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Quantitative Measurement of Reduction of Boron Diffusion by Substitutional Carbon Incorporation

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Abstract

Recently, the suppression of boron diffusion due to both thermal and transient enhanced diffusion (TED) has been demonstrated through the incorporation of 0.5% substitutional carbon in the base of Si/SiGe/Si heterojunction transistor's (HBT)[1,2]. Because the devices are sensitive to diffusion on a scale less than that we can detect with SIMS, in this paper combined process and device modeling (TMA TSUPREM4 and MEDICI) are used to relate observed electrical characteristics (collector saturation currents and Early voltages) of the HBT's to boron diffusion, with a sensitivity of 20-30Å. Boron diffusivity in the SiGeC base is ~8 times slower than that of the boron diffusivity in the SiGe base without implant damage (no TED). In the case of ion implant damage in an overlying layer to cause TED the excess interstitial concentration due to ion implant damage is reduced by approximately 99% through incorporation of 0.5% substitutional carbon in the HBT SiGe bases. This demonstrates that carbon incorporation acts as an effective sink for interstitials.

Introduction

Si/SiGe/Si heterojunction bipolar transistor (HBT) technology has achieved record high frequencies for silicon compatible devices with low base sheet resistances because boron doping levels of $\sim 10^{20}/\mathrm{cm}^3$ in the bases are crucial to this result [3]. However, HBT electrical performance is very sensitive to the formation of conduction band barriers at the emitter/base and base/collector interfaces due to small amounts of boron outdiffusion during processing leading to dramatic reductions in collector current and early voltages [4] (see figure 1). Recently, through the intentional introduction of high concentrations of substitutional carbon, the reduction of boron outdiffusion has been demonstrated for both annealing, and implantion and annealing conditions, greatly increasing the thermal budget for HBT targeted processes [1,2].

The reduction of boron diffusion and its transient diffusion in and near carbon-rich silicon or silicon-germanium has gathered much attention recently for its potential technological applications to control boron diffusion in processes that have ever increasingly restricted geometries [5,6,7]. In this paper we seek to quantify the reduction of boron diffusion. Because the devices are greatly affected by diffusion at levels too small to be detected by SIMS, we use modelling of the device electrical characteristics to infer the changes in boron profile and hence the changes in boron diffusion coefficients.

In n-Si/p+SiGeC/n-Si HBTs, as boron diffuses from the p+SiGeC base into n-Si emitter and collector, parasitic barriers are formed in the conduction band which impede the flow of electrons from the emitter to collector [2,8]. The parasitic barrier that arises due to boron outdiffusion is strongly dependent on the boron concentration that diffuses into the silicon, and small amounts of boron outdiffusion $L_d \sim 10$Å can already cause large parasitic barriers evident in HBT's [8] because the collector current is exponentially dependent on the barrier height. This can be observed by directly measuring collector saturation current, or even more sensitively by observing the effect of collector-emitter bias on collector current (the Early effect).

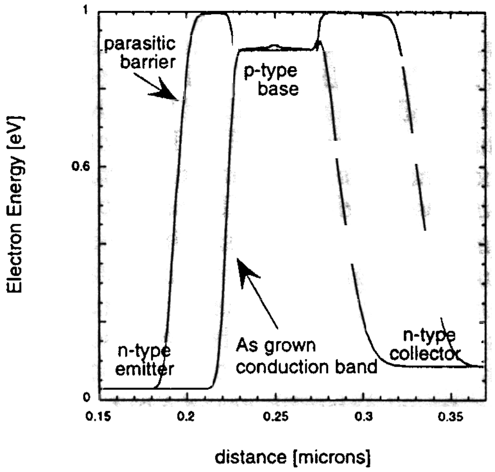


Figure 1 Qualitative conduction band diagram of a (n-)Si/(p+)SiGeC/(n-)Si HBT as grown and after annealing showing the creation of a parasitic conduction band barrier as a result of boron diffusion from the base into the n-type Si emitter and collector region.

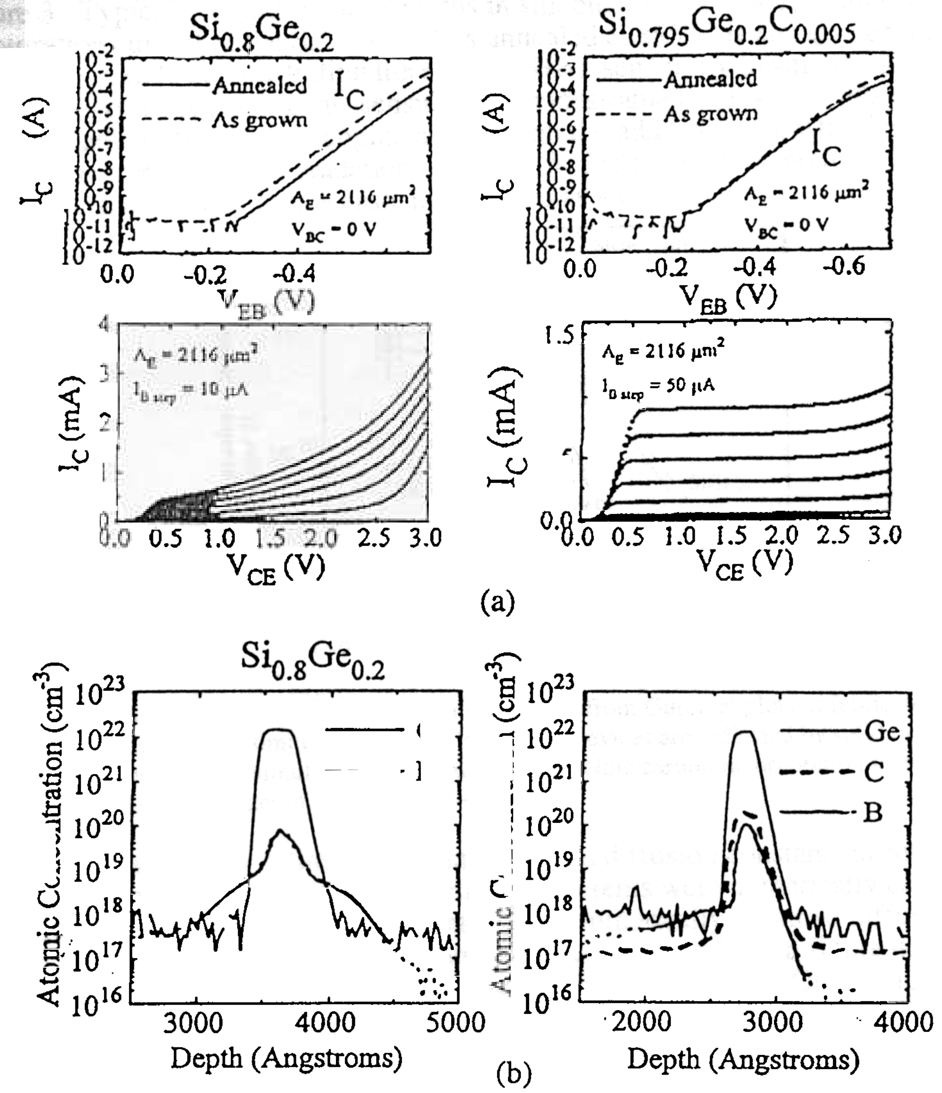
The Early voltage changes because the barrier height, and hence the collector current, is affected by the collector-emitter bias. In this paper we use HBT electrical characteristics to quantitatively compare boron diffusion in SiGe to boron diffusion in SiGeC for annealing or implant and annealing conditions. We report that boron diffusion in SiGeC at 855°C is 1/8th that in SiGe, that the SiGeC layer acts as an interstitial sink for ~99% of the excess interstitials due to ion implant damage, and that the HBTs are far more sensitive to boron diffusion than SIMS.

Experiment

The HBT's were grown by RTCVD [9] at 575-700°C, with boron levels in the base of $\sim 10^{20}/\mathrm{cm}^3$ and bases of ~20 nm of $Si_{0.8}Ge_{0.2}$ or $Si_{0.8}Ge_{0.2}C_{0.005}$. The device fabrication was done using all low-temperature processing to avoid unnecessary diffusion and is described elsewhere [1,2]. Photoluminescence and X-ray diffraction studies on similar alloy layers show that the alloy layers are biaxially compressively strained to match the silicon lattice, and transmission electron microscopy (TEM) showed no dislocations, defects, or SiC precipitates in any of the as-grown layers [2]. As-grown Gummel plots and common emitter characteristics of HBT's without and with 0.5% substitutional carbon in the bases are shown in figures 2(a) and (b) respectively. High Early voltages and SIMS verifies that there is no significant boron outdiffusion [1,2] in such HBT's fabricated without annealing.

Two different cases are considered for HBT processing to study boron outdiffusion. Case (1): the effect that substitutional carbon has on the intrinsic boron diffusion rates (N_2 anneal, 15 minutes, 800-950°C); and case (2): The effect of substitutional carbon on the transient enhanced diffusion of boron due to ion implant damage in the overlying emitter layer ($1.5\times10^{15}/\mathrm{cm}^2$ 30 keV and $3\times10^{14}/\mathrm{cm}^2$ 15 keV into the silicon 2000Å n- emitter) with subsequent 15 minute activation anneals in N_2 at 647°C and 742°C.

SIMS, Gummel plots and common emitter characteristics of the processed HBT's with ion implant damage are shown in figure 2. Saturation currents and Early voltages were then extracted from the electrical characteristics for comparison and fitting to simulated electrical characteristics. The decrease in Ic and reduced Early voltages in the transistors annealed at 647°C without carbon, figure 2 (a), show that boron has outdiffused even though this annealing condition is far less than the emitter thermal budget. However the high Early voltages in the HBT devices with carbon show that much of the TED effects have been suppresed. However, even in this case the Early voltage is not as high as that of the as grown HBTs, evidence that some slight TED effects still remain, despite no evidence of boron


$Si_{0.8}Ge_{0.2}$
$Si_{0.795}Ge_{0.2}C_{0.005}$
Annealed
As grown
I_C
I_C (A)
$A_E = 2116\ \mu m^2$
$V_{BC} = 0$ V
V_{EB} (V)
0.0
-0.2
-0.4
-0.6
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
I_C (mA)
$A_E = 2116\ \mu m^2$
$I_{B\ step} = 10\ \mu A$
$I_{B\ step} = 50\ \mu A$
V_{CE} (V)
0.0 0.5 1.0 1.5 2.0 2.5 3.0
0 1 2 3 4
0.0 1.5
(a)
$Si_{0.8}Ge_{0.2}$
Atomic Concentration (cm^{-3})
10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22} 10^{23}
Ge
C
B
Depth (Angstroms)
3000 4000 5000
2000 3000 4000
(b)

The HBT electrical characteristics were numerically simulated using the doping profiles obtained above to make comparison to experimental data. Bandgap differences of 160 meV and 147 meV were used for SiGe and SiGeC bases respectively. The effective density of states in the $Si_{1-x}Ge_x$ base, approximately $\frac{N_C N_V^{SiGe}}{N_C N_V^{Si}} \cong 0.33$ for x=0.2, is assumed not to change in the SiGeC base; and a bandgap narrowing model commensurate with observed bandgap narrowing in SiGe due to high doping densities in SiGe [10], which is less than that observed in Si, was also included.

Results & Discussion

Collector saturation currents (y axis intercept) extracted from gummel plots (collector current vs. base emitter voltage) of fabricated HBT's for case I, intrinsic diffusion, are shown in figure 3. Typical boron diffusion lengths in silicon at 855°C for 15 minutes are ~75Å [15]. The saturation current of the Si/SiGe HBT's annealed at 855°C is already reduced nearly two orders of magnitude demonstrating the extreme HBT sensitivity to small boron diffusion lengths. For HBT processing this sensitivity is undesirable because it limits the total thermal budget available to the process engineer. Through the addition of substitutional carbon the onset of saturation current degradation can be shifted to higher temperatures increasing the available thermal budget, in this case, by as much as ~100°C.

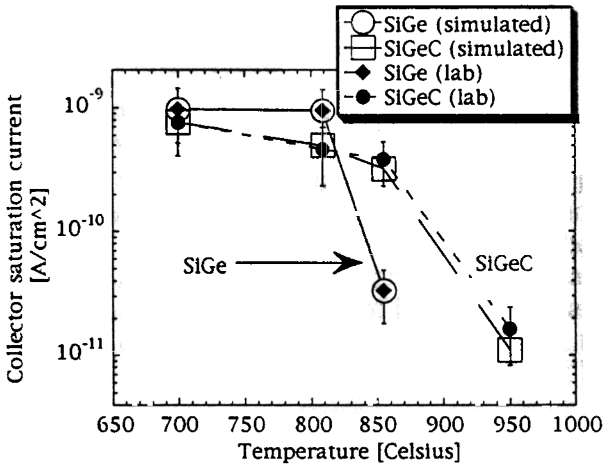


Figure 3 HBT saturation currents extracted from Gummel plots of fabricated and numerically simulated devices. Fabricated devices are indicated by solid markers, numerically simulated by hollow markers. Note carbon incorporation increases thermal budget of HBT process ~100°C.

To quantitatively estimate the relative boron diffusion constants in SiGe and SiGeC, the experimentally observed collector saturation currents were numerically calculated and fit, see figure 3, to a single diffusion parameter. The numerically obtained diffusion constants for boron in the SiGe and SiGeC are compared to that of silicon [15] in figure 4. The fitted boron diffusivities in SiGeC are uniformly slower than those in Si and SiGe. Simple best fits, using the same boron diffusion activation energy as that in silicon, yield boron diffusivities in SiGeC that are ~8 times less than that in SiGe. This agrees with previously reported boron diffusivities in SiGe and SiGeC that find boron to move slower in SiGeC than in SiGe and both diffusivities to be slower than that in silicon [12,13], but the absolute diffusivities extracted from the HBT data are approximately 2-3 times faster than those reported. Various sources of error can contribute to disagreement with the referenced values. The numerically calculated profiles are simulated with a single diffusion constant for boron. The extracted diffusivity will represent an average diffusivity of that in the alloy layer and that in silicon. For long difffusion lengths, with respect to the width of the HBT base, the numerically found boron diffusivity in the alloy should be faster than that of the actual boron diffusivities in the