Effect of Regular and Irregular Potential Perturbations in Mesoscopic Cavities

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Summary. We present a numerical investigation of the shot noise suppression in a mesoscopic cavity containing hard-wall obstacles or potential fluctuations. We show that, while in the absence of obstacles the suppression factor is 1/4, in the presence of a random distribution of strong scatterers it becomes 1/3. If instead the scatterers are regularly distributed, the value of the Fano factor depends on the relative position of the obstacles with respect to the apertures.

1 Introduction

As was shown by Schottky, when charge carriers move independently (giving rise to a Poissonian process), the shot noise associated with a current $I$ is equal to $S_I = 2e|I|$ (where $e$ is the elementary charge). Phenomena of shot noise suppression, with respect to such a value, are often found in mesoscopic structures, due to the correlations between charge carriers resulting from Fermi exclusion or from Coulomb interaction. In particular, great effort has been devoted to the theoretical and experimental study of diffusive conductors [1,2], for which the suppression factor (Fano factor) has been proved to be 1/3 if $l << L << Nl$ (with $L$ being the length of the conductor, $l$ the elastic scattering length and $N$ the number of propagating modes), and of mesoscopic cavities [3,4], in which the Fano factor is equal to 1/4.

In particular, mesoscopic cavities are regions a few microns wide delimited by constrictions; a suppression factor 1/4 is found if the constrictions are symmetric and much narrower than the cavity width. Such a result is true also for classically non chaotic shapes of the cavity and is mainly due to discontinuities of the potential at the constrictions and to the resulting
diffraction, which determines a quantum chaotic dynamics of the charge carriers [5,6].

We investigate the case in which the cavity contains, in addition, regular or irregular arrays of hard-wall obstacles or potential fluctuations associated with the discrete nature and random position of donors, with the aim of understanding how this type of scattering influences the shot noise behavior.

2 Numerical method and model

For our numerical simulations we have applied the recursive Green's function formalism [7]. The structure is subdivided into transverse slices, in each of which the potential is constant along the longitudinal direction. We have computed the Green's function for each separate slice and then we have recursively composed the Green's functions of the slices using the Dyson equation. From the overall Green's function matrix, it is straightforward to obtain the transmission matrix $t$ of the structure and thus the conductance $G$ using the Landauer-Büttiker formula, the shot noise power spectral density $S_I$ following Büttiker [8] and the Fano factor by computing the ratio of $S_I$ to $2e|I|=2e|V|G$ (where $V$ is the externally applied voltage).

In our simulations we have considered a 5 μm long and 8 μm wide rectangular cavity defined by hard-wall boundaries, for various values of the constriction width. The structure has been discretized with a mesh of about 200×800 points.

We have uniformly averaged over 61 values of the Fermi energy in the range between 9.03 meV and 9.24 meV. Averaging has been performed separately for the numerator and the denominator of the Fano factor expression, as it would be done in the actual measurement process.

3 Numerical results

For an empty rectangular cavity the Fano factor equals 1/4 also in the case of a perfectly regular rectangular hard-wall geometry, because, as already stated, the main source of diffraction is at the interface between the wide and the narrow regions.
We have then added a random distribution of hard-wall obstacles inside the cavity (in the case of Fig.1(a), 240 square obstacles with edge size equal to 200 nm). The coordinates of each obstacle are generated as a pair of uniformly distributed random numbers.

Fig. 1. Mesoscopic cavity with a random distribution of 240 hard-wall scatterers (a); or with potential fluctuations due to the presence of discrete dopants (b).

If the obstacles are sufficiently opaque and not too large, we obtain a Fano factor equal to 1/3, thus recovering the result for diffusive conductors. We point out that, although the presence of random scatterers leads to a distribution of transmission eigenvalues analogous to that of a cavity (i.e. a binomial distribution), the Fano factor raises to 1/3 if the conditions for diffusive transport are satisfied.

A more realistic source of random scattering in a cavity is represented by the potential fluctuations caused by the presence of ionized dopants in the delta-doping layer (Fig. 1(b)). Their effect on the potential has been modeled with a semi-analytical technique, with the inclusion of the screening (for the point-like charges corresponding to the ionized dopants) due to the 2DEG, adapting the theory of Stern and Howard [9] to the case of gallium arsenide. The resulting Fano factor is intermediate between 1/4 and 1/3 (0.29), because the fluctuations of the potential are of the order of a few millielectronvolts and therefore do not represent opaque enough obstacles for electrons at the Fermi energy.

Then we have considered the effect of a regular array of hard-wall obstacles inside the cavity (Fig. 2). In particular, we have focused on square obstacles of various sizes, with separation equal to the obstacle size in both directions.

As long as the obstacles are large compared with the constrictions, we observe a reduction of the Fano factor below 1/4 if the central “corridor” between obstacles is aligned with the constrictions (Fig. 2(a)) and an enhancement if a row of obstacles lies exactly between the constrictions (Fig.
2(b)). This can be easily understood in terms of an increase or decrease of direct (noiseless) transmission between the constrictions.

This result is preserved if the width of the vertical channels separating the obstacles is reduced with respect to the obstacle width and that of the horizontal channels.

![Image](image_url)

**Fig. 2.** Mesoscopic cavity with a regular array of hard-wall obstacles, with a channel between obstacles (a) or a row of obstacles (b) aligned with the apertures defining the cavity.

We acknowledge financial support from the Italian Ministry of Education, University and Research (MIUR) through the PRIN project “Excess Noise in Nanoscale Devices” and the FIRB project “Nanotechnologies and Nanodevices for the Information Society”

**References**