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Small-Sized Collector-Up Ge/GaAs Heterojunction Bipolar Transistors with High Gain, Low Base Resistance, and High f_{max}

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Small-sized collector-up Ge/GaAs HBTs have been successfully fabricated and they operated at high collector current density for the first time. A current gain of these devices took a peak value of as large as 200 at a current density of 6×10^4 Acm^{-2}, and no degradation in the current gain was observed with decreasing a collector width down to 2 μm. The capability of lower voltage operation was also shown. Intrinsic and extrinsic base resistance were as low as 180 Ω/□ and 90 Ω/□, respectively. The calibrated values of f_T and f_{max} were 25 GHz and 60 GHz, respectively. Larger value of f_{max} compared with f_T might be attributed to low base resistance and low base-collector capacitance expected from the collector-up structure.

1. Introduction

The combination of Ge and GaAs is ideally suited for high-speed and low-power *n-p-n* heterojunction bipolar transistors (HBTs),[1-6] because of lower operating voltage, lower contact resistance, and lower base resistance due to narrower bandgap and higher hole mobility of Ge than other conventional material systems. Moreover, collector-up *n*-Ge/*p*-Ge/*n*-GaAs HBTs have structural advantages over emitter-up structures for lower base-collector capacitance.[7] From the viewpoint of epitaxial growth, Ge-on-GaAs (nonpolar-on-polar epitaxy) structures are also desirable to realize anti-phase-domain-free epitaxial growth.

We have previously reported the fabrication of Ge/GaAs HBTs with a collector-up structure using molecular beam epitaxy (MBE) for the first time and they exhibited a current gain of 45.[3] In this paper, we report the fabrication of small-sized collector-up Ge/GaAs HBTs with a collector width of 2 μm, the minimum size in the present fabrication, and the static and RF performance of these HBTs operating at high collector current density for the first time.

2. Device Structure and Fabrication

The HBT layer structures are shown in Table I. The HBT structures used for this study were grown using an MBE system[8] with two growth chambers. Initially, a Si-doped GaAs sub-emitter layer ($n = 1 \times 10^{19}$ cm^{-3}, 1 μm), a Si-doped GaAs emitter layer ($n = 7 \times 10^{16}$ cm^{-3}, 2500 Å) were grown on n^+-GaAs (100) substrates in the GaAs growth chamber. The substrates were then transferred into the Ge growth chamber with a low arsenic back pressure, which avoids arsenic contamination into the Ge film during the Ge growth process. Subsequently, a nondope Ge base layer (1000 Å) was grown. The base layer was automatically doped to *p*-type with the sheet carrier density of 2×10^{14} cm^{-2} by the selective diffusion of Ga atoms from GaAs surface with controlling GaAs surface superstructures. The Ga density in the base layer gradually decreased from Ge/GaAs interface to base-collector junction, and the drift-base structure was formed. Finally, an arsenic-doped Ge collector layer ($n = 2 \times 10^{17}$ cm^{-3}, 4000 Å), and an arsenic-doped Ge sub-collector layer ($n = 5 \times 10^{19}$ cm^{-3}, 2000 Å) were sequentially grown. Arsenic doping for Ge was achieved by newly developed doping method using GeAs

TABLE I Device Epitaxial Structure

Layer	Material	Thickness	Doping
Sub-collector	n^+-Ge	2000 Å	5×10^{19} cm^{-3}
Collector	n-Ge	4000 Å	2×10^{17} cm^{-3}
Base	*p-Ge	1000 Å	**2×10^{14} cm^{-2}
Emitter	n-GaAs	2500 Å	7×10^{16} cm^{-3}
Sub-emitter	n^+-GaAs	1 μm	1×10^{19} cm^{-3}
Substrate	n^+-GaAs	---	2×10^{18} cm^{-3}

* doping by Ga-diffusion into Ge from GaAs surface

** sheet carrier density

sources.[9)]

A schematic cross section of the HBT structure is shown in Fig. 1. Ti/Pt/Au was used for collector contact. The collector layer region was formed by reactive ion etching with CF_4 using the collector contact metal as a mask. Boron ions were implanted twice using the same metal mask as is used in the formation of the collector region. Boron ions were first implanted into GaAs layer through Ge external base region at 130 keV at a dose of 3×10^{13} cm^{-2}; this limits the active area of the emitter junction. Next to make the external base region heavily *p*-type, boron ions were implanted into the external base region at 70 keV at a dose of 2×10^{14} cm^{-2}. Alloyed AuGe/Ni/Au was used for emitter contact and non-alloyed Ti/Pt/Au was used for base contact.

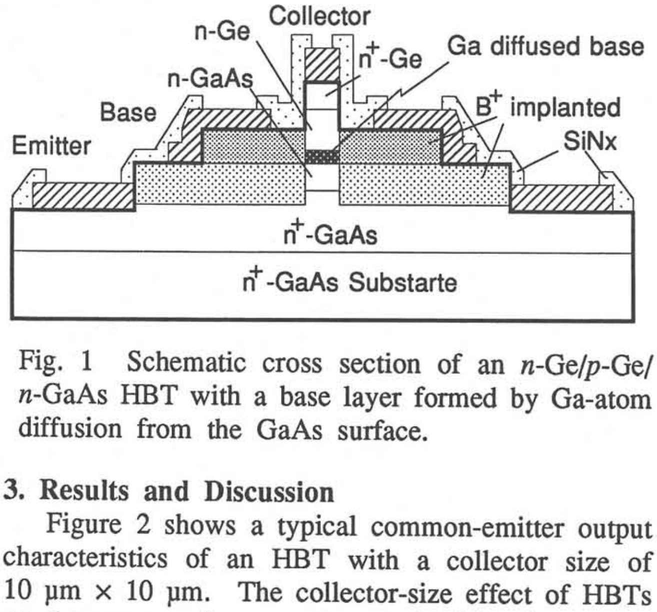

Fig. 1 Schematic cross section of an *n*-Ge/*p*-Ge/*n*-GaAs HBT with a base layer formed by Ga-atom diffusion from the GaAs surface.

3. Results and Discussion

Figure 2 shows a typical common-emitter output characteristics of an HBT with a collector size of 10 µm × 10 µm. The collector-size effect of HBTs on the same wafer was characterized by the current gain at $J_C = 5 \times 10^4$ Acm^{-2}, which is shown in Fig.3. Collector length was kept to be 5 µm in this characterization with the collector width varied. A typical current gain was 200 for these devices. No degradation in the current gain was observed with decreasing a collector width down to 2 µm, the minimum size in the present fabrication. This implies little surface recombination occurred at base edge. The excellent high gain of the device is attributed to a large valence band offset,[10)] which blocks hole injection into the emitter.

Figure 4 shows the dependence of the current gain h_{FE} and the current gain efficiency h_{fe} on the collector current density for a device of nominal dimension 2 µm × 5 µm. A current gain of the HBTs took a peak value of as large as 200 at a current density of 6×10^4 Acm^{-2}, and the dependence of gain on the collector current was fairly flat. This weak dependence of the current

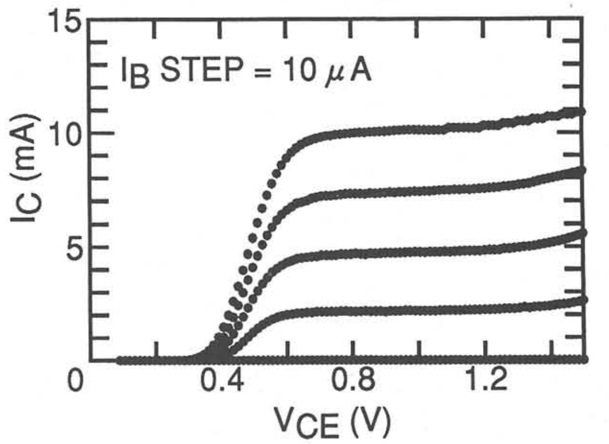

Fig. 2 Common-emitter characteristics of Ge/GaAs HBTs having an emitter area of 10 µm × 10 µm. The current gain of more than 200 was obtained.

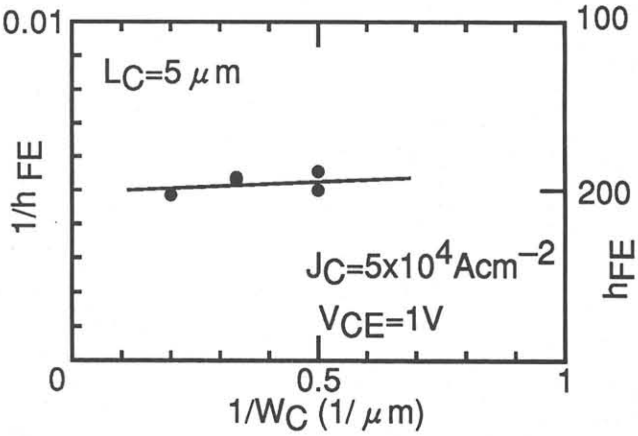

Fig. 3 $1/h_{FE}$ versus collector width for Ge/GaAs HBTs. No significant decrease of current gain occurred as their collector width decreased.

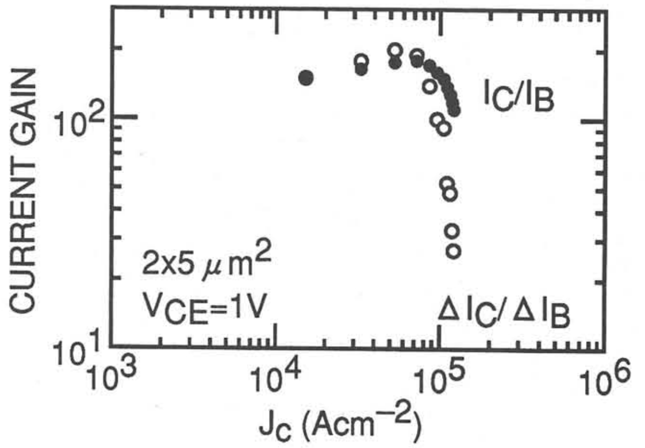

Fig. 4 Current gain versus collector current density for Ge/GaAs HBTs. A peak value of current gain was taken at a current density of 6×10^4 Acm^{-2}.

gain on the collector current is indicative of low surface recombination velocity of the Ge base. No time-dependent degradation in the static characteristics was observed even when operating at a current density over 1 × 10^5 Acm^{-2}. In the Gummel plot, the collector current was expressed as $I_1 exp(qV_{EB}/nkT)$ with an ideal factor n nearly equal to unity. The constant I_1 was 1 × 10^{-12} Acm^{-2}, which was about 7 times as large as that of AlGaAs/GaAs HBTs. This implies the capability of lower voltage operation in the circuit application. Intrinsic and extrinsic base resistances were as low as 180 Ω/□ and 90 Ω/□, respectively, due to a large Gummel number of 2 × 10^{14} cm^{-2} and to high hole mobility in Ge.

RF-characteristics of the HBT with a collector width of 2 μm were measured. The HBT structure was grown on n^+ substrate, which led to a large pad parasitic. In this case, the S-parameters of the device were determined by the following procedures; the F-parameters of pads were calculated from the measured S-parameters of through-pad-patterns and the F-parameters of the real device were determined by subtracting the F-parameters of the pads from the F-parameters transformed from the measured S-parameters of devices. In this way, a cutoff frequency, f_T, and a maximum oscillation frequency, f_{max}, were evaluated without the parasitic effects associated with the pad structure. The calibrated values of f_T and f_{max} were 25 GHz and 60 GHz, respectively, as shown in Fig. 5. Larger value of f_{max} compared with f_T might be attributed to low base resistance and low base-collector capacitance expected from the collector-up structure. The width of the extrinsic base region is 12 μm for a device with a collector width of 2 μm. An extrinsic emitter-base capacitance was supposed to be large, which suppressed the value of f_T. The RF performance is expected to be improved considerably, when the self-aligned structure is adopted.

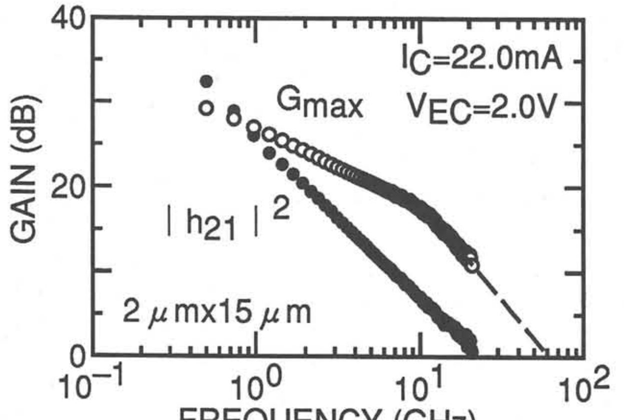

Fig. 5 AC performance measured in the common-emitter configuration.

4. Summary

We have demonstrated small-sized collector-up Ge/GaAs HBTs with operating at high collector current density for the first time. A high current gain of 200 was achieved for these devices at a current density of 6 × 10^4 Acm^{-2}, and no degradation in the current gain was observed with decreasing a collector width down to 2 μm. Intrinsic and extrinsic base resistance were as low as 180 Ω/□ and 90 Ω/□, respectively. The calibrated values of f_T and f_{max} were 25 GHz and 60 GHz, respectively.

These results for the small-sized collector-up Ge/GaAs HBTs suggest that they have promising potential for high-speed and low-power digital circuit and high-frequency device applications. The RF performance is expected to be improved considerably, with further reduction of the device size through self-alignment, and optimization of the layer structures.

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