

Monolithic integration of a GaAlAs buried-heterostructure laser and a bipolar phototransistor

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A GaAlAs buried-heterostructure laser has been monolithically integrated with a bipolar phototransistor. The heterojunction transistor was formed by the regrowth of the burying layers of the laser. Typical threshold current values for the lasers were 30 mA. Common-emitter current gains for the phototransistor of 100–400 and light responsivity of 75 A/W (for wavelengths of 0.82 μm) at collector current levels of 15 mA were obtained.

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One of the key elements in the fabrication of GaAlAs/GaAs integrated optoelectronic circuits is the semiconductor laser. A crucial parameter for the laser is its threshold current, which should be minimized in order to reduce the heat dissipation of the integrated device. A very attractive candidate with this feature is the buried-heterostructure (BH) laser which has been fabricated on conductive¹ as well as on semi-insulating² GaAs substrates. This type of laser is characterized by a very low threshold current (~ 20 mA for a stripe width of 2 μm) and oscillates in a single lateral and longitudinal mode. Since the active waveguiding region of this laser is completely embedded in the lower refractive index GaAlAs material, a two-step liquid-phase epitaxial (LPE) growth is necessary—growth of the double heterojunction followed by growth of the burying layer. The fabrication process of these lasers is consequently more complicated than that of other conventional double-heterostructure lasers (e.g. stripe geometry lasers) which require only one epitaxial growth. A judicious choice of the type of burying layers grown in the second step, however, can be used as an advantage in the fabrication of new devices which are monolithically integrated with the laser on the same crystal chip. In so doing, one has only to keep the higher index active region embedded in the lower index material which forms the laser waveguide. This process is typically compatible with the fabrication of several electronic devices, e.g. field-effect transistors, bipolar transistors, and photodiodes. In

this letter we report on the successful use of the regrowth process to fabricate bipolar phototransistors with a wide band-gap emitter and a narrow band-gap base. The monolithic integration of a GaAs/GaAlAs bipolar transistor and a heterostructure laser has been recently demonstrated³ using Be-ion implantation, which formed a stripe geometry laser. In the present work we have employed, for the first time, the superior BH laser as the light source to be integrated with the bipolar transistor, using the second LPE growth to form both the bipolar transistor and the cladding layers for the laser waveguide.

The cross section of the device is schematically shown in Fig. 1. The first LPE growth, which involves the laser section, consists of four layers: $n\text{-GaAs}$ (4 μm , $4 \times 10^{17} \text{ cm}^{-3}$), $n\text{-Ga}_{0.65}\text{Al}_{0.35}\text{As}$ (1.5–2 μm , 10^{17} cm^{-3}), undoped $\text{Ga}_{0.95}\text{Al}_{0.05}\text{As}$ (0.25 μm), and $p\text{-Ga}_{0.65}\text{Al}_{0.35}\text{As}$ (1.5–2 μm , 10^{17} cm^{-3}). After etching mesa stripes down to the $n\text{-GaAs}$ layer (stripe width 4 μm) with $\text{H}_2\text{SO}_4\text{:H}_2\text{O:H}_2\text{O}_2$ (1:8:8) in the $\langle 1\bar{1}0 \rangle$ direction (inverted trapezoidal shape) the second LPE growth is performed in order to obtain the bipolar transistor structure. The regrown layers are $n\text{-GaAs}$ (0.5 μm , undoped), $p\text{-GaAs}$ (0.3 μm , 10^{18} cm^{-3}), and $n\text{-Ga}_{0.65}\text{Al}_{0.35}\text{As}$ ($5 \cdot 10^{16} \text{ cm}^{-3}$). The wafer is then coated with SiO_2 and two Zn diffusion processes are performed from a ZnAs_2 source: a shallow diffusion into the $p\text{-GaAlAs}$ layer on top of the mesa (to improve the p contact of the laser) and a deep diffusion down to the $p\text{-GaAs}$ regrown layer

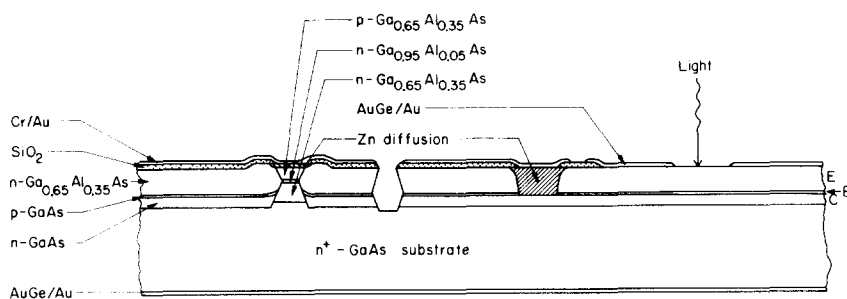


FIG. 1. Schematic cross section of the device (not to scale).

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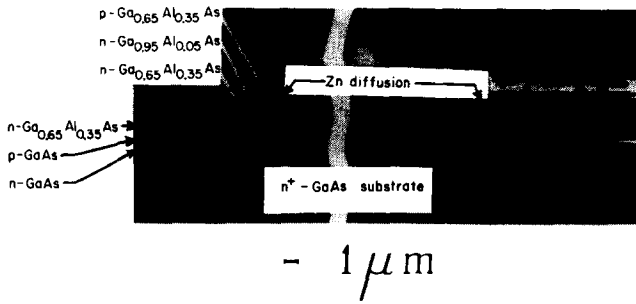


FIG. 2. SEM photomicrograph of the device cross section. The laser section is shown on the left and the transistor section is shown on the right. The lower bright line in the transistor section corresponds to the base layer. The collector substrate interface is not rendered visible in this photograph due to the similarity of materials.

(which serves as the base contact of the transistor). Finally, the contacts are applied by thermal evaporation and alloying: Cr-Au for laser anode and the transistor base, and Au-Ge/Au for the laser cathode (which serves also as the collector of the *npn* transistor) and the transistor emitter. The laser is isolated from the emitter and base by etching a narrow stripe in the wafer down to the lower *n*-GaAs layer, which serves as the collector. A scanning electron microscopy (SEM) photomicrograph of the device cross section is shown in Fig. 2.

The threshold current of the laser was 30 mA for 300- μm cavity length, and the external differential quantum efficiency was $\sim 50\%$ from both facets. Since the stripe width was 4 μm , the laser did not oscillate in the fundamental lateral mode. The leakage through the burying layers was minimized due to the *npn* blocking layers which form the transistor structure. The transistors have typical common-emitter current gains β in the range of 100–400, at collector current levels of several milliamperes. The thin base layer (0.3 μm) and the high band-gap emitter contribute to the current gain of the transistor by reducing the minority-carrier transit time and increasing the injection efficiency, respectively. Since the laser and the transistor are connected in series, as shown in Fig. 3, the laser optical output can be easily modulated by the transistor. Although field-effect transistors are somewhat faster than heterojunction bipolar transistors, the latter is projected to operate up to the range of 5 GHz.^{4–6} In the present case the modulation bandwidth was limited by the high emitter contact resistance, due to the moderately doped GaAlAs emitter layer. This will be overcome by the growth of an additional n^+ -GaAs layer on top of the GaAlAs layer.

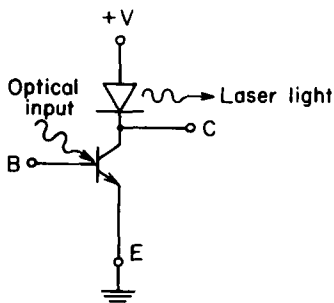


FIG. 3. Schematic diagram of the device.

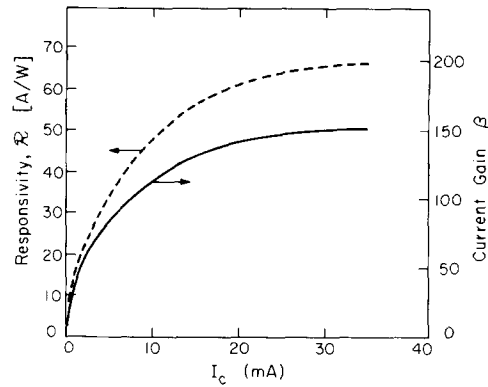


FIG. 4. Phototransistor responsivity R and common-emitter current gain β vs collector current I_c .

We have also operated the transistors as photodetectors. This was achieved by removing the emitter contact from a 50- μm -diam circular area and inserting light from a fiber coupled to GaAlAs laser source ($\lambda = 0.82 \mu\text{m}$). The phototransistor responsivity R was measured to be 50–75 A/W at collector current levels of 15–20 mA. The fact that the collector is made of GaAs provides additional phototransistor responsivity due to the additional absorption in the collector side of the depletion region. This is an improvement compared to the former laser-bipolar-transistor integration³ which utilized high band-gap collector. Figure 4 shows a typical dependence of the light responsivity R and the common-emitter small-signal current gain β on the collector current I_c . For currents above 20 mA, the values of both R and β remain virtually constant. This collector current is obtained by applying a base current through the Zn diffused area. Its value can be reduced by optimizing the emitter geometry to smaller dimensions. Thus, the circuit can be operated as an optical repeater, having both the detector, the amplifier, and the laser on the same crystal. A similar device using metal-semiconductor field-effect transistors was already demonstrated.⁷

In conclusion, we have used the LPE regrowth of a BH laser to form heterostructure *npn* bipolar phototransistors. This creates a naturally integrated translaser (a laser-transistor circuit) that can be operated as a modulator or a repeater. The ease of interfacing the bipolar transistor with conventional electronic circuits, the optical gain (light out/light in), and the possibility of high frequency modulation make it a potentially useful device in many optical communication applications.

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