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AlGaN/GaN HEMTs on Diamond Substrate

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We present AlGaN/GaN high electron mobility transistors (HEMTs) fabricated on diamond substrate. Epitaxial AlGaN/GaN layers were first grown on high resistivity Si (111) substrate and transferred to polycrystalline diamond substrate, which was separately grown by chemical vapor deposition (CVD). As per our knowledge, these are the best-reported results for a transistor using GaN on diamond material.

AlGaN/GaN heterostructure is extremely promising for ultra-high power transistors [1] due to high charge density and breakdown voltage. Further, high saturation velocity and mobility of channel electrons make it attractive for high frequency applications [2]. While extremely high power transistors are being reported using GaN, the prime concern is to manage huge amount of heat generated by such devices. Single crystal SiC substrate which allows direct epitaxial growth and offers a high thermal conductivity is predominantly used for GaN HEMTs. High cost and unavailability of larger than 3-inch SiC substrates have led to cheaper substrate like Si where promising results have been reported [3] but thermal management is even more challenging due to poor thermal conductivity of Si. Diamond, being nature's most thermally conductive material, is the best substrate option for heat transfer. Thus, attempts to integrate GaN layers with diamond are expected. Further, artificially grown polycrystalline diamond may give a significant cost advantage over single crystal SiC substrate. GaN can not be grown directly on diamond. Therefore, growth of GaN films on cost-effective substrate like Si and then transferring the epi-films to diamond substrate seems a highly favorable approach.

GaN on diamond material for this work was supplied by Group4 Labs, California, USA. Group4 Labs has developed a pioneering technique to atomically attach epitaxial AlGaN/GaN layers on CVD diamond substrates. AlGaN/GaN films used here were originally grown on Si (111) substrate by metal-organic chemical vapor deposition at Nitronex, North Carolina, USA. Epi-structure on Si substrate consisted of a 1.3 μm semi-insulating (SI) GaN buffer, 10 Å AlN sub-barrier, 185 Å $Al_{0.27}Ga_{0.73}N$ Schottky layer and 15 Å GaN cap layer. To protect surface during epi-transfer to diamond substrate, 2300 Å SiN_x was deposited at 750 °C on GaN on Si wafers. Wafers were then mounted upside-down on a carrier and Si substrate was completely removed using wet etching. Revealed GaN buffer layer after Si-removal was then atomically attached to a 25-μm thick poly-crystalline CVD diamond substrate. This process required annealing at 810 °C. The carrier wafer from the frontside was subsequently removed. Fig. 1 shows the cross section of the starting material for device fabrication. Samples sizes were small ($< 2 \times 2$ cm^2).

First, 2300 Å SiN_x was completely removed using reactive ion etching (RIE). Manual lithography was used for patterning. Mesas were fabricated using BCl3-based dry-etch. TiAlNiAu stack was evaporated and rapid thermal anneal was done to realize Ohmic contacts. Source-drain spacing was 4.5 μm. Using transfer length measurements (TLM), contact resistance (R_c) of 0.48 Ω-mm and sheet resistance (R_{sheet}) of 478 Ω/Sq. were derived (Fig. 2). About 1.2 μm length gates were defined using photolithography and evaporated Pt/Au metal. DC and RF performances were measured. Drain current characteristics (Fig. 3) and transfer characteristics (Fig. 4) of 50 μm gate-width HEMTs, show excellent pinch-off performance, high current (800 mA/mm) and peak transconductance (180 mS/mm). Using Agilent network analyzer 8510C, s-parameters of 75 μm (2×37.5 μm) HEMTs were measured. Cut-off frequency (f_t) of 12.3 GHz and maximum oscillation frequency (f_{max}) of 21.8 GHz were extracted (Fig. 5) from s-parameters at drain voltage of 10 V. Also, f_t and f_{max} were measured at different drain voltages (Fig. 6) up to 20 V. Results presented here are significantly better than only published results [4] of AlGaN/GaN transistors on diamond substrate.

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[3] D.C. Dumka et al., *Electronics Lett.*, vol. 40, p. 1023 (2004)
[4] G.H. Jessen et al., *Compound Semiconductor IC Symposium*, San Antonio, TX, USA, Late News (2006)

2300 Å SiN_x
15 Å GaN Cap
185 Å $Al_{0.27}Ga_{0.73}N$ Schottky
10 Å AlN Sub-barrier
1.3 µm SI-GaN Buffer
25 µm CVD Diamond

Fig. 1. *Cross-section of the starting material for fabrication of GaN HEMTs on diamond substrate.*

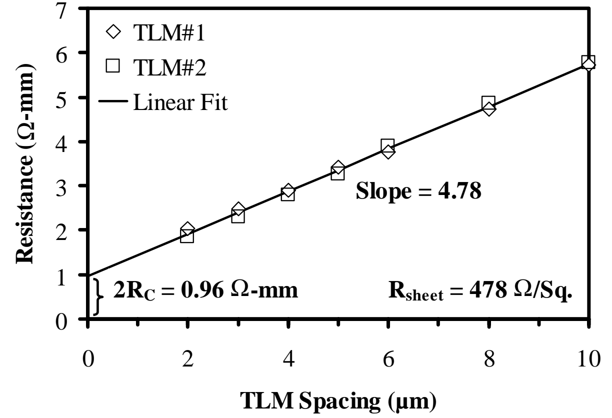

Fig. 2. *Measured resistance of two TLM structures on AlGaN/GaN HEMT layers on diamond. Derived R_C and R_{sheet} are shown in the figure.*

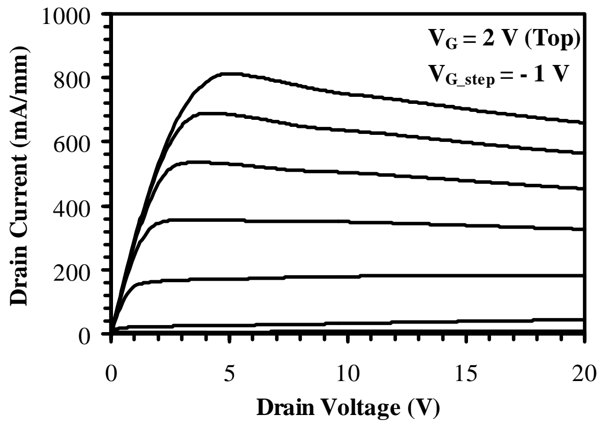

Fig. 3. *Drain current characteristics of a 50 µm gate-width AlGaN/GaN HEMTs on diamond substrate.*

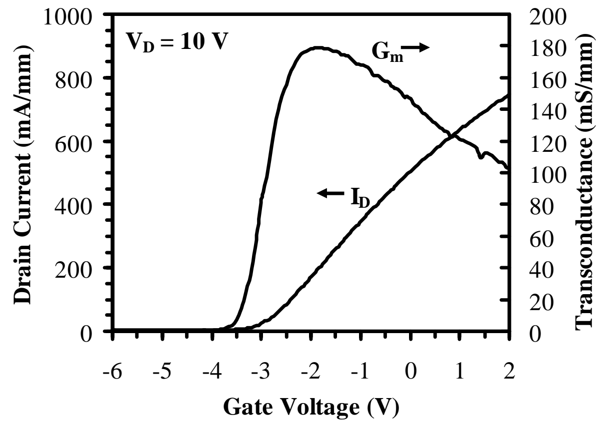

Fig. 4. *Transfer characteristics of a 50 µm gate-width AlGaN/GaN HEMTs on diamond substrate measured at drain voltage of 10 V.*

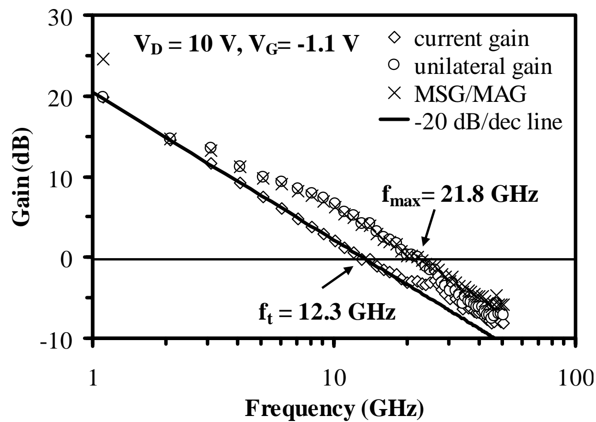

Fig. 5. *Small signal gain characteristics of a 75 µm (2×37.5 µm) gate-width AlGaN/GaN HEMT on diamond substrate.*

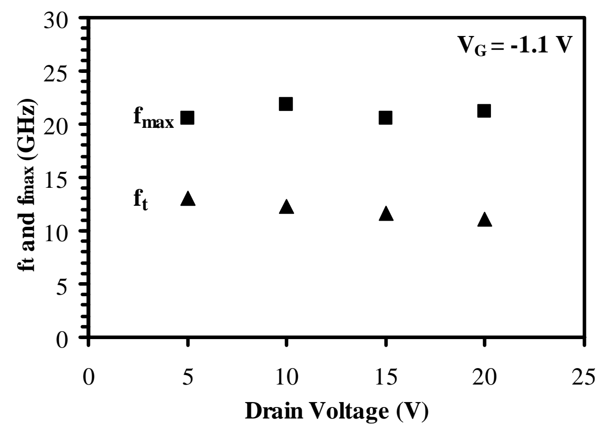

Fig. 6. *f_t and f_{max} vs. drain voltage of a 75 µm (2×37.5 µm) gate-width AlGaN/GaN HEMT on diamond substrate.*