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Pnp AlGaN/InGaN Heterojunction Bipolar Light-Emitting Transistors with a Quantum Well in the Base

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1. Introduction

A light-emitting transistor (LET), which was demonstrated using GaAs-based materials by M. Feng *et al.* in 2004 [1], is based on the heterojunction bipolar transistor (HBT) and has two outputs for electrical and optical signals. Although a radiative recombination current has been regarded as a waste current in HBT operation in the past, it is possible to modulate light at transistor speed in a LET. In 2009, G. Walter *et al.* achieved a modulation speed of 4.3 GHz for a GaAs-based LET [2]. Nitride-based light-emitting diodes (LEDs) have been widely used for blue and white light, so they are promising for visible-light communications. As for nitride-based LETs, a 1-kHz modulation input has been demonstrated using conventional HBTs [3], though there has been no report on nitride-based LETs with a quantum well (QW) to our knowledge. Therefore, in this work, we fabricated *Pnp* heterojunction bipolar light-emitting transistors (HBLETs) with a InGaN QW in the base layer and investigated their electrical and optical characteristics.

2. Experimental

The device structure of a *Pnp* HBLET is shown in Fig. 1. The structure was grown on *c*-face sapphire substrate by low-pressure metalorganic vapor phase epitaxy (MOVPE). As a buffer layer for the nitride growth on the sapphire substrates, we used a separately deposited Al_2O_3/AlN/graded-AlON/Al_2O_3 layer [4]. The buffer layer was formed by Ar-plasma electron cyclotron resonance (ECR) plasma sputtering at room temperature. Using the substrates with the buffer layer, we conducted MOVPE growth to grow the HBLET layer structure. The precursors were trimethylgallium, triethylgallium, trimethylaluminum, trimethylindium, and ammonia. The *n*-type and *p*-type dopant sources were silane and bis-cyclopentadienylmagnesium, respectively. The substrate with the buffer layer was introduced into the MOVPE reactor and heated to the growth temperature of about 980 °C. A 2-μm-thick undoped GaN layer was directly grown on the substrate. Then, a 4-μm-thick Mg-doped AlGaN/GaN superlattice subcollector and a 0.5-μm-thick undoped GaN collector were grown at 980 °C. Either a Si-doped uniform InGaN base or a base with a 3-nm-thick InGaN quantum well, and a 50-nm-thick Mg-doped AlGaN/GaN superlattice emitter were grown at 790 °C. The thickness of the bases were 50 nm. The superlattices consisted of the AlGaN barrier and GaN well whose thicknesses (L) were kept equal. The Al mole fractions of the barrier layer in the subcollector and the emitter were 0.2 and 0.6, respectively. The period thicknesses (2L) of the subcollector and emitter superlattices were 40 and 10 nm, respectively. From secondary ion mass spectroscopy, the Mg doping concentrations were estimated to be 3×10^{19} cm^{-3} in both the subcollector and emitter layers. Separate Hall effect measurement showed the Si doping concentration in the InGaN base layer to be 2×10^{19} cm^{-3}. The typical dislocation density of the GaN layer grown on the sapphire substrate was around 6×10^{8} cm^{-2} when the buffer layer was used under a similar growth condition. The emitter and base mesas were defined by conventional photolithography and ECR plasma etching with Cl_2 at a microwave input power of 50 W. The emitter area of the HBLET was 30 μm × 50 μm. Pd/Au metals were deposited by electron beam evaporation for the emitter and subcollector contacts, and Ti/Au was used for the base contact. Current-voltage (*I-V*) characteristics of the fabricated transistors were measured in the common-emitter configuration at room temperature using a Keithley 4200-SCS. Spectral measurements were simultaneously performed with an Ocean Optics QE65000 spectrometer. Light emission from the edges of the metal was collected because the contact metal was not transparent. To investigate the electrical and optical properties of the HBLETs, the QW was arranged in the base layer at the position *x* of 12.5, 25, and 37.5 nm from the emitter – base interface.

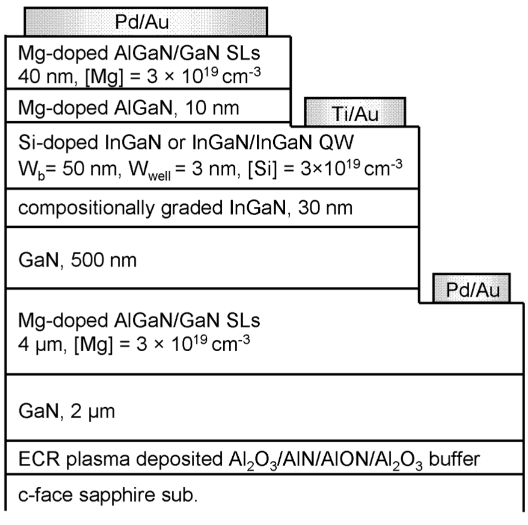
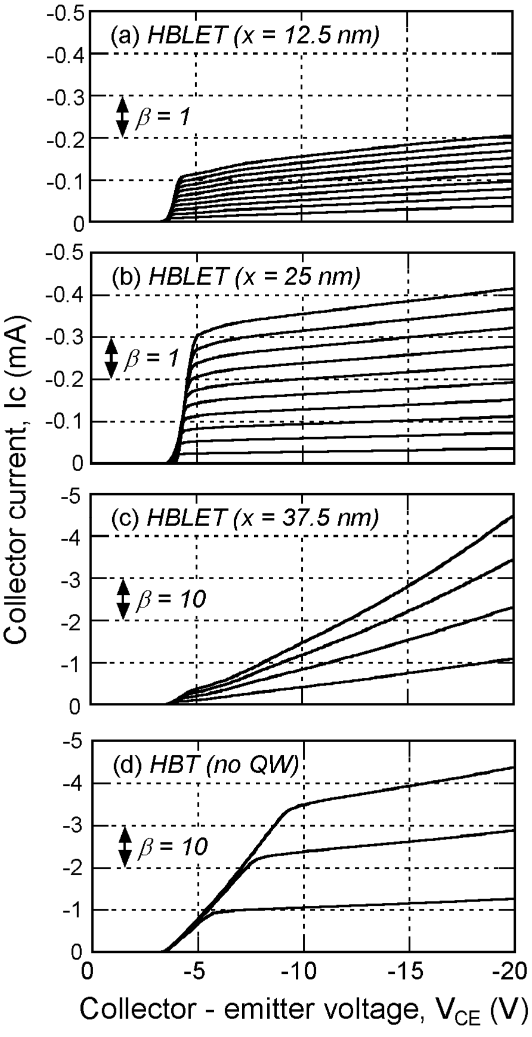


Fig. 1. Device structure of a *Pnp* HBLET.

3. Results and Discussion

The common-emitter *I-V* characteristics are shown in Figs. 2(a) - (d) with base current I_B swept in steps of -0.1 mA. The HBLET with no QW, namely, the conventional HBT, showed a maximum current gain of 16 at collector current I_C of 5 mA. In the HBTs with the QW in the base, the current gain were clearly lower than that of the conventional HBT and strongly depend on the QW position. The values at V_{CE} = -20 V were 0.2, 0.4, and 10 for the x = 12.5, 25, and 37.5 nm respectively.

Figure 3 shows the emission spectra of the HBLETs at the I_B of -0.3 mA and the collector-emitter voltage V_{CE} of -20 V. We confirm that the visible light only came from the edges of the emitter metal. We observed a single peak at the peak wavelength of 380 nm for the conventional HBT. The peak wavelength corresponds to the band-gap energy of the InGaN base layer, indicating that the injected minority holes recombined with electrons at the n-type InGaN base. We observed strong emission at the peak wavelength of around 410 nm for the HBLETs with x = 12.5 and 25 nm. The emission would originate from the QW. On the other hand, the spectra of the HBLETs with x = 37.5 nm showed



Figs. 2. Common-emitter *I-V* characteristics of the HBLETs. I_B was swept in steps of -0.1 mA.

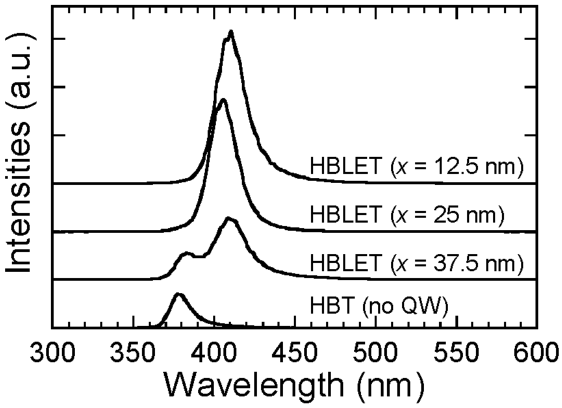


Fig. 3 Emission spectra of the HBLETs
(I_B = -0.3 mA; V_{CE} = -20 V).

peaks at the wavelengths of around 380 and 410 nm. Both peak positions are almost the same as those of the HBT and HBLETs. Therefore, the emissions at 380 and 410 nm would originate from the recombination in the InGaN base layer and in the QW.

In the HBLET with the QW near the base-collector junction, the current gains increased with increasing the V_{CE} as shown in Fig. 2(c). By increasing V_{CE}, the QW near the base-collector junction would be located in an expanded depletion layer. The increased carrier velocity due to the electric field in the depletion region would make the recombination probability in the QW lower. The lower recombination probability in the base mentioned above would result in the increase of current gain because the recombination in the base decreases the collector current. This is consistent with the results of the *I-V* characteristics shown above.

4. Conclusions

We fabricated *Pnp* HBLETs and investigated their electrical and optical properties. Their *I-V* and optical characteristics strongly depended on the QW position. This would be related to the recombination probability of the injected carriers in the base. Because there is a trade-off between the electrical gain and optical emission of an HBT, optimizing the structural parameters, such as the QW position, would be the key to improving the HBLET characteristics.

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