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Extended Abstracts of the 2011 International Conference on Solid State Devices and Materials, Nagoya, 2011, pp576-577

# Low-turn-on voltage heterojunction bipolar transistors with a C-doped $In_xGa_{1-x}As_{1-y}Sb_y$ base grown by metalorganic chemical vapor deposition

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## 1. Introduction

InP-based heterojunction bipolar transistors (HBTs) are key devices for high-bit-rate optical communications systems. To date, InGaAs has been widely used as a base-layer material for InP-based HBTs. With these material systems, however, it is difficult to reduce the current turn-on voltage due to the presence of type-I conduction-band-edge discontinuity at the emitter-base heterojunction.

Recently, InP-based HBTs with a GaAsSb base have attracted a lot of attention because they have a favorable type-II band lineup for *npn* HBT structures.[1-3)] For these material systems, the turn-on voltage is determined simply by the base band-gap energy. Thus, further reduction of the turn-on voltage is possible by employing narrow-band-gap material, such as InGaAsSb.[4,5)] In fact, Chen *et al*. demonstrated InP/$In_{0.37}Ga_{0.63}As_{0.89}Sb_{0.11}$ HBTs that exhibit the base-emitter, $V_{BE}$, turn-on voltage as low as 0.35 V at collector current density, $J_C$, of 1 A/cm$^2$. These HBTs were grown by molecular beam epitaxy with Be as a *p*-type dopant. On the other hand, there has been no report of InGaAsSb-base HBTs grown by metal-organic chemical vapor deposition (MOCVD). In this paper, we demonstrate InP-based HBTs with a C-doped InGaAsSb base grown by MOCVD. One of the lowest collector turn-on voltages of 0.353 V at $J_C$ of 1 A/cm$^2$ was obtained for a HBT with a highly C-doped $In_{0.22}Ga_{0.78}As_{0.73}Sb_{0.27}$ base.

## 2. Experiments

All the samples were grown on semi-insulating (001) InP substrates in a low-pressure vertical MOCVD reactor. Carbon tetrabromide was used for *p*-type dopant for the InGaAsSb base. The details are described elsewhere.[6)] Alloy compositions of $In_xGa_{1-x}As_{1-y}Sb_y$ films were determined by x-ray diffraction and inductively coupled plasma atomic emission spectroscopy. Photoluminescence (PL) was used to investigate the relationship between alloy composition and band structure of $In_xGa_{1-x}As_{1-y}Sb_y$.

The HBT-layer structures consist of an $n^+$ InP/InGaAs subcollector, a 200-nm-thick unintentionally doped InP collector, a 32-nm-thick $p^+$ $In_xGa_{1-x}As_{1-y}Sb_y$ base, a 70-nm-thick unintentionally doped InP emitter, and a $n^+$ InGaAs/InP cap layer. Hole concentrations, solid In and Sb contents ($x$, $y$), and base sheet resistances, $R_{B,sh}$, determined by transmission-line-measurement, are summarized in Table I. The HBT-layer structures, except for the base, were the same among the samples. For comparison, the HBTs with a C-doped $GaAs_{0.50}Sb_{0.50}$ base nearly lattice-matched to InP were also prepared.

Table 1. Base layer of the HBTs.

| C-doped $In_xGa_{1-x}As_{1-y}Sb_y$ base | | | |
|---|---|---|---|
| $(x, y) =$ | (0, 0.50) | (0.11, 0.39) | (0.22, 0.27) |
| $p$ (cm$^{-3}$) | $4.3\times10^{19}$ | $3.3\times10^{19}$ | $1.2\times10^{19}$ |
| $R_{B,sh}$ (Ω/sq.) | 2110 | 2318 | 12167 |

Devices with an emitter junction area of 100 × 100 μm$^2$ were fabricated by conventional wet-etching and lift-off process. The Ti/Pt/Au electrode metals were deposited by electron-beam evaporation. The direct current characteristics of the HBTs were measured using an Agilent 4156C semiconductor parameter analyzer.

## 3. Results and discussion

Figure 1 shows typical excitation-power dependence of PL spectra of approximately 100-nm-thick undoped $In_xGa_{1-x}As_{1-y}Sb_y$ films at 6.5 K. For $GaAs_{0.50}Sb_{0.50}$ film, we observed near-band-edge (NBE) emission at 0.798 eV and pronounced broad emission originating from spacially separated type-II recombination at the InP/GaAsSb interface at around 0.72 - 0.76 eV. On the other hand, spectra for $In_{0.27}Ga_{0.73}As_{0.70}Sb_{0.30}$ film exhibited single-peak NBE emission at around 0.66 eV and no type-II emission was observed in the measurement range. The peak energy was approximately 0.14 eV lower than that for $GaAs_{0.50}Sb_{0.50}$ film.

Figure 2 shows typical Gummel plots for the HBTs with a C-doped $In_xGa_{1-x}As_{1-y}Sb_y$ base. Plots for the GaAsSb-base HBT are also shown for comparison. Clearly, the $V_{BE}$ turn-on voltage decreases with increasing solid In

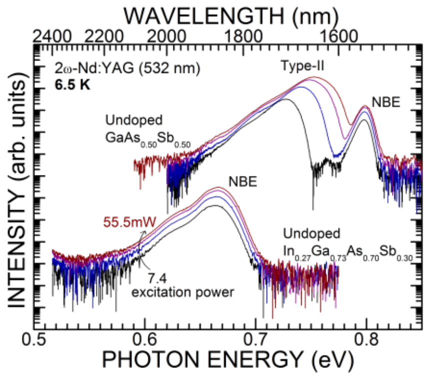


Fig. 1. Excitation-power dependence of PL spectra of undoped $GaAs_{0.50}Sb_{0.50}$ and $In_{0.27}Ga_{0.73}As_{0.70}Sb_{0.30}$ films.

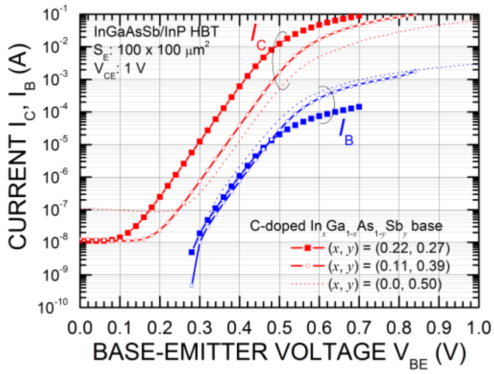


Fig. 2. Gummel plots for the HBTs with a C-doped $In_xGa_{1-x}As_{1-y}Sb_y$ and $GaAs_{0.50}Sb_{0.50}$ base.

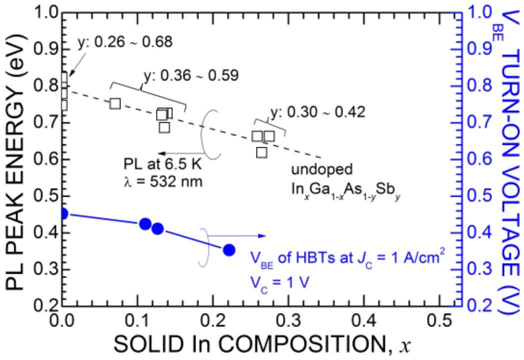


Fig. 3. PL peak energy of undoped $In_xGa_{1-x}As_{1-y}Sb_y$ films (open squares) and $V_{BE}$ turn-on voltages (closed circles) vs. solid In content *x*.

content, *x*. Figure 3 shows the variation in NBE-emission-peak energies for the $In_xGa_{1-x}As_{1-y}Sb_y$ films and $V_{BE}$ turn-on voltage at $J_C$ = 1 A/cm$^2$ for the $In_xGa_{1-x}As_{1-y}Sb_y$-base HBTs as a function of *x*. NBE peaks for undoped $In_xGa_{1-x}As_{1-y}Sb_y$ films are strongly dependent on *x* and linearly decrease with increasing *x* for $x \leq 0.27$. Furthermore, as *x* increases, not only the PL peak energy but also $V_{BE}$ turn-on voltage decreases. Built-in potential of the $p^+$-$n$ junction is determined by band gap of the *p*-type layer and conduction band offset ($\Delta E_C$) at the interface.[7] For nearly lattice-matched $p^+$-InGaAsSb/$n^-$-InP, $V_{BE}$ turn-on voltage is approximately independent of $\Delta E_C$ and the band gap of base layer is dominant when *x* is relatively low. Thus, this linear dependence on $V_{BE}$ turn-on voltage is due to the band-gap reduction in the $In_xGa_{1-x}As_{1-y}Sb_y$ base with increasing *x*. The HBTs with an $In_{0.22}Ga_{0.78}As_{0.63}Sb_{0.27}$ base exhibited $V_{BE}$ turn-on voltage of 0.353 V at $J_C$ = 1 A/cm$^2$. This value is approximately 0.15-V lower than that of the HBTs with an InGaAs base. Note that slight solid-Sb-content, *y*, dependence of PL peak energy was observed for the ranges of $0.26 \leq y \leq 0.68$.

The ideality factors for the base current, $n_B$, are very close to unity for the InGaAsSb-base HBTs. These values are slightly lower than those for the GaAsSb-base HBTs ($n_B \sim 1.1$). The lower ideality factor suggests that nonideal recombination current in the space charge region is suppressed owing to the reduction of the potential barrier at the type-II emitter-base heterojunction.

Figure 4 shows the collector current dependence of dc

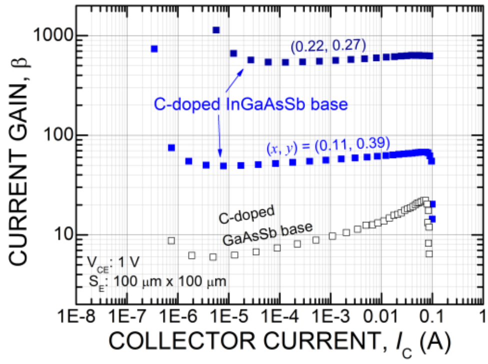


Fig. 4. Static current gain vs. collector current characteristics for the HBTs.

current gain, *β*. For the $In_{0.11}Ga_{0.89}As_{0.61}Sb_{0.39}$ and $In_{0.22}Ga_{0.78}As_{0.63}Sb_{0.27}$ base, the maximum *β* values are 67.5 and 632.3 at $J_C$ of around 6 × 10$^2$ A/cm$^2$ against the base sheet resistance of 2318 and 12167 Ω/sq, while the ideality factor, which is derived from the relationship $\beta \sim I_C^{(1-1/m)}$, is nearly unity ($m$ = 1.04 and 1.03). These results indicate that the current gain for the InGaAsSb-base HBTs is primary determined by the minority-electron transport and/or recombination current in the neutral base region. Thus, it is necessary to improve the crystal quality of the InGaAsSb base in order to increase the current gain.

## 4. Summary


InP-based HBTs with a C-doped InGaAsSb base grown by MOCVD were demonstrated. To reduce the band-gap energy of the base, we grew InGaAsSb films and found that PL NBE-peak energy decreased with increasing solid In content in the films. $V_{BE}$ turn-on voltage of the InGaAsSb-base HBTs also decreased due to the band-gap reduction in $In_xGa_{1-x}As_{1-y}Sb_y$ base. Finally, the fabricated devices exhibited a significant reduction of turn-on voltage to 0.353 V at a $J_C$ = 1 A/cm$^2$. These results make the InGaAsSb-base HBTs very attractive for use in low-power ICs.



## Acknowledgements

The authors thank M. Mitsuhara for fruitful discussions.


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