Heat generation in silicon nanometric semiconductor devices

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Summary. This paper is concerned with electron transport and heat generation in nanometric silicon semiconductor devices. An improved Monte Carlo method has been used, with the aim to reduce statistical fluctuations. Simulation results are presented for a 2D MOSFET device.

1 Introduction

In nano-devices the presence of very high and rapidly varying electric fields is the cause of thermal heating of the carriers and the crystal lattice. In fact, the external electric field transfers energy to the electrons and in turn to the lattice through the scattering mechanism. This self-heating process can influence significantly the electrical behaviour because the dissipated electrical energy causes a temperature rise in the device resulting in increased power dissipation. Power dissipation limits the performance of electronics from handheld devices ($\simeq 10^3$ W) to massive data centers ($\simeq 10^9$ W), all primarily based on silicon micro/nanotechnology [2].

In a diffusion-like regime, where the charge carriers are in thermal equilibrium with the lattice, there are small temperature gradients, and the device length is much larger than the phonon mean free path, the electro-thermal transport can be described accurately using the non isothermal drift-diffusion model [9]. Here the classical drift-diffusion equations are coupled with the Fourier law via the heat generation rate term

$$H_D = \mathbf{J} \cdot \mathbf{E} + (R - G)(E_G + 3k_B T) \tag{1}$$

where the cross product of the electric field ($\mathbf{E}$) and the current density ($\mathbf{J}$) represents the Joule heating, and the second term represents the heating rate due to the generation-recombination processes. But this field-dependent method does not give accurate for nanometric devices, where the regime is ballistic [2]. The mechanism through which lattice self-heating occurs is that of electron scattering with phonons, and therefore a model which deliberately incorporates all scattering events will also capture such energy dissipation details. The Monte Carlo method originally developed for studying hot electron effects, is also well-suited for computing a detailed picture of energy dissipation. In this case, the distribution of the heat generation rate is determined by counting the number of phonon emission and absorption events that result from electron-phonon scattering processes within the simulated region [3–5, 8]. This *counting estimator* writes

$$\left\langle H^C \right\rangle (x,y) = \frac{n}{N_p \Delta t} \sum_j \hbar\omega_j \left[C_j^+ - C_j^- \right] \tag{2}$$

where n is the electron density, N_p is the particle number in the (x,y)-cell, Δt is time interval in which the counting is made, $\hbar\omega_j$ the energy of the exchanged phonon, and C_j^+, C_j^- are the numbers of the j-th phonon emitted and absorbed respectively.

This counting method is a more fundamental approach, as it calculates power dissipation directly from the number of phonon emissions and absorptions. Furthermore, the method allows the investigation of the relative contribution of different phonon types to heat dissipation, which is not possible with most other methods. The main drawback of this method is the computational effort, because the estimator (2) is very noisy. In a recent paper [1], we have proposed a new estimator for the heat generation rate, which is based on the integrated probability scattering for the i-th phonon, i.e.

$$\lambda_i^{\pm}(\varepsilon, T_L) = \int w_i(\mathbf{k}, \mathbf{k}', T_L) d\mathbf{k}' \tag{3}$$

where ε the electron energy, T_L is the lattice temperature, w_i is the electron-phonon scattering rate,and + means emission of a phonon whereas - absorption of a phonon. The *integrated probability estimator* is

$$\left\langle H^F \right\rangle (x) = \frac{n}{N_p} \sum_{i=1}^{N_p} G(\varepsilon(\mathbf{k}_i)) \tag{4}$$

where

$$G(\varepsilon) = \sum_j \hbar\omega_j \left[\lambda_j^+(\varepsilon) - \lambda_j^-(\varepsilon) \right] \quad . \tag{5}$$

2 Simulation results

A npn silicon MOSFET is simulated via the Monte Carlo method to provide the heat generation rate. The MOSFET domain is 480 x 240 nm (see [6] for geometric details). The source/drain regions have a uniform n-type doping of 10^{18}cm^{-3}, the substrate a uniform p-type doping of 10^{14}cm^{-3}, and the gate oxide

is 40 nm thick with a gate length of 160 nm. The bias voltages applied are V_s=0, $V_g = 0.4$ V, $V_d = 1$ V. We have considered quasi-parabolic band approximation, scattering with acoustic phonons (in the elastic approximation) and optical phonons. The Monte Carlo device simulation is marched at a time step of 0.2 fs to steady state with 200,000 particles considered in the simulation. Once steady state is reached, statistics of electron-phonon scattering are collected over a time period of 5 ps. The results obtained by the integrated probability estimator (4) shown in the figure 1, have significantly lower fluctuations compared to those obtained by the counting estimator (2), plotted in the figure 2. Consequently a more efficient evaluation of the heat generation rate can be achieved using the new estimator (4). Moreover, the heat generation rate can

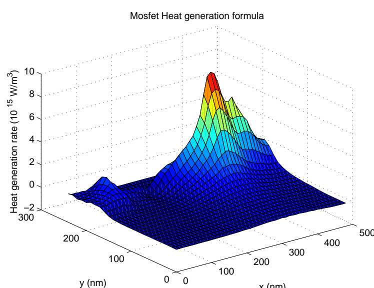

Fig. 1. Heat generation rate in the device obtained with the integrated probability estimator (4).

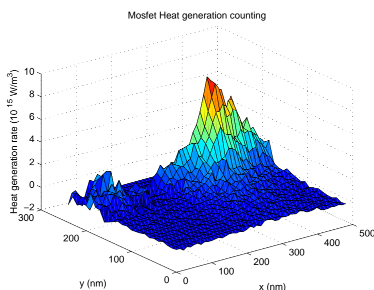

Fig. 2. Heat generation rate in the device obtained with the counting estimator (2).

be used to evaluate correctly the drain resistance in the device [7].

Acknowledgement. This work has been supported by Università degli Studi di Catania, by MIUR PRIN 2009 ”Problemi Matematici delle Teorie Cinetiche e Applicazioni”, and the CINECA Award N. HP10C3U0CA 2011 for the availability of high performance computing resources and support.

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