On the Iterative Schemes to Obtain Base Doping Profiles for Reducing Base Transit Time in a Bipolar Transistor

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Abstract—This paper shows that base doping profiles obtained using any iterative scheme for reducing the base transit time \( T_b \), in bipolar transistors for a given neutral base width must take into account the heavy doping effects implicitly. Comparing our results with those reported earlier, we demonstrate that if the heavy doping effects are not implicitly included in the iterative scheme it will result in a completely different base doping profile leading to an overestimation of base transit time and underestimation of base resistance.

Index Terms—Base doping profile, base transit time, bipolar transistors.

I. INTRODUCTION

In silicon bipolar transistors, the base transit time \( n \) is often the single largest contributor to the total delay time and determines the transistor's high frequency performance. The design of the base doping profile for reducing \( n \), by keeping the intrinsic base resistance constant, has been studied extensively in literature. For example, while Wijnen and Gardner [1] and Suzuki [2] compared some easily realizable base profiles, Winterton et al. [3] suggested an interesting and not so easily realizable base dopant distribution using a discretized relation for \( r_b \) and an iterative procedure. Although the final iterative scheme in [3] includes the effect of dopant induced bandgap narrowing and dopant dependent diffusivity, both these factors are not considered while developing the iterative scheme in [3]. However, both these factors are important in submicron narrow base bipolar transistors in which the base doping can far exceed \( 10^{17} \text{cm}^{-3} \).

The objective of the present paper is, therefore, to show that if the iterative scheme used for obtaining the base profile to reduce \( n \) implicitly includes the effect of dopant induced bandgap narrowing and dopant dependent diffusivity, the resultant base doping distribution will be different. By comparing our results with that of [3], we demonstrate that the iterative scheme suggested in [3] underestimates the base resistance and overestimates the base transit time since it does not implicitly take into account the heavy doping parameters.

II. MODELS USED IN THE ANALYSIS

A. Model for Base Transit Time

The base transit time in a n-p-n bipolar transistor is given by Kroemer's double integration relation as [4]

\[
I = \int_0^{L_b} \frac{n_i \cdot \tau_r}{N_A(x)} \int_x^{L_b} \frac{D_n(y) n_i^e(y)}{N_A} dy dx
\]

where

- \( r_i \) intrinsic carrier concentration;
- \( N_A \) acceptor impurity concentration;
- \( D_n \) minority carrier diffusion coefficient in the base;
- \( W_b \) neutral base width.

By dividing the neutral base into \( M \) sections of equal length, the discretized base transit time expression can be written as [3]:

\[
T_b = \frac{W_b^2}{M^2} \sum_{l=1}^{M} \left( \int_{x_l}^{x_{l+1}} \frac{N_{Al} N_{ai}}{D_n} \right)
\]

where \( N_{Al}, n_{ai} \) and \( D_{ni} \) are piecewise constant functions in the \( l \)th section. To minimize \( n \) with respect to \( N_{Alm} \), the first derivative of \( T_b \) is set to zero, in which case (2) becomes

\[
\frac{d}{dN_{Alm}} \left[ \frac{n_i^e}{N_{Alm}} \right] \frac{N_{Alm}}{D_n n_i^2} + \frac{d}{dN_{Alm}} \left[ \frac{1}{D_{nm}} \right] = 0.
\]

A fixed point iterative scheme for \( N_{Alm} \) derived from the above expression will converge if and only if the iteration function is differentiable in the interval of interest, and the absolute value of its derivative is less than unity [5]. Therefore, we need to choose appropriate models for \( D_{nm} \) and \( n_{nm} \) in (3) to obtain an iterative scheme that converges.

B. Models for Heavy doping Parameters

The dependence of diffusion coefficient \( D_{nm} \) on doping concentration \( N_{Alm} \) in the \( m \)th section of the base may be modeled using an empirical fit to PISCES mobility data [6], [7], as

\[
D_{nm} = \frac{M N_{Alm}^2}{n_{01}^2 N^{2/3}_{Alm}}
\]
where \( M_n = 2.86 \times 10^8 \text{ cm}^{0.7} \text{A}^{-1} \) and \( m_n = 0.42 \). The intrinsic carrier concentration is expressed as a function of the apparent bandgap narrowing due to heavy doping effects as [8]

\[
n_{i,m}^2 = n_{A,0}^2 \exp \left( \frac{\Delta E_{g,app}^{m}}{k_B T} \right)
\]

(5)

where

- \( n_{A,0}^2 \): intrinsic carrier concentration in undoped silicon;
- \( \Delta E_{g,app}^{m} \): dopant induced bandgap narrowing in the mth section of the base;
- \( k_B \): Boltzmann constant;
- \( T \): temperature in degrees Kelvin.

The apparent bandgap narrowing may be modeled as [7], [9]

\[
\Delta E_{g,app}^{m} = 18 \times n \left( \frac{N}{10^7} \right) \text{ meV}, \quad N > 10^{17} \text{ cm}^{-3}
\]

(6)

= 0 \text{ meV}, \quad N < 10^{17} \text{ cm}^{-3}.

Although there are alternative models for heavy doping parameters [10], we have chosen the above simple models so that the iterative scheme converges. It is important to note that the above models are simple and accurate enough to highlight why the iterative scheme suggested in [3] does not give a correct base doping distribution as discussed in the following sections.

III. ITERATIVE SCHEMES FOR OBTAINING OPTIMUM BASE DOPANT DISTRIBUTION

A. Both \( D_{nm} \) and \( n_{im} \) Are Dopant Independent

While evaluating (3), Winterton et al. [3] have assumed that both \( D_{nm} \) and \( n_{im} \) are independent of \( N_{Am} \) and have suggested the following iterative scheme for \( N_{Am} \) for finding the optimum base dopant distribution:

\[
N_{Am(i+1)} = D_{nm(i)}^{1/2} n_{im(i)}^{2} \left[ \frac{\sum_{i=0}^{M} \frac{N_{Am(i)}}{n_{im(i)} D_{nm(i)}}}{\sum_{i=0}^{M} \frac{1}{D_{nm(i)}} - \frac{1}{n_{im(i)}}} \right]^{1/2}
\]

(7)

where \( D_{nm} \) and \( n_{im} \) are given by (4)-(6).

B. Both \( D_{nm} \) and \( r_{ii,m} \) Are Dopant Dependent

In this case, by substituting (4)-(6) in (3), the following iterative scheme can be obtained for the optimum base dopant distribution

\[
N_{Am(i+1)} = \left[ \frac{1}{D_{nm(i)}} \sum_{i=0}^{M} \frac{N_{Am(i)}}{n_{im(i)} D_{nm(i)}} \right]^{1/2}
\]

(8)

where

- \( k_1 \) = 1;
- \( k_2 \) = \( k_1 + m_n \);
- \( N_{Am(i+1)} \): doping concentration in the mth section resulting from the \( i \)th iteration;
- \( jV_{Am(i)} \): dopant concentration resulting from the \( (i - 1) \)th iteration.

After constraining the maximum doping concentration to the value at the emitter edge of the base and the minimum doping concentration to the doping level at the collector edge of the base as suggested in [3], we have compared the iterative schemes given by (7), (8), as discussed below.

IV. RESULTS AND DISCUSSION

For a neutral base width of 0.1 \( \mu \text{m} \), Fig. 1 shows both the base doping profiles generated by the two iterative schemes (7), (8), using the diffusivity model of (4) and the bandgap narrowing model given by (6) for a peak base doping \( N_{A,max} = 10^{19} \text{ cm}^{-3} \) at the emitter edge of the base and a minimum base doping \( N_{A,min} = 2 \times 10^{17} \text{ cm}^{-3} \) at the collectoredge of the base. These base doping values are particularly chosen so that bandgap narrowing effects are predominant in the entire base region. Although identical diffusivity and bandgap narrowing models are used in (7) and (8), we note in Fig. 1 that the profiles generated by the two iterative schemes are not identical. In our scheme, the nonuniform profile is more steeper than that obtained using Winterton’s model. Further, the uniform base region on the emitter side is 18.5% of base width in the case of Winterton’s profile while it is only 4.5% of base width in our case. Therefore, the reduction in base transit time using our iterative scheme results due to both the above factors i.e., a steep nonuniform profile region and a reduced (from 18.5 to 4.5%) length of the uniform profile region on the emitter side. The base transit time values calculated for each of these profiles are also indicated in Fig. 1. It is clearly evident that if the heavy doping parameters are implicitly taken into account in the iterative scheme, the resultant base doping profile is completely different leading to a lower value of \( r_b \) and a higher base resistance. On the contrary, the base doping distribution obtained from the iterative scheme of [3] overestimates the base transit time and underestimates the base resistance.

V. CONCLUSION

In conclusion, we have shown that base doping profiles obtained using any iterative scheme for reducing the base transit time \( r_b \) in narrow base bipolar transistors for a given neutral
base width must take into consideration the effect of dopant dependent diffusivity and dopant induced bandgap narrowing. By comparing our results with that of Winterton et al. [3], we have demonstrated that an iterative scheme which does not implicitly take into account the heavy doping parameters will result in a totally different base doping profile leading to an overestimation of the base transit time and underestimation of the base resistance.

REFERENCES


M. Jagadesh Kumar (SM’99) was born in Manidala, Nalgonda District, Andhra Pradesh. He received the M.S. and Ph.D. degrees in electrical engineering from the Indian Institute of Technology, Madras. From 1991 to 1994, he did his Post-Doctoral research in modeling and processing of high-speed bipolar transistors with Prof. David J. Roulston at the University of Waterloo, Waterloo, ON, Canada. During his stay at Waterloo, he also collaborated with Prof. Savvas G. Chamberlain on amorphous silicon TFTs. From July 1994 to December 1995, he first taught at the Indian Institute of Technology, Kharagpur, and later moved to the Indian Institute of Technology, Delhi, where he was made an Associate Professor in the Department of Electrical Engineering in July 1997. His research interests are in VLSI device modeling and simulation, IC technology, and power semiconductor devices.

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