Characterization of the Effectiveness of Carbon Incorporation in SiGe for the Elimination of Parasitic Energy Barriers in SiGe HBT's

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***Abstract*—An electrical method is applied to SiGe and SiGe:C heterojunction bipolar transistors (HBT's) to extract the bandgap narrowing in the base layer and to characterize the presence of parasitic energy barriers in the conduction band, arising from boron transient enhanced out-diffusion from the SiGe layer. It is shown that a background carbon concentration within the base (≈10^{20} cm^{-3}) eliminates parasitic energy barriers at the collector/base junction, and hence shows that transient enhanced diffusion of boron from the base has been completely suppressed.**

I. Introduction

THE SiGe heterojunction bipolar transistors (HBT's) shows considerable potential for high-frequency applications, as can be seen from the reported cut-off and maximum oscillation frequencies of 130 and 160GHz, respectively [1], [2]. When integrating SiGe HBT's in a CMOS process, it is useful to be able to use some of the implantation steps needed to fabricate the MOS transistors to also fabricate the SiGe HBT's. One such step is the p-channel source/drain implant that could also be used for the extrinsic base of the SiGe HBT. Unfortunately, transient enhanced diffusion of boron poses a problem since it limits the achievable basewidth, and in cases where the boron diffuses outside of the SiGe base, causes the formation of parasitic energy barriers [3], which degrade both the collector current and the high-frequency performance. Recent research [4], [5] has shown that the incorporation of a background concentration of carbon (≈10^{20} cm^{-3}) in the SiGe layer can suppress transient enhanced diffusion.

In this letter, an electrical method [6], [7] is applied to characterize parasitic energy barriers in SiGe HBT's, with and without a background C concentration (≈10^{20} cm^{-3}). This method is extremely sensitive to small amounts of boron out-diffusion from the base and hence allows accurate determination of the presence of parasitic energy barriers. It is shown that this relatively low background carbon concentration is completely effective in suppressing the transient ehanced boron diffusion in SiGe HBT's.

II. Experimental Procedure

The epitaxial bases were grown by solid source molecular beam epitaxy, consisting of a 30-nm $Si_{0.8}Ge_{0.2}$ layer with a highly-doped boron region, approximately 5 nm thick, centered within the Ge profile. In addition, some devices contained a background C concentration (≈10^{20} cm^{-3}) incorporated substitutionally by coevaporation. Low-doped collector and emitter regions were then formed by P (2×10^{12} cm^{-2}, 190 keV and 8×10^{11} cm^{-2}, 110 keV) and As implantation (6×10^{12} cm^{-2}, 100 keV), respectively. These implants are immediately above and below the SiGe base and are therefore expectd to give rise to transient enhanced diffusion. The polysilicon emitter contact was then formed by As implantation into a CVD-deposited amorphous Si layer. After emitter structuring, the base contacts were made using a high-dose BF_2 implant (5×10^{14} cm^{-2}, 45 keV). Device fabrication was completed by a thermal anneal cycle (800 °C, 15 min + 1000 °C, 30 s), salicidation and low-temperature oxide passivation.

The collector current and base sheet resistance were measured as a function of temperature in the range of 200 to 400 K. The measured collector current is normalized against a saturation current density J_O, given by

$$J_O(T) = 4qC(T)\left\{\frac{2\pi}{h^2}\right\}^3 (m_n m_p)^{3/2}(kT)^4 \mu_{nBSi}(T) \cdot \mu_{pBSi}(T) R_B(T) \exp\left\{\frac{qV_{BE} - E_G(T)}{kT}\right\} \quad (1)$$

where

$$C(T) = \left\{\frac{N_C N_{VSiGe}(T)\mu_{nBSiGe}(T)}{N_C N_{VSi}(T)\mu_{nBSi}(T)}\right\}.$$

A graph of $\ln(J_C(T)/J_O(T)$ as a function of reciprocal temperature gives a straight line with the slope equal to the total bandgap narrowing (BGN) in the base (due to heavy doping effects and the presence of Ge) [6], [7].

The slope of the graph is used to characterize the parasitic energy barriers, since a lower slope is observed when a barrier is present [7]. The existence of barriers is confirmed by varying the collector-base reverse bias. If a parasitic energy barrier is present, an increase in reverse bias decreases the barrier height and gives an increased slope.

III. Results

Gummel plot measurements showed that the collector characteristic of the SiGe:C device is near-ideal, with an ideality

Manuscript received July 9, 1998; revised September 18, 1998.
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Publisher Item Identifier S 0741-3106(99)01778-4.

factor of 1.01, whilst the characteristic of the SiGe device is less ideal with an ideality factor of 1.04. The degradation of the collector current ideality in the SiGe device suggests a parasitic energy barrier may be present at the emitter-base junction [8]. The applied forward bias to the emitter-base junction modulates the emitter-base depletion width and sweeps the edge of the depletion region across any parasitic energy barrier. In devices with a small amount of boron out-diffusion from the base, an increase in the emitter-base forward bias reduces the depletion width and increases the effective height of the parasitic energy barrier. This leads to a smaller increase in the collector current with emitter-base bias than would be expected, giving a corresponding increase in the collector current ideality factor.

In addition, the collector current of the SiGe:C HBT is a factor of six times higher than that of the SiGe HBT at room temperature, dropping to a factor of three higher at 200 K. This suggests that a parasitic energy barrier may also be present at the collector-base junction. Comparisons between the $I_C - V_{\rm CE}$ characteristics showed that the Early voltages of the two devices are significantly different, with values of 1 V and 10 V for the SiGe and SiGe:C HBT's, respectively. This is also consistent with a collector-base parasitic energy barrier [8].

Fig. 1(a) shows plots on the normalized collector current as a function of reciprocal temperature for the SiGe and SiGe:C HBT's with zero collector-base reverse bias. A slope of 104 meV is obtained for the SiGe HBT and 172 meV for the SiGe:C HBT. The slope of 104 meV for the SiGe HBT is much lower than the predicted bandgap narrowing value of 168 meV, given by the model of Jain *et al.* [9], calculated using a mean base doping level of 1.6×10^{18} cm^{-3} and Ge concentration of 20%. The mean base doping level was determined in an iterative manner by fitting to the measured base sheet resistance. The predicted value given by the model of Jain represents the total bandgap narrowing in the SiGe layer, due to both Ge-induced and heavy doping-induced bandgap narrowing. The small amount of carbon in the base of the SiGe:C HBT (0.2% or 10^{20} cm^{-3}) is unlikely to significantly alter the bandgap narrowing from that expected for SiGe [10]. The predicted value of bandgap narrowing for the SiGe:C device is identical to that obtained for the SiGe device and can be explained by noting that in the Jain model [9], for doping concentrations below 7×10^{18} cm^{-3}, the bandgap narrowing is not significantly influenced by the doping level. In summary, the results in Fig. 1(a) suggest that there is considerable out-diffusion of boron from the SiGe base layer in the SiGe HBT, but little in the SiGe:C HBT.

Confirmation of the presence of a parasitic energy barrier at the collector/base junction can be obtained by varying the collector/base reverse bias, which modulates the barrier height and therefore changes the slope of the characteristic [7]. Fig. 1(b) shows plots of the normalized collector current as function of reciprocal temperature for an increased collector/base reverse bias of 1 V. An increase in slope from 104 to 140 meV is observed for the SiGe HBT, which confirms the presence of a parasitic energy barrier at the collector/base junction. An estimate of the barrier height can be obtained using the method in [7], which gives a value of 68 meV. For the SiGe:C device, the slope does not change at all when the collector/base bias is increased from 0 V to 1 V. This shows that no barrier is present at the collector/base junction of the SiGe:C HBT, and hence carbon has completely suppressed the transient enhanced out-diffusion of boron from the base due to point defects created by the low-doped emitter and collector implants.

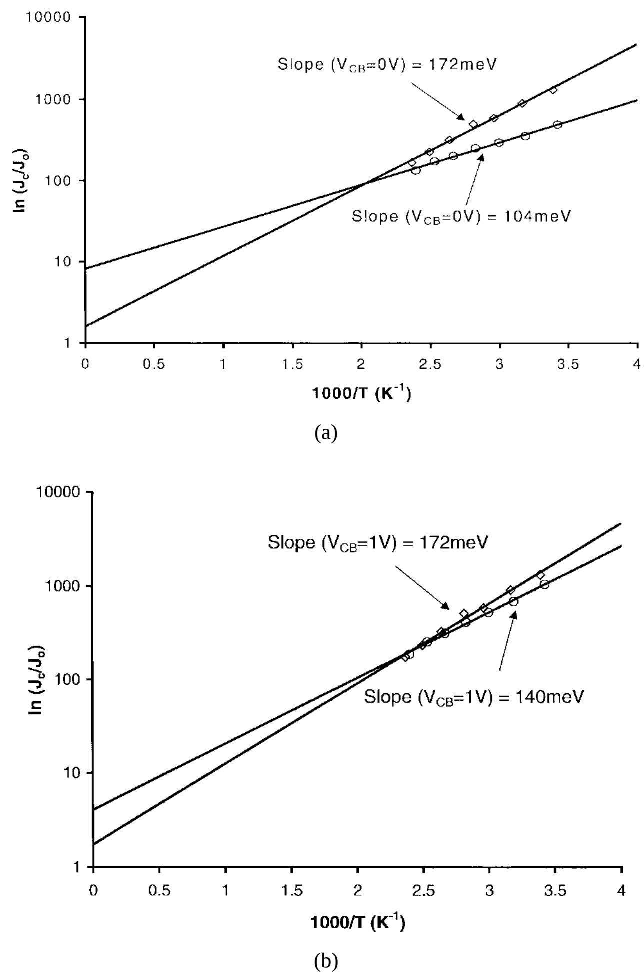

Fig. 1. Plots of the normalized collector current versus reciprocal temperature for the SiGe (○) and SiGe:C (◇) HBT's, measured at collector/base reverse biases of (a) 0 V and (b) 1 V.

To confirm that TED has been eliminated, SIMS analysis was performed on the device wafers using specific SIMS structures. These structures were subjected to the same low-doped emitter and collector implants and subsequent annealing cycles as the devices, and will therefore show the effect of the addition of carbon. Fig. 2 shows the boron profiles obtained from the SIMS analysis. From Fig. 2 it can be seen that the boron profile for the SiGe layer is broad, giving a basewidth of 45 nm and a peak concentration of 6×10^{18} cm^{-3}. For the SiGe:C layer, the base profile is much sharper, giving a basewidth of 30 nm and a peak concentration of 2×10^{19} cm^{-3}. These results confirm that transient enhanced diffusion has occurred in the SiGe layer, due to implantation damage caused by the low-doped emitter and collector implants, but has been

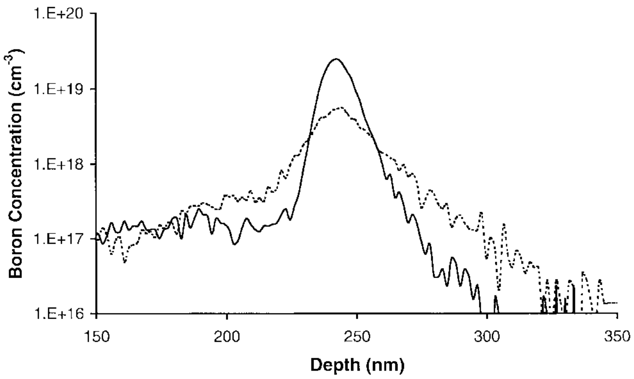

Fig. 2. Boron SIMS profiles for the SiGe (dashed line) and SiGe:C (solid line) HBT base layers.

completely suppressed by the presence of carbon in the SiGe:C layer.

REFERENCES

[1] K. Oda, E. Ohue, M. Tanabe, T. Onai, and K. Washio, "130 GHz f_T SiGe HBT technology," in *IEDM Tech. Dig.*, 1997, pp. 791–794.

[2] A. Schuppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher, and U. Konig, "Enhanced SiGe heterojunction bipolar transistors with 160 GHz $f_{\max}$," in *IEDM Tech. Dig.*, 1995, p. 743.

[3] J. Slotboom, G. Streutker, A. Pruijmboom, and D. Gravesteijn, "Parasitic energy barriers in SiGe HBT's," *IEEE Electron Device Lett.*, vol. 12, pp. 486–488, Sept. 1991.

[4] L. Lanzerotti, J. Sturm, E. Stach, R. Hull, T. Buyuklimanli, and C. Magee, "Suppression of boron transient enhanced diffusion in SiGe heterojunction bipolar transistors by carbon incorporation," *Appl. Phys. Lett.*, vol. 70, no. 23, pp. 3125–3127, 1997.

[5] H. J. Osten, G. Lippert, D. Knoll, R. Barth, B Heinemann, H. Rucker, and P. Schley, "The effect of carbon incorporation on SiGe heterobipolar transistor performance and process margin," in *IEDM Tech. Dig.*, 1997, pp. 803–806.

[6] P. Ashburn, H. Boussetta, M. Hashim, A. Chantre, M. Mouis, G. Parker, and G. Vincent, "Electrical determination of bandgap narrowing in bipolar transistors with epitaxial Si, epitaxial $Si_{1-x}Ge_x$, and ion implanted bases," *IEEE Trans. Electron Devices*, vol. 43, pp. 774–782, May 1996.

[7] B. Le Tron, M. Hashim, P. Ashburn, M. Mouis, A. Chantre, and G. Vincent, "Determination of bandgap narrowing and parasitic energy barriers in SiGe HBT's integrated in a bipolar technology," *IEEE Trans. Electron Devices*, vol. 44, pp. 715–722, May 1997.

[8] A. Gruhle, "The influence of emitter-base junction design on collector saturation current, ideality factor, Early voltage, and device switching speed of Si/SiGe HBT's," *IEEE Trans. Electron Devices*, vol. 41, pp. 198–203, Feb. 1994.

[9] S. C. Jain, J. Poortmans, S. S. Iyer, J. Loferski, J. Nijs, R. Mertens, and R. van Overstraeten, "Electrical and optical bandgaps of Ge_xSi_{1-x} strained layers," *IEEE Trans. Electron Devices*, vol. 40, pp. 2338–2342, Dec. 1993.

[10] K. Eberl, K. Brunner, and W. Winter, "Pseudomorphic $Si_{1-y}C_y$ and $Si_{1-x-y}Ge_xC_y$ alloy layers on Si," *Thin Solid Films*, vol. 294, pp. 98–104, 1997.