Record >10 MV/cm mesa breakdown fields in Al$_{0.85}$Ga$_{0.15}$N/Al$_{0.6}$Ga$_{0.4}$N high electron mobility transistors on native AlN substrates

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ABSTRACT

The ultra-wide bandgap of Al-rich AlGaN is expected to support a significantly larger breakdown field compared to GaN, but the reported performance thus far has been limited by the use of foreign substrates. In this Letter, the material and electrical properties of Al$_{0.85}$Ga$_{0.15}$N/Al$_{0.6}$Ga$_{0.4}$N high electron mobility transistors (HEMTs) grown on a 2-in. single crystal AlN substrate are investigated, and it is demonstrated that native AlN substrates unlock the potential for Al-rich AlGaN to sustain large fields in such devices. We further study how Ohmic contacts made directly to a Si-doped channel layer reduce the knee voltage and increase the output current density. High-quality AlGaN growth is confirmed via scanning transmission electron microscopy, which also reveals the absence of metal penetration at the Ohmic contact interface and is in contrast to established GaN HEMT technology. Two-terminal mesa breakdown characteristics with 1.3 $\mu$m separation possess a record-high breakdown field strength of $\sim$11.5 MV/cm for an undoped Al$_{0.6}$Ga$_{0.4}$N-channel layer. The breakdown voltages for three-terminal devices measured with gate-drain distances of 4 and 9 $\mu$m are 850 and 1500 V, respectively.

GaN channel high electron mobility transistors (HEMTs) have become exciting candidates for high-frequency and high-power switching applications. With the ever-present demand for higher performance, ultra-wide bandgap (UWBG) semiconductors are gaining attention as next-generation high-power and high-frequency electronics due to their higher breakdown fields and capability to operate at higher temperatures. In particular, Al-rich AlGaN-based transistors possess large Johnson’s and Baliga’s figures of merit due to their large critical electric field ($E_C$), which increases rapidly from $\sim$3.7 MV/cm for GaN to $\sim$17 MV/cm for AlN. Most Al-rich AlGaN-based transistors are grown on sapphire substrates with AlN templates. The larger dislocation density in such films limits the $E_C$. For example, Abid et al. measured a breakdown field of $\sim$6.6 MV/cm between isolated contacts in the AlN buffer layer grown on sapphire substrates. While relatively high, the reported E-field is low compared to the ideal $E_C$ for AlN. In this work, we report a record high breakdown field of $\sim$11.5 MV/cm in the Al$_{0.6}$Ga$_{0.4}$N layer measured via mesa isolation structures between Al$_{0.85}$Ga$_{0.15}$N/Al$_{0.6}$Ga$_{0.4}$N heterojunctions grown on native AlN substrates. These results underscore the potential of Al-rich AlGaN when state-of-the-art quality epilayers (TDD $< 10^3$ cm$^{-2}$) are used. We also study the impact of the Ohmic contact layout on the knee voltage and current density when the top of the channel layer is Si-doped. We recently reported preliminary results for this structure. In this Letter, we expand on this; we analyze the voltage dependence of the mesa breakdown I–V characteristics, report three-terminal breakdown characteristics for the HEMTs, and further analyze Al$_{0.85}$Ga$_{0.15}$N/Al$_{0.6}$Ga$_{0.4}$N heterojunctions via C–V. Moreover, we demonstrate the high-quality growth of these structures on native AlN substrates via transmission electron microscopy (TEM) analysis.
AlGaN-channel HEMT epilayers were grown using a vertical, cold-wall, radio frequency (RF) heated, low-pressure metalorganic chemical vapor deposition (MOCVD) system on 2-in. diameter (0001)-plane single crystal, PVT AlN substrates with dislocation density <10^4 cm^-2. The HEMT structure consists, bottom to top, of a 500 nm unintentionally doped (UID) AlN layer, a 300 nm of Al_{0.6}Ga_{0.4}N channel layer, and a 20 nm of Al_{0.6}Ga_{0.4}N barrier layer [Fig. 1(a)]. The upper half (150 nm) of the Al_{0.6}Ga_{0.4}N channel layer is doped with Si at 5 x 10^{17} cm^-3. The reason for introducing doping in the channel layer instead of the barrier layer is to avoid high gate leakage. This also allows Ohmic contacts to be made directly to the doped channel layer, as discussed below. The RMS roughness of the AlN substrate shows 2.5-times higher leakage. This also allows Ohmic contacts to be made directly to the doped channel layer, as discussed below. The RMS roughness of the AlN substrate shows 2.5-times higher leakage.

Device fabrication started with a 230 nm deep mesa etch with a 12° bevel sidewall, confirmed via AFM. V/Al/Ni/Au (30/100/70/120 nm) were deposited via e-beam evaporation for the source (S) and drain (D) contacts. Two types of S/D contact geometries were realized: (1) S/D contacts only on top of the mesa (device-A) [Fig. 1(b)] and (2) S/D contacts extended over the beveled mesa sidewall (device-B) [Fig. 1(c)]. The S/D contacts were then annealed at 950 °C for 60 s in N₂ ambient. Gates were formed via e-beam evaporation of Ni/Au contacts. SEM images of device-A and device-B post-fabrication are shown in Figs. 1(d) and 1(e), respectively. It should be noted that these HEMTs are unpassivated.

Figure 1(f) shows the temperature-dependent Hall measurements performed via the van der Pauw method. A sheet carrier density (nS) of ~1.9 x 10^{12} cm^-2, a mobility (μS) of 140 cm²/V s, and a sheet resistance (RSH) of 2500 Ω/□ are measured at room temperature. It should be noted that nS is the total density from the two-dimensional electron gas (2DEG) region and a 150 nm n-type doped Al_{0.6}Ga_{0.4}N channel. The experimentally measured sheet carrier density is in agreement with the simulated sheet carrier density via a BandEng simulator. At temperatures lower than 200 K, temperature-independent nS and μS are observed, confirming the 2DEG's presence. At 90 K, nS ~ 1.7 x 10^{13} cm^-2, and μS ~ 200 cm²/V s. From room temperature to high temperature, an exponential rise in nS and a reduction in μS are observed due to the activation of carriers in the Si-doped n-type Al_{0.6}Ga_{0.4}N channel. At 750 K, nS ~ 3.9 x 10^{13} cm^-2, and μS ~ 30 cm²/V s. The same structure grown on a sapphire substrate (dislocation density ~ 10^10 cm^-2) shows nS ~ 7.6 x 10^{12} cm^-2, μS ~ 92 cm²/V s, and RSH ~ 8900 Ω/□ at room temperature. Thus, the HEMT on the AlN substrate shows 2.5-times higher nS and 1.5-times higher μS at room temperature, indicating better transport properties due to lower dislocation density.

Figure 2(a) shows the capacitance–voltage (C–V) characteristics measured on the HEMT diode at 100 kHz. Two distinct regions are observed in reverse bias due to the depletion of the 2DEG and the doped channel. The nS under the gate contact, obtained by integrating the C–V, is ~1.5 x 10^{12} cm^-2, which agrees with Hall. Figure 2(b) and the inset graph show the doping vs depth as extracted from C–V. These graphs confirm the presence of the 2DEG 18 nm below the barrier's surface and >10^{17} cm^-3 n-type doping in the Al_{0.6}Ga_{0.4}N channel up to 150 nm.

The HEMT output characteristics of each device are compared in Fig. 3(a). For both devices, values are reported for gate-to-source voltage (VGS) from 2 to −4 V with a step of −1 V. The drain to source spacing for device-A and device-B are 7 and 5 μm, respectively. The gate length for both devices is 1.5 μm. For device-A, the maximum drain current (ID_{max}) is 6 mA/mm at VGS = 2 V, and the drain saturation current (ID_{sat}) is 2 mA/mm at VGS = 0 V. In comparison, for device-B, ID_{max} is 10 mA/mm at VGS = 2 V, and ID_{sat} is 8 mA/mm at VGS = 0 V. It should also be noted that device-A has a large turn-on
voltage and knee voltage of ~2 V larger than that of device-B. This is attributed to the difference in Ohmic contact design; in the latter case, the contacts are connected to the doped channel layer through the mesa sidewall, which helps reduce the contact resistance. It is, therefore, expected that in device-B, carriers are primarily injected directly into the channel layer from the sidewall when \( V_{DS} < 2 \) V; above this range, the total current is comprised of both sidewall and topside injection. These mechanisms will be studied more carefully in the future. Compared to GaN HEMTs, the lower mobility and significantly larger contact resistance in AlGaN HEMTs reduce the current density. Nevertheless, the dependence on the contact designs shown in our work shows promise for future performance improvements.

Figure 3(b) shows the transfer characteristics of the HEMT in the linear scale for the device-B geometry measured at drain-source voltage (\( V_{DS} \)) = 10 V. The extracted threshold voltage (\( V_{th} \)) is \(-2.9\) V, and the maximum transconductance (\( g_{m,max} \)) is 3.6 mS/mm. Figure 3(c) shows the drain current density (\( J_D \)) and gate current density (\( J_{G} \)) on a semi-log plot. When the device is OFF, the drain current leakage is lower than 1 pA/mm, and the gate current also stays in the same current level. The on/off ratio of the HEMT is \(-10^8\), as seen from Fig. 3(c). It should also be noted that no hysteresis was observed.

To better understand the S/D contact behavior, scanning transmission electron microscopy (STEM) was performed. Figure 4(a) shows the STEM of the alloyed metal/Al\(_{0.85}\)Ga\(_{0.15}\)N barrier/Al\(_{0.6}\)Ga\(_{0.4}\)N channel/AlN epilayer. The STEM does not show any defects in the epilayers, which confirms the high-quality growth on the native AlN substrate. Figure 4(b) shows the STEM image of the interface between the alloyed metal contact and the Al\(_{0.85}\)Ga\(_{0.15}\)N barrier layer from the region highlighted in Fig. 4(a). The images show that metals do not penetrate through the barrier layer after alloying the contacts, which might be the reason for poor S/D Ohmic contacts. Limited metal penetration into Al-rich AlGaN has also been reported elsewhere,\(^{18,19}\) which has prompted studies of various contact metallurgies,\(^{19}\) regrown contacts,\(^{20}\) and graded AlGaN layer contacts.\(^{21}\) These results differ from what is observed in GaN HEMT technology.\(^{22-24}\)

The two-terminal mesa breakdown characteristics were measured to estimate the electric field strength of the Al\(_{0.6}\)Ga\(_{0.4}\)N channel layer. Figure 5(a) shows the result for two mesa separations \( d \): 1.3 and 3.3 \( \mu \)m. These were measured via AFM and defined as the distance between the two UID Al\(_{0.6}\)Ga\(_{0.4}\)N layers at the base of the mesa etch. The cross-sectional schematic of the mesa separation structure is shown in the inset of Fig. 5(a). The 1.3 \( \mu \)m mesa separation shows breakdown at ~1500 V, which corresponds to a breakdown electric field of 11.5 MV/cm across the UID Al\(_{0.6}\)Ga\(_{0.4}\)N layer. This is the highest breakdown field measured for Al-rich AlGaN layers.
In comparison, it is ~2× and ~4× higher than the UID AlN buffer mesa breakdown field reported for AlN/Al0.6Ga0.4N/AlN HEMTs11,12 and AlN MESFETs,25 respectively. The 3.3 μm mesa separation device is measured up to 2200 V as shown in Fig. 5(a) due to the measurement instrument limitation. The device does not break down across this range, indicating that it can sustain an electric field of >6.7 MV/cm. These findings support the conclusion that growth on AlN substrates leads to high-quality epilayers with very low dislocation densities. This is also in agreement with approximately 10 MV/cm breakdown fields observed in the avalanche photodiodes (APDs) grown on AlN substrates.14,15,26

To investigate the leakage conduction mechanism in the mesa breakdown structure, the I–V characteristic for a mesa separation of 1.3 μm is analyzed by plotting in the log-log scale, as shown in Fig. 5(b). The leakage does not show an appreciable increase until approximately 300 V. Between 300 V and breakdown at 1.5 kV, the leakage current follows a voltage-dependent power law (J ∝ V^n). In the 300–500 V regime, the leakage current follows Ohm’s law (n = 1), implying weak injection from the metal contacts into UID Al0.6Ga0.4N where the trap states are partially filled. Above 500 V, a J ∝ V^2 (i.e., n = 2) dependence is observed, which indicates the onset of space charge limited conduction (SCLC).27,28 As AlGaN HEMT technology matures, more studies of buffer leakage mechanisms will be pursued.29

The three-terminal HEMT breakdown characteristics for two different gate-to-drain (LGD) distances, 4 and 9 μm, are shown in Fig. 5(c). In both cases, the source-to-gate (LSG) distance and gate length (LG) are 1.5 μm each and VGS is ~−20 V. As seen, the 4 and 9 μm devices break down at VDS 850 and 1500 V, respectively, without using any edge termination techniques. It should be noted that the off-state current stays below 10 nA/mm for both cases before breakdown. These results are comparable to the reported breakdown values for HEMTs in the literature, even though the channel layer is doped in our case. The estimation of the maximum electric field for these devices requires TCAD simulations, which are left for the future work.

In summary, high-quality Al0.85Ga0.15N/Al0.6Ga0.4N HEMT structures were grown on a 2-inch native AlN substrate via MOCVD. We report a breakdown field of ~11.5 MV/cm in the UID Al0.6Ga0.4N layer via mesa isolation structures. This is the largest experimentally observed field in such devices thus far and underlines the promise of UWBG nitrides for extreme electronics.

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**AUTHOR DECLARATIONS**

Conflict of Interest

The authors have no conflicts to disclose.

**DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**REFERENCES**

12. The authors have no conflicts to disclose.