

GaN-HEMT Epilayers on Diamond Substrates: Recent Progress

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Abstract

Gallium-nitride high-electron-mobility transistors fabricated on diamond substrates are highly desired for use in high-power amplifiers for X-Band radar systems and commercial cellular-base stations. Diamond substrates have high thermal conductivity which enables highly efficient removal of heat from the active device regions. This paper describes our progress towards manufacturability of commercial-grade gallium-nitride-transistor epilayers on diamond substrates. We report on the fabrication of the thickest (100 μm) and largest (4") GaN-on-Diamond composite wafers to date and show selected material characterization results.

INTRODUCTION

The performance and reliability of present-day microwave power amplifiers in the X-band are limited by high operating temperatures resulting from self-heating [1-3]. Efficient thermal management is essential for lowering the heat generation and active area temperature. The use of large metal heat-sinks with active cooling provides low-thermal conductivity backgrounds, but cannot reduce the temperature drop in the immediate neighborhood of small submicron heat sources such as field-effect transistor gates. Heat conductivity around such small geometries is best accomplished by spreading heat to larger areas and volumes. Heat spreading is most efficient when a high thermal conductivity material is brought into the immediate vicinity of the heat source, which means that the distance from the heat source to the heat spreader has to be comparable to the heat-source size. For semiconductor devices this means on the order of a micrometer. This level of proximity is only possible with highly thermally conductive substrates onto which the semiconductor devices are directly attached or on top of which the device epilayers are grown.

The ideal substrate for gallium nitride (GaN) high-power transistors would be a substrate that is highly thermally conductive, electrically insulating, and has cost comparable to that of silicon. Synthetic

diamond wafers manufactured by chemical vapor deposition (CVD) are likely candidates to optimally satisfy these requirements. The greatest advantage of diamond substrates is their thermal conductivity. In insulators, heat is conducted by lattice vibrations. With sound velocity exceeding 17 km/s, diamond has heat conductivity higher than any other man-made substance: Polycrystalline diamond typically has thermal conductivity between 1200 and 1500 W/mK. This thermal conductivity is three times better than silicon carbide ($\kappa \approx 400$ W/mK). Silicon and sapphire (also common GaN-epilayer substrates) have thermal conductivities around 150 W/mK and 35 W/mK, respectively. The electrical resistivity of polycrystalline diamond ranges between 10^{13} to 10^{16} Ωcm , which is comparable to that of sapphire (10^{17} Ωcm) and significantly better than that of SiC (typically 10^6 Ωcm).

Polycrystalline synthetic diamond is most commonly manufactured using CVD technique [6] in which carbon plasma is created with methane and hydrogen ionized with microwave plasma, high-voltage arc, or hot filament. The deposition occurs at a pressure of several Torr and substrate temperatures between 800°C and 1400°C.

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. Using GaN-on-Diamond wafers, X-band electronic systems are expected to exhibit substantial increase in power handling capacity, reliability, lower system-level cooling costs, and simpler device packaging.

PROCESS DESCRIPTION

The proprietary Group4 Labs process is schematically illustrated in Figure 1. The process starts with GaN HEMT epilayers grown on a silicon substrate, but other materials, such as, sapphire, silicon carbide, or aluminum nitride may be used. The top surface of the GaN epilayers is the surface on

which the gates of the HEMT will be realized in the last step of transistor manufacturing. In the first step of the process a sacrificial carrier wafer is attached to the top surface of the gallium nitride layers. During this step the surface of the GaN layers remains protected. The original substrate on which the GaN layers were grown is now removed using either a wet chemical or dry etch process that is selective to GaN.

Figure 1 – Semiconductor-on-diamond composite wafer manufacturing process

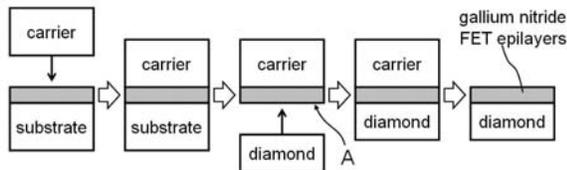


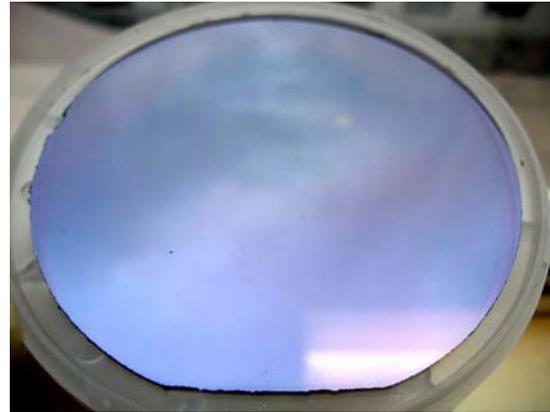
Figure 2 shows a photograph of a 4” wafer at this stage with the back of the GaN epilayers shown (arrow “A”). The exposed GaN epi backside is specially treated with a nanometer-thin dielectric coating and the structure is atomically attached to a synthetic diamond wafer. In the attachment process the first layer of diamond atoms chemically bonds to the back side of the specially treated GaN epi. The sacrificial carrier wafer is subsequently removed leaving a composite wafer in which the GaN epilayers are attached to the diamond substrate. The revealed surface is the surface upon which the GaN HEMT will be manufactured. This process maintains the growth direction and the orientation of the built-in polarization fields of the GaN HEMT necessary for the realization of the 2D electron gas in the field-effect transistor. Group4 Labs has successfully transferred fully formed GaN epitaxial layers (epi) to a prepared CVD diamond substrate and GaN HEMT transistors have been demonstrated using this technology [7]. In the following text we report on the composite wafer material characterization.

EXPERIMENTAL RESULTS

AlGaIn HEMT structure with a 2D gas was grown by OMVPE and subsequently transferred to diamond according to the process described in Figure 1. A sample of size $1.8 \times 2.8 \text{ cm}^2$ was used in the measurements. Photoluminescence mapping was used to determine the aluminum concentration in the AlGaIn layers before and after the attachment to diamond. The results show that the aluminum composition remained unchanged to the resolution of the measurement (better than 0.75% in composition). The electrical conductivity in the 2D electron gas was measured using Lehighton method and showed no change to the sheet resistivity from as-grown to

diamond-attached wafers. The value on the tested sample was $325 \Omega/\square$ and the pre-to-post value change was less than 0.3% of this value.

Figure 2 – Back of a 4” GaN HEMT Epi-layers attached to a carrier before diamond attachment.



Low-temperature (18 K) photoluminescence measurements were performed to compare the emissions from a reference sample of GaN epi on silicon and the same gallium nitride epilayer attached to diamond. The pump source was a HeCd 325 nm laser at power 1 mW. Figure 3 shows the photoluminescence spectra. The following features are visible: (a) The intensity of the on-diamond epilayers is smaller than the on-silicon epilayers, (b) the exciton peaks can be resolved for the on-silicon layers but not for the on-diamond layers, (c) the PL spectra of the on-diamond epilayers is shifted towards higher energy by approximately 37 meV, and (d) the yellow and blue luminescence (present GaN) is more pronounced in the on-diamond samples. Observations (a) and (b) may be due to the fact that GaN on silicon is still of higher crystalline quality than GaN on diamond. Also, the increase in YL and BL are commonly described by an increase in defect population. For the YL a local increase in gallium vacancies at the interface between the GaN and the diamond is likely, while the BL may be attributed to local carbon contamination. In addition to these characteristics a drop in blue luminescence (BL) was observed upon continuous laser exposure for 30 minutes and again after 60 minutes. The yellow luminescence does not show any time effects. The drop in BL intensity is more pronounced for the samples attached to diamond. This optical instability was recorded before [8] and will likely have electrical effects as trapping / charging occurs. We expect persistent photoconductivity to occur for the samples on diamond and – to a lesser degree – for the GaN on silicon sample.

GaN epilayers grown on silicon or attached to diamond are under tension at any temperature below the growth (or attachment) conditions. This is because the GaN thermal expansion coefficient perpendicular to the c-axis ($3.3 \cdot 10^{-6}/\text{K}$) is larger than that of silicon ($2.8 \cdot 10^{-6}/\text{K}$) and diamond ($0.8 \cdot 10^{-6}/\text{K}$). Part of the PL energy shift – feature (c) - can be attributed to the strain induced by the difference in the thermal expansion coefficients between epilayers and substrate. At room temperature this difference is merely 12meV. However, the relative energy shifts due to the thermal effect can only account for about one fourth of the observed PL shift. At present it is unknown what is the role the dielectric adhesion layer in these shifts. More insight may be achieved when utilizing advanced TEM analysis, for example when local strains can be measured by convergent beam electron diffraction (CBED) techniques. Also, the local population of defects may be accessible through a VEELS analysis [9].

The mechanical properties of the composite wafers are still under investigation. Free-standing wafers of several tens of micrometers are fragile and bowed due to internal stress. Composite wafers with thicker diamond substrates ($>80 \mu\text{m}$) have been fabricated and exhibit lower bowing. Figure 5 shows such a wafer.

MANUFACTURING CHALLENGES AHEAD

High-volume manufacturing of GaN-on-diamond composite wafers presents several challenges: providing low wafer bow, epi-ready surface morphology, and a process that is scalable to large wafer diameters. We describe briefly the most important issues below.

The greatest challenge in developing GaN-on-diamond composite wafers is managing the strain induced by different thermal expansion between the two attached materials. In the Group4 Labs' process, the interface between the GaN and the diamond materials has been stress-engineered so that the materials stay attached and exhibit efficient heat transfer from room temperature up to growth temperatures ($>1000^\circ\text{C}$).

Conventional approach to eliminate the bow in diamond wafers is by polishing. However, this process is costly, time consuming, and inadequate for preparing the diamond's surface for attachment to GaN. Group4 Labs uses thicker diamond wafers that are stress balanced to reduce the bow. Thicker wafers are also easier to handle. A typical carrier-mounted 2" wafer with diamond thickness of $25 \mu\text{m}$ has bow

between 100 and $500 \mu\text{m}$. Diamond wafers with thicknesses of 80 to $100 \mu\text{m}$ exhibit bow less than 100 microns. Wafer bows of less than $50 \mu\text{m}$ over a 2" wafer appear readily achievable in the near future.

Scaling up the wafer size involves managing the wafer bow and the thermal expansion mismatch. To do this efficiently, one has to account for the over-temperature behavior of three materials: GaN epilayers, diamond, and carrier-wafer material. Group4 Labs' process involves removal of the GaN epilayers from the growth substrate and then, in a separate step, attaching it to diamond. The diamond wafer is attached to the composite GaN-on-carrier wafer (Figure 6) rather than the growth wafer. During cool-down after diamond attachment, the two wafers must remain well attached. Group4 Labs' uses a flexible carrier wafer which fully absorbs the thermal expansion mismatches by a counter-bowing action. The wafer's thickness has an influence on all stress-related phenomena described above. Increasing the thickness increases the force applied at the interface between the temporary carrier (that holds the GaN epilayers) and the diamond wafer. This increased force too is compensated by elasticity of the carrier wafer. These processes have been successfully implemented on wafers up to 4" in diameter.

Maintaining epi-ready (or device-ready) GaN surface morphology on the composite wafer is critical for product acceptance. During attachment (epilayer flip and diamond attachment) and removal steps, the GaN epi layers are protected with an inert dielectric material. Prior to shipment, this dielectric material is removed. No degradation in the ohmic contacts between the as-grown GaN and so-protected GaN surface has been observed in repeated on-site experiments with Group4 Lab's wafers. Furthermore, successful demonstration of a GaN HEMT [7] attests to the quality of the surface protection.

In conclusion, GaN-on-diamond wafer technology has been demonstrated with 80 to $100 \mu\text{m}$ thick diamond substrates. These wafers are mechanically stronger and flatter than the thin ($25\mu\text{m}$ -thick) wafers demonstrated previously. The successful GaN HEMT demonstration reveals quality surface and excellent thermal characteristics that bodes well for the field of high-power GaN amplifiers.

Figure 3 – Low-temperature (18 K) photoluminescence data

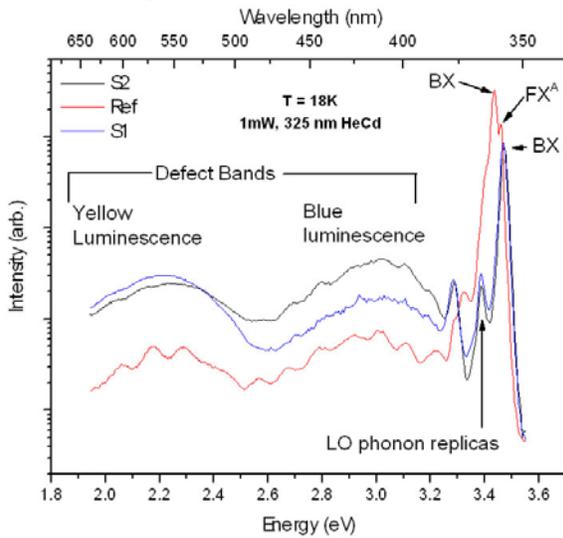


Figure 4 – Low-temperature (18 K) photoluminescence data

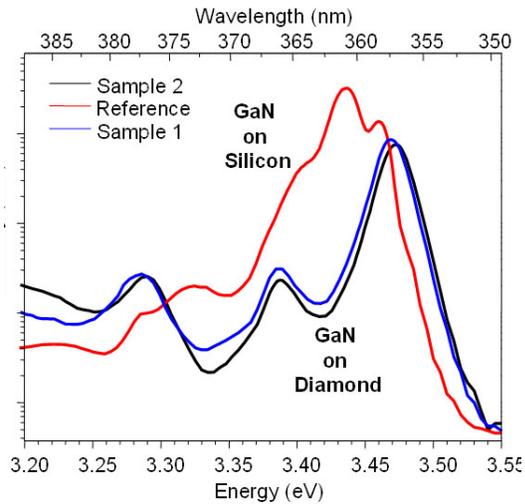
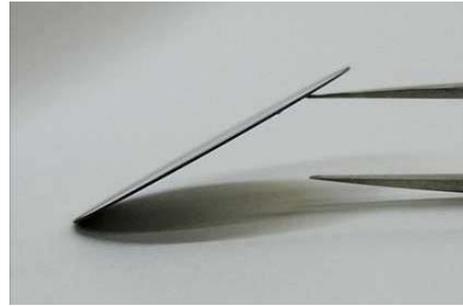


Figure 5a – Top view of a completed composite 1.25” wafer with 100- μ m thick diamond



Figure 5b – Edge view of a completed composite 1.25” wafer with 100- μ m thick diamond



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Acronyms: CVD: Chemical Vapor Deposition, GaN: Gallium nitride. HEMT: High-electron mobility transistor

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