94-GHz $f_T$, 0.4-dB NF$_{\text{min}}$ HBT with Optimized Si-cap and Extrinsic Base using Blanket SiGeC Epitaxy for Consumer Wireless Applications


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1. Introduction
Recent advance in SiGe HBT BiCMOS technology has expanded the potential of silicon LSI to high frequency applications. These applications can be classified into two categories. One category includes tens of giga-bit wireline communication and millimetre wave applications in which very high-speed HBTs are used [1]. The other category is a consumer wireless electronics. In this case, BiCMOS process which can minimize the complexity to achieve short turn-around-time is required rather than extremely high-frequency characteristics [2]. Since these wireless systems operate at frequency of 2-5 GHz, the required $f_T$ of HBT is in a range of 50 to 100 GHz.

We have developed 0.25-µm HBT BiCMOS for consumer wireless electronics. It uses LOCOS isolation and blanket SiGeC epitaxy, thus it has low-complexity [3]. In this paper, we describe the profile design of Si cap in SiGeC epitaxial layer to enhance the high frequency characteristics. The extrinsic base design, which includes link base implantation and cobalt silicidation, is also discussed. There are a lot of papers on the intrinsic profile optimization of HBT, however, we could hardly find simultaneous discussion on the intrinsic profile and the extrinsic base design. The optimized profile resulted in HBT with $f_T$ of 94 GHz, and NF$_{\text{min}}$ of 0.4 dB at 2 GHz and 0.7 dB at 5GHz, respectively.

2. HBT Structure and Profiles
A transmission electron micrograph of the emitter and base region of HBT is shown in Fig. 1. The base region is fabricated by blanket SiGeC epitaxy. The extrinsic base region is implanted with BF$_2$ just after patterning the emitter poly-Si. Then cobalt silicide is formed both on the extrinsic base and poly emitter. Typical Ge and boron profiles in epitaxial layer are illustrated in Fig. 2. The boron concentration in base region was $7 \times 10^{19}$ cm$^{-3}$, and the as-grown base width was 5 nm. Thinner Si cap in the intrinsic region is necessary to make thin base layer which leads to higher $f_T$, however, poly-Si cap in the extrinsic region should be thick enough to avoid Ge and Co reaction, which causes highly resistive compounds [4]. So it is an important issue to optimize the Si cap of blanket SiGeC epitaxy for obtaining high $f_T$, low base resistance, and low noise figure.

3. Si Cap and Extrinsic Base Design

Si Cap Design

The cutoff frequency $f_T$ of HBTs with different Si cap thickness was measured at $V_{\text{CE}}$ of 1V and shown in Fig. 3. Thinner cap led to higher $f_T$ due to thinner base width. The forward transit time, $\tau_F$, was reduced from 2.1 ps to 1.8 ps when we changed the Si cap thickness from 45 to 35 nm. Since these HBTs have an identical collector profiles, this $\tau_F$ reduction is attributed to thinner base, i.e. reduction in the base transit time. The peak values of $f_T$ and $f_{\text{max}}$ are plotted as a function of Si cap thickness in Fig. 4. There is an optimum Si cap thickness of 40 nm for obtaining higher $f_{\text{max}}$. $f_{\text{max}}$ is determined not only by the vertical profile but also by parasitic components in extrinsic base layer. The design of extrinsic base is described in the next section.

Extrinsic Base Design

The extrinsic base design includes BF$_2$ implantation and silicidation together with the Si cap. Figure 6 shows the dependence of an extrinsic base resistance $R_{\text{ext}}$ and a collector capacitance $C_{\text{JC}}$ on the extrinsic base implantation energy. The extrinsic base resistance was extracted by using dual base structure [5]. Higher implantation energy resulted in high $C_{\text{JC}}$ and low $R_{\text{ext}}$ due to deeply diffused boron. We found that HBT with 35-keV implantation energy showed the highest AC characteristics.

$F_T$ and $f_{\text{max}}$ of HBTs with different Co thickness are shown in Fig. 7. $F_T$ is independent of the Co thickness, however, $f_{\text{max}}$ is drastically improved by thicker cobalt layer. The sheet resistance of cobalt silicide layer was decreased from 6 to 3 ohm/sq. when the cobalt thickness was increased from 10 to 15 nm. A 15% reduction in $R_{\text{ext}}$ was also observed. The combination of 40-nm Si cap and 15-nm Co has effectively reduced the sheet resistance without forming high resistive compound of Co and Ge.

The $f_T$ and $f_{\text{max}}$ characteristics for optimized HBT using above mentioned design of the Si cap and the extrinsic base are shown in Fig. 8. 94-GHz $f_T$ and 81-GHz $f_{\text{max}}$ were obtained at $V_{\text{CE}}$ of 2 V. Noise figure was measured at 2 and 5 GHz as shown in Fig. 9. The minimum
noise figures are 0.4 dB at 2 GHz and 0.7 dB at 5 GHz. Higher $f_T$ and lower extrinsic base resistance resulted in $\text{NF}_{\text{min}}$ reduction in half compared with that of control HBT without optimization. These characteristics show capability of the HBT to be used in consumer wireless applications.

5. Conclusions

The characteristics of SiGeC HBTs were described from the viewpoint of the Si cap and the extrinsic base design. In accordance with the profile in the intrinsic region, the extrinsic base process was designed to obtain low resistance without forming highly-resistive compounds of Ge and Co. These design resulted in HBTs with 94-GHz $f_T$, 81-GHz $f_{\text{max}}$, 0.4-dB and 0.7-dB $\text{NF}_{\text{min}}$ at 2 GHz and 5 GHz, respectively.

Acknowledgements

The authors acknowledge H. Miwa, T. Gomi, M. Nakamura and T. Kobayashi for their continuous encouragement. We thank to H. Kawakami for noise measurement. We also express sincere thanks to all of the development project members.

References