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Current instability and shot noise in nanometric semiconductor heterostructures

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Abstract. We investigate electron transport and shot noise in single barrier GaAs/AlGaAs heterostructure of nanometric sizes. The coupling between space charge and the dependence of the transmission coefficient on energy is found to provide the positive feedback which enhances shot noise and ultimately leads to a current instability of S-type. Theoretical results are in qualitative agreement with existing experiments and confirm recent Monte Carlo simulations evidencing shot-noise enhancement in GaAs/AlGaAs heterostructures.

Introduction

The aim of this work is to provide a theoretical basis for the understanding of the current-voltage (I–V) and shot-noise as measured by the Fano factor $\gamma = S_I/(2qI)$ (with S_I the noise power and q the unit charge) in single barrier semiconductor structures characterized by ultra-short distances between the emitter and the barrier. The theory 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. When this feedback is negligible, long range Coulomb correlations between current pulses dominate and shot noise is suppressed. When this feedback is strong enough, shot noise is enhanced and ultimately we observe the onset of an S-type I–V characteristic.

1. Results and discussion

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. Electron transport is then described by the following analytical model [1]. The distribution function of particles injected from the emitter is taken of Maxwell type with concentration and temperature independent of applied voltage. In the region between the emitter and the barrier carriers are subdivided into two groups: one group contains *ballistic* particles, which do not perform any scattering, and the other contains *thermalised* particles which performed at least one scattering. Tunneling is finally described by a quasi classical triangular barrier.

The theory concerns with a model material of static dielectric constant $\kappa = 12.9$ and parabolic conduction band with effective mass $m = 0.067m_0$, m_0 being the free electron

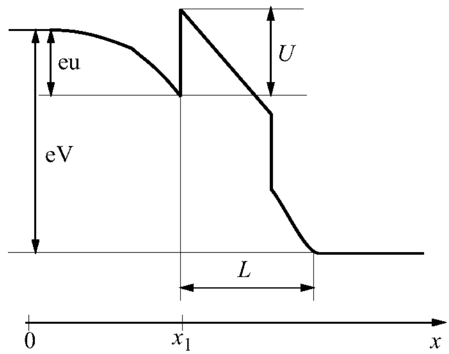

Fig. 1. Band diagram sketch of the considered single barrier structure.

mass. These values correspond to GaAs, being this a material appropriate for an experimental validation of the results. The theory is based on five independent external parameters, respectively, injected carrier concentration n_b, barrier energy U, fraction of balistic carriers β, temperature T, barrier-collector length L. 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, $\beta \to 1$, is associated with ballistic particles and corresponds to ultra-short emitter-barrier distances. By contrast, $\beta \to 0$, is associated with scattered particles, and corresponds to long distances. A limited series of a complete set of results is presented in Fig. 2 where transport and noise are investigated at different values of β (see Fig. 2(a)) and T (see Fig. 2(b)). The I–V characteristics are reported in the left scale of Fig. 2. As a general trend, the current increases monotonically at increasing voltages to finally saturates at sufficiently high voltages. 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, I_0. The reason for such a value of current saturation is the absence of any current flow to the emitter coming from both: (i) ballistic particles reflected by the barrier, and (ii) thermalised 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, and with the decrease of T as shown for the case of β and T in Fig. 2. 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 U. 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 Fig. 2 it is clear that the increase of β or the decrease of T leads to the increase of the maximum value of the differential conductance $\mathrm{d}I/\mathrm{d}V$ towards I–V characteristics of S-type.

The dependence of the Fano factor on voltage is reported on the right scale of Fig. 2. One can see that γ exhibits minima and maxima. In all cases, at the lowest and highest voltages (above current saturation) $\gamma = 1$ indicating full shot-noise. In the intermediate region of voltages for the considered values of injection concentration $n_b = 5 \times 10^{17}\,\mathrm{cm}^{-3}$ γ exhibits both a maximum, corresponding to shot noise enhancement, followed by a minimum corresponding to shot noise suppression. The maximum value of γ exhibits a dramatic increase with increasing β and/or decreasing T while the minimum value remains close to 0.5. Deviations from full shot noise are interpreted in terms of the voltage dependence

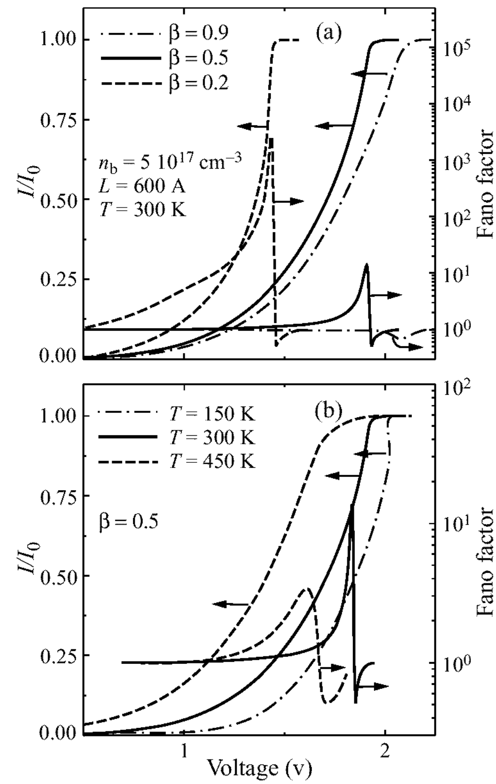

Fig. 2. Current normalized to the saturation value I_0 and Fano factors vs applied voltage for the barrier structure in Fig. 1 with $U = 0.2$ eV for different β (a) and for different T (b).

of the collector lifetime τ_c associated with the rate equation for the fluctuation of the total number of carrier inside the sample controlled by the collector δN_c. When τ_c is positive, any δN_c is damped and only shot-noise suppression due to long range Coulomb interaction is possible. When τ_c is negative, a positive feed-back between tunneling and space charge amplifies any δN_c and shot-noise enhancement becomes possible. When this positive feed-back is rather weak (i.e. $|\tau_c|$ is very long) the maximum of the Fano factor is absent, as seen in Fig. 2(a) by the curve for $\beta = 0.2$. The general trends are that the increase of β and the decrease of T rises the strength of the positive feedback and in turn enhanced shot noise becomes more pronounced as reported in Fig. 2. This positive feedback is ultimately responsible for a decrease of the electrical stability of the structure. Accordingly, when its strength is sufficiently strong (i.e. $|\tau_c|$ is very short), the I–V characteristics become of S-type as seen by the curve corresponding to $T = 150$ K in Fig. 2(b). It is well known, that a region where the differential conductance is negative is unstable under a constant applied voltage. Therefore, instead of being damped, fluctuations grow being only limited by boundary conditions. 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. We remark that shot noise is for these structures a very sensitive indicator of the fact that the system is moving towards an instability region, this situation resembling that of phase transitions.

2. Conclusions

A theoretical analysis of electron transport and shot noise in ultra-short single barrier structures is presented. Results are interpreted in terms of a positive feedback between Coulomb interactions and the dependence of the barrier transparency on energy for ballistic particles which, in turn, weaks significantly the damping of carrier number fluctuations. 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. By contrast, when the strength of the feedback is weak shot noise suppression is observed. The general trends of the model developed here is in qualitative agreement with existing experiments [2] and numerical simulations performed with Monte Carlo techniques [3].

Acknowledgements

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