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Device Physics Analysis of Parasitic Conduction Band Barrier Formation in SiGe HBTs

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ABSTRACT

This paper presents a physics-based model describing the current-induced formation of a parasitic barrier in the conduction band at the base-collector heterojunction in npn SiGe heterojunction bipolar transistors (HBTs). Due to the valence band discontinuity ΔE_V, hole injection into the collector at the onset of base pushout is impeded, which gives rise to formation of a barrier to electron transport which degrades the device's high frequency performance. In this paper, we present results from an analytical model for the height of the barrier calculated from the device's structure as a function of the collector junction bias and collector current density.

INTRODUCTION

In recent years SiGe heterojunction bipolar transistors (HBTs) have been reported with high gain and impressive high frequency performance [1,2]. These devices employ Ge in the base and compositional base grading so that a heterojunction is formed at the collector junction. While the conduction band discontinuity is small, the presence of a valence band discontinuity ΔE_V at the junction modifies the physics of electron transport across the collector junction at high current densities. Dynamic formation of a parasitic barrier in the conduction band occurs, which degrades device performance [3-5]. The effect is important for device design since transistor operation at high collector current densities (J_C ~1mA/μm^2) is essential to achieve high gain at microwave frequencies. Previously, Joseph et al. [6] employed a numerical simulator and showed that a parasitic barrier as large as 34 meV forms at current densities of ~4 mA/μm^2. Song and Yuan [7] and Mazhari and Morkoc [8] have reported simple, physics-based models to describe the formation of this parasitic barrier predicting similar and much larger barrier heights, respectively. The motivation for this study is to develop an enhanced description of the physics of this barrier formation for use in device design.

ANALYTICAL MODEL

Shown in Figure 1 is a schematic profile of the electric field assumed at the base-collector junction during formation of the parasitic barrier. This profile is similar to that reported by Joseph et al. [6], which they derived from their numerical simulator. Due to device operation at high current density, the peak field is pushed to the subcollector interface corresponding to the onset of base pushout. However, for SiGe HBTs, the valence band discontinuity at the base-collector junction blocks hole flow out of the base. As a result, a current-induced, parasitic barrier forms near the junction corresponding to a positive field region. This barrier inhibits electron injection into the collector from the base producing electron buildup at the end of the base, increased base recombination and degradation in the current gain.

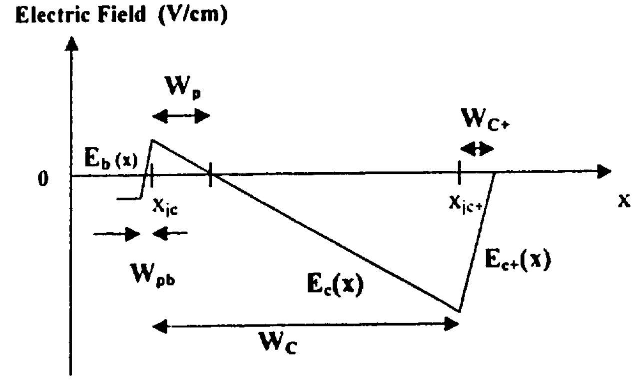

Figure 1 Electric field profile at B-C junction at high current density during formation of parasitic barrier.

For development of this device model, we note that the electron concentration n_s is nearly constant in the high electric field in the base-collector space charge region (BC-SCR) near the subcollector due to velocity saturation v_s. As a result, the electron concentration is given by $n_s = J_C/qv_s$, where J_C is the collector current density and the term arises from the need for a finite electron concentration sufficient to carry the collector current. Substituting this n_s in Poisson's equation, we integrate to get the electric field in the depleted collector $E_c(x)$, which varies linearly as shown in Figure 1. On the base side of the heterojunction, we note that we have majority carrier hole accumulation due to the valence band discontinuity ΔE_V, which we take into account in determining the electric field in the base $E_b(x)$. The location where the electric field is zero in the collector corresponds to the peak of the parasitic potential barrier.

To analyze the formation of the barrier, we initially match the fields at the base-collector and subcollector junctions. Subsequently, we piecewise integrate the electric field across the junction to relate our results to the collector doping and width and the applied junction reverse bias V_{CB}. Combining these results, we get a single equation for the potential at the base-collector junction $\psi(x_{jc})$, where our zero for the potential was taken to be in the quasi-neutral base. After simplification, the solution is expressed in terms of the function $f(\psi(x_{jc}))$ as

$$f(\psi)=\frac{J_k^2}{2J_b[J_{l+}+J_C-J_l]} \quad (1)$$

where $J_l = qN_Cv_s$, $J_{l+} = qN_{C+}v_s$, $J_b = qN_Bv_s$, and $f(\psi(x_{jc}))$ is given by

$$f(\psi(x_{jc}))=\sqrt{\frac{2\varepsilon V_T}{qN_BW_C^2}\left\{e^{-\psi(x_{jc})/V_T}-1+\frac{(\psi(x_{jc}))}{V_T}\right\}} \quad (2)$$

where J_k is given by

$$J_k=\sqrt{J_C(J_C+J_{l+}-2J_l)-J_l(J_{l+}-J_l)-\frac{2\varepsilon v_s J_{l+}}{W_C^2}\left[V_{bi}^C+V_{CB}-\psi(x_{jc})\right]} \quad (3)$$

From (1)-(3) it is apparent that $\psi(x_{jc})$ is a function of the device structure, current density J_C and V_{CB}. From (3), we see that J_k is nearly independent of $\psi(x_{jc})$ so we can neglect it in calculating J_k, find $f(\psi)$ from (1), and then determine $\psi(x_{jc})$ from (2). We can then determine the height of the parasitic potential barrier ϕ_b from the expression below, which corresponds to the magnitude of the potential at the point where the electric field in the depleted collector $E_c(x_{jc} + W_p)$ is equal to zero.

$$\phi_b(J_C)=\frac{W_C^2}{2\varepsilon\, v_s}\frac{J_b^2 f^2(\psi(x_{jc}))}{J_C-J_l} \quad (4)$$

SIMULATION RESULTS

The above described device model was used to investigate the extent of the formation of the parasitic barrier ϕ_B and base pushout W_{cib} for a typical device structure similar to that of Joseph et al. [6]. Linear compositional grading from zero at the emitter to 10% Ge at the collector end of the base was assumed corresponding to ΔE_V = 75 meV at the collector junction. A base width of 90 nm was assumed with a doping of $1\times10^{18}/cm^3$. A collector width W_C of 0.5 μm and doping of $1\times10^{17}/cm^3$ was used. The current density constants J_l, J_{l+} and J_b were calculated to be 1.6, 160, and 16 mA/μm^2, respectively. A builtin potential of 0.75V and a junction reverse bias of 1V were assumed.

Shown in Figure 2 is the parasitic barrier ϕ_b plotted as a function of the collector current density. The onset of formation of the parasitic barrier ϕ_b occurs at a current density of 1.75 mA/μm^2, which is slightly larger than J_l = 1.6 mA/μm^2. The parasitic barrier shows a sharp increase with increasing J_C, which is comparable to that described by Mazhari and Morkoc [8], but larger than that reported by Joseph et al. [6] and Song and Yuan [7].

Since the formation of this parasitic barrier leads to excess electron buildup at the collector end of the quasi-neutral base, it produces a saturation effect in the collector current and an increase in the quasi-neutral base recombination, with a corresponding falloff in the current gain. This also degrades the base transit time and the cutoff frequency so that delay of the phenomena to higher current densities is desirable. Increasing the collector junction reverse bias and the collector doping help in this regard.

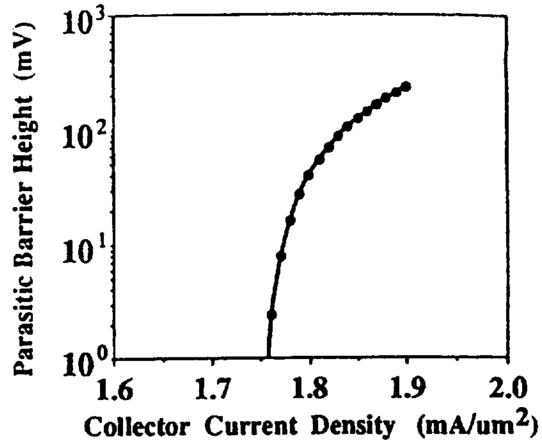

Figure 2 Parasitic barrier height ϕ_b as a function of collector current density.

CONCLUSIONS

In summary, we have developed an improved description of the physics associated with the onset of the dynamic formation of the parasitic barrier at the base-collector junction at high collector current densities. The model will provide a useful tool for device engineers in the design of the base-collector junction for optimizing the device's performance at high current densities near the onset of base pushout.

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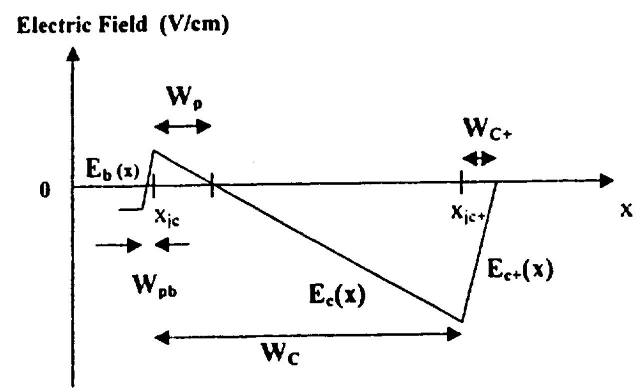

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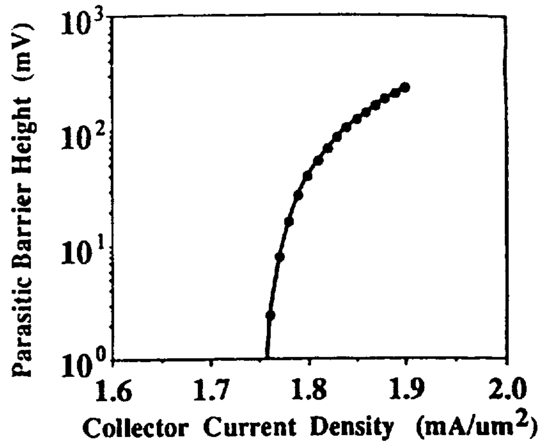

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