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AlGaN Channel High Electron Mobility Transistors with Regrown Ohmic Contacts

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Abstract: High power electronics using wide bandgap materials are maturing rapidly, and significant market growth is expected in a near future. Ultra wide bandgap materials, which have an even larger bandgap than GaN (3.4 eV), represent an attractive choice of materials to further push the performance limits of power devices. In this work, we report on the fabrication of AlN/AlGaN/AlN high-electron mobility transistors (HEMTs) using 50% Al-content on the AlGaN channel, which has a much wider bandgap than the commonly used GaN channel. The structure was grown by metalorganic chemical vapor deposition (MOCVD) on AlN/sapphire templates. A buffer breakdown field as high as 5.5 MV/cm was reported for short contact distances. Furthermore, transistors have been successfully fabricated on this heterostructure, with low leakage current and low on-resistance. A remarkable three-terminal breakdown voltage above 4 kV with an off-state leakage current below 1 µA/mm was achieved. A regrown ohmic contact was used to reduce the source/drain ohmic contact resistance, yielding a drain current density of about 0.1 A/mm.

Keywords: AlGaN channel; high-electron-mobility-transistor (HEMT); AlN; Ultra-wide BandGap

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1. Introduction

Wide band gap (WBG) semiconductors such as GaN and SiC are becoming the material of choice for high power applications. Devices and circuits based on these emerging materials are more suited to operate at higher voltages and temperatures than Si-based devices owing to their superior physical properties [1–3]. Recently, AlGaN/GaN based high electron mobility transistors (HEMTs) on low cost silicon substrate have been extensively demonstrated as attractive candidates for next generation power devices in the 100–650 V range with low on-resistances [4–9]. However, in order to further push the limits for high voltage applications (>1200 V) and address new requirements, the use of ultra wide band gap (UWBG) materials such as AlN is appealing due to their even better intrinsic properties [10–13]. UWBG are defined by a bandgap larger than that of GaN (3.4 eV) and SiC (3.2 eV), including β-Ga2O3 (4.9 eV) [14,15], diamond (5.5 eV) [16,17], or AlN (6.2 eV) [18,19]. Employing AlN as a buffer layer enables it to handle extremely high voltages due to its large electric breakdown field [20,21]. AlN enables it to uniquely combine higher critical electric field [22] and thermal conductivity [23] than those of GaN material. Furthermore, an improved electron confinement within the two-dimensional electron gas (2DEG) can also be expected when using AlN as a buffer layer, which acts as a back barrier. In turn, the AlN buffer can potentially not only increase the electron

confinement in the transistor channel but can also help boosting the breakdown voltage (BV), owing to its wider bandgap. In this frame, the implementation of high Al content (>40%) AlGaN channel instead of GaN should allow for extremely high voltage transistor operations due to an increased critical electric field [24–26].

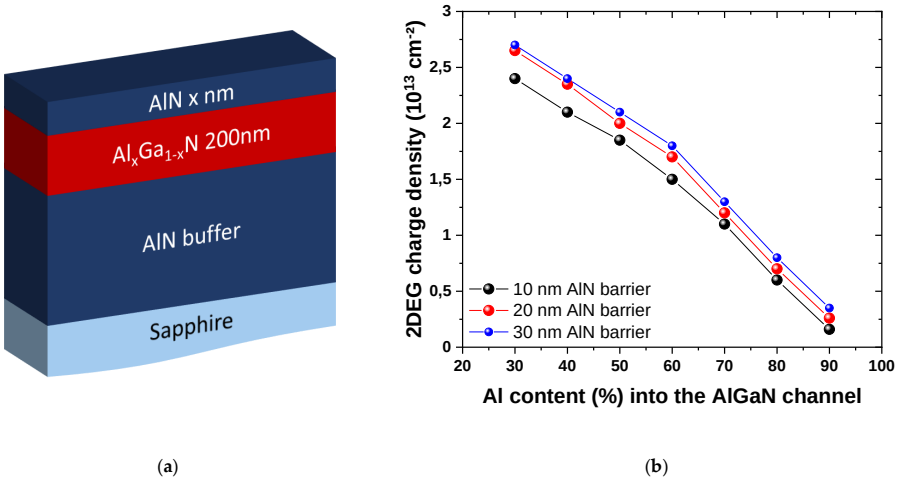
However, beyond the material quality, one of the main bottlenecks for AlGaN-channel-based devices is the achievement of low ohmic contacts and related high current density. As the bandgap of the material increases with higher Al composition, low ohmic contact resistance is a critical challenge limiting the on-state performance of these types of devices, although this material has about the same electron saturation velocity as GaN. This is due to the significant energy barrier height between the ohmic metal and barrier layer in the case of AlGaN with high Al content.

In this work, we demonstrate the successful fabrication of AlN/$Al_{0.5}Ga_{0.5}$N/AlN HEMTs delivering a high three-terminal off-state breakdown voltage (BV) > 4 kV while showing an improved on-state current density by using regrown ohmic contacts.

2. Simulation of the 2DEG Density

To investigate the two-dimensional electron gas (2DEG) properties of Al-rich AlGaN channel heterostructures, various barrier thicknesses and Al content into the AlGaN channel were simulated using the commercial software for semiconductor nanodevices, "Nextnano". The solver includes both piezoelectric and spontaneous polarization contributions [27]. The layers are considered pseudomorphic on AlN. After optimizing the meshing parameters, especially around the 2DEG, a good agreement between the electron density values from a variety of measured literature data could be achieved.

Figure 1 depicts the 2DEG density as a function of the Al content on the channel for various barrier thicknesses (10 nm, 20 nm, and 30 nm). We observed a slight increase of the electron density with the AlN barrier thickness. However, we noticed a rather limited variation of about 15%. On the other hand, the impact of the Al content on the AlGaN channel for this material configuration was quite significant. As expected from the AlN/Al_xGa_{1-x}N spontaneous and piezoelectric polarizations, the lower the Al content in the channel, the higher the electron density, reaching significant values well-above $2 \times 10^{13}/cm^2$. As previously mentioned, in order to increase the breakdown voltage, a wider bandgap and thus a high Al content in the channel were desired. Therefore, in this case, an Al content of about 50% (as chosen experimentally) seems to provide a good trade-off between the 2DEG density ($\approx 2 \times 10^{13}/cm^2$) and an increased breakdown field as compared to standard GaN channel HEMTs. As a matter of fact, this configuration enables both a significant electron density and channel band gap increase that should result in high current density and enhanced breakdown voltage.



(**a**) (**b**)

Figure 1. Schematic cross section of the simulated AlN/AlGaN/AlN heterostructure (**a**) and 2DEG charge density dependence on the Al content in the AlGaN channel (**b**).

3. Materials and Methods

Figure 2 shows the cross-sections of the fabricated AlGaN channel transistors with two different ohmic contact schemes. An AlN film with 200 nm thickness was deposited on c-plane sapphire substrates by sputtering, followed by annealing at 1700 °C for 3 h. Typical densities of edge-type and mixed-type dislocations in the AlN are 8×10^8 cm^{-2} and 2×10^6 cm^{-2}, respectively [28,29]. Epitaxial layers consisting of a 170-nm-thick AlN buffer, a 200-nm-thick $Al_{0.5}Ga_{0.5}N$ channel, and a 20-nm thick AlN barrier capped with a 20-nm thick SiN layer, were grown by metal–organic vapor phase epitaxy (MOCVD). The whole epi-layers were unintentionally doped.

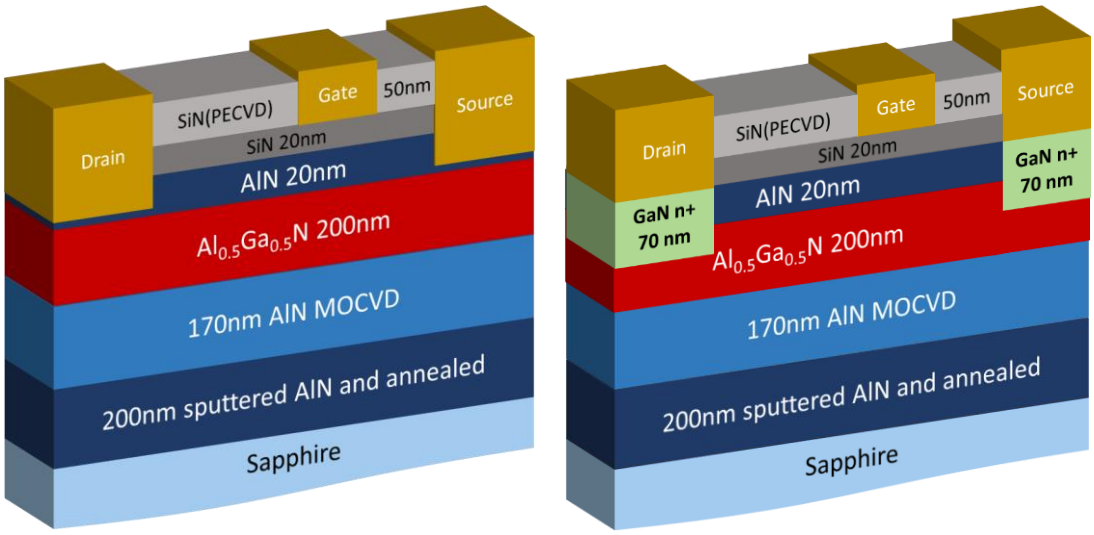


Figure 2. Schematic cross section of the AlN/AlGaN/AlN high-electron mobility transistors (HEMTs) with partially recessed annealed ohmic contacts (**a**) and non-alloyed regrown ohmic contacts (**b**).

The fabrication process has been performed as follows:

- The source/drain ohmic contacts were performed in two ways:
  1. Ti/Al/Ni/Au metal stack annealed at 875 °C deposited on top of the barrier after etching the 20-nm thick in-situ SiN cap layer using a Fluorine-based etching as well as a large part of the AlN barrier using a Chlorine/Argon plasma in order to leave about 3-nm thin barrier to facilitate the diffusion process (Figure 1a),
  2. Etching of the SiN cap, the barrier layer, and part of the AlGaN channel (total etching depth of 70 nm) prior to a selective regrowth by ammonia-source molecular beam epitaxy (MBE) below 800 °C with highly doped silicon (>5×10^{19} cm^{-3}) n+ GaN by MBE using a SiO_2 mask. A Ti/Au metal stack was then deposited (Figure 1b). The stack was not annealed.
- Device isolation was realized by mesa etching with a depth of 350 nm.
- Ni/Au metals were deposited on top of the in-situ SiN cap layer to obtain metal insulator semiconductor (MIS) gates. The transistor gate length and source–gate distances were 2 µm and 1 µm, respectively, with various gate-drain (GD) distances.
- Finally, Ti/Au pads were evaporated, followed by a plasma enhanced chemical vapor deposition (PECVD) of a SiN passivation film.

The 2DEG properties were obtained by Hall effect measurements, showing a carrier density of 2×10^{13} cm^{-2}, an electron mobility of 150 cm^2/V.s, and a sheet resistivity of 1.6 kΩ/□, which is in agreement with previous simulations. The rather low electron mobility was comparable to previously reported values [30] and was mainly limited by increased electron scattering in the Al-rich AlGaN channel.

Planar (not recessed) ohmic contacts were reported for HEMT heterostructures with an Al composition well above 50% in the AlGaN channel. The specific contact resistivity was shown to degrade when increasing the Al content [31–35]. In order to favor the electron tunnelling and thus the current injection, we implemented a recessed ohmic contact. We locally reduced the barrier thickness down to 3 nm. It was noticed that a significant carrier density well above 1×10^{13} cm^{-2} was still expected with such a thin barrier considering the AlN polarization charges. In turn, such a design was used in other RF technologies delivering high electron density [36]. Transmission line method (TLM) patterns were fabricated to assess the contact resistance. A rather high specific contact resistance of about 1.8×10^{-2} Ω.cm^2 (58 Ω.mm) was obtained (see Figure 3), which indicated that the residual barrier was still too high for proper electron injection at the metal/semiconductor interface. Plasma induced damage as well as native oxide formed during the transfer to the evaporation tool are most probably limiting factors to this approach.

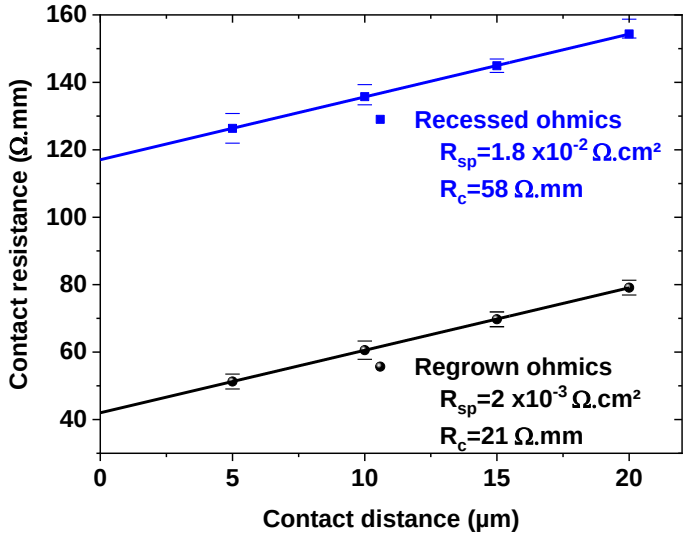


Figure 3. Contact distance dependence on transmission line method (TLM) resistance for recessed/annealed and regrown n+ GaN ohmic contacts on the fabricated AlGaN channel HEMTs.

The use of regrown ohmic contacts has been extensively investigated over the last decade showing reduced contact resistances and improved device performance [37]. We adopted this technique for this specific material configuration. As shown in Figure 3, strongly reduced contact resistances could be achieved as compared to recessed ohmic contacts with a specific contact resistance of 2×10^{-3} Ω.cm^2 (21 Ω.mm). In both cases, a sheet resistance of 1.8 kΩ/□ was extracted, confirming the validity of the measurements as this value was rather close to the one obtained with Hall effect.

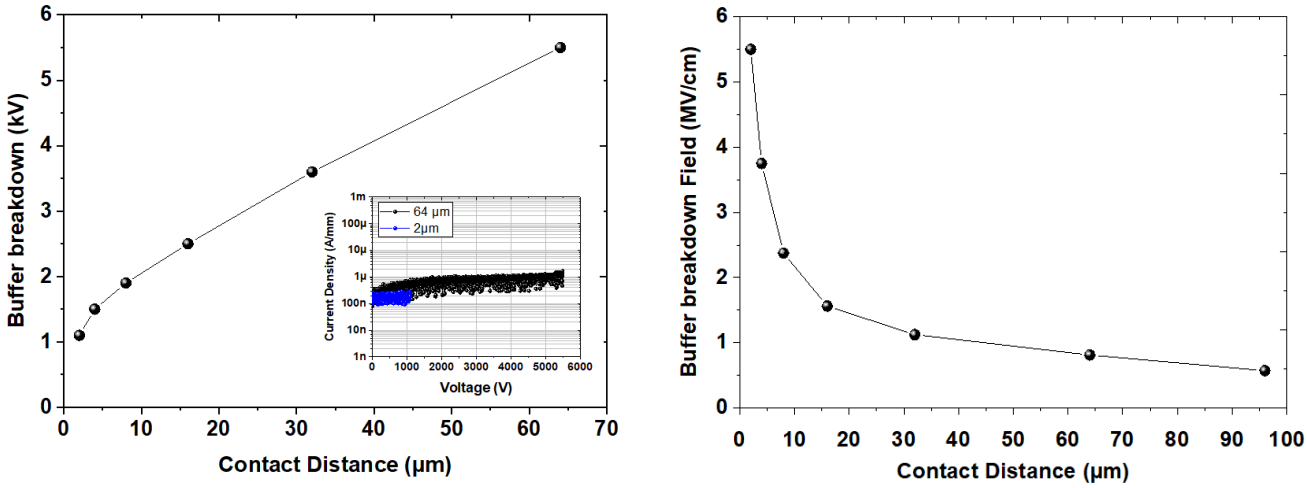
Reduction of plasma damage together with the removal of the residual native oxide prior to the n+ GaN growth may certainly allow further improvement of the contact resistance of this material system.

4. Results and Discussions

Lateral buffer breakdown measurements were carried out between isolated contacts for various distances using a Keysight B1505A with N1268A ultra high voltage expander. The measurements were performed on-wafer, and the samples were immerged in a Fluorinert solution to avoid arcing in air.

An almost linear lateral buffer breakdown voltage (BV) scaling was observed on isolated ohmic contacts for various contact distances reaching values above 5 kV (see Figure 4). BV was defined at 1 µA/mm. Interestingly, a remarkable breakdown field >5 MV/cm (well above the theoretical limit of GaN material) was observed for short distances limited by

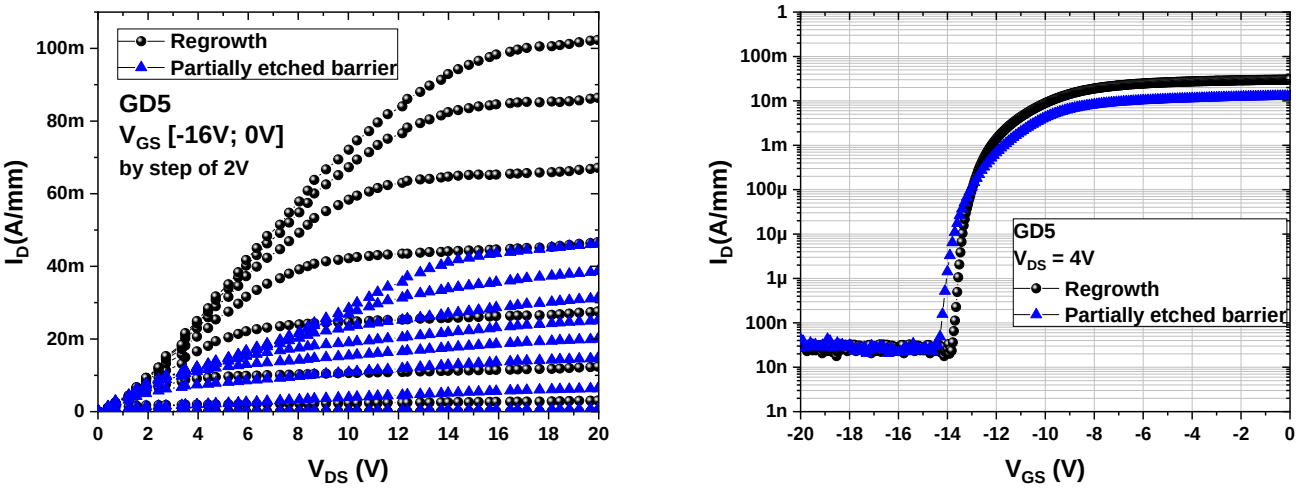
the sapphire substrate (≈1 MV/cm) for larger contact distances. This confirms the benefit of AlN as compared to GaN-based buffer layers.



(**a**) (**b**)

Figure 4. Buffer breakdown voltage (BV) (**a**) and related breakdown field (**b**) for various contact distances of AlN/AlGaN/AlN HEMTs.

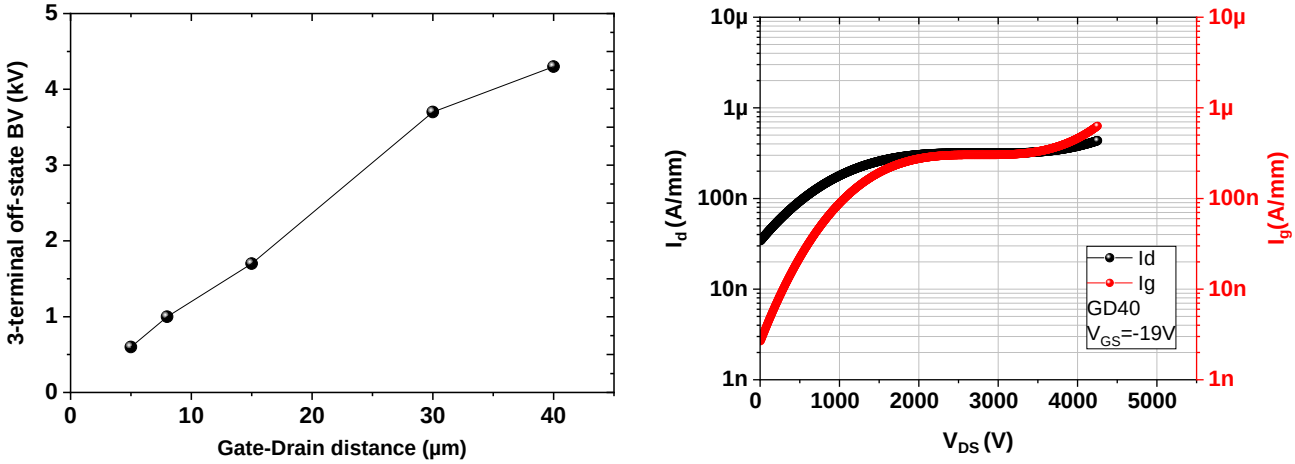
Electrical characterizations were carried out on transistors with gate width/length = 50 µm/2 µm and gate-to-drain spacing varied from 5 to 40 µm. All transistors were fully functional with a high on/off drain current ratio, an excellent pinch-off behavior reflecting the absence of parasitic punch-through effects, and low off-state leakage current (see Figure 5b). The large pinch-off voltage around −15 V was due to the relatively thick SiN deposited for the MIS gate. Due to the quite poor ohmic contacts, the transistors with recessed ohmic contacts show a rather low on-state current density of about 40 mA/mm. On the other hand, as can be seen in Figure 5a, the output characteristics of transistors with regrown non-alloyed contacts show a significantly improved current density above 100 mA/mm as compared to devices with partially etched barrier and annealed contacts. This clearly results from the drastic drop of the contact resistances by a factor 2.5.



(**a**) (**b**)

Figure 5. Output characteristics (**a**) and transfer characteristics (**b**) for a gate-drain distance of 5 µm of AlN/AlGaN/AlN HEMTs using regrown ohmic contacts and partially etched barrier.

The 3-terminal BV as a function of the transistor gate-drain distances were measured at $V_{GS} = -19$ V. Despite a rather high defect density and the sapphire substrate limitation [38], a record BV of 4300 V with an off-state leakage current below 1 µA/mm was achieved for AlGaN-based channel HEMTs (see Figure 6).



(**a**) (**b**)

Figure 6. Three-terminal off-state BV for various GD distances (**a**) and for a gate-drain distance of 40 µm (**b**) of AlN/AlGaN/AlN HEMTs.

Figure 7 shows that compared with the state-of-the-art AlGaN channel HEMTs, the present transistors exhibit a noticeable increase of 3-terminal breakdown voltage without a dramatic drop in the drain current density.

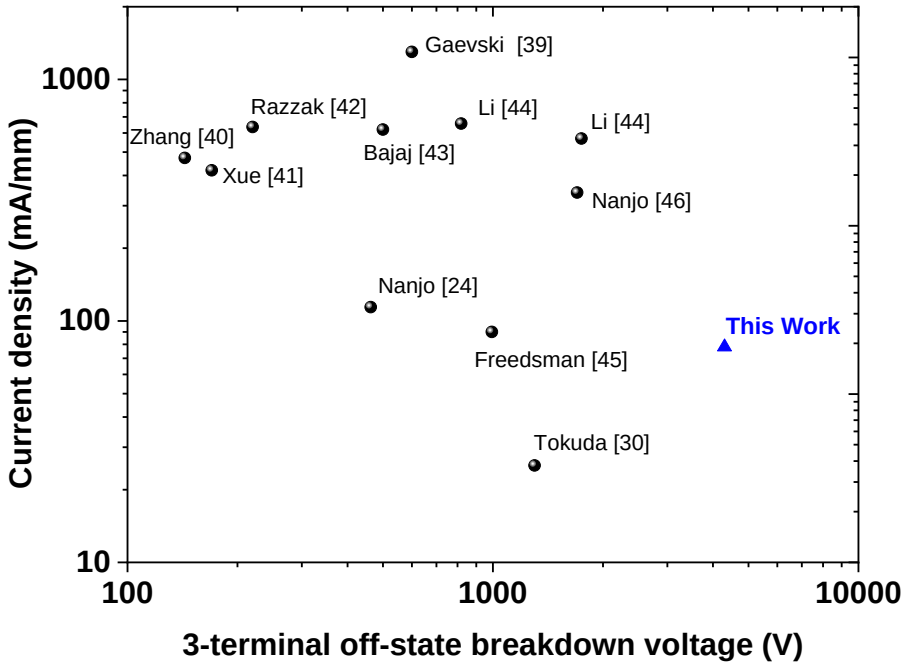


Figure 7. Benchmark of AlGaN channel HEMT devices in terms of current density and 3-terminal breakdown voltage [39–46].

5. Conclusions

In summary, we have shown the possibility to operate at high voltage using an AlN/AlGaN/AlN heterostructure with 50% Al content in the channel. This resulted in an

increase in the critical electric field with respect to more standard GaN HEMTs. The major bottleneck of this material system was the achievement of low ohmic contact resistances in order to deliver a high current density. Regrown ohmic contacts were promising in this frame. A significant reduction of the contact resistances was indeed observed as compared to the more standard recessed annealed ohmic contacts.

Therefore, Al-rich AlGaN channel combined with high-crystalline quality AlN offers great potential as the material of choice for future power switching applications. Although epitaxial growth efforts were mainly conducted on sapphire substrates, AlN may be the best substrate for Al-rich transistors long-term. Its advantages include better thermal conductivity and improved crystalline quality, due to near lattice-matched growth conditions for $Al_xGa_{1-x}N$ with large x.

Author Contributions: H.M. produced the AlN on sapphire templates; S.D. and J.D. performed the growth of the heterostructure; Y.C. carried out the regrown ohmic contacts; I.A., J.M., and F.M. completed the device fabrication and characterizations. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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