AlGaAs/Ge/GaAs Heterojunction Bipolar Transistors Grown by Molecular Beam Epitaxy

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Abstract—**The first N-$Al_{0.22}Ga_{0.78}As$ emitter, p-Ge base, and n-GaAs collector (AlGaAs/Ge/GaAs) heterojunction bipolar transistor (HBT) has been grown by molecular beam epitaxy. Devices exhibited common-emitter current gains of as high as 300 at a collector current density of 2000 A/cm^2 and a collector voltage of 4 V. As the device area is reduced from 50 × 50 to 10 × 40 μm, the current gain did not show significant changes, suggesting a low surface recombination velocity in the Ge base.**

I. Introduction

A PROBLEM fundamental to N-p-n AlGaAs/GaAs HBT's is the low hole mobility of the GaAs base. This leads to a high base resistance which limits the maximum oscillation frequency f_{max} and increases the high-frequency noise figure. One possible solution to this problem is the P-n-p AlGaAs/GaAs HBT with extremely thin base widths (300 Å) [1], but such a narrow base challenges the limits of fabrication technology. Another is to use a semiconductor with a high hole mobility as the base.

Ge is a small bandgap semiconductor (0.66 eV) which has the highest dopant concentration–hole mobility product among device grade semiconductors. The large valence-band discontinuity of Ge with AlGaAs suppresses reverse hole injection current and allows the base to be very heavily doped without compromising high emitter injection efficiency and overall current gain. Due to its narrow bandgap, Ge has a high minority-carrier lifetime, low surface recombination velocity, low contact resistance, and a reduced emitter–base turn-on voltage. These properties, and the nearly perfect lattice match of Ge to GaAs, suggest the potential of Ge for low-noise microwave and millimeter-wave HBT's that can operate at low power levels. Despite the possibility of improved HBT performance, relatively little work has been undertaken.

The first effort towards a Ge-base HBT was by Jadus and Feucht [2] who used vapor phase epitaxy to grow an N-GaAs emitter on an n-type Ge substrate into which Ga had been diffused to form a heavily doped p-type base region. A current gain of 15 was achieved, but at a fairly high current density of 3500 A/cm^2. Along the same lines Chand *et al.* [3] demonstrated a high-gain emitter-up GaAs/Ge/Ge phototransistor. Recently, Kimura *et al.* [4] presented an emitter-down GaAs/Ge/Ge HBT that had a current gain of 45. The choice of an emitter-down structure may have been motivated by the relative ease with which Ge can be grown on GaAs, but a Ge collector has many disadvantages, namely a low breakdown voltage, a large electron transit time, and high leakage current. We have overcome significant obstacles in polar-on-nonpolar epitaxy [5], and in this letter report the first AlGaAs/Ge/GaAs HBT in the emitter-up configuration.

II. Experimental

The GaAs growth was done in a Perkin Elmer 430 molecular beam epitaxy (MBE) machine while Ge deposition took place in an adjacent deposition chamber to minimize cross-contamination. The sample was kept under vacuum during the several minutes of growth interruption required to transfer between the chambers. All sources were solid source effusion cells.

A semi-insulating (100) GaAs substrate misoriented 4° towards $[0\bar{1}1]$ was used to eliminate antiphase disorder in the polar-on-nonpolar growth [5]. A schematic cross section of the device structure is shown in Fig. 1. After the growth of the collector, the samples were transferred under vacuum to the Ge deposition chamber. Ge growth was interrupted every 75 Å and the sample was transferred back to the GaAs MBE chamber for Ga planar doping. Full Ga activation was not achieved. From our measured sheet resistance values, which varied from 2000 to 8000 Ω/□, and the bulk mobility of Ge, we estimate the base doping to be between 1 and 5 × 10^{17} cm^{-3}. After Ge deposition, the AlGaAs emitter was initiated with an As prelayer at 570°C and the temperature was quickly stabilized at 610°C. Finally, a GaAs cap layer was grown to facilitate ohmic contact to the emitter. The necessity of initiating the emitter growth at low temperature in order to discourage cross-diffusion may have been responsible for the higher than usual emitter resistivities observed in these devices.

Standard wet chemical etching techniques were used to fabricate devices using a mask set containing various pattern

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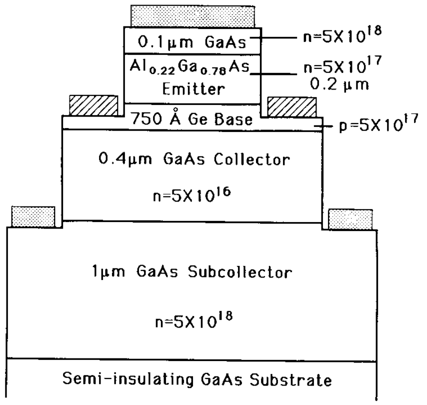

Fig. 1. Cross section of $Al_{0.22}Ga_{0.78}As$/Ge/GaAs HBT.

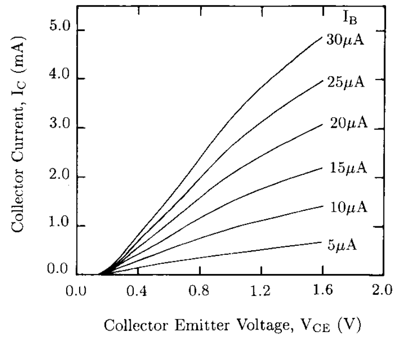

Fig. 2. Common-emitter characteristic for $Al_{0.22}Ga_{0.78}As$/Ge/GaAs HBT.

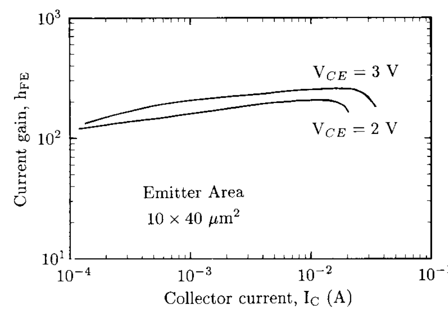

Fig. 3. Plot of common-emitter gain versus collector current.

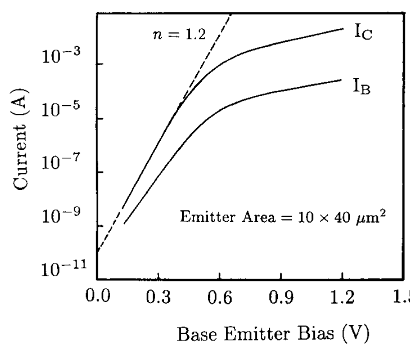

Fig. 4. Gummel plot for $Al_{0.22}Ga_{0.78}As$/Ge/GaAs HBT ($V_{CB} = 0$ V).

dimensions. AuGe/Ni/Au was evaporated to contact the emitter and collector regions while chemical palladium plating was used for the base contact. Polyimide was then deposited, vias etched to the metal contacts, and Ti/Au overlay metal evaporated.

III. Results and Discussion

We first discuss the electrical characteristics of the two heterojunctions. The collector–base junction showed excellent diode characteristics. Under forward bias we observed a unity ideality factor over more than five decades of current and a saturation current of 1.5×10^{-7} A/cm^2. A sharp reverse breakdown occurred at 17 V and a reverse leakage current of 8×10^{-5} A/cm^2 at 5 V was measured in the collector–base junction. The polar-on-nonpolar emitter–base junction had an ideality factor of $n = 1.4$ and a saturation current of 3×10^{-6} A/cm^2 while under reverse bias a soft breakdown was observed at 5 V with a leakage current of 75 A/cm^2 at 3 V. The turn-on voltage for the emitter–base junction was about 0.5 V. Devices annealed at 600–700°C for 10–20 min showed improved characteristics, possibly as a result of Ga acceptor activation in the base, but as annealing time and temperature increased, the reverse leakage current of the collector–base junction increased rapidly.

Resistive effects were apparent at large forward bias in the emitter–base junction. The sources of this resistance are most likely the high sheet resistance of the Ge layer combined with a large lateral base access resistance due to the thinness of the base layer. For a 10×40-μm^2 emitter size device the lateral access resistance is estimated to be about 20 Ω whereas the measured emitter resistance for the same size device was less than 10 Ω. The ideality factor of $n = 1.4$ indicates that the majority of the current is due to diffusion with a significant amount of recombination current. The current gain of the fabricated HBT's was not sensitive to the device size (in fact, the highest gains were observed in the relatively smaller devices) leading us to suggest that the $n = 2$ current component is a result of space charge and bulk recombination in the base, and not surface recombination. This conclusion is supported by a separate study of Ge/GaAs heterojunctions in which the nearly ideal current-voltage characteristics were observed to be almost completely independent of the device size as the area varied over two orders of magnitude [6]. To our knowledge, these are the first reported electrical characteristics for an AlGaAs (or GaAs) on Ge junction.

Fig. 2 shows a common-emitter output characteristic of a 10×40-μm^2 device which exhibited a gain of 180 at a current density of 1.25 A/cm^2. A maximum current gain of 300 at a collector current density of 2×10^3 A/cm^2 and a collector voltage of 4 V was observed in this device. The thinness of the base and the light base doping are reflected in the low value of the Early voltage. The large emitter resistance is responsible for the high resistance below saturation apparent in Fig. 2.

Figs. 3 and 4 show the current dependence of common-emitter gain and the Gummel plot, respectively, for the same device. The dependence of gain on the collector current is fairly flat. At a collector–emitter bias of 3 V the measured common-emitter current gains are 150, 220, and 250 for collector current densities of 50, 500, and 5000 A/cm^2, respectively. Linearity in the Gummel plot is maintained to very low current levels and the ideality of $n = 1.2$ is comparable to the best AlGaAs/GaAs devices [7]. The weak dependence of the current gain on the collector current and device size is indicative of low surface recombination velocity of the Ge base.

IV. Summary

We have successfully grown and fabricated the first AlGaAs/Ge/GaAs HBT in the emitter-up configuration and measured a maximum dc current gain of 300. Measurements at low current levels and nearly ideal Ge/GaAs diode characteristics indicate that devices are relatively free of surface recombination current in the Ge base. The present device is limited by low acceptor activation in the Ge base and by the polar-on-nonpolar emitter–base heterojunction.

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