Towards Power Optimization in Nanoscale Systems through the use of Many-electron Correlations

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Power consumption is one of the main drawbacks that electronics must face up to when scaling down any new technology. Thus, in last few years, the electronic development is being driven not only by the desire of improving circuit density and speed, but also by the aim of reducing power consumption. During last years, the ITRS is being identifying this last constraint as one of the top three overall challenges for the next years [1].

The openness of classical and quantum electron systems has been studied extensively in the literature, but few works are devoted to discuss its effect on the computation of electric power. Here, we provide a novel expression for the accurate estimation of the electric power in nanoscale open systems deduced from a many-particle electron transport formalism that goes beyond the standard mean field approximation [2,3]. Surprisingly, we show that the usual expression of the electric power in the device active region,

$$P_{no-corr} = \langle I\ t \rangle_T \langle V\ t \rangle_T , \tag{1}$$

written as the product of the (time-averaged) current $\langle I \rangle_T$ through the device and the voltage $\langle V \rangle_T$ drop there, is not fully appropriate when referring to open systems with (time-dependent) correlations beyond the mean field. When such correlations are taken into account, a much more complex recipe is needed for the computation of the electric power of the electrons in the active region. This new receipt opens the path to an original use of the electron correlations to manipulate the way energy is dissipated in different regions of a circuit.

In order to provide a common classical and quantum language for our argumentation, we formulate the problem in terms of the correlation between the (Bohm or classcial) velocity of the *i* electron $\vec{v}_i\ t$ and the electrostatic force $q_i \vec{E}_i\ t$ made by the rest of electrons of the whole (closed) system on it [3]. We use the Bohm approach for extending also our results towards quantum mechanics for a non-relativistic (spinless) Coulomb-interacting electrons system [2-4]. It can be then shown that the mean electric power, P_{corr}, corresponding to the *N(t)* electrons comprised in the open system of figure 1 reads:

$$P_{corr} = \sum_{i=1}^{N\ t} q_i \langle \vec{v}_i\ t\ \vec{E}_i\ t \rangle_T , \tag{2}$$

Let us notice that although the electric power defined in (2) refers only to those electrons enclosed in the open system, its value is crucially affected by all the *M* particles composing the whole closed circuit (see Fig. 1a.). Since energy is continuously entering and leaving an open system through the interaction among carriers inside and outside its spatial limits, it is of critical importance to properly model the boundary conditions through which the dynamics of electrons within and outside the open system become correlated [4] (see Fig. 1b.). In addition, it is important to remark that it can be shown that overall energy conservation requirements for the whole (reservoirs plus active region) system states that expression (1) gives the correct value for overall power consumption in the whole circuit. In summary, electron-electron correlations play a crucial role in the conservation of the energy in the whole (reservoirs, active region) system and also on its consumption on each of its parts.

With the aim of highlighting the influence of the electron many-particle correlations in the value of the electrical power, we define the correlation power factor as the following (dimensionless) parameter

$$G = P_{no\_corr} / P_{corr} = \langle I \rangle_T \cdot \langle V \rangle_T / P_{corr} , \tag{3}$$

Expression (3) represents the “unexpected” effects of the many-particle correlations on the electric power in open systems. As it will be shown below, by switching off the Coulomb interaction among electrons we immediately recover the standard expression (1) of the power consumption, i.e. $G = 1$.

In order to numerically demonstrate the above results, we have simulated a nanoscale resistance using, both, a standard single-particle Monte Carlo simulator and a many-particle electron transport approach explained in Refs. [2-4]. In Fig. 2a, we have represented the current-voltage characteristic for a nanoscale resistance using a single-particle (i.e. time-independent electric-field) electron transport approach. As expected, the value of G reduces to unit, indicating that many-particle Coulomb-interaction effects in the power computation are not accessible with single-particle electron transport simulations (Fig.2b). On the contrary, when the many-particle electron transport formalism explained in Refs [2-4] is used, the relevance of correlations in the average power becomes evident (at low bias) in the correlation power factor G depicted in Fig. 3b (see also Fig. 3a). Preliminary results corresponding to double-gate field effect transistors can be also found in Ref. [5].

In this work, we have shown that the expression (1) of electric power consumption is valid when describing the whole (reservoir and active region) circuit consumption. However, the consumption of each (open) part composing it has to be computed according to expression (2). This result opens a new path toward the manipulation of energy consumption in different parts of a circuit by accelerating or slowing down carrier dynamics there through the control of electron-electron correlations.

References:

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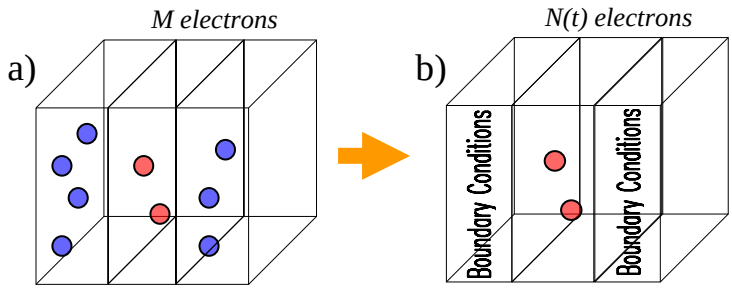

Fig.1. Schematic representation of the electrons in an electron device. a) A closed (whole) system of *M* electrons in the active region and the reservoirs and b) the open system of *N(t)* electrons in the active region.

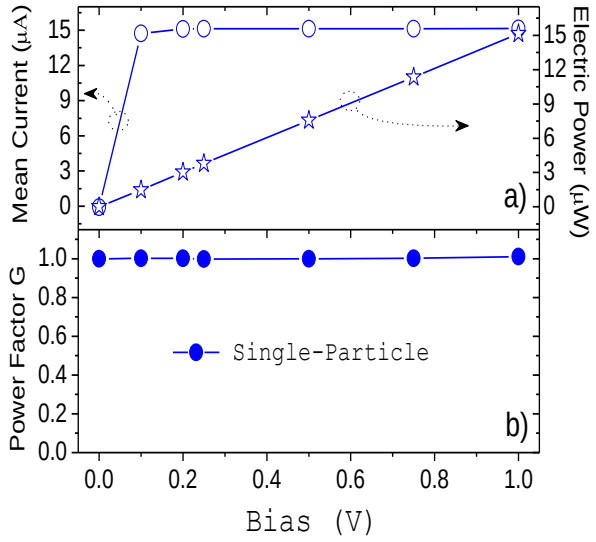

Fig.2. a) Average current, electric power, and b) correlation power factor, G, defined in the text as a function of bias. Electron transport is computed from a single-particle approach.

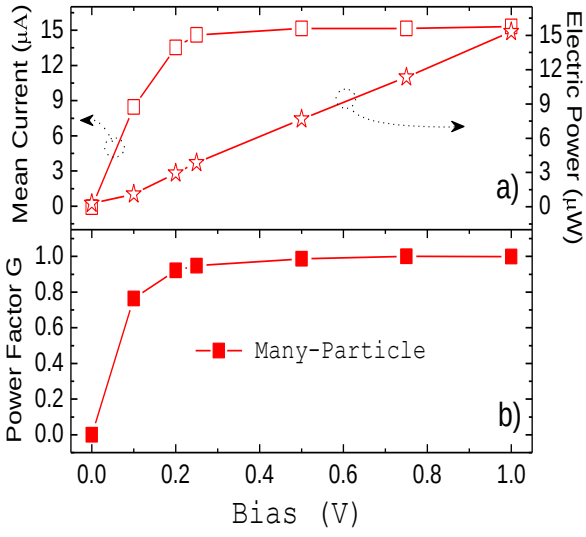

Fig.3. a) Average current, electric power, and b) correlation power factor, G, defined in the text as a function of bias. Electron transport is computed from the many-particle approach described in [2-4].