMIC [9].

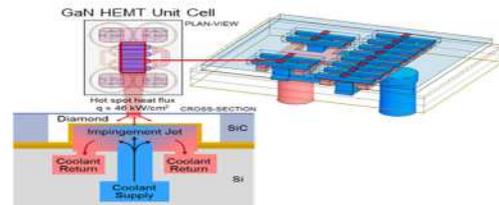


Figure 4: NGAS Impingement Cooled Embedded Diamond.

Raytheon is leveraging their existing GaN-on-Diamond technology to further incorporate an intra-chip cooling solution comprised of a GaN-on-Diamond MMIC with integral microfluidic channels. Cooling fluid is supplied using a silicon manifold structure bonded to the GaN-on-Diamond chip. This approach combines the near junction heat spreading capability of diamond with integrated diamond microfluidics to achieve a scalable, low thermal resistance solution. Co-design simulations predicted both the TDV and EDV to meet all thermal flux requirements. Raytheon is targeting >4X RF output power with their EDV design over their baseline GaN-on-SiC MMIC (Figure 5) [6].

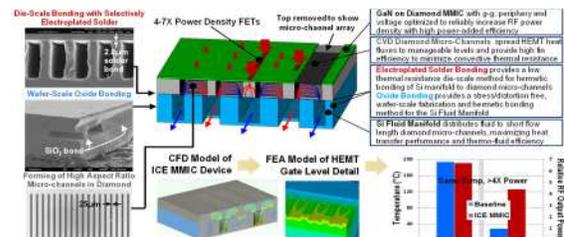


Figure 5: Raytheon integrated circuit enhancement through microfluidic MMIC intra-chip cooling.

Currently, Lockheed Martin is the only ICECool performer not relying upon the superior heat spreading capability of diamond in their design. Their ICECool approach utilizes a single phase, micro-jet impingement on the SiC backside for cooling their GaN MMIC (Figure 6) [8]. This approach utilizes a palladium microfluidic manifold bonded to the SiC backside for fluid distribution. The manifold is a stand-alone micro cooler manufactured utilizing a wafer-scale process to create a multi-layered structure by additive, electrodeposition processes [11]. This GaN MMIC design taps directly into an existing cold

plate coolant loop and re-routes it directly into the manifold to enable near junction cooling. Co-design simulations predicted the TDV to satisfy the thermal heat flux requirements while reducing the thermal resistance >3X (Figure 5) [8]. The use of microfluidic manifold cooling is expected to garner significant improvements to RF output power, PAE, gain and reduced junction temperatures perhaps leading to improved lifetime.

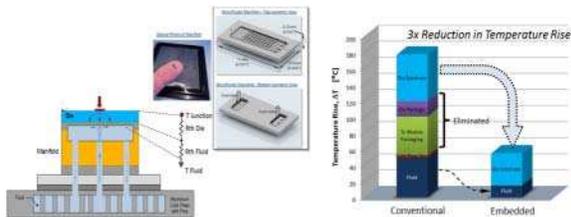


Figure 6: Lockheed Martin embedded cooling approach utilizes palladium micro-cooler manifold to reduce thermal resistance >3X.

RESULTS AND DISCUSSION

During the first 18-months ICECool performers were required to design, fabricate, test and deliver four TDV's each. Lockheed Martin's TDV design utilized Qorvo's 0.15 μ m process. Their design consisted of five TaN resistive heaters and four GaN HEMTs to simulate die level and hot spot heat fluxes. The GaN-on-SiC TDV die was attached to a multi-layered palladium manifold consisting of internal jets and coolant flow channels optimized for flow and thermal management. Lockheed Martin's TDV hardware was tested and determined to meet both the 1kW/cm² die-level heat flux and the 30kW/cm² HEMT hot spot metrics. Figure 7 provides measured IR images displaying a >5X higher heat flux enabled by near junction, embedded microchannel cooling [11]. These experimental results were in excellent agreement with their co-design simulations thus validating their model predictions.

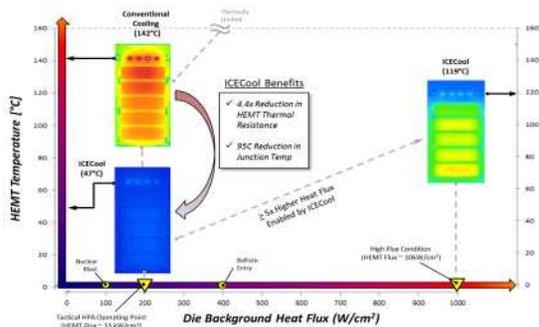


Figure 7: Measured IR images of Lockheed Martin ICECool TDV versus conventional cooling methods.

Northrop Grumman's TDV is a DC device consisting of thin film resistor test structures to simulate their EDV GaN MMIC layout as well as

satisfy the required die heat flux. Figure 8 shows IR data taken on the baseline GaN MMIC and TDV. The diamond lined vias with jet impingement cooling enabled a 3X increase in power dissipation while concurrently reducing hot spot temperature >50C. The TDV was also shown to meet both the 1kW/cm² die-level heat flux and 30kW/cm² HEMT hot spot metrics [9]. These experimental results validate their co-design simulations.

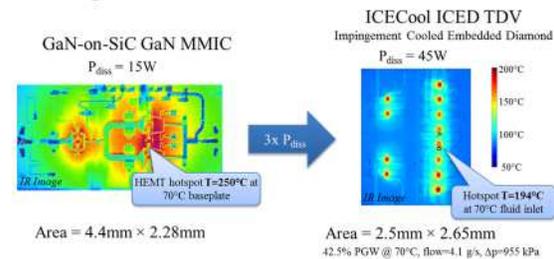


Figure 8: Measured IR images of ICECool TDV versus conventional GaN-on-SiC MMIC.

CONCLUSIONS

DARPA ICECool Program performers have used a co-design process to integrate near junction embedded microchannel cooling into thermally limited GaN MMICs. Performer TDV designs have demonstrated microchannel cooling to significantly reduce thermal resistance and enhance localized thermal management. Future work under the ICECool Program will demonstrate microchannel cooling within functional GaN MMICs.

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