Noise properties of mesoscopic devices with realistic potential profile

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The influence of disorder in mesoscopic structures on the value of shot noise suppression, i.e. on the Fano factor, has been the subject of significant research effort in the last two decades. Theoretical studies [1], [2], confirmed by numerical studies [3], [4] and experimental mesurements [5], have shown that the Fano factor should assume the value 1/3 if the conditions for diffusive trasport are reached.

This result has been theoretically found also for a series of tunnel barriers, using a semiclassical model [6]. However, using a numerical quantum-mechanical analysis based on a hard-wall approximation for the tunnel barriers, our group has recently found [7] that the 1/3 limit is not reached for a series of unevenly spaced ideal tunnel barriers, due to the presence of strong localization. Here we show that we obtain similar results also in the case of realistic tunnel barriers, since strong localization effects are preserved.

Another intriguing issue in this context is represented by the so-called "direct processes," i.e., events of direct transmission between the entrance and the exit constrictions of the cavity. These non-universal processes are expected to lead to a deviation from the additivity of constriction resistances and to a reduction of shot noise. Here we propose a cavity layout (see Fig. 3) that should allow an experimental verification of the properties of direct processes.

We have considered GaAs/AlGaAs heterostructures with the 2-dimensional electron gas (2DEG) at a depth d from the surface and we have studied devices defined by means of depletion gates in the 2DEG. For a fast but reasonable estimation of the confinement potential at the 2DEG level without solving the complete self-consistent problem (which would involve too heavy a computational burden for large parameter scans), we have used a technique based on the semianalytical evaluation of the potential, with the inclusion of screening from the charge in the 2DEG [8]. To increase the computational efficiency, we have reduced the number of transverse slices used for the discretization by merging adjacent slices with similar potential. Then we have computed the transmission matrix t of the structure using the recursive Green's function technique and we have found the conductance G and the Fano factor γ in the device using the Landauer-Büttiker formalism.

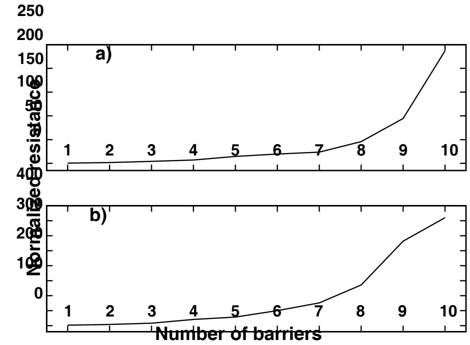

Fig. 1. Normalized resistance as a function of the number of barriers for ideal gates all biased at -0.9 V (a) and for gates with edges roughness biased in a range from -0.5 V to 0.8 V (b).

We show the numerical results we have obtained for a series of realistic tunnel barriers (in this case we have considered $d = 50$ nm). We have first generated the tunnel barriers with ideal 20 nm wide unevenly spaced rectangular gates; the value of each interbarrier spacing has been randomly chosen between 500 nm and 520 nm. In order to obtain an average value, we have repeated our conductance and Fano factor calculations on 50 structures of this kind with different sets of interbarrier spacings and we have averaged over the 50 obtained results. Analogous calculations have then been performed introducing edge roughness in the gates defining the tunnel barriers. In particular, we have considered random deviations from the ideal rectangular shape in a range of $\pm$ 5 nm, with correlations between adjacent deviations, as in actual fabrication procedures. In the upper panel of Fig. 1 we show the results obtained for the resistance of a series of tunnel barriers defined with ideal gates, represented as a function of the number of barriers. In the lower panel of Fig. 1 we show a similar result for the resistance in the presence of edge roughness on the gates defining the barriers. The exponential behavior is a clear evidence of the presence of strong localization in the structure. In Fig. 2 instead we report the behavior of the Fano factor as a function of the number of barriers in the case of ideal gates (solid line) and gates with edge roughness (dashed line). In both cases, no 1/3 limit is observed for this structure and the behavior is quite similar to the one observed for hard-wall tunnel barriers [7].

We have also studied the noise properties of a mesoscopic cavity with tunable openings and gate voltages, the latter being located at different positions of the cavity (see Fig. 3; in this case $d = 70$ nm). We have considered a “depletion” gate located in the upper left corner of the cavity, and a so-called “deflector” gate, located in the middle of the bottom boundary of the cavity. Such a “deflector” gate can disrupt direct processes occurring between the two quantum point contacts. We have first focused on the “quantum” regime, with narrow constrictions that allow propagation of just a few transverse modes ($N \approx 3$). Setting one of the two gates to zero voltage and tuning the other gate away from zero voltage, we have found sligthly increased Fano factors (see Fig. 4): the two gates seemingly play analogous roles here. This behavior can be well understood by considering that in the “quantum” regime direct processes are strongly suppressed, but symmetry considerations become very important. In the “classical” regime of high mode numbers ($N \approx 34$) the situation is quite different. Here we have found that activating the deflector gate systematically increases the noise (from $F \approx 0.14$ to $F \approx 0.22$), both in the case of an active and of an inactive depletion gate (the latter case is shown with the red dashed curve in Fig. 5). On the contrary, varying the depletion gate voltage affects the noise properties of the cavity only slightly (from $F \approx 0.14$ to $F \approx 0.16$) as shown in Fig. 5 (black solid curve). This behavior nicely corresponds to a classical scattering picture in which direct trajectories between the openings are disrupted by the deflector gate but are left unchanged by the depletion gate.

In summary, we have numerically investigated the noise properties of different mesoscopic devices with a realistic potential profile. For a series of realistic tunnel barriers we have found that the strong localization effect is dominant. Finally, for a cavity with different tunable gates, we have investigated the role of direct processes in the “quantum” and in the “classical” regime.

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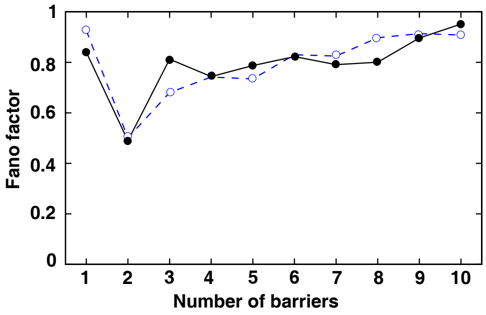

Fig. 2. Fano factor as a function of the number of barriers for ideal gates (solid line) and gates with edges roughness (dashed line).

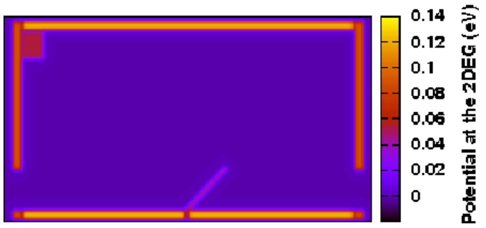

Fig. 3. Potential landscape at the 2DEG level for a mesoscopic cavity with a depletion gate at the upper left corner and a deflector gate in the middle of the bottom boundary of the cavity.

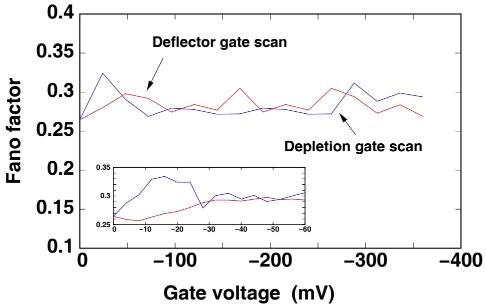

Fig. 4. Fano factor in the “quantum” regime of small cavity openings (split-gate gap: 250 nm). In the inset we show the behavior for small gate voltages.

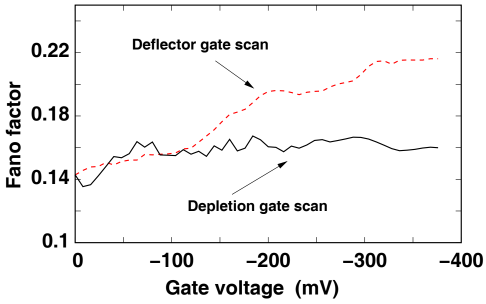

Fig. 5. Fano factor in the “classical” regime of large cavity openings (split-gate gap: 900 nm).