New High Power GaN HEMT with Low Temperature Bonded Diamond Substrate Technology

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Size, weight and power (SWaP) constraints significantly exacerbate the thermal management problem in military systems - as chips move to higher power levels, the need to design smaller electronic packages with these more powerful components fitting into tighter spaces makes thermal management very challenging. Since heat adversely affects both the performance and reliability of electronics, good thermal management through reductions in components' bulk and interface thermal resistances are of the utmost importance for military applications. In most modern military electronic systems, the electronic device is typically the warmest element in the system. Although the thermal resistance of many military high-power electronic components can be as large as that of the remaining elements of the system combined, spreaders, heatsinks or coldplates do not directly access the active region where heat is generated, and cannot materially affect the device junction temperature. Since the junction temperature of a power transistor is dominated by the intra-chip heat spreading capability, to lower the device temperature one needs to place materials with high thermal conductivities immediately adjacent to the hot spot of the chip. In this paper, we describe an innovative approach of placing the very high thermal conductivity diamond within 1μm of the hot spot in a high power GaN HEMT. With this GaN-on-Diamond HEMT, one expects that the GaN device thermal resistance can be reduced, allowing the device to run cooler and therefore more reliably and efficiently. The power performance of the GaN technology is also projected to be significantly improved.

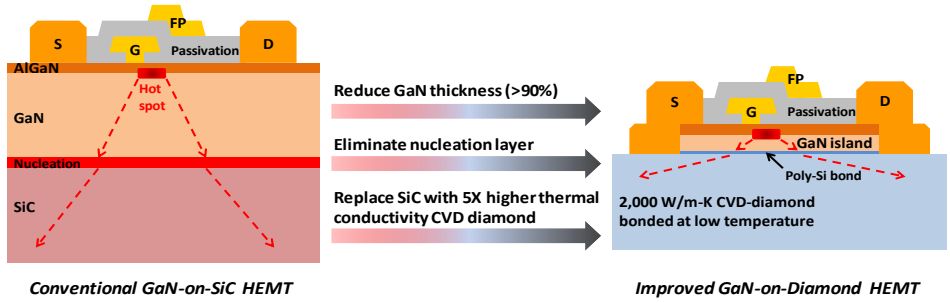

Fig. 1. Our GaN-on-Diamond device approach provides lower junction temperature and vast improvement in device power handling capability over the existing GaN-on-SiC HEMT.

Figure 1 depicts the device structure that achieves a quantum improvement in device thermal performance. GaN epi bulk thermal conductivity, interfaces and substrate material play a significant role in the device temperature rise. The new GaN-on-Diamond is projected to reduce channel temperature by ~40°C for the same operating conditions (P_{diss}). Using GaN-on-Diamond wafers, the GaN device can expect an increase in power handling capability as well as operate at higher baseplate temperatures, which would reduce system-level cooling requirements. Since GaN-on-Diamond runs cooler, a significant improvement in device reliability (10,000X longer operating lifetime) is expected, which can be traded for smaller hardware size, increased transmit power and higher efficiency. In strong contrast to the conventional GaN-on-Diamond wafer approach reported in [1], the diamond substrate in our device is attached to the GaN layer using a low-temperature bonding technology to greatly reduce the impact of GaN/diamond CTE mismatch. This also allows the GaN devices to be fully fabricated before the diamond bonding, eliminating wafer bow related processing issues - due to GaN/diamond CTE mismatch - observed in conventional GaN-on-Diamond wafers.

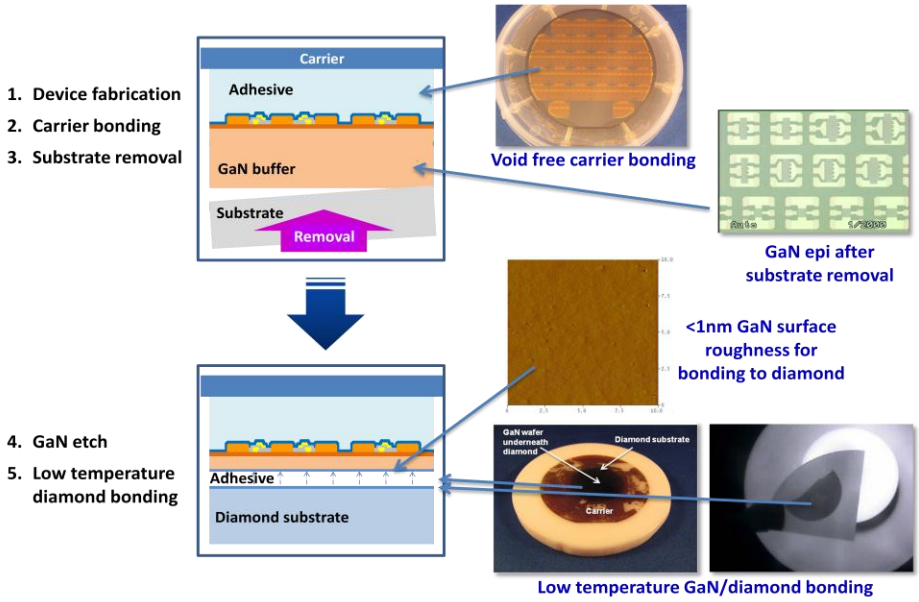

Fig. 2. "Device first" GaN-on-Diamond (completing device processing before diamond bonding) process flow and achieved results at each step.

Figure 2 shows the "device first" wafer process flow and demonstrated technology at each processing step. The diamond bonding process, performed at room temperature, is fully compatible with the GaN wafer processing. The challenge in realizing this device technology remains in the ability to achieve a mechanically strong and uniform diamond bond with very low GaN/diamond thermal interface resistance. As shown in Figure 2, the end result is a GaN-on-Diamond device with projected >3X improvement in power handling capability over GaN-on-SiC, together with uncompromised reliability that will enable higher power RF sources in smaller footprints, and major reductions in system SWaP due to associated relaxation of prime power and cooling requirements.

GaN-on-Diamond is ideally suited to wideband EW amplifiers as they are the most thermally challenging – efficiencies are only half those of narrower bandwidth amplifiers used in radar or communications due to impedance-matching constraints, and these systems typically operate CW in tough environments, with high baseplate temperatures. Several BAE Systems wideband applications would benefit greatly from the enhanced thermal properties of the GaN-on-Diamond technology. For example, in one application we envision replacing three GaAs PHEMT chips in a power amplifier (PA) with one GaN-on-diamond HEMT chip, resulting in doubling the RF power while reducing module footprint by 75%.

In this paper, the GaN-on-Diamond device design and fabrication will be described. Device electrical and thermal performance, technical challenges and factors affecting device reliability will also be discussed.

[1] J. Wasserbauer, F. Falli, D. Babic, D. Francis and F. Ejeckam, "Diamond cools high-power transistors," Compound Semiconductor, p.25, Nov. 2007.

This work is supported by DARPA NJTT program under the guidance of Drs. Avi Bar-Cohen, Joseph Maurer and Jonathan Felbinger.