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A Novel Approach for the Fabrication of Highly Stable Be-Doped InGaAs/InP HBTs by ALE/MOVPE Hybrid Process

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In this paper, we report the successful fabrication of the epitaxial layer structure for InGaAs/InP heterojunction bipolar transistors having a 50 nm thick base layer with a doping level of 4×10^{19} cm^{-3}. It was found that when the Be-doped base layer and the emitter layer were directly adjacent to each other, drastic diffusion of Be into the InP layer occurred. To overcome this problem, we inserted an undoped InGaAs spacer layer between the base and emitter layers, and optimized the thickness of the former layer to 20 nm. A HBT fabricated using this technique was found to have a current gain β=47.

1. Introduction

Heterojunction bipolar transistors (HBTs) of $In_{0.53}Ga_{0.47}As$/InP are very attractive devices because of their superior high-frequency performance[1)] and low electric power consumption[2)]. Growth of p^+-InGaAs base layers is a key technology in the fabrication of HBTs and have been grown by several growth techniques. In metalorganic vapor phase epitaxy (MOVPE), Zn has been commonly used as a p-type dopant. However, it is difficult to realize an abrupt doping profile at the emitter/base junction, especially when high Zn-doping is involved, because of the relatively high diffusion coefficient of Zn[3)]. Alternatively, C-doped InGaAs layers, grown by MOVPE using CCl_4, have been used as carbon sources. In this case, hydrogen passivation is found to obstruct the incorporation of C to high doping levels[4)]. Furthermore, short period GaAs(C)/InAs superlattices grown by metalorganic molecular beam epitaxy (MOMBE)[5)] have some problems in thermal stability. At present, Be-doped InGaAs layers grown by gas source MBE (GSMBE) is the most promising material for the base layer. But it is questionable whether GSMBE will be adapted to mass production. Atomic layer epitaxy (ALE) is a promising growth technique for achieving highly Be-doped InGaAs layers[6)]. However it is difficult to make a complete HBT structure by ALE alone because of its slow growth rate. Thus, we have developed a ALE/MOVPE hybrid process which combines the advantages of both growth methods by using ALE to grow the highly Be-doped InGaAs layer, and MOVPE can make the higher growth rate for the full structure.

In this paper, we report a successful fabrication of InGaAs/InP HBT structures by ALE/MOVPE hybrid process in which the p^+-InGaAs base layer and other layers were grown by ALE and MOVPE, respectively.

2. Experimental procedure

The whole growth procedure was carried out in a low-pressure, RF-heated, cold wall, chimney reactor which is schematically illustrated in Fig. 1. The reactor was equipped with fast vent-run gas manifold valves, a rotating susceptor, and an optimized gas distributor, so that ALE and MOVPE growths can be performed consecutively. All layers for HBT devices were grown on Fe-doped semi-insulating (100) InP substrates misoriented 2° toward $[0\bar{1}1]$. The growth precursors

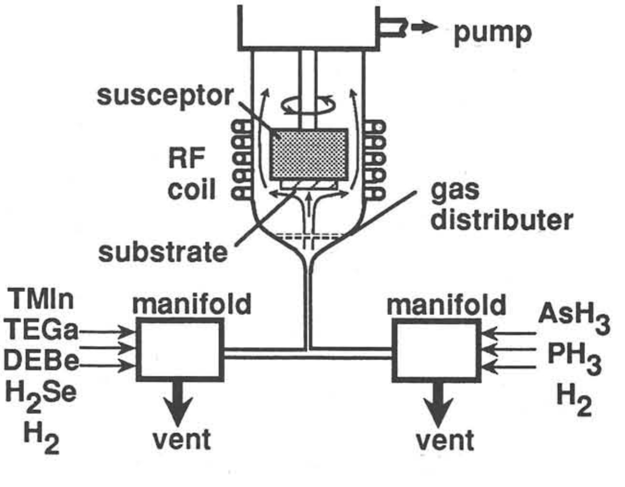

Fig.1 Schematic illustration of the reactor.

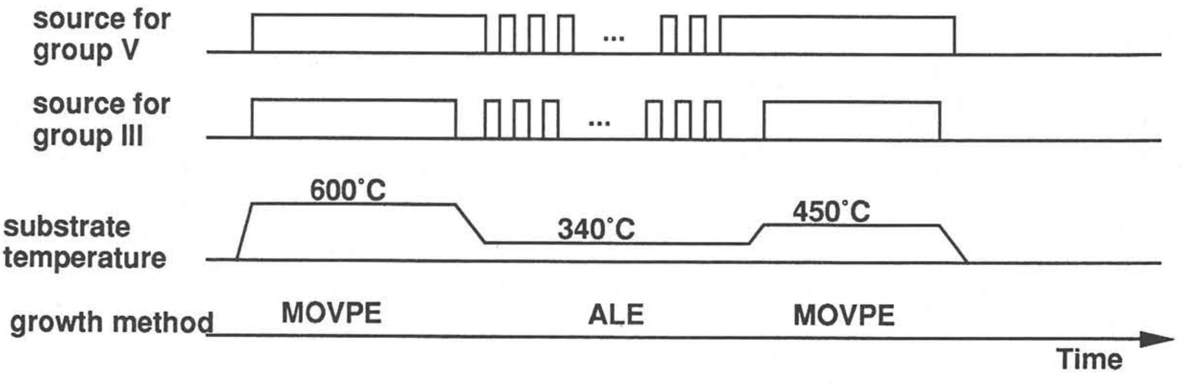

Fig.2 Growth procedure of ALE/MOVPE hybrid process.

were trimethylindium (TMIn), triethylgallium (TEGa), arsine (AsH_3), and phosphine (PH_3). Diethylberyllium (DEBe) and H_2Se were used as sources for p- and n-type doping respectively. The carrier gas used was H_2 and total gas flow rate was kept at 2000 ccm.

Fig. 2 shows the typical growth procedure. In this procedure, the InP buffer, n^+-$In_{0.53}Ga_{0.47}As$ sub-collector and n-$In_{0.53}Ga_{0.47}As$ collector layers were grown by conventional MOVPE at 600°C. Then, the substrate temperature was lowered to 340°C and a Be-doped p^+-$In_{0.53}Ga_{0.47}As$ base layer and an undoped $In_{0.53}Ga_{0.47}As$ spacer layer, which suppresses Be-diffusion, were grown by ALE. Finally, the substrate temperature was raised to 450°C and a n-InP emitter layer and a n^+-$In_{0.53}Ga_{0.47}As$ cap layer were grown by conventional MOVPE. Only a few minutes are required to set the substrate temperatures for either MOVPE and ALE modes.

The thickness of the epitaxial layers was determined by surface profilometery measurement of selectively etched samples. Secondary ion mass spectrometry (SIMS) was used to study the Be and Se concentration profiles in the epitaxial layers. The carrier concentration of the epitaxial layers was measured by the Van der Pauw method and capacitance-voltage (C-V) measurements.

3. Results and discussion

3.1 Effect of spacer layer on Be-diffusion

To evaluate the effect of insertion of the spacer layer on the degree of diffusion of Be, we fabricated test structures with various thicknesses of the undoped InGaAs spacer layer (Δ=0, 10, 15 and 20 nm). The layer structure for the samples is shown in Table 1. The total thickness of the spacer and the base layers was kept at 50 nm.

Table 1
Layer structure of samples.

InP	undoped	100nm	MOVPE	450°C
InGaAs	undoped	Δ nm	ALE	340°C
p^+-InGaAs	Be: $6x10^{19}cm^{-3}$	50-Δ nm	ALE	340°C
InGaAs	undoped	300nm	MOVPE	600°C
InP Substrate	Fe	450μm		

Δ=0, 10, 15, 20nm

Fig.3 shows the SIMS depth profile of the test structures. When the base layer was located adjacent to the emitter layer (Δ=0), a drastic diffusion of Be into the InP layer was observed. The anomalous shape of the Be-profile in the InP layer is similar to previous reports[7)8)]. On the other hand, no diffusion of Be into the InGaAs layer was found. These results indicate that Be has a higher diffusion coefficient in InP than in InGaAs under these conditions. Thus, the use of an undoped InGaAs spacer layer suppresses Be diffusion into the emitter layer.

In addition, when the thickness (Δ) of the spacer layer was increased the degree of diffusion of Be into the InP layer decreased. When Δ=20 nm, the redistribution of Be into InP was completely suppressed. The undoped InGaAs spacer layer became p^+-layer by the diffusion of Be into this layer during growth of the InP layer. As a result, a Be-doped InGaAs layer with a

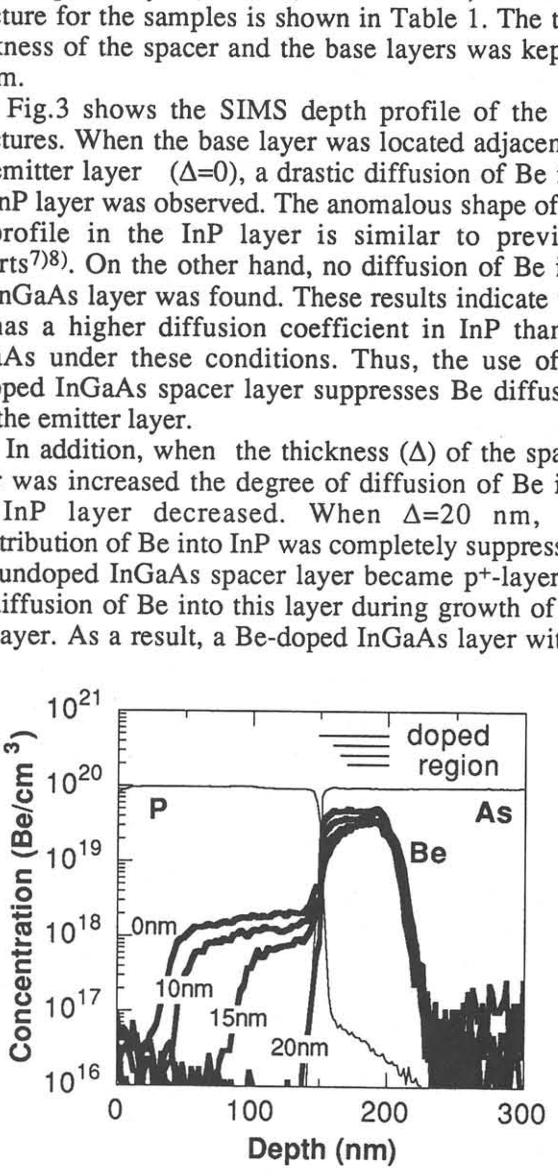

Fig.3 SIMS depth profiles of Be-doping of base and emitter regions of HBTs with various undoped spacer layer thicknesses.

thickness of 50 nm and an average Be-concentration of 4×10^{19} cm^{-3} was formed.

3.2 Growth of InGaAs/InP HBT layer structure

Based on the results described in 3.1, we have optimized the layer structure and growth conditions for HBTs as shown in Table 2. In this structure, the optimized thickness of the spacer layer is 20 nm.

Fig. 4 shows a SIMS depth profile of the structure. An epitaxial layer structure with a well-defined base layer was obtained. The position of the hetero-interface between the emitter and the base layers exactly coincides with that of the p-n junction. In spite of a Se-doping in the InP emitter layer the diffusion of Be was not enhanced by an increase of the electric field of the p-n junction.

Subsequently, HBTs were fabricated using this epitaxial layer structure. The emitter size of the fabricated HBTs was 5x20 μm^2. A DC current gain of 47 was obtained at a collector bias of V_{CE}=1.0V and a collector current of I_C=50mA(which corresponds to $J_C \approx 5\times10^4$ A/cm^2).

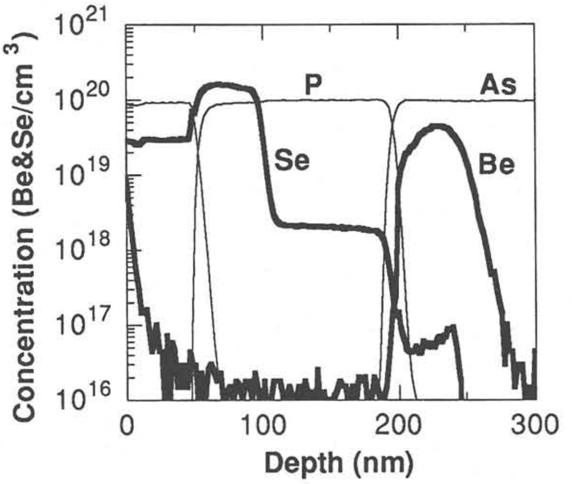

Fig.4 SIMS depth profile of optimized HBT structure.

4. Conclusion

We have fabricated the epitaxial layer structure for InGaAs/InP HBTs having a 50 nm thick base with a doping level of 4×10^{19} cm^{-3} by ALE/MOVPE hybrid process. Since the positioning of the Be-doped base layer directly adjacent to the emitter layer resulted in severe Be diffusion into the latter layer, we used undoped InGaAs as a diffusion barrier between these layers. The optimum thickness of the InGaAs layer was determined to be 20 nm. A HBT device fabricated using this approach had a measured current gain of β=47.

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Table 2 Layer structure and growth conditions for InGaAs/InP HBT.

Cap Layer	n^+-InGaAs	Se	$5\times10^{19}cm^{-3}$	50 nm	MOVPE	450°C
Emitter Layer	n^+-InP	Se	$1\times10^{20}cm^{-3}$	50 nm	MOVPE	450°C
	n-InP	Se	$2\times10^{18}cm^{-3}$	100 nm	MOVPE	450°C
Spacer Layer	InGaAs		undoped	20 nm	ALE	340°C
Base Layer	p^+-InGaAs	Be	$6\times10^{19}cm^{-3}$	30 nm	ALE	340°C
Collector Layer	n-InGaAs		undoped	300 nm	MOVPE	600°C
Sub-Collector Layer	n^+-InGaAs	Se	$5\times10^{18}cm^{-3}$	350 nm	MOVPE	600°C
Buffer Layer	InP		undoped	300 nm	MOVPE	600°C
Substrate	S.I.-InP	Fe	-	450 μm		