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Validation of an extended hydrodynamic model for a submicron npn bipolar junction transistor

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Abstract

Transport phenomena in a submicron npn silicon bipolar junction transistor are described by using an 8-moment model for the electrons, combined with a solution of the drift–diffusion model for the holes.

The validity of the constitutive equations for the fluxes and the production terms, obtained by means of the maximum entropy principle, and the hyperbolicity conditions are checked with direct simulation Monte Carlo. We verify numerically that the quadratic closure is more accurate with respect to the zero-order one, but some irregularities can appear in the solution due to the loss of hyperbolicity in some regions of the device.

Keywords: Theory of electron transport; Non-equilibrium thermodynamics; Bipolar transistors

1. Introduction

In modern-day submicron silicon devices, high electric field and high field-gradient conditions are routinely encountered during operation, and the carrier dynamics are far from thermal equilibrium. The Monte Carlo (MC) solution of the Boltzmann transport equation (BTE) provides a more accurate description of carrier transport even under such highly non-equilibrium conditions. This because various scattering mechanisms and band structure models are taken into account explicitly. However, the extensive computation required by MC simulations and the noisy results makes them impractical for device design on a regular basis.

In order to study the high-field transport properties in semiconductors, macroscopic transport equations are originally obtained by taking different moments of the BTE, which are referred to as hydrodynamic equations (HD). The use of HD approaches poses some problems such as the closure of the hierarchy of moment equations and the modeling of the production terms (i.e., the moments of the collisional operator). Recently these problems have been tackled by using a drifted Maxwellian closure [1] or by introducing phenomenological constitutive functionals for the fluxes and the production terms containing free parameters to be determined, each time, by means of experimental data or MC simulations [2].

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Another possibility for studying non-equilibrium phenomena, which has been widely investigated during the last years, is to use the theory of extended thermodynamics [3,4]. It provides a systematic method to obtain closure equations for fluxes and production terms by following the entropy principle [3] or the maximum entropy principle (MEP) [5] which, under suitable assumptions, are proved to be equivalent [6]. This theory has been developed for electron carrier transport in Refs. [7–11]. It has been tested in bulk silicon [12,13] by mean of MC simulations, used to simulate submicron devices such as 1D $n^+ - n - n^+$ silicon diodes [14–17] and 2D unipolar MESFET devices [18].

In this preliminary paper we want to use the existing electron HD model [9] combined with a solution of the DD model for the holes, for describing transport phenomena in a realistic submicron 2D bipolar junction transistor (BJT) operating in quasi-ballistic regime, and validate this model by direct comparison with MC simulations.

The plan of the paper is the following. In Section 2 the basic physics of an npn BJT is discussed. Then we introduce the semiclassical BTE for electrons, the collision operator comprising the main scattering mechanisms occurring in silicon, and the DD model for holes. In Section 3 the electron HD model [9] with the MEP closure for the higher order fluxes and the production terms is outlined. In Section 4 the analysis of the hyperbolicity for the above model is tackled. In Section 5 the validity of the closure relations and the hyperbolicity conditions for the 2D BJT are checked with MC simulations, and finally, in Section 6 conclusions are drawn.

2. Physics and basic equations

A fundamental component in most integrated circuits is the BJT, which is an active three-terminal device that can be used as amplifier or switch. This transistor consists of a layer of p-type silicon (called base) sandwiched between two layers of n-type silicon (called emitter and collector). In this case it is referred as an

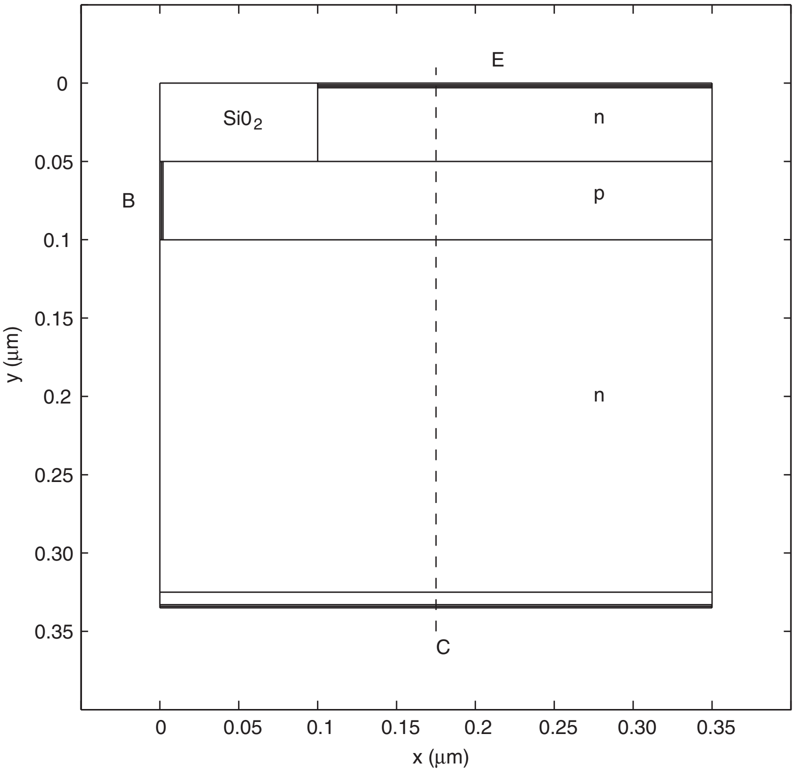

Fig. 1. Cross-section of the npn BJT used in the simulation. The electrical contacts are marked with thick lines. The different doping regions of the device are labelled by n and p. The dashed line is the cross-section at $x = 0.175\,\mu\text{m}$.