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Noise Suppression in Mesoscopic Structures Due to Long-Range Coulomb Interaction

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We present a microscopic analysis of shot-noise suppression due to long-range Coulomb interaction in semiconductor samples operating between ballistic and diffusive transport regimes. We find that the strong suppression observed under the ballistic regime persists under quasi-ballistic conditions, before being washed out when a complete diffusive regime is achieved.

Introduction. The phenomenon of shot noise, associated with the randomness in the flux of carriers crossing the active region of a device, has become a fundamental issue in the study of electron transport through mesoscopic devices. A matter of particular interest is the suppression of shot noise resulting from the correlation among carriers in their transmission through a device (see some recent experiments [1,2] and the status of theoretical developments [3]). Among the different mechanisms of suppression, most attention has been paid to the correlations imposed by Pauli principle under degenerate conditions. The current theories [3] invoked to interpret the experimentally observed shot-noise suppression assume that carriers move inside a device without inducing any redistribution of the electric potential.

In this contribution we use a more rigorous approach which includes long-range Coulomb interaction between electrons by considering carrier transport in the *self-consistent* potential. We demonstrate that apart from Pauli correlations, Coulomb interaction between carriers can also be a source of relevant shot noise suppression.

Physical Model. We consider a lightly-doped semiconductor sample in which a flow of carriers move under ballistic transport regime and in the crossover to diffusive regime. The sample is sandwiched between two heavily-doped contacts subject to a dc voltage bias U. To exclude correlations due to Fermi statistics, the electron gas is assumed to be nondegenerate. The contacts are considered as thermal reservoirs injecting electrons according to a Maxwell-Boltzmann distribution at the lattice temperature T. Electrons are

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injected with a Poissonian statistics, i.e., the time between two consecutive injections is generated with a probability per unit time $P(t) = \Gamma e^{-\Gamma t}$, where Γ is the injection rate, proportional to the carrier concentration at the contact n_c. By assuming the sample doping to be much lower than that of the contacts, the potential distribution and, as a consequence, the electron dynamics are governed by the screening parameter $\lambda = L/L_{Dc}$, where L is the length of the sample and L_{Dc} the Debye screening length associated with the electron injection rate [4]. Along with λ, we introduce the ballistic parameter $\ell = v_{th}\tau/L$ which characterizes the crossover between diffusive ($\ell \ll 1$) and ballistic ($\ell \gg 1$) transport regimes (v_{th} is the thermal velocity, and τ the average time between collisions in the bulk). We assume that τ is isotropic and independent of energy, and perform simulations for the two opposite cases when scattering is of elastic or inelastic type. For simplicity each inelastic scattering is assumed to relax the carrier energy at its thermal equilibrium value.

Results. We calculate the time-averaged current I and its low-frequency fluctuation spectrum S_I by means of an ensemble Monte Carlo simulator self-consistently coupled with a one-dimensional Poisson solver [4,5]. We find that the steady-state potential profile exhibits a minimum inside the sample whenever the current is space-charge limited. This minimum acts as a potential barrier for the electrons and, while the static characteristics remain the same, the noise behaviour is shown to depend crucially whether the potential barrier fluctuations follow (self-consistently) the random injection of carriers from the contact (dynamic case) or not (static case). In Fig. 1 we compare the low-frequency spectral density of current fluctuations S_I for these two cases as a function of ℓ, calculated for $\lambda = 30.9$ and an applied voltage $U = 40k_BT/q$. In the ballistic limit ($\ell \gg 1$) the static case recovers the classical formula $2qI$ (full shot noise), while the dynamic case evidences a strong suppression of S_I due to long-range Coulomb interaction induced by the self-consistent potential. In the diffusive limit ($\ell \to 0$) both cases

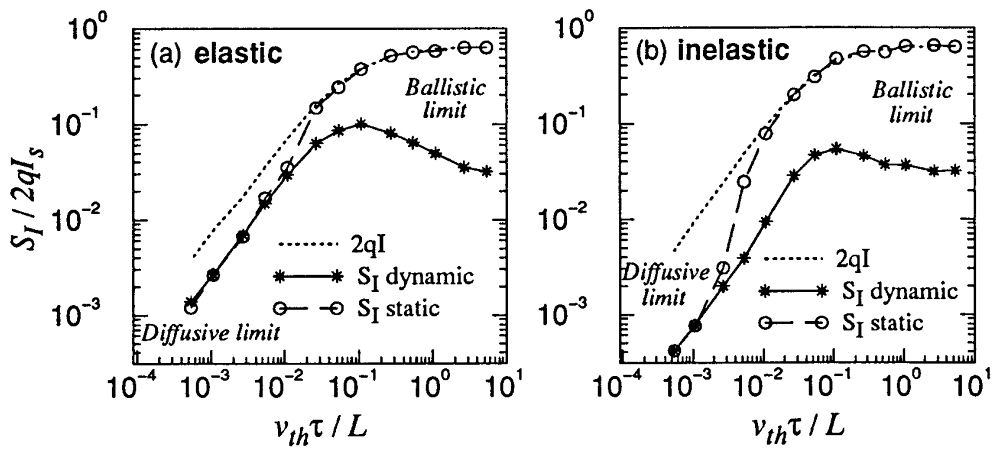

Fig. 1. Current–noise spectral density S_I vs. ballistic parameter $\ell = v_{th}\tau/L$ calculated by using static (circles, dashed line) and dynamic (stars, solid line) potentials for the case of a) elastic and b) inelastic scattering. The dotted line represents $2qI$. The results are normalized to $2qI_s$, where $I_s = q\Gamma$ is the saturation current

provide identical results, since the strong scattering washes out the influence of the self-consistent field fluctuations. We remark the wide region covered by the suppression effect which remains active in the quasi-ballistic regime and is more pronounced for the case of inelastic scattering (compare Fig. 1a, b). The dynamic noise, after having a maximum value at $\ell \approx 0.1$, decreases with increasing ℓ, which is somewhat surprising in view of the corresponding increase of the current. Notice that the importance of the self-consistency starts to appear already at $\ell \approx 10^{-2}$ for elastic and $\ell \approx 3 \times 10^{-3}$ for inelastic scattering, which means that the long-range Coulomb interaction influences the noise even for "almost" diffusive transport when an electron undergoes $\approx 10^2$ scattering events while crossing the active region of the device. Another remarkable result is that in the static case S_I already follows the $2qI$ law for $\ell \approx 3 \times 10^{-2}$ for elastic and $\ell \approx 10^{-2}$ for inelastic scattering although under these conditions a carrier undergoes about $\approx 10^2$ scattering processes in its transfer between contacts.

In conclusion, self-consistent Monte Carlo simulations of non-degenerate electron transport show that long-range Coulomb interaction is responsible for relevant shot-noise suppression under ballistic and quasi-ballistic transport regimes. Calculations evidence that shot-noise suppression cannot be neglected even in the presence of a significant number of collision events.

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