A Stripe-Geometry InGaAsP/InP Heterojunction Bipolar Transistor Suitable for Optical Integration

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Abstract—**A stripe-geometry InGaAsP/InP heterojunction bipolar transistor (HBT) was fabricated for the first time. High current gain ($\beta >$ 500) and high collector current ($I_c >$ 200 mA) were obtained in devices with an emitter-down configuration. The HBT was successfully integrated with a double-heterostructure (DH) laser, resulting in the first realization of laser operation in a vertical integration.**

I. Introduction

Heterojunction bipolar transistors (HBT's) have gained increased attention in recent years [1]–[5]. Compared to FET's, HBT's are potentially faster, less noisy at high frequencies, and possess better device-to-device uniformity. There have been considerable efforts to integrate a double-heterostructure (DH) laser with an HBT [6]–[9]. From the fabrication point of view, the making of an HBT is compatible with that of a high-performance DH laser. Moreover, the HBT's benefit from the use of heteroepitaxial technology in the same way as DH lasers, i.e., using the energy-gap variations in addition to electric field to control the distribution and flow of electrons and holes independently. Furthermore, the HBT's are more versatile than FET's; for example, an HBT can be operated as a phototransistor and offers an alternative to an APD. When an HBT and a laser are placed sufficiently close to each other, as in the case of a vertical integration [7], optical coupling as well as electronic interaction can take place, resulting in new functions which cannot be expected for the constituent devices.

Much effort has been devoted to the development of high-performance HBT's [2]–[5]. In this paper, we report on the fabrication and characteristics of an InGaAsP/InP stripe-geometry HBT. High current gain and high collector current were obtained. The HBT has been integrated with a DH laser, resulting in the first laser operation in a vertical integration.

II. Structure

The InGaAsP/InP HBT was specially designed for optoelectronic integration. In order to drive the laser diode to a reasonable output power level, the HBT must be capable of delivering high collector current. For effective control of laser operation, the gain of the HBT should be high. High speed is also desirable.

A schematic structure of the integrated DH laser and HBT is shown in Fig. 1(a). A cross-sectional view of the fabricated HBT is presented in Fig. 1(b). The transistor consists of five epitaxial layers grown on an n^+-InP conduction substrate. The HBT has the following features. The integration is based on an n^+-InP substrate, and the HBT is then designed to be operated in an emitter-down configuration. In order to better match a stripe laser, the HBT was fabricated for the first time in a stripe geometry. In favor of high-speed operation, the dimensions of the HBT have been made small: collector and base stripes are $\sim 10\ \mu$m wide, and base width is only $\sim 0.2\ \mu$m. The device employed both a wide-gap emitter and a wide-gap collector [1], which offered the interchangeability of collector and emitter. To overcome the possible "electron-repelling" [1], [4], [5] effect arising from the abrupt collector–base junction, a thin InGaAsP layer was inserted between the InP collector layer and InGaAsP base layer, forming a joint n-InGaAsP and n-InP collector layer [5]. A Zn diffusion through the n-InP, n-InGaAsP, and p-InGaAsP layers was performed; in this way, no critical etching step was needed to obtain base contact [5]. Finally, Cd, as well as Zn, were used as p-dopants for the base layer. Cd is less diffusive than Zn, which prevents its diffusion into the adjacent layers, resulting in better device performances.

III. Fabrication

The fabrication process of the HBT involves only standard semiconductor technology. The five-layer structure was grown by one-step LPE. The growth temperature for the base layer was 635°C. The composition, layer thickness, and doping concentration of the layers are: n^+-InP buffer layer ($\sim 5\ \mu$m thick, Sn doped to $2 \times 10^{18}/cm^3$); p-InGaAsP base layer (bandgap wavelength $\lambda_g = 1.3\ \mu$m, ~ 0.2–$0.4\ \mu$m thick, Zn or Cd doped to 1–$3 \times 10^{17}/cm^3$); n-InGaAsP collector layer ($\lambda_g = 1.3\ \mu$m, $\sim 0.1\ \mu$m thick, undoped or Sn doped to 1–$3 \times 10^{17}/cm^3$); n-InP collector layer (2–3 μm thick, undoped or Sn doped to 1–$3 \times 10^{17}/cm^3$); and n^+-InGaAsP contact layer ($\lambda_g = 1.1\ \mu$m, $\sim 0.2\ \mu$m thick, Sn doped to $2 \times 10^{18}/cm^3$). In order to obtain high collector current and high current gain simultaneously, the doping level in the base layer is in accordance with a previous study [7, Table I]. After crystal growth, Si_3N_4 was deposited on the wafer, and ~ 10-

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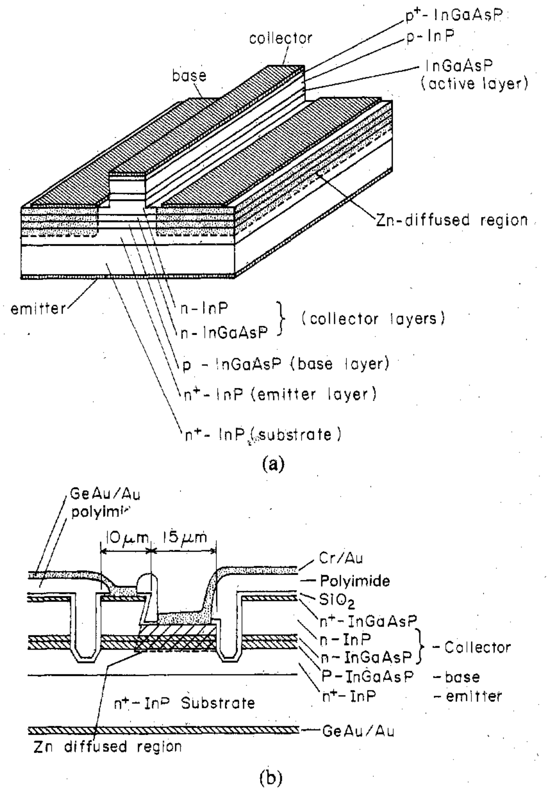

Fig. 1. (a) A schematic structure of a vertical integration of a DH laser and an HBT. (b) A cross-sectional view of the fabricated HBT.

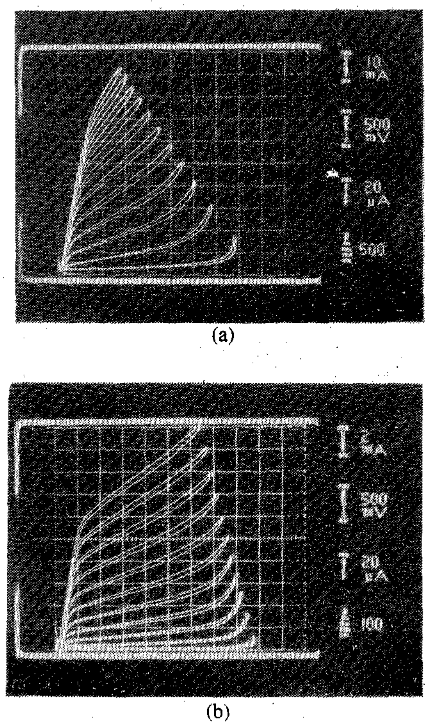

Fig. 2. (a) I–V characteristics of an HBT operated in emitter-down configuration showing $\beta > 500$ and $I_c > 80$ mA. Horizontal scale = 500 mV/div; vertical scale = 10 mA/div; step increment = 20 μA/step (β = 500/div). (b) I–V characteristics of the same device as in (a) operated in emitter-up configuration. Horizontal scale = 500 mV/div; vertical scale = 2 mA/div; step increment = 20 μA/step (β = 100/div).

μm-wide mesa stripes and $\sim$15-μm-wide grooves were defined by standard photolithography followed by chemical etching. The etchant was 10-percent iodic acid. The etching was stopped in the n-InP collector layer $\sim$0.5 μm above the n-InGaAsP layer. A Zn diffusion was then performed in a sealed ampule at 620°C for $\sim$15 min. The diffusion front penetrated the p-InGaAsP base layer and stopped in the n^+-InP emitter region. A pair of grooves parallel to the collector stripe ($\sim$5 μm wide and $\sim$8 μm deep) were etched into the n^+-InP substrate to isolate each individual device. Finally, GeAu/Au, Cr/Au (or ZnAu/Au), and GeAu/Au were evaporated and annealed to form collector, base and emitter contact, respectively. Polyimide or photoresist was used to fill the ditches, and bonding pads were made which gave the device a planar surface and facilitated device measurement (see Fig. 1(b)). For the sake of simplicity, the Zn diffusion was usually carried out only on one side of the collector stripe.

IV. Device Characteristics

Typical I–V characteristics for an HBT with Cd-doped base layer are shown in Fig. 2. Fig. 2(a) presents the characteristics when an HBT is operated in an emitter-down geometry. High common-emitter current gain and high collector current have been obtained. A common-emitter current gain β of over 500 (at $I_c \simeq 30$ mA, $V_{ce} \simeq 3$ V) and a collector current of over 80 mA were typical. For some devices, collector currents were driven to as high as 200 mA (dc). In a pulse excitation (pulse width = 300 ns, repetition rate = 2 kHz), collector current can be pushed to 650 mA without damaging the device (at a collector voltage of 10 V and a base current of $\sim$5 mA). Considering the small junction area of the device (10 × 250 μm^2), this value is quite pronounced. A current gain of larger than 1500 (at a collector current of $\sim$2 mA, $V_{ce} \geq 2$ V) was also observed. Among devices from a given wafer, the performances were quite uniform.

Fig. 2(b) shows the characteristics of the same device (as in Fig. 2(a)) operated in an emitter-up configuration. The β seems several times smaller. This is not difficult to understand if one notices that the layer structure was not optimized when the HBT was operated in an emitter-up geometry. The advantages arising from the wide-gap emitter no longer existed. A reduction in β is expected consistent with theoretical prediction [1]. It is noticed that the current gain β decreases slightly with increasing collector current I_c in the emitter-down configuration. However, in the emitter-up geometry, the β increases gradually with collector current.

The emitter-down HBT was vertically integrated with a DH laser on an n^+-InP substrate. The HBT served as a driving and controlling circuit for the laser. The threshold of the laser was $\sim$30 mA. The laser was driven to $\sim$200-mA injection current and delivered an output light power of $\sim$30 mW. Electronically controlled optical bistable laser operation was also demonstrated. Fig. 3 shows the bistable operation of one integrated device. When the base current I_b increases to 1.6 mA, the collector current jumps to 210 mA (not shown in the figure), and the laser delivers an output light power P_o of 32 mW.

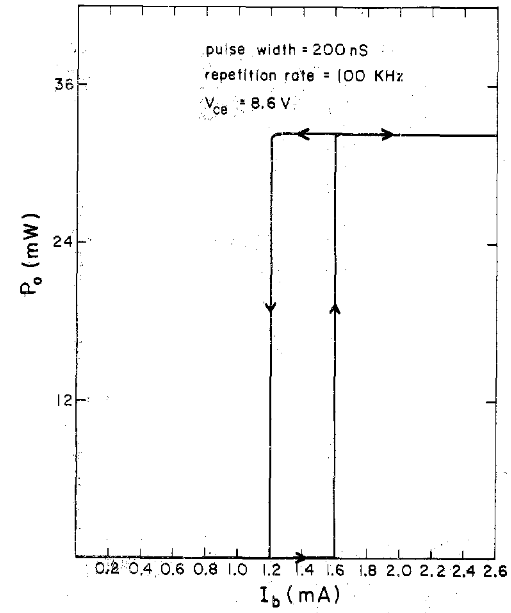

Fig. 3. Bistable operation of an integrated device. Vertical: Laser power p_o in milliwatts. Horizontal: HBT base current I_b in milliamperes.

In conclusion, stripe-geometry InGaAsP/InP HBT devices with emitter-down configuration have been fabricated by LPE growth technique and conventional semiconductor technology. A β of 500 and I_c of 200 mA (dc) were observed. This stripe-geometry HBT has been integrated monolithically with a stripe DH laser, resulting in the first realization of a laser operation in a vertical integration.

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