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Base Current Control in Low V_{BE} Operated SiGeC Heterojunction Bipolar Transistors Using SiGe-cap Structure and High Carbon Content Base

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1. Introduction

SiGeC heterojunction bipolar transistors (HBT) have been attracted as low power high frequency devices. According to the already reported SiGeC HBTs, Ge and C contents are usually used less than about 20% and 0.4%, respectively [1-2]. To use the further higher Ge content in the base layer enables to obtain higher collector current (I_C) due to the effect of band gap narrowing. Therefore, we can expect to realize high performance at lower V_{BE} by using higher Ge content. Additionally, increasing the C content as well as the Ge content expands the freedom of device design since narrow-band-gap crystal can be obtained with suppressing the increase of lattice strain [3]. However, in order to achieve practical use of such high I_C HBTs, base current (I_B) control is very important for optimizing device parameters such as h_{FE} and BV_{CEO}.

In this study, we demonstrated a low V_{BE} operation of SiGeC HBTs by introducing a novel device design concept using the SiGe cap structure and high Ge (up to 25%) and C (up to 0.8%) content base. We successfully controlled I_B by designing the SiGe cap structure and C content, which enables to obtain the proper values of h_{FE} and BV_{CEO} with maintaining high I_C and without sacrificing f_T.

2. Device Design Concept

Fig.1 shows schematic profiles of the base layer in the fabricated HBTs having the SiGe cap structure. Lightly B-doped SiGe cap layer is grown on the heavily B-doped SiGeC graded base layers. Emitter-base (E-B) junction is located in the SiGe cap layer by controlling the emitter drive in condition. By using such device structure, low V_{BE} operation can be realized because of low E-B built in potential in the narrow-band-gap SiGe cap layer. In order to keep high frequency performance using the SiGe cap structure, high Ge content graded base layer is adopted.

3. Results and Discussion

Fig.2 shows the comparison of gummel plots of HBTs with and without SiGe cap (15%, 20nm) structure. Increase of I_C by using the SiGe cap structure is clearly seen. The same I_C can be obtained at about 0.06V lower V_{BE} compared with the sample without SiGe cap. This proves the advantage of our device concept using the SiGe cap.

Fig.3 shows the h_{FE} and BV_{CEO} as a function of the C content in the base layer. For the samples with SiGe cap, results showed extremely high h_{FE} and low BV_{CEO} at C content=0.2% due to the increase of I_C. However, h_{FE} decreased and BV_{CEO} increased drastically with increasing the C content, while very small changes were seen in the samples without SiGe cap.

Fig.4 shows the I_B (at V_{BE}=0.8V) of the samples having different SiGe cap structures as a function of C content. I_B increases with increasing the C content, also with increasing the Ge content and thickness of the SiGe cap layers. These results indicate that I_B can be controlled by designing the SiGe cap structure and C content. By controlling I_B using this technique, we can tune h_{FE} and BV_{CEO}, as shown in Fig.3, to practically usable values with maintaining high I_C.

Fig.5 shows the f_T-I_C characteristic of the HBT having SiGe cap (8%, 20nm) and 0.5%-C content base. The f_{Tmax} was 84GHz with BV_{CEO}=2.52V. This shows that high frequency performance can be realized in low V_{BE}-operated HBTs with keeping BV_{CEO} at proper values.

We speculated that the dependency of I_B on the SiGe cap structure and C content is related to the enhancement of recombination around the E-B junction. To make sure this predict, we have evaluated the recombination around the E-B junction by the I_B-V_{CB} output characteristics (forced V_{BE}) of the inverted HBTs. Fig.6 shows the measured I_B-V_{CB} characteristics, where the vertical axis indicates the decrease of I_B from the value at V_{CB}=0V. The decreasing rate versus V_{CB} depended on both C content (a) and SiGe cap structure (b). The decrease of I_B observed here can be interpreted due to a reduction of recombination component around the E-B junction caused by changing the depletion layer width with V_{CB} [4]. We estimated the recombination by the inclination of the I_B-V_{CB} characteristic (dI_B/dV_{CB}) at V_{CB}=0-0.3V. Fig.7 shows the dI_B/dV_{CB} as a function of the C content. The dI_B/dV_{CB} increased with increasing the C content, and also increased with increasing the Ge content and thickness of the SiGe cap layer, which well agrees with the dependency of I_B on the C content. Since such a dependency was not clearly seen in the measurements of normal (not inverted) HBTs, we believe that the increase of I_B by introducing the SiGe cap and high C content is caused by the enhancement of recombination around the E-B junction.

We discuss on the origin of the increase of recombination by using SiGe cap and high content C base. By introducing the SiGe cap layer, the valence band offset is formed at the Si cap/SiGe cap interface. From this effect, holes are accumulated in the SiGe cap layer, which enhance the recombination of injected electrons as explained by a simulation result shown in Fig.8. We speculate that the enhancement of recombination by increasing C content is related to the crystalline quality in SiGeC layers. Although we confirmed that almost all C atoms are located at substitutional sites, very small amount of non-substitutional C atoms or vacancies would exist in the high C content SiGeC layers. We believe that they strongly influence the electric properties of HBTs.

4. Conclusions

We successfully demonstrated a low V_{BE} operation of SiGeC HBTs by introducing a novel device concept using the SiGe cap structure and high Ge and C content base. We clarified that I_B can be controlled by designing the SiGe cap and C content, which enables us to optimize the h_{FE} and BV_{CEO} to proper values with maintaining high I_C. By using these techniques, f_{Tmax}=84GHz was achieved at BV_{CEO}=2.52V, with realizing 0.06V-lower V_{BE} operation compared with conventional HBTs without SiGe cap.

References

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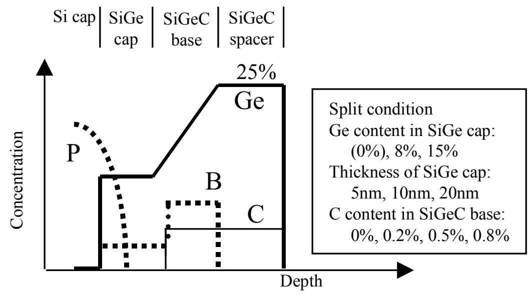

Fig.1 Schematic depth profiles of Ge, C, B and P in the fabricated HBT with SiGe cap structure.

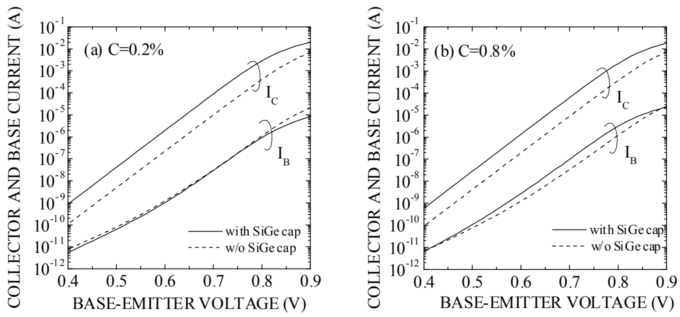

Fig.2 Gummel plots of HBTs with and without SiGe cap (15%, 20nm) in cases that the C content in the base layer is 0.2% (a) and 0.8% (b).

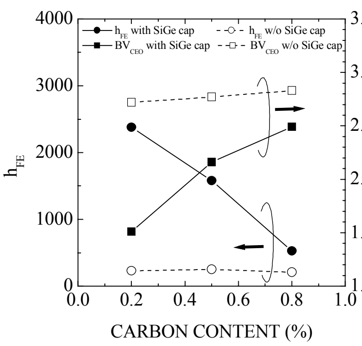

Fig.3 h_{FE} and BV_{CEO} of HBTs with and without SiGe cap (15%, 20nm) as a function of the C content in the base layer.

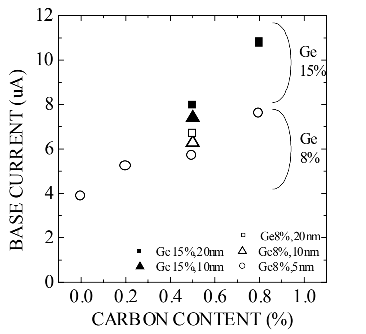

Fig.4 I_B at V_{BE}=0.8V as a function of the C content. Ge content and thickness of the SiGe cap layer are indicated in the figure.

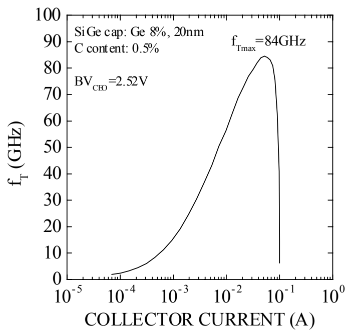

Fig.5 f_T versus I_C curve of the HBT with SiGe cap structure (8%, 20nm). The C content in the base layer was 0.5%.

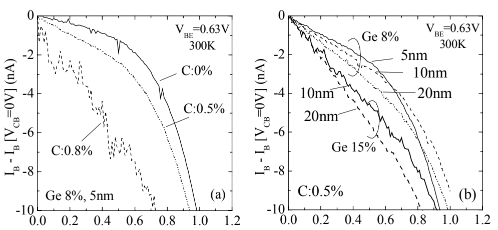

Fig.6 I_B versus V_{CB} output characteristic (forced V_{BE}) in the inverted HBTs compared with C content (a) and SiGe cap structure (b). The vertical indicates the decrease of I_B from the value at V_{CB}=0V. The decrease of I_B in the low V_{CB} region is due to a reduction of recombination component caused by changing depletion layer width with V_{CB}.

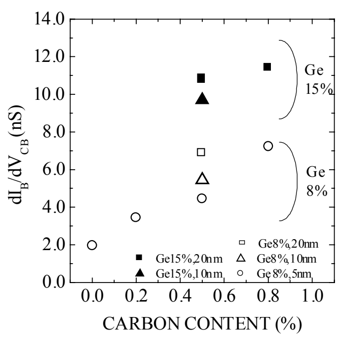

Fig.7 Inclination of the I_B-V_{CB} characteristic (dI_B/dV_{CB}) shown in Fig.6 as a function of the C content. The dI_B/dV_{CB} is strongly influenced by recombination around the E-B junction.

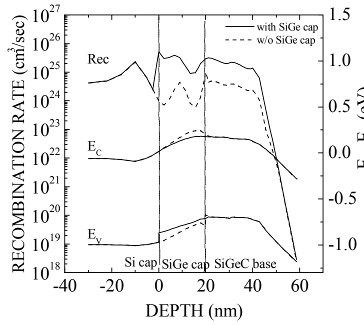

Fig.8 Simulation results of the depth profiles of recombination rate, E_C and E_V in cases of with and without SiGe cap (15%, 20nm). Recombination is enhanced by introducing the SiGe cap, since holes are accumulated in the SiGe cap layer due to formation of valence band offset.