D-5-02

Extended Abstracts of the 2020 International Conference on Solid State Devices and Materials, VIRTUAL conference, 2020, pp223-224

Impact of Growth Direction on Crystal Quality and DC Characteristics of In(Ga)P/InGaAsSb DHBTs Transferred onto SiC Substrate

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Abstract

Impact of epitaxial growth direction on crystal quality and DC characteristics of In(Ga)P/InGaAsSb DHBTs transferred onto (inverted on) SiC substrate was investigated by comparing them with DHBTs grown on an InP substrate with the conventional layer-stacking sequence. TEM and EDX analysis revealed Sb segregation during growth at the base-emitter and collector-base interfaces in conventional and inverted DHBTs, respectively. Such poor interface abruptness does not affect DC characteristics significantly. Common-emitter breakdown voltages similarly depend on InP collector thickness in both device structures and are not affected by the growth direction. Maximum current gains also similarly depend on the base sheet resistance in both structures. These results indicate that the DHBT structure with a wide-gap InGaP emitter and compositionally graded InGaAsSb base is robust against the substrate-transfer process and beneficial for maintaining the excellent DC characteristics available with the conventional structure.

1. Introduction

Owing to their excellent Johnson's figure of merit[1-6], InP-based double heterojunction bipolar transistors (DHBTs) with an antimonide base are attracting great interest for the use in amplifiers for high-capacity optical/wireless telecommunications systems. To further boost the high-frequency performance of the DHBTs, increases in junction temperature must be carefully managed because it cannot be scaled as device size shrinks. The substrate-transfer technique[5], where InP substrate is replaced with a high-thermal-conductivity SiC substrate is one of the key approaches to deal with this issue. In conventional DHBTs, epitaxial layers are grown in the direction from collector contact to emitter cap. In the substrate-transfer process, epitaxial layers are inversely grown (from emitter cap to collector contact), and then the epitaxial wafer is inverted and transferred onto SiC substrate. For further improvement of device performance, the impact of the growth direction on the crystal quality and DC characteristics of DHBTs should be evaluated in detail.

In this work, we carefully compared the crystal quality and DC characteristics between conventional and transferred (inverted) DHBTs and investigated the impact of the epitaxial growth direction.

TABLE I Layer structures of fabricated DHBTs.

	Emitter	InP:Si	InGaP:Si
	Base	Graded InGaAsSb:C (20-30 nm)	GaAsSb:C (~3 nm) /graded InGaAsSb:C (10-17 nm)
Substrate	3-inch S.I. InP	Group-I (o)	Group-II (◊)
	Transferred onto 3-inch S.I. SiC	Group-III (o)	Group-IV (◊)

2. Experiments

Four types of the DHBTs were grown by metal-organic chemical vapor deposition. They are summarized in Table I. All the samples used a simple 40-to-150-nm-thick InP:Si collector. Group I and III samples consisted of a compositionally-graded InGaAsSb base and a simple InP emitter. Group II and IV samples consisted of a compositionally graded InGaAsSb base with a highly doped GaAsSb contact layer and an InGaP emitter. Here, the conduction band alignments were designed to be almost continuous and type-I for InP/InGaAsSb and InGaP/GaAsSb emitter-base heterojunctions, respectively. The epitaxial growth of Group I and II DHBTs was performed in the conventional order of collector, base, and emitter. Group III and IV DHBTs were grown in inverse order from the emitter to the collector and transferred onto SiC substrates.

We used x-ray diffraction (XRD) to evaluate the crystal quality of the epitaxial wafers. We also performed scanning transmission electron microscopy (STEM) and energy dispersion x-ray spectroscopy (EDX) to investigate interface abruptness. Note that inversely grown wafers that were not transferred onto SiC were used as reference wafers for the crystal quality evaluation.

DHBTs with the emitter width of 0.2-0.35 μm were fabricated by the *i*-line stepper process. Details of the fabrication process are described elsewhere [3-5]. Maximum DC current gain (β_{max}) and common-emitter breakdown voltage (BV_{CEO}) were estimated from Gummel plots and I_C-V_{CE} characteristics.

3. Results and Discussion

Figure 1 shows XRD (004) ω-2θ scan profiles of samples grown in (a) conventional and (b) inverted direction. The inversely grown sample (reference) was not transferred to SiC wafer. A slight difference in the peak position originating from the InGaP emitter is found between the samples, although these two samples were grown in the same reactor with almost the same machine time. The profile analysis revealed that slight Sb incorporation (~2%) into the InGaP emitter

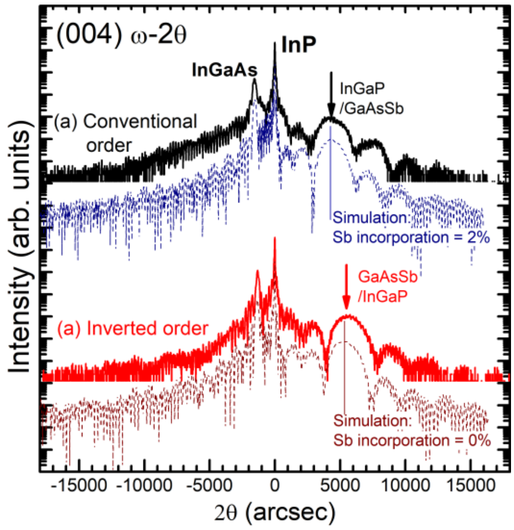

Fig. 1. XRD profiles of the wafers.

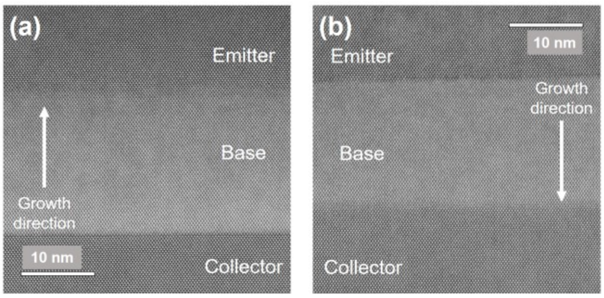

Fig. 2. BF-STEM images of DHBT wafer.

seemed to cause the difference in the peak position.

Figure 2 shows STEM images of the emitter-base-collector heterointerfaces of samples grown in the (a) conventional and (b) inverted direction. Sharp lattice image contrasts are observed at the collector-base and base-emitter interfaces in Fig. 2(a) and (b), respectively. In contrast, they are not clear at the interfaces of the base-emitter in Fig. 2(a) and collector-base in Fig. 2(b). The poor interface abruptness in the images is due to Sb segregation from the InGaAsSb base layer. EDX analysis revealed Sb segregation into the InGaP emitter and InP collector from InGaAsSb base in the samples grown in the conventional and inverted direction, respectively, which is consistent with the XRD and TEM results.

Figure 3(a) shows the dependence of BV_{CEO} on InP collector thickness. BV_{CEO} proportionally increases with increasing InP collector thickness. The BV_{CEO} of the DHBTs transferred onto SiC substrates is almost the same as that of the conventional ones and shows similar dependence on collector thickness. DC current gains of fabricated DHBTs are summarized in Fig. 3(b). DC current gain of the device transferred onto SiC substrate is almost equal to that of conventional devices. Their dependence on base sheet resistance is similar between the conventional and transferred DHBTs. These results suggest that the impact of the growth order and the transfer process on the DC characteristics is almost negligible.

Considering the results in Fig. 3(a) and (b), we can conclude that the Sb segregation is too small to affect the DC

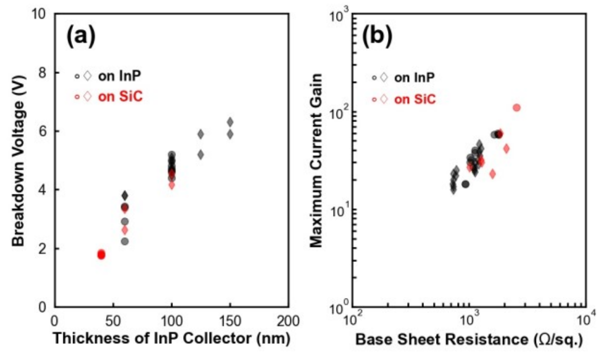

Fig. 3. (a) Dependence of BV_{CEO} on thickness of InP collector in fabricated DHBTs. (b) Dependence of β_{max} on base sheet resistance of fabricated DHBTs.

characteristics in the In(Ga)P/InGaAsSb DHBT structures. The amount of Sb segregation into the InP collector is too small (as small as 2%) to affect breakdown voltages. The almost continuous or type-I band line-up at emitter-base junctions consisting of the In(Ga)P emitter and compositionally graded InGaAsSb base is one of reasons current gain degradation is suppressed at the operating condition of high collector current density. Controlling the doping level of the InP collector might also be effective for maintaining the reverse bias characteristics. These results indicate that DHBTs with an In(Ga)P emitter and compositionally graded base are robust against the substrate-transfer process and beneficial for enhancing device performance.

4. Conclusion

We investigated the impact of the crystal growth direction on the crystal quality and DC characteristics of In(Ga)P/InGaAsSb DHBTs fabricated on conventional InP and transferred (inverted) onto SiC substrates. The crystal quality analysis revealed that the abruptness of base-emitter and collector-base interface is affected by Sb segregation in both the conventional and inverted DHBT structures. However, DC current gain and common-emitter breakdown voltages are comparable between the conventional and transferred DHBTs. An InGaP emitter and compositionally graded InGaAsSb base are useful for suppressing the influence of Sb segregation. These DHBT structures are beneficial for the substrate-transfer technique and for further boosting high-frequency performance.

References

[1] N. Kashio *et al*., IEEE EDL 35, 1209 (2014).
[2] N. Kashio *et al*., IEEE EDL 36, 657 (2015).
[3] T. Hoshi *et al*., IEICE ELEX 16, 1 (2019).
[4] Y. Shiratori *et al*., IEEE EDL 41, 697 (2020).
[5] Y. Shiratori *et al*., IEEE EDL 39, 807 (2018).
[6] T. Hoshi *et al*., APEX 7, 114102 (2014).