Novel InGaP/GaAsSb/GaAs DHBTs

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Abstract -A study of the InGaP/GaAsSb/GaAs double heterojunction bipolar transistor (DHBT) is presented. Novel device structure is designed. A fully strained pseudomorphic GaAsSb with 8.0% Sb composition is used as the base layer, while 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 22.6 has been obtained from the InGaP/GaAsSb/GaAs DHBT. Typical turn-on voltage of the device is 0.973 V which is 0.116V lower than that of traditional InGaP/GaAs HBT. Moreover, the current transport mechanism of the InGaP/GaAsSb/GaAs DHBTs is investigated. These results show that GaAsSb is a promising 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, we have 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 8% 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. 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} GaAs sub-collector, a 500 nm $n=5\times10^{16}cm^{-3}$ GaAs collector, a 30 nm $p=10^{11}cm^{-3}$ GaAsSb base (Sb composition: 8.0 %), a 50 nm $n=3\times10^{17}cm^{-3}$ InGaP emitter, a 150 nm $n=4\times10^{18}cm^{-3}$ GaAs layer, a 50 nm $n>1\times10^{19}cm^{-3}$ compositionally graded In_xGaAs_{1-x}cap layer (x=0-0.5), and a 50 nm $n>1\times10^{19}cm^{-3}$ $In_{0.5}GaAs_{0.5}$ 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 [10].

III. RESULTS AND DISCUSSION

All the experimental measurements of DC performance of our devices are carried out by using Singatone S-1160 Probe Station.

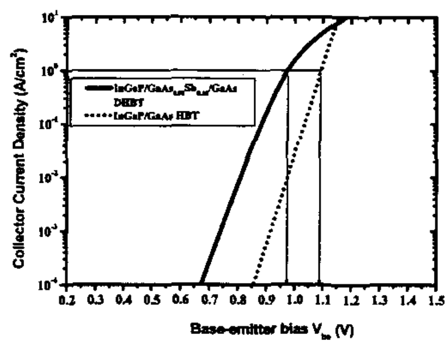


Figure 1: The dependence of collector current density on emitter-base voltage V_{BE} of an InGaP/GaAsSb/GaAs DHBT and a conventional InGaP/GaAs HBT.

Our device is emitter-up DHBT. It was biased in the common emitter configuration. From Figure 1, we can clearly see that the dependence of the collector current density J_c on the emitter-base voltage V_{BE} of an InGaP/$GaAs_{0.92}Sb_{0.08}$/GaAs DHBT and a traditional InGaP/GaAs HBT. Both of them have an emitter size of 100×100 μm^2. With the same collector current density, J_c=1A/cm^2, the turn-on voltage of InGaP/ $GaAs_{0.92}Sb_{0.08}$/GaAs DHBT is 0.973 V while that of conventional InGaP/GaAs HBT is 1.089V. The turn-on voltage of InGaP/ $GaAs_{0.92}Sb_{0.08}$/GaAs DHBT is 0.116 V lower than that of conventional InGaP/GaAs HBT. It indicates that GaAsSb is a good base material for low turn-on voltage GaAs-based DHBTs.

Figure 2a & b show the common-emitter I-V characteristics for a large area (100×100 μm^2) InGaP/GaAsSb/GaAs DHBT under a small current and a large current respectively. The device displays uniform current gain under the small current level. The dc current gain reaches 20 at the base current level of 10 μA. Measured emitter-collector offset voltage is about 250 mV and the breakdown voltage of emitter-collector BV_{ce0} is more than 7 V. At large current level, the device still displays uniform current gain but a high knee voltage, which is attributed to collector current blocking and high base resistance.

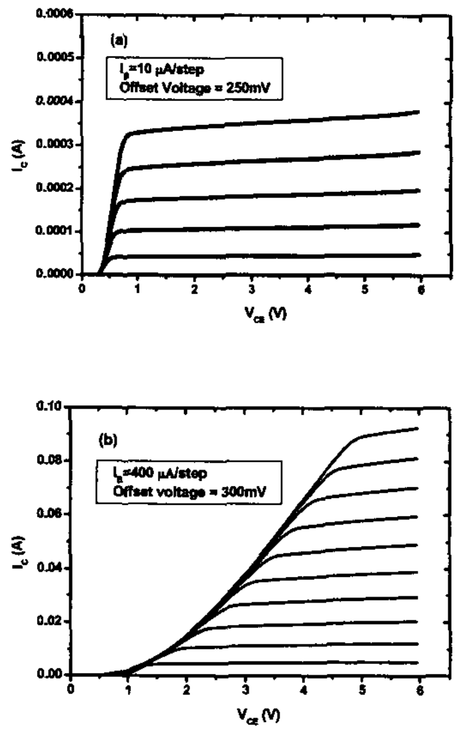


Figure 2: Common-emitter I-V characteristics for a large area (100×100 μm^2) InGaP/GaAsSb/GaAs DHBT under (a) small current (b) large current.

Figure 3 shows the dependence of current gain on the collector current. Maximum β and h_{fe} are equal to 18.9 and 22.6 when I_c = 50mA and I_c = 40mA respectively. After that, they showed a sharp drop-off as they have past by their crests. This observation is in good agreement with the result in the large area device. On the other hand, the continual increase in the incremental current gain h_{fe} indicates that the base-emitter space charge recombination current is the main base current combination [10]. However, the current gain obtained this time is small. We believe that the low base doping make the difference.

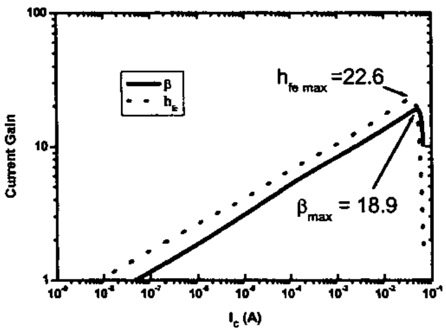


Figure 3: DC gain β and incremental current gain h_{fe} as a function of the collector current I_c.

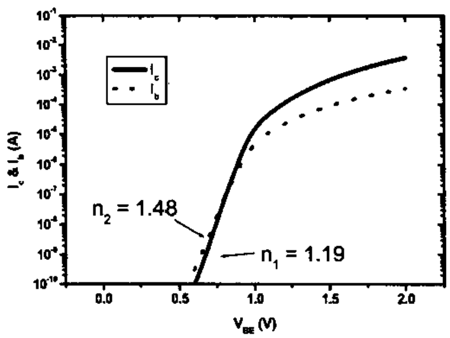


Figure 4: Representative Gummel plots for InGaP/GaAsSb/GaAs DHBT with an emitter size of 100×100 μm^2.

Figure 4 shows a representative Gummel plot for the large area $InGaP/GaAs_{0.92}Sb_{0.08}/GaAs$ DHBT. The ideality factor n_1 of the collector current I_c is 1.19 while the ideality factor n_2 of the base current I_b is 1.48. Indeed, in comparison with GaAs/GaAsSb/GaAs DHBT [8], the base recombination current of InGaP/GaAsSb/GaAs DHBT is greatly reduced. It is due to the use of InGaP as emitter layer. Make use of InGaP as emitter layer also improve the devices' reliability. This further proves InGaP/GaAsSb/GaAs DHBT grown by MOCVD to be a good candidate for the low turn-on voltage device.

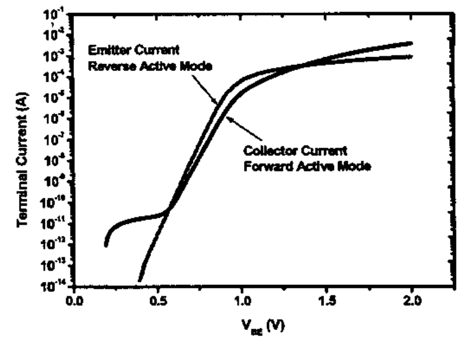
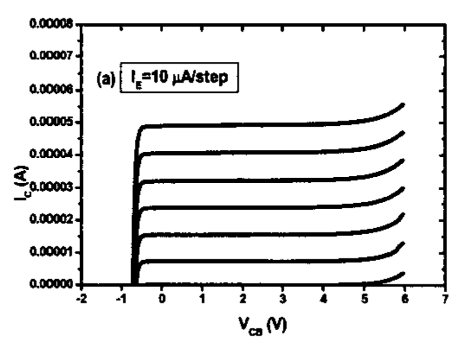


Figure 5: Measured terminal currents of the InGaP/GaAsSb/GaAs DHBT with emitter size of 100x100μm^2.

Figure 5 shows the measured terminal currents of the InGaP/GaAsSb/GaAs DHBT upon a large emitter size of 100x100μm^2. This is determined by the collector current in the forward active mode and emitter current in the reverse active mode. Theoretically, when the device is in the forward active mode, the conduction carriers are emitted from the emitter-base junction; when the device is in the reverse active mode, the conduction carriers are emitted from the base-collector junction. From figure 5, it can be seen that both the terminal currents increase with V_{BE}. However, the terminal currents seem not to overlay perfectly with each other. It is not only due to different materials being used to make up the emitter and the collector layers [11] but also because of the collector current blocking effect in the GaAsSb DHBT.

Actually, to find out whether there is the collector current blocking in the GaAsSb DHBTs, we have measured their common-base I-V characteristics, as shown in Figure 6(a) and 6(b).



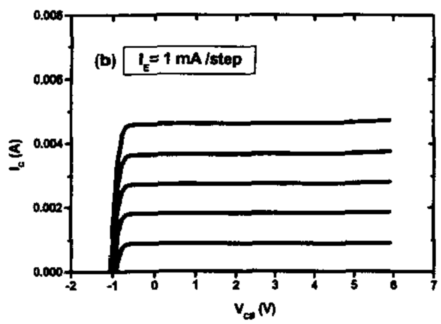


Figure 6. Common-base I-V characteristics of InGaP/GaAsSb/GaAs DHBT with an emitter size of $100 \cdot 100\mu m^2$ under a (a) small current and (b) large current.

It can be seen that, at small current level, the transistor is free of collector current blocking because the turn-on near V_{CB}= -0.8 V is abrupt and the collector current is very nearly independent of V_{CB} in the turn-on region. At large current level, however, the turn-on near V_{CB}= -1.0 V is not abrupt and the collector current is dependent of V_{CB} in the turn-on region. We believe this phenomenon is not due to the collector current blocking but is caused by the high base resistance. This is because the collector current blocking effect comes from a large conduction band discontinuity at BC junction. If there is indeed such a large conduction band discontinuity at the BC junction, the collector current even at small current level should also be dependent on V_{CB} within the turn-on region. Furthermore, were there such large conduction band discontinuities at the BC junction, the measured terminal characteristics in both the forward active mode and the reverse active mode would not be identical but should be clearly different, that is as shown in Figure 5. Further studies by other measurement methods are needed to clarify the mechanism. The work is under way.

IV. CONCLUSION

In summary, we have demonstrated the low turn on voltage InGaP/GaAsSb/GaAs DHBT, which exhibits good DC performances. The device shows a low turn-on voltage, which is 0.116 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. Work is under way to optimize material properties to further improve the DC performance and RF performances of our device.

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