

## Addition spectrum of a lateral dot from Coulomb and spin-blockade spectroscopy

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Transport measurements are presented on a class of electrostatically defined lateral dots within a high mobility two-dimensional electron gas (2DEG). The design allows Coulomb blockade (CB) measurements to be performed on a single lateral dot containing 0, 1 to over 50 electrons. The CB measurements are enhanced by the spin polarized injection from and into 2DEG magnetic edge states. This combines the measurement of charge with the measurement of spin through spin-blockade spectroscopy. The results of Coulomb and spin-blockade spectroscopy for the first 45 electrons enable us to construct the addition spectrum of a lateral device. We also demonstrate that a lateral dot containing a single electron is an effective local probe of a 2DEG edge.

The ability to confine, manipulate, and probe individual electrons in a solid state environment is a prerequisite for a variety of transport nanoscale applications, from single electron transistors to gates in a quantum computer.<sup>1-3</sup> It is an important task, therefore, to construct a quantum dot in which one can simultaneously tune the number of electrons and interrogate them spectroscopically. This has been achieved previously in vertical quantum dots in which the number of confined electrons has been successfully controlled down to zero and a number of spectacular new discoveries made using both capacitance and Coulomb blockade techniques.<sup>4,5</sup> Vertical devices are pillars formed by etching out material in a double barrier tunneling device. The electrons are injected into the pillar from  $n^+$  contacts. Early pioneering investigations have also been performed on lateral devices.<sup>6</sup> While the versatility of electrostatically defined lateral dots formed within a high mobility two-dimensional electron gas (2DEG) was well established, it has always been assumed to be impossible to empty a lateral dot while maintaining operating tunneling barriers.<sup>7</sup> It has also proved difficult to extend measurements to very high magnetic fields as a result of pinch-off effects associated with magnetic depopulation within the tunneling barriers. Recently, we managed to reduce the number of electrons in a lateral dot to around 10.<sup>8,9</sup> It was discovered in those measurements that above a certain magnetic field, electrons entering the dot were spin polarized. This was a direct consequence of their injection from spin polarized magnetic edge states in the 2DEG which formed at the tunneling barriers into and out of the dot. We were able to make use of this additional “spin spectroscopy” to confirm the role that spin textures play in the spin-flip regime ( $2 > \nu > 1$  where  $\nu$  is the filling factor).<sup>9,10</sup>

In this paper we demonstrate that lateral dots defined in a 2DEG can be completely and controllably emptied of electrons. We are able not only to measure the addition spectrum of a lateral dot but are able to extend the “spin” spectroscopy to this lower field regime (i.e.,  $\nu > 2$ ) and *directly* observe quantum dot spin phenomena. Previously spin related physics such as Hund’s rule and single-triplet transitions were

indirectly deduced from the addition spectrum. Finally, we discuss how the quantum dot can be used as a local probe of the 2DEG edge.

The lower inset of Fig. 1 is a scanning electron microscopy (SEM) micrograph of a device similar to the one used in our measurements. The dot is electrostatically defined by four gates above a GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  heterostructure. A top “T” gate in combination with left and right finger gates is used to define the dot geometry. A narrow plunger gate, located in the gap between the left and right finger gates is used to vary the number of electrons. The lithographic width and height of the triangular dots was approximately  $0.45 \mu\text{m}$ . The bulk density (mobility) of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$  wafer used were  $1.7 \times 10^{11} \text{ cm}^{-2}$  ( $2 \times 10^6 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ ). To operate the device in the Coulomb blockade mode, the top and finger gates are used to create tunneling barriers between the 2DEG and the dot. The plunger gate is used to vary the number of electrons in the

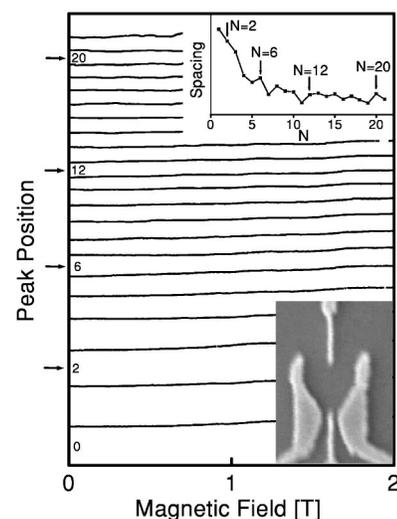


FIG. 1. A plot of the first 22 Coulomb blockade peaks. The arrows refer to the expected full shells for a circular dot. The upper inset shows the peak spacing. The lower inset is a SEM of a device similar to the one used in the measurements.

dot. A Coulomb blockade peak is observed whenever the electron number in the dot changes. As was first shown by McEuen *et al.*,<sup>6</sup> the gate voltage position of the Coulomb blockade peaks is related not only to the charging energy, but also provides information about the kinetic energy spectrum of the dot. The shape, gate design, and molecular beam epitaxy (MBE) wafer were chosen to enable us to reach the minimum number of electrons in the dot while still enjoying operating tunnel barriers. In particular, it is crucial that two gates define each tunneling barrier, one with large and one with small contributions to the dot perimeter. This allowed several operations to be achieved that were critical to (i) the successful emptying of the lateral dot and (ii) for extending spectroscopic measurements to high magnetic fields (18 T). Applying a more negative voltage to the finger gates while keeping the same tunnel barrier height (achieved by simultaneously reducing the voltage applied to the T gate) reduced the size of the dot. Magnetic depopulation effects in the barrier region were compensated for by miniscule reductions (millivolts) in the voltage applied to the T gate.

Figure 1 plots the first 22 peaks at low magnetic fields, from 0 to 2 T. A series of sweeps is made using the techniques described above to systematically reduce the size of the dot and number of electrons. Overlapping ranges are chosen to ensure that the changes made are sufficiently adiabatic that identical behavior is observed for the peaks present in overlapping sweeps. The gate voltage scale in Fig. 1 was set by normalizing the overlapping curves at 1 T. In any device with soft confinement, the single particle energy spectrum  $E(m,n) = \Omega_-(m+1/2) + \Omega_+(n+1/2)$  is that of a pair of harmonic oscillators with magnetic field tunable frequencies  $\Omega_{\pm}$ , the Fock-Darwin (FD) spectrum.<sup>11,12</sup> At zero magnetic field, electronic shells of degenerate levels exist. Weakly interacting electrons fill up these shells according to Hund's rules. The complete shell filling is expected for  $N = 2, 6, 12, 20, \dots$  electrons. When a shell is filled, it costs extra kinetic energy to add an electron leading to an increased peak spacing. The inset in Fig. 1 plots the zero field peak spacing between the  $N$  and  $N+1$  peaks against  $N$ . The spacing between peaks generally increases as the number of electrons and the size of the dot is reduced. This is particularly apparent for the first few electrons. The arrows mark the electron number corresponding to the expected full shells.<sup>4</sup> Agreement with shell effects (i.e., increased peak spacing) is apparent only at 6 electrons. Consequences of the dot rapidly shrinking may mask an increased peak level spacing at 2 electrons but the spacing after the 12th and 20th electrons shows no evidence of shell structure. A simple interpretation in terms of shells seems unlikely. We speculate that this is related to the reduced screening conditions in lateral dots which might be expected to result in a more strongly interacting electron system. There is, in addition, no obvious spin-related odd-even behavior in peak spacing at zero field, such as might be expected if the confinement energy dominated over the interaction terms.

The first 45 peaks in the same magnetic field range as in Fig. 1, but with the charging energy removed by shifting the peaks together are illustrated in Fig. 2. The CB peak positions plot out the addition spectrum for a dot with a fixed number of electrons. The addition spectrum reflects the kinetic energy of the added electron. In the simplest model of

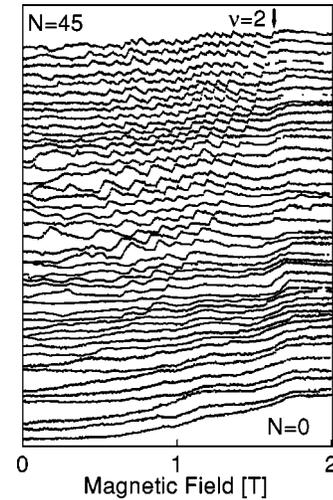


FIG. 2. The first 45 peaks with the charging energy manually removed. The arrow points to the  $\nu=2$  line which extrapolates to zero magnetic field as we empty the dot.

a parabolic dot, the magnetic field induces level crossings of single particle eigenstates. Level crossings appear as cusps in the peak positions. The oscillations in peak positions associated with the level crossings terminate at the  $\nu=2$  boundary. There are several experimental confirmations that we have fully emptied the dot. Firstly, no further CB peaks are found using the systematic techniques similar to those described above. Secondly, the experimental curves of Fig. 2 clearly show the  $\nu=2$  line extrapolating completely to zero magnetic field, as expected for an emptying dot and as observed in the vertical dot experiments. Thirdly, we can extract the number of electrons from the number of spin flips from the  $\nu=2$  to  $\nu=1$  dot.<sup>9</sup> Clearly, one needs to flip half the spins to polarize an unpolarized dot. We can confirm, based on results from these new dots, that this technique is consistent with the electron number obtained by counting peaks upwards from an empty dot.

We now concentrate on two important features of these measurements that are a direct consequence of using 2DEG leads rather than  $n^+$  contacts.

The benefits of spin polarized injection for spectroscopic purposes reveals itself in the amplitude of the Coulomb blockade peaks. Spin effects can be “directly” observed by current readout (i.e., by monitoring the effects of spin blockade on the Coulomb blockade peak amplitude). The inset in Fig. 3 plots the peak amplitude in the Fock-Darwin regime of the addition spectrum for several peaks. Starting around 0.4 T (the same magnetic field at which the spin resolution of the 2DEG Shubnikov-de Haas oscillations is first seen in this GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As wafer) a digital amplitude behavior can be observed in the amplitude spectrum. We expect a reduced peak amplitude if the difference between the  $N$  and  $N+1$  electron groundstates is either (i) a spin up electron (since only spin down electrons are injected from the innermost edge state) or (ii) an electron near the center of the dot (due to a reduced wave-function overlap with the electrons at the edge). Figure 3 relates the amplitude to the peak position spectrum for a few typical “digital” features, as shown in the inset. A pattern is seen to repeat itself. Downward sloping lines of roughly equal length  $A-B$  and  $C-D$  correspond to adding the incoming electron to  $(m,0)$  and  $(m+1,0)$  levels

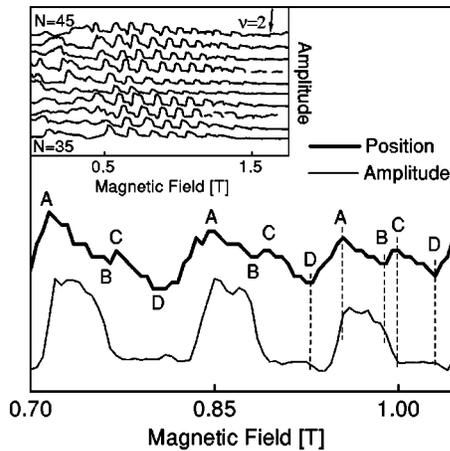


FIG. 3. A comparison of the peak position and amplitude behavior at low fields for peak 43. The inset shows the low field amplitude spectrum of peaks (36 to 45).

(i.e., from the lowest Landau level) at the edge of the dot. The short (*B-C*) and long (*D-A*) vertical steps both correspond to adding an electron to higher Landau level eigenstates closer to the center of the dot. The short (long) vertical step occurs at a large (small) to small (large) peak amplitude transition for the downward sloping lines. Since the *A-B* and *C-D* regions correspond to adding an electron at the dot edge, their amplitude simply reflects whether the difference between the  $N$  and  $N+1$  electron ground states is a spin up or down electron. It is important to note that this alternating large/small amplitude behavior is not consistent within a noninteracting picture in which the downward sloping regions would either have a small (spin up) or a large (spin down) amplitude but not alternating large/small amplitudes along a single peak (nb. Zeeman splitting can be ignored at these low fields). We have observed identical behavior for lower electron numbers at the less complex theoretically  $\nu=2$  boundary where the effect can be accurately attributed to an interaction related singlet-triplet transition<sup>13</sup> (further details of these spin effects at  $\nu=2$  and a comparison with calculations will be published elsewhere). Tarucha *et al.*<sup>14</sup> have also deduced the singlet-triplet transitions at  $\nu=2$  using the position of CB peaks in the addition spectrum alone. The similarity with the  $\nu=2$  regime suggests that similar interaction driven spin effects also occur at much lower fields. By analogy with the theory at  $\nu=2$ , the data is consistent with the following description of the magnetic field evolution of even number ground states in the Fock-Darwin regime. As the magnetic field is lowered, electrons at the edge are transferred one by one to higher Landau levels near the center of the dot. Each of the kinetic energy levels at the edge contains a spin down and a spin up electron. The spin up electron is transferred first as the field is lowered, but due to interactions it is energetically favorable for it to flip spin and form a triplet state with its former partner. As the field is lowered further, the singlet pairing is reinstated as the second electron is transferred to the same state as the first but as a spin up electron. The cycle is then repeated. The additional dip in amplitude during the *D-A* step occurs because the incoming electron in that region is being added to the center of the dot.

Secondly, let us consider the effect of the 2DEG chemical potential jumps associated with Landau level depopulation

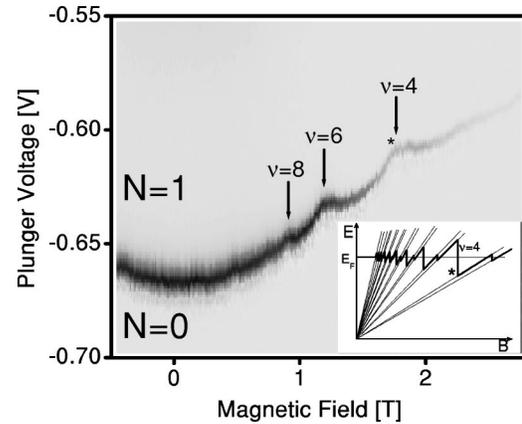


FIG. 4. The data for the first peak. The steplike structures are a consequence of the chemical potential jumps in the 2DEG. The inset is a schematic of the 2DEG chemical potential.

on our measurements. While most cusps in Fig. 2 are peak number dependent, certain features are identical for all peaks. These can be seen most clearly for  $N=1$  peak where we do not expect or see any features related to level crossings. Figure 4 shows this peak from  $B=-0.5$  to 3 T. To understand the origin of the steplike structures observed on this Coulomb blockade peak, it is important to remember that the Coulomb blockade occurs when the chemical potentials of the dot and leads are matched. The  $1/B$  steplike features are due to the chemical potential jumps in the 2DEG. The  $\nu=1$  and  $\nu=2$  2DEG chemical potential jumps at higher fields have also been observed. The inset in Fig. 4 shows a schematic of the bulk chemical potential of a 2DEG. We note that with the exception of  $\nu=1$ , only the even filling factor steps are resolved experimentally. The 2DEG chemical potential steps are observed in an inverted fashion in the data since a drop in the 2DEG chemical potential requires a less negative plunger gate voltage to maintain the resonance condition. The first peak (i.e., that observed on adding the first electron) is crucial for spectroscopic investigations since it can be used to separate 2DEG effects which will be present on this peak from intrinsic quantum dot effects which will not. The observations shown in Fig. 4 also confirm that a lateral dot containing a single electron can be used as a local probe of the 2DEG edge chemical potential.<sup>15</sup>

In conclusion, we have demonstrated two important features of the lateral nature of a quantum dot which emerge when we are capable of emptying the dot and also able to perform transport measurements. We have demonstrated that even in the Fock-Darwin regime of the addition spectrum, the use of a high mobility 2DEG leads to spin polarized injection into the dot. This provides a spectroscopic tool, the spin blockade, which directly measures the spin state of the dot through “current readout” and allows spin phenomena to be identified in the addition spectrum. The second feature is the application of an empty quantum dot as a spectrometer of edge states of 2DEG. The first,  $N=1$ , peak may be used for locally probing the 2DEG edge, and these studies, interesting in themselves, can then be utilized to separate quantum dot features for higher electron numbers. Finally we note that isolation of a single spin and its probing with a spin polarized source of electrons constitutes readout of a spin qubit in a quantum computer.

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