On the weak measurement of the electrical THz current: a new source of noise ?

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I. INTRODUCTION

What does it mean measuring the electrical current at Tera Hertz (THz) frequency? Answering this questions is not easy neither from an experimental nor theoretical point of view. At such frequencies, the displacement current (time-dependent variations of the electric field) becomes even more important than the conduction (particle) current. For semi-classical electron device simulations, it is assumed that the interaction with an external measuring apparatus does not alter the properties of the system itself. On the contrary, for rigorous quantum device simulations, one must take into account the effect of the measuring apparatus on the measured system (the quantum device evolves differently if the system is measured or not!).

The traditional procedure to describe the interaction between a quantum system and a measuring apparatus is by *encapsulating* through a non-unitary operator. However, *which is the operator that determines the (non-unitary) evolution of the wave function when measuring the electrical THz current? Is it "continuous" or "instantaneous"? with a "weak" or "strong" perturbation of the wave function?*[1] To the best of our knowledge, no such THz-total-current operator has been presented.

In this conference we will discuss a present an original and accurate modelization for the quantum measurement of the total (conduction plus displacement) current at THz frequency. We will consider the interaction between the electrons in a metal surface, working as a sensing electrode, and the electrons in the device active region. We will show that the measurement of the THz current is weak (in the sense of Aharonov *et al.*[2]), implying a small perturbation of the quantum system and a new source of noise[3].

II. A NOVEL QUANTUM APPROACH TO INCLUDE THE THZ MEASURING APPARATUS

The interaction between the quantum system and the measuring apparatus is studied here through quantum (Bohmian) trajectories, without the need of postulating an operator. In principle, we need to consider all the particles of Fig. 1 a). However, because of the large distance between the system and the ammeter, we consider only the interaction between the particle x_1 belonging to the quantum system, and the near electrons, $\mathbf{x}_2, ..., \mathbf{x}_N$, in the metal surface S_m (see Fig. 1 b)). Therefore, we compute the total current on the surface S_L, while the rest of not simulated particles, which do not have a direct effect on the back-action suffered by the particle x_1, are the responsible of translating the value of the total current on S_L until the ammeter. The conditional (Bohmian) wave function[4] of the system (i.e. the wave function of the quantum subsystem in the active region of the device) provides an excellent tool to numerically computing the interaction between the particles plotted in Fig. 1 b). Under the approximation reported in Ref. [5], the conditional (Bohmian) wave function evolves as

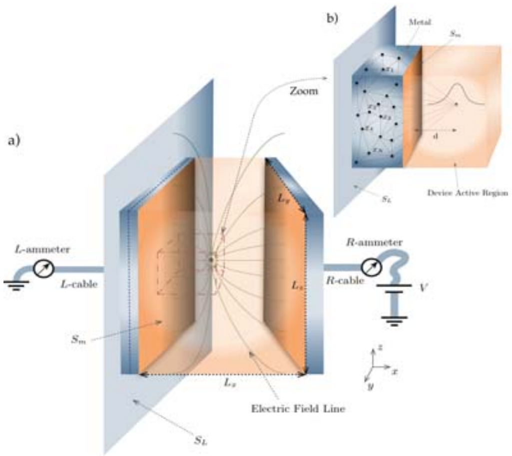

FIG. 1. a) Schematic representation of a two terminal device. The ideal surface S_L collects all the electric field lines. b) Zoom of the red region in Fig. 1 a). It is schematically depicted the coulomb interaction (red dashed lines) and the conditional wave function (black solid line) defined in Eq. (1).

$$i\hbar \frac{\partial \psi(x_1, t)}{\partial t} = [H_0 + V]\, \psi(x_1, t), \tag{1}$$

where $V = V(x_1, \mathbf{X}_2(t), ..., \mathbf{X}_N(t))$ is the conditional Coulomb potential felt by the system and H_0 is its free Hamiltonian. With capital letter, we denote the actual positions of the (Bohmian) particles. The total current, $I_T(t) = I_p(t) + I_d(t)$, is composed by the displacement component $I_d(t)$ plus the particle component, $I_p(t)$, defined as the net number of electron crossing a surface S_L. For simplicity, we shall focus only on the displacement component of the total current (no electrons crossing the surface where the current is measured). So, $I_d(t)$ can be computed as the time derivative of the flux F of the electric field $\mathbf{E}(\mathbf{r}, t)$ produced by all N electrons (system *plus* metal) on the large ideal surface S_L using the relation:

$$I_T(t) = \int_{S_L} \epsilon(\mathbf{r}) \frac{d\mathbf{E}}{dt} \cdot d\mathbf{s} = \sum_{i=1}^{N} \nabla F(\mathbf{X}_i(t)) \cdot \mathbf{v}_i(t), \tag{2}$$

where the flux F depends on each electron position and $\mathbf{v}_i$ is the Bohmian velocity.[3,6] From the numerical simulation, we see that the quantum system is only slightly affected by the interaction with the electrons in the metal.[3] On the other hand, in Fig. 2, we show that the instantaneous current measured in the surface S_L when considering the contribution of all the electrons in the metal or when considering only the electron in the device active region, i.e. without including the apparatus, differs considerably. The large fluctuations in the current reported in Fig. 2 means an additional source of noise due to the interaction of the electrons in the metal with the particle x_1 in the active region of the device (it can be seen as the unavoidable effect of plasmons in the sensing electrodes).

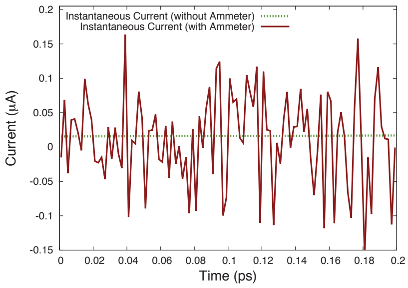

FIG. 2. Value of the total current. With solid line is reported the instantaneous value of the total current calculated from Eq. (2) (with ammeter) and with dashed lines obtained from a mean field simulation for particle x_1 alone (without ammeter).

III. WEAK MEASUREMENT

The measurement scheme present in Sec. II, implies that when the information of the measured total current is very noisy, the quantum system is only slightly perturbed, and vice versa.[3] This fact is completely in agreement with the fundamental rules of quantum weak[2] measurement: if one looks for precise information, one has to pay the price of perturbing the system significantly (the so-called collapse of the wave function). On the other hand if one does not require such a precise information (for example, the instantaneous value of the total current seen in Fig. 2) one can leave the wave function of the system almost unaltered[2]). Repeating many times the same (numerical) experiment the mean value of the (weak) measured total current computed from Eq. (2) is equal to the value obtained without considering the ammeter. See Fig. 3. Thus, we show that the measurement of the high-frequency current is weak in the sense of Aharanov *et al.*[2].

IV. CONCLUSIONS AND DISCUSSIONS

In this work, we have studied the quantum backaction associated to the quantum measurement of the THz electrical current of electronic devices. According to our analysis, when a large fluctuation in the current appears, the measurement of the THz current implies a slightly perturbation of the quantum system, and vice versa. Additionally, we have also shown that the mean value obtained from repeating many times the same experiment provides the strong value of the measurement. Therefore, we conclude:

- The measurement of the total current in a quantum device at THz regime is a *weak measurement*.[2]
- The weak measurement implies that another source of noise needs to be considered when predicting high frequencies quantum transport.

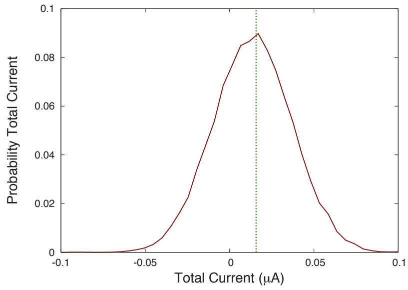

FIG. 3. Red solid line probability distribution of the measured total current from Eq. (2) in a time interval $T = 0.2$ *ps* of the simulation from 39000 experiments. Green dashed line mean value obtained form a mean field simulation.

Finally, it should also be mentioned that the weak measurement of the total current at high frequency opens a new path for envisioning experiments for reconstructing (Bohmian) trajectories and wave function in solid state systems, similar to those already performed for photons.[7]

ACKNOWLEDGMENTS

Work supported by the "Ministerio de Ciencia e Innovación" through the Spanish Project TEC2012-31330 and by the Grant agreement no: 604391 of the Flagship initiative "Graphene-Based Revolutions in ICT and Beyond". N. Z. is supported in part by INFN.

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