Ge Profile for Minimum Neutral Base Transit Time in $Si/Si_{1-y}Ge_y$ Heterojunction Bipolar Transistors

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Abstract

A simple but effective numerical method for the determination of Ge profiles leading to minimum neutral base transit time τ_B is presented. The profiles under consideration have been taken from a large general class of functions. The resulting profiles show that significant reductions in τ_B can be achieved when they are compared to other investigated profile types. Moreover the position dependence of these optimum profiles has a simple structure. Thus there are no additional technological difficulties for their realization.

1. Introduction

The increasing interest in $Si/Si_{1-y}Ge_y$ heterojunction bipolar transistors (HBTs) raises the question of how to design the vertical Ge profile y in the base layer. For high speed applications, a minimum base transit time τ_B is extremely important. These considerations lead to the specific question of which Ge profile minimizes τ_B. As we will see later, for a negligible dependence of electron diffusivity D on y, base transit time can be minimized with respect to intrinsic carrier concentration profile n_i.

A mathematically equivalent question arises in the context of bandgap narrowing caused by high doping. It has been treated so far mostly by restricting the class of admissible profiles to a small set of trial functions with one parameter each, like exponential or gaussian doping profiles [1, 2, 3]. In those cases, τ_B has been minimized with respect to the corresponding parameter for each of the functions separately and the result has been compared to that of a uniform doping. To the author's knowledge there has been only one attempt which tries to solve the problem in a much more general sense by using the analytical methods of Variational Calculus [4]. But the differential of the considered functional is not zero anywhere on a reasonable domain. Thus the Euler-Lagrange equation leads to contradictory results [5] and the original question in its general sense has not been answered yet. For the first time in this investigation the problem is successfully solved by utilizing a numerical approach and by posing reasonable additional constraints on the considered functions.

2. Procedure

Similar to the work of McGregor et al. [4] we use the formula by Kroemer [6] to define base transit time τ_B in terms of n_i^2, hole concentration p and electron diffusivity D.

$$\tau_B\left(n_i^2, p, D\right) = \int\limits_{[0,W]} \frac{n_i^2}{p}(x) \int\limits_{[x,W]} \frac{p}{D n_i^2}(z)\, dz\, dx$$

All three of them are functions of position through their dependence on base doping profile N and Ge profile y. The space coordinate is chosen to have a value of zero at the emitter side of the base and that of W at the collector side. In the neutral base, p can be approximated by N in the low injection regime. For any given N and for negligible dependence of D on y, τ_B can be minimized with respect to n_i^2, thus solving the problem for any one-to-one correspondence between n_i^2 and y.

This procedure has been carried out for the special case of constant N in the neutral base for which D and p can be assumed to be also constant functions of position. Additionally we fix the value of W as well as the values of n_i^2 at the boundaries of the base. Furthermore we limit the minimum and maximum value of n_i^2 to the same values. These additional constraints are not only technologically and physically reasonable but moreover avoid the problems which can be expected by the mentioned features of the differential of the functional for τ_B. Since it is nowhere equal to zero the solutions might come to lie at a boundary. For the discrete approximation this means some interpolation points should take the limiting values.

For the numerical treatment, a library routine for constraint optimization from the numerical package MATLAB® is employed. Using the above a discrete approximation of τ_B is minimized with respect to the function values of about 50 evenly spaced interpolation points of n_i^2 in the base interval.

The solution is expressed in terms of y using the common model for the dependence of n_i^2 on y as given in [7, 8].

$$n_i^2(y) = n_{i,\mathrm{Si}}^2 \frac{2 + \exp\left(-\frac{E_s(y)}{E_{th}}\right)}{3} \left(\frac{m_v(y)}{m_{v,\mathrm{Si}}}\right)^{\frac{3}{2}} \exp\left(\frac{E_{g,\mathrm{Si}} - E_g(y)}{E_{\mathrm{th}}}\right)$$

The six conduction band minima are split into two groups of four and two. The difference in energy E_s is a function of the Ge content y. The curvatures of the two valence bands are also functions of y. Their combined effect on n_i^2 is represented by the effective hole mass m_v. Furthermore there is the dependence of the energy gap E_g on y, E_{th} being the value of thermal energy. The minimum value of Ge content is chosen to be 0%, maximum values have been selected from an interval between 0% and 25%.

3. Results

Four examples of the solutions in terms of Ge profiles can be seen in Fig. 1 with maximum values of 5, 10, 15 and 20%. They consist of three clearly discernible parts. In the border regions of the base, the Ge content is limited by the inequality constraints. These plateaus are connected by a region where the intrinsic carrier concentration n_i^2 is exponentially varying, giving an almost exactly linear Ge profile. For small differences in the limiting values, the positions where the plateaus meet the linear part are near the middle of the base and for large differences they come to lie

near the boundaries of the base resulting in a linear profile over most of the neutral base. The dependence of the location and meeting points of the three parts on the maximum Ge content are shown by the shades and curves in Fig. 2.

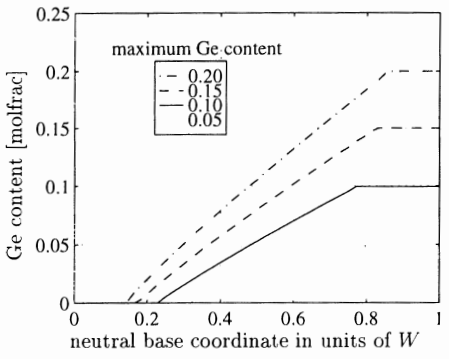

Fig. 1: Four examples of optimum Ge profiles for different values of maximum Ge content which are given in the legend.

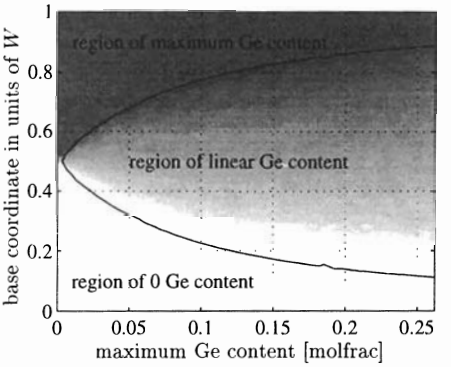

Fig. 2: Location of the three different parts of optimum Ge profiles and the points where they meet with their dependence on maximum Ge content.

In Fig. 3 the dependence of minimum neutral base transit time on maximum Ge content for the calculated optimum profile is compared to two other profile types. The first one has no Ge in the emitter sided half of the base and a constant value towards the collector. The location of the step is placed in the centre of the base, which is the optimum position for this type of profile. The second one has an exponentially varying n_i^2 over the whole neutral base, i.e. a linear Ge grading from zero to the maximum value. The values of τ_B are normalized to a value obtained with constant n_i^2, which corresponds to a constant Ge content. The detailed comparison of the linear case and the calculated optimum in Fig. 4 shows an improvement of more than 10% in τ_B over a range from 5% maximum Ge content to well above 20%. Compared to the step profile the reduction in τ_B is more than 10% for any value of maximum Ge content above 10%. This reduction is increasing with increasing maximum Ge content and τ_B can even be lower by a factor of two at 25% maximum Ge content.

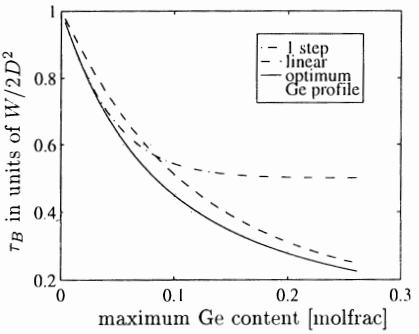

Fig. 3: Dependence of neutral base transit time τ_B on maximum Ge content for different Ge profile types.

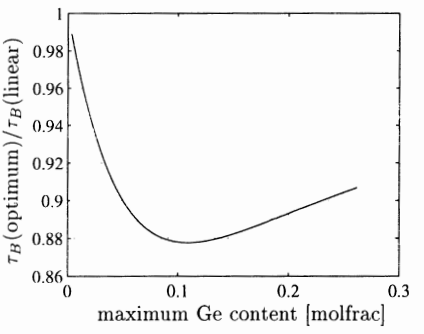

Fig. 4: Ratio of τ_B for optimum and linear profile for maximum Ge contents from 0 to 25%.

4. Conclusions

We have calculated the Ge profile in the base of a HBT that minimizes base transit time. By this we have demonstrated that the optimum Ge profile can lead to a significant reduction in neutral base transit time compared to profile types employed in existing HBTs and those usually investigated in modelling and device simulation. In addition the result clearly shows that the optimum profile is a simple function of position which is not without practical relevance. On the contrary it is as technologically feasible as the above 'ad hoc' profiles using advanced processing techniques like selective epitaxial growth or ultrahigh vacuum chemical vapor deposition [9].

References

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