AlGaN/GaN-on-Diamond HEMT Recent Progress

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Abstract
The performance of AlGaN/GaN high-electron-mobility transistors (HEMTs) fabricated on freestanding diamond substrates is reported. GaN-on-diamond transistors with periphery 2 × 100 µm × 0.1 µm yield a power density of 4.1 W/mm at 10 GHz. The properties of HEMTs fabricated in parallel on identical epitaxial layers atop silicon and diamond substrates is compared; the latter demonstrate f_T = 70 GHz for a 2 × 50 µm × 0.06 µm HEMT. This is the first comparison of device results for AlGaN/AlN/GaN-on-diamond alongside same-wafer AlGaN/AlN/GaN as-grown on Si.

Keywords: GaN-on-diamond, high-electron-mobility transistor (HEMT), microwave power

1. INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) are well-suited to high-frequency and high-power applications [1,2]. Electron mobility has been observed to decrease in AlGaN/GaN HEMTs as a function of temperature rise, i.e. $\mu \sim T_0/T^{1.8}$ [3]. To ameliorate the thermal limitations to high-power device performance, the device structure ought be located within close proximity to a material with high thermal conductivity. Polycrystalline diamond exhibits a thermal conductivity approximately 3.5 and 8 times that of SiC and Si, respectively.

Group4 Labs has developed composite wafers in which GaN epitaxial layers 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 2 µm-thick GaN layer is lifted from its host silicon substrate and transferred to a CVD-grown diamond substrate. Group4 Labs' GaN-on-diamond process has been extended to four-inch diameter, 100 µm-thick substrates with estimated thermal conductivity of 1200–1500 W/m-K. Fig. 1 shows three GaN-on-diamond wafers with diameters of 1.5, 2, and 4 inches, all 100 µm in thickness.

2. EXPERIMENTAL PROCEDURE

2.1 Material Preparation

AlGaN/GaN is grown epitaxially on a silicon substrate, the front side is mounted onto a sacrificial carrier, and the Si substrate is etched away. The exposed buffer is treated with a proprietary dielectric coating and atomically attached to 40–100 µm polycrystalline diamond. Finally, the AlGaN/GaN surface is liberated as the sacrificial carrier wafer is wet-etched from the front side of the material stack. As previously reported and supported by our results, the attachment process leaves the two-dimensional electron gas (2DEG) undamaged [4].

The epitaxial layers are comprised of 175 Å $Al_{0.26}Ga_{0.74}N$ pseudomorphically grown on 0.8 µm unintentionally-doped (UID) GaN atop a 1.1 µm AlGaN transition layer. A 20 Å GaN cap improves ohmic contact formation and a 50 nm interface layer located at the bottom of the AlGaN transition promotes the attachment to the diamond substrate. Note that material for one of the experiments, identified below, includes a 10 Å AlN interbarrier grown at the AlGaN/GaN interface.

The 2DEG is characterized by Lehighton and wetted-Hg probe C-V measurements. For these experiments, the material was laser cut into 15 × 15 mm pieces to facilitate processing.

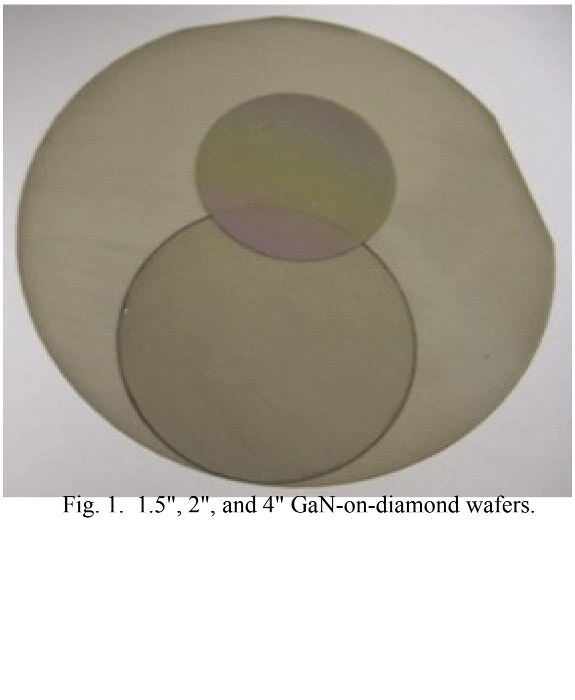

Fig. 1. 1.5", 2", and 4" GaN-on-diamond wafers.

2.2 Device Fabrication

The devices were fabricated at the Cornell NanoScale Science & Technology Facility via electron-beam lithography. To facilitate handling, the 40 µm-thick GaN-on-diamond wafer was mounted to a carrier wafer using Crystalbond 509 adhesive and dismounted before steps that exceeded 170 °C. In multiple recent fabrication runs, 75 µm- and 100 µm-thick material was processed entirely freestanding.

A standard Ta/Ti/Al/Mo/Au ohmic recipe was used [5]. Mesa isolation was achieved via an inductively-coupled plasma $Cl_2/BCl_3/Ar$ etch. The wafers were passivated with ~45nm PECVD SiN_x deposited at 375°C. The SiN_x was etched using an CF_4 RIE resulting in 70° sidewalls. The gates were Γ-shaped, following the 70° SiN_x sidewalls plus a 50% field plate extension toward the drain.

Transfer length method (TLM) measurements were performed via four-probe technique. DC and small-signal characterization were performed using an HP 4142 and an HP 8510C with Cascade on-wafer probes. Pulsed dc measurements were made using an Accent DIVA system. Large-signal measurements were completed using Maury and Focus load-pull systems at 10 GHz.

3. EXPERIMENTAL RESULTS

3.1 AlGaN/GaN-on-Diamond Performance

Before processing, C-V measurements indicated a threshold voltage of -2.1 V and a sheet density $n_s = 8.1\times10^{12}$ cm^{-2}. After fabrication, TLM measurements averaged over eight sites across the wafer revealed a GaN-on-diamond contact resistance of 0.47 ±0.07 Ω-mm and a sheet resistance of 440.5±13.7 Ω/sq.

Across the wafer, dc and small-signal device performance was consistent, indicating good process and material uniformity as shown in Table 1. Devices were tested under continuous-wave (CW) class AB operation. A 2 × 100 × 0.1 µm AlGaN/GaN-on-diamond HEMT demonstrated a peak output power of 4.1 W/mm with power-added efficiency (PAE) of 42.8% when biased at $V_{DS} = 35$ V (Fig. 2). Drain-lag pulsed I-V measurements revealed 15% dispersion in the knee region, which correlates to dc-rf dispersion and limits the output power.

3.2 Comparison Between AlGaN/AlN/GaN HEMTs on Diamond and Si Substrates

Pre-fabrication C-V measurements indicated a a sheet density $n_s = 7\text{–}9\times10^{12}$ cm^{-2} for the identical epitaxial layers on transferred diamond and as-grown Si substrates. TLM measurements indicated a contact resistance $R_c = 1.1$ Ω-mm on GaN-on-diamond and GaN-on-Si.

A 2 × 50 × 0.06 µm AlGaN/AlN/GaN-on-diamond HEMT exhibited a full-channel current $I_{Dmax} = 685$ mA/mm and a zero-gate-bias current $I_{D0} = 636$ mA/mm. This device exhibited a unity-current-gain frequency $f_T = 70.1$ GHz, while a similar HEMT on Si substrate exhibited only $f_T = 55.3$ GHz.

Table 1. Characteristics of an AlGaN/GaN HEMT averaged over more than 20 2 × 100 µm devices.

	L_G = 0.10 µm	L_G = 0.15 µm
V_t (V)	-2.1±0.1	-2.0±0.1
I_{Dmax} (mA/mm)	797±32	786±16
I_{D0} (mA/mm)	604±32	591±9
g_m (mS/mm)	355±11	346±7
f_T (GHz)	57.1±2.2	48.0±0.6

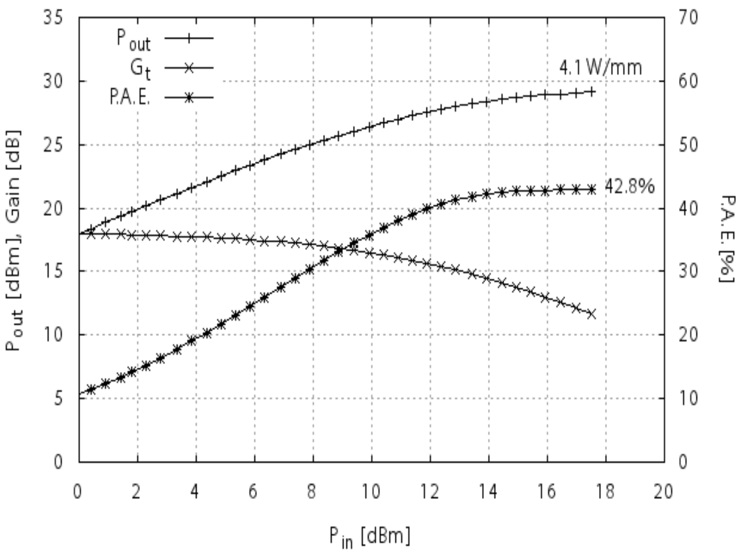

Fig. 2. Output power measured at 10 GHz CW, $V_{DS} = 35$ V class AB for a 2 × 100 × 0.1 µm AlGaN/GaN-on-diamond HEMT.

Averaged over more than twenty devices on each substrate, the threshold voltage was $V_t = -3.2 \pm 0.1$ V on both substrates.

Equal-gate-length devices with gate footprint lengths of 60, 80, and 100 nm atop AlGaN/AlN/GaN epitaxial layers were compared between diamond and as-grown Si substrates. This initial comparison indicated that the devices on diamond exhibited ~9% higher current density (Fig. 3) and 29% higher unity-current-gain frequency than identical structures on Si substrate.

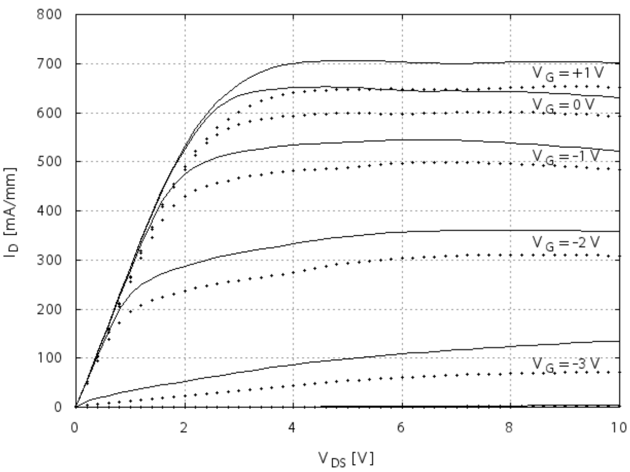

Fig. 3. I-V characteristics for a 2 × 50 × 0.06 µm GaN-on-diamond (solid) and GaN-on-Si (dotted) HEMT.

4. CONCLUSIONS

Good process and material uniformity has been demonstrated for AlGaN/GaN-on-diamond HEMTs. Output power is presently limited by dc-rf dispersion, which prompts a passivation optimization study.

The results of our first comparison between identical AlGaN/AlN/GaN epitaxial layers on diamond and Si substrates indicate improved HEMT performance on the material transferred to diamond. Buffer leakage native to the AlGaN/AlN/GaN-on-Si material precluded high-bias measurements, such as large-signal characterization.

Forthcoming work involves optimizing device dimensions for K_a-band performance. Recently, a 2 × 50 µm × 0.04 µm GaN-on-diamond HEMT exhibited $f_T = 85$ GHz and $f_{max} = 95$ GHz, the latter of which was limited by relatively high source resistance [6]. Further mm-wave performance enhancement demands a thinned epitaxial layer design with higher aluminum composition; meanwhile, a gate recess recess process and ALD surface passivation recipe are being developed. High-frequency, short-gate and high-power, multi-finger devices are presently being fabricated atop identical epitaxial layers on diamond and Si substrates.

5. ACKNOWLEDGMENT

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6. REFERENCES

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