

GaAs quantum well laser and heterojunction bipolar transistor integration using molecular beam epitaxial regrowth

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To explore monolithically integrated phototransmitters, a graded-index quantum well laser was integrated with a selectivity regrown heterojunction bipolar transistor (HBT).

The laser utilized a p -up configuration, and the HBT used collector down geometry. This scheme allowed the devices to be interconnected through the n^+ -GaAs substrate.

The threshold current (I_{th}) for the ridge waveguide laser was ~ 70 mA. The HBT exhibited a small signal gain of 26 at a collector current of 30 mA. The modulation index defined as the change in light output per unit change in base current is 1.2 mW/mA for our device.

Optoelectronic integrated circuits (OEIC) have tremendous potential for future lightwave transmission and switching applications. As research continues, the performance level of integrated devices are approaching their hybrid counterparts.¹⁻¹⁰ To integrate two devices of dissimilar structures monolithically, three epitaxial growth schemes exist. They are (i) modifying the growth sequence and design of each device such that a single epitaxial growth (with alternate fabrication steps) is compatible with both the optical and electronic device,^{1,3} (ii) epitaxially growing one device on top of the other in a vertical scheme,^{4,6,8} and (iii) epitaxially growing the two devices side by side in a planarized scheme^{2,5,7,9,10} by growing the first epitaxial layer and then patterning into mesas, beside which, the second epitaxial regrowth takes place. The first method suffers from the limitations put on device design. By compromising each device structure, neither structure has the potential to equal hybrid integrations.^{1,3} The second method creates a distributed capacitance between the doped layers of the underlying device with the top device, which limits high speed performance.⁸ The third method has to contend with nonoptimal growth conditions for the regrown device and interdiffusion of the first device structure during regrowth.¹¹⁻¹³ However, these two issues for the planarized scheme can be more easily addressed through judicious choice of regrowth conditions than the more fundamental limitations imposed on the other two integration schemes. Selective area molecular beam epitaxial (MBE) regrowth over patterned wafers with dielectric masks¹⁴ is one scheme to produce a planarized integration. MBE growth on the dielectric mask is polycrystalline and can later be patterned and removed, while growth on the bare surface is single crystalline.

Selective area MBE regrowth has been utilized for integration of many combinations of devices.^{2,5,7,9,10} The particular optoelectronic combination we investigated was a graded-index quantum well laser integrated with a heterojunction bipolar transistor (HBT) which functions as a phototransmitter. Previous work^{1,4} on this combination have utilized two growth schemes, the compatible and vertical growth schemes. We have pursued a planarized scheme using selective area regrowth. Using a planarized

scheme, Shibata *et al.*² have made an InGaAs/InP laser diode with HBT, using liquid phase epitaxy (LPE) regrowth. We used MBE regrowth which allows greater control over thin layers and sharp interfaces, however MBE suffers from having no *in situ* etching process to remove the thin damaged region on the bare surface created by the etching process. Although field effect transistors (FET)⁶ have been integrated with lasers, we have chosen a laser-HBT combination, due to the higher current handling of the HBT. In this letter, we report a planarized integration using MBE selective area regrowth via dielectric masks to couple a ridge waveguide laser with an HBT to produce a monolithic phototransmitter.

The schematic of the integrated structure is shown in Fig. 1. Since optical processes of emission and detection are more sensitive to the defect related centers created by nonoptimal regrowth conditions than electron conduction, it is advantageous to grow the optical device before the electronic device. It was shown^{11,13} that regrown photodiodes exhibited a long decay tail associated with generation-recombination current from the defect centers near the regrown interface. Regrown modulation doped field effect transistors (MODFET) from the same study¹³ showed degraded dc gain, however, high frequency operation such as cutoff frequency was equivalent to as-grown MODFETs.¹³ The type of laser structure used for this experiment is a weakly index guided ridge waveguide laser.^{15,16} The HBT is a NpN structure, with the collector electrically connected to the n -contact of the laser through the n^+ -GaAs substrate. The fabrication involves the following steps. First, the GaAs quantum well laser is grown over an n^+ -GaAs substrate, which comprises: (i) a $1 \mu\text{m}$ n^+ -GaAs buffer layer, (ii) a $1 \mu\text{m}$ $n\text{-Al}_{0.4}\text{Ga}_{0.6}\text{As}$ lower cladding layer, (iii) a $0.2 \mu\text{m}$ $n\text{-Al}_x\text{Ga}_{1-x}\text{As}$ compositionally graded layer (from $x = 0.4$ to 0.15), (iv) three 100 \AA GaAs wells with 100 \AA $\text{Al}_{0.15}\text{Ga}_{0.85}\text{As}$ barriers, (v) a $0.2 \mu\text{m}$ $p\text{-Al}_x\text{Ga}_{1-x}\text{As}$ compositionally graded layer (from $x = 0.15$ to 0.4), (vi) a $1.5 \mu\text{m}$ $p\text{-Al}_{0.4}\text{Ga}_{0.6}\text{As}$ upper cladding layer, (vii) a $0.1 \mu\text{m}$ $p\text{-GaAs}$ contact layer, and (viii) a 300 \AA $p^+\text{-GaAs}$ cap layer. The carrier concentrations are $5 \times 10^{17} \text{ cm}^{-3}$ in the cladding regions and 2×10^{18} in the contact regions. After growth, a 3000 \AA SiO_2 film was

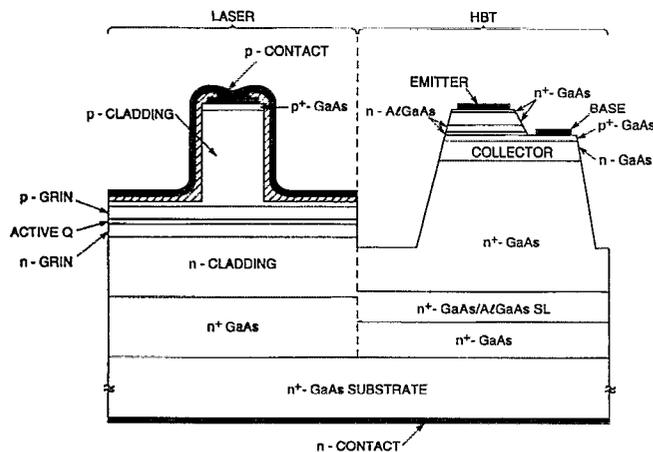


FIG. 1. Growth schematic of the laser-HBT integrated structure.

deposited with plasma enhanced chemical vapor deposition. Then $100\ \mu\text{m}$ wide photoresist stripes, separated by $400\ \mu\text{m}$ were delineated on the grown wafer using standard photolithography. Mesas were then chemically defined by etching through the SiO_2 and down to the n^+ -GaAs substrate.

After chemical cleaning, the patterned wafer was reinserted along with a planar n^+ -GaAs substrate into the MBE chamber for growth of the GaAs HBT. The HBT structure should exactly fill the etched hole, in order for the laser and HBT to be planarized and facilitate reliable lithography. To increase the overall thickness to fill the hole and minimize the effect of defects at the regrown interface on the active layer, the HBT structure used a thick buffer layer. The overall structure consisted of (i) a fifty period $50\ \text{\AA}$ n^+ -GaAs and $50\ \text{\AA}$ n^+ - $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ superlattice buffer, (ii) a $2.15\ \mu\text{m}$ n^+ -GaAs buffer, (iii) $0.3\ \mu\text{m}$ n -GaAs collector ($5 \times 10^{16}\ \text{cm}^{-3}$), (iv) a $0.1\ \mu\text{m}$ p^+ -GaAs base ($3 \times 10^{19}\ \text{cm}^{-3}$), (v) a $100\ \text{\AA}$ i -GaAs spacer, (vi) a $500\ \text{\AA}$ n - $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ emitter ($5 \times 10^{17}\ \text{cm}^{-3}$), (vii) a $0.1\ \mu\text{m}$ n - $\text{Al}_x\text{Ga}_{1-x}\text{As}$ compositionally graded layer (from $x = 0.3$ to 0.0), (viii) a $0.2\ \mu\text{m}$ n -GaAs

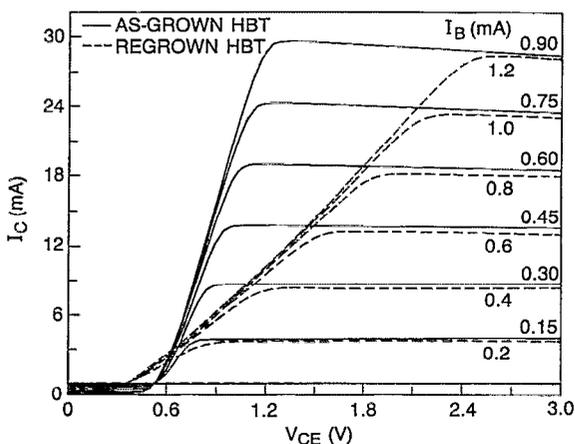


FIG. 2. I - V characteristics of an as-grown $50 \times 50\ \mu\text{m}$ size emitter GaAs HBT (solid line) and a regrown $60\ \mu\text{m}$ diam size emitter GaAs HBT (dashed line).

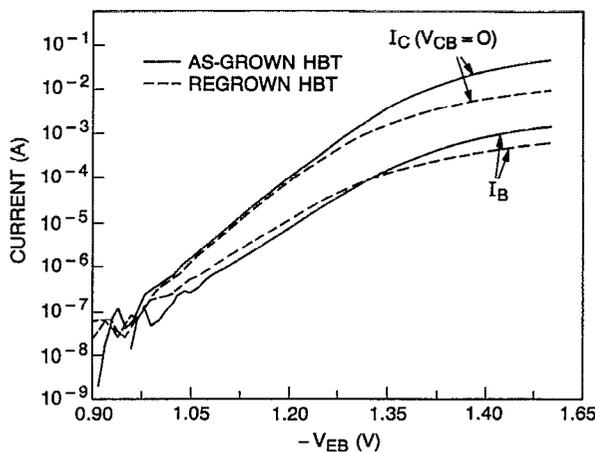


FIG. 3. Gummel plot of an as-grown (solid line) and regrown (dashed line) GaAs HBT.

contact layer, and (ix) a $500\ \text{\AA}$ n^+ -GaAs cap layer.

After regrowth, the polycrystalline epitaxial material on the SiO_2 regrowth mask is removed by photolithography and chemical etching, and the SiO_2 removed leaving a planarized wafer. Fabrication of the devices was accomplished by photolithography and chemically etching the HBT mesas using $\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}$ (1:1:50). The ridge waveguide laser was etched using reactive ion etching (RIE) with a SiCl_3 chemistry to produce vertical sidewalls. Any possible ion damage from the RIE process was removed by completing the mesa etch with a dilute sulfuric acid etch which removed an additional $1500\ \text{\AA}$ of material from the surface. The base contact and p -contact for the laser used a AuBe/Ti/Au metallization, and the remaining n -contacts used a AuGe/Ni/Ti/Au metallization. To complete the fabrication, the wafer was thinned and cleaved into $250 \times 500\ \mu\text{m}$ chips.

The common-emitter characteristics of the HBTs were measured at room temperature using a parameter analyzer. The current-voltage (I - V) characteristics of the as-grown HBTs with $50 \times 50\ \mu\text{m}^2$ emitter size, and regrown HBTs with $60\ \mu\text{m}$ diam emitters are shown in Fig. 2. In Fig. 2, the most significant feature is the added series resistance of

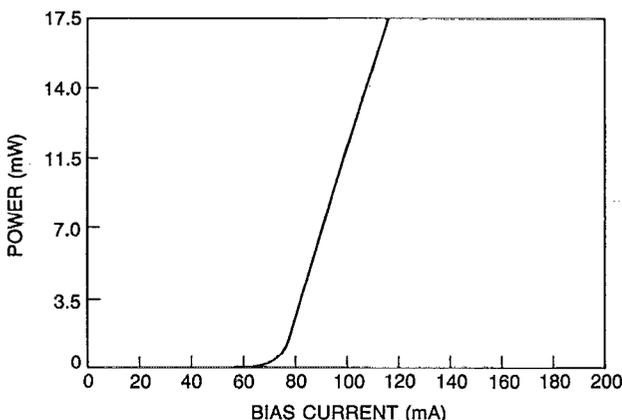


FIG. 4. L - I characteristics of an integrated graded-index laser.

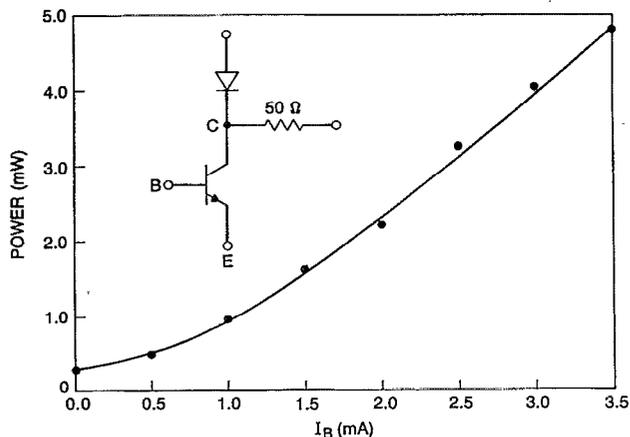


FIG. 5. Photodiode response to laser-HBT output with application of base current.

the regrown HBT. The added resistance is expected to be due to conduction through the depletion-accumulation region which occurs at the regrown interface.^{11,13} Also, there is about a 20% decrease in the dc gain from 33 to 26 for the regrown HBT.

The ideality factors of the collector and base currents obtained from the Gummel plots, shown in Fig. 3, were 1.37 and 1.85 for the as-grown HBT and 1.38 and 1.93 for the regrown HBT, respectively, which demonstrates very little performance degradation due to regrowth. Variation of small signal current gains with I_C in both types of devices were measured for a $V_{CE} = 3$ V, and show a weak dependence on I_C for both devices. The regrown HBT current gain performance parallels that of the as-grown HBT, except that overall gain is reduced slightly.

The $L-I$ characteristics of the laser are shown in Fig. 4. The lasers have typical threshold currents in the 70–80 mA range. Discrete lasers were fabricated from the same wafer, using a section that did not undergo the heat treatment of regrowth, and exhibited higher thresholds of 120 mA, due to the differences in ridge fabrication. This suggests that the temperature cycling from regrowth did not significantly alter laser performance via interdiffusion of the quantum wells, when the laser epilayer is grown before the HBT, which agrees with our previous results.¹³

The optical response of the laser-HBT circuit was tested by biasing the HBT to $V_{CE} = 5.2$ V, and the laser was biased to below threshold. The emitted light was measured as a function of base current and is shown in Fig. 5. At a base current of $I_B = 4.0$ mA, the collector current was $I_C \sim 110$ mA, and the laser delivered about 4.8 mW of optical power. Biasing at maximum laser modulation provided 1.2 mW/mA of laser output with the application of base current. Maximum laser modulation occurs around 2 mA of base current, with a slope of 2 mW/mA of base current.

In summary, we have successfully fabricated an OEIC comprising of a GaAs quantum well laser diode with a GaAs/AlGaAs HBT. Application of a small signal to the base modulates the light output. The modulation index defined as the change in light output for unit change in base current is 1.2 mW/mA for our device.

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