Enhanced Shot Noise in Resonant Tunneling via Interacting Localized States

S. S. Safonov,[1] A. K. Savchenko,[1] D. A. Bagrets,[2] O. N. Jouravlev,[2] Y. V. Nazarov,[2] E. H. Linfield,[3] and D. A. Ritchie[3]
[1]School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, United Kingdom
[2]Department of Applied Physics, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
[3]Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, United Kingdom
(Received 3 March 2003; published 25 September 2003)

In a variety of mesoscopic systems shot noise is seen to be suppressed in comparison with its Poisson value. In this work we observe a considerable enhancement of shot noise in the case of resonant tunneling via localized states. We present a model of correlated transport through two localized states which provides both a qualitative and a quantitative description of this effect.

DOI: 10.1103/PhysRevLett.91.136801 PACS numbers: 73.20.Hb, 72.70.+m, 73.40.Gk

Understanding the role of electron coherence and Coulomb interaction in electron transport is one of the main directions of contemporary research in mesoscopic physics. Recently, shot noise measurements have proved to be a useful tool for these studies, since they provide information which is not available from standard conductance measurements [1]. Shot noise, i.e., fluctuations of the current in time due to the discrete nature of electrons, is a measure of temporal correlations between individual electron transfers through a mesoscopic system. Uncorrelated transfers result in the Poisson shot noise with the noise power $S_I = 2eI$ (e is the electron charge, and I is the average current). The effects on noise of the Pauli exclusion principle [2] and the Coulomb repulsion [3] turn out to be similar in most mesoscopic systems. Both were predicted to impose a time delay between two consecutive electron transfers, which results in negative correlations between them and, therefore, suppression of shot noise. This idea has been intensively explored in studies of the shot noise properties in ballistic and diffusive systems [4,5].

Electron transport via localized states in a potential barrier between two contacts has been a subject of intensive investigations. If the size of a mesoscopic barrier is small, resonant tunneling (RT) through a single localized state (impurity) becomes responsible for conduction across the barrier [6]. When the resonant level (R) coincides with either of the Fermi levels in the contacts, $\mu_{L,R}$, a peak in the conductance appears. The amplitude of the peak is determined by the ratio of the leak rates $\Gamma_{L,R} \propto \exp(-2r_{L,R}/a)$ from the resonant impurity to the contacts, where $r_{L,R}$ are the distances between the impurity and the left or right contacts, and a is the localization radius of the state, Fig. 1(a). The current is given by the relation $I_0 = e\Gamma_L\Gamma_R/(\Gamma_L + \Gamma_R)$. It has been predicted in [7,8] that for RT via a localized state shot noise is suppressed by the Fano factor $F \equiv S_I/2eI_0 = (\Gamma_L^2 + \Gamma_R^2)/(\Gamma_L + \Gamma_R)^2$. The Fano factor then depends on the position of the impurity inside the barrier and ranges from 0.5 (for equal rates) to 1 (for significantly different rates). Suppression of shot noise in accordance with this relation has been first observed in a resonant tunneling structure [9]. Similar suppression of shot noise in the Coulomb blockade regime has been seen in a quantum dot [10]. In electron hopping (sequential tunneling) through N equivalent barriers the Fano factor is also expected to be suppressed as $F = 1/N$ [11].

In this Letter we present a study of time-dependent fluctuations of the RT current through a short (0.2 μm) tunnel barrier. Surprisingly, we observe a significant *enhancement* of shot noise. We explain this effect by correlated resonant tunneling involving two interacting localized states.

The experiment has been carried out on a n-GaAs MESFET consisting of a GaAs layer of 0.15 μm (donor concentration 10^{17} cm^{-3}) grown on an undoped GaAs substrate. On the top of the structure an Au gate is deposited with dimensions $L = 0.2$ μm in the direction of the current and $W = 20$ μm across it, Fig. 1(b). By applying a negative gate voltage, V_g, a lateral potential barrier is formed between the Ohmic contacts (source and drain). When a source-drain voltage V_{sd} is applied, fluctuations of the current between the Ohmic contacts are measured by two low-noise amplifiers. The cross-correlation

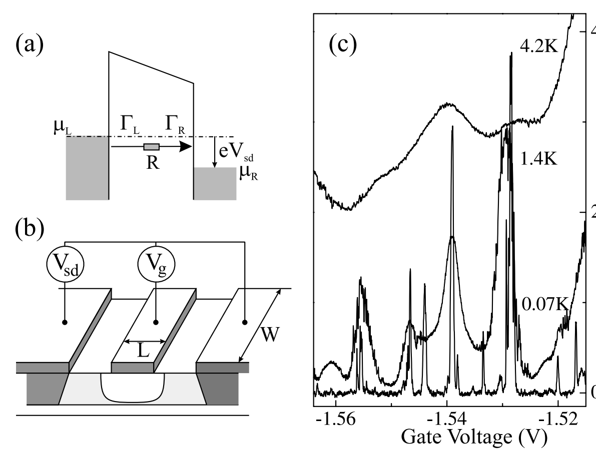

FIG. 1. (a) Resonant tunneling through a localized state in a barrier. (b) Cross section of the transistor structure with two Ohmic contacts and the gate between them. (c) Typical RT peaks in the Ohmic conductance at different temperatures.

spectrum in the frequency range 50–100 kHz is detected by a spectrum analyzer [12]. This technique removes noise generated by the amplifiers and leads.

Figure 1(c) shows an example of conductance peaks as a function of V_g at $V_{sd} = 0$ and different temperatures down to $T = 0.07$ K. One can see that with lowering temperature the background conduction (due to electron hopping) decreases and the amplitude of the conductance peaks increases. This increase is a typical feature of resonant tunneling through an impurity [6].

The box in Fig. 2(a) indicates the range of V_g where shot noise has been studied at $1.85\ \mathrm{K} < T < 4.2$ K. In Fig. 2(b) (inset) an example of the excess noise spectrum is shown at a gate voltage near the RT peak in Fig. 2(a). (In this spectrum thermal noise has been subtracted and the effect of the stray capacitance has been taken into account according to [12].) Shot noise is determined from the flat region of the spectrum above 40 kHz where one can neglect the contribution of $1/f^\gamma$ noise ($\gamma \sim 1.6$), Fig. 2(b) (inset).

Figure 2(b) shows the dependence of the shot noise power on V_{sd} at two temperatures. At small biases ($V_{sd} <$ 3 mV) a pronounced peak in noise is observed with an unexpectedly large Fano factor, $F > 1$. This is seen by plotting the phenomenological expression for excess noise in the case of RT through a single impurity [cf. Eq. (62) in [1] and Eq. (11) in [8]]:

$$S_I = F2eI_{sd}\coth\left(\frac{eV_{sd}}{2k_BT}\right) - F4k_BTG_S. \qquad (1)$$

The expression describes the evolution of excess noise into $S_I = F2eI_{sd}$ at $eV_{sd} \gg k_BT$; G_S is the Ohmic conductance of the sample. At large biases ($V_{sd} > 3$ mV) shot noise is seen to decrease to a conventional sub-Poisson value, $F \sim 0.6$.

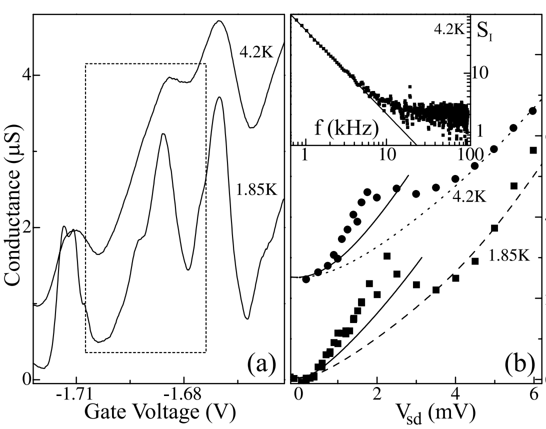

FIG. 2. (a) Conductance peaks in the region of V_g where the current noise has been measured. (b) Excess noise power as a function of V_{sd}: at $V_g = -1.6945$ V for $T = 1.85$ K and $V_g = -1.696$ V for $T = 4.2$ K. (The latter is offset for clarity.) Lines show the dependences $S_I(V_{sd})$ expected for resonant tunneling through a single impurity from Eq. (1), with $F = 1$ (solid), $F = 0.63$ (dashed), and $F = 0.52$ (dotted). Inset: Excess noise spectrum at $V_g = -1.696$ V and $V_{sd} = 1.5$ mV.

We have established that such an increase of shot noise exists only in some ranges of V_g. In other cooldowns of the sample, when the microscopic configuration of impurities is different [which is reflected in different positions of peaks in $G(V_g)$], we have also detected regions of V_g-V_{sd} with increased noise. In addition, we have seen such regions in another sample with the same geometry. It is worth noting that there is no negative differential conductance in the region where the peak in the noise appears, and, therefore, we cannot link this enhancement to some sort of instability [13]. Instead, we will show that in this region of V_{sd}-V_g the resonant current is carried by two interacting impurities and this leads to the increase of shot noise.

We will first show that interaction between two states can indeed considerably increase shot noise. Let us start with an illustrative model and consider two spatially close impurity levels, R and M, separated in the energy scale by $\triangle\epsilon$. If impurity M is charged, the energy level of R is shifted upwards by the Coulomb energy $U \sim e^2/\kappa r$, where r is the separation between the impurities and κ is the dielectric constant, Fig. 3 (diagram 1). Thus, dependent on the occupancy of M, impurity R can be in two states: $R1$ or $R2$. Further we assume that V_{sd} is small enough so that state $R2$ is above the Fermi level in the left contact, Fig. 3 (diagram 2). Then electrons are transferred via R with the rates $\Gamma_{L,R}$ if M is empty, and *cannot* be transferred if M is charged. Initially it is assumed that impurity M (modulator) changes its states independently of the state of impurity R: from empty to charged state

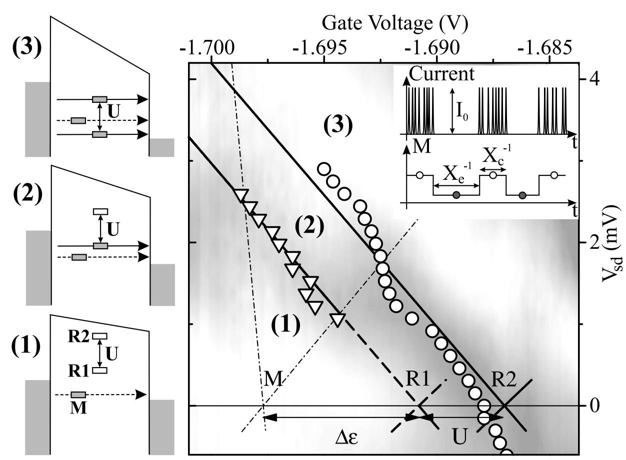

FIG. 3. Left panel: Energy diagrams of the two impurities for different positive V_{sd}: $V_{sd}^{(1)} < V_{sd}^{(2)} < V_{sd}^{(3)}$. Inset: Schematic representation of the modulation of the current through impurity R by changing the occupancy of modulator M. Main part: Gray-scale plot of the differential conductance as a function of V_g and V_{sd} at $T = 1.85$ K (darker regions correspond to higher differential conductance, background hopping contribution is subtracted). Lines show the positions of the conductance peaks of impurity R and modulator M, obtained from the analysis.

with the rate X_c and from charged to empty state with the rate X_e. If $X_{e,c} \ll \Gamma_{L,R}$, the contribution of M to the current is negligible, but the current through R jumps randomly between zero, when M is occupied, and I_0, when M is empty, Fig. 3 (inset). If the bias is increased, the upper state $R2$ is shifted down into the conducting energy strip and the modulation of the current via impurity R vanishes, Fig. 3 (diagram 3).

In the modulation regime, the average current through impurity R and the corresponding zero-frequency Fano factor can be written as

$$I = \frac{e\Gamma_L\Gamma_R}{\Gamma_L + \Gamma_R}\frac{X_e}{X_e + X_c} \tag{2}$$

and

$$F = \frac{\Gamma_L^2 + \Gamma_R^2}{(\Gamma_L + \Gamma_R)^2} + 2\frac{\Gamma_L\Gamma_R}{\Gamma_L + \Gamma_R}\frac{X_c}{(X_e + X_c)^2}. \tag{3}$$

The first term in Eq. (3) describes the conventional suppression of the Fano factor [8], whereas the second term gives its enhancement. To illustrate its origin, one can think of the modulated current as random telegraph noise (RTN), i.e., spontaneous jumps between zero and I_0. The second term can then be obtained from the spectrum of RTN [14] with characteristic times of the upper and lower states—$1/X_e$ and $1/X_c$, respectively. If $X_{e,c} \ll \Gamma_{L,R}$, a substantial enhancement of shot noise, $F \gg 1$, is expected from Eq. (3). Another way to illustrate the origin of this effect is to assume that M is close to the left contact. As a result, impurity M spends more time in its charged state, i.e., $X_e \ll X_c$ and the current through R is transferred in bunches, with the average duration of a bunch $\tau_e = 1/X_c$. The noise due to the "chopping" of the current can then be estimated as $S_I = 2QI$, where Q is the average charge transferred in one bunch. This charge is equal to $I_0\tau_e$, and this again gives the second term in Eq. (3).

There have been a lot of experiments on establishing the role of modulating impurities in the origin of $1/f$ noise, which is the resistance noise [14,15]. The traps there modulate the resistance of the system and the current is only needed to detect these fluctuations [16]. In our case, however, it is essential that there is a correlated current through the two impurities. The slow impurity modulates the current through the fast impurity, and this results in an increase of shot noise—noise of the current. Physically, this situation resembles increased flux-flow noise in superconductors when vortices move in bundles [17].

This model of a slow modulator which changes its state independently of impurity R may look too simplistic. However, its generalization (for any relation between X and Γ) is straightforward and provides a consistent quantitative description of the observed effect. Our theoretical model is based on the master equation formalism [8,18]. It is applicable when $\hbar\Gamma_{L,R} < k_BT$—the condition satisfied in our experiment. Then the system of interacting impurities R and M can be in four possible states. The transition rates between these states are determined by tunneling between the contacts and impurities and depend on temperature and the level positions with respect to the Fermi levels $\mu_{L,R}$. The resulting transport problem is reduced to numerical diagonalization of a 4×4 matrix. As a result, the current and the Fano factor are obtained as a function of the energy positions of the two impurities which are linearly dependent on $V_{\rm sd}$ and V_g. In our calculations the effect of temperature, which suppresses the enhanced Fano factor in Eq. (3), is taken into account. (In a similar master equation approach an increase of shot noise for two interacting quantum dots was also obtained in [19], however at $T = 0$.)

By measuring the differential conductance as a function of V_g and $V_{\rm sd}$ we have been able to show directly that the increase of shot noise occurs in the region of V_g-$V_{\rm sd}$ where two interacting impurities carry the current in a correlated way. Figure 3 presents the gray scale of the differential conductance plotted versus V_g and $V_{\rm sd}$. When a source-drain bias is applied, a single resonant impurity gives rise to two peaks in $dI/dV(V_g)$, which occur when the resonant level aligns with the Fermi levels $\mu_{L,R}$. On the gray scale these peaks would lie on two lines crossing at $V_{\rm sd} = 0$. Consider, for example, point M in Fig. 3. The central area between the two dash-dotted lines comprising regions 1, 2, and 3, corresponds to the impurity level between μ_L and μ_R, when the impurity is in its conducting state. Outside this region the impurity does not conduct, as it is either empty (on the left of the central region) or filled (on the right of it).

Experimentally, at small $V_{\rm sd}$ we see such a crosslike feature near point $R2$, with the left line being more pronounced. (The exact positions of the maxima of the conductance peaks of this line are indicated by circles.) It is seen, however, that with increasing $V_{\rm sd}$, a new parallel line $R1$ appears at $V_g \approx -1.694$ V and $V_{\rm sd} \approx 1$ mV, shifted to the left by $\triangle V_g \approx 4$ mV. (The maxima of the conductance peaks of this line are shown by triangles.)

In Fig. 3 the modulator cross is plotted according to the analysis below—experimentally we cannot observe these lines because the modulator conductance peaks are too small, due to low leak rates X_e and X_c. It is noticeable that the $R1$ line occurs in the inner region of the modulator cross, i.e., where the modulator occupancy changes in time. Therefore, lines $R1$ and $R2$ reflect the Coulomb shift of level R due to the modulator. The modulation of the current should then occur in region (2): the central part of cross M between lines $R1$ and $R2$, Fig. 3. [In region (3) there is no modulation as both states $R1$ and $R2$ conduct, and in region (1) there is no current as the low state $R1$ is still above μ_L.]

In Fig. 4 current noise and the Fano factor are presented as functions of $V_{\rm sd}$ for different V_g. It shows that indeed the increase of noise occurs only in region (2) in Fig. 3. Namely, it appears only between $V_g = -1.699$ V and

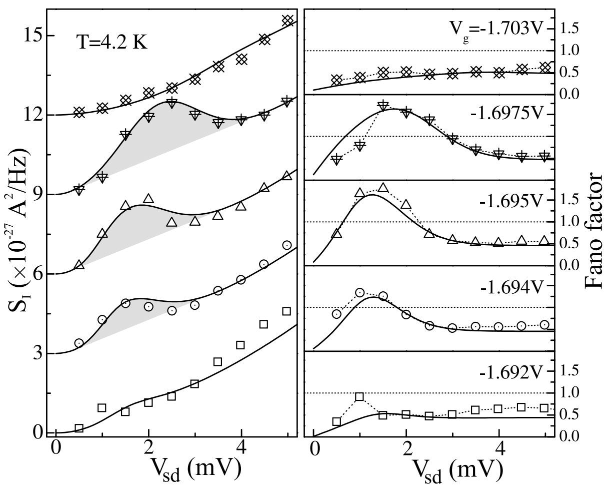

FIG. 4. Excess noise and the corresponding Fano factor as functions of source-drain bias at different gate voltages. (The noise data for different V_g are offset for clarity.) Solid lines show the results of the numerical calculations.

$V_g = -1.693$ V. In addition, when V_{sd} is swept at fixed V_g, one can see that the hump in the Fano factor exists only between lines $R1$ and $R2$.

In order to quantitatively compare the model with the experiment we have to take into account that in our experiment resonant tunneling via state R exists in parallel with the background hopping. Then the total Fano factor has to be expressed as $F = (F_{RT}I_{RT} + F_B I_B)/(I_{RT} + I_B)$, where F_{RT}, F_B and I_{RT}, I_B are the Fano factors and currents for RT and hopping, respectively. In order to get information about the background hopping we have measured noise at $V_g > -1.681$ V, i.e., away from the RT peak under study in Fig. 3. It has been estimated that $F_B \sim 0.4$. This value of the Fano factor is expected for shot noise in hopping through $N \sim 2$–3 potential barriers (1–2 impurities in series [12,20]). The bias dependence of the background current at this V_g is also consistent with hopping current via two impurities: $dI/dV \propto V_{sd}^{4/3}$ [18].

In the numerical analysis of noise in Fig. 4, we have combined the contribution from impurities R and M, and from hopping, assuming that the background current is the same for all studied gate voltages. The numerical results have been fitted to the experimental $dI/dV(V_{sd}, V_g)$ and $S_I(V_{sd}, V_g)$. The fitting parameters are the leak rates of R and M ($\hbar\Gamma_L \simeq 394$ μeV, $\hbar\Gamma_R \simeq 9.8$ μeV, and $\hbar X_e \simeq 0.08$ μeV, $\hbar X_c \simeq 0.16$ μeV), the energy difference between R and M ($\triangle\varepsilon = 1$ meV), and the Fano factor for the background hopping ($F_B = 0.45$). The coefficients in the linear relation between the energy levels M, R and V_{sd}, V_g have also been found to match both the experimental data in Fig. 4 and the position of lines $R1$ and $R2$ in Fig. 3. One can see that the model gives good agreement with the data in both figures. The Coulomb shift ($U \sim 0.55$ meV) found from Fig. 3 agrees with the estimation for the Coulomb interaction between two impurities not screened by the metallic gate: $U \sim e^2/\kappa d \sim 1$ meV, where $d \sim 1000$ Å is the distance between the gate and the conducting channel.

It is interesting to note that the hopping background effectively hampers the manifestation of the enhanced Fano factor F_{RT}, i.e., without the background the Fano factor enhancement would be much stronger. The largest experimental value of F in Fig. 4 (at $V_g = -1.6975$ V) is approximately 1.5, while a numerical value for RT at this V_g is $F_{RT} \approx 8$.

In conclusion, we have observed enhanced shot noise in resonant tunneling via localized states in a short-barrier structure. We have demonstrated that this effect originates from Coulomb interaction between two localized states which imposes correlations between electron transfers. A simple model is shown to provide a quantitative description of the observed enhancement.

We are grateful to E.V. Sukhorukov for stimulating discussions, FOM, EPSRC, and ORS fund for financial support.

[1] Y. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).
[2] G. B. Lesovik, JETP Lett. **49**, 592 (1989); M. Büttiker, Phys. Rev. Lett. **65**, 2901 (1990).
[3] A. N. Korotkov, Phys. Rev. B **49**, 10 381 (1994).
[4] M. Reznikov *et al.*, Phys. Rev. Lett. **75**, 3340 (1995); A. Kumar *et al.*, Phys. Rev. Lett. **76**, 2778 (1996).
[5] F. Liefrink *et al.*, Phys. Rev. B **49**, 14 066 (1994); A. H. Steinbach, J. M. Martinis, and M. H. Devoret, Phys. Rev. Lett. **76**, 3806 (1996); M. Henny *et al.*, Phys. Rev. B **59**, 2871 (1999).
[6] A. B. Fowler, G. L. Timp, J. J. Wainer, and R. A. Webb, Phys. Rev. Lett. **57**, 138 (1986); T. E. Kopley, P. L. McEuen, and R. G. Wheeler, Phys. Rev. Lett. **61**, 1654 (1988).
[7] L. Y. Chen and C. S. Ting, Phys. Rev. B **46**, 4714 (1992).
[8] Y. V. Nazarov and J. J. R. Struben, Phys. Rev. B **53**, 15 466 (1996).
[9] Y. P. Li *et al.*, Phys. Rev. B **41**, 8388 (1990).
[10] H. Birk *et al.*, Phys. Rev. Lett. **75**, 1610 (1995).
[11] V. V. Kuznetsov *et al.*, Phys. Rev. Lett. **85**, 397 (2000).
[12] S. H. Roshko *et al.*, Physica (Amsterdam) **12E**, 861 (2001).
[13] G. Iannaccone *et al.*, Phys. Rev. Lett. **80**, 1054 (1998); Ya. M. Blanter and M. Büttiker, Phys. Rev. B **59**, 10 217 (1999).
[14] M. J. Kirton and M. J. Uren, Adv. Phys. **38**, 367 (1989).
[15] M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[16] Sh. Kogan, *Electronic Noise and Fluctuations in Solids* (Cambridge University Press, Cambridge, England, 1996).
[17] J. R. Clem, Phys. Rep. **75**, 1 (1981).
[18] L. I. Glazman and K. A. Matveev, Zh. Eksp. Teor. Fiz. **94**, 332 (1988) [Sov. Phys. JETP **67**, 1276 (1988)].
[19] M. Eto, Jpn. J. Appl. Phys. **36**, 4004 (1997).
[20] A. N. Korotkov and K. K. Likharev, Phys. Rev. B **61**, 15 975 (2000).