Spin and Polarized Current from Coulomb Blockaded Quantum Dots

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We report measurements of spin transitions for GaAs quantum dots in the Coulomb blockade regime, and compare ground and excited state transport spectroscopy to direct measurements of the spin polarization of emitted current. Transport spectroscopy reveals both spin-increasing and spin-decreasing transitions as well as higher-spin ground states, and allows g-factors to be measured down to a single electron. The spin of emitted current in the Coulomb blockade regime, measured using spin-sensitive electron focusing, is found to be polarized along the direction of the applied magnetic field regardless of the ground state spin transition.

Quantum dots in the Coulomb blockade (CB) regime have for several years provided a valuable tool to study spin in confined systems. Systems with small interactions, such as nanotubes and nonmagnetic metal grains, show signatures of spin degenerate orbital levels with electrons filling in a simple Pauli scheme of spin 0, 1 2, 3 2, ... In contrast, recent transport measurements in lateral GaAs quantum dots suggest the existence of higher-spin ground states.

In this Letter, we explore ground and excited spin states of few- and many-electron lateral GaAs dots in the weak tunneling regime, using both transport spectroscopy as well as a focusing measurement that allows a direct determination of the spin polarization of emitted current. Consistent with previous work, we find, as evidence of higher-spin ground states in the larger dot, that spin transitions (increasing or decreasing) are often followed by a second transition in the same direction as electrons are added to the dot. Excited state spin transitions and spin degeneracy for several quantum levels are also explored using nonlinear bias spectroscopy, and clear spin splitting is found for the N=1 electron case in the few-electron dot. It is generally believed that opposite state spin transitions lead to opposite spin polarizations of the emitted current on Coulomb blockade peaks. We find instead that the spin polarization of the current is the same for CB peaks corresponding to spin-increasing and spin-decreasing transitions, with the polarization always aligned with the external magnetic field.

Measurements were performed on two quantum dots, one with many electrons (N ~ 100) and the other with few electrons (N < 10). In the small dot we concentrate on the N = 0 → 1 electron transition. For the larger quantum dot. The device was fabricated using Cr/Au depletion gates on the surface of a GaAs/AlxGa1−xAs heterostructure; the two dimensional electron gas (2DEG) at the interface was contacted electrically using nonmagnetic Pt/AuGe ohmics. For the larger dot (Fig. 1(a)) we used a heterostructure (x = 0.36) with the 2DEG lying 102 nm from the surface and with electron density n = 1.3 × 1011 cm−2. The high mobility of this 2DEG, μ = 5.5 × 106 cm2/Vs, allowed the observation of several clear focusing peaks. Characteristic energy scales for the larger quantum dot include a level spacing ∆ ~ 70μeV and a charging energy EC~ 800μeV. The smaller quantum dot (Fig. 2(b), inset) was fabricated on a different heterostructure (x = 0.3) with density 2.3 × 1011 cm−2; the mobility was 5 × 105 cm2/Vs.

Experiments were carried out in a dilution refrigerator with base electron temperature Tc = 70 mK (determined by CB peak width), using standard ac lock-in techniques with an excitation voltage of 5μV. A pair of transverse superconducting magnets was used to provide independent control of field in the plane of (B||) and perpendicular to (B⊥) the 2DEG.

On a CB peak, transport through an N-electron dot occurs via the addition and removal of the N + 1 electron, with the corresponding z-component of the dot spin, Sz(N), changing to Sz(N + 1) and back again. The energy required for this transition as measured by CB peak position depends on the effective magnetic field B through a Zeeman term, −gμB(Sz(N + 1) − Sz(N)) = −gμB(ΔSz). The spacing between N → N + 1 and N + 1 → N + 2 CB peaks is given by −gμB(Sz(N + 2) − Sz(N + 1) − (Sz(N + 1) − Sz(N))). (The effect of the magnetic field on the orbital energies is minimized in this experiment by changing only the in-plane component, B||.) A CB peak position that moves upward in gate voltage (upward in the energy required to add an additional electron) as a function of field indicates a spin-decreasing transition; downward motion in gate voltage indicates a spin-increasing transition. In terms of peak spacings, a spin-increasing transition of ΔSz followed by an spin-decreasing transition of −ΔSz yields a spacing that increases with field; for the opposite sequence, the peak spacing decreases with field. For the case of ΔSz = 1 2 transitions, the slopes of the spacings will be ±gμ. Consecutive transitions of the same magnitude and in the same direction, for instance Sz = 0 → 1 2 → 1, yield a peak spacing that does not change with field.

Six consecutive CB peaks as a function of magnetic
electron dot, spin transitions for the dot as additional electrons are added to the device (for example, for the 1 → 2 electron transition, see Fig. 2(b)). Splitting of excited state features with field is only occasionally observed, suggesting a lack of spin degeneracy for many of these transitions. At the same time, some distinct transitions move toward or away from each other with slopes ±gμ, possibly indicating differences in dot spin for initial and final states.

To eliminate the complicating effects of a many-electron system, we also measured spin transitions for the N = 0 → 1 electron transition using the smaller dot (Fig. 2(b), inset). Finite drain-source measurements were used to find the 0 → 1 electron transition, see Fig. 2(b). This transition displays clear splittings for both the ground and first excited states (Fig. 2(c)), with g-factors measured to be g ≈ 0.37. When more electrons were added to the device (for example, for the 1 → 2 electron transition or even more clearly for 2 → 3 or higher transitions) splittings were only occasionally observed (data not shown). The simpler behavior for the 0 → 1 electron transition may indicate the important effect of interactions on the spin structure of multi-electron dots.

In the absence of spin blockade, one would expect $S_z$ of the dot to change by the the spin $s_z = ±\frac{1}{2}$ of the electron added to it: $S_z(N + 1) = S_z(N) + s_z$. This would imply opposite polarization of transport current for spin-increasing and spin-decreasing transitions. We examine this expectation experimentally by comparing the spin transitions determined by CB peak position to a direct measurement of the spin polarization of current emitted on a CB peak.

The spin polarization of current from the quantum dot was measured in a transverse focusing geometry (Fig. 1(a)) and plotted as a function of magnetic field. The occurrence of peak spacings with zero slope is evidence of higher-spin ground states. We note that no two consecutive spacings both have slopes ±gμ. This indicates that spin changes of $\frac{1}{2}$ or greater upon adding an electron are not seen. (Due to the negative g-factor in GaAs, the lower-energy spin state for a single electron will generally be anti-aligned with an external magnetic field; therefore we will define $S_z = ±\frac{1}{2}$ to be anti-aligned with the field, and for consistency the reader may then use a positive g-factor for energy calculations.)

Excited state spin transitions can be observed using finite dc drain-source bias, $V_{ds} > gμB$. A change in spin between two states (either ground or excited) of the N and N + 1 electron systems would be expected to cause the corresponding peak in differential conductance to shift with B. Furthermore, any transition which is spin degenerate at B = 0 should split as a function of field. Excited state transitions from several consecutive Coulomb blockade peaks in the larger dot are shown at $V_{ds} = 400μV$ as a function of B and $V_g$ in Fig. 2(a).

Beginning from an arbitrary value of spin for the N electron dot, $S_z(N)$, we can enumerate the ground state spin transitions for the dot as additional electrons are added (peak spacings provide no information on the absolute magnitude of spin, only spin transitions). For example, in Fig. 1(c) at 2.5T, the spacing for the two peaks at the most negative gate voltage (fewest electrons) decreases with $B_{||}$, suggesting that $S_z(N + 1) = S_z(N) + \frac{1}{2}$ and $S_z(N) = S_z(N - 1) - \frac{1}{2}$. Taking $S_z(N) = \frac{1}{2}$ gives a spin structure for the states shown in Fig. 1 (labelled N – 1, N,..., N + 5) of (1, 1, 0, 0, 0, 1) at $B = 2.5T$. The occurrence of peak spacings with zero slope is evidence of higher-spin ground states.

The parabolic dependence of peak position on $B_{||}$ is believed to result from the effect of the field on the well confinement potential; this effect gives the same shift for all CB peaks, and so disappears when the peak spacing is extracted. Corresponding CB spacings, shown in Fig. 1(c), display linear motion with slopes ±gμ and zero, where the g-factor is consistent with the bulk value for GaAs, $g = -0.44$.
FIG. 2: (a) Color plot of the differential conductance of Coulomb blockade peaks at $V_{\text{ds}} = 400 \mu V$, as a function of $V_g$ and $B_{\parallel}$ ($B_{\perp}$ held constant at $-110 mT$) for the quantum dot shown in Fig. 1. (All $V_g$ traces were shifted to align the rightmost peak.) For comparison the dashed lines show an energy separation of $g \mu B$, taking $g = 0.44$. Splitting is only occasionally observed. (b) Similar measurements taken on a different quantum dot (micrograph shown in Fig. 2(b) inset, scale bar is $1 \mu m$). (b) Coulomb diamond at $B_{\parallel} = 0$ and $B_{\perp} = -200 mT$ demonstrating that the CB peak near $V_g = 0$ is the $0 \rightarrow 1$ electron transition. (c) Differential conductance of the $0 \rightarrow 1$ electron CB peak at $V_{\text{ds}} = 1200 \mu V$ from $B_{\parallel} = 0$ to $9 T$ (curves offset for clarity, and individually rescaled to have a constant height for the rightmost peak). In contrast to (a), clear spin splitting of ground and excited states is seen for this transition (dashed yellow lines are guides to the eye). Inset: splitting as a function of $B$ for the ground state (solid circles) and first excited state (solid triangles). Solid line shows best fit to the data, and gives a $g$-factor of 0.37.

1(a)). As described previously [14], the height of a focusing peak reflects the degree (and direction) of spin polarization of current from the emitter when the collector QPC is spin selective, according to the relation $V_c = \alpha I_e (h/2e^2)(1 + P_{\parallel}P_{\perp})$. Here $V_c$ is the focusing peak height, $I_e$ is the total emitter current with polarization $P_{\parallel} = (I_{\parallel e} - I_{\perp e})/(I_{\parallel e} + I_{\perp e})$, and $P_{\perp} = (T_{\parallel e} - T_{\perp e})/(T_{\parallel e} + T_{\perp e})$ is the spin selectivity of the collector. (The efficiency parameter $\alpha$ ($0 < \alpha < 1$) accounts for spin-independent imperfections in the focusing process.)

Using a Coulomb blockaded quantum dot as the emitter favors the use of a voltage bias between emitter and base, rather than a current bias as used in Refs. [2, 14]. In this case, changes in the emitter current, $I_e$, lead to changes in the focusing peak height even when its polarization remains constant. To study spin polarization, we measure the emitter current along with the collector voltage (Figs. 3(a) and 3(b)) and use the quantity $V_c/I_e$, a nonlocal resistance, as a measure of the spin polariza-

FIG. 3: (a) Conductance of a CB peak as a function of both $V_g$ and $B_{\perp}$, for the dot shown in Fig. 1(a) in a focusing geometry. (b) Base-Collector voltage, $V_c$, measured at the same time as the dot conductance, with $B_{\perp} = -110 mT$ set to correspond to the second focusing peak (the second peak was used because it was affected least by $B_{\parallel}$ in this device). (c) The nonlocal resistance $V_c/I_e$ most clearly shows the effect of focusing. The diagrams indicate the electron focusing condition for fields near the second focusing peak. The location of the focusing peak in $B_{\perp}$ remained constant for all CB peaks studied. Data does not appear when $g_e < 0.1 e^2/h$ ($I_e < 20 pA$, $V_c \lesssim 40 mV$) because the ratio $V_c/I_e$ becomes unreliable.

tion of the current from the CB quantum dot when the collector is spin selective. For a spin-selective collector ($g_e = 0.5 e^2/h$, in an in-plane field), the value of $V_c/I_e$ should range from twice the value found in the unpolarized case ($g_e = 2 e^2/h$), when emitter polarization and collector selectivity are oriented in the same direction, to zero, when the spin directions are oppositely oriented.

Simultaneous focusing and conductance measurements at $B_0 = 6 T$ for both spin-selective and spin-independent collector are presented in Figs. 4(a,b), as the dot is tuned from the semi-open to the weak tunneling regimes using the voltage, $V_{\text{gs}}$, on the side gate. We find that the focusing signal $V_c/I_e$ with spin-selective collector ($g_e = 0.5 e^2/h$) always lies above the signal with spin-independent collector ($g_e = 2 e^2/h$) once the dot is tuned into the weak tunneling regime. This suggests that the current emitted from the quantum dot at low conductance is always spin polarized in the same direction as the collector, over a range of gate voltage where many electrons are added.

Figure 4(c) shows focusing measurements for the same peaks shown Fig. 1, at $B_0 = 4 T$. Spin transitions of both directions were observed based on peak motion (see Fig. 1) whereas spin polarization of emitted current is again found to remain nearly constant over all measured CB peaks. This observation is inconsistent with the pic-
emitter. (Collector selectivity depends only weakly on $B$ (a), we would have expected the focusing peak to be suppressed to $V_T$ fields and temperatures [6].) Based on the increase in $V_c/I_c$ to 3.5$k\Omega$ from 1.9$k\Omega$ with the spin selective collector in (a), we would have expected the focusing peak to be suppressed to $V_c/I_c \sim 0.3k\Omega$ if the opposite polarization were generated at the leads of a quantum dot become spin polarized in the same direction as the QPC collector, for both spin-increasing and spin-decreasing transitions of the dot. These observations necessitate a revised picture of spin transitions in lateral quantum dot in an in-plane magnetic field. In conclusion, we have found signatures of spin-increasing and spin-decreasing transitions in transport measurements, including spin splitting of the $N = 0 \rightarrow 1$ transition. Measurements of polarization of the current emitted from a quantum dot in the CB regime show that the emitted current is in all cases polarized in the same direction as the QPC collector, for both spin-increasing and spin-decreasing transitions of the dot. These observations necessitate a revised picture of spin transitions in lateral quantum dot in an in-plane magnetic field.

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FIG. 4: (a) Focusing signal at $B_z = 6T$ from the quantum dot shown in Fig. 1, with spin-selective ($g_c = 0.5e^2/h$, red curve) and spin-independent ($g_c = 2e^2/h$, black curve) collector. The polarization of current fluctuations on a typical gate voltage scale of $V_g = 5mV$, but these fluctuations are suppressed as $V_g$ is reduced below $30mV$. At the same time, the spin selective curve rises to nearly twice the value as the curve at $g_c = 2e^2/h$, indicating spin polarization of emitter current (see text). (b) Conductance measured simultaneously with data in (a). (c) Focusing signal and conductance measured for the CB peaks shown in Fig. 1 ($N + 1$ to $N + 6$) at $B_z = 4T$ and $g_c = 0.5e^2/h$. Again, only small fluctuations in focusing signal are observed despite different spin transitions observed for these peaks in Fig. 1. Based on the increase of $V_c/I_c$ to 3.5$k\Omega$ from 1.9$k\Omega$ with the spin selective collector in (a), we would have expected the focusing peak to be suppressed to $V_c/I_c \sim 0.3k\Omega$ if the opposite polarization were generated at the emitter. (Collector selectivity depends only weakly on $B$ at these fields and temperatures.)

We note as well that there is no apparent correlation between peak height and spin transition in a large in-plane field. It was shown in Refs. [4] and [14] that the leads of a quantum dot become spin polarized in the same way as single QPC’s in an in-plane field. However, a spin dependent tunnel barrier should lead to a dramatic suppression in CB peak height for spin-decreasing transitions. As seen in Fig. 1, this was not observed in our measurement. Taken together, these observations may indicate that spin polarization in the leads is playing a role in the spin state of the quantum dot on a CB peak.

In conclusion, we have found signatures of spin transitions leading to $S_z(N+1) = S_z(N) + s_z$ discussed earlier.

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