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Influence of Ge profile on the noise behavior of SiGe HBTs under high injection conditions

M.J. Martín-Martínez*, S. Pérez, D. Pardo, T. González

Dpto. de Física Aplicada, Universidad de Salamanca, Plaza de la Merced s/n., 37008 Salamanca, Spain

Abstract

We present a Monte Carlo analysis of the influence of the Ge profile shape in the base of SiGe HBTs on their noise performance under high injection conditions. While the base and collector spectral densities show a similar overall behavior for the different Ge profiles considered, they are lower than that in an analogous BJT. The Ge profile determines the onset of hot-carrier effects in the base, as clearly identified in both static and noise characteristics of the transistors. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

SiGe HBTs are becoming increasingly popular because of their numerous advantages over conventional Si transistors: better current gain, β, cutoff frequency, f_T, early voltage or minimum noise figure, NF_{min}. Thus, SiGe technology is expected to be a low-cost alternative to GaAs and offers strong competition for high-speed RF and microwave circuits [1]. The dynamic and noise performance of these devices when operating under the bias conditions providing the maximum β and f_T are strongly degraded by the presence of hot carriers and high injection effects, which take place mainly in the high-field base–collector region. To minimize this degradation different base Ge profiles can be considered. A detailed microscopic understanding of all these phenomena is compulsory to further improve the HBT performance. In this work, we report a Monte Carlo (MC) analysis of the noise behavior of SiGe HBTs in common-emitter configuration at microwave frequencies considering different Ge profiles. A Si BJT is also considered for comparison.

2. Simulated structures, transport model and static results

The topology of the Si BJT and SiGe HBTs simulated in this work is shown in Fig. 1. All the structures exhibit identical geometry and doping levels. The different Ge profiles considered in the HBT base (box, triangular and trapezoidal) are also shown in Fig. 1. For a fixed base thickness the total Ge content has been kept constant in the

*Corresponding author. Tel.: +34-923-294-400; fax: +34-923-294-584.

E-mail address: mjmm@usal.es (M.J. Martín-Martínez).

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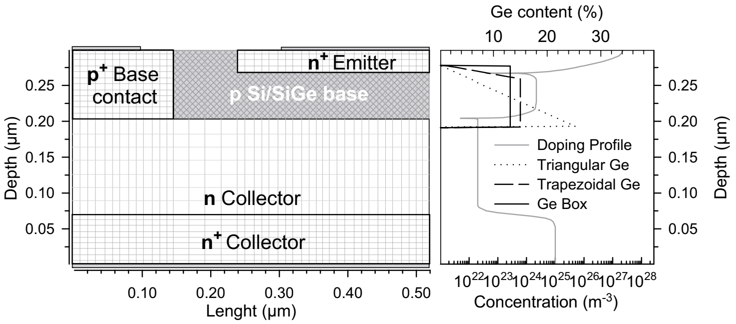

Fig. 1. Geometry of the simulated structures. Doping and Ge profiles of the different HBTs as a function of the vertical depth.

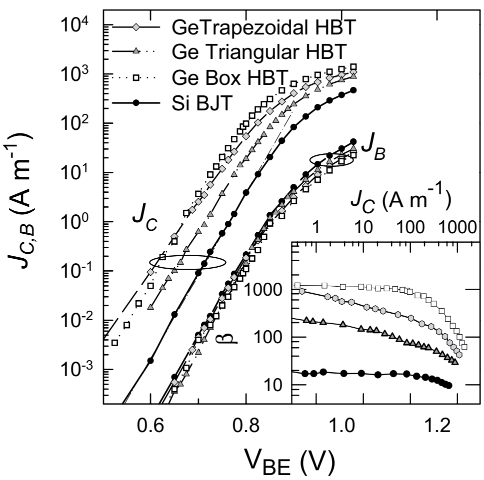

Fig. 2. Simulated base- and collector-current densities (J_B and J_C) as a function of V_{BE} for $V_{CB} = 1.0\,V$. Current gain β versus J_C (inset).

three HBTs to achieve a base layer with identical Ge stability. Several DC, AC and noise figures of merit of the HBTs (as β, f_T or NF_{min}) depend on the Ge profile in the base. For the calculations we use an ensemble MC model, coupled with a two-dimensional Poisson solver [2], that includes electron and hole dynamics simultaneously [3]. The main characteristics of the simulator can be found in Ref. [3].

Fig. 2 reports the J_C, J_B–V_{BE} characteristics of the different transistors. At low-bias conditions, J_B and J_C in the BJT follow the typical dependence with V_{BE} proportional to $\exp(qV_{BE}/K_BT)$. The constant Ge content in the base of the Ge box HBT lowers the potential emitter–base (EB) barrier for electrons, thus exponentially increasing the number of injected electrons while maintaining the same typical dependence of J_C with V_{BE}. Thus, the Ge box HBT provides a given level of J_C (Fig. 2) requiring a much lower value of J_B than the BJT (*heterojunction* effect). Accordingly, while both structures exhibit bias-independent values of current gain β (Fig. 2, inset), this is much higher in the HBT. On the other hand, the trapezoidal and triangular Ge profiles prevent J_C to exhibit the typical slope of 60 mV per decade in the low injection regime. This slope decreases when V_{BE} increases due to the fact that the movement of the edge of the space charge region in the base has an effect of J_C. Thus, a decreasing β at increasing J_C, more remarkable in the trapezoidal Ge profile, is found in both structures. High-injection phenomena are responsible for the drop in the device performance, which takes place at high collector current densities (responsible for the β fall-off in all the structures).

We depict the features of transport inside the devices under high injection conditions ($J_C = 200\,A\,m^{-1}$) in Fig. 3 by showing average profiles of several physically relevant quantities. Various effects derived from the different Ge profiles can be observed. High-level injection at the EB junction takes place when the minority carrier density in the base reaches a value around 10% of the majority carrier concentration, leading the hole density to increase to maintain the quasi-neutrality. In Fig. 3(a) high-level injection in the base is already fully reached in the Si BJT and Ge

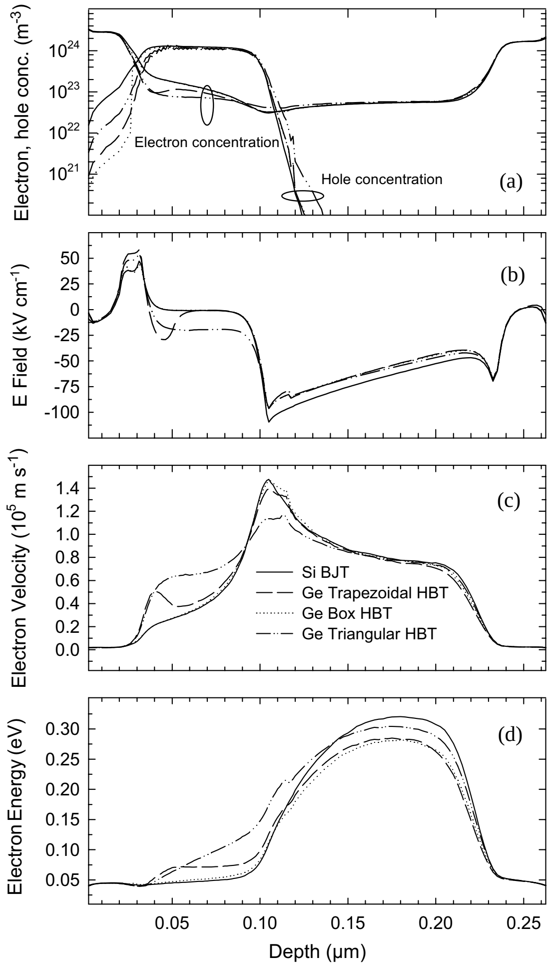

Fig. 3. Average profiles of (a) electron and hole concentrations, (b) electric field, (c) electron velocity and (d) energy in the region localized below the emitter under high injection conditions ($J_C = 200\,\mathrm{A\,m^{-1}}$).

box HBT, and the electric field has almost an identical shape in both structures (Fig. 3(b)). However, there is a more effective confinement of holes in the Ge box base (Fig. 3(a)). Regarding the trapezoidal and the triangular Ge profile HBTs, due to the spatial dependence of the Ge content in the SiGe base, a negative quasi-electric field is built in the base region, which helps the electrons to reach the collector. In the trapezoidal HBT this region extends only over the space in which the linear Ge variation takes place while a bias-independent quasi-electric field ($=19\,\mathrm{kV\,cm^{-1}}$) extends over the entire SiGe region in the triangular case (Fig. 3(b)). As a consequence of this "aiding" electric field, the electron velocity is boosted in the trapezoidal and triangular structures (Fig. 3(c)), reaching values larger than $5\times10^4\,\mathrm{ms^{-1}}$ at the beginning of the neutral SiGe region (0.04 μm depth). While in the trapezoidal profile the energy gained at the end of the Ge ramp is maintained along the base, in the triangular profile the energy linearly increases over the length of the base (Fig. 3(d)). This effect does not depend on the bias conditions. After a quasi-neutral base, electrons travel towards the base–collector (BC) junction in which the electric field gets a very high value (around $100\,\mathrm{kV\,cm^{-1}}$), which makes them exhibit velocity overshoot (around $1.4\times10^5\,\mathrm{ms^{-1}}$). This velocity overshoot is not so strong in the triangular Ge profile HBT because of the smaller field step due to the previous constant "aiding" field at the base. For the bias condition shown in Fig. 3, the phenomena of push-out of the base or Kirk effect becomes an important high injection contribution, which leads to a widening of the base that penetrates into the collector, and causes a displacement of the highest electric field towards the sub-collector region [3].

3. Noise results

The instantaneous current densities at each electrode obtained with our ensemble MC simulation allow the calculation of the two noise current generators, S_{J_B} (base) and S_{J_C} (collector) and their correlation $S_{J_{BC}}$ (reported in Fig. 4). These noise sources are typically used to represent the noise behavior of BJTs and HBTs and related to internal mechanisms that differ between the HBTs as band discontinuities, hot carrier effects, etc. [4]. At low injection level (for $J_C < 50\,\mathrm{A\,m^{-1}}$), the presence of different Ge profiles does not modify the general behavior of $S_{J_{BC}}$ and S_{J_C}in the HBTs as compared with that found in the BJT. For this injection range, when the EB barrier controls J_C, S_{J_C} exhibits shot-noise dependence, $2qJ_C$, as usually assumed in circuit models [4–5]. For larger J_C, under high injection conditions, the Webster and Kirk effects favor the appearance of hot carriers in

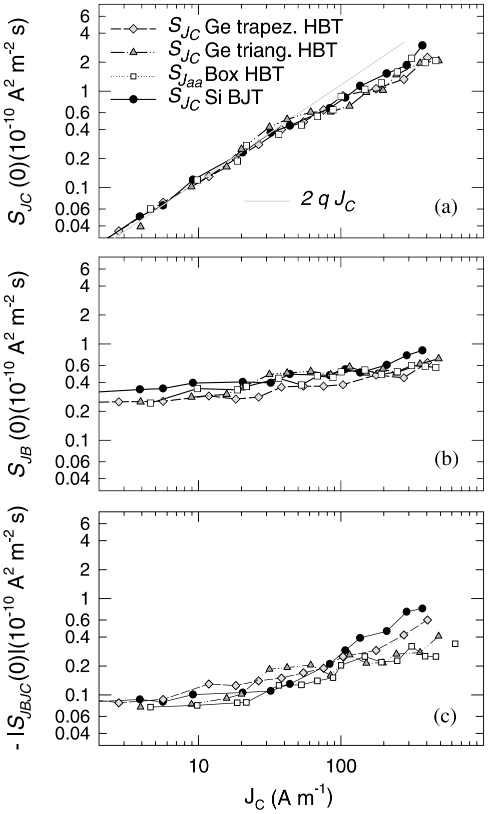

Fig. 4. Spectral densities of (a) base and (b) collector current fluctuations and (c) their cross-correlation calculated in the RF range.

the BC junction (which can be reduced in the HBTs by tailoring the Ge profile, Fig. 3(d)), leading to the deviation of S_{J_C} from the pure shot-noise behavior [3]. By modifying the Ge profile, the onset of these effects takes place at different J_C values. In the high injection regime, S_{J_C} becomes lower in the HBTs with respect to the BJT because of the Ge content benefits. In the HBT with a Ge box profile, the abrupt heterojunction leads to the phenomenon of high injection in the base to appear for lower values of J_C than in the other HBTs. Hence S_{J_C} deviates from the typical shot-noise behavior for values of J_C around $40\,\mathrm{A\,m^{-1}}$, becoming $<2qJ_C$ when bias increases (this structure also exhibits a much better performance in terms of β). The other HBTs maintain the typical shot-noise behavior up to slightly larger values of J_C. For higher J_C, the consequences of the Webster and Kirk effects make the collector noise increase significantly due to the appearance of hot carriers (Fig. 4(d)). In the low injection regime S_{J_B} is related to the base resistance (thermal noise). This noise source is located at the base terminal and accounts for the 2D contribution of the base resistance. In general, the value of S_{J_B} does not show large differences between the HBTs, while maintaining lower values than in the BJT (Fig. 4(b)). For the highest bias conditions, this base resistance becomes bias dependent, giving rise to larger values of S_{J_B}. In all the structures the expansion of the quasi-neutral base, when the base push-out effect takes place, also increments the S_{J_B} contribution (more significantly in the triangular Ge profile in which the aiding field extends over a wide base region). In the low injection regime, the values of the $S_{J_BJ_C}$ term are lower when compared with S_{J_B} (Fig. 4(c)). For larger J_C values, the type of heterojunction determines the influence that the electron heating has over the excess noise of the transistors. In an intermediate current range (10–$50\,\mathrm{A\,m^{-1}}$) the bias-independent "quasi-electric field" built when the Ge profile is not constant leads to an important increase of $S_{J_BJ_C}$ due to hot-carrier effects, which is more significant in the case of the triangular profile. As J_C increases the Kirk effect leads $S_{J_{BC}}$ to increase due to the larger contribution to the excess noise that comes from the hot carriers appearing in the collector of all the structures. The SiGe/Si heterointerface slightly prevents the electron energy to increase in the collector of the HBTs when compared with the BJT (Fig. 3(d)), especially in the case of the Ge box profile HBT.

Acknowledgements

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