Fabrication of GaAsBi Heterojunction Bipolar Transistors

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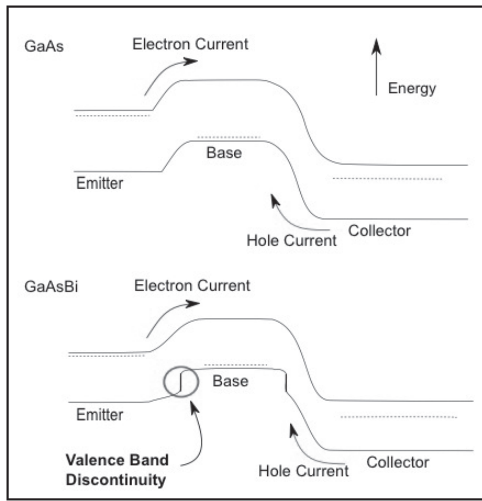

Figure 1: HBT forward bias band-energy diagram.

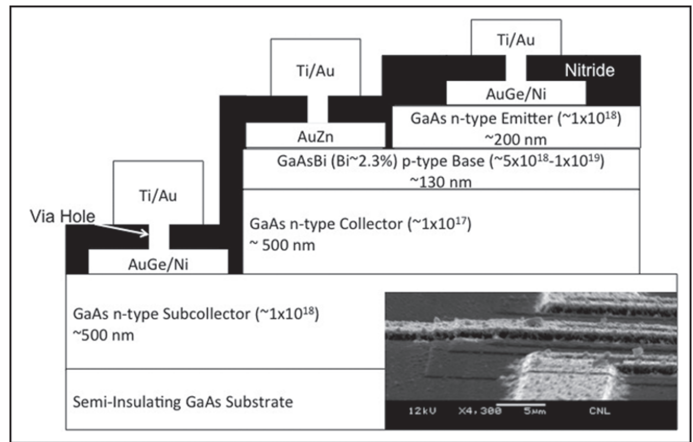

Figure 2: GaAsBi HBT cross-section and SEM image of the actual device.

Abstract and Introduction:

III-V semiconductor based bipolar junction transistors are favored in high performance circuits because of their high transconductance and low output conductance. Heterojunction bipolar transistors (HBTs), which utilize a junction of lattice-matched semiconductors with different bandgap energies, excel in high frequency applications. The gain of a HBT depends exponentially on the discontinuity between the base and emitter band junction [1]. This allows for higher doping in the base, lowering base resistance and improving RF performance.

Gallium arsenide bismuthide ($GaAs_{(1-x)}Bi_x$) is a novel material for HBTs. $GaAs_{(1-x)}Bi_x$ is lattice matched to GaAs and narrows the bandgap by ~ 90 meV/%Bi [2]. As shown in Figure 1, the band discontinuity in $GaAs_{(1-x)}Bi_x$ is entirely in the valence band, which preserves the electron mobility but negatively affects the hole mobility. The smaller bandgap in $GaAs_{(1-x)}Bi_x$ allows for a lower turn-on voltage, therefore HBTs fabricated using $GaAs_{(1-x)}Bi_x$ have the potential to be more efficient than homojunction GaAs transistors. The focus of the project is to characterize $GaAs_{(1-x)}Bi_x$ pn junctions and to create a new $GaAs_{(1-x)}Bi_x$ HBT device for RF power amplifiers.

Methodology:

An epitaxially grown wafer with a bismuth concentration of x ~ 2.3% was used, and a schematic of the HBT design is shown in Figure 2. A double-mesa structure was designed to contact the base and subcollector, with ohmic contacts for the emitter, base, and collector. The base *p*-type material was doped higher than the *n*-type collector for lower capacitance and maximum current; a higher-doped subcollector was used for ohmic contacts. Gold germanium (AuGe) was used as the emitter/collector metal; gold zinc (AuZn) for the base contacts. Gold (Au) with a titanium (Ti) adhesion layer was used as a common metal contact to eliminate variation in contact resistance.

Fabrication was completed in six optical lithography steps, and samples were placed in a 30s reactive ion etch (RIE) to remove excess photoresist (PR) after each lithography. The emitter and base isolation etches were completed using AZP4210 positive PR with 8s exposure and 35s AZ400K spinner development. Samples were etched in a 1:8:160 $H_2SO_4:H_2O_2:H_2O$ solution at a rate of 260 nm/min [3], verified by etch tests.

For the emitter, collector, and base metals, the samples were patterned with NR71-1500PY negative PR with 80s exposure and 10s RD6 spinner development. 50 nm of AuGe, 20 nm nickel (Ni) and 50 nm Au were evaporated to form the emitter and collector contacts. Capping AuGe with nickel and a layer of gold smoothed the contact surface. Excess metal was removed using lift-off, and the wafers were again patterned. 100 nm AuZn was evaporated onto the wafer and lifted off to form the base contact. Finally the samples were placed in a 45s rapid thermal anneal (RTA).

In order to isolate the common metal, a 250 nm layer of nitride (SiN_x) was deposited using a 20 min plasma-enhanced chemical vapor deposition (PECVD). After deposition, the samples were patterned with NR9-1000P negative PR, exposed for 8s and spinner developed for 10s with RD6. The nitride layer was etched in a PlasmaTherm RIE for 5 min at a rate of 50 nm/min to create via holes with which to contact the sample. Finally, the common metal lithography was completed in the same manner as the emitter and base metals using NR71-1500PY. 20 nm of Ti and 300 nm of Au were evaporated and excess metal was removed using lift-off.

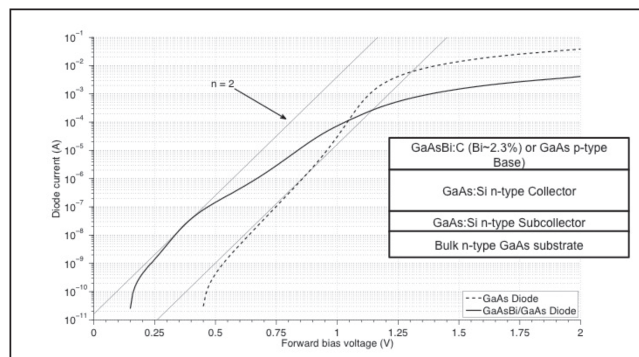

Figure 3: PN junction characteristics. PN junctions were characterized using material with a doped p-type layer of Bismuthide or GaAs on top of a doped n-type layer of GaAs and a GaAs substrate.

Results and Conclusions:

Electrical tests of GaAs:$GaAs_{(1-x)}Bi_x$ pn junctions were conducted as shown in Figure 3. GaAs pn diodes exhibited an ideality factor of n = 2 or lower, and $GaAs_{(1-x)}Bi_x$ diodes exhibited ideal behavior at a lower turn-on voltage than the GaAs diodes corresponding to a smaller bandgap in the transistor base material as expected. The ideality factor of the $GaAs_{(1-x)}Bi_x$ diodes rose rapidly above n = 2.

In material characterization tests, $GaAs_{(1-x)}Bi_x$ was found to have a sheet resistance of 2,010 Ω/☐, resistivity ρ = 6 × 10^{-2} Ω-cm and a hole mobility of 13 cm^2/V·s. Hole mobility was significantly higher in GaAs (93 cm^2/V·s) while sheet resistance and resistivity were lower (450 Ω/☐, ρ = 1.35 × 10^{-2} Ω-cm respectively). This agrees with theory and previous material characterizations [2]. Capacitance measurements showed the material to exhibit uniform doping slightly below 10^{17} atoms/cm^3 as expected. The pn junction exhibited a linear relationship between applied voltage and the inverse square of capacitance.

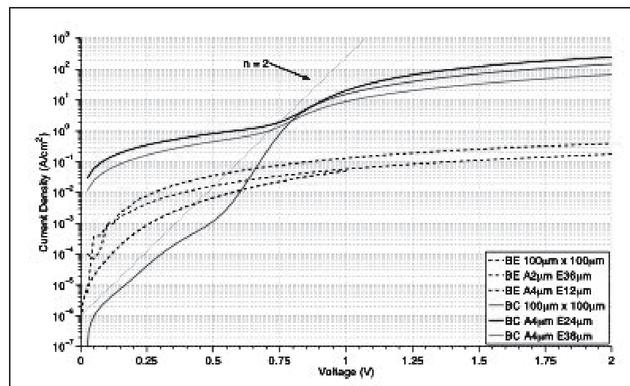

Figure 4: Base-emitter and base-collector characteristics (see Figure 2 for material structure).

HBT devices were fabricated with a minimum emitter mesa size of 12 μm × 100 μm. Poor contacts made devices difficult to test because the common metal deposition did not cover the large step from the subcollector to the emitter. Transistors were not achieved and diode characteristics were measured rather than true transistor curves. A thicker nitride layer or metal deposition could mitigate the issue. As shown in Figure 4 the base-collector junction exhibited ideal behavior, but the base-emitter junction showed poor rectification, possibly due to traps at the heterojunction. Future experiments are needed to improve the HBT fabrication process, particularly the contacts, and to further understand the behavior of $GaAs_{(1-x)}Bi_x$ in the HBT base-emitter junction.

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