High-Frequency Characteristic Optimization of Heterojunction Bipolar Transistors

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ABSTRACT

With the downward scaling of IC critical dimension, the speed of SiGe heterojunction bipolar transistors has been increased dramatically. The speed of HBTs is dominated by the base transit time, which may be strongly influenced by the doping profile in the base region and the Ge concentration of base region. Therefore, the determination of the doping profile and Ge concentration of base region is crucial for design of SiGe HBTs in advanced communication circuits. In this study, the design of HBTs is transformed to a convex optimization problem, and solved efficiently by geometric programming approach. The result shows that a 23% Ge fraction may maximize the current gain and a 12.5% Ge can maximize the cut-off frequency, where 254 GHz is achieved. The accuracy of the optimization technique was confirmed by TCAD simulation. This study successfully transforms the device characteristic and manufacturing limitation into a geometric programming model and provides an insight into design of SiGe HBTs.

Keywords: Bipolar Transistors, Impurity Doping, SiGe, HBT, High Frequency, Optimization.

1 INTRODUCTION

SiGe heterojunction bipolar transistors (HBTs) have undergone substantial development for nearly two decades. The speed of SiGe HBTs has increased dramatically, with the consequence of relentless vertical and lateral scaling. The HBTs' speed is dominated by the transit time of base region, which is strongly influenced by the doping profile and Ge concentration in the base region [1-6].The determination of the doping profile and Ge concentration o is crucial for design of SiGe HBTs in advanced communication circuits.

Diverse approaches have been proposed to optimize the base transient time [3-6]. An analytical optimum base doping profile by using variation calculus considering the dependence of diffusion coefficient on base doping concentration is firstly derived [3]. The analytical approach has been extended to consider the dependence of intrinsic carrier concentration on base doping concentration [4]. An iterative approach is proposed by Winterton to obtain the optimum base doping profile [5], where the dependence of mobility and bandgap narrowing on the base doping concentration is further considered by Kumar [6]. However, the solution can not be guaranteed to be the global optimal.

A geometric program (GP) is a type of mathematical optimization problem characterized by objective and constraint functions with special form. Recently, numbers of practical problems, particularly in semiconductor and electrical circuit design, have been found to be equivalent (or can be well transformed) to GP's form [8-13]. For the SiGe HBTs, it has been reported that the triangular Ge profiles are best suited to achieve the minimum base transit time and trapezoidal Ge profiles are best suited to get high current gain in SiGe HBTs [7]. The geometric programming approach has been utilized to simultaneously optimize the Ge-dose and base doping profile in SiGe HBTs [1, 2]. However, the co-optimization of cutoff frequency and current gain in SiGe HBTs is lacked.

In this study, the GP approach is used to obtain the optimal Ge-dose and doping profile to get high cutoff frequency or the high current gain in SiGe HBTs. The design of HBTs is first expressed as a special form of optimization problem, called geometric programming. The background doping profile is adjustable to improve the cutoff frequency and current gain. The result shows that a 23% Ge fraction may maximize the current gain, where a factor, current gain divided by emitter Gummel number, of 1100 is attained. To maximize the cut-off frequency of HBTs, a Ge-dose concentration of 12.5% is used, where the cut-off frequency can achieve 254 GHz. The accuracy of the optimization technique was confirmed by TCAD simulation. This study successfully transforms the device characteristic and manufacturing limitation into a geometric programming model and provides an insight into design of SiGe HBTs.

The paper is organized as follows. In Sec. 2, the design of HBTs and manufacturing limitation are transformed to a geometric programming model. In Sec. 3, the cut-off frequency and current gain are optimized. Finally we draw conclusions.

2 THEORY AND METHODOLOGY

Mathematically, a doping profile tuning problem for the frequency property of SiGe HBTs can be formulated as an optimization problem:

$$\begin{aligned} &\text{Minimize} && \tau_B \\ &\text{s.t.} && N_{\min} \le N_A(x) \le N_{\max}, 0 \le x \le W_B, \\ & && Ge_{AVG} \le 0.23 \end{aligned} \tag{1}$$

where the base doping profile denoted $N_A(x)$ is a spatial-

dependent positive function over the interval $0 \le x \le W_B$. The base doping profile is lower than the doping level of emitter-base junction $N_{\max}$ and higher than background doping $N_{\min}$. W_B is the base width of the transistor. Ge_{AVG} is the average value of Ge fraction. Due to the manufactory limitation, the average value of Ge fraction should be less than 0.23. For SiGe HBTs, the base transit time τ_B as shown in Eq. (1), is given by [6]:

$$\tau_B = \int_0^{W_B} \frac{n_{i,SiGe}^2(x)}{N_A(x)} \left(\int_x^{W_B} \frac{N_A(y)}{n_{i,SiGe}^2(y) D_{n,SiGe}(y)} dy \right) dx, \quad (2)$$

where $n_{i,SiGe}(x)$ is the intrinsic carrier concentration in SiGe, and $D_{n,SiGe}(y)$ is the carrier diffusion coefficient of SiGe. The $D_{n,SiGe}(y)$ can be rewritten as

$$D_{n,SiGe}(y) = (1 + k_{SiGe} Ge_{AVG}) D_n(y), \quad (3)$$

where k_{SiGe} is a constant, and $D_n(y)$ is the carrier diffusion coefficient of Si. In the present work, peak base doping $N_{\max}$ of 1x10^{19} cm^{-3} at emitter edge of base and a minimum base doping $N_{\min}$ of 5x10^{16} cm^{-3} at collector edge has been chosen to include the heavy doping induced band gap narrowing effect in the entire base region. A neutral base width of 100 nm is chosen. We can change Eq. (1)-(3) to a function of $N_A(x)$, Ge_{AVG} and formulate it to GP's form. For a SiGe HBT; the cutoff frequency f_t of a HBT is given by [2]:

$$\frac{1}{2\pi f_t} = \tau_F + \frac{C_{J,BE} + C_{J,BC}}{g_n} + R_C C_{J,BC}, \quad (4)$$

where τ_F is the forward transit time , $C_{J,BE}$ is the base–emitter junction or depletion layer capacitance, $C_{J,BC}$ is the base–collector junction or depletion layer capacitance , g_m is the transconductance, R_C is the collector resistance. For this model, the base transit time is often the major part to determine the value of τ_F and govern the f_t. We can also change (4) as a function of $N_A(x)$.Without loss of generality, we may assume the doping profile to be the form

$$N_A(x) = bx^m, 0 \le x \le 0.05W_B \quad (6)$$

Here we assume m=0 for liner doping within 5 nm base width near the emitter-base junction. To figure out an ideal shape of the optimal doping profile that maximizes the f_t, we consider the optimal problem:

$$\begin{aligned} &\text{Minimize} && \tau_B + AN_A(x)^{1/2} G_B (1 + k_{SiGe} Geavg)^{-1} + B \\ &\text{s.t.} && N_{\min} \le N_A(x) \le N_{\max}, i = 0,1,...,M-1, \\ & && N_A(x), x = 0 \le x \le 0.05W_B \\ & && Ge_{AVG} \le 0.23 \end{aligned} \quad , \quad (7)$$

where A and B are constants, G_B is the base Gummel number, which is also a function of $N_A(x)$. The SiGe HBT with various Ge-dose concentration, 2%, 8%, 12%, are then explored in Fig. 1(a). The device with higher Ge-dose concentration shows a higher f_t. Moreover, the obtained optimzied doping profile changes with different Ge-dose concentration. The dependence of f_t as a function of Ge-dose concentration is plotted in Fig. 1(a). The device with maximum f_t is with 12% Ge dose concentration, as studied in Fig.1(b).

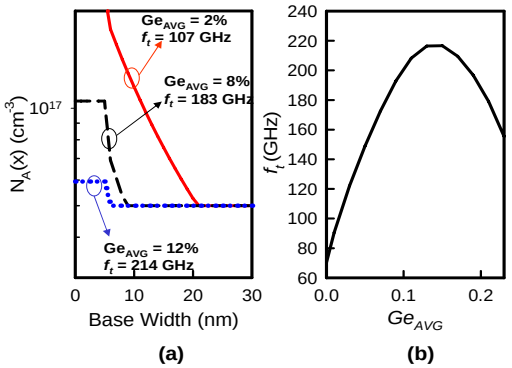

Fig.1(a). Doping profile and the corresponding f_t with 2%, 8%, and 12% Ge-dose. (b) f_t with various Ge-dose.

Besides the optimization of f_t, the current gain, β, is also significantly influenced by the base doping profile. The current gain is defended by the ratio of collector and can be expressed as ratio of Gummel numbers:

$$\beta = \frac{G_{E,Sige}}{G_{B,SiGe}} \quad (8)$$

where $G_{E,SiGe}$ is the emitter Gummel number, and $G_{B,SiGe}$ is the base Gummel number. Since the emitter Gummel number depends mostly on the emitter doping profile, and thus can be treated as a positive constant. For the base Gummel number, the dependence of Gummel number depends on the base doping profile:

$$G_B = \int_0^{W_B} \frac{N_A(x) n_{i0}^2}{D_n(x) n_i^2(x)} dx \quad (9)$$

where n_{i0} is the intrinsic carrier concentration in a undoped Si . $n_i(x)$ is the intrinsic carrier concentration in SiGe. The relationship Eq.(7) and Eq. (8) are then transformed as the

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current gain constraint and added in the GP model. The background doping of the doping profile is also a factor in optimization of base doping profile. Figure 3 shows the impact o f background doping profile on f_t. As the background doping, N_{min}, is decreased from 5x10^{16} cm^{-3} to 3x10^{16} cm^{-3}, the obtained optimal f_t could be increased from 71 GHz to 85 GHz.. To ensure the accuracy of the optimized doping profile, the doping profile is implemented in the TCAD tool, as shown in Fig. 3, where the solid line shows the optimized doping profile and the dashed line shows the doping profile in TCAD. The f_t in TCAD simulation approaches 70 GHz, which is very similar to the f_t in the GP model, 71 GHz. The result confirms the reliability of the GP model.

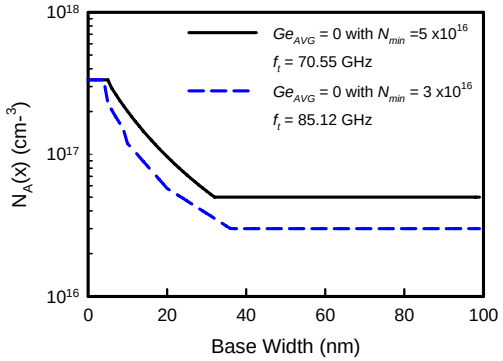

Fig. 2. Doping profile of decreasing background doping to 3x10^{16} cm^{-3} for 0% Ge content.

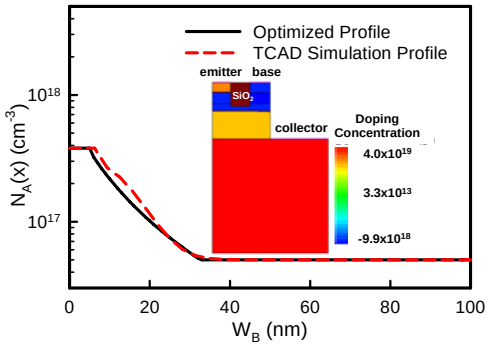

Fig. 3. Two-dimensianal device structure of a SiGe HBTs and the doping profile obtained from GP model and TCAD simulation.

3 RESULTS AND DISSCUSSION

The dependence of f_t and gain on Ge-dose and base doping profile are discussed above. In this section, Due to the strong influence of the shape and content of Ge on the base transit time [4], the f_t and gain of SiGe HBT are co-optimized with subject to the constraint mentioned above.

Figure 4 shows the f_t as a function of background doping and Ge-dose. As expected, the maximum f_t can be obtained at 12% Ge-dose with low background doping. Figure 5 shows the f_t as a function of the current gain. Since the f_t is related to the gain and bandwidth, the obtained f_t will be smaller with higher current gain constraint. As expected, device with higher Ge-dose could provide higher gain and thus release the design constraint. The tuning point, in which the current gain constraint starts to significantly reduce the f_t, is crucial in obtaining the maximum current gain with sufficient f_t. Therefore, by careful selection of the maximum current gain constraint, we could find the optimal current gain constraint, $\beta / G_{E,SiGe} \times 10^{11}$, with sufficient f_t, as shown in Figure 6, where the lower background doping and higher Ge-dose may provide the largest current gain. In Figure 4, it's found that 12.5% Ge-dose and 2×10^{16} cm^{-3} background doping can maximize the f_t. The higheset f_t can reach 254 GHz. On the other hand, for obtaining the maximum current gain in Fig. 6, the Ge-dose concentration is about 23% and the background doping is about 2×10^{16} cm^{-3}, where maximize current gain constraint $\beta / G_{E,SiGe} \times 10^{11}$ = 1100.

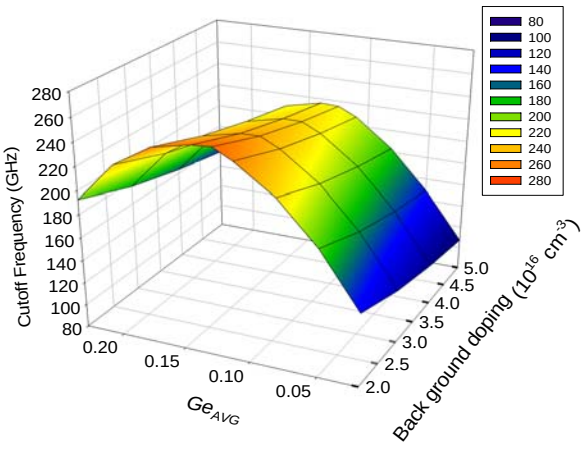

Fig. 4. The f_t as a function of Ge-dose and background doping concentrations.

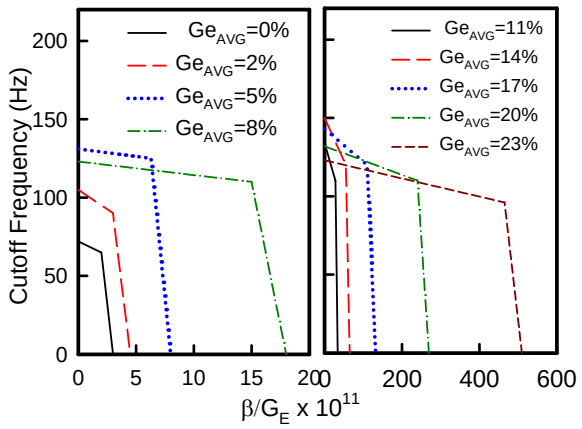

Fig. 5. The maximize current gain constraint can add for 0%, 5%, and 8% Ge content.

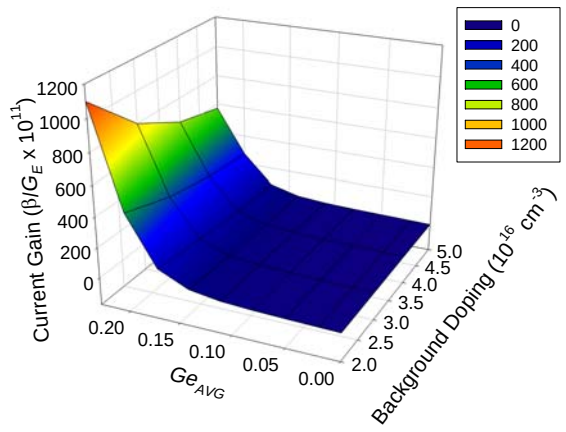

Fig. 6. The maximum current gain constraint can add for every Ge content and background doping to maintain sufficient f_t.

The obtained optimal doping profile and Ge-dose concentration are plotted in Fig. 7. Result shows that for the SiGe HBTs, the triangular Ge profiles are best suited to achieve the minimum base transit time and trapezoidal Ge profiles are best suited to get high current gain in SiGe HBTs, which matches the result in [7].

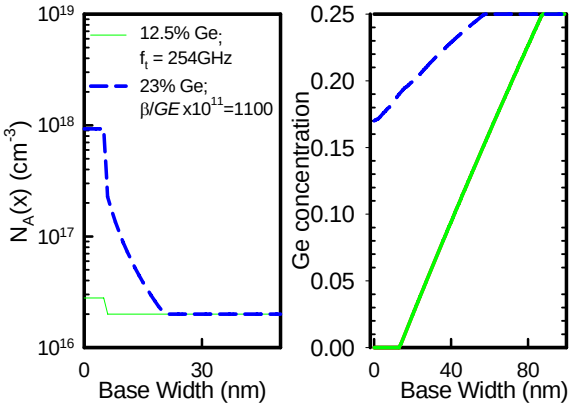

Fig. 7. Optimal Si and Ge doping profile for f_t maximize and maximize current gain constraint.

4 CONCLUSION

In this study, the cutoff frequency and the current gain of SiGe HBT are optimized by geometric programming approach. The design of HBTs is transformed to a convex problem, and solved efficiently. The result shows that a 23% Ge fraction may maximize the current gain and a 12.5% Ge can maximize the cut-off frequency, where 254 GHz cut-off frequency is achieved. The accuracy of the optimization technique was confirmed by TCAD simulation. This study successfully transforms the device characteristic and manufacturing limitation into a geometric programming model and provides an insight into design of SiGe HBTs. We are currently applying the GP approach for multifinger HBTs' optimization.

5 ACKNOWLEDGEMENT

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REFERENCES

[1] Gagan Khanduri, "Simultaneous Optimization of Doping Profile and Ge-Dose in Base in SiGe HBTs," in IEEE Southeast Conf., 579, 2007.

[2] S. Joshi, S. Boyd, and R. Dutton, "Optimal doping profiles via geometric programming," IEEE Trans. Electron Device, 52, 2660-2675, 2005.

[3] A. H. Marshak, "Optimum doping distribution for minimum base transit time," IEEE Trans. Electron Devices, ED-14, 190, 1967.

[4] S. Szeto and R. Reif, "Reduction of f by nonuniform base bandgap narrowing," IEEE Electron Device Lett., 10, 341, 1989.

[5] S. S. Winterton, S. Searles, C. J. Peters, N. G. Tarr, and D. L. Pulfrey, "Distribution of base dopant for transit time minimization in a bipolar transistor," IEEE Trans. Electron Devices, 43, 170, 1996.

[6] M. J. Kumar and V. S. Patri, "On the iterative schemes to obtain optimum base profiles for transit time minimization in a bipolar transistor," IEEE Trans. Electron Devices, at press.

[7] Kyunghae Kim, Jinhee Heo, Sunghoon Kim, D. Mangalaraj, and Junsin Y, "Optimum Ge Profile for the High Cut-off Frequency and the DC Current Gain of an SiGe HBT for MMIC," IEEE Trans. Electron Device, 40, 584, 2002.

[8] K. Kortanek, X. Xu, and Y. Ye, "An infeasible interior-point algorithm for solving primal and dual geometric progams," Math. Program., 76, 155, 1996.

[9] M. Avriel, R. Dembo, and U. Passy, "Solution of generalized geometric programs," Int. J. Numer. Methods Eng., 9, 149, 1975.

[10] C. S. Beightler and D. T. Phillips, Applied Geometric Programming. New York: Wiley, 1976.

[11] R. J. Duffin, "Linearizing geometric programs," SIAM Rev., 12, 211, 1970.

[12] R. J. Duffin, E. L. Peterson, and C. Zener, Geometric Programming—Theory and Applications: Wiley, 1967

[13] J. Ecker, "Geometric programming: Methods, computations and applications," SIAM Rev., 22, 338, 1980.