Solid-State Electronics 60 (2011) 58–64

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Improving the high-frequency performance of SiGe HBTs by a global additional uniaxial stress

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ARTICLE INFO

Article history:
Available online 21 February 2011

Keywords:
HBT
SiGe
Uniaxial stress
Cutoff frequency
FB-MC
SHE

ABSTRACT

A global additional uniaxial stress ranging from −1 GPa to 1 GPa along different directions has been applied to SiGe HBTs in order to improve the high-frequency performance of these devices. Two transistors have been investigated: a slow one (peak f_T = 110 GHz) and a fast one (peak f_T = 750 GHz). The results from full-band Monte Carlo simulations show that the cutoff frequency of both devices can be improved by more than 30 percent under suitable stress conditions. A spherical-harmonics-expansion simulator is also used to investigate the spatial origin of this improvement, where it is found that the transit times are reduced in all regions (base, collector, emitter).

1. Introduction

With a strong demand for integrating all multimedia and online applications into one end-user device, very high-speed circuits, hence very high-speed transistors, are needed. Moreover, high-speed communication systems such as optical system for handling very large amounts of data also require very fast transistors for their transmitters and receivers. Cost-efficient silicon–germanium hetereojunction bipolar transistors (SiGe HBTs) have been widely deployed for these high-speed applications due to their excellent radio frequency (RF) performance and compatibility with silicon-based CMOS technologies [1–3]. Therefore, it has been tried to push the cutoff frequency f_T of these transistors upward by various methods [4–13]. One of these examples is the ongoing EU project *DOTFIVE* which has the target of successfully developing 0.5 THz SiGe HBTs [14].

Strain engineering is a promising technology to improve f_T due to the following reasons. First, strain technology has been widely adopted as a booster for transistors due to the increased carrier mobility in strained materials. Uniaxially strained Si is the dominant technology for CMOS today [15], whereas biaxially strained SiGe, where the stress is due to the lattice mismatch between Si and SiGe layers, is applied in SiGe HBTs in order to shape the conduction and valance bands [1,4]. The biaxially strained layer in SiGe HBTs can be modified by adjusting the Ge profile [2]. Furthermore, the electron and hole mobilities can be enhanced by uniaxial and biaxial strain for Si and SiGe [16]. This fact leads to an expectation that applying an additional uniaxial stress to a SiGe HBT might be beneficial.

However, recent attempts of applying strain engineering to improve the performance of SiGe HBTs [17–20] have resulted only in an increase of current gain and not in cutoff frequency. In [19], the authors tried small uniaxial stresses (max. ±250 MPa) in only one direction, which gave a slight increase in the current gain (16% for the best case) and no gain in f_T. Due to technical issues, larger stresses or other stress directions could not be implemented. In [20], the authors applied biaxial strain in the collector by a virtual Ge substrate, which resulted in a very high current gain; however f_T was not discussed. Therefore, further investigation of HBTs under various strain conditions should be done, not only by experiments but also by device simulations. Compared to experiments, simulations are more effective to explore the behavior of those devices as well as to offer insights into charge transport within the devices.

In this work, SiGe HBTs under an additional uniaxial stress are investigated. Since it is non-trivial, in a technological point of view, to apply a uniaxial stress locally at a specific region of the device, a global additional uniaxial stress should be applied to the whole device. A wide range of stress magnitude, from −1 GPa to 1 GPa, along different stress directions is considered. Two devices are explored: one with a peak f_T of around 110 GHz, named *slow HBT*, and the other with a peak f_T of around 750 GHz, named *fast HBT*.

A full-band Monte Carlo (FB-MC) [21] and a spherical-harmonics-expansion (SHE) [22] simulator are used to thoroughly investigate such stressed SiGe HBTs. FB-MC is considered as the most accurate solver for the Boltzmann transport equation (BTE) [23]. Its solution is often taken as a reference for other numerical device simulators.

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0038-1101/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.sse.2011.01.027

Moreover, it can handle band structures of the material under complicated stress/strain conditions provided that such realistic band structures are available. However, it is very time consuming to calculate AC quantities by FB-MC. Therefore, the SHE simulator which is a deterministic solver of the BTE is also used. A combination of these two simulators is expected to be an efficient tool for understanding HBTs' behavior under various stress conditions.

The paper is organized as follows. The structures of the devices under investigation are presented in Section 2. The device simulators are described in Section 3. In Section 4, simulation results for these devices are presented. Finally, we summarize the key findings and conclude the paper.

2. Device structures

The schematic description of a SiGe HBT under a global additional uniaxial stress is shown in Fig. 1. The SiGe layer is grown on a relaxed Si substrate along the [1 0 0] direction. This orientation is chosen since it is the most common direction for growing strained SiGe over relaxed Si in HBT today [3]. Other crystal orientations, e.g. [1 1 0] or [1 1 1], are either difficult in term of technology for growing or not beneficial to the device's performance. A uniaxial stress along the [0 *x x*] directions, i.e. from 0 to 90 degree, will be applied to the whole device. Since the stress directions at 0 and 45 degree can be the best representatives for all directions, the directions [0 1 0] and [0 1 1] are investigated in this work. It is noted that a positive force causes a tensile stress and a negative force causes a compressive one. The SiGe HBT under an additional stress is shortly called *s-HBT*. The geometry of the devices is also shown in Fig. 1. The slow HBT has a body width of $W = 0.1$ μm and a collector–emitter length of $L = 0.5$ μm, whereas the respective parameters for the fast HBT are $W = 0.1$ μm and $L = 0.07$ μm.

Fig. 2 shows the doping and Ge profiles of the investigated HBTs. The maximum donor concentration in the slow HBT is $4 \times 10^{19}/\text{cm}^3$ (to reduce the CPU time of the FB-MC simulations) while this quantity in the fast HBT is one order of magnitude higher, $4\times 10^{20}/\text{cm}^3$ (and cannot be reduced without distorting the device characteristics). The maximum acceptor concentration in the base is $5 \times 10^{19}/\text{cm}^3$ and $8 \times 10^{19}/\text{cm}^3$ for the slow and fast HBT, respectively.

The maximum Ge concentration is 20% and 18% for the slow and fast device, respectively. The Ge layer has a graded box shape extending slightly into the lowly doped collector.

3. Device simulation

3.1. Full-band Monte Carlo

A self-consistent full-band Monte Carlo simulator [21], which solves the BTE and Poisson equation (PE) self-consistently, is used

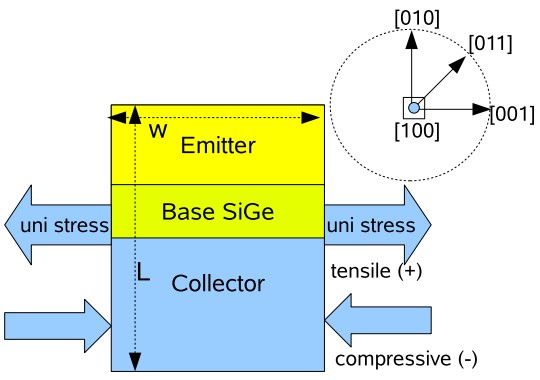
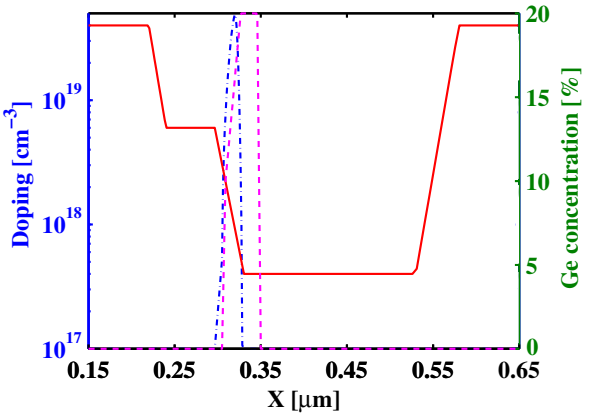
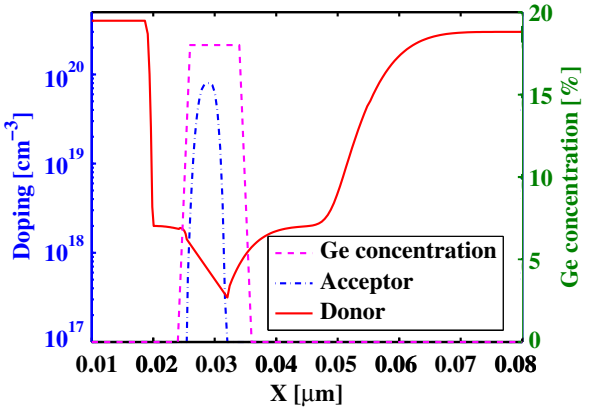


Fig. 1. Schematic diagram of the investigated HBTs. Dimension of the slow HBT: $W = 0.1$ μm, $L = 0.5$ μm and the fast HBT: $W = 0.1$ μm, $L = 0.07$ μm; Growth direction: [1 0 0]; Uniaxial stress directions: [0 1 0] and [0 1 1].



(a) Slow HBT



(b) Fast HBT

Fig. 2. Doping and Ge profile for the investigated HBTs.

to simulate one-dimensional HBTs. Normally, both electrons and holes have to be simulated by the MC method in all semiconductor regions of the device to calculate the particle densities. However, in this case, since the hole density p can be described by a constant quasifermi potential given by the base bias [24,25], p is directly evaluated by the following equation

$$p = n_i \exp\left(\frac{\Phi_p - \Psi - \Psi_h}{V_T}\right), \tag{1}$$

where Φ_p is the quasifermi potential for holes, Ψ is the electrostatic potential, Ψ_h is the workfunction difference relative to relaxed silicon, n_i is the intrinsic carrier density and V_T is the thermal voltage [21]. With this assumption, the PE becomes nonlinear [26]. Consequently, for each time step of the simulation, the nonlinear PE has to be solved.

3.1.1. Band structure calculations

The empirical nonlocal pseudopotential method (EPM) [27,28], which was shown to be able to give realistic band structures under complex stress/strain conditions [29], is used to calculate the band structures for the strained SiGe in this work. From Fig. 1, we see that there are two types of strain in the investiated HBTs:

- Type 1: Uniaxially strained Si in the emitter and collector.
- Type 2: Biaxially strained SiGe under an additional uniaxial stress, which is called uni-biaxially strained SiGe. This strain type occurs in the base.

For uniaxially strained Si, the strain tensor is straightforwardly determined and presented in detail somewhere else [29,30]. The