Giant suppression of shot noise as signature of coherent transport in double barrier resonant diodes

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Abstract
Shot noise suppression in double barrier resonant tunnelling diodes with a Fano factor well below the value of 0.5 is theoretically predicted. This giant suppression is found to be a signature of the coherent transport regime and can occur near zero temperature as a consequence of the Pauli principle or above about 77 K as a consequence of long range Coulomb interaction. These predictions are validated by experimental data.

1. Introduction

Since its realization, the double barrier resonant diode (DBRD) has proved to be an electron device of broad physical interest because of its peculiar non-Ohmic current voltage (*I–V*) characteristic [1, 2]. Even the shot noise characteristics are of relevant interest due to the fact that suppressed as well as enhanced shot noise with respect to its full Poissonian value has been observed [3]. The microscopic interpretation of these features is found to admit a coherent [1] or a sequential tunnelling [2] approach. The intriguing feature of these two approaches is that from the existing literature it emerges that both of them are capable of explaining the *I–V* experiments as well as most of the shot noise characteristics [3, 4]. Therefore, to our knowledge there is no way to distinguish between these two transport regimes and the natural question whether the tunnelling transport is coherent or sequential remains an unsolved one.

Here we answer this question by announcing that a giant suppression of shot noise occurring before the peak value of the current with a Fano factor (noise power to current ratio) below 0.5 is a signature of coherent transport in DBRDs. To this purpose, we have formulated a coherent approach for transport in DBRDs that includes both the Pauli principle and the long range Coulomb interaction.

2. Model and results

The typical structure investigated is reported in figure 1. We denote by $\Gamma = \Gamma_L + \Gamma_R$ the resonant state width due to the tunnelling through left and right barriers, respectively, and by ε_r the energy of the resonant level as measured from the centre of the potential well. For simplicity, we consider the case of coherent tunnelling when there is only one resonant state with $\Gamma_L = \Gamma_R = \Gamma/2$ and we take unit square contacts. The kinetic model assumes that the electron distribution functions in the emitter and in the collector of the DBRT are Fermi Dirac equilibrium-like, with electro-chemical potentials shifted by the value of the applied voltage. For convenience calculations are carried out using the CGS system. The double barrier transparency $D(\varepsilon_z)$ is given by [3]

$$D(\varepsilon_z) = \frac{\Gamma^2/4}{(\varepsilon_z - \varepsilon_r + qu)^2 + \Gamma^2/4} \quad (1)$$

where $\varepsilon_{z,\perp}$ are the energies for electron motion perpendicular and along barriers, and u is the voltage drop between the emitter and the centre of the potential well (see figure 1). For the current flowing from the emitter to the collector we found [5]:

$$I = -\frac{qm}{2\pi^2\hbar^3} \int_{-g_L}^{\infty} \int_0^{\infty} \mathrm{d}\varepsilon_z \, \mathrm{d}\varepsilon_\perp \, D(\varepsilon_z)[f_L(\varepsilon) - f_R(\varepsilon)] \quad (2)$$

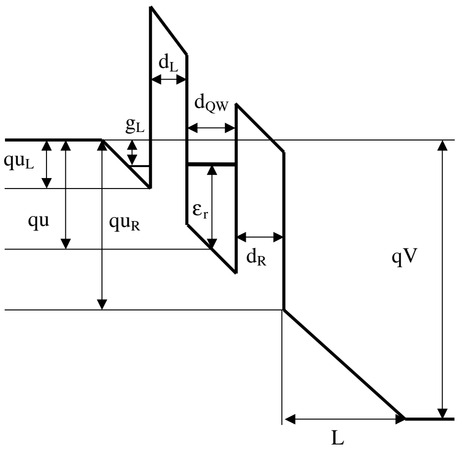

Figure 1. Band diagram of the double barrier structure considered here under an applied voltage V. The bottom of the conduction band in the emitter in the well and in the collector coincide at $V = 0$.

with q the electron charge, m its effective mass and $\hbar$ the reduced Planck constant. In our model, we suppose that in the emitter there are no electron states with energy below $-g_L$ and that electron states with energy higher than this value are three dimensional. Furthermore, the relation between u and the total applied voltage V is calculated self-consistently by using the condition of electroneutrality of the device [5]. To calculate noise we implemented the wave packet approach [6] to account for the self-consistent potential. Accordingly, for the spectral density of current fluctuations we obtain: [5]

$$S_I = \frac{q^2 m}{\pi^2 \hbar^3} \int_0^\infty d\varepsilon_\perp \int_{-g_L}^\infty d\varepsilon_z \{ D[(q_{\rm eff}^+)^2 f_L (1 - f_R) + (q_{\rm eff}^-)^2 f_R (1 - f_L)] - D^2 (f_L - f_R)^2 \} \quad (3)$$

with $|q_{\rm eff}^\pm| < \infty$ a dimensionless effective charge accounting for the self-consistent potential. When $q_{\rm eff}^\pm = 1$ the self-consistent potential is neglected, and equation (3) coincides with that derived by [6]. From equations (2) and (3) the Fano factor $\gamma = S_I/(2qI)$ is directly obtained.

We compare theory with two sets of experiments performed on DBRDs with barriers sufficiently narrow to expect that coherent tunnelling is of importance. In both cases the comparison is limited to the voltage region up to the peak current since theory neglects energy levels higher than the first one in the quantum well.

Figure 2 reports the experiments of [7] at 77 K and the results of present calculations at 77 and 4.2 K. Numerical results make use of the following values for the parameters entering the model: $\varepsilon_r = 104$ meV, $\Gamma_R = \Gamma_L = 0.48$ meV, carrier concentration at the contacts $n = 2 \times 10^{16}$ cm^{-3}, same width of the left barrier, right barrier and quantum well $d_L = d_R = d_{QW} = 5$ nm, width of the spacer in the collector $L = 50$ nm, $m = 0.067 m_0$, with m_0 the free electron mass and $\kappa = 12.9$. The only two fitting parameters are ε_r and $\Gamma = 0.5\Gamma_{L,R}$. Their values control the location and the amplitude of the current peak, respectively, and are chosen by optimizing the agreement between the experimental and the calculated *I–V* characteristics. All other parameters are provided by the experimental conditions, and we want to stress that the Fano factor is obtained from the same set of parameter values. The function $g_L(u_L)$, u_L being the voltage drop in front of the left barrier edge, is calculated by solving the Schrödinger equation. For the values used, the dependence $g_L(u_L)$ is found to be almost linear and well approximated

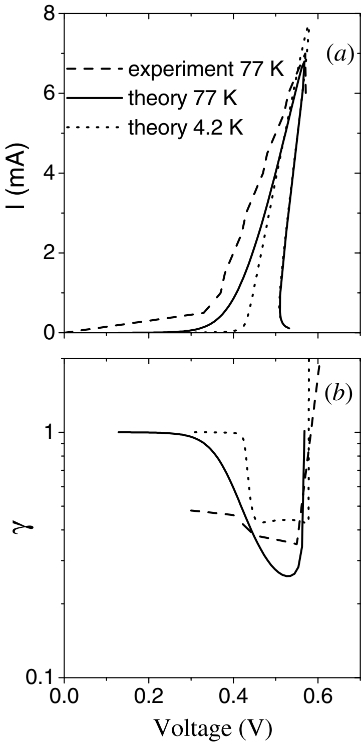

Figure 2. Experimental and calculated dependences of current (*a*) and the Fano factor (*b*) on applied voltage for the structure in [7]. Experiments refer to $T = 77$ K and theory to $T = 4.2$ and 77 K, respectively.

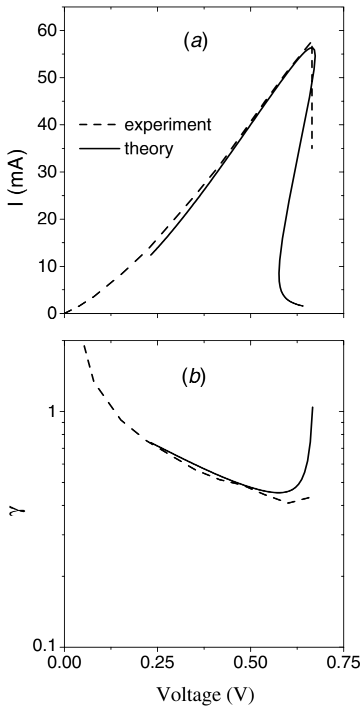

Figure 3. Experimental and calculated dependences of current (*a*) and the Fano factor (*b*) on applied voltage for the structure in [5] at $T = 300$ K.

by $g_L(u_L) \approx 0.44(qu_L - 1.5k_BT) - 0.07k_BT$ for 77 K and $g_L(u_L) \approx 0.28(qu_L - 110k_BT) - 14k_BT$ for 4.2 K. The agreement between theory and experiments reported in figure 2 is considered to be satisfactory. We remark that numerical results at 4.2 K do not differ significantly from those at 77 K in agreement with what is claimed in [7]. Thus, the giant suppression of shot noise predicted by present theory extends the previous findings of Wei *et al* [8] and is confirmed by these experiments.

A recent set of experiments [5] carried out at 300 K on a DBRD with barriers thinner than those of [7], thus more adequate to check coherent tunnelling at high temperature, is reported in figure 3 together with theoretical calculations. The structure consisted of two 2 nm AlAs layers separated by 6 nm InGaAs quantum well [9]. Measurements were carried out at 300 K using a noise figure meter (XK5-49), that allows us to measure simultaneously noise figure and power gain of two-port networks in the 50 Ω feed circuit. Numerical results make use of the following values for the parameters entering the model: $\varepsilon_r = 93$ meV, $\Gamma_R = \Gamma_L = 0.9$ meV, $n = 7.5 \times 10^{16}$ cm^{-3}, $d_L = d_R = 2$ nm, $d_{QW} = 6$ nm $L = 50$ nm, $g_L(u_L) = 0.43(qu_L - 1.5k_BT) + 0.44k_BT$. Also here the only two fitting parameters are ε_r and $\Gamma = 0.5\Gamma_{L,R}$, all other parameters being provided by the experimental conditions. Figure 3(*a*) reports the *I–V* characteristics which show a region of positive differential conductance (PDC) up to about 0.7 V followed by an instability region. In the same PDC region, the Fano factor is found to exhibit a suppression with a minimum value of about 0.4 at around 0.6 V (see figure 3(*b*)). The agreement between theory and experiments is within experimental uncertainty and thus is considered to be satisfactory even in this case. In particular, here the Coulomb interaction is found to be determinant in leading to the Fano factor below the value of 0.5. Thus, the comparison between theory and experiments supports the physical interpretation of the giant suppression of shot noise in DBRDs and in particular confirms that coherent transport occurs under such a condition.

3. Conclusions

We have investigated coherent tunnelling by implementing the wave packet approach for transport in DBRDs that includes both the Pauli principle and the long range Coulomb interaction. In agreement with existing results, we have found that at 4.2 K shot noise is suppressed mostly because of the Pauli correlation. Moreover, the suppression exhibits the Fano factor of 0.5 in a wide region of applied voltages, with a minimum of 0.391 at the current peak in agreement with experiments. Interestingly, we have found that shot noise can be suppressed well below the value of 0.5 also because of Coulomb interaction. This giant suppression is here confirmed by existing experiments at 77 K and recent measurements performed at room temperature. Therefore, shot noise suppression below one-half of the full Poissonian value is proved to be a signature of coherent tunnelling against sequential tunnelling in double barrier resonant diodes. We finally want to stress that the main reason for the difference between these approaches stems from the fact that the sequential tunnelling is based on a master equation [4] for treating fluctuations of carrier numbers inside the quantum well while coherent tunnelling uses the quantum partition noise within the wave packet approach [6]. The master equation describes implicitly a sequential mechanism for a carrier entering/exiting from the well and, as a consequence, its intrinsic limit coincides with that of two independent resistors (or vacuum diodes) connected in series and each of them exhibiting full shot noise. This system yields a maximum suppression of shot noise down to the value of 0.5. By contrast, partition noise, inherent to the wave packet formalism, can be fully suppressed down to zero in the presence of a fully transparent barrier and/or of Coulomb interaction such as in vacuum diodes.

Acknowledgments

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