Techniques and applications of graded-composition InGaAlAs alloys

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As molecular-beam epitaxy crystal growth techniques steadily progress from the research stage into full-scale production, the need for precise control of the crystal growth process becomes increasingly important. This is particularly true for epitaxial layer structures requiring precisely controlled compositional gradients. We have developed techiques for the growth of linearly graded InGaAlAs, while precisely maintaining lattice matching to the InP substrate, such that x-ray full widths at half-maximum close to the theoretical limit have been achieved. Through the use of these techniques, heterojunction bipolar transistors and graded-index separate confinement heterostructure laser diodes have been grown, fabricated, and tested.

I. INTRODUCTION

The InGaAlAs quaternary alloy system, lattice-matched to InP substrates, is an ideal candidate for the implementation of both electronic and optical devices, due to its unique band structure. This band structure not only spans the 1.3–1.5 μm optical wavelength range, but affords as well a conduction band offset of up to 500 mV, between the ternaries $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$. Further, this material system is well-suited to growth by traditional, solid-source molecular-beam epitaxy (MBE). To fully realize the promise of this material system, epitaxial layers incorporating compositional grading are necessary. Achievement of this goal, however, is complicated by the need to maintain lattice-matching to the InP substrate while varying the constituent fluxes during MBE growth.

Through careful calibration of effusion cell fluxes, it has been demonstrated that the growth of graded and lattice-matched InGaAlAs alloys is not significantly more difficult than the growth of the lattice-matched ternaries $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$, as evidenced by the growth of uniformly graded InGaAlAs layers with x-ray full widths at half-maximum (FWHM) close to the theoretical limit.[1] Techniques for the reduction of flux under- and overshoot at the endpoints of flux gradients have also been developed, resulting in the reduction of such transient effects by a factor of 50% or greater.

To demonstrate the usefulness of graded alloys in this material system, we present their application to both an electronic device, a doubly graded heterojunction bipolar transistor (HBT) (in which both the base-emitter and base-collector junctions are compositionally graded) that utilizes the large band gap span available in InGaAlAs as well as the high room temperature mobility of $In_{0.53}Ga_{0.47}As$ to advantage; and an optical device, a graded-index separate confinement heterostructure (GRINSCH) laser diode emitting which uses $In_{0.53}Ga_{0.47}As$ quantum wells and graded InGaAlAs optical and electrical confinement layers to achieve efficient emission at 1.5 μm.

II. DOUBLY GRADED HETEROJUNCTION BIPOLAR TRANSISTOR (HBT)

In the doubly graded HBT,[2] the base is of a narrower band gap than both the emitter and the collector, and the alloy composition is smoothly varied through both junction regions.

This provides improved output characteristics, owing to the use of the wide gap collector, in addition to the enhanced current gain intrinsic to the HBT design. A wide gap collector is of particular importance in devices, which would utilize the ternary $In_{0.53}Ga_{0.47}As$ for the base region.[3]

To provide sufficient band gap difference between the emitter and base, the quaternary composition $In_{0.53}Ga_{0.09}Al_{0.38}As$ (corresponding to four parts of aluminum for every one of gallium) was chosen. This provided a 560 mV band gap difference between the emitter and base, of which roughly 160 mV lies in the valence band.

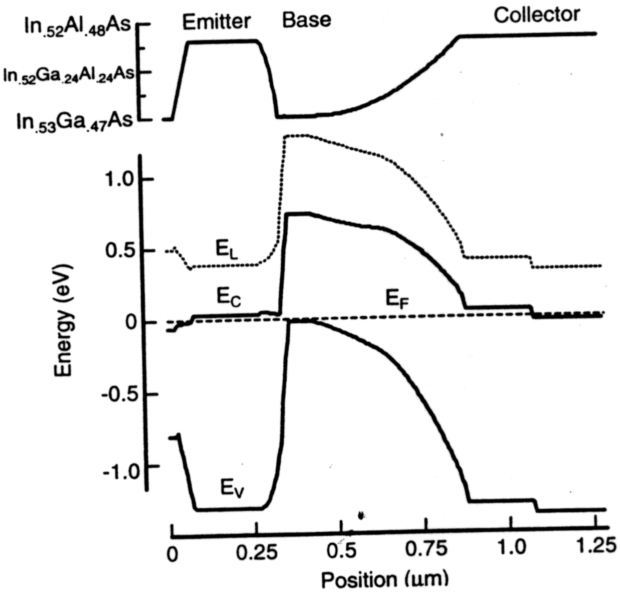

FIG. 1. Band structure of doubly graded InGaAlAs/InP HBT. The L valley minimum is shown as E_L. The alloy composition profile, aligned t band profile, is shown at top.

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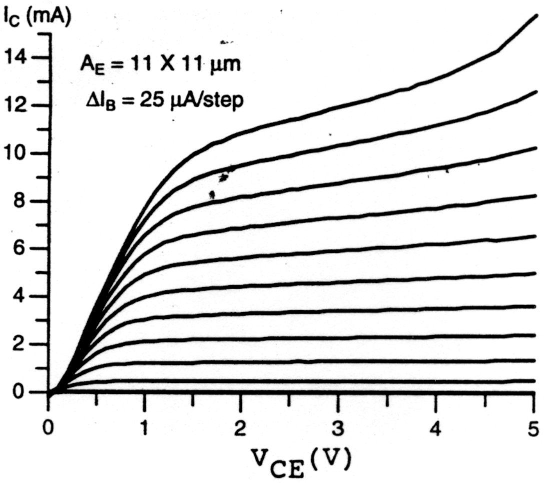

FIG. 2. I_C vs V_{CE} characteristics of an 11 μm×11 μm emitter doubly graded HBT.

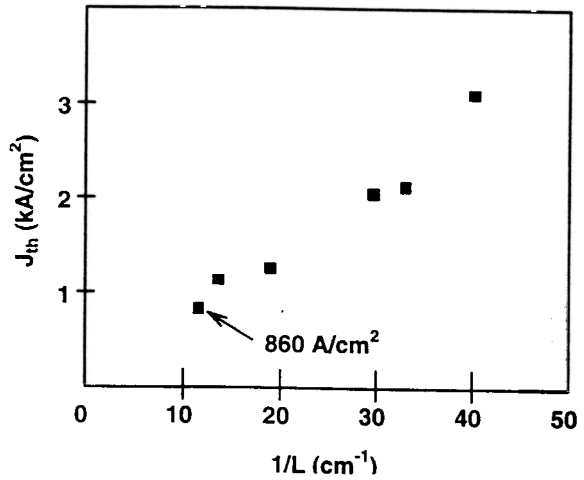

FIG. 4. Dependence of threshold current density upon inverse cavity length for 100 μm stripe broad area device.

The collector composition was chosen to match that of the emitter. A spacer layer thickness of 200 A provided protection against diffusion of base dopant into the wide gap emitter. The graded base-emitter transition layer thickness was matched to the emitter doping level of $n = 2\times10^{17}$ cm^{-3}; to avoid the formation of a spike in the conduction band in this junction, the composition was graded parabolically through the transition region.

A p-type collector transition region was employed in this device to provide a downward curving band edge profile, as seen in Fig. 1. This places the lowest field region of the base-collector transition layer nearest the base, maximizing the velocity in that region (due to the negative differential velocity of $In_{0.53}Ga_{0.47}As$), and minimizing the distance over which carriers may avalanche. The beryllium concentration was graded exponentially over the transition region to provide the desired band edge profile.

Figure 2 shows the output characteristics of an 11 μm square doubly graded HBT. An Early voltage greater than 25 V at a collector current density of 3 kA/cm^2 is achieved, while the open base and open emitter breakdown voltages exceed 13 and 20 V, respectively. These values clearly demonstrate the effectiveness of the collector compositional grading in improving the device output characteristics. Further, the offset voltage characteristic of HBTs has been reduced to less than 20 mV, demonstrating that the grading of the base-emitter junction has reduced the turn-on voltage of that device to close to that of the $In_{0.53}Ga_{0.47}As$ homojunction.

III. 1.5 μm GRINSCH-MULTIPLE QUANTUM WELL (MQW) LASER DIODES

The epitaxial layer structure employed in the GRINSCH-MQW laser diodes fabricated is depicted in Fig. 3. A 1 μm thick Si-doped ($n = 5\times10^{17}$ cm^{-3}) $In_{0.52}Al_{0.48}As$ layer was first grown on an n^+ InP substrate. Then, a 0.18 μm linearly graded waveguide layer was grown, with the material composition varying between $In_{0.52}Al_{0.48}As$ and the quaternary $In_{0.52}Ga_{0.24}Al_{0.24}As$. This thickness was chosen to yield the maximum confinement

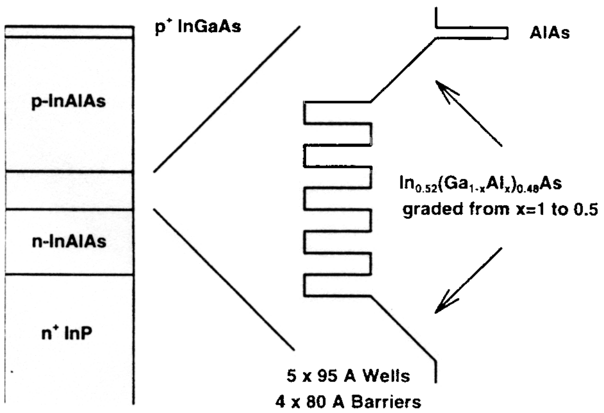

FIG. 3. Epitaxial layer structure of 1.55 μm InGaAlAs GRINSCH-MQW laser diode. AlAs layer above graded cladding region provides etch stop layer for ridge formation (Ref. 4).

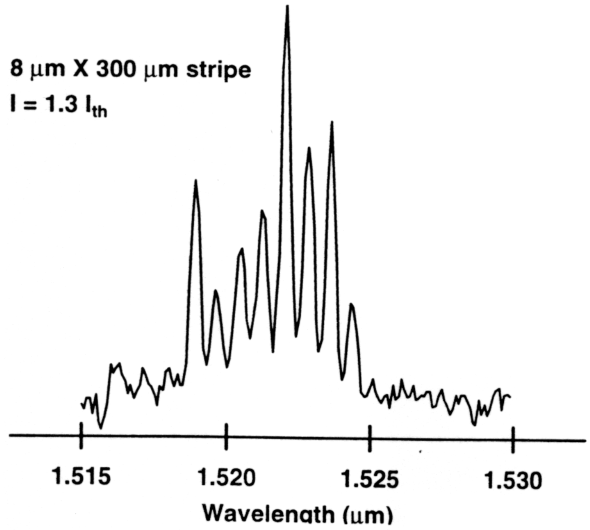

FIG. 5. Lasing spectrum of 4 μm×290 μm ridge stripe laser.

factor, as determined from numerical calculations of the mode profiles of the waveguide structure. The active region has five 9.5 nm quantum wells separated by 8 nm thick $In_{0.52}Ga_{0.24}Al_{0.24}As$ barriers. The two separate confinement heterostructure (SCH) regions are symmetric, and neither the SCH regions nor the multiquantum well region were intentionally doped. A 2 μm thick, $p = 5 \times 10^{17}$ cm^{-3} $In_{0.52}Al_{0.48}As$ top cladding layer and a 1000 Å $p = 1 \times 10^{20}$ $In_{0.53}Ga_{0.47}As$ contact layer complete the structure. The substrate temperature was held at 530 °C during the growth of $In_{0.52}Al_{0.48}As$ layers, 510 °C during the growth of the quantum wells and barriers, and 400 °C during the growth of the $In_{0.53}Ga_{0.47}As$ contact layer. The As beam equivalent pressure was maintained at 1×10^{-5} T.

For the device fabrication, stripes of different widths were formed by etching two parallel channels next to the stripe by a solution of de-ionized water, phosphoric acid, and hydrogen peroxide. SiO_x was then plasma-deposited and etched to form contact openings, and Cr/Au was sputtered onto the top surface to form the ohmic contact an bonding pads. After backside lapping and AuGe evaporation, the sample was cleaved into bars of different length and cut into individual devices for characterization.

Figure 4 shows the dependence of threshold curren density on the inverse cavity length for several 100 μ wide broad area stripe devices. The lowest threshold current density achieved was 860 A/cm^2 for a cavity length o 865 μm. Finally, the lasing spectrum of an 8 μm × 300 μ device is shown in Fig. 5.

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