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A monolithic integration of GaAs/GaAlAs bipolar transistor and heterostructure laser

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A GaAlAs double-heterostructure laser has been monolithically integrated with a heterojunction bipolar transistor on a GaAs substrate. Integration is achieved by means of a mutually compatible structure formed by Be ion implantation. Typical pulsed threshold currents for the laser are 60 mA, and the transistors have a typical common-emitter current gain of 900.

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Most of the many applications envisaged for the semiconductor injection laser call for modulation of its light output. Some of these applications, especially those involving data transmission through optical fibers, will require modulation capability at high frequencies. It is thus natural to consider efficient means for current modulation of injection lasers.

We have recently[1,2] demonstrated the monolithic integration of a field-effect transistor (MESFET) with an injection laser on a single-crystal epitaxially grown GaAs/GaAlAs configuration. A similar device was later described by Fukuzawa *et al.*[3]

In this letter we report on a new type of device which involves monolithic integration of an injection laser and a heterojunction bipolar transistor on an n^+ GaAs substrate. The laser structure which we have used is a stripe-geometry laser formed by Be ion implantation.[4] The process used to form the lasers is compatible with the fabrication of heterojunction transistors having a wide-band-gap emitter and a narrow-band-gap base. Such heterojunction transistors are known to have large common-emitter current gains.[5-7] Since in heterostructure transistors the emitter injection efficiency is enhanced by the larger band gap of the $Al_xGa_{1-x}As$ emitter layer, the base doping can be increased, thus improving transistor performance by reducing the base resistance, reducing the amount of emitter crowding, improving the frequency response, and effectively eliminating possible punchthrough. The structure of the device is shown in Fig. 1(a). The building block of the device is a 250-μm-wide region defined as a liquid-phase-epitaxy (LPE)-grown *n*-AlGaAs/*p*-GaAs/*n*-AlGaAs double heterostructure. Each such unit can operate independently as either an injection laser or a bipolar transistor. In the first case, terminal 1 is the anode terminal of a Be-implanted laser and terminal 2 (the substrate) is the laser cathode. In the second case, terminal 3 is the emitter of the transistor, terminal 2 is the collector of the transistor, and the base contact (terminal 4) is formed via the Be-implanted region.

It is important to note that the laser is structurally a bipolar transistor operated with the base as the positive terminal while the emitter terminal is left open. The usual assignment of the terminals is shown in Fig. 1(b). Another point worth noting is that in previous work[6,7] the transistor base was contacted directly after etching the top AlGaAs layer. Because of the small thickness of the base region, alloying the contact can cause leakage in the collector base junction. We have solved this problem by achieving contact to the base by means of a Be implantation. The parasitic *p-n* junction which is formed by this implantation in the GaAlAs emitter layer has a higher built-in voltage than the emitter-base *p-n* junction and therefore contributes only minimal leakage current.

Fabrication of the device starts with the growth of four layers on n^+ GaAs substrate by LPE. The typical layer thicknesses are 3 μm for the lower n-$Ga_{0.6}Al_{0.4}As$, 0.25 μm for the *p*-GaAs active (or base) layer, 1 μm for the upper n-$Ga_{0.6}Al_{0.4}As$ layer, and 0.7 μm for the emitter *n*-GaAs contact layer. This contact layer is removed in the region to be implanted in order to assure diffusion of the Be-implanted stripe down to the active region. After deposition of 2500 Å of SiO_2 on the wafer, it is coated with photoresist in which stripes of width 6 μm are opened. After etching the SiO_2 in these openings, a 100-keV Be implantation is performed at room temperature with a dose of 3×10^{15} cm^{-2}. After removal of the photoresist mask the wafer is annealed for 40 min at 800 °C. This results in diffusion of the Be-implanted stripe down to, but not beyond, the GaAs active region, which is in accord with our finding that the Be diffusion

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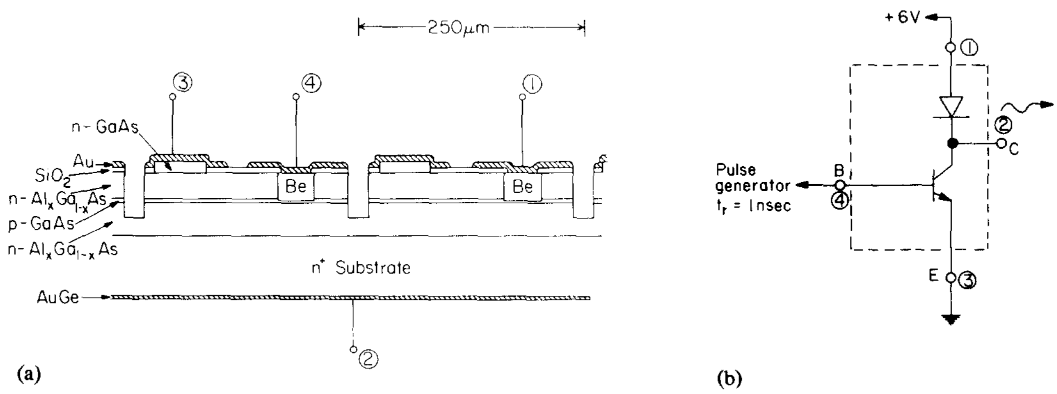

FIG. 1. (a) Cross section of the device structure, (b) schematic drawing of the device.

depth is strongly dependent on Al content of the material.[4] Because of the use of photoresist as an implanting mask above the SiO_2 layer, the Be region has minimal lateral diffusion.[4] After a shallow Zn diffusion and evaporation of Cr and Au, windows of 100 μm width are opened down to the GaAs top layer. An evaporation of AuGe and Au is then performed to form the emitter contact of the transistor. The emitter contact is separated from the base contact by etching the metals between them in a stripe of 10 μm width. The laser is then isolated from the emitter and base by etching another 10-μm-wide stripe in the wafer down to the lower GaAlAs layer, which serves as the collector. The etchant used was 1:8:8 (H_2SO_4:H_2O_2:H_2O). The substrate is then lapped and the *n*-type substrate is deposited with AuGe and Au followed by alloying at 380 °C. The base layer doping is approximately 10^{18} cm^{-3}. This concentration is not high enough to cause a substantial increase of the free-carrier optical absorption. Since the base sheet resistance remains relatively high (~ 1 kΩ /□), the current spreading also does not increase considerably.

The collector current versus collector-emitter voltage curve ($I_C - V_{CE}$) of the transistor is shown in Fig. 2. The transistor was tested at current levels up to 200 mA. Figure 3 shows the dependence of the dc current gain β on the collector current I_C. At low currents the value of β increases with current. For currents above 80 mA, the value of β remains approximately constant. Values of β exceeding 900 were obtained.

Threshold currents of the lasers were as low as 55 mA, with 60 mA being a typical value for a 250-μm cavity length. Near- and far-field patterns parallel to the junction plane are shown in Fig. 4, both of which exhibit single-mode behavior. The half-width of the near-field intensity pattern is about 5 μm, and the half-width angle of the far-field pattern is about 6°. The temporal performance of the total device was tested using an avalanche photodiode. The modulation capability of the device was demonstrated by a pulse response with a rise time of 1.1 nsec (corresponding to a modulation rate exceeding 300 MHz). Higher-frequency response of bipolar GaAlAs/GaAs transistors has been obtained.[8] The attractiveness of this integration lies in the ease of interfacing the bipolar transistor with conventional electronic circuits, e.g., TTL, and the compatibility of the laser and the transistor structures in the fabrication process. The time response can be improved by using a base electrode structure more suitable for high-frequency applications. cw operation of the device with the substrate side bonded to a copper heat sink was

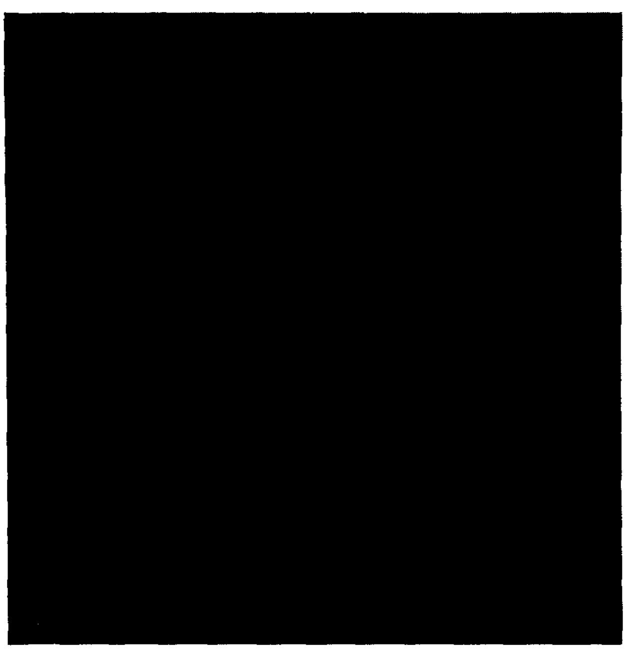

FIG. 2. Collector current I_C vs collector-emitter voltage V_{CE} characteristics of the bipolar transistor (horizontal scale: 0.5 V/div, vertical scale: 10 mA/div; base current: 20 μA/step).

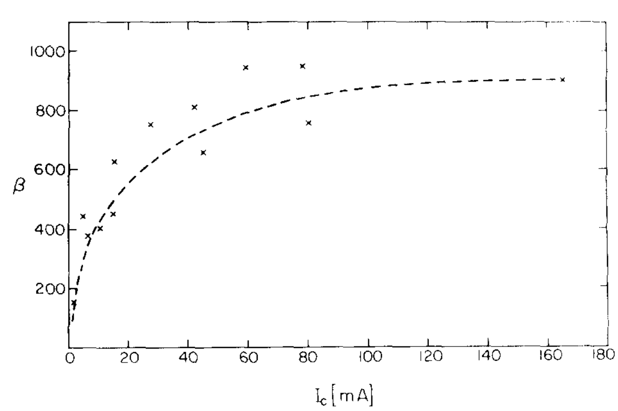

FIG. 3. dc common-emitter current gain β vs collector current I_C.

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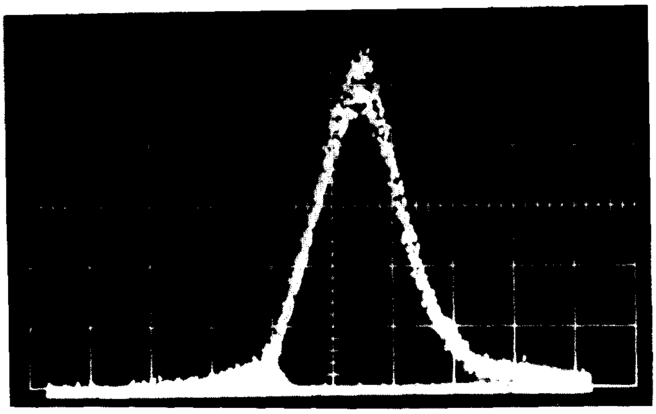
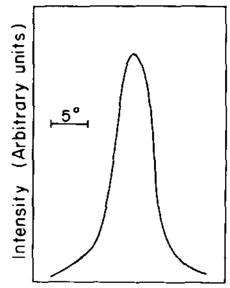


(a)



(b)

FIG 4. Lateral optical characteristics of the laser ($I \simeq 1.3 \times I_{th}$): (a) near-field pattern (2.7 μm/div), (b) far-field pattern.

obtained. The threshold currents in this case are typically 20% higher than the pulsed threshold currents. The light versus current characteristic was linear to 10 mW and no self-pulsation was observed after a few hundred hours of operation. Operation of similar devices in which Zn diffusion instead of Be implantation was used, was also accomplished. The characteristics of the Be-implanted devices were slightly better, in terms of the threshold current and the quantum efficiency. The better performance of the Be-implanted lasers is the result of the minimum lateral diffusion of the Be in the fabrication process, which minimizes the area of the *p-n* junction in the GaAlAs upper layer.

In conclusion, we have integrated a Be-implanted GaAlAs laser with a bipolar transistor on a GaAs substrate. This device is attractive in high-speed optical communication systems. Fabrication of this device on semi-insulating GaAs substrates can be easily done. We believe that the superior modulation potential of the laser-transistor combination will make it a standard component in the optoelectronic art, and take this occasion to name it the "Translaser."

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Preparation of conducting and transparent thin films of tin-doped indium oxide by magnetron sputtering

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High-quality 800-Å-thick films of tin-doped indium oxide have been prepared by magnetron sputtering. It is shown that films with low resistivity ($\sim 4 \times 10^{-4}\ \Omega$ cm) and high optical transmission (> 85% between 4000 and 8000 Å) can be prepared on low-temperature (40–180 °C) substrates with O_2 partial pressures of $(2\text{–}7) \times 10^{-5}$ Torr.

PACS numbers:

Oxygen-deficient indium tin oxide (ITO) films exhibit a high electrical conductivity combined with high transmission in the visible spectral region. This combination of properties has led to its use in antistatic coatings, infrared coatings, and more recently in semiconductor-insulator-semiconductor (SIS) solar cells.[1,2] In addition to forming the necessary heterojunction with the semiconductor absorber layer, it simultaneously acts as the transparent front conducting electrode, an encapsulation layer, and an antireflecting coating (at ~800 Å thickness for silicon). The potential applications of ITO in large-area devices, solar cells, or electro-optic displays has led to a resurgence of studies of its properties.

It is naturally attractive to be able to prepare transparent, conductive, and stable ITO films over large areas by a technique which needs no postpreparative treatment as well

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