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Comparison of GaN HEMTs on Diamond and SiC Substrates

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***Abstract*–The performance of AlGaN/GaN high-electron-mobility transistors on diamond and SiC substrates is examined. We demonstrate GaN-on-diamond transistors with periphery $W_G = 250$ µm exhibiting $f_t = 27.4$ GHz and yielding a power density of 2.79 W/mm at 10 GHz. Additionally, the temperature rise in similar devices on diamond and SiC substrates is reported. To the best of our knowledge, these represent the highest frequency of operation and first-reported thermal and X-band power measurements of GaN-on-diamond HEMTs.**

***Index Terms*–GaN-on-diamond, high-electron-mobility transistor (HEMT), microwave power, thermal effects in AlGaN, X-band**

INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) are well-suited to high-frequency and high-power applications [1,2]. SiC is presently the substrate of choice for the epitaxial growth of high-performance GaN HEMT structures with a thermal conductivity an order of magnitude greater than that of sapphire. However, regardless of substrate, thermal limitations on device performance emerge under conditions of high bias and power drive [3]. Electron mobility has been observed to decrease in AlGaN/GaN HEMTs as a function of temperature rise, $\mu \sim T^{-1.8}$ [4]. This decrease induces an increase in knee voltage, which limits the dynamic range of large-signal operation.

Further advancement of GaN HEMTs for high-power applications requires reducing the temperature rise of the devices. The solution investigated in this paper involves locating the device structure within close proximity to a material with high thermal conductivity. The thermal conductivity of chemical vapor deposition (CVD) polycrystalline diamond is 3–4 times that of SiC [5]. Group4 Labs has developed a method to atomically attach GaN epitaxial layers to polycrystalline diamond [5]. Organometallic vapor phase epitaxy (OMVPE) AlGaN/GaN is grown epitaxially on a silicon substrate, the material then flipped and mounted to a carrier, and the substrate etched away. The exposed GaN surface is treated with a proprietary dielectric coating and the epitaxial layer is atomically attached to CVD polycrystalline diamond. Finally, the carrier wafer is etched from the front side of the epitaxial layer, resulting in the material structure similar to that shown in the SEM cross-section (Fig. 1.) As previously

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reported [6] and supported by our results, the attachment process leaves the two-dimensional electron gas (2DEG) confinement layer intact.

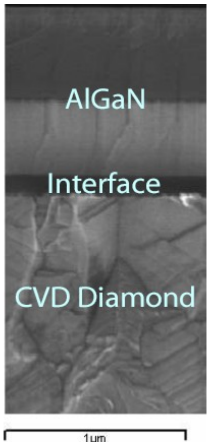

Figure 1 SEM cross-section of freestanding GaN-on-diamond

Comparative experimental study of HEMT channel temperature rise requires a localized technique. Over the past two decades, scanning thermal microscopy (SThM) has emerged as a means for the high-resolution measurement of temperature [7]; however, it has only recently been applied to AlGaN/GaN HEMTs [8]. One AFM-based SThM implementation involves the replacement of the AFM tip by a microscopic resistive filament, which acts as one leg of a Wheatstone bridge. A platinum-based filament offers linear response in resistance to changes in temperature. A small amount of current is passed through the probe below its self-heating threshold. After calibrating against known temperatures, the output voltage of the Wheatstone bridge may be extrapolated to the absolute temperature of the filament. Channel temperature measurements were completed as a function of dissipated power density, in W/mm, on diamond and SiC substrates.

The GaN-on-diamond material was prepared by Group4 Labs for processing. The epitaxial layer was comprised of 175 Å $Al_{.26}Ga_{.74}N$ pseudomorphically grown on 1.0 µm unintentionally-doped (UID) GaN atop 0.9 µm AlGaN. A 20 nm interface layer promotes atomic attachment to ~25 µm diamond. The structure has a thin GaN cap, which sublimes away during the ohmic contact anneal. The surface was cleaned by Group4 Labs via wet and dry etching. On the SiC substrate, the epitaxial layer included ~200 Å $Al_xGa_{1-x}N$, $x \approx 26\%$, atop ~1.5 µm UID GaN.

Fabrication and Measurement

The devices were fabricated at the Cornell NanoScale Science & Technology Facility. The HEMTs on SiC substrate were processed using a mix of optical and electron beam lithography, while the devices on diamond substrate were fabricated exclusively via electron beam lithography. The bowing of the latter material, on the order of 50 µm over 1 cm^2, precluded use of available optical lithography techniques. To ease handling, the GaN-on-diamond wafer was mounted to a 15 mm × 15 mm carrier using Crystalbond 509 adhesive and dismounted before each processing step that exceeded 170 °C temperature.

A standard Ti/Al/Mo/Au ohmic recipe was used, including a post-deposition anneal. For the devices on the SiC substrate, an initial Ta layer was added to improve contact to the AlGaN/AlN/GaN structure of other wafers in the same process lot [9].

For both material structures, mesa isolation was achieved after ohmic contact anneal via an inductively coupled plasma (ICP) $Cl_2/BCl_3/Ar$ etch. The Ni/Au gate structure of the HEMTs on diamond was rectangular, while the gates on the SiC substrate included field plate extensions [10]. Finally, both wafers were passivated with ~85 nm SiN_x deposited by plasma enhanced chemical vapor deposition (PECVD) at 375 °C.

Transfer length method (TLM) measurements were performed via four-probe technique using Keithley source measurement units (SMUs.) DC characterization was performed using an HP 4142 and small-signal measurements were completed with an HP 8510 using Cascade on-wafer probes. Large-signal measurements were made using a Focus load-pull system powered by a traveling wave tube at 10 GHz.

Thermal measurements were performed on the HEMTs using a ThermoMicroscopes AFM-based SThM system. Since the thermal probe is conducting, measurements were performed in contact with the insulating SiN_x passivation layer. The 5 µm-diameter platinum (or Pt/10%Rh alloy) filament was connected to the Wollaston wire cantilever arms. The probe tip was positioned in contact with the SiN_x atop the channel between the gate and drain. The filament was not necessarily contacting the passivation layer; however, our measurements showed a negligible* difference in temperature reading at an elevation of 25 µm from the surface.

EXPERIMENTAL RESULTS

TLM measurements revealed a GaN-on-diamond contact resistance of 1.2* Ω-mm and a sheet resistance of 419* Ω/sq. The ohmic contact recipe was not optimized for this particular material. The processed GaN-on-SiC exhibited a contact resistance of 0.5* Ω-mm and a sheet resistance of 159* Ω/sq.

A full-channel current of 670 mA/mm was recorded at $V_{GS} = +1$ V and a peak g_m of 187 mS/mm was observed at $V_{GS} = -2.0$ V and $V_{DS} = 10$ V on a 2 × 125 × 0.25 µm device on GaN-on-diamond (Figs. 2 & 3.) The pinch-off voltage was -3.1 V. The unity-current-gain frequency f_t was found to be 27.4 GHz (Fig. 4.) Source–drain spacing was 5.3 µm.

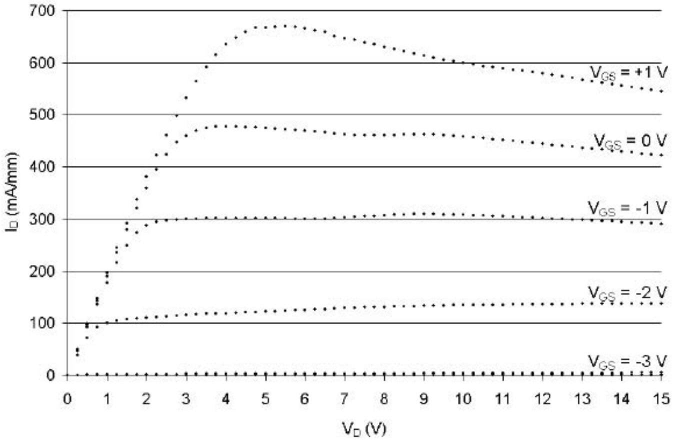

Figure 2 GaN-on-diamond I-V characteristics

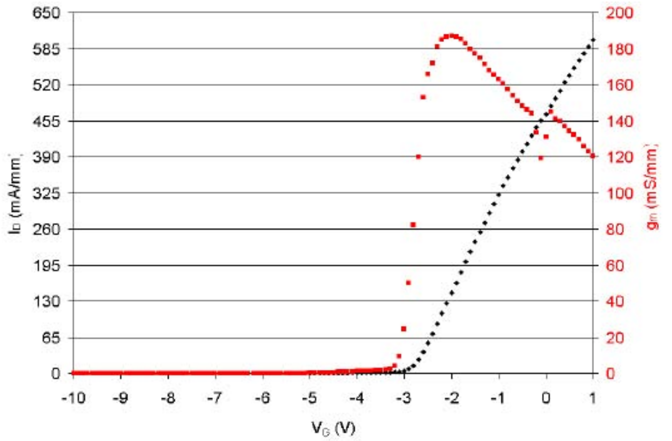

Figure 3 GaN-on-diamond I-V characteristics

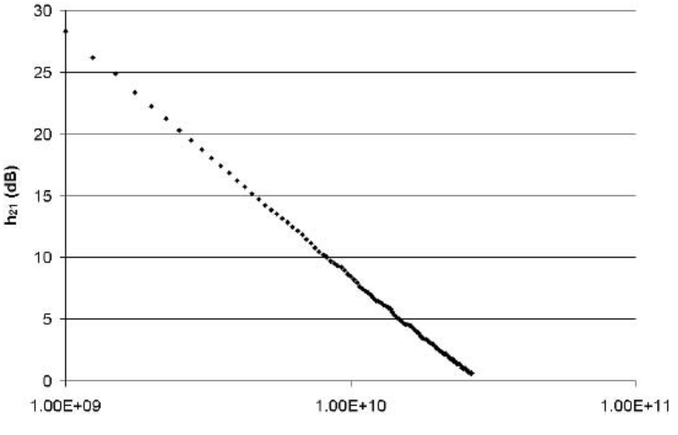

Figure 4 GaN-on-diamond small-signal characteristics

Two-finger HEMTs of total periphery 200 µm with 0.25 µm gates featuring field plate extensions and source–drain spacing of 5.5 µm were fabricated on GaN-on-SiC. Peak current of 920 mA/mm was observed at V_{GS} = +1 V and pinch-off was measured at -4.0 V. The unity-gain frequency f_t was measured to be 44 GHz.

The devices were then tested under continuous wave (CW) class B operation. The GaN-on-diamond HEMT showed a peak output power of 2.79 W/mm and peak power-added efficiency (PAE) of 47% when biased at V_{DS} = 25 V (Fig. 5.) The similar GaN-on-SiC device demonstrated a peak output power of 3.29 W/mm with PAE of 31% when biased at V_{DS} = 20 V (Fig. 6.) Gate leakage in the latter device precluded the application of higher drain bias.

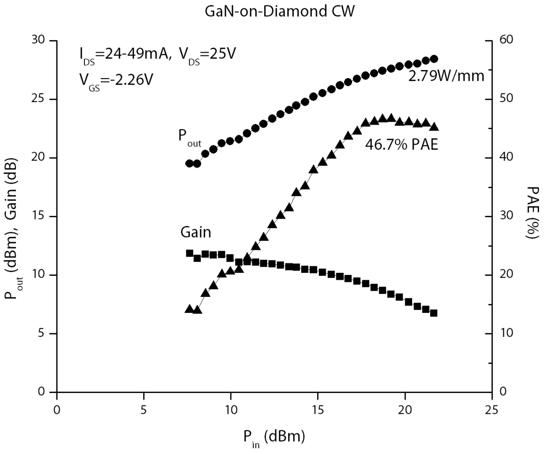

Figure 5 Output power measured at 10 GHz CW, V_{DS} = 25 V, V_{GS} = -2.26 V for a 2 × 125 × 0.25 μm AlGaN/GaN-on-diamond HEMT

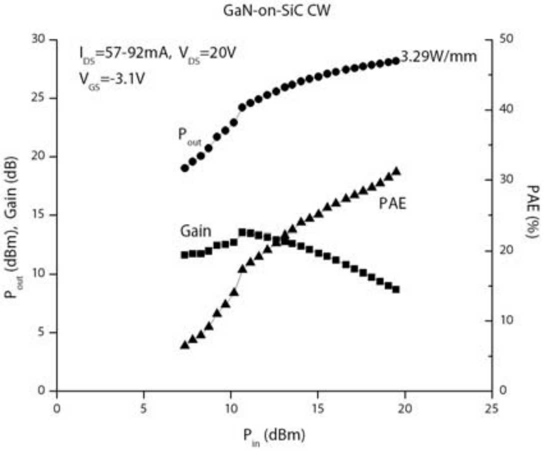

Figure 6 Output power measured at 10 GHz CW, V_{DS} = 20 V, V_{GS} = -3.10 V for a 2 × 100 × 0.25 μm AlGaN/GaN-on-SiC HEMT

Thermal measurements were performed with a DC drain-source bias applied across one channel of the device, in both cases, while the gate was left to float. Between each measurement, the applied voltage was zeroed. Results of steady-state temperature versus DC power are plotted in Fig. 7. The temperature rise of the devices on SiC was observed to be ~12 °C/(W/mm), whereas the temperature rise of the devices on diamond was observed to be ~6 °C/(W/mm).

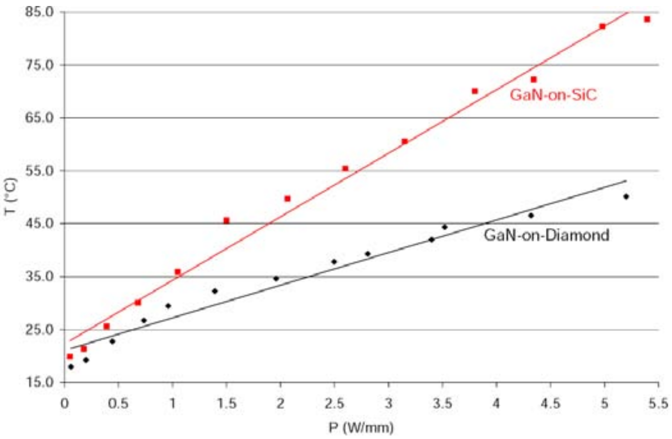

Figure 7 Channel temperature of single-finger GaN-on-diamond and GaN-on-SiC HEMTs

CONCLUSIONS

With respect to thermal dissipation, the device on SiC had a number of dimensional variables in its favor. First, its GaN buffer was thinner; since SiC has a superior thermal conductivity to GaN, the thermal rise in the device was closer to the substrate. For comparison, Group4 simulations localize 50% of the thermal dissipation to within the GaN buffer layer of the processed GaN-on-diamond structure. Additionally, the channel width on SiC was less, allowing heat to escape a bit more readily at the ends of the device. Furthermore, the ~370 µm SiC, whose thermal conductivity is on par with that of copper, offered a much larger volume for the heat to spread compared to the ~25 µm diamond substrate, which was resting on thin bonding wax. Despite these dimensional advantages, the devices on GaN-on-SiC exhibited a temperature rise twice that of GaN-on-diamond. The thermal dissipation in the GaN and interface layers further reduce the full ~3:1 benefit in thermal conductivity of diamond over SiC. Nevertheless, GaN-on-diamond offers promise for higher power outputs and higher-density layouts compared to devices on thermally-limited SiC substrates. These GaN-on-diamond devices may be appropriately mounted to a larger heat-sink to further mitigate the detrimental effects of device heating.

To our knowledge, these represent the highest frequency of operation and first-reported thermal and X-band power measurements of GaN-on-diamond HEMTs. The relatively low current densities observed in the GaN-on-diamond devices limited the output power compared to the devices on GaN-on-SiC. Future directions include optimizing the AlGaN barrier layer for an electron sheet density of

10^{13} cm^{-2} and thinning the GaN buffer layer for enhanced thermal spreading. Additionally, future work will include wire bonding to measure the channel temperature of GaN HEMTs under two finger operation with the gates grounded. High-frequency, short-gate and high-power, multi-finger devices are presently being fabricated on diamond, SiC, and GaN substrates. Additionally, multi-finger devices are being fabricated to achieve higher power output and lower channel-to-channel pitch, minimizing phase dispersion, than is feasible on SiC.

ACKNOWLEDGMENT

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