HIGH-FREQUENCY SIGE HBT'S WITH IMPLANTED EMITTERS.

L.K. Nanver, E.J.G. Goudena, C. Visser, H.W. van Zeijl, J.W. Slotboom[a]

DIMES IC Process Research Sector, Delft University of Technology
P.O.box 5053, 2600 GB Delft, The Netherlands
[a]Philips Research Labs, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands

Abstract

A method is presented by which the implantation damage induced transient enhanced diffusion of boron and phosphorus is used to fabricate high-frequency SiGe HBT's with implanted emitters. A device with 30 nm basewidth and f_T *= 44 GHz is demonstrated.*

1. Introduction

The frequency performance and overall attractive device characteristics offered by SiGe heterojunction bipolar transistors, have made SiGe IC-processes interesting candidates for portable telecommunication applications. In this field, next to low power dissipation, limiting the cost has the highest priority when designing an IC-process. Particularly the manufacturability of SiGe HBT's has therefore become a critical question. At present the SiGe processes which are considered production ripe, involve polysilicon emitters and processing steps such as rapid thermal annealing, double poly, selective epitaxy and other self-aligned structures. Much lower process complexity can be achieved by using implanted emitters. However, the damage created by the emitter implantation has several times been shown to result in an severe out-diffusion of the boron base doping [1, 2]. This not only broadens the basewidth, but may also create undesirable potential barriers which seriously degrade the frequency performance [2, 3].

In this paper, a method is presented by which it has been possible to nevertheless combine high-frequency performance with implanted emitters. In these devices the implantation damage induced transient enhanced diffusion of both the phosphorus implanted emitter and epitaxially grown boron base is used with advantage to produce attractive emitter-base doping profiles. Essential in this structure is the use of $Si_{1-x}Ge_x$ 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 transient enhanced diffusion is witnessed for both boron and phosphorus in the Si, but in the $Si0_{0.7}Ge_{0.3}$ layer this anomalous diffusion is suppressed. This effect results in a restriction of the boron to the SiGe region, while at the same time impeding the penetration of the phosphorus into this region. The e-b junction is thus to a large degree automatically aligned to the Si/SiGe interface.

The Si/SiGe epi layers are grown in the ASM Epsilon CVD reactor, which is a production tool for epitaxial growth of Si and SiGe. All other process steps, including the formation of the e-b structure, are straightforward and involve only well established production techniques. This, the low process complexity and the partial self-alignment of the e-b junction to the Si/SiGe interface, results in high reproducibility from run to run, and good uniformity over the wafer.

2. Processing

A cross section of the SiGe HBT and the fabrication process flow are shown in Figs.1 and 2. 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 base layer which is isolated by shallow trenches. A 300 nm LPCVD TEOS is deposited at 700°C and all contact windows are plasma etched. The base contact doping and the emitter are both implanted at 15 keV in their respective contact windows by resist masking. 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 c-b junction.

3. Device characteristics

The device characteristics of a 44 GHz device are shown in Fig. 3. The ideal current gain is very high but is attenuated by base leakage and high current effects, resulting in a maximum h_{FE} of about 500. Evaluation of the phosphorus emitter injection efficiency in a pure Si device indicates that the base current is 3 - 4 times higher than that observed with a typical arsenic emitter (activated at 950°C and 0.2 μm deep [4]). The poor performance of the phosphorus emitter is overly compensated by the gain enhancement from the bandgap discontinuity, and the ideal current gain is at least 2000.

The limiting factor on the f_T is not the basewidth, but the large area if the c-b junction, which has not yet been optimised for this application. In future experiments the high gain will also be traded off for lower base resistance and higher e-c breakdown voltage. The expectations are that this optimisation procedure will result in a device with both an f_T and an f_{max} of at least 50 GHz.

4. Emitter-base formation

Some degree of boron out-diffusion of the SiGe base as a result of post-processing steps (usually in combination with temperature steps around 800°C) is a problem commonly encountered in SiGe HBT processes. On the one hand this effect degrades frequency performance due to broadening of the basewidth, and in the worst case due to the formation of parasitic conduction band barriers. On the other hand, such process dependent out-diffusion will often lead to poor reproducibility of the position of the e-b junction entailing large fluctuations in current gain. The latter is also the case even when undoped SiGe spacer layers are grown to accommodate the boron out-diffusion. For this reason the partial self-alignment of the e-b junction to the Si/SiGe interface, as achieved in the present SiGe HBT, is very interesting.

The SIMS plots in Fig. 4 show the e-b profiles of the device described in Section 3. As a result of the processing the basewidth increases from about 5 nm to 30 nm. At the e-b junction the boron doping level is a factor 5 lower than the peak doping. The transient enhanced diffusion of the phosphorus is large and compensates the boron which has diffused past the SiGe region, forming the e-b junction at the Si/SiGe interface. The implantation damage region is thus located well away from the SiGe, and the implanted phosphorus can in this manner form the entire emitter region. The Si cap layer can therefore be p-doped and no other isolation techniques are needed to localize the emitter.

Fig. 5 compares the phosphorus SIMS profiles with and without a $Si_{0.7}Ge_{0.3}$ layer. Also shown in this figure is the influence of a 40 keV arsenic preamorphization on the phosphorus profile. Both the channelling and the transient enhanced diffusion are reduced by this measure. This preamphization, however, has no significant influence on the device characteristics, which confirms that the position of the e-b junction is primarily determined by the low diffusivity of the dopants in the $Si_{0.7}Ge_{0.3}$ region. For devices produced with lower Ge concentrations, the sensitivity to the preamorphization dose increases with decreasing Ge concentration. An example is given in Table II for devices containing a $Si_{0.8}Ge_{0.2}$ base layer. While the current gain is very sensitive to the arsenic dose, the intrinsic base sheet resistance only increases very slightly as the arsenic dose is increased.

5. Conclusions

By using high Ge concentration, in combination with a phosphorus implanted emitter and 700 °C thermal annealing, e-b doping profiles suitable for high-frequency device performance are achieved. The implantation damage induced transient enhanced diffusion brings the e-b junction away from the residual implantation damage region and positions it reproducibly at the Si/SiGe interface.

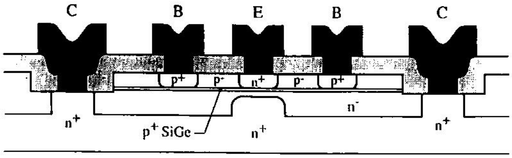
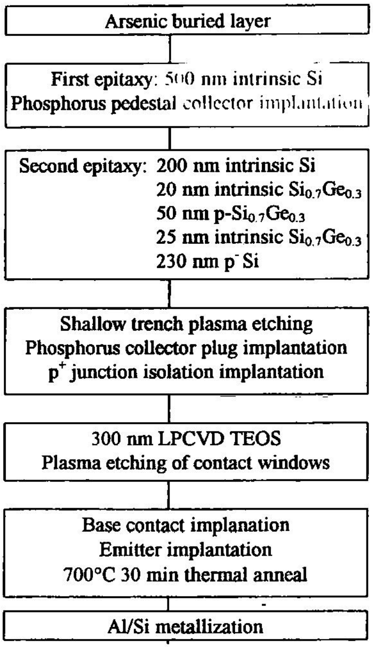


Fig. 1: Schematic cross-section of the SiGe HBT to the first metallization.

Fig. 2: Process flow of the SiGe HBT.



Arsenic buried layer

First epitaxy: 500 nm intrinsic Si
Phosphorus pedestal collector implantation

Second epitaxy: 200 nm intrinsic Si
20 nm intrinsic $Si_{0.7}Ge_{0.3}$
50 nm p-$Si_{0.7}Ge_{0.3}$
25 nm intrinsic $Si_{0.7}Ge_{0.3}$
230 nm p^- Si

Shallow trench plasma etching
Phosphorus collector plug implantation
p^+ junction isolation implantation

300 nm LPCVD TEOS
Plasma etching of contact windows

Base contact implanation
Emitter implantation
700°C 30 min thermal anneal

Al/Si metallization

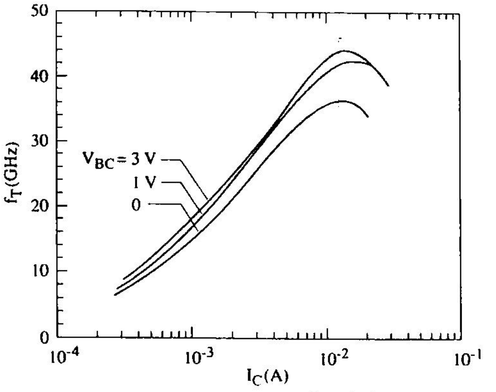
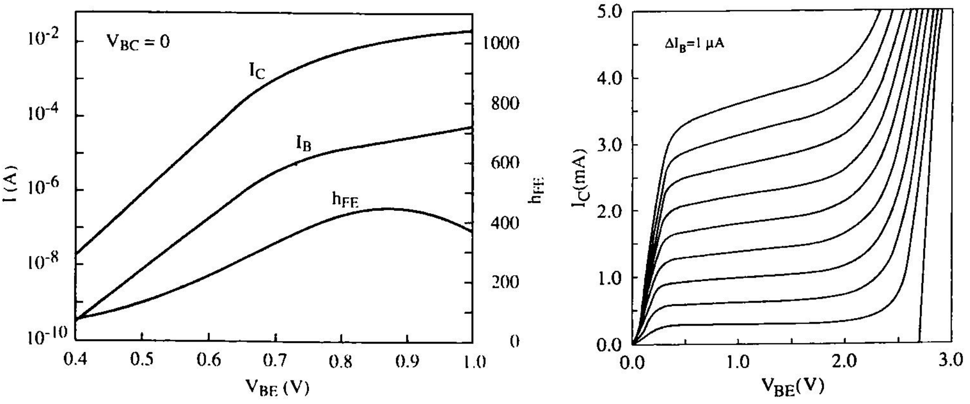


Fig. 3: Gummel plot (a), output characteristics (b) and frequency response (c) of a 44 GHz SiGe HBT with emitter area 20 x 1 μm^2.



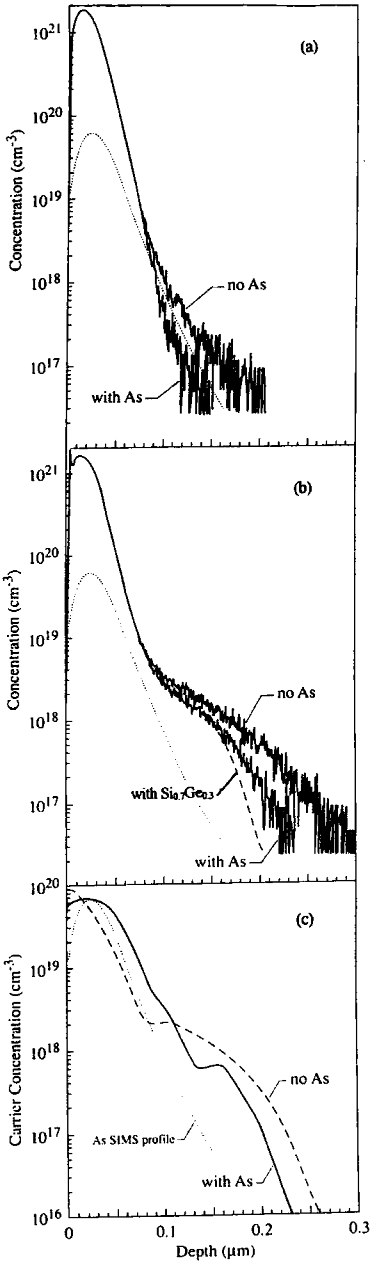


Fig. 5: SIMS plots, (a) and (b), and spreading sheet resistance measurements (c) of the 5 x 10^{15} /cm^2 15 keV phosphorus emitter implantation, with and without a 40 keV arsenic preamorphization (dose 2.5 x 10^{14}/cm^2). Graph (a) is as-implanted, while (b) and (c) are after thermal annealing at 700 °C for 30 min.

Fig. 4: SIMS plots of the e-b doping profiles (a) as-grown with the 15 keV 5 x 10^{15}/cm^2 phosphorus emitter implantation, and (b) after thermal annealing at 700 °C for 30 min.

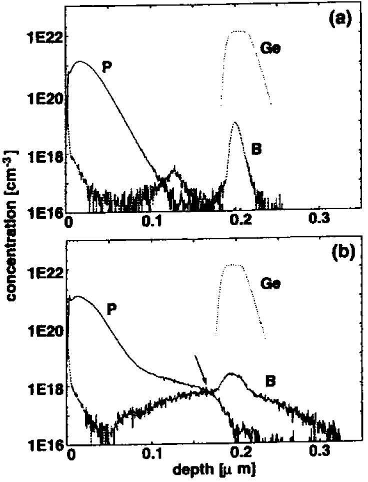


Table I: Device parameters.

On mask emitter area	20x1 μm^2
Current gain, h_{FE}	500
Forward Early Voltage	7.5 V
Emitter-base breakdown voltage, BV_{EB}	5 V
Emitter-collector breakdown voltage, BV_{CEO}	2.7 V
Intrinsic base sheet resistance, R_{bi}	7 kΩ/□
Emitter contact resistance	5 Ω
Base resistance	60 Ω
Emitter-base capacitance, C_{eb}	50 fF
Collector-base capacitance, C_{bc}	120 fF
Cutoff frequency f_{Tmax}, V_{CB} = 3 V	44 GHz
Max. osc. freq. f_{max} ,V_{BC} = 3 V	15 GHz

Table II: The h_{FE} and R_{bi} dependence on preamorphization dose for a $Si_{0.8}Ge_{0.2}$ HBT with a second epitaxy layer of (25 nm intr $Si_{0.8}Ge_{0.2}$)/ (50 nm $Si_{0.8}Ge_{0.2}$ p-doped to 2 x 10^{18}/cm^2)/ (25 nm intr $Si_{0.8}Ge_{0.2}$)/ (200 nm p$^-$ Si).

As dose (cm^{-2})	maximum h_{FE}	R_{bi} (Ω/□)
0	70	3600
10^{14}	100	3450
1.5 x 10^{14}	126	3350
2.5 x 10^{14}	132	3300

References

[1] T. Ghani, et. al., J. of Electronic Materials, 24, p. 999, 1995.
[2] E.J. Prinz, et. al., IEEE-EDL, 12, p. 42, 1991.
[3] A.Pruijmboom, et.al., IEEE-EDL, 12, p. 357, 1991.
[4] L.K. Nanver, et. al., IEEE-TED, 43, no. 6, 1996.