Shot noise enhancement and suppression in systems of coupled quantum dots

M. Gattobigio
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni, Università di Pisa
Giuseppe Iannaccone
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni, Università di Pisa
Massimo Macucci
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica, Telecomunicazioni, Università di Pisa

M. Gattobigio, G. Iannaccone, M. Macucci, Shot noise enhancement and suppression in systems of coupled quantum dots, 16th International Conference on Noise in Physical Systems and 1/f fluctuations, Gainesville, Florida 2001, p.447.

SHOT NOISE ENHANCEMENT AND SUPPRESSION IN SYSTEMS OF COUPLED QUANTUM DOTS

M. GATTOBIGIO, G. IANNACCONE AND M. MACUCCI.

Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Pisa, Via Diotisalvi 2, I-56122 Pisa, Italy

We present the singular noise behavior of bistable systems of coupled quantum dots during switching between the two stable states. Shot noise of the current through different branches of the system can be suppressed and/or enhanced up to a few times the "full" shot level. Results from Monte Carlo simulations and from an analytical model are presented.

1 Introduction

In the search of alternative logic architectures that would overcome the limits of conventional semiconductor technology, several logic circuits based on coupled quantum dots have been proposed. Among them, the Quantum Cellular Automata (QCA) architecture, initially proposed by Lent *et al.* [1], has been the subject of considerable interest, for its distinctive originality.

A QCA cell consists of four metal islands or semiconductor quantum dots located at the corners of a square, as shown in the inset of Fig. 1. Tunneling is allowed only between adjacent dots, i.e. for example between dots 1 and 2, and between dots 3 and 4. When two excess electrons are put into a QCA cell, the electrostatic repulsion causes the electrons to occupy opposite sites. In this way two different logical states can be represented, corresponding to electrons being aligned along one of the diagonals.

A properly working QCA cell switches between the two logical states in response to an external electric field. Detection of QCA operation requires a measurement system capable of detecting a single electron tunneling between two dots. If all the four dots are connected to external leads via tunneling junctions, as represented in Fig. 1, we can allow current to flow between two leads through dots 1 and 2 (current i_D), and through dots 3 and 4 (current i_U), via three tunneling junctions in series. A measurement procedure has been recently proposed which allows to detect cell switching from the correlation between the two currents [2], without the use of single electron detectors, which are difficult to fabricate in semiconductor structures defined by etching.

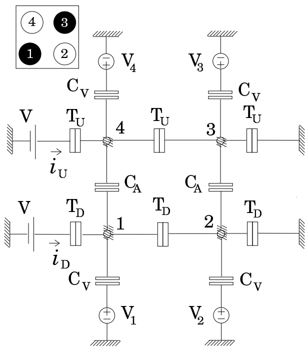

Figure 1. Equivalent circuit of a QCA cell. The inset shows a sketch of a QCA cell where the black dots contain one exceeding electron.

As is well known, noise is a unique probe of the correlated motion of electrons (for a recent review of experimental and theoretic research in that field see Ref. [3]) and can therefore be used to investigate QCA operation from a point of view complementary to that of DC measurements. In this paper we present the noise properties of the currents through the two pairs of dots that form a cell.

In the QCA cell that we are considering the logical state is enforced by means of external gate voltages V_1, V_2, V_3 and V_4. The two source voltages, referred as V in Fig. 1, allow currents i_D and i_U to flow.

For a given control voltage configuration the cell is in one logical state, for instance with the excess electrons in dots 2 and 4 (logical "1"). In this configuration currents i_D and i_U exhibit full shot noise. By varying the control voltages we can drive the cell to switch into the logical "0", where the excess electrons are in dots 1 and 3. In particular, we apply a voltage ramp V_D with a positive slope to dots 2 and 4 and with a negative slope to dots 1 and 3. During the switching we observe a peculiar noise behavior: one current exhibits suppressed shot noise while the other exhibits strongly enhanced shot noise. The enhancement is strongly emphasized at cryogenic temperatures. When the new logical state is reached, shot noise of both currents becomes Poissonian again.

In order to evaluate the shot noise of currents i_U and i_D, we have used the circuit reported in Fig. 1, which is a simplified version of the complete equivalent circuit. The circuit is made up of tunneling junctions T_D in the lower part, with capacitance C_D and resistance R_D, and tunneling junctions T_U in the upper one, with capacitance C_U and resistance R_U. Interaction between the two pairs of dots is introduced by means of the normal capacitors C_A. C_V represents the capacitive coupling with the external gates. In our simulation we have used the following numerical values: $C_U = 0.5$ aF, $C_D = 0.5$ aF, $C_A = 1.2$ aF, $C_V = 0.42$ aF, $R_D = R_U = 5$ MΩ and $V = 2$ mV.

The power spectral density of a real random process $i(t)$ is defined as the Fourier transform of the correlation function

$$S(\omega) = 2\int_{-\infty}^{\infty} dt\, \mathrm{e}^{-i\omega t}(\overline{i(t)i(0)} - \overline{i(t)}\;\overline{i(t)}) \quad . \tag{1}$$

In equation (1) we have used the overline notation to denote *ensemble* averages. In our model the random process is the current that flows through the external voltage source when an electron tunneling event occurs. The expression of this current is $i(t) = \sum_{0\leq t_k \leq \mathcal{T}} \delta q_k\, \delta(t - t_k)$ where δq_k is the charge flowing through the voltage generator at the tunneling event time t_k. The pulse shape can be described as a delta because we are interested only in low frequency noise. $\mathcal{T}$ is the time of observation therefore we will perform the integral in (1) from zero to $\mathcal{T}$. Substituting $i(t)$ into (1) we get the functional expression for the Fano factor γ, i.e. the ratio of the noise spectral density to the *full* shot noise spectral density $2q\overline{i(t)}$

$$\gamma \equiv \frac{S(0)}{2q\overline{i(t)}} = \frac{\overline{\sum_{k,j} \delta q_k\, \delta q_j} - \overline{\sum_k \delta q_k}^2}{q\overline{\sum_k \delta q_k}} \, . \tag{2}$$

In the Monte Carlo simulation for a given voltage configuration we have collected a few thousands time evolutions characterized by a time of observation $\mathcal{T}$. This sample is used to evaluate the averages of (2) and therefore to calculate the Fano factor.

2 Results

Before illustrating what happens when the upper and the lower pairs of dots interact, we consider the case without interaction. Let us concentrate only on the lower pair. We are dealing with a device known as *single electron pump.* In this configuration i_D exhibits suppressed shot noise. The higher i_D, the smaller the Fano factor γ. In Fig. 2 we plot in greyscale the Fano factor of i_D as a function of V_1 and V_2. Dark regions correspond to $\gamma \approx 1$, white regions correspond to smaller γ. As can be seen, the Fano factor reproduces the honeycomb structure well known in the case of the DC current. At the vertices of the honeycomb structures the Fano factor reaches the minimum value of 1/3. For such voltage configurations the chemical potentials of dots 1 and 2 are aligned with the Fermi levels of the external voltage sources. This causes maximum current and maximum suppression of shot noise.

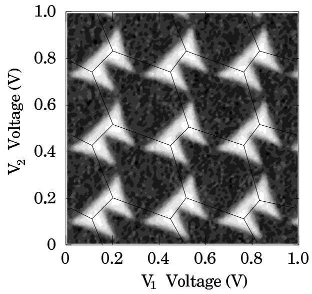

Figure 2. Fano factor γ of a single the electron pump at the temperature of 20 K. Dark regions correspond to $\gamma \approx 1$, bright regions to smaller γ.

When the two pairs of dots interact, there is a positive correlation between i_D and i_U. In Fig. 3 we plot the currents and the associated Fano factor during the cell switch.

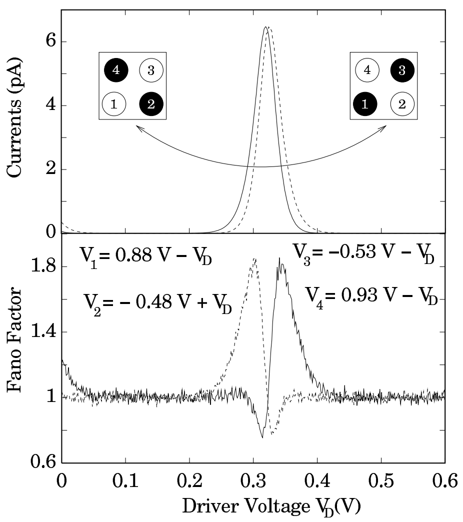

Figure 3. Currents (above) and associated Fano Factor (below) when the cell switches in response to the control voltages, as a function of V_D. Solid lines refer to i_D, dashed lines refer to i_U

As reported in the expressions of the control voltages in Fig. 3, we have applied a little shift of 50 mV between the upper and lower voltage gates. This setup was used in [2] to propose a new method to detect QCA cell operation. With this shift and without the interaction between the two pairs of dots, the lower current peak and the upper one would be well separated. If the interaction is included, we observe a synchronization between the two peaks, as shown in Fig. 3 (a detailed discussion of this *locking* effect is included in Ref. [2]).

The same mechanism that leads to current locking is responsible for the change of the Fano factor. During the switching between the two logical states, the larger current exhibits suppressed shot noise, due to the negative correlation between tunneling events, while the smaller current exhibits strongly enhanced shot noise, since tunneling events become positively correlated. In the case of weak electrostatic interaction, no enhancement is observed.

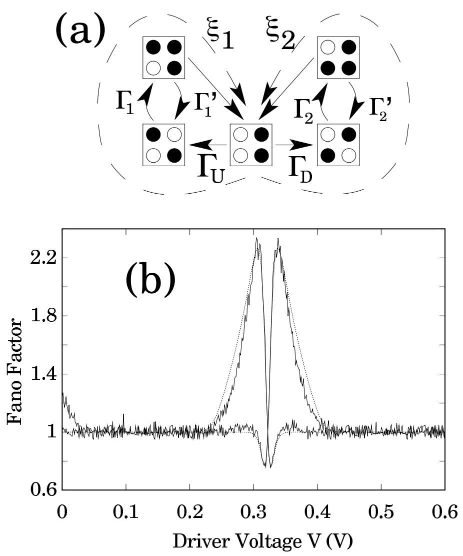

Figure 4. (a) Sketch of the dominant transitions in the zero temperature limit. (b) Comparison of the Fano factor computed with the analytical expression with the results of a Monte Carlo simulation at the temperature of 10 K.

We have also developed an analytical model valid in the zero temperature limit, when only few transitions are allowed. In Fig. 4(a) the relevant transitions are shown along with their rates. In the same figure we have sketched the two *paths* (in the configuration space) that allow current to flow in the upper (path ξ_1) and in the lower (path ξ_2) pair of dots. Following the analysis proposed by Koroktov [4], based on the decomposition of the transport process in simple paths in the charge configuration space, we have obtained the following expression for the Fano factor of the upper (γ_U) and of the lower (γ_D) currents

$$\gamma_U = 1 + \frac{2\Gamma_1}{\Gamma_1 + \Gamma_1'} \frac{1-\delta}{(\delta+\epsilon)^2}\epsilon \qquad (3)$$

$$\gamma_D = 1 + \frac{2\Gamma_2}{\Gamma_2 + \Gamma_2'} \frac{\delta-1}{(\delta+\epsilon)^2}\epsilon\delta \quad , (4)$$

where $\epsilon = \Gamma_D/\Gamma_U$, $\delta = (\Gamma_2 + \Gamma_2')(\Gamma_1 + \Gamma_1')$ and Γ_1, Γ_1', Γ_2 and Γ_2' are the transition rates indicated in Fig. 4(a). The analytical expressions are in very good agreement with the full Monte Carlo simulations at the temperature of 10 K, as can be seen in Fig 4(b).

3 Conclusion

We have described a significant deviation from full shot noise occurring in bistable systems of coupled quantum dots when the system is switched between the two stable configurations. We have predicted an enhancement of shot noise up to a few times the Poissonian shot noise at cryogenic temperatures, and have also proposed a simple analytical model capable of reproducing the noise behavior obtained with complete Monte Carlo simulations.

The authors gratefully acknowledge support from the ESPRIT Project ANSWERS (n. 28667) and from the CNR Nanotechnology project.

References

1. C. S. Lent, P. D. Tougaw and W. Porod, *Appl. Phys. Lett.* **62**, 714 (1993)
2. M. Macucci, M. Gattobigio and G. Iannaccone, *submitted to JAP.*
3. Ya.M. Blanter and M. Büttiker, *Phys. Rep.* **336**, 1 (2000)
4. A. N. Korotkov, *Phys. Rev. B* **49**, 10381 (1994)