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Influence of trapping–detrapping processes on shot noise in nondegenerate quasi-ballistic transport

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Abstract
We present a microscopic analysis of current fluctuations in semiconductor structures under nondegenerate quasi-ballistic transport conditions, in the presence of generation-recombination processes with electron traps. These processes introduce positive correlations between the carriers contributing to the current and lead to a shot-noise level systematically higher than that found in the purely ballistic case. Calculations are performed by means of an ensemble Monte Carlo simulator self-consistently coupled with a Poisson solver. Shot-noise suppression/enhancement, originating from the combined action of long-range Coulomb interaction and trapping–detrapping processes, is found depending on the characteristic parameters of the structures and the frequency range of observation. When transport becomes diffusive, the influence of the trapping–detrapping processes disappears.

1. Introduction

Shot noise, associated with the discrete character of the electric charge, is originated by the randomness in the flux of carriers crossing the active region of a given device [1]. At low frequency, in comparison with the inverse of the transit time through the active region ($f \ll 1/\tau_T$), and far from equilibrium, the spectral density of current fluctuations is given by $S_I(0) = \gamma 2qI$, where γ is the Fano factor, q is the electron charge and I is the dc current. Uncorrelated carriers following Poissonian statistics are known to exhibit full shot noise with $\gamma = 1$. However, when they are negatively or positively correlated, shot-noise suppression ($\gamma < 1$) or enhancement ($\gamma > 1$), respectively, is observed. Several interactions and mechanisms can introduce correlations between carriers, thus leading to different levels of suppressed/enhanced shot noise, which can provide valuable information about the carrier kinetics inside the structures not available from dc characteristics or low-frequency conductance [2]. For this reason, the analysis of shot noise in mesoscopic structures has attracted increasing efforts in recent years [3].

In contrast with the large attention payed in the literature to shot-noise suppression, the possibility of enhancement has been much less explored. So far, apart from Andreev reflections [4–7], the only mechanism found to be responsible for shot-noise enhancement is the positive feedback between Coulomb interaction and tunnelling probability, as evidenced in structures controlled by tunnelling such as double-barrier resonant tunnelling diodes [8–12] and single-barrier structures [13–15]. In this paper we present another mechanism able to increase the level of shot noise also related to the action of Coulomb interaction, but in this case combined with the presence of generation–recombination (GR) processes with electron traps in an otherwise ballistic structure.

The low-frequency noise of electronic structures is known to be very sensitive to defects introduced during the semiconductor growth process and the different steps of the fabrication technology. In particular, GR phenomena associated with these defects may be a fundamental noise source in this frequency range. In this paper we analyse the influence of electron trapping–detrapping processes on shot noise in nondegenerate quasi-ballistic structures when the characteristic time of recombination is longer than the transit time ($\tau_r > \tau_T$). In the absence of electron traps, when transport is completely ballistic, these structures exhibit suppressed shot noise due to the action of long-range Coulomb interaction, which introduces negative correlations between carriers by means of the fluctuating potential barrier (related to the presence of space charge) that controls the current [16–19]. Since trapped carriers act as negative (and fluctuating) fixed charge that, via Coulomb interaction, can modify the height of the potential barrier, the presence of electron GR processes is expected to have an influence on both carrier transport and noise. In particular, we show that Coulomb repulsion originates positive correlations between transmitted electrons due to the fluctuations of the fixed charge, thus leading to an increase of the shot-noise level (which in some cases reaches values corresponding to enhanced shot noise, $\gamma > 1$, revealing the presence of super-Poissonian carrier statistics) with respect to that found in the purely ballistic case.

We analyse the joint action of GR processes and Coulomb repulsion by means of an ensemble Monte Carlo (MC) simulator self-consistently coupled with a one-dimensional (1D) Poisson solver (PS). The MC method [20] has been proven to be specially appropriate for the analysis of shot noise when a microscopic description of the system accounting for Coulomb interaction is required [13, 16–18, 21–23], as in our case. Trapping–detrapping processes are modelled in a simple way [24, 25] by means of energy- and space-independent generation and recombination times.

2. Physical model

For the calculations we use the following simple model: a lightly doped active region of a semiconductor sample of length L, where the presence of electron traps is considered, sandwiched between two heavily doped contacts (of the same semiconductor) which act as thermal reservoirs by injecting carriers into the active region. The sample is assumed to have a transversal size sufficiently thick to allow a 1D electrostatic treatment. Accordingly, the simulation is 1D in real space and three-dimensional (3D) in momentum space. The doping of the contacts n_c is taken to be much higher than that of the active region N_D, so that the voltage drop inside them is considered to be negligible and they remain always at thermal equilibrium. The electron gas is assumed to be nondegenerate to exclude possible correlations due to Fermi statistics. Thus, electrons are emitted from the contacts according to a thermal-equilibrium Maxwell–Boltzmann distribution at the lattice temperature, and they are injected following a Poissonian statistics, i.e. the time between two consecutive electron emissions is generated with a probability $P(t) = \Gamma e^{-\Gamma t}$, where $\Gamma = \frac{1}{2} n_c v_{th} S$ is the injection rate, with $v_{th} = \sqrt{2k_B T/\pi m}$ the thermal velocity, S the cross-sectional area of the device, k_B the Boltzmann constant, T the lattice temperature and m the electron effective mass [18]. This Poissonian injection is at the origin of the presence of shot noise in the structures. Any carrier inside the active region reaching the boundary with a contact during its dynamics is absorbed by the thermal reservoir and cancelled from the simulation. Thus, the net injection rate at the contacts is Γ minus the number of absorbed carriers per unit time. While the incoming rate Γ is imposed by the presence of the ideal thermal reservoirs, the exiting rate depends on the carrier dynamics inside the active region, and thus on the applied voltage, so that the resulting net injection rate is also bias dependent.

For the simulations we have used the following set of parameters: $L = 200$ nm, $T = 300$ K, relative dielectric constant $\varepsilon_r = 11.7$, $n_c = 4 \times 10^{17}$ cm^{-3} and $m = 0.25 m_0$ (m_0 being the free-electron mass). The above set of values yields for the dimensionless parameter $\lambda = L/L_{Dc}$ (with L_{Dc} the Debye length corresponding to n_c), which characterizes the importance of electrostatic screening [18, 19], the value 30.9. This high value of λ implies significant space-charge effects inside the structure, and, as a consequence, significant noise suppression when transport is completely ballistic [16, 18].

A single type of electron trap, initially neutral and empty, at an energy E_n below the bottom of the conduction band is present in the active region. We use the following simplified model [24, 25] for the trapping–detrapping processes in order to detect plainly their influence on the noise. It is assumed that the traps only interact with electrons in the conduction band. Two time constants are involved in these processes: the recombination time τ_r (average *free time* of an electron), and the generation time τ_g (average *captured time* of an electron). These times are respectively given by the expressions [26]: $1/\tau_r = v_{th} s (N_t - n_t)$, where s is the capture cross section of the traps, N_t is the density of electron traps, and n_t is the density of trapped electrons; and $1/\tau_g = \nu_0 \exp(-q E_n / k_B T)$, where ν_0 is a vibration frequency. As long as $n_t \ll N_t$, and N_t is uniform in the active region (as it is assumed in our model), τ_r can be considered to be independent of the electron position. To evidence more clearly the predicted effect, as a first approximation τ_r is also considered energy independent [24]. It is assumed that the scattering mean free path ℓ is much longer than the sample length, $\ell \gg L$; consequently, electrons move ballistically inside the active region, only interrupted by trapping processes. Accordingly, the free-flight time (before an electron is trapped) is determined stochastically as $t_f = -\tau_r \ln r$, where r is a random number uniformly distributed between 0 and 1. Once a carrier is captured, it remains trapped (with null velocity) for a time $t_t = -\tau_g \ln r$. When the electron is released, its velocity components are randomly determined according to a Maxwellian distribution at the lattice temperature. Traps become negatively charged when electrons are captured. The values of τ_r and τ_g considered in our calculations are $\tau_r = 20$ ps and τ_g ranging between 1 and 7.5 ps. These times, being short enough to bring about affordable computation times [25], are still within the range of real values [26]. Taking into account that the average transit time of electrons through the active region of the structure τ_T is about 1.05 ps under equilibrium conditions, which fulfils $\tau_T < \tau_r$, electrons will cross the sample in a quasi-ballistic way, with very low probability of suffering a trapping process. Anyway, due to the continuous flux of carriers, a significant density of negative fixed charge is present in the active region (according to the model used for GR processes [1], $n_t(x) = n(x)\tau_g/(\tau_r + \tau_g)$, with $n(x)$ being the local free carrier concentration), which affects the carrier transport. As concerns fluctuations, since $\tau_T < \tau_r$, number fluctuations associated with the trapping–detrapping processes are not expected to be significant. However, the fluctuations of the fixed negative charge may have a very important influence on the noise via Coulomb interaction.

In our analysis, a constant voltage U is applied to the structure terminals and current noise is analysed. The temporal correlation between carriers is studied by means of the autocorrelation function of current fluctuations $C_I(t)$, which can be decomposed into three main contributions: $C_V(t)$,

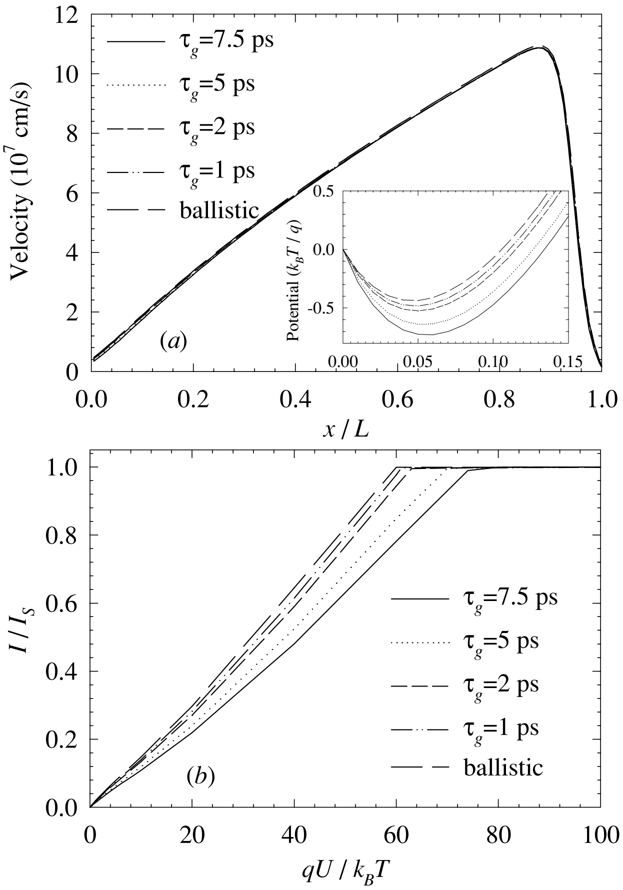

Figure 1. (*a*) Spatial profiles along the active region of average velocity and (inset) normalized potential barrier $q\varphi(x)/k_BT$ at an applied voltage of $40k_BT/q$ and (*b*) current flowing through the sample normalized to the saturation value $I_S = q\Gamma$ as a function of the applied voltage, for $\tau_r = 20$ ps and different values of τ_g. The ballistic case is also plotted for comparison.

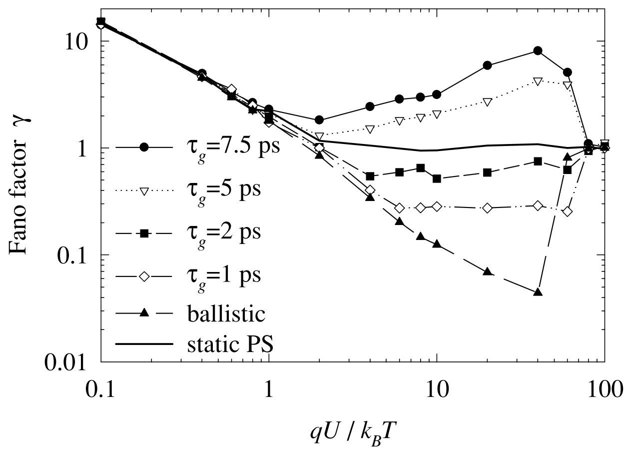

Figure 2. Fano factor versus bias voltage for $\tau_r = 20$ ps and different values of τ_g, and in the ballistic case. The thick solid line corresponds to the case when long-range Coulomb interaction is not considered (for any of the previous conditions).

associated with the fluctuations of the mean velocity of electrons; $C_N(t)$, relative to the fluctuations of the free-carrier number (caused by the random injection at the contacts and the GR processes); and their cross-correlation $C_{VN}(t)$ [18]. The corresponding spectral densities are determined by Fourier transform of the respective correlation functions. The Fano factor, the key parameter to characterize the level of shot-noise suppression/enhancement, is then evaluated as $\gamma = S_I/2qI$.

3. Results

Figure 1(*a*) shows the mean velocity of free electrons in the active region of the structure, for an applied voltage of $40k_BT/q$, when GR processes are characterized by $\tau_r = 20$ ps and several values of τ_g are considered. The purely ballistic case is also plotted for comparison. The velocity increases continuously along the structure until approaching the end of the active region, where it decreases due to the thermal carriers injected by the anode [18]. No significant differences are observed between the diverse curves. The probability of suffering a recombination mechanism by an electron crossing the active region is so low that the transport characteristic is not substantially altered by the presence of the traps and, thus, it remains quasi-ballistic. For this applied voltage the potential profile presents a minimum close to the cathode acting as a potential barrier for the electrons moving between the contacts [16–19]. This potential minimum is reported in the inset of figure 1(*a*) for the previous cases. For a fixed value of τ_r, as τ_g increases electrons remain trapped longer, and thus a higher concentration of fixed charge $n_t(x)$ is present. This increment of n_t leads to a higher potential barrier and, as a consequence, to lower values of the current for a given applied voltage, as observed in the current–voltage characteristics shown in figure 1(*b*). We remark that the current decreases because there are less free electrons injected with sufficient energy to pass over the barrier, and not because of a reduction of the mean velocity associated with the GR processes. The saturation of the current (due to the disappearance of the barrier) in the presence of GR processes takes place for higher applied voltages (increasing with τ_g) than in the ballistic case, in accordance with the larger potential barrier originated by the fixed charge concentration. Two processes with different characteristic times can lead to fluctuations in the amplitude of this barrier controlling the current: the flow of carriers through the structure, characterized by the transit time τ_T; and the trapping–detrapping processes, characterized by the electron lifetime $\tau_l = \tau_r\tau_g/(\tau_r + \tau_g)$ [1]. The former process is known to lead to shot-noise suppression by introducing negative correlations between transmitted carriers [16–19], while the latter, as we show in the following, leads to positive correlations which increase the level of noise with respect to that found in the purely ballistic case.

Figure 2 shows the Fano factor at low frequency as a function of the applied voltage for the same cases of the previous figure. Calculations performed with a *frozen* potential profile (static PS) [16], thus in the absence of long-range Coulomb interaction, coincide for all cases, and are represented by the thick solid line. Without this interaction, full shot noise associated with the Poissonian carrier injection at the contacts is always found, which indicates that all the differences observed between the reported results are related to Coulomb repulsion. The presence of GR processes increases

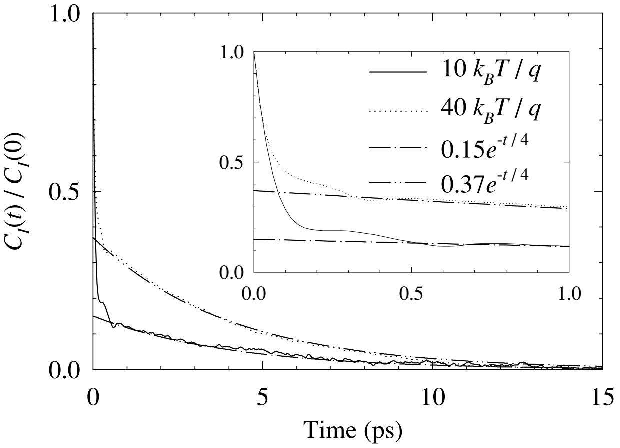

Figure 3. Autocorrelation function of current fluctuations $C_I(t)$ normalized to the zero-time value $C_I(0)$ corresponding to two applied voltages for which enhanced shot noise is found. The short-time decay is reported in the inset. The GR characteristic times are $\tau_r = 20$ ps and $\tau_g = 5$ ps.

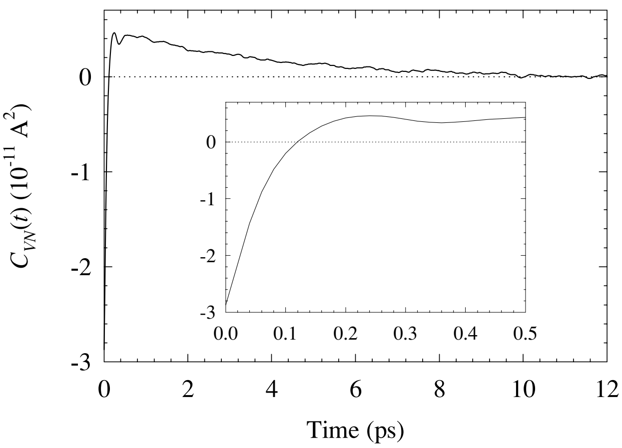

Figure 4. Velocity-number contribution $C_{VN}(t)$ to the autocorrelation function $C_I(t)$ for an applied voltage of $40k_BT/q$ and GR characteristic times $\tau_r = 20$ ps and $\tau_g = 5$. The inset details the short-time behaviour.

the level of shot noise with respect to the ballistic case in the range of applied voltages for which suppression was found under ballistic conditions. As τ_g becomes longer, so that the influence of capture processes is more important (a higher density of fixed charge is present), increasing values of the Fano factor are found, even reaching enhanced shot noise ($\gamma > 1$) for $\tau_g = 5$ and 7.5 ps. Remarkably, the maximum enhancement of noise in the presence of GR processes occurs for the applied voltages for which the most significant suppression takes place in the ballistic case ($40k_BT/q$), that is, when Coulomb interaction exerts the strongest influence on the noise. For applied voltages for which this interaction is not expected to modify the noise, the values of the Fano factor for the different τ_g and in the ballistic case are practically the same. This happens for low applied voltages, when the noise is basically thermal, and under saturation conditions, when there is no longer a barrier modulating the current. The fact that the noise level under saturation does not increase with respect to the ballistic case confirms that, as expected since $\tau_r > \tau_T$, number fluctuations related to GR processes provide a negligible direct contribution to the current noise; their influence takes place only by means of Coulomb interaction.

In the following we illustrate the origin of the outstanding result reported in figure 2. To this end we focus on the significant cases of $\tau_r = 20$ ps and $\tau_g = 5$ ps, for which enhanced shot noise appears. Figure 3 shows the autocorrelation function of current fluctuations $C_I(t)$ for applied voltages of 10 and $40k_BT/q$, at which the potential barrier modulates the current and enhances the noise. Firstly, a short-time decay related to the transit time through the active region (about 0.2–0.4 ps for these values of U) is observed (inset), also found when transport is completely ballistic [18]. Then, the autocorrelation functions present a further exponential decay with a characteristic time of about 4 ps (as indicated by the exponential fits shown in the figure), which corresponds exactly to the lifetime τ_l of the trapping–detrapping processes. Thus, this exponential contribution, responsible for the noise enhancement, is clearly associated with the GR phenomena, its influence being more significant the higher the applied voltage (and therefore the current). Remarkably, the long-time decay is not observed when a static PS is used, or under conditions when long-range Coulomb interaction is not expected to affect the noise, such as saturation (in the absence of a potential barrier). This confirms again that the exponential contribution is not caused directly by number fluctuations related to GR phenomena. Actually, the shot-noise enhancement found in our results is due to the influence of the trapped-charge fluctuations on the current taking place by means of the associated potential barrier modulation induced by long-range Coulomb interaction.

To identify more clearly the origin of the enhanced shot noise related to the exponential decay found in $C_I(t)$, figure 4 shows the velocity-number component $C_{VN}(t)$ of the autocorrelation function for an applied voltage of $40k_BT/q$. It can be observed that the previous positive long-time contribution is also present in the cross correlation between fluctuations of mean velocity and free-carrier number N. Initially, at the shortest times, $C_{VN}(t)$ is negative, like under ballistic conditions [16], due to the transit of carriers through the active region. However, $C_{VN}(t)$ becomes positive at longer times, thus revealing a positive correlation between carriers related to the trapping–detrapping processes. When an electron is captured, it becomes a negative fixed charge which increases the potential barrier (leading to a decrease of N). As a consequence, less electrons have sufficient energy to pass over this barrier; the electron mean velocity and the current decrease. On the other hand, when a trapped electron is released, the potential barrier decreases (allowing an increase of N) and more electrons are able to surpass the barrier; the mean velocity and the current increase. Thus, a positive correlation is established between carriers contributing to the current with energies around the potential barrier, leading to a super-Poissonian distribution of transmitted carriers and therefore to shot-noise enhancement. Of course, the characteristic time of these correlations is the lifetime associated with the GR processes, since this is the time which governs the time evolution of captured electrons. We have checked that the described effect is more pronounced the closer the captured electron is to the potential barrier [27].

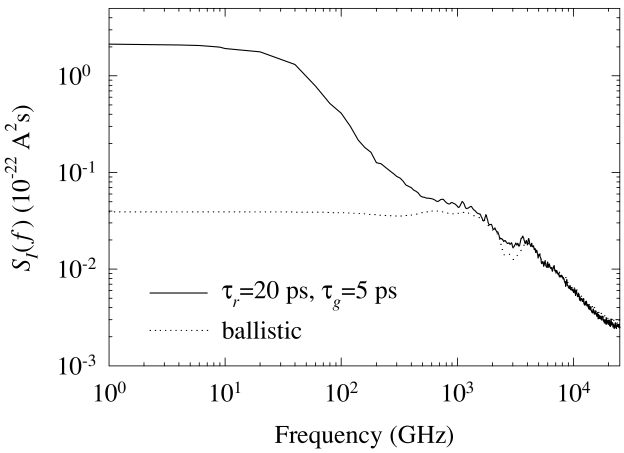

Figure 5. Spectral density of current fluctuations $S_I(f)$ as a function of frequency for an applied voltage of $40k_BT/q$ and GR characteristic times $\tau_r = 20$ ps and $\tau_g = 5$. $S_I(f)$ in the ballistic case is also plotted.

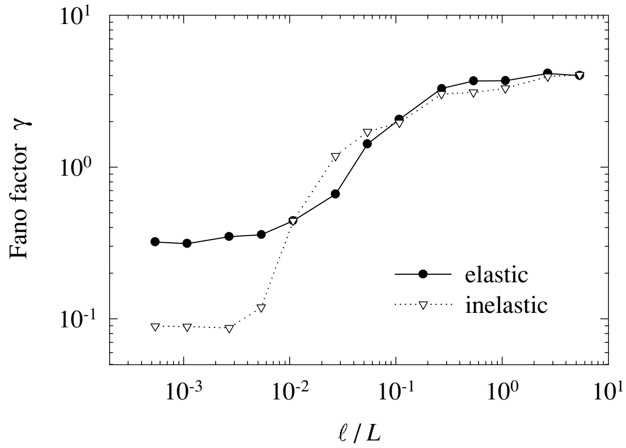

Figure 6. Fano factor versus ℓ/L in the transition from quasi-ballistic to diffusive regime considering elastic and inelastic scattering mechanisms (separately) and GR processes characterized by $\tau_r = 20$ ps and $\tau_g = 5$ ps.

The spectral density of current fluctuations $S_I(f)$ for an applied voltage of $40k_BT/q$ is shown in figure 5, calculated as the Fourier transform of the corresponding $C_I(t)$ reported in figure 3. $S_I(f)$ in the ballistic case is also plotted for comparison. According to the short- and long-time behaviours found in $C_I(t)$, two plateaus are observed in $S_I(f)$. At low frequency, a first plateau relative to the enhanced shot noise due to GR processes is observed, associated with the long-range decay in the autocorrelation function. At high frequency, beyond the cut-off of GR phenomena ($f \gg 1/2\pi\tau_l$), a second plateau is detected, associated with the short-time decay. The value of $S_I(f)$ in the second plateau practically coincides with the low-frequency value of $S_I(f)$ in the ballistic case, related to shot-noise suppression. Therefore, our system displays enhanced or suppressed shot noise depending on the frequency range of observation.

The effect of the trapping–detrapping processes on the noise takes place because of the determining control that the potential barriers exert on the current flow. If such a control is diminished, or even washed out, the observed enhanced shot noise is predicted to disappear. To check this fact, we consider now, apart from GR processes, the additional presence of elastic and inelastic (completely thermalizing) scattering mechanisms in the active region of the structure, characterized by an energy-independent relaxation time τ_s and assumed to be isotropic [21, 22]. In this new situation, the free-flight time is stochastically determined according to the expression $t_f = -\tau_f \ln r$, where $\tau_f = \tau_r\tau_s/(\tau_r + \tau_s)$ [25]. At the end of the free flight, the type of process taking place, scattering or trapping, is randomly selected according to the respective probabilities $1/\tau_s$ and $1/\tau_r$. This model for scattering, even if it is simple and does not contain all the details of the typical scattering processes in semiconductors, yields a clear idea of the influence that elastic interactions and thermalizing processes have on the noise, as illustrated in previous works [21, 22]. The transition between quasi-ballistic and diffusive transport regimes is monitored by the ratio ℓ/L, where $\ell = v_{th}\tau_s$ is the carrier mean free path. Figure 6 presents the Fano factor at low frequency as a function of ℓ/L, for an applied voltage of $40k_BT/q$, when τ_s is decreased from 10 to 0.001 ps, in the presence of GR processes characterized by $\tau_r = 20$ ps and $\tau_g = 5$ ps. Both elastic and inelastic mechanisms are considered (separately). For the highest values of ℓ/L, when transport is quasi-ballistic, the Fano factor exhibits values corresponding to the enhanced shot noise related to GR processes. For lower values of ℓ/L (as the scattering probability increases) in the transition from the quasi-ballistic to diffusive regime, γ decreases and enters a range of values corresponding to shot-noise suppression ($\gamma < 1$). Finally, under the fully diffusive regime ($\ell/L < 3 \times 10^{-3}$), γ becomes independent of the scattering rate. Remarkably, in this regime the Fano factor exhibits the same values as those found in the absence of GR processes: about 1/3 in the case of elastic diffusive transport, and about 0.08 in the inelastic case [21, 22]. These levels of shot-noise suppression are due to the joint action of Coulomb repulsion and scattering mechanisms under space-charge limited conduction [28, 29]. When a scattering process occurs, the velocity is randomized; in particular, the electron energy in the direction of the potential barrier is modified . As a consequence, in the diffusive regime the potential barrier no longer controls the current flowing through the device, and GR processes lose their influence on the noise. Therefore, the presence of GR processes is determining in the noise behaviour under the quasi-ballistic regime, but it has no influence under diffusive conditions.

4. Conclusions

An ensemble self-consistent MC simulation has been used to investigate the influence of trapping–detrapping processes on the shot-noise suppression observed in nondegenerate ballistic transport. A simple model in which the involved times are considered to be energy and position independent is used in order to detect distinctly the influence of the GR phenomena. An increase of the noise level at low frequency with respect to the values found in the ballistic case is observed, and even enhanced shot noise is obtained. The potential barrier fluctuations induced by the fluctuating fixed charge via long-range Coulomb interaction are at the origin of this effect.

At high frequency, beyond the cut-off of GR phenomena, the suppressed shot noise of the ballistic case is recovered. When carrier transport becomes diffusive, the potential barrier does not control the current, and thus no influence of GR processes is observed. Finally, we point out that if more realistic models including energy and space dependence of τ_r are considered, the predicted effect is reduced, but it is still clearly noticeable [27].

Acknowledgments

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