Control over Power Dissipation through the use of Many-body Coulomb Correlations

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INTRODUCTION

Power dissipation constitutes a major constriction in modern and future nanoelectronic design. In this context, predictive models elucidating new criterions to control Joule heating would be extremely valuable. In this work we demonstrate that an accurate formulation of the many-body Coulomb correlations among carriers could lead to new perspectives on the design of power-optimized electron devices.

DOES MANY-BODY CORRELATIONS AFFECT THE ELECTRIC POWER?

Most electron transport models assume electron-phonon interaction as the only mechanism of energy transfer among the different degrees of freedom that form the device active region. Therefore, in ballistic scenarios, energy is considered to be a constant of motion for each electron. In consequence, the rate of kinetic energy gained by all carriers along the active region (which will be ultimately transferred as heat at the reservoirs) is:

$$\langle P(t)\rangle = \langle I\rangle \langle V\rangle\,, \qquad (1)$$

being $\langle I\rangle = I$ the average current and $\langle V\rangle = V$ the applied bias in the active region [1]. However, while shrinking device dimensions reduces the number of collisions with phonons, the closer proximity of high-density of carriers at source, drain, and gate regions unavoidably increases the strength of carrier-carrier interaction so that reaching ballistic transport may remain unattainable [2]. In this context, energy of a single carrier is no longer a constant of motion even if their mean-free path is larger than the device active region. Thus, the rate of gain of the kinetic energy in the (open) active region is no longer given by Eq. (1). Certainly, the Coulomb interaction is a conservative force that cannot generate or dissipate energy in the whole (active region, reservoirs, gates,..) circuit, but this is not true for the active region alone. Thus, in principle, one can use Coulomb correlations to manipulate the way in which all carriers distribute their kinetic energy among the different parts of the circuit.

ELECTRIC POWER COMPUTATION IN CORRELATED OPEN SYSTEMS

In order to identify which are the effects that carrier-carrier interactions introduce on the computation of electric power, we switch-off electron-phonon interaction in the simulation done in the nano-resistor of Fig. 1. Then, the time derivative of the work done by a (self-consistent) electric field over $N(t)$ carriers inside the active region is directly related to the rate at which these carriers gain or loose kinetic energy. For classical or quantum (under a hydrodynamic formulation[3]) particles, the mean value of the electric power can be then written, under a classical or quantum many particle formulation[4], as:

$$\langle P(t)\rangle = \sum_{i=1}^{N(t)} q_i \left\langle \vec{v}_i\,(t)\,\vec{E}_i\,(t)\right\rangle, \qquad (2)$$

Expression (2) becomes different from (1) when there are correlations between $\vec{v}_i\,(t)$, the (Bohmian) velocity of the $i-th$ electron, and $q_i\vec{E}_i\,(t)$, the electrostatic force induced by the rest of electrons on it. See Fig. 2 and 3 for single-particle (i.e ballistic) and many-particle[4] simulations. Although in expression (2) only the correlation among the electrons in the open active region appears explicitly, the effect of the electrons in the leads and reservoirs appears implicit through the boundary conditions use when computing the electrostatic force [5]. It can be seen in Figs. 4 and 5 that power dissipation

can be redistributed in the different parts of an electron device, by a proper design of the device electrostatics.

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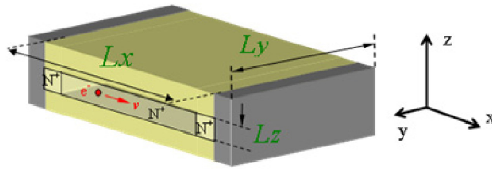

Fig. 1. Schematic picture of a simulated Silicon nanoscale resistor. $N^{+} = 6.25e^{18}, L_x = 10nm, L_y = 30nm, L_z = 30nm$

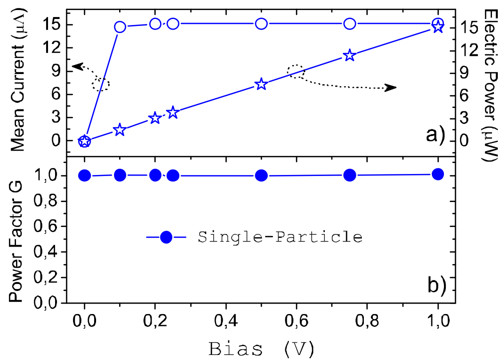

Fig. 2. (a) Monte Carlo single-particle (i..e ballistic) simulation of the Silicon nanoresistor of Fig. 1. (b) The parameter G is the quotient of Eq. 1 over Eq. 2. The consumed electric power in the open active region is exactly equal to the product IV given by Eq. 1.

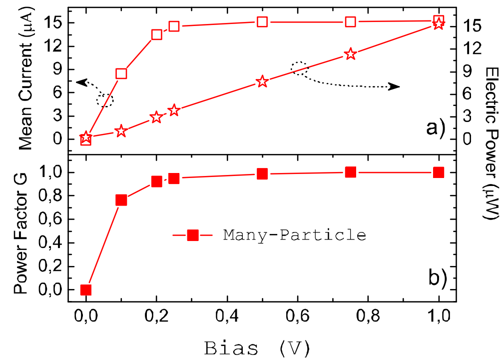

Fig. 3. (a) Monte Carlo many-particle simulation of the Silicon nanoresistor of Fig. 1. (b) The parameter G defined in Fig. 2. Electric power is no longer IV in the open active region but depends on carrier-carrier correlations. The standard IV is only recovered at high applied bias.

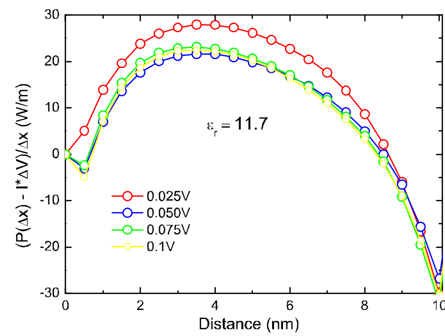

Fig. 4. Difference between Eq. 2 and Eq. 1 along the x direction for different bias. Carrier bunching in the active region causes a positive discrepancy, while the contrary happens in presence of antibunching dynamics.

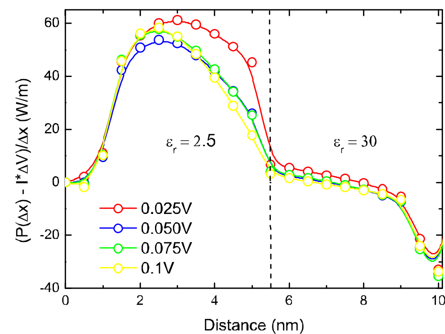

Fig. 5. Difference between Eq. 2 and Eq. 1 along the x direction for different bias. The manipulation of the active region electrostatic parameters (electrostatic parameters) increase bunching and antibunching dynamics. The discrepancy between Eq. 2 and Eq. 1 can be manipulated.