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InGaP/GaAs Heterojunction Bipolar Transistors (HBTs) with a Ultra-High Carbon-Doped Base ($p=1.5\times10^{21}$ cm^{-3})

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$In_{0.5}Ga_{0.5}P$/GaAs heterojunction bipolar transistors (HBTs) having a heavily carbon (C)-doped GaAs base with an ultra-high hole concentration of 1.5×10^{21} cm^{-3} were successfully fabricated by metalorganic molecular beam epitaxy (MOMBE) for the first time. Tertiarybutylphosphine (TBP), elemental In and elemental Ga were used as source materials for the growth of $In_{0.5}Ga_{0.5}P$ emitter and trimethylgallium (TMG) and elemental arsenic (As_4) for the growth of GaAs base. Small signal current gain h_{fe} of 16 and DC current gain h_{FE} of 12 were obtained for devices with a base thickness of 15 nm despite the ultra-high doping in the base layer.

1. INTRODUCTION

Heterojunction bipolar transistors (HBTs) are becoming important for high speed digital and analog electronics applications, especially for the recent mobile communication systems. For the application of conventional GaAs-based HBTs, excellent progress in the performances has been made by the use of carbon (C) as a replacement for the conventional p-type dopants such as Be and Zn[1-4]. We have investigated the carbon-doping technique in GaAs[5,6] and InGaAs[7,8] by metalorganic molecular beam epitaxy (MOMBE) using trimethylgallium (TMG) and elemental sources. The hole concentrations of as high as 1.5×10^{21} cm^{-3} and 5×10^{19} cm^{-3} were obtained in the case of GaAs and $In_{0.5}Ga_{0.5}As$, respectively. Since the reduction of base resistance is one of the key factors for improving the high frequency performances in the HBTs, heavily doped base HBTs will be available if there is no significant degradation of current gains in that structure. Therefore, these carbon-doping techniques by MOMBE are suitable for the growth of carbon-doped base HBTs with a extremely high hole concentration in the base layer.

Although AlGaAs has been widely used as emitter material in the GaAs-based HBT structure, there are several problems caused by carbon contamination in the n-type AlGaAs emitter of AlGaAs/GaAs HBTs grown by MOMBE using metalorganic Al precursors. This is due to that the carbon from the metalorganic precursors is incorporated as acceptor in the AlGaAs, resulting in heavy compensation in n-type AlGaAs emitter. One of the approaches to overcome these problems is the use of InGaP as emitter material[4,9,10], in which carbon is less incorporated as acceptor than AlGaAs. Furthermore, as compared with AlGaAs, InGaP has advantages suitable for the HBT application such as lower surface recombination velocity, larger valence band offset to GaAs, high etching selectivity and no DX center problem. In the MOMBE growth of $In_{0.5}Ga_{0.5}P$, recently, tertiarybutylphosphine (TBP) has been a successful alternative precursor to phosphine (PH_3) from the viewpoint of both less toxicity and development of safer MOMBE growth technology[11,12].

In this study, the fabrication of InGaP/GaAs HBTs having a heavily C-doped GaAs base with a hole concentration of as high as 1.5×10^{21} cm^{-3} is investigated for the first time. We also report that current gains of above 10 could be obtained in the devices despite the ultra-high doping in the base layer.

2. DEVICE FABRICATION

The modified VG-V80H MOMBE chamber with handmade gas-handling systems was used for the fabrication of the devices. The carbon-doped base InGaP/GaAs HBT structures were grown by MOMBE using elemental In and elemental Ga as group III sources and TBP and elemental arsenic (As_4) as group V sources. Table I shows the layer structure of the HBTs. The base thickness was varied from 15 to 70 nm in the HBT structure.

Table I. Layer structure of heavily carbon-doped $In_{0.5}Ga_{0.5}P/GaAs$ HBTs

Function	Layer	Thickness (nm)	Doping (cm^{-3})
Cap	n^{+}- $In_{0.5}Ga_{0.5}As$	15	$1x10^{18}$
Cap	n^{+}- GaAs	100	$1x10^{18}$
Cap	n^{+}- $In_{0.5}Ga_{0.5}P$	100	$4x10^{18}$
Emitter	n - $In_{0.5}Ga_{0.5}P$	110	$1x10^{18}$
Base	p^{++}- GaAs	15, 35, 70	$1.5x10^{21}$
Spacer	un - GaAs	10	—
Collector	n - GaAs	600	$3x10^{16}$
Buffer	n^{+}- GaAs	600	$1x10^{18}$

The Si-doped GaAs buffer ($n=1x10^{18}$ cm^{-3}) and collector ($n=3x10^{16}$ cm^{-3}) layers were grown by MBE using cracked Si_2H_6 as n-type dopant source. Following the growth of the undoped GaAs spacer layer, As_4 flux and the growth temperature were set to the growth condition at which the ultra-high doping of carbon into GaAs could be possible. During the variation of the temperature of the arsenic cell, the HBT sample was continuously exposed to the As_4 flux to suppress the desorption of arsenic from the surface. Then, the C-doped GaAs base layer with a hole concentration of as high as $1.5x10^{21}$ cm^{-3} was grown by MOMBE using TMG and As_4. After that, the As_4 flux was directly switched to the phosphorus flux from the cracked TBP. Finally, the Si-doped $In_{0.5}Ga_{0.5}P$ emitter layer was grown by MOMBE with TBP. Cap layers were also formed to reduce the emitter contact resistance. The details of the MOMBE growth of GaAs, InGaAs and InGaP were described elsewhere[5-8,10]. Growth interruption at base-collector and base-emitter junction is necessary to stabilize the growth temperature and the group V fluxes.

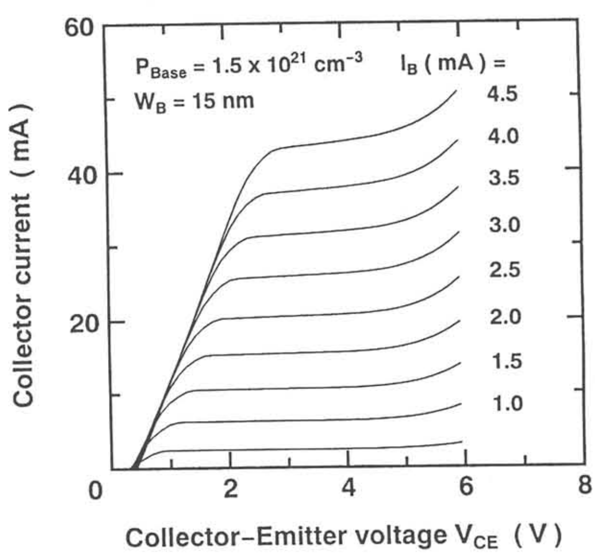

Figure 1. Common-emitter DC characteristics of InGaP/GaAs HBT with a hole concentration of $1.5x10^{21}$ cm^{-3} in the base and the base thickness of 15 nm.

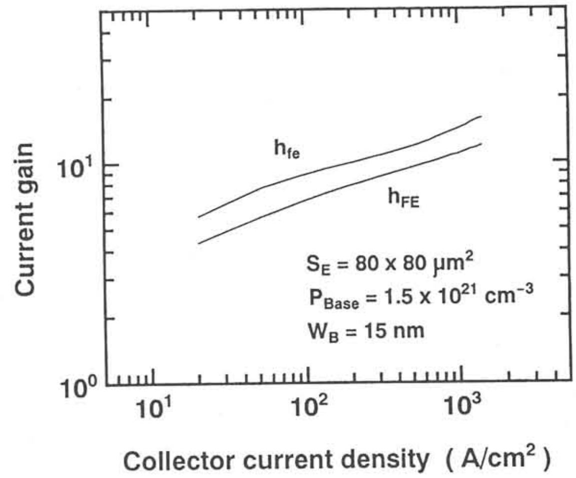

Figure 2. Common-emitter current gains as a function of collector current density for a device with the emitter area of 80x80 μm^2, base hole concentration of $1.5x10^{21}$ cm^{-3} and the base thickness of 15 nm.

Conventional wet chemical etching and lift-off process were used to identify the devices with double mesa structure. HCl was utilized to selectively etch the $In_{0.5}Ga_{0.5}P$ emitter. Ti/Pt/Au and AuGe/Ni/Au were employed to form ohmic contacts to p- and n-type layers, respectively. Polyimide was used as surface passivation film. HP-4145B semiconductor parameter analyzer was used for the measurements of current -voltage characteristics.

3. RESULTS AND DISCUSSION

Figure 1 shows common-emitter current-voltage characteristics for a device with a base hole concentration of $1.5x10^{21}$ cm^{-3} and a base thickness of 15 nm. In this device, emitter area is 80 x 80 μm^2. Small signal current gain h_{fe} of 12.7 and DC current gain h_{FE} of 10 were obtained at a collector current of 45 mA (collector current density J_C of 0.7 kA/cm^2). The Gummel plot of this device shows the ideality factors of 1.1 for the base-collector junction and 1.7 for the base-emitter junction. In order to estimate the abruptness at the heterointerface, the depth profile of the elements was taken by Auger electron spectroscopy (AES), and it is revealed that abrupt change of chemical composition is obtained at the heterointerface even though ultra-high doping in the base layer.

Common-emitter current gains as a function of collector current density is shown in Fig. 2. It should be noted that relatively high h_{fe} of 16 and h_{FE} of 12 were

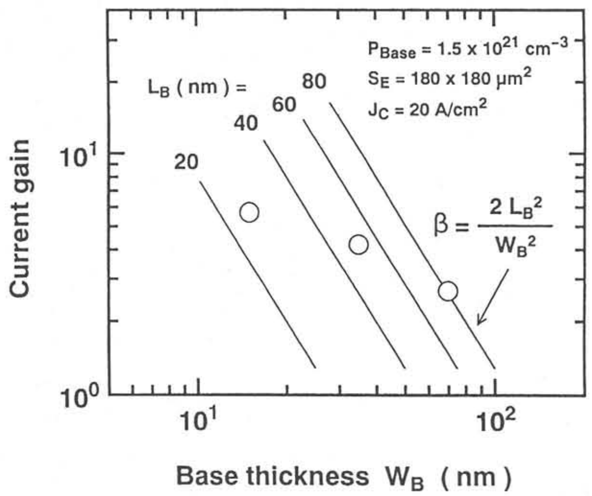

Figure 3. Dependence of current gain on the base thickness in carbon-doped base InGaP/GaAs HBTs with ultra-high doping in the base layer.

obtained at J_C of 1.4 kA/cm^2 in this device. These results clearly suggest that heavily carbon-doped p-type GaAs with a hole concentration of as high as $1.5x10^{21}$ cm^{-3} could be available for the InGaP/GaAs HBT application. To our knowledge, this is the first report on the InGaP/GaAs HBTs with ultra-high doping in the base layer.

In order to investigate the influence of the base thickness on current gains, the devices with different base thicknesses were fabricated. Figure 3 shows dependence of current gain on the base thickness at J_C of 20 A/cm^2. As generally expected, the current gain was increased with decreasing the base thickness. However, the slope obtained from the experimental data is smaller than that under assumption in which the current gain is determined by only the base transport efficiency. This may be due to the influence of recombination centers at emitter-base junction as observed in poor ideality factor of the base current.

4. CONCLUSION

We have studied InGaP/GaAs HBTs having a heavily C-doped GaAs base with a hole concentration of as high as $1.5x10^{21}$ cm^{-3} for the first time. In order to achieve such high doping of carbon in the GaAs base layer, MOMBE techniques have been utilized for the growth of the HBT structure. TBP, elemental In and elemental Ga were used as source materials for the growth of $In_{0.5}Ga_{0.5}P$ and TMG and As_4 for the growth of GaAs. Small signal current gain h_{fe} of 16 and DC current gain h_{FE} of 12 have been obtained for devices with a base thickness of 15 nm despite the ultra-high doping in the base layer. These preliminary results clearly show that MOMBE-grown heterointerface between InGaP and heavily carbon-doped GaAs is of high quality, and the electron lifetime in the carbon-doped GaAs with a hole concentration of $1.5x10^{21}$ cm^{-3} is considerably enough for applications to minority carrier devices such as HBTs.

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