

## Coulomb-blockade spectroscopy on a small quantum dot in a parallel magnetic field

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Coulomb-blockade spectroscopy measurements are made on a small GaAs/AlGaAs quantum dot in a magnetic field oriented parallel to the plane of the sample. Coulomb-blockade peak motion is observed which can be explained by changes in the spin of successive ground states as single electrons are added. The peak movement at low field is consistent with that expected from Zeeman coupling, from which it can be inferred that electrons are not added to the dot in a strictly alternating spin up/spin down manner. © 2000 American Institute of Physics. [S0003-6951(00)00840-8]

The role of electron spin in the energy spectra of nanostructures has been the subject of much recent experimental<sup>1–5</sup> and theoretical<sup>6,7</sup> interest. Spin manifests itself differently in different types of nanostructures. Studies of planar semiconductor quantum dots have yielded no evidence for a spin-degenerate picture of state filling. For example, the effects of electron spin degeneracy have not been observed in statistical measurements on Coulomb-blockade peak spacings.<sup>1</sup> Similarly, correlations between ground and excited state spectra in an asymmetric dot have supported a single particle picture of state filling, but without spin degeneracy.<sup>2</sup> On the other hand, in a vertical, cylindrically symmetric semiconductor dot, shell structure has been observed in agreement with a spin-degenerate single-particle picture modified according to Hund's rules.<sup>3</sup> Spin effects have also been observed in other types of nanostructures, including metallic nanoparticles<sup>4</sup> and carbon nanotubes.<sup>5</sup> Understanding the role of spin in nanostructures is important for potential applications ranging from spin-based electronics to quantum computers.<sup>8</sup>

In this letter, we investigate manifestations of spin in the energy spectra of laterally defined GaAs/AlGaAs quantum dots using Coulomb-blockade spectroscopy measurements in a magnetic field oriented parallel to the plane of the sample. By noting the shift of successive Coulomb-blockade peaks upon application of a parallel field, we are able to observe behavior consistent with spin effects while minimizing the influence of the magnetic field on electrons' spatial states. We analyze our data in terms of spin together with orbital effects that can also be important, particularly at higher magnetic fields. Following this interpretation, we are able to determine how the total ground state spin changes as each successive electron is added, and we note that these changes do not occur in a strictly alternating spin up/spin down manner. We also observe features in our data that are not adequately described in terms of spin, and we discuss orbital effects as the possible cause.

Figure 1 shows a scanning electron micrograph of the device, a quantum dot defined inside a GaAs/AlGaAs heterostructure by electrostatic gates. A two-dimensional electron gas (2DEG) with mobility  $5 \times 10^5$  cm<sup>2</sup>/V s and sheet density  $3.5 \times 10^{11}$  cm<sup>-2</sup> is located 47 nm below the surface. Metal gates fabricated using electron beam lithography and Cr–Au metallization are used to locally deplete the 2DEG and to control the occupancy of the dot. As shown in Fig. 1, two quantum point contacts connect the dot to the 2DEG outside, and gate voltages  $V_{g1}$  and  $V_{g2}$  induce charge on the dot. The lithographic size of the dot is  $200 \times 250$  nm<sup>2</sup>, and the size of the electron pool was  $\cong 100 \times 150$  nm<sup>2</sup>. The resulting quantum dot is quite small and contains  $\sim 50$  electrons. The quantum dot sample is cooled in a dilution refrigerator to base temperature 12 mK. A magnetic field in the plane of the 2DEG is applied by a superconducting solenoid. Measurements of dot conductance in the Coulomb-blockade regime use ac lock-in techniques with weak tunneling ( $G \ll 2e^2/h$ ) through the quantum point contacts. The charging energy  $e^2/C \cong 2$  meV and the average spacing between energy levels  $\Delta \epsilon \cong 200 \mu\text{eV} \gg kT$  are determined from nonlinear conductance measurements. The linear conductance  $G_{\text{dot}}$  of the

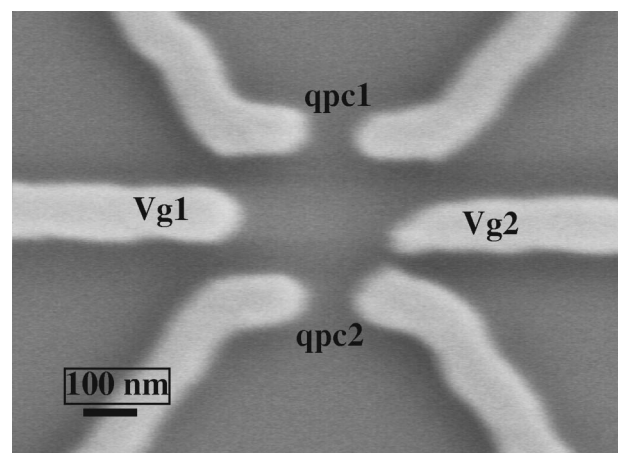


FIG. 1. Scanning electron micrograph of the quantum dot, defined in the 2DEG inside a GaAs/AlGaAs heterostructure.

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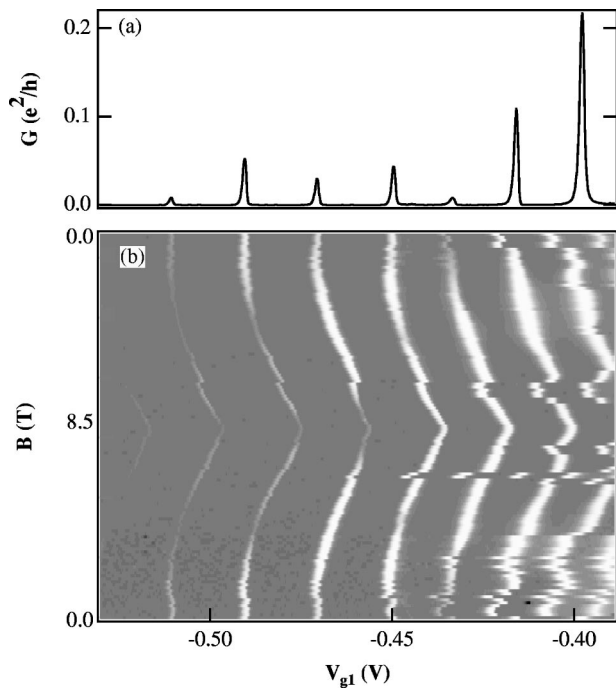


FIG. 2. (a) Conductance trace  $G_{\text{dot}}$  in the Coulomb-blockade regime vs gate voltage  $V_{g1}$  at  $B=0$  T, with regularly spaced peaks. (b) Conductance  $G_{\text{dot}}$  in the Coulomb-blockade regime vs gate voltage  $V_{g1}$  and in-plane magnetic field  $B$ , plotted in inverse gray-scale; lighter regions conduct more. The magnetic field is swept up from  $B=0$  to 8.5 T and back down to 0 T in order to distinguish between peak motion due to  $B$  and peak motion due to switching noise in the 2DEG heterostructure.

dot in the Coulomb-blockade regime at low applied voltages is recorded as the gate voltage  $V_{g1}$  and magnetic field  $B$  are swept.

Figure 2(a) shows a series of Coulomb-blockade conductance peaks in a plot of the measured conductance of the dot at zero bias voltage as the gate voltage  $V_{g1}$  is swept. The position of each peak is determined by the energy necessary to add one additional electron to the dot. This energy has components originating from both Coulomb charging and spatial quantization. Figure 2(b) shows the principal data: how the Coulomb-blockade peaks in dot conductance  $G_{\text{dot}}$  versus gate voltage  $V_{g1}$  shift in position with in-plane magnetic field  $B$ ; dark regions correspond to high conductance, light regions to low. From Fig. 2(b) it is clear that the addition energy is altered by magnetic field: as the magnetic field is swept from 0 to 8.5 T, all peak positions are observed to curve. This peak motion provides information on how electron spin and orbital effects combine to determine the ground state energy of a quantum dot. The motion of each peak can be separated into two principal components: a large shift common to all peaks, and smaller, independent peak shifts which require more careful analysis. The common shift has been observed previously<sup>9</sup> and is caused by coupling between the magnetic field and the transverse components of electron wave functions in the dot and in the leads.<sup>10</sup> The independent, smaller peak motion we interpret as due to a Zeeman contribution to the dot ground state energy, a consequence of the electron spin. The Zeeman contribution to the peak position is negative when the electron added is spin up, and positive when the electron added is spin down.<sup>11</sup> However, orbital effects may also contribute to the relative

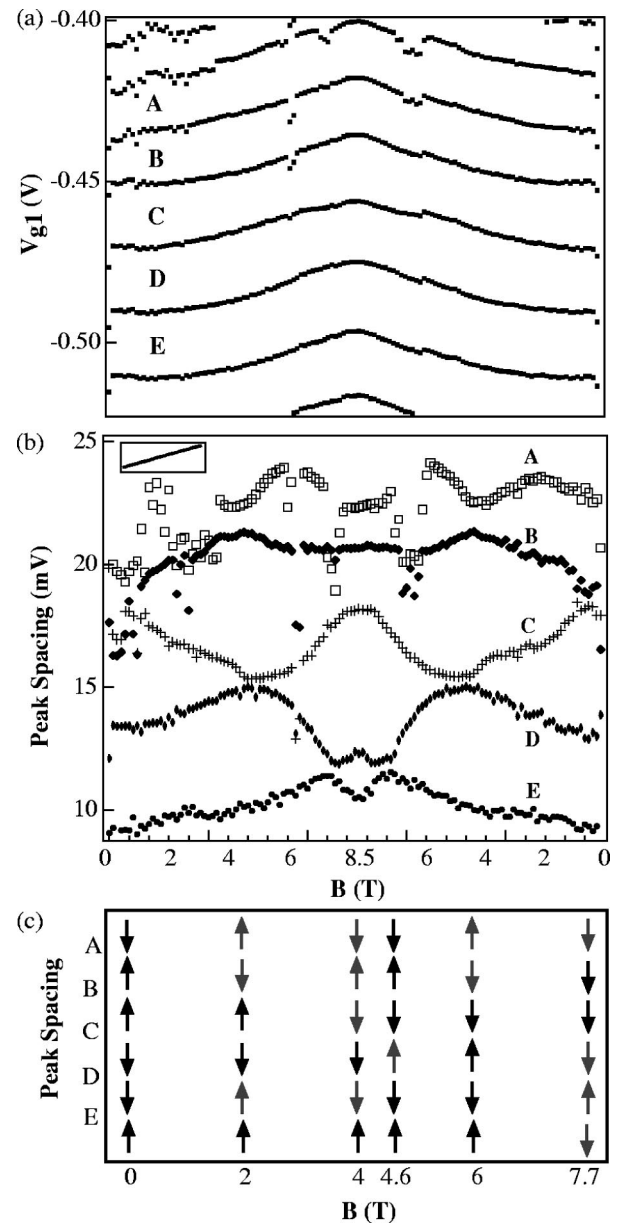


FIG. 3. (a) Fitted Coulomb-blockade peak positions in  $V_{g1}$  vs in-plane magnetic field  $B$ . Peak spacings are labeled A–E. (b) Evolution of peak spacings A–E with magnetic field  $B$ . The slope vs  $B$  corresponds to the change in ground state spin as each electron is added and hence measures the  $g$  factor. Inset shows the slope for the bulk GaAs  $g$  factor  $|g|=0.44$ . Breaks in slope correspond to changes in spin of added electrons. (c) Spin state of added electron for each Coulomb-blockade peak, shown for magnetic fields  $B$  at which breaks in slope occur; changed spins are gray. Added electrons do not alternate spin up and spin down.

peak motion: because there is a distribution of quantized energy levels in the dot, the parallel magnetic field could cause a level-dependent shift in the ground state energy. Another possible cause of peak motion may be a small perpendicular component of the magnetic field, shown by Shubnikov–de Haas measurements to be  $\approx 3^\circ$  out of plane. This component is not likely to be significant, at least at low fields, as it corresponds to only one flux quantum penetrating the dot at 8.5 T, the highest field used in our measurements. Abrupt shifts in the location of individual peaks are caused by switching noise as for other Coulomb-blockade measurements.

Figure 3 presents the key result of our experiment and

provides evidence for the role of electron spin in the addition energy for electrons in our dot. Figure 3(a) shows peak positions versus gate voltage  $V_{g1}$  and magnetic field  $B$ , precisely obtained by fitting each peak in Fig. 2(b) to the form for thermally broadened resonant tunneling through a single quantum state. The evolution with magnetic field of the spacings between successive peaks is depicted in Fig. 3(b). Using spacings rather than simply positions eliminates common peak motion with magnetic field and minimizes the impact of switching noise. The variation of spacings A–E in Figs. 3(a) and 3(b) with magnetic field gives information about the spin states of electrons added to the dot. For example, spacing E in Fig. 3(b) increases with magnetic field. This means that the two electrons added on the Coulomb-blockade peaks bracketing E are added spin up and spin down, respectively. Spacing E increases with magnetic field, because the energy to add the first, spin up, electron is lowered by the Zeeman energy, and the energy to add the second, spin down, electron is raised by the Zeeman energy. Conversely, a spacing that decreases with field must occur between two Coulomb-blockade peaks at which electrons are added spin down and up, respectively, and a constant spacing implies that two successive electrons of the same spin are added.

The Coulomb-blockade spacings in Fig. 3(b) are evidence that electrons are not added to the dot in an alternating spin up/spin down manner. The spin state of each added electron is shown in Fig. 3(c). The leftmost vertical column depicts the zero magnetic field series of added spins. In some cases two successive electrons are added with the same spin, as shown by spacing D, which is constant at low field. The  $g$  factors of added electrons can be obtained from the slope of spacings with magnetic field  $g\mu_B/\alpha$ , where  $\alpha \equiv C_g/C = 0.072$  for our dot and  $\mu_B$  is the Bohr magneton. At low field, the absolute value of all slopes are roughly equal, with  $g$  factors 0.43 to 0.57 comparable to the  $g$  factor in bulk GaAs  $|g| = 0.44$  shown in the inset in Fig. 3(b). These measurements can not distinguish the sign of the  $g$  factor. These  $g$ -factor data point to the importance of spin effects for in-plane magnetic fields.

Figure 3(b) shows interesting structure with increasing magnetic field. The Coulomb-blockade peak spacings tend to change with magnetic field in a series of connected segments. For example, spacing B changes from downward sloping to flat at 6 T. Similar breaks in slope occurred for cylindrically symmetric dots,<sup>3</sup> and some evidence of similar breaks was seen in Ref. 2. If spin were the principal cause, breaks in slope of Coulomb-blockade peak spacings could occur when the spin of the ground state changes with mag-

netic field. Recent theory has proposed that statistics of breaks in peak slope could be used to estimate the exchange energy of electrons in a quantum dot,<sup>12</sup> though the present data are not sufficient for such an analysis.

From Fig. 3 it is clear that both spin and orbital effects play a role in our data. The most significant orbital effect is the common shift of the Coulomb-blockade peak positions with magnetic field, seen in previous experiments.<sup>9</sup> However, in a small quantum dot, in which Coulomb-blockade conduction occurs through a series of discrete electron states, the orbital shift can vary from one peak to another as electrons are added, increasing in size with magnetic field. The Zeeman effect combined with this orbital shift at higher field determines the evolution of the addition spectrum of this small dot in a parallel magnetic field.

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