Suppression of boron transient enhanced diffusion in SiGe heterojunction bipolar transistors by carbon incorporation

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In this work, we demonstrate that the incorporation of carbon in the base of a *npn* Si/SiGe/Si heterojunction bipolar transistor dramatically reduces the outdiffusion of boron from the base under postgrowth implantation and annealing procedures. Without the addition of C, these processes would lead to transistors with vastly degraded transistor characteristics. This reduction in B diffusion, when compared to devices without C, has been observed by both secondary ion mass spectroscopy and improved electrical characteristics. © *1997 American Institute of Physics.* [S0003-6951(97)00223-4]

Record high-frequency *npn* $Si/Si_{1-x}Ge_x/Si$ bipolar transistor performance has been achieved by reducing the base sheet resistance using base boron doping levels greater than 10^{20} cm^{-3}.[1] However, high boron concentrations are susceptible to outdiffusion from the SiGe base into the Si emitter and collector following postgrowth thermal processing or implantation and annealing due to transient enhanced diffusion (TED) effects. This outdiffusion causes the formation of conduction-band barriers at the emitter-base and base–collector interfaces, which reduce the transistor's gain, early voltage, and frequency performance.[2–5] To accommodate any boron movement during postgrowth processing, undoped SiGe spacer layers are grown on either side of the doped SiGe base.[3] However, the thickness of these undoped spacer layers is limited by the critical thickness of the SiGe strained film. The necessity of maintaining low thermal budgets and the absence of implantation and annealing to minimize boron diffusion in heterojunction bipolar transistor (HBT) processes pose a severe limit on the integration of SiGe into base line silicon technology.

Boron outdiffusion may be caused by (1) thermal annealing,[3] (2) transient enhanced diffusion effects due to an arsenic emitter implantation and anneal,[2] or (3) TED due to an extrinsic boron implantation and anneal.[6] We have found that the addition of carbon to the base of SiGe HBTs sharply reduces boron outdiffusion and improves collector electrical characteristics in all cases. In this letter, we present results on TED due to an As emitter implant.

The *npn* Si/SiGeC/Si device epilayers were grown by rapid thermal chemical vapor deposition on (100) *p*-Si substrates.[7] Following an *n*-type collector buffer layer, the 2000 Å $5\times10^{17}-10^{18}$ cm^{-3} collector was grown at 1000 °C. The 20% SiGe base was then grown at 625 °C, doped 10^{20} cm^{-3} boron, with nominally undoped spacer layers on either side of the doped SiGe base to compensate for any boron movement during the emitter growth. Identical wafers were grown using methylsilane to incorporate 0.5 at. % carbon in the doped SiGe, as well as in the undoped SiGe spacer layers. The emitter was then grown at 700 °C for 73 min, doped 10^{19} cm^{-3} with phosphorus. Transmission electron microscopy (TEM) showed no dislocations, defects, or SiC precipitates in any of the as-grown layers. Figures 1(a) and 1(b) show secondary ion mass spectroscopy (SIMS) profiles of Ge, B, and C levels in the base region of as-grown layers without and with carbon, respectively, which demonstrate that the boron is contained well within the SiGe (or SiGeC) layers by the undoped spacer layers. Base oxygen levels are $\sim2\times10^{18}$ cm^{-3} in all cases. Transistors were processed from the as-grown wafers using a simple double mesa process in which the emitter metal is used as a mask for a selective wet etch, which etches the Si emitter but stops on the SiGe base. The collector is revealed by a plasma etch and, subsequently, the base and collector contacts are formed by lift-off. This process, which includes no high-temperature steps, is advantageous for this study because it prevents the base doping from moving during transistor fabrication. While the transistors have the ideal collector currents required for this study, they do suffer from nonideal base currents due to the lack of surface passivation.

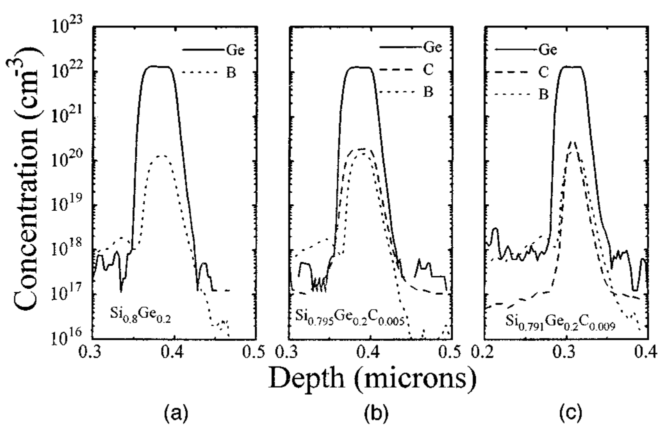

FIG. 1. SIMS profiles showing Ge, C, and B in as-grown base regions. Nominal structures are (a) *n*-Si/50 Å undoped SiGe spacer/200 Å SiGe: B-doped base/50 Å undoped SiGe spacer/*n*-Si, (b) *n*-Si/50 Å undoped SiGeC spacer/200 Å SiGeC: B-doped base/50 Å undoped SiGeC spacer/*n*-Si, and (c) *n*-Si/50 Å undoped SiGe spacer/50 Å SiGe: B-doped base/100 Å SiGeC(0.9%C): B-doped base/50 Å SiGe:B-doped base/50 Å undoped SiGe spacer/*n*-Si.

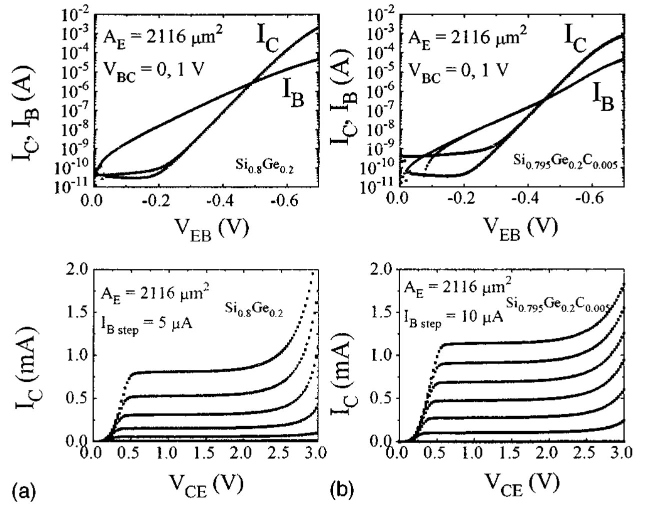

FIG. 2. Room-temperature Gummel plots and common-emitter characteristics of devices processed from Figs. 1(a) and 1(b) wafers without implantation or thermal annealing.

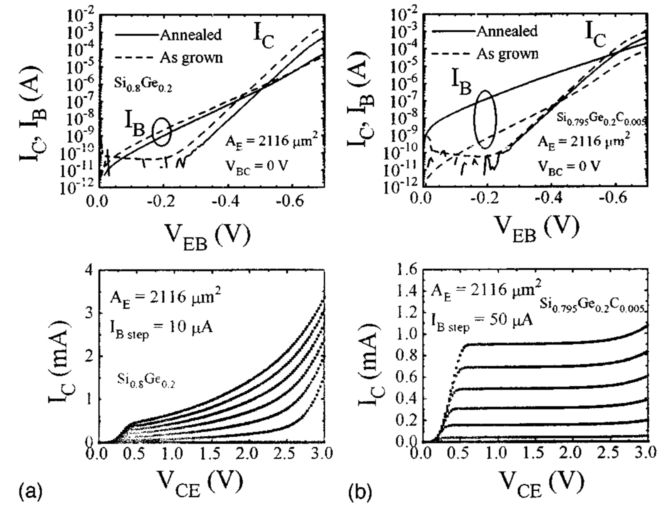

FIG. 3. Room-temperature Gummel plots and common-emitter characteristics of Figs. 1(a) and 1(b) wafers following As-emitter implantation and anneal at 647 °C.

Previous work on SiGeC HBTs has shown that the addition of carbon to SiGe to form SiGeC alloys increases the band gap by ~26 meV/%C.[8] Figures 2(a) and 2(b) show the Gummel plots and common emitter characteristics for the as-grown $Si_{0.8}Ge_{0.2}$ and $Si_{0.795}Ge_{0.2}C_{0.005}$ HBTs, respectively. The collector currents for both types of transistors have no observable dependence on base–collector reverse bias, which is reflected in the common-emitter characteristics by the high Early voltages. Since an increase in collector current with increased V_{CB} indicates a decrease in the parasitic barrier limiting I_C [evidence that outdiffusion has occurred], these electrical characteristics confirm the SIMS measurements that the as-grown transistors have no conduction-band barriers.

Pieces of the as-grown wafers with and without carbon were blanket implanted with As (1.5×10^{15} cm^{-2}, 30 keV; 3×10^{14} cm^{-2}, 15 keV; chosen to follow Ref. 9) to form the emitter contact. Arsenic emitter implantation and annealing have been previously shown[2] to enhance boron diffusion in SiGe bases even though the As implantation range (~1000 Å) is less than the emitter thickness (3000 Å). Different implanted pieces were annealed at different temperatures ranging from 647 to 742 °C for 15 min in nitrogen, and, subsequently, double mesa transistors were fabricated on the as-annealed pieces. Figures 3(a) and 3(b) show Gummel plots and common-emitter characteristics of transistors following As implantation and annealing at 647 °C for wafers without and with carbon. The decrease in I_C and reduced Early voltage in the transistors without carbon show that boron has outdiffused even though this annealing condition is far less than the emitter thermal budget. Samples, which were not subjected to the As implant but underwent the same thermal annealing cycle, did not show any evidence of boron diffusion. This confirms that TED effects are responsible for the boron movement. However, the high Early voltages for the transistors with carbon illustrate that carbon in SiGe has suppressed the TED effects of an As emitter implant. Electrical results for 742 °C anneals are consistent with those at 647 °C, although the degradation due to diffusion in the device without carbon is even more severe. Figure 4(a) and 4(b) show SIMS from no carbon and carbon wafers that underwent As implantation and a 755 °C, 15 min N_2 anneal. It is readily apparent that B has outdiffused in the transistor without carbon but has not in the transistor with carbon.

At both 647 and 742 °C, the samples with carbon showed large increases in base currents [Fig. 3(b)], indicative of the formation of deep level defects and a reduced lifetime in the base-emitter space-charge region. Since this did not occur in the devices without carbon, we conclude that this defect depends on carbon. It was confirmed that the excess base current was caused by recombination in the base-emitter depletion region by growing another sample where the B-doped SiGeC was sandwiched between SiGe layers (*without carbon*) of similar doping, which in turn were surrounded by the undoped SiGe (*without carbon*) spacers, as shown in Fig. 1(c). This prevents the penetration of the depletion regions into the SiGeC regions. These devices had only slight increases in base currents upon As implantation and annealing, as shown in Fig. 5 [in contrast to Fig. 3(b)]. In these structures, boron outdiffusion should also be anticipated, however, since at the $p-n$ junctions, the boron doping exists in layers without carbon. However, as shown in Fig. 5,

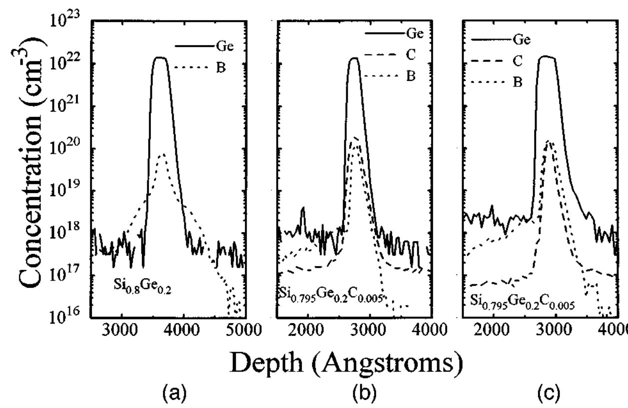

FIG. 4. SIMS profiles of Figs. 1(a), 1(b), and 1(c) (0.5% C) wafers following ion implantation and anneal at 755 °C.

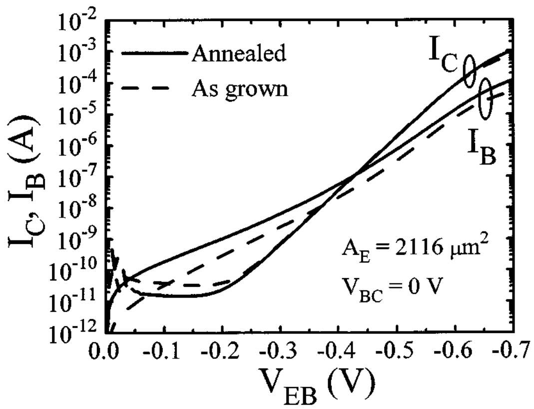

FIG. 5. Gummel plot of wafer of Fig. 4(c) (sandwich base structure) processed both with and without ion implantation and annealing at 742 °C showing no evidence of B diffusion or barrier formation.

the as-grown and annealed (742 °C after As implantation) collector currents are identical, indicating that no outdiffusion has occurred [in contrast to Fig. 3(a)]. Figure 4(c) shows SIMS of the sandwich base following As implantation and anneal, also showing no diffusion. Note that although boron is *outside* the carbon layer, there are no tails due to outdiffusion, as occur in the case for SiGe bases without carbon anywhere. These data suggest that carbon has a nonlocal ability to reduce boron diffusion.

We have shown that carbon in SiGe bases reduces TED-mediated outdiffusion of boron caused by an As-emitter implant and anneal. Other results in our laboratory show a similar reduction in boron diffusion due to thermal annealing without implants and due to TED caused by extrinsic base implants.[10] Previous workers have shown that oxygen levels of 10^{20} cm^{-3} also suppress B diffusion.[9] Since the oxygen concentration in these bases is low ($\sim 2\times 10^{18}$ cm^{-3}) and identical in both wafers with and without carbon, we conclude that carbon is the mechanism that reduces boron diffusion. Carbon in Si has previously been shown to reduce TED of B in silicon due to a Si ion implant and anneal.[11] These previous results and our new results suggest that carbon in SiGe is a sink for point defects (presumably interstitials), the mechanism that causes boron diffusion. This would also explain the suppression of boron diffusion in regions nearby the SiGeC, as demonstrated by the sandwiched base structure. The suppression of boron diffusion by carbon is also accompanied by a decrease in minority carrier lifetime. TEM of all as-grown and implanted and annealed samples shows no evidence of any defects or precipitates in the emitter–base depletion region down to a resolution of $\sim < 20$ Å. Therefore, the C-related complex responsible for the sinking of point defects must be very small. It is known that Si interstitials and substitutional carbon can interact in silicon to form small stable complexes on the scale of a few atoms.[12] Further investigation is required to confirm the exact mechanism, however.

In summary, we have shown that the addition of small amounts of C to SiGe layers greatly reduces boron motion due to transient enhanced diffusion. This greatly improves the allowable thermal budgets in Si/SiGe/Si HBT processing and should improve options for the integration of these devices into existing processes.

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