InAlAs/GaAsSb/InP DHBTs grown by Production MBE

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Abstract

We investigate the growth of GaAsSb base DHBTs with InAlAs emitter. The epi materials are grown using 4 x 4" multi-wafer production MBE system fully equipped with real-time in-situ sensors such as absorption band edge spectroscopy (ABES) and optical-based flux monitor (OFM). State-of-the-art hole mobilities are obtained from 100 nm thick carbon-doped GaAsSb. Sb composition variation of less than ± 0.1 atomic percentage across a 4 x 4" platen configuration has been achieved. Large area InAlAs/GaAsSb/InP DHBT device with excellent DC characteristics such as BV_{CEO} > 6 V, and DC current gain of 45 at 1 kA/cm^2 are obtained with 40 nm thick GaAsSb base at 4.5e19 cm^{-3} doping. These results demonstrate the feasibility of multi-wafer MBE for mass production of GaAsSb based HBTs.

INTRODUCTION

InP/InGaAs-based DHBTs have demonstrated excellent microwave characteristics for OC-768 communication system applications. However, complicated collector-base design is required to overcome the collector current blocking problem resulting from the type I band alignment between InGaAs base and InP collector. By replacing the conventional InGaAs base with GaAsSb, the type II band alignment between InP and $GaAs_{0.51}Sb_{0.49}$ permits the use of a single InP layer as the collector without the problem of collector current blocking [1-3]. Recent MOCVD-grown DHBTs result with abrupt InP/GaAsSb/InP heterojunctions has demonstrated f_T and f_{MAX} as high as 300 GHz at high current density [4]. InP has typically been the preferred emitter material for InP/GaAsSb DHBTs for the superior etching selectivity. However, the negative conduction band discontinuity of InP emitter to GaAsSb base is an inherent disadvantage for InP/GaAsSb emitter-base junction. In addition, it has been difficult to grow good InP on GaAsSb by MBE. Therefore, it is important to explore different emitter materials design for MBE. Moreover, because GaAsSb is a mixed group V compound semiconductor, good composition uniformity has been difficult to achieve even with small single wafer MBE systems, let alone large multi-wafer system.

In this paper, we demonstrate that highly uniform GaAsSb on 4" wafer with state-of-the-art hole mobility can be obtained with our 4x4" multi-wafer MBE reactor. We also report the growth and development of GaAsSb HBTs with InAlAs emitter using multi-wafer MBE. The importance of in-situ sensors, such as absorption band edge spectroscopy (ABES) [5, 6] and optical-based flux monitor (OFM) [7, 8] for monitoring and control of the growth conditions during the production environments is also illustrated.

EXPERIMENTAL

For this work, the epi materials are grown using a multi-wafer Riber 49 MBE system. The reactor is equipped with Al, Ga, and In solid source effusion cells for the group III elements, and As, P, and Sb valve crackers for group V. Silicon is used for n-type dopant; and gas source CBr_4 for p-type doping. The growth temperature is measured by ABES, and the group III fluxes are monitored by OFM. The optimal growth conditions are obtained by systematically varying the substrate temperature, total group V pressure, and As/Sb flux ratio.

For GaAsSb materials characterization, 100 nm thick carbon-doped GaAsSb were grown on (100) semi-insulating InP:Fe substrates under optimized growth condition. Carrier concentration and mobility were measured with a Hall setup. GaAsSb material composition was characterized with a double crystal x-ray diffraction in the (400) orientation.

For DHBT device fabrication, the steps consist of emitter and based etch, follow by Ti/Au non-alloy ohmic evaporation. The large area device measurements were taken from device with 50 x 50 um^2 emitter.

RESULTS and DISCUSSION

(A) HOLE MOBILITIES

Featureless surfaces with excellent morphology were found in all the samples grown. Typical diffraction peak position for the $GaAs_{1-x}Sb_x$ was less than 200 arc-sec apart from the InP substrate peak, which was corresponding to less than 1 atomic percentage mismatch (x=0.487) to InP substrates. Figure 1 shows the room temperature hole mobility of our carbon-doped GaAsSb as a function of the hole concentration. Hole concentration as high as 1E20 cm^{-3} has been achieved with our MBE grown GaAsSb. However, the hole mobility decreases from 46 cm^2/V-sec to 36 cm^2/V-sec as the hole concentration increases from 4.3E19 cm-3 to 1E20 cm^{-3}, showing a weak dependence of hole mobility on doping level. The relative low hole mobilities compared with InGaAs were attributed to strong alloy scattering in GaAsSb [9,10]. Compared to the reported data from MOCVD [10, 11] and GSMBE [11], favorable hole mobility values were obtained by our MBE.

(B) UNIFORMITY

Under normal MBE growth condition with unity sticking coefficient for the group III elements, the GaAsSb growth rate is limited by the Ga growth rate. The only unknown is the composition of the mixed group V, i.e., the ratio between As and Sb across the platen. From experience, the Ga growth rate for Riber 49 under normal platen rotation is within ± 1% across the substrate platen with the approximate shape of a 9" square. For a Riber 49 4 x 4" platen configuration, the 4" substrates are placed symmetrically in a square configuration. X-ray diffraction is used to quantify the composition uniformity of 100 nm CBr4 doped GaAsSb epi layer grown on a 4" semi-insulating InP:Fe substrate in a 4 x 4" platen. The uniformity of GaAsSb:C is an important criteria for any GaAsSb based HBT circuits development in the industry.

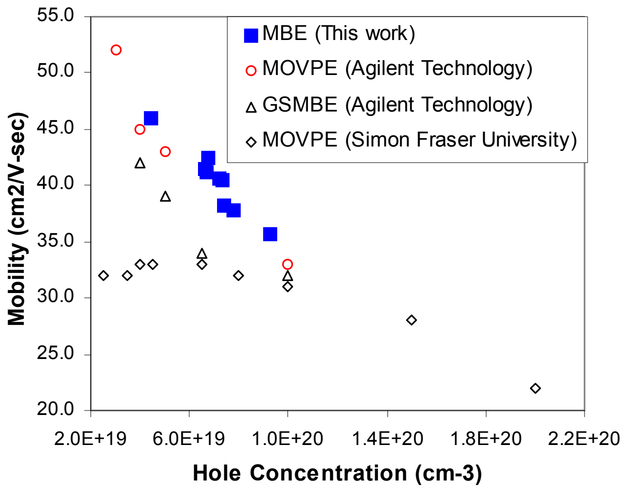

Fig. 1: Room temperature hole mobility of CBr_4-doped GaAsSb as a function of carrier concentration.

The non-uniformity in the composition and doping concentration control of the GaAsSb:C will affect the V_{be} of the HBT and, hence, the performance of the HBT circuits. We purposely mismatched the growth so that the diffraction peak of GaAsSb can be easily distinguished from that of the InP:Fe. Fig. 2 shows the rocking curves of the 4" GaAsSb:C wafer measured at multiple points across the diameter of the wafer along the radial direction of the platen. The GaAsSb diffraction peaks are ~500 arc-sec away from the InP substrate peak position, their shapes and peak positions are almost identical to each other. This indicates that the substrate temperature distribution in the radial direction of the 4 x 4" platen is very uniform. X-ray rocking curves of the 4" GaAsSb epi layer at different locations, but at the same platen radial coordinate, show the same composition. Fig. 3 summarizes the composition and uniformity variation of the 4" GaAsSb:C grown on this 4 X 4" platen. The Sb composition fluctuation is less than ± 0.1 atomic percentage across the 4" wafer and the whole platen. This high composition uniformity assures that we can grow 4 X 4" GaAsSb HBTs in one growth run, which is very important for fabrication processing development of HBT circuits and technology.

The uniformity of carbon doping across this 4" GaAsSb epi layer was measured with the Lehighton sheet resistivity mapping with a standard 36-point pattern across the 4" wafer. The average sheet resistance was ~ 347.1 Ohm/square, with a cross-wafer standard deviation of < 2.3%. The sheet resistivity uniformity should be adequate for GaAsSb based DHBT circuit development. It could be improved with further optimization of CBr_4 injector showerhead.

(C) InAlAs/GaAsSb/InP DHBTs

To further evaluate the material quality of our GaAsSb:C grown in our multi-wafer MBE, we explored the growth of InAlAs/GaAsSb/InP DHBTs with the help of in-situ ABES and OFM sensors. Figure 4 shows an example of the ABES taken during a complete InAlAs/GaAsSb/InP DHBT growth. We were able to reproduce the HBT characteristics from run to run by repeating the ABES growth temperature profile in both InGaAs and GaAsSb-base HBTs. Note that infrared pyrometer does not work for substrate temperature in the range much below 500 C. During low substrate growth temperature, thermal reflection signal from group III and/or dopant cells can easily drown out the true substrate pyrometer signal.

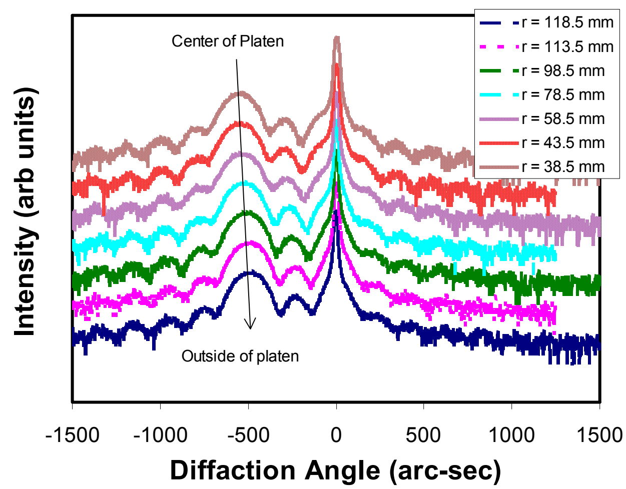

Fig. 2: Double-crystal x-ray diffraction spectra of a 4" GaAsSb at different locations along the radiant direction on the 4 X 4" platen.

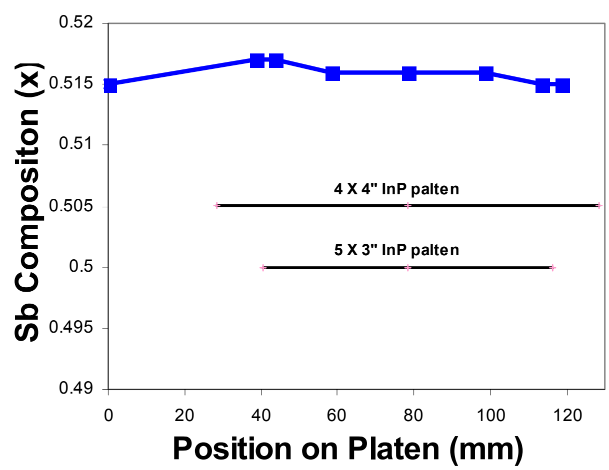

Fig. 3: Composition uniformity of GaAsSb vs. radial position across the platens of Riber 49 MBE system.

We further fabricated and tested large-area devices (LADs) of InAlAs/GaAsSb/InP DHBTs with 50 µm X 50 µm emitter mesa. Fig. 5 shows the common emitter I_c-V_{ce} characteristics of an InAlAs/GaAsSb/InP DHBT with 40 nm base thickness and 4.5E19 cm^{-3} base doping. The InP:Si collector thickness is 200 nm. The LAD has BV_{ceo}> 6V with dc current gain of 45 at $1kA/cm^2$. The base sheet resistivity is ~1000 Ohm/sq as measured by transmission line method (TLM). The collector and base ideality factor is 1.35 and 1.91, respectively. The uniformity of the device characteristics is excellent. A Gummel plot is shown in Figure 6.

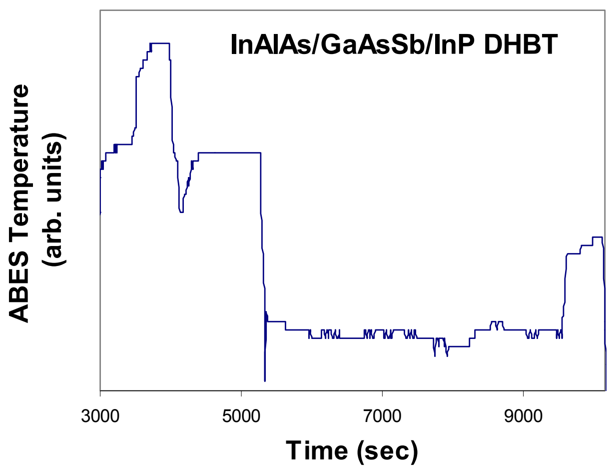

Fig. 4: ABES substrate temperature profile of an InAlAs/GaAsSb/InP DHBT during the growth in Riber 49.

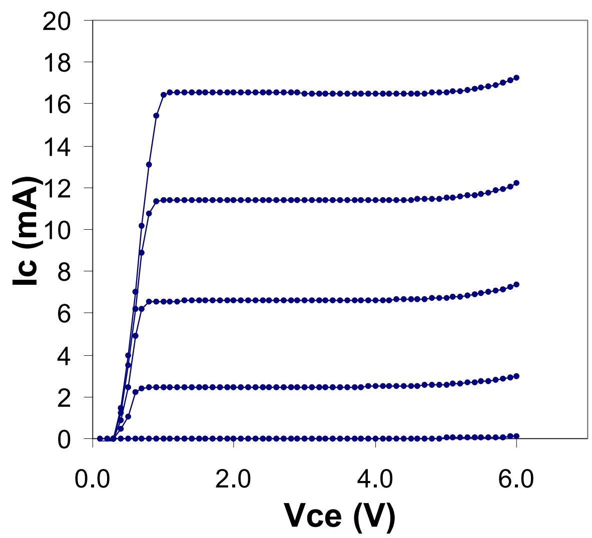

Fig. 5: Common-emitter Ic-Vce characteristics of a 50 µm X 50 µm InAlAs/GaAsSb/InP DHBT.

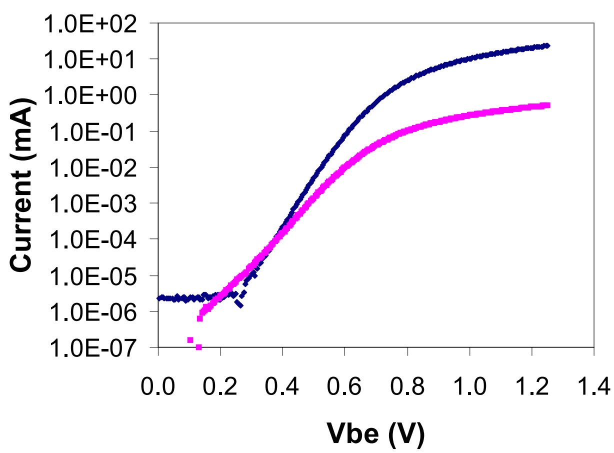

Fig. 6: Gummel plot from InAlAs/GaAsSb/InP DHBT with 4.5E19 cm^{-3} base doping.

CONCLUSIONS

In summary, we have investigated GaAsSb DHBTs with InAlAs emitter using multi-wafer production MBE equipped with ABES and OFM sensors. State-of-the-art hole mobilities were obtained for 100 nm thick carbon-doped GaAsSb. We have also demonstrated that the Sb composition fluctuation is less than ±0.1 atomic percentage across a 4" wafer grown on a 4 X 4" platen. The uniformity of GaAsSb and the excellent electrical properties of InAlAs/GaAsSb/InP DHBTs demonstrate that multi-wafer MBE is feasible for mass production of GaAsSb based DHBTs.

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REFERENCES

[1] C. R. Bolognesi, N. Matine, M. W. Dvorak, P. Yeo, X. G. Xu, and S. P. Watkins, IEEE Trans. Electro Devices, vol. 48, pp. 2631-2638, 2001.

[2] N. Matine, M. W. Dvorak, S. Lam, C. R. Bolognesi, Y. M. Houng, and N. Moll, Conf. Proc. of the 2000 Intl. Conf. on Indium Phosphide and Related Materials, pp. 239 -242, 2003.

[3] C. R. Bolognesi, M. W. Dvorak, N. Matine, O. J. Pitts, and S. P. Watkins, Jpn. J. Appl. Phys. Vol. 41, pp. 1131-1135, 2002.

[4] M. W. Dvorak, C. R. Bolognesi, O. J. Pitts, and S. P. Watkins, IEEE Electron Device Lett., vol 22, pp. 361-363, 2001.

[5] S. R. Johnson, C. Lavoie, T. Tiedje, and J. A. Mackenzie, J. Vac. Sci. Technol. B, vol. 11, pp. 1007-1110, 1993.

[6] J. A. Roth, T. J. De Lyon, and M. E. Adel, in Proc. Mater. Res. Soc. Symp., vol. 324, pp. 353-356, 1994.

[7] P. Pinsukanjana, A. Jackson, J. Tofte, K. Maranowski, S. Campbell, J. English, S. Chalmers, L. Coldren, and A. Gossard, JVST B, vol.14 (3), pp. 2147-2150, 1996.

[8] P. R. Pinsukanjana, J. M. Marquis, J. Hubbard, M. A. Trivedi, R. F. Dickey, J. M.-S. Tsai, S. P. Kuo, P. S. Kao, and Y.C. Kao, J. Crystal Growth, vol. 251, pp. 124-127, 2003.

[9] M. J. Cherng, R. M. Cohen, and G. B. Stringfellow, J. Electron Material, vol. 13, pp. 799-813, 1984.

[10] S. P. Watkins, O. J. Pitts, C. Dale, X. G. Xu, M. W. Dvorak, N. Matine, and C. R. Bolognesi, J. Crystal Growth, vol. 221, pp. 59-65, 2000.

[11] S. S. Yi, S. J. Chung, H. Rohdin, M. Hueschen, D. Bour, N. Moll, D. R. Chamberlin, and J. Amano, Conf. Proc. of the 2003 Intl. Conf. on Indium Phosphide and Related Materials, pp.380-383, 2003.