Semicond. Sci. Technol. **18** (2003) L35–L38 PII: S0268-1242(03)60270-1

LETTER TO THE EDITOR

Giant suppression of shot noise in double barrier resonant diode: a signature of coherent transport

V Ya Aleshkin[1], **L Reggiani**[2], **N V Alkeev**[3], **V E Lyubchenko**[3], **C N Ironside**[4], **J M L Figueiredo**[4,5] **and C R Stanley**[4]

[1] Institute for Physics of Microstructures, Nizhny Novgorod GSP-105 603600, Russia
[2] National Nanostructure Laboratory of INFM, Dipartimento di Ingegneria dell' Innovazione, Università di Lecce, Via Arnesano s/n, 73100 Lecce, Italy
[3] Institute of Radioengineering & Electronics, Russian Academy of Sciences, Russia
[4] Department of Electronic and Electrical Engineering, University of Glasgow, UK
[5] Department de Física, Faculdade de Ciências e Technologia, Universidade do Algarve, 8000-117 Faro, Portugal

Received 3 March 2003, in final form 4 April 2003
Published 25 April 2003
Online at stacks.iop.org/SST/18/L35

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 coherent transport regime and can occur at zero temperature as a consequence of the Pauli principle or at sufficiently high temperatures above 77 K as a consequence of a long-range Coulomb interaction. These predictions are in agreement with experimental data.

Since its realization [1], the double barrier resonant diode (DBRD) proved to be an electron device of broad physical interest because of its peculiar non-Ohmic current voltage (*I*–*V*) characteristic. Indeed, after a strong superOhmic increase of current, it exhibits a negative differential conductance and eventually hysteresis effects [2]. Even the shot noise characteristics are of relevant interest, since suppressed as well as enhanced shot noise with respect to its full Poissonian value has been observed (see [3] for a review on the subject). These electrical and noise features are controlled by the mechanism of carrier tunnelling through the double potential barriers. The microscopic interpretation of these features is found to admit a coherent [4] or a sequential [5] tunnelling approach. The intriguing feature of these two approaches is that from the literature, it emerges that both of them explain the *I*–*V* experimental data as well as most of the shot noise characteristics. 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.

The coherent approach to shot noise in DBRD has received wide attention since the first experimental evidence by Li *et al* [6] of shot noise suppression with a minimum value of the Fano factor $\gamma = S_I/(2qI) = 0.5$, where S_I is the current spectral density and q the absolute value of the unit charge responsible of current. Remarkably, most of the coherent approaches developed so far predict a maximum suppression $\gamma = 0.5$ even if there is clear experimental evidence of suppression below this value (here referred as giant suppression) [7–9] down to values of $\gamma = 0.25$ [8, 9]. To this purpose, some authors obtained theoretical values of the Fano factor just below the value of 0.5, 0.45 [10] and 0.38 [11], respectively. However, the physical interpretation of these results remains mostly qualitative and quoting [3] this direction of research looks promising but certainly requires more efforts.

In this letter, we announce that a giant suppression of shot noise occurring before the peak value of the current is a signature of coherent transport in DBRDs. To this purpose, we present a theoretical model which predicts this phenomenon and is validated by experiments.

The typical structure here investigated is the standard symmetric double well reported in figure 1. We denote by

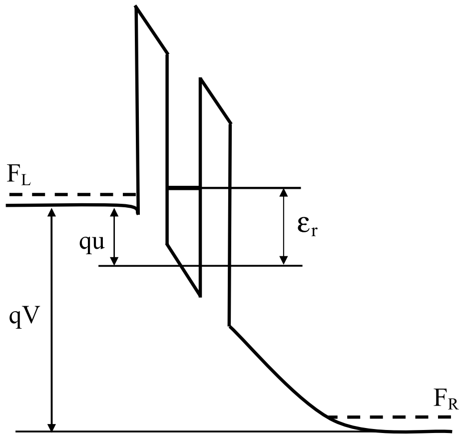

Figure 1. Band diagram of the double barrier structure considered here under an applied voltage V. The bottom of the conduction band in the emitter in the well and in the collector coincides at $V = 0$.

$\Gamma = \Gamma_L + \Gamma_R$ the resonant states width and by ε_r the energy of the resonant level as measured from the centre of the potential well. Here $\Gamma_{L,R}$ are the partial widths due to the tunnelling through left and right barrier, respectively. 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 is developed by assuming that the electron distribution functions in the emitter and in the collector of the DBRT are equilibrium-like, with different electro-chemical potentials F_i:

$$f_i(\varepsilon, F_i) = \frac{1}{1 + \exp\left(\frac{\varepsilon - F_i}{k_B T}\right)} \qquad (1)$$

here $i = L$ stands for the emitter, $i = R$ for the collector; k_B is the Boltzmann constant, T the temperature and ε the kinetic carrier energy. The double barrier transparency $D(\varepsilon_z)$ can be written in the following form:

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

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

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

with m the carrier effective mass and $\hbar$ the reduced Planck constant.

The relation between u and the total applied voltage V is given by

$$C_R V = (C_R + C_L)u - Q_{\mathrm{QW}} \qquad (4)$$

where $C_{L,R}$ are the capacitances corresponding to the emitter and the collector junctions, and $Q_{\mathrm{QW}} = q\left(N^+_{\mathrm{DQW}} - N_{\mathrm{QW}}\right)$, the charge in the quantum well with $N^+_{\mathrm{DQW}}, N_{\mathrm{QW}}$ the concentrations of charged donors and free electrons, respectively. The expression for N_{QW} writes

$$N_{\mathrm{QW}} = \frac{m}{\pi^2\hbar^2\Gamma}\int_0^\infty \mathrm{d}\varepsilon_z D(\varepsilon_z)\int_0^\infty \mathrm{d}\varepsilon_\perp[f_L(\varepsilon) + f_R(\varepsilon)] + \frac{2m}{\pi^2\hbar^2\Gamma}\int_{-qV}^0 \mathrm{d}\varepsilon_z D(\varepsilon_z)\int_0^\infty \mathrm{d}\varepsilon_\perp f_R(\varepsilon). \qquad (5)$$

In the right-hand side of equation (5), the first term is the contribution of electrons inside the energy interval in which there are electron fluxes from the emitter and the collector to the quantum well; the second term corresponds to the energy interval where there is only one electron flux from the collector to the quantum well.

To calculate noise, we shall use the wave packet approach [12] here implemented to account for the self-consistent potential following the theory developed for the vacuum diode [13]. Accordingly, for the spectral density of current fluctuations, we obtain

$$S_I = \frac{q^2 m}{\pi^2\hbar^3}\int_0^\infty \mathrm{d}\varepsilon_\perp\,\mathrm{d}\varepsilon_z\Big\{D\Big[\big(q^+_{\mathrm{eff}}\big)^2 f_L(1 - f_R) + \big(q^-_{\mathrm{eff}}\big)^2 f_R(1 - f_L)\Big] - D^2(f_L - f_R)^2\Big\} \qquad (6)$$

with $q^\pm_{\mathrm{eff}}$ the dimensionless effective charge accounting for the self-consistent potential [14]

$$q^\pm_{\mathrm{eff}}(\varepsilon) = 1 \pm \frac{2\hbar}{\Gamma}\frac{[1 - f_L(\varepsilon) - f_R(\varepsilon)]}{\left[C_L + C_R + q\frac{\partial N_{\mathrm{QW}}}{\partial u}\right]}\frac{\partial I}{\partial u}. \qquad (7)$$

When $q^\pm_{\mathrm{eff}} = 1$, the self-consistent potential is neglected and equation (6) coincides with that derived by [12]. At zero applied voltage, equation (6) satisfies the Nyquist theorem. Furthermore, the same equation gives $S_I = \infty$ on the border of the instability region where also $\mathrm{d}I/\mathrm{d}V = \infty$. Both tests, by recovering expected features of the spectral density, prove the physical reliability of the present approach.

We now consider the case of zero temperature where Pauli principle is expected to play a dominant role. In this case, only such states for which $f_L = 1$ and $f_R = 0$ take part to the current transmission. Therefore, the second term in the right-hand side of equation (6) is zero and from equation (7), we see that $q^+_{\mathrm{eff}} = 1$. These conditions are valid everywhere with exception of the border stability region where $\mathrm{d}I/\mathrm{d}V = \infty = q^+_{\mathrm{eff}}$. In other words, as expected, long-range Coulomb interactions are suppressed at zero temperature. Then, we analyse the case of high applied voltages, when $qV > F_R$, because it is that more close to experiments, and for convenience, we express the applied voltage and the electrochemical potentials by the dimensionless parameters: $\xi = 2(qu - \varepsilon_r)/\Gamma$, $f = 2F_L/\Gamma$. Figure 2 reports the current (figure 2(*a*)) and the Fano factor $\gamma(\xi)$ (figure 2(*b*)) as the function of ξ for different values of f. Curves labelled 1, 2 and 3 correspond to $f = 1, 15$ and ∞, respectively. The current exhibits the well-known peaked behaviour reducing to zero at the highest voltages because we neglect resonant states above the first one. Of interest is the behaviour of the Fano factor in figure 2(*b*). The common features of all curves is the presence of a minimum of γ near to the current peak and the evidence of full shot noise in regions where the current is relatively small. Remarkably, the minimum value of the Fano factor is found to be always less than 0.5, taking the value 0.391 at $\xi = -0.801$ for $f = \infty$ and being systematically lower than this value at decreasing value of f. More precisely, for $f = \infty$ the current increase towards the peak is widely broadened in the positive differential conductance region and, in close analogy with the one-dimensional system considered [15], the Fano factor takes the universal expression:

$$\gamma(\xi) = 1 - \frac{1}{2}\left\{1 - \frac{\xi}{(1 + \xi^2)\left[\frac{\pi}{2} - \arctan(\xi)\right]}\right\}. \qquad (8)$$

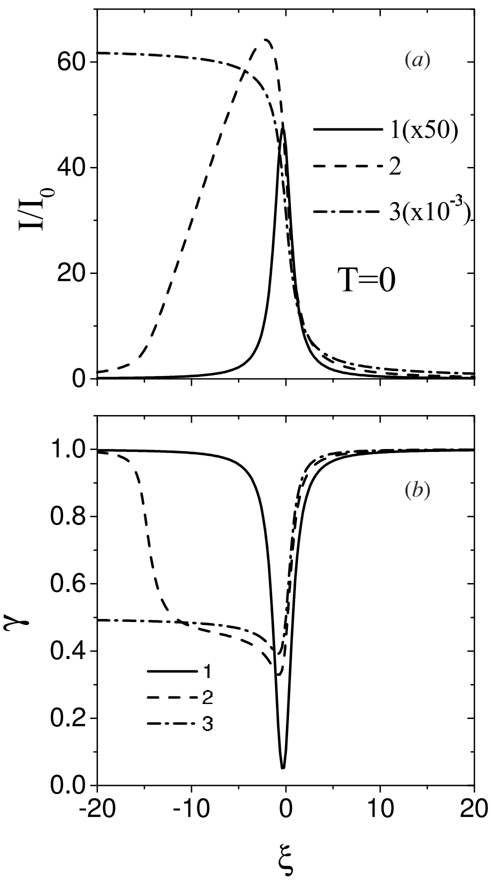

Figure 2. Dependence of current (a) and Fano factor (b) on applied voltage in a typical symmetric DBRD at zero temperature. For convenience, dimensionless current and voltages are used with $I_0 = qm\Gamma_L\Gamma_R/(2\pi^2\hbar^3)$ and $\xi = 2/(qu - \varepsilon_r)\Gamma$. Curves labelled as 1, 2, 3 correspond to values of the dimensionless electrochemical potentials: $f = 1, 15, \infty$ ($f = 2F_L/\Gamma$), respectively.

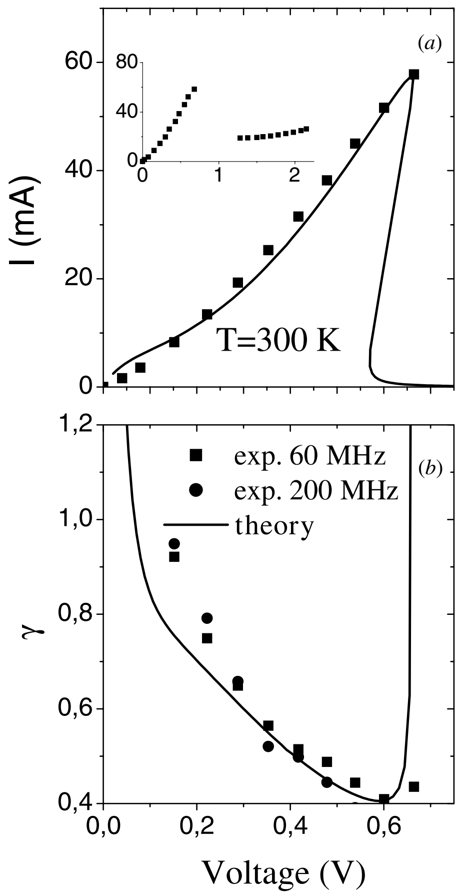

Figure 3. Dependence of current (a) and Fano factor (b) on applied voltage in a symmetric DBRD at room temperature. Continuos curves refer to theoretical calculations and symbols to experiments. The insert in figure 3(a) reports the complete set of I–V experiments.

We remark that experiments at temperatures around 4 K [6], by exhibiting $\gamma = 0.5$ fall inside the case of $f \to \infty$ and well agree with the present model. In particular, the minimum value of suppression $\gamma = 0.391$ is in agreement with the value of 0.35 found in experiments [7]. From figure 2(b), it is clear that by decreasing the value of f also the minimum of the Fano factor decreases systematically up to a zero value. To understand the physical reason of this behaviour, we discuss the limiting condition when $f \ll 1$. In this case, the width of the electron energy distribution is lower than that of the resonant state. As a consequence, the transmission probability becomes the same for all the electrons and we obtain the standard partition expression for the Fano factor [12] $\gamma(\xi) = 1 - D(0)$. When $D(0)$ is close to unity γ tends to zero as found by Lesovik [16] for the analogous case of a quantum point contact. We conclude, that the main reason for shot noise suppression in DBRDs at zero temperature is connected with Pauli principle and, because of the coherent tunnelling regime, the Fano factor can take values significantly lower than 0.5 near to the current peak.

For relatively high temperatures (i.e., $\geqslant$77 K), the Coulomb interaction is expected to play the main role in suppressing shot noise. The present coherent approach in the limit of Boltzmann statistics yields for the Fano factor:

$$\gamma = \left[1 + \frac{2\hbar}{\Gamma}\frac{1}{\left(C_L + C_R + q\frac{\partial N_{QW}}{\partial u}\right)}\frac{\partial I}{\partial u}\right]^2 \tag{9}$$

where the suppression is found to be controlled by the differential conductance $\mathrm{d}I/\mathrm{d}u$ as expected [13]. For suitable parameters of the DBRD, the above equation predicts the possibility of a giant shot noise suppression to values of the Fano factor well below the value of 0.5, in contrast to what found for the sequential tunnelling model where at most suppression is of 0.5. The above possibility has been verified by room temperature experiments in a DBRD with barriers sufficiently thin to expect coherent tunnelling. The structure consists of two 2 nm AlAs layers separated by 6 nm InGaAs quantum well [17]. Measurements are carried out using a noise figure meter (XK5-49), that allows to measure simultaneously noise figure and power gain of two-port networks in the 50 Ω feed circuit. Simultaneously with the noise, the I–V curve was measured. Noise measurements at frequencies 60 and 200 MHz showed the same results within an experimental uncertainty at worst of 20%, thus indicating that $1/f$ noise contribution is negligible. Figure 3 reports the I–V characteristics (see figure 3(a)) and the Fano factor (see figure 3(b)). Here the I–V characteristic [see figure 3(a)] shows a region of positive differential conductance (pdc) up to about 0.7 V followed by an instability region terminated around 1.3 V as reported in the insert of figure 3(*a*). In the same pdc region, the Fano factor is found to exhibit a suppression with a minimum value of about 0.4 around 0.6 V [see figure 3(*b*)]. Present theory is compared with experiments in the positive differential resistance region of the *I–V* characteristic. Theoretical calculations performed on the basis of equations (3) and (6) make use of the following values for the parameters entering the model: $m = 0.045m_0$, with m_0 the free electron mass, $\Gamma = 1.3$ meV, $\varepsilon_r = 85$ meV, $C_L = 2.04pF$, $C_R = 0.274pF$, electron concentration on the border of the left barrier $n = 2.4 \times 10^{17}$ cm^{-3}. The values of C_L and C_R are optimized for the fitting, while other parameters are typical of the materials used for DBRDs. The agreement between theory and experiments catch the relevant features of the experiments and is considered to be satisfactory for the purpose of the paper. 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 tunnelling occurs under such a condition.

The reason why shot noise suppression is more effective for coherent than for sequential tunnelling can be physically explained as follows. Starting from the fact that the two mechanisms responsible for shot noise suppression are Pauli principle an Coulomb interaction, we note that both of them act simultaneously for coherent and sequential tunnelling. Let us consider the first of them, which is the most relevant at zero temperature, in the case when the Fermi energy is so small that all the electrons exhibit the same transparency. For coherent transport, it is possible to have the transparency equal to unity, which implies $\gamma = 1 - D$ according to Lesovik findings [16]. For sequential transport, the total transparency is always less than unity, since the flux of electrons reflected by the barrier always exists. As a consequence, under coherent transport for the case $D = 1$, there is no noise; by contrast, under sequential transport the presence of scattering always introduces noise. This example illustrates why Pauli principle is more efficient in suppressing shot noise under coherent than sequential transport. By considering Coulomb interaction, which is more relevant at higher temperatures, we recall that in the absence of collisions it provides giant shot noise suppression as in the vacuum tubes [13] because electron reflection in this case is due only to Coulomb interaction. It is clear that the presence of scattering provides additional random mechanisms for electrons returning to the emitter and, therefore, provides additional source of noise. Even this example shows that Coulomb interaction is more efficient in suppressing shot noise under coherent than sequential transport.

In conclusion, we have investigated coherent tunnelling by implementing the wave packet approach for transport in DBRDs that includes both Pauli principle and long-range Coulomb interaction. In agreement with existing results, we have found that around zero temperature shot noise is suppressed because of Pauli principle alone. Moreover, under normal conditions (i.e., $f \to \infty$) the suppression exhibits a Fano factor of 0.5 in a wide region of applied voltages, with a minimum of 0.391 near 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 experimental measurements performed at room temperature. Therefore, shot noise suppression below one-half of the full Poissonian value is proven to be a signature of coherent tunnelling against sequential tunnelling in double barrier resonant diodes. We finally want to stress that the main reason of the difference between these approaches stems from the fact that the sequential tunnelling is based on a master equation [18, 19] for treating fluctuations of carrier numbers inside the quantum well while coherent tunnelling uses the quantum partition noise within the wave-packet approach [12]. 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 like in vacuum diodes.

Acknowledgments

Prof V Volkov of Moscow Institute of Radioengineering and Electronics is thanked for having suggested the problem of this research. Partial support from the Italian Ministry of Foreign Affairs through the Volta Landau Centre (the fellowship of VYaA), and the SPOT-NOSED project IST-2001-38899 of the EC is gratefully acknowledged.

References

[1] Tsu R and Esaki L 1973 *Appl. Phys. Lett.* **22** 562
[2] Goldman V, Tsui D and Cunningham J 1987 *Phys. Rev. Lett.* **58** 1256
[3] Blanter Y M and Büttiker M 2000 *Phys. Rep.* **336** 1
[4] Chang L L, Esaki L and Tsui R 1974 *Appl. Phys. Lett.* **24** 593
[5] Luryi S 1985 *Appl. Phys. Lett.* **47** 490
[6] Li Y P, Zaslavsky A, Tsui D C, Santos M and Shayegan M 1990 *Phys. Rev.* B **41** 8388
[7] Brown E R 1992 *IEEE Trans Electron Devices* **39** 2686
[8] Przadka A, Webb K J, Janes D B, Liu H C and Wasilewski Z R 1997 *Appl. Phys. Lett.* **71** 530
[9] Kuznetsov V, Mendez E, Bruno J and Pham J 1998 *Phys. Rev.* B **58** R10159
[10] Egues J C, Hershfield S and Wilkins J V 1994 *Phys. Rev.* B **49** 13517
[11] Jahan M M and Anwar A F M 1995 *Solid-State Electron.* **38** 429
[12] Martin T and Landauer R 1992 *Phys. Rev.* B **45** 1742
[13] Van der Ziel A 1954 *Noise* (New York: Prentice Hall) p 89
[14] Aleshkin V Ya, Reggiani L, Alkeev N V, Lyubchenko V E, Ironside C N, Figueiredo J M L and Stanley C R 2003 *Preprint* cond-matter/0304077v1
[15] Averin D V 1993 *J. Appl. Phys.* **73** 2593
[16] Lesovik G B 1989 *JETP Lett.* **49**
[17] Alkeev N V, Lyubchenko V E, Ironside C N, Figuiredo J M L and Stanley C R 2000 *J. Commun. Technol. Electron.* **45** 911
[18] Davies J H, Egues J C and Wilkins J W 1995 *Phys. Rev.* B **55** 11259
[19] Iannaccone G, Macucci M and Pellegrini B 1997 *Phys. Rev.* B **55** 4539