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Effect of dimensionality on shot-noise suppression in nondegenerate diffusive conductors

T. González [a,*], J. Mateos [a], D. Pardo [a], O.M. Bulashenko [b], L. Reggiani [c]

[a] *Departamento de Física Aplicada, Universidad de Salamanca, Plaza de la Merced s/n, E-37008 Salamanca, Spain*
[b] *Departament de Física Fonamental, Universitat de Barcelona, Av. Diagonal 647, E-08028 Barcelona, Spain*
[c] *Dipartimento di Scienza dei Materiali, Istituto Nazionale di Fisica della Materia, Università Lecce, Via Arnesano, 73100 Lecce, Italy*

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Abstract

We present a theoretical investigation of shot-noise suppression due to long-range Coulomb interaction in nondegenerate diffusive conductors. Calculations make use of an ensemble Monte-Carlo simulator, self-consistently coupled with a one-dimensional Poisson solver. We analyze the noise in a lightly doped active region surrounded by two contacts acting as thermal reservoirs. The effect of momentum space dimensionality on shot-noise suppression is analyzed. Provided significant space-charge effects take place inside the active region, long-range Coulomb interaction is found to play an essential role in suppressing the shot noise at $qU \gg k_B T$. In the elastic diffusive regime, dimensionality is found to modify the suppression factor γ, which within numerical uncertainty takes values of about 1/3, 1/2 and 0.7 in the cases of 3, 2 and 1 dimensions, respectively. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The subject of shot-noise suppression in diffusive conductors is attracting significant attention in recent years. In particular, in the case of degenerate conductors, the suppression factor $\gamma = S_I(0)/2qI$ (with $S_I(0)$ the low-frequency spectral density, q the electron charge and I the dc current) has been predicted to be 1/3 by both coherent and incoherent theoretical approaches [1,2] and confirmed experimentally [3]. This is a universal result independent of the number d of momentum space dimensions of the system. On the other hand, a suppression factor close to 1/3 has also been obtained in nondegenerate diffusive conductors with $d = 3$ [4,5]. However, in this case, a dependence of γ on d is expected.

While in the degenerate case, Pauli exclusion principle is the origin of the suppression, in the nondegenerate case, the noise reduction is ultimately due to the presence of long-range Coulomb interaction, which introduces a negative correlation among carriers.

The aim of this work is to provide a theoretical evidence of the dependence upon momentum space dimensionality of the shot-noise suppression factor in nondegenerate diffusive conductors. By using a Monte-Carlo (MC) simulator self-consistently coupled with a Poisson solver (PS), we analyze the shot noise associated with electron transport in a two-terminal semiconductor structure under the influence of isotropic elastic scattering in the presence of an external applied voltage U. Different values of γ are obtained for $d = 1$, 2, 3 at $qU \gg k_B T$.

Very recently, analytical calculations performed by Beenakker et al. [6,7] have provided values for the dependence of the suppression factor on dimensionality, which are in close agreement with the MC calculations.

2. Physical model

For our analysis, we consider the simple structure shown in Fig. 1. It consists of a lightly doped active region of length L sandwiched between two heavily

* Corresponding author. Tel.: +34-923-294436; fax: +34-923-294584.
E-mail address: tomasg@gugu.usal.es (T. González).

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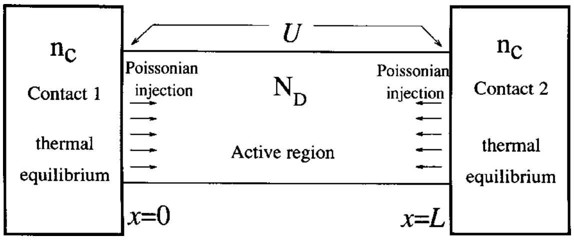

Fig. 1. Schematic drawing of the structure under analysis.

doped contacts, which act as thermal reservoirs and inject carriers into the active region. The structure is assumed to be sufficiently thick in transversal directions to allow a 1D electrostatic treatment. Accordingly, the MC simulation is 1D in real space. The doping of the contacts n_c is always taken to be much higher than that of the active region N_D. Hence, when a voltage U is applied to the structure, all the potential drop is assumed to take place inside the active region between positions $x = 0$ and $x = L$.

The contacts are nondegenerate and are considered to be at thermal equilibrium. Accordingly, the velocity of the injected electrons follows a Maxwell–Boltzmann distribution at the lattice temperature T, and the fluctuating injection rate is taken to follow Poissonian statistics, i.e., the time between two consecutive electron injections is generated with a probability $P(t) = \Gamma e^{-\Gamma t}$, where $\Gamma = (1/2)n_c v_{th} S$ is the injection rate, $v_{th} = \sqrt{2k_B T/\pi m}$ is the thermal velocity, S is the cross-sectional area of the device and m the electron effective mass. This injection rate is consistent with the case $d = 3$. In the cases of $d = 1, 2$, we will consider the same values of Γ and S to ensure equivalent space-charge effects inside the active region of the structures and thus analyze just the role of dimensionality.

For the calculations, we have used the following set of parameters: $T = 300$ K, $m = 0.25m_0$, relative dielectric constant $\varepsilon = 11.7$ and $L = 200$ nm. Most of the reported results correspond to $n_c = 4 \times 10^{17}$ cm^{-3}, which, with the above set of values, yields for the dimensionless parameter $\lambda = L/L_{Dc}$ (with L_{Dc} being the Debye length corresponding to n_c), which characterizes the importance of the electrostatic screening [8], the value $\lambda = 30.9$. This high value of λ implies significant action of space-charge effects inside the structure. Elastic isotropic collisions are introduced in the simulation by means of an energy-independent scattering time τ, which is varied from 10^{-11} s to 10^{-15} s to continuously cover the transition from ballistic to diffusive transport regime. This transition will be characterized by the ratio between the carrier mean free path ℓ (estimated as $v_{th}\tau$) and the sample length L. When $d = 2$, the carrier velocity is randomized in two components after each scattering event, and when $d = 1$, the isotropic character of scattering is accomplished by inverting the carrier velocity with an average (back scattering) probability $P_b = 0.5$.

The structure operates under a constant applied bias. Under these conditions, the MC approach employed in the calculations allows the direct evaluation of the instantaneous fluctuating current to be carried out. The behavior of the noise in the time domain is then determined by means of the autocorrelation function of current fluctuations, which, by Fourier transformation, provides the spectral density.

3. Results

The origin of shot-noise suppression in the analyzed structures is related to the action of long-range Coulomb interaction. In order to check to which extent this interaction is determinant for noise suppression, Fig. 2 reports γ, and the three contributions into which it can be decomposed [8], as a function of λ for $d = 3$ and high applied voltage ($U = 100k_B T/q$). These contributions correspond to velocity fluctuations (S_V), number fluctuations (S_N) and velocity–number cross-correlation (S_{VN}). For the lowest values of λ, when space-charge effects and in turn Coulomb interaction are negligible, full shot noise is observed ($\gamma = 1$). As λ increases, γ starts decreasing from unity until reaching a constant value close to 1/3 for $\lambda \geqslant 30$. It is remarkable that the contribution of velocity fluctuations to γ does not vary significantly with λ. On the contrary, the contributions associated with number and velocity–number fluctuations are strongly affected by the increase of λ. Indeed, their absolute value decreases systematically and, being opposite in sign, they compensate each other at the highest values of λ, where $S_I = S_V$. Therefore, Coulomb interaction mainly affects the contributions related to carrier number fluctuations. In the following, the results

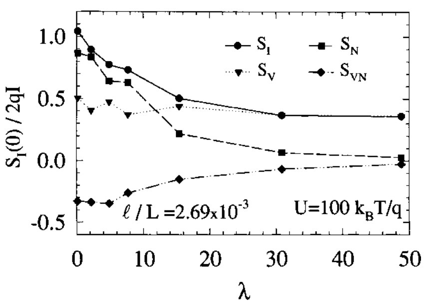

Fig. 2. Shot-noise suppression factor as a function of the characteristic parameter of space-charge λ calculated under elastic diffusive regime for $qU \gg k_B T$ in the case $d = 3$. Velocity (S_V), number (S_N), and velocity–number (S_{VN}) contributions to the suppression factor are also shown in the figure.

will correspond to $\lambda = 30.9$ (strong space-charge effects), when γ is practically independent of λ.

In nondegenerate conductors under the action of elastic scattering, the presence of velocity components transversal to the electric field direction constitutes a channel of energy redistribution, which may affect the transport and noise properties of the structures. Indeed, the suppression factor is found to depend significantly on d. Fig. 3(a) reports γ as a function of ℓ/L for the cases of $d = 1, 2, 3$ at $U = 40k_BT/q$. For the highest values of ℓ/L (quasi-ballistic regime), in all the three cases, γ approaches the asymptotic value corresponding to the ballistic limit ($\gamma = 0.045$) [8], where the behavior is independent of d. At a given value of ℓ/L, a higher deviation of γ from the asymptotic ballistic value is observed for a lower d. This is due to the fact that, in average, elastic interactions introduce higher fluctuations of the carrier velocity component along the field direction, the lower is the number of available momentum states after the scattering mechanism (e.g., two states for $d = 1$). For the same reason, the increasing presence of scattering, as ℓ/L is reduced, leads to higher values of the suppression factor, the lower is the dimensionality. When elastic scattering is strong enough to determine a significant energy redistribution among momentum directions [5], γ reaches a value independent of ℓ/L. Remarkably, within numerical uncertainty, this limit value reached by γ in the perfect diffusive regime (lowest values of ℓ/L) is found to be, respectively, of 1/3, 1/2, and 0.7 for d =3, 2, and 1. Fig. 3(b), by reporting γ in the diffusive regime as a function of the applied voltage, provides evidence that these limit values are independent of the bias when $qU \gg k_BT$. The origin of the suppression is the same in all three cases: the joint action of Coulomb correlations and elastic scattering, leading to the result $S_I(0) \cong S_V(0)$ (as shown in Fig. 2 in the case $d = 3$), where, under perfect diffusive regime, $S_V(0)/2qI$ is a function of the dimensionality of momentum space. When the applied bias is reduced, γ takes higher values, thus revealing the increasing influence of thermal noise. We remark that, when calculated with a *static* PS scheme (*frozen* stationary potential profile, thus in the absence of Coulomb correlations) [8], the results shown in Figs. 2 and 3 do not exhibit any suppression [5]. Moreover, the results shown in Figs. 2 and 3(b), corresponding to diffusive regime, are independent of the carrier injecting statistics [5].

In a recent work, Beenakker [6] has developed an analytical theory, which explains the dependence of γ on d. In particular, the theory predicts the values of 0.34 and 0.51 for γ, respectively, for the cases $d = 3$ and 2, in agreement with present findings. From that analysis, it was concluded that the proximity of γ to $1/d$ is accidental. Present simulations support this conclusion, since in the case $d = 1$ we obtain $\gamma = 0.7$, a value far from that of full shot noise.

For reason of completeness, we have finally analyzed the possible influence of an anisotropic elastic scattering on transport and noise in the case $d = 1$. Fig. 4 reports γ and the current as a function of ℓ/L for three different values of P_b: 0.5 (isotropic case), 0.25 and 0.10 (less pronounced back scattering). The noise results differ only in the quasi-ballistic regime, where the current remains nearly constant. Once the diffusive regime is

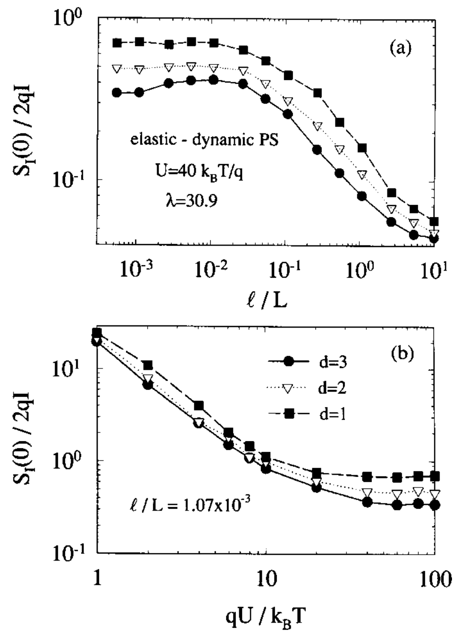

Fig. 3. Shot-noise suppression factor under elastic scattering for the cases of 1, 2 and 3 dimensions of momentum space as a function of (a) ballistic parameter ℓ/L with an applied voltage $U = 40k_BT/q$ and (b) applied bias U under diffusive regime ($\ell/L = 1.07 \times 10^{-3}$).

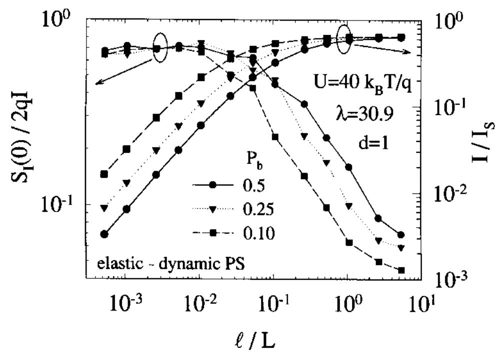

Fig. 4. Shot-noise suppression factor and normalized current versus ℓ/L under elastic scattering in the case of $d = 1$. Different curves refer to the reported values of the probability of scattering in the backward direction P_b. The applied voltage is $U = 40k_BT/q$.

achieved, the current decreases linearly with ℓ/L and γ takes the same value of about 0.7 independent of the degree of scattering anisotropy. As expected for conditions closer to the ballistic regime, we have found that the smaller the value of P_b, the wider the quasi-ballistic range is, and a stronger suppression is observed for a given value of ℓ/L in this range.

4. Conclusions

As final conclusion, we point out that within our model, the value of γ obtained for a given value of d in the diffusive regime exhibits several *universal* properties, namely, it is independent of (i) the scattering strength (once $\ell \ll L$), (ii) the applied voltage (once $qU \gg k_B T$), (iii) the screening length (once $\lambda \gg 1$), and (iv) the carrier injecting statistics. However, the consideration of an energy-dependent scattering rate (here considered energy independent) can lead to different suppression factors, thus breaking the *universality* of the result [6].

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