# Using gate voltages to tune the noise properties of a mesoscopic cavity

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**Abstract.** We propose a layout for a tunable mesoscopic cavity that allows to probe the conductance and noise properties of direct transmission channels ("noiseless scattering states"). Our numerical simulations demonstrate how the variation of different gate voltages in the cavity leads to characteristic signatures of such non-universal processes. Using realistic assumptions about scattering in two-dimensional heterostructures, our proposed layout should define a viable protocol for an experimental realization.

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## **INTRODUCTION**

Shot noise suppression in mesoscopic cavities is an active research field to which many investigations have recently been dedicated (see [1] for an introduction to the field). On the experimental side, high precision measurements of current shot noise have become possible. These have revealed detailed device characteristics which were unaccessible by way of conventional measurements of the average current. On the theoretical side, different approaches, such as those based on Random Matrix Theory, on semiclassical formulations, and on numerical simulations, have been applied to the evaluation of the shot noise suppression factor (Fano factor).

A particularly intriguing subject in this context is represented by so-called "direct processes," i.e., events of direct transmission between the entrance and the exit constrictions of a cavity. It has been shown recently that such non-universal processes can behave like classical ("noiseless") transmission channels, thereby leading to deviations from universal values for shot noise [2].

Here we propose a cavity layout (see Fig. 1(a)) that should allow for an experimental verification of the noise properties of direct processes. In order to provide useful indications for such an envisioned experiment, we performed detailed numerical investigations based on realistic assumptions on scattering in two-dimensional semiconductor heterostructures.

In particular, we have focused on a model that, although still relatively easy to handle in terms of computation, retains the capability of providing a realistic description of the confinement potential landscape and of the transport and noise processes.

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**FIGURE 1.** (a) Proposed gate layout, with a  $500 \times 600$  nm depletion gate (top left corner) and a 1272 nm long, 130 nm wide deflector gate, placed at an angle of  $45^{\circ}$  (bottom center); (b) Effect of gate voltages on the Fano factor, for a cavity with both apertures 250 nm wide; the inset contains an enlargement of the low-gate-voltage region.

#### MODEL

We consider a cavity defined by means of depletion gates in a 2-dimensional electron gas (2DEG) obtained by modulation doping in a conventional GaAs/AlGaAs heterostructure. For a fast but reasonable estimation of the confinement potential at the 2DEG level without solving the complete self-consistent problem (which would be too costly numerically for large parameter scans), we use a technique based on the semianalytical evaluation of the potential, with the inclusion of screening from the charge in the 2DEG [3].

This approach is derived in the approximation of linear response, assuming that the change in kinetic energy of the two-dimensional electron gas is small compared to the contribution from the electrostatic potential. With such an assumption, the 2DEG can be considered as an equipotential surface for the solution of the Poisson equation. Then the charge density induced in the 2DEG is computed from Coulomb's theorem as  $\delta \sigma = -\varepsilon_0 \varepsilon_r \partial \phi / \partial z \Big|_{z=d}$ , where  $\varepsilon_0$  is the vacuum permittivity,  $\varepsilon_r$  is the relative permittivity of the semiconductor,  $\phi$  is the electrostatic potential and d is the depth of the 2DEG.

Following Ref. [3], the variation in kinetic energy is given, to first order, by

$$\delta E = \frac{\delta N}{\frac{\delta N}{\delta E}} = \frac{\frac{\delta \sigma}{e}}{\frac{m}{\pi \hbar^2}} = -\frac{\pi \hbar^2}{m} \frac{\varepsilon_o \varepsilon_r}{e} \frac{\partial \phi}{\partial z} \Big|_{z=d},$$
(1)

where e is the electron charge, m is the electron effective mass,  $\hbar$  is the reduced Planck constant, and the expression for the density of states in a two-dimensional electron gas has been used. Finally, it is sufficient to divide the variation in kinetic energy by the electron charge, in order to obtain the screened potential.

A graphic representation of a typical electrostatic potential in a cavity is presented in Fig. 1(a), obtained with the procedure described above. Such a potential is then decimated along the longitudinal direction, by coalescing all the slices that are characterized by potential values that differ along the longitudinal direction by less than a given amount. This step is important to reduce the computational time in the recursive Green's function calculation [4] which we use to determine the transmission matrix through the structure. The Fano factor is finally obtained from the transmission matrix [5] by dividing the actual shot noise power spectral density by the one expected from Schottky's theorem [6]. Both quantities in this fraction are independently averaged over energy values in a window, centered around a Fermi energy of 9 meV, with a width corresponding to the bias realistically applicable between the entrance and the exit of the cavity (about 10 kT, to prevent excessive heating of the electron gas while keeping the shot noise level well above thermal noise). A temperature of T=30 mK has been assumed.

### RESULTS

We have focused specifically on the action of tunable cavity openings [7] and gate voltages, the latter being located at different positions of the cavity (see Fig. 1(a)). We consider 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. As being located right between the two quantum point contacts, such a "deflector" gate should be able to suppress direct processes. The "depletion" gate, on the contrary, should not influence the direct processes in a systematic way. To test this picture, we explicitly study the dependence of the shot noise on both gate voltages and thereby extract interesting information on the scattering dynamics in the system.



**FIGURE 2.** (a) Fano factor as a function of the bias voltages applied to the depletion and the deflector gate for a cavity with 900 nm constrictions; (b) same as in (a), but for a constant null bias applied to one of the two gates.

We first focus on the "quantum" regime with two narrow (250 nm) cavity openings that allow for a 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 find slightly increased Fano factors (see Fig. 1(b)); the two gates seemingly play analogous roles here. This behavior can be well understood by considering that, in the regime of low mode numbers N propagating in the constrictions, direct processes are strongly suppressed, but symmetry considerations become very important. For this regime of low mode numbers Random Matrix Theory predicts that cavities with a left-right symmetry (i.e., with both gate voltages set to zero) have a Fano factor of F = 1/4. Asymmetric cavities (i.e., with either gate at finite voltage) are expected to lead to significantly higher noise values [8]. Since our numerical results follow these predictions, we may thus conclude that the slightly increased noise values (F > 1/4) observed in Fig. 1(b) are produced by a gate-voltage induced breaking of the left-right cavity symmetry. (Earlier studies have shown that a transition from regular to chaotic scattering dynamics can be excluded here as a reason for increased noise values [9, 10].)

In the "classical" regime of high mode numbers in both cavity openings ( $N \approx 34$ , for a width of 900 nm) the situation is quite different. Here we find 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 or an inactive depletion gate. (See Fig. 2(a) for a plot of the dependence of the Fano factor on the two gate voltages). By tuning the depletion gate bias, on the contrary, the noise properties of the cavity are changed only slightly, regardless of the deflector gate bias (the action of each single gate, when the other one is kept at zero bias, is shown in Fig. 2(b)). We emphasize that this behavior of shot noise can be directly understood by way of 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. Since the direct scattering processes are less noisy than those that explore the cavity [2], blocking direct processes by way of the deflector gate increases the noise, as observed in our numerical data.

We note parenthetically that we have also explicitly studied the dependence of the conductance on the two gate voltages and on the cavity openings. These results (not shown due to space constraints) demonstrate an explicit dependence of the conductance on the deflector gate voltage for wide cavity openings (as expected from the above findings).

In summary, we have numerically investigated a layout for a mesoscopic cavity which should allow for an experimental investigation of the conductance and noise properties of direct scattering processes. Our results clearly show that in the "classical" regime of many open modes direct scattering processes indeed play an important role, which, as we demonstrate, can be probed by way of tunable gate voltages. In the "quantum" regime of small mode numbers direct processes are suppressed and the symmetry properties of a cavity dominate its noise characteristics.

#### REFERENCES

- 1. Ya. M. Blanter and M. Büttiker, Phys. Rep. 336, 1 (2000).
- 2. P. G. Silvestrov, M. C. Goorden, and C. W. J. Beenakker, Phys. Rev. B 67, 241301(R) (2003).
- 3. J.H. Davies, I.A. Larkin and E. V. Sukhorukov, J. Appl. Phys. 77, 4504 (1995).
- 4. F. Sols, M. Macucci, U. Ravaioli and Karl Hess, J. Appl. Phys. 66, 3892 (1989).
- 5. M. Büttiker, Phys. Rev. Lett. 65, 2901 (1990).
- 6. W. Schottky, Ann. Phys. (Leipzig) 57, 541 (1918).
- 7. S. Oberholzer, E.V. Sukhorukov, and C. Schönenberger, Nature (London) 415, 765 (2002).
- 8. V. A. Gopar, S. Rotter, and H. Schomerus, Phys. Rev. B 73, 165308 (2006).
- 9. P. Marconcini, M. Macucci, G. Iannaccone, B. Pellegrini and G. Marola, Europhys. Lett. 73, 574 (2006).
- 10. F. Aigner, S. Rotter, J. Burgdörfer, Phys. Rev. Lett. 94, 216801 (2005).

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