

Spin-related transport in ultra small Si quantum dots

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Abstract We investigated electron transport through ultra small Si quantum dots. We found that the B -dependence of energy levels is dominated by the Zeeman shift, allowing us to measure the spin difference between two successive ground states directly. In some dots the number of electrons N in the dot can be tuned starting from zero, and the total spin of the dot can be mapped as a function of N and B . For one of the dots we deduced that the dot becomes spontaneously polarized at $N = 6$ with a large spin change $\Delta S = 3/2$, demonstrating the essential features of spin blockade. Surprisingly, for $N > 20$, the transitions with $\Delta S > 1/2$ do not lead to the suppression of the corresponding peaks at low temperatures.

1 Introduction

Recent advances in nanotechnology has made it possible to fabricate quantum dots so small that Coulomb blockade can be observed up to room temperature. In such small dots, single-particle energies due to the size quantization are comparable to the electrostatic charging energy and interaction effects can modify the entire energy spectrum. Important information about interactions in such quantum systems can be obtained by studying the spin states. However, it proved to be a formidable task to measure the spin of a few-electron system experimentally. So far, the most successful mapping of spins in a few-electron dot has been achieved indirectly, by comparing an experimentally obtained addition spectrum to the theoretically calculated energy spectrum for a particular geometry[1,2]. The problem of measuring spin directly in the most versatile and well studied vertical and lateral quantum dots is that the magnetic field B dependence of their energy levels is dominated by orbital effects due to the weak confinement of electrons by electrostatic gates.

In our small Si samples we are able to measure the spin of a few-electron quantum dot directly. The dots uniquely combine the flexibility to change the number of electrons N starting from 0 with the strong electron confinement provided by the sharp Si/SiO₂ interface. At $B < 13$ T, the B -dependence of energy levels is dominated by the Zeeman shift and we are able to measure the difference between the spin of the successive ground states $\Delta S = S(N) - S(N - 1)$ directly as electrons are added into the dot one by one. Also, we can follow the change of the spin configuration of the dot with a fixed number of electrons as a function of B . For

one of the samples we can explain observed transition for the groundstates with up to 5 electrons within a simple model of a few energy levels which cross each other in magnetic field as a result of Zeeman splitting. Some many-body effects, such as spontaneous dot polarization and spin blockade[3] due to the spin change $\Delta S > 1/2$ has been observed.

2 Samples

The measurements were performed on small Si quantum dot fabricated from a silicon-on-insulator wafer. The dot resides inside a narrow bridge patterned from the top Si layer. A 50 nm thick layer of thermal oxide is grown around the bridge followed by a poly-Si gate. The fabrication steps have been described previously in details[4]. Spacing between excited levels $\delta \sim 0.5 - 4$ meV, measured using non-zero bias spectroscopy, is comparable to the charging energy $U_c = e/C \approx 10$ meV and is consistent with the lithographical size of the dot $l \approx \sqrt{\hbar/m^*\delta} \approx 100 - 190$ Å.

3 Results and discussion

Peak position as a function of V_g is determined by the degeneracy condition that the electrochemical potentials for the ground states with $N - 1$ and N electrons in the dot are equal. It has long been realized that for non-interacting electrons the field dependence of the peak positions $V_g^p(B)$ can be directly mapped onto the single-particle energy spectrum of the dot $E(N, B)$, provided that the Fermi energy E_F in the contacts is field independent. For a dot with a weak confining potential we expect energy levels to shift by $\hbar\omega_c$ or by the level spacing, whichever energy is smaller, and the shift should strongly depend on the direction of the magnetic field due to the dot anisotropy.

In Fig. 1a the conductance is plotted as a function of the gate voltage for sample E5-5b. The dot contains a few electrons (we estimate ≈ 15 electrons at $V_g = 1$ V) and the number of electrons can be changed by varying the gate voltage, each peak corresponding to an electron added to or removed from the dot. In Fig. 1b, the shift of each peak at $B = 10$ T, relative to its zero-field position, is plotted. The average peak shift is much less than $\hbar\omega_c = 6$ meV ($\Delta V_g = 52$ mV for this sample) and is determined by the level spacing. The most striking result is that the shift is almost independent on the B direction, which suggests that spin effects dominate.

It is possible to separate orbital and spin effects if contacts are spin polarized, as shown in Fig. 2. In the

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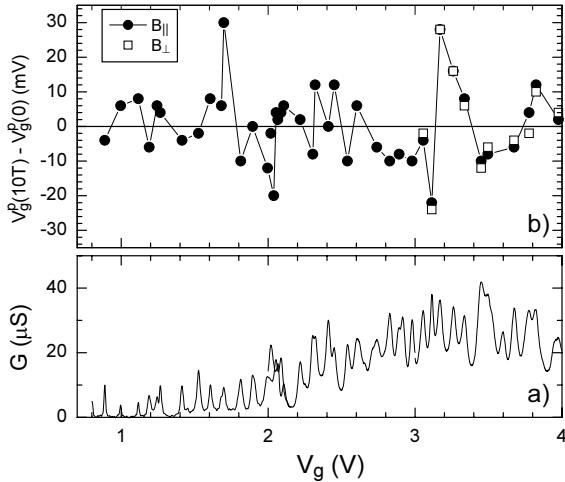


Fig. 1 a) Conductance as a function of the gate voltage for sample E5-5B was measured at $T = 1.5$ K and $B = 0$. In b) a relative shift of the peaks shown after an application of $B = 10$ T.

plot an excitation spectrum of another dot, E5-3b, is shown for the entrance of the first electron. At low gate voltage $V_g < 0.1$ V the contact is spin polarized for $B > 1$ T and the Zeeman shift of the first energy level is fully compensated by the Zeeman shift of the Fermi energy in the contacts. Thus, the resulting shift is solely due to orbital effects (assuming that g -factors in the dot and in the contacts are the same). The net shift of the levels in a parallel field (the smallest cross section) is negligible, while there is a small but measurable parabolic dependence on B_\perp (the largest cross section). The net shift at 10 T is < 0.4 meV and Zeeman energy should dominate the B dependence ($\frac{1}{2}g^*\mu_B B = 0.6$ meV at $B = 10$ T). It is interesting to notice, that although orbital effects are not effecting the position of the energy levels appreciably, they can considerably change transmission coefficients. For example, at high perpendicular field the peaks, marked with the dot and triangle in Fig. 2, become suppressed, while the third peak is enhanced, compared to the $B = 0$ value.

For a larger number of electrons $N > 3$ the contacts are spin-degenerate up to the highest experimental field of 13 T and the shift of energy levels mainly reflects the Zeeman shift of the tunneling electron. Peaks shift with a slope $\frac{1}{2}g^*\mu_B$ as a function of B and the slope changes sign every time the two levels with different spin cross each other. Evolution of the peaks for up to 5 electrons in the dot can be understood within a model of non-interacting electrons and singlet-triplet and triplet-polarized transitions are identified as a function of B . Peak 6 has a large slope $\approx \frac{3}{2}g^*\mu_B$ at low B and is strongly suppressed at low T . We conclude that the $N = 6$ ground state is spontaneously polarized at $B = 0$ and the peak suppression is due to the long predicted spin blockade[3]. For larger numbers of electrons, $N > 20$, we observed transitions with $\Delta S = 3/2$ with

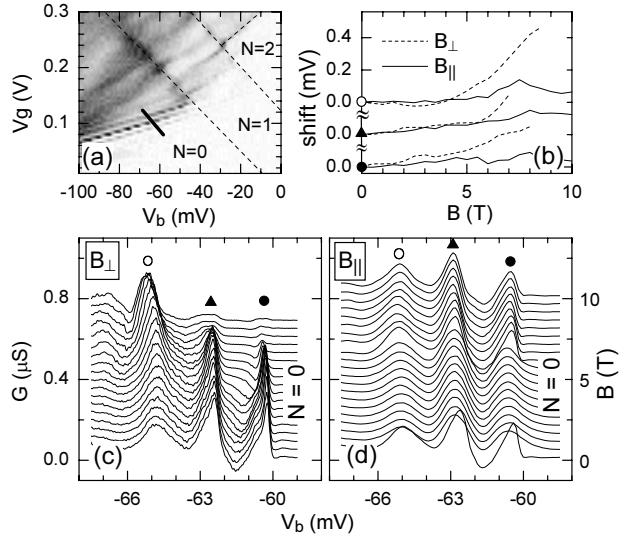


Fig. 2 a) High bias spectroscopy of a dot (E5-3b) is shown in a gray scale plot of conductance. White areas correspond to zero conductance (Coulomb blockade for $N > 0$) and dark lines are the positions of the excited levels. In c) and d) conductance as a function of bias, measured along the thick line in a), is plotted for two configurations of the magnetic field: along the current direction ($B_{||}$) and perpendicular to the surface of the sample (B_\perp). The curves are offset by 0.08 μ S/T. The data in c) and d) appears slightly different because they were taken at different conditions: c) ac bias 30 μ V and $T = 1.5$ K, d) ac bias 100 μ V and $T = 1.5$ K, except the $0.5 < B < 6$ T curves which were taken at 4 K. In b) shifts of the three peaks, marked by a dot, a triangle and a circle in c) and d), are plotted as a function of $B_{||}$ and B_\perp . According to the capacitance model the conversion factor for the shift into energy $\beta = e\Delta V_b/\Delta E = 2$. However, the slope of the lowest- V_g peaks in the $V_g - V_b$ plane is increased by a factor of 4, compared to the slopes for the peaks with $N > 1$, suggesting that it requires an extra bias to force the first electron into the dot. Thus, we estimate $\beta \sim 8$.

no apparent suppression of the peaks at low T . The spin scattering mechanism involved is not currently understood. These data will be published elsewhere[5].

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