Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 383-385

Orientation Effect on AlGaAs/GaAs Heterojunction Bipolar Transistors

Hidetoshi ISHIDA and Daisuke UEDA

Electronics Research Laboratory, Matsushita Electronics Corporation.
1-1 Saiwai-cho Takatsuki-shi, Osaka 569, Japan.

Orientation effect on AlGaAs/GaAs heterojunction bipolar transistors have been demonstrated. We have observed that the current gains and the collector-emitter saturation voltage (Vcesat) of HBTs fabricated on the same wafer are strongly dependent on the emitter direction. The HBTs with emitter direction of [010] show the highest current gain and the smallest emitter-size-effect. These orientation effects could be attributed to the piezoelectric effect. The numerical simulation by using PISCES shows good agreement with the experimental results.

1. Introduction

AlGaAs/GaAs heterojunction bipolar transistors (HBTs) are promising devices for high speed circuits. Although scaling down HBTs is essential to obtain higher f_T and f_{max}, there arises so-called emitter-size-effect that is attributed to the surface recombination at the emitter periphery [1)-4)]. A lot of works have been devoted to characterize the surface recombination process, however, few reports are available on the relationship between emitter orientation and emitter-size-effect. In this work we have examined the HBTs with different emitter directions to obtain the minimum emitter-size-effect. We experimentally found the current gain of fabricated HBTs have strong dependency on the emitter direction on the same epitaxial wafer. The smallest emitter-size-effect is obtainable in the direction of [010]. The device simulation taking piezoelectric effect into consideration showed good agreement with the experimental results.

2. Device Fabrication Process

The epitaxial structure of the HBTs used in this work is shown in Table.1. These layers were grown by MOCVD

Table 1 Epitaxial Structure of HBTs

layer	material	doping (cm^{-3})	thickness (nm)
Cap	InGaAs	$2x10^{19}$	50
Cap	InGaAs	$2x10^{19}$	50
Cap	GaAs	$5x10^{18}$	100
Emitter	AlGaAs	$2x10^{18}$	25
Emitter	AlGaAs	$5x10^{17}$	100
Base	GaAs	$2x10^{19}$	100
Collector	GaAs	$3x10^{16}$	600
Subcollector	GaAs	$5x10^{18}$	500
Buffer	GaAs	-	500
Substrate	GaAs	-	-

on semi-insulating (100) GaAs substrates with E.J. flat orientation. The base layer was carbon-doped with the concentration up to $2x10^{19}$ cm^{-3}. There was no grading between emitter-base junction. The fabricated HBTs on the same wafer is schematically shown in Fig.1. Three

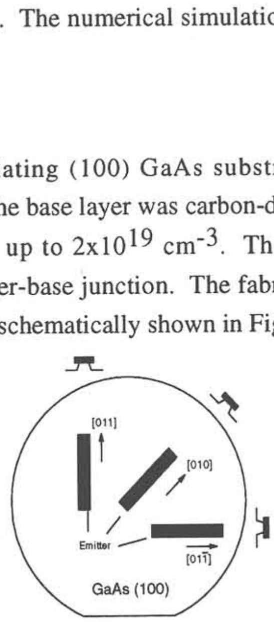
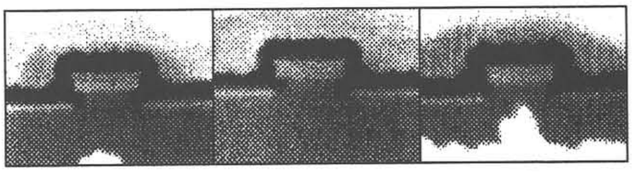


Fig.1 HBTs with different emitter direction

emitter directions of [011], [010] and [01$\bar{1}$] are compared because these orientations are not equivalent on GaAs (100) wafer. WSi metal was used as emitter electrodes to make non-alloyed ohmic contact to InGaAs cap layer. The base region was exposed by using H_3PO_4 :H_2O_2 :H_2O solution (4:1:45 by volume). It is noted that the etchant gives the same mesa profile at emitter periphery regardless of the crystal orientation as shown in Fig.2



[011] [010] [01$\bar{1}$]

Fig.2 Cross section of HBTs

because it has diffusion-limited etching characteristics. Pt/Ti/Pt/Au was used to make base electrodes in self-aligned manner [5)]. AuGeNi/Au metal was used as collector electrodes after collector exposing process. Gold-plating was made after SiN deposition. Finally SiN passivation layer was deposited.

3. Results and Discussion

Fabricated HBTs were measured in the small segment of the same wafer to avoid the non-uniformity of the epitaxial growth. All the devices were compared within the distance of 3 mm in those segments. The current gain is shown in Fig.3 as a function of a collector current of HBTs for three different orientations. You can see the HBTs oriented along [010] direction show the highest current gain, while those of $[01\bar{1}]$ show the poorest one. Emitter-size-effect was examined for

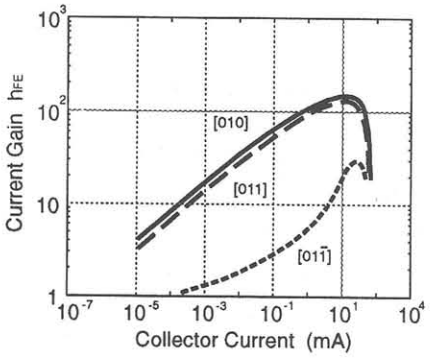


Fig.3 Current gain as a function of a collecor current

those HBTs with different orientations. The base current density is described as follows :

jbase=jc/hFE=(jb+js+jp)+Ks(L/S)

where jb, js, and jp are the base recombination current density in the intrinsic base layer, the base-emitter space-charge recombination current density and the base-to-emitter back-injected current density, respectively. Ks denotes the surface recombination current density. L and S are emitter peripheral length and emitter area, respectively. Figure 4 shows base current density as a function of L/S of the fabricated HBTs. You can see the base current density of HBTs oriented along [010] and [011] directions are not dependent on L/S, while that of HBTs along $[01\bar{1}]$ direction increases drastically as the emitter width is reduced. This means the base recombination process is affected by the emitter orientation of AlGaAs/GaAs HBTs.

We measured the ideality factors of emitter-base junction from the Gummel-plots to estimate which base current was dominant in the $[01\bar{1}]$ HBTs. This results are shown in Fig.5. The ideality factors of the [010] and [011] devices show almost the same value of 1.7-1.8 in the measured L/S range, while that of the $[01\bar{1}]$ devices goes down to unity. Although only the ideality factors of Ks and jb are unity, jb does not depend on emitter direction. Therefore, this experimental results mean the surface recombination current Ks drastically increases at the extrinsic base region for the HBTs oriented along $[01\bar{1}]$ direction [6].

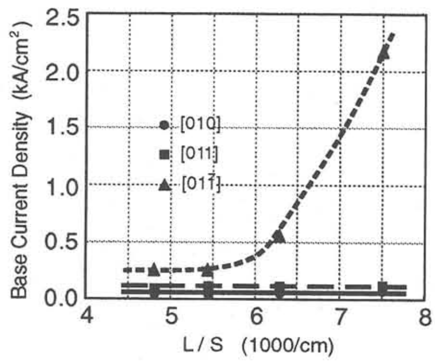


Fig.4 Base current density as a function of L/S

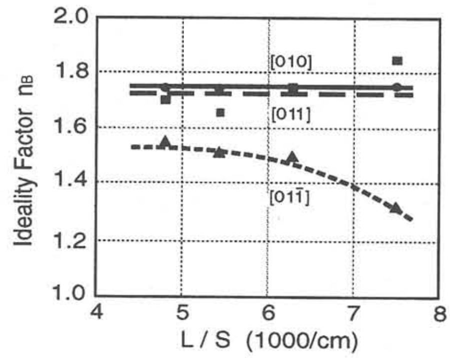


Fig.5 Ideality factor as afunction of L/S

We compared the collector-emitter saturation voltages (V_{cesat}) of those HBTs on the same wafer. The experimentally obtained V_{cesat} of the HBTs along $[01\bar{1}]$, [011] and [010] are 298 mV, 280 mV and 273 mV, respectively. The V_{cesat} here we use is the emitter-collector voltage under the condition of zero collector current. Although we take larger base current of the $[01\bar{1}]$ HBTs into consideration, there still have a meaningful difference of V_{cesat} between the [010] and the [011] HBTs. It is noted that the V_{cesat} is approximately described as follows :

$$V_{cesat}=Vbi-\Delta Ec/e$$

where the eVbi is a built-in-potential and ΔEc is a discontinuous energy between the emitter and the base . Since the ΔEc is constant, the Vcesat directly represents Vbi. The results is similar to the case of GaAs MESFET. It is known that the MESFETs with the gate direction of $[01\bar{1}]$ and [011] have more charges under the gate due to the piezoelectric effect caused by the stress, while that of [010] is free from such a effect [7)-9)] . The difference of V_{cesat} of different emitter direction could be attributed to the superposed piezoelectric charges induced by the stress. Positive charges are induced in the emitter region in the case of the [01$\bar{1}$] HBTs, while negative charges can be induced in the [011] HBTs by the same compressive stress. Even in the case of small stress in the order of 10^8 dyn/cm^2, the piezoelectric charge under the condition reaches the order of 10^{17} cm^{-3} [8), 10)]. The quantity of superposed charges is large enough to change the Vbi because the emitter region has a comparable carrier concentration of 5×10^{17} cm^{-3}. A little large V_{cesat} obtained from the [01$\bar{1}$] HBTs is attributed to the induced piezoelectric charges that reduce the original emitter doping.

Although the stress origin has not clarified at present, the piezoelectric effect at the emitter periphery could explain the previous results. Figure 6 shows the piezoelectric charge distribution when the compressive stress in the order of 10^8 dyn/cm^2 was assumed at the corner of the emitter mesa in the [011] HBTs [8)]. When the direction of the stress is opposite or the emitter direction is perpendicular to [011], the piezoelectric charge have the same density with opposite sign. The electric field caused by the piezoelectric charge could affect on the minority carriers injected from the emitter. The characteristics of HBTs with different emitter direction were simulated by using PISCES taking piezoelectric effect into consideration. Figure 7 shows the current gain as a function of a collector current with and without piezoelectric charge. The HBTs without piezoelectric charge have higher current gain than the HBTs with piezoelectric charge. Figure 8 shows the contour plot of the recombination current at emitter periphery in the [010] HBTs. The recombination current of the [010] HBTs is less than that of the HBTs with piezoelectric charge. These results show good agreement with the experimental results.

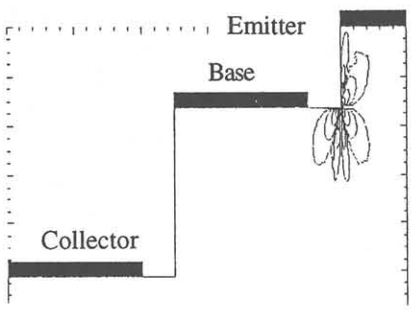


Fig.6 Piezoelectric charge distribution

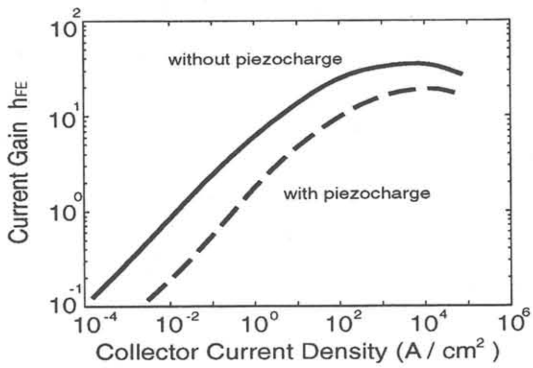


Fig.7 Simulated current gain

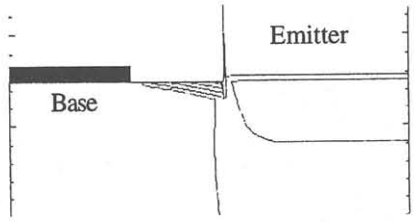


Fig.8 Simulated recombination current contour plot

4. Conclusion

We have examined the emitter orientation effect in view of emitter-size effect of the self-aligned AlGaAs/GaAs HBTs. Fabricated HBTs with the emitter orientation of [010] have the highest current gain and the smallest emitter-size-effect. Measured V_{cesat} of those HBTs suggests the superposed piezoelectric charges in the emitter region where the sign can be changed by the stress or by the emitter orientation. The device simulation taking piezoelectric effect into consideration showed good agreement with the experimental results.

Acknowledgment

The authors would like to thank Drs. G.Kano and K.Itoh for their encouragement, T.Tanaka, K.Miyatsuji and T.Ueda for fruitful discussion.

Reference

1) W.S.Lee et. al., IEEE EDL **10** (1989) 200.
2) W.Liu et. al., Appl.Phys.Lett. **59** (1991) 691.
3) R.J.Maric et. al., Electron Lett. **25** (1989) 1175.
4) N.Hayama et. al. IEEE EDL **11** (1990) 388.
5) T.Sugiyama et. al., SSDM (1993) 1062.
6) W.Liu et. al., IEEE ED **39** (1992) 2726.
7) C.P.Lee et. al., Appl. Phys. Lett. **37** (1980) 311.
8) P.M.Asbeck et. al., IEEE ED **31** (1984) 1377.
9) J.C.Ramirenz et. al., IEEE ED **35** (1988) 1232.
10) S.Adachi, J.Appl.Phys., **58** (1985) R1