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We report on the performance of AlGaN/GaN/AlN heterostructure field-effect transistors (HFETs) grown over slightly-off c-axis, single-crystal, bulk AlN substrates. Dc and rf characteristics of these devices were comparable to HFETs grown on semi-insulating SiC. The obtained results demonstrate that bulk AlN substrates are suitable for fabricating high-power microwave AlGaN/GaN transistors.


Most work in GaN-based, high-power transistor development has been done using SiC substrates for improved thermal management. Heteroepitaxial growth of transistor structures on SiC results in a large dislocation density (typically varying from \(10^6\) to \(10^{10}\) cm\(^{-2}\)), which reduces device reliability and lifetime, causes premature breakdown, and degrades noise performance. One way to reduce the dislocation density is to use lateral epitaxial overgrowth (LEO) or related technologies. However, a large background doping of GaN with silicon penetrating from the masking layers degrades high-frequency performance of the LEO-grown devices.

To reduce the number of growth defects and dislocation density in GaN-based heterostructure field-effect transistors (HFETs), we used bulk AlN substrates. The use of a bulk AlN substrate allows one to reduce the dislocation density in the epitaxial layers by more than four orders of magnitude down to \(10^2 – 10^3\) cm\(^{-2}\).1 At the same time, bulk AlN substrates have superior thermal conductivity (3 W/cm K or higher), comparable to that of semi-insulating 4H-SiC (3.9 W/cm K). Hence, we expect that AlN/GaN/InN high electron mobility transistors on bulk AlN substrates will exhibit major improvements in lifetime and reliability without compromising thermal management of high-power devices.

The device structures were grown on 10° off c-axis, Al-face, single-crystal, bulk AlN substrates. The same structures were deposited on SiC substrates in the same metalorganic chemical vapor deposition run for comparison. The growth of approximately 0.3-μm-thick, homoepitaxial AlN was followed by the deposition of 0.1-μm-thick, nominally undoped GaN capped with 25-nm-thick, 20% AlGaN barrier layer. (A very thin AlGaN layer with much higher molar fraction of Al was deposited at the heterointerface.) The cross-sectional view of the epilayer design is shown in Fig. 1. The room-temperature electron Hall concentration was \(10^{13}\) cm\(^{-2}\), while the electron Hall mobility was 1100 cm\(^2\)/V s. The two-dimensional (2D) electron sheet carrier density and Hall mobility for the same structures grown on SiC substrates were \(1.7 \times 10^{13}\) cm\(^{-2}\) and 1.200 cm\(^2\)/V s, respectively.

We fabricated 200-μm-wide devices with a gate length of 1.5 μm. A CCD image of the processed wafer is shown in Fig. 2(a). The Ti/Al/Ti/Au contact resistance was approximately 0.8 Ω mm, and the specific contact resistance was around \(1.3 \times 10^{-5}\) Ω cm\(^2\). Reactive-ion etching of mesas was used for device isolation. For the Ni/Au Schottky gate, the forward turn-on voltage was approximately 1.2 V with the reverse leakage current as low as 5 μA at a gate bias of −10 V [see Fig. 2(b)]. The maximum saturation current was close to 600 and 650 mA/mm for bulk AlN and SiC substrates, respectively. We attribute a higher saturation current of the devices on SiC to a larger sheet carrier density.

Our calculations of the ground state and the Fermi level position of the 2D electron gas at the heterointerface show that the Fermi level at the Al\(_x\)Ga\(_{1-x}\)/GaN interface enters the AlGaN barrier layer with \(x = 20\%\) at the 2D electron gas (2DEG) densities exceeding \(10^{13}\) cm\(^{-2}\), as illustrated in Fig. 3. Such electron distribution should lead to a very low electron mobility because of a strong alloy scattering in AlGaN and a higher electron effective mass. Our recent magnetotransport data point to the two-channel conduction in the

![FIG. 1. Schematic epilayer design of AlGaN/GaN/AlN HFETs.](Image)
2DEG in AlGaN/GaN heterostructures. Since the measured electron Hall mobility is fairly high (over 1000 cm²/V s), we conclude that a very thin layer with a high Al molar fraction deposited at the heterointerface in our device structures plays an important role by creating a barrier for the electron penetration into the AlGaN layer. A higher value of the electron mobility measured in our structures grown on SiC (~1200 cm²/V s for \(1.7 \times 10^{13} \) cm\(^{-2}\) compared to 1000 cm²/V s for \(10^{13} \) cm\(^{-3}\)) also shows that the electron penetration into the AlGaN layer in low electric fields is not a dominant factor in our structures due to the enhanced Al molar fraction at the heterointerface. We expect that the electron penetration into the AlGaN layer would be more pronounced for hot electrons in high electric fields. Such partial electron penetration in the AlGaN layer might be responsible for a relatively low effective electron saturation velocity \(v_s\), estimated from the measured cutoff frequency \(f_T\); see Fig. 4:

\[
v_s = 2\pi L f_T = 0.47 \times 10^5 \text{ cm/s.} \tag{1}
\]

Since the thickness of the GaN epitaxial layer in our structures is much larger than the critical thickness for the strain relaxation, piezoelectric charges from the AlN/GaN interface should be quite small. However, one might expect a large depleting charge at AlN/GaN interface due to the difference in spontaneous polarizations. The difference in the electron sheet densities of \(0.7 \times 10^{13} \) cm\(^{-2}\) for the devices on the SiC and AlN substrates corresponds to the charge of \(-0.011 \text{ C/m}^2\). The difference in the spontaneous polarizations for AlN and GaN is estimated to be \(0.049 \text{ C/m}^2\). This would correspond to the electron sheet density of \(3.05 \times 10^{13} \) cm\(^{-2}\). Our simulation results indicate a possible for-
formation of the 2D hole gas at the GaN/AlN interface that partially compensates the depleting charge from the spontaneous polarization (see Fig. 5).

In conclusion, our results show that high-quality AlGaN/GaN HFETs can be fabricated on bulk AlN substrates that have potential to yield more reliable and longer lifetime devices because of much smaller dislocation density. The comparison with the measured characteristics of the identical HFETs grown on SiC structures shows that the enhanced molar fraction of Al at the AlGaN/GaN heterointerface decreases the electron spillover into the AlGaN layer. A relatively low effective electron saturation velocity extracted from the measured cutoff frequency indicates that such spillover might be important at high drain bias.

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9 According to our unpublished calculations, this difference is somewhat, but not much, smaller for the slightly off-axis substrates used in this work.