Prospects for Gallium Nitride-on-Diamond Transistors

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Abstract — Strategies aimed at improving the near junction heat removal of Gallium Nitride (GaN) High Electron Mobility Transistors (HEMTs) are presently limiting GaN device technology from realization of its true capability [1]. Approximately ten years ago, Cree demonstrated AlGaN/GaN HEMTs with power densities exceeding 40 W/mm [2]. Control of the GaN junction temperature requires integration of thermal transport solutions near the heat source to ensure optimal performance and reliable operation [3]. An approach under consideration is the use of Chemical Vapor Deposition (CVD) polycrystalline diamond inserted within microns of the device junction. Recent AFRL and Defense Advanced Research Projects Agency (DARPA) efforts have shown that replacing the epitaxial host substrate with high thermal conductivity polycrystalline diamond substrates can improve the GaN HEMT areal power density >3Xs [4-9]. This paper will examine the motivation behind the use of diamond, integration approaches, material/device results and key technological challenges going forward.

Index Terms — GaN, HEMT, CVD polycrystalline diamond, thermal management.

I. INTRODUCTION

GaN power amplifiers are rapidly becoming the technology of choice for 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 [10].

Fig. 1. Conventional GaN-on-SiC HEMT stack-up [10].

Silicon, silicon carbide (SiC) sapphire and GaN are commercially available to support GaN device fabrication. However, even use of SiC substrates, with a thermal conductivity of 400W/m-K, cannot effectively manage device self-heating. A typical GaN-on-SiC HEMT thermal profile is shown in Fig. 1. The GaN epitaxy, interfaces and SiC substrate dominate the overall temperature rise. In order to mitigate thermally-induced performance and reliability degradation, useable power densities are limited to 5-8 W/mm [5].

Military electronics reliance on “remote” cooling solutions has resulted in thermal management hardware accounting for a large fraction of the SWaPC of RF components [11]. 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 [12]. The continued use of conventional thermal conduction and spreading techniques combined with remote cooling is limiting the realization of GaN’s intrinsic electronic capabilities.

Improved thermal transport solutions capable of managing localized device hot spots are required to obtain peak performance and reliable operation. Replacing SiC with a higher thermal conductivity substrate could substantially improve heat spreader near the hot spot lowering the overall temperature rise. The most promising approaches under development involve the integration of high thermal conductivity CVD polycrystalline diamond in close proximity of the device hot spots. The electrically insulating and thermal conductivity properties of CVD polycrystalline diamond provide an attractive option. Recent demonstrations of diamond integrated within microns of the GaN 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 [12]. The decreased thermal resistance between the heat sources and diamond reduces the thermal constraints providing the device designer additional options to exploit the inherent characteristics of GaN

[11]. 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. BAE has shown the gate pitch of a GaN-on-Diamond HEMT can be reduced from $49\mu\text{m}$ to $10\mu\text{m}$, enabling a $>5X$ improvement in power over GaN-on-SiC HEMT [3].

Fig. 2. The use of embedded polycrystalline diamond provides flexibility to reduce gate pitch to increase device periphery or reduce device area [3].

II. DIAMOND PROCESS DESCRIPTIONS

Since 2012, DARPA's Near Junction Thermal Transport (NJTT) Program performers have focused on developing an integrated embedded cooling approach using high thermal conductivity polycrystalline diamond [9]. NJTT Program demonstrations of GaN-on-Diamond HEMTs have proven to be effective at reducing intra-device thermal resistance enabling $>3X$'s increase in GaN HEMT areal power density (W/mm^2) without commensurate increases in operating temperature [9]. Presently, there are three primary GaN-on-Diamond fabrication processes under development. Notwithstanding the process differences and difficulties, each has shown performance benefits.

A. Direct Growth of CVD Diamond

This process deposits a CVD film of polycrystalline diamond on the N-face of a GaN HEMT epi wafer. Use of this material led to the first demonstration of a GaN-on-Diamond transistor by AFRL in 2007 [4]. The process flow is shown in Fig. 3. It begins with AlGaIn/GaN epitaxial layers grown on silicon (111) substrates. A sacrificial silicon handle wafer is attached to the front-side of the epi wafer to facilitate removal of the silicon host substrate. The silicon substrate and epitaxial transition layers are subsequently removed and a nominal 30nm dielectric layer is deposited on the GaN buffer backside to facilitate microwave plasma CVD polycrystalline diamond growth. The addition

of the dielectric layer does introduce a thermal boundary resistance (TBR) that must be minimized. Growth of approximately $100\mu\text{m}$ of polycrystalline diamond provides the necessary mechanical and thermal robustness for subsequent front side device fabrication as well as being compatible with micro-strip MMIC backside processing requirements. The handle wafer is removed and the GaN-on-Diamond wafer is ready for standard front side processing. Prolonged high temperature exposure during CVD polycrystalline diamond growth does induce wafer strain resulting in significant wafer bow. This bow must be carefully managed to facilitate wafer scale processing. Several groups, including NJTT Program performers Raytheon and Qorvo (RFMD/ Triquint), along with AFRL have demonstrated that the diamond integration process did not significantly degrade the electrical performance and clear trends show improved thermal performance utilizing variants of this diamond integration approach [4-13].

Fig. 3. Direct diamond growth process flow, 75mm GaN-on-Diamond device wafer and example of HEMT area reduction due to compaction of gate to gate spacing [15].

B. Wafer Bonding

BAE is developing a diamond wafer bonding process as shown in Fig. 4 that takes full advantage of their standard 100mm GaN-on-SiC MMIC fabrication process. This process utilizes a "device first" process that leverages a mature, reproducible GaN-on-SiC MMIC process. Following front side completion of a 100mm GaN-on-SiC wafer, a silicon carrier wafer is bonded to the front side facilitate SiC substrate removal. A plasma etch is used to remove the SiC substrate and expose the backside GaN epi layer. The GaN epitaxial layer is further etched and chemical-mechanical polished (CMP) to a target of $<1\text{nm}$ RMS surface roughness. A thin SiN bonding layer is deposited on the GaN buffer and polycrystalline diamond surfaces to facilitate low temperature atomic attachment.

Fig. 4. Process flow for wafer bonding GaN device layers to a free-standing polycrystalline diamond substrate [10].

C. Selective Polycrystalline Diamond Growth

Northrop Grumman Aerospace Systems (NGAS) is developing an approach that selectively deposits CVD polycrystalline diamond in “thermal” via’s located under device hot spots. This approach is fully compatible with existing GaN-on-SiC MMIC manufacturing processes. A cross section of a GaN-on-Diamond HEMT with large thermal via’s filled with polycrystalline diamond is shown in Fig. 5. This approach deposits CVD polycrystalline diamond in areas requiring improved thermal spreading rather than covering the entire SiC backside. As such wafer stress resulting from CVD polycrystalline diamond growth is reduced. Thermal via’s are formed using a high selectivity SiC dry etch that uses the AlN epilayer in the GaN buffer as an etch stop. Microwave plasma CVD polycrystalline diamond is grown in the via’s to form a conformal lining [14]. Additional backside planarization processes are used to remove any diamond growth out of the via. The completed wafer then undergoes standard front side processing. Simulations point to a 3X increase in output power density (W/mm^2) over baseline GaN-on-SiC but have yet to be experimentally validated.

Fig. 5. Diamond filled via GaN HEMT device.

III. RESULTS

BAE discrete HEMT devices fabricated using the device first process have achieved the highest microwave output power density reported to date for a GaN-on-Diamond device. Fig. 6 shows constant power (CW) load-pull measurements performed on a $12 \times 50 \mu\text{m}$ GaN-on-Diamond device at 10GHz produced 11.0W/mm at a 40V drain bias with 51% PAE [10]. This is the first reported GaN-on-Diamond device result utilizing SOA GaN epitaxy from SiC substrates.

Fig. 6. Comparison of 10GHz input-output power curves for a GaN-on-SiC and GaN-on-Diamond HEMT [10].

Fig. 7 shows infrared images taken on a $12 \times 50 \mu\text{m}$ GaN-on-Diamond and a $4 \times 50 \mu\text{m}$ GaN-on-SiC HEMT at 20W/mm. or comparison with the device. The use of a diamond substrate clearly demonstrates improved heat extraction despite 3X higher dissipated power within the same active area [10].

Fig. 7. Comparison of IR images for a $4 \times 50 \mu\text{m}$ GaN-on-SiC HEMT (left) to that of a $12 \times 50 \mu\text{m}$ GaN-on-Diamond HEMT (right) [10].

Both the direct growth and wafer bonding processes require the use of a thin dielectric layer to mechanically bond the diamond substrate to the GaN device layer. The thermal boundary resistance introduced by this interface layer must be minimized to fully exploit diamond's thermal transport properties. Modeling estimates suggest the GaN-Diamond interface resistance remain $<35 \text{ m}^2\text{K/GW}$ to achieve $>3\times$ increase in GaN HEMT areal power density (W/mm^2). Fig. 8 shows thermal boundary resistance measurements performed by the University of Bristol using a thermoreflectance technique. Numerous regions on the wafer were explored to create a map that provides insight into the homogeneity of the wafer.

Fig. 8. Thermal boundary resistance ($\text{m}^2\text{K/GW}$) measurements on an Element 6 75mm GaN-on-Diamond wafer.

CONCLUSION

Future system designs will demand higher levels of electronics integration and miniaturization driving improved thermal management solutions. Initial results of embedding polycrystalline diamond clearly show diamond's improved thermal spreading capability enabling increased areal power density (W/mm^2) while maintaining an acceptable junction temperature. While GaN-on-Diamond RF performance has yet to replicate GaN-on-SiC capabilities, this innovative embedded cooling technology shows promise but significant improvements with material quality and producibility are necessary.

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