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GaAs Pseudo-Heterojunction Bipolar Transistor with a Heavily Carbon-Doped Base

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A GaAs Pseudo-heterojunction bipolar transistor with a carbon doped base grown by metalorganic molecular beam epitaxy was fabricated for the first time, and the highest dc current gain of 1.7 was obtained, which evidences bandgap narrowing in the base. However, the hole injection from the base into the emitter cannot be still ignored, and use of a heavily carbon-doped InGaAs base is proposed to improve transistor characteristics.

1. INTRODUCTION

Recently an interest in an AlGaAs/GaAs heterojunction bipolar transistor (HBT) with a carbon-doped base has been growing.[1,2] Carbon can be doped to as high as 1.5×10^{21} cm^{-3} in GaAs by metalorganic molecular beam epitaxy (MOMBE).[3] However, it is difficult to obtain a high-quality AlGaAs layer little contaminated with carbon residual after use of a large amount of trimethylgallium (TMG), which is typically used as a carbon source in the MOMBE growth of GaAs.

In this paper, we discuss a GaAs pseudo-HBT with a heavily carbon-doped base grown by MOMBE. In the GaAs pseudo-HBT all layers are made of GaAs, and the bandgap of the base is smaller than those of the emitter and collector due to the bandgap narrowing effect. As a result, there is a valence-band offset at the emitter/base junction, which suppresses the hole injection from the base into the emitter. The pseudo-HBT was proposed and demonstrated for Si,[4,5] but this is the first time to report the GaAs pseudo-HBT.

2. EPITAXIAL GROWTH AND HBT FABRICATION

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The GaAs pseudo-HBT structure was grown on (100) SI GaAs substrate in a V-80H MBE chamber made by VG Semicon. For all layers except the base, solid gallium and arsenic were used as source materials, but for the base TMG was substituted for solid gallium and introduced into the chamber with use of a He carrier gas to incorporate a large amount of carbon in the GaAs base.[3] The n-type layers were formed using solid silicon as a dopant source. The growth temperature was 580 °C for all layers.

The parameters for doping concentration and thickness are shown in Table 1. Conventional photolithography and wet chemical etching were

Table 1 Epitaxial structure parameters of the fabricated GaAs pseudo-heterojunction bipolar transistor.

Layer	Thickness(nm)	Doping(cm^{-3})
n^+ cap	200	5×10^{18}
n emitter	450	5×10^{17}
p^+ base	100	1×10^{20}
n collector	1000	1×10^{17}
n^+ buffer	500	5×10^{18}

used to define the emitter, base and collector regions. Evaporation and liftoff of AuGe/Ni/Au (80 nm/10 nm/200 nm) for metallization of the emitter and collector contacts were followed by alloying at 380 °C for 5 min under N_2 flow. The base contact was made using non alloyed AuBe/Au (80 nm/200 nm). The emitter size was 50x50 μm^2.

3. RESULTS AND DISCUSSION

As seen in Fig. 1 the carrier concentrations profiled by the electrochemical capacitance–voltage (C–V) measurement using a Polaron model PN4200 system confirm the parameters listed in Table 1. The growth time of the base is 10 min, which is short enough not to contaminate the emitter with a large amount of carbon.[6] The structure exhibits abrupt emitter/base and base/collector junctions.

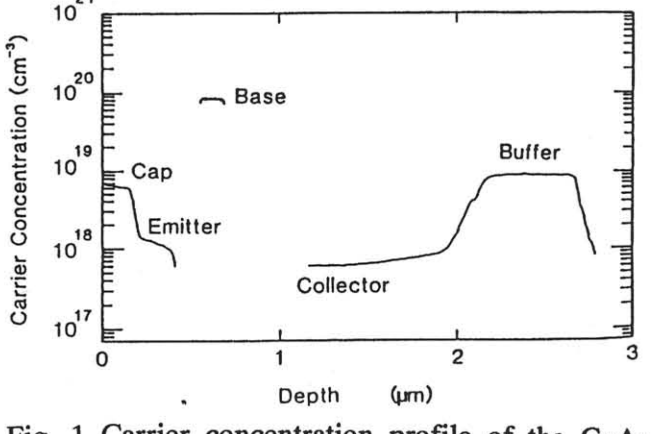

Fig. 1 Carrier concentration profile of the GaAs pseudo–heterojunction bipolar transistor.

Figure 2 shows the common-emitter I–V characteristic. At I_B=16 mA, a dc current gain of 1.7 is obtained. The value of β_{max} is estimated to be 2.3 for the bandgap narrowing by 100 meV, which is expected for a hole concentration of $1x10^{20}$ cm^{-3},[7] from the equation for an HBT with an abrupt emitter/base junction[8]:

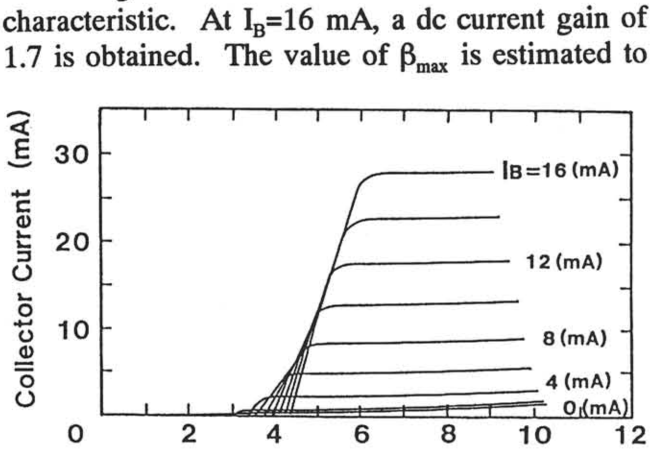

Fig. 2 Common–emitter characteristic of the GaAs pseudo–heterojunction bipolar transistor.

$$\beta_{max} = (N_E/P_B)(\upsilon_{nB}/\upsilon_{pE})\exp(\Delta E_v/kT), \quad (1)$$

where N_E and P_B are the shallow doping concentrations in the emitter and base, respectively, and ΔE_v is the valence–band offset at the emitter/base junction. The ratio of the mean electron velocity in the base, υ_{nB}, to the mean hole velocity in the emitter, υ_{pE}, is assumed to be 10 in the calculation. The β_{max} without the bandgap narrowing in the base is 0.05 at most. Therefore, the obtained gain suggests presence of a valence–band offset at the emitter/base junction.

In Fig. 2 a large offset voltage is noticed, and the offset voltage increases with increasing the base current. Since the fabricated HBT has a double heterostructure, where the bandgaps of the emitter and collector are equal, the offset voltage should be negligible. However, for large emitter series resistance, R_E, the offset voltage, V_{CE}(offset), becomes proportional to the base current:[9]

$$V_{CE}(\text{offset}) \propto R_E I_B. \quad (2)$$

The emitter series resistance calculated from equation (2) is 75 Ω. The high resistance is most probably due to high resistance of the emitter ohmic contact. In addition, a large base current also contributes to a large offset voltage. The valence–band offset at the emitter/base junction may not be large enough to prevent the hole injection from the base into the emitter. An increase of the valence–band offset can more effectively suppress the hole injection and reduce the offset voltage.

As one technique to increase the valence–band offset, we propose use of heavily carbon–doped InGaAs as a base and discuss MOMBE growth of carbon–doped InGaAs next.

4. MOMBE GROWTH OF InGaAs

Carbon incorporation using a graphite filament in MBE–grown InGaAs was extensively studied by Ito and Ishibashi,[10] who reported that the conductivity type changed from p to n at an indium molar fraction of 0.6 with increasing the indium molar fraction because of an amphoteric nature of carbon in InGaAs. Carbon acts as an acceptor in GaAs but as a donor in InAs.

However, we achieved a large hole concentration even at an indium molar fraction of 0.53 by MOMBE using TMG, solid indium and arsenic, and the conductivity-type changes at a larger indium content in contrast with the MBE growth as shown in Fig. 3. In the MOMBE growth of InGaAs monomethylgallium is believed to effectively contribute to carbon incorporation at the arsenic sites as an acceptor.

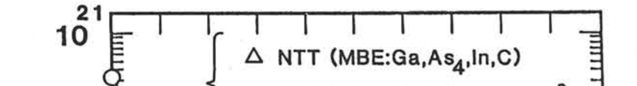

Fig. 3 Carrier concentration of heavily carbon-doped InGaAs as a function of an indium molar fraction. The carrier concentrations for MBE-grown InGaAs[10] are also shown.

The valence-band offset at the interface of GaAs and $In_{0.1}Ga_{0.9}As$ is ~0.08 eV,[11] and then the emitter/base junction with the carbon-doped $In_{0.1}Ga_{0.9}As$, which has effective bandgap narrowing by 0.08 eV, estimated from carbon-doped GaAs with a hole concentration of $6x10^{19}$ cm^{-3}, may exhibit a valence-band offset of 0.16 eV. With this offset β_{max} can be 39 from equation (1). Therefore, replacement of carbon-doped GaAs with carbon-doped $In_{0.1}Ga_{0.9}As$ will significantly improve transistor characteristics.

5. CONCLUSIONS

A GaAs pseudo-HBT with a heavily carbon-doped base grown by MOMBE, which takes an advantage of the bandgap narrowing in the base, was successfully fabricated and exhibited a dc gain as high as 1.7. The observed offset voltage is attributed to high emitter series resistance and large base current, which implies that the hole injection from the base into the emitter cannot be still ignored. An increase of the valence-band offset by replacing the carbon-doped GaAs base with the carbon-doped $In_{0.1}Ga_{0.9}As$ is expected to significantly increase the gain and improve transistor characteristic.

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