High-resolution numerical study of conductance and noise imaging of mesoscopic devices

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In the last few years advanced high-vacuum, ultra-low-temperature scanning probe techniques [1,2] have allowed imaging of the current flow in mesoscopic devices based on a 2-dimensional electron gas (2DEG). The basic concept behind these very successful experiments consists in the observation of how conductance through the device varies as a negatively charged probe is scanned over the semiconductor surface, locally depleting the 2DEG.

Besides conductance, the shot noise power spectral density is another quantity that could be taken into consideration for imaging purposes. The power spectral density of shot noise is related to the transmission matrix through Büttiker's relationship: $S_I = 4q^3/h|V|\mathrm{Tr}[t^\dagger t(I - t^\dagger t)]$, where q is the electron charge, h is Planck's constant, V the potential drop across the device, and t is the transmission matrix. Thus the depleted spot due to the scanning probe, through its action on the transmission matrix, will also affect the shot noise level.

In particular, for devices which exhibit clear conductance quantization (such as quantum point contacts), shot noise is almost zero in the flat region of the conductance plateaus. The scattering action of the scanning probe thus determines a relative increase of shot noise, which is in principle larger than the relative decrease of conductance. Shot noise measurements, however, are more challenging than conductance measurements, therefore it is difficult to establish a priori which quantity may provide more easily detectable information. On the other hand, there can be situations in which noise yields qualitatively different (and possibly richer) information with respect to conductance, due to the more complex functional dependence on the elements of the transmission matrix.

While Topinka *et al.* [1] have computed the pattern of electron flow directly, from the solution of the Schrödinger equation in the device potential, Grasso *et al.* [3] have performed a simulation of the actual action of a scanning probe, but on a very limited (15 by 11) domain. The same domain has been considered by Guang-Ping He *et al.* [4], who have assumed a delta-function potential for modeling the probe.

Our approach, based on an optimized recursive Green's function formalism, allows us to remove most of such approximations: we can treat, withing reasonable computational time limits, a 2-D scan on a grid of at least 200×300 points (larger grids up to 600×1000 should be accessible) and, if needed, we can model the actual potential due to the scanning probe over an area of about 200 mesh points. We have also added the possibility of treating impurities and dopants, with an approach based on the generation of a random distribution of point charges, whose contribution to the potential at the 2DEG level is computed with the inclusion of screening via a semi-analytical expression.

In Fig. 1 we show the potential landscape on which some preliminary calculations have been performed: it is the result of a split gate with a 300 nm gap, and the potential bump due to the probe is represented with a rectangular obstacle 0.3 eV high (the Fermi energy in this example has been chosen around 30 meV).

The behavior of the conductance for a 1-D scan as a function of the position of the probe along the transverse direction (with respect to electron flow), at a distance of 320 nm from the center of the split gate is shown in Fig. 2, while in Fig. 3 we report the result for the shot noise power spectral density (in units of the full shot value $2qI$, where I is the average current through the device). The number of modes propagating through the split gate for this choice of the Fermi energy is about 3, which already leads to a nontrivial relationship between the behavior of the shot noise power spectral density and that of the conductance.

Large-scale calculations for 2-D scans on quantum point contacts and more complex structures are currently in progress.
A full journal publication of this work will be published in the Journal of Computational Electronics

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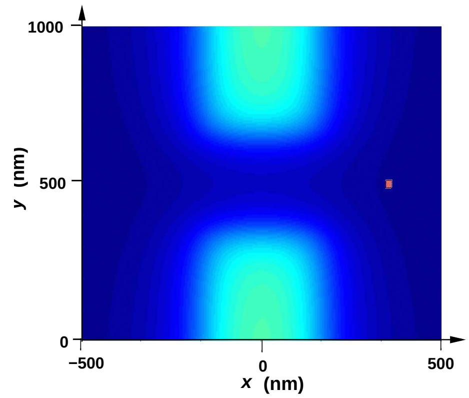

Fig. 1: Potential landscape used for preliminary simulations: a split gate defines a wire in the middle; the lighter rectangle to the right represents the effect of the scanning probe.

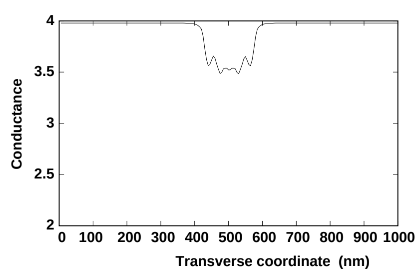

Fig. 2: Ratio of the computed shot noise power spectral density to that for full shot noise (Fano factor) as a function of vertical probe position at a distance of 320 nm from the center of the split gate.

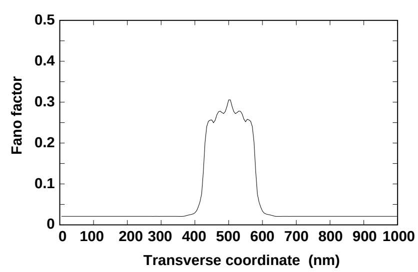

Fig. 3: Conductance (in units of $2q^2/h$) of the device as a function of vertical probe position at a distance of 320 nm from the center of the split gate.