Effect of Recombination Lifetime and Velocity Saturation on Ge Profile Design for The Base Transit Time of Si/SiGe HBTs

S. T. Chang, C. W. Liu[*], and S. C. Lu[**]
Department of Electrical Engineering, National Taiwan University, Taipei 106, Taiwan, R.O.C.
[*]TEL: 886-2-3635251 ext. 515, FAX: 886-2-3640076, E-mail: chee@cc.ee.ntu.edu.tw
[**] Electronic Research and Service Organization, Industrial Technology Research Institute, Hsinchu 300,Taiwan, R.O.C.

I. INTRODUCTION

SiGe-base HBTs technology, because it has higher intrinsic performance than Si BJT technology at similar process complexity and delivers lower cost-performance than GaAs technology, has recently emerged as a contender for the RF market. SiGe-base HBTs has been reached to have a maximum oscillation frequency of 180GHz [1] and a cut-off frequency of 130GHz [2]. The narrow-bandgap of SiGe allows heavy doping in the base with a concentration up to 2×10^{20} cm^{-3} [3], which significantly reduces the base resistance and hence increases the maximum oscillation frequency, as compared to conventional Si bipolar junction transistors. However, due to the heavy doping, the minority carrier recombination lifetime in the base also decreases and affects the base transit time, which is a major component of the cut-off frequency. Note that the defects such as oxygen, SiC precipitates, and dislocations in the base further decreases the recombination lifetime. The conventional Kroemer's model gave an integral expression of the base transit time by neglecting the effects of recombination lifetime and velocity saturation [4]. Suzuki and Nakayama modified the Kroemer's expression by taking finite saturation velocity into account [5]. Mohammadi derived a complex integral expression by considering recombination lifetime but neglecting velocity saturation [6]. In this paper, a fully analytical base transit time model for a SiGe-base HBTs with various shapes of germanium profiles in the base region considering both finite recombination lifetime and finite saturation velocity. The design of optimal Ge profile to minimize base transit time in the base can be achieved by using our model. The base structure for optimization has a linear ramp over the central portion of the base, similar to Winterton's structures [7], and this Ge profile has been also used in Si/SiGe HBT fabrication [8].

II. THEORY

The electron current density J_n for arbitrary base doping concentration N_B is given by

$$J_n = qn(x)\mu_n(x)\mathcal{E}(x) + qD_n(x)\frac{dn(x)}{dx} \qquad (1)$$

Since most SiGe bases of HBT's are doped epitaxially and heavily, electric field becomes

$$\mathcal{E}(x) = \frac{-V_T}{n_{ie}^2(x)}\frac{d}{dx}\left(n_{ie}^2(x)\right) \qquad (2)$$

where $n^2_{ie}(x)$ is intrinsic carrier concentration. To determine minority carrier concentration $n(x)$, the continuity equation for electron is used

$$\nabla \cdot J_n = \frac{q\Delta n}{\tau_n} \qquad (3)$$

where $\Delta n=n-n_o$, $n_o= n^2_{ie}(x)/N_B$, and τ_n is recombination lifetime. Let us assume the conventional boundary conditions, namely,

$$n(0)=\frac{n^2_{ie}(0)}{N_B}\exp(qV_{BE}/V_T)\ ,\quad n(w)=\frac{-J_n(w)}{qv_s} \tag{4}$$

where v_s is saturation velocity , V_{BE} is the applied voltage, and V_T is thermal voltage. The base transit time is given by

$$\tau_B=\frac{-q\int_0^w n(x)dx}{J_n(w)} \tag{5}$$

Two kinds of constraints have been used in the optimum design of the Ge profile: fixed Ge content at base collector junction and constant integral Ge content in the base. In our illustration, the former constraint is adopted to obtain optimal Ge profile, but similar analysis can be also applied to the constraint of constant integral Ge content in the base. Note that the constraint with constant Ge content at base-collector junction can be easily implemented using either the rapid thermal chemical vapor deposition or ultrahigh vacuum chemical vapor deposition.

III. RESULTS AND DISCUSSION

Three types of Ge profiles, two-graded region, trapezoid, and shift triangle (Fig. 1(a), (b), and (c)), are used to investigate the base transit time by considering four different conditions: (1) τ_n= infinite and v_S= infinite, (2) τ_n= infinite and v_S=7.5x10^6 cm/s, (3) τ_n= 2.5×10^{-11} s and v_S= infinite, and (4) τ_n= 2.5×10^{-11}s and v_S= 7.5x10^6 cm/s. The Ge content at base-collector junction is fixed at 10% in analysis. The finite recombination lifetime has the approximate diffusion length of 100nm, which is comparable with the base width of 50nm used in the analysis.

Fig. 2(a) shows the variation of the base transit time with X_T/W of trapezoidal Ge profile in the base for above four conditions. The optimum value of X_T/W for all four conditions are about 0.8~0.9. It is clear that finite recombination lifetime can increases the base transit time, and the finite saturation velocity also increases the base transit time for all value of X_T as compared to the condition of infinite saturation velocity and infinite recombination lifetime. The effect of finite saturation velocity is to move the position of optimum X_T/W point toward to base collector junction slightly, and the effect of finite recombination lifetime does not change the position of optimum X_T/W point significantly. The shift-triangle and two-graded Ge profiles have the similar results as shown in Fig. 2(b) and Fig. 2(c), respectively. The optimum value of X_T/W in shift-triangle Ge profile is approximately 0.1, close to emitter-base junction, and the optimum values of X_T/W in two-graded Ge profile for four these conditions are approximately 0.45. Fig. 2(d) shows that shift triangle Ge profile has the smallest base transit time among all three Ge profiles under the condition (4). Similar results are obtained for the other three conditions. This indicates that the electric field in the central base is the most effective to reduce the base transit time.

The dependence of base transit time on base doping for trapezoidal Ge profile (X_T/W=0.88,W=50nm) with 5% Ge content in average in the base region is shown in Fig. 3. The dependence for other two profiles is similar. The diffusion length vs base doping is given in the inset. L_{n1} and L_{n2} are the diffusion lengths in the linear region and the flat region of trapezoidal Ge profile, respectively. The decreasing mobility slightly increases base transit time up to base doping of 1×10^{20}cm^{-3}, and the base transit time start to increase rapidly for the base doping larger than 2×10^{20}cm^{-3}. At the base doping of 2×10^{20}cm^{-3}, the diffusion length (~20 nm) is smaller than base width (~50 nm), and most electrons injected from the emitter recombine with holes in the base, and can not reach the collector. The transistor does not operate normally. The extremely heavy doping of the base requires small base width, as compared to diffusion length, to reduce the base sheet resistance without increasing the base transit time significantly.

For the constraint with Ge concentration fixed at base-collector junction, Winterton et al.[7] demonstrated that the central graded Ge profile is the optimal profile for base transit time by using an iterative method. The central graded Ge profile shown in Fig. 1(d) is adopted in our optimization calculation to find the optimal value of (X_{T1}/W, X_{T2} /W). In this profile, the drift filed is at the central base, since the central filed is the most effective to decrease the base transit time as shown in discussion given above. For given X_{T1}/W, the base transit time vs X_{T2}/W is shown in Fig.4. The optimal position of X_{T2}/W is around 0.86, similar to trapezoidal profile. For given X_{T2}/W=0.86, the optimal base transit time decreases with increasing X_{T1}/W, reaches a minimum and then increase with X_{T1}/W (the inset of Fig. 4), and the optimal X_{T1}/W is around 0.16.

IV. SUMMARY

In this paper, an analytical base transit time model of Si/SiGe HBTs considering minority carrier recombination lifetime and velocity saturation at base-collector junction for the multi-graded Ge base has been studied. The reduction of recombination lifetime in the neutral base region increases the base transit time as compared to infinite recombination lifetime, and the finite saturation velocity also degrades the base transit time, as compared to infinite saturation velocity. The extremely heavy doping of the base requires a small base width, comparable with diffusion length, to decrease the base sheet resistance without sacrificing the base transit time significantly. The optimum Ge profile of the base can be obtained for given Ge content at base-collector junction with a drift electric field over the central portion of base. This optimum Ge profile agrees with Winterton' s structures and is also applied in modern HBT technology [8].

ACKNOWLEDGMENTS

The support of National Science council, Taiwan, R. O. C. (Contact No. 90-2212-E-002-226) is highly appreciated.

REFERENCES

[1] Katsuyoshi Washio, Eiji Ohue, Hiromi Shimamoto, Katsuya Oda, Reiko Hayami, Yukihiro Kiyota, Masamichi Tanabe, Masao Kondo, Takashi Hashimoto, and Takashi Harada, "A 0.2-μm 180-GHz-f_{max} 6.7-ps-ECL SOI/HRS self-aligned SEG SiGe HBT/COMS technology for microwave and high-speed digital applications," in *IEDM Tech. Dig*., pp741-744, 2000.

[2] K. Oda, E. Ohue, M. Tanabe, H. Shimamotot, T. Onai, and K. Washio,"130-GHzf_T SiGe HBT technology, "in *IEDM Tech.Dig*, pp791-794, 1997

[3] A. Schuppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher, and U. Konig, "Enhanced SiGe heterojunction bipolar transistor with 160 GHz f_{max} ,"in *IEDM Tech.Dig.*, pp743-746, 1995

[4] H. Kroemer, "Two integral relations pertaining to the electron transport through a bipolar transistor with a nonuniform energy gap in the base region ,"*Solid-State Electronics* ,vol. 28, pp1101-1103, 1985.

[5] K. Suzuki and N. Nakayama, " Base transit time of shallow-base bipolar transistor considering velocity saturation at base-collector junction ,"*IEEE Trans Electron Devices*, vol. 39 , pp623-628, 1992.

[6] S. Mohammadi , and C. R. Selvakumar ,"Analysis of BJT' s, pseudo-HBT' s, and HBT' s by including the effect of neutral base recombination," *IEEE Trans. Electron Devices*, vol.41, pp1708-1714, 1994.

[7] S. S. Winterton, C. J. Peters and N. G. Tarr, "Composition grading for base transit time minimization in SiGe-base heterojunction bipolar transistor," *Solid-State electronics*, vol.36, pp1161-1164, 1993.

[8] J. Bock, T. F. Meister, H. Knapp, D. Zoschg, H. Schafer, K. Aufinger, M. Wurzer, S. Boguth, M. Franosch, R. Stengl, R. Schreiter, M. Rest, and L. Treitinger, "SiGe bipolar technology for mixed digital and analogue rf application,"in *IEDM Tech.Dig.*,pp745-748, 2000.

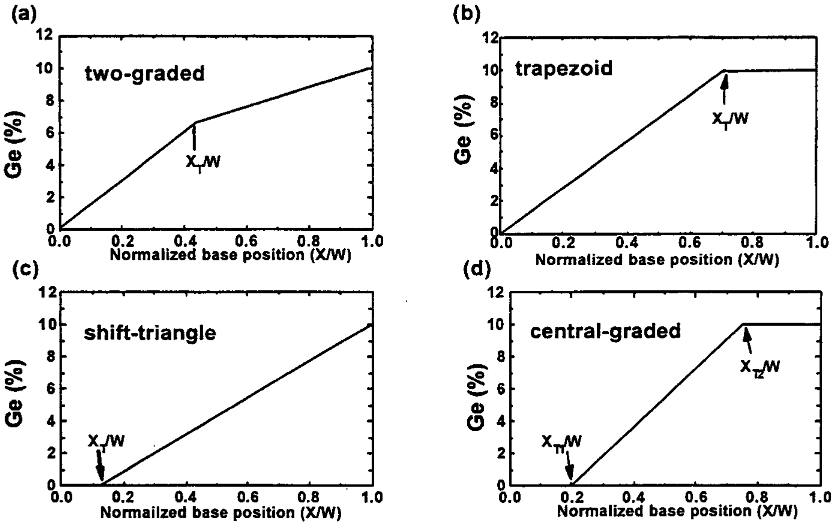

Fig. 1 The Ge profiles used in our analysis: (a) two-graded region Ge profile, (b) trapezoid Ge profile, (c) shift-triangle Ge profile, and (d) central-graded Ge profile in the base.

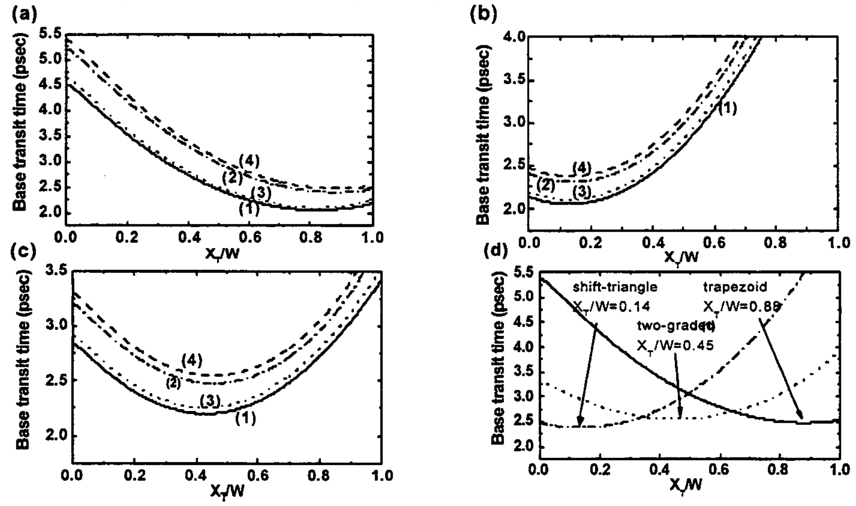

Fig. 2 The base transit time vs X_T/W of (a) trapezoidal, (b) shift trangle, and (c) two graded Ge profile in base under four different conditions:(1) τ_n=infinite and v_S=infinite (solid line), (2) τ_n= infinite and v_S=7.5×10^6 cm/s(dash dot line), (3) τ_n= 2.5×10^{11} s and v_S= infinite (dot line), and (4) τ_n=2.5×10^{-11}s and v_S= 7.5×10^6 cm/s(dash line). (d) is the base transit time versus X_T/W for three Ge profiles in base under the condition (4).

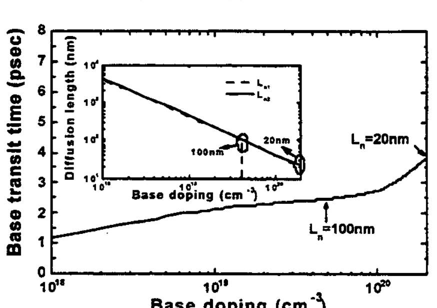

Fig. 3 The base transit time vs base doping in trapezoidal Ge profile. The diffusion length vs base doping is shown in the inset. L_{n1} (L_{n2}) is diffusion length in the linear (flat) region of trapezoidal Ge profile.

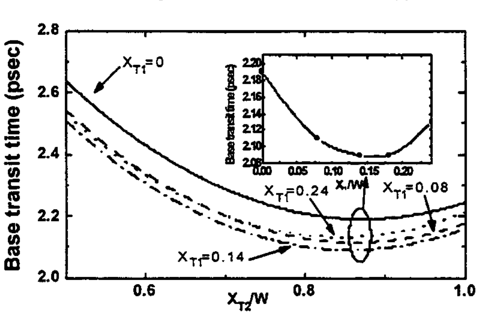

Fig. 4 Base transit time vs X_{T2}/W for different X_{T1}/W in central-graded Ge profile in the base. The Ge profile is shown in Fig. 1(d). The inset shows base transit time vs X_{T1}/W for the optimal value X_{T2}/W of 0.86.