Mat. Res. Soc. Symp. Proc. Vol. 798 © 2004 Materials Research Society

Wafer-fused n-AlGaAs/p-GaAs/n-GaN Heterojunction Bipolar Transistor with uid-GaAs Base-Collector Setback

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ABSTRACT

Recently we reported the first AlGaAs-GaAs-GaN heterojunction bipolar transistor (HBT), a device that potentially combines the high-breakdown voltage of an n-GaN collector with the high mobility of an AlGaAs-GaAs emitter-base.[1,2] Because of the high degree of lattice mismatch between GaAs (lattice constant of 5.65A) and GaN (3.19A), we formed these devices through wafer fusion, also called direct wafer bonding. Measurements on the first generations of wafer fused HBTs revealed good current modulation, with modest output current (0.83 KA/cm^2) and a current gain of 1.2.[3] Limitations to the current gain may be related to traps and defects introduced by the fusion process, or may be a consequence of the natural conduction band offset between GaAs and GaN, which is not well known. This paper describes our new HBT structure that included a thin (20nm) uid-GaAs base-collector "setback" layer. The setback layer shifted the fused GaAs-GaN interface slightly into the collector. This new HBT structure also incorporated a reduced base thickness of 100 nm. HBTs with setback layers demonstrate increased output current (1.7 KA/cm^2) and increased current gain (1.9).

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).[4-9] Although results thus far 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.[4] We describe the use of wafer fusion to form HBTs with an AlGaAs-GaAs emitter-base and 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. 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 fabricate the GaAs-GaN heterostructure via the novel technique of wafer fusion.

Our previous work on the wafer-fused (Al)GaAs-GaN HBTs identified the range of fusing conditions and temperatures to produce devices with modest output current and gain (1.2). In further improvements of the device performance, it is important to understand whether the principal limitations to increased gain arise from defects, traps, and interface discontinuities associated with the wafer fusing process, or whether other means of bandgap engineering and device design can be used. The conduction band offset (ΔE_C) of the wafer-fused GaAs-GaN heterojunction is unknown. However, preliminary measurements and calculations indicated that a positive ΔE_C is likely.[1,2] This positive ΔE_C would seriously impede current flow across the base-collector junction even in the absence of any defects or traps. To counteract a positive ΔE_C, our new device structure included a uid-GaAs base-collector "setback" layer. By decreasing the barrier in the conduction band at the base-collector junction, this new device structure increased collector current and hence current gain.

EXPERIMENT

Starting materials are depicted in Figure 1. The AlGaAs-GaAs emitter-base structure was grown by molecular beam epitaxy (MBE) at 585°C in a Varian Gen-II system. Carbon, rather than beryllium, was used as the p-GaAs dopant in order to minimize dopant diffusion during the high-temperature fusion procedure. The GaN collector structure was grown by metal-organic chemical vapor deposition (MOCVD) on c-plane (0001) sapphire at 1160°C. AlGaAs-GaAs and GaN were cleaved into rectangles (5-10mm), cleaned, rinsed in methanol, joined together in

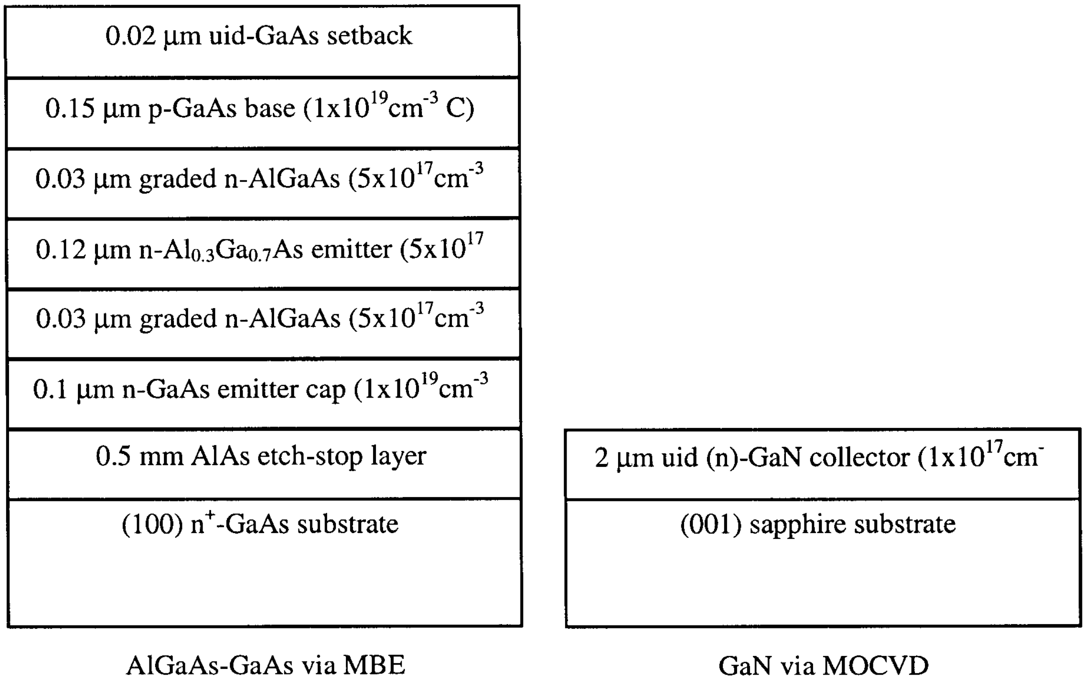


Figure 1. Starting materials for the wafer fusion of the third-generation n-AlGaAs/p-GaAs/n-GaN HBT. In the formation of the HBT, the GaAs and GaN top surfaces are fused together, and then the GaAs substrate and AlAs etch-stop layer are sequentially removed.

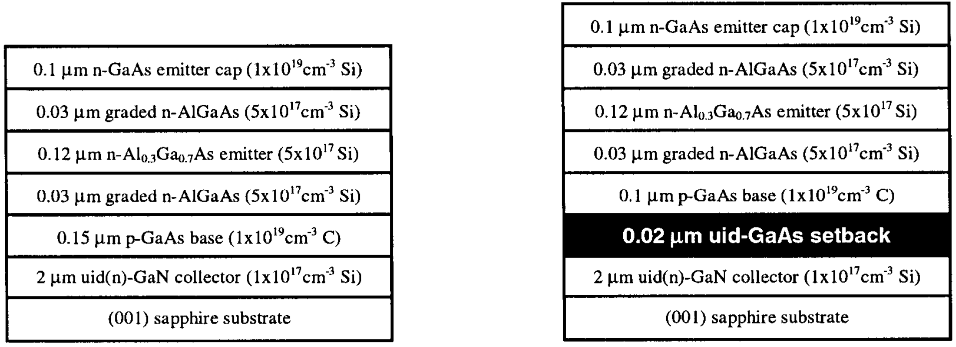
methanol, and annealed ("wafer-fused") for one hour under a uniaxial pressure of 2 MPa in a nitrogen ambient. HBTs were fused over a wide range of systematically varied temperatures (550-750°C).

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. n-AlGaAs emitter mesas ($1x10^{-5}cm^2$) and p-GaAs base mesas ($5x10^{-5}cm^2$) were defined via wet etching in H_3PO_4:H_2O_2:H_2O. n-GaAs contacts were AuGeNi annealed at 415°C, p-GaAs contacts were ZnAu, and n-GaN contacts were unannealed AlAu.

RESULTS & CONCLUSIONS

This study demonstrated improved HBT electrical performance, due to the addition of a uid-GaAs base-collector setback layer. Figure 2 shows the materials structures and the common-

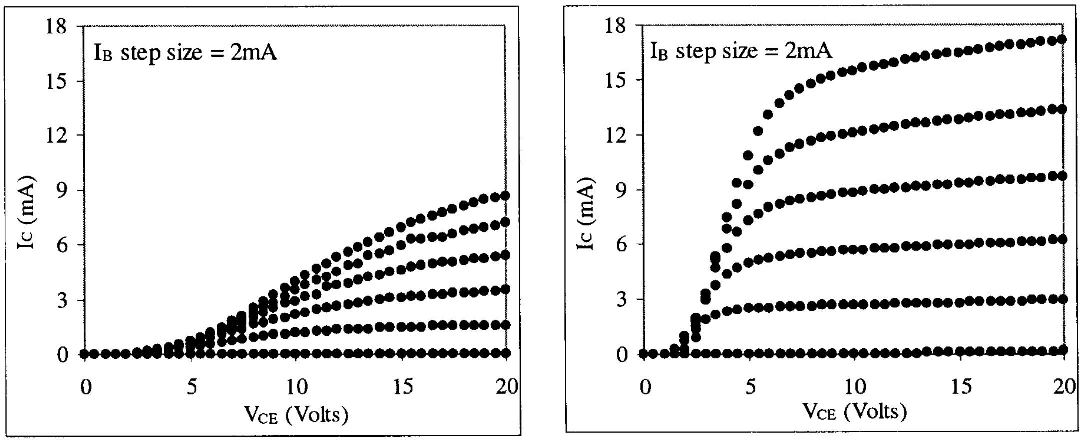
(a) Materials structures



0.1 μm n-GaAs emitter cap ($1x10^{19}cm^{-3}$ Si)
0.03 μm graded n-AlGaAs ($5x10^{17}cm^{-3}$ Si)
0.12 μm n-$Al_{0.3}Ga_{0.7}As$ emitter ($5x10^{17}$ Si)
0.03 μm graded n-AlGaAs ($5x10^{17}cm^{-3}$ Si)
0.15 μm p-GaAs base ($1x10^{19}cm^{-3}$ C)
2 μm uid(n)-GaN collector ($1x10^{17}cm^{-3}$ Si)
(001) sapphire substrate

0.1 μm n-GaAs emitter cap ($1x10^{19}cm^{-3}$ Si)
0.03 μm graded n-AlGaAs ($5x10^{17}cm^{-3}$ Si)
0.12 μm n-$Al_{0.3}Ga_{0.7}As$ emitter ($5x10^{17}$ Si)
0.03 μm graded n-AlGaAs ($5x10^{17}cm^{-3}$ Si)
0.1 μm p-GaAs base ($1x10^{19}cm^{-3}$ C)
0.02 μm uid-GaAs setback
2 μm uid(n)-GaN collector ($1x10^{17}cm^{-3}$ Si)
(001) sapphire substrate

(b) Common-emitter characteristics



(i) Generation 2 HBT [3]

(ii) Generation 3 HBT

Figure 2. (a) Materials structures and (b) common-emitter characteristics of (i) Generation 2 and (ii) Generation 3 HBTs fused at 600°C. Generation 2 HBTs have no base-collector setback layer and have a thicker base.

emitter characteristics for Generation 2 and 3 HBTs fused at 600°C for one hour. Both generations of HBT devices were operable to a V_{CE} of 40V without breakdown. Devices were not tested at a V_{CE} greater than 40V, due to limitations of the testing equipment. A more detailed study of second-generation HBTs has been published elsewhere.[3] Unlike Generation 2, Generation 3 HBTs include a base-collector setback layer. A setback layer shifts the fused GaAs-GaN interface slightly into the collector, decreasing the barrier prior to the conduction band spike at the fused junction. This accounts for the marked improvement in collector current and current gain demonstrated in Figure 2. Also, the Generation 3 HBT utilizes a thinner base (100nm rather than 150nm).

ACKNOWLEDGMENTS

This work was supported by the Department of Defense Multidisciplinary University Research Initiative (MURI) program administered by the Office of Naval Research under Grant N00014-98-1-0654, with Project Monitors Drs. Harry Dietrich and John Zolper. We acknowledge the contributions of Santa Barbara High School Apprentice Researchers Chelsea Teall and Craig Silverman.

REFERENCES

[1] S. Estrada, A. Stonas, A. Huntington, H. Xing, L. Coldren, S. DenBaars, U. Mishra, and E. Hu, in *The First Wafer-Fused AlGaAs-GaAs-GaN Heterojunction Bipolar Transistor*, Boston, Massachusetts, Fall 2002 (Materials Research Society), p. L12.10.

[2] S. Estrada, H. L. Xing, A. Stonas, A. Huntington, U. Mishra, S. DenBaars, L. Coldren, and E. Hu, Applied Physics Letters **82,** 820-822 (2003).

[3] S. Estrada, A. Huntington, A. Stonas, H. Xing, U. Mishra, S. DenBaars, L. Coldren, and E. Hu, Applied Physics Letters **83,** 560-562 (2003).

[4] Y. M. Zhang, C. Cai, and P. P. Ruden, Journal of Applied Physics **88,** 1067-1072 (2000).

[5] S. Y. Chiu, A. F. M. Anwar, and S. L. Wu, MRS Internet Journal of Nitride Semiconductor Research **4,** G6.7 (1999).

[6] J. T. Torvik, M. Leksono, J. I. Pankove, and B. Van Zeghbroeck, MRS Internet Journal of Nitride Semiconductor Research **4** (1999).

[7] S. Yoshida and J. Suzuki, Japanese Journal of Applied Physics Part 2-Letters **38,** L851-L853 (1999).

[8] J. Han, A. G. Baca, R. J. Shul, C. G. Willison, L. Zhang, F. Ren, A. P. Zhang, G. T. Dang, S. M. Donovan, X. A. Cao, H. Cho, K. B. Jung, C. R. Abernathy, S. J. Pearton, and R. G. Wilson, Applied Physics Letters **74,** 2702-2704 (1999).

[9] H. Xing, S. Keller, Y. F. Wu, L. McCarthy, I. P. Smorchkova, D. Buttari, R. Coffie, D. S. Green, G. Parish, S. Heikman, L. Shen, N. Zhang, J. J. Xu, B. P. Keller, S. P. DenBaars, and U. K. Mishra, Journal of Physics-Condensed Matter **13,** 7139-7157 (2001).