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Effect of threading dislocations on AlGaN/GaN heterojunction bipolar transistors

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We demonstrate an AlGaN/GaN heterojunction bipolar transistor on a substrate grown using the lateral epitaxial overgrowth (LEO) technique. Common emitter characteristics show a current gain of 3. Active layers were grown by plasma-assisted molecular-beam epitaxy on metal–organic chemical-vapor-deposition-grown templates on sapphire. The collector–emitter leakage mechanism in these devices is found to be local punch-through associated with base layer compensation near the dislocations. LEO wing regions (nondislocated) were found to reduce the emitter–collector leakage by four orders of magnitude over adjacent window regions which had a dislocation density of $10^8\ \mathrm{cm}^{-2}$. Varying the doping profile through the base confirms that the mechanism for leakage is local punch-through due to compensation. This compensation mechanism is consistent with simulations which assume a donor-state line density of $10^7\ \mathrm{cm}^{-1}$. The implications of the emitter–collector leakage for dc device characterization are also discussed. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1358358]

The past several years have seen a dramatic increase in research of GaN materials and devices. Progress has been made in areas including electronic devices such as field-effect transistors (FETs) (Ref. 1) and bipolar transistors,[2–6] as well as optoelectronics devices including light emitters, lasers,[7] and detectors.[8] GaN is desirable for electronics applications due to saturated electron velocities of 2×10^7 cm/s,[9] and its 3.4 eV band gap which leads to a critical breakdown field of 2 MV/cm (Ref. 10) and stability at high temperatures.

There have been several reports of GaN HBTs in the literature, but the results are still preliminary. A common obstacle to the development of GaN HBTs is the existence of an emitter–collector leakage path. We found this leakage to be due to a local punch-through effect surrounding threading dislocations that propagate through the device structure. The reduction in dislocation density in GaN using techniques such as lateral epitaxial overgrowth (LEO) has been shown to reduce vertical leakage in optoelectronic and electronic devices.[7,11,12] In the present study, experiments on GaN HBTs and (BJTs) were performed on LEO substrates offering adjacent regions with varying dislocation density. The compensatory nature of these dislocations was also verified by measuring leakage with varying dopant densities in the base.

Due to the lattice mismatch between GaN and sapphire or SiC, thin GaN films (≈2 μm) grown on these substrates have a threading dislocation density on the order of $5\times10^8\ \mathrm{cm}^{-2}$. To investigate the connection between threading dislocations (TDs), doping, and collector–emitter leakage currents, devices were fabricated on material grown using the LEO technique. The details of the LEO process are described by Fini *et al.*[13] LEO is well suited for this experiment because adjacent devices can be measured with and without dislocations. The window regions were 5 μm wide, repeated with a period of 40 μm. A full device structure is then grown on this sample by molecular-beam epitaxy (MBE). Over dislocated (window) regions the TDs continue, while over the wing regions, the lateral GaN growth is nearly dislocation free. Figure 1 shows the spiral MBE growth indicative of screw component TDs (Ref. 14) in the window

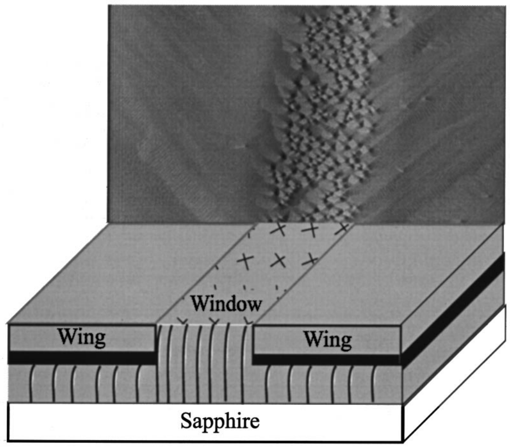

FIG. 1. Atomic-force microscopy image of a LEO substrate (above) showing window and ring regions. Spiral growth mode in the window region is associated with the screw component of threading dislocations. Wing regions consist of atomically flat steps.

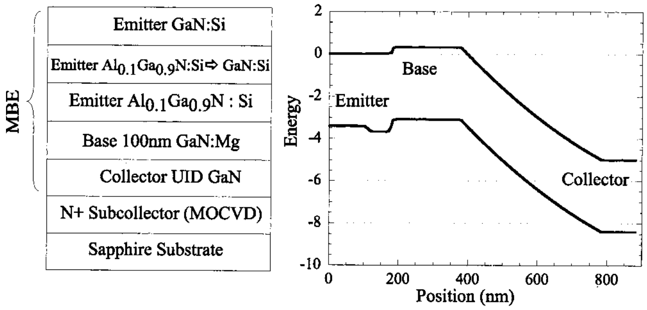

FIG. 2. Left: typical structure for an AlGaN/GaN HBT grown by plasma-assisted MBE on a MOCVD GaN on sapphire. The collector is unintentionally doped (UID) GaN $N_D \approx 10^{17}\,\mathrm{cm}^{-3}$. Right: simulated band diagram of typical device. The $\mathrm{Al_{0.1}Ga_{0.9}N}$ heterojunction provides 10 kT barrier-to-hole injection into the emitter.

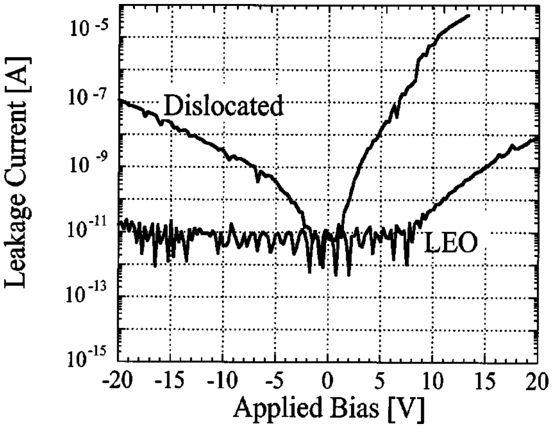

FIG. 3. Leakage current of the LEO window compared to the wing region. The plot shows reduction of leakage by four orders of magnitude for the wing region as compared to the window region.

region, and the lack of this spiral growth mode on the wing regions, indicative of low TD density in the wing.

Several device structures were used to investigate the role of dislocations on emitter/collector leakage. In addition to the HBT structure shown in Fig. 2, two BJT structures were used with thicker base layers (150 nm) and varying base dopant concentrations. Device structures were grown by plasma-assisted MBE on metal–organic chemical-vapor-deposition (MOCVD) GaN templates on sapphire. The emitter was $\mathrm{Al_{0.1}Ga_{0.9}N{:}Si}(N_D = 10^{18}\,\mathrm{cm}^{-3})$ with a GaN:Si emitter contact layer. The base layer was 100 nm GaN:Mg, $N_A = 1\times10^{19}\,\mathrm{cm}^{-3}$. Magnesium is a deep acceptor, $E_A - E_V \approx 110-200\,\mathrm{meV}$,[15] resulting in a carrier concentration of $p = 2\times10^{17}\,\mathrm{cm}^{-3}$ for this acceptor density. The collector was 500 nm unintentionally doped (UID) GaN with a background donor concentration of $5\times10^{18}\,\mathrm{cm}^{-3}$. The subcollector was GaN:Si, $N_D = 10^{18}\,\mathrm{cm}^{-3}$. Emitter and collector contacts were Ti/Al/Ni/Au, while the base contacts were Pd/Au. Emitter and base mesas are etched with a chlorine reactive ion etch. The emitter mesa area was 300 $\mu\mathrm{m}^2$ and the base mesa area was 1725 $\mu\mathrm{m}^2$.

Holes in GaN, with an effective mass of $2.2m_0$,[16] were measured to have mobilities between 5 and 20 $\mathrm{cm^2(V\,s)^{-1}}$ in highly doped GaN:Mg layers. Consequently, the base of an NPN transistor is expected to have a resistivity on the order of 1 Ω cm, with a sheet resistivity for a 100 nm base of 100 $\mathrm{k}\Omega/\square$. This is significant even for devices tested at dc, because the resistance causes severe current crowding in the emitter as well as a large lateral voltage differential in the base. This lateral voltage difference in the base causes a large collector current offset voltage in the common emitter configuration, as well as causing emitter–collector leakage currents during a Gummel plot measurement, even if the base–collector contact voltages are zero.

The collector–emitter leakage of adjacent devices (Fig. 3) was seen to drop by four orders of magnitude in the forward direction on the wing relative to the window region of the LEO substrate. Common-emitter characteristics of HBT on a wing region are shown in Fig. 4. The gain of the wing device is comparable to devices in the window (dislocated) regions. This result suggests that although dislocations are the dominant cause of collector–emitter leakage in these devices, at the present levels ($10^8\,\mathrm{cm}^{-2}$) they are not the cause of the high recombination rates in the base, which are expected to be related to the high Mg concentration ($10^{20}\,\mathrm{cm}^{-3}$), high levels of point defects, and a high surface recombination rate at the sidewall.

The mechanism for collector–emitter leakage is found to be a localized punch-through effect. The literature suggests that in *n*-type material TDs behave as electron traps, negatively charged when filled. In *p*-type material, the TDs are expected to behave as donors, or hole traps, and thus be positively charged.[17] A recurring problem with GaN HBTs has been the presence of significant collector–emitter leakage.[5,6] The GaN HBT on LEO shows the connection between dislocations and leakage. A hypothesis was developed for the mechanism of this leakage using the following model: We examine the case where each TD contributes a line of charge in *p*-type GaN equivalent to one donor for every 10 Å vertically (about 1/2 the lattice sites), or $10^7\,\mathrm{cm}^{-1}$. We simulated this one-dimensionally as a column doped *n*-type at $3\times10^{20}\,\mathrm{cm}^{-3}$ and having a radius of 1 nm. This radius was chosen in conjunction with the three-dimensional doping density to approximate a line of charge. Figure 5 shows the effect of this local compensation on the *p*-type base. The result of this compensation in moderately doped cases ($N_A = 10^{19} \Rightarrow p = 10^{17}\,\mathrm{cm}^{-3}$) is a device that is shorted from collector to emitter. When the base doping concentration is sufficiently high ($N_A = 10^{20} \Rightarrow p = 10^{18}\,\mathrm{cm}^{-3}$), however, a barrier remains to prevent the short. This result is confirmed by an experiment in which two devices were fabricated, both with lightly doped bases ($N_A = 10^{19} \Rightarrow p$

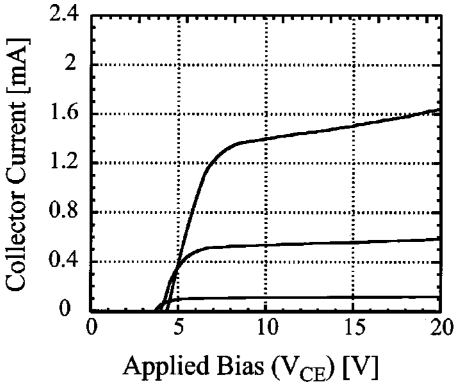

FIG. 4. Common-emitter characteristics of the GaN HBT on the LEO wing (nondislocated region). Base current steps are 400 μA.

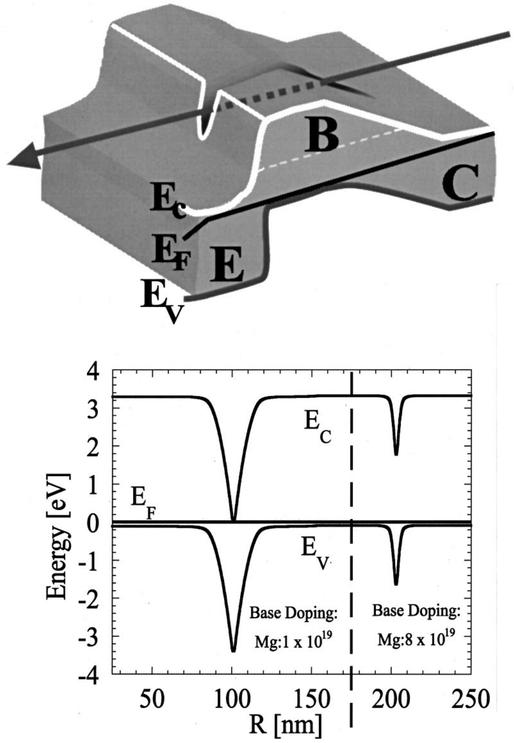

FIG. 5. Above: Three-dimensional rendering of the band diagram of a HBT with a dislocation (arrow) causing local compensation of the *p*-type base. Below: Simulation of the band diagram of a locally compensated area surrounding a dislocation in *p*-type GaN. A lightly doped base (left) is fully compensated near the dislocation, while a heavily doped base (right) is only partially compensated.

$=10^{17}\,\mathrm{cm}^{-3}$) 100 nm thick, on areas of the same template with approximately the same dislocation density ($5\times10^{8}\,\mathrm{cm}^{-2}$). One of the samples was grown with a 15 nm p^{+}($N_A=10^{20}\Rightarrow p=10^{18}\,\mathrm{cm}^{-3}$) spike in the center of the base to block emitter/collector leakage. The results of this experiment (Fig. 6) show that the heavily doped spike in the neutral region of the base eliminated the emitter–collector short, confirming that the mechanism for emitter–collector leakage is the local compensation of the base layer. Although in this case the dislocations were found to be the dominant source of emitter–collector leakage, it should be noted that surface states and mesa sidewall damage may lead to emitter–base and base–collector leakage currents in addition to the dislocation-induced leakage paths.

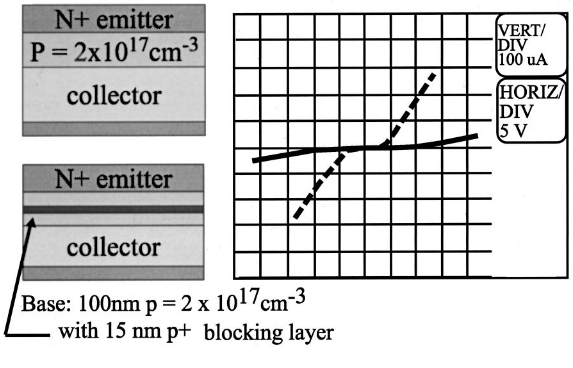

FIG. 6. Emitter–collector leakage is reduced by the addition of a p^{+} spike in the neutral base of a transistor structure.

The demonstration of a GaN HBT on a LEO substrate shows a connection between threading dislocations and collector–emitter leakage. As in other devices on GaN, threading dislocations are found to contribute to vertical leakage paths in HBTs. The leakage is caused by local compensation of the base material near the dislocation, and results in a punch-through from the collector to emitter under bias. In addition to dissipating power and possibly contributing to device degradation, this leakage can also cause erroneous information from Gummel plots and common base device measurements. Because of a large voltage drop across the base contact, the collector/base bias under the emitter is substantially higher than the bias under the base contact. This results in emitter–collector leakage when the base–collector contact voltage is zero, providing a forward current, which may appear in a Gummel plot as current gain. For this reason, only the common-emitter configuration, which requires low output conductance in the device, is reliable for establishing the current gain of the device. Although the current gain of these devices is not limited by the dislocation density, it is clear from these results that for working devices, dislocation densities must be reduced.

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