Solid-State Electronics 121 (2016) 12–15

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Efficient light output power for InGaP/GaAs heterojunction bipolar transistors incorporated with InGaAs quantum wells

Tzu-Hsuan Huang, Meng-Chyi Wu *

Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan

ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form 12 March 2016
Accepted 31 March 2016
Available online 12 April 2016

The review of this paper was arranged by Prof. E. Calleja

Keywords:
Heterojunction bipolar transistor (HBT)
Heterojunction bipolar light-emitting transistor (HBLET)
Light output power
Frequency response

ABSTRACT

In this work, the current gain and optical frequency response of the heterojunction bipolar transistor (HBT) and heterojunction bipolar light-emitting transistor (HBLET) are investigated. Compared to the conventional HBT, two-pair quantum wells are embedded in the base region of the HBLET. The current gain of HBLET increases with temperature, which shows dissimilar electrical properties to the HBT. Although the current gain of HBLET is much smaller than that of HBT, the decrement of current gain is converted to enhance the light output power. The light output power of HBLET can reach 0.96 mW at 90 mA. The HBLET exhibits the 3-dB bandwidths (f_{3dB}) of 554 and 559 MHz at 30 and 50 mA, respectively. It is found that the 3-dB frequency is proportional to the square root of base current density, while the minority carrier lifetime is inversely proportional to the square root of base current density. Therefore, our results suggest that HBLET with the high light output power shows a great potential in the short range optical data communications.

1. Introduction

A novel integration technique, one which utilizes a common epitaxial layer structure to achieve dual function devices is investigated [1]. Now future possibilities emerge based on the observation of modulated light emission from the base layer of InGaP/GaAs heterojunction bipolar transistor (HBT), leading to the three-port operation of a heterojunction bipolar light-emitting transistor (HBLET) [2]. The characteristic of three-port light-emitting transistor can be substantially modified and improved by incorporating quantum wells (QWs) into the base region, to tailor-make the base recombination and the transistor electrical and optical properties [3]. The presence of the tilted charge population in the base region of the HBLET has been known to cause a competition between the minority carrier lifetime in the base and the collection time (the transition time of base) of the electrons at the reverse-biased base–collector junction. Thus, it leads to select or allow the "fast" recombination (or called short lifetime) in the base [4]. It has been noted by many works that InGaP/GaAs HBLET typically exhibits high frequency operation by the collector layer beneath the p-type base. Practically, various optoelectronic applications based upon these high-speed transistors expect them to being operated at high temperatures. Under such circumstance, the output performance of the devices will be degraded significantly by increasing junction temperature. In this work, we analyze and compare the electrical and optical characteristics of InGaP/GaAs HBLET and HBT.

2. Experimental

The studied HBLET was grown on a (100)-oriented semi-insulating GaAs substrate by metal–organic chemical vapor deposition (MOCVD) system. The used epitaxial structure consists of a 300 nm undoped GaAs buffer layer, an n-type subcollector layer (60 nm, $n > 5 \times 10^{18}$ cm^{-3}), an n-type GaAs collector layer (300 nm, $n = 1 \times 10^{16}$ cm^{-3}), and a two-pair InGaAs (11.2 nm)/GaAs (17.92 nm) multiple-quantum-well containing a base layer (106.1 nm, $p = 3 \times 10^{19}$ cm^{-3}), sequentially. Afterward an n-type InGaP emitter layer (50 nm, $n = 3 \times 10^{17}$ cm^{-3}) was grown. Finally, the HBLET structure was capped with a heavily doped n-type GaAs contact layer (200 nm, $n > 3 \times 10^{18}$ cm^{-3}). The cross section of the HBLET structure is shown in Fig. 1(a). Fig. 1(b) shows the band diagram of the HBLET. For comparison, a conventional HBT without the quantum well structure is also presented [5–8]. The base layer of the HBT was designed with a thickness of 80 nm and a hole concentration of 4×10^{19} cm^{-3}. The conventional processes including photolithography, vacuum evaporation, and selective wet etching were

* Corresponding author. Tel.: +886 3 5162218; fax: +886 3 5715971.
E-mail address: mcwu@ee.nthu.edu.tw (M.-C. Wu).

http://dx.doi.org/10.1016/j.sse.2016.03.012
0038-1101/

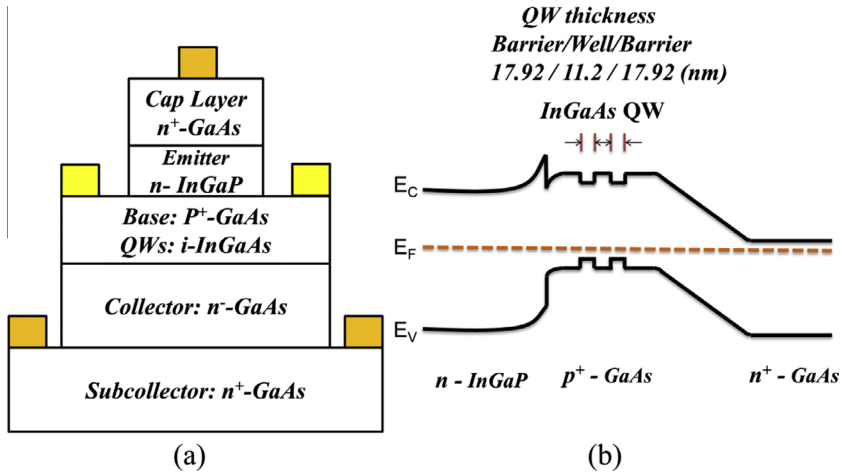

Fig. 1. (a) Device structure of the heterojunction bipolar light-emitting transistor (HBLET) incorporated with two QWs in the base region. (b) The band diagram of the HBLET.

used to fabricate HBLET and HBT. Selective wet etching methods were used to define the emitter mesa, the emitter/base contact, and the base/subcollector mesa. The HBLET and HBT were passivated with silicon oxide (SiO_2) by plasma-enhanced chemical vapor deposition (PECVD). After the passivation treatment, the metallization of emitter and subcollector were deposited with AuGe/Au by thermal evaporation and then annealed at 330 °C for 20 s in N_2 ambient by rapid thermal annealing (RTA) to form the ohmic contact with a specific contact resistance of $1.7 \times 10^{-4}\ \Omega\ cm^2$. The base contact metallization was then deposited by AuZn/Au but without thermal annealing. The protective SiO_2 layer was removed by buffer oxide etch (BOE), and the surface treatment to remove the native oxide was carried out by wet etching in HCl:10H_2O in volume prior to contact deposition. The completed HBLET was bound on the TO-46 package and measured by two terminals. The HBLET devices have a light-emitting aperture size of $150 \times 150\ \mu m^2$. The fabricated HBLET devices were characterized by high speed of electrical switching and high luminescence of light generation capability. The optical characteristics were measured by electronic luminous, integrating sphere, and Agilent N5225A.

3. Results and discussion

Fig. 2(a) illustrates the common-emitter current–voltage (*I–V*) characteristics. The step of base current is 0.5 mA in HBLET and the base current increases for the step of 5 μA in HBT. The offset voltage of the HBLET and HBT is 0.24 and 0.12 V, respectively. Fig. 2(b) compares the Gummel plots at 300 K for the InGaP/GaAs HBLET and HBT. The peak value of common-emitter current gain β of the InGaP/GaAs HBT is 62.2 at 300 K, whereas that of the InGaP/GaAs HBLET is 0.45. It is evident that there are significant differences in the *I–V* characteristics between HBT and HBLET. The collector-current ideality factor (η_c) of InGaP/GaAs HBLET is 1.003, which is higher than that of the InGaP/GaAs HBT ($\eta_c = 1.0009$). The HBLET and HBT exhibit an ideality factor of 1.6 and 1.7 for the base current and the differential on-resistance of 689 and 251 Ω calculated from the common-emitter *I–V* characteristics, respectively. The collector current is part of the injected current from the emitter. The magnitude of the collector current is affected by how many injected carriers are recombined with the holes as they passing through the base region. Although the HBLET and HBT are very similar in the structure, the only difference is that the HBLET contains quantum well in the structure. The comparison of the current gain for the HBLET and HBT at the substrate temperatures of 300, 310, 320, 330, 340, and 350 K is shown in Fig. 3. In the measurement system, a probe station was used to probe and inject the current into the measured device and a temperature controller was beneath the probe station. The temperature controller was used for heating by reversing the electric current flow. The current gain of HBLET is in the range of 0.45–0.70, which is much

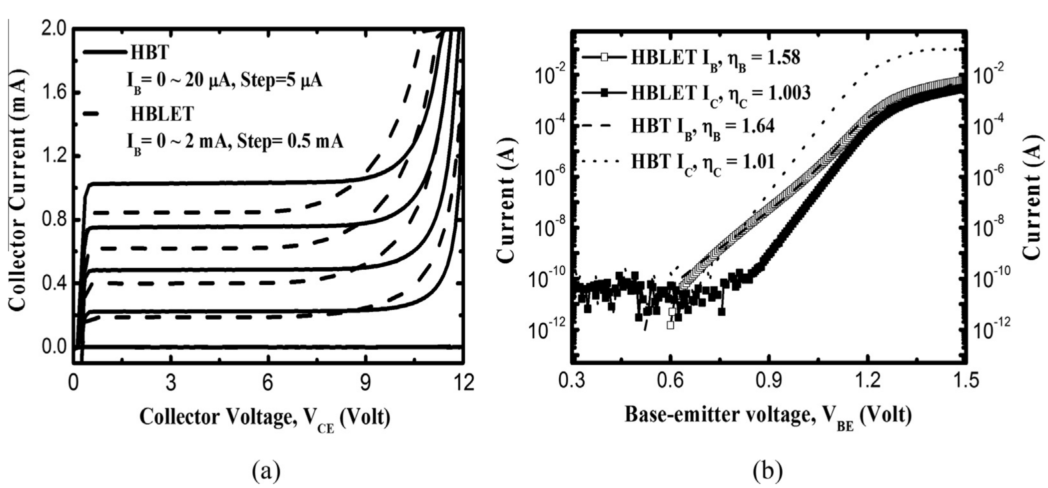

Fig. 2. (a) Common-emitter *I–V* characteristics and (b) Gummel plots of the InGaP/GaAs HBT and InGaP/GaAs HBLET incorporated with QWs.