I. INTRODUCTION

InP-based electronic devices are attractive for ultrahigh-speed communication and integrated circuit applications. Among them, InP/InGaAs N-p-Zn single heterojunction bipolar transistors (SHBTs) have reached a record high cutoff frequency $f_T$ of over 600 GHz.\(^1\) Double heterojunction HBTs (DHBTs) using InP related material systems, with a theoretically better performance than SHBTs, have also been intensively studied. Among them, the GaAsSb/InP material system with a type-II energy band alignment has shown several unique advantages over other material systems.\(^2,3\) Due to the large difference in atomic size between As and Sb and the surface segregation effect of Sb, high crystal quality GaAsSb lattice matched to InP substrate is difficult to obtain. We have demonstrated that single phase, high quality GaAsSb lattice matched to InP can be grown at very low substrate temperature using gas-source molecular beam epitaxy (GSMBE).\(^4\) In this study, high crystal quality GaAsSb was grown at a relatively high temperature in order to better match conditions for the growth of InP and related materials. The GaAsSb/InP DHBTs grown by GSMBE technique with excellent $f_T$ near 350 GHz have been successfully developed.

II. MATERIAL GROWTH

The growth of GaAsSb bulk material and DHBT devices were carried out in a GSMBE system equipped with a 2200 l/s turbopump and a 9000 l/s cryopump. The samples were grown on nominally exact (001) InP:Fe semi-insulating substrates. Arsine and phosphine were used as arsenic and phosphorous sources, respectively, and a solid antimony cracker cell with adjustable precision valve was used as the antimony source. Standard effusion cells were used to provide elemental group III fluxes. The group III deposition rate was calibrated by the intensity oscillation of reflected high-energy electron diffraction. The growth temperature was chosen as 35 °C below the InP passivation oxide desorption temperature ($T_d$), which is compatible to the growth temperature of InP and related materials. In this study, the InP surface oxide desorption temperature was about 535 °C.

Since the growth of GaAsSb is sensitive to the growth temperature,\(^4\) two 300 nm GaAsSb samples, samples A and B, with different growth temperature profiles were grown on InP substrates. The growth rate was determined by Ga flux and kept constant at 0.8 ML/s. The growth temperature of sample A was raised from $T_d-30$ °C to $T_d+10$ °C during growth, and sample B was grown with a reduced V/III ratio of ~70% of that of sample A and at a constant substrate temperature of $T_d-35$ °C. The reason for the ramping of the growth temperature of sample A is to eliminate the Sb-composition variation along the growth direction.\(^4\) High-resolution x-ray diffraction (HRXRD) spectra in a (004) reflection of both samples are shown in Fig. 1. From the HRXRD spectrum, sample A suffers from the formation of natural superlattice indicated by the satellite peaks. The natural superlattice has a period of 82 Å and was confirmed by transmission electron microscopy (TEM).\(^4\) Since Sb atoms tend to segregate and accumulate at the growth front, the excess Sb atoms could promote the phase separation in the form of nature superlattices in the growth direction. On the other hand, sample B grown under reduced V/III ratio shows high crystal quality. Narrow linewidths (21.86 arc sec) and clear Pendellösung fringes can be observed in the HRXRD spectrum.

III. DC DHBT RESULTS

Two InP/GaAs$_{0.3}$Sb$_{0.7}$/InP N-p-n DHBTs, samples C and D, were grown. The layer structure of the DHBTs, samples C and D, was identical as shown in Table I, except that the base growth conditions were similar to samples A and B, respectively. In addition, the growth temperature of both samples was kept constant at $T_d-35$ °C. Carbon tetrabromide and silicon tetrabromide injected through a low temperature gas injector were used as p-type and n-type dopants, respectively. The p-type GaAsSb base doping was $7 \times 10^{19}$ cm$^{-3}$.

Large size DHBT devices with emitter mesas ranging from $20 \times 20$ to $120 \times 120$ μm$^2$ were fabricated using standard processing techniques. The device characteristics were
measured using HP4145B semiconductor parameter analyzer and summarized in Fig. 2. A dc gain ($\beta$) lower than 10 is obtained for sample C. This is due to the existence of the natural compositional superlattice, where electrons experience additional scatterings when they are launched from the emitter into the base. Therefore a higher base recombination current will form and results in a lower dc gain. With a high quality base, the base recombination current decreases. Therefore sample D shows a significant improvement of $\beta$ higher than 40.

IV. RF DHBT RESULTS

A DHBT structure was grown to investigate the high-speed characteristics of the GaAsSb/InP DHBT with the base layer grown under the same condition as sample D. The layer structure of the radio frequency (rf) DHBT is similar to that shown in Table I except that the thicknesses of the emitter, base, and collector were reduced to 400, 250, 650 Å, respectively. Thinner layers can reduce the carrier transit time in each layer, therefore, higher speed can be achieved. The doping concentration in each layer was kept the same as the dc DHBT, as shown in Table I. The GaAsSb base was grown with the same parameters as sample D, except the decrease of thickness from 500 to 250 Å. The base sheet resistance is measured to be 1575 Ω/sq, determined by transmission line model (TLM) measurements.

RF DHBT devices were fabricated using a triple mesa process.5 Due to the small emitter size and small alignment tolerance, the emitter and base metals were defined by electron beam lithography. The collector mesa was defined by optical lithography. Wet chemicals were used to etch the mesas. The base contact was connected to the intrinsic base by a microbridge, which was undercut to eliminate the extrinsic base-collector capacitance associated with the extrinsic base contact. Following the isolation of the base contact, the device was planarized by bisbenzocyclobutene (BCB). The BCB was then etched back to expose the contacts and the final metal layer was deposited.

The common-emitter family curves for a $0.35 \times 8$ µm$^2$ device is shown as Fig. 3. The breakdown voltage $BV_{CEO}$ is $>3$ V and the dc gain reaches a maximum value of 27 at

<table>
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<tr>
<th>TABLE I. Layer structure of the large size DHBT samples C and D.</th>
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<td>Thickness</td>
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<td>InP semi-insulating substrate</td>
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a collector current of 35 mA. The devices had a Gummel collector/base current ratio \( I_C/I_B \) crossover at 0.34 V.

The rf measurements were done on an HP 8510C network analyzer, measuring from 500 MHz to 50 GHz. The measurements were calibrated using a standard on-wafer short-open-load-thru (SOLT) calibration. The device was measured with no base-collector bias \( (V_{CB}=0 \text{ V}) \) since the rf device performance has very little dependence on the collector-base voltage due to the thin collector layer. The extrapolation calculated from the \( S \) parameters at 35 GHz, assuming a \(-20 \text{ dB/decade rolloff}\), is shown as Fig. 4. The DHBT device achieved a peak performance of a current gain cutoff frequency \( f_T = 346 \text{ GHz} \) and a maximum oscillation frequency \( f_{max} = 145 \text{ GHz} \) at a collector current density \( J_C = 850 \text{ kA/cm}^2 \). The \( f_T \) and \( f_{max} \) versus the frequency plot of the device does not vary rapidly as with the extrapolation frequency, as shown in the inset of Fig. 4. Figure 5 shows the \( f_T \) and \( f_{max} \) performance versus the collector current density. The \( f_T \) and \( f_{max} \) rolloff at higher collector current density indicates heating in the junctions at higher collector current density. The \( f_{max} \) is undesirably low, due to a relatively high base sheet resistance. This can be further improved by optimizing the base crystal quality. The relatively low breakdown voltage can be improved by optimizing the source switching sequences of the base-collector junction during growth.

V. SUMMARY

High quality GaAsSb lattice matched to InP was grown using GSMBE at a growth temperature of 35 °C below the InP surface oxide desorption temperature. The temperature is compatible with the growth temperature of InP and related materials. With reduced V/III ratio during the base layer growth, the dc gain of the GaAsSb/InP DHBTs with a 500 Å thick carbon doped \( (7 \times 10^{19} \text{ cm}^{-3}) \) base improved from less than 10 to over 40. A DHBT with a 250 Å GaAsSb base shows a maximum dc gain of 27. The \( f_T \) and \( f_{max} \) are 346 and 145 GHz, respectively, which are among the best values of GaAsSb/InP DHBTs achieved by any growth technology.

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