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Cite as: Appl. Phys. Lett. **74**, 2702 (1999); <https://doi.org/10.1063/1.123942>

Submitted: 01 February 1999 . Accepted: 08 March 1999 . Published Online: 27 April 1999

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Growth and fabrication of GaN/AlGaN heterojunction bipolar transistor

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(Received 1 February 1999; accepted for publication 8 March 1999)

A GaN/AlGaN heterojunction bipolar transistor structure with Mg doping in the base and Si doping in the emitter and collector regions was grown by metalorganic chemical vapor deposition on *c*-axis Al₂O₃. Secondary ion mass spectrometry measurements showed no increase in the O concentration ($2-3 \times 10^{18} \text{ cm}^{-3}$) in the AlGaN emitter and fairly low levels of C ($\sim 4-5 \times 10^{17} \text{ cm}^{-3}$) throughout the structure. Due to the nonohmic behavior of the base contact at room temperature, the current gain of large area ($\sim 90 \mu\text{m}$ diameter) devices was < 3 . Increasing the device operating temperature led to higher ionization fractions of the Mg acceptors in the base, and current gains of ~ 10 were obtained at 300 °C. © 1999 American Institute of Physics. [S0003-6951(99)02218-4]

There is a strong interest in GaN-based electronics for applications involving high temperature or high power operation, based on the excellent transport properties of the III-nitride materials system.¹⁻⁷ Impressive advances in the performance of AlGaN/GaN high electron mobility transistors continue to be reported, due in part to the formation of piezoelectrically induced carriers in a two-dimensional electron gas at the heterointerface.⁵⁻¹⁶ There is also interest in the development of GaN/AlGaN heterojunction bipolar transistors (HBTs) to meet the linearity requirements of some future electromagnetic systems, particularly for military applications where ultrawide bandwidth and linearity are key issues. In these vertical device structures, minority carrier lifetime,¹⁷ interface quality and doping control are important factors.⁵

There have been two recent reports on initial GaN/AlGaN HBTs.^{18,19} In one case, extrinsic base regions were grown by metalorganic chemical vapor deposition (MOCVD) before base mesa etching to contact the collector. This was performed to overcome the high base resistance arising from the relatively low hole concentration (typically $\leq 10^{18} \text{ cm}^{-3}$) achievable in GaN (Mg).¹⁸ Devices with $3 \times 20 \mu\text{m}^2$ emitters produced a dc current gain at 25 °C of ~ 3 . In the other report, the active layer structure was grown by rf plasma-assisted molecular beam epitaxy (MBE) on top of a MOCVD buffer.¹⁹ Large area (90 μm diameter) devices were fabricated by a low damage dry etch process similar to that developed for GaAs/AlGaAs HBTs. The dc gain at 25 °C was in the range 1-3, but increasing the operation temperature to 300 °C produced a gain of ~ 10 by increasing the ionization efficiency of the Mg acceptors in the base layer.

In this letter we report on the growth by MOCVD of a

graded emitter HBT structure, the measurement of typical background impurities (C, O, H) by secondary ion mass spectrometry (SIMS) (since these could potentially have a strong influence on device performance), and finally on the dc characteristics of HBTs fabricated on this material.

The layer structure is shown schematically in Fig. 1, and was grown at $\sim 1050 \text{ °C}$ following deposition of the GaN buffer at $\sim 550 \text{ °C}$ on the *c*-plane Al₂O₃ substrate. The growth system has been described in detail previously,²⁰ but in brief is a quartz-walled rotating (1200 rpm) disk MOCVD reactor. Ammonia (NH₃), trimethylgallium (TMGa) and trimethylaluminum (TMAI) were used as precursors, while silane (SiH₄) and bis-cyclopentadienyl-magnesium (Cp₂Mg) were employed for *n*- and *p*-type doping, respectively. High purity H₂ was used as the carrier gas. Both *p*- and *n*-type GaN was grown at 140 Torr while AlGaN was grown at 80 Torr. After growth the sample was annealed at 1050 °C for 7-10 s under flowing N₂ to activate the Mg acceptors.²¹ Separate Hall-effect measurements on a 1.5 μm *p*-GaN grown at the same condition as that employed in the base region yielded a free hole concentration of $7 \times 10^{17} \text{ cm}^{-3}$ at 300 K.

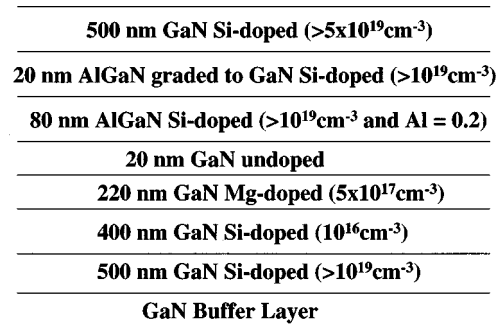


FIG. 1. Schematic of GaN/AlGaN HBT structure.

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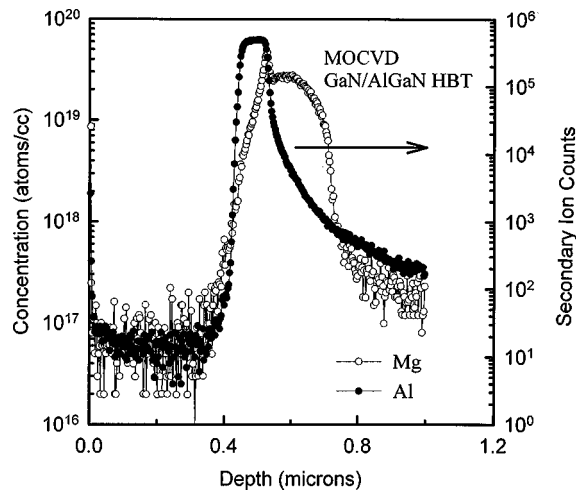


FIG. 2. SIMS profiles of Mg in the GaN/AlGaIn structure.

There are two important aspects to dopant and background impurity control in HBT structures. The first is that the *p*-type dopant should be rapidly switched on and off around the base region, and not spill over into the adjacent *n*-type AlGaIn emitter, where it could cause displacement of the junction and hence the loss of the advantage of the heterostructure. Figure 2 shows SIMS profiles of the Al marker (solid circle), signifying the position of AlGaIn emitter layer, and also the Mg doping profile (open circle) in the adjacent base layer. The so-called “memory effect” associated with the use of Cp_2Mg^{21} is illustrated by the appearance of a spike-like feature in the Mg profile after the Cp_2Mg has been switched off. We note that growth rate for the *n*-AlGaIn emitter ($\sim 0.4 \mu\text{m/h}$) is about three times less than that for the *p*-GaN base ($\sim 1.2 \mu\text{m/h}$), this would explain the observed enhancement (or spiking) of Mg incorporation during the initial base-emitter transition. It is clear that the reactor memory effect for Cp_2Mg has produced incorporation of Mg in the emitter, although the real situation is not quite as severe as it seems in the data because of “carry over” of the matrix Al signal during the depth profiling. The fact that HBT characteristics can still be obtained on this material means there is a net surplus of donor over acceptors, and thus not all of the Mg can be electrically active in the AlGaIn. In addition, the Mg has a large ionization level (170 meV)²² and only a few percent will contribute holes in the base region.

The second aspect of impurity control is to minimize the concentration of O (which probably creates a shallow donor state in GaN),²³ C (which may lead to compensated material) and H (which can passivate the Mg acceptors in the base).²⁴ Figure 3 shows SIMS profiles for these elements, as well as for the intentional Si doping. Note that the C concentration throughout most of the structure is well below that of the Si, suggesting it will have no significant effect on the electrical properties of the material. The O concentration is also relatively constant and at a density well below that of the Si. Note that residual hydrogen still decorates the Mg doping in the base, but since a reactivation anneal was performed, the hydrogen most likely is in the form of electrically inactive molecules or larger clusters, through the reactions

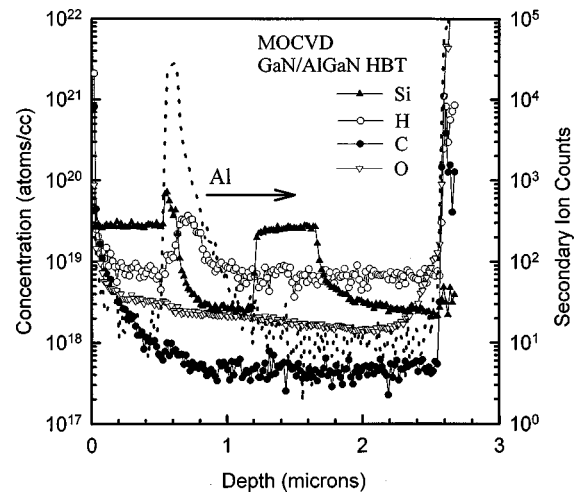
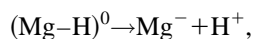
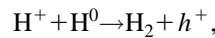
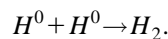


FIG. 3. SIMS profiles of Si, C, O and H in the GaN/AlGaIn structure.



or



These are in analogy with the behavior of hydrogen in other *p*-type semiconductors.²⁵ The concentrations of oxygen and carbon in GaN are a factor of 3–5 higher than that in comparable GaAs/AlGaAs HBTs.²⁶ It remains to be established as to the relative contributions of background impurities and structural defects to degradation of gain in GaN/AlGaIn HBTs.

A Gummel plot from a 90 μm diam device operated at 300 °C is shown in Fig. 4. The maximum gain is ~ 10 , similar to the previous report.¹⁹ In general, we could not obtain common-emitter characteristics, because the resistance of the extrinsic base region is too high to achieve modulation. The performance of the HBT is dominated by this high base resistance, and the resultant high specific contact resistivity of the ohmic metallization. At room temperature the alloyed (700 °C, 30 s) Ni/Au is rectifying (Fig. 5). However, as the measurement temperature is increased the *p* contact becomes ohmic, concomitant with the improved performance of the device. From separate transmission line measurements, we determined the specific contact resistivity to be in the $10^{-2} \Omega \text{cm}^2$ range at 300 °C.

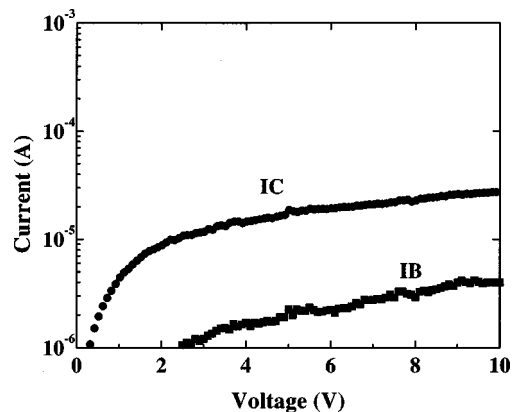


FIG. 4. Gummel plot of GaN/AlGaIn HBT measured at 300 °C.

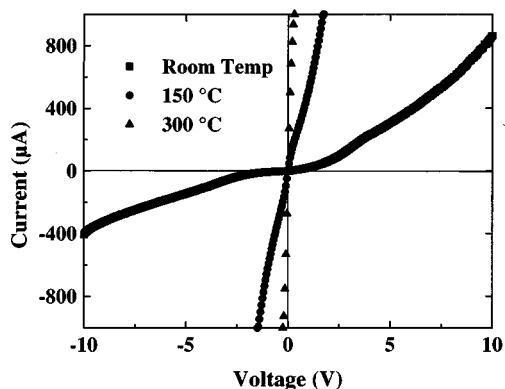


FIG. 5. I - V characteristics for Ni/Au base contact at different measurement temperatures.

In conclusion, we have shown that even in high quality GaN/AlGaIn heterojunctions with relatively low background concentration of C, O and H, the HBT device performance is dominated by the high base resistance; this should be a focus for future development work.

Sandia is a multiprogram laboratory operated for the U.S. Department of Energy by Sandia Corporation, a Lockheed-Martin company, under Grant No. DEAC04-94-AL-85000. The work at UF is partially supported by a DARPA/EPRI Grant (D. Radack and J. Melcher), No. MDA 972-98-1-0006, and by an ONR Grant (No. N00014-98-1-0204) monitored by J. C. Zolper. The work of R.G.W. is partially supported by an ARO grant (J. M. Zavada).

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