Electron transport and shot noise in ultrashort single-barrier semiconductor heterostructures

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(Received 19 April 2000; published 31 January 2001)

We present a theoretical study of electron transport and shot noise in ultrashort single barrier semiconductor structures. Calculations are applied to a simple GaAs semiconductor model in the presence of ballistic and thermalized carriers. The coupling between space charge and the dependence of the transmission coefficient on energy is found to provide the positive feedback that enhances shot noise and ultimately leads to a current instability of *S* type. When the strength of this feedback is weak, shot-noise suppression is observed. The occurrence of enhanced shot noise is explained in terms of a negative lifetime related to carrier escape through the collector contact. The model also predicts shot-noise enhancement in single barrier structures with constant transparency in the region of current saturation. Theoretical results are in qualitative agreement with existing current-voltage experiments and confirm recent Monte Carlo simulations evidencing shot-noise enhancement in GaAs/AlGaAs semiconductor heterostructures. Shot-noise enhancement is found to be a precursor indicator that the device is approaching an instability regime in analogy with the case of phase transitions.

DOI: 10.1103/PhysRevB.63.085302 PACS number(s): 72.70.+m, 72.20.−i, 73.23.Ad

I. INTRODUCTION

Semiconductor heterostructures are very interesting nonlinear devices showing several kind of electrical instabilities if a sufficiently high bias is applied. In particular they exhibit *S*-shaped current voltage (I-V) characteristics that can be conveniently used for fast switching, microwave generators, and amplifying devices.[1,2] The single barrier heterostructure is the prototype of these devices, and as such received great interest since it appeared in as heterostructure hot electron diode.[3–10] The microscopic mechanisms responsible for the I-V characteristics have been associated with the tunneling and thermionic regimes that control the transport at different applied voltages. Accordingly, several theoretical modelings, mostly based on detailed Monte Carlo simulations, have been applied to understand and predict the salient features of the transport properties of these devices.[5–8,11,10] Despite this interest in the I-V characteristics, the study of the noise property of these structures has received some attention only recently in the context of the problem of shot-noise suppression and/or enhancement.[12–15] It is very interesting and useful to study noise in switching devices, because noise is the same tool, which indicates how far the system is from the instability region. Since the transport properties of these devices are controlled by carrier number, shot noise is the primary noise source of interest.

Shot noise is the electrical fluctuation due to discreteness of the charge that provides direct information on the correlation of different current pulses and as such is receiving increased attention from the scientific community. A convenient analysis of shot noise is usually performed by introducing the dimensionless Fano factor $\gamma \geqslant 0$ defined as $\gamma = S_I(0)/(2qI)$, $S_I(0)$ being the spectral density of current fluctuations at low frequency, I the current flowing in the device, and q the elementary quantum of charge determining I. In the absence of correlation between current pulses it is $\gamma = 1$, and this case corresponds to full shot noise. Deviations from this ideal case is a signature of existing correlations between different pulses and the two possibilities of suppressed (i.e., $\gamma < 1$) and enhanced (i.e., $\gamma > 1$) shot noise are in principle possible.

Shot-noise suppression is associated with a negative correlation between current pulses as due to Coulomb interaction and Pauli principle, and has been theoretically predicted and experimentally evidenced in a variety of electron devices[16] and mesoscopic structures.[17–26] Shot-noise enhancement is associated with a positive correlation between current pulses and has been experimentally evidenced in double barrier resonant diodes.[27–30] Theoretical models based on the existence of a negative differential conductivity (NDC) region in the I-V characteristic has been also proposed for its explanation.[29,31] Recently, shot-noise enhancement has been observed in Monte Carlo calculations of a single barrier GaAs/AlGaAs structure when the distance between the emitter and the barrier is comparable with the scattering length.[15] The positive feedback between tunneling and space charge has been proposed as the mechanism responsible for the positive correlation between current pulses. However, a quantitative theoretical basis supporting this indication is still lacking.

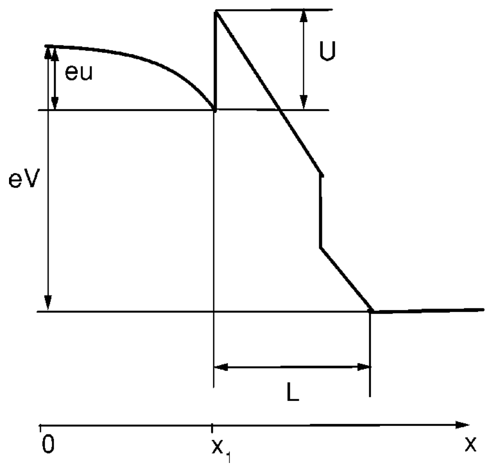

FIG. 1. Sketch of the band diagram of the single barrier structure considered here. Contact resistance at the terminals is neglected for simplicity.

The aim of this paper is to provide a theoretical basis for the understanding of the *I-V* and shot-noise characteristics in single barrier semiconductor structures characterized by ultrashort distances between the emitter and the barrier. Under these conditions, ballistic transport plays a dominant role in determining the current flowing in the structure. Furthermore, because of such a length scale the device enters the realm of the nanostructures, which are attracting most of the attention, to date, in research and development.

The theory developed here is able to explain both sub- and super-Poissonian shot-noise behaviors in terms of the interplay among tunneling, space charge, and ballistic transport. In particular we investigate the positive feedback between tunneling and space charge due to the dependence of the transmission coefficient on the energy of ballistic moving electrons. If this feedback is negligible, then long-range Coulomb correlations between current pulses dominate and shot noise is suppressed. If this feedback is strong enough then an *S*-type *I-V* characteristic appears. In this case the region with NDC is unstable (i.e., here fluctuations grow instead of being damped). Remarkably, enhanced shot noise is found to act as a precursory indicator that the device is approaching an instability regime.

II. THE MODEL

The physical system we analyze is a single barrier structure, as depicted in Fig. 1. By taking a one-dimensional x space and a three-dimensional momentum space, it is assumed the presence of an applied voltage high enough so that carrier injection from the collector is negligible. To describe the electron transport through this structure we use the following analytical model that is supported by Monte Carlo calculations.[15] First we suppose that the distribution function of the particles injected into the structure from the left contact, taken as an ideal thermal reservoir, and acting as an emitter, is of Maxwell type with the concentration and temperature independent of applied voltage, i.e., in the emitter contact

$$f_e(\mathbf{p},x=0)=\exp(-p^2/2mT)n_b/N_c, \qquad \text{for} \qquad p>0, \tag{1}$$

where m is the electron effective mass, T is the temperature measured in energy units, $\mathbf{p}$ is the electron momentum, n_b is the injected carrier concentration, and N_c is the effective density-of-states in the conduction band. Second we assume that in the region between the emitter and the barrier there are two groups of particles. One group contains *ballistic* particles, which do not perform any scattering with the lattice. The other group contains *thermalized* particles that performed at least one scattering. The assumption of a distribution function composed by ballistic and thermalized particles is a reasonable one. Indeed, after a single optical-phonon emission, a ballistic electron is converted into a thermalized one because it cannot return to the emitting contact, and thus it spends a relatively long time in the well when the transparency of the barrier is much smaller than unity. This means that most part of electrons that emit at least one phonon are converted to thermalized electrons. Accordingly, the distribution function of thermalized particles in any point is given by

$$f_{th}(\mathbf{p},x)=n_t\exp[(q\varphi-\varepsilon_k)/T]/N_c, \tag{2}$$

where n_t is a normalization constant, φ the local electric potential, and ε_k the particle kinetic energy. The value of n_t can be calculated from the balance equation for thermalized particles as follows. The incoming rate to the thermalized particle group is the sum of two terms $S_{b1}+S_{b2}$: the first belonging to ballistic particles moving from the emitter to the barrier and the second to ballistic particles moving from the barrier to the emitter after reflection from the barrier. The distribution function of ballistic particles is

$$f_b(\mathbf{p},x)=\begin{cases}\dfrac{n_b}{N_c}\exp\left(-\dfrac{p^2}{2mT}+\dfrac{q\varphi(x)}{T}\right)\beta_1(x), & \text{if} \quad p_x>\sqrt{2mq\varphi(x)},\\ 0, \quad \text{if} \quad -\sqrt{2mq\varphi(x)}<p_x<\sqrt{2mq\varphi(x)}, & \\ \dfrac{n_b}{N_c}\exp\left(-\dfrac{p^2}{2mT}+\dfrac{q\varphi(x)}{T}\right)\beta_2(x)\{1-D(\varepsilon+qu,E)\}, & \text{if} \quad p_x<-\sqrt{2mq\varphi(x)},\end{cases} \tag{3}$$

where $0 \leqslant \beta_1(x) \leqslant 1$ is the probability of nonscattering associated with the motion of ballistic particles from the emitter to the point x, $\beta_2(x)$ is the analogous probability when the particle moves from the emitter to the barrier and back to point x, $D(\varepsilon_k,E)$ is the barrier transparency for ballistic particles depending upon kinetic energy ε_k and the modulus of the electric field E both at the barrier edge, $\mathbf{p}$ is the particle momentum in point x, and $u=\varphi(x_1)$ is the electric potential at the barrier border nearest to the emitter (the first barrier edge), $\varepsilon=p_x^2/2m-q\varphi$. We have chosen the coordinate of contact with the emitter $x=0$ and $\varphi(0)=0$. The first line on the right-hand side of Eq. (3) is the distribution function of ballistic particles moving to the barrier and the third line that of ballistic particles moving towards the emitter after reflection from the barrier.

The term S_{b1} is given by

$$S_{b1}=J_{b1}-J_{b2}=J_{b1}(1-\beta), \tag{4}$$

where the first equality represents the difference between ballistic particle flows from the emitter to the barrier in point $x=0$ (J_{b1}) and in point $x=x_1$ (J_{b2}), and $\beta=\beta_1(x_1)=\sqrt{\beta_2(0)}$ is the probability that the particle crosses the region between the emitter and the barrier without making scattering. Analogously, S_{b2} is given by

$$S_{b2}=J_{b3}-J_{b4}=J_{b3}(1-\beta), \tag{5}$$

where the first equality represents the difference between ballistic particle flows from the barrier to the emitter in point $x=x_1$ (J_{b3}) and in point $x=0$ (J_{b4}), respectively. By using Eq. (3) we can write the following expressions for J_{bi} ($i=1,3$):

$$J_{b1}=An_b v_t,$$

$$J_{b3}=\frac{An_b v_t \beta}{T}\int_0^\infty \exp(-\varepsilon/T)\times[1-D(\varepsilon+qu,E)]d\varepsilon, \tag{6}$$

where A is the cross section of the device and $v_t=(T/2m\pi)^{1/2}$ the thermal velocity .

The escaping rate from the group of thermalized particles is also the sum of two terms $r_{t1}+r_{t2}$: the first being the rate through the emitter and the second the rate through the collector. By using the distribution function for thermalized particles, r_{t1}, r_{t2} take the forms

$$r_{t1}=An_t v_t, \tag{7}$$

$$r_{t2}=\frac{An_t v_t}{T}\int_0^\infty \exp\left(\frac{qu-\varepsilon}{T}\right)D(\varepsilon,E)d\varepsilon. \tag{8}$$

From Eqs. (5) to (8) n_t becomes

$$n_t=n_b\frac{(1-\beta)\left\{T+\beta\int_0^\infty \exp\left(-\frac{\varepsilon}{T}\right)[1-D(\varepsilon+qu,E)]d\varepsilon\right\}}{T+\int_0^\infty \exp\left(\frac{qu-\varepsilon}{T}\right)D(\varepsilon,E)d\varepsilon}. \tag{9}$$

The dependence of $D(\varepsilon)$ is taken within the quasiclassical approximation for a triangle barrier, as

$$D(\varepsilon,E)=\begin{cases}\exp\left(-\frac{4\sqrt{2m}(U-\varepsilon)^{3/2}}{3\hbar qE}\right), & \text{if } \varepsilon<U,\\ 1, & \text{if } \varepsilon>U,\end{cases} \tag{10}$$

where U is the barrier height.

III. CURRENT-VOLTAGE CHARACTERISTIC

The I-V characteristic is determined as follows. The total current through barrier I is the sum of the ballistic, I_b, and thermalized particle current I_t, given by

$$I=I_b+I_t=-q(r_{b2}+r_{t2}), \tag{11}$$

where r_{b2} is the flow of ballistic particles through the barrier given by

$$r_{b2}=An_b v_t\beta\frac{1}{T}\int_0^\infty \exp(-\varepsilon/T)D(\varepsilon+qu,E)d\varepsilon. \tag{12}$$

By neglecting the charge density in the region between the first barrier border and the collector and denoting this region length by L (see Fig. 1), the total voltage V is related to u as

$$V=u+EL. \tag{13}$$

To determine E as function of u we solve the Poisson equation in the region between the emitter and the barrier. Accordingly, we assume that the fixed donor concentration in the structure is negligible with respect to the concentration of the injected particle and, therefore, the space charge in this region is caused by injected carriers. From Eq. (3) it is clear that the ballistic particle concentration drops with the rise of φ (for a monochromatic flow the concentration goes inversely with velocity) and therefore the ballistic particle charge takes the maximum value near to the emitter contact. On the contrary, the charge density of thermalized particles takes the minimum value near to the emitter contact and the maximum value near to the barrier border, where they are accumulated. To calculate the charge density of ballistic particles we need to know the spatial profiles, $\beta_{1,2}(x)$, in Eq. (3). To this purpose we take $\beta_1(x)=\beta_1(0)=1$ and $\beta_2(x)=\beta_2(0)=\beta^2$. This choice is a good approximation for the charge of the ballistic particle in the region near to the emitter, where this charge is important. Thus, in the region between the emitter and the barrier, the Poisson equation is well approximated as

$$\frac{d^2\varphi}{dx^2}=\frac{4\pi q}{\kappa}\left[\frac{n_b}{2\sqrt{\pi T}}\int_0^\infty \frac{\exp(-\varepsilon/T)[1+\beta^2\{1-D(\varepsilon+qu,E)\}]}{\sqrt{2(\varepsilon+q\varphi)}}d\varepsilon+n_t\exp(q\varphi/T)\right]. \quad (14)$$

By integrating Eq. (14) we find that E is given implicitly by

$$E=\sqrt{\frac{8\pi}{\kappa}\{F(u,E)+n_tT[\exp(qu/T)-1]\}+E_e^2}, \quad (15)$$

where

$$F(u,E)=\frac{n_b}{\sqrt{\pi T}}\int_0^\infty \exp(-\varepsilon/T)[\sqrt{\varepsilon+qu}-\sqrt{\varepsilon}]\times[1+\beta^2\{1-D(\varepsilon+qu,E)\}]d\varepsilon, \quad (16)$$

and E_e is electric field in the emitter contact.

For high enough voltages, E is defined by the space charge between the emitter and the barrier, thus $E\gg E_e$ and E_e in Eq. (15) can be neglected. We note, that D is a function of E [see Eq. (10)] and, therefore, by solving Eq. (15) we can find the dependence $E(u)$. Thus, Eqs. (11), (13), and (15) provide the parametric dependence of the total current on the total voltage $I(u)$, $V(u)$.

IV. NOISE

In the present model electron transport is controlled by the voltage drop between the emitter and the barrier, or by the electric field in the barrier [these values are connected by Eq. (15)]. Since the electric field in the barrier is proportional to the total number of particles between the emitter and the barrier N, the electron transport is ultimately governed by N. An analogous situation takes place in the resonant tunneling diode,[29] and we will take advantage of the corresponding results. Accordingly, for the spectral density of current fluctuations we use Eq. (45) of Ref. [29], which pertains to the same condition of an applied voltage high enough to neglect the electron flow from the collector into the device. In the Appendix we present an alternative derivation of Eq. (45) of Ref. [29]. Thus, the Fano factor is conveniently written as

$$\gamma=1-2\alpha+2\alpha^2\frac{\overline{g_1}}{\overline{r_2}}, \quad (17)$$

where

$$\alpha=\frac{\nu_2}{\nu_2+\nu_1}. \quad (18)$$

Here g_1 is the injected particle flow from the emitter (i.e., the generation rate of particle in the device), r_1, r_2 are the particle flows to the emitter and to the collector respectively (i.e., the recombination rates through the emitter and the collector, respectively), and the overline denotes time average. Furthermore, $\nu^{-1}=(\nu_1+\nu_2)^{-1}$ is the lifetime associated with the rate equation for carrier number fluctuations δN with ν_1^{-1} and ν_2^{-1} being the lifetimes related to the damping of δN due to the corresponding current fluctuation through the emitter and the collector, respectively. The inverse lifetimes $\nu_{1,2}$ are given by

$$\nu_1=\frac{dr_1}{dN}-\frac{dg_1}{dN}, \quad \nu_2=\frac{dr_2}{dN}. \quad (19)$$

In the above equations the values of the derivatives must be taken at $N=\overline{N}$. We note also that the generation rate is independent of N and, therefore, $dg_1/dN=0$. The recombination rates are the sums of a ballistic with a thermalized part as $r_i=r_{bi}+r_{ti}$ (i=1,2). The expressions for $r_{t1,t2}$ and r_{b2} are given in Eqs. (7), (8), and (12), respectively. By using Eq. (3), r_{b1} takes the form

$$r_{b1}=\frac{An_bv_t\beta^2}{T}\int_0^\infty \exp(-\varepsilon/T)[1-D(\varepsilon+qu,E)]d\varepsilon. \quad (20)$$

Since the value of the electric field at contact with the emitter is small when compared with that on the first barrier border, E is defined by N as

$$E=\frac{4\pi qN}{A\kappa}. \quad (21)$$

Under constant voltage conditions there is no voltage fluctuations, i.e., $\delta V=0$, and by using Eqs. (13) and (21) it is

$$\frac{du}{dN}=-\frac{4\pi qL}{A\kappa}. \quad (22)$$

To calculate $\nu_{1,2}$ we must first find the follow derivative dn_t/dN. By using Eqs. (21) and (15) we arrive at the following expression for dn_t/dN:

$$\frac{dn_t}{dN}=\frac{\{q^2E/A-qn_t\exp(qu/T)du/dN-\partial F(u,E)/\partial u du/dN-\partial F(u,E)/\partial N 4\pi qN/A\kappa\}}{T[\exp(qu/T)-1]}. \tag{23}$$

We note that $\nu_{1,2}$, being expressed through $r_{1,2}$, are sum of two terms, one corresponding to ballistic particles and the other to thermalized particles as $\nu_i=\nu_{bi}+\nu_{ti}$, $(i=1,2)$. The different terms ν_{b1}, ν_{b2} and ν_{t1}, ν_{t2} take the following expressions:

$$\nu_{b1}=-An_b v_t \beta^2 \frac{1}{T}\int_0^\infty \exp\left(-\frac{\varepsilon}{T}\right)\frac{dD(\varepsilon+qu,E)}{dN}d\varepsilon, \tag{24}$$

$$\nu_{b2}=An_b v_t \beta \frac{1}{T}\int_0^\infty \exp\left(-\frac{\varepsilon}{T}\right)\frac{dD(\varepsilon+qu,E)}{dN}d\varepsilon, \tag{25}$$

$$\nu_{t1}=Av_t\frac{dn_t}{dN}, \tag{26}$$

$$\nu_{t2}=Av_t\frac{1}{T}\left(\frac{qn_t}{T}\frac{du}{dN}+\frac{dn_t}{dN}\right)\int_0^\infty \exp\left(\frac{qu-\varepsilon}{T}\right)D(\varepsilon)d\varepsilon, \tag{27}$$

where

$$\frac{dD(\varepsilon+qu,E)}{dN}=\left[\frac{q\partial D(\varepsilon+qu,E)}{\partial u}\frac{du}{dN}+\frac{\partial D(\varepsilon+qu,E)}{\partial E}\frac{4\pi qN}{A\kappa}\right]. \tag{28}$$

The set of Eqs. (10) and (16)–(19) provide the analytical representation of the Fano factor as a function of the applied voltage corresponding to the I-V characteristic reported in the previous section.

A. Remarks on noise formula

Before applying the theory developed above to concrete cases of electron transport in single barrier structures, let us analyze the general properties associated with the Fano factor expressed by Eq. (17) as applied to the present structure. From the electrical point of view, the single barrier structure is a two terminal device with an emitter contact, an active region, and a collector contact. Because of the high-voltage conditions here considered, the active region is comprised between the emitter and the first edge of the barrier. Within this scheme, the instantaneous total current can be decomposed into two contributions (see Appendix): the first gives the average total current and its fluctuations are Poissonian, the second is null in average and is connected with the fluctuations of the total number of carriers inside the active region δN. As it is shown in Appendix A the three terms on the right-hand side of Eq. (17) for the Fano factor are understood as follows. The first term is equal to unity and is due to the autocorrelation of the Poissonian current contribution. The second term provides a negative contribution and is due to the cross correlation between the Poissonian current and the number fluctuation current. Being in the present case $\nu_1+\nu_2\geqslant 0$, the sign of the contribution itself is determined by the sign of ν_2. For $\nu_2>0$, when the change of the current flow to the collector due to δN promotes the enhancement of the damping rate for this fluctuation, the sign of this contribution is positive, thus leading to suppress full shot noise. In this case we speak of a negative feedback between tunneling and space charge. For $\nu_2<0$, when the change of the current flow to the collector due to δN promotes the suppression of the damping rate for this fluctuation, the sign of this contribution is negative, thus leading to enhanced shot noise. In this case we speak of a positive feedback between tunneling and space charge. The third term is always positive and is due to the autocorrelation of the current connected with δN. This contribution always yields enhanced shot noise.

Remarkably, we note that full shot noise (i.e., $\gamma=1$) is recovered in two cases. The former case corresponds to the condition $\nu_2=0$, when the current contains only the Poissonian contribution and $\gamma=1$. The latter case corresponds to the condition $r_{1,2}=N\nu_{1,2}$, when particles cross the device independently and $\gamma=1$. Indeed, in this latter case $r_{1,2}=N\nu_{1,2}$ since the flows of independent crossing particles is proportional to N and therefore the sum of the second and the third contributions in the right-hand side of Eq. (17) equals zero. It is also clear from Eq. (17) that for $(\overline{r_2}/\overline{g_1})\alpha>0$, shot noise is suppressed, while outside this region it is enhanced. At the borders of the suppressed region, where $\alpha=0$ and $\alpha=\overline{r_2}/\overline{g_1}$ there is full Poissonian noise and $\gamma=1$. The whole scenario for the possible values of the Fano factor is shown in Fig. 2. Here, one region of suppressed shot noise, two regions of enhanced shot noise, and the region of electrical instability are shown in the plane ν_1,ν_2 for a given value of $(\overline{r_2}/\overline{g_1})<1$. The maximum value of the Fano factor tends to infinity and takes place at the boundary of the instability region, where $\nu_1+\nu_2=0$ and $\alpha\to\infty$. The minimum value of the Fano factor equals $\gamma=\gamma_{\min}=1-\overline{r_2}/(2\overline{g_1})$ and takes places when $\nu_2=\nu_1\overline{r_2}/(2\overline{g_1}-\overline{r_2})$. We note that $\overline{r_2}/\overline{g_1}=I/I_0$ is the part of the current injected from the emitter I_0, which passes to the collector. In the instability region, where $\nu_1+\nu_2<0$, we assist to the growth of current fluctuations instead of its damping and the Fano factor loses of physical meaning.

As was mentioned above in the first enhanced noise region, where $\nu_1>0$ and $-\nu_1<\nu_2<0$, the change of flow to the collector δr_2 due to δN promotes the decrease of fluctuation damping. In the second enhanced noise region, where $\nu_2>0$, $-\nu_2<\nu_1<\nu_2(\overline{r_1}/\overline{r_2})$, if $\overline{r_1}\neq 0$, then there are regions where $\nu_{1,2}>0$. Here the noise enhancement is connected with the prevailing of the third term in Eq. (17) over the second one. Below, we shall show that this situation can take place in a single barrier structure with a constant barrier transparency. In the remaining part of this region $\nu_1<0$ and

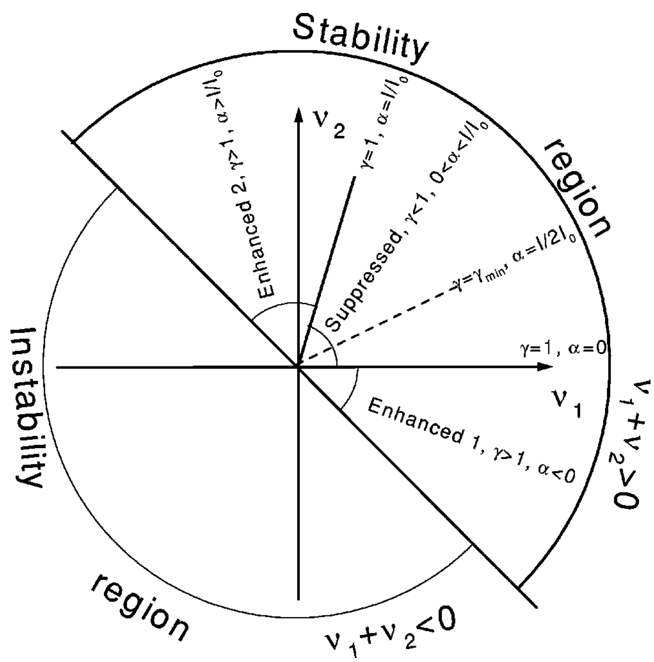

FIG. 2. Lifetime plane of different transport regimes and shot-noise behaviors of a two terminal device with current controlled by number of particles in it under high voltages when $\overline{g_2}=0$.

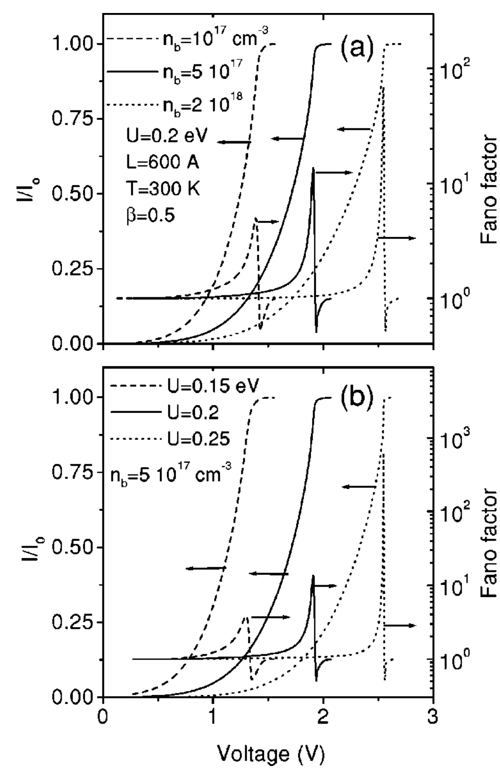

FIG. 3. Current-voltage characteristics and Fano factors for the barrier structure in Fig. 1 for different n_b (a) and different U (b).

the situation is similar to the first enhanced noise region. In this region the change of flow to the emitter δr_1 due to δN promotes the decrease of the fluctuation damping.

V. RESULTS AND DISCUSSION

Here we report numerical calculations with the objective of providing a complete analysis of the electrical and noise properties of semiconductor single barrier heterostructures. The theory developed so far is concerned with a model material of static dielectric constant κ and parabolic conduction band with effective mass m. In calculation, we use everywhere, values for m and κ corresponding to GaAs: $m = 0.067m_0$, $\kappa = 12.9$, and m_0 is the free electron mass, as this is a material appropriate for an experimental validation of the present results. The theory is based on the five external parameters, respectively n_b, U, β, T, and L with the meaning given previously. In Sec. V A the I-V characteristics and the associated Fano factor are analyzed systematically for the case of a triangular barrier structure. Then, for the sake of completeness, Sec. V B will consider also the case of a barrier with constant transparency. The results so presented are intended to predict general trends and should be of interest to address an experimental verification. In some cases, they enable a direct interpretation of Monte Carlo simulations to be carried out.

A. Triangle barrier transparency

According to the general model developed here, in this section we consider the case of a tunneling described by a quasiclassical triangular barrier. First we will discuss the I-V characteristics and then the noise behavior.

1. Current-voltage characteristics

The current-voltage characteristics of triangle barrier structures for different values of the parameters n_b, U, β, T, and L are presented in Figs. 3–5. We note that in the present model the distance between the emitter and the barrier is not considered explicitly but it influences the current through the value of β. Accordingly, $\beta \rightarrow 1$ is associated with ballistic particles and corresponds to short emitter-barrier distances. By contrast, $\beta \rightarrow 0$ is associated with scattered particles, and corresponds to long distances. From these figures one can see the role that is individually played by all the parameters. As a general trend, the current increases monotonically at increasing voltages to finally saturate at sufficiently high voltages. We note, that if we account for the contact resistance, then there is no current saturation due to the voltage drop on the contact resistance. However, since we are interested in the operation mode of the active region of the device, contact resistance will be neglected here. In the increasing region, the current exhibits a strong super-Ohmic behavior due to tunneling processes. In the saturation region the value of the current equals that of the current injected from the emitter. The reason for such a value of current saturation is the absence of any current flow to the emitter coming from both (i) the reflection of ballistic particles by the barrier, and (ii) the thermalized particle. Indeed, because of the high voltages ballistic particles pass over the barrier, and thermalized particles remain confined in the potential well just before the barrier.

The value of the voltage corresponding to the onset for current saturation rises with the increase of n_b, U, β, and L,

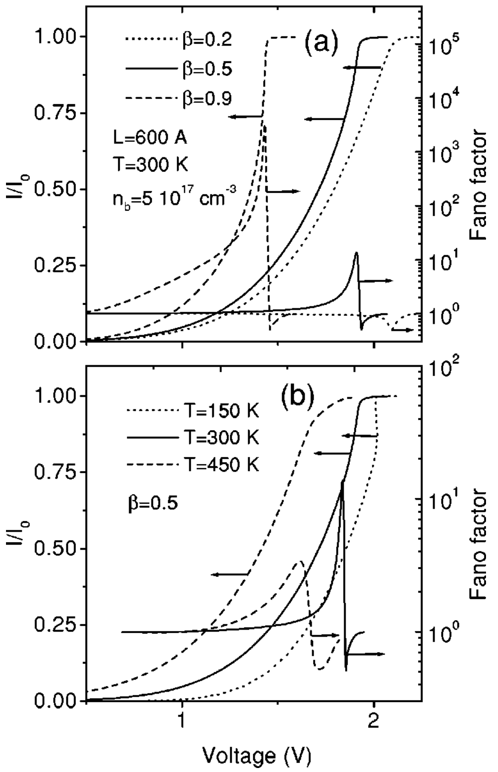

FIG. 4. Current-voltage characteristics and Fano factors for the barrier structure in Fig. 1 for different β (a) and for different T (b).

and with the decrease of T as shown in Figs. 3–5. To understand these behaviors we note that the current starts saturating always when the voltage drop between the emitter and the barrier u is a little bit greater than the barrier height. For a given value of u, the increase of n_b and β leads to the rise of the number of particles accumulated in front of the barrier and, therefore, to an increase of both E and V. For a given value of E the increase of L leads to the rise of V and the increase of U leads to an increase of u ultimately responsible for current saturation. The increase of temperature leads to the decrease of the value of the voltage corresponding to the onset of current saturation. Indeed, on one hand it decreases the part of ballistic particles, which are reflected from the barrier thus reducing the incoming flow to the thermalized group; from another hand it increases the thermionic current from the thermalized group. Both processes reduce the number of particles in the device and, therefore E and V.

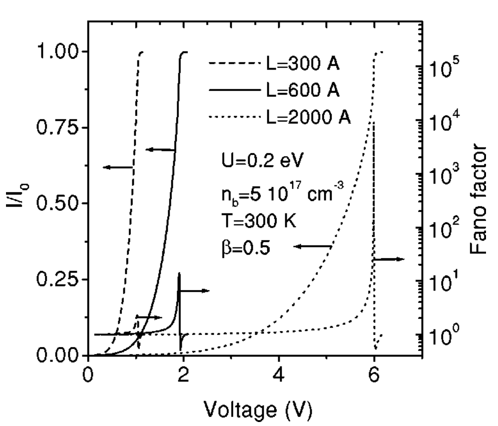

FIG. 5. Current-voltage characteristics and Fano factors for the barrier structure in Fig. 1 for different L.

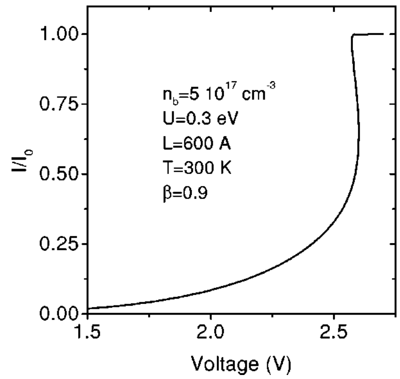

FIG. 6. *S*-type current-voltage characteristics for for the barrier structure in Fig. 1.

In the current saturation region, the ratio of the ballistic current to the total current is independent of n_b and it is determined only by β. From Figs. 3–5 it is clear that the increase of n_b, U, β, L or the decrease of T leads to the increase of the maximum value of the differential conductance dI/dV towards current-voltage characteristics of S type as reported in Figs. 4 and 6. This last figure shows an S-type characteristic that is obtained by a slight increase of the barrier height with respect to the cases presented in Fig. 4.

2. Noise

The dependence of the Fano factor on voltage is reported together with the I-V characteristics in Figs. 3–5. Figures 7 and 8 report the relevant inverse lifetimes as a function of voltages. From Figs. 3–5 one can see that γ depends on voltage for a large variety of parameters and exhibits minima and maxima. In all cases, at the lowest and highest voltages (above current saturation) $\gamma=1$. At the lowest applied voltages, when $qu \ll U$, the damping of δN is provided by the induced increase of the flow of thermalized particles to the emitter. Since the back flow to the emitter is much more important than the flow to the collector, it is $\nu_1 \gg \nu_2$ (see Fig. 7) and $\gamma=1$. At the highest applied voltages, in the saturation current region, the damping of δN is provided by the corresponding change of the flow of thermalized particles to the collector. Accordingly, $\nu_2 \gg \nu_1$ and $\langle g_1 \rangle = \langle r_2 \rangle$, because the flow to the emitter is absent, and therefore again it is $\gamma=1$. In the intermediate region of voltages for the considered values of injection concentration $10^{17} \leq n_b \leq 2\times 10^{18}$ cm^{-3} γ exhibits both a maximum, corresponding to shot-noise enhancement, followed by a minimum corresponding to shot-noise suppression. The maximum value of the Fano factor exhibits a dramatic increase with increasing n_b while the minima remain practically the same with a value around 0.5. Deviations from full shot noise are interpreted in terms of the voltage dependence of the lifetimes, which in turn control the value of α in Eq. (17) (see Figs 7 and 8). To understand the reason for the enhanced shot noise we note that such an

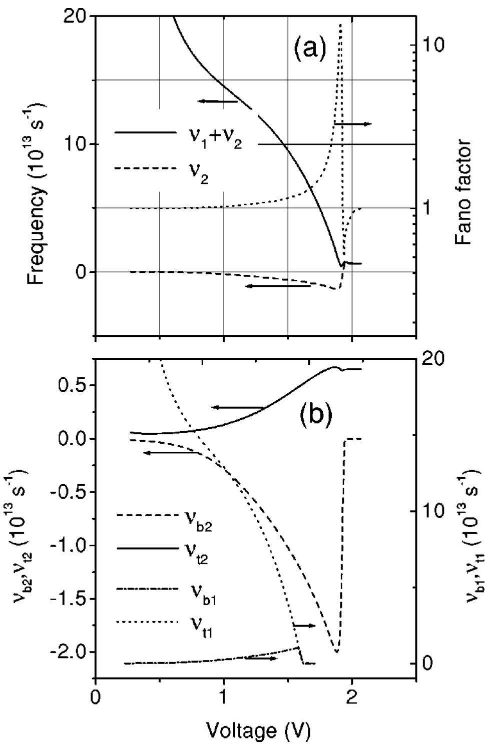

FIG. 7. Inverse lifetimes $(\nu_1+\nu_2)$, ν_2 (a), and relevant rates ν_{bi}, ν_{ti} $(i=1,2)$ (b) for the barrier structure in Fig. 1 with $n_b=5\times10^{17}$ cm^{-3}, $U=0.2$ eV, $L=600$ Å, $T=300$ K, and $\beta=0.5$.

enhancement is related to $\nu_2<0$ [see Fig. 6(a)], and, from Fig. 6(b), one can see that $\nu_2<0$ implies $\nu_{t2}>0$ and $\nu_{b2}<0$. The reason for the negativity of ν_2 when determined by ν_{b2} is as follows. The appearance of $\delta N>0$, according to Eq. (22) is accompanied with $\delta u<0$, i.e., an increase of the barrier height for ballistic particles, and, in turn, a corresponding decrease of the flow of ballistic particles to the collector. Thus, the change of the barrier transparency, which is caused by δN, prevents the damping of the same fluctuation. Of course, if the sum $\nu_1+\nu_2$ is positive then the damping of δN is provided by the corresponding enhancement of the particle flow to the emitter. As a consequence, the dependence $u(N)$ together with the dependence of the barrier transparency on the energy of ballistic particles yield a decrease of the damping rate for δN. This interrelation plays the role of a positive feedback between tunneling and space charge, which ultimately decreases the electrical stability of the structure. We note, that if in Eqs. (15) and (16) we set $dD(\varepsilon+qu,E)/dN=0$, then for any value of the parameters the Fano factor does not exceed unity. We remark that the details of the band structure (nonparabolicity and upper valleys) are not important for bias drop between the emitter and the barrier less than the valley energy separation as considered here.

When $|\nu_{b2}|<\nu_{t2}$ it follows that $\nu_2>0$ and this positive feedback becomes rather weak. As a consequence, the maximum of the Fano factor is absent, as seen in Fig. 4(a) by the curve for $\beta=0.2$. In the presence of high enough voltages, just before current saturation, ballistic particles pass over the barrier and this positive feedback is washed out. Thus, shot noise is suppressed as evidenced by the minima of γ in Figs. 3–5. From Figs. 3–5 one can see that the increase of n_b, U, β, and L or the decrease of T leads to a remarkable increase of the maximum value of γ and also of the maximum of the differential conductivity, i.e., to an increase of the positive feedback. The general trends are that an increase of n_b and U increases the particle accumulation near the barrier and thus Coulomb correlation. The increase of β increases the role of ballistic particles in the current and thus enforces the effect of shot-noise enhancement. The increase of L rises the value of δu for a given δN, the decrease of T rises the sensitivity of the ballistic particle flow to δu.

3. Instability

When the strength of the positive feedback between tunneling and space charge is sufficiently strong, the *I-V* characteristics become of *S*-type [see curve corresponding $T=150$ K in Fig. 4(b) and Fig. 6]. It is known, that a region where the differential conductance is negative is unstable under a constant applied voltage and therefore, instead of being damped, fluctuations grow being only limited by boundary conditions. In this region three values of the total voltage are present for a single value of u and $dV/du<0$ (but the current is a rising function of u). From Fig. 8, where the dependencies of $(\nu_1+\nu_2)$ and dV/du on u are reported, one can see that $(\nu_1+\nu_2)<0$ when $dV/du<0$. This is a relevant condition for the noise description. In the unstable region, the Fano factor loses of physical meaning. However, at voltages near to the instability the Fano factor increases dramatically and tends to infinity when $(\nu_1+\nu_2)=0$. We conclude that shot noise is a sensitive indicator of the fact that the system is moving towards an instability region, this situation resembling that of phase transitions.

From Fig. 8 one can see that most of the instability region $|\nu_1+\nu_2|\sim10^{12}$ s^{-1} corresponds to a very short current switching time ($\approx10^{-12}$ s).

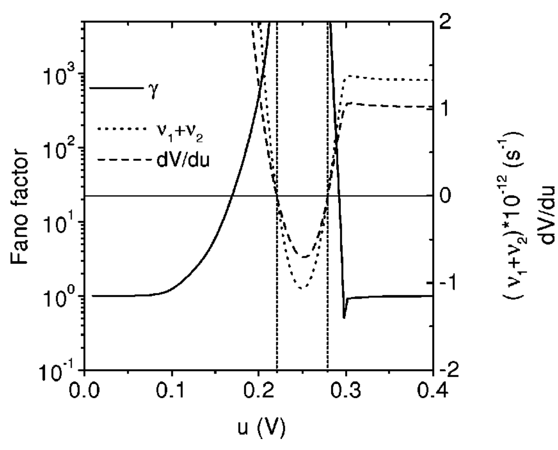

FIG. 8. Fano factor γ, inverse lifetime $(\nu_1+\nu_2)$, and differential voltage drop dV/du as a function of the voltage drop between the emitter and the barrier u for the barrier structure in Fig. 1 in the presence of *S*-type current instability. The structure parameters are the same of those in Fig. 6.

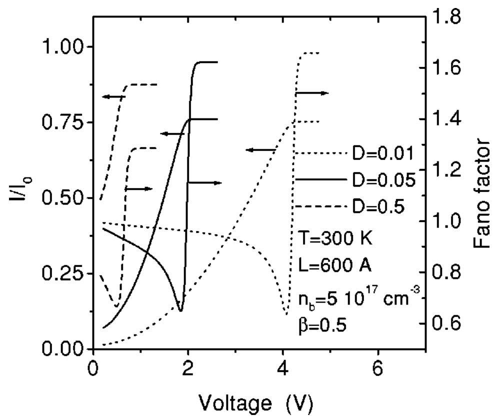

FIG. 9. Current-voltage characteristics and Fano factors for the single barrier structure in Fig. 1 with a constant barrier transparency for different values of the transmission coefficient D.

B. Constant barrier transparency

In the framework of the present model, it is interesting to analyze the situation, when the barrier transparency is independent of energy (it corresponds to the practical case of very high and thin barriers). To this purpose, in Fig. 9 we report the I-V characteristic and γ for the structure with $n_b=5\times10^{17}$ cm^{-3}, $L=600$ Å, $T=300$ K, $\beta=0.5$, and $D=0.01$, 0.05, and 0.5. Here one can see that under high enough voltages the current saturates, but at values smaller than those of the injected current. The reason for such a saturation is the absence of the flow of thermalized particles to the emitter.

In particular, the value of the current of ballistic particles reflected from the barrier to the emitter I_s is given by

$$I_s=Aqn_bv_t\{1-\beta^2(1-D)\}. \tag{29}$$

Thus I_s is increasing with both the increase of the barrier transparency D and/or the decrease of β. It is important to remark, that contrary to the case of the triangle barrier structures, in the saturation region $\overline{g_1}/\overline{r_2}=1/[1-\beta^2(1-D)]>1$. On the other hand, in structures with constant barrier transparency $\nu_{b1}=\nu_{b2}=0$ and in the current saturation region $\nu_2=\nu_{t2}\gg\nu_1=\nu_{t1}$, because the flow of thermalized particles to the emitter is negligible. As a consequence, here $\alpha=1$. By using Eq. (17), in the current saturation region, γ takes the form

$$\gamma=1+\frac{2\beta^2(1-D)}{1-\beta^2(1-D)}\geqslant 1. \tag{30}$$

For these kind of barriers the current saturation region is placed in the second region of enhanced noise of Fig. 2, where $\nu_1\geqslant 0$. The reason for noise enhancement here is the dominant role played in the current noise by the third term on the right-hand side of Eq. (17), which is connected with number fluctuations. From Eq. (30) one can see that the value of γ increases in this region with the increase of β and with the decrease of D as shown in Fig. 9. In the region before current saturation γ exhibits a minimum, and this value decreases with the increase of n_b or the decrease of β and/or of D. The change of T or L changes only the values of the applied voltage at which γ is minimum and the onset of the current saturation region is observed, but it has a little influence on the minimum value taken by γ. We note that, at low applied voltages $\gamma=1$ due to the same reason given for the case of the triangle barrier structure.

VI. CONCLUSIONS

We have presented a theoretical analysis of electron transport and shot noise in ultrashort single barrier semiconductor structures. By using a simple GaAs model, we have studied in detail the influence of the relevant parameters of the device on current transport and shot noise at voltages sufficiently high to neglect carrier injection from the collector. Results evidence the presence of a positive feedback between long-range Coulomb interactions and the dependence of the barrier transparency on energy for ballistic particles, which weakens significantly the damping of carrier number fluctuations. Accordingly, this positive feedback is responsible for shot-noise enhancement in triangular barrier structure, and if its strength is high enough we observe the onset of an S-type I-V instability. We remark that the physical mechanism responsible for enhanced shot noise found here differs from that analyzed for the case of a double resonant diode,[29,30] which is associated with Coulomb effects in electron transport through the resonant state under a N-type I-V characteristics. By contrast, when the strength of the feedback is weak, shot-noise suppression is observed. The model also predicts shot-noise enhancement in single barrier structures with constant transparency in the region of current saturation. The general trends of the model developed here reproduces the qualitative features of the I-V characteristics found in experiments[3–5,9] and agrees with numerical simulations performed with Monte Carlo techniques, which predict shot-noise enhancement.[15] Quantitative agreement is limited by the simplicity of the model, which does not account for details of scattering mechanisms and conduction-band structure to the advantage of a more direct physical insight of calculations. Remarkably, shot-noise enhancement is found to be a precursor indicator that the device is approaching an instability regime, in strict analogy with the general case of a phase transition.

ACKNOWLEDGMENTS

Partial support from the Italian Ministry of Foreign Affairs through the Volta Landau Center (the fellowship of V.Ya.A.) and the NATO collaborative-linkage Grant No. PST.CLG.976340, is gratefully acknowledged.

APPENDIX: NOISE FORMULA

Below we present a derivation of the noise formula in Eq. (17), which is an alternative to that of Ref. 29. The present structure has two contacts, with the emitter and with the collector, respectively. Thus, under steady-state conditions two instantaneous currents can be considered: the emitter I_1 and the collector current I_2 defined as

$$I_1 = -q\sum_N [g_1(N) - r_1(N)]P(N), \quad (A1)$$

$$I_2 = -q\sum_N [r_2(N) - g_2(N)]P(N), \quad (A2)$$

where $g_1(N)$, $r_1(N)$ are the probability per unit time for electron transitions from the emitter to the device and from the device to the emitter, respectively. Analogously g_2, r_2 are those from the collector to the device and from the device to the collector, respectively. The quantity $P(N)$ is the probability to find N electrons in the device at time t. For high enough voltages, as in this case, $g_2=0$.

Under stationary conditions the currents I_1 and I_2 are related by

$$\overline{I_1} = \overline{I_2}, \quad (A3)$$

where their correlators satisfy the following relations:

$$\overline{I_1(0)I_1(t)} = \overline{I_2(0)I_1(t)} = \overline{I_1(0)I_2(t)} = \overline{I_2(0)I_2(t)}. \quad (A4)$$

Equation (A4) has been obtained by direct calculations in Ref. 29. We can also use the Ramo-Shockley[32,33] theorem for the full current $I=\lambda_1 I_1 + \lambda_2 I_2$, where $\lambda_{1,2}$ are some coefficients satisfying $\lambda_1+\lambda_2=1$. However, from Eq. (A4) it is

$$\overline{I(0)I(t)} = \overline{I_2(0)I_2(t)} = q^2\sum_{M,N} r_2(M)P(M)r_2(N)P(N,t|M-1,0), \quad (A5)$$

where $P(N,t|M,0)$ is the conditional probability to find in the device N electrons at time t, given that M electrons were in the device at the previous time $t=0$.

To calculate the correlator of Eq. (A5) we assume that $P(N)$ is sufficiently peaked so that one can use the following expansions:[34,35]

$$r_2(N) = r_2(\overline{N}) + \Delta N \nu_2, \quad \Delta N = N - \overline{N}, \quad (A6)$$

where $\overline{N}$ is the average number of electrons in the device. In this case the instantaneous current can be decomposed into two contributions as

$$I = I_P + I_{\Delta N} = q\sum_N r_2(\overline{N})P(N) + q\nu_2 \sum_N \Delta N P(N) \quad (A7)$$

the first current contribution I_P is of Poissonian type since the transition probability is constant. The second current contribution is connected with the fluctuations of N. From Eq. (A7) it is $\overline{I} = \overline{I_P}$ and $\overline{I_{\Delta N}}=0$. Thus, by using Eq. (A7) we obtain

$$\overline{I(0)I(t)} = \overline{I_P(0)I_P(t)} + \overline{I_{\Delta N}(0)I_P(t)} + \overline{I_P(0)I_{\Delta N}(t)} + \overline{I_{\Delta N}(0)I_{\Delta N}(t)}. \quad (A8)$$

The correlator for Poissonian current is well known[16] and given by

$$\overline{I_P(0)I_P(t)} = q\overline{I}\delta(t) = q^2 r_2(\overline{N})\,\delta(t) = q^2\overline{r_2}\delta(t). \quad (A9)$$

By using Eq. (A5) we can obtain the following expressions for the second, third, and fourth terms in Eq. (A8)

$$\overline{I_{\Delta N}(0)I_P(t)} = q^2\nu_2 \sum_{M,N} \Delta M P(M) r_2(\overline{N}) P(N,t|M-1,0) = \nu_2 r_2(\overline{N})\sum_M \Delta M P(M) = 0, \quad (A10)$$

$$\overline{I_P(0)I_{\Delta N}(t)} = q^2 \nu_2 r_2(\overline{N})\sum_{M,N} P(M)\Delta N P(N,t|M-1,0), \quad (A11)$$

$$\overline{I_{\Delta N}(0)I_{\Delta N}(t)} = q^2\nu_2^2 \sum_{M,N} \Delta M P(M)\Delta N P(N,t|M-1,0). \quad (A12)$$

To calculate Eqs. (A10) and (A11) we note that the term $\Sigma_N \Delta N P(N,t|M-1,0)$ depends on $\Delta N(t)$, and it is $\Delta N(0) = M-1-\overline{N} = \Delta M - 1$. For $\Delta N(t)$ we can use the Langevin equation

$$\frac{d\Delta N}{dt} = -\Delta N \nu + H(t), \quad (A13)$$

where $H(t)$ is the stochastic force. Thus, we have

$$\Delta N(t) = (\Delta M - 1)\exp(-|t|\nu) + \int_0^t H(y)dy. \quad (A14)$$

By using Eq. (A13) we obtain

$$\overline{I_P(0)I_{\Delta N}(t)} = -q^2\nu_2 r_2 \exp(-|t|\nu), \quad (A15)$$

$$\overline{I_{\Delta N}(0)I_{\Delta N}(t)} = q^2\nu_2^2 \overline{\Delta N^2}\exp(-|t|\nu). \quad (A16)$$

Now we can write the expression for the total current correlator as

$$\overline{I(0)I(t)} = q\overline{I}\delta(t) - q\nu_2\overline{I}\exp(-|t|\nu) + + q^2\nu_2^2\overline{\Delta N^2} \times \exp(-|t|\nu). \quad (A17)$$

By using (see Ref. 16)

$$\overline{\Delta N^2} = \frac{\overline{g_1}}{\nu} \quad (A18)$$

and making the Fourier transform, we obtain the formula for the spectral density of current fluctuations, $S(\omega)$

$$S(\omega) = 2q\overline{I}\left(1 - 2\frac{\nu_2}{\nu}\frac{1}{1+\omega^2/\nu^2} + 2\frac{\nu_2^2}{\nu^2}\frac{\overline{g_1}}{\overline{r_2}}\frac{1}{1+\omega^2/\nu^2}\right). \quad (A19)$$

From Eq. (A19) the Fano factor γ is given by

$$\gamma = \frac{S(0)}{2q\overline{I}} = 1 - 2\frac{\nu_2}{\nu} + 2\frac{\nu_2^2}{\nu^2}\frac{\overline{g_1}}{\overline{r_2}}, \tag{A20}$$

which coincides with the formula obtained in a different way in Ref. 29. The physical meaning of the three terms in the right-hand side of Eq. (A20) are given as follows. The first term is connected with the correlator of the Poissonian current contribution I_P. The second term is connected with the cross correlator between I_P and the current contribution $I_{\Delta N}$ connected with fluctuations of N. The third term is connected with the correlator of $I_{\Delta N}$. We finally note, that the formula for the Fano factor in the general situation, when $g_2 \neq 0$ [formula (35) Ref. 35], can be obtained analogously.

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