High fidelity measurement of singlet–triplet state in a quantum dot

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We demonstrate experimentally a read-out method that distinguishes between two-electron spin states in a quantum dot. This scheme combines the advantages of the two existing mechanisms for spin-to-charge conversion with single-shot charge detection: a large difference in energy between the two states and a large difference in tunnel rate between the states and a reservoir. As a result, a spin measurement fidelity of 97% was achieved, which is much higher than previously reported fidelities.

Electron spins in quantum dots have received a lot of attention over the last decade. The main reason is that the spin degree of freedom is very well protected from the environment. Therefore, spins are good candidates to be the building block of spintronic or quantum information processing devices [1]. In this context, it is desirable to be able to measure the spin state associated to a single electron with high fidelity [2].

A direct spin state measurement is difficult because of the tiny magnetic moment associated with the electron spin. In quantum dots, single electron charge is easily measured. By correlating the spin states to different charge states, it is possible to determine the spin state in a single shot. Such spin to charge conversion has been achieved experimentally in two ways. First, by positioning the electrochemical potential of the lead in between the two relevant spin states, one electron can tunnel off the dot from the high-energy spin state whereas tunneling off the dot is energetically forbidden from the ground state [3, 4]. The fidelity of such energy selective read-out (ERO), was limited to 82.5% by the detector bandwidth [4]. Indeed, in order to record tunnel events, one has to make a compromise: tunneling has to be fast enough to minimize relaxation before spin-to-charge conversion, but not faster than the charge measurement bandwidth. In a second method, one can distinguish two spins states when the rates for tunneling on and off the dot are very different from each other. The fidelity of such a tunnel rate selective read-out (TRRO) is limited by the ratio of the two tunnel rates. Experimentally, a 90% fidelity was achieved, for a ratio of 20 in the two tunnel rates, in agreement with theory [5].

Here, we propose to use an energy selective read-out assisted by a difference in tunnel rates, for distinguishing between two-electron singlet and triplet states in a single quantum dot. In this scheme, an electron is energetically allowed to leave the dot if and only if the spins are in a triplet state (which is here higher in energy than the singlet state). The tunnel rate from the triplet state is very fast. As a result, if the spins are in a triplet state, the electron will almost always leave the dot before the spins have a

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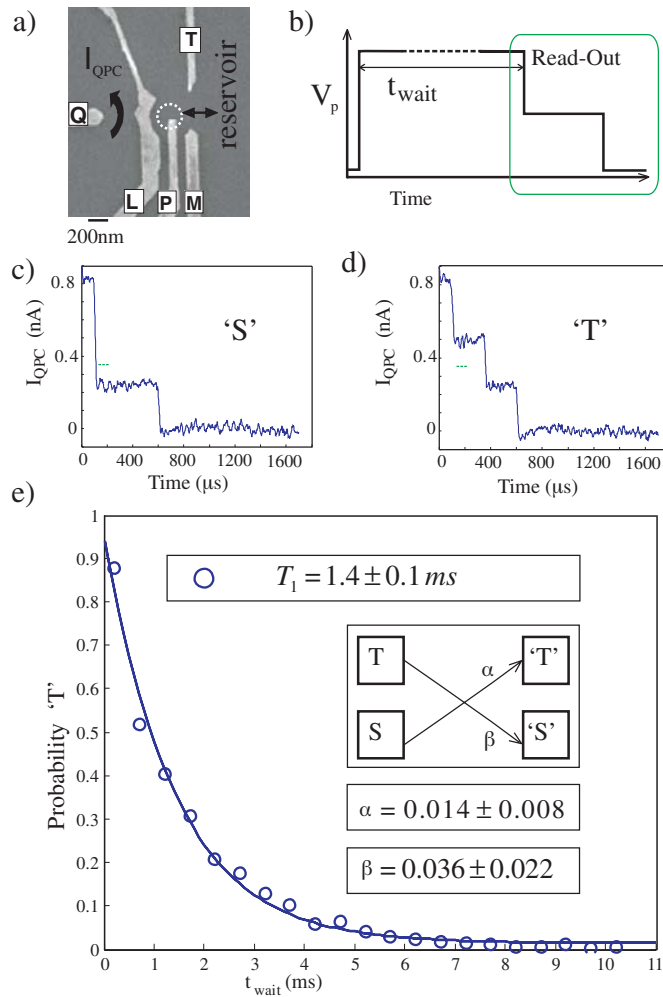
Fig. 1 (online colour at: www.pss-b.com)   (a) Scanning electronic micrograph showing the sample design. (b) Voltage pulse applied to the gate 'P'. (c, d) Time resolved QPC response when the two-electron state before the measurement was declared singlet (c) and triplet (d) (the time interval corresponds to the part surrounded by a square in the pulse sequence presented in Fig. (b)). The threshold is shown with a dashed line. (e) Probability of 'triplet' traces as a function of the waiting time t_{wait}, out of 500 traces. The solid line is the exponential fit to the data. α (β) is defined as the probability for the measurement to return triplet 'T' (singlet 'S') if the actual state is singlet S (triplet T). α and β are obtained from the fit.

chance to relax to the singlet state. After one electron has left the dot, another electron can tunnel into the dot again, into the singlet state (the triplet is not energetically accessible). The tunnel rate to the singlet state is very slow, much slower than the charge measurement time in the experiment. The expected steps in the charge detection signal (indicating that the dot contains temporarily only one electron instead of two) will thus be clearly visible. In summary, when the tunnel rate from the dot excited state (triplet) to the reservoir is much larger than the tunnel rate from the reservoir to the ground state of the dot (singlet), the two main contributions to errors in the conventional energy selective read-out are strongly suppressed (relaxation before tunneling and missed steps), and very high read-out fidelities could be achieved.

    We test the high visibility energy read out with a quantum dot (white dotted circle in Fig. 1(a)) and a quantum point contact (QPC) defined in a two-dimensional electron gas (2DEG) with an electron density

of 1.3×10^{15} m^{-2}, 90 nm below the surface of a GaAs/AlGaAs heterostructure, by applying negative voltages to gates L, M, T and Q. Fast voltage pulses on gate P are used to rapidly change the electrochemical potential of the dot. All measurements are performed at zero magnetic field. We tune the dot to the few-electron regime [6, 8], and completely pinch off the tunnel barrier between gates L and T, so that the dot is only coupled to the reservoir on the top [9]. The conductance of the QPC is tuned to about e^2/h, making it very sensitive to the number of electrons on the dot [7]. A voltage bias of 0.7 mV induces a current through the QPC, I_{QPC}, of about 30 nA. Tunneling of an electron on or off the dot gives steps in I_{QPC} of 300 pA [11, 10] and we observe them in the experiment with a measurement bandwidth of 60 kHz, corresponding to a rise time $t_R = 5\,\mu$s. The difference of tunneling rate between singlet and triplet states arises from the distribution of electrons in the orbitals for the two states. In the case of the singlet state, both electrons are in the ground orbital whereas for the triplet state, one electron is in the first excited orbital. The excited orbital has a stronger overlap with the reservoir than the lowest orbital, causing the tunnel rate to and from the triplet state, Γ_T, to be much larger than the tunnel rate to and from the singlet state, Γ_S [5]. In this measurement, when the electrochemical of the reservoir is in between those associated to singlet and triplet state $\Gamma_T/\Gamma_S \sim 17$.

In order to extract the visibility, we reconstruct a relaxation curve from the triplet to the singlet state. The protocol is illustrated in Fig. 1(b). The starting point is a dot with one electron in the ground state. A first pulse is applied to gate 'P' to move the singlet and the triplet electrochemical potentials below the Fermi energy and a second electron tunnels into the dot. In this situation, the ratio Γ_T/Γ_S is higher than 17 and we observe that only the triplet state will be formed (perfect initialisation in the excited state with an estimated error below 0.5%). After a waiting time that we vary, we pulse the electrochemical potential of the triplet state above the Fermi energy while the electrochemical potential of the singlet is still below. If the system is in the triplet state, an electron will tunnel off the dot on a timescale $1/\Gamma_T \sim 5$ µs (faster than the measurement time resolution) and another electron will tunnel on the dot to form a singlet on a timescale $1/\Gamma_S$ (slower than the measurement bandwidth and measured to be 7.8 kHz). If the system is in the singlet state, tunneling is forbidden energetically and the system remains in the singlet state (see Fig. 1(c, d)).

Due to the direct capacitive coupling of gate P to the QPC channel, ΔI_{QPC} follows the pulse shape (see Fig. 1(c, d)). As a consequence of the tunneling events allowed for triplet initial state, a step in the QPC response occurs during the read-out stage. If ΔI_{QPC} goes above a predefined threshold during the read-out stage then we conclude that the state was triplet. If ΔI_{QPC} remains below the threshold we conclude that the state was singlet. For each waiting time, we record 500 individual traces and we extract the probability to detect a triplet state. As expected, we observe an exponential decay of the triplet population as a function of the waiting time, giving a relaxation time, T_1, equal to 1.4 ± 0.1 ms (see Fig. 1(e)). The experimentally determined measurement errors are $\alpha = 0.014$ and $\beta = 0.036$, where α (β) is defined as the probability for the measurement outcome to be triplet (singlet) if the state was singlet (triplet).

α is mainly explained by thermally activated tunneling from the singlet, a process suppressed in the experiment because the energy splitting between the singlet and the reservoir, 0.45 meV, is substantially larger than the electron temperature (20 µeV). Two mechanisms are necessary to explain β. Some errors occur when a triplet relaxed to a singlet before an electron tunnels off the dot. The probability $\beta_1 = 1/(1 + T_1 \Gamma_T)$ of such a process is 0.5% in the present experimental set-up. The dominant error process is tunneling into the dot on a timescale faster than the charge measurement time. The probability of this error process is $\beta_2 = 1 - e^{-\Gamma_S t_R} \sim 4\%$.

We thus observe experimentally a read-out fidelity $1 - (\alpha + \beta)/2 = 97.5\%$ for distinguishing between the singlet and the triplet states of a two-electron quantum dot. If the two spin states would have the same tunneling rate, an optimal fidelity equal to 93% can be expected in the present measurement set-up with an optimal tunnel rate of 17 kHz. We see thus that the difference in tunnel rates between the two spin states significantly improves the spin measurement fidelity. Alternatively, the fidelity can be enhanced by increasing the bandwidth of the single electron charge measurement, but this represents a real experimental challenge.

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