Band-gap shifts in silicon-germanium heterojunction bipolar transistors

J. C. Sturm, E. J. Prinz, P. M. Garone, and P. V. Schwartz
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

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The band gap of the base of $Si_{1-x}Ge_x$ strained-layer base heterojunction bipolar transistors has been investigated using minority-carrier transport measurements. We have found a band-gap reduction of 131 meV for a base of $Si_{0.82}Ge_{0.18}$, which is in reasonable agreement with theoretical calculations. Our measurements for a base of $Si_{0.85}Ge_{0.15}$ show a band-gap reduction less than predicted, suggesting a reduction of strain in the structure.

Recently there has been considerable interest in heterojunction bipolar transistors on silicon with a narrow band-gap base, using a strained-layer $Si_{1-x}Ge_x$ base on a silicon collector with a silicon emitter.[1,2,3] A key issue in these structures is the exact magnitude of the band-gap difference between the silicon emitter and the $Si_{1-x}Ge_x$ base regions. This is vitally important since the collector current enhancement depends exponentially on this amount. In this letter we present transistor data showing a larger band-gap shift than that observed by Patton *et al.*[1]

The transistor test structure was fabricated using a planar process from uniform epitaxial layers grown by a modified version of the limited reaction processing (LRP) technique[4] (Fig. 1). This technique is a novel combination of chemical vapor deposition and rapid thermal annealing. The starting materials for our experiments were *n*-type ⟨100⟩ silicon wafers, which were loaded into our LRP reactor after a chemical clean. After a high-temperature (1200 °C) bake in hydrogen to remove surface contamination, the wafer temperature was lowered to 1000 °C, and an n^+ silicon buffer layer was grown using dichlorosilane as the source gas in a hydrogen carrier. This layer was used to make contact to the collector of the transistors. An n^- layer grown at 850 °C would eventually become the collector region of the transistor. The growth temperature was then lowered to 680 °C, and the $Si_{1-x}Ge_x$ base layer was grown with a constant germanium content and constant *p*-type doping, using germane and diborane as the additional sources. The base width was approximately 500 Å, and the boron concentration was on the order of 5×10^{18} cm^{-3}. The three different wafers considered in this work were grown with different germanium concentrations for the base region, 0% germanium, $Si_{0.85}Ge_{0.15}$, and $Si_{0.82}Ge_{0.18}$. After the growth of the base layer, the wafer temperature was raised to 850 °C and a moderately doped (roughly 10^{17} cm^{-3}) *n*-type silicon emitter layer was grown to a thickness of 3000 Å. The germanium content in the base region was measured for each wafer in areas adjacent to those from which the transistor samples were taken by secondary-ion mass spectroscopy, calibrated against standards measured by Rutherford backscattering. Because of variations in the growth process there is a factor of 2 uncertainty in doping and of ±20% in layer thickness.

After the layer growth, the wafers were processed to form planar transistor structures. Contacts to the emitter and base layers were made by arsenic and boron implants, respectively. After implanting, the structures received a single anneal at 850 °C for 10 s. The emitter size was 62 μm × 62 μm, and the isolation etch was performed by plasma etching. The sidewalls of the mesa were passivated with plasma-deposited SiO_2. The metal contacts consisted of 1 μm of aluminum on top of 2000 Å of titanium.

The devices were evaluated by performing measurements of collector current (I_C) and base current (I_B) as a function of base-emitter bias (V_{be}). The base collector voltage (V_{bc}) was held at zero. Typical results of transistors from two wafers at room temperature are shown in Fig. 2. For all devices, the collector current follows the ideal characteristic

$$I_C \propto e^{qV_{be}/kT}. \qquad (1)$$

This must be the case in any true bipolar transistor structure with $V_{bc} = 0$ V, since the only mechanism for collector current is for electrons to be injected from the base into the emitter and then to diffuse to the collector. On the other hand, the base current in our devices is nonideal. This suggests a dominant recombination in the base emitter space-charge region. When such non-ideal base currents are observed the current gain of the device (I_C/I_B) is a measure not of the emitter efficiency, but of parasitic base recombination, and hence it is not a useful measure of the effect of the narrow band-gap base on the transistor performance. Because of this parasitic base current, the current gain in our devices was strongly dependent on base emitter bias.

In a heterojunction bipolar transistor in which the junctions are not perfectly abrupt (no "spike and notch"

Si	n emitter	10^{17}cm^{-3}	3000 Å
$Si_{1-x}Ge_x$	p base	$5\cdot10^{18}$cm^{-3}	500 Å
Si	n collector	10^{17}cm^{-3}	3000 Å
Si	n^+ buffer	10^{20}cm^{-3}	2 μm
	<100> Si substrate		

FIG. 1. Schematic cross section of the epitaxially grown layers.

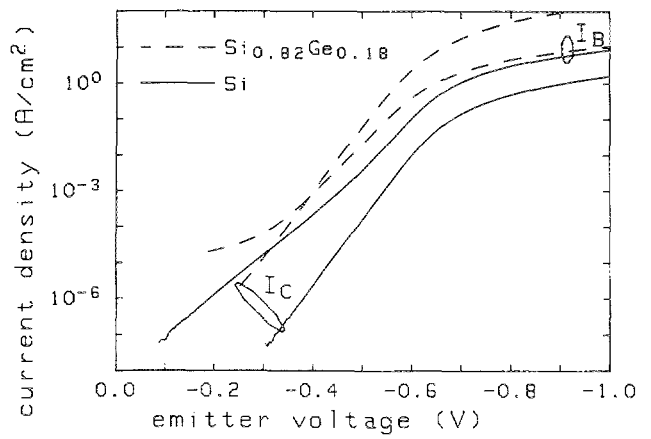

FIG. 2. Typical plots of collector and base current density vs base emitter bias at room temperature for homojunction and heterojunction devices.

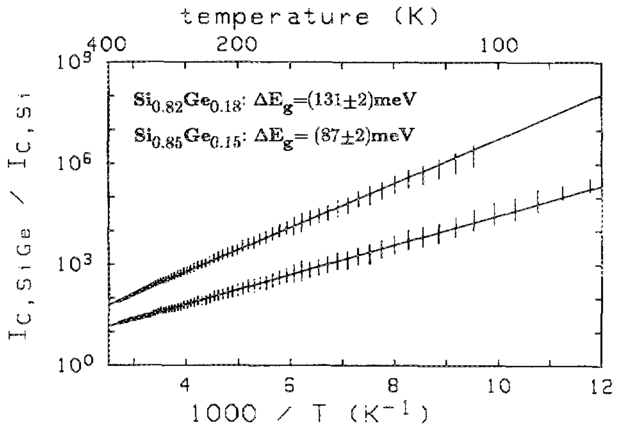

FIG. 3. Normalized collector current vs inverse temperature for varying amounts of germanium in the base. The lines represent best least-squares fits.

effects[5]), one expects the number of electrons injected into the base (and hence the collector current) to go as

$$n_p \simeq (n_i^2/N_A) e^{qV_{be}/kT}, \tag{2}$$

where n_i is the intrinsic carrier concentration in the base and N_A is the base doping. For a transistor with flat doping profiles, we can then write

$$J_C = (qD_n N_C N_V / W N_A) e^{-E_g/kT} e^{qV_{be}/kT} \tag{3}$$

or

$$J_C = J_C^0 e^{qV_{be}/kT}, \tag{4}$$

where

$$J_C^0 = (qD_n N_C N_V / W N_A) e^{-E_g/kT}, \tag{5}$$

J_C is collector current density, D_n is the electron diffusion coefficient in the $Si_{1-x}Ge_x$ layer, N_C, N_V, E_g, W, and N_A are densities of states, band gap, basewidth, and doping in the base region, respectively. Hence, as the band gap of the base is reduced by ΔE_g, we expect an increase in the collector current by a factor of $e^{\Delta E_g/kT}$. Similarly, one can show that the number of holes injected into the emitter (the base current in the ideal case) is unchanged as the *base* band gap is changed.

Hence, our transistor structures, since they exhibit ideal collector currents, can be used to infer ΔE_g as germanium is added to the base. In the ideal exponential regions (as seen in Fig. 2), the collector current data of the heterojunction transistors were normalized to those of a homojunction device with the same size over the range of 85–373 K. This ratio was plotted versus inverse temperature for both heterojunction devices, and an exponential was fit to the data using the best least-squares fit (Fig. 3). Assuming the same temperature dependence of D_n, N_C, and N_V for the homojunction and heterojunction devices, this fit yields the band-gap difference of the base regions.

Our data show an extracted $\Delta E_g = 131$ meV for $Si_{0.82}Ge_{0.18}$, and $\Delta E_g = 87$ meV for $Si_{0.85}Ge_{0.15}$. People has calculated a theoretical curve for the band gap of strained $Si_{1-x}Ge_x$ on silicon,[6] which was confirmed by optical measurements[7] (Fig. 4). A ΔE_g for 18% Ge of 173 meV is predicted. Thus, our experimental results for 18% Ge from transport measurements are in reasonable agreement with those calculations and confirm the strain in our structure. Earlier work on similar structures grown by molecular beam epitaxy showed a ΔE_g extracted by a similar technique to be only 59 meV for a base with 12% Ge.[1]

Assuming that the Ge concentration was accurately known in that work and that the base layers were strained, it is possible that deleterious spike and notch effects in their structure accounted for part of the difference. In any case, since the collector current depends exponentially on this ΔE_g, it appears significantly more advantageous to build heterojunction bipolar transistors with $Si_{1-x}Ge_x$ bases than previously reported. Possible reasons for the discrepancy between our measured 131 meV and the predicted 173 meV include spike and notch effects and a difference in the temperature dependence of N_C, N_V, and D_n [Eq. (5)] in the Si and $Si_{1-x}Ge_x$ samples. Work is under way to discriminate between these effects. For 15% Ge, our ΔE_g of 87 meV is significantly less than the 146 meV of People, which suggests that the strain in the base layer was somewhat relaxed. This is consistent with transmission electron microscopy studies

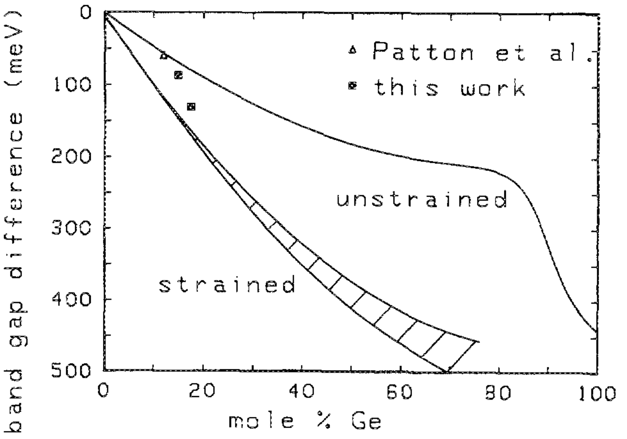

FIG. 4. Base band gap vs germanium content. Our points have been superimposed on People's calculation.

showing misfit dislocations (spacing $\simeq 0.5\ \mu m$) in this sample. The error bars on our points in fig. 4 are 0.01 in germanium fraction and 2 meV for ΔE_g

In conclusion, we have shown that one can expect a collector current enhancement in silicon-germanium strained-layer base heterojunction bipolar transistors higher than previously reported. The enhancement is in reasonable agreement with theoretical calculations of the band-gap shift for our sample with 18% germanium in the base.

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