Ultralow reverse leakage current in AlGaN/GaN lateral Schottky barrier diodes grown on bulk GaN substrate
We report on a study of AlGaN/GaN heterostructure lateral Schottky barrier diodes (L-SBDs) grown on a bulk GaN substrate. The L-SBDs exhibited an ultralow reverse leakage current below 10^{-4} A/cm² without employing any extra treatments, which was over 4 orders of magnitude lower than that of a reference device on a sapphire substrate. The superior performance was attributed to the high crystalline quality of the heterostructure achieved by homoepitaxy. The comparison also revealed that the absence of high-density trap states in the homoepitaxial L-SBD grown on the bulk GaN substrate played a key role in achieving a low reverse leakage current.
result was benchmarked with other reported AlGaN/GaN L-SBDs in the literature using different leakage reduction approaches, as listed in Table I. Our work exhibited a state-of-the-art low reverse leakage current without employing any extra treatments. The effective barrier height ($\phi_b$) and ideality factor ($n$) of the L-SBDs can be extracted from the forward bias characteristics using the standard thermionic emission mechanism.\textsuperscript{11,12} In this study, the experimental values of $\phi_b/n$ for the L-SBDs grown on the bulk GaN and sapphire substrates are 1.25 eV/1.60 and 0.96 eV/1.92, respectively. Furthermore, a much higher turn on voltage was observed for the L-SBD grown on the bulk GaN substrate when compared with that on the sapphire substrate, as shown by the linear plot of the forward currents in the inset of Fig. 1. The high turn-on voltage of the AlGaN/GaN L-SBDs could be explained by the two-diode model,\textsuperscript{18,19} where the heterojunction barrier between the AlGaN and GaN layers suppresses the forward current at a relatively high forward bias (1.5–2 V in this study). The Schottky contact with a sufficient $\phi_b$, which controls both the depletion width and carrier transport across the interface, and a low leakage current is one of the critical factors for the realization of high-performance AlGaN/GaN-based electronic devices.

The better electrical characteristics of the L-SBD grown on the bulk GaN substrate compared with that on the sapphire substrate should be attributed to the higher crystalline quality, i.e., low defect/dislocation density, of the AlGaN/GaN structure by homoepitaxy. To evaluate the defect/dislocation density quantitatively, XRD was performed for both samples. Table II shows the full widths at half maximum (FWHMs) of the $\omega$-rocking curves for the AlGaN/GaN structures grown on the bulk GaN and sapphire substrates (unit: arcsec).

The surface morphology of the two samples was investigated by AFM, as shown in Fig. 3. The AlGaN/GaN structure grown on the bulk GaN substrate showed a very smooth surface and well-aligned atomic step flow patterns, with a root-mean-square (RMS) roughness of 0.24 nm across a $5 \times 5 \mu m^2$ scanned area. In contrast, the atomic steps are disordered for the heterostructure grown on the sapphire substrate, while they did not appear for the bulk GaN substrate. The surface pits seem to be pinholes that originated from the extended dislocations to the AlGaN barrier from the buffer layer.\textsuperscript{20,21} We consider that these high-density pinholes also give rise to the large reverse leakage current and low $\phi_b$ in the L-SBD grown on the sapphire substrate.

The emission of electrons via a trap state into a continuum of states associated with the presence of conductive dislocations was the dominant leakage mechanism in an AlGaN/GaN L-SBD,\textsuperscript{11,12} which could be successfully explained by the Frenkel–Poole emission model. The current density associated with Frenkel–Poole emission is given by

$$J = C E_b \exp \left[ -\frac{\phi_T - \sqrt{E_b/\pi e E_0}}{kT} \right],$$

where $E_b$ is the electric field in the semiconductor barrier, $\phi_T$ is the barrier height for electron emission from the trap state, and $C$ is a constant. As shown in Fig. 4, the linear dependence of $\ln(J/E_b)$ on $\sqrt{E_b}$ is a proof of the Frenkel–Poole effect of the AlGaN/GaN L-SBDs in this study.
To further investigate the trapping effects in the AlGaN/GaN L-SBDs, we performed a frequency-dependent conductance analysis in the frequency range from 1 kHz to 1 MHz for both samples. Figure 5 shows the plots of parallel conductance ($G_p/\omega$) as a function of radial frequency ($\omega$) for selected gate voltages near the threshold voltage between the two L-SBDs. Two different types of trap states with short and long time constants, designated as “fast” and “slow” trap states, respectively, were identified for the L-SBD grown on the sapphire substrate [in Fig. 5(b)], while only fast trap states could be observed in the L-SBD on the bulk GaN substrate [in Fig. 5(a)]. The fast trap states in both L-SBDs exhibited similar low densities of $(1-4) \times 10^{12}$ cm$^{-2}$ eV$^{-1}$ and their time constants were in the range between 0.05 and 200 µs. However, the densities of the slow trap states found in the L-SBD on the sapphire substrate were as high as $\sim 1 \times 10^{16}$ cm$^{-2}$ eV$^{-1}$ and the time constants were relatively long, in the range of 0.04–4 s. The energy level of the slow trap states was deduced to be 0.6–0.7 eV below the conduction band according to the Shockley–Read–Hall statistics. The trap states, which are considered to result from the dislocations and nitrogen vacancies, could be located both within the AlGaN barrier and at the heterojunction interface. These high-density trap states could be the major cause of the high reverse leakage current in the L-SBD grown on the sapphire substrate, which provides a path for electron transport from the metal gate to the AlGaN barrier layer through a trap-assisted tunneling mechanism, as schematically shown in Fig. 6. However, such a leakage path in the L-SBD grown on the bulk GaN substrate has been significantly suppressed owing to the absence of high-density slow trap states. Thus, the very low reverse leakage current was experimentally obtained.

Nevertheless, the defect/dislocation density of the epitaxial structure could not be totally uniform across the whole sample even using a bulk GaN substrate. Some devices with a high reverse leakage current density of $\sim 10^{-3}$ A/cm$^2$ were found at the deflected area of the sample grown on the bulk GaN substrate. Under the microscope, some dark spots could be observed on the metal gate of the leaky devices, while they did not appear for the nonleaky ones with very low leakage currents, as shown in Fig. 7. We suspect that those dark spots could result from the surface defects and were one of the
culprits for the relatively high leakage current. This result could, in turn, be evidence of the correlation of defects with device leakage current.

In summary, on a bulk GaN substrate, we grew and fabricated an AlGaN/GaN L-SBD showing ultralow reverse leakage current density below \(10^{-6} \text{A/cm}^2\), which was over 4 orders of magnitude lower than that of the reference L-SBD grown on the sapphire substrate. Owing to the high crystalline quality and good surface morphology achieved by homoepitaxy, the high-density slow trap states were not found in the L-SBD grown on the bulk GaN substrate. As a result, the leakage path through the trap-assisted tunneling mechanism was significantly suppressed.

Acknowledgments This work was supported in part by the Research Grants Council (RGC) theme-based research scheme (TRS) of the Hong Kong Special Administrative Region Government under Grant No. T23-612/12-R and in part by the National Natural Science Foundation of China under Grant No. 51507131. The authors would like to thank the staff of NFF and MCPF of HKUST for technical support.