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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.
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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 10^8 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 10^4–10^5 cm^2.[1] At the same time, bulk AlN substrates have superior thermal conductivity (3 W/cm K or higher),[2] 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 1.7×10^{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 1.3×10^{-5} $\Omega\,cm^2$. 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[3] show that the Fermi level at the $Al_xGa_{1-x}N$/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[4] 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

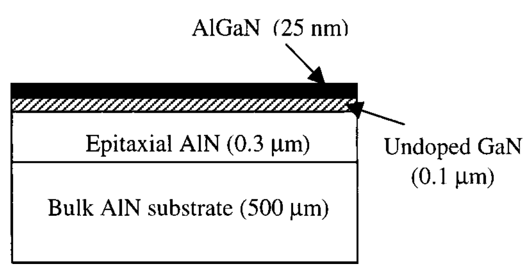

FIG. 1. Schematic epilayer design of AlGaN/GaN/AlN HFETs.

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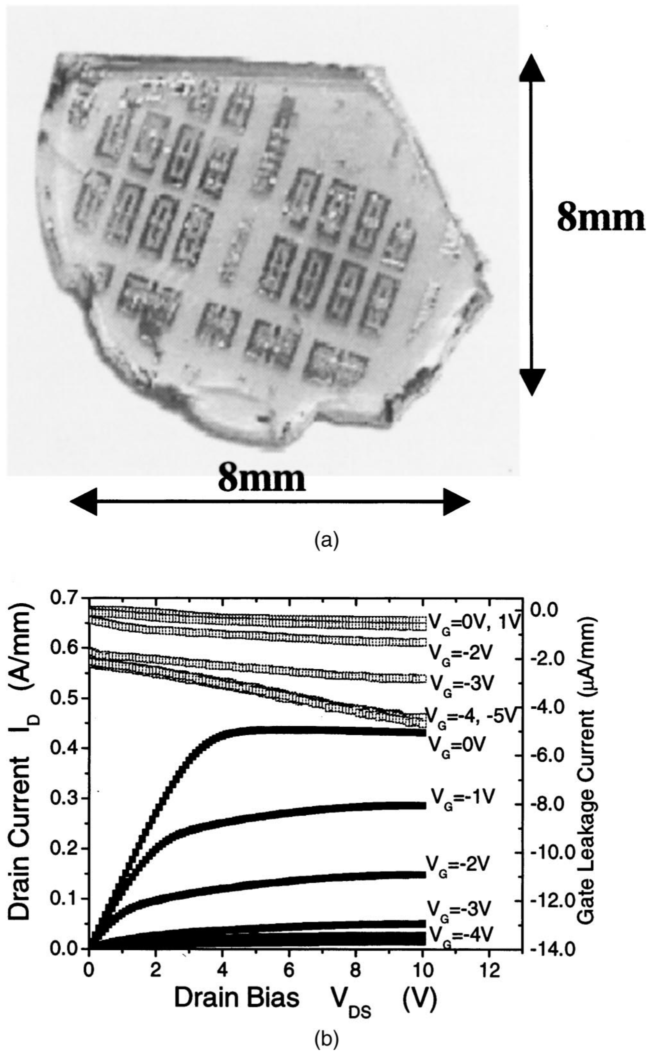

FIG. 2. (a) Picture of AlGaN/GaN/AlN double HFET sample grown and processed on bulk AlN substrate. (b) Typical dc characteristics of HFETs on bulk AlN. Gate bias is indicated for each $I-V$ curve. Top curves show gate leakage current.

2DEG in AlGaN/GaN heterostructures.[5] Since the measured electron Hall mobility is fairly high (over 1000 $cm^2/V\,s$), 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 $cm^2/V\,s$ for 1.7×10^{13} cm^{-2} compared to 1000 $cm^2/V\,s$ 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 a relatively low effective electron saturation velocity ν_s, estimated from the measured cutoff frequency (f_T~5 GHz, see Fig. 4):

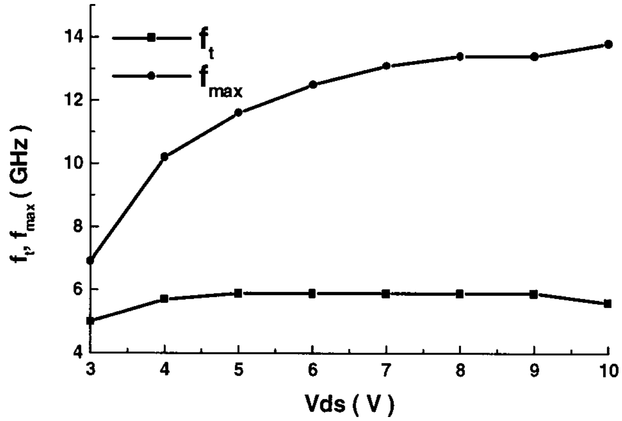

FIG. 4. f_T and $f_{\max}$ versus drain bias.

$$\nu_s = 2\pi L f_T \approx 0.47\times10^5 \ \text{cm/s}. \tag{1}$$

Since the thickness of the GaN epitaxial layer in our structures is much larger than the critical thickness for the strain relaxation,[6,7] 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 0.7×10^{13} cm^{-2} for the devices on the SiC and AlN substrates corresponds to the charge of ~0.011 C/m^2. The difference in the spontaneous polarizations for AlN and GaN is estimated,[8,9] to be 0.049 C/m^2. This would correspond to the electron sheet density of 3.05 $\times10^{13}$ cm^{-2}. Our simulation results indicate a possible for-

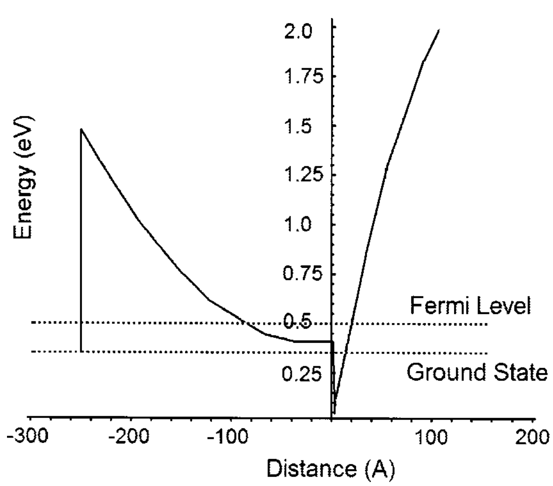

FIG. 3. Band diagram near heterointerface and Fermi level position.

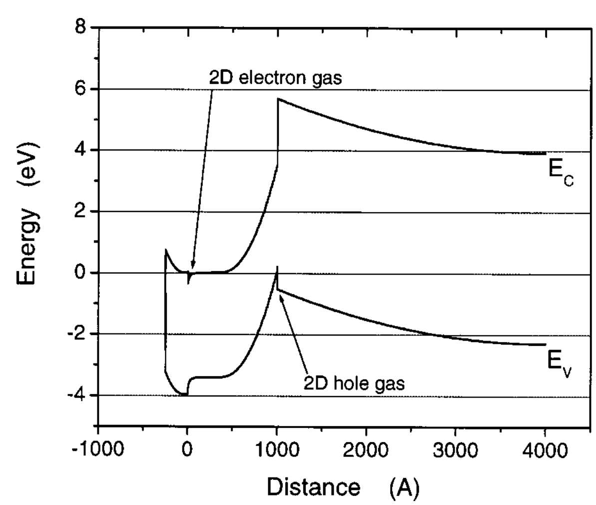

FIG. 5. AlGaN/GaN/AlN HFET band diagram.

mation 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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