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Reduction of Base Resistance and Enhancement of Cutoff Frequency of High-Speed Si Bipolar Transistor Using Rapid Vapor-Phase Doping

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1. Introduction

To achieve high-speed Si bipolar transistors, shallow base regions with high impurity concentrations are needed. Shallow base provides a high cutoff frequency f_T, but also tends to increase the base resistance r_b. Si and SiGe epitaxial bases should enable both high f_T and low r_b [1,2]. However, silicon homo-junction bipolar transistors made with an advanced base formation process has advantages over the epitaxial base such as process simplicity and large-scale integration capability, while also providing high f_T and low r_b. [3].

We have developed Rapid Vapor-phase Doping (RVD) for shallow doping [4]. This technique uses a hydrogen carrier gas and a B_2H_6 doping gas. It is suitable for making shallow high-concentration bases since dopants with almost "zero-energy", i.e., there applied without implantation energy, are supplied to the clean Si. Using RVD, extremely high f_T has been obtained using a metal/in-situ doped poly-Si base electrode, however, it has been difficult to reduce the r_b [5]. In this paper, we describe the application of RVD to a conventional double poly-Si self-aligned transistor in a production line to realize both higher f_T and lower r_b than 3-keV BF_2 base implantation.

2. Device fabrication

The cross-section of the fabricated transistor is shown in Fig. 1. The fabrication processes were described elsewhere [6]. Intrinsic bases were formed by RVD and by BF_2 ion implantation for reference. The base formation processes are shown in Fig. 2. For the reference sample, two-step-annealing [6] that included RTA for activation and wet oxidation to control the boron concentration was applied. For RVD, only the wet oxidation was used, since RVD introduces no defects and the activation is almost complete just after doping. The doping conditions for base are summarized in Table 1. After RVD, post annealing was carried out in a hydrogen atmosphere to enhance the out-diffusion of boron from the Si surface. The boron profiles of RVD with 5-min post annealing and BF_2 implantation with RTA are shown in Fig. 3. A 40-nm junction with high concentration is formed by RVD. This was 20 nm shallower than with the BF_2 implantation. High-concentration boron at the surface was reduced during the wet oxidation by segregation and enhanced diffusion. The base width of the fabricated transistor using RVD is expected to be 40 nm.

3. Device characteristics

A gummel plot of an RVD transistor with a 0.2 μm x 0.7 μm emitter is shown in Fig. 4. The suppressed leaky base current shows the effect of wet oxidation after RVD. The results for the cutoff frequency and base resistance are shown in Figs. 5 and 6, respectively. Compared to when BF_2 implantation was used, the cutoff frequency was increased up to 54 GHz by RVD with 1-min post annealing, although the base resistances were almost identical. By increasing the post annealing time to 5 min, the base resistance was reduced to 400 Ω, although over-50-GHz f_T was maintained. That is, compared to 3-keV BF_2 implantation, a 15% reduction of the base resistance and a 20% increase in the cutoff frequency were realized through RVD. These results are due to the shallow high-concentration base enabled by RVD. The merit of RVD can also be seen in the maximum oscillation frequency f_{max} as in Fig. 7. Here, the emitter length was varied from 0.7 to 8.2 μm. At any emitter length, RVD transistors showed higher f_T and f_{max} than those made by BF_2 ion implantation. As the emitter length increased, f_T gradually decreased but f_{max} rose rapidly. The base resistance r_b and the capacitance between base and collector C_{TC} were also measured and shown in Fig. 8. In RVD transistors, when L_E was increased from 0.7 to 4 μm, r_b was reduced to 20%, although C_{TC} increased. This drastic reduction in the base resistance caused the reduced time constant (r_b x C_{TC}), then, it was probably responsible for the increase in f_{max} as in Fig. 7. Figure 9 shows the schematic configuration of base doping by RVD. During RVD, the link base and the sidewall of the base poly-Si as well as the intrinsic region are simultaneously doped, since RVD is an isotropic process. This doping characteristic leads to low base resistance although the shallow boron profile in the intrinsic region is maintained. On the contrary, when using BF_2 ion implantation, it is difficult to reduce the resistance in the link base region because boron ions are introduced only in the intrinsic region. The transistor parameters are summarized in Table 2. Higher f_T and lower r_b were simultaneously obtained without specific degradation of other parameters.

4. Conclusion

Enhancement of the performance of Si homo-junction bipolar transistors, that is, reduction of the base resistance and increase in the cutoff frequency, was realized through Rapid Vapor-phase Doping. 50-GHz f_T and 400-Ω r_b, which are 20% higher and 15% lower than those for 3-keV BF_2 implantation, were obtained. The isotropic doping characteristic of RVD leads to reduced resistance not only in the intrinsic base region, but also in the link base region.

Acknowledgement

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References

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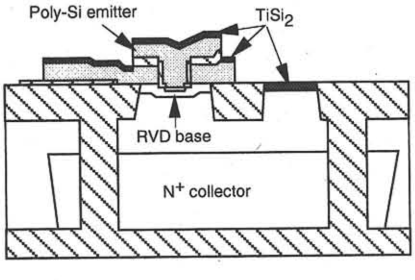

Fig. 1 Transistor cross section.

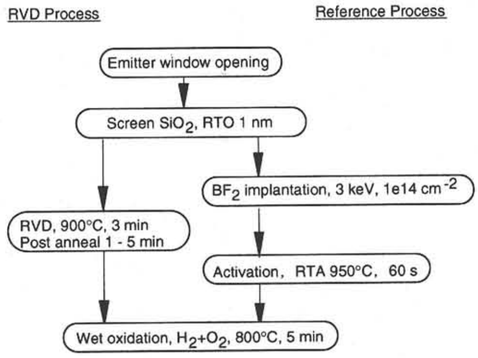

Fig. 2 Base formation processes.

Table 1 Doping conditions for base

Temperature (°C)	900°C
Doping time (min)	3
Post annealing (min)	1-5
B_2H_6 concentration (ppm)	5
H_2 flow rate (l/min)	25
Pressure (Torr)	700

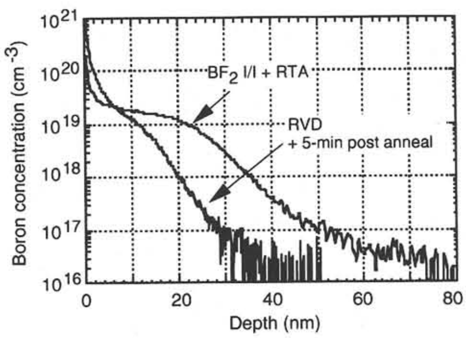

Fig. 3 Boron profiles in base region.

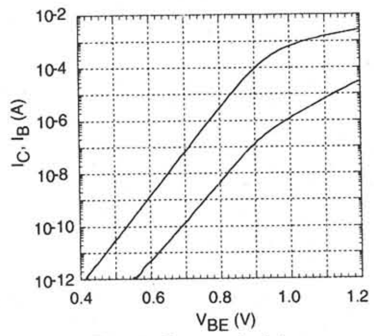

Fig. 4 Gummel plot.
$A_E = 0.2\ \mu m \times 0.7\ \mu m$.

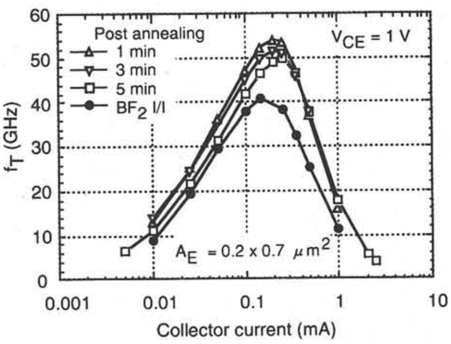

Fig. 5 Cutoff frequency.

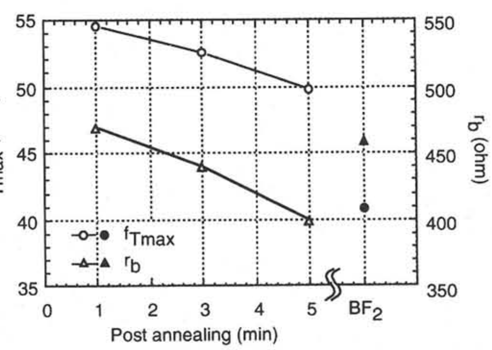

Fig. 6 f_T and r_b.

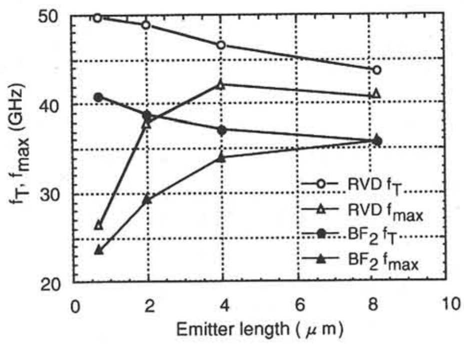

Fig. 7 f_T, f_{max} vs. L_E

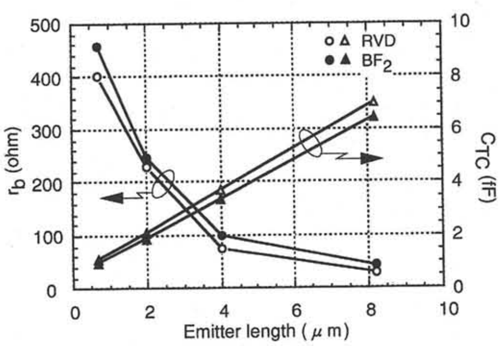

Fig. 8 r_b, C_{TC} vs. L_E

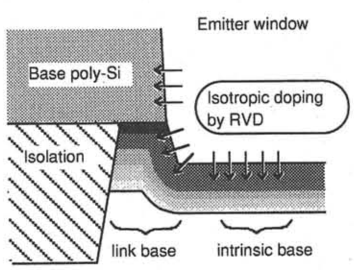

Fig. 9 Isotropic doping by RVD.

Table 2 Bipolar transistor characteristics

Base formation	RVD	BF2 I/I
Emitter area (μm)	0.2×0.7	
hFEmax	870	360
BVCEI (V)	3.1	3.4
BVEBO (V)	6.5	5.2
BVCBO (V)	13.7	13.5
CTC (fF)	1.1	1.0
CTE (fF)	2.1	1.9
RE (Ω)	53	56
RC (Ω)	27	25
fT@VCE=1V (GHz)	50	41
fT@VCE=2.5V (GHz)	58	46
rb (Ω)	400	460