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Enhanced Boron Diffusion in the Base of SiGe HBTs Induced by Implants into Polysilicon Emitters

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The impact of phosphorus implants into polysilicon emitters on the boron diffusion in the underlying single-crystal base region has been investigated. Significantly enhanced boron diffusion, which is believed to be induced by implant-induced excess interstitials diffusing into the single-crystal region through the polysilicon emitter, is observed after annealing. *In situ* phosphorus-doped polysilicon is shown to effectively suppress the enhanced boron diffusion, resulting in a very sharp boron profile.

1. INTRODUCTION

Improved emitter efficiency due to the small band gap in the SiGe base enables the inversion of the doping levels in the emitter and in the base. This HBT concept offers very thin base layers with acceptably low base resistance, leading to excellent high-frequency performance.[1)] In order to take full advantage of the benefits provided by the concept, boron diffusion, which results in the broadening of the base width and hence increased base transit time, during the growth and the subsequent fabrication processes must be minimized. Furthermore, if boron in the SiGe base outdiffuses into silicon, parasitic barriers in the conduction band near the heterojunctions are created and severely degrade the dc and ac performance of HBTs.[2)] Therefore, any processes which cause the enhanced boron diffusion are not tolerated.

Mesa-type HBT implementation often requires the single-crystal silicon emitter to receive n-type implants to reduce contact resistance. The implant-induced point defects, however, have been shown to cause severely enhanced boron diffusion in the underlying layer (i.e., a boron diffusivity enhancement factor of more than 300).[3)] State-of-the-art self-aligned bipolar structures complicate the use of epitaxially grown emitters and favor the use of polysilicon emitters, and implant-induced point defects are believed to be a minor concern for polysilicon emitters. A recent report, in fact, revealed that the enhancement in boron diffusivity in the underlying layer is much smaller than that for aforementioned single-crystal silicon emitters by studying the effect of boron implants into polysilicon emitters for pnp transistor fabrication.[4)]

Here, we study the impact of phosphorus implants into polysilicon emitters for npn transistor fabrication and show that even implants into polysilicon emitters induce marked boron diffusion in the underlying single-crystal base region.

2. EXPERIMENT

The experimental structure is schematically shown in Fig. 1. On an n-type (100) silicon substrate, an undoped $Si_{0.9}Ge_{0.1}$ layer, a $Si_{0.9}Ge_{0.1}$ layer doped with boron to 2×10^{19} cm^{-3}, an undoped $Si_{0.9}Ge_{0.1}$ layer, and a silicon layer doped with phosphorus to 5×10^{17} cm^{-3}, which serves as a low-doped emitter region, were sequentially grown using a single-wafer epitaxial reactor operating at reduced pressure at 650 and 800°C for the $Si_{0.9}Ge_{0.1}$ layers and the silicon layer, respectively. High-resolution x-ray diffraction measurements revealed that the $Si_{0.9}Ge_{0.1}$ layers were fully strained. Then an undoped polysilicon layer was deposited by LPCVD at 620°C, after cleaning with H_2O_2/H_2SO_4 solution followed by dipping in dilute HF.

Phosphorus is known to provide lower resistivity and thus lower emitter resistance than arsenic in the reduced thermal budget.[5)] Therefore, we chose phosphorus as a polysilicon doping impurity in this experiment. Phosphorus was implanted into some of the samples with a dose of 1×10^{16} cm^{-2} at room temperature. After the deposition of an oxide layer at 400°C, samples were subjected to a furnace anneal at 750°C for 30min and RTA at 850°C for 10sec, both in nitrogen ambient. Boron, phosphorus, and germanium depth profiles were obtained by secondary ion mass spectrometry (SIMS).

3. RESULTS AND DISCUSSION

Even if HF dip is used at the final cleaning step, a thin native oxide layer is known to grow prior to and during loading into an LPCVD reactor for polysilicon deposition, resulting in an interfacial layer between the poly- and single-crystal silicon. SIMS measurements revealed that for the samples used in this study, the areal density of oxygen is ~3×10^{15} cm^{-2}. The resistivity of the polysilicon layers with phosphorus implants after annealing was found to be ~1 mΩ-cm, which is low enough for emitter contact layers.

Figure 2 shows boron profiles after annealing for samples with and without phosphorus implant together with the as-grown profile. For the sample without implant, the boron profile remains almost identical to the as-grown profile, which is expected from the normal diffusion behavior. For the sample with a 30keV phosphorus implant, on the other hand, significantly enhanced boron diffusion is observed; as a result, the boron profile is no longer confined inside the $Si_{0.9}Ge_{0.1}$ layer. Figure 3 demonstrates the implant energy dependence of the boron profile after annealing. It is seen that reducing the implant energy to 20 or 10keV has a nominal effect on the diffusion enhancement. The ratio of the time-averaged enhanced boron diffusivity to the normal intrinsic diffusivity in silicon is estimated to be approximately 60 by fitting the profile calculated by a process simulator to the measured profile. It has been reported that boron diffuses more slowly in strained SiGe than in silicon.[6] Our separate experiment has confirmed that this is indeed the case for the SiGe layers grown using our epitaxial reactor, as shown in Fig. 4. In the experiment, a multilayer structure consisting of a strained $Si_{0.85}Ge_{0.15}$ layer and a silicon layer both with a boron-doped marker was subjected to a furnace anneal at 825 or 875°C for 30min in nitrogen ambient. A clear retardation of boron diffusion is seen in the strained $Si_{0.85}Ge_{0.15}$ layer. In the above fitting procedure, therefore, this effect was taken into account by reducing the diffusivity associated with singly charged defects, since in the high-concentration region within the $Si_{0.9}Ge_{0.1}$ layer, this diffusivity plays a major role.

It is known that boron diffusion is mediated mainly by its interaction with silicon interstitials.[7] Therefore, the observed enhancement of boron diffusion is believed to be related to excess interstitials created by some mechanisms during the processes. There are two possible sources of the excess interstitials: (1) the implant-induced interstitials as in the case of single-crystal emitters and (2) creation of interstitials during the diffusion of high-concentration phosphorus from polysilicon into single-crystal silicon.[8] To determine which of these two possibilities is the primary source, 200-nm-thick *in situ* phosphorus-doped polysilicon layers were deposited on some samples so that phosphorus was introduced in the polysilicon layers without any damage, and then the samples were subjected to the same thermal treatments as before, which causes the diffusion of phosphorus from polysilicon into single-crystal silicon. Figure 5 indicates a boron profile in the samples together with the as-grown profile. It is clear that the sample with an *in situ* phosphorus-doped polysilicon layer exhibits no enhanced diffusion, eliminating the possibility (2). Therefore, it can be concluded that implant-induced interstitials play a dominant role in the observed diffusion enhancement. Additionally, an almost no energy dependence of the boron profile shown in Fig. 3 implies that the interstitials generated by phosphorus implants entirely inside the polysilicon layer, rather than in single-crystal silicon due to the tailing of the defect distribution, are responsible for the diffusion enhancement.

In the polysilicon layer, grain boundaries are likely to act as effective sinks for interstitials. Furthermore, interstitials reaching the interface between poly- and single-crystal silicon are possibly blocked by the interfacial oxide layer. An estimated boron diffusivity enhancement factor of ~60, however, demonstrates that a substantial number of interstitials are still able to diffuse into the single-crystal region. Our experimental results are in qualitative agreement with those in Ref. 4, although the enhancement factor estimated in the present study is much greater than that in Ref. 4 (i.e., an enhancement factor of ~2). The discrepancy in the enhancement factors is speculated to arise from the differences in annealing and implant conditions between two studies. Another observation supporting our interpretation for the mechanism of the enhanced diffusion is that oxidation-enhanced diffusion of boron in a silicon substrate is operative even if a polysilicon layer formed on top of the substrate is oxidized, although the characteristic decay length, which is related to the annihilation rate of excess interstitials, in the polysilicon layer is much shorter than that in single-crystal silicon.[9] This observation shows that some of the interstitials generated by oxidation are indeed able to diffuse into single-crystal silicon through the polysilicon layer.

Figure 6 shows SIMS profiles of boron and phosphorus concentration together with germanium secondary ion intensity for a complete HBT structure with an *in situ* doped polysilicon layer after annealing. A very thin base layer with a polysilicon emitter doped with phosphorus at $\sim 2 \times 10^{20}$ cm^{-3} is realized. This profile promises excellent performance of the HBTs fabricated using *in situ* doped polysilicon layers combined with state-of-the-art self-aligned structures.

4. CONCLUSIONS

It has been shown that even phosphorus implants into polysilicon emitters induce a boron diffusivity enhancement factor of ~60 in the underlying single-crystal base region of SiGe HBTs after a furnace anneal at 750°C for 30min followed by RTA at 850°C for 10sec. Implant-induced excess interstitials are believed to play a dominant role in the observed diffusion enhancement. Our study has demonstrated that *in situ* phosphorus-doped polysilicon is effective to suppress the enhanced diffusion and to realize a very abrupt boron profile.

Acknowledgments

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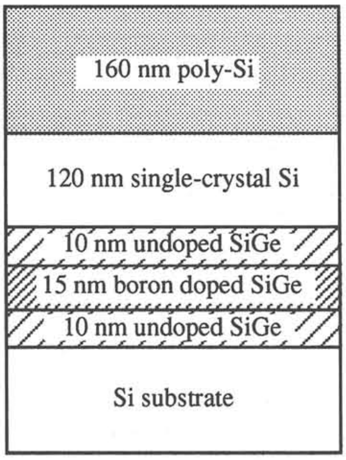

Fig. 1 Schematic cross section of the experimental structure.

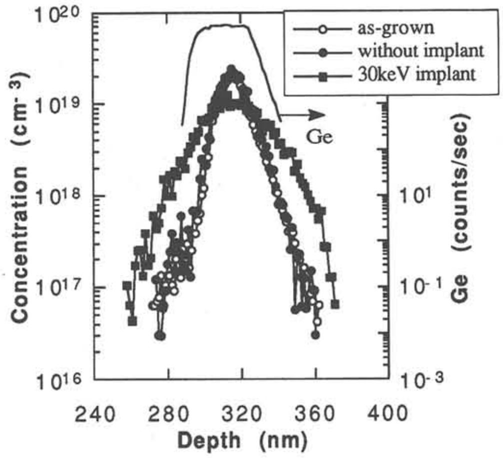

Fig. 2 SIMS profiles of boron concentration and Ge secondary ion intensity for an as-grown sample as well as samples with and without implant after annealing at 750℃ for 30min + at 850℃ for 10sec.

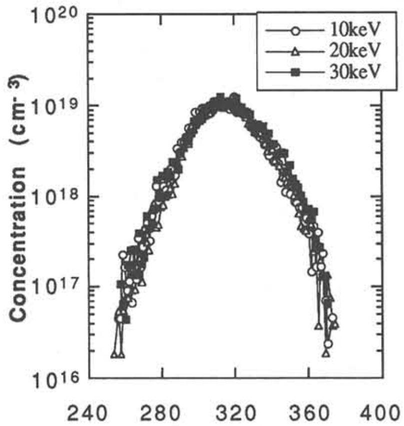

Fig. 3 SIMS profiles of boron concentration for samples with 10, 20, or 30keV implant after annealing at 750℃ for 30min + at 850℃ for 10sec.

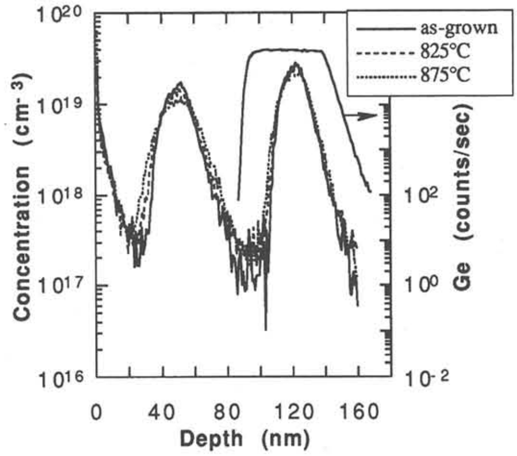

Fig. 4 SIMS profiles of boron concentration and Ge secondary ion intensity for an as-grown sample as well as samples annealed at 825 or 875℃ for 30min.

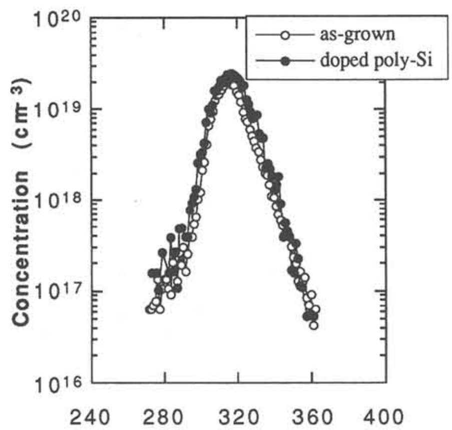

Fig. 5 SIMS profiles of boron concentration for an as-grown sample and a sample with an *in situ* doped poly-Si layer after annealing at 750℃ for 30min + at 850℃ for 10sec.

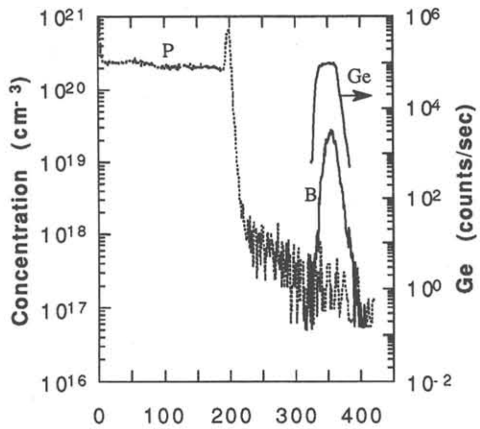

Fig. 6 SIMS profiles of boron as well as phosphorus concentration and Ge secondary ion intensity for a sample with an *in situ* doped poly-Si layer after annealing at 750℃ for 30min + at 850℃ for 10sec.