First demonstration of N-polar GaN/AlGaN/AlN HEMT on Single Crystal AlN Substrates

Eungkyun Kim[1], Zexuan Zhang[1], Jashan Singhal[1], Kazuki Nomoto[1], Austin Hickman[1], Masato Toita[2], Debdeep Jena[1], and Huili Grace Xing[1]

[1]*Cornell University, Ithaca, NY 14853, USA*

[2]*Asahi Kasei Corporation, Chiyoda, Tokyo, Japan*

Email: ek543@cornell.edu / Phone: (407) 409-4188

Gallium nitride's wide bandgap and high electron velocity make it highly attractive for both commercial and defense mm-wave applications. Gallium nitride high-electron-mobility-transistors (GaN HEMTs) today can supply high power at millimeter-wave frequencies, thereby counteracting high atmospheric attenuation at these frequencies [1]. However, power amplifiers based on GaN HEMTs continue to be limited by heat dissipation issues, highlighting the importance of the thermal management in HEMTs.

In this work, we introduce N-polar HEMTs on single crystal aluminum nitride (AlN) substrates with a GaN/AlGaN/AlN heterostructure. AlN buffer layer offers two primary advantages. It provides a high thermal conductivity of ~340 W/mK, which is approximately 50% higher than that of GaN [2]. Secondly, it is expected to reduce buffer leakage and increase the breakdown voltage owing to its large bandgap of ~6 eV [3]. In addition to the advantages provided by AlN, N-polar heterostructures provide several benefits over the metal-polar technology. An inherent wide-bandgap AlGaN or AlN back-barrier provides stronger electron confinement, and low-resistivity ohmic contact can be formed directly to the GaN channel layer [4].

Fig. 1(a) illustrates the device cross section and the energy band diagram showing the two-dimensional electron gas (2DEG) above the GaN/$Al_{0.85}Ga_{0.15}N$ interface. The epitaxial structure grown by plasma-assisted molecular beam epitaxy consists of an 8 nm-thick GaN channel, a 50-nm thick $Al_{0.85}Ga_{0.15}N$ back barrier, and a 1-μm thick AlN buffer layer on bulk AlN substrate. The atomic force microscopy image on the as-grown surface shown in Fig. 1(b) demonstrates a smooth surface with sub-nm root-mean-square roughness, and Hall-effect measurements at 300 K on the as-grown heterostructure demonstrated electron mobility of 491 $cm^2/V{\cdot}s$ and the 2DEG density of 4.09×10^{13} cm^{-2}, corresponding to a sheet resistance of 311 Ω/sq. When cooling down to 77 K, almost no change in the electron density was observed, consistent with the polarization-induced nature of the 2DEG. The fabrication flow began with deposition of a thin Al_2O_3 layer via atomic layer deposition to protect the reactive N-polar GaN surface during processing. The ohmic contacts were then defined by photolithography and Ti/Al/Ni/Au metal stack was deposited via electron beam evaporation and annealed at 780 °C for 30 seconds in N_2 environment. The HEMTs were then isolated via chlorine-based ICP dry etch and a 10-nm silicon nitride gate dielectric layer was deposited via high density plasma chemical vapor deposition. Finally, the gate contacts (Ni/Au) were defined by photolithography.

Following the device fabrication, contact resistance of R_c = 0.256 Ω·mm was measured using transfer-length method (TLM) patterns as shown in Fig. 2. As expected, fabricated devices exhibited very low leakage current through the AlN buffer layer as shown in Fig. 3. Fig. 4 shows DC characteristics of the fabricated HEMT with a gate length of L_G = 1.5 μm, a gate to source distance and a gate to drain distance of $L_{GS} = L_{GD}$ = 2.25 μm. Transfer I-V characteristics shown in Fig. 4(a, b) reveal a peak transconductance of ~100 mS/mm and an on/off ratio of ~12. This on/off ratio is relatively moderate compared to that of many other reported N-polar HEMTs as well as metal-polar HEMTs [1], [3], and it is limited by high gate leakage current resulting from a non-optimized gate dielectric layer. Efforts to reduce gate leakage are currently underway, including a development of a gate-recessed structure to lower the channel charge density and an optimization of dielectric layers. Despite the high gate leakage current, the fabricated HEMTs also show promising characteristics, such as drain current exceeding 0.94 A/mm as shown in Fig 4(c), a low contact resistance without the regrowth process, and low buffer leakage. The contact resistance is anticipated to decrease further after incorporating a thin in-situ Si-doped GaN layer atop the unintentionally doped GaN channel layer. A detailed study of ohmic contacts is underway. To the best of the authors' knowledge, this is the first demonstration of N-polar GaN/AlGaN/AlN HEMTs on N-polar bulk AlN substrate. These results will play a pivotal role in creating high performance RF HEMTs with minimal thermal issues.

The authors would like to thank Asahi Kasei Corporation for their support. This work was performed in part at the Cornell NanoScale Facility, an NNCI member supported by NSF Grant NNCI-2025233.

[1] B. Romanczyk *et al*., *IEEE Trans. Elec. Dev.*, vol.65, no. 1, p. 45 (2020). [2] R. Rounds *et al*., *Appl. Phys. Express.*, 11 071001 (2018). [3] A. Hickman *et al.*, *IEEE-EDL,* vol. 40, no. 8, p. 1293 (2019). [4] M. H. Wong *et al*., *Semicond. Sci. Technol.*, 28 074009 (2013).

2022 Device Research Conference (DRC) | 978-1-6654-9883-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/DRC55272.2022.9855776

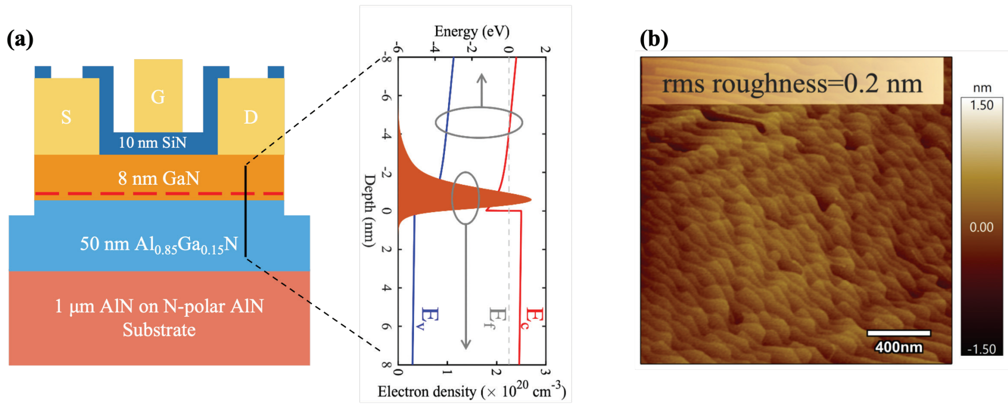

Fig. 1 (a) Schematic cross-section of a processed N-polar GaN/$Al_{0.85}Ga_{0.15}N$/AlN HEMT on bulk AlN substrates with the energy band diagram shown on the right. The location of the 2DEG is shown in dashed red line. (b) 2×2 um^2 atomic force microscopy image on the as-grown surface of the sample.

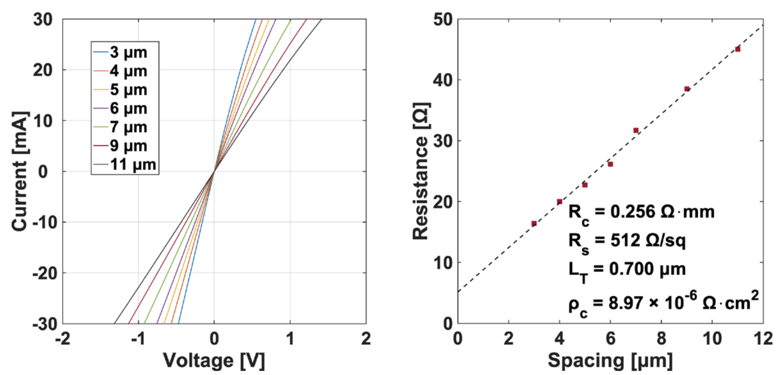

Fig. 2 TLM measurements of the source and drain ohmic contact to the 2DEG, showing R_c = 0.256 Ω·mm.

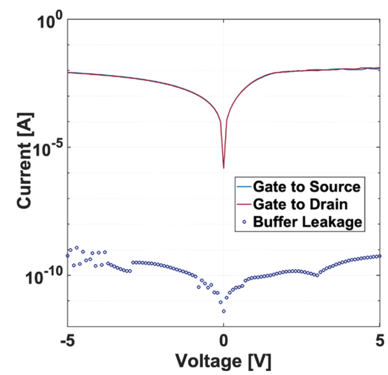

Fig. 3 Two terminal measurements showing low buffer leakage through AlN buffer layer.

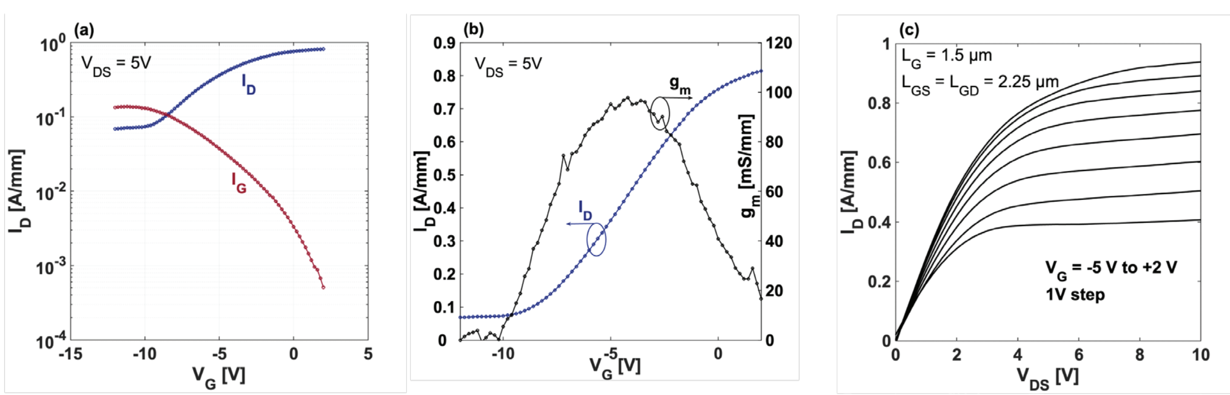

Fig. 4 (a) The transfer curve in semi-log scale with the gate leakage shown in red. (b) The transfer curve in linear scale showing an on/off ratio of ~12 and a peak transconductance of ~100 mS/mm. (c) Family of curves showing the maximum drain current density of 0.94 A/mm.

978-1-6654-9883-8/22/$31.00 ©2022 IEEE