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GaN–AlGaN heterostructure field-effect transistors over bulk GaN substrates

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We report on AlGaN/GaN heterostructures and heterostructure field-effect transistors (HFETs) fabricated on high-pressure-grown bulk GaN substrates. The $2d$ electron gas channel exhibits excellent electronic properties with room-temperature electron Hall mobility as high as $\mu = 1650\,\mathrm{cm^2/V\,s}$ combined with a very large electron sheet density $n_s \approx 1.4\times10^{13}\,\mathrm{cm^{-2}}$. The HFET devices demonstrated better linearity of transconductance and low gate leakage, especially at elevated temperatures. We also present the comparative study of high-current AlGaN/GaN HFETs ($n_s\mu > 2\times10^{16}\,\mathrm{V^{-1}\,s^{-1}}$) grown on bulk GaN, sapphire, and SiC substrates under the same conditions. We demonstrate that in the high-power regime, the self-heating effects, and not a dislocation density, is the dominant factor determining the device behavior. © *2000 American Institute of Physics.* [S0003-6951(00)02425-6]

Since the early demonstration of two-dimensional electron gas[1] (2 DEG) and heterostructure field-effect transistors[2] (HFETs), significant progress has been made towards development of GaN–AlGaN-based high-power[3] and low-noise[4] microwave devices. To date, nearly all the microwave devices have been fabricated on sapphire or insulating SiC substrates. This lattice-mismatched epitaxy is known to result in a large number of threading dislocations in excess of 10^8 per cm^2.[5] Dislocations significantly affect the performance of electronic devices by reducing carrier mobility, increasing noise and gate leakages, and resulting in a premature device breakdown. Significant improvements in material quality and device performance are expected using homoepitaxially grown GaN. However, until recently, insulating bulk GaN substrates were not available.

During the last few years we demonstrated conducting GaN bulk substrates, which allowed us to grow high-quality GaN epilayers with very low impurity and dislocation density.[6,7] This leads to photoluminescence spectra with very well-resolved excitonic transition lines of widths below 1 meV.[8] Recently, Mg-doped high-pressure-grown bulk GaN crystals were shown to be semi-insulating with perfect crystallographic structure. The dislocation density in these crystals was determined by selective defect etching and was found to be of the order of 10^2 per cm^2, which is more than 6–7 orders of magnitude less than in heteroepitaxially grown GaN. This makes the Mg-doped high-pressure-grown GaN bulk crystals extremely attractive for the development of HFET and other GaN-based electronic devices.

In this letter, we report the growth, processing, and characterization of high-quality AlGaN/GaN heterostructures and HFETs over semi-insulating bulk GaN substrates. We also present a comparative study of AlGaN/GaN HFETs grown under the same conditions over sapphire, insulating SiC, and bulk GaN substrates.

In order to prepare the ''epiready'' substrate, the bulk GaN crystals were polished mechanically and chemically. Subsequently, a 5-μm-thick i-GaN layer was grown using metal–organic chemical-vapor deposition (MOCVD). The high quality of this template was verified by 1.8 K photoluminescence and x-ray measurements. The characteristic pho-

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toluminescence linewidth for bound excitons was less than 0.5 meV, which is comparable to that observed in good-quality homoepitaxial GaAs or InP layers. This indicates that inhomogeneous disorder, which is responsible for the broadening of recombination lines observed in GaN grown on SiC and sapphire, is absent in GaN layers grown on the bulk substrates. X-ray measurements showed also that the full width at half maximum of (0004) Cu $K\alpha$ reflection is of about 20 arc s. These results clearly indicate the absence of stress distribution, low dislocation density, and high material quality of homoepitaxial GaN ''epiready'' substrates.

The GaN template layer over sapphire and SiC substrates as well as the AlGaN/GaN heterostructures on all three types of substrates (sapphire, SiC, and bulk GaN) were grown by low-pressure MOCVD using a process reported earlier.[9,10] It should be noted that for sapphire and the SiC substrates, a buffer AlN layer was also grown prior to the GaN template. For our comparative studies, we deposited $Al_{0.2}Ga_{0.8}N$/GaN heterojunctions. The thicknesses of the GaN and the $Al_{0.2}Ga_{0.8}N$ barrier layer were 1 and 0.05 μm, respectively. Both the GaN and the $Al_{0.2}Ga_{0.8}N$ layers of the heterostructure were nominally undoped.

We then measured the room-temperature electron sheet density n_s and Hall mobility μ for all grown samples. The electron sheet density values for the three sample types are close to the best reported for two-dimensional (2D) gas in AlGaN/GaN heterostructures and vary between 1.3×10^{13} and $1.6\times10^{13}\,cm^{-2}$. These values are close to the maximum sheet density estimated for polarization-induced charge in undoped and fully strained $Al_{0.2}Ga_{0.8}N$/GaN heterostructures.[11,12]

The value of the $n_s\mu$ product, which is an important characteristic of the current-carrying capability of the HFETs, is nearly the same for the heterostructures grown on SiC and bulk GaN and is about 20% higher than for those grown on sapphire. The highest room-temperature mobility of 1650 $cm^2/V\,s$ was measured for homoepitaxial layers, which is about 15% higher than for the heterostructures grown on 4H–SiC. Since the estimated number of threading dislocations in the two samples differs by a factor of 10^4-10^6, the observed close values of the low-field mobility in the homoepitaxial and heteroepitaxial structures confirm strong screening of ionized impurities and other scattering centers by the high density of the 2DEG.

In order to establish the effect of dislocation scattering on electron mobility we calculated the mobility limited by dislocation scattering in the temperature range from 77 K to room temperature for different dislocation densities. The results of the calculations show that at room temperature the dislocation scattering limits the mobility at the level of $\mu \sim 1500\,cm^2/V\,s$ only when the dislocation density exceeds $10^{10}\,cm^{-2}$. At 77 K the 2DEG mobility $\mu_{77} \sim 30\,000\,cm^2/V\,s$ was measured for the bulk GaN sample. For these high values of mobility the dislocation scattering limits the mobility at much smaller dislocation densities, below $10^9\,cm^{-2}$.

Identical geometry AlGaN/GaN HFETs, with a source–drain separation of 4 μm and a gate width and length of 100 and 2 μm, respectively, were then fabricated on the three samples described above. Electron-beam-evaporated Ti(150

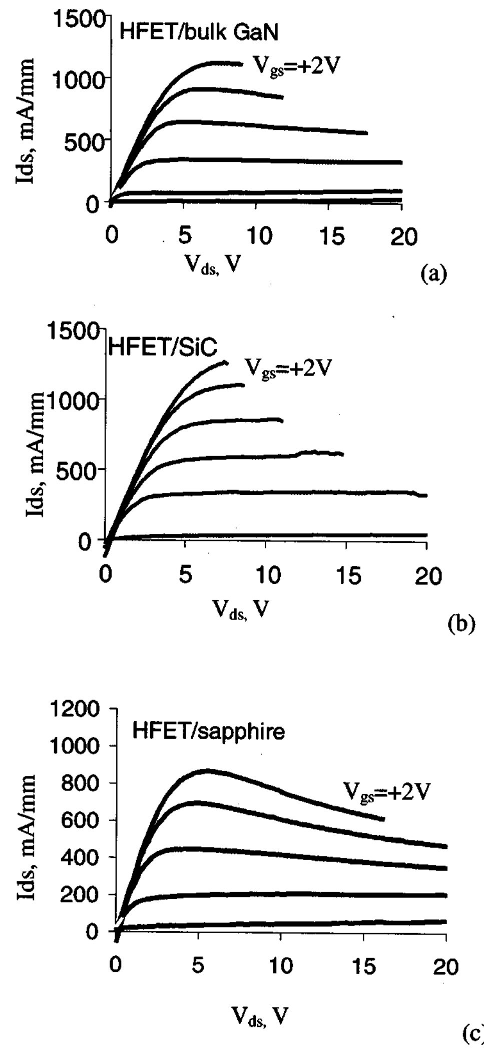

FIG. 1. Output characteristics of AlGaN/GaN HFET devices, $L_g = 2\,\mu$m $\times 100\,\mu$m. The gate sweep begins at $V_{gs} = +2$ V with -2 V steps.

A)/Al(300 A)/Ti(250 A)/Au(750 A) source–drain Ohmic contacts, annealed at 850 °C for 1 min in flowing nitrogen, were used for all the device structures. Ni(150 A)/Au(500 A) metallization was then used for the gate Schottky barrier.

In Figs. 1(a), 1(b), and 1(c), we show the room-temperature source–drain current–voltage characteristics for the HFETs on the bulk GaN, 4H–SiC, and sapphire substrates, respectively. From the data of Fig. 1, we can make several observations. First, the peak saturation currents for devices over the SiC and the bulk GaN substrates are similar and are close to 1.1 A/mm. This is to be expected based on similar values for the sheet-carrier density, mobility, and the specific-contact resistance. However, the negative slope in the current–voltage characteristics, which is usually attributed to the self-heating effects in AlGaN/GaN HFETs,[13] is the smallest for the devices grown on SiC substrates and the highest in the HFETs on sapphire. This can be explained by the highest thermal conductivity of SiC, followed by GaN and the sapphire substrates.

In Fig. 2 we compare the room-temperature transconductance for the devices on all three substrate types. The maximum transconductances for the devices on SiC, bulk GaN, and sapphire were 150, 140, and 130 mS/mm, respectively. The gate bias for the transconductance maximum shifted

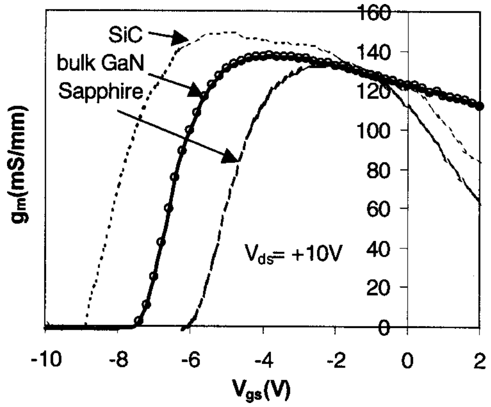

FIG. 2. HFETs transconductance vs gate-to-source voltage at drain voltage $V_{ds}=+10$ V. $Lg=2\ \mu m\times 100\ \mu m$.

from -2 V for the devices on sapphire to approximately -5 V for the HFETs on 4H–SiC. The highest threshold was measured for the devices grown on SiC and was close to $V_{th}=-9$ V. The lower threshold values for the HFETs on sapphire and bulk GaN are in a good agreement with the lower electron sheet densities in these devices. The reason for such a significant difference in the values of n_s and threshold voltages for the devices grown under the same conditions is not quite clear. One possible explanation for this effect can be the difference in the residual strain in GaN grown on different substrates. Indeed, due to the lattice mismatch, GaN structures grown on sapphire exhibit the presence of tensile strain, GaN layers on SiC are growing under compressive strain, whereas the homoepitaxial growth of GaN leads to the deposition of strain-free structures. The compressive strain in GaN layers grown on SiC substrates in combination with the tensile strain in AlGaN barriers leads to an increased total charge density in the channel and higher threshold voltage. In the same way, GaN layers grown on sapphire exhibit lower total charge density and threshold voltage.

The half width of the transconductance peak in the g_m dependence on the gate bias is larger for the device grown on bulk GaN. This linearity should translate into lower intermodulation distortions in bulk GaN-based power microwave amplifiers.

The devices grown on bulk GaN demonstrated stable performance at elevated temperatures up to 300 °C. Figure 3 shows the gate current for the HFET on the bulk GaN substrate measured at room temperature and at 300 °C. At the gate bias of -10 V (pinched-off device), the room-temperature gate leakage current was as low as 8 μA. Even at temperatures as high as 300 °C, the HFETs on bulk GaN had a gate leakage current below 20 μA, which compares to our best devices grown on SiC.[10]

In conclusion, we demonstrated homoepitaxial growth of high-quality AlGaN/GaN heterostructures with 2D electron gas over bulk GaN substrates. The obtained results indicate that at high sheet densities and high temperatures threading dislocations are screened and play only minor role in 2D electron transport. Our results also show the that thermal impedance of the substrate primarily controls the device operation, especially in the high-power regime.

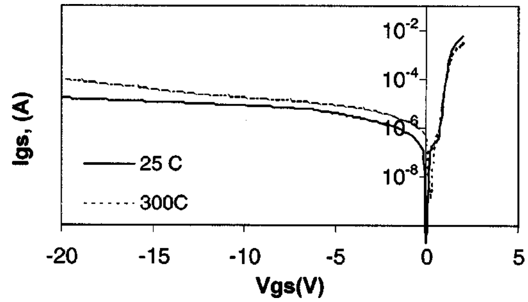

FIG. 3. Gate $I-V$ characteristics of HFET over the bulk GaN substrate at room temperature (solid line) and at 300 °C (dashed line).

The HFETs grown on bulk GaN substrates showed stable operation at temperatures as high as 300 °C and have a slightly better linearity, which might be important for their applications in power microwave amplifiers. These results clearly show the feasibility of high-performance HFET devices on bulk GaN substrates. Further studies are needed to establish noise, breakdown, and reliability of HFET devices over bulk GaN substrates.

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[1] M. Asif Khan, J. M. Van Hove, J. N. Kuznia, and D. T. Olsen, Appl. Phys. Lett. **58**, 2408 (1991); and also: M. Asif Khan, J. N. Kuznia, J. M. Van Hove, N. Pan, and N. Carter, *ibid.* **60**, 3027 (1992).
[2] M. Asif Khan, A. Bhattarai, J. N. Kuznia, and D. T. Olson, Appl. Phys. Lett. **63**, 1214 (1993).
[3] S. T. Sheppard, K. Doverspike, W. L. Pribble, S. T. Allen, and J. W. Palmour, IEEE Electron Device Lett. **20**, 161 (1999).
[4] A. T. Ping, E. Piner, J. Redwing, M. Asif Khan, and I. Adesida, Electron. Lett. **36**, 175 (2000).
[5] C. Youtsey, L. T. Romano, R. J. Molnar, and I. Adesida, Appl. Phys. Lett. **74**, 3537 (1999).
[6] S. Porowski, MRS Internet J. Nitride Semicond. Res. **4S1**, G1 (1999).
[7] M. Leszczynski, B. Beaumont, E. Frayssinet, W. Knap, P. Prystawko, T. Suski, I. Grzegory, and S. Porowski, Appl. Phys. Lett. **75**, 1276 (1999).
[8] J. L. Weyher, P. D. Brown, J. L. Rouviere, T. Wosinski, A. R. A. Zauner, and I. Grzegory, J. Cryst. Growth **210**, 151 (2000).
[9] M. Asif Khan, X. Hu, G. Simin, A. Lunev, R. Gaska, and M. S. Shur, IEEE Electron Device Lett. **21**, 63 (2000).
[10] M. Asif Khan, X. Hu, G. Simin, J. Yang, R. Gaska, and M. S. Shur, submitted for publication.
[11] M. Asif Khan, J. W. Yang, G. Simin, R. Gaska, M. S. Shur, and A. Bykhovski, Appl. Phys. Lett. **75**, 2806 (1999).
[12] A. D. Bykhovski, R. Gaska, and M. S. Shur, Appl. Phys. Lett. **73**, 3577 (1998).
[13] R. Gaska, J. Yang, A. Osinsky, and M. S. Shur, IEEE Electron Device Lett. **19**, 89 (1998).