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Shot-noise suppression in nondegenerate semiconductors: the role of an energy-dependent scattering time

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Abstract

We present a Monte Carlo analysis of shot-noise suppression associated with long-range Coulomb interaction in nondegenerate diffusive conductors. Different energy dependencies of the elastic scattering time $\tau(\varepsilon) \propto \varepsilon^{\alpha}$ are considered. The shot-noise suppression factor γ is found to increase from about $\frac{1}{3}$ to 0.9 when α decreases from 1 to -1.5. The simulations evidence dramatic changes in the profiles of electric field, carrier concentration and velocity in the above range of α values.

Keywords: Noise; Mesoscopic; Scattering; Monte Carlo

1. Introduction

Recently, Monte Carlo (MC) simulations have evidenced the suppression of low-frequency shot-noise in nondegenerate semiconductors associated with long-range Coulomb interaction [1]. Remarkably, in the case of a 3D momentum space, and for elastic scattering characterised by an energy-independent scattering time $\tau(\varepsilon) = \text{const.}$, a suppression factor $\gamma = S_I/2qI$ (with S_I the low-frequency current spectral density, q the electron charge and I the DC current) about $\frac{1}{3}$ is obtained provided the following conditions are satisfied: (i) $qU \gg k_B T$, applied voltage much larger than the thermal value, (ii) $L \gg \ell, L_{DC}$, length of the device much longer than both the elastic mean free path (diffusive transport regime) and the Debye length at the contacts (strong-space charge effects). By fully suppressing carrier-number fluctuations, long-range Coulomb interaction is found to be determinant in providing the $\frac{1}{3}$ value. Once these conditions are fulfilled, the $\frac{1}{3}$ suppression exhibits several *universal* properties [2], namely, it is independent of: material parameters, applied voltage, value of the scattering time, screening length, and carrier injecting statistics. Recently, the MC results [1] have been analytically interpreted by Beenakker [3] and Schomerus et al. [4] on the basis of a Boltzmann–Langevin approach. These authors and Nagaev [5] have independently predicted that, even if for a given dimensionality there is no dependence on material parameters, shot-noise suppression in nondegenerate conductors does depend

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on the energy-dependence of the scattering time, thus spoiling its possible *universality*.

The aim of this paper is to report MC simulations performed with energy-dependent scattering times which, by confirming the variation of γ with the chosen energy dependence, shed new light on the microscopic origin of such a suppression.

2. Physical model

For the calculations we consider a simple structure consisting of a lightly doped active region of a semiconductor sandwiched between two heavily doped contacts which act as ideal thermal reservoirs. The structure is assumed to be sufficiently thick in transversal dimensions to allow a 1D electrostatic treatment. Accordingly, the carrier dynamics in the presence of elastic scattering is simulated in the active region by an ensemble MC 3D in momentum space self-consistently coupled with a 1D Poisson solver to account for Coulomb correlations, responsible for shot-noise suppression. For the calculations we use the following parameters: temperature $T = 300$ K, effective mass $m = 0.25m_0$, dielectric constant $\varepsilon = 11.7\varepsilon_0$, sample length $L = 2000$ Å and contact doping $n_C = 4\times10^{17}\ \mathrm{cm}^{-3}$. The above parameters lead to a value of 30.9 for the characteristic parameter of electrostatic screening $\lambda = L/L_{DC}$ [6], which implies important space-charge effects. Further details of the calculations can be found in Refs. [2,6].

We take a power-law dependence of the scattering time of the form $\tau(\varepsilon) = \tau_0\varepsilon^\alpha$ and perform calculations for the following values of α (and associated τ_0): $-3/2$ (6.76×10^{-16} s $\mathrm{eV}^{3/2}$), -1 (3.88×10^{-16} s eV), $-1/2$ (4.41×10^{-16} s $\mathrm{eV}^{1/2}$), 0 (2.00×10^{-15} s, energy-independent case), 1/2 (3.11×10^{-15} s $\mathrm{eV}^{-1/2}$) and 1 (1.55×10^{-14} s eV^{-1}). The values of τ_0 are chosen in such a way to ensure diffusive transport in the wide range of electron energies found in the simulations and to make computer times affordable. Formally, one can analyse any value of α [5], however, only some of the values here considered correspond to real cases of elastic scattering mechanisms, like short-range impurity scattering [3,4] or scattering with acoustic phonons by deformation potential ($\alpha = -1/2$), neutral impurities ($\alpha = 0$), and acoustic piezoelectric phonons ($\alpha = 1/2$).

3. Results and discussion

Fig. 1 reports the shot-noise suppression factor γ as a function of the energy exponent α for applied voltages $qU \gg k_BT$, for which γ achieves a value independent of U within numerical uncertainty. The current in this range (see inset) exhibits different behaviour for each value of α, going from sublinear ($\alpha = -\frac{3}{2}, -1, -\frac{1}{2}$) to superlinear ($\alpha = 0, \frac{1}{2}, 1$) dependence on U. Closed circles in Fig. 1 refer to MC simulations and the continuous curve to analytical results obtained within a drift model [4]:

$$\gamma = \frac{6(\alpha-1)(\alpha+2)(16\alpha^2+36\alpha-157)}{5(2\alpha-5)(8\alpha-17)(13\alpha+8\alpha)}. \tag{1}$$

The uncertainty of MC results increases for high values of $|\alpha|$ due to the difficulty in achieving diffusive conditions along the whole sample. For $qU \gg k_BT$ there exists a large difference in carrier energy along the active region, which for high $|\alpha|$ may result in a range of scattering times differing for several orders of magnitude in going from opposite contacts [see Fig. 2(d)]. Present results give values of γ always below unity, with tendency to saturate at about 1/3 for increasing positive values of α. MC data compare well with analytical results

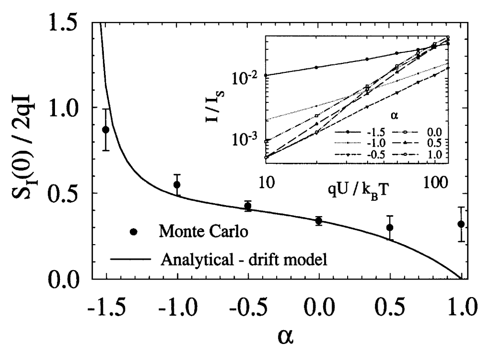

Fig. 1. Suppression factor γ in the limit $qU \gg k_BT$ as a function of the energy exponent of the relaxation time α. Symbols correspond to MC results, solid line to analytical calculations within a drift approximation [Eq. (1)] [6]. The I–U curves for the different values of α are shown in the inset.

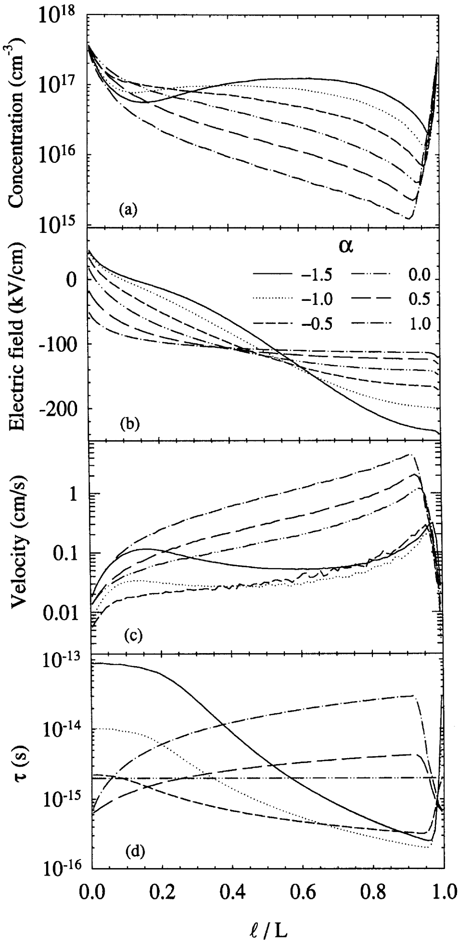

Fig. 2. Spatial profiles of average quantities along the active region of the semiconductor for an applied voltage of $80k_B T/q$ and several values of the energy exponent of the relaxation time α. (a) Concentration, (b) electric field, (c) velocity, and (d) scattering time.

in the limited range of values $-\frac{3}{2} < \alpha < \frac{1}{2}$. Outside this range, the analytical theory predicts somewhat anomalous values of γ corresponding to enhanced (at $\alpha < -\frac{3}{2}$) and full suppressed (at $\alpha = 1$) shot noise, probably due to the simplifying assumptions inherent to the drift model [4]. In any case, we confirm that the suppression factor associated with Coulomb correlations is in general a sensitive probe of the energy dependence of the scattering time.

To provide a microscopic interpretation of the above results, Fig. 2 reports the profiles of the relevant average quantities for an applied voltage of $80k_B T/q$ and different α. In going from the left to the right contact the following three transport regions can be identified:

(i) A short quasi-ballistic region next to the left contact, mostly evidenced by the fast increase of velocity, and especially pronounced for the cases of $\alpha = -3/2, -1$ due to the high values of τ near the contact [Fig. 2(d)].

(ii) A diffusive region, covering most of the sample and finishing near the right contact, evidenced by regular behaviours of all quantities. The transition from the ballistic to the diffusive region in the cases $\alpha = -3/2, -1$ leads to the appearance of a local maximum (minimum) in the velocity (concentration) due to the specific $\tau(\varepsilon)$ dependence.

(iii) A braking region, covering the final part of the device, evidenced by an inverted behaviour of all quantities determined by the injection of thermal carriers from the right contact and simultaneous ballistic ejection of carriers arriving from the left contact.

We conclude that the tendency of γ to saturate at a value about $\frac{1}{3}$ for $\alpha \geqslant 0$ correlates with the tendency to flatten observed in the field profile [Fig. 2(b)], thus making regular the slope of the profile of other relevant quantities, i.e., the decrease of concentration and the increase of velocity and scattering time.

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References

[1] T. González, C. González, J. Mateos, D. Pardo, L. Reggiani, O.M. Bulashenko, J.M. Rubí, Phys. Rev. Lett. 80 (1998) 2901.
[2] T. González, J. Mateos, D. Pardo, O.M. Bulashenko, L. Reggiani, Phys. Rev. B, 60 (1999) 2670.
[3] C.W.J. Beenakker, Phys. Rev. Lett. 82 (1999) 2761.
[4] H. Schomerus, E.G. Mishchenko, C.W. Beenakker, Phys. Rev. B 60 (1999) 5839.
[5] K.E. Nagaev, Phys. Rev. Lett. 83 (1999) 1267.
[6] T. González, J. Mateos, D. Pardo, O.M. Bulashenko, L. Reggiani, Semicond. Sci. Technol. 13 (1998) 714.