GERMANIUM GRADIENT OPTIMIZATION FOR HIGH-SPEED SILICON GERMANIUM HETERO-JUNCTION BIPOLAR TRANSISTORS

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Article Info	Abstract
<p>Received: 29.09.2019 Accepted: 27.11.2019</p> <p>Keywords: SiGe HBT; SILVACO; Trapezoidal profile; Current Gain; Cut-off frequency; Maximum oscillation frequency.</p>	<p>The effect of germanium trapezoidal profile shape on the direct current (DC) current gain (β_F), cut-off frequency (f_T) and maximum oscillation frequency (f_{MAX}) of silicon-germanium (SiGe) hetero-junction bipolar transistors (HBTs) has been investigated. The energy balance (EB), hydrodynamic (HD) and drift-diffusion (DD) physical transport models in SILVACO technology computer aided design (T-CAD) simulator were used. It was found that the current gain values using energy balance model are higher than hydrodynamic and much higher than those corresponding to drift-diffusion. Moreover, decreasing the germanium gradient slope towards the collector side of the base enhances the maximum oscillation frequencies using HD and EB models whilst, they remain stable for DD model.</p>

1. Introduction

Despite that silicon (Si) and germanium (Ge) combination idea for use in bipolar transistor engineering is old, it was only in 1987 where the first SiGe hetero-structure bipolar transistor (HBT) was reported [1]. In the 1990s with the revolution in bipolar transistor design, SiGe HBTs have emerged as serious contenders for analog, digital and mixed signal radio frequency (RF) application [2]. Previously, hetero-junction bipolar transistors had only been available in compound semiconductor technologies, such as AlGaAs/GaAs [2]. The formation of an effective hetero-junction requires two semiconductors with similar lattice spacing. Si and Ge have a relatively large lattice mismatch of 4.2%, so it is very difficult to form a hetero-junction between Si and SiGe without misfit dislocations at the interface. Fortunately, however, in the 1980s a good hetero-junction was obtained with thin SiGe layers and low Ge content (relatively below 30%) [3, 4]. In these cases, SiGe layer grows under

strain so that it fits perfectly onto the silicon lattice without the generation of misfit dislocations. The vital technology breakthrough that led to the emergence of SiGe is the epitaxial growth of reproducible strained or pseudomorphic, SiGe layers. Nowadays, the market for SiGe HBTs has grown rapidly to satisfy the demand for applications such as wireless communications, high-data-rate wireline and automotive radar [5]. SiGe HBTs with cut-off frequencies of 300 and 505 GHz and maximum oscillation frequencies of 500 and 720 GHz were demonstrated [5-8]. In this paper, we investigate the effect of Ge gradient profile in SiGe base on β_F , f_T , and f_{MAX} of SiGe HBTs using the drift-diffusion, hydrodynamic and energy balance models implanted in the two-dimensional (2D) Atlas module from SILVACO T-CAD. The SiGe HBT structure is based on the state-of-the-art SiGe HBT technology [5, 6]. In section 2, the structure and physical models used in this work are described. The results with analysis are discussed in section 4. Finally, a conclusion is given in the last section.

2. Modeling and simulation

The drift-diffusion model is the simplest model for describing charge transport in semiconductor devices [9]; it neglects non-local transport effects. In some cases such low dimensional structures, the DD model is not sufficient. More suitable models have to be used such as energy balance and hydrodynamic. The energy balance transport model (EBTM) follows the derivation by Stratton from the Boltzmann transport equation [10, 11, 12]. With some assumptions, it will decompose into the hydrodynamic model [13, 14, 15].

2.1. Device structure

In this work, a comparison of three SiGe HBTs is carried out using three different germanium trapezoidal profile shapes: profile 1 (HBT1), profile 2 (HBT2) and profile 3 (HBT3). Figure 1 shows the geometry of the studied SiGe HBT. All perimeters are the same for the devices and the only difference resides in the base germanium profile. The total emitter area is assumed to be $0.12 \times 0.96 \mu m^2$ [5].

Fig. 1. SiGe HBT simulated structure.

The germanium profile in the base and vertical one-dimension (1D) doping profile are presented in Figure 2. The germanium peak composition equals to 0.28. In this figure, the net doping concentration in the three regions of the SiGe HBT; emitter, base, and collector (left axis) is presented with blue solid line. The emitter region is high n-doped with a uniform concentration which falls from 10^{21}cm^{-3} ($1/\text{cm}^3$) near the emitter contact to $2 \times 10^{18}\text{cm}^{-3}$ ($1/\text{cm}^3$) near the base region (cm^{-3} means dopant concentration per cm^3). The base is p-doped with a Gaussian doping profile of a peak concentration of $8 \times 10^{19}\text{cm}^{-3}$ which is inspired from [16]. The collector doping is low near the base side and is being increased gradually to be high in the collector bulk and near its contact to reduce the collector resistance. From its side, the germanium composition in the base is presented with dashed lines for the three devices (right axis). The germanium composition in the base varies according to x ratio in $\text{Si}_{1-x}\text{Ge}_x$; when $x=0$ we get silicon and when $x=1$ we get germanium. In our case x varies from about 0.25 at the emitter side of the base to 0.28 at the collector side of the base with three different shapes (trapezoidal profile).

The parameters used in this simulation such as doping, band-gap narrowing, low-field mobility, effective lifetime, germanium band-gap narrowing and others are taken from [10, 17]. During all simulations, material parameters, physical models and structure dimensions and perimeters are being kept unchanged.

Fig. 2. Germanium profile shapes and doping used in the simulation [16]

2.2. Physical parameters

Advances in silicon and $\text{Si}_{1-x}\text{Ge}_x$ alloys growth have allowed the potential for using bandgap engineering to construct hetero-junction devices such as HBTs and HEMTs using these materials.

The following section describes the functional relationship between Ge mole fraction x , and SiGe material characteristics necessary for device simulation.

2. 2.1. Bandgap

Bandgap is one of the most fundamental parameters for any material. For SiGe, the dependence of bandgap on Ge mole fraction, x , is divided into ranges as follows [10, 18]:

$$\begin{aligned} &\text{For } x \leq 0.245 \\ &E_g = 1.08 + (x \times (0.945 - 1.08))/0.245 \end{aligned} \quad (1)$$

$$\begin{aligned} &\text{For } 0.245 \leq x \leq 0.35 \\ &E_g = 0.945 + (x - 0.245) \times (0.87 - 0.945)/(0.35 - 0.245) \end{aligned} \quad (2)$$

Temperature dependence of the bandgap of SiGe is calculated the same as for silicon

except that $E_{g\alpha}$ and $E_{g\beta}$ are a function of Ge mole fraction x as follows:

$$E_g(T_L) = E_g + E_{g\alpha} \left[\frac{300^2}{300 + E_{g\beta}} - \frac{T_L^2}{T_L + E_{g\beta}} \right] \quad (3)$$

Where:

$$E_{g\alpha} = (4.73 + x \times (4.77 - 4.73)) \times 10^{-4}$$

$$E_{g\beta} = 636 + x \times (235 - 636)$$

2.2.2. Electron Affinity

The electron affinity of SiGe is taken to be constant (4.17) with respect to composition.

2.2.3. Density of States

The density of states for SiGe depends upon Ge mole fraction, x composition, according to :

$$N_C = 2.8 \times 10^{19} + x \times (1.04 \times 10^{19} - 2.8 \times 10^{19}) \quad (4)$$

$$N_V = 1.04 \times 10^{19} + x \times (6.0 \times 10^{18} - 1.04 \times 10^{19}) \quad (5)$$

2.2.4. Dielectric Function

Compositional dependence of static dielectric constant of SiGe is given by:

$$\varepsilon = 11.8 + 4.2 \times x \quad (6)$$

2.2.5 Low Field Mobility

SiGe low field electron and hole mobilities at room temperature are given by [17] as:

$$\mu_n \approx (1396 - 4315 \times x)_{cm^2 V^{-1} S^{-1}} \quad 0 \leq x \leq 0.3 \text{ at } 300 K \quad (7)$$

$$\mu_p \approx (450 - 865 \times x)_{cm^2 V^{-1} S^{-1}} \quad 0 \leq x \leq 0.3 \text{ at } 300 K \quad (8)$$

2.2.6 Velocity Saturation

In SiGe, the temperature dependent velocity saturation, used in field dependent mobility model is defined by the following equations.

$$V_{SATN} = 1.38 \times 10^7 \cdot \sqrt{\tanh\left(\frac{175}{T_L}\right)} \quad (9)$$

$$V_{SATP} = 9.05 \times 10^6 \cdot \sqrt{\tanh\left(\frac{312}{T_L}\right)} \quad (10)$$

Where T_L denotes the lattice temperature.

3. Results and discussions

The effects of germanium trapezoidal profile shapes on the DC current gain, the cut-

off frequency and the maximum oscillation frequency using drift diffusion, hydrodynamic and energy balance models are performed by the use of Atlas module from SILVACO TCAD. The electric parameters results from this simulation are presented and compared. The DC current gain versus base-emitter voltage of the three HBTs is shown in Figure 3. We notice that HBT1, HBT2 and HBT3 have a maximum current gain of 717, 705 and 680 using EB model, respectively. The change of the germanium profile shape affects slightly the DC current gain; the gain decreases about 8% for DD and 5% for HD and EB transport models from HBT1 to HBT3. The change of the trapezoidal profile from profile1 to profile 3 induces a small reduction of the collector current, base current and the current gain, too and this agrees with theory, which indicates that the gain enhancement varies exponentially with the germanium composition at the emitter end of the base, whereas it varies linearly with the grading [19]. The values of β_F using EB model are higher than HD (about 1.67 times) and much higher than DD (about 3.5 times). The experimental results that are used for comparison in our work are taken from [5]. In these experimental results, the currents are normalized to an effective emitter width of $0.12\mu\text{m}$ which is the case in our device giving a peak current gain of 700 reached at $V_{CB}=0\text{V}$, room temperature, and at a base-emitter voltage of 0.8V . This peak current gain is close to our results in the case of using energy balance transport model. Figure 3 shows clearly that the EB current gain values are so close to those obtained experimentally used for comparison (specifically for HBT1) which means that EB transport model is more accurate than HD and DD models. This difference in current gain values between the models is due to temperature effects that could give an explanation between the transport models differences.

Figure 4 shows the overlay of the gummel plots of the three devices using EB simulation alongside with experimental results from [5]. Experimental collector and base current plots are normalized to an emitter width of $0.12\mu\text{m}$ at $V_{CB}=0\text{V}$ and at room temperature as the same as of our work. HBT1 gummel plots exhibits an excellent characteristics for both collector and base currents. We notice that both I_C and I_B currents match well experimental results (particularly HBT1) until a base-emitter voltage of 0.8V after which they undergo a slight decrease. These results confirm that EB transport model is more accurate than other models.

Fig. 3. DC current gain versus base-emitter voltage. Half up diamond are for experimental results from [5].

Fig. 4. EB simulation gummel plots. Stars are for experimental results [5].

Fig. 5. The calculated cut-off frequency f_T for devices HBT1 and HBT3.

The cut-off frequency f_T was first calculated according to $f_T = g_{cb} / (6.28 \times C_{bb})$ as shown in Figure 5, then extracted directly from the ac current gain. The maximum oscillation frequency f_{MAX} was obtained from the unilateral power gain U , as shown in Figure 6. Table 1 recapitulates and compares the electrical parameters of the three devices under load.

Table 1. Results of β_F , f_T and f_{MAX} for devices HBT1, HBT2 and HBT3.

	DD			HD			EB		
	HBT1	HBT2	HBT3	HBT1	HBT2	HBT3	HBT1	HBT2	HBT3
β_F	212.7	204.8	194.8	427.8	429.4	407.2	717.1	705	680.7
f_T (GHz): calculated	354	311	268	566	538	527	559	547	531
f_T (GHz) : from ac current gain	322	314	268	432	563	612	263	442	521
f_{MAX} (GHz) : from U	312	314	312	304	411	434	163	312	361

From these values in Table 1, we can notice that the calculated and extracted cut-off frequencies using DD transport model are close to each other and decrease from HBT1 to HBT3. f_{MAX} remains the same for the three devices. On the other hand, the calculated cut-off frequency decreases slightly using HD and EB models from HBT1 to HBT3. The cut-off and the maximum oscillation frequencies extracted directly from the ac current gain and unilateral power gain, respectively increase from HBT1 to HBT3 using HD and EB transport models. This increase in figures of merit could be explained by that the reduction in the germanium concentration at the emitter side and the shifting of the germanium peak towards the base-collector junction has as consequence a decrease in the transit time leading to an enhancement in the frequencies, particularly in the maximum oscillation frequency f_{MAX} [19].

Fig. 6. Unilateral power gain against frequency to determine f_{MAX} for device HBT3

4. Conclusion

In this work, the effects of the change of the trapezoidal profile shape on the performance of the SiGe HBT are studied (especially on the DC current gain β_F , the cut-off frequency f_T and the maximum oscillation frequency f_{MAX}). A two-dimensional energy balance (EB), hydrodynamic (HD) and drift-diffusion (DD) carriers transport models were used in the simulation. It was found that the values of the current gain using EB model are higher than the HD (about 1.7 times) and much higher than the DD (more than 3.5 times) and these EB values are in agreement with experimental. For DD transport model, the f_T

calculated and f_T extracted from the ac current gain are quite the same and decrease from HBT1 to HBT3. f_{MAX} remains the same for the three devices. The calculated cut-off frequency decreases using HD model from HBT1 to HBT3 and shows no significant change using EB model. f_T and f_{MAX} extracted directly from the ac current gain and unilateral power gain, respectively augment from HBT1 to HBT3 using HD and EB transport models. The results of the three transport models show remarkable differences. The phenomenon leading to these differences must be determined to keep using device simulation to develop compact models leading to understand the physical effects that occurs in a device.

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