Shot noise behavior in single-electron quantum dot-based structures

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As a direct consequence of the granularity of charge, shot noise (SN) has an important role in nanodevices. It has been studied intensively in various mesoscopic systems during the last two decades [1]. Its behavior provides additional information on the transport regime, not accessible through conductance measurements.

The Fano factor characterizes the fluctuations of a transport process, and is defined as the ratio of the variance and the average of the number of events in a given time. It measures the deviation of the SN from the poissonian noise. If $F = 1$, the transport is poissonian, if $F < 1$ (> 1), the transport is sub-(super)poissonian.

In this work, we have studied the SN behavior of Si QD double tunnel junctions (DTJs) using our simulator SENS for quantum dot-based single-electron devices [2]. The first calculation step is the self-consistent solution of 3D Poisson/ Schrödinger equations. The resulting wave functions are used to compute the bias-dependent tunneling rates. Then, we can use either the master equation or the Monte-Carlo (MC) method to determine the current and the Fano factor.

Korotkov has derived the master equation to obtain a general expression for the spectral density of current fluctuations, at zero frequency $S(0)$ [3]. Its comparison with the spectral density $2e\langle I\rangle$ of a system with uncorrelated events, i.e a Poissonian process, leads to the Fano factor $F=S(0)/2e\langle I\rangle$. This method is fast and exact, but does not offer a transparent understanding of the origin of SN.

The other method consists in using a MC algorithm. On the basis of tunneling rates, the times between two events and the type of events are selected randomly. We can count the number N of electrons that have passed through one tunnel junction during a given simulation time τ_{sim}. By repeating the simulation multiple times, the full statistics on N can be established, as shown in Fig. 1. The comparison with the equivalent Poisson distribution informs us about the transport regime (sub/super/poissonian). The Fano factor is then given by $F=var(N)/\langle N\rangle$.

As one can see on Fig. 2, both methods (MC and Korotkov) are equivalent. One can observe that for this particular device exhibiting a negative differential conductance (NDC) the SN is subpoissonian in the first two Coulomb steps, increases to become super-poissonian in the NDC zone and takes a poissonian form at high bias.

To make clear the explanation of this behavior, we have chosen to limit at two the number of electrons in the dot. There are thus three possible states: (0), (1) and (2). The resulting current and Fano factor are given in Fig. 3, together with the corresponding tunneling rates. Additionally, typical time evolutions of N are plotted in Fig. 4 for the three regimes.

In the sub-poissonian regime (V = 0.50 V), we have $\Gamma_{in}(1) > \Gamma_{out}(1)$ and $\Gamma_{in}(1) \approx \Gamma_{\text{out}}(2)$. Thus the system tends to oscillate essentially between the two states (1) and (2) with equivalent rates to change of state. It is a typical situation of subpoissonian SN. For V = 0.76 V, $\Gamma_{in}(1)$ and $\Gamma_{out}(1)$ are very close, so that all three states are possible, though the average time passed in the different states are not the same. It leads to the superpoissonian SN. At high bias (V = 1.3 V), $\Gamma_{in}(1) << \Gamma_{out}(1)$, which makes the state (2) very improbable. The system oscillates between states (0) and (1) with dissymmetric rates $\Gamma_{out}(1) >> \Gamma_{in}(0)$, which leads to a pure Poissonian behavior.

Finally, the analysis of tunneling rates in different structures allows us to establish the conditions to be met to enhance or reduce the superpoissonian SN in semiconducting DTJs.

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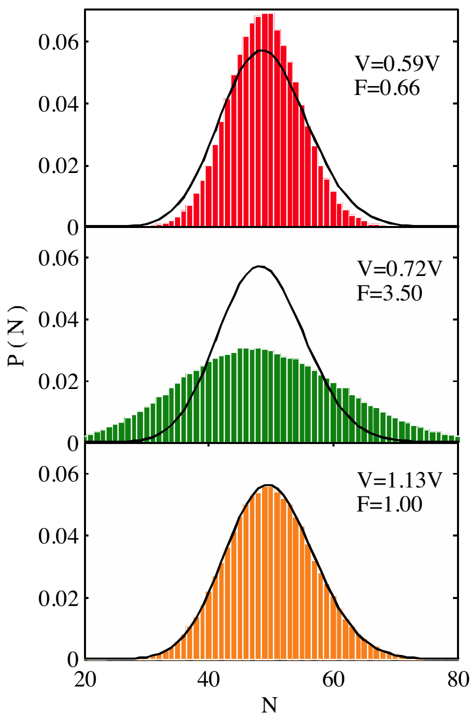

Fig. 1. Statistical distribution of the number of electrons going through one junction, compared to the Poisson distribution corresponding to the mean number of electrons (solid line) for a typical DTJ with dot diameter of 10 nm and barrier thicknesses of 1.2 nm and 1.7 nm.

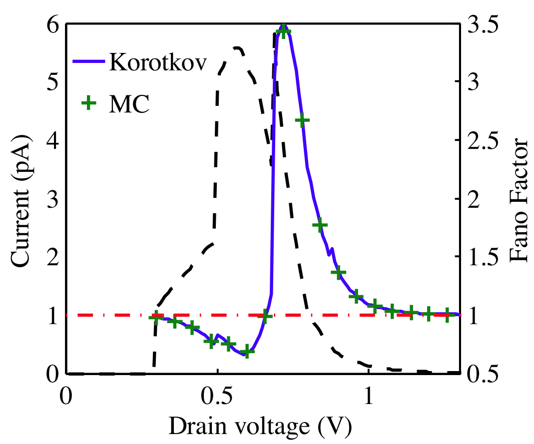

Fig. 2. Current (dashed line) and the corresponding Fano factor obtained by Korotkov's formalism (solid) and Monte-Carlo algorithm (crosses), as a function of drain voltage (same structure as in Fig. 1).

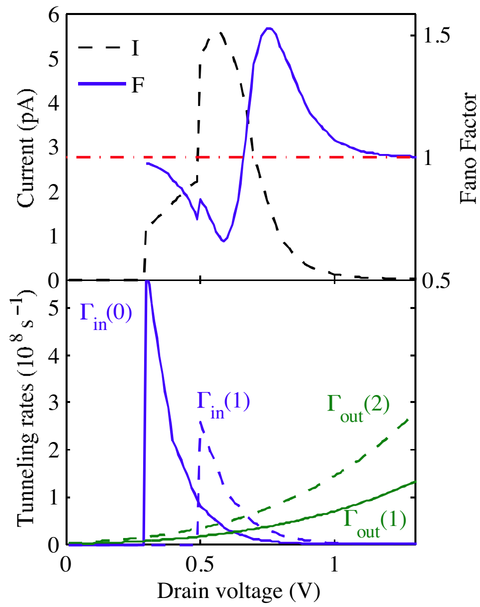

Fig. 3. Monte Carlo Current (dashed line) and the corresponding Fano factor, and tunneling rates, as a function of drain voltage, for a 3-state system.

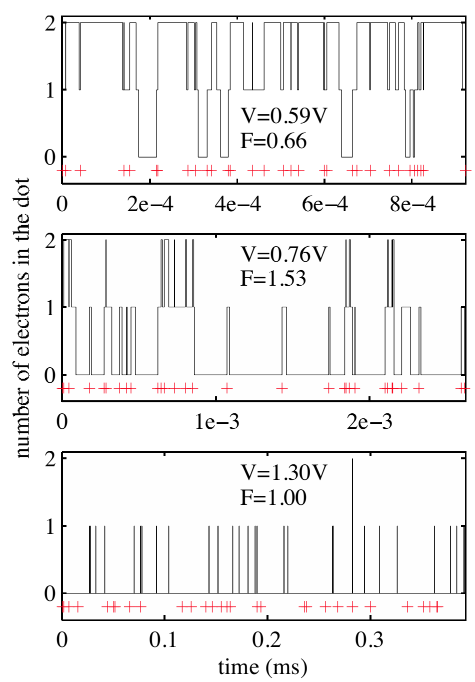

Fig. 4. Time evolution of the number of electrons in the dot for different SN regimes. A single-transmission through the source barrier is symbolized by a cross.