

# Electrical Determination of Bandgap Narrowing in Bipolar Transistors with Epitaxial Si, Epitaxial Si<sub>1-X</sub>Ge<sub>X</sub>, and Ion Implanted Bases

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**Abstract**—The apparent bandgap narrowing in bipolar transistors with epitaxial Si, epitaxial SiGe and ion implanted bases is measured from the temperature dependence of the collector current density  $J_c(T)$ . A graph of  $\ln J_c(T)/J_o(T)$  as a function of reciprocal temperature is plotted, and the apparent bandgap narrowing obtained from the slope. For epitaxial base transistors, in which the boron base profiles are abrupt, a linear  $J_c(T)/J_o(T)$  characteristic is obtained, which allows the unambiguous determination of the apparent bandgap narrowing. The measured values for epitaxial Si bases are in good agreement with the theoretical model of Klaassen over a range of base doping concentrations. For Si<sub>0.88</sub>Ge<sub>0.12</sub> and Si<sub>0.87</sub>Ge<sub>0.13</sub> epitaxial base heterojunction bipolar transistors (HBT's), values of bandgap narrowing of 119 and 121 meV are obtained due to the presence of the Ge, which can be compared with theoretical values of 111 and 118 meV. For the implanted base transistor, the  $J_c(T)/J_o(T)$  characteristic is not linear, and its slope is larger at high temperatures than at low. This behavior is explained by the presence of a tail on the ion implanted profile, which dominates the Gummel number of the transistor at low temperatures.

## I. INTRODUCTION

THE temperature dependence of the current gain of a bipolar transistor has long been used as an effective means of studying device physics. More recently, however, it has been of interest because of the possibility of BiCMOS circuit operation at liquid nitrogen temperature [1]–[4]. This interest is fuelled primarily by the benefits that can be obtained when CMOS circuitry is operated at low temperatures [5], such as improved circuit speed due to increased mobility at low temperatures. However, recent work [6]–[8] has shown that excellent performance can also be obtained from bipolar circuits at liquid nitrogen temperature. The advantages of bipolar transistors that are obtained at room temperature, such as better current drive, higher transconductance and smaller

signal swing can therefore be successfully transferred to liquid nitrogen temperature. The combination of bipolar and CMOS circuits in a cryogenic BiCMOS technology therefore offers the prospect of additional leverage for optimising overall system performance.

Historically, the main problem in achieving satisfactory operation of bipolar transistors at low temperatures was the large decrease in current gain observed on cooling [9], [10]. For this reason, much of the research on the behavior of silicon bipolar transistors at low temperatures has concentrated on the current gain. However, there are benefits to be obtained by analyzing the collector and base currents separately, since they are often controlled by different physical mechanisms. Of the two currents, the collector current lends itself more readily to unambiguous analysis, since it is generally much more ideal than the base current. Mechanisms such as recombination in the emitter/base depletion region [11] and polysilicon emitter action [12] often contribute to the base current, and make it difficult to unambiguously interpret the temperature dependence. In contrast, the collector current almost always has an ideality factor very close to unity, and is determined solely by the base doping profile. Analysis of the collector current of a bipolar transistor can, in principle, therefore give valuable information on physical parameters related to the base profile.

Studies relating to the base profiles of silicon bipolar transistors are currently highly relevant because thinner bases are required in order to achieve higher values of cut-off frequency and faster circuit speeds. Basewidths below 100 nm are difficult to achieve using conventional ion implantation because of channelling tails on the boron base profiles [4]. An alternative approach is to use low-temperature silicon epitaxy to produce the base [13]–[15], which has the advantage of allowing much sharper profiles, and hence much thinner bases. Furthermore, the addition of a small percentage of Ge into the epitaxial base makes it possible to produce a Si/SiGe Heterojunction Bipolar Transistor (HBT) [16], [17]. With this device, additional degrees of freedom are introduced into the device design as a result of bandgap engineering. The reduced bandgap in the SiGe base gives markedly higher gains, which can then be traded for increased base doping and reduced base resistance. In addition, the increased base doping

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gives a reduced penetration of the depletion regions into the base, and hence an increased punch-through voltage. There is therefore considerable scope for reducing the basewidth, thereby reducing the forward transit time and increasing the cut-off frequency. Cut-off frequencies as high as 116 GHz have been reported for Si/SiGe HBT's [18].

In this paper, a method is described for analyzing the temperature dependence of the collector current of a Si homojunction or Si/SiGe HBT. The method gives information on the bandgap narrowing in the base, due either to the presence of a high concentration of dopant or to the presence of Ge. Experimental results are presented on transistors with epitaxial Si bases, epitaxial SiGe bases and ion implanted bases. Different behavior is observed for the ion implanted and epitaxial bases, which is explained by the presence of a tail on the ion implanted base profile. The analysis method therefore provides a qualitative measure of the sharpness of the base profile.

## II. THE ANALYSIS METHOD

For bipolar transistors with epitaxial bases, the boron concentration in the base is generally uniform across the base. In the first instance, it is therefore assumed that the base doping is constant. The case of nonuniform base doping will be considered later in the paper. For an n-p-n transistor with a uniform base doping concentration, the collector current density  $J_c(T)$  can be simply expressed as

$$J_c(T) = \frac{kT\mu_n(T)n_{io}^2(T)}{N_{AB}(T)W_B(T)} \exp \frac{qV_{BE}}{kT} \exp \frac{\Delta E_{GB}}{kT} \quad (1)$$

where  $k$  is Boltzmann's constant,  $T$  the temperature,  $\mu_n(T)$  the minority carrier electron mobility in the base,  $n_{io}(T)$  the intrinsic carrier concentration for undoped material,  $N_{AB}(T)$  the ionized doping concentration in the base,  $W_B(T)$  the neutral basewidth,  $V_{BE}$  the base/emitter voltage which is assumed to be much greater than  $kT/q$ , and  $\Delta E_{GB}$  the apparent bandgap narrowing (doping-induced) in the base.

The base doping concentration  $N_{AB}(T)$  can decrease with cooling as a result of freeze-out of carriers in the base. This causes the intrinsic base sheet resistance  $R_B(T)$  of the transistor to increase at low temperatures, as can be seen from the following equation:

$$R_B(T) = \frac{1}{q\mu_p(T)N_{AB}(T)W_B(T)} \quad (2)$$

where  $\mu_p(T)$  is the majority carrier hole mobility in the base. This equation can be used to calculate both the number of free carriers per unit area ( $N_{AB}(T)W_B(T)$ ) required in (1), assuming that the majority carrier mobility is known, and the ionized doping concentration in the base  $N_{AB}(T)$ , assuming that the majority carrier mobility and the basewidth are known. It should be noted that for a heavily doped base,  $W_B$  is almost constant over the temperature range of interest. The temperature dependence of the intrinsic carrier concentration in (1) can be expressed as [19]

$$n_{io}^2(T) = 4 \left( \frac{2\pi kT}{h^2} \right)^3 (m_n m_p)^{1.5} \exp \frac{-E_G(T)}{kT} \quad (3)$$

where  $h$  is Planck's constant,  $m_n$  and  $m_p$  the effective masses for electrons and holes, and  $E_G(T)$  the undoped silicon bandgap, which varies with temperature.

Combining (1)–(3) gives an equation for the temperature dependence of the collector current density

$$J_c(T) = J_o(T) \exp \left( \frac{\Delta E_{GB}}{kT} \right) \quad (4)$$

where  $J_o$  is a pre-exponential term which can be written as

$$J_o(T) = 4q \left( \frac{2\pi}{h^2} \right)^3 (m_n m_p)^{1.5} (kT)^4 \mu_n(T) \mu_p(T) \times R_B(T) \exp \frac{qV_{BE} - E_G(T)}{kT} \quad (5)$$

The value of the apparent bandgap narrowing in the base  $\Delta E_{GB}$  can then be obtained from the slope of a graph of

$$\ln \left( \frac{J_c(T)}{J_o(T)} \right) \quad \text{vs} \quad 1/T. \quad (6)$$

A similar approach can be used for Si/SiGe HBT's. In this case, the temperature dependence of the collector current density is given by

$$J_c(T) = J_o(T) \exp \frac{\Delta E_{GB}}{kT} \exp \frac{\Delta E_g - \Delta E_S}{kT} \quad (7)$$

where  $\Delta E_g$  is the bandgap narrowing in the base due to the presence of the Ge and  $\Delta E_S$  is the protrusion of the conduction band spike over the conduction band in the SiGe. In this case, a graph of (6) yields a value for  $(\Delta E_{GB} + \Delta E_g - \Delta E_S)$ . In most practical devices at moderate forward bias, the conduction band spike does not protrude over the edge of the conduction band and so  $\Delta E_S = 0$ . In this case, a graph of (6) gives a value for the total bandgap narrowing in the base  $(\Delta E_{GB} + \Delta E_g)$ . It should be noted that the value of  $J_o(T)$  for SiGe is not necessarily the same as that for Si, since the values of effective mass could be different. In the following results, the effective masses for Si have been used in all the calculations. A comparison of the intercepts obtained from a graph of (6) for Si and SiGe devices should therefore provide useful information on the comparative values of effective mass in Si and SiGe.

In order to use (6), it is necessary to know the temperature dependences of the minority carrier electron mobility  $\mu_n(T)$ , the majority carrier hole mobility  $\mu_p(T)$ , the bandgap  $E_G(T)$ , and the effective masses  $m_n$  and  $m_p$ . The temperature dependence of the majority carrier mobility is reasonably well known [20] but very little has been published on the temperature dependence of the minority carrier mobility. Swirhun *et al.* [21] have measured the minority carrier electron mobility at temperatures between 100 and 400 K, and Klaassen has presented a physics-based mobility model which unifies the descriptions of the majority and minority carrier mobility [22], [23] and describes their temperature dependences. In this work, the Klaassen model has been used to describe the temperature dependences of both the minority carrier electron mobility and the majority carrier hole mobility in the base. The temperature dependence of the silicon bandgap has been described by the model of Thurmond [24]. The effective masses vary very

little with temperature, and we have used their mean values between 77 and 300 K:  $1.08 m_0$  for electrons and  $0.97 m_0$  for holes [25]. For SiGe, there is very little measured data in the literature on the temperature dependences of  $\mu_n(T)$ ,  $\mu_p(T)$  and  $E_G(T)$ , so for the purposes of this work the temperature dependences of these parameters in SiGe have been assumed to be the same as those in Si.

### III. EXPERIMENTAL PROCEDURE

The analysis method described in Section II has been applied to three different types of device, namely Si/SiGe HBT's, silicon bipolar transistors with ion implanted bases, and silicon bipolar transistors with epitaxial bases. The first type of device was a mesa transistor, fabricated using a process similar to that described in [26]. It had a polysilicon emitter in order to avoid the point defects which are generated when an emitter implant is made directly into silicon; these cause an enhancement of the diffusivity of the boron in the base and an undesirable broadening of the basewidth [27]. In addition, the Si/SiGe HBT's incorporated 15-nm undoped SiGe spacers at the emitter and collector junctions to take up any out-diffusion of boron from the SiGe base during the layer growth and the subsequent emitter drive-in of 30 s at 900°C. The second type of transistor was a single polysilicon, self-aligned polysilicon emitter bipolar transistor, fabricated using a process similar to that described in [28]. Some of the third type of transistor were fabricated using the mesa process, and others using the self-aligned process.

For the epitaxial base transistors, a variety of base doping concentrations were used, as summarized in Table I. The mean base doping concentration  $N_{AB}(T)$  was calculated from the measured intrinsic base sheet resistance  $R_B(T)$  at room temperature using (2). The basewidth  $W_B$  required for the calculation was obtained by measuring the metallurgical basewidth from SIMS doping profiles, and then applying a correction for the penetration of the emitter/base and collector/base depletion regions into the base at zero bias. The Ge concentrations in the Si/SiGe HBT's were measured using SIMS and found to be 13% and 12% in the devices with base doping concentrations of  $1.6 \times 10^{18} \text{ cm}^{-3}$  and  $6.2 \times 10^{18} \text{ cm}^{-3}$ , respectively.

Measurements of collector current as a function of base/emitter voltage were made in the temperature range 77 to 380 K. The temperature was calculated from the gradient of a graph of  $\ln I_c$  versus  $V_{BE}$  after checking the current ideality. The collector current ideality was checked at room temperature, and for all devices found to be  $\leq 1.005$ . By making the temperature measurement on the device itself, the possibility of a thermal lag between the thermocouple and the device itself is avoided. The intrinsic base sheet resistance was measured on an adjacent Van der Pauw test structure or a large area test transistor with two separate base contacts.

### IV. RESULTS

Fig. 1 shows typical SIMS doping profiles for transistors with epitaxial and ion implanted bases. Fig. 1(a) shows emitter and base profiles for an epitaxial base transistor (Si epi 1 in

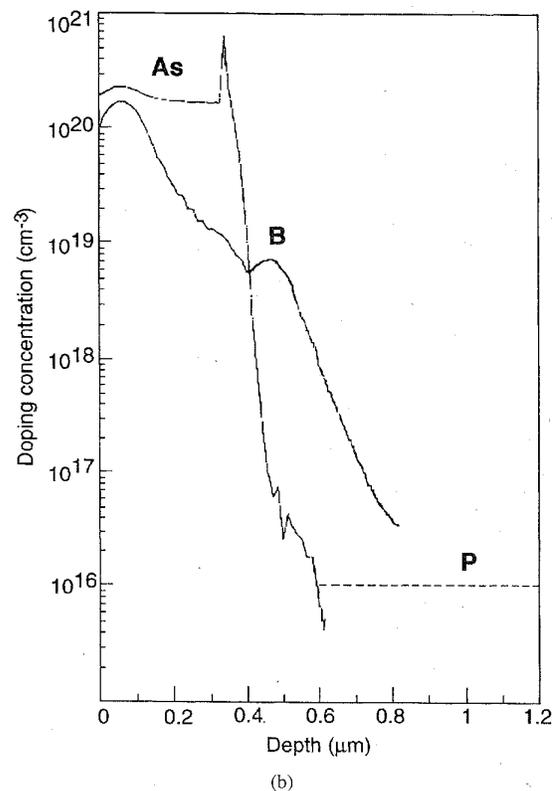
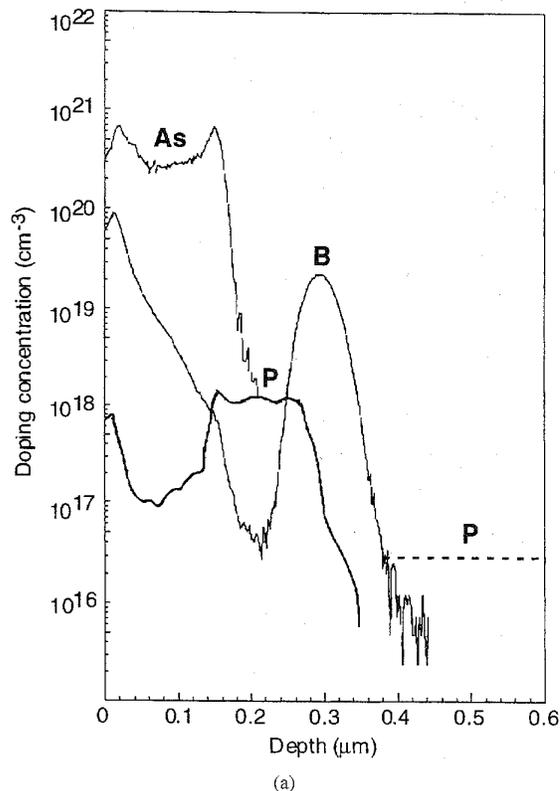


Fig. 1. Typical SIMS profiles for the devices studied: (a) Profiles for a transistor with an epitaxial base (mean base doping concentration  $1.1 \times 10^{19} \text{ cm}^{-3}$ ). (b) Profiles for the transistor with an ion implanted base.

TABLE I  
SUMMARY OF THE DOPING CONCENTRATIONS, BASEWIDTHS, AND ELECTRICAL CHARACTERISTICS OF THE DIFFERENT TYPES OF BASES STUDIED

Base type	Metallurgical base width nm	$R_B$ $\Omega/\square$	Mean base doping $\text{cm}^{-3}$	$J_c/J_o$ intercept: all data	$J_c/J_o$ intercept: data for $1/T < 5\text{K}^{-1}$
Si epi 1	125	710	$1.1 \times 10^{19}$	2.7	2.0
Si epi 2	100	1330	$6.3 \times 10^{18}$	1.5	1.5
Si epi 3	114	1510	$4.6 \times 10^{18}$	1.6	1.3
Si epi 4	105	3300	$2.0 \times 10^{18}$	0.93	0.87
Si epi 5	92	4190	$1.6 \times 10^{18}$	1.2	0.97
$\text{Si}_{0.98}\text{Ge}_{0.12}$ epi	68	2040	$6.2 \times 10^{18}$	1.5	0.78
$\text{Si}_{0.87}\text{Ge}_{0.13}$ epi	66	6920	$1.6 \times 10^{18}$	0.97	0.26
ion implanted	480	1130	$7 \times 10^{17}$	-	-

Table I), and Fig. 1(b) the profiles for the ion implanted base transistor. For the epitaxial base, the base profile is sharp and hence the approximation of a uniform doping concentration in the base is reasonable. For the profile shown in Fig. 1(a), the mean base doping concentration calculated using the above method is  $1.1 \times 10^{19} \text{ cm}^{-3}$ , which compares with a peak doping concentration of just over  $2 \times 10^{19} \text{ cm}^{-3}$ . In contrast, the ion implanted base profile is not uniform, and a tail is present which extends deep into the silicon.

#### A. Epitaxial Si Bases

Fig. 2 shows the variation of the intrinsic base sheet resistance with temperature for two devices with mean base doping concentrations of  $1.1 \times 10^{19} \text{ cm}^{-3}$  and  $2.0 \times 10^{18} \text{ cm}^{-3}$ . For the heavily doped base, the resistance increases slightly with temperature at high temperatures due to a decrease in the majority carrier hole mobility. At low temperatures, the resistance remains approximately constant, indicating that freeze-out of carriers in the base is not occurring to any significant extent. This is as expected, since the base is heavily doped and the base profile very sharp, and hence the doping concentration through most of the base is above the Mott transition of approximately  $3 \times 10^{18} \text{ cm}^{-3}$  [29]. In contrast, for the lightly doped base, the resistance increases strongly at low temperatures, indicating that freeze-out of dopant in the base is occurring. This is again expected since the base doping concentration in this device is below the Mott transition.

Fig. 3 shows a bandgap narrowing plot (6) for two transistors with mean base doping concentrations of  $1.1 \times 10^{19} \text{ cm}^{-3}$  (Si epi 1) and  $2.0 \times 10^{18} \text{ cm}^{-3}$  (Si epi 4). The characteristics obtained are linear over more than two decades and therefore the extraction of the bandgap narrowing from the slopes is straightforward. Useful information on the validity of the analysis method can be obtained by considering the intercepts of the extrapolated characteristics as  $1/T$  approaches zero. For the device with a base doping of  $2 \times 10^{18} \text{ cm}^{-3}$  the  $J_c/J_o$  intercept is 0.93, which can be compared with the expected value of unity. This is remarkable agreement considering the uncertainties in the values of some of the constants in (5), and provides excellent confirmation of the analysis method. The slope of the characteristic for this device gives a doping-induced apparent bandgap narrowing of 39 meV, which compares with theoretical values of 38, 54, and 20

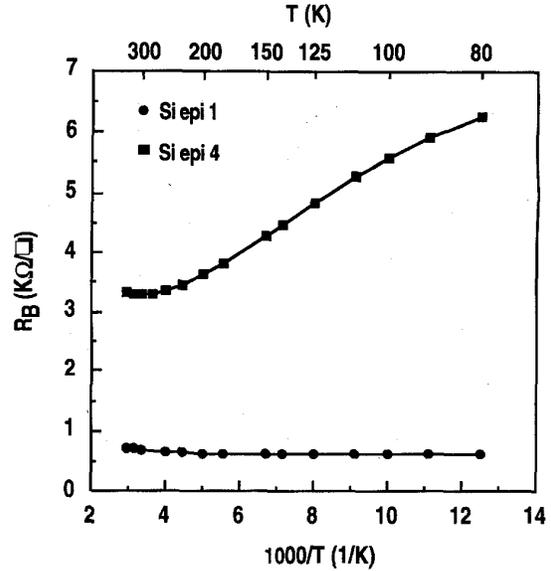


Fig. 2. Intrinsic base sheet resistance as a function of reciprocal temperature for devices with mean base doping concentrations of  $1.1 \times 10^{19}$  and  $2.0 \times 10^{18} \text{ cm}^{-3}$ .

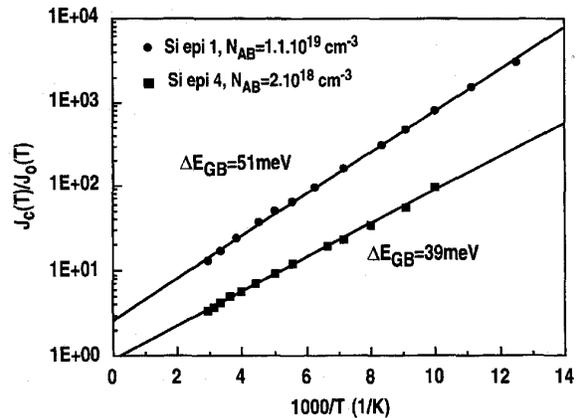


Fig. 3. Graph of  $J_c(T)/J_o(T)$  as a function of reciprocal temperature for bipolar transistors with epitaxial Si bases with mean base doping concentrations of  $1.1 \times 10^{19}$  and  $2.0 \times 10^{18} \text{ cm}^{-3}$ .

meV for the apparent bandgap narrowing models of Klaassen [19], Slotboom [30], and del Alamo [31], respectively. For the device with a base doping concentration of  $1.1 \times 10^{19} \text{ cm}^{-3}$ , a value of 2.7 is obtained for the intercept which is higher than expected. Table I summarizes the intercepts for all the devices studied. In general, the intercepts are reasonably close to the expected value of unity, although there is a trend of increasing values at high base doping concentrations. The possible reasons for this trend will be discussed later in the paper.

#### B. Epitaxial SiGe Bases

The variation of intrinsic base sheet resistance with temperature for the Si/SiGe HBT's were similar to those shown

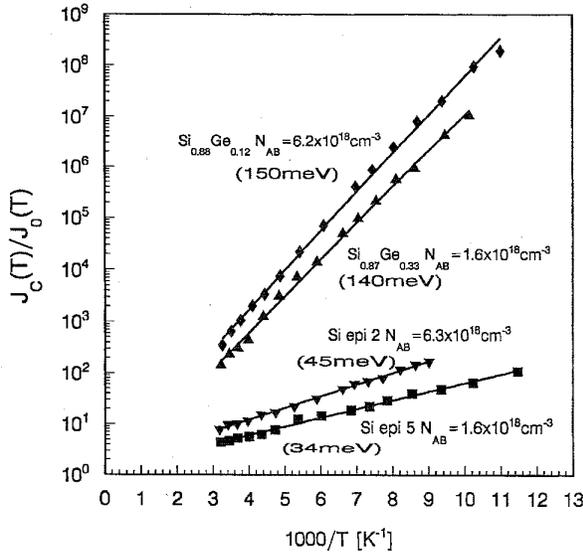


Fig. 4. Graphs of  $J_c(T)/J_o(T)$  as a function of reciprocal temperature for SiGe HBT's with base doping concentrations of  $6.2 \times 10^{18} \text{ cm}^{-3}$  and  $1.6 \times 10^{18} \text{ cm}^{-3}$  and for Si epitaxial base bipolar transistors with comparable base doping concentrations.

in Fig. 2 for the silicon homojunction bipolar transistors. For the high-doped device ( $6.2 \times 10^{18} \text{ cm}^{-3}$ ), the sheet resistance was approximately constant at low temperatures, indicating that freeze-out of base dopant was not occurring. For the low-doped device ( $1.6 \times 10^{18} \text{ cm}^{-3}$ ), the resistance increased at lower temperatures, indicating the presence of some freeze-out. This is consistent with the low base doping concentration in this device, which is below the Mott transition [29].

Fig. 4 shows the bandgap narrowing plots for the Si/SiGe HBT's, and for comparison the plots for Si bipolar transistors with similar base doping concentrations. It can be seen that the slopes of the characteristics for the SiGe HBT's are considerably greater than those of the Si devices as a result of the additional bandgap narrowing in the base due to the presence of the Ge. For the high-doped devices, the slope of the characteristic of the SiGe HBT gives a bandgap narrowing of 150 meV, compared with 45 meV for the comparable Si device. For the low-doped devices the corresponding values are 140 meV and 34 meV, respectively.

### C. Ion Implanted Bases

Fig. 5 shows a bandgap narrowing plot for the Si bipolar transistor with an ion implanted base. In this case, a nonlinear characteristic is obtained and the slope is larger at high temperatures than at low. At first sight, this result appears to suggest that the bandgap narrowing is temperature dependent, with a lower value at low temperatures than at high. However, there was no evidence of a temperature dependent bandgap narrowing in the devices with epitaxial bases (Fig. 3). A more plausible explanation is that the tail on the ion implanted base profile is giving rise to the nonlinearity on the bandgap narrowing plot. Chantre and Nouailhat [4] have shown that the doping in the profile tail increasingly dominates the base Gummel Number as the temperature is reduced. This expla-

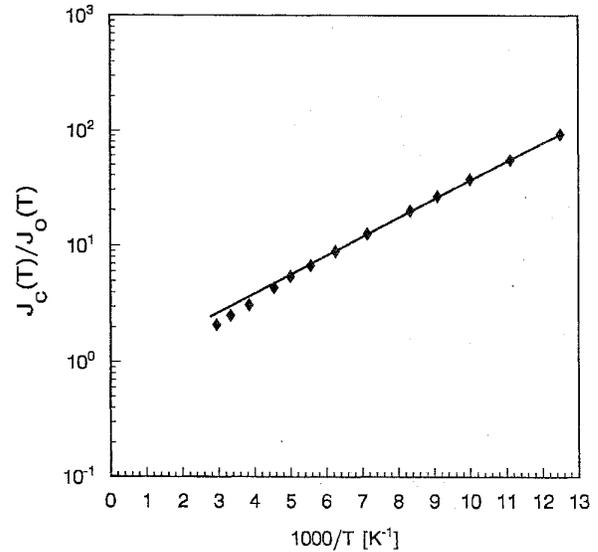


Fig. 5. Graph of  $J_c(T)/J_o(T)$  as a function of reciprocal temperature for the bipolar transistor with an ion implanted base.

nation would account for the apparent decrease in bandgap narrowing in Fig. 5 as the temperature is reduced.

In order to test the above hypothesis, device simulations have been carried out for the base doping profile in Fig. 6(a), which comprises a uniformly doped region of concentration  $1.5 \times 10^{19} \text{ cm}^{-3}$  and an exponential tail extending from a depth of 0.04 to 0.10  $\mu\text{m}$ . In these simulations, the del Alamo [31] apparent bandgap narrowing model was used, freeze-out of base dopant was not modeled, and the temperature dependence of the minority carrier mobility was modeled as  $T^{-0.5}$ . The form of the pre-exponential term is therefore slightly different than that in (5). Fig. 6(b) shows the bandgap narrowing plot, which clearly has a similar shape to that for the transistor with an ion implanted base in Fig. 5. The slope of the characteristic at high temperatures gives an apparent bandgap narrowing of 56 meV, while that at lower temperatures gives a value of 33 meV. The expected apparent bandgap narrowing from the del Alamo model is 57 meV for a base doping concentration of  $1.5 \times 10^{19} \text{ cm}^{-3}$ , which is in good agreement with the value obtained from the slope of the characteristic at high temperatures. These results clearly demonstrate that a doping tail on the base profile gives rise to a nonuniform bandgap narrowing plot, as was observed for the transistor with the ion implanted base in Fig. 5.

Further verification of the influence of nonuniformities in the base doping concentration was obtained by analyzing an epitaxial base sample with a deliberately grown secondary peak in the base doping. The SIMS profile is shown in Fig. 7. The main doping is around  $1 \times 10^{19} \text{ cm}^{-3}$  but a shoulder is clearly visible on the collector side with a doping level around  $2 \times 10^{18} \text{ cm}^{-3}$ . The bandgap narrowing plot for this sample is given in Fig. 8. The characteristic is clearly nonlinear, and two regions can be identified in the Arrhenius plot, the first between 250 and 350 K with an activation energy of 49 meV and the second between 80 and 150 K with an energy of 39 meV.

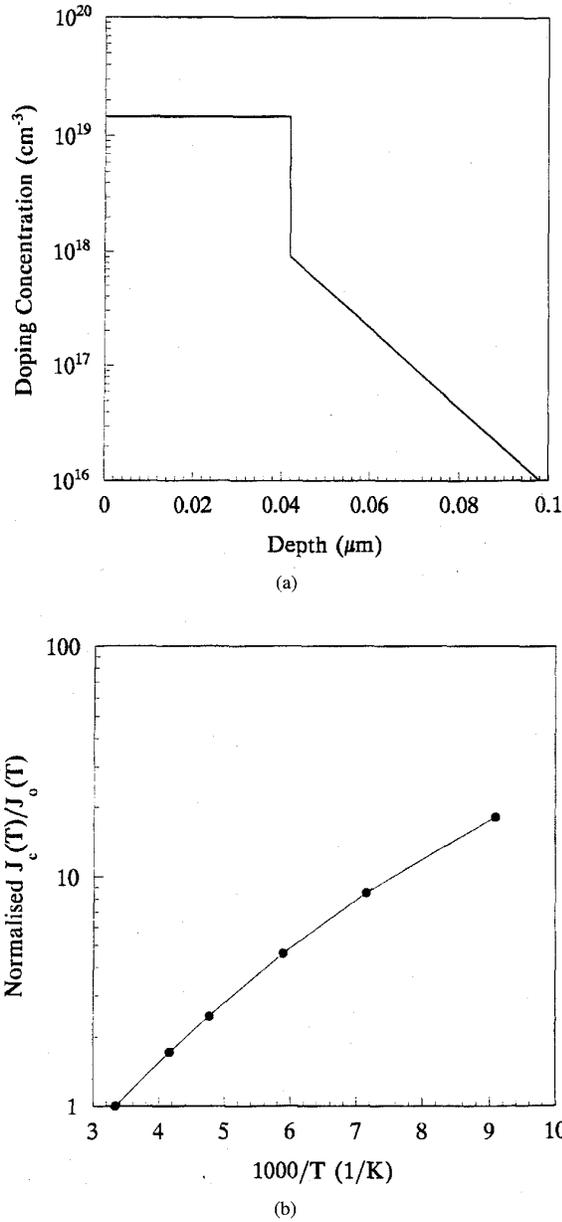


Fig. 6. Simulation of the collector current of a Si bipolar transistor with a uniformly doped base and an exponential doping tail: (a) The base doping profile used in the device simulations. (b) The simulated  $J_c(T)/J_o(T)$ , normalized to the value at  $T = 300$  K, as a function of reciprocal temperature.

A quantitative description of the results in Fig. 8 can be obtained in the following way. The doping profile in Fig. 7 can be approximated by two adjacent uniformly doped regions of the base with different doping concentrations. In this case, the current density can be expressed as [32]

$$J_c(T) = \frac{qn_{i0}^2(T) \exp \frac{qV_{BE}}{kT}}{G_{B1} + G_{B2}} \quad (8)$$

where  $G_{B1}$  and  $G_{B2}$  are the Gummel numbers of the two parts of the base. In our case, the first part is 60-nm thick and doped

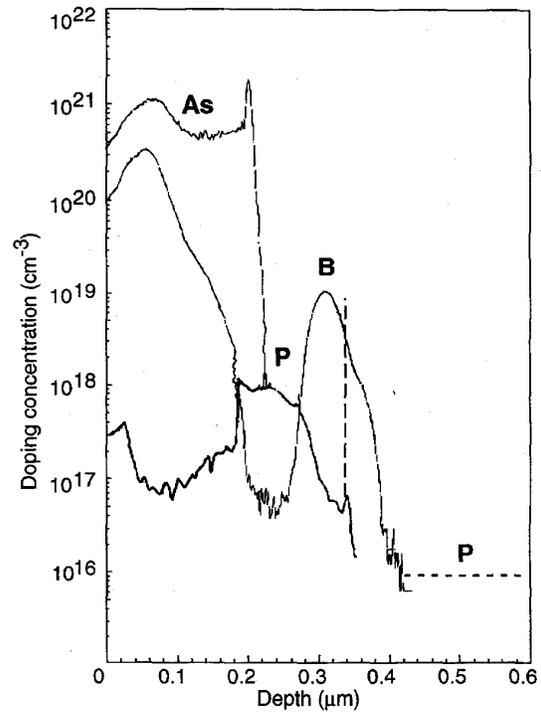


Fig. 7. SIMS doping profiles for an epitaxial base Si transistor with a deliberately grown residual peak in the base doping.

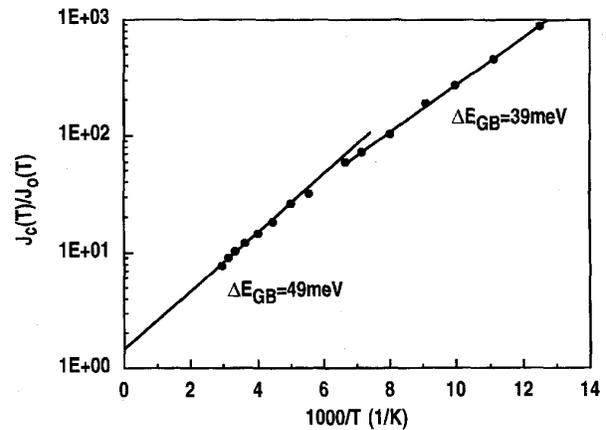


Fig. 8. Graph of  $J_c(T)/J_o(T)$  as a function of reciprocal temperature for an epitaxial base Si transistor with a deliberately grown residual peak in the base doping.

at  $1 \times 10^{19} \text{ cm}^{-3}$  and the second is 60-nm thick and doped at  $2 \times 10^{18} \text{ cm}^{-3}$ . We have calculated and plotted these two Gummel numbers as a function of temperature in Fig. 9. It can be seen that, at high temperatures, the Gummel number of the high-doped part of the base is larger and therefore dominates the collector current, as can be seen from (8). The contrary occurs at low temperatures, where the collector current is dominated by the low-doped part of the base. The measured activation energy at high temperatures of 49 meV in Fig. 9 is close to the expected value of 51 meV for a doping of

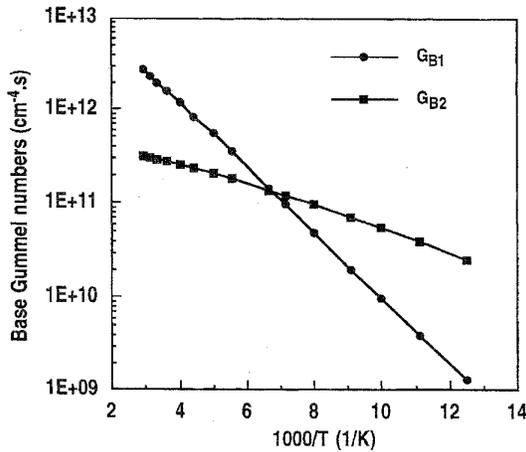


Fig. 9. Base Gummel numbers for the high- and low-doped regions of the doping profile in Fig. 8 as a function of reciprocal temperature.

$1 \times 10^{19} \text{ cm}^{-3}$ , and the measured energy at low temperatures of 39 meV coincides exactly with the expected value of 39 meV for a doping of  $2 \times 10^{18} \text{ cm}^{-3}$ . It can therefore be concluded that the analysis method gives a good indication of the bandgap narrowing in the base even in the situation where the doping is not uniform. However, in this case the data at higher temperatures must be used in order to obtain a reliable value for the bandgap narrowing.

## V. DISCUSSION

Having identified the effect of dopant tails on the analysis method, it is instructive to consider again the increase in the value of the  $J_c/J_o$  intercept with base doping concentration observed in Table I. The device with the highest base doping concentration (Si epi 1) had an intercept of 2.7. A close inspection of the bandgap narrowing plot for this device in Fig. 3 shows clear evidence of an increase in activation energy at higher temperatures. If only the high-temperature data ( $1000/T < 5 \text{ K}^{-1}$ ) is used in the analysis, an activation energy of 58 meV and an intercept of 2.0 are obtained. Similar calculations have been made for the other devices and are summarized in Table I. These results suggest that the increase in intercept with increasing base doping concentration is largely due to the presence of a small tail on the doping profile. Evidence for such a tail can be seen on the doping profile in Fig. 1(a), although it is much less severe than that seen in Fig. 1(b) for the ion implanted device. The accuracy of the temperature measurement has been checked as a possible cause of the high values of intercept and found to be around 1 K. In any case, an inaccurate temperature measurement could not explain the doping dependence of the intercept. Similarly, the measured electrical parameters like  $R_B(T)$  and  $V_{BE}$  are determined with a very good accuracy. Another possibility is that the equations used to model the majority and minority carrier mobilities are inaccurate. The least well characterized of these is the minority carrier mobility, and hence this is the most likely origin of an inaccuracy. If this was the case, the results in Table I would suggest that the modeled electron

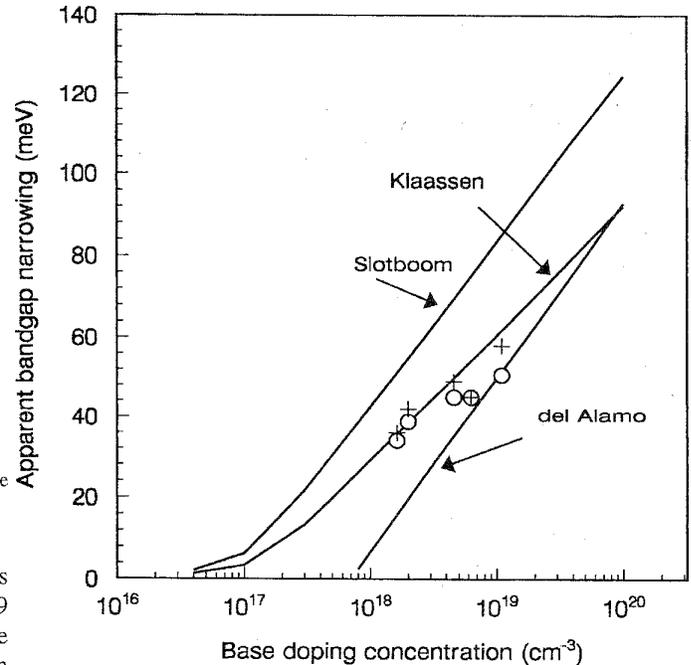


Fig. 10. Comparison of the measured values of apparent bandgap narrowing in the base with the predictions of the models of Klaassen *et al.* [19], Slotboom *et al.* [30] and del Alamo *et al.* [31], for p-type Si. The circles represent values of apparent bandgap narrowing obtained using all of the measured data points and the crosses represent values obtained using only the high-temperature ( $1000/T < 5 \text{ K}^{-1}$ ) data points.

mobility in the base was pessimistic at high base doping concentrations.

In order to better compare the measured and predicted values of doping-induced apparent bandgap narrowing, the analysis method has been applied to other devices with different base doping concentrations. The results are shown in Fig. 10 where the measured apparent bandgap narrowing is plotted as a function of base doping concentration. The circles in Fig. 10 represent least squares fits using all of the measured data points, while the crosses represent fits using only the high-temperature data points ( $1000/T < 5 \text{ K}^{-1}$ ). Also shown are the predicted values of apparent bandgap narrowing for the models of Klaassen, Slotboom and del Alamo. It is clear that Klaassen's model agrees very well with the measured data, but that the high-temperature data has to be used at higher base doping concentrations in order to obtain reliable values for the bandgap narrowing.

For the SiGe devices shown in Fig. 4, the bandgap narrowing due to the presence of the Ge can be calculated by subtracting the doping-induced bandgap narrowing from the total bandgap narrowing. If it is assumed that the doping-induced bandgap narrowing in SiGe is the same as that in Si, then a value of 105 meV is obtained for the heavily doped  $\text{Si}_{0.88}\text{Ge}_{0.12}$  HBT, and a value of 106 meV for the lightly doped  $\text{Si}_{0.87}\text{Ge}_{0.13}$  HBT. If only the high-temperature data ( $1000/T < 5 \text{ K}^{-1}$ ) is used to calculate the slopes, values of 164 and 157 meV are obtained for the  $\text{Si}_{0.88}\text{Ge}_{0.12}$  HBT and the  $\text{Si}_{0.87}\text{Ge}_{0.13}$  HBT, respectively, and values of 45 and 36 meV for Si epi devices 2 and 5, respectively.

This data gives values of bandgap narrowing due to the Ge of 119 meV for the  $\text{Si}_{0.88}\text{Ge}_{0.12}$  HBT and 121 meV for the  $\text{Si}_{0.87}\text{Ge}_{0.13}$  HBT, respectively. These values can be compared with theoretical bandgap reductions of 111 meV and 118 meV for 12% and 13% Ge, respectively [33]. The agreement between the measured and predicted values of bandgap narrowing is excellent considering the uncertainty in the percentage of Ge, which was measured using the SIMS technique. The assumption of equal values of doping-induced bandgap narrowing in SiGe and Si has been shown by Poortmans *et al.* [34] to be very good for base doping concentrations below  $1 \times 10^{19} \text{ cm}^{-3}$ , but inaccurate at higher doping concentrations. Since the doping concentrations in the HBT's measured in this work were below  $1 \times 10^{19} \text{ cm}^{-3}$ , the above assumption is clearly reasonable. In the above calculations, it has also been assumed that the conduction band spike at the heterojunction interface does not protrude above the conduction band in the base and hence that  $\Delta E_s$  is equal to zero. Device simulations, performed using the measured SIMS profiles, have confirmed this assumption.

A comparison of the values of intercept for the SiGe and Si devices in Table I shows that slightly lower values are obtained for SiGe. This indicates that  $J_o(T)$  is higher in SiGe than Si, and hence that the product of the effective masses (or the density of states) is slightly higher in SiGe than Si. This result is surprising and contradicts the results of Prinz *et al.*, [35] who estimated that the ratio of the product of the density of states in SiGe and Si  $N_C N_V(\text{SiGe})/N_C N_V(\text{Si})$  had a value of approximately 0.4. The explanation for these contradictory results is unclear at the present time; further detailed measurements on SiGe HBT's will be needed to clarify this point.

## VI. CONCLUSION

An analysis method has been presented for determining the apparent bandgap narrowing in the base of a Si homojunction or SiGe HBT from the temperature dependence of the collector current. The method has been shown to work well on transistors with epitaxial Si and SiGe bases, where the boron base profiles are abrupt. Measured values of apparent bandgap narrowing in Si have been obtained for a range of boron base doping concentrations and a comparison made with the predictions of apparent bandgap narrowing models reported in the literature; good agreement has been obtained with the model of Klaassen. For transistors with ion implanted bases, a nonlinear  $J_c(T)/J_o(T)$  characteristic is obtained in which the slope is greater at high temperatures than at low. This behavior has been explained by the presence of a tail on the ion implanted boron profile. At liquid nitrogen temperature, the dopant in the tail dominates the Gummel number, whereas at room temperature the dopant in the peak of the profile dominates. This causes the slope of the  $J_c(T)/J_o(T)$  characteristic to decrease as the temperature decreases. The linearity of the  $J_c(T)/J_o(T)$  characteristic therefore provides a good measure of the abruptness of the base doping profile.

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