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OPTIMUM Ge PROFILE DESIGN FOR BASE TRANSIT TIME MINIMIZATION OF SiGe HBT

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A analytical equation of the base transit time including the effects of minority carrier recombination lifetime and velocity saturation for Si/SiGe HBT's with different Ge profiles has been derived. The reduction of recombination lifetime in the neutral base region due to the heavy base doping can shorten the base transit time, while the finite saturation velocity degrades the base transit time, as compared to infinite saturation velocity. The optimum design of Ge profiles in the base to minimize the base transit time can be obtained by the analytical model.

1 Introduction

Since the first Si/SiGe heterojunction bipolar transistor (HBT) was reported in 1988[1], the tremendous progress of Si/SiGe HBT's has been reached to have a maximum oscillation frequency of 180GHz [2], a cut-off frequency of 130GHz [3], and circuit applications on wireless [4] and optical communication [5]. The narrow bandgap in SiGe allows heavy doping in the base with a concentration up to 2×10^{20} cm^{-3} [6], which significantly reduces the base resistance and hence increases the maximum oscillation frequency, as compared to conventional Si bipolar junction transistors. However, the minority carrier recombination lifetime in the base also decreases due to the heavy doping and affects base transit time, which is a dominated component of the cut-off frequency. The conventional Kroemer's model gives an integral expression of the base transit time by neglecting the effects of recombination lifetime and velocity saturation [7]. Suzuki and Nakayama modified the Kroemer's expression by taking finite saturation velocity into account [8]. Mohammadi derived a complex integral expression by considering recombination lifetime but neglecting velocity saturation [9]. Cressler et al. [10, 11] derived a simple analytical expression for trapezoidal Ge profile based on Kroemer's model. Recently, Patri and Kumar use Suzuki's model to study the optimal Ge profile for minimizing base transit time in SiGe HBT's [12, 13]. In this paper, an analytical expression for the base transit time, based on minority carrier continuity equation, considering both finite recombination lifetime and finite saturation velocity has been derived. The design of optimal Ge profile to minimize base transit time in the base can be achieved by using our model. The optimal Ge profile has a linear ramp over the central portion of the base, neither near the emitter nor the collector, similar to Winterton's results [14], and this optimum Ge profile has been also used in Si/SiGe HBT fabrication [15].

2 Theory

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

$$J_n = q\,D_n \frac{dn(x)}{dx} + q\,\mu_n E \cdot n(x) \tag{1}$$

The Ge profile in neutral base is illustrated in Fig.1. The low-field electron mobility in SiGe is modeled using Manku's model [16]. The field dependence of carrier mobility is taken into account using a modified Caughey-Thomas electric field dependent mobility model [17]. For the SiGe base, the intrinsic carrier concentration is function of Ge bandgap grading and bandgap narrowing from heavily doping effects:

$$n^2_{ie}(x) = n^2_{ie}(0)\exp(\frac{\Delta E_G}{kT}) \tag{2}$$

where $n_{ie}(0)$ is the intrinsic carrier concentration at x=0, ΔE_G (x) is the position dependent bandgap

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reduction due to Ge content and bandgap narrowing effect in the base. To determine minority carrier concentration *n(x),* the continuity equation for electron is used

$$\nabla \cdot J_n = -\frac{\Delta n}{\tau_n} \tag{3}$$

where $\Delta n = n - n_o$, $n_o = n^2_{ie}(x)/N_B$, and τ_n is minority carrier lifetime.

Combining (1) and (2), then the differential equation can be shown to be

$$\frac{d^2 n}{d x^2} + \frac{\mu_n E}{D_n}\frac{dn}{dx} - \frac{n}{L_n^2} = -(\frac{n_o}{L_n^2}) \tag{4}$$

In the linear-graded region of the base, the electrical filed E is constant field in Eq. (1), and can be analytically solved. The coefficients in the solution are determined by the following boundary conditions and are given in appendix. *n(0)* is expressed as :

$$n(0) = \frac{\mathrm{n}^2_{\mathrm{ie}}(0)}{N_B}\exp(qV_{BE}/kT) \tag{5}$$

Assuming the electron velocity in the base-collector depletion region saturates at v_s, *n(w)* is expressed as:

$$n(W) = \frac{-J_n(W)}{q\,vs} \tag{6}$$

At the interface between region I and region II, the electron concentration and the total current (the sum of diffusion and drift current) are continuous

$$n_I(X_T) = n_{II}(X_T)$$
$$J_{nI}(X_T) = J_{nII}(X_T) \tag{7}$$

The base transit time is given by

$$\tau_B = \int_0^W \frac{1}{v_{eff}}dx \tag{8}$$

where $v_{eff}(x) = \frac{-J_n(x)}{qn(x)}$

The results are applied for the base with two linearly graded Ge regions, and similar analysis can be performed in three or multi graded-Ge profiles.

3 Results and discussion

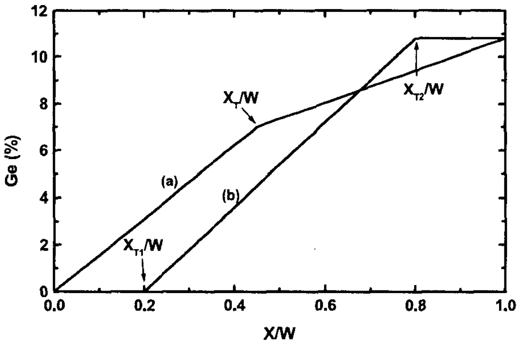

Fig. 1 Schematic Ge profile versus vertical depth in base region for our calculation. (a) Two graded Ge profile. (b) Three linear graded Ge profile (special case: step-linear ramp-step) in base.

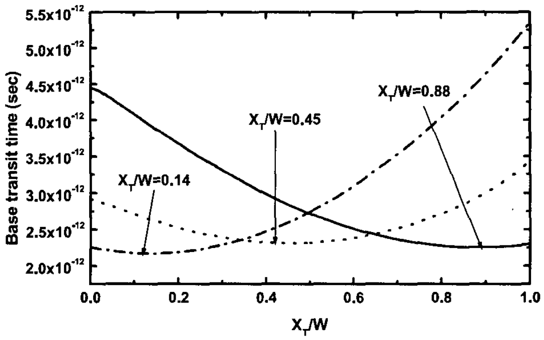

Fig.2 Base transit time versus X_T/W for three Ge profiles in base. Solid curve represents trapezoidal Ge profile, dash dot curve represents shift triangle Ge profile, and dot curve represents two graded Ge profile.

Fig.2 shows that the shift triangle Ge profile has the smallest base transit time of all three Ge profiles. For the same electron saturation velocity, base transit time decrease as minority lifetime decrease for all three Ge profiles. The dependence of base transit time on minority lifetime is shown in Fig. 3. We can see that as recombination lifetime decreases, base transit time also decreases if base doping is larger than 5×10^{19}cm^{-3}. Similar reduction occurs for other two Ge profiles due to the decrease of recombination lifetime. The heavy doping in the base can not only improve the oscillation frequency, but also reduce the base transit time. As can be seen from Fig. 3, the base transit time can reduce about 4% when base doping increases from 5×10^{19} to 1.0×10^{20}cm^{-3}. When recombination lifetime is 6×10^{-12} s, base doping should increase to 1.0×10^{20} cm^{-3} as shown in the inset of Fig. 3. We conclude that the key technology to make an ultra high speed SiGe HBT is increasing base concentration as high as possible. Following the constrained condition which Ge concentration is specified at edges of base for three linear graded Ge profiles as shown in Fig.1, the optimum Ge profile has been found.

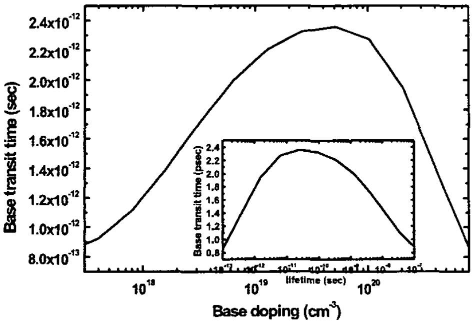

Fig.3 The base transit time vs. base doping in trapezoidal Ge profile The base transit time vs. recombination lifetime is shown in the inset.

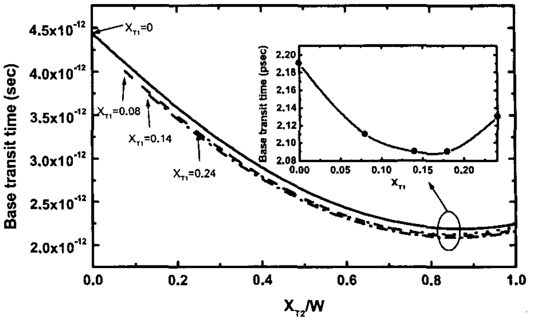

Fig.4 Base transit time vs. X_{T2}/W for different X_{T1}/W in three regional Ge profile in the base. The Ge profile is shown in profile (b) of Fig.1. Inset figure shows optimal base transit time vs. X_{T1}/W.

Fig.4 shows that the X_{T1} is fixed for various values and the X_{T2} is varied to find the minimum base transit time. The inset of Fig.4 shows optimal base transit time vs. X_{T1}/W. The optimal base transit time decreases with increasing X_{T1}/W, reaches a minimum and then increases with X_{T1}/W. The X_{T1}/W of the minimum optimum base transit has been founded. For X_{T1}/W=0 and X_{T2}/W=0.86, namely, trapezoidal Ge profile, the optimum base transit time (solid curve in Fig.4) is larger than that of our optimal three region Ge profile. For X_{T1}/W=0.14 and X_{T2}/W=1(shift triangle Ge profile) the optimal base transit time (dash dot curve in Fig.4) is larger than that of our optimal three region Ge profile but smaller than that of trapezoidal Ge profile. From above analysis, we find the optimal Ge profile is that a linear ramp over the central portion of the base, but is flat near the emitter and collector. Our model is in agreement with that of Winterton [14].

4 Conclusion

A closed-form analytical base transit time model considering minority carrier recombination lifetime and velocity saturation at base-collector junction based on multi graded Ge profile for a SiGe HBT has been evaluated. Our results show that the base transit time decreases with decreasing minority carrier recombination lifetime. Minority carrier recombination is very important for base transit time as base doping increasing much highly. We predict that base transit time will begin to decreases if base doping exceeds 5×10^{19}cm^{-3}. Our model successfully determines the optimum points (X_{T1} ,X_{T2}) of multi graded Ge profile for SiGe HBT. The optimum Ge profile of SiGe for specified Ge content at ends of base is a linear ramp over the central portion of base and flat near emitter and collector. This optimum Ge profile is agreement with Winterton's prediction and that also applied in modern HBT technology [14].

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