Dead-Space Effects Under Near-Breakdown Conditions in AlGaAs/GaAs HBT's

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Abstract—**By using a self-consistent Monte Carlo simulation, we demonstrate the importance of dead-space effects in the near-avalanche regime of AlGaAs/GaAs HBT's. We show that the space-dependent ionization coefficient reaches its maximum inside the collector region, displaced by several hundred angstroms from the peak electric field at the collector–base junction, and from the maximum of the carrier average energy. A delay equation is then proposed that overcomes the failure of local models in describing such effects.**

MULTIPLICATION phenomena connected to impact ionization processes are of fundamental importance for the operation of a semiconductor device, since they determine its breakdown voltage. The modeling of such processes is unfortunately extremely complex, since it requires accurate representation of hot-carrier regimes. Local approaches based on analytical formulations are very popular [1], [2], as they can be easily incorporated into drift-diffusion (DD) simulators [3]. Nevertheless, they suffer from several unphysical assumptions [4], [5]. More accurate models have been presented [6]–[8], which have been coupled to physical simulators based on the solution of Boltzmann equation, either via hydrodynamical (HD) schemes [9] or via Monte Carlo (MC) techniques [10].

In this paper, we present a study of near avalanche condition in AlGaAs/ GaAs heterojunction bipolar transistor (HBT's) based on a self consistent Monte Carlo simulation. The HBT is attracting considerable attention because of its high-speed performance and high current-handling capability [11]–[13]. Despite the importance of the breakdown voltage in limiting the microwave performance of the device [14], no thorough investigation of its occurrence exists so far for HBT's. Our theoretical investigation focuses on carrier multiplication phenomena occurring at the base–collector (BC) region, in a prebreakdown regime where impact ionization is the dominant mechanism. We use a new general-purpose weighted MC procedure which accounts for both electrons and holes, described within a three-valley/ three-band nonparabolic model with inclusion of band boundary effects, self-consistently coupled to a 1D Poisson solver. The band diagram and cross section of the simulated device is shown in Fig. 1. Impact ionization (II) is simulated on the basis of Kane's model [15] which relates the II energy dependence to the density of state. The free parameter present in Kane's approach was determined through the fit of the bulk ionization coefficient. In order to properly account for impact ionization and carrier multiplication processes, we have developed a series of original numerical algorithms that allow variance reduction in rare regions of phase space. These techniques are also useful for low injection regimes, required to avoid the occurrence of Kirk effect in the collector. Details of the MC procedure and the parameters used in the simulation have been given elsewhere [16]. Preliminary results, also containing a comparison with experimental results, have been presented in [17]. The electrical characterization of the HBT, whose structure was identical to the simulated one, exhibited a sign reversal of the base current [18]. Such behavior was attributed to the onset of impact ionization process at high collector bias. In fact, at $V_{CB} = 0$ V, impact ionization does not occur and I_B is always positive. On increasing V_{CB} the number of electron–hole pairs generated by impact ionization increases. The generated electrons are swept towards the subcollector contributing a positive term to I_C, while the generated holes are collected at the base electrode, contributing a negative term to I_B. In particular, at $V_{CB} = 8.6$ V this contribution is so high that I_B reverses its sign and becomes negative.

In order to understand the details of the ionization process which leads to the base current reversal, we have performed the MC simulation for high V_{CB}'s and low emitter currents. Fig. 2 shows the electric field profile, the average carrier energy and ionization coefficient for $V_{CB} = 18$ V, that is the near breakdown regime. Electrons are strongly heated by the high electric field at the B–C junction, reaching their maximum energy at about 80 nm inside the collector. Most of them are found in the satellite L and X valleys, and move through the collector at saturated velocity. The electron ionization coefficient is further delayed due to finite time (and distance) required to reach the ionization threshold. As a consequence, ionization events do not occur in correspondence to maximum electric field, rather well into the collector. Such a phenomenon is usually referred to as the dead space (DS) effect [19]. The effective width of the DS region l_{DS} is calculated from the simulation as the distance between

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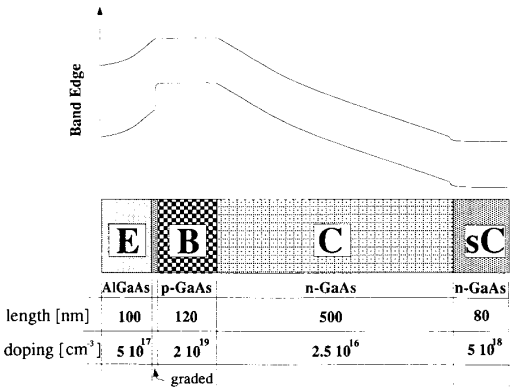

Fig. 1. Schematic band diagram and cross section of the simulated AlGaAs/GaAs n-p-n HBT. The dimension and doping levels of the structure are indicated in the lowest panel.

the maximum electric field and the half-height of the electron ionization rate. It should be noticed that the peak of the electron ionization coefficient is displaced even from the maximum of the average electron energy, an occurrence which puts energy-dependent models (such as the HD approach) into questions. This is due to the nonlocality of the transport processes, which causes the high-energy tail of the electron distribution function (which in turn controls the ionization rate) to slightly increase even when the average energy starts decreasing.

II depends heavily on the applied voltage. Such bias dependence is reflected in the behavior of the measured $M-1$ factor illustrated by closed circles in Fig. 3. The change in slope around 18 V can indeed be attributed to the onset of higher order ionization process. Near breakdown, the holes generated by primary ionizations are able to ionize before reaching the base, thus creating electrons that will in turn ionize while drifting along the collector region. As we have shown in [17], such positive feedback marks, in fact, the onset of breakdown, occurring at a collector voltage of 18.6 V. It should be remarked here that our MC results agrees well with the measured $M-1$ factor.

The good agreement between MC simulation and experiment is certainly no surprise, but comes at the cost of heavy computation. As pointed out earlier, multiplication phenomena in devices are usually treated within local schemes which allow a straightforward implementation into drift-diffusion simulators, much faster and less demanding than MC techniques. The starting point for such schemes is the current equation

$$\frac{dI_n}{dx} = \alpha_p(x)I_p(x) + \alpha_n(x)I_n(x) \tag{1}$$

where α's are the II coefficients, and the subscript n and p refer to electrons and holes, respectively. Equation (1) leads to the definition of the multiplication factor as

$$1 - \frac{1}{M} = \int_0^W \alpha_n(E(x))e^{-\int_0^x[\alpha_n(E(y))-\alpha_p(E(y))]\,dy}\,dx \tag{2}$$

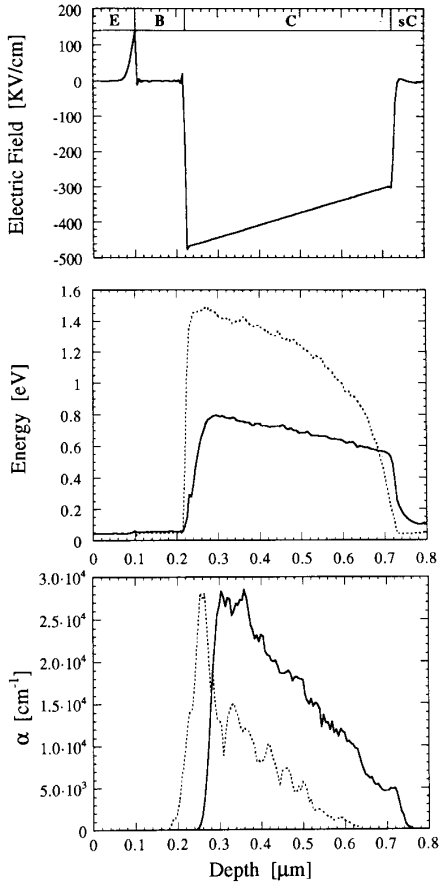

Fig. 2. Electric field, average energy for electrons (solid line) and holes (dashed line), and ionization coefficient for electrons (solid line) and holes (dashed line) as a function of position in the device, as calculated from the MC simulation at a collector–base voltage of 18 V.

where W is the collector width and E the electric field. The ionization coefficients are usually expressed by the following functions:

$$\alpha_n(E(x)) = A_n e^{-(b_n/E(x))^{m_n}}$$
$$\alpha_p(E(x)) = A_p e^{-(b_p/E(x))^{m_p}} \tag{3}$$

where A, b, and m are fitting parameters. The $M-1$ factor calculated from (2) using the parameters given in [20] is shown in Fig. 3 by the dashed line. Clearly, neglecting DS effects leads to an overestimation of the result. A simple way to account for DS corrections is to introduce l_{DS} as lower limits of the integrals in (2). Once hole contributions in the DS are taken into account, the following expression is found [19]:

$$1 - \frac{1}{M} = \left[\int_{l_{DS}}^W \alpha_n(E(x))e^{-\int_{l_{DS}}^x[\alpha_n(E(y))-\alpha_p(E(y))]\,dy}\,dx\right] \cdot\left(1 + \int_0^{l_{DS}} \alpha_p(E(x))\,dx\right). \tag{4}$$

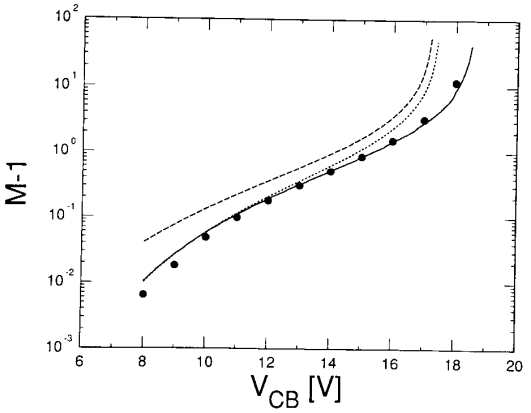

Fig. 3. Experimental multiplication factor versus collector–base voltage (closed circles, from [18]), compared with three different threoretical approaches. The dashed line is obtained from the local model of (2) (see text), the dotted line includes correction due to dead-space effects (see (4)), and the solid line refers to the delay equation (see (5)). For the two last cases the dead-space dependence on the bias voltage is accounted for by an hyperbolic interpolation $l_{DS} = A/V_{CB} + B$, where the coefficients A and B are determined from the MC values at 8 V (l_{DS} = 90 nm) and 18 V (l_{DS} = 55 nm), respectively.

The $M - 1$ factor obtained from (4) by taking the width of the DS region directly from the MC simulation are shown by the dotted line in Fig. 3. The result agrees well with experimental data for V_{CB} less than 16 V, while at higher voltages the hole correction does not reduce the overestimation of the result. The sharp increase around 17 V shows that, despite the incorporation of DS corrections, the simple model of (4) cannot fully reproduce the multiplication process occurring in the device.

A more rigorous approach can be actually taken by including DS effects directly into the starting (1), by transforming it into an *equation with delay* of the type

$$\frac{dI_n}{dx} = \alpha_n(x) I_n(x - l_{DS})\theta(x - l_{DS}) + \alpha_p(x) I_p(x + l_{DS})\theta(W - l_{DS} - x) \quad (5)$$

where the Heaviside function θ accounts for the fact that electrons (holes) can only ionize after a distance l_{DS} from the base–collector (collector–subcollector) junction. As mentioned above, the introduction of a delay accounts for the fact that the ionization rate at position x depends on the carriers that are displaced by l_{DS} from it (that is on the electron current at $x - l_{DS}$ and the hole current at $x + l_{DS}$). Clearly, (5) leads, as limiting cases, to both (2) and (4). Although general prescriptions concerning the existence of solutions for such equations can be given (see [21] and references therein), analytical solutions exists only for some special cases. We have therefore solved it numerically within a finite difference scheme [3], using for the field profile the solution of Poisson's equation. Once the electron and hole currents are determined, the multiplication factor is calculated as the ratio between the electrons current at the end and at the beginning of the collector. The result is given by the solid line in Fig. 3. As for (4), the value of l_{DS} is taken from the MC simulation. The agreement with the experimental results is excellent, and the correct value of the breakdown voltage is obtained. We believe that the approach based on (5) can overcome the limitation of local models, still allowing straightforward implementation into standard device simulators.

In summary, we have presented an analysis of ionization phenomena in AlGaAs/ GaAs HBT's based on the MC self-consistent simulation which include both electrons and holes. The simulation describes the microscopic processes leading to the measured bias dependence of the multiplication factor. The importance of the dead-space effects has been shown, and a simplified analytical approach that accounts for such effects has been given.

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