InGaP/GaAsSb/GaAs DHBTs with Low Turn-on Voltage and High Current Gain

B. P. Yan, C. C. Hsu†, X. Q. Wang, Y. K. Bai and E. S. Yang

Department of Electrical and Electronic Engineering
The University of Hong Kong, Pokfulam Road, Hong Kong
fax: (852) 2540 6215, e-mail: bpyan@eee.hku.hk

†Department of Electronic Engineering
The Chinese University of Hong Kong
Hong Kong

Abstract

An InGaP/GaAsSb/GaAs double heterojunction bipolar transistor (DHBT) is presented. It features the use of a fully strained pseudomorphic GaAsSb (Sb composition: 10.4%) as the base layer and an InGaP layer as the emitter, which both eliminates the misfit dislocations and increases the valence band discontinuity at the InGaP/GaAsSb interface. A current gain of 200 has been obtained from the InGaP/GaAsSb/GaAs DHBT, which is the highest value obtained from GaAsSb base GaAs-based HBTs. The turn-on voltage of the device is typically 0.914 V for the 10.4% Sb composition, which is 0.176V lower than that of traditional InGaP/GaAs HBT. The results show that GaAsSb is a suitable base material for reducing the turn-on voltage of GaAs HBTs.

I. Introduction

One of the major trends for future high-performance mobile handsets is to realize low-power operation so as to reduce the power dissipation and extend the talk-time before recharging of the battery. In order to meet the requirements of low-power operation, several different HBT material systems have been investigated. One of the attractive material systems is InGaAsN base HBT [1-3]. By incorporating a proper amount of nitrogen and indium into GaAs, GaInAsN lattice-matched to GaAs can be obtained with a significant energy band-gap reduction. However, because of the large conduction band discontinuity between InGaAsN base and GaAs collector, a collector current blocking effect would occur, giving rise to a drastic degradation of current gain at a high collector current density. Although by the insertion of graded layers between the base and collector junction, the current blocking effect can be suppressed, this complicates the transistor design and fabrication.

Another effort is to use GaAsSb as the narrow band gap material for the base layer of GaAs HBTs. In comparison with a lattice-matched GaAs base, the smaller band gap of GaAsSb can reduce the turn-on voltage, thus the power dissipation in circuits. Moreover, the band lineup at the GaAsSb/GaAs interface is staggered ("type II") lineup [4], which would eliminate any collector current blocking. GaAs-based HBTs with GaAsSb base layers have been already reported [5-8], but only limited information was given. In the previous work, the grown emitter-base junction was either an AlGaAs/GaAsSb [5-7] or a GaAs/GaAsSb heterojunction [8], and the devices showed poor dc current gain and large recombination current. It was attributed to the large surface recombination at GaAs surface and depletion region. Recently, our group implemented a novel InGaP/$GaAs_{0.94}Sb_{0.06}$/GaAs DHBT, which has an improved current gain and a low turn-on voltage [9]. In this work we increase Sb composition to 10.4% in pseudomorphic GaAsSb base to further reduce the turn-on voltage. At the same time, InGaP is still used instead of GaAs as the emitter to increase the valence band discontinuity at the emitter-base heterojunction. Thus, we have implemented the InGaP/GaAsSb/GaAs DHBT with a lower turn-on voltage and a higher current gain.

II. Material Growth and Device Fabrication

InGaP/GaAsSb/GaAs DHBT structure was grown on a semi-insulating (100) GaAs substrate by MOCVD. TMGa, TMIn, TMSb, TBP, and TBA were used as the organometallic sources. Carbon and silicon were used as p- and n-type dopants, respectively. The device structure consists of a 500 nm $n>3\times 10^{18}$ cm^{-3}

0-7803-7320-0/02/$17.00©2002IEEE

GaAs sub-collector, a 500 nm n=5×10^{16}cm^{-3} GaAs collector, a 30 nm p=8×10^{18}cm^{-3} GaAsSb base (Sb composition: 10.4 %), a 50 nm n=3×10^{17}cm^{-3} InGaP emitter, a 150 nm n=4×10^{18}cm^{-3} GaAs layer, a 50 nm n>1×10^{19}cm^{-3} compositionally graded In_xGaAs_{1-x}cap layer (x=0-0.5), and a 50 nm n>1×10^{19}cm^{-3} $In_{0.5}GaAs_{0.5}$ cap ohmic contact layer. The Sb composition was confirmed by high-resolution x-ray diffraction measurement. The surface morphology was observed by atomic force microscope (AFM) and no crosshatched patterns associated with misfit dislocations were observed. This suggests that the GaAsSb base layer is fully strained. The structure was fabricated into devices using optical lithography and chemical wet selective etching for mesa definition.

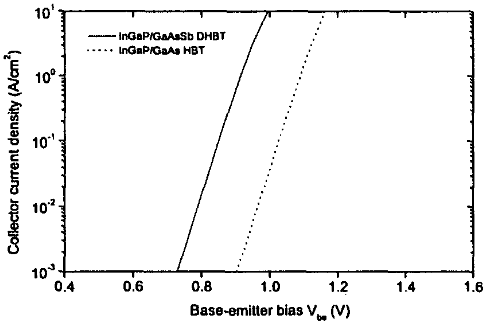

Fig. 1: The dependence of collector current density on emitter-base voltage V_{BE} of an InGaP/GaAsSb/GaAs DHBT and an conventional InGaP/GaAs HBT

III. Device Performance and Discussion

The dc performances of the devices were measured using a HP4155 semiconductor parameter analyzer. The devices were biased in the common emitter configuration. Figure 1 shows the dependence of the collector current density J_c on the emitter-base voltage V_{BE} of an InGaP/GaAsSb/GaAs DHBT and an InGaP/GaAs HBT with an emitter size of 100×100 μm^2. It can be seen that the turn-on voltage of the conventional InGaP/GaAs HBT at J_c=1A/cm^2 is 1.09 V and the turn-on voltage of InGaP/GaAsSb/GaAs DHBT is 0.914 V. The turn-on voltage of InGaP/GaAsSb/GaAs DHBT is 0.176 V lower than that of conventional InGaP/GaAs HBT, indicating that GaAsSb is a suitable material for reducing the turn-on voltage of GaAs-based HBTs.

Large area InGaP/GaAsSb/GaAs DHBTs (100×100 μm^2) were fabricated on the three layers to assess the epitaxial material quality. Figure 2 shows the common-emitter I-V characteristics of the InGaP/GaAsSb/GaAs DHBT. The device displays uniform current gain under the small current level. The dc current gain reaches 100 even at the base current level of 1 μA. Measured current gain is much higher than previously reported for GaAs/GaAsSb DHBTs [5][7]. The improvement of the current gain is attributed to the use of a fully strained pseudomorphic GaAsSb layer, which effectively eliminates the misfit dislocation. Another cause is due to the use of InGaP as the emitter layer, which has a low surface recombination velocity. Measured emitter-collector offset voltage is about 200 mV and the breakdown voltage of emitter-collector BV_{ce0} is 6-7 V.

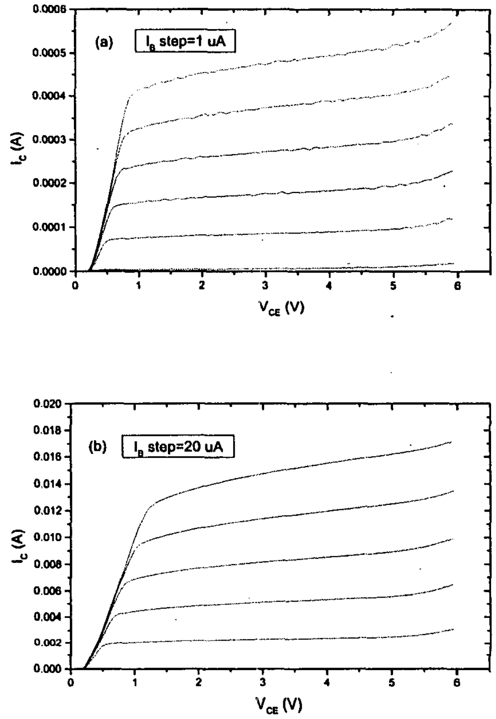

Fig. 2: Common-emitter I-V characteristics for a large area (100×100 μm^2) InGaP/GaAsSb/GaAs DHBT under (a) small current (b) large current

Figure 3 shows the dependence of current gain on the collector current. As shown in Fig. 3, when the collector current increases from 0.1 mA to 50 mA, the incremental current gain H_{fe} gain continues to increase. This observation indicates that the base-emitter space charge recombination current is the main base current component [10]. It is understandable, because the base doping is only 8×10^{18} /cm^3 in this work. A maximum current gain H_{fe}

of 200 has been obtained at a collector current of 50 mA around.

Figure 4 shows a representative Gummel plot for the large area InGaP/GaAsSb/GaAs DHBT. The ideality factor of the collector current is 1.01. The base current is significantly divided into two parts. When Vbe<0.8 V, the ideality factor of the base current is more than 2.0 and the dominant recombination is the EB junction space charge recombination. When Vbe>0.8 V, the ideality factor of the base current is 1.47, indicating that both the space charge and the base bulk recombination simultaneously make difference. In comparison with GaAs/GaAsSb/GaAs DHBT [8], the base recombination current of InGaP/GaAsSb/GaAs DHBT is greatly reduced due to the use of InGaP as emitter layer. In addition to the improvement of the current gain, the use of InGaP emitter layer is also beneficial to the improvement of device reliability [11]. This work indicates that InGaP/GaAsSb/GaAs DHBT grown by MOCVD in present study is better than GaAs/GaAsSb/GaAs DHBT and can be a better candidate for the low turn-on voltage device.

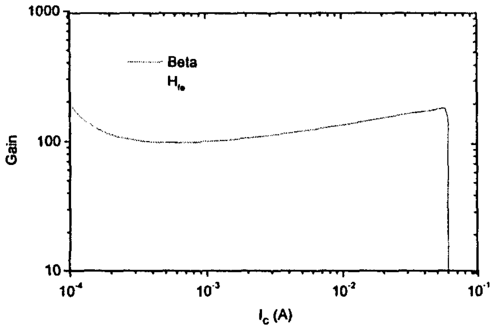

Fig. 3: DC gain β and incremental current gain H_{fe} as a function of the collector current Ic.

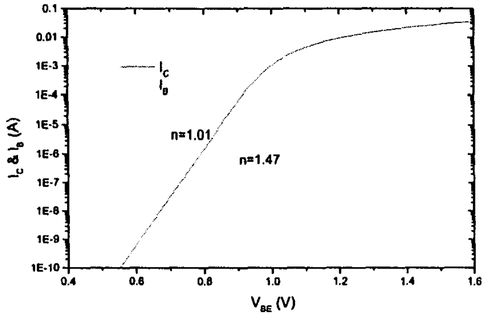

Fig. 4: Representative Gummel plots for InGaP/ GaAsSb/GaAs DHBT with an emitter size of 100×100 μm^2.

Figure 5 and 6 shows the common-emitter I-V characteristics and Gummel plots for a small area InGaP/GaAsSb/GaAs DHBT, respectively. Devices show a large "knee" voltage and a significant output conductance, which is attributed to the low base doping and the large base ohmic contact resistance.

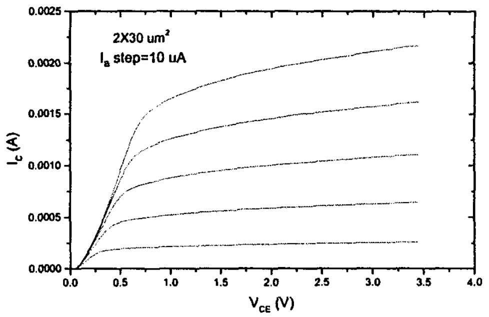

Fig. 5: Common-emitter I-V characteristics of InGaP/GaAsSb/GaAs DHBT with an emitter size of 2×30 μm^2.

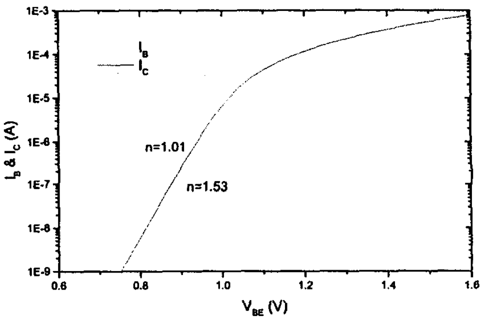

Fig. 6: Representative Gummel plots for InGaP/ GaAsSb/GaAs DHBT with an emitter size of 2×30μm^2.

IV. Conclusion

In summary, we have demonstrated the low turn on voltage InGaP/GaAsSb/GaAs DHBT, which exhibits excellent DC performances. The device shows a low turn-on voltage, which is 0.17-0.19 V lower than that of conventional InGaP/GaAs HBTs. These results show that GaAsSb is a suitable base material for reducing the turn-on voltage of GaAs HBTs. Our results also reveal that InGaP/GaAsSb/GaAs DHBT grown by MOCVD is better than reported GaAs/GaAsSb/GaAs DHBT. Work is under way to optimize material properties to improve further the DC performance and RF performances.

Acknowledgement

The authors would like to thank the support of Research Grants Council of Hong Kong Special Administrative Region, China (Project No. HKU 7057/98E) and CRCG grants (A/C Nos. 37/062/0047 and 10201982). We wish to thank Mr. Ng Fai-Lun in HKUST for his valuable assistance.

References

[1] N. Y. Li, P. C. Chang, A. G. Baca, X. M. Xie, P. R. Sharps and H. Q. Hou, "DC characteristics of MOVPE-grown Npn InGaP/InGaAsN DHBT," *Electron. Lett.*, vol.36, pp81-83, 2000.

[2] R. E. Welser, P. M. DeLuca, and N. Pan, "Turn-on voltage investigation of GaAs-based bipolar transistors with $Ga_{1-x}In_xAs_{1-y}N_y$ base layers," *IEEE Electron Device Lett.*, vol.21, pp554-556.

[3] H. Xin, C. W. Tu, P. M. Asbeck, and R. Welty, "Investigation of p-type GaInNAs for heterojunction bipolar transistor base layers," in *Proc. Electronics Materials Conf.*, Santa Barbara, CA, 1999, p.13

[4] R. Teissier, D. Sicault, J. C. Harmand, G. Ungaro, G. Le Roux, and L. Largeau, "Temperature-dependent valence band offset and band-gap energies of pseudomorphic GaAsSb on GaAs," *J. Appl. Phys.*, vol.89, pp5473-5477, 2001.

[5] B. Khamsehpour and K. E. Singer, "GaAs-GaAsSb based heterojunction bipolar transistors," *Electron. Lett.*, vol.26, pp 965-967, 1990.

[6] K. Ikossi-Anastasiou, A. Ezis, K. R. Evans, and C. E. Stutz, "Double heterojunction bipolar transistor in $Al_xGa_{1-x}As/GaAs_{1-y}Sb_y$ system" *Electron. Lett.*, vol.27, pp142-144, 1991.

[7] K. Ikossi-Anastasiou, "GaAsSb for heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol.40, pp878-884, 1993.

[8] T. Oka, T. Mishima, and M. Kudo, "Low turn-on voltage GsAs heterojunction bipolar transistors with a pseudomorphic GaAsSb base," *Appl. Phys. Lett.*, vol.78, pp483-485, 2001.

[9] B. P. Yan, C. C. Hsu, X. Q. Wang, and E. S. Yang, "A InGaP/$GaAs_{0.94}Sb_{0.06}$/GaAs double heterojunction bipolar transistor", *IEE Electron. Lett.* vol. 38 (6). 2002

[10] W. Liu, "Experimental comparison of base recombination currents in abrupt and graded AlGaAs/GaAs heterojunction bipolar transistors," *Electron. Lett.*, vol. 27, pp2115-2116,1991

[11] T. Takahashi, S. Sasa, A. Kawano, T. Iwai, T. Fujii, "High reliability InGaP/GaAs HBT fabricated by self-aligned process," In: *Proc. IEDM*, pp.191-194, 1994