Frequency-dependent shot noise in single-electron devices interpreted by means of waiting time distributions

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I. INTRODUCTION

Silicon quantum dot (QD)-based single-electron devices, in particular single-electron transistors (SETs), can now operate at room-temperature, thanks to the recent progress in nanofabrication techniques, scaling QDs down to 5 nm[1], then paving the way to various applications for logic or memory circuits, or random number generator.

Meanwhile, the detection of single-electron processes is available experimentally thanks to quantum point contacts, giving access to current fluctuations[2]. In particular, interests are focused on the shot noise (SN), consequence of charge granularity, that gives more information about electronic transport, thus has been intensively studied during the past decades[3]. The SN is often characterized by the ratio of the current spectral density of the device $S(f)$ to the spectral density of a Poissonian process $2qI$ where I is the mean current. At zero-frequency, the ratio $F = S(0)/2qI$ is called Fano factor. Most of the theoretical studies of the SN are performed at zero-frequency, using the full counting-statistics tool (FCS), which calculates current-correlations from probability distributions of number of electrons transferred during a long period of time[4]. For example, it has been shown that in a case of a multi-level QD, the noise can be enhanced up to super-Poissonian noise[5] ($F > 1$).

The time- and frequency-dependent SN, through autocorrelation functions (AFs) and current spectral density respectively have been less explored. Recently, a new method emerged called waiting time distribution (WTD), focusing on the distributions of times between two single-electron events[6].

The aim of this work is to present the close link between WTDs and AFs, thus the current spectral densities in a Si-QD-based double-tunnel junction (DTJ), shown in Fig. (1), in order to understand the specific dynamics of the electronic transport in this device. The structure is simulated through the homemade 3D self-consistent code SENS[7] (Single-Electron Nanodevices Simulation).

II. SENS CODE

To take into account the quantization effects in Si-QD, the first stage of the simulation relies on the calculation of the electronic structure of the QD according to the bias voltage and the number of electrons inside it by solving the Poisson-Schrödinger coupled equations within the Hartree and effective mass approximations.

The resulting wave functions are then used to compute the tunnel transfer rates source-to-dot $\Gamma_{in}(N)$ and dot-to-drain $\Gamma_{out}(N)$ depending on the number of electrons N in the QD by means of the Fermi golden rule and Bardeen formalism.

Finally, the transfer rates are introduced in analytic expressions or a Monte-Carlo algorithm to reach all electrical characteristics, such as current, AFs and current spectral densities. The WTDs are also obtained from tunnel transfer rates.

III. RESULTS AND DISCUSSION

The simulated DTJ consists in an 8-nm-diameter Si-QD; with source and drain tunnel barriers of 1.2 nm and 1.8 nm thicknesses, respectively. The current and Fano factor, F, are shown in Fig. (2). The current shows a positive differential conductance in the first two Coulomb stairs, while a negative differential conductance is observed in subsequent stairs. F decreases on the two first stairs, reaching its minimum just before the third step, and then increases until reaching its maximum value at the beginning of the fourth step. The behavior of the current and F are explained in previous articles[7,8].

The current spectral densities for three different regimes (sub-, super- and Poissonian Fano factor) as well as their corresponding autocorrelation functions are plotted in Fig (3) and (4), respectively. In the case of a super- (sub-)Poissonian Fano factor, the spectral density remains higher (lower) than the Poissonian spectral density $2qI$ with frequency, which is the consequence of an always positive (negative) AF with time lag. However, we notice that in the case of a Fano factor slightly higher than 1, the spectral density goes below the Poissonian value in the [10^6 10^7] frequency range, thus indicating specific dynamics. This peculiar behavior is also noticeable on the corresponding AF, the correlation going from negative to positive values before reaching the uncorrelated value.

This specific dynamic occurs in the third step of the Coulomb staircase ($V = 0.95$V), i.e., when 4 states are available (0, 1, 2 or 3 electrons in the dot). To clarify the understanding of this behavior around Poissonian SN, we have simulated the same device with only 3 states available. In this case, looking at the source junction, only two tunnel events are adding one electron in the QD: the transitions $0\rightarrow1$ (01) and $1\rightarrow2$ (12). In Fig. (5), the WTDs and auto- and cross-correlations between those two tunnel events are shown. We see that the autocorrelation of (12) events $C_{12\text{-}12}$ is responsible of the behavior global autocorrelation C_{II}. At low times, the WTD between two 12 events is zero, due to the fact that another transition (21 – the second electron is exiting the QD through the drain junction) is necessary to reach an other (12) event. Therefore, it is very unlikely to have two (12) events within such low time lag, and $C_{12\text{-}12}$ is negative. Then, the AF increases with its corresponding WTD, and eventually reaches positive value around the maximum of WTD. The WTD and AF decrease then accordingly, to finally reach the uncorrelated value.

ACKNOWLEDGEMENTS

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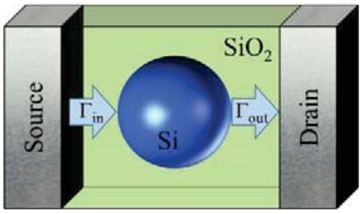

FIG .1. Schematic view of a DTJ.

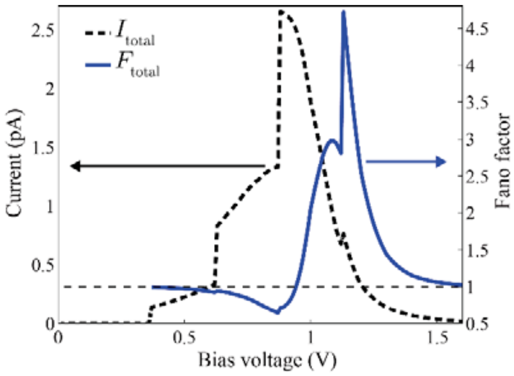

FIG. 2. Current (dashed) and Fano factor (solid) as a function of the applied voltage.

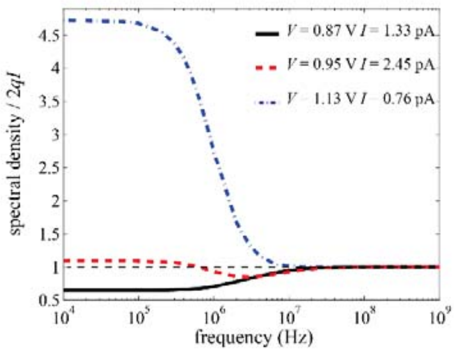

FIG. 3. Current spectral density as a function of frequency for three different biases corresponding to different transport regimes.

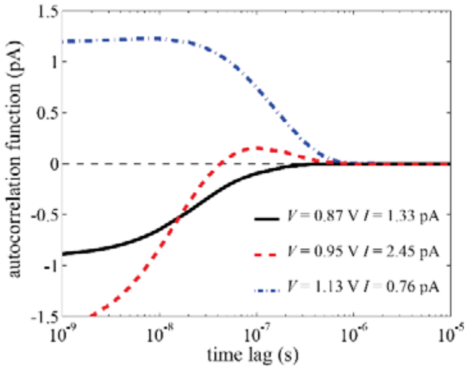

FIG. 4. Current autocorrelation functions as a function of time lag for three different biases corresponding to different transport regimes

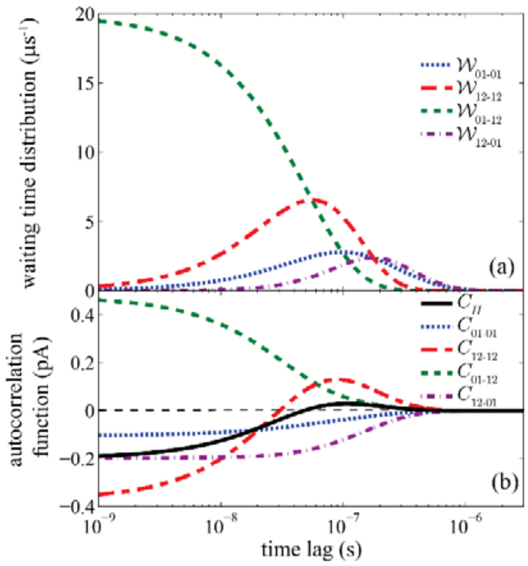

FIG. 5. (a) WTDs and (b) Auto- and cross-correlation functions between (01) and (12) current pulses as a function of time, for a bias corresponding to Poissonian Fano factor $F \sim 1$ in the 3-state case.