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Physics-Based Hot-Carrier Degradation Model for SiGe HBTs

Hamed Kamrani*, Dominic Jabs*, Vincenzo d'Alessandro†, Niccolò Rinaldi† , and Christoph Jungemann*
*Chair of Electromagnetic Theory, RWTH Aachen University, Aachen, Germany
†Dept. of Electrical Eng. and Information Tech., University Federico II, Naples, Italy
Email: hk@ithe.rwth-aachen.de

***Abstract*—We present hot-carrier degradation analysis for SiGe heterojunction bipolar transistors based on deterministic solutions of the Boltzmann transport equations for a coupled system of electrons and holes. The full-band transport model provides the distribution function of the charge carriers interacting with the passivated Si-H bonds along the Si/SiO_2 interface. Investigation of the density of hot carriers along the emitter-base spacer oxide interface asserts the significant role of hot holes in the long-term degradation of SiGe HBTs under DC mixed-mode stress conditions. The creation of interface trap states by hot carriers is calculated by an energy-driven microscopic model. These traps increase the forward base current via Shockley-Read-Hall recombination and degrade the overall device performance.**

***Index Terms*—Boltzmann equations, hot-carrier degradation, mixed-mode stress conditions, SiGe HBT, spherical harmonics expansion.**

I. Introduction

The main reliability challenge in bipolar transistors is the base current degradation via trap generation at the emitter-base (EB) spacer oxide interface [1]. In general, imperfections at the Si/SiO_2 interface lead to silicon dangling bonds which can capture electrons or holes. Thus, these dangling bonds are intentionally passivated by incorporating hydrogen atoms. However, hot carriers can supply enough energy to break the passivated Si-H bonds. The interface trap states resulting from the Si-H bond dissociation can produce a leakage base current via Shockley-Read-Hall (SRH) recombination, which degrades the main device parameters such as current gain and noise figure [2]. Although conventional methods for physics-based modeling of hot-carrier degradation (HCD) in bipolar transistors, such as the lucky electron model, are electric field driven [2], [3], it has been shown that the trap generation rate at the interface depends only on the energy of the interacting charge carriers and is not determined by the electric field [4], [5]. Furthermore, while hot enough carriers can directly trigger the bond dissociation in a single collision, several colder carriers can also induce multiple vibrational excitation (MVE) of the bond followed by hydrogen release from the last bonded level [6]. Hence, an energy driven paradigm has been proposed to include both single- and multiple-carrier processes of the bond dissociation in the degradation analysis of the n-channel MOSFETs [7], [8]. In the proposed model, instead of the electric field or the carrier temperature, the carrier acceleration integral (AI) obtained from the carrier energy distribution function controls HCD.

In this paper, we present an energy driven physics-based model for the HCD analysis, which accounts for both hot electrons and hot holes. Therefore, we solve a coupled system of Boltzmann transport equations (BTEs) for electrons and holes to obtain the energy distribution of the carriers required for the calculation of the AIs. For this purpose, a deterministic solver for the full-band BTEs based on the spherical harmonics expansion (SHE) method is used [9], [10]. To study HCD in bipolar devices, we investigate a two-dimensional SiGe HBT which is degraded under the conventional mixed-mode stress conditions. Using the degradation model, we calculate the trap density profile along the EB spacer oxide interface as a function of the stress time. Then, the interface trap density is used to calculate the forward I-V characteristics of the degraded device which is influenced by the SRH recombination process.

II. Theory

Hot-carrier degradation in bipolar transistors is associated with the bond dissociation events at the passivated Si-H bonds of the EB spacer oxide interface. Charge carriers can supply enough energy to excite and eventually break these bonds. Hence, the bond-breakage rate is determined effectively by the carrier energy distribution function. To obtain the distribution function of the carriers $f^{\mathrm{e/h}}(\vec{r},\vec{k},t)$, a coupled system of the BTEs for electrons and holes has to be solved. The BTE for electrons in the stationary case is written as

$$L^{\mathrm{e}}\{f^{\mathrm{e}}\} = S\{f^{\mathrm{e}}\} + Q\{f^{\mathrm{e}},f^{\mathrm{h}}\} - \Gamma^{\mathrm{e}}\{f^{\mathrm{e}},f^{\mathrm{h}}\} \qquad (1)$$

where $L^{\mathrm{e}}\{f^{\mathrm{e}}\}$ is the free-streaming operator, $S\{f^{\mathrm{e}}\}$ is the scattering operator, which takes carrier-phonon scattering, impurity scattering, alloy scattering, and impact ionization scattering of primary particles into account, $Q\{f^{\mathrm{e}},f^{\mathrm{h}}\}$ is the generation operator due to impact ionization of secondary particles [11], and $\Gamma^{\mathrm{e}}\{f^{\mathrm{e}},f^{\mathrm{h}}\}$ is the recombination operator due to SRH recombination [12], [13]. This coupled system of the BTEs is solved deterministically based on the SHE method. The projection of the full-band carrier BTE onto spherical harmonics has been discussed comprehensively in [9], [10].

Since the bond-breakage rate is determined by the interaction of the charge carriers with the passivated Si-H bonds,

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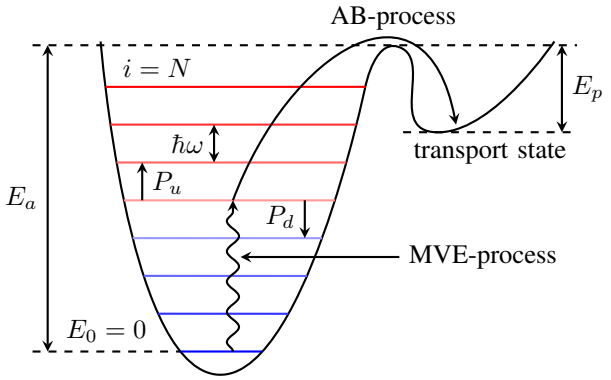

Fig. 1. The energy configuration of the Si-H bond modeled as a truncated harmonic oscillator.

the energy configuration of these bonds has to be taken into account. The Si-H bond is modeled as a truncated harmonic oscillator characterized by a system of eigenstate energies [14], which is illustrated in Fig. 1. The bond dissociation occurs via excitation of one bonding electron to the transport state which is known as an antibonding (AB) process. As a result, a repulsive force is induced, which detaches the hydrogen atom. The dissociation rate from the ith level with the energy E_i is given by

$$R_{\mathrm{AB},i} = I^{\mathrm{e}}_{\mathrm{AB},i} + I^{\mathrm{h}}_{\mathrm{AB},i} + v_r \exp\left(-\frac{E_a - d\cdot E_{\mathrm{ox}} - E_i}{k_{\mathrm{B}}T_0}\right) \quad (2)$$

where $I^{\mathrm{e}}_{\mathrm{AB},i}$ and $I^{\mathrm{h}}_{\mathrm{AB},i}$ are the AB acceleration integrals due to electrons and holes, respectively, v_r is an attempt frequency, E_a is the activation energy, E_{ox} is the oxide electric field, and d is the bond dipole moment. For the AB process, the AI is defined as

$$I^{\mathrm{e/h}}_{\mathrm{AB},i} = \sigma_0^{\mathrm{AB}} \int_{E_{\mathrm{th},i}}^{\infty} f^{\mathrm{e/h}}(E) Z^{\mathrm{e/h}}(E) v_g^{\mathrm{e/h}}(E) \left[(E - E_{\mathrm{th},i})/E_{\mathrm{ref}}\right]^{11} dE \quad (3)$$

where $E_{\mathrm{th},i} = E_a - E_{\mathrm{ox}}d - E_i$ is a threshold energy for the ith level, σ_0^{AB} is the AB reaction cross section, $Z^{\mathrm{e/h}}(E)$ is the carrier density of states, $v_g^{\mathrm{e/h}}(E)$ is the carrier group velocity, and $E_{\mathrm{ref}} = 1\mathrm{eV}$.

If a charge carrier does not provide enough energy to trigger the AB mechanism, it can still contribute to the MVE process. In a consistent consideration of the MVE and AB mechanisms, the bond can be firstly excited by several colder particles to an intermediate level, and then dissociated by a carrier with a relatively high energy. The bond excitation and deexcitation rates which can be triggered by either a cold electron or a cold hole, are given by

$$P_u = I^{\mathrm{e}}_{\mathrm{MVE}} + I^{\mathrm{h}}_{\mathrm{MVE}} + \omega_{\mathrm{e}} \exp\left(-\frac{\hbar\omega}{k_{\mathrm{B}}T_0}\right) \quad (4)$$

$$P_d = I^{\mathrm{e}}_{\mathrm{MVE}} + I^{\mathrm{h}}_{\mathrm{MVE}} + \omega_{\mathrm{e}} \quad (5)$$

where ω_{e} is the reciprocal phonon life-time, $\hbar\omega$ is the energy distance between the oscillator levels, and the AI for the MVE process is defined as

$$I^{\mathrm{e/h}}_{\mathrm{MVE}} = \sigma_0^{\mathrm{MVE}} \int_{\hbar\omega}^{\infty} f^{\mathrm{e/h}}(E) Z^{\mathrm{e/h}}(E) v_g^{\mathrm{e/h}}(E) \left[(E - \hbar\omega)/E_{\mathrm{ref}}\right]^{11} dE \quad (6)$$

The cumulative bond-breakage rate, which accounts for all possible superpositions of the AB and MVE mechanisms, is calculated as

$$R_a = \frac{1}{k}\sum_i R_{\mathrm{AB},i}\left(\frac{P_u}{P_d}\right)^i \quad (7)$$

where k is a normalization prefactor given by

$$k = \sum_i \left(\frac{P_u}{P_d}\right)^i \quad (8)$$

The generated traps can also be annihilated by back diffusing hydrogen atoms. However, this reaction is thermally activated and the rate at room temperature is very small due to a large potential barrier E_p. The recovery rate of the broken Si-H bonds is modeled by an Arrhenius law as

$$R_p = v_p \exp\left(-\frac{E_p}{k_{\mathrm{B}}T_0}\right) \quad (9)$$

where v_p is an attempt frequency prefactor.

The rate equation for the generation and recombination of the interface trap states is written as

$$\frac{\partial N_{it}}{\partial t} = (N_0 - N_{it})R_a - N_{it}^2 R_p \quad (10)$$

where N_0 is the density of the primary passivated Si-H bonds, and N_{it} is the density of the generated interface traps, which their energy level is assumed in the middle of the bandgap. In our simulation approach, the SHE solver is used to obtain the carrier energy distribution functions for a SiGe HBT under stress conditions. Then, the $N_{it}(\vec{r}, t)$ profile calculated at each stress time step is used again in the SHE solver to simulate the characteristics of the degraded device which is changed due to SRH recombination.

III. Results

A two-dimensional structure corresponding to a state-of-the-art SiGe HBT, designed and fabricated for the European DOTFIVE project, was employed to investigate HCD mechanisms. To accelerate the degradation process, mixed-mode stress conditions are applied at the border of the safe operating area. Therefore, we apply simultaneously a high collector-emitter voltage $V_{\mathrm{CE}} = 3\mathrm{V}$ and a high collector current density $J_{\mathrm{C}} = 1\mathrm{mA}/\mu\mathrm{m}^2$. In this stress mode, charge carriers gain enough energy from the high electric field at the collector-base junction to generate electron-hole pairs by impact ionization. Fig. 2 shows the impact ionization generation rate initiated by electrons and holes separately.

Since the bond-breakage rate is determined by the distribution of the carriers over energy, their energy distribution

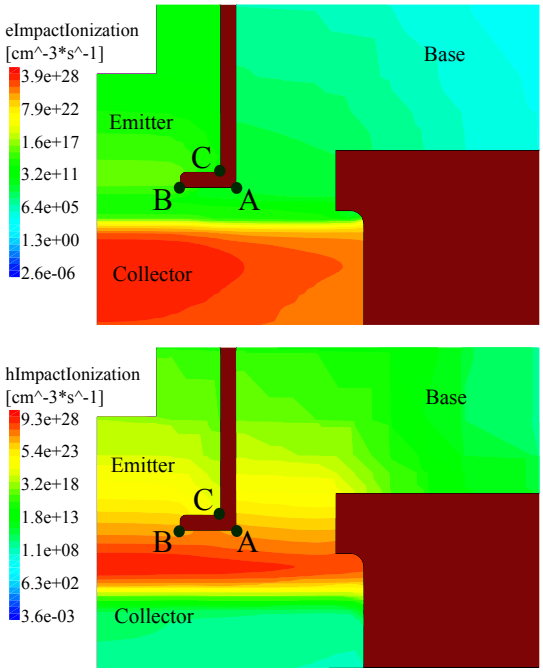

Fig. 2. Impact ionization generation rates in the SiGe HBT due to electrons (top), and holes (bottom).

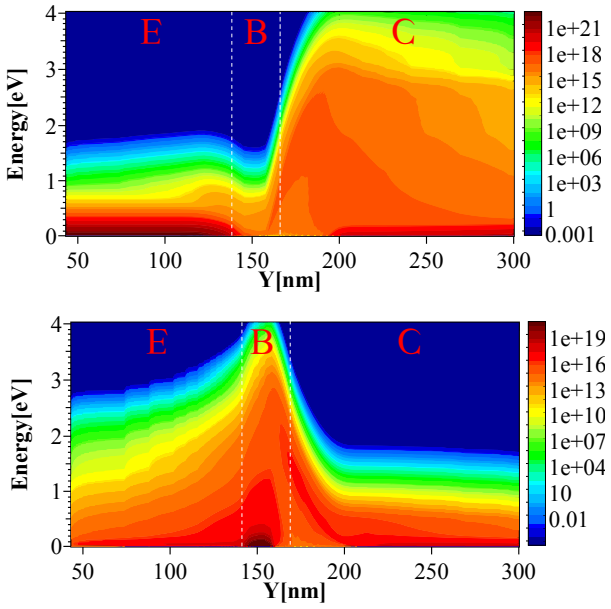

Fig. 3. Energy distribution function [$\mathrm{eV}^{-1}\mathrm{cm}^{-3}$] of electrons (top) and holes (bottom) along the symmetry axis of the HBT.

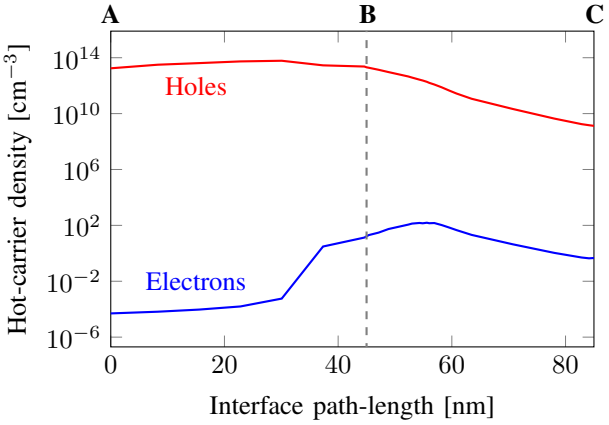

Fig. 4. Density of electrons and holes with energies higher than 1.5 eV along the EB spacer oxide interface from node A to C denoted in Fig. 2.

functions can give us a better understanding of which hot carriers participate in the degradation process. Fig. 3 depicts a cut of the energy distribution functions for electrons and holes along the symmetry axis of the investigated SiGe HBT. The non-equilibrium tails of the distribution functions at high energies reveal that hot electrons are deep in the collector region while hot holes are mainly found in the base and emitter regions. This is caused by the fact that the electrons move to the collector, whereas the holes generated by impact ionization in the collector due to hot electrons (Fig. 2 top) are accelerated towards the base and gain a lot of energy. Due to this high energy some of the holes can shoot through the base into the emitter, where they still have a relatively large energy (Fig. 3 bottom). A certain fraction of these holes hits the EB spacer oxide, where they might break Si-H bonds. This effect can only be described by a model which resolves the dependence of the carriers on energy. Thus, it is not possible to capture this effect with a drift-diffusion or hydrodynamic model, because in both cases the hole gas in the base is assumed to be close to equilibrium and no hot holes are simulated in the base. Although cold carriers can also participate in the MVE of the Si-H bonds, hot carriers with energies greater than 1.5 eV have a much higher chance to dissociate the Si-H bonds directly [8]. The density of carriers with energies higher than 1.5 eV along the EB spacer oxide interface is shown in Fig. 4, which clarifies the dominant role of hot holes in the degradation process of bipolar transistors under mixed-mode stress conditions.

The trap densities along the EB spacer oxide interface are shown in Fig. 5 for several stress time steps. These results show that the peak value of the interface trap density saturates after some time. This corresponds to the saturation of the excess base-current due to HCD reported in [1], [15]. Consequently, these traps created at the EB spacer oxide interface cause a non-ideal increase in the forward-mode base current via SRH recombination. Fig. 6 shows the Gummel characteristics ($V_{\mathrm{CB}} = 0\mathrm{V}$) of the investigated SiGe HBT before and after stress. Since the recombination process has no considerable impact on the collector current, the resulting increase in the base current degrades the current gain of the transistor.

IV. Conclusion

We have presented a physics-based investigation of HCD in SiGe HBTs based on the distribution function calculated by a deterministic solver for the BTE. Consistent modeling of

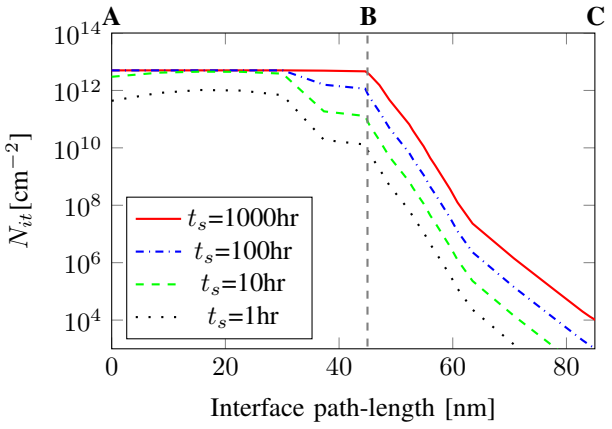

Fig. 5. Trap densities generated at different stress times along the EB spacer oxide interface.

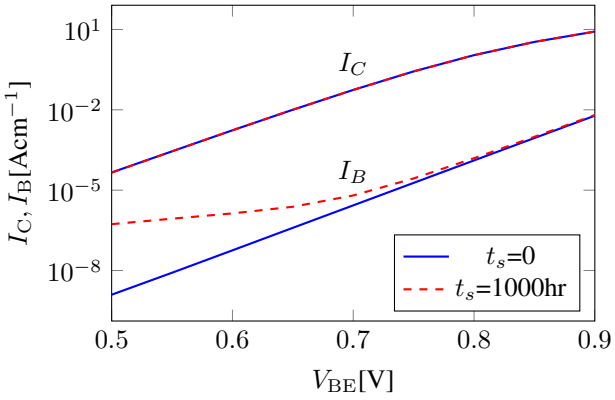

Fig. 6. Gummel characteristics of the SiGe HBT before and after stress. The leakage base current after 1000 hours of mixed-mode stress application degrades the current gain of the transistor.

the MVE and the AB processes for the dissociation of the Si-H bonds has been demonstrated for both electrons and holes. By investigating the hot carrier densities along the EB spacer oxide interface, it was shown that HCD in SiGe HBTs under mixed-mode stress is dominantly due to hot holes impinging on the oxide interface. The interface trap states, which are mainly generated by hot holes, increase the forward base current via SRH recombination. This leakage base current degrades the current gain of the bipolar transistors.

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