APPLIED PHYSICS LETTERS VOLUME 85, NUMBER 20 15 NOVEMBER 2004

Laser operation of a heterojunction bipolar light-emitting transistor

G. Walter,[a] N. Holonyak, Jr., M. Feng, and R. Chan
Electrical Engineering Research Laboratory and Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, 1406 W. Green Street, Urbana, Illinois 61801

(Received 21 July 2004; accepted 23 August 2004)

Data are presented demonstrating the laser operation (quasicontinuous, ~200 K) of an InGaP–GaAs–InGaAs heterojunction bipolar light-emitting transistor with AlGaAs confining layers and an InGaAs recombination quantum well incorporated in the *p*-type base region. Besides the usual spectral narrowing and mode development occurring at laser threshold, the transistor current gain $\beta=\Delta I_c/\Delta I_b$ in common emitter operation decreases sharply at laser threshold $(6.5\rightarrow 2.5, \beta>1)$. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1818331]

Since the discovery of the transistor (16 December 1947, Bardeen and Brattain[1]), the base current (minority carrier recombination) has been the key to the device operation, the base current separating the low impedance input (emitter) from the high impedance output (collector) and thus yielding a "transfer resistor" ("transistor"). The base current, electron–hole recombination, is usually lost (dissipated as heat) but can for a direct-band-gap semiconductor yield substantial recombination radiation. As the transistor has evolved from point contact, to $p-n$ junction, to III–V semiconductor heterojunction bipolar (HBT), to particularly high-current density high-speed HBT,[2] we arrive at the possibility that the transistor (HBT) can be modified and operated as a three-port light-emitting device (an electrical input, electrical output, and a third port optical output).[3] The three-port light-emitting transistor (HBT→HBLET) can be substantially modified and improved by incorporating a quantum well, or multiple quantum wells (QWs), into the *p*-type base region in order to "tailor-make" (redesign) the base recombination and thus the transistor electrical and optical properties.[4,5] This letter shows that the HBLET can be further designed to support stimulated recombination and be operated as a laser. We describe a three-port HBLET laser, and show how stimulated emission (stimulated recombination) is manifest in a transistor.

The epitaxial layers of the crystal used for the hetrojunction bipolar light-emitting transistor (HBLET) laser are shown schematically in Fig. 1, with as usual first a 4000 Å *n*-type heavily doped GaAs buffer layer, followed by a 600 Å *n*-type $Al_{0.40}Ga_{0.60}As$ layer, a 3500 Å *n*-type $Al_{0.98}Ga_{0.02}As$ layer, and a 400 Å *n*-type $Al_{0.40}Ga_{0.60}As$ layer forming the bottom cladding layers. These layers are followed by a 400 Å *n*-type subcollector layer, then a 200 Å $In_{0.49}Ga_{0.51}P$ etch stop layer (not shown), a 650 Å undoped GaAs collector layer, and a 940 Å *p*-type GaAs base layer (the active layer), which also includes (in the base region) a 120 Å InGaAs QW (designed for $\lambda\approx 980$ nm). The epitaxial HBLET laser structure is completed with the growth of the upper cladding layers, which consist of a 1200 Å *n*-type $In_{0.49}Ga_{0.51}P$ wide-gap emitter layer, a 300 Å *n*-type $Al_{0.70}Ga_{0.30}As$ oxidation buffer layer, a 3500 Å *n*-type $Al_{0.98}Ga_{0.02}As$ oxidizable layer,[6] and a 1000 Å *n*-type $Al_{0.40}Ga_{0.60}As$ layer. Finally, the HBLET laser structure is capped with a 1000 Å heavily doped *n*-type GaAs contact layer.

The HBLET laser fabrication is performed by first patterning 6 μm protective SiN_4 stripes on the crystal. The top *n*-type $Al_{0.98}Ga_{0.02}As$ oxidizable layer is then exposed by wet etching $(1:8:160\ H_2O_2:H_2SO_4:H_2O)$ to form a ~6 μm emitter mesa. Next, a wide 150 μm protective photoresist (PR) stripe is placed over the emitter mesa and the unprotected $Al_{0.98}Ga_{0.02}As$ layer is completely removed $(1:4:80\ H_2O_2:H_2SO_4:H_2O)$, revealing the $In_{0.49}Ga_{0.51}P$ wide-gap emitter layer. The protective PR stripe is then removed and the sample is oxidized for 7.5 min at 425 °C in a furnace supplied with N_2+H_2O, resulting in a ~1.0 μm lateral oxidation which forms ~4 μm oxide-defined apertures in the 6 μm emitter mesa.[6,7] The samples are annealed (in N_2) at 430 °C for 7 min to reactivate *p*-dopants before the protective SiN_4 is removed by plasma (CF_4) etching. A 100 μm PR window is formed over the emitter mesa and oxide layer, and Au–Ge/Au is deposited over the sample to form metal contact. After lift-off of the PR to remove excess metal, the $In_{0.49}Ga_{0.51}P$ layer is removed using a wet etch $(4:1\ HCl:H_2O)$, exposing the *p*-type GaAs base layer. An 80-μm wide PR window is then patterned ~15 μm away from the emitter mesa edge, and Ti–Pt–Au is evaporated for contact to the base. Another lift-off process is then performed

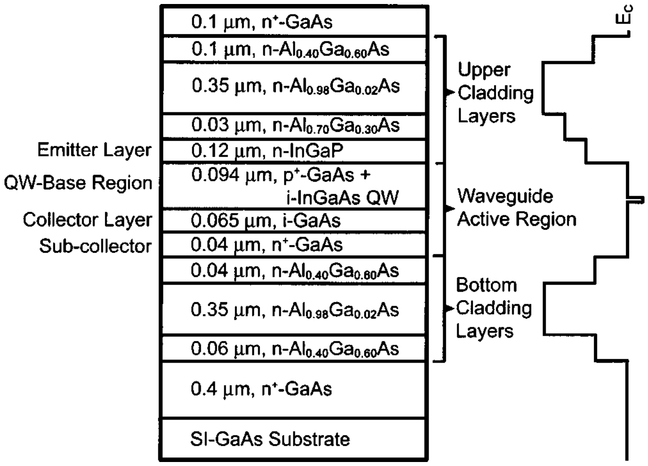

FIG. 1. Diagram of the epitaxial layers of a crystal used for a heterojunction bipolar light emitting transistor (HBLET) operating as a transistor and laser. A recombination quantum well (QW) is incorporated in the *p*-type base and cladding structure.

---

[a] Electronic mail: walter1@uiuc.edu

0003-6951/2004/85(20)/4768/3/$22.00

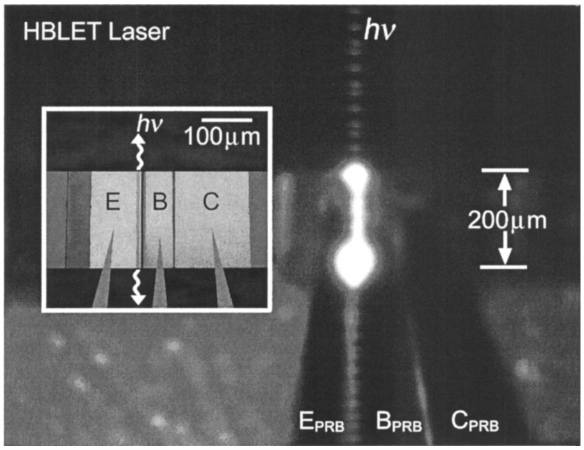

FIG. 2. Top view (left photograph) of the HBLET crystal of Fig. 1 etched in steps and metallized for transistor emitter (E), base (B), and collector (C) contacts. On the right the HBLET laser, with 200 μm Fabry–Perot facet spacing, is pulse operated so as not to saturate the CCD camera. The laser light beam is scattered from a Cu platform and labeled $h\nu$ at the top. The contact probes (dark shadows) on the emitter (E), base (B), and collector (C) are labeled E_{PRB}, B_{PRB}, and C_{PRB}.

to remove excess base contact metal. A 150 μm PR window is then patterned $\sim$6 μm away from the base contact. The GaAs base and collector layers are removed using a selective etch (4:1 $C_6H_8O_7$:H_2O_2), and the $In_{0.49}Ga_{0.51}P$ etch-stop layer is removed by a wet etch (16:15 HCl:H_2O), exposing the heavily doped *n*-type GaAs subcollector layer. Au–Ge/Au metal alloy is evaporated over the sample for contact to the exposed subcollector layer, and another lift-off process is performed to remove excess metal. The sample is then lapped to a thickness of $\sim$75 μm and the contacts annealed. The HBLET samples are cleaved normal to the emitter stripes to form Fabry–Perot facets, and the substrate side of the crystal is alloyed onto Cu heat sinks coated with In.

A processed, metallized, and cleaved HBLET laser (top view) is shown on the left-hand side in Fig. 2. The contact probes on the emitter (E), base (B), and collector (C) are shown schematically resembling the actual probes (E_{PRB}, B_{PRB}, and C_{PRB}) on the operating device at the right. The image on the right-hand side is obtained with a video CCD detector and shows ($h\nu$) the device laser beam (photons) scattered from a Cu platform located slightly lower than the laser crystal, which, as shown, has a $\sim$200 μm spacing between the cleaved Fabry–Perot facets. Current and bias voltage (common emitter operation) are provided using a Tektronix Model 370 high resolution curve tracer connected to the HBLET by the three probes labeled E_{PRB}, B_{PRB}, and C_{PRB} in Fig. 2. The HBLET laser is operated $\sim$200 K in a dry N_2 environment.

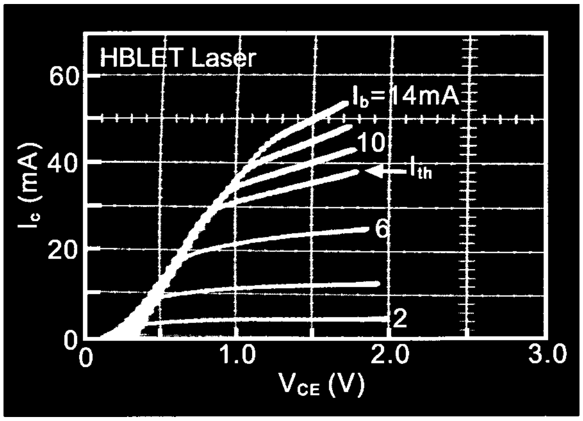

FIG. 3. The transistor $I-V$ curves of an HBLET laser (crystal of Figs. 1 and 2) with $\sim$260 μm spacing between the Fabry–Perot facets. At a base current $I_b \gtrsim 8$ mA, the HBLET reaches laser threshold and changes transistor gain, $\beta=\Delta I_c/\Delta I_b$, from β=6.5 to 2.5 or ($\alpha=\beta/(\beta+1)=0.87\rightarrow 0.71$).

The transistor $I-V$ curves of another HBLET laser with $\sim$260 μm spacing between the Fabry–Perot facets are shown in Fig. 3. As the base current, I_b, is increased in 2 mA intervals from 0 to 8 mA, we observe the usual increase of differential current gain, $\beta=\Delta I_c/\Delta I_b$, in this case from $\beta \sim 2$ at lower current to 6.5 at higher current. Light versus V_{CE} measurements (I_b constant, data not shown) indicate that radiative recombination improves as V_{CE} increases and then decreases at the onset of reverse breakdown. Near I_b =8 mA, and as V_{CE} is increased, however, stimulated recombination (stimulated emission) becomes significant, and the HBLET operates both as a laser and a transistor but with a distinct decrease in the current gain β. Beyond threshold, $I_b \gtrsim I_{th} \sim 8$ mA, the differential gain β decreases from 6.5 to a nearly constant value of 2.5 ($\alpha=\beta/(\beta+1)=I_c/I_e=0.71$). Since β can be approximated as the simple ratio τ_n/τ_t,[8] where τ_t is the average (carrier) base transit time (which is almost the same below and above threshold) and τ_n is the average electron lifetime in the base, the electron lifetime is reduced by a factor of 2.6 because of the stimulated recombination of the carriers collected in the 120 Å QW. The QW operates as a pseudocollector[9] and can be adjusted to govern the base recombination and thus both the optical output and transistor gain (β). We mention for comparison that at room temperature we observe (data not shown) a differential current gain β of 10 at I_b=2 mA and 30 at 8 mA (or current transfer ratio, $\alpha=I_c/I_e$ of 0.91 and 0.96).

In Fig. 4 we show, in quasicontinuous operation (88% duty cycle at 60 Hz), the recombination radiation spectra of the HBLET device of Fig. 3, but with slightly increased voltage bias V_{CE} to increase the reverse bias on the base-collector junction. At (a) I_b=6 mA, the HBLET recombination radiation exhibits a peak wavelength of 954 nm and a spectral width of $\sim$280 Å. At (b) I_b=8 mA, we see the onset of stimulated emission with distinct spectral narrowing and mode development. At (c) I_b=10 mA the laser modes are

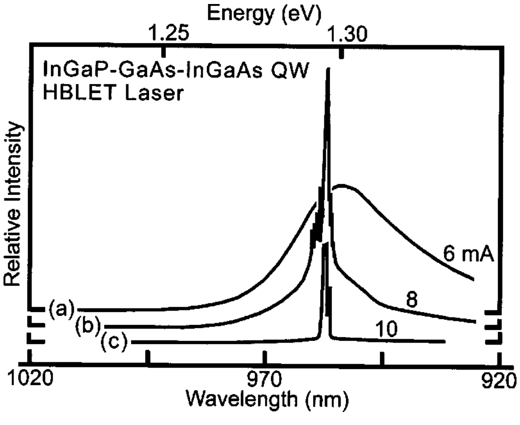

FIG. 4. The recombination radiation spectra corresponding to the transistor $I-V$ characteristics of the HBLET laser of Fig. 3. At (a) I_b=6 mA, the HBLET recombination radiation exhibits a peak at $\lambda \approx 954$ nm and a spectral width of $\sim$280 Å. Spectral narrowing and laser modes appear at (b) I_b=8 mA, and only laser modes at (c) I_b=10 mA (λ=958 nm).

fully developed ($\lambda = 958$ nm), clearly indicating transistor laser operation, which is evident also in Fig. 2. We note that the 200-μm-long HBLET laser of Fig. 2. (right-hand side) is operated with pulsed base current (1% duty cycle at 1 MHz) to prevent saturation of the Si-CCD viewing camera.

These data make it apparent that an HBLET, suitably modified with a resonator cavity and a recombination QW (or QWs) in the *p*-type base (a pseudocollector, a second collector), can be operated simultaneously as a laser and transistor with gain $\beta = \Delta I_c / \Delta I_b > 1$. At laser threshold the transistor gain decreases sharply, but still supports three-port operation (electrical input, electrical output, and optical output). It is evident that there is much more room for HBLET laser development.

The authors are grateful for the support of DARPA Contract No. HR0011-04-1-0034 (Hyper-Uniform Nanophotonics Technologies, HUNT Center). The authors also wish to thank instrument makers S. McDonald and R. Feller for help in constructing some of the experimental apparatus, and B.L Payne for manuscript preparation. N.H. wishes to thank the Sony Corporation for the support of the John Bardeen Chair.

[1] J. Bardeen and W.H. Brattain, Phys. Rev. **74**, 230 (1948).
[2] W. Hafez, J.W. Lai, and M. Feng, Electron. Lett. **39**, 1475 (2003).
[3] M. Feng, N. Holonyak, Jr., and W. Hafez, Appl. Phys. Lett. **84**, 151 (2004).
[4] M. Feng, N. Holonyak, Jr., and R. Chan, Appl. Phys. Lett. **84**, 1952 (2004).
[5] R. Chan, G. Walter, M. Feng, and N. Holonyak, Jr. (unpublished).
[6] J. M. Dallesasse, N. Holonyak, Jr., A. R. Sugg, T. A. Richard, and N. El-Zein, Appl. Phys. Lett. **57**, 2844 (1990).
[7] S. A. Maranowski, A. R. Sugg, E. I. Chen, and N. Holonyak, Jr., Appl. Phys. Lett. **63**, 1660 (1993).
[8] B. G. Streetman and S. Banerjee, *Solid State Electronic Devices*, 5th ed. (Pearson, 2004), p. 328.
[9] E. A. Rezek, H. Shichijo, B. A. Vojak, and N. Holonyak, Jr., Appl. Phys. Lett. **31**, 534 (1977).