

THE EFFECT OF BASE-EMITTER SPACERS AND STRAIN-DEPENDENT DENSITIES OF STATES IN Si/Si_{1-x}Ge_x/Si HETEROJUNCTION BIPOLAR TRANSISTORS

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ABSTRACT

We describe two new effects which can significantly affect the transport of electrons across the base region of Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors (HBT) and limit the effective bandgap reduction. These effects are the formation of a parasitic electron barrier due to a nonabrupt base emitter junction and the reduction of the density of states in the Si_{1-x}Ge_x base layer because of the nonisotropic strain. Junction spacers have been found to eliminate the parasitic barriers for optimum devices.

INTRODUCTION

Recently, npn Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors have shown much promise for high speed bipolar transistor technology (1, 2). The central feature of these devices is the narrow bandgap base which increases the electron current injected from the emitter into the base and hence the collector current by $e^{\Delta E_{G,eff}/k_B T}$ compared to a similar homojunction device at the same bias. $\Delta E_{G,eff}$ is the effective bandgap reduction in the base and is a figure of merit for the structure. This increase in the collector current allows the device to have a high emitter efficiency and thus high gain even with a lightly doped emitter and a heavily doped base. The expression for collector current density then becomes

$$J_C = \frac{qD_n N_C N_V}{W N_A} e^{\frac{-E_{G,eff}}{k_B T}} e^{\frac{qV_{be}}{k_B T}} \quad (1)$$

where $E_{G,eff}$ is the effective bandgap for electron transport across the base, D_n is the minority carrier diffusion coefficient in the Si_{1-x}Ge_x base, N_C , N_V , W , and N_A are conduction and valence band densities of states, basewidth, and base doping, respectively. In the ideal case, $\Delta E_{G,eff}$ is equal to the valence band offset which is 80% of the actual bandgap difference ΔE_G in the material system.

This paper describes how the non-abruptness of the base emitter junction and the reduction of the density of states in the Si_{1-x}Ge_x base can reduce the collector current increase and the effective band gap reduction $\Delta E_{G,eff}$.

INFLUENCE OF NON-ABRUPT JUNCTIONS ON $\Delta E_{G,eff}$

In a simple npn HBT structure, the entire Si_{1-x}Ge_x base layer is heavily doped with boron, however mixing during growth, autodoping, and diffusion during subsequent processing can cause some outdiffusion of the boron dopant from the base into the silicon emitter region. This pushes the p⁺n base emitter junction into the silicon and introduces parasitic electron barriers between the emitter and base as well as between base and collector.

A simulation of the effect of base dopant outdiffusion on the effective bandgap reduction for the HBT structure of Fig. 1 is considered. The emitter and collector are lightly doped compared to the base, and boron outdiffusion is modelled by Gaussian boron tails of half width of half maximum L_D extending from the Si_{1-x}Ge_x base into emitter and collector. All simulations were performed with a modified version of SEDAN III (3). The band diagram in the forward active region in Fig. 1 shows parasitic barriers at the base emitter and the base collector junctions whose heights increase with increasing L_D . These barriers cause a reduction in the effective bandgap difference. It can be found from the temperature dependence of the collector current density of the HBT which is usually normalized to the corresponding value of a homojunction device to eliminate the temperature dependences of mobility and effective density of states in Eqn. 1, which are here assumed to be equal for homo- and heterojunction devices. The slope of a plot of this collector current ratio vs. $1/T$, shown in Fig. 2, yields the effective bandgap reduction in the base. These calculations show that even small amounts of outdiffusion can cause significant shifts in bandgap difference.

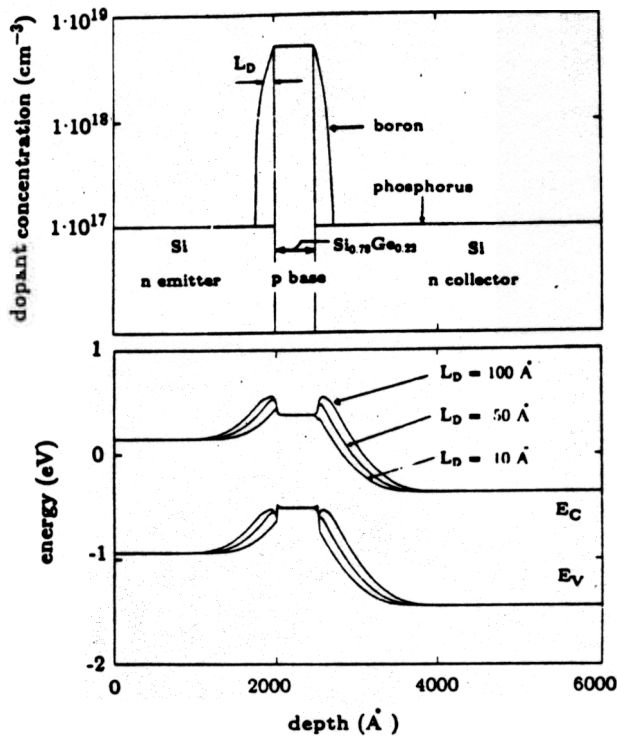


Fig. 1. HBT structure used in simulating the effect of boron outdiffusion on device performance, and resulting band structures in forward active mode. Simulations were done with outdiffusion tails from the ideal box profile of $L_D=10, 50,$ and 100 \AA . Note the parasitic electron barriers formed by the outdiffusion.

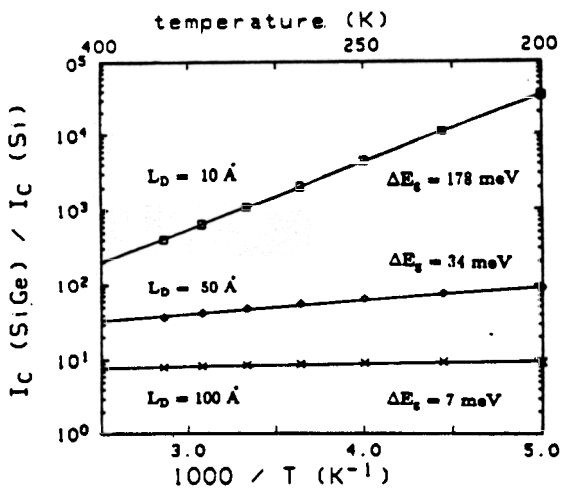


Fig. 2. Simulation plots of collector current ratio in HBT to that in control Si device vs. $1/T$ for varying amounts of outdiffusion. The slope yields the effective bandgap reduction in the base (Large outdiffusion \Rightarrow small bandgap shift).

To test this hypothesis, test transistor structures were grown in-situ on $\langle 100 \rangle$ n-type silicon substrates by a modified version of Limited Reaction Processing (5). This technique is a combination of rapid thermal annealing and chemical vapor deposition. After a chemical cleaning, the wafers were loaded into the reactor and then given a hydrogen bake at 1150°C for 2 minutes. In hydrogen carrier gas n^+ buffer layers were grown at 1000°C using dichlorosilane and phosphine, followed by the n collector layers doped 10^{17} cm^{-3} at 850°C . The base layers doped 10^{19} cm^{-3} were grown at 825°C using dichlorosilane, germane and diborane. Finally, emitter layers were grown at 800°C and doped 10^{17} cm^{-3} . Doping profiles and germanium concentrations on all samples were measured by calibrated SIMS. Transmission electron microscopy on all samples revealed a negligible amount of misfit dislocations confirming the strain in the $\text{Si}_{1-x}\text{Ge}_x$ layers.

In some of the devices undoped $\text{Si}_{1-x}\text{Ge}_x$ spacer layers ($\sim 100 \text{ \AA}$) were intentionally introduced on both sides of the heavily doped base. The purpose of these spacers is to keep the electrical junction at the $\text{Si}_{1-x}\text{Ge}_x$ interface even if slight boron outdiffusion does occur and thus to prevent the formation of parasitic barriers.

Using these layered structures, devices were fabricated using a planar process (Fig. 3). Contact to the base layer was established by implanting boron. Since the base contact implant surrounds the active device area, perimeter recombination due to interface states is negligible. A shallow arsenic implant was used to form ohmic emitter contacts. The devices were passivated by a low temperature deposited silicon dioxide film, and implants were annealed for two minutes at 800°C . Titanium/aluminum metallization and patterning completed the processing.

Typical collector current characteristics for homo- and heterojunction devices at different temperatures are shown in Fig. 4. As expected from Eqn. 1, the collector current of the HBT is enhanced by several orders of magnitude. In Fig. 5 the normalized collector current for several devices is plotted vs. $1/T$ to obtain $\Delta E_{G, \text{eff}}$. This value is then compared in Fig. 6 to calculated values of ΔE_G by People (3) which were confirmed by optical measurements of Lang et al (6). The devices with spacers have shifts in close agreement with those calculations since the valence band difference is about 80% of the full bandgap difference. The bandgap shift of the device without spacers is significantly smaller, indicating the existence of parasitic barriers for electrons.

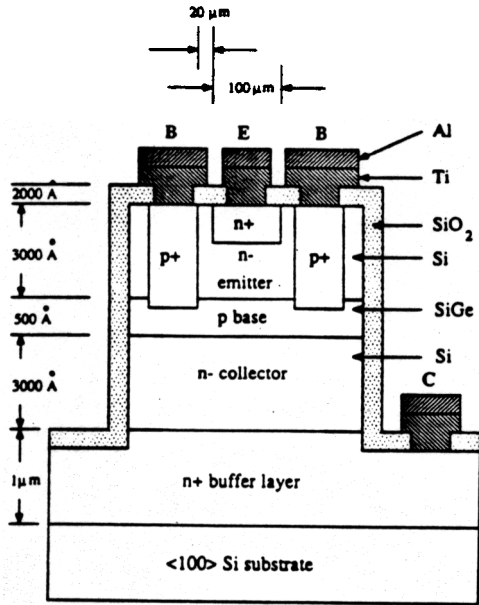


Fig. 3. Test transistor structure used for HBT experiments.

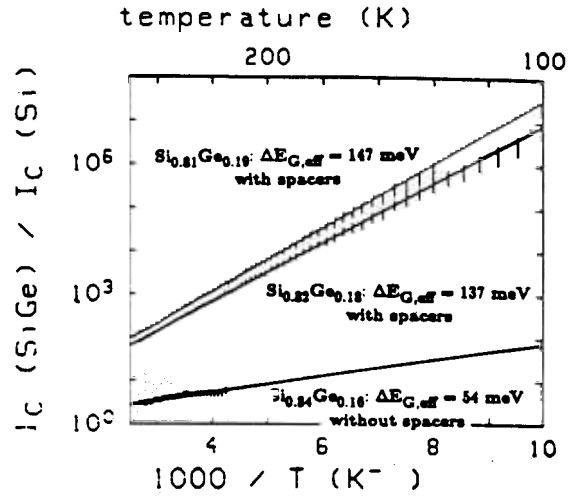


Fig. 5. Data showing ratio of collector current in HBT device to that in Si control device for HBT devices with and without spacers. Both devices have approximately 18% Ge in the base. The slope is the effective bandgap reduction $\Delta E_{G,eff}$.

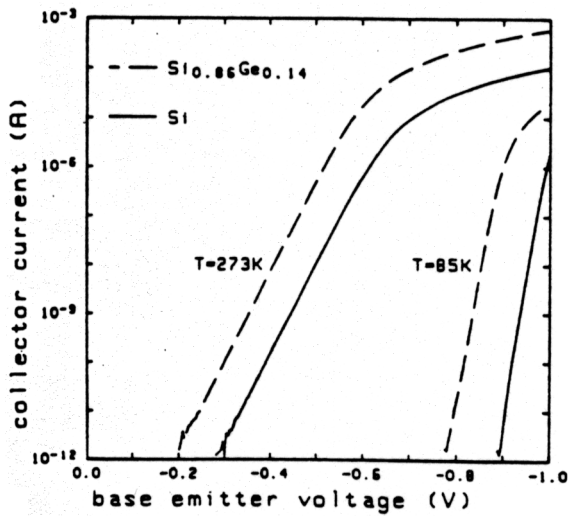


Fig. 4. Typical plot of collector current I_C vs base emitter voltage V_{be} for control and HBT device at several temperatures.

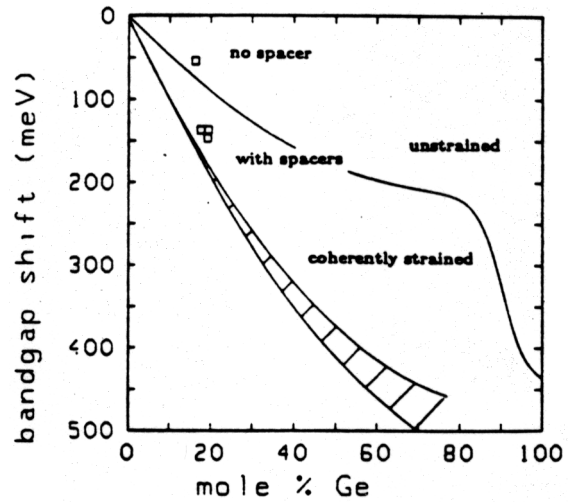


Fig. 6. Extracted bandgap shift $\Delta E_{G,eff}$ of HBT devices superimposed on the full band gap difference ΔE_G of $\text{Si}_{1-x}\text{Ge}_x$ calculated by People. All samples have negligible dislocations and are hence fully strained. Samples with spacers have shifts in close agreement with the valence band offset ($\sim 80\%$ of the full ΔE_G).

THE INFLUENCE OF THE STRAIN DEPENDENT DENSITIES OF STATES ON COLLECTOR CURRENT

The second effect investigated results from the fundamental splitting of the conduction and valence band degeneracies in the non-isotropically strained $\text{Si}_{1-x}\text{Ge}_x$ (Fig. 7). The usual effective densities of states of the bands are then altered by a temperature dependent term which describes the relative population of the higher lying bands which are degenerate with no strain. The advantages of a smaller bandgap are thus diminished by a lower density of states, reducing the collector current in the device (Eqn. 1). Simple analysis using People's results (3) for conduction and valence band splitting shows a current reduction by a factor of ~ 2 for a device with over 20% Ge, compared to devices with the same bandgap but with "Si-like" bands in the base (Fig. 8). This is consistent with our device results for 19% Ge and spacers to avoid parasitic barrier effects. Comparing these devices to homojunction devices with the same base doping, the collector current is consistently lower by a factor of 1.5 - 2 than one would expect for the measured bandgap shift after correcting for Gummel number differences, and assuming the same temperature dependence of the minority carrier diffusion coefficient for homo- and heterojunction devices. When the splitting is on the order of $k_B T$, e.g. for low Ge content, a strong temperature dependence of the density of states can be expected, and hence the extracted base bandgap will be affected.

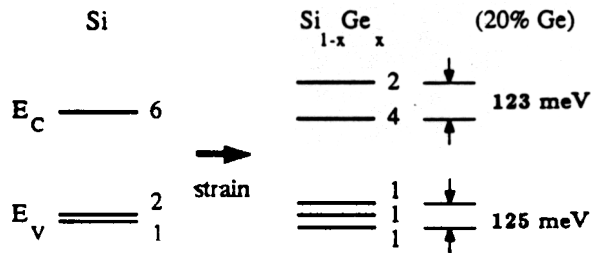


Fig. 7. Schematic view of band degeneracy splitting in strained $\text{Si}_{1-x}\text{Ge}_x$ and reduction of the effective density of states.

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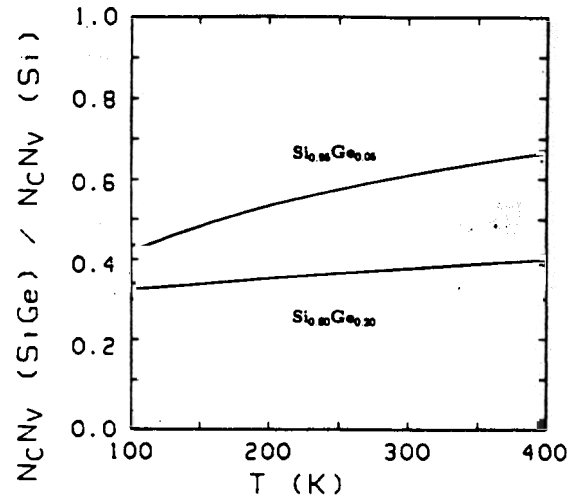


Fig. 8. Calculated ratio of $N_C \cdot N_V$ in $\text{Si}_{1-x}\text{Ge}_x$ to that in Si (using equal effective masses) for $x = 0.05$ and $x = 0.20$. This reduction is reflected in reduced collector current.

CONCLUSIONS

The effects of interfacial abruptness and discontinuity of densities of states in $\text{Si}_{1-x}\text{Ge}_x$ heterojunction bipolar transistors have been investigated. For optimum device performance it is necessary to keep the Si/Si_{1-x}Ge_x interfaces in the junction depletion region. The strain dependence of the densities of states in the base region lowers collector current.

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