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X. Hu

J. Deng


N. Pala

R. Gaska

M. S. Shur

See next page for additional authors

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Author(s)

X. Hu, J. Deng, N. Pala, R. Gaska, M. S. Shur, C. Q. Chen, J. Yang, Grigory Simin, M. A. Khan, J. C. Rojo, and L. J. Schowalter

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AlGaN/GaN heterostructure field-effect transistors on single-crystal bulk AlN

X. Hu, J. Deng, N. Pala,^{a)} and R. Gaska
Sensor Electronic Technology, Inc., Columbia, South Carolina 29209

M. S. Shur
Broadband Center and ECSE, Rensselaer Polytechnic Institute, Troy New York 12180

C. Q. Chen, J. Yang, G. Simin, and M. A. Khan
University of South Carolina, Columbia, South Carolina 29208

J. C. Rojo and L. J. Schowalter^{b)}
Crystal IS, Inc., Latham, New York 12110

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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 $\text{cm}^2/\text{V s}$. 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 1200 $\text{cm}^2/\text{V s}$, 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} 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 heterointerface³ show that the Fermi level at the $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ 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 lead⁴ 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

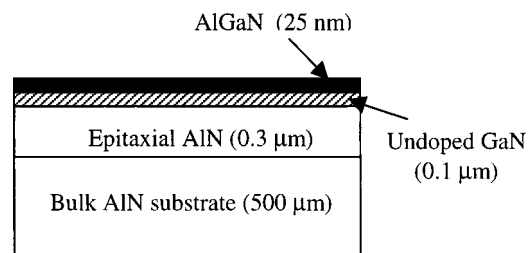


FIG. 1. Schematic epilayer design of AlGaN/GaN/AlN HFETs.

^{a)}Electronic mail: nezih@s-et.com

^{b)}On leave of absence from: Rensselaer Polytechnic Institute.

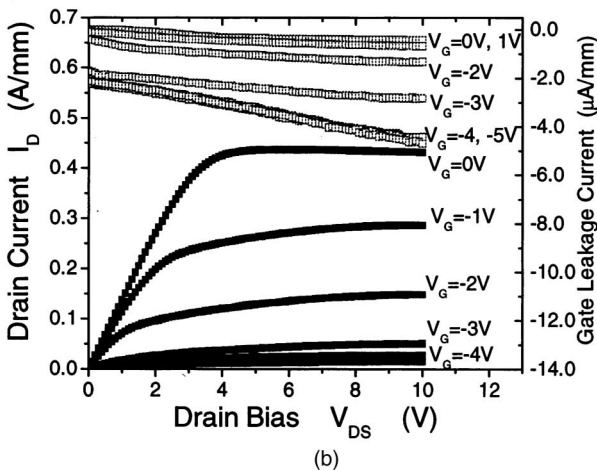
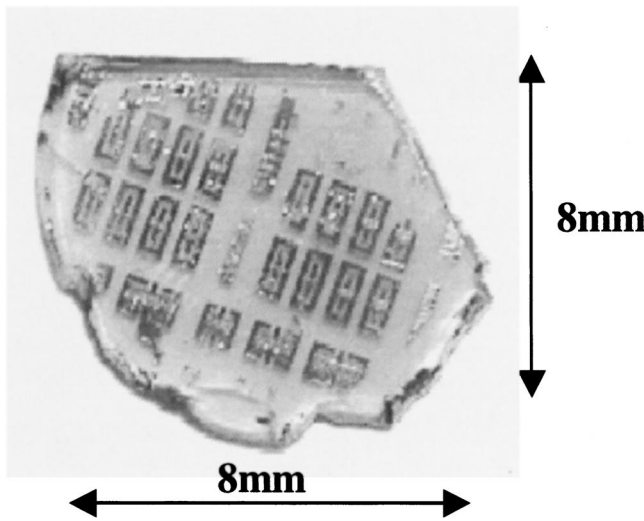


FIG. 2. (a) Picture of AlGaIn/GaN/AlN double HFET sample grown and processed on bulk AlN substrate. (b) Typical dc characteristics of HFETs on bulk AlN. Gate bias is indicated for each $I-V$ curve. Top curves show gate leakage current.

2DEG in AlGaIn/GaN heterostructures.⁵ Since the measured electron Hall mobility is fairly high (over $1000 \text{ cm}^2/\text{Vs}$), 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 pen-

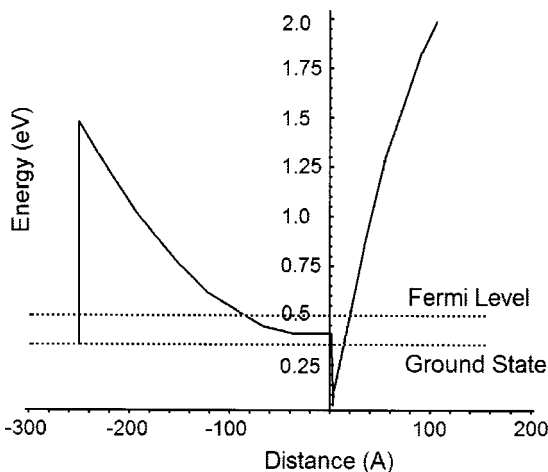


FIG. 3. Band diagram near heterointerface and Fermi level position.

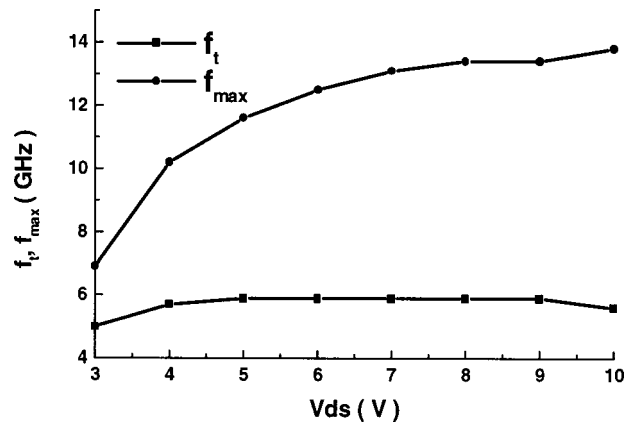


FIG. 4. f_T and f_{max} versus drain bias.

etration into the AlGaIn layer. A higher value of the electron mobility measured in our structures grown on SiC ($1200 \text{ cm}^2/\text{Vs}$ for $1.7 \times 10^{13} \text{ cm}^{-2}$ compared to $1000 \text{ cm}^2/\text{Vs}$ for 10^{13} cm^{-3}) also shows that the electron penetration into the AlGaIn 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 AlGaIn layer would be more pronounced for hot electrons in high electric fields. Such partial electron penetration in the AlGaIn layer might be responsible a relatively low effective electron saturation velocity v_s , estimated from the measured cutoff frequency ($f_T \sim 5 \text{ GHz}$, see Fig. 4):

$$v_s = 2\pi L f_T \approx 0.47 \times 10^5 \text{ cm/s.} \quad (1)$$

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 $0.7 \times 10^{13} \text{ cm}^{-2}$ for the devices on the SiC and AlN substrates corresponds to the charge of $\sim 0.011 \text{ C/m}^2$. 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 $3.05 \times 10^{13} \text{ cm}^{-2}$. Our simulation results indicate a possible for-

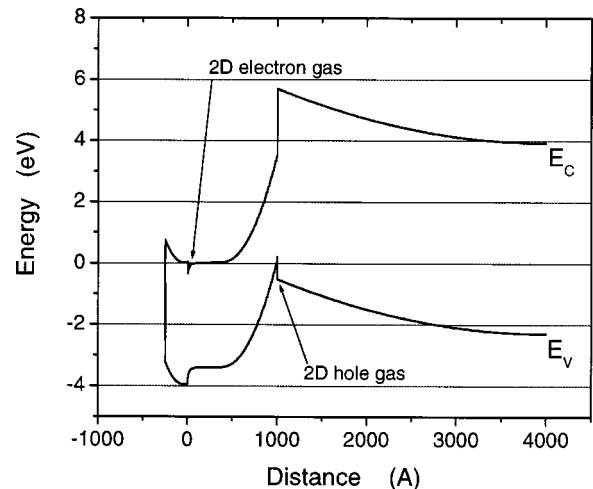


FIG. 5. AlGaIn/GaN/AlN HFET band diagram.

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 AlGaIn/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 AlGaIn/GaN heterointerface decreases the electron spillover into the AlGaIn 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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