Magnetically Induced Reconstruction of the Ground State in a Few-Electron Si Quantum Dot

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We report unexpected fluctuations in the positions of Coulomb blockade peaks at high magnetic fields in a small Si quantum dot. The fluctuations have a distinctive sawtooth pattern: as a function of magnetic field, linear shifts of peak positions are compensated by abrupt jumps in the opposite direction. The linear shifts have large slopes, suggesting formation of the ground state with a nonzero angular momentum. The value of the momentum is found to be well defined, despite the absence of the rotational symmetry in the dot.

The basics of Coulomb blockade (CB) phenomena can be understood within the so-called "orthodox theory" [1]. In this theory, electron-electron interactions are hidden in the charging energy, and the electrostatic coupling is assumed to be independent of the nature of the ground state, namely, on the particular distribution of electrons inside the dot. Early experiments on large vertical quantum dots have already revealed significant deviations from the "orthodox theory," noting that several electrons can enter the dot at almost the same energy [2]. The deviations were later attributed to localization of electrons in local minima of the confining potential [3]. In a smooth confining potential, magnetic field forces a redistribution of charges within the dot to form quantum Hall edge states [4]. Charge redistribution is a focus of much theoretical work, especially in the regime of high magnetic field [5]. A competition between the attractive confining potential and the repulsive electron-electron interactions is expected to produce a rich variety of exotic patterns of charge distribution [6]. In a recent experiment, high-field (filling factor $\nu < 1$) redistribution of charges in a large vertical dot $>0.5\ \mu$m has been reported [7].

So far, most of the experiments were performed on two-dimensional dots with weak and smooth confining potential electrostatically created by gating. In such dots, the magnetic field B dependence of energy levels is dominated by orbital effects even at low B. Recently, it has become possible to investigate quantum dots in a different regime of very small size, strong confinement, and strong local disorder [8]. This regime is realized in three-dimensional Si dots with confining potential provided by a sharp Si/SiO₂ interface. In these dots, states with different angular momenta are mixed due to the absence of rotational symmetry, eliminating the linear in the B term of the orbital energy, and the parabolic B^2 term is suppressed by strong confinement. Thus, the B dependence of the energy levels is expected to be simple and to consist of linear Zeeman shifts. Indeed, earlier we demonstrated that the shifts of CB peak positions are dominated by the Zeeman effect [9]. In this work we focus on small fluctuations in the peak position, which appear at high B and low T in a Si quantum dot with a few electrons, $N \approx 4$–6.

The fluctuations have a distinct sawtooth pattern: as a function of B, fast linear shifts in the peak position are interrupted by abrupt jumps in the opposite direction. We show that the linear segments of the fluctuations have an orbital origin, indicating formation of states with a relatively well-defined nonzero angular momentum close to 1 or 2. This is an unexpected result, taking into account the geometry of the sample. Also, we show that the jumps are intrinsic to the dot, presumably due to some magnetically induced rearrangement of charges inside the dot. We discuss the data within a simplified single-particle picture. However, the observed phenomenon is clearly a many-body effect, and a proper treatment of interactions, strong confinement, and disorder is needed.

The small Si quantum dot is lithographically defined from a silicon-on-insulator wafer, and a sample layout is shown schematically in the inset of Fig. 1. A detailed description of sample preparation can be found in Ref. [8].
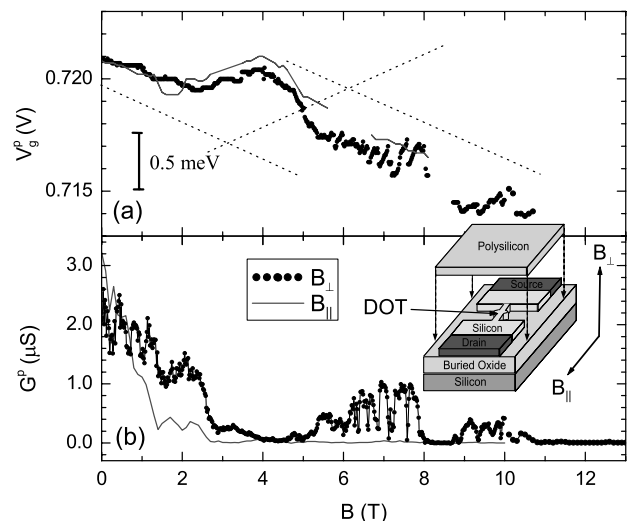

FIG. 1. (a) Position and (b) amplitude of peak 5 plotted as a function of magnetic field for two field directions: in-plane field $B_\parallel$ along the current direction (solid line) and $B_\perp$ perpendicular to the Si wafer (dots). The inset shows a schematic of the sample. The data was measured at $T = 60$ mK with 10 μV ac bias. The dashed lines have slopes $\frac{1}{2}g^*\mu_B$, $g^* = 2$.

The dot is three dimensional, asymmetric, and is elongated in the current flow direction. A poly-Si gate is wrapped around the dot and is used to control the number of electrons in the dot starting from $N = 0$; the gate is separated from the dot by 500 Å of SiO_2. The dot is connected to two two-dimensional source and drain contacts via tunneling barriers; the coupling is weak and even at the lowest temperature, $T = 60$ mK, the CB peaks remain thermally broadened. From excitation spectra we deduce single-particle energies to be 1–5 meV, comparable to the charging energy 5–7 meV.

The size of the dot is ~ 150–250 Å along the current flow axis and $\lesssim 100$ Å in cross section, and the electrons are confined to the dot by the Si/SiO_2 heterojunction potential of ~ 3 eV. The strength of the confinement is clearly seen from the analysis of the first peak; see Fig. 2 of Ref. [10]. The first energy level has a weak parabolic B dependence due to magnetic confinement $(\hbar\omega_c)^2/E_0$, where $\omega_c = eB/m^*$ is the cyclotron frequency. Characteristic energy E_0 depends on the direction of B: $E_0 \approx 100$ meV for B applied perpendicular to the sample, $B_\perp$, and there is no measurable shift of the first level for in-plane B aligned with the current direction, $B_\parallel$. For both B directions the magnetically induced confinement is smaller than the Zeeman energy in the experimental range of B.

The number of electrons in the dot can be tuned between 0 and 30 with the gate voltage V_g. The overall B dependence of the energy levels in this sample was analyzed previously in Ref. [9]. Evolution of the fifth CB peak with B is plotted in Fig. 1a. According to the previous analysis, the $V_g^p(B)$ curve consists of three segments, each having $\approx \frac{1}{2}g^*\mu_B/\alpha$ slope, where $g^* = 2$ is the g factor in Si, $\mu_B = e\hbar/2m_0$ is the Bohr magneton, and $\alpha = 14$ mV/meV. The two kinks at $B \approx 2.5$ T and $B \approx 4$ T have been identified as crossings of Zeeman split spin-up and spin-down levels, originating from different single-particle energy states. Indeed, the average peak position does not depend on the direction of B. However, there is a noticeable difference between the $V_g^p(B_\parallel)$ and $V_g^p(B_\perp)$ curves at high B: V_g^p changes linearly with $B_\parallel$ but fluctuates as a function of $B_\perp$. The appearance of these fluctuations is accompanied by a dramatic increase of the peak amplitude G^p by more than 2 orders of magnitude, as shown in Fig. 1b. The fluctuations are most pronounced at our base temperature of 60 mK and are still observable at 200 mK, while at $T \approx 1$ K they are washed out completely. No fluctuations were observed for $N > 20$ or $N < 4$. The fluctuations are highly reproducible: the measured V_g^p and G^p from different scans are identical if the scans are performed within the same cooldown; patterns from different cooldowns are similar, although positions of the jumps may vary.

Fluctuations of V_g^p for peaks 4, 5, and 6 are magnified in Fig. 2. The fluctuations have a distinctive sawtooth pattern: V_g^p increases linearly with $B_\perp$, then decreases abruptly. Most of the linear segments have slopes close to
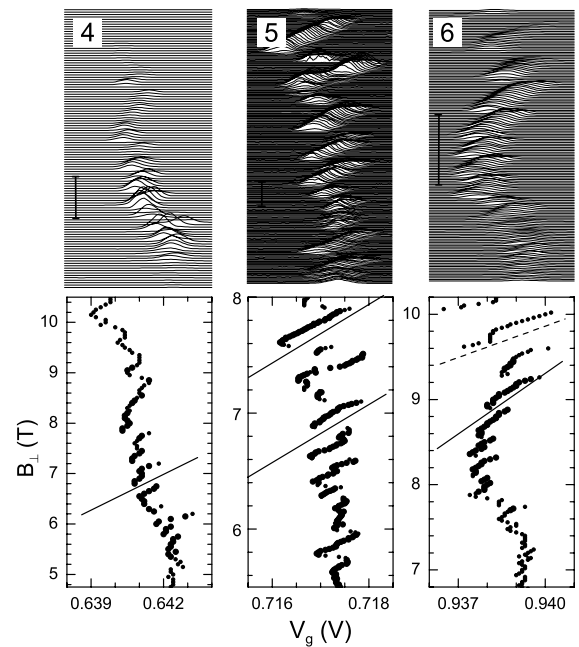

FIG. 2. Evolution of peaks 4, 5, and 6 as a function of perpendicular magnetic field $B_\perp$. In the top panels, a series of G vs V_g traces are plotted, each linearly offset with $B_\perp$. The bars are 4 μS scales. In the bottom panels, peak positions are extracted and plotted as a function of $B_\perp$ for the same range of $B_\perp$ as in the corresponding top panels. The solid and dashed lines have the slopes $\frac{1}{2}\hbar\omega_c/B$ and $\hbar\omega_c/B$.

4 mV/T (0.3 meV/T) or 8 mV/T (0.6 meV/T). These slopes are much larger than $\frac{1}{2}g^*\mu_B = 0.06$ meV/T and are grouped within 15% around $\frac{1}{2}\hbar\omega_c/B$ and $\hbar\omega_c/B$. The linear shifts are interrupted by abrupt jumps of the peak position, which occur within <20 mT. These jumps compensate the linear shifts and, on average, the peaks follow the weak V_g^p vs $B_\parallel$ field dependence due to the Zeeman shift of energy levels.

Orbital effects can be distinguished from spin effects by studying the evolution of peak positions in a tilted magnetic field. In Fig. 3, V_g^p of peak 5 is plotted as a function
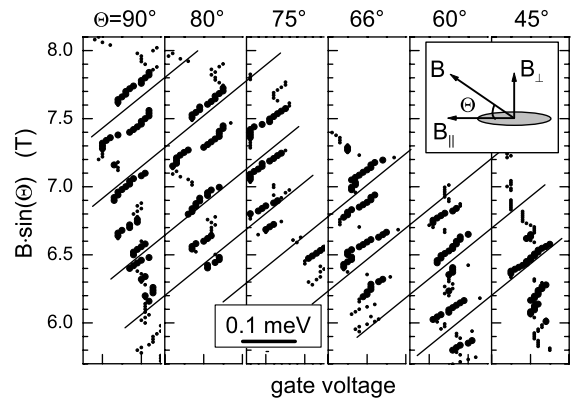

FIG. 3. Position of peak 5 as a function of $B_\perp = B\sin\Theta$ plotted for different angles Θ. The angle is defined in the inset. The lines have a slope $\frac{1}{2}\hbar\omega_c/B$ and are guides to the eye.

of $B\sin(\Theta)$ for different angles Θ between B and I. Linear peak shifts depend on the perpendicular component $B_\perp \approx B\sin(\Theta)$, rather than on the total field B (solid lines provide guides for the eye). Curves at different angles do not scale with $\sin(\Theta)$ exactly, as is expected for a three-dimensional structure. Taking into account that the energy shift due to the magnetic confinement is negligible, we attribute the slopes $\approx \frac{1}{2}\hbar\omega_c/B$ to the formation of states with a nonzero angular momentum $m \approx 1$. Segments with larger slope $\approx \hbar\omega_c/B$ have also been observed and we attribute them to the formation of states with $m \approx 2$.

Fast linear shifts of V_g^p as a function of $B_\perp$ are interrupted by abrupt jumps in the opposite direction. These jumps occur within $\Delta B < 20$ mT and, if attributed to a state with large angular momentum, would correspond to an unrealistic $m > 10$. Ground state (GS) energy of the dot should be a continuous function of all variables, including B, unless the GS is bistable. Bistability of the GS should reveal itself through a hysteresis of the conductance in V_g or B scans. Experimentally, the traces were found to be identical, independent of the scan direction. Thus, jumps in the peak position should reflect either abrupt changes in the environment or abrupt changes in the electrostatic coupling between the dot and the environment.

In the CB regime, conductance is nonzero only when the electrochemical potential of the dot equals the electrochemical potential of the leads. Peak position V_g^p is determined from the condition [11]

$$\frac{e[(N-1/2) - C_g V_g^p]}{C_\Sigma} +$$
$$[E(N) - E(N-1)] + e\phi_{\text{ex}} = E_F,$$

where $e^2/2C_\Sigma$ is the Coulomb energy for one additional electron, C_g and C_Σ denote, respectively, the gate and the total capacitances, $E(N)$ is the kinetic energy of the state with N electrons, E_F is the Fermi energy in the leads, and ϕ_{ex} is a potential induced by external charges. According to the above equation, there are three possibilities for a jump of V_g^p: (i) an abrupt change in E_F, (ii) a discrete change of the background charge distribution and, thus, ϕ_{ex}, or (iii) an abrupt change in the electrostatic coupling C_g. It is easy to rule out E_F as a source of the jumps, since depopulation of Landau levels should lead to the jumps of V_g^p in the opposite direction.

It is appealing to attribute the jumps to a magnetically induced depopulation of a charge trap. However, such an explanation is inconsistent with the data. One has to assume the existence of a large two-dimensional trap capacitively coupled to the dot, which does not participate in the charge transport. Qualitatively, there are rather general arguments against such a scenario. If jumps are related to the magnetic confinement of electrons in the trap, we expect the frequency of the jumps to increase with B, and there should be no low-field cutoff for their appearance. Experimentally, the jumps appear suddenly at $B \approx 5$ T,

and the frequency of the jumps slightly decreases with B; there are no jumps at lower fields. In Si nanostructures, traps are formed inside the oxide layer [12], and it is hard to explain their existence only at high $B_\perp > 5$ T and in a limited range of gate voltages 0.5 V $< V_g < 1$ V. Quantitatively, in order to account for the data, one has to assume the existence of several traps within the tunneling range from the dot. This conjecture is inconsistent with the geometry of the sample. Electrostatically, discharging of a trap leads to a fixed shift $\Delta V_g^p = -C_c/C_\Sigma^{\text{ex}} \times e/C_g$, where C_c is the dot-trap cross capacitance, and C_Σ and C_Σ^{ex} are the corresponding total capacitances. In Fig. 4a, values of the V_g^p shifts are extracted for each jump in the range 5 T $< B_\perp < 8.2$ T. First, there is a *positive* shift at $B_\perp = 7.4$ T, inconsistent with the trap discharging model. Second, the amplitude of the negative shifts ranges from 0.2 to 1.0 mV with no systematic pattern. Thus, a single trap cannot account for the observed oscillations. Subsequent discharging of several traps can be ruled out using the following arguments. In the V_g-B plane the number of electrons in the dot differs by one across the jump, as shown schematically in the inset in Fig. 4b. Following the analysis of a two-dot system [13], there should be a peak in the conductance along the jump, unless the trap and the dot are connected by tunneling (in this case an electron tunnels between the dot and the trap, and the total number of electrons in the dot-trap system remains constant). Experimentally, there is no peak in conductance if B is swept across the jump at a fixed V_g, as shown in Fig. 4b. An
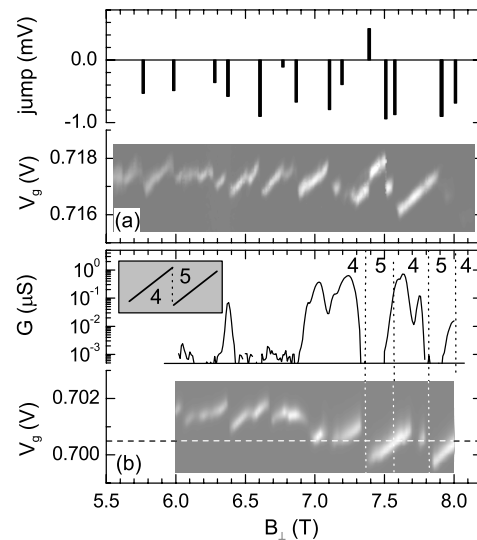

FIG. 4. Gray-scale plots show conductance as a function of V_g and $B_\perp$ near peak 5. The data was taken by scanning V_g at different fixed values of $B_\perp$. In (a) the amplitude of each V_g^p jump is extracted. In (b) the conductance as a function of $B_\perp$ was measured at a fixed $V_g = 0.7005$ V, marked by the dashed horizontal line in the gray-scale plot. Note the logarithmic scale of G. The vertical dotted lines separate ground states with a different number of electrons along the curve. The data in (a) and (b) were collected during different cooldowns.

assumption that several large traps are in close proximity of the dot is inconsistent with the small size of the device.

It is very suggestive that all the observed effects, namely, jumps in peak position, enhanced conductivity, appearance of large slopes, and an apparent mutual compensation of shifts and jumps, are related and originate from the dot. Presumably, the jumps are related to the magnetically induced rearrangement of electron density inside the dot. In our dots, we expect strong fluctuations of the confining potential, because Si/SiO_2 interface roughness directly translates into large fluctuations of the local potential. At low B fields the electron wave function is spread over the entire dot. At high B fields the extent of the wave function is determined by the magnetic length $l_m = (\hbar/eB)^{1/2}$. When l_m becomes smaller than the average distance between electrons, Coulomb repulsion favors localization of electrons. We expect fluctuations of the local potential to facilitate the redistribution of charge. A strong increase in the peak height hints that electrons are rearranged closer to the dot boundary, where their wave functions have larger overlap with electrons in the leads. It was pointed out in Ref. [14] that electrostatic coupling to the gate C_g is not necessarily a constant, but depends on the particular distribution of electron density inside the dot. In order for a peak to shift by 1 mV, only a small change $\Delta C_g/C_g \approx \Delta V_g^p/V_g^p < 0.2\%$ is required.

The most unexpected and surprising result is the appearance of states with nonzero angular momentum. In the absence of rotational symmetry, states with different angular momenta are mixed, and angular momentum is not a good quantum number. However, the dot asymmetry becomes less important if an electron can complete a classical cyclotron orbit faster than the time $\tau = L/\sqrt{2E/m^*}$ needed to traverse the dot. For an electron with kinetic energy $E = 4$ meV in a dot of size $L = 200$ Å, the crossover $\omega_c^{-1} < \tau$ should occur at $B \approx 5$ T. Note that $E \approx N\Delta$ increases with the number of electrons (here Δ is the level spacing), leading to the increase of the crossover field with N. We speculate that, for a few electrons in the dot, high B provides a mechanism to suppress the mixing of different angular momentum states.

Electron-electron interactions in our sample are rather strong ($e^2/4\pi\epsilon\epsilon_0 r = 12$ meV for $r = 100$ Å). They reveal themselves in the spontaneous polarization of the $N = 6$ ground state at low fields and in the suppression of the corresponding CB peak due to spin blockade [9]. Thus, a many-body description of the ground state is required.

To summarize, we explored a quantum dot in a new regime of small size, strong confinement, and strong electron-electron interactions. We observed fluctuations in the CB peak positions at high B for few-electron states. The fine structure consists of fast linear shifts, followed by abrupt jumps in peak positions. We argue that the fluctuations are intrinsic to the dot and reflect changes in the many-body wave function. We attribute jumps to the magnetically induced spatial rearrangement of charges inside the dot. The linear segments have large slopes, reflecting an unexpected formation of states with relatively well-defined nonzero angular momentum. The observed phenomenon is a many-body effect and is clearly beyond the description of a single-particle picture.

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