

Controlling transient enhanced diffusion effects in high-frequency Si_{0.7}Ge_{0.3} heterojunction bipolar transistors with implanted emitters

L. K. Nanver,^{a)} C. C. G. Visser, and A. van den Bogaard

DIMES, Laboratory of Electrical Components, Technology and Materials, Delft University of Technology, 2600 GB Delft, The Netherlands

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A method is presented by which the implantation damage induced transient enhanced diffusion of boron and phosphorus is used to advantage to fabricate high-frequency Si_{0.7}Ge_{0.3} heterojunction bipolar transistors with implanted phosphorus emitters. A device with 300 Å basewidth, 7 kΩ/□ intrinsic base sheet resistance, and $f_T=44$ GHz is demonstrated. The very low diffusivity of both boron and phosphorus in high Ge concentration SiGe during 700 °C thermal annealing results in a self-alignment of the emitter–base junction to the Si/SiGe interface, giving high current gain with good reproducibility. Methods of counteracting the boron outdiffusion in the Si collector are considered. Rather than reducing this outdiffusion, results indicate that it can be better compensated for by introducing a narrow phosphorus doped peak, epitaxially grown on the collector side of the SiGe. The n doping of this peak, as is also the case for that of the emitter, barely penetrates the SiGe and the p -doped base is well preserved. © 1998 American Vacuum Society. [S0734-211X(98)05303-7]

I. INTRODUCTION

For the future of SiGe heterojunction bipolar processes in the area of portable telecommunication, the cost and particularly the manufacturability of these processes have become critical questions. In the process discussed here it has been possible to combine high-frequency performance and good reproducibility in a low cost process flow by using implanted phosphorus emitters.¹ The damage created by such emitter implantations has previously been shown to result in a severe outdiffusion of the boron base doping.^{2,3} This not only broadens the basewidth, but may also create undesirable potential barriers which seriously degrade the frequency performance.^{3,4} Previous studies generally involved germanium percentages up to 20% and rapid thermal annealing to activate an arsenic implanted emitter. The implantation is used to contact an epitaxially grown n region with which the actual emitter–base junction is formed.

In the present structure the emitter–base junction is formed between the epitaxially grown SiGe base and the implanted phosphorus. The emitter can therefore be defined in p -type epi by resist or oxide masking instead of by mesa etching. Attractive emitter–base (e–b) doping profiles are formed due to the implantation damage induced transient enhanced diffusion (TED) of both the phosphorus implanted emitter and the epitaxially grown boron base. Essential in this process is the use of SiGe with high Ge concentration (30%) in combination with 700 °C thermal processing to activate the implanted dopants. At this temperature, a very high level of implantation damage induced TED is witnessed for both boron and phosphorus in the Si, but in the Si_{0.7}Ge_{0.3} layer the diffusion is suppressed. This effect results in a partial restriction of the boron to the SiGe region, while at the same time impeding the penetration of the phosphorus into

the SiGe. The e–b junction is thus to a large degree automatically aligned to the Si/SiGe interface and good reproducibility is achieved.

On the collector side, the boron outdiffusion limits the doping of the base. A 44 GHz heterojunction bipolar transistor (HBT) with an intrinsic base sheet resistance of 7 kΩ/□ was fabricated by using a pedestal collector. A lower intrinsic base resistance would require even higher collector doping. Here the feasibility of using a narrow epitaxially grown phosphorus doped n^+ peak placed just in front of the SiGe layer to compensate the boron outdiffusion and thus improve the overall device characteristics is demonstrated.

II. PROCESSING

The layers were grown in a commercially available single wafer epitaxial reactor (ASM-Epsilon One) at atmospheric pressure. The wafers were loaded and unloaded in a nitrogen purged loadlock, and then placed on a SiC coated graphite susceptor. The quartz reaction chamber is lamp heated. Before each deposition the chamber was cleaned with HCl at 1150 °C. The wafers were prebaked in H₂ at 1120 °C for 2 min. The phosphorus doped layers and the SiGe layers were deposited at 700 °C, as were all subsequent layers. The Si_{0.7}Ge_{0.3} layers used in all the experiments here were grown with 20 sccm SiCl₂H₂ and 200 sccm GeH₄ (1% in H₂) as the precursors and 20 slm H₂ as the carrier gas. The dopant sources were, respectively, 200 ppm B₂H₆, 50 ppm AsH₃, and 0.5% PH₃ in H₂. Deposition times varied from 25 min for the silicon cap layers to 10 s for the SiGe layers. Ge percentages were measured by Rutherford backscattering.

A cross section of the SiGe HBT and the fabrication process flow are shown in Fig. 1. The epitaxy is performed in two steps where the first Si epi layer is used to accommodate a 180 keV phosphorus pedestal collector implantation. The second epi layer, grown at 700 °C, contains the p^+ SiGe

^{a)}Electronic mail: lis@dimes.tudelft.nl

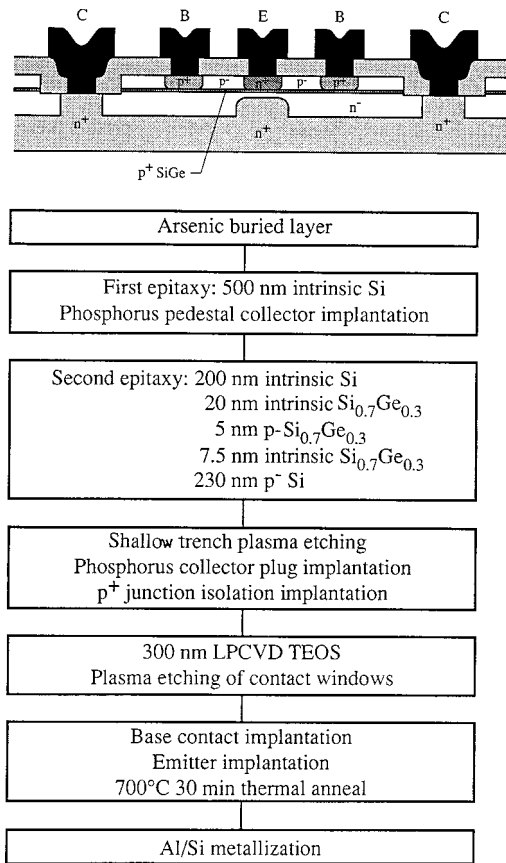


FIG. 1. Schematic cross section and process flow of the SiGe HBT to the first metallization.

base layer which is isolated by shallow trenches. A 3000 Å low-pressure chemical vapor deposition (LPCVD) tetraethylorthosilicate (TEOS) oxide is deposited at 700 °C and all contact windows are plasma etched. The boron base contact and the phosphorus emitter are both implanted at 15 keV, in their respective contact windows by resist masking. The emitter implantation dose is $5 \times 10^{15}/\text{cm}^2$. The dopants are activated by a single 30 min thermal anneal step at 700 °C, and the windows are contacted by sputtering Al/1% Si. The metal pitch is 3 μm and determines the size of the collector–base (c–b) junction.

III. DEVICE CHARACTERISTICS

The secondary ion mass spectroscopy (SIMS) doping profiles of a 44 GHz device are shown in Fig. 2. The as-grown 50 Å boron base layer has a peak doping of $10^{19}/\text{cm}^3$. After annealing, the basewidth is about 300 Å with a sheet resistance of 7 kΩ/□. The corresponding device characteristics are shown in Fig. 3. The ideal current gain is high, but is attenuated by base leakage and high current effects, resulting in a maximum h_{FE} of about 500. The pedestal collector doping is high so the emitter–collector (e–c) breakdown voltage and the Early voltage are low. The main device parameters are listed in Table I together with those of a device with a collector uniformly doped to $3 \times 10^{16}/\text{cm}^3$. The values of $h_{FE} \times V_A = 10\,500\text{ V}$ and $f_T \times BV_{CE0} = 182\text{ GHz V}$ are high

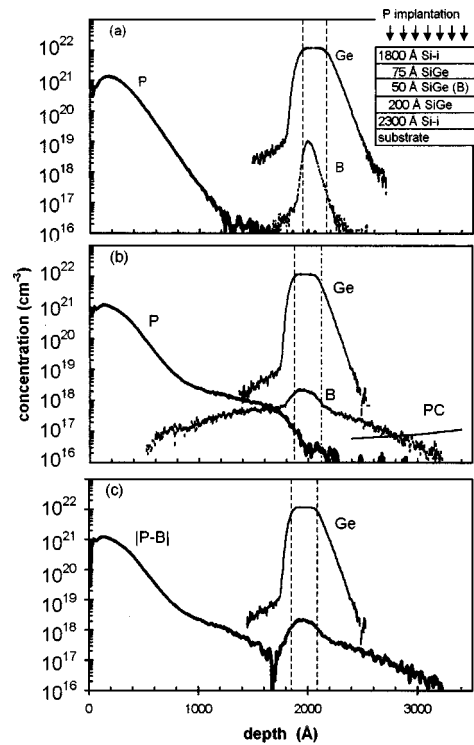


FIG. 2. SIMS plots of the e–b doping profiles: (a) as-grown with the 15 keV $5 \times 10^{15}/\text{cm}^2$ phosphorus emitter implantation and (b) after thermal annealing at 700 °C. The graph in (c) gives the absolute difference of the boron and phosphorus concentrations in (b). The pedestal collector doping (measured separately by a spreading resistance profile) is also indicated in (b).

and in both devices the collector current shows ideal behavior. Thus any detrimental effects from undesirable potential barriers are not directly apparent.

IV. EMITTER–BASE FORMATION

The formation of the whole emitter region by implanting and thermally annealing phosphorus has several advantages. With an anneal temperature of 700 °C the activation of the phosphorus at the surface is about $10^{20}/\text{cm}^3$ which is high enough to achieve low-resistance ohmic contact to the metal. In the rest of the emitter the doping must be in the $10^{18}/\text{cm}^3$ range to achieve the necessary emitter efficiency. This emitter doping is supplied here by the implantation damage induced TED tail of the phosphorus, which at the same time moves the (e–b) junction out of the residual implantation damage region.

To achieve good heterojunction behavior with current gain enhancement, the e–b junction must be aligned to the Si/SiGe interface. Although this can be readily achieved in the as-grown material, further processing often involves temperature steps higher than 600 °C, which, for example, in combination with implantation or plasma etch steps, may cause outdiffusion of the boron doped base layer. Undoped SiGe spacer layers are, as a standard procedure, grown around the base layer to accommodate the boron outdiffusion, but even then such process dependent outdiffusion will

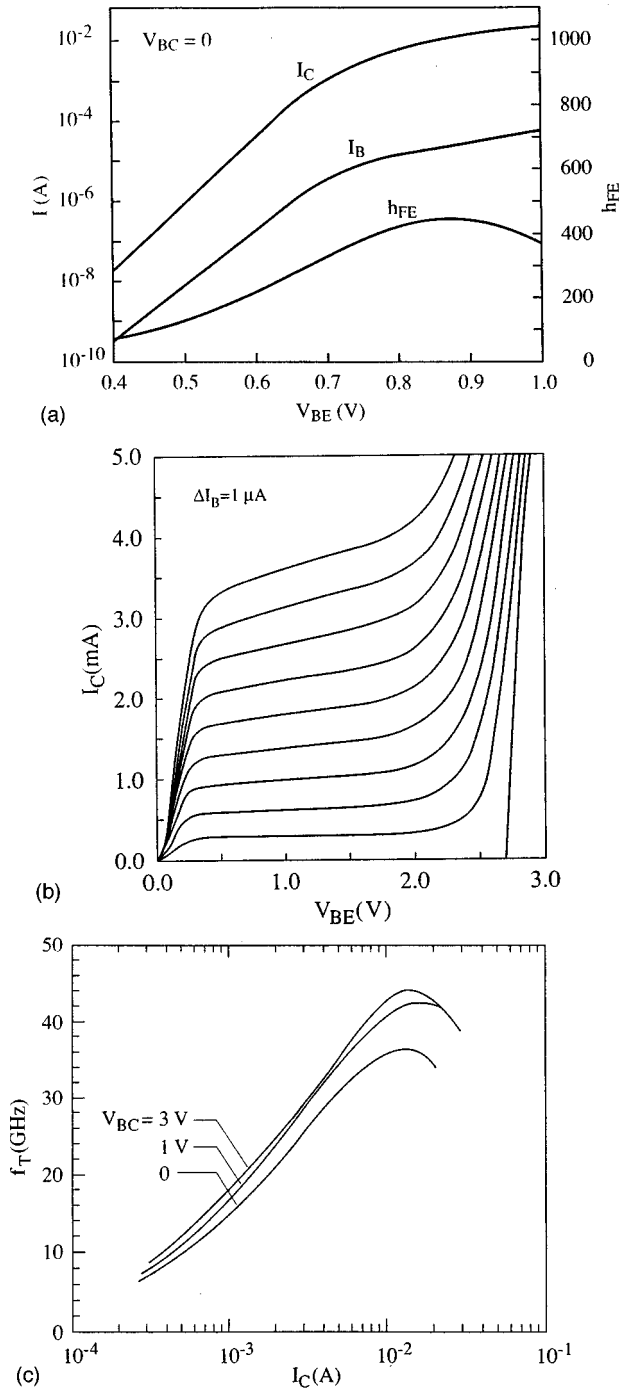


FIG. 3. (a) Gummel plot, (b) output characteristics, and (c) frequency response of a 44 GHz SiGe HBT with an emitter area $20 \times 1 \mu m^2$.

often lead to poor reproducibility of the position of the e–b junction and give large fluctuations in device parameters.

In the present structure there is a considerable amount of implantation damage induced diffusion of the base doping. However, due to the high Ge concentration,⁵ the diffusivity in the SiGe is orders of magnitude lower than that in the Si. Over the very small distance of 100 Å from the boron peak to the Si top layer, the boron concentration drops by a factor of 5 from 30 to $6 \times 10^{17}/cm^3$. In the Si top layer the diffusivity is high, and the boron doping remains high until the

TABLE I. Device parameters for HBTs with an emitter area of $20 \times 1 \mu m^2$ and either a (a) pedestal collector implantation or (b) a collector uniformly doped to $3 \times 10^{16}/cm^3$.

Device parameter	(a)	(b)
Maximum current gain, h_{FE} ($V_{CB}=0$)	500	350
Forward early voltage	7.5 V	30 V
Emitter–base breakdown voltage, BV_{EB}	5 V	5 V
Emitter–collector breakdown voltage, BV_{CEO}	2.7 V	6.5 V
Intrinsic base sheet resistance, R_{bi}	7 k Ω/\square	7 k Ω/\square
Emitter contact resistance	5 Ω	5 Ω
Base resistance	60 Ω	60 Ω
Emitter–base capacitance, C_{eb}	50 fF	50 fF
Collector–base capacitance, C_{bc}	120 fF	110 fF
Cutoff frequency f_{Tmax} , $V_{CB}=3$ V	44 GHz	28 GHz
Maximum oscillation frequency f_{max} , $V_{CB}=3$ V	15 GHz	13 GHz

outdiffusion is stopped at the amorphous/crystalline transition region created by the implantation.

The phosphorus diffusivity is low in the SiGe and only very little phosphorus diffuses into the SiGe. The strong drop in the phosphorus concentration at the Si/SiGe interface combined with the correspondingly sharp rise in the boron concentration means that within the SiGe the boron will amply overdope the phosphorus, and on the Si emitter side the phosphorus will readily rise above the boron doping. This has the effect of aligning the resulting e–b junction to the interface, as can be seen in Fig. 2(c) where the phosphorus doping concentration is subtracted from that of boron. This self-alignment effect is effective over a wide range of processing parameters. Device experiments have shown that the high current gain enhancement is maintained in structures where either the Si top layer thickness is varied up to 300 Å or where the intrinsic base sheet resistance is varied from 2 to 12 k Ω/\square . The desired canceling of the phosphorus and boron doping is also seen in the extreme situation of Fig. 4,

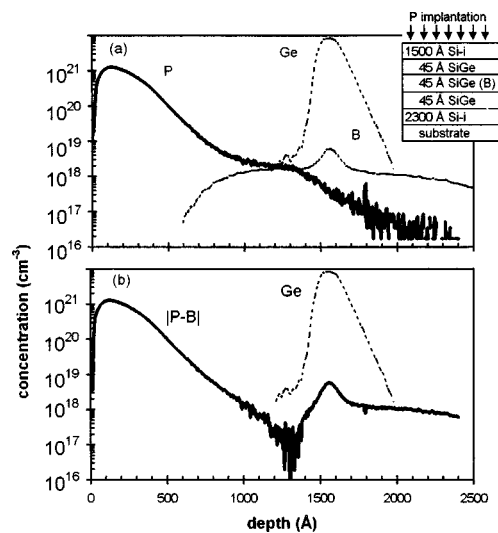


FIG. 4. SIMS plots of the e–b doping profiles for a sample with narrow emitter and base widths. Graph (a) is the sample after thermal annealing at 700 °C and (b) gives the absolute difference of the boron and phosphorus concentrations.

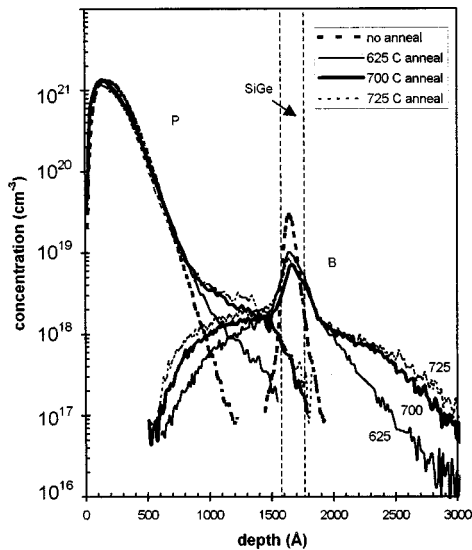


FIG. 5. SIMS plots showing the dependence of the emitter-base doping profiles on the anneal temperature. The anneal time is 30 min.

where the Si top layer is reduced from 1800 to 1500 Å and the SiGe spacer is reduced from 75 to 45 Å. As a device, however, this situation gives high base leakage due to the proximity of the residual implantation damage region to the e-b junction. For lower Ge concentrations (<25%), the self-alignment effect is, for all practical purposes, lost, due to the much higher diffusivity of the dopants in the SiGe region. Of course, the lower Ge percentage gives the advantage that wider SiGe spacers can be applied, and devices with enhanced current gain characteristics have been fabricated with implanted phosphorus emitters and a 20% Ge base layer.¹ However, the reproducibility from run to run is poor due to the high susceptibility of the position of the e-b junction to the exact process parameters.

V. THE COLLECTOR-BASE JUNCTION

In the situation of Fig. 2, the boron doping on the collector side drops a factor of 10 to about $3 \times 10^{17}/\text{cm}^3$ over the 200 Å thick SiGe spacer. The further outdiffusion of the boron into the silicon collector region is then sufficiently compensated by the *n* doping of the collector, giving good dc and ac device characteristics. It would, however, be attractive to trade-off the high current gain for lower base resistance and higher Early voltage. This is not directly possible because a higher boron peak doping also increases the outdiffusion into the collector. A corresponding increase in either the collector epilayer doping or the phosphorus pedestal doping to counteract this effect would seriously compromise the e-c breakdown voltage.

The boron outdiffusion into the silicon can be reduced by either increasing the SiGe spacer width or by reducing the thermal anneal temperature. Increasing the spacer width poses problems for the stability of the material and is not considered here. Reducing the anneal temperature can give a considerable decrease in outdiffusion, as can be seen in the SIMS plots of Fig. 5. For this experiment, individual pieces

of the same wafer were annealed at 625, 700, and 725 °C, respectively. The as-grown boron peak doping is high ($3 \times 10^{19}/\text{cm}^3$), but at 625 °C the boron diffusion into the collector is so low that an appropriate c-b junction results. On the emitter side, however, the boron outdiffusion is still high and is not compensated for by the very modest phosphorus TED tail. Moreover, the latter does not suffice for the formation of a suitable emitter profile. At 725 °C the outdiffusion of both boron and phosphorus is slightly higher than at 700 °C. The 700 °C anneal has proven to be the best choice for, on the one hand, activating and diffusing the phosphorus and, on the other hand, limiting the boron diffusion and preserving the material's stability.

A more promising method of containing a highly doped neutral base region in the SiGe is to use very narrow *n*⁺ peaks to compensate for the boron diffusion into the silicon. Phosphorus doped peaks can be epitaxially grown just before the SiGe deposition. Heinemann *et al.*⁶ demonstrated that such an *n*⁺ peak near the base junction can also improve the saturation behavior of the transistor in the high current mode. The additional doping peak retards the onset of the Kirk effect and the accumulation of charge carriers at the c-b heterojunction, thus giving high *f_T* and *f_{max}* over a wider *I_C* range. Because the peak is narrow, it is readily depleted and the c-b capacitance and the breakdown voltages are only marginally influenced by its presence.

Phosphorus peaks, 200 Å wide and doped to $10^{18}/\text{cm}^3$, were epitaxially grown just before the SiGe deposition. The exact distance between the *n*⁺ peak and the onset of SiGe growth was varied by introducing a Si spacer of either 0, 200, or 400 Å. In this experiment the Si top layer is chosen to be 5000 Å thick so that the phosphorus emitter can be implanted and annealed without the risk of overdoping the resulting profile of the *n*⁺ peak.

SIMS profiles of the *n*⁺ peaks before and after annealing are shown in Fig. 6. From the as-grown profiles of the two samples with finite Si spacer width, it is clear that a small measure of phosphorus autodoping is present. This effect appears to lead to a broadening of the peak in the first sample, perhaps because phosphorus is more readily incorporated in SiGe.⁷ In all cases the phosphorus autodoping terminates quite abruptly in the boron peak region. The exact mechanism that is responsible for this effect is not known at present.

In the process of thermally annealing the *n*⁺ peak, the reduced diffusivity of phosphorus in the SiGe is, as on the emitter side, advantageous for the final result. In the first sample, due to the severe autodoping a considerable amount of phosphorus diffuses past the boron into the emitter region. For the other two samples, however, the phosphorus peak doping is largely contained and is broadened on the collector side. The resulting profile corresponds well with the boron outdiffusion from highly doped *p*⁺ peaks such as that seen in Fig. 5. Comparison of these profiles indicates that it is possible to compensate for the boron outdiffusion and even overdope it with phosphorus so that a highly doped neutral base region combined with a narrow *n*⁺ peak results. As

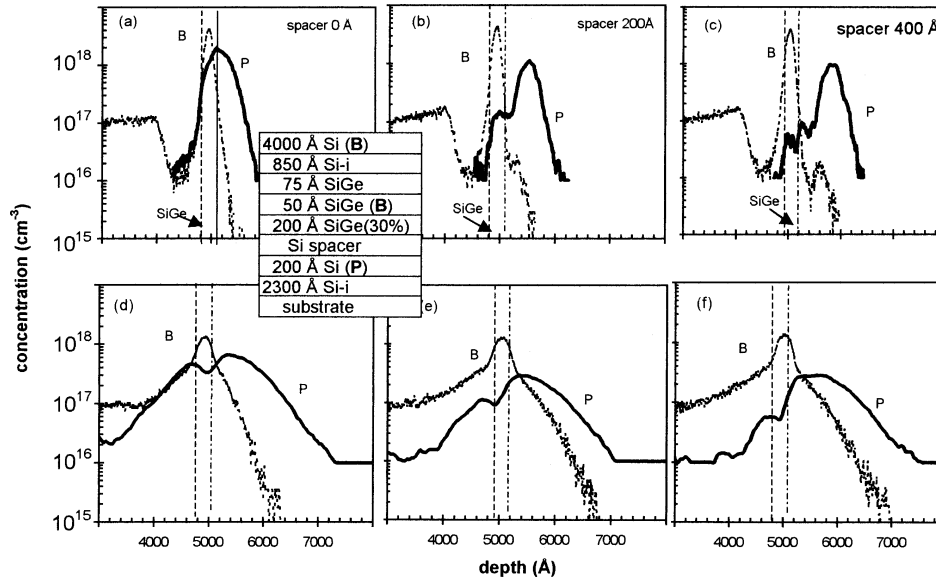


FIG. 6. SIMS plots of the doping profiles of phosphorus and boron peaks, where a Si spacer is grown between the n peak and the SiGe layer. The spacer width is 0 in (a) and (d), 200 Å in (b) and (e), and 400 Å in (c) and (f). Graphs (a), (b), and (c) show the situation before annealing and (d), (e), and (f) that after annealing at 700 °C.

discussed above, this could be very beneficial to the overall device characteristics.

VI. CONCLUSIONS

The very low diffusivity of both boron and phosphorus in high Ge concentration SiGe during 700 °C thermal annealing makes it possible to place high n -type doping on both sides of a p^+ boron doped Si_{0.7}Ge_{0.3} layer without significantly attenuating the boron peak. The transient enhanced diffusion induced by the annealing of an implanted phosphorus emitter nevertheless gives considerable outdiffusion by all dopants. On the emitter side this effect aligns the e - b junction to the Si/SiGe interface and doping profiles are formed which are demonstrated to be suitable for high-frequency device fabrication. On the collector side boron outdiffusion must be minimized by limiting the boron peak doping. However, it is shown that a phosphorus doped n^+ peak grown just before the SiGe base can be well used to compensate for the boron outdiffusion even for more highly doped boron peaks. In this manner the intrinsic base resistance could be considerably decreased and the overall device parameters improved.

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