n-AlGaAs/*p*-GaAs/*n*-GaN heterojunction bipolar transistor wafer-fused at 550–750 °C

Sarah Estrada,[a)] Andrew Huntington, Andreas Stonas, Huili Xing, Umesh Mishra, Steven DenBaars, Larry Coldren, and Evelyn Hu
Departments of Materials and Electrical & Computer Engineering, University of California, Santa Barbara, California 93106-5050

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We recently reported an initial AlGaAs/GaAs/GaN heterojunction bipolar transistor (HBT), formed via wafer fusion of a *p*-GaAs base to an *n*-GaN collector. The device was formed by fusion at a high temperature (750 °C) and demonstrated low output current (~100 A/cm^2) and low common-emitter current gain (0.5). This letter describes a systematic variation of fusion temperature (550–750 °C) in the formation of the HBT, and reveals the correlation between fusion temperature, base–collector leakage, and emitter–base degradation. With reduced fusion temperatures, devices demonstrate improvements in leakage, output current (~1 kA/cm^2), and common-emitter current gain (>1). Optimization of device structure should further improve performance. [DOI: 10.1063/1.1592887]

Recently, we introduced an AlGaAs/GaAs/GaN heterojunction bipolar transistor (HBT),[1] a device that might combine the high-breakdown voltage of a GaN collector with the high mobility of a technologically mature AlGaAs–GaAs emitter–base. Because the high degree of lattice mismatch between GaAs and GaN precludes an all-epitaxial formation of this device, we formed the GaAs–GaN heterostructure via wafer fusion, also called direct wafer bonding. Unfortunately, wafer fusion of GaN requires the use of elevated temperature. Earlier work with the fusion of *n*-GaAs and *p*-GaAs to *n*-GaN revealed that higher fusion temperatures produced greater diffusion of substrate dopants, in some cases resulting in dopant compensation across $p-n$ junctions.[2] Lower fusion temperatures would thus seem to be desirable, but for our device application, the fusion conditions must provide enough thermal energy to form a mechanically stable and electrically active fused interface. (Given the thermal stability of GaN, GaN fusion has been reported at temperatures up to 1000 °C).[3–5] The studies described here reveal that fusion temperatures as low as 550 °C can be used to produce GaAs–GaN HBTs with electrically active fused interfaces. In fact, the device characteristics of the HBT *improve* with reduced fusion temperature.

The AlGaAs–GaAs emitter–base was grown by molecular beam epitaxy (MBE) at 585 °C in a Varian Gen-II system. Sacrificial undoped AlAs (0.5 μm) was grown on a (100) Si-doped n^+-GaAs substrate, followed by a contact layer (0.1-μm n^+-GaAs, 1×10^{19} cm^{-3} Si), the emitter (0.12-μm n-Al$_x$Ga$_{1-x}$As flanked on top and bottom by 0.03-μm Al grading at $x=0$ to 0.3, all with 5×10^{17} cm^{-3} Si), and finally the base (0.15-μm p^+-GaAs, 1×10^{19} cm^{-3} C). Carbon, rather than beryllium, was chosen as the *p*-type dopant in order to minimize dopant diffusion during the high-temperature fusion procedure. For similar reasons, the GaAs base was designed to be thick enough to prevent complete dopant compensation, as dopants would diffuse across the emitter–base and base–collector interfaces during the high-temperature fusion process. The GaN collector (5×10^{16} cm^{-3} Si) was grown by metalorganic chemical vapor deposition on *c*-plane (0001) sapphire at 1160 °C.

GaAs and GaN were cleaved into rectangles (5–10 mm), cleaned with acetone and isopropanol, and soaked in NH_4OH to dissolve surface oxides. Wafers were rinsed and joined together in methanol, then annealed at 550–750 °C for 1 h in a nitrogen ambient under 2 MPa of uniaxial pressure. After fusion, the GaAs substrate and AlAs etch-stop were removed sequentially via selective wet etching in H_2O_2:NH_4OH and HF, respectively. Onto the *n*-GaAs emitter cap layer, AuGeNi contacts (15×45 μm^2) were deposited by electron-beam evaporation and annealed at 415 °C. Emitter (1×10^{-5} cm^2) and base mesas (5×10^{-5} cm^2) were defined via wet etching in H_3PO_4:H_2O_2:H_2O. Unannealed ZnAu contacts (2.3×10^3 μm^2) were thermally evaporated onto the *p*-GaAs base. Unannealed AlAu contacts (20×40 μm^2) were deposited by electron-beam evaporation onto the *n*-GaN collector.

Since the characteristics of the $n-p-n$ HBT must depend on the behavior of the two constituent back-to-back diodes, we first examine the $I-V$ characteristics of the base–collector and emitter–base junctions. Figure 1 shows the $I-V$ characteristics of base–collector diodes fused at 550–750 °C. The base–collector leakage current increases with elevated fusion temperature, ranging from 4×10^{-5} mA for $T_f=550$ °C, to 20 mA for $T_f=750$ °C. Additionally, the ideality factor n increases with increasing fusion temperature T_f, from $n=2.3$–2.9 at $T_f=550$–700 °C, to $n=5.9$ at $T_f=750$ °C. It may appear that the wafer fusion produces a high value of n; we note that epitaxially grown GaN $p-n$ junctions have also been reported with high ideality factors ($n\sim1.5$–9).[6,7]

The AlGaAs–GaAs emitter–base junction is formed directly through MBE growth, but it is important to assess the diffusion effects of the fusion conditions on the quality of that junction (i.e., the elevated fusion temperature for 1 h).

[a)]Electronic mail: estrada@engineering.ucsb.edu

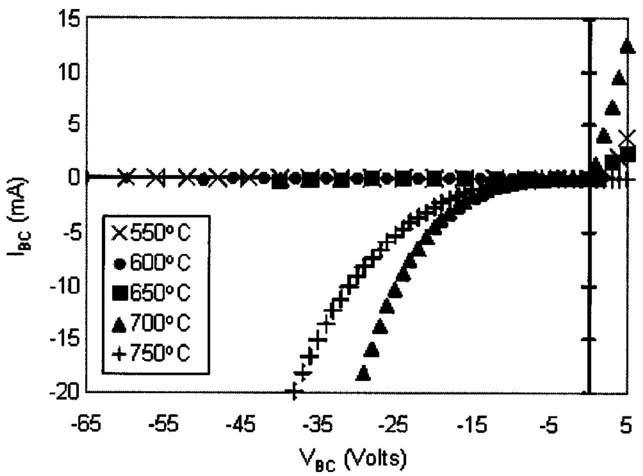

FIG. 1. Room-temperature $I-V$ characteristics for the *p*-GaAs–*n*-GaN base–collector diode, fabricated via wafer fusion at systematically varied temperatures (550–750 °C for 1 h).

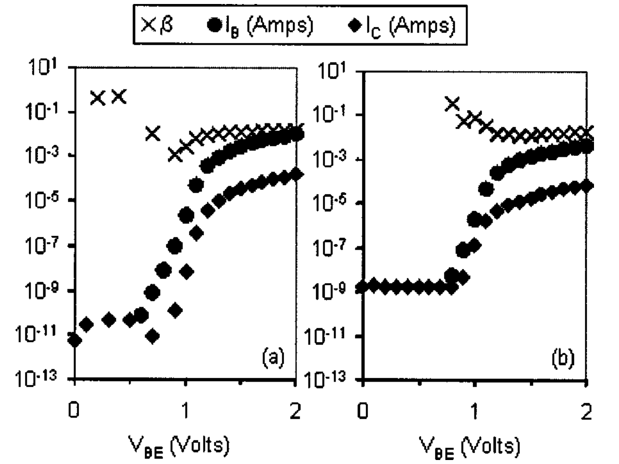

FIG. 3. Room-temperature Gummel plots for the *n*-AlGaAs–*p*-GaAs–*n*-GaN HBT fused (a) at 600 °C and (b) at 750 °C.

All emitter–base $I-V$ characteristics appear to be identical to those of the as-grown sample, *except* for the emitter–base diode subjected to the highest fusion temperature 750 °C, yielding a lower current at a given voltage. A subset of these data is displayed in Fig. 2. All emitter–base diodes exhibit an ideality factor of 1.2–1.5, similar turn-on, low reverse-bias leakage current, and similar breakdown.

Gummel plots and common-emitter characteristics were measured for HBTs fused at 550, 600, 650, 700, and 750 °C. Figures 3 and 4 display the $I-V$ data for HBTs fused at 600 °C and 750 °C. Gummel plots indicate that the base current (I_B) is reasonably high for fusion temperatures (T_f) of 550–700 °C (I_B=10–15 mA at V_{BE}=2 V), but I_B is much lower for the highest T_f of 750 °C (I_B=4 mA at V_{BE} =2 V). This reduction in base current is to be expected, given the emitter–base degradation in the HBT fused at 750 °C (Fig. 2). Common-emitter $I-V$ curves are dominated by base–collector leakage for HBTs fused at 700–750 °C, but are well-behaved for the lower T_f of 550–650 °C. Current gain increases with increasing T_f, but consistently remains low. Common-emitter current gain β increases from β=0.29 for T_f=550 °C, to β=1.2 for T_f=600 °C. The gain is undetermined for HBTs fused at 700–750 °C, as these devices are dominated by base–collector leakage. It is important to note[8] that the observed collector current is not due to emitter–collector leakage, which remains at least an order of magnitude lower than the base and collector currents given high enough voltage ($V\sim V_{\text{E-B turn-on}}$). It is interesting to note that the emitter–collector leakage current increases with increasing T_f, as does the base–collector leakage current.

This study demonstrates a marked improvement in device performance due to a substantial reduction of the fusion temperature. We expect further improvements in future investigations as we optimize device structure. By introducing a GaAs base–collector setback layer, we hope to shift the fused GaAs–GaN interface slightly into the collector, decreasing the barrier prior to the possible spike at the fused junction. Also, by utilizing lower fusion temperatures, the device is less susceptible to dopant diffusion, which should allow the use of a thinner base. We believe that these experiments will ultimately provide much insight into the applicability of wafer fusion for electronically active, lattice-mismatched heterodevices, especially involving GaN.

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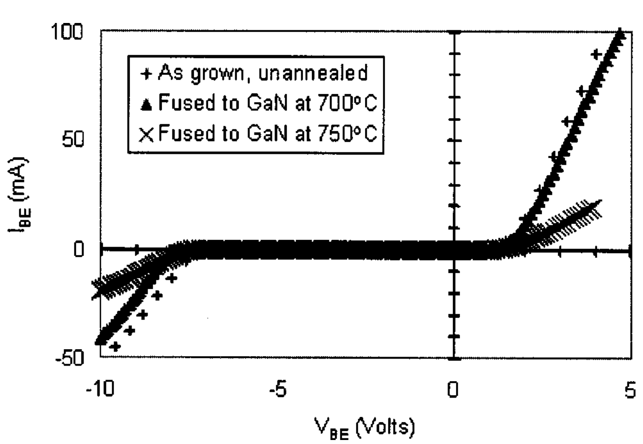

FIG. 2. Room-temperature $I-V$ characteristics for the *p*-GaAs–*n*-AlGaAs base–emitter diode as grown, and after this structure is wafer-fused to an *n*-GaN collector at 700 and 750 °C.

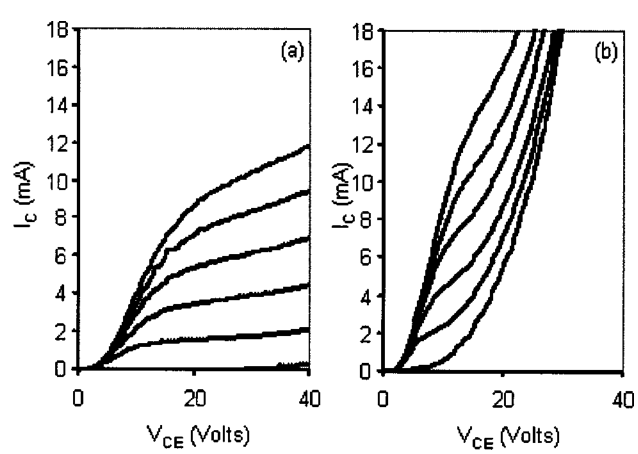

FIG. 4. Room-temperature common-emitter characteristics for the *n*-AlGaAs–*p*-GaAs–*n*-GaN HBT fused (a) at 600 °C and (b) at 750 °C. I_B step size=2 mA.

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