Nonequilibrium Carrier Dynamics in Semiconductors, Proceedings of the 14th International Conference, July 25-29, 2005,
Chicago, Series: Springer Proceedings in Physics, Vol. 110
Saraniti, Marco; Ravaioli, Umberto (Eds.), 2006 **PREPRINT**

Super-Poissonian current fluctuations in tunneling through coupled quantum dots

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Summary. The shot noise behavior of sequential tunneling through two vertically coupled quantum dots is studied by means of a master equation approach. In particular, we propose a mechanism to observe super-Poissonian shot noise in such a system. The crucial ingredient is the Coulomb interaction between electrons in individual quantum dots.

The measurement of fluctuations in the current through resonant tunneling devices is a powerful tool to obtain information which is not solely accessible from conductance measurements [1]. For instance, the tunnel barrier geometry or the impact of Coulomb interaction on the transport through single quantum dots (QDs) can be extracted by studying their shot noise properties [2,3]. Here, we consider the tunneling through two vertically coupled QDs. Such a system was experimentally considered with respect to the average tunneling current e.g. in Ref.[4]. Additionally, the shot noise for tunneling through such a self-organized QD stack was recently measured in [5]. In this experiment some indications for super-Poissonian noise in the bias range of current resonances were reported which we theoretically address in this work. We attribute this observation to the effect of Coulomb interaction between carriers in individual QDs. Positive correlations as a consequence of Coulomb interaction were also experimentally found in resonant tunneling diodes [6] or in a single-electron transistor setup [7]. For parallel QDs the emergence of super-Poissonian noise was theoretically examined in Refs.[3,8].

In Fig. 1a the coupled QD system is sketched: QD1 is connected to the (e)mitter contact with rate Γ_e and QD2 is coupled to the (c)ollector contact with rate Γ_c. They are mutually coupled with Γ_i. These rates enter the model which is based on the master equation description elaborately introduced in [9]. Therein the coupling between the QDs is treated within Fermi's golden rule: $\Gamma_i = 4|\Omega|^2/(\Gamma_e+\Gamma_c)$, where Ω denotes the matrix element for tunneling between the QDs. Note that in this description the inter-QD coupling also depends on the couplings to the reservoirs. Even though in this framework any effects due to quantum coherence in the tunneling process are neglected, the average current surprisingly provides full agreement with the coherent result [9]. QD1/QD2 contains one spin-degenerate single-particle state with energy $\varepsilon_1/\varepsilon_2$, respectively. The interaction of electrons inside QD1 and QD2 is described with constant charging energies U_1 and U_2 , respectively. Carriers in different QDs interact via U_{inter} which is assumed to be zero throughout this paper.

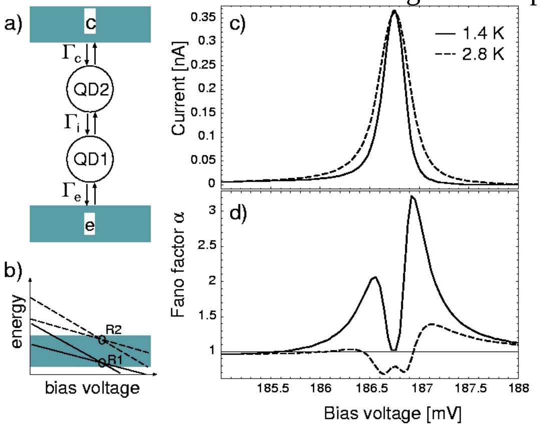

Fig. 1. a) Sketch of the coupled quantum dot system with (e)mitter and (c)ollector contact. b) Resonances of single-particle states R1 and resonances of two-particle states R2. c) Calculated current vs. bias voltage. d) Fano factor vs. bias voltage. Parameters: Γ_e=40μeV, Γ_c=1μeV, Ω=15μeV, $\varepsilon_1(0)$=48meV, $\varepsilon_2(0)$=104.025meV, η_1=0.25, η_2=0.55, $U_1=U_2$=10meV, U_{inter}=0, μ_e=11.7meV, T=1.4K (solid line), T=2.8K (dashed line).

The average current I and the zero-frequency noise S are calculated along the lines of Ref.[3]. The Fano factor as a measure for deviations from uncorrelated tunneling (Poissonian noise) is defined as $\alpha=S/(2eI)$. Then, $\alpha<1$ indicates sub-Poissonian noise corresponding to negative temporal correlations and $\alpha>1$ refers to super-Poissonian noise corresponding to positive temporal correlations or bunching of tunneling events.

The single-particle energies of the QDs depend linearly on the applied bias voltage V as $\varepsilon_{1/2}(V)=\varepsilon_{1/2}-e\eta_{1/2}V$ with the leverage factors $\eta_{1/2}$ for QD1/QD2, respectively. Fig. 1b sketches the energy vs. bias voltage dependence of the single-particle levels (solid lines) and the two-particle states (dashed lines). The shaded region indicates the occupied states in the emitter contact, the chemical potential of collector states is assumed to be energetically much lower. Then, a current is flowing through the QD system if a resonance of states in different QDs exhibits in this energy range. The specific situation depicted in Fig. 1b leads to super-Poissonian noise in the tunneling current: the charging energies of both QDs are assumed to be equal $U_1=U_2$, and the resonances of single-particle states R1 and of the doubly-occupied states R2 are available for emitter electrons.

For this regime the current-voltage characteristic and the Fano factor vs. bias voltage are shown in Fig. 1c and d, respectively. The parameters were estimated with respect to the experiment [5]. Two transport channels R1 and R2 contribute in one current peak. Since R2 lies slightly below the chemical potential in the emitter μ_e the current peak broadens with increasing temperature. In the bias range of the current peak the Fano factor shows an interesting behavior for a temperature T=1.4 K: super-Poissonian noise at the edges of the current peak and almost Poissonian noise at the current peak maximum. For increasing temperature the on-resonance Fano factor becomes sub-Poissonian and the super-Poissonian noise at the edges of the current peak vanishes. This striking temperature dependence is due to the thermal occupancy of the two-particle states (R2).

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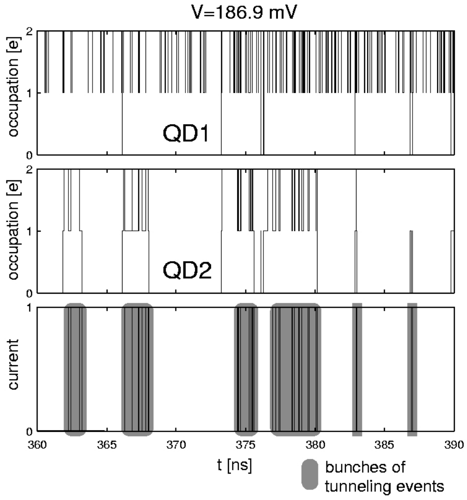

Fig. 2. Monte-Carlo simulation of the occupations in QD1 and QD2 and the electron jumps into the collector (current) for a bias voltage V=186.9mV. Parameters are the same as in Fig. 1.

How can one understand this behavior? For this purpose we look at the time evolution of the occupations in QD1 and QD2 and the current given by the jumps of electrons into the collector. To obtain a realisation for the stochastic process we apply a Monte Carlo simulation with the same parameters leading to the master equation results in Fig. 1c and d (for details of the simulation see [10]). A section of the realisation is shown in Fig. 2 for a bias voltage V=186.9 mV (at the voltage of the right Fano factor maximum in Fig. 1d). The upper graph corresponds to the occupation in QD1, the middle graph shows the occupation of QD2, and the lower graph contains the jumps of electrons into the collector. It can be seen that QD1 is mostly occupied with one electron. Therefore QD1 can easily be occupied with two electrons. Crucial for the occurrence of a tunneling current is the occupation of the single-particle state in QD2. The probability that one electron can enter the single-particle level in QD2 is highest when the levels are aligned which occurs for V=186.75 mV. This becomes apparent in the time series of the QD2 occupation (not shown here) and consequently in the respective current: the tunneling events are statistically distributed and the noise is Poissonian. In contrast, for a slight misalignment of the levels the probability for entering QD2 with one electron decreases. Such events are less frequent now. But, whenever one electron enters QD2 the R2 channel is opened which results in a bunching of tunneling events (shaded regions in Fig. 2). Note that the interaction between carriers in different QDs reduces this bunching effect.

To conclude, we have presented a guideline to observe super-Poissonian noise in tunneling through two vertically coupled QDs. The proposed mechanism is based on the effect of Coulomb interaction between carriers in individual QDs within one QD stack, i.e. the tunneling of electrons through the resonance of single-particle states and the two-particle states at the same bias voltage.

Acknowledgments: We acknowledge helpful discussions with F. Hohls regarding the experiment. This work was supported by Deutsche Forschungsgemeinschaft in the framework of Sfb 296.

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