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The First Wafer-fused AlGaAs-GaAs-GaN Heterojunction Bipolar Transistor

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ABSTRACT

We describe the use of wafer fusion to form a heterojunction bipolar transistor (HBT), with an AlGaAs-GaAs emitter-base fused to a GaN collector. In this way, we hope to make use of both the high breakdown voltage of the GaN and the high mobility of the technologically more mature GaAs-based materials. This paper reports the first dc device characteristics of a wafer-fused transistor, and demonstrates the potential of wafer fusion for forming electronically active, lattice-mismatched heterojunctions. Devices utilized a thick base (0.15um) and exhibited limited common-emitter current gain (0.2-0.5) at an output current density of ~100A/cm^2. Devices were operated to V_{CE} greater than 20V, with a low V_{CE} offset (1V). Improvements in both device structure and wafer fusion conditions should provide further improvements in HBT performance. The HBT was wafer-fused at 750^{o}C for one hour. Current-voltage characteristics of wafer-fused p-GaAs/n-GaN diodes suggest that the fusion temperature could be reduced to 500^{o}C. Such a reduction in process temperature should mitigate detrimental diffusion effects in future HBTs.

INTRODUCTION

The large breakdown field and anticipated saturation velocity of GaN make this novel material particularly promising for high-frequency, high-power devices. With this goal in mind, quite a few researchers are working to develop GaN-based heterojunction bipolar transistors (HBTs).[1,2,3,4,5] Although results have been promising, there are still a number of outstanding materials issues. For example, AlGaN/GaN HBTs appear to be limited by large acceptor ionization energies and low hole mobilities.[6]

An HBT structure utilizing AlGaAs-GaAs for the emitter-base, with GaN as the collector, could potentially combine the high-breakdown voltage of GaN with the high mobility of the technologically mature AlGaAs-GaAs heterostructure. Because the high degree of lattice mismatch between GaAs (lattice constant of 5.65A) and GaN (3.19A) precludes an all-epitaxial formation of this device, we have formed the GaAs-GaN heterostructure via the novel technique of wafer fusion, also called direct wafer bonding. The HBT demonstrates a modest current output and a current gain less than unity; however, the common-emitter I-V characteristic and Gummel plot are promising for the first wafer-fused HBT. Optimization of device structure and fusion conditions should improve electrical performance.

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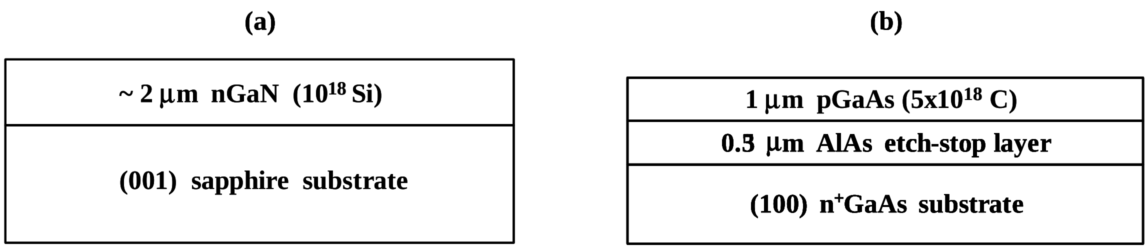

Figure 1. Starting materials for the diode structures: (a) the n-GaN structure grown by MOCVD, and (b) the p-GaAs structure grown by MBE.

DEVICE STRUCTURE AND FABRICATION

Two device structures were studied, a wafer-fused p-GaAs/n-GaN diode and an AlGaAs/GaAs/GaN HBT. Diode starting materials are shown in Figure 1 and HBT starting materials are depicted in Figure 2. The AlGaAs-GaAs emitter-base was grown by molecular beam epitaxy (MBE) at 585°C in a Varian Gen-II system. Carbon, rather than beryllium, was chosen as the p-type dopant in order to minimize dopant diffusion during the high-temperature fusion procedure. The GaN collector (unintentionally doped and nominally n-type) was grown by metal-organic chemical vapor deposition (MOCVD) on c-plane (0001) sapphire at 1160°C.

Prior to fusion "escape channels" were etched into GaAs, to prevent liquid and gas from being trapped at the interface when GaAs and GaN were later brought together. The wafers were cleaved into rectangles (5-10mm) and cleaned with acetone and isopropanol. In order to minimize surface contamination, the wafers underwent two sequential oxidation steps (first by oxygen plasma, then by UV-ozone) and oxide removal steps (in NH_4OH). GaN and GaAs were rinsed in methanol, joined together in methanol, and annealed ("wafer-fused") for 1 hour under a uniaxial pressure of 2 MPa in a nitrogen ambient. The HBT structure was fused at 750°C. The diode structures were fused over a wide range of systematically varied temperatures (500-750°C). Wafer-fused interfaces can be disordered on the scale of several monolayers (often with amorphous layers, probably oxides). By high resolution transmission electron microscopy

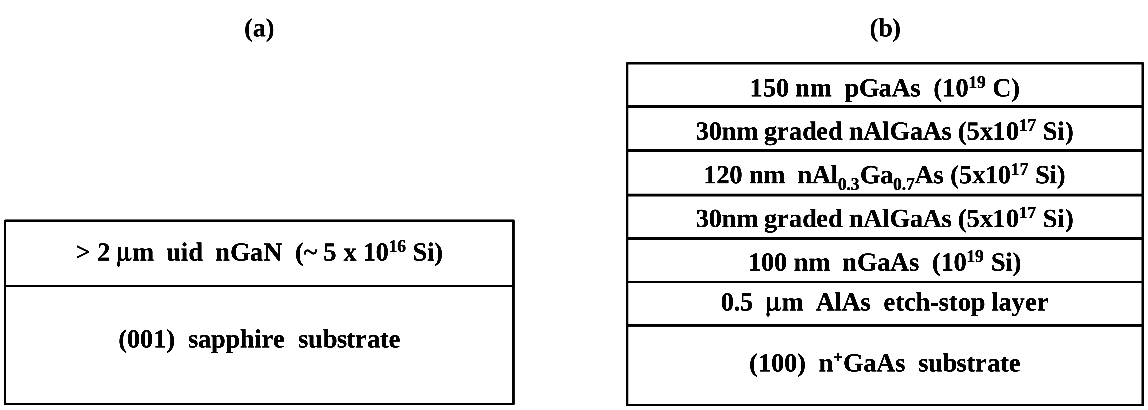

Figure 2. Starting materials for the HBT: (a) the n-GaN collector structure grown by MOCVD, and (b) the n-AlGaAs/p-GaAs emitter-base structure grown by MBE.

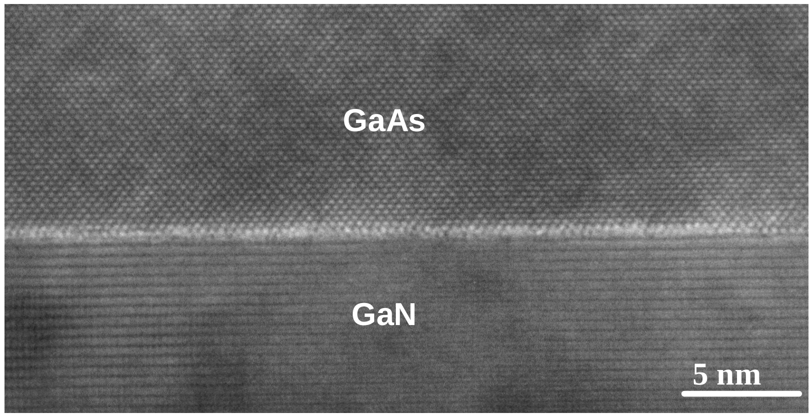

Figure 3. Cross-sectional image of the wafer-fused GaAs-GaN interface, obtained via high resolution transmission electron microscopy, in collaboration with J. Jasinski and Z. Liliental-Weber at Lawrence Berkeley National Laboratory in Berkeley, California.

(Figure 3), it was determined that our GaAs-GaN interface fused at 750^oC for 0.25-1 hour exhibits disorder which is limited to 5-10A.[7]

After fusion the GaAs substrate was removed via wet etching in H_2O_2:NH_4OH. This selective etch terminated at the AlAs layer, which was subsequently removed in HF. For the HBT structure, n-GaAs emitter contacts were AuGeNi annealed at 415^oC. Emitter mesas ($1x10^{-5}cm^2$) and base mesas ($5x10^{-5}cm^2$) were defined via wet etching in H_3PO_4:H_2O_2:H_2O. For the diode structures, larger p-GaAs mesas ($100x100um^2$) were wet-etched. For both the diode and HBT device structures, p-GaAs contacts were ZnAu and n-GaN contacts were AlAu.

DISCUSSION

Figures 4 and 5 display the common-emitter current-voltage characteristic and Gummel plot. The output current density is a modest but encouraging ~100A/cm^2. The low V_{CE} offset (1V) indicates low parasitic resistance. The offset can be further decreased by annealing the base contacts. Most prominently, the current gain is less than one, and it is important to understand the major limitations of the current gain.

Wafer fusion has proven to be effective in forming a number of heterogeneous devices from lattice-mismatched materials. These devices include GaAs-InP vertical-cavity[8] and microdisk[9] lasers, InGaAs-Si photodetectors,[10] and InGaAsP-AlGaAs photonic crystal lasers[11]. However, the device demonstrated here places stringent demands on the electronic quality of the fused interface, as it serves also as the base-collector junction of an HBT. Uncontrolled bond reconstruction or residual impurities at the fused interface can produce electronic traps, which in turn may produce the less than unity common-emitter current gain observed in these devices. Aside from the issue of bond reconstruction at the fused interface, the elevated temperature of the fusion process (750^oC) may itself accelerate dopant and defect diffusion, degrading the entire material structure. We note that the fusion temperature is much higher than the growth temperature of the AlGaAs-GaAs materials (585^oC). Fusion at lower temperatures should mitigate the effects of defect and dopant diffusion. Additionally, reduced dopant diffusion

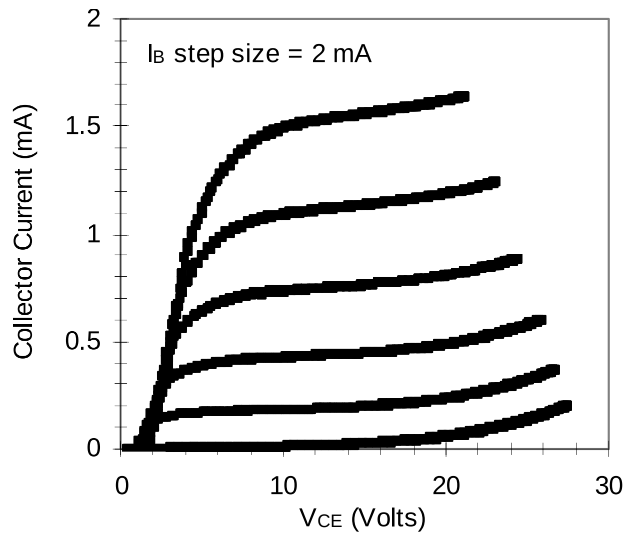

Figure 4. Room-temperature common-emitter current-voltage characteristic for the wafer-fused n-AlGaAs/p-GaAs/n-GaN HBT.

would allow a thinner base, which should reduce base recombination and improve current gain. (In this initial study the p-GaAs base was designed to be thick enough to prevent complete dopant compensation, as dopants cross-diffused across the emitter-base and base-collector interfaces during the high-temperature fusion process.) Our work with wafer-fused GaAs-GaN diodes (Figure 6) suggests that a dramatically reduced temperature (500^{o}C) should still be sufficient in fusing a mechanically stable, electronically active base-collector junction in future HBTs.

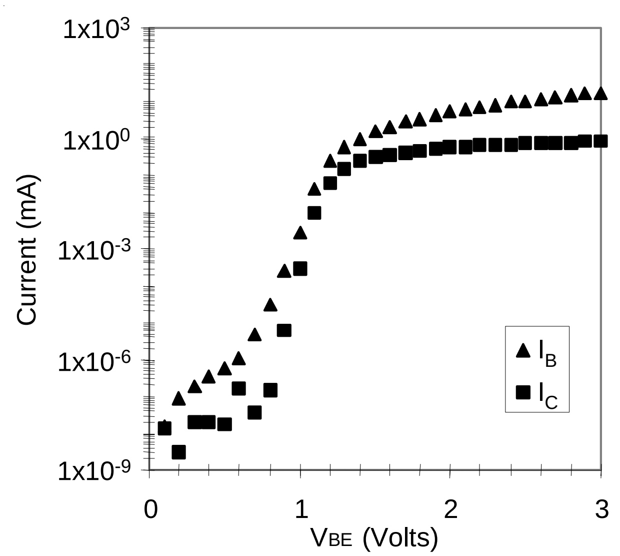

Figure 5. Room-temperature Gummel plot for the wafer-fused n-AlGaAs/p-GaAs/n-GaN HBT.

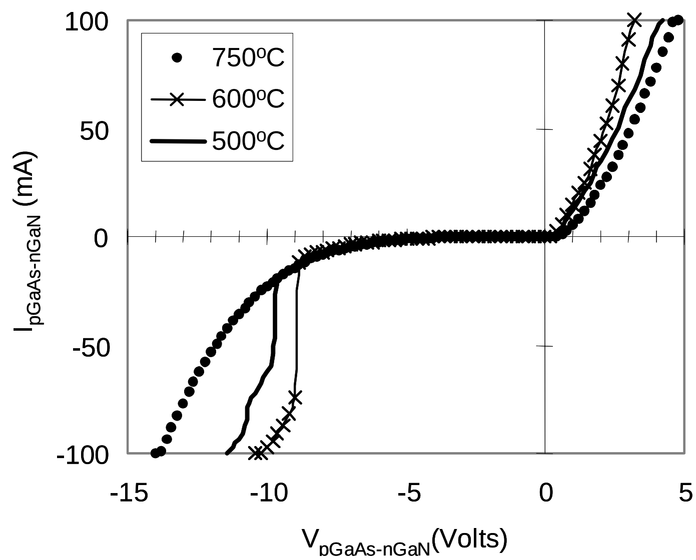

Figure 6. Room-temperature current-voltage characteristic of the p-GaAs/n-GaN diode, wafer-fused over a wide range of systematically varied fusion temperatures (500-750^{o}C).

Moreover, the true GaAs-GaN band gap offset is unknown. It may be that the GaAs-GaN heterojunction (regardless of any fusion-induced conduction band barriers) has a natural barrier or spike in the conduction band, which would also limit collector current and hence current gain. In future work, our HBT will include a setback layer at the base-collector junction. The setback should shift the fused GaAs-GaN interface slightly into the collector, decreasing the barrier prior to the possible spike at the fused GaAs-GaN junction, potentially improving collector current.

CONCLUSIONS

This study demonstrated the first n-AlGaAs/p-GaAs/n-GaN HBT, in which the lattice-mismatched GaAs-GaN junction was achieved via wafer fusion. The devices displayed low V_{CE} offset, with a less-than-unity common-emitter current gain. This initial attempt at a wafer-fused HBT provided promising results, with expected improvements in future investigations as we introduce a base-collector setback layer, decrease fusion temperature, and utilize a thinner base. Our work with wafer-fused p-GaAs/n-GaN diodes suggests that the fusion temperature could be reduced to 500^{o}C, which should mitigate detrimental diffusion effects in future HBTs. We believe that these experiments will provide much insight into the applicability of wafer fusion for electronically active, lattice-mismatched heterojunctions, especially involving GaN.

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