Materials Characterization Comparison of GaN HEMT-on-Diamond Layers Pre- and Post-Attachment

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Abstract

Atomic attachment of GaN high-electron mobility transistor epilayers to synthetic diamond is a novel technology for thermal management and reduction of RF losses in these transistors. Material characterization of GaN epilayers prior and after the atomic attachment is presented.

INTRODUCTION

Gallium nitride (GaN) devices are presently used in microwave power amplifiers at X-band frequencies. Use of GaN-on-Diamond in these devices has the potential to improve the power and range of the amplifiers by efficiently removing the heat from the active region. Numerical analysis and experiments have shown the effectiveness of the thin diamond substrate in efficiently cooling the semiconductor active region [1, 2]. Group4 Labs has developed composite wafers in which GaN epilayers are atomically attached to synthetic diamond substrates. This technology provides high thermal conductivity substrates for high-power GaN devices and exhibits near-optimal heat spreading. In the epitaxial transfer process a full two-inch wide and two-micron thick GaN layer is lifted from its host silicon wafer and transferred to diamond. The transferred GaN layer on diamond has been shown to survive all the steps of standard processing including anneal at 850°C [3]. In this paper, we show that the electronic characteristics of the GaN-epilayers remain intact during the epitaxial transfer process.

MEASUREMENTS

The samples used in variable-temperature Hall measurements and cathodoluminescence measurements were prepared by growing AlGaN/GaN HEMT epitaxial layers originally grown on (100) Si substrates and subsequently transferred to CVD diamond wafers. The epilayers comprised of a 1.2 μm GaN/AlGaN transition layer grown on silicon, undoped 0.8 μm GaN buffer layer, and 20 nm 26% AlGaN layer. The 2DEG is located at the top of the GaN layer just below the 20-nm AlGaN layer.

The processed wafers were compared to a reference structure: the as-grown GaN epilayers on the silicon wafer. The process is briefly described in reference [3]. The surface exposed for characterization is the Ga-face of the hexagonal GaN grown on silicon – note that the epilayer flips twice in the substrate transfer process [3]. We performed variable-temperature Hall measurements to obtain electron mobility, sheet resistance, and carrier concentrations in both wafers. Maintaining the electron transport properties unchanged and 2DEG density is paramount for successful implementation these wafers in GaN transistor manufacturing.

Low-temperature (10 K) cathodoluminescence (CL) data are shown in Figure 1. An increase in both blue and yellow defect-band emissions is observed for GaN-on-Diamond structure relative to the reference, which indicates an increase in the defect densities related to these emission bands due to the GaN-on-Diamond fabrication process. These yellow and blue defect-band emissions were also observed in our photoluminescence measurements in ref. [3]. The two cathodoluminescence measurements shown in Figure 1 correspond to two different acceleration voltages (1 keV and 2 keV) and give an indication on the depth distribution of the defects: the defect emission increases with depth into the crystal.

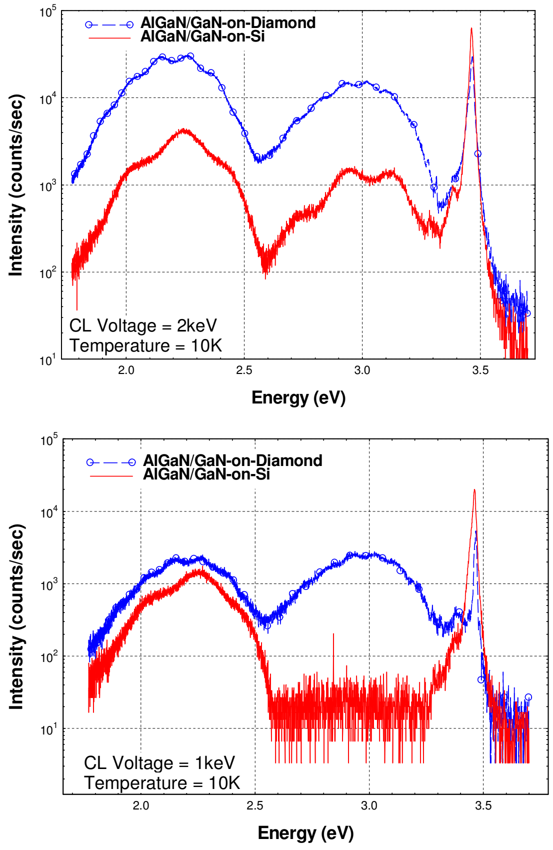

Figure 1: Low temperature cathodoluminescence (CL) data of AlGaN/GaN HEMT structures on Si (before transfer) and diamond (after transfer) at different accelerating voltages: (a, above) 1keV and (b, below) 2keV. The reduced penetration depth for the lower accelerating voltage (1keV) indicates that the additional defects introduced in the material during the transfer process to the diamond substrate are located near the surface of the HEMT epi structure, especially those defects associated with the "blue" (2.6-3.3eV) emission.

Cathodoluminescence measurement method has relatively shallow penetration depth (typically 20 nm for 1 keV in GaN). In our measurement we hence observe increased defect density within the depth of the 2D electron gas. It was necessary to verify whether any damage has occurred to the transport properties of the 2DEG. This was done using variable-temperature Hall measurements on two GaN-on-Diamond samples and the results are shown in Figure 2. The data indicates that the GaN-on-Diamond fabrication process has had minimal impact on the mobility of the electrons in the 2DEG. In fact, small signal, DC, and load-pull measurements performed on HEMTs fabricated on the GaN-on-Diamond materials are on par with the expected results and similar to the performance found for other GaN-on-Si HEMT devices.

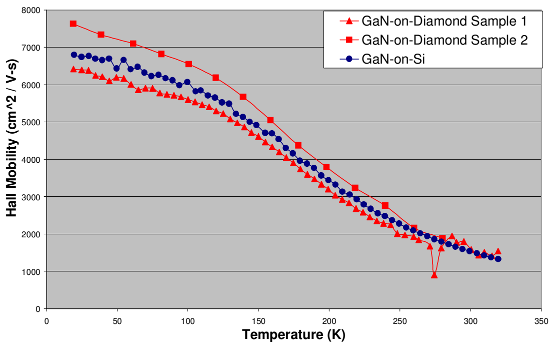

Figure 2: Variable temperature Hall mobility data for AlGaN/GaN HEMT structures on Si (before transfer) and diamond (after transfer).

Furthermore, sheet resistivity measurements using TLM method on the same HEMT device epiwafer (¼ of 3" wafer) was found to be uniform to within 2.5%. Figure 3 shows sheet resistance results obtained over a processed ¼-3" wafer and Figure 4 a photograph of a similar quarter of a three inch GaN-on-diamond wafer mounted on a quartz substrate.

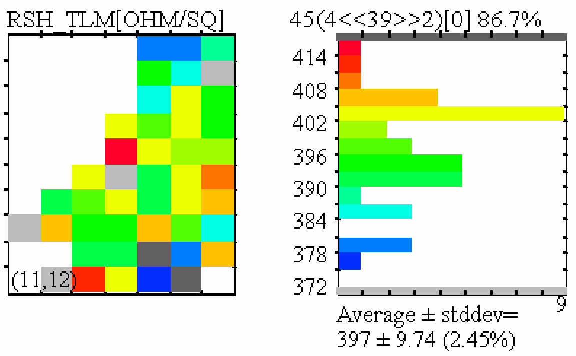

Figure 3: Sheet resistance map of a quarter of a 3" GaN-on-Diamond HEMT wafer as measured from TLM structures on wafer. The average value was 397 Ohms/sq with standard deviation of 2.5%.

CONCLUSION

We have shown that atomic attachment of GaN HEMT epilayers to CVD diamond is capable of producing uniform and undamaged 2DEG over a large area. These results show a clear path towards scaling of the process and commercialization of the GaN-on-Diamond wafers. In the presentation, we will present additional characterization and wafer scale device data for the GaN-on-Diamond and GaN-on-Si epi structures.

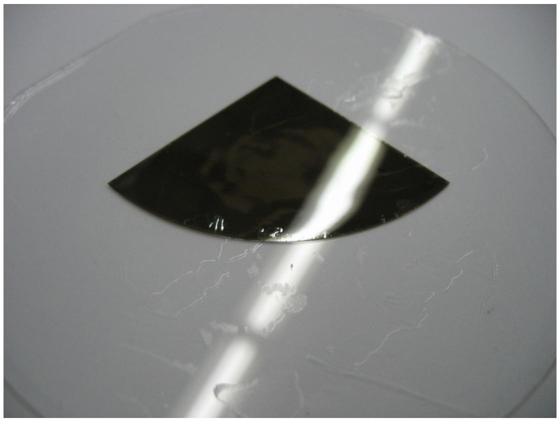

Figure 4 – One quarter of a 3” GaN-on-diamond wafer mounted on a quartz carrier; diamond on bottom. Diamond thickness is 50 µm.

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ACRONYMS

GaN: Gallium Nitride,
TLM: Transmission-Line Method
2DEG: Two-dimensional electron gas
HEMT: High-electron mobility transistor
CL: Cathodoluminescence