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Enhanced shot-noise in mesoscopic non-degenerate diffusive semiconductors

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Abstract

We report on Monte Carlo simulations exhibiting the presence of enhanced shot-noise in mesoscopic non-degenerate diffusive semiconductors. We identify a sufficient condition for the presence of enhanced shot-noise as the occurrence of negative differential conductivity in energy space. The enhancement is attributed to a positive correlation between velocity and potential fluctuations, which occur when the elastic scattering time is a strongly decreasing function of energy. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Mesoscopic diffusive semiconductors are characterized by a sample length, L, much smaller than the inelastic mean free path, $\ell_{\rm in}$, and much larger than the elastic mean free path, $\ell_{\rm el}$. They exhibit shot noise when the applied voltage, V, is much higher than the thermal voltage $V_{\rm T} = k_{\rm B}T/q$, where $k_{\rm B}$ is the Boltzman constant, T the temperature and q the absolute value of the electron charge. Interestingly, the Fano factor γ associated with this shot noise (defined as $\gamma = S_{\rm I}(0)/2qI$, where $S_{\rm I}(0)$ is the low frequency current spectral density and I the electric current) is found to depend on the interplay between the long-range Coulomb interaction and the energy dependence of the elastic scattering time. For the relevant case of a three-dimensional system with an energy-dependent elastic scattering time of the form $\tau \sim \varepsilon^{\alpha}$, Monte Carlo simulations [1] have shown that the Fano factor lies close to the value of 1/3 for α between 0 and 1. In contrast, the Fano factor increases systematically from 1/3 towards 1 when α decreases from 0 to -1.5. The existing theories [2–4] provide a reasonable description of these results in a limited range of values of α, thus supporting the general view of a suppressed shot noise for these mesoscopic systems. Until now, the possibility to observe enhanced shot-noise (with $\gamma > 1$) in these systems has not been considered. The object of the present paper is to address this issue.

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2. System under study

Following previous works [1–4] we consider a simple structure consisting of a semiconductor with a moderately doped active region sandwiched between two heavily doped contacts, which, by injecting carriers into the active region, act as ideal thermal reservoirs. The structure is assumed to be sufficiently thick in transversal dimensions to allow a one-dimensional electrostatic treatment. Accordingly, for the purpose of the simulations the system is considered one-dimensional in real space and three-dimensional in momentum space. We further assume that only elastic scattering processes take place in the system and that the energy dependence of the elastic scattering time is of the form $\tau(\varepsilon) = \tau_0 \varepsilon^{\alpha}$. We assume values of τ_0 that ensure diffusive transport in most of the sample active region. Formally, any value of the exponent α is possible, although only some particular values correspond to well known scattering mechanisms, like short-range impurity scattering or scattering with acoustic phonons by deformation potentials ($\alpha = -1/2$), neutral impurities ($\alpha = 0$), and acoustic piezoelectric phonons ($\alpha = 1/2$).

3. Theory and results

Recently, some of the Authors [5] predicted the presence of enhanced shot-noise in mesoscopic non-degenerate diffusive conductors on the basis of an exact decomposition of the Fano factor into the sum of three contributions

$$\gamma = \gamma_{\text{in}} + \gamma_{\phi} + \gamma_{\text{in},\phi}. \tag{1}$$

The first contribution, γ_{in}, is related to the intrinsic current fluctuations, the second one, γ_{ϕ}, to those associated with the self-consistent potential, and the third one, $\gamma_{\text{in},\phi}$, to those associated with their cross correlations (see Ref. [5] for a more detailed description of each term). For non-degenerate conductors under far-from-equilibrium conditions it was shown that $\gamma_{\text{in}} = 1$. Moreover, γ_{ϕ} is positively defined, while sign of the cross term $\gamma_{\text{in},\phi}$ is the opposite to that of the differential conductivity in energy space $\sigma'(\varepsilon) = \mathrm{d}\sigma(\varepsilon)/\mathrm{d}\varepsilon$. For the system under study the conductivity in energy space is given by Ref. [5]

$$\sigma(\varepsilon) = \tfrac{1}{3}\nu(\varepsilon) q^2 v(\varepsilon)^2 \tau(\varepsilon), \tag{2}$$

where $\nu(\varepsilon) = 4\pi(2\,m^3\varepsilon/h^2)^{1/2}$ is the density of states, m the effective mass, h the Planck constant and $v(\varepsilon) = \sqrt{2m\varepsilon}$ the velocity. This yields the differential conductivity in energy space as $\sigma'(\varepsilon) = \text{const}(\alpha + 3/2)\varepsilon^{\alpha+1/2}$. Consequently, the inequality $\alpha < -3/2$ constitutes a sufficient condition for the existence of negative differential conductivity in energy space and, hence, of enhanced shot-noise ($\gamma > 1$), in elastic diffusive semiconductors under far-from-equilibrium conditions.

To verify the theoretical predictions we have developed an ensemble Monte Carlo simulator which is three-dimensional in momentum space, self-consistently coupled with a one-dimensional Poisson solver for an elastic diffusive semiconductor with the exponent α ranging from -2 to 0. In the calculation we used the following parameters: $T = 300\,\text{K}$, effective mass $m = 0.25\,m_0$, dielectric constant $\varepsilon = 11.7\varepsilon_0$, sample length $L = 200\,\text{nm}$ and contact doping $n_{\text{C}} = 4 \times 10^{17}\,\text{cm}^{-3}$. Further details of the calculation can be found in Refs. [6,7]. We performed calculations for the following values of α (and associated value of τ_0): -2 ($8.35 \times 10^{-16}\,\text{s}\,\text{eV}^2$); $-3/2$ ($6.76 \times 10^{-16}\text{s}\,\text{eV}^{3/2}$); -1 ($3.88 \times 10^{-16}\,\text{s}\,\text{eV}$); $-1/2$ ($4.41 \times 10^{-16}\text{s}\,\text{eV}^{1/2}$) and 0 ($2.00 \times 10^{-15}\,\text{s}$). The values of τ_0 are chosen in such a way as to ensure a diffusive transport regime.

Fig. 1 exhibits the Fano factor γ as a function of applied bias for the various values of the energy exponent α used in the simulations. Focusing attention on the highest voltages, it is clearly seen that for the case $\alpha = -2 < -3/2$ we obtain values of the Fano factor larger than 1 (enhanced shot-noise) in good agreement with theoretical predictions. To further investigate the mechanism responsible for shot-noise enhancement we show in Fig. 2 the profiles of the relevant average quantities for an applied voltage $qV/k_{\text{B}}T = 80$. We note that the profiles change qualitatively for values of α below about -1. For these values we note the appearance of a quasi-ballistic region near the injecting contact. The transition from the

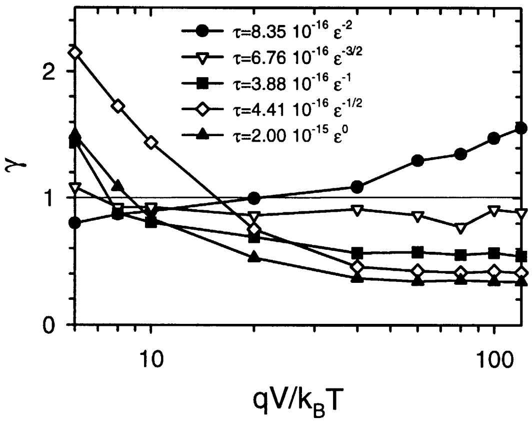

Fig. 1. Fano factor as a function of applied bias for various energy dependences of the scattering time.

quasi-ballistic region near the contact to the diffusive region inside the structure leads to the appearance of a maximum (minimum) in the velocity (concentration) profile. The appearance of the maximum in the velocity profile corresponds to the onset of a region of negative differential mobility in real space that covers most of the active region of the structure. These qualitative changes are accompanied by a systematic increase of the Fano factor, as can be seen in Fig. 1, which indicates the onset of a mechanism inducing positive correlation among the fluctuations. We conclude that for $\alpha < -3/2$ the structure exhibits the simultaneous presence of two distinct transport regimes, a ballistic one near to the contacts and a diffusive one inside the structure. The presence of these regimes leads to a region of dynamical negative differential mobility, which in turns moves the structure towards a state of electrical instability, as well known for the analogous case of Gunn diodes. The increase of the Fano factor is then a precursor of the fact that the system is evolving towards such an electrical instability. The conditions under which enhanced shot-noise is observed coincides with the analytical condition that the differential conductivity in energy space becomes negative. A quantitative analysis of this physical situation requires further research.

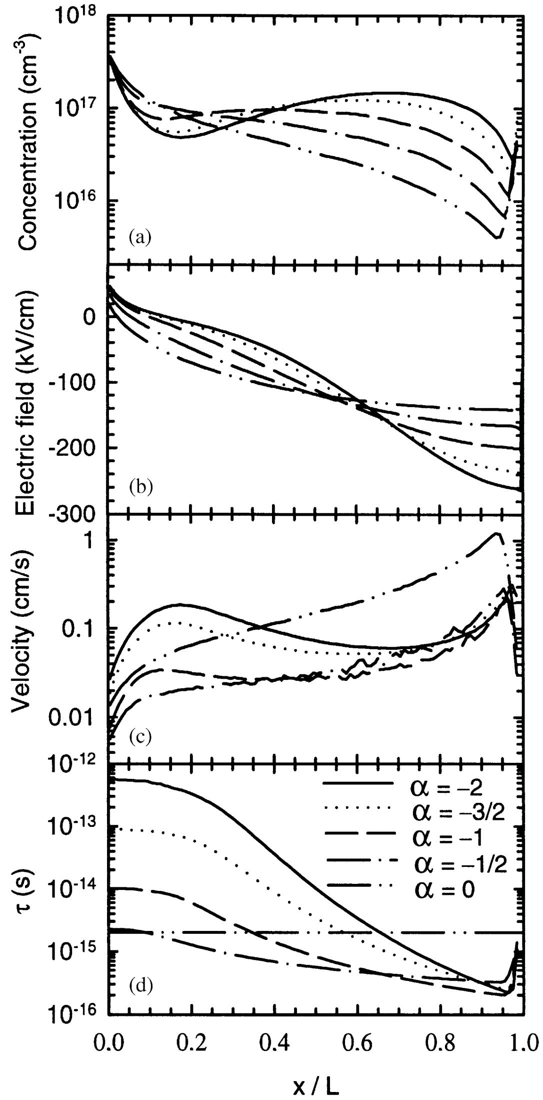

Fig. 2. Spatial profiles of average quantities along the active region of the semiconductor for an applied voltage of $80\,k_B T/q$ and several values of the energy exponent α of the relaxation time. (a) Carrier concentration; (b) electric field; (c) velocity; and (d) scattering time.

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