

Graded-Base Si/Si_{1-x}Ge_x/Si Heterojunction Bipolar Transistors Grown by Rapid Thermal Chemical Vapor Deposition with Near-Ideal Electrical Characteristics

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Abstract—Graded-base and uniform base Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors with near-ideal base and collector currents have been fabricated by rapid thermal chemical vapor deposition (RTCVD). The temperature dependences of the collector currents are shown to obey a simple analytical model that can be applied to devices which have arbitrary base profiles. The base currents are independent of base composition, and current gains in excess of 11 000 have been observed at 133 K.

I. INTRODUCTION

NARROW-bandgap-base Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors are attractive devices for high-speed bipolar integrated circuits. To date, HBT's have been reported in material grown by molecular beam epitaxy (MBE) [1], limited reaction processing (LRP) [2], and by ultrahigh-vacuum chemical vapor deposition (UHV-CVD) [3], [4]. To date, only the UHV-CVD technique has produced devices with ideal collector characteristics and ideally low base currents. In this letter we report the successful fabrication of graded-base and uniform-base Si/Si_{1-x}Ge_x/Si HBT's with near-ideal electrical characteristics by rapid thermal chemical vapor deposition (RTCVD). A simple model is presented to explain the temperature dependence of the collector current in the graded-base devices, and current gains as large as 11 000 at 133 K have been observed.

II. STRUCTURE AND FABRICATION

The RTCVD growth technique is a combination of rapid thermal processing and chemical vapor deposition, but differs from LRP [5] in that fast gas switching, rather than the sample temperature, is used to start and stop growth periods. This avoids the potential drawback of low-quality growth during the temperature ramps, but allows for the growth temperature of each layer to be optimized in a multilayer structure. The reactor essentially consists of a 175-mm quartz

tube which is evacuated only by a rotary-vane pump. Except for a loadlock apparatus which allows wafers to be introduced into the reactor without venting to atmospheric pressure, the vacuum system is similar to that in a conventional LPCVD system. The wafer is heated by tungsten-halogen lamps located outside the quartz tube, and the wafer temperature is accurately controlled by the infrared transmission method [6] for temperatures under 800°C. Typical growth conditions use dichlorosilane and germane sources in a hydrogen carrier at 6 torr. Diborane and phosphine are used for *in-situ* doping.

The vertical transistor structures discussed in this paper are described in Table I. The entire device structure (collector/base/emitter) was grown epitaxially *in situ*, and was the same on all devices except for the base. A control device had an all-silicon base, four graded-base devices had germanium fractions varying linearly from emitter to collector of 0–20%, 7–20%, 13–20%, and 20–20% (no grading) atomic germanium fraction, respectively. The grading in the base bandgap provides a built-in field to decrease the base transit time [4], [8]. The device structures were grown on 4-in n-type (100) silicon wafers which were loaded into the reactor after a chemical clean. After a 1000°C bake in hydrogen (1 min), an n⁺ (10¹⁹ cm⁻³, ~ 1 μm thick, 1000°C) subcollector was first grown, followed by the collector (~ 5 × 10¹⁷ cm⁻³, 0.3 μm, 1000°C). The wafer temperature was then lowered to grow the base layers. All base layers with less than x = 0.13 were grown at 700°C, and those with over x = 0.13 were grown at 625°C. The grading was accomplished by varying the germane flow as a function of time. The diborane flow was also adjusted with time to achieve an approximately flat boron profile across all bases of 2–5 × 10¹⁸ cm⁻³. The nominal base thicknesses were 500 Å, except device #5 which was ~ 350 Å. After the base growth, the temperature was raised to 850°C and the emitter layer was grown (~ 5 × 10¹⁷ cm⁻³, 0.25 μm). Based on X-ray diffraction measurements on these samples and previous transmission electron microscopy (TEM) of similar samples, it is thought that the SiGe layers are strained without misfit dislocations. Calibrated secondary ion mass spectroscopy (SIMS) profiles of a typical epitaxial structure before the emitter implant (#1, 0–20% grading) are shown in Fig. 1. The germanium profile (plotted on a linear scale)

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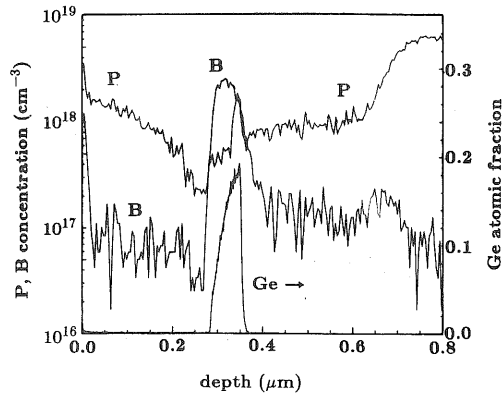


Fig. 1. SIMS profile of device #1 (Ge profile 0–20%) before the emitter implant. Note that the Ge is plotted on a linear scale.

TABLE I
DEVICE STRUCTURES OF THIS EXPERIMENT; BANDGAPS ARE FROM [7]

device #	% Ge at base-emitter junction	$\Delta E_{G,1}$ (meV)	% Ge at base-collector junction	$\Delta E_{G,2}$ (meV)
1	0	0	20	168
2	7	59	20	168
3	13	109	20	168
4	20	168	20	168
5	0	0	0	0

confirms the grading. The small phosphorus spike at the base-collector interface is an unintentional anomaly related to the low base growth temperature. It is thought to be due to a combination of residual phosphorus in the growth chamber from the collector growth and the vastly increased sticking coefficient of phosphorus at low temperature [9]. Subsequent experiments have shown that it can be eliminated by purging the reactor between the collector and base growth cycles. Except for device #3 (discussed later), it is thought that it has little effect on the device performance other than to partially compensate a small fraction (10%) of the base.

The back-end processing was nearly identical to that described by King *et al.* [2], except that an anneal of 800°C, 10 min was used to activate the emitter implant (10^{15} cm^{-2} , 15 keV As⁺) and base contact implants (boron, total dose = $1.5 \times 10^{15} \text{ cm}^{-2}$). In brief, the base-emitter is junction isolated and the base-collector is mesa isolated. SiO₂ sidewall passivation and Ti/Al metallization were used. The base-emitter area of the final devices was $80 \times 80 \mu\text{m}^2$. The measured intrinsic base sheet resistance in the final devices ranged from 6 to 12 k Ω/\square , consistent with the base thicknesses and doping ranges, except on device #3, which had an anomalously high resistance of $\sim 44 \text{ k}\Omega/\square$. SIMS revealed that an exceptionally large phosphorus spike compensated most of the intended base region, leading to a grading of only 13 to $\sim 15\%$ Ge across the p-type base region instead of the desired 13 to 20%.

III. RESULTS AND DISCUSSION

Gummel plots of all five devices are shown in Fig. 2. As can be seen, despite the different base profiles, all devices have nearly identical base currents, with a near-ideal slope of

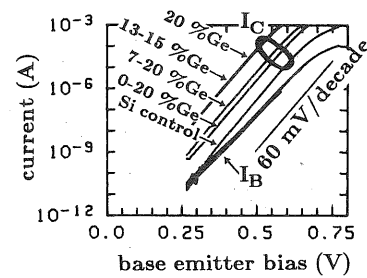


Fig. 2. Base and collector currents versus base-emitter bias for the devices of Fig. 1 for zero base-collector bias. Note that the base currents of the five devices are indistinguishable.

$\sim 60 \text{ mV/decade}$. Since the emitter structure is the same in all devices, all Si- and SiGe-base devices with similar emitters should have identical base currents. This has indeed been observed in devices grown by UHV-CVD [3], although in the UHV-CVD devices the critical base-emitter junction was formed by diffusion from polysilicon, and there was at most 5% Ge at that junction. Previous Si/SiGe/Si HBT's grown by non-UHV techniques (LRP), however, had base currents with a 60-mV/decade slope, but which were ~ 50 times larger than those of the all-silicon control devices. As pointed out by King *et al.* [2], the high base currents may have been due to low lifetime in the SiGe, leading to $n = 1$ recombination in the heavily doped, narrow-bandgap (SiGe) side of the base-emitter junction depletion region. (The SiGe layers in those devices contained $\sim 10^{20} \text{ cm}^{-3}$ oxygen). Through the use of a load lock, we have reduced the oxygen levels in our SiGe layers grown at 625°C to less than the SIMS resolution of 10^{18} cm^{-3} . That the base currents in all of our SiGe-base devices were nearly identical to the base current in the all silicon-device suggests that the high oxygen levels were indeed responsible for the high base currents in the HBT's of [2]. Further evidence of the deleterious effects of high oxygen levels is given by the fact that high oxygen levels in SiGe quench the photoluminescence signal normally seen in our films [10].

The collector currents have an ideal slope of 60 mV/decade at room temperature, with the collector current increasing as expected as the germanium level is raised in the base. The collector current enhancement in flat-base n-p-n HBT's compared to silicon devices is known to be well approximated by $\exp[\Delta E_V/kT]$, where ΔE_V is the valence-band offset [1], [2]. In graded-base devices, conventional Gummel number theory can be modified by realizing that for equal Fermi levels, p-type SiGe-doped N_A and Si-doped $N_A \cdot \exp(-\Delta E_G/kT)$ present the same conduction-band-edge potential to an electron, where ΔE_G is the bandgap reduction in the SiGe compared to Si. By "transforming" the HBT into a silicon device, one can then model the HBT as having an "effective" base Gummel number $N_{G, \text{eff}}$ [11]:

$$N_{G, \text{eff}} = \int_{\text{neutral base}} \frac{\text{DOS}(\text{Si})}{\text{DOS}(\text{SiGe})} N_A(x) e^{-\Delta E_G(x)/kT} dx \quad (1)$$

where DOS refers to the band-edge effective density-of-states product, $N_C N_V$. In the case of linear grading (and ignoring the DOS ratio), this can easily be evaluated analytically to

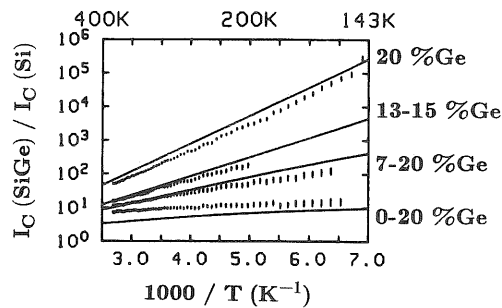


Fig. 3. Temperature dependence of the collector current enhancement of the various HBT samples, plotted along with the predictions of (1) using the structural data of Fig. 1 (except device #3, 13–15% Ge).

yield

$$N_{G,\text{eff}} = \frac{W \cdot N_A \cdot kT}{\Delta E_{G,2} - \Delta E_{G,1}} e^{-\frac{\Delta E_{G,1}}{kT}} \left(1 - e^{-\frac{-(\Delta E_{G,2} - \Delta E_{G,1})}{kT}} \right) \quad (2)$$

where W is the neutral base width and $\Delta E_{G,1}$ and $\Delta E_{G,2}$ are the minimum and maximum bandgap reductions compared to silicon. Differences in mobilities and spike-and-notch effects have been omitted in this model for simplicity.

Using (1) and the target growth parameters of Table I (except for 13–15% Ge grading in device #3 as discussed above), the results of this model for the collector current enhancement of the HBT's have been compared to the data from 143 to 373 K (Fig. 3). The results were corrected for any known differences in the Gummel numbers of the different devices (from base sheet resistance and SIMS measurements), and density-of-states effects were included [12]. No parameters were adjusted. The small discrepancies between the model and the data can all be explained by uncertainties in the base compositions on the order of $\Delta x = 0.01$, and by possible mobility differences between Si and $\text{Si}_{1-x}\text{Ge}_x$. At low temperatures, the current gain of silicon bipolar transistors typically degrades because of the increased effect of bandgap narrowing in the heavily doped emitter. (Note that our devices also include a heavily doped silicon emitter.) Because the narrow-bandgap base can more than compensate for this effect, the gains of the HBT's with more than 7% Ge at the base-emitter junction increase substantially at lower temperatures (Fig. 4). Device #4 (20% Ge base) has a maximum current gain over 11 000 at 133 K. To the best knowledge of the authors, this is the highest current gain ever been reported for a silicon-based bipolar transistor in this temperature range.

IV. CONCLUSIONS

$\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ graded-base and flat-base HBT's have been fabricated by rapid thermal chemical vapor deposition.

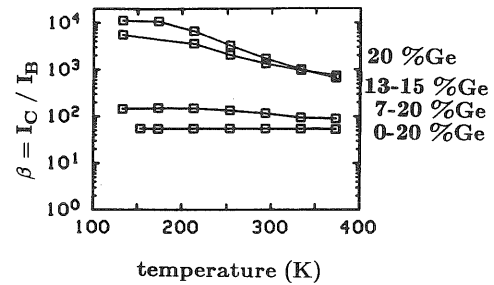


Fig. 4. Maximum current gain versus temperature of the HBT's.

Low oxygen concentrations in $\text{Si}_{1-x}\text{Ge}_x$ grown at 625°C and near-ideal base currents that do not increase as Ge is added to the base can be achieved without the use of UHV techniques. A simple analytical model of an effective Gummel number can be used to accurately describe the temperature performance of the collector current in graded base HBT's. Current gains as large as 11 000 have been obtained at cryogenic temperatures.

REFERENCES

- [1] G. L. Patton, S. S. Iyer, S. L. Delage, S. Tiwari, and J. M. C. Stork, "Silicon-germanium-base heterojunction bipolar transistors by molecular beam epitaxy," *IEEE Electron Device Lett.*, vol. 9, pp. 165–167, 1988.
- [2] C. A. King, J. L. Hoyt, and J. F. Gibbons, "Bandgap and transport properties of $\text{Si}_{1-x}\text{Ge}_x$ by analysis of nearly ideal $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 36, pp. 2093–2104, 1989.
- [3] G. L. Patton *et al.*, "Graded-SiGe-base, poly-emitter heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. 10, pp. 534–536, 1989.
- [4] G. L. Patton *et al.*, "75-GHz f_T SiGe-base heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. 11, pp. 171–173, 1990.
- [5] J. F. Gibbons, C. M. Gronet, and K. E. Williams, "Limited reaction processing: Silicon epitaxy," *Appl. Phys. Lett.*, vol. 47, pp. 721–723, 1985.
- [6] J. C. Sturm, P. M. Garone, and P. V. Schwartz, "Temperature control of silicon-germanium epitaxial growth on silicon substrates by infrared transmission," *J. Appl. Phys.*, vol. 69, pp. 542–544, 1991.
- [7] R. People and J. C. Bean, "Band alignments of coherently strained $\text{Ge}_x\text{Si}_{1-x}/\text{Si}$ heterostructures on (001) $\text{Ge}_y\text{Si}_{1-y}$ substrates," *Appl. Phys. Lett.*, vol. 48, pp. 538–540, 1986.
- [8] H. Kroemer, "Zur Theorie des Diffusions- und Drift-transistors," *Arch. Elect. Übertragung*, vol. 8, pp. 223–228, 1954.
- [9] B. S. Meyerson and M. L. Yu, "Phosphorus-doped polycrystalline silicon via LPCVD, II: Surface interactions of the silane/phosphine/silicon system," *J. Electrochem. Soc.*, vol. 131, pp. 2366–2368, 1984.
- [10] J. C. Sturm *et al.*, "Well-resolved band-edge photoluminescence of excitons confined in strained $\text{Si}_{1-x}\text{Ge}_x$ quantum wells," *Phys. Rev. Lett.*, vol. 66, pp. 1362–1365, 1991.
- [11] H. Kroemer, "Two integral relationships pertaining to the electron transport through a bipolar transistor with a nonuniform energy gap in the base region," *Solid-State Electron.*, vol. 28, pp. 1101–1103, 1985.
- [12] E. J. Prinz, P. M. Garone, P. V. Schwartz, X. Xiao, and J. C. Sturm, "The effect of base-emitter spacers and strain-dependent densities of states in $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ heterojunction bipolar transistors," in *IEDM Tech. Dig.*, 1989, pp. 639–642.