AlGaN/GaN-on-Diamond HEMT Recent Progress

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Abstract:

The performance of aluminium gallium nitride (AlGaN)/GaN high-electron-mobility transistors (HEMTs) fabricated on freestanding diamond substrates is reported. GaN-on-diamond transistors with periphery $2 \times 100 \, \mu \text{m} \times 0.1 \, \mu \text{m}$ 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 $f_T = 70 \, \text{GHz}$ for a $2 \times 50 \, \mu \text{m} \times 0.06 \, \mu \text{m}$ HEMT. This is the first comparison of device results for AlGaN/AlN/GaN-on-diamond alongside same-wafer AlGaN/AlN/GaN as-grown on silicon (Si).

Summary of Research:

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 should be located within close proximity to a material with high thermal conductivity such as polycrystalline diamond, which 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. In the epitaxial transfer process, a 4”-diameter, 2 µm-thick GaN layer is lifted from its host silicon substrate and transferred to a CVD-grown diamond substrate.

175 Å Al$_{0.26}$Ga$_{0.74}$N/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 50 nm proprietary dielectric coating and 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 2DEG undamaged [4].

A standard Ta/Ti/Al/Mo/Au ohmic recipe was used. Mesa isolation was achieved via an inductively-coupled plasma Cl$_2$/BCl$_3$/Ar etch. The wafers were passivated with ~ 45 nm 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.

Before processing, C-V measurements indicated a threshold voltage of -2.1 V and a sheet density $n_s = 8.1 \times 10^{12} \, \text{cm}^{-2}$. After fabrication, four-point-probe transfer-length-method (TLM) measurements averaged over eight sites across the wafer revealed a GaN-on-diamond contact resistance of $0.47 \pm 0.07 \, \Omega$-mm and a sheet resistance of $440.5 \pm 13.7 \, \Omega$/sq.

<table>
<thead>
<tr>
<th>$L_{G1} = 0.10 , \mu \text{m}$</th>
<th>$L_{G2} = 0.15 , \mu \text{m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_\text{T}$ (V)</td>
<td>-2.1 ± 0.1</td>
</tr>
<tr>
<td>$I_{D_{\text{max}}}$ (mA/mm)</td>
<td>797 ± 32</td>
</tr>
<tr>
<td>$I_{D_{0}}$ (mA/mm)</td>
<td>604 ± 32</td>
</tr>
<tr>
<td>$g_m$ (mS/mm)</td>
<td>355 ± 11</td>
</tr>
<tr>
<td>$f_T$ (GHz)</td>
<td>57.1 ± 2.2</td>
</tr>
</tbody>
</table>

Table 1: Characteristics of an AlGaN/GaN-on-diamond HEMT averaged of more than twenty $2 \times 100 \, \mu \text{m}$ devices.
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 $2 \times 100 \times 0.1 \, \mu m$ 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 $V_{DS} = 35 \, V$ (Figure 1). Drain-lag pulsed I-V measurements revealed 15% dispersion in the knee region, which correlates to dc-rf dispersion and limits the output power.

Pre-fabrication C-V measurements indicated a sheet density $n_s = 7-9 \times 10^{12} \, \text{cm}^{-2}$ for the identical epitaxial layers on transferred diamond and as-grown Si substrates. TLM measurements indicated a contact resistance $R_c = 1.1 \, \Omega \cdot \text{mm}$ on GaN-on-diamond and GaN-on-Si.

A $2 \times 50 \times 0.06 \, \mu m$ AlGaN/AlN/GaN-on-diamond HEMT exhibited a full-channel current $I_{Dmax} = 685 \, \text{mA/mm}$ and a zero-gate-bias current $I_{DG0} = 636 \, \text{mA/mm}$. This device exhibited a unity-current-gain frequency $f_T = 70.1 \, \text{GHz}$, while a similar HEMT on Si substrate exhibited only $f_T = 55.3 \, \text{GHz}$. Averaged over more than twenty devices on each substrate, the threshold voltage was $V_t = -3.2 \pm 0.1 \, V$ on both substrates.

Figure 1: Output power measured at 10 GHz CW, $V_{DS} = 35 \, V$ class AB for a $2 \times 100 \times 0.1 \, \mu m$ AlGaN/GaN-on-diamond HEMT.

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; the devices on diamond exhibited ~9% higher current density (Figure 2) than identical structures on Si substrate. Good process and material uniformity has been demonstrated for AlGaN/GaN-on-diamond HEMTs. 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.

Recently, a $2 \times 50 \, \mu m \times 0.04 \, \mu m$ GaN-on-diamond HEMT exhibited $f_T = 85 \, \text{GHz}$ and $f_{max} = 95 \, \text{GHz}$, the latter of which was limited by relatively high source resistance [5]. Forthcoming work involves further mitigating dc-rf dispersion and optimizing device dimensions for K$_a$-band performance.

References:


