

# Wafer-fused AlGaAs/GaAs/GaN HBTs with current gain of $\sim 20$ and $V_{BR} \sim 35$ V

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## Abstract

AlGaAs/GaAs/GaN HBTs have been fabricated by wafer fusion at various fusion temperatures 450 – 550 °C. The best current gain of  $\sim 20$  was achieved in HBTs fused at 450 °C for 2 h, and the HBT breakdown voltage was measured to be  $\sim 35$  V ( $\sim 3$  times that of the as-grown AlGaAs/GaAs HBTs), a result of mitigation of base degradation and fusion interface barrier. These results indicate that wafer fusion is a promising technique to fabricate high-speed power transistors by combining the superb injector AlGaAs/GaAs and the wide bandgap GaN collector.

## INTRODUCTION

In the last two decades, III-nitrides have attracted great research interest due to their unique potentials in both electronic and photonic device applications. The large breakdown voltages of the wide bandgap (Al)GaN materials make them very promising candidates for power electronics applications. Both HEMTs and HBTs can be used as high frequency, high power devices. In comparison with the rapid development of AlGaN/GaN HEMTs, however, AlGaN/GaN HBTs have been largely plagued by the highly resistive p-GaN base [1]. An alternative base material with higher conductivity is needed and p-GaAs is a promising candidate which can be doped with pretty high acceptor densities while remaining very large electron mobility. Besides, AlGaAs/GaAs heterojunctions have almost unity electron injection efficiency and can be easily grown by the mature MBE technique. By making use of the advantages of both GaAs and GaN materials, HBTs fabricated on AlGaAs/GaAs/GaN double heterostructures are expected to be able to work at high speed and high power densities. Unfortunately, the epitaxial growth of the whole structure is ruled out due to the large lattice mismatch between GaAs and GaN. Instead, wafer fusion, also called direct wafer bonding, has been utilized to integrate GaAs and GaN [2-4].

When the degenerately doped p-GaAs base is directly fused with the lightly doped n-GaN collector, a spike-like energy barrier is produced right at the base-collector junction. At forward active regime of an npn HBT, electrons are injected from the emitter into the base, diffuse through the base and finally reach the collector contributing to the collector current. Therefore, it is desirable to eliminate any electron energy barrier at the base-collector junction. By

inserting a lightly doped GaAs setback layer between p<sup>+</sup>-GaAs and n-GaN, the energy potential spike can be pulled down, enabling more electrons to arrive at the collector and increase the HBT current gain. Figure 1 illustrates the effect of the setback layer with a conduction band diagram. AlGaAs/GaAs/GaN HBTs with setback layers showing current gain of 5-10 have been obtained by wafer fusion at 550 °C for 1 h [3, 4].

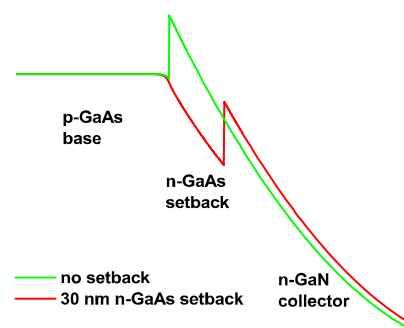


Figure 1. Conduction band diagram of a GaAs/GaN heterojunction with or without a setback layer

Despite the encouraging current gain reported by us, wafer-fused AlGaAs/GaAs/GaN HBTs, even with setback layers, exhibit considerable device degradation compared with MBE as-grown AlGaAs/GaAs/GaAs HBTs. One of the gain reduction mechanisms has been attributed to the p-GaAs base degradation after the high temperature annealing employed in the fusion process to strengthen the bonding between GaAs and GaN [4]. The higher the annealing temperature is, the more the base degrades. Low fusion temperature is therefore preferred to alleviate the adverse effect of annealing as long as a reasonably good GaAs/GaN interface can be formed at low temperature. In this work, we have fabricated AlGaAs/GaAs/GaN HBTs fused at 500 °C and 450 °C, respectively. A substantially improved current gain of  $\sim 20$  has been achieved by wafer fusion at 450 °C for 2 h.

## EXPERIMENTS

All the AlGaAs/GaAs wafers in this study were grown by MBE on GaAs substrates and GaN wafers by MOCVD on double-polished sapphire. The size of the samples to be fused was around 1 cm  $\times$  1 cm. Before wafer fusion, the GaAs and

GaN samples were cleaned in solvent and the native oxides were removed by soaking in  $\text{NH}_4\text{OH}$ . Then the two wafers were brought into intimate contact in methanol to avoid surface oxidation when joined in air. After the two wafers were moved from methanol to the annealing fixture, an external pressure of  $\sim 5$  MPa was applied onto the two samples which remained during the following annealing process. High temperature annealing was carried out in a  $\text{N}_2$  atmosphere with a pressure of  $\sim 600$  mT inside the furnace tube. After the two wafers were fused together, the GaAs substrate was removed by polishing and wet etch in  $\text{H}_2\text{O}_2:\text{NH}_4\text{OH}$  which stopped at an AlGaAs etch stop layer. The etch stop layer could be easily removed by HF. Figure 2 shows a sketch of the fusion process flow and Figure 3 shows the detailed device layer structure. The fused HBTs have alloyed AuGe/Ni/Au ( $415^\circ\text{C}$  for 5 s) emitter contacts (on an n-GaAs emitter cap layer), non-alloyed Ti/Au base contacts (on p-GaAs) and non-alloyed Al/Au collector contacts (on n-GaN).

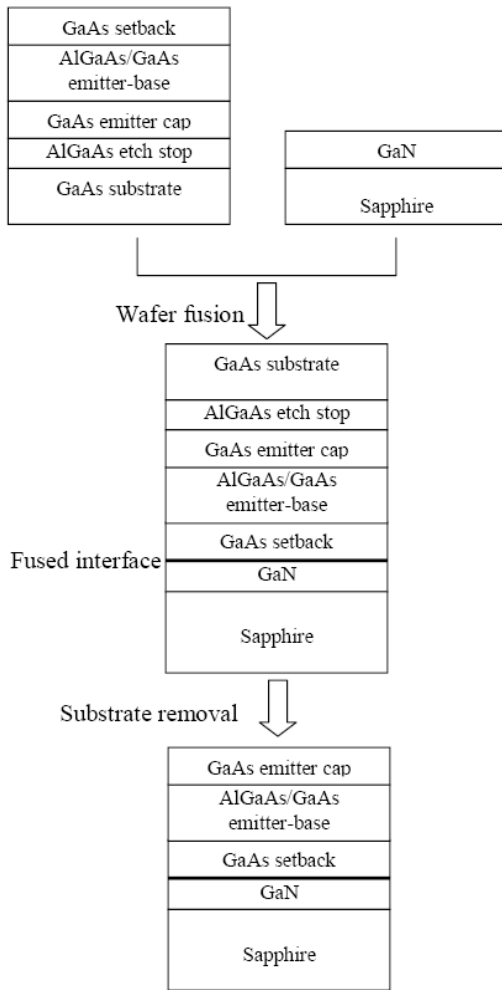


Figure 2. Sketch of the wafer fusion flow with the bold line showing the fused GaAs/GaN interface

0.1 $\mu\text{m}$ n-GaAs emitter cap ( $1 \times 10^{19} \text{ cm}^{-3} \text{ Si}$ )
0.03 $\mu\text{m}$ graded n-AlGaAs ( $5 \times 10^{17} \text{ cm}^{-3} \text{ Si}$ )
0.12 $\mu\text{m}$ n- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ( $5 \times 10^{17} \text{ cm}^{-3} \text{ Si}$ )
0.03 $\mu\text{m}$ graded n-AlGaAs ( $5 \times 10^{17} \text{ cm}^{-3} \text{ Si}$ )
100 nm p-GaAs base ( $1 \times 10^{19} \text{ cm}^{-3} \text{ C}$ )
30 nm n-GaAs setback ( $\sim 1 \times 10^{17} \text{ cm}^{-3} \text{ Si}$ )
1 $\mu\text{m}$ GaN collector ( $5 \times 10^{16} \text{ cm}^{-3} \text{ Si}$ )
1 $\mu\text{m}$ n-GaN sub-collector ( $4 \times 10^{18} \text{ cm}^{-3} \text{ Si}$ )
(0001) Sapphire

Figure 3. Detailed layer structure of AlGaAs/GaAs/GaN HBTs

### RESULTS AND DISCUSSIONS

After the initial optimization of the fusion conditions, large area and smooth (Al)GaAs films could be obtained on GaN after substrate removal, as shown in Figure 4(a). The roughness of the top GaAs emitter cap was measured to be  $\sim 1$  nm (RMS), a reasonably good value considering that of the as-grown GaN surface,  $\sim 0.5$  nm and the as-grown GaAs surface,  $\sim 0.3$  nm. After etching emitter mesas, the thin p-GaAs film (100 nm) was smooth and continuous as well, as shown in Figure 4(b)

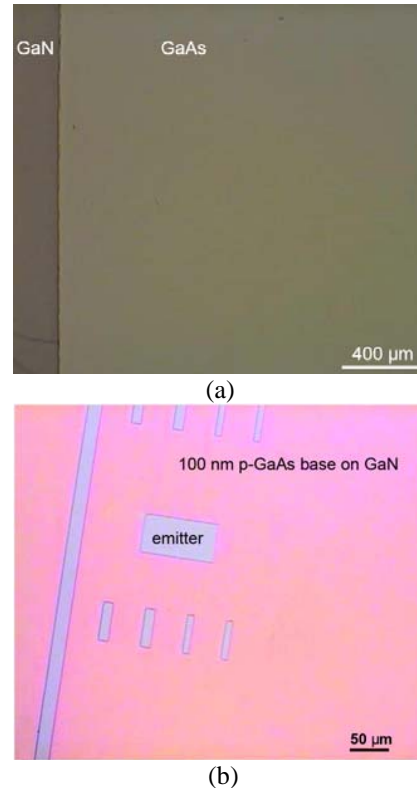


Figure 4. Optical images of (Al)GaAs on GaN after (a) substrate removal and (b) emitter mesa etch.

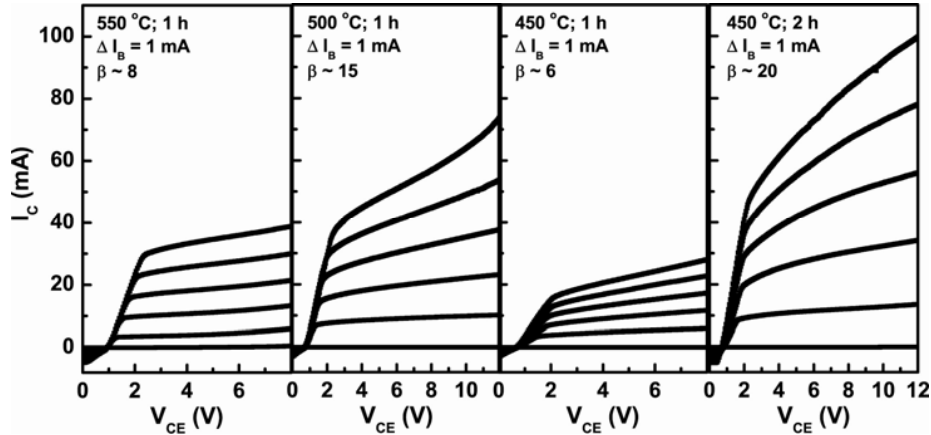


Figure 5. Common-emitter I-Vs of wafer fused AlGaAs/GaAs/GaN HBTs

Figure 5 shows the common-emitter I-V characteristics of wafer-fused AlGaAs/GaAs/GaN HBTs measured at room temperature. The best current gain of the HBTs fused at 500 °C for 1 h is ~ 15, almost double of those fused at 550 °C for 1 h. However, when the fusion temperature decreases to 450 °C, the best current gain is only ~ 6, smaller than expected since the base degradation is supposed to be less severe at lower annealing temperatures. The TEM cross section images of the fused GaAs/GaN heterostructure revealed a thin layer of disordered material at the interface [5], which tends to be thicker at lower fusion temperatures for the same annealing time. Since this disordered material may behave as a barrier for electrons to enter the collector, the smaller current gain observed in the 450 °C (1 h) fused devices is ascribed to this phenomenon. By increasing the fusion time while keeping the temperature at 450 °C, the device performance is expected to improve if a thinner interface could form. This assumption was justified by the HBTs fused at 450 °C for 2 h showing the best current gain of ~ 20, a very encouraging result indicating the feasibility of making applicable HBTs by wafer fusion. The fused HBTs on the same wafer were found to have high breakdown voltage of ~ 35 V. In comparison, the as-grown AlGaAs/GaAs/GaAs HBTs with similar structures have a breakdown voltage of 10 V (current gain of ~ 170). Figure 6 shows the measured  $V_{CEO}$  of a fused HBT and an as-grown HBT. The soft breakdown behavior of the fused HBT is believed to be due to the leakage current through the base-collector junction.

#### CONCLUSIONS

AlGaAs/GaAs/GaN HBTs have been fabricated by wafer fusion at different temperatures. The current gain was doubled when the fusion temperature decreased from 550 °C to 500 °C while the fusion time, 1 h, kept unchanged. HBTs fused at 450 °C for 1 h did not show further gain improvement. When the fusion time was increased to 2 h, HBTs fused at 450 °C exhibited the best gain of ~ 20 along with a breakdown voltage of ~ 35 V, more than three times

the breakdown voltage of the MBE as-grown AlGaAs/GaAs/GaAs HBTs. The significant performance improvement of devices fused at 450 °C for 2 h is a result of mitigation of base degradation and fusion interface barrier.

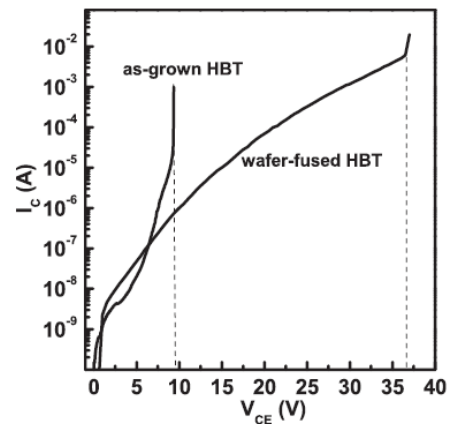


Figure 6. Breakdown characteristics of AlGaAs/GaAs/GaAs HBT grown by MBE and AlGaAs/GaAs/GaN HBT formed by wafer fusion

#### ACKNOWLEDGEMENTS

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#### ACRONYMS

HBT: Heterojunction Bipolar Transistor  
HEMT: High Electron Mobility Transistor

MBE: Molecular Beam Epitaxy  
MOCVD: Metal-organic Chemical Vapor Deposition  
RMS: Root Mean Square  
I-V: Current-Voltage  
 $V_{CE0}$ : Common-emitter breakdown voltage