Analytical models for the base transit time of a bipolar transistor with double base epilayers*

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Abstract: The doping profile function of a double base epilayer is constructed according to drift–diffusion theory. Then an analytical model for the base transit time τ_b is developed assuming a small-level injection based on the characteristics of the 4H-SiC material and the principle of the 4H-SiC BJTs. The device is numerically simulated and validated based on two-dimensional simulation models. The results show that the built-in electric field generated by the double base epilayer configuration can accelerate the carriers when transiting the base region and reduce the base transit time. From the simulation results, the base transit time reaches a minimal value when the ratio of L_2/L_1 is about 2.

Key words: 4H-SiC; bipolar junction transistors; build-in electric field; base transit time
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1. Introduction

Silicon carbide (SiC) is a semiconductor combining several excellent features such as high critical field ($E_c \approx 2.2$ MV/cm), high thermal conductivity ($\lambda \approx 3.0$–3.8 W/(cm·K)) and high saturated carrier velocity ($v_{sat} \approx 2.0 \times 10^7$ cm/s)[1]. These properties make it a promising candidate for RF power transistors. Among SiC power switching devices, bipolar junction transistors (BJTs) show excellent on-state characteristics at both room temperature and elevated temperatures. Also, they are intrinsically normally off-switching devices, free of gate-oxide reliability problems.

The transit time (τ_b) is an important parameter in determining different performance features of BJTs, like the maximum oscillation frequency, cut-off frequency and the noise margin. In previous work[2–5], the base transit time was studied for uniform, exponential or Gaussian base doping profiles and most of them were based on iterative techniques[6]. But exponential and Gaussian doping profiles cannot be realized easily by the epitaxial method. Besides, in SiC device fabrication, ion implantation is often a key process for forming highly doped p-type ohmic contacts but it is difficult to achieve complete dopant activation[7, 8]. In the present work, we introduce a new structure with double base epilayers. This configuration can accelerate the carriers by the built-in electric field in the base region and reduce the base transit time. Also it can avoid the ion implantation process and reduce the defects introduced by high-temperature annealing. An analytical expression for the base transit time is calculated and is applicable for low levels of injection. The equation can offer a physical insight into the device and is a useful tool in device design and optimization. The performance of 4H-SiC BJTs with a double base layer is also presented in this paper, and it is found to be good.

2. Device structure and analysis

A schematic cross-sectional view of the fabricated 4H-SiC BJTs is shown in Fig. 1. The collector region is 15 μm thick with an n-doping layer of 5×10^{15} cm^{-3} grown on n-type substrate with a concentration of 1×10^{19} cm^{-3}. The base was grown as a two-layer structure with Al doping: 0.35 μm with 1×10^{17} cm^{-3} followed by 0.15 μm with 4.6×10^{18} cm^{-3} on top. The emitter n-type epilayer is 0.5 μm thick and is doped to 3×10^{19} cm^{-3}.

Figure 2 shows the simplified structure used in this paper. The base region includes a two-layer structure with aluminum doping. Because of the existence of a concentration gradient at the P$^+$/P junction, a built-in electric field pointing from the P$^+$ region to the P region is formed, as shown in Fig. 2. This electric field can accelerate the transport of the electrons in the base region, and then reduce the base transit time to improve the current gain and frequency properties.

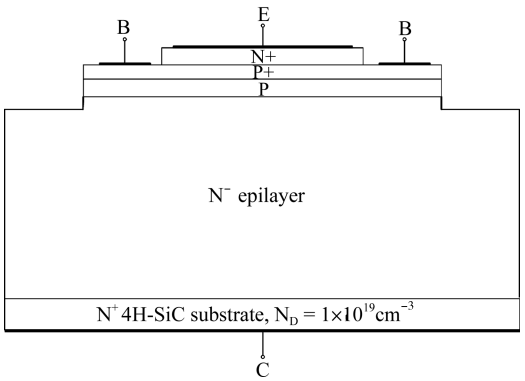

Fig. 1. Schematic structure of the NPN 4H-SiC BJT.

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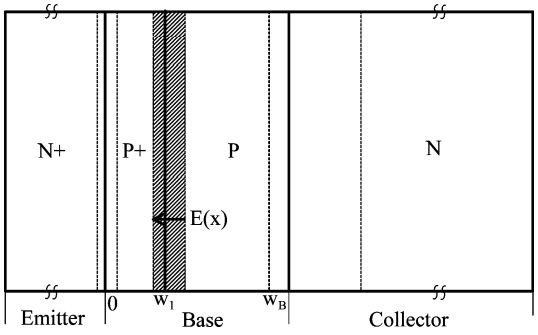

Fig. 2. Simplified diagram of the device structure.

This paper principally investigates the operational state under the condition of low injection. The electrical parameter models during simulation consist of a bandgap narrowing model, a mobility model, an incomplete ionization and impact ionization model, an SRH and Auger recombination model. The influence of surface recombination and anisotropy of the 4H-SiC are ignored.

The following equation gives the base transit time of an npn BJTs:

$$\tau_b = q\int_0^{W_B}\frac{n(x)}{J_n(x)}dx, \tag{1}$$

where x is the distance of a point in the base from the base side of the base–emitter junction, $n(x)$ is the injected electron concentration, $J_n(x)$ is the electron current density in the base, q is the electronic charge, and W_B is the width of the base. For an arbitrary base doping, $J_n(x)$ is given by[9]

$$-J_n(x) = qD_n(x)\frac{dn(x)}{dx} + q\mu_n(x)E(x)n(x). \tag{2}$$

Using Einstein's relation, the electric field $E(x)$ is:

$$E(x) = \frac{kT}{q}\frac{1}{p_B(x)}\frac{dp_B(x)}{dx}, \tag{3}$$

where D_n is the diffusion coefficient for electrons, and p is the hole concentration.

Substituting Eq. (3) into Eq. (2), we get:

$$J_{nB}(x) = \frac{qD_{nB}}{p_B(x)}\frac{d}{dx}\left[n_B(x)p_B(x)\right]. \tag{4}$$

For low injection, the quasi-neutral condition becomes $N_B(x) + n(x) \approx N_B(x)$. Using this equation, Equation (4) becomes:

$$J_{nB}(x) = \frac{qD_{nB}}{N_B(x)}\frac{d}{dx}\left[n_B(x)N_B(x)\right]. \tag{5}$$

From Eq. (5), Equation (6) is obtained:

$$\frac{J_{nB}(x)N_B(x)}{qD_{nB}} = \frac{d}{dx}\left[n_B(x)N_B(x)\right]. \tag{6}$$

To simplify the derivation, we restrict ourselves to considering low injection levels and neglect the minority-carrier concentration at thermal equilibrium, making J_n a constant. For a very thin base region, recombination can be negligible. Therefore, it does not affect the distribution of minority carrier within the base region. Integrating Eq. (6) from x to W_B, the minority-carrier concentration profile is solved as shown in Eq. (7):

$$n_B(x) = -\frac{J_{nE}}{qD_{nB}}\frac{1}{N_B(x)}\int_x^{W_B}N_B(x)dx. \tag{7}$$

After that, the minority-carrier current density is expressed by integrating Eq. (6) from 0 to W_B. The result is:

$$J_{nE} = \frac{-qD_{nB}n_{i0}^2\exp(qV_E/kT)}{\int_0^{W_B}N_B(x)dx} = \frac{-qD_{nB}n_{i0}^2\exp(qV_E/kT)}{Q_B}, \tag{8}$$

where $Q_B = \int_0^{W_B}N_B(x)dx$. From Eqs. (1), (7) and (8),

$$\tau_b = q\int_0^{W_B}\frac{n(x)}{J_n(x)}dx = \frac{q\int_0^{W_B}n(x)dx}{J_{nE}}$$

$$= \frac{Q_BJ_{nE}}{qD_{nB}^2n_{i0}^2\exp(qV_E/kT)}\int_0^{W_B}\frac{\int_x^{W_B}N_B(x')dx'}{N_B(x)}dx. \tag{9}$$

For a double base epilayer structure, the doping profile in the base region can be described by:

$$N_B(x) = \begin{cases} N_1, & 0 < x < W_1, \\ N_2, & W_1 < x < W_B, \end{cases}$$

where N_1 and W_1 are the doping concentration and the thickness of the P^+ layer, and N_2 is the doping concentration of the P layer.

Substituting the doping profile function into Eq. (9), we get:

$$\tau_b = \frac{Q_BJ_{nE}}{qD_{nB}^2n_{i0}^2\exp(qV_E/kT)}\left[\frac{1}{2}L_1^2 + \frac{N_2}{N_1}L_1L_2 + \frac{N_1}{N_2}L_2\left(L_1 - \frac{1}{2}L_2\right) + L_2^2\right], \tag{10}$$

where L_1 and L_2 is given by $L_1 = W_1$, $L_2 = W_B - W_1$.

From Eq. (10) we can find that in order to reduce the base transit time, the third term in the square brackets is 0 when $L_2 = 2L_1$, and also, N_2 should be smaller than N_1. But in this case, the concentration of the P^+ region should not be too high, or the injection efficiency of the 4H-SiC BJT would decrease.

3. Results and analysis

Based on the models and analysis above, numerical simulations were performed with the two-dimensional device simulator ISE. Figure 3 shows the profile of the electric field in the base region. We can see that the electric field is shown near the P^+/P junction because of the concentration gradient of the doping profile, so the drift component dominates the electron current in this region. Also, the accumulation of hole carriers in the P region side has no obvious boundary. 90% of the charge is centralized in the $3d$ range in which $d^2 = \varepsilon_1 kT/2q^2N_{A_1}$.

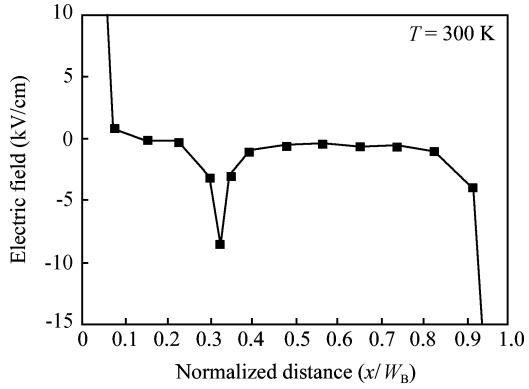

Fig. 3. Electric-field profiles in the base region.

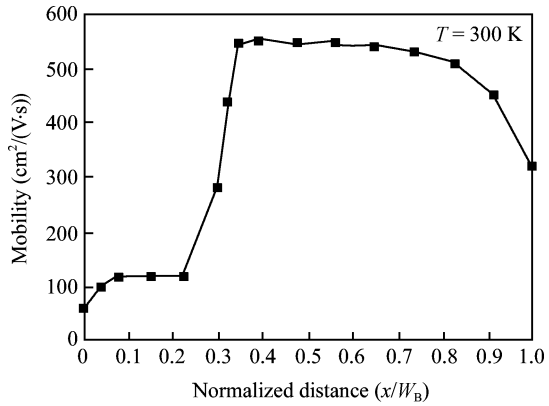

Fig. 4. Mobility profile in the base region.

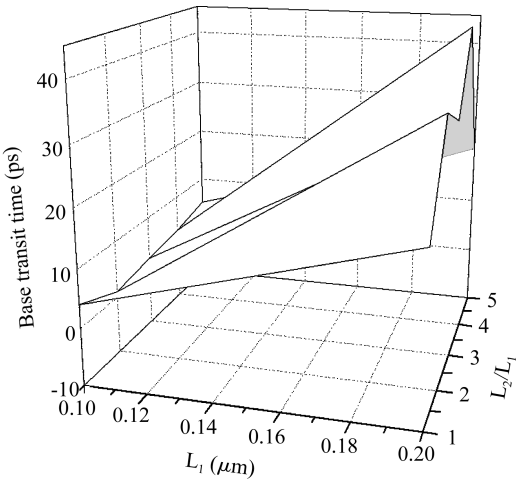

Fig. 5. Dependence of base transit time on different base widths.

At low electric field the electron velocity increases almost linearly with the field and the mobility has a constant value μ_0. The impurity scattering is the main scattering mechanism. The low electric field mobility is given by:

$$\mu_{\rm n} = \frac{947 \times \left(\dfrac{T}{300}\right)^{-2}}{1 + \left(\dfrac{N_{\rm i}}{1.94 \times 10^{17}}\right)^{0.61}} \quad {\rm cm}^2/({\rm V \cdot s}), \qquad (11)$$

where $N_{\rm i}$ is the total doping concentration. Figure 4 shows the profile of the electron mobility in the base region. The mobility increases as the doping decreases and remains approximately constant in each base epilayer.

Figure 5 shows the dependence of $\tau_{\rm b}$ on the length of the P+ region and the ratio of the L_2/L_1. For a double base epilayer structure, L_1 should be very thin. For each L_1, the minimal value of the base transit time occurs when L_2/L_1 is approximately 2. This conclusion is obvious from Eq. (10).

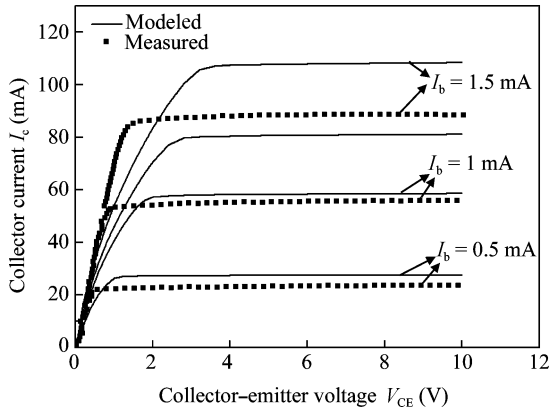

Fig. 6. On-state characteristics and open-base breakdown voltages of the SiC BJT.

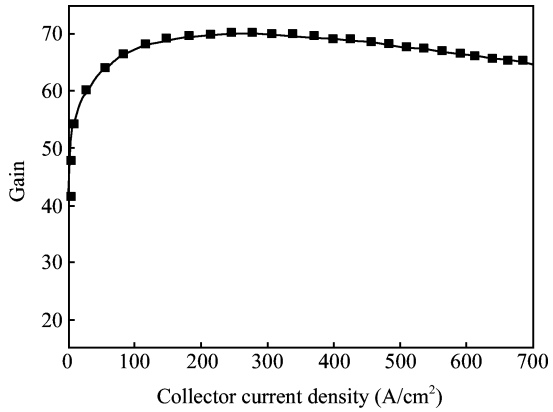

Fig. 7. Variation of current gain with collector current.

From the discussion and the numerical simulation above we can see that the built-in electric field caused by the double base epilayer can reduce the base transit time. Figure 6 shows the on-state characteristics of the whole device compared to the single base structure which is linearly graded p-doped[11]. The solid lines represent the simulation results of the device discussed in this paper and the dotted lines denote the simulation results of the device with a linearly graded p-doped base epilayer. From this we can conclude that the double layers can clearly improve the output characteristic and raise the response speed.

Figure 7 shows the variation of the current gain with the collector current. From this figure we can see that the current gain remains during a wide range of the collector current. It decreases appreciably after $J_{\rm c} > 510$ A/cm^2 because of the self-heating effect and the emitter current crowding effect under the large current.

4. Conclusion

A 4H-SiC power BJT with double base epilayer structure is demonstrated in this paper. By analyzing the built-in electric field in the base and calculating the base transit time, the simulated DC current gain is compared with the single base

epilayer structure. The results show that the built-in electric field caused by the double base epilayer configuration can accelerate the carriers when transiting the base region and reduce the base transit time. The base transit time reaches a minimal value when the ratio L_2/L_1 is about 2. This conclusion offers a physical insight into the device and is a useful tool in device design and optimization.

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