Device Noise as a Probe of Electron Motion in Quantum Dots at High Magnetic Fields

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We study the noise characteristics of gated quantum dots in the edge state (ES) regime. For samples cooled in the dark, and with one or more ES transmitted through the dot, zero current voltage fluctuations, thought to result from the influence of charged defects on the confining potential of the dot, are observed. Increasing the height of the point contact barriers to the dot, all occupied edge states are ultimately localised within it, and discrete resistance switching or "telegraph noise" is then found to emerge. The switching is present in both illuminated and unilluminated devices, consistent with a model in which the noise results from an intrinsic effect, in which single electrons tunnel between different edge states localised within the dot.

I. Introduction

Spurred by advances in micro-fabrication technology, much recent interest has focused on the noise properties of mesoscopic devices, in which effects due to phase coherence and energy quantisation have been found to strongly modify the resulting electrical characteristics[1-4]. In this report we therefore investigate the noise properties of micron scale quantum dots, by studying the influence of a quantising magnetic field upon their low temperature transport properties. The dots are realised using a standard split gate technique, in which commonly biased quantum point contacts are used to control the transmission of electrons in to and out of the dot. At high magnetic fields, current flows via edge states (ES)[5] and, by suitable adjustment of the point contact barriers, the dot is able to selectively trap higher lying edge states, while allowing others to pass freely through it[6]. Studying the noise characteristics in this regime we then find very different behaviour, as the coupling of the dot to the source and drain is varied.

In particular, with one or more ES transmitted through the dot transport is in the strong coupling regime. Here we find that the dots may generate voltage noise, which *persists in the absence of an applied current!* An extrinsic origin for the phenomenon is suggested by the strong illumination dependence of the voltage noise, which is only observed in samples cooled in the dark. While currently unable to provide a definitive model for the generation of the noise, we propose a possible mechanism in which time dependent perturbations to the dot geometry, induced by charge fluctuations on sample defects, give rise to corresponding fluctuations in the coupling between the transmitted and confined ES. In other words, the voltage noise is thought to be a direct probe, of the time dependent motion of the electronic distribution within the dot.

Further increasing the height of the point contact barriers, all occupied edge states ultimately become localised within it and discrete resistance switching, or "telegraph noise", is found to emerge. The switching is present in both illuminated and unilluminated devices, consistent with a recent interpretation in which the noise has been argued to result from an intrinsic effect, in which single electrons tunnel between different edge states localised within the dot[3,5].

II. Sample preparation and measurement technique

Split gate quantum dots were realised in a GaAs/AlGaAs heterojunction, using standard electron-beam lithographic techniques. The wafer was patterned

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in to a Hall bar geometry, with a typical carrier density 4.10^{15} m^{-2}, and mobility 40 m^2/Vs. The gates consisted of a stub like design, in which a lithographically square dot was separated from the source and drain by quantum point contacts (Fig. 1 inset)[7]. Independently tunable dots with gate dimensions 1.0- and 2.0-μm were defined within close separation on the same Hall bar wafer. The samples were clamped to the mixing chamber of a dilution refrigerator, and magneto-transport measurements were made at cryostat temperatures down to 10 mK. The four probe configuration employed[7] included a series contribution due to the source and drain regions, and at low magnetic fields the resistance of this was much smaller than that of the dot. At higher fields, however, the probe configuration was only sensitive to the edge state transmission of the dot[6]. Great care was taken to ensure good thermal contact to the samples, and a source-drain excitation of less than 3 μV was employed for the current bias measurements.

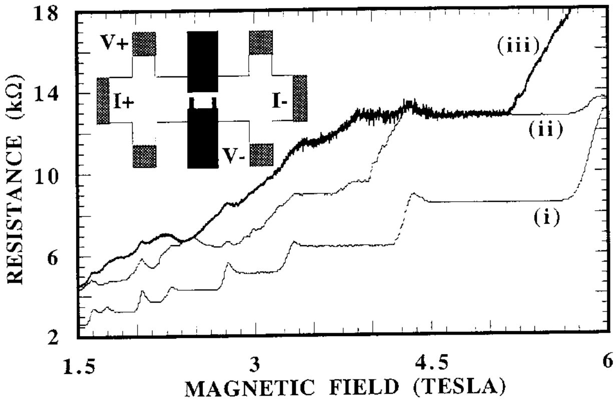

Figure 1. Magneto-resistance of a dark-cooled 1-μm dot (sweep rate=0.25 mTs^{-1}, current=0.2 nA). Trace i: $V_g = 0V\&T = 10$ mK, trace ii: $V_g = -1.60V\&T = 10$mK, and trace iii: $V_g = -1.65V\&T = 80$ mK (in the region of overlap of traces ii and iii, the noise is associated with trace iii). Insert: Schematic diagram of Hall bar geometry, with the gates shown in black.

III. Experimental results: zero current voltage fluctuations

We begin by considering the characteristics of devices cooled in the dark, and measured prior to LED illumination at low temperatures (Fig. 1). With the gates grounded, the magneto-resistance is found to exhibit clear quantum Hall plateaux. With a negative gate bias applied, the initial effect is to shift the plateaux to lower fields, indicating selective confinement of ES in the dot[6]. As the gate bias is further increased, the plateaux continue to shift to lower fields, and a strong increase in the high field noise level is observed. The characteristics of this noise are found to be unaltered on sitting at fixed magnetic field and, *disconnecting the current leads, the fluctuations are found to persist in the dots, while no such noise is observed with the gates grounded* (Fig. 2)! Subsequent current-voltage measurements have shown the voltage noise to be constant over nearly three decades of current, indicating its origin to be a true voltage fluctuation. As for sample dependent variations, the noise was observed in all dark-cooled devices and was found to remain on thermal cycling. Similar characteristics were observed in both the 1- and 2-μm dots, when the gate voltage was adjusted to achieve roughly equivalent ES transmissions. The amplitude of the noise was a sensitive function of the gate voltage, however, and at even higher biases than those shown here, could ultimately obscure any average features in the high field magneto-resistance.

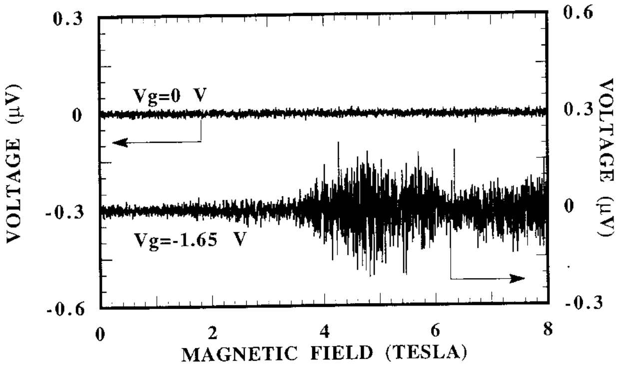

Figure 2. Zero-current voltage fluctuations in the dark cooled dot of Fig. 1 at 4.2 K.

From Fig. 1 it can be seen that, over the magnetic field range where the noise is observed, one or more ES are confined within the dot. For example, at 4.5 T the bulk magneto-resistance has just reached the ν=3 quantum Hall state, while that of trace (iii) is already at the ν=2 plateau. Two spin resolved ES are therefore passing freely through the dot and the number of confined ES $\nu_d = 1$. Indeed, in all cases we have studied, confinement is found to be a crucial condition for the observation of the voltage noise. With regards to the magnetic field dependence of the noise, a white frequency spectrum was obtained at all fields where the noise was observed.

IV. Experimental results: resistance switching or "telegraph noise"

An important feature of the voltage noise discussed in Section III is that it is not observed in devices subjected to strong LED illumination. Such devices actually exhibit a separate noise phenomenon at high magnetic fields; in particular, increasing the point contact barriers to the dot until all occupied ES become localised within it, we generally find that resistance switching is observed (Figs. 3 and 4). An important feature of this "telegraph noise" is that it is only observed in the presence of a strong magnetic field, and is not detected simply by pinching off the gates to form well defined tunnel barriers at zero field. Qualitatively similar noise has previously been widely reported in single point contacts, and in these devices is associated with remote impurities inducing changes in the electrostatic potential by trapping[2]. The time scale τ between successive trapping events is typically only of order a fraction of a second in these devices, however, and the noise is still observed with the device resistance less than $h/2e^2$. In contrast, the switching noise here occurs with a characteristic τ of up to tens of minutes at the highest magnetic fields. Similar results have recently been reported by van der Vaart et al, who suggest that the switching is actually an intrinsic effect, due to single electrons tunneling between different edge states within the dot[3].

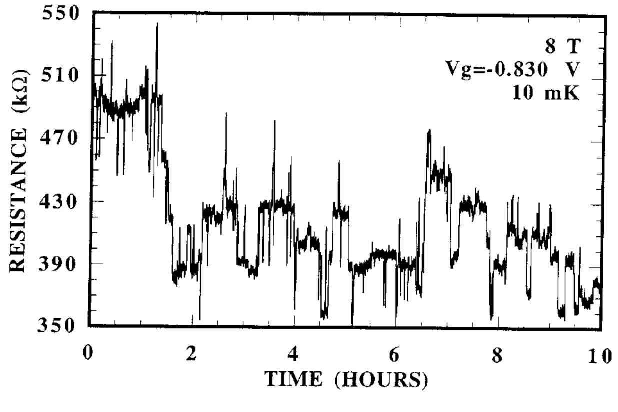

Figure 3. Switching noise observed in the magnetoresistance of a 2-μm quantum dot. The average dot resistance of 450 kΩ corresponds to an edge state transmission of only 6% i.e. the dot is strongly in the tunneling regime.

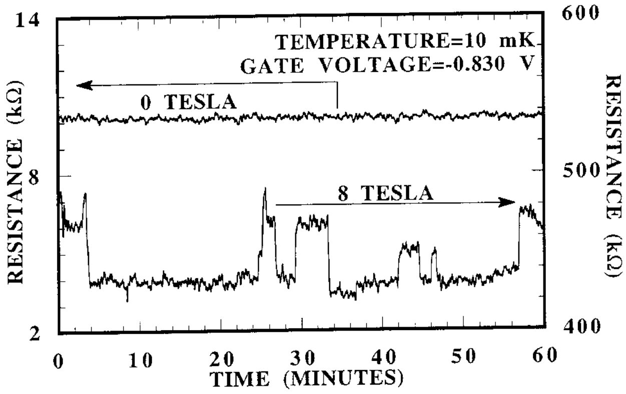

Figure 4. Switching noise is only observed for magnetic fields such that transport through the dot occurs by tunneling. In this figure, a 2-μm dot was configured to be "open" at zero magnetic field, and magnetic depopulation of the dot point contacts resulted in a transition to tunneling at higher fields.

V. Discussion

Although currently unable to provide a definitive model for the generation of the voltage noise, on the basis of our investigations we propose a possible mechanism, the key requirements of which are: the presence of small, time-dependent perturbations to the dot geometry and; the confinement of one or more ES within the dot. With regards to the first requirement, previous studies have shown that the confining potential induced in gated devices is influenced by fluctuations, in the charge state of impurities in the doped AlGaAs layer[2]. With multiple impurities present, the resistance of split gate channels has been found to show a time dependent decay at fixed gate voltage[4], and we observe a similar effect in our dark-cooled devices after initially setting the gate bias. The decay implies a gradual increase in the dot size with time and, while the measurements discussed here were performed after the resistance had reached a stable equilibrium, from the exponential nature of the decay we imagine that the dot shape was continuously fluctuating, by some small amount, in the course of the experiments.

Since voltage noise is only observed with one or more ES confined in the dot, this suggests the confined charge acts as an additional reservoir, to influence the electrochemical potential of the transmitted ES. In order to appreciate how this might occur, consider the case where all ES states are transmitted through the dot. In the absence of an applied current, the oppositely propagating ES populate to the same electrochemical potential, and the voltage measured across the dot will be zero. If we allow the dot size to increase by some small amount, the strong Lorentz force will push the ES towards the walls, but since this does not affect their chemical potential the measured voltage will remain zero. Now consider a similar size increase, when one or more ES are confined in the dot. The transmitted ES will again be pushed towards the walls, but the confined ES will maintain their position at the centre of the dot. This latter property is a consequence of flux quantisation, which forces the confined ES to maintain fixed cross sectional area. In other words, small perturbations to the dot geometry should give rise to a time dependent capacative coupling, between the transmitted ES and the confined charge at the centre of the dot. Since the perturbations are expected to occur randomly in time, the electrochemical potential difference between the oppositely propagating ES, and so the measured voltage, should then also fluctuate randomly.

On the basis of the above discussion it should be apparent that no voltage noise is expected, in the absence of time dependent perturbations to the dot geometry, or of confined charge at the centre of the dot. With regards to the first condition, we note that the voltage noise was not observed in devices subjected to strong LED illumination. The time dependent decay of the resistance was also absent in these devices, and the resulting magneto-resistance characteristics were found to be highly reproducible. As for the nature of the charged impurities, the white noise spectrum points to a many impurity effect. While it may seem surprising that fluctuations in the dot shape should persist to milli-Kelvin temperatures, the small thermal energy available here should actually ensure that the relaxation of the dot to equilibrium occurs only very slowly. This in turn would explain the observed persistence of the noise, with unaltered characteristics, over the several week periods during which the experiments were performed.

In contrast to the zero current voltage noise, a more intrinsic origin has been proposed for the telegraph noise observed in the tunneling regime. In particular, the noise has been argued to result from single electron tunneling, between different edge states localised within the dot[3]. The authors associate the long characteristic τ for the process with the fact that tunneling occurs across broad regions of incompressible electron gas, whose width increases with magnetic field[5]. Our results certainly favour such an "intrinsic" picture; the noise is only observed with all edge states localised in the dot, under which conditions tunneling of an electron between two edge states is expected to result in a re-adjustment of their respective chemical potentials. This re-adjustment is in turn believed to be responsible for the discrete change in the dot conductance observed experimentally.

VI. Conclusions

In conclusion, we have studied the noise characteristics of gated quantum dots in the edge state regime. For samples cooled in the dark, and with one or more ES transmitted through the dot, zero current voltage fluctuations were observed, and are thought to result from the influence of sample impurities on the confining potential of the dot. Further increasing the height of the point contact barriers, all occupied edge states ultimately became localised within the dot, and discrete switching or "telegraph noise" was observed in the magneto-resistance. The switching was present in both illuminated and unilluminated devices, consistent with a model in which the noise is argued to result from an intrinsic effect, in which single electrons tunnel between different edge states localised within the dot.

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