Magnetically-induced reconstructions 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 saw-tooth 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 non-zero angular momentum. The value of the momentum is found to be well defined, despite the absence of the rotational symmetry in the dot.

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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 $> 0.5 \, \mu\text{m}$ 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/SiO$_2$ interface. In these dots states with different angular momenta are mixed due to the absence of rotational symmetry, eliminating the linear in $B$ 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 appears at high $B$ and low $T$ in a Si quantum dot with a few electrons, $N \approx 4 - 6$. The fluctuations have a distinct saw-tooth 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 orbital origin, indicating formation of states with a relatively well defined non-zero 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 phenomena 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 in Fig. 1. A detailed description of sample preparation can be found in Ref. [8]. 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, $T = 60 \, \text{mK}$, the CB peaks remain thermally broadened. From excitation spectra we deduce single-particle energies to be $1 - 5 \, \text{meV}$, comparable to the charging energy $5 - 7 \, \text{meV}$.

The uniqueness of our dot is its small size ($\sim 100 - 200$ Å long and $\lesssim 100$ Å in cross section) and the extremely strong confining potential provided by the Si/SiO$_2$ interface ($\sim 3 \, \text{eV}$). 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 ($\hbar \omega_c l^2 / E_0$), where $\omega_c = eB/m^*$ is the cyclotron frequency. Characteristic energy $E_0$ depends on the direction of $B$:...
segments, each having $V$ to the previous analysis, the fifth CB peak with been analyzed previously in Ref. [9]. Evolution of the $B$ dependence of the energy levels in this sample has are identical if the scans are performed within the same range for $B$ aligned with the current direction, $B_{||}$. 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 has been analyzed previously in Ref. [9]. Evolution of the fifth CB peak with $B$ is plotted in Fig. 1a. According to the previous analysis, the $V_p^j(B)$ curve consists of 3 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, average peak position does not depend on the direction of $B$. However, there is a noticeable difference between the $V_p^j(B_{||})$ and $V_p^j(B_{\perp})$ curves at high $B$: $V_p^j$ changes linearly with $B_{||}$ 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 two orders of magnitude, as shown in Fig. 2. 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 $V_p^j$ 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 $V_p^j$ for peaks 4, 5 and 6 are magnified in Fig. 2. The fluctuations have a distinctive saw-tooth pattern: $V_p^j$ increases linearly with $B_{\perp}$, then decreases abruptly. Most of the linear segments have slopes close to 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 $V_p^j$ vs $B_{||}$ 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, $V_p^j$ of peak 5 is plotted as a function of $B \sin(\Theta)$ for different angles $\Theta$ between $B$ and $I$. Linear peak shifts depend on the perpendicular component $B_{\perp} \approx B \sin(\Theta)$, rather than on the total filed $B$ (solid lines provide a guide 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 non-zero angular momentum.
m ≈ 1. Segments with larger slope ≈ \( h\omega_c / B \) have also been observed and we attribute them to the formation of states with \( m \approx 2 \).

Fast linear shifts of \( V_p^g \) as a function of \( B_\perp \) are interrupted by abrupt jumps in the opposite direction. These jumps occur within \( \Delta B < 20 \text{ mT} \) 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 bi-stable. Bi-stability 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 non-zero 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]

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

where \( e^2/2C_\Sigma \) is the Coulomb energy for one additional electron, \( C_g \) and \( C_\Sigma \) 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 \( \phi_{ex} \) 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, \( \phi_{ex} \), 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 cut-off for their appearance. Experimentally, the jumps appear suddenly at \( B \approx 5 \text{ T} \) 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 \( B_\perp > 5 \text{ T} \) and in a limited range of gate voltages 0.5 V < \( V_g < 1 \text{ V} \). Quantitatively, in order to account for the data, one has to assume the existence of a) several traps, b) all within the tunneling range from the dot, inconsistent with the geometry of the sample. Electrostatically, discharging of a trap leads to a fixed shift \( \Delta V_g^p = -C_c / C_\Sigma^2 \cdot E/c_g \), where \( C_c \) is the dot–trap cross capacitance, and \( C_\Sigma \) and \( C_\Sigma^2 \) are the corresponding total capacitances. In Fig. 4, values of the \( V_g^p \) shifts are

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

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) conductance as a function of \( B_\perp \) was measured at a fixed \( V_g = 0.7005 \text{ V} \), 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 different number of electrons along the curve. The data in (a) and (b) were collected during different cooldowns.
extracted for each jump in the range 5 T < B⊥ < 8.2 T. First, there is a positive shift at B⊥ = 7.4 T, inconsistent with the trap discharging model. Second, 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 the 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 assumption that several large traps are in a 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 wavefunction is spread over the entire dot. At high B fields the extent of the wavefunction is determined by the magnetic length ℓ m = (ℏ/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. Strong increase in the peak height hints that electrons are rearranged closer to the dot boundary, where their wavefunctions have larger overlap with electrons in the leads. It has been pointed out in Ref. [4] 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 \( \Delta C_g/C_g \approx \Delta V_p^r/V_p^r < 0.2\% \) is required.

The most unexpected and surprising result is the appearance of states with non-zero 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 \( E = 4 \text{ meV} \) in a dot of size \( L = 200 \text{ Å} \), the cross over \( \omega^{-1} < \tau \) should occur at \( B \approx 5 \text{ T} \). Note that \( E \approx N\Delta \) increases with the number of electrons (here \( \Delta \) is the level spacing), leading to the increase of the cross over field with \( N \). We speculate that, for a few electrons in the dot, high B provides a mechanism to suppresses the mixing of different angular momentum states.

Electron-electron interactions in our sample are rather strong \( \left( e^2/\pi \varepsilon_0 \varepsilon_r \right) = 12 \text{ meV} \) for \( r = 100 \text{ Å} \). 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 [1]. 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 a 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 wavefunction. We attribute jumps to the magnetically induced spatial rearrangement of charges inside the dot. The linear segments have large slopes, reflecting unexpected formation of states with relatively well defined non-zero angular momentum. The observed phenomena is a many-body effect and is clearly beyond the description of a single-particle picture.

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