

Base Resistance and Effective Bandgap Reduction in n-p-n Si/Si_{1-x}Ge_x/Si HBT's with Heavy Base Doping

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Abstract—This paper presents a comprehensive study of the effects of heavy doping and germanium in the base on the dc performance of Si/Si_{1-x}Ge_x/Si npn Heterojunction Bipolar Transistors (HBT's). The lateral drift mobility of holes in heavily doped epitaxial SiGe bases affects the base sheet resistance while the effective bandgap is crucial for the vertical minority carrier transport. The devices used in this study were Si_{1-x}Ge_x npn HBT's with flat Ge and B profiles in the base grown by Rapid Thermal Chemical Vapor Deposition (RTCVD).

Hall and drift lateral hole mobilities were measured in a wide range of dopings and Ge concentrations. The drift mobility was indirectly measured based on measured sheet resistivity and SIMS measurements, and no clear Ge dependence was found. The Hall scattering factor is less than unity and decreases with increasing Ge concentration. The effective bandgap narrowing, including doping and Ge effects, was extracted from the room temperature collector current measurements over a wide range of Ge and heavy doping for the first time. We have observed bandgap narrowing due to heavy base doping which is, to first order, independent of Ge concentration, but less than that observed in silicon, due to the effect of a lower density of states. A model for the collector current enhancement with respect to Si devices versus base sheet resistance is presented.

I. INTRODUCTION

IN recent years, Si/Si_{1-x}Ge_x HBT's have received increasing attention because of their improved performance compared to Si bipolar transistors, and the possibility of integration into Si technology. Since the first high f_T reported in 1990 [1] the HBT design has advanced rapidly and f_T 's of over 100 GHz were reported more recently [2], [3]. A DAC circuit built in SiGe technology showed a significant improvement in speed performance compared to typical Si circuit [4].

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Although high performance devices have been demonstrated, experimental data for even dc modeling of these devices is still particularly lacking. For example, the effects of heavy base doping on vertical electron and lateral hole currents have not been substantially experimentally measured. Such heavy base doping is often employed in the design of narrow-base devices. Vertical minority carrier transport, crucial for accurate modeling of collector current, depends on the bandgap narrowing induced by heavy doping. Lateral hole current, which is important for base resistance, depends on the hole drift mobility. One needs to study both the effects of Ge and the doping to understand and accurately predict the performance of Si/Si_{1-x}Ge_x HBT's.

In this paper, we present the first set of comprehensive measurements of lateral hole current and vertical electron current across the strained Si_{1-x}Ge_x base of an npn HBT over a wide range of base dopings and Ge concentrations. Based on room temperature measurements, we have extracted the effective bandgap for electron transport. We have also developed an empirical model for the collector current enhancement with respect to all-Si devices versus base sheet resistance.

II. DEVICE FABRICATION

For this study, we fabricated Si/Si_{1-x}Ge_x/Si HBT's with flat Ge and B profiles in the base grown by Rapid Thermal Chemical Vapor Deposition (RTCVD) [5]. Dichlorosilane was used as the Si source, germane and diborane as Ge and B gas sources in the base, respectively, and phosphine as a P source for emitter doping, all in a hydrogen carrier. Si_{1-x}Ge_x layers were grown at 625°C, while Si emitters were grown at 800°C for 7.5 min. Base dopings ranged from 10¹⁸ cm⁻³ to 10²⁰ cm⁻³ and Ge concentrations ranged from 0–27%. Base widths varied from 300–2000 Å. The devices with more Ge in the base had narrower bases to avoid strain relaxation, which was confirmed by defect etching. The Ge concentrations were measured by x-ray diffraction. The Ge fraction was measured by the shift of the (400) peak (Cu K α radiation line) using: $x = 0.178 \times \Delta(2\theta)$. The estimated error in x is ± 0.01 . Undoped SiGe base-emitter and base-collector layers, 50–200 Å thick were introduced to avoid parasitic barriers due to boron outdiffusion during the emitter growth [6]. SIMS measurements confirmed flat profiles, base dopings,

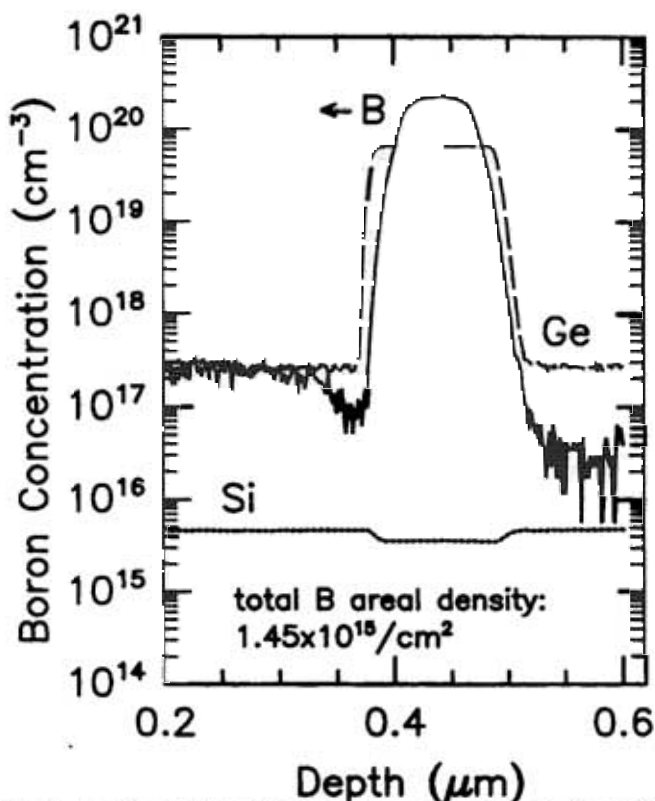


Fig. 1. A typical SIMS profile of a device used in this study. Si and Ge are in arbitrary units. B was contained within the SiGe layer even for the heaviest doped devices.

and widths, and that the B-doping was contained within the SiGe layer (Fig. 1).

The device structure is shown in Fig. 2. Van der Pauw patterns for base resistance measurements were made on each sample in addition to transistors. A simple double mesa wet-etch process without any thermal cycles over 400°C was used to prevent any possibility of parasitic barriers due to the thermal diffusion. No emitter implants were used since these can cause anomalous base dopant diffusion in $\text{Si}_{1-x}\text{Ge}_x$ HBT's for even moderate temperatures [7] and thus cause parasitic barriers. A selective wet etch [8] was used to remove the emitter for contacting the base layer. The highest temperature step in the whole process was during the emitter growth. We have done experiments prior to this study to confirm that the $\text{Si}_{1-x}\text{Ge}_x$ layers were fully strained and no barrier formation occurred during the emitter growth (also confirmed by SIMS). The emitter area of transistors ranged from 20×20 – $100 \times 100 \mu\text{m}^2$. No significant perimeter effects in the collector current measurements were observed.

III. MAJORITY CARRIER PROPERTIES

Lateral hole mobility in p-type heavily doped $\text{Si}_{1-x}\text{Ge}_x$ is of great importance for accurate modeling of base sheet resistance. The mobility important for base sheet resistance is the low-field drift mobility. However, the most often measured mobility is the one measured by Hall measurements, i.e., Hall mobility. Drift and Hall mobilities reflect the band structure

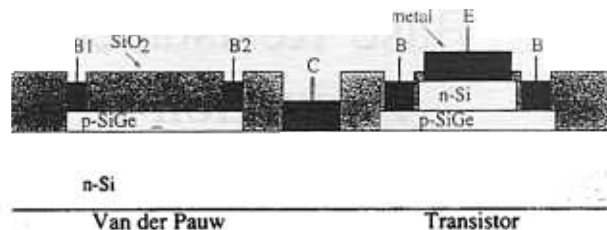


Fig. 2. A typical device structure used in this study. Van der Pauw patterns were fabricated next to transistor devices.

and scattering mechanism in different ways. They are the same in case of parabolic or spherical energy bands and energy-independent carrier scattering times. This is not the case, however, in heavily doped, strained $\text{Si}_{1-x}\text{Ge}_x$. The ratio of Hall and drift mobility is usually defined as the Hall scattering factor ($r_H = \mu_{p, \text{Hall}} / \mu_{p, \text{drift}}$).

The strain affects the band structure in $\text{Si}_{1-x}\text{Ge}_x$ alloys. The degeneracy of conduction and valence bands is lifted, moving four conduction band minima in the growth plane down with respect to the other two, and splitting heavy and light hole bands with the heavy hole band lying higher. Because of strain-induced changes in the energy bands of $\text{Si}_{1-x}\text{Ge}_x$ alloys, a reduction in hole effective mass compared to bulk Si is expected [9]. This would tend to cause a higher drift mobility [10], [11]. The effect is expected to be more pronounced in the direction perpendicular to the growth direction. On the other hand, the presence of alloy scattering would tend to reduce the hole mobility. Some experimental evidence exists to support an enhancement in hole drift mobility with increasing Ge concentration at a single doping level [12]. In this work we measured hole Hall mobilities, sheet resistivities, drift mobilities and Hall scattering factors over a wide range of dopings (10^{18} – 10^{20} cm^{-3}) and Ge concentrations (0–27%).

Fig. 3(a) shows the measured Hall mobility ($\mu_{p, \text{Hall}}$) of holes at room temperature as a function of base doping. Different symbols represent different Ge concentrations (x). A decrease in the Hall mobility with increasing doping is obvious, as expected due to the increase in ionized impurity scattering. However, for similar doping levels, Hall mobilities decrease with the increasing Ge concentration. This is clearly shown in Fig. 3(b) where the Hall mobility is plotted versus Ge concentration for devices with similar doping levels. The estimated errors in the base resistances and Hall mobilities are $\pm 10\%$ and $\pm 15\%$, respectively.

The measurement of drift mobility ($\mu_{p, \text{drift}}$) and Hall scattering factor requires an independent measurement of carrier concentration in the base, in addition to Hall measurements. The integrated hole concentration was obtained from SIMS profiles, assuming full dopant activation. The SIMS results were calibrated by implanted standards into similar $\text{Si}_{1-x}\text{Ge}_x$ layers. The results were also corrected for the expected effects of base-emitter and base-collector depletion regions, although these effects changed the total base charge by only $\sim 10\%$ in lightly doped bases (10^{18} cm^{-3}) and less than 1% in heavily doped bases. The full activation of B atoms is a reasonable assumption, since the emitters were grown at 800°C for 7.5 min. after the *in-situ* doped $\text{Si}_{1-x}\text{Ge}_x$ base layers. By

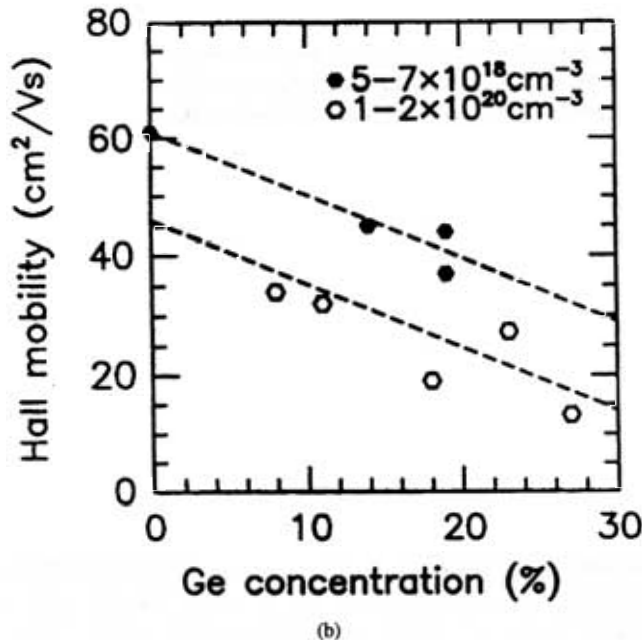
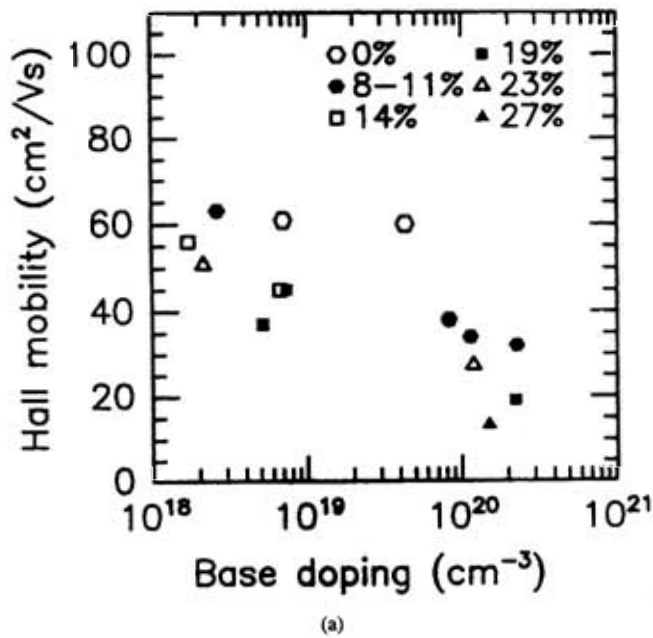


Fig. 3. (a) Hole lateral Hall mobility as a function of base doping for various Ge concentrations. (b) Hole lateral Hall mobility as a function of Ge concentration for different doping levels. The lines are drawn to guide the eye.

comparing the measured integrated hole concentration in the base by Hall measurements to those measured by SIMS, we extracted the Hall scattering factor. The accuracy of the extracted values for Hall scattering factor and drift mobility is expected to be $\pm 25\%$.

Fig. 4 shows the Hall scattering factor as a function of x . It is obvious that the Hall scattering factor decreases with increasing Ge content and for $x \geq 0.1$ is actually less than unity. No clear doping dependence of Hall scattering factor was observed. Note that if the hole concentrations were lower

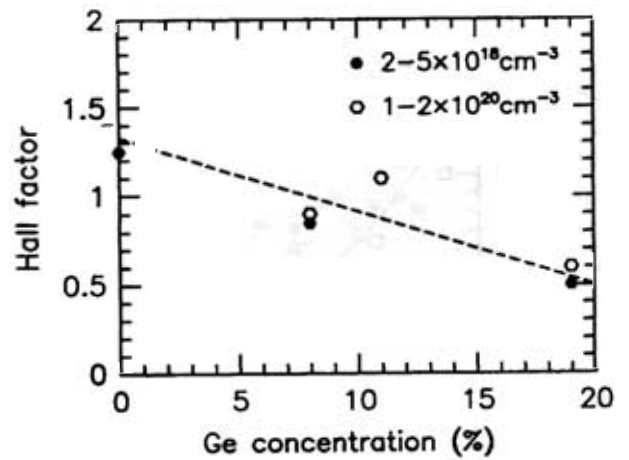


Fig. 4. Hall scattering factor for holes as a function of Ge concentration. The line is drawn to guide the eye.

than the chemical boron concentrations obtained by SIMS (due to incomplete dopant activation), the resulting Hall scattering factor would be even lower. A similar trend of decreasing Hall scattering factor with increasing Ge concentration was also observed by McGregor *et al.*, although over a much narrower doping range ($1.5\text{--}2.0 \times 10^{19} \text{ cm}^{-3}$). This behavior is not yet well understood. The difference between Hall and drift mobility depends on the detailed structure of the valence bands and hole scattering mechanisms which, to the knowledge of the authors, has not been addressed in $\text{Si}_{1-x}\text{Ge}_x$ strained alloys.

Fig. 5 shows drift mobility as a function of base doping for different Ge concentrations. The drift mobility clearly decreases with increasing doping. For similar doping levels a slight trend toward higher drift mobility with more Ge was seen. However, this trend was smaller than the error bars ($\pm 25\%$). Therefore, no definite trend of lateral hole mobility was obvious from our data. (Note that McGregor *et al.*, did observe an increase in drift mobility from 50–100 $\text{cm}^2/\text{V}\cdot\text{s}$ from $x = 0$ to $x = 0.2$ for a doping of $1.5\text{--}2.0 \times 10^{19} \text{ cm}^{-3}$). For subsequent modeling purposes, a best fit to experimental data is given by:

$$\mu_{p\text{drift}} = 20 + \frac{350}{1 + \left(\frac{N_A}{10^{17} \text{ cm}^{-3}}\right)^{0.5}} \quad (1)$$

This is plotted as a solid line in Fig. 5, and it is independent of Ge concentration. This model of hole drift mobility in a wide range of doping and Ge concentrations enables the prediction of base sheet resistance for an arbitrary structure. Within the vertical error bars ($\pm 25\%$), twelve of the fourteen points in Fig. 5 fall on the line given by (1).

IV. EFFECTIVE BANDGAP MEASUREMENTS

The effect of bandgap narrowing in heavily doped Si, relevant for electrical device performance, is often modeled as an increase in intrinsic effective minority carrier concentration [13]–[15]:

$$\begin{aligned} pn &= n_{i,eff}^2 \\ &= n_{i0}^2 e^{\Delta E_{G,eff}/k_B T} \end{aligned} \quad (2)$$

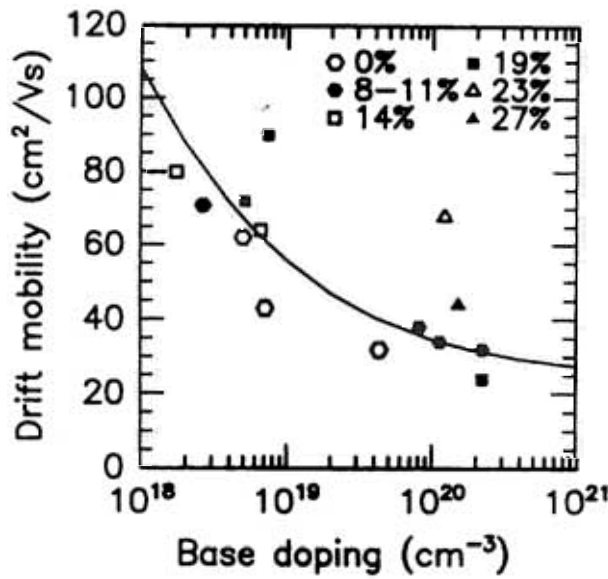


Fig. 5. Lateral hole drift mobility as a function of base doping for various Ge concentrations. The solid line is the best fit to our data.

where $n_{i,eff}$ is the effective intrinsic carrier concentration, n_{i0} is the true intrinsic carrier concentration and $\Delta E_{G,eff}$ is the effective (apparent) bandgap narrowing. We have extended this approach to HBT's, where $\Delta E_{G,eff}$ includes bandgap narrowing due to Ge in the base as well as heavy doping.

It is well known that the collector current density (J_C) of an HBT with flat Ge and doping profiles without parasitic conduction band barriers or spikes due to conduction band offsets in the base can be modeled as:

$$J_C = J_{C0} \times e^{qV_{BE}/k_B T} \quad (3)$$

where J_{C0} is the collector saturation current density:

$$J_{C0} = \frac{qD_n N_c N_v}{G_B} e^{-E_{G,eff}/k_B T} \quad (4)$$

D_n is the minority carrier diffusion coefficient, N_c and N_v are conduction and valence band densities of states, G_B is the Gummel number, and $E_{G,eff}$ is the effective bandgap for minority carrier concentration (all referring to the $\text{Si}_{1-x}\text{Ge}_x$ base). Because of the presence of spacer layers, any possible small conduction band offsets should not affect the collector current, so that a true $\Delta E_{G,eff}$ and not just a valence band offset is measured. The effective bandgap includes the effects of Ge and narrowing due to heavy doping. Equation (4) can be rewritten as follows:

$$J_{C0} = \frac{qD_{n,\text{SiGe}}}{G_{B,\text{SiGe}}} \frac{(N_c N_v)_{\text{SiGe}}}{(N_c N_v)_{\text{Si}}} n_{i0,\text{Si}}^2 e^{\Delta E_{G,eff}/k_B T} \quad (5)$$

where $\Delta E_{G,eff}$ is the effective bandgap reduction with respect to intrinsic Si. The ratio $(N_c N_v)_{\text{SiGe}}/(N_c N_v)_{\text{Si}}$ represents the reduction in effective densities of states in lightly doped $\text{Si}_{1-x}\text{Ge}_x$ due to strain-induced splitting of the bands. All heavy doping effects are included in $\Delta E_{G,eff}$.

Based on (5) there are two ways in which $\Delta E_{G,eff}$ may be found. The first possibility is to compare J_{C0} of the HBT to that of a similar all-Si device as a function of temperature

[16]–[19]. If one assumes a similar temperature dependence of mobility, densities of states and bandgap in the $\text{Si}_{1-x}\text{Ge}_x$ as in Si, one can extract a $\Delta E_{G,eff}$ from the temperature dependence of the ratio of J_{C0} in the two devices. This method has the advantage that no knowledge of electron diffusion coefficient D_n or base doping level is required. However, if one uses a lightly doped Si sample as a reference, one makes an implicit error because of the known difference in the temperature dependence of D_n in p-type Si at different doping levels [20]. For example, from room temperature down to 200K, the ratio of D_n in p-type Si doped $\sim 5 \times 10^{18} \text{ cm}^{-3}$ to that doped $6 \times 10^{19} \text{ cm}^{-3}$ changes from 1.1 to 0.3 [20], [21]. This could introduce an error of $\sim 65 \text{ meV}$ in $\Delta E_{G,eff}$ if it were extracted from a fit of the ratio of J_{C0} 's over this same temperature range. This might be overcome if one had all-Si transistors with the same base dopings as all of the HBT's (which is difficult to obtain experimentally), but this would not give an absolute number for the bandgap reduction due to heavy doping. Furthermore, because of alloy scattering, one might expect a different temperature dependence of D_n in Si and SiGe of similar dopings. Finally, while the $\Delta E_{G,eff}$ extracted by this method will by definition accurately model the temperature dependence of the collector current, it may not be a good predictor of the absolute value of room temperature collector current, which is more important than its temperature scaling for most modeling applications.

Therefore, in this study we have chosen to make measurements of G_B and to make reasonable assumptions for D_n and the densities of states ratio (given in the next two paragraphs), so that an absolute value of $\Delta E_{G,eff}$ (compared to undoped Si as represented by n_{i0}^2) can be extracted. Fig. 6 shows a typical Gummel plot of a transistor used in this study. The collector current is ideal over several orders of magnitude, and the negligible effect of the reverse collector bias indicates no parasitic barriers due to boron outdiffusion, even for very heavy dopings in the base (10^{20} cm^{-3}), as confirmed by SIMS. Measurements on different area devices showed negligible perimeter effects on collector current. Note that the base currents were nonideal ($n \approx 1.3$), but this is thought to result from recombination at the unpassivated mesa edges. HBT's with appropriate base isolation fabricated in SiGe grown by RTCVD in our lab show ideal base currents ($n = 1$) which are independent of the Ge content [18], indicating that the layers do not have excess oxygen contamination [16]. Therefore, we believe the data presented in this paper represents properties of boron-doped silicon-germanium alloys independent of contamination, and that the applicability of the results is not limited to material grown by RTCVD.

Since both conduction and valence bands split in strained $\text{Si}_{1-x}\text{Ge}_x$, the effective densities of states will be lower than in Si. To take the reduction of densities of states into account, we used the model of Prinz *et al.* [6]. This model assumes a rigid splitting of both the conduction and valence band degeneracies due to uniaxial strain. This analytical model has the advantage over a full band structure calculation in that it is easily scaled to any desired Ge fraction and temperature. N_C and N_V are

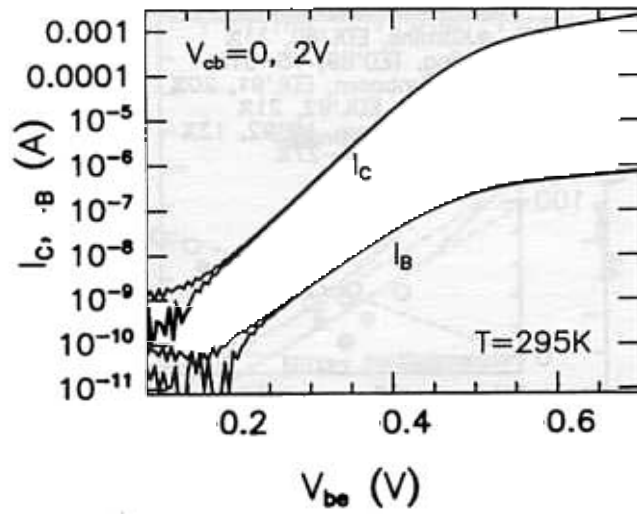


Fig. 6. Typical Gummel plot of an HBT used in this study. Ge concentration in this device was 23% with the base doping of $3 \times 10^{18} \text{ cm}^{-3}$.

given by

$$\frac{(N_C)_{\text{SiGe}}}{(N_C)_{\text{Si}}} \approx \frac{4 + 2e^{-(\Delta E_{cb}/k_B T)}}{6} \quad (6)$$

and

$$\frac{(N_V)_{\text{SiGe}}}{(N_V)_{\text{Si}}} \approx \frac{1 + e^{-(\Delta E_{hl}/k_B T)} + e^{-(\Delta E_{so, \text{SiGe}}/k_B T)}}{2 + e^{-(\Delta E_{so, \text{Si}}/k_B T)}} \quad (7)$$

ΔE_{hl} is the splitting between the heavy and light hole valence bands in $\text{Si}_{1-x}\text{Ge}_x$ and $\Delta E_{so, \text{SiGe}}$ and $\Delta E_{so, \text{Si}}$ are the distances between the split-off band and valence band edge in $\text{Si}_{1-x}\text{Ge}_x$ and Si, respectively, and ΔE_{cb} is the conduction band splitting due to the biaxial strain, all taken from the calculation of People [22]. The resulting $(N_C N_V)_{\text{SiGe}}/(N_C N_V)_{\text{Si}}$ is weakly dependent on temperature, with values of ~ 0.6 for $x = 0.07$ and ~ 0.3 for $x = 0.27$ at room temperature. A more rigorous calculation using the band structure of [23] would predict a slightly lower value for the $N_C N_V$ product (0.3 reduction in N_V alone for $x = 0.2$) [11].

To model the minority carrier mobility in the base, we used the Si model of Swirhun *et al.* [21] for electron mobilities as a function of B-doping. (Klaasen's model for minority carrier mobility in silicon is similar [15].) This is a reasonable approximation since calculations by Kay and Tang [24] of minority electron mobility in strained $\text{Si}_{1-x}\text{Ge}_x$ alloys predict at most an enhancement of 20% over Si values in the doping range of interest. Note also that we observed no clear evidence of significant enhancement of lateral hole drift mobilities with increased Ge concentrations, especially at high doping levels. The base Gummel number G_B was measured directly by SIMS on the same wafer on which the devices were made. On devices where no SIMS data was available, the Gummel number obtained by Hall measurements was used, corrected by the Hall scattering factor of Fig. 4. Finally, for $n_{i0, \text{Si}}^2$ the accepted value of $1 \times 10^{20} \text{ cm}^{-3}$ at 295 K was used. The estimated total uncertainty in the prefactor in (5) (combined uncertainty of D_n , G_B , and the densities of states ratio) was a factor of 2. This corresponds to an uncertainty of 17 meV in the extracted $\Delta E_{G, \text{eff}}$.

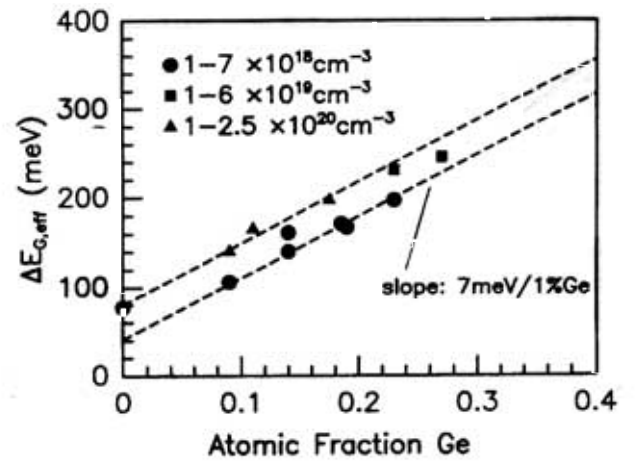


Fig. 7. Effective bandgap reduction with respect to intrinsic Si versus Ge concentration.

Using this method, Fig. 7 shows the extracted effective bandgap narrowing at room temperature as a function of Ge concentration for different doping levels. For the devices with similar dopings, the linear dependence on Ge concentration is obvious. Fitting the data at the same doping level gives an effective bandgap reduction with respect to Si of ~ 7 meV/1% Ge. Assuming that this linear dependence on Ge concentration is independent of doping, we have separated the two effects contributing to the effective bandgap reduction with respect to undoped Si: bandgap reduction due to Ge ($\Delta E_{G, \text{Ge}}$) and bandgap narrowing due to heavy doping effects ($\Delta E_{G, \text{dop}}$).

$$\Delta E_{G, \text{eff}} = \Delta E_{G, \text{Ge}} + \Delta E_{G, \text{dop}} \quad (8)$$

Assuming a $\Delta E_{G, \text{dop}}$ of the form:

$$\Delta E_{G, \text{dop}} = A + B \times \log \left(\frac{N_A}{10^{18} \text{ cm}^{-3}} \right) \quad (9)$$

and a linear dependence of $\Delta E_{G, \text{Ge}}$ on x as Cx , a three-parameter best fit to our data was found to be:

$$\Delta E_{G, \text{eff}} = 28.6 + 27.4 \times \log_{10} \left(\frac{N_A}{10^{18} \text{ cm}^{-3}} \right) + 688 \times x \quad (\text{meV}) \quad (10)$$

where N_A is the base doping and x the Ge concentration. Equation (10) is only valid for doping levels over 10^{18} cm^{-3} . The first two terms represent bandgap narrowing due to doping and the last term is the Ge contribution. $\Delta E_{G, \text{eff}}$ is not the measure of the actual bandgap reduction, but the *effective* (apparent) bandgap reduction, relevant for minority carrier concentration and thus electron transport across the $\text{Si}_{1-x}\text{Ge}_x$ base. The apparent bandgap is larger than the true bandgap due to valence band filling in the degenerately doped semiconductor and hence, the effects of Fermi-Dirac statistics [14], as will be discussed in detail later. The effective bandgap reduction is the useful parameter to model the collector current of Si/Si_{1-x}Ge_x/Si HBT's and predict the enhancement over Si-base devices.

Experimental values for $\Delta E_{G, \text{dop}}$ for $\text{Si}_{1-x}\text{Ge}_x$ are obtained by subtracting the germanium contribution ($688 \cdot x$

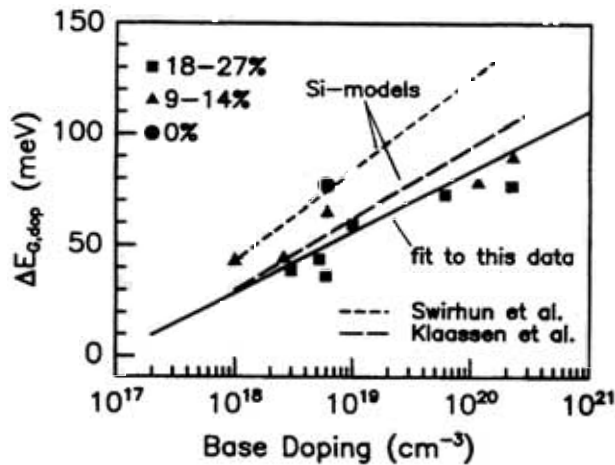


Fig. 8. Apparent bandgap narrowing versus base doping after linear dependence of the bandgap reduction on Ge content has been subtracted. The fit is given by the heavy doping part of (10) [i.e., (10) with $x = 0$].

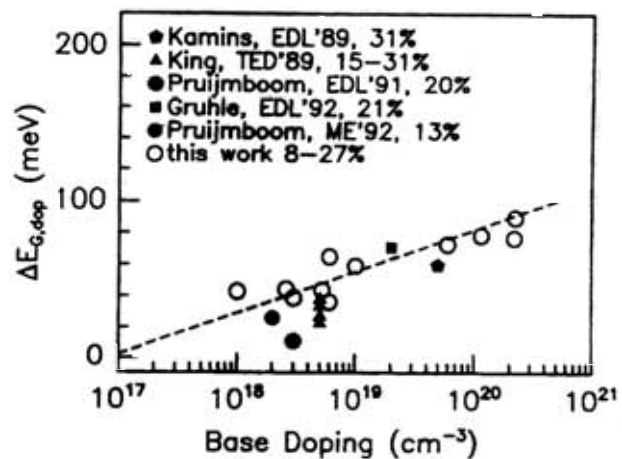


Fig. 9. Heavy doping contribution to the effective bandgap narrowing in SiGe HBT's including the data from literature. The dotted line is (10) with $x = 0$.

meV) from the measured $\Delta E_{G,eff}$. These values are plotted in Fig. 8 versus base doping. This is the first time that such data has been collected for such a wide range of dopings and Ge concentrations in Si/Si_{1-x}Ge_x/Si HBT's. Also plotted are previously reported results by Swirhun *et al.* [21] and a model by Klaassen *et al.* [15] for apparent bandgap narrowing in p-type Si. The apparent bandgap narrowing clearly increases with increased doping, as expected. No clear Ge dependence is observed after the linear dependence has been subtracted. The bandgap narrowing of 27 meV/decade agrees well with the 25–33 meV narrowing at various Ge concentrations with the doping increase from $5 \times 10^{17} \text{ cm}^{-3}$ to $5 \times 10^{18} \text{ cm}^{-3}$, obtained from temperature dependent measurements by Poortmans *et al.* [25]. Although our results for $\Delta E_{G,dop}$ consistently lie below the Si data of Swirhun and the Si modeling results of Klaassen, it should be noted that the Si model of Klaassen differs from our best fit for dopings over 10^{18} cm^{-3} by only ~13%. Hence, Klaassen's model would do a reasonable first-order job of modeling SiGe devices as well.

Plotted in Fig. 9 are data points for $\Delta E_{G,dop}$ extracted in the same way for other SiGe HBT's reported in the literature [7], [16], [19], [26], [27], along with our data of Fig. 8 and the model for $\Delta E_{G,dop}$. $\Delta E_{G,eff}$, as defined in this work, was not directly given in these papers, but adequate information on base doping, basewidth, collector current, etc., was given so that $\Delta E_{G,eff}$ could be calculated. $\Delta E_{G,dop}$ was then found after subtracting the linear dependence on Ge, as described earlier. In general the data of the other work also lie near our best fit for $\Delta E_{G,eff}$. It is interesting to note that nearly all of the data points from earlier work which fall substantially below the best fit to our data are from devices which were fabricated using an implanted emitter process, which is known to give rise to excess base dopant diffusion (and possible parasitic barrier formation resulting in smaller $\Delta E_{G,eff}$) [7], or from work without spacers so that ΔE_C effects could be important and parasitic barriers might be expected. For example, the effect of barriers was explicitly noted in the 1991 data of Pruijboom for $V_{BC} = 0$ (the data used to generate the point in Fig. 9). If

one were to use the data for $V_{BC} = -4 \text{ V}$, which pulls down the parasitic base-collector barrier and increases the collector current by a factor of ~3 in that work, the point in Fig. 9 would move up by 28 meV and then closely agree with the best fit of our data.

V. EFFECTIVE BANDGAP MODEL

Note that our results for $\Delta E_{G,dop}$ are consistently lower than those found in Si (as represented by the work of Swirhun [21] and Klaassen [15]), although calculations by Jain *et al.* [28] predict $\Delta E_{G,dop}$ to be slightly higher in SiGe than in Si, and strain-dependent. A possible explanation for smaller apparent bandgap narrowing compared to Si lies in the fact that at the same doping level, due to the band splitting and thus, reduced densities of states, the Fermi level in degenerately doped Si_{1-x}Ge_x would be expected to lie further into the valence band, and thus cause a smaller apparent bandgap reduction. To relate the apparent bandgap narrowing to the true bandgap reduction ($\Delta E_{G,true}$) one needs to know the position of the Fermi level in the degenerately doped material and take into account the effect of degenerate statistics (Fermi-Dirac instead of Boltzmann). The exact calculation of the Fermi level position in a heavily-doped semiconductor is difficult due to band tails, occupation of higher lying bands (e.g., the split-off band in the valence band), band nonparabolicities, etc. To facilitate a tractable approach for modeling, we will make simple assumptions of a rigid shift of band edges, that the bands are parabolic, and that the effective valence band density of states (N_V) for low doping levels may be applied to calculate the Fermi level position in the case of heavy doping, i.e.:

$$p = N_A = N_V \times F_{1/2} \left(\frac{E_V - E_F}{k_B T} \right) \quad (11)$$

where $F_{1/2}(E_F/k_B T)$ is the Fermi-Dirac integral. While simple, this model will be shown to yield reasonable results. The room temperature value of $N_V = 1.04 \times 10^{19} \text{ cm}^{-3}$ was used for Si, and (7) was used to calculate N_V for Si_{1-x}Ge_x.

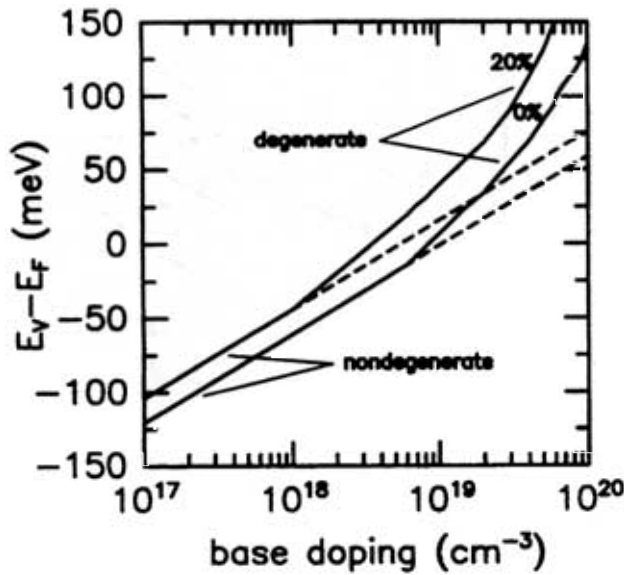


Fig. 10. Position of the Fermi level with respect to the valence band edge for Si and $\text{Si}_{0.8}\text{Ge}_{0.2}$ versus doping.

Using these approximations, Fig. 10 shows the calculated position of the Fermi level with respect to the valence band edge as a function of base doping for Si and $\text{Si}_{0.8}\text{Ge}_{0.2}$. Note that the position of the Fermi level starts to diverge from the straight line (which is the nondegenerate approximation) in the case of $\text{Si}_{0.8}\text{Ge}_{0.2}$ at a lower doping level, and diverges much faster with increasing doping, thus having a bigger effect on $\Delta E_{G,eff}$ than in Si at the same doping level.

Possin *et al.* [14] have formally given the apparent bandgap narrowing due to heavy doping ($\Delta E_{G,dop}$ in our notation, > 0) as the sum of the true bandgap narrowing ($\Delta E_{G,true}$, > 0), representing the distance between the band-edges, and a negative term representing this difference between Fermi-Dirac and Boltzmann statistics ($\Delta E_{G,FD}$):

$$\Delta E_{G,eff} = \Delta E_{G,true} + \Delta E_{G,FD}. \quad (12)$$

The Fermi-Dirac correction ($\Delta E_{G,FD}$) is determined by the position of the Fermi level, representing the difference between the curve in Fig. 10 and the extrapolated straight line for a fixed Ge concentration. $\Delta E_{G,FD}$ is always negative and it is given by:

$$\begin{aligned} \Delta E_{G,FD} &= k_B T \ln \left[e^{-(E_V - E_F)/k_B T} F_{1/2} \left(\frac{E_V - E_F}{k_B T} \right) \right] \\ &= -(E_V - E_F) + k_B T \ln \frac{N_A}{N_V}. \end{aligned} \quad (13)$$

The calculated $|\Delta E_{G,FD}|$ versus doping is shown in Fig. 11. The magnitude of $\Delta E_{G,FD}$ is zero at low doping levels and increases at high dopings. Because of the lower N_V in $\text{Si}_{1-x}\text{Ge}_x$, $|\Delta E_{G,FD}|$ is larger in $\text{Si}_{1-x}\text{Ge}_x$ than in Si at similar dopings, which reduces the effective bandgap reduction.

To see if this difference in $\Delta E_{G,FD}$ can fully account for the observed difference in the $\Delta E_{G,dop}$ between $\text{Si}_{1-x}\text{Ge}_x$ and Si, we have calculated the true bandgap reduction

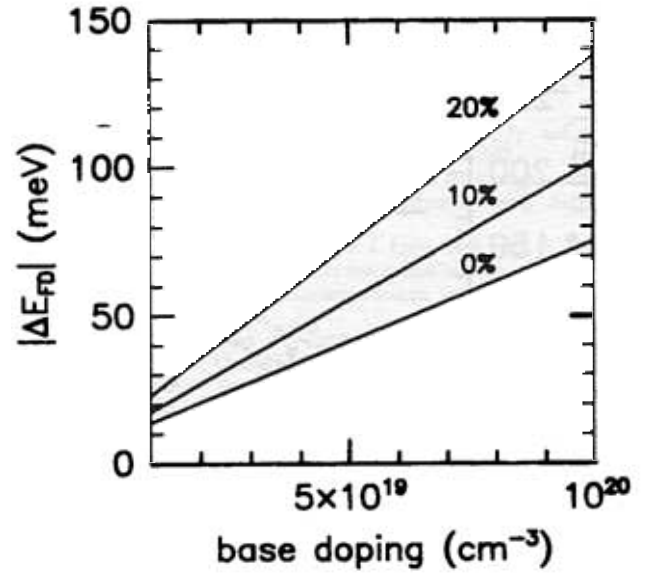


Fig. 11. The difference between the true bandgap narrowing and the effective bandgap narrowing ($|\Delta E_{G,FD}|$) versus doping for $x = 0, 0.1$, and 0.2 , as given by (12).

($\Delta E_{G,true}$) from our measured $\Delta E_{G,dop}$ by using (12) and (13). This is shown in Fig. 12. The calculation was also applied to the Si data of Swirhun *et al.* [21] and Si model of Klaassen *et al.* [15] from Fig. 8 for effective bandgap reduction. Note that in contrast to Fig. 8, which showed results for the effective bandgap reduction, Fig. 12 shows good agreement on the true bandgap reduction due to doping between our $\text{Si}_{1-x}\text{Ge}_x$ results and the previous Si model and data. Therefore, it is not necessary to postulate a change in the true bandgap reduction due to heavy doping to explain the discrepancy between our $\text{Si}_{1-x}\text{Ge}_x$ data and previous Si work for the effective bandgap narrowing. It appears that the difference is consistent with the expected difference in valence band densities of states between Si and strained $\text{Si}_{1-x}\text{Ge}_x$. This reduction in the effective valence band density of states as the germanium fraction increases has also been shown (as a reduction in the densities-of-states effective mass) in [29]. It has been calculated that the true bandgap reduction (referred to as a "rigid bandgap narrowing") in strained $\text{Si}_{1-x}\text{Ge}_x$ is higher than that in Si at high p-type doping levels, but an increase in this rigid shift compared to that in Si of only < 10 meV at a doping level of 10^{19} cm^{-3} was predicted [30]. It should be pointed out that from photoluminescence measurements of heavily doped layers, the exact position of the true valence band edge may be inferred [31], [32]. Therefore, future luminescence measurements of heavily doped $\text{Si}_{1-x}\text{Ge}_x$ layers may offer a method to confirm the similarity of the true bandgap reduction between Si and $\text{Si}_{1-x}\text{Ge}_x$.

VI. COLLECTOR CURRENT VERSUS BASE RESISTANCE MODEL

The two important parameters for the dc design of $\text{Si}_{1-x}\text{Ge}_x$ HBT's are the base sheet resistance and the collector current enhancement with respect to Si. The base sheet resistance is

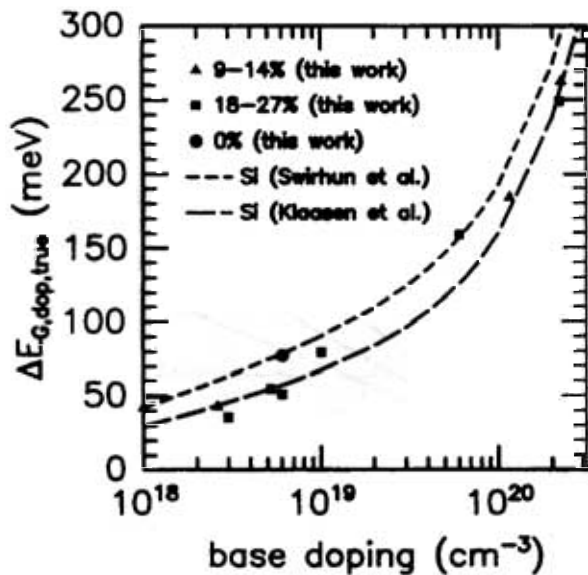


Fig. 12. The heavy-doping contribution to the true bandgap reduction in strained $\text{Si}_{1-x}\text{Ge}_x$ calculated as: $\Delta E_{G,dop,true} = \Delta E_{G,dop} - \Delta E_{G,FD}$, where $\Delta E_{G,dop}$ is the effective doping contribution to the bandgap narrowing for minority carrier transport. Also shown for comparison are the Si data of Swirhun *et al.*, and Si model of Klaassen *et al.*, from Fig. 8 corrected in the same way.

important for high-speed application of $\text{Si}_{1-x}\text{Ge}_x$ HBT's and is often more easily measured (and more relevant) than the actual doping in the base or the integrated hole concentration. The effective bandgap reduction determines the collector current enhancement factor over the similarly doped all-Si device. By using $R_{B,sheet} = (q\mu_p G_B)^{-1}$ one can rewrite (5) to model the collector current as a function of these two parameters:

$$J_{co} = q^2 \frac{(N_C N_V)_{\text{SiGe}}}{(N_C N_V)_{\text{Si}}} \cdot n_{i0,\text{Si}}^2 D_n \mu_p R_{B,sheet} e^{\Delta E_{G,eff}/k_B T} \quad (14)$$

where μ_p and D_n are the lateral drift hole mobility and vertical electron diffusion coefficient in p^+ -base, respectively. Equation (14) shows a clear trade-off between collector current (gain) and base sheet resistance. This is summarized in Fig. 13. The relative collector current with respect to Si is plotted as a function of base sheet resistance for various Ge concentrations. A relative collector current factor of one is defined for Si at a base sheet resistance of 1 $\text{k}\Omega/\text{sq}$, which corresponds approximately to a base doping of $3 \times 10^{19} \text{ cm}^{-3}$ and a base width of 500 Å. The lines are the model calculations assuming base widths of 500 Å, hole drift mobilities given by (10), bandgap reduction by (1), strain-induced correction for densities of states given by (6) and (7) [6], electron mobility by [21], and assuming a temperature of 295 K. The points are measured data in our HBT's scaled to 500 Å basewidths. Note especially the effect of the bandgap narrowing due to heavy base doping, which has a more significant effect than the lateral and vertical mobility reduction at heavy dopings. The bandgap narrowing causes curves not to be linear, and limits the reduction in collector current at low base resistances.

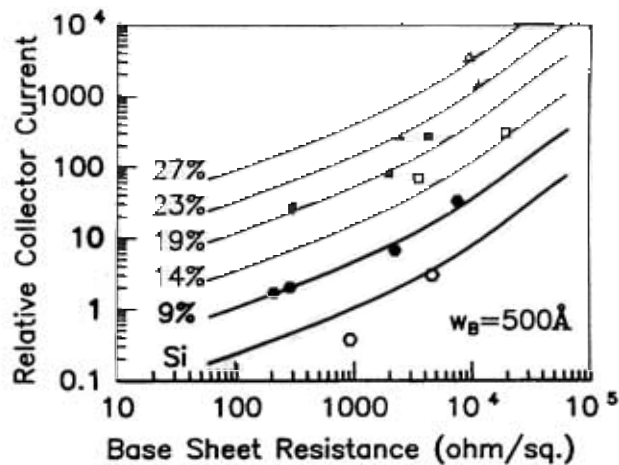


Fig. 13. Relative collector current versus base sheet resistance. The lines correspond to the model, the points are the data scaled to 500 Å basewidths.

Note also that the Si curve in Fig. 13 was calculated assuming bandgap narrowing due to doping according to (10), which was the best fit to our SiGe points. Since it appears that bandgap narrowing due to doping is slightly larger in silicon than in SiGe (e.g., Klaassen's model versus our data in Fig. 8), the model results in Fig. 13 probably somewhat underestimates the collector current in Si devices for low base resistances (heavy base dopings).

VII. CONCLUSIONS

We have characterized lateral majority carrier properties in heavily B-doped strained $\text{Si}_{1-x}\text{Ge}_x$ layers as well as collector currents of HBT's over a wide range of dopings and Ge concentrations for the first time. The hole Hall mobility decreases with increasing Ge concentration at a fixed doping level, and the Hall scattering factor decreases as Ge is added. The lateral hole drift mobility remains approximately constant as Ge is added, with perhaps a slight increase at low doping levels. The apparent bandgap narrowing in p-type strained $\text{Si}_{1-x}\text{Ge}_x$ was measured for the first time over a wide range of doping and Ge levels. The dependence of the narrowing on Ge was independent of doping, and the heavy doping contribution to the effective bandgap narrowing is found to be independent of Ge concentration but slightly lower than that obtained for Si at the same doping level, attributed to the lower density of states in $\text{Si}_{1-x}\text{Ge}_x$ valence band. Finally, a trade-off between the collector current enhancement and base sheet resistance is presented for dc modeling of $\text{Si}_{1-x}\text{Ge}_x$ HBT's. The bandgap narrowing at heavy doping levels (low base sheet resistances) has a larger impact than that of reduced mobility at high doping levels.

REFERENCES

- [1] G. L. Patton, J. H. Comfort, B. S. Meyerson, E. F. Crabbé, G. J. Scilla, E. de Frésart, J. M. C. Stork, J. Y.-C. Sun, D. L. Harnome, and J. N. Burghartz, "75-GHz f_T SiGe-base heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. 11, pp. 171-173, 1990.

- [2] E. Crabbe, B. Mayerson, J. Stork, and D. Haramé, "Vertical profile optimization of very high frequency epitaxial Si- and SiGe-base bipolar transistors," *Int. Electron Devices Meet. Tech. Dig.*, pp. 83-86, 1993.
- [3] E. Kasper, A. Grühle, and H. Kibbel, "The influence of MBE-layer design on the high frequency performance of Si/SiGe HBT's," *Int. Electron Devices Meet. Tech. Dig.*, pp. 79-82, 1993.
- [4] D. Haramé, J. M. C. Stork, B. S. Meyerson, K.-J. Hsu, J. Cotte, K. A. Jenkins, J. D. Cressler, P. Restle, E. F. Crabbe, S. S. T. E. Tice, B. W. Scharf, and J. A. Jasaitis, "Optimization of SiGe HBT technology for high speed analog and mixed signal applications," *Int. Electron Devices Meet. Tech. Dig.*, pp. 71-74, 1993.
- [5] J. C. Sturm, P. V. Schwartz, E. J. Prinz, and H. Manoharan, "Growth of Si_{1-x}Ge_x by rapid thermal chemical vapor deposition and application to heterojunction bipolar transistors," *J. Vac. Sci. Technol. B*, vol. 9, pp. 2011-2016, 1991.
- [6] 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 Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors," *Int. Electron Devices Meet. Tech. Dig.*, pp. 639-642, 1989.
- [7] A. Pruijboom, C. E. Timmering, J. M. L. van Rooij-Mulder, D. J. Gravesteijn, W. B. de Boer, W. J. Kersten, J. W. Slotboom, C. J. Vriezema, and R. de Kruijff, "Heterojunction bipolar transistors with SiGe base," *Microelect. Eng.*, vol. 19, pp. 427-434, 1992.
- [8] P. Narozny, H. Dämkes, H. Kibbel, and E. Kasper, "Si/SiGe heterojunction bipolar transistors made by molecular beam epitaxy," *IEEE Trans. Electron Devices*, vol. 36, pp. 2363-2366, 1989.
- [9] T. Manku and A. Nathan, "Effective mass for strained p-type Si_{1-x}Ge_x," *J. Appl. Phys.*, vol. 69, pp. 8414-8416, 1991.
- [10] ———, "Lattice mobility of holes in strained and unstrained Si_{1-x}Ge_x alloys," *IEEE Electron Device Lett.*, vol. 12, pp. 704-706, 1991.
- [11] T. Manku, J. M. McGregor, A. Nathan, D. J. Roulston, J.-P. Noel, and D. C. Houghton, "Drift hole mobility in strained and unstrained doped Si_{1-x}Ge_x alloys," *IEEE Trans. Electron Devices*, vol. 40, pp. 1990-1995, 1993.
- [12] J. M. McGregor, T. Manku, J.-P. Noel, D. J. Roulston, A. Nathan, and D. C. Houghton, "Measured in-plane hole drift and hall mobility in heavily-doped strained p-type Si_{1-x}Ge_x," *J. Electron. Mater.*, vol. 22, pp. 319-421, 1993.
- [13] J. Slotboom and H. de Graaff, "Measurements of bandgap narrowing in silicon bipolar transistors," *Solid-State Electron.*, vol. 19, 1976.
- [14] G. E. Possin, M. S. Adler, and B. J. Baliga, "Measurements of the p-n product in heavily doped epitaxial emitters," *IEEE Trans. Electron Devices*, vol. 31, pp. 3-17, 1984.
- [15] D. Klaassen, J. Slotboom, and H. de Graaff, "Unified apparent bandgap narrowing in n- and p-type Silicon," *Solid-State Electron.*, vol. 35, 1992.
- [16] C. A. King, J. L. Hoyt, and J. F. Gibbons, "Bandgap and transport properties of Si_{1-x}Ge_x by analysis of nearly ideal Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors," *IEEE Trans. Electron Devices*, vol. 36, pp. 2093-2104, 1989.
- [17] J. C. Sturm, E. J. Prinz, P. M. Garone, and P. V. Schwartz, "Band-gap shifts in silicon germanium heterojunction bipolar transistors," *Appl. Phys. Lett.*, vol. 54, pp. 2707-2709, 1989.
- [18] J. C. Sturm and E. J. Prinz, "Graded base Si/Si_{1-x}Ge_x/Si heterojunction bipolar transistors grown by rapid thermal chemical vapor deposition with near-ideal electrical characteristics," *IEEE Electron Device Lett.*, vol. 12, pp. 303-305, 1991.
- [19] A. Pruijboom, J. W. Slotboom, D. J. Gravesteijn, C. W. Fredriksz, A. A. van Gorkum, R. A. van de Heuvel, J. M. L. van Rooij-Mulder, G. Streutker, and G. F. A. van de Walle, "Heterojunction bipolar transistors with SiGe base grown by molecular beam epitaxy," *IEEE Electron Device Lett.*, vol. 12, pp. 357-359, 1991.
- [20] S. Swirhun, D. Kane, and R. M. Swanson, "Temperature dependence of minority electron mobility and bandgap narrowing in p⁺ Si," *Int. Electron Devices Meet. Tech. Dig.*, 1988.
- [21] S. Swirhun, Y.-H. Kwark, and R. M. Swanson, "Measurement of electron lifetime, electron mobility and bandgap narrowing in heavily doped p-type Silicon," *Int. Electron Devices Meet. Tech. Dig.*, 1986.
- [22] R. People, "Indirect bandgap of coherently strained Si_{1-x}Ge_x bulk alloys on (001) silicon substrates," *Phys. Rev. B*, vol. 32, pp. 1405-1408, 1985.
- [23] T. Manku and A. Nathan, "Energy band structure for strained p-type Si_{1-x}Ge_x," *Phys. Rev. B*, vol. 43, pp. 12634-12637, 1991.
- [24] L. E. Kay and T.-W. Wang, "Monte Carlo calculation of strained and unstrained electron mobilities in Si_{1-x}Ge_x using an improved ionized-impurity model," *J. Appl. Phys.*, vol. 70, pp. 1483-1488, 1991.
- [25] J. Poortmans, S. C. Jain, M. Caymax, A. V. Ammel, J. Nijs, R. P. Mertens, and R. V. Overstraeten, "Evidence of the influence of heavy doping induced bandgap narrowing on the collector current of strained SiGe-base HBT's," *Microelect. Eng.*, vol. 19, 1992.
- [26] T. I. Kamins, K. Nauka, J. B. Kruger, J. L. Hoyt, C. A. King, D. B. Noble, C. M. Gronet, and J. F. Gibbons, "Small-geometry, high-performance, Si-Si_{1-x}Ge_x heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. 10, pp. 503-505, 1989.
- [27] A. Grühle, "MBE-grown Si/SiGe HBT's with high β , f_T , and f_{max} ," *IEEE Electron Device Lett.*, vol. 13, pp. 206-208, 1992.
- [28] S. Jain and D. Roulston, "A simple expression for bandgap narrowing in heavily doped Si, Ge, GaAs, and GeSi strained layers," *Solid-State Electron.*, vol. 34, 1991.
- [29] S. C. Jain, J. Poortmans, S. S. Iyer, J. J. Loferski, J. Nijs, R. Mertens, and R. Van Overstraeten, "Electrical and optical bandgaps of Ge₂Si_{1-x} strained layers," *IEEE Trans. Electron Devices*, vol. 40, pp. 2338-2343, 1993.
- [30] J. Poortmans, S. C. Jain, H. Totterdell, M. Caymax, J. Nijs, R. P. Mertens, and R. V. Overstraeten, "Theoretical calculation and experimental evidence of the real and apparent bandgap narrowing due to heavy doping in p-type Si and strained Si_{1-x}Ge_x layers," *Solid State Electron.*, vol. 36, 1993.
- [31] J. Wagner, "Bandgap narrowing in heavily doped silicon at 20 and 300K studied by photoluminescence," *Phys. Rev. B*, vol. 32, 1985.
- [32] W. P. Dumke, "Bandgap narrowing from luminescence in p-type Si," *J. Appl. Phys.*, vol. 54, 1983.



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