BASE TRANSPORT PROPERTIES OF *npn* SiGe HETEROJUNCTION BIPOLAR TRANSISTORS: PHYSICS AND MODELLING

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Keywords: semiconductors, bipolar transistors, HBT, heterojunction bipolar transistors, BJT, bipolar junction transistors, physical properties, comparison of properties, SiGe HBT, SiGe heterojunction bipolar transistors, base transport properties, base transit times, bandgap narrowing, effective mass, collector current, base transit time, Fermi-Dirac statistics,analitical modelling.

Abstract: The base transport properties of *npn* SiGe heterojunction bipolar transistors (HBTs) are analyzed. Physical effects influencing the electron current in the base and the base transit time are discussed, and the modelling of these effects is described. The results of modelling demonstrate that the improvement of SiGe HBTs compared to Si BJTs increases with cooling and decreases with increasing doping concentration in the base, and that Fermi-Dirac statistics influence significantly the electron current in the base. The analytical approach to the modelling of base transport properties is presented, rendering simple and accurate evaluation of the electron current in the base and the base transit time in the wide range of doping concentrations at 77*K* and 300*K*.

Transportne lastnosti baze v *npn* SiGe heterospojnih bipolarnih tranzistorjih: fizikalna slika in modeliranje

Ključne besede: polprevodniki, transistorji bipolarni, HBT transistorji bipolarni heterospojni, BJT transistorji s spojem bipolarnim, lastnosti fizikalne, primerjava lastnosti, SiGe HBT transistorji bipolarni heterospojni, lastnosti transportne baze transistorja, časi tranzitni baze transistorjev, oženje pasu prepovedanega, masa efektivna, tok kolektorski, čas tranzitni baze, Fermi-Dirac statistika, modeliranje analitično

Povzetek: V delu so analizirane transportne lastnosti baze v *npn* SiGe heterospojnih bipolarnih tranzistorjih (HBT). Razloženi so fizikalni efekti, ki vplivajo na tok elektronov v bazi in na tranzitni čas baze. Opisano je modeliranje teh efektov. Rezultati modeliranja kažejo, da se izboljšanje lastnosti SiGe HBT-jev v primerjavi s silicijevimi bipolarnimi tranzistorji povečuje z nižanjem temperature in znižuje z višanjem koncentracije primesi v bazi, ter da Fermi-Diracova statistika bistveno vpliva na tok elektronov v bazi. Predstavljen je pristop k analitičnemu modeliranju transportnih lastnosti baze, ki pripelje do enostavnega in natančnega izračuna toka elektronov v bazi in tranzitnega časa baze v širokem območju koncentracij primesi pri 77*K* in 300*K*.

1. Introduction

Heterojunction bipolar transistors (HBTs) with strained SiGe layers in the base have been the subject of intensive research in the last few years /1-7/. Compared to Si BJTs, SiGe HBTs with better current gain and greatly improved cutoff frequencies have been reported /1-3/. Moreover, SiGe BiCMOS technology has been presented, combining unique capabilities of SiGe HBTs with the advantages of CMOS devices /4/. It has been also demonstrated that SiGe HBTs are well suited for low temperature operation and that their performances improve naturally with cooling /5,6/. SiGe HBTs optimized for 77*K* operation have been recently reported /7/, exhibiting better performances than those of the same technology operating at 300*K*. In addition to the superior performances of SiGe HBTs, their compatibility with existing silicon technology represent an important advantage for these devices to find wide use in the semiconductor market.

The improvement of SiGe HBTs compared to Si BJTs is closely related to the transport properties of the SiGe base /1/. As a consequence of germanium and compressive strain, several effects influencing carrier transport appear in the base. The most important effect - bandgap reduction due to strain and alloying in the base - results in increased electron injection from the emitter to the base and, consequently, increased electron current in the base /1/. Further, graded germanium profile in the base introduces graded energy gap in the base and, consequently, a beneficial effective electrical field in the base, improving the high frequency characteristics of SiGe HBTs /1/. Beside the bandgap reduction, several other effects in the base additionally influence the device characteristics.

The insight into the physics of the base transport mechanisms and related effects is inevitable for an understanding of the possibilities for further improvement of SiGe HBTs. Besides, the modelling of these effects is important for accurate analysis and optimization of SiGe HBTs. Since the current gain and the base transit time are controlled by the Ge profile in the base rather than by the doping profile, doping profile in the base can be optimized, resulting in additional freedom for device designers. Bearing in mind also the possibilities for low-temperature operation of SiGe HBTs, it is obvious that the germanium, doping and temperature dependence of mechanisms related to the base transport properties should be known for adequate modelling of SiGe HBTs.

The purpose of this paper is to discuss the physical effects in the base related to the transport of carriers, and to suggest the models which are required for evaluation of the electron current in the base and the base transit time. In the following, the physics of SiGe base is examined and corresponding models are reviewed. The device performance issues such as SiGe HBT vs. Si BJT improvement, 77*K* vs. 300*K* operation, and the importance of Fermi-Dirac statistics for the carrier transport in the base are analyzed. Finally, an approach to the accurate analytical modelling of the electron current in the base and the base transit time is presented.

2. Physics of the SiGe base

Due to the presence of germanium, the physics of carrier transport in the SiGe base differs from that in the conventional Si base. In this section we analyze the electron current in the base, which is the main contributor to the collector current in SiGe HBT. We examine the base transit time which is a parameter influencing significantly the high frequency performance of SiGe HBTs. Finally, we address the evaluation of *pn* product in the base which is an important base transport parameter.

2.1 Electron current in the base

The electron current in the SiGe base can be described by the generalized Moll-Ross relation /8/, which takes into account the influence of nonuniform doping and energy gap grading in the base:

$$j_n = \frac{qn_{i,Si}^2\left(exp\left(\frac{qV_{BE}}{kT}\right)-1\right)}{\int_0^{W_b} exp\left(-\frac{\Delta D_{SiGe}(x)}{kT}\right)\frac{N_A(x)dx}{D_{n,SiGe}(x)}}, \qquad (1)$$

where N_A is the acceptor concentration in the base, $n_{i,Si}$ is intrinsic carrier concentration in silicon, $D_{n,SiGe}$ is electron diffusion constant in the SiGe base, ΔG_{SiGe} is an apparent bandgap narrowing in the base which accounts for the deviation of *pn* product in SiGe from that in intrinsic silicon; the other symbols have their usual meaning.

In contrast to most GaAs based heterojunction devices -where the carrier transport is controlled by the heterojunction barriers - the electron current in SiGe HBTs is determined by drift and diffusion and depends almost entirely on the bulk base properties. This is a consequence of the small conduction band discontinuity (approximately 10 *meV* /9/) which appears on the Si/SiGe heterojunction. It has been shown recently that even if thermionic emission of electrons over the conduction band discontinuity is taken into account, the small barrier does not influence the electron transport unless the temperature is extremely low ($T < 50$ *K*) /10/. The minority electron diffusion constant and the apparent bandgap narrowing are thus the most important parameters determining the stationary electron transport in the base. Beside the effects related to the apparent bandgap narrowing, which will be addressed in more detail in the following, it is necessary to stress the Ge-dependence of electron diffusion constant in the base. It has been observed experimentally that the minority carrier mobility in SiGe is higher than that in silicon as a consequence of germanium and strain /11/. A simple empirical model for diffusion constant enhancement due to strain and germanium has been recently presented /12/, where it has been assumed that the temperature and doping dependence of electron mobility in SiGe is the same as that in silicon.

2.2 Base transit time

Taking into account the influence of nonuniform energy gap in the base, the base transit time (τ_B) can be described as proposed in /8/:

$$\tau_B = \int_0^{W_B}\left[exp\left(\frac{\Delta G_{SiGe}(z)}{kT}\right)\int_z^{W_B} exp\left(-\frac{\Delta G_{SiGe}(x)}{kT}\right)\frac{N_A(x)dx}{D_{n,SiGe}(x)}\right]dz \qquad (2)$$

The base transit time is controlled by the same physical effects as the electron current. However, in contrast to the electron current, which is influenced mostly by bandgap narrowing at the base side of the emitter-base depletion region, the base transit time is affected mainly by the grade of the apparent bandgap narrowing in the base.

2.3 *pn* product in the base

The *pn* product in the SiGe base is an important parameter which influences significantly the electron current in the base and the base transit time. It is affected by the structure of conduction and the valence band in SiGe, which is modified as a result of compressive strain and alloying /9,13/. The conduction band of strained SiGe splits into fourfold degenerate and twofold degenerate states, influencing the effective density of states in the conduction band ($N_{C,SiGe}$) /13/. In the valence band of SiGe the heavy hole and the light hole bands split, with the heavy hole band moving up and the light hole band moving down in the energy diagram /9,13/. Both bands, together with the split-off band, are highly distorted and non-parabolic. As a result, the energy gap in SiGe is reduced compared to the energy gap in silicon /9,13,14/. Furthermore, the effective density of states in the valence band ($N_{V,SiGe}$) is changed owing to the lower hole effective mass (m_p*) in SiGe /15-17/. Besides, the high doping concentration causes additional bandgap reduction ($\Delta E_{g,hd}$), which appears to be of the same origin as a corresponding bandgap reduction in silicon /18,19/.

An apparent bandgap narrowing (ΔG_{SiGe}) can be defined to account for the difference between *pn* product in the SiGe base and the intrinsic carrier concentration in silicon:

$$(pn)_{SiGe} = n_{i,Si}^2 \exp\left(\frac{\Delta G_{SiGe}}{kT}\right), \quad (3)$$

Under the assumption of space charge neutrality, quasi-equilibrium and reparabolization of nonparabolic energy bands in the *p*-type SiGe base, a relation between Fermi level and the doping concentration in the base can be defined by the Fermi integral:

$$p_{SiGe} = N_A = N_{V,SiGe} \frac{2}{\sqrt{\pi}} F_{1/2}\left(\frac{E_{V,SiGe} - E_F}{kT}\right), \quad (4)$$

where E_F is equilibrium Fermi level and $E_{V,SiGe}$ is the edge of reparabolized and shifted valence band. E_F can be expressed by minority electron concentration:

$$E_F = E_{C,SiGe} + kT\, ln\left(\frac{n_{SiGe}}{N_{C,SiGe}}\right). \quad (5)$$

If n_{SiGe} is expressed by ΔG_{SiGe} (3), and the difference between the energy gap in intrinsic silicon and the energy gap in SiGe is expressed by $\Delta E_{g,SiGe} + \Delta E_{g,hd}$, where $\Delta E_{g,SiGe}$ corresponds to the bandgap reduction due to strain and germanium and $\Delta E_{g,hd}$ corresponds to the bandgap narrowing due to high doping concentration, we arrive at the expression:

$$N_A = N_{V,SiGe} \frac{2}{\sqrt{\pi}} F_{1/2}\left(\frac{\Delta E_{g,Ge} + \Delta E_{g,hd} - \Delta G_{SiGe}}{kT} - ln\left(\frac{N_{C,Si,i} N_{V,Si,i}}{N_{C,SiGe} N_A}\right)\right), \quad (6)$$

where $N_{C,Si,i}$ and $N_{V,Si,i}$ represent effective densities of states in the conduction and the valence band in intrinsic silicon. By applying the inverse Fermi integral to (6), a closed form expression for ΔG_{SiGe} can be found:

$$\Delta G_{SiGe} = \underbrace{[\Delta E_{g,hd}]}_{A} + \underbrace{[\Delta E_{g,Ge}]}_{B} + \underbrace{\left[kT\, ln\left(\frac{N_{C,SiGe} N_{V,SiGe}}{N_{C,Si,i} N_{V,Si,i}}\right)\right]}_{C} + \underbrace{\left[kT\, ln\left(\frac{N_A}{N_{V,SiGe}}\right) - kTG_{1/2}\left(\frac{N_A}{N_{V,SiGe}}\right)\right]}_{D}, \quad (7)$$

where contributions denoted A-D have clear physical meaning: A represents the doping induced actual bandgap reduction, B represents the bandgap narrowing due to strain and alloying, C represents an effective bandgap reduction due to lower effective densities of states in SiGe compared to effective densities of states in intrinsic silicon, and D corresponds to the Fermi level shift due to Fermi-Dirac statistics (degeneracy). Careful analysis of (7) indicates that for the evaluation of ΔG_{SiGe} at an arbitrary temperature, doping level and germanium content, several parameters should be known: $\Delta E_{g,hd}$, $\Delta E_{g,Ge}$, $N_{C,SiGe}$ and $N_{V,SiGe}$.

A. Effective densities of states

Since the lowest conduction band edge is fourfold degenerate and the character of the conduction band in SiGe is the same as that of silicon /13/, the effective density of states in the conduction band of SiGe is approximately 2/3 of that in silicon. For low Ge-fractions, where it is taken into account that also the twofold degenerate upper conduction band states contribute to the electron concentration, $N_{C,SiGe}/N_{C,Si,i}$ can be described by the model from /20/. Since the electron effective mass in silicon, which determines $N_{C,Si,i}$, is a weak function of temperature /21/, it can be assumed that its doping dependence in the degenerate regime is negligible.

In contrast to $N_{C,SiGe}$, the modelling of $N_{V,SiGe}$ is more complicated due to the distortion and nonparabolicity of the valence band /15,16/. However, by means of properly defined hole effective mass (m_p*), the correct relationship between Fermi level and the majority carrier concentration can be accomplished without loss of validity of the Fermi integral /15,16/. The hole effective mass in SiGe is severely influenced by distortion and nonparabolicity of the valence band, and is lower than that in silicon. Moreover, it depends on temperature (T), doping concentration and Ge content (x_{Ge}) /15-17/, thus influencing the effective density of states in the valence band ($N_{V,SiGe}$).

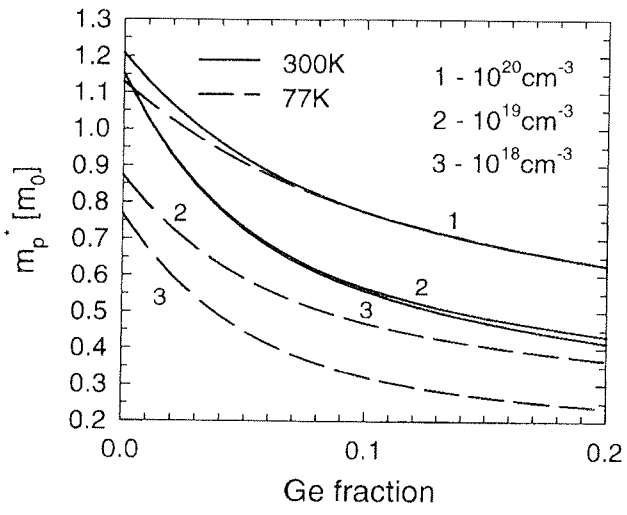


Fig. 1: The hole effective mass calculated with the model proposed in /17/.

A model for $m_p^*(N_A,T,x_{Ge})$ for $77\,K \le T \le 300$ K, $N_A \le 10^{20}$ cm^{-3} and $x_{Ge} \le 0.2$ - taking into consideration both the available experimental data and the theoretical studies of the valence band structure /15,16/ -has been recently proposed /17/. Fig. 1 indicates the most important features of m_p^* in SiGe: strong doping dependence at low temperatures, low temperature dependence at high doping concentrations and strong Ge dependence. The ratio of densities of states between SiGe and intrinsic silicon is presented in Fig. 2, indicating that N_CN_V in SiGe is considerably lower than that in silicon.

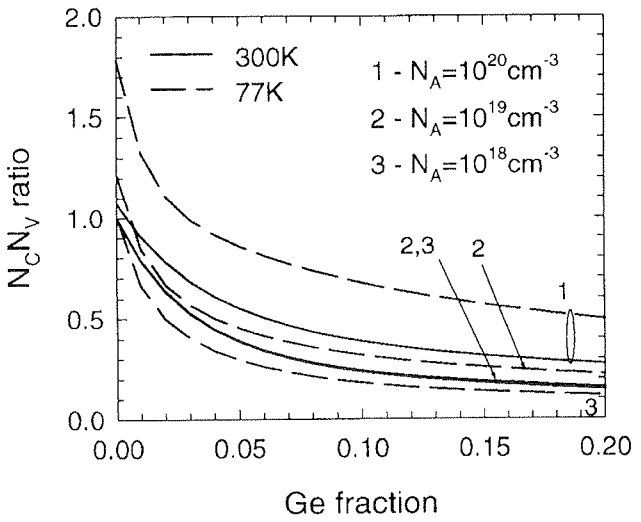


Fig. 2: The ratio of the product of effective densities of states in doped SiGe (including doped Si) and intrinsic Si.

B. Bandgap narrowing due to doping

For doping concentrations higher than $10^{18} cm^{-3}$, the interactions of carriers and dopant atoms cause reduction of the energy gap ($\Delta E_{g,hd}$). Based on the assumption that the doping induced bandgap narrowing in SiGe is of the same origin as, and of the comparable magnitude to the doping induced bandgap reduction in silicon /18,19/, $\Delta E_{g,hd}$ in p-type silicon can be regarded as a measure of doping induced bandgap narrowing in SiGe. A model for $\Delta E_{g,hd}$ in p-type silicon has been recently determined /22/ from measured characteristics of Si BJTs, where it has been assumed that the contribution of Fermi-Dirac statistics can be accounted for by means of the model for $m_p^*(N_A,T,x_{Ge}=0)$ from /17/ (see Fig. 3):

$$\Delta E_{g,hd} = \left(\left(6.76 \cdot 10^{-11} N_A^{0.5}\right)^{-4} + \left(3.58 \cdot 10^{-7} N_A^{0.28}\right)^{-4}\right)^{-1/4} [eV]. \quad (8)$$

Bearing in mind that the doping concentration in the base of an optimized SiGe HBT exceeds $10^{18}\,cm^{-3}$ /1,2/, and in some cases approaches $10^{20}\,cm^{-3}$ /3/, the doping induced bandgap narrowing is an important effect that should be taken into account for analysis and optimization of the base transport properties of SiGe HBTs.

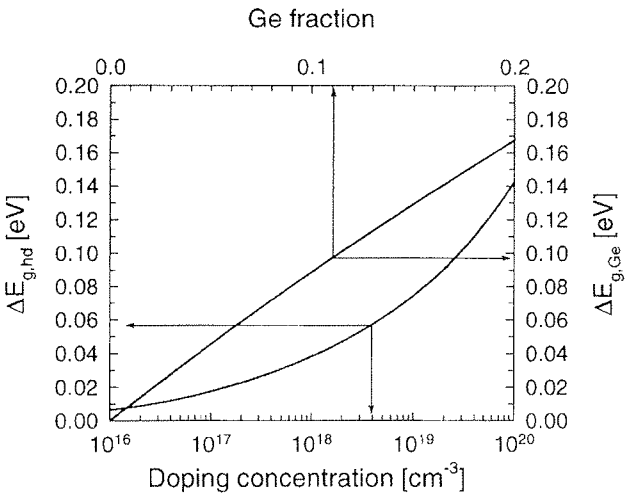


Fig. 3: $\Delta E_{g,hd}$ and $\Delta E_{g,Ge}$ as a function of doping and Ge-fraction, respectively.

C. Bandgap narrowing due to strain and alloying

Compressive strain and alloying cause the energy gap reduction in SiGe base ($\Delta E_{g,Ge}$). Based on a comprehensive analysis of experimental data of SiGe HBTs, and on the assumption that the model for $m_p^*(N_A,T,x_{Ge})$ from /22/ determines the Fermi level shift and $N_{V,SiGe}$ reduction in SiGe, a model for $\Delta E_{g,Ge}$ has been recently proposed /17/ (see Fig.3):

$$\Delta E_{g,Ge} = 0.937 x_{Ge} - 0.5 x_{Ge}^2 \quad [eV]. \quad (9)$$

As can be seen from Fig. 4, even a few percents of germanium result in influential bandgap reduction in the base, consequently influencing the base transport properties of SiGe HBTs. It is worth mentioning that this effect is the most important consequence of germanium in the base, which is basically responsible for the improved properties of SiGe HBTs compared to Si BJTs.

D. Apparent bandgap narrowing

Apparent bandgap narrowing, calculated according to (7) with the models described above, is presented in Fig.4. As expected, ΔG_{SiGe} increases with increasing doping concentration and Ge content. However, eq. (7) indicates that it is generally difficult to isolate the doping effects from those caused by germanium and alloying in ΔG_{SiGe} due to doping and Ge dependence of $N_{V,SiGe}$. An important qualitative difference between apparent

bandgap narrowing in SiGe and Si is temperature dependence /25/. While apparent bandgap narrowing in silicon is temperature independent in the most conditions of interest, ΔG_{SiGe} decreases with increasing temperature even at moderate doping concentrations. This temperature dependence is a result of lower densities of states in SiGe than in silicon, and at very low temperatures or at very high doping concentrations a consequence of Fermi-Dirac statistics. However, as discussed in /23/, the influence of this temperature dependence on transistor characteristics is significant, consequently affecting the interpretation of corresponding experimental data.

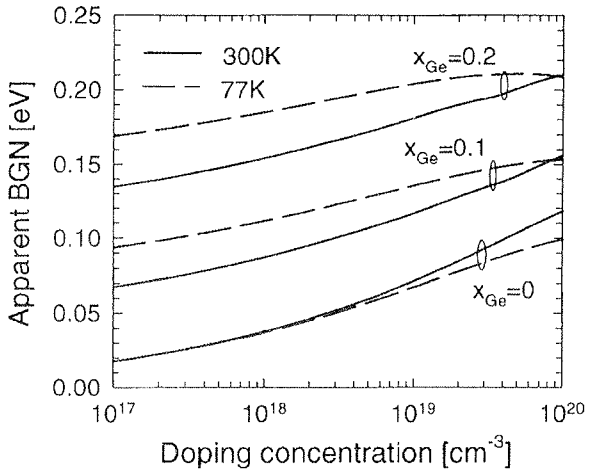


Fig. 4: Apparent bandgap narrowing as a function of doping calculated according to (7).

The model for apparent bandgap narrowing in silicon proposed by Klaassen *et al.* /24/, which is frequently used to account for $\Delta E_{g,hd}$ or even for the complete doping effects ($\Delta E_{g,hd}$ + Fermi-Dirac statistics) in the SiGe base, generally does not correspond to $\Delta E_{g,hd}$. For the doping concentrations higher than 10^{19} cm^{-3} it accounts also for the influence of Fermi-Dirac statistics, which is different in silicon than in SiGe due to lower hole effective mass in SiGe. This difference should be carefully taken into account when Si data are used for modelling doping effects in SiGe devices.

3. Modelling results

It is well known that one of the main advantages of SiGe HBTs compared to Si BJTs - in cases where both devices differ only by the presence of germanium in the base - is increased collector current due to reduced energy gap in the base, resulting in increased current gain (base current of SiGe HBT is comparable to the base current of Si BJT) /1/. Further, the base transit time in SiGe HBTs is decreased due to increased minority carrier mobility and due to energy gap grading which induces an effective electrical field in the base /1/. In this section we analyze several issues related to the base transport properties of SiGe HBTs. In addition to the model for apparent bandgap narrowing in the base and the model for Ge-induced mobility enhancement described above, we also use the model for minority electron mobility in silicon proposed by Klaassen /26/, and the model for intrinsic carrier concentration in silicon suggested by Green /21/.

3.1 SiGe HBT vs. Si BJT performance

The ratio of the current gain between SiGe HBT and Si BJT is presented in Fig. 5. As can be seen, the box Ge profile in the base with 6% of germanium generates almost 3 times higher current gain at 300 *K* than that in Si BJT. The current gain improvement is slightly lower for trapezoidal Ge profile with the same Ge dose, because the electron current in the base is influenced significantly by the bandgap narrowing at the base side of the emitter-base depletion region. As can be seen from Fig. 5, the current gain ratio decreases with increasing doping concentration. This is a consequence of the lower hole effective mass in SiGe, which induces a higher Fermi level shift due to Fermi-Dirac statistics in the SiGe base at high doping concentrations and, consequently, a decrease of electron concentration in SiGe compared to that in Si.

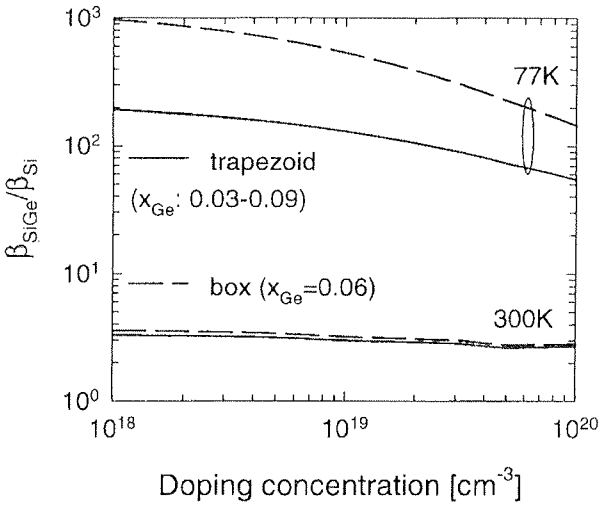


Fig. 5: The ratio of the current gain between SiGe HBT and Si BJT where both devices have the same doping profile.

The base transit time ratio (SiGe HBT vs Si BJT) is presented in Fig.6. While box Ge profile introduces only a minor decrease of τ_B (Ge dependence of minority electron mobility), the trapezoidal Ge profile results in significant improvement of the base transit time. As in the case of base current gain, the base transit time improvement is lowered at high doping concentrations. This result can again be explained by the higher influence of Fermi-Dirac statistics at high doping concentrations, which effectively lowers the grade of germanium in the base.

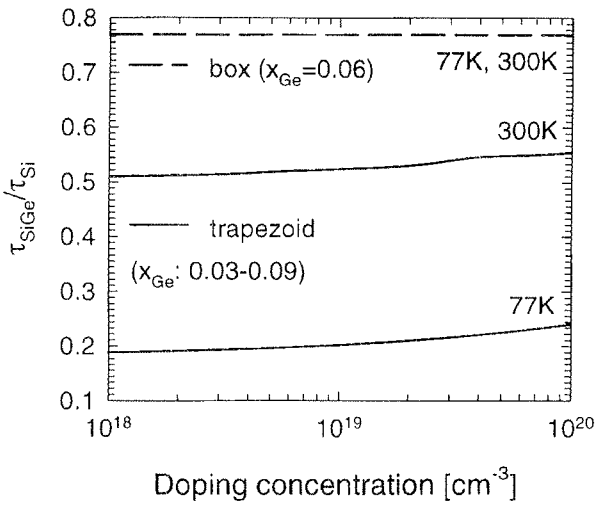


Fig. 6: The ratio of the base transit time between SiGe HBT and Si BJT where both devices have the same doping profile.

3.2 77 *K* vs. 300 *K* operation

It has been demonstrated that SiGe HBTs exhibit completely different behaviour at 77*K* than Si BJTs /5,6/. The current gain of Si BJTs decreases exponentially with decreasing temperature and the current gain degradation of Si BJT is the main reason for these devices being considered as useless for low temperature electronics. In contrast to Si BJTs, the current gain increases with decreasing temperature in SiGe HBTs, resulting in an important achievement for low temperature electronics. In first order approximation this behaviour can be explained by observing apparent bandgap narrowing, because the current gain is proportional to the difference between apparent bandgap narrowing in the base and in the emitter, which is thermally activated ($\beta \propto \exp(\Delta G(BASE) - \Delta G(EMITTER))$; since, in the case of SiGe HBTs $\Delta G(BASE) > \Delta G(EMITTER)$, the current gain naturally improves with cooling. Thermal activation of the apparent bandgap narrowing in the base is also responsible for the improvement of the base transit time at low temperatures. The improvement of SiGe HBTs at 77 *K* is evident from a comparison of 300 *K* and 77 *K* characteristics presented in Fig. 5 and Fig. 6.

3.3 Influence of Fermi-Dirac statistics

The importance of Fermi-Dirac statistics has been traditionally related to the operation of heavily doped emitters of Si BJTs. However, due to the lower hole effective mass in SiGe than in Si, lower possible temperature of operation, and higher doping concentrations in the base, it is expected that the Fermi-Dirac statistics will influence the base transport properties of SiGe HBTs.

The influence of Fermi-Dirac statistics on the collector current of SiGe HBTs at low temperatures has been recently analyzed /27/. It has been shown that Fermi-Dirac statistics is responsible for two effects: the Fermi level shift, which lowers the collector current (a contribution of term D in (7)) and is a major effect of Fermi-Dirac statistics, and an increase of $N_{V,SiGe}$ which attenuates the Fermi level shift (a contribution of term C in (7)) and is a minor effect of Fermi-Dirac statistics. The ratio of the collector current and the base transit time calculated by Fermi-Dirac and Boltzmann statistics is presented in Fig. 7 and Fig. 8, respectively. As can be seen, the Fermi-Dirac statistics influence the collector current more than the base transit time, especially if the temperature is low. In the case of collector current, the box Ge profile is more sensitive to the Fermi-Dirac statistics due to the increased importance of Fermi-Dirac statistics at higher Ge content (lower hole effective mass). It is clear that Fermi-Dirac statistics significantly influences the collector current of SiGe HBTs at 77*K* for all doping concentrations in the base of interest, and

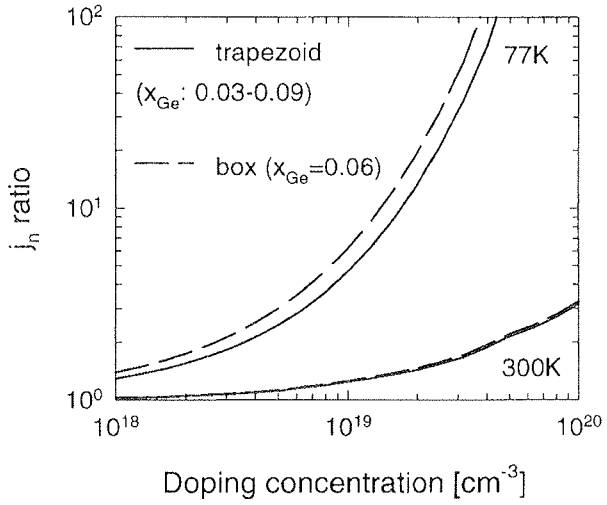


Fig. 7: The ratio of the electron current in the base calculated with Boltzmann and Fermi-Dirac statistics.

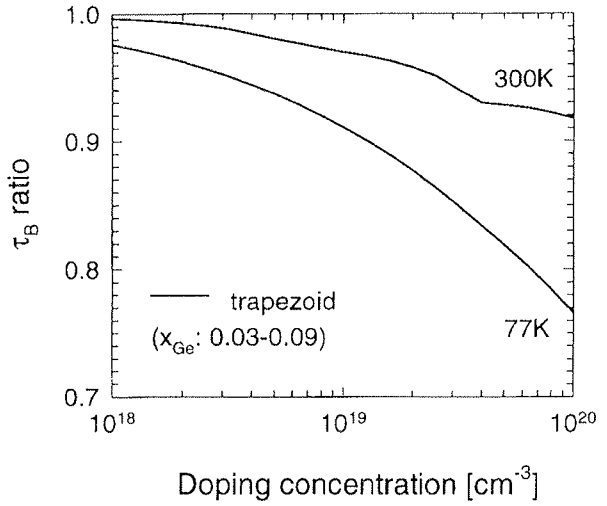


Fig. 8: The ratio of the base transit time calculated with Boltzmann and Fermi-Dirac statistics.

should be taken into account for optimization of these devices. If doping concentration in the base exceeds $4 \cdot 10^{18} cm^{-3}$, the Fermi-Dirac statistics are important for the collector current also at 300 *K*. The base transit time is affected by Fermi-Dirac statistics only if the base doping concentration is very high and operating temperature approaches 77 *K*.

4. Analytical modelling of base transport properties

The analytical model describing carrier transport in the base with uniform impurity profile doped up to $10^{20} cm^3$ and trapezoidal Ge profile with arbitrary grade is important for efficient analysis of the current gain and the base transit time of SiGe HBTs at both 77*K* and 300*K*. Present approaches to the analytical modelling of base transport properties are restricted to the exact consideration of $\Delta E_{g,Ge}$ /1/. Although fundamental insight into the influence of Ge profile on collector current or base transit time can be obtained in this way, accurate modelling and optimization also requires the consideration of Fermi-Dirac statistics as well as the Ge dependence of effective densities of states and diffusion constant.

An approach to the analytical modelling of collector current at 77*K* has been recently presented in /27/. This idea has been further extended for 300*K* analysis and for the modelling of base transit time in /28/. The analytical approach here presented is based on effective Ge induced bandgap narrowing ($\Delta E_{g,Ge,eff}$) /27,28/, which takes into account all Ge dependent effects responsible for minority electron current in the base:

$$\Delta E_{g,Ge,eff} = \Delta E_{g,Ge} + kT\, ln\left(\frac{N_{C,SiGe} N_{V,SiGe}}{N_{C,Si,i} N_{V,Si,i}}\right) + \tag{10}$$

$$+kT\, ln\left(\frac{N_A}{N_{V,SiGe}}\right) - kT\, G_{1/2}\left(\frac{N_A}{N_{V,SiGe}}\right) + kT\, ln(\eta),$$

where η is $D_{n,SiGe}/D_{n,Si}$. Since $\Delta E_{g,Ge,eff}$ is nearly a linear function of Ge fraction at both 300 *K* and 77 *K* (see Fig. 9), an effective trapezoidal Ge profile can be found for every grown trapezoidal Ge profile. By means of an effective trapezoidal Ge profile, analytical expressions for $I_{C,SiGe}$ and $\tau_{B,SiGe}$ can be derived:

$$j_n = \frac{q n_{i,Si}^2 D_{n,Si}}{W_B N_A} exp\left(\frac{qV_{BE}}{kT}\right) \tag{11}$$

$$\frac{\left(\Delta E_{g,Ge,eff}(W_B) - \Delta E_{g,Ge,eff}(0)\right) exp\left(\frac{\Delta E_{g,Ge,eff}(0) + \Delta E_{g,hd}}{kT}\right)}{kT\left(1 - exp\left(\frac{\Delta E_{g,Ge,eff}(W_B) - \Delta E_{g,Ge,eff}(0)}{kT}\right)\right)},$$

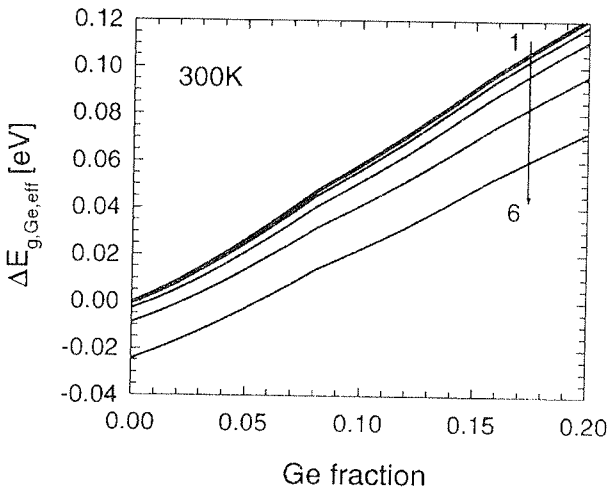
$$\tau_B = \frac{W_B^2}{D_{n,Si}\tilde{\eta}} \frac{kT}{\Delta E_{g,Ge,eff}(W_B) - \Delta E_{g,Ge,eff}(0)} \tag{12}$$

$$\left(1 - \frac{kT\left(1 - exp\left(\frac{\Delta E_{g,Ge,eff}(0) - \Delta E_{g,Ge,eff}(W_B)}{kT}\right)\right)}{\Delta E_{g,Ge,eff}(W_B) - \Delta E_{g,Ge,eff}(0)}\right)$$

where $\tilde{\eta}$ represents a position-averaged quantity of $D_{n,SiGe}/D_{n,Si}$. Since η does not significantly depend on x_{Ge}, its averaging appears not to be serious limitation of the model. To complete the model, accurate analytical expressions for $\Delta E_{g,Ge,eff}$ for both 300*K* and 77*K* should be found and these are presented in /28/. Expression (11) clearly demonstrates that the electron current in the base depends significantly on $\Delta E_{g,Ge,eff}(0) + \Delta E_{g,hd}$, which represent the apparent bandgap narrowing and the Ge enhancement of diffusion constant at the base side of the emitter-base depletion region. On the other hand, eq. (12) indicates that the base transit time depends only on the grade of $\Delta E_{g,Ge,eff}$ in the base $(\Delta E_{g,Ge,eff}(W_B) - \Delta E_{g,Ge,eff}(0))$.

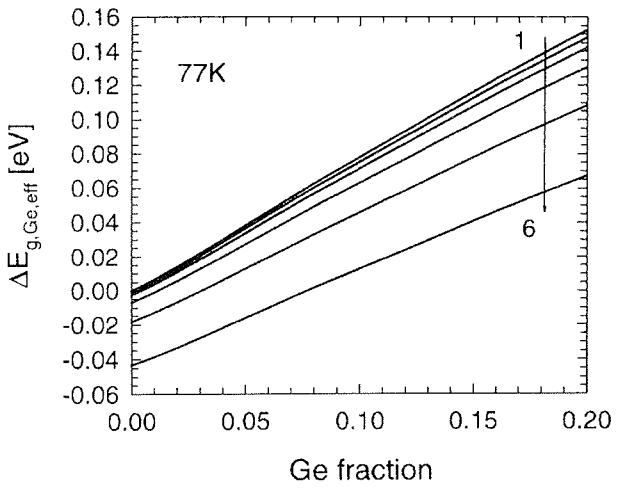
5. Conclusions

The electron current in the base and the base transit time are analyzed. The physical mechanisms in the base influencing the base transport properties are described. It is shown that the bandgap narrowing due to strain and alloying, as well as hole effective mass reduction due to distortion and nonparabolicity of the valence



(a)

Fig. 9: Effective Ge-induced bandgap narrowing as a function of Ge fraction. Curves 1-6 correspond to different doping concentrations: $10^{17} cm^{-3}$, $10^{18} cm^{-3}$, $3.2 \cdot 10^{18} cm^{-3}$, $10^{19} cm^{-3}$ $3.2 \cdot 10^{19} cm^{-3}$ and $10^{20} cm^{-3}$. (a) 300 K.



(b)

Fig. 9: Effective Ge-induced bandgap narrowing as a function of Ge fraction. Curves 1-6 correspond to different doping concentrations: $10^{17}cm^{-3}$, $10^{18}cm^{-3}$, $3.2\cdot10^{18}cm^{-3}$, $10^{19}cm^{-3}$ $3.2\cdot10^{19}cm^{-3}$ and $10^{20}cm^{-3}$. (b) 77 K.

band are the most important effects induced by Ge in the base. A set of required models is suggested, and an analytical approach to the modelling of electron current in the base and the base transit time is presented. It has been demonstrated that the improvement of SiGe HBTs compared to Si BJTs decreases slightly with increased doping concentration, and increases significantly with cooling. It has been shown that Fermi-Dirac statistics significantly influence the electron current in the base and should be taken into account for accurate analysis and optimization of SiGe HBTs.

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References:

/1/ D. L. Harame, J. H. Comfort, J. D. Cressler, E. F. Crabbé, J. Y.-C. Sun, B. S. Meyerson, and T. Tice, *IEEE Trans. Electron Devices.* **42**, 455 (1995), and the references therein.

/2/ D. L. Harame, J. H. Comfort, J. D. Cressler, E. F. Crabbé, J. Y.-C. Sun, B. S. Meyerson, and T. Tice, *IEEE Trans. Electron Devices.* **42**, 469 (1995), and the references therein.

/3/ A. Gruhle, H. Kibbel, U. König, U. Erben, and E. Kasper, *IEEE Electron Dev. Lett.* **13**, 206 (1992).

/4/ D. L. Harame, E. F. Crabbé, J. D. Cressler, J. H. Comfort, J. Y.-C. Sun, S. R. Stiffer, E. Kobeda, J. N. Burghartz, M. M. Gilbert, J. C. Malinowski, and A. J. Dally, *IEDM Tech. Dig.* p. 19 (1992).

/5/ J. D. Cressler, J. H. Comfort, E. F. Crabbé, G. L. Patton, J. M. C. Stork, J. Y.-C. Sun, and B. S. Meyerson, *IEEE Trans. Electron Devices* **40**, 525 (1993).

/6/ J. D. Cressler, *J. Phys. IV* **4**, C6-101 (1994).

/7/ J. D. Cressler, E. F. Crabbé, J. H. Comfort, J. Y.-C. Sun, and J. M. C. Stork, *IEEE Electron Dev. Lett.* **15**, 472 (1994).

/8/ H. Kroemer, *Solid-State Electron.* **28**, 1101 (1985).

/9/ J. C. Bean, *Proc. IEEE* **80**, 571 (1992).

/10/ S. Sokolić, and S. Amon, *Proc. MIEL'95*, p. 385, Čatež, Slovenia (1995).

/11/ J. Poortmans, M. Caymax, A. Van Ammel, M. Libezny, K. Werner, S. C. Jain, J. Nijs, and R. Mertens, *Proc. ESSDERC'93*, p. 317, Grenoble, France (1993).

/12/ S. Decoutere, J. Poortmans, L. Deferm, and J. Nijs, *Solid-State Electron.* **38**, 157 (1995).

/13/ R. People, *IEEE J. Quantum Electron.* **QE-22**, 1696 (1986).

/14/ D. J. Robins, L. T. Canham, S. J. Barnett, A. D. Pitt, and P. Calcott, *J. Appl. Phys.* **71**, 1407 (1992).

/15/ T. Manku, and A. Nathan, *J. Appl. Phys.* **69**, 8414 (1991).

/16/ Y. Fu, S. C. Jain, M. Willander, and J. J. Loferski, *J. Appl. Phys.* **74**, 402 (1993).

/17/ S. Sokolić, and S. Amon, *J. Phys. IV* **6**, C3-137 (1996).

/18/ J. Poortmans, S. C. Jain, D. H. J. Totterdell, M. Caymax, J. Nijs, R. Mertens, and R. Van Overstraeten, *Solid-State Electron.* **36**, 1763 (1993).

/19/ A. Souifi, G. Brémond, T. Benyattou, and G. Guillot, *Appl. Phys. Lett.* **62**, 2986 (1993).

/20/ B. Pejčinović, L. E. Kay, T.-W. Tang, and D. H. Navon, *IEEE Trans. Electron Dev.* **36**, 2129 (1989).

/21/ M. A. Green, *J. Appl. Phys.* **67**, 2944 (1990).

/22/ S. Sokolić, and S. Amon, to be published in *Proc. ESSDERC'96*, Bologna, Italy (1996).

/23/ S. Sokolić, and S. Amon, submitted for publication.

/24/ D. B. M. Klaassen, J. W. Slotboom, and H. C. de Graaff, *Solid-State Electron.* **35**, 125 (1992).

/25/ S. Sokolić, and S. Amon, *Proc. of the 1995 ECS Symp. on Low Temperature Electronics and High Temperature Superconductivity* (ECS PV 95-9, The Electrochemical Society, Pennington), p. 199, Reno, Nevada (1995).

/26/ D. B. M. Klaassen, *Solid-State Electron.* **35**, 953 (1992); *Solid-State Electron.* **35**, 961 (1992).

/27/ S. Sokolić, and S. Amon, *J. Phys. IV* **6**, C3-131 (1996).

/28/ S. Sokolić, and S. Amon, to be published in *Proc. MIEL'96*, Nova Gorica, Slovenia (1996).

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