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Single-shot readout of electron spins in a semiconductor quantum dot

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Abstract

We report on a method for single-shot readout of spin states in a semiconductor quantum dot that is robust against charge noise and can be used even when the electron temperature exceeds the energy splitting between the states. The spin states are first correlated to different charge states using a spin dependence of the tunnel rates. A subsequent fast measurement of the charge on the dot then reveals the original spin state. The method is analyzed theoretically, and compared to a previously used method. We experimentally demonstrate the method by performing readout of the two-electron spin states, achieving a single-shot visibility of more than 80%. We find very long triplet-to-singlet relaxation times (up to several milliseconds), with a strong dependence on in-plane magnetic field.

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Keywords: Electron spin; Quantum dot; Quantum computing; Readout

1. Introduction

The spin degree of freedom of electrons is considered a promising candidate for carrying classical information (spintronics) [1] and quantum information (spin quantum bits) [2]. Electron spins can be conveniently studied when confined to a semiconductor quantum dot [3], since here the number of electrons can be precisely controlled (down to zero) [4,5], the tunnel coupling to the reservoir is tunable over a wide range [5,6] and single-electron tunneling can be monitored in real time using a nearby quantum point contact (QPC) [7,8] or a single-electron transistor [9,10] as an electrometer. Using excited-state spectroscopy, the Zeeman energy of a single electron spin on a dot has been measured [11,12]. For applications in quantum computing as well as for fundamental research such as a measurement Bell's inequalities, it is essential that the spin state of the electrons can be read out.

2. Spin-to-charge conversion

The magnetic moment associated with the electron spin is very small (equal to the Bohr magneton μ_B) and therefore hard to measure directly. However, by correlating the spin states to different charge states and subsequently measuring the charge on the dot, the spin state can be determined [2]. This way, the measurement of a single spin is replaced by the measurement of a single charge, which is a much easier task. The remaining challenge is to find a reliable method for correlating the spin states to different charge states. Here, we discuss two methods for such a spin-to-charge conversion. They are outlined in Fig. 1a,b. We note that both methods presented here can in principle also be used to read out the orbital state.

In one method, a difference in *energy* between the spin states is used for spin-to-charge conversion. In this energy-selective readout (E-RO), the spin levels are positioned around the electrochemical potential of the reservoir μ_{res} as depicted in Fig. 1a, such that one electron can tunnel off the dot from the spin excited state, $|ES\rangle$, whereas tunneling from the ground state, $|GS\rangle$, is energetically forbidden. Therefore, if the charge measurement reveals that one electron tunnels off the dot, the state was $|ES\rangle$, while if no

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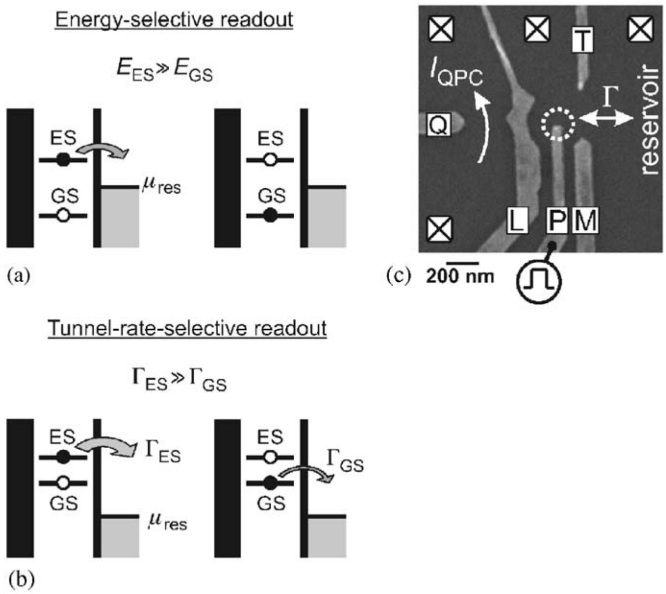

Fig. 1. (a)–(b) Energy diagrams depicting two different methods for spin-to-charge conversion as explained in the text: (a) energy-selective readout (E-RO) and (b) tunnel-rate-selective readout (TR-RO). (c) Scanning electron micrograph of the device used for demonstrating TR-RO. A quantum dot (white dotted circle) is defined by voltages on the surface gates *T*, *L* and *M*. Gate *P* is used to apply fast voltage pulses, and gate *Q* in combination with gate *L* creates a quantum point contact that serves as the electrometer. The dot is tunnel coupled to the reservoir on the right.

electron tunnels off the dot, the state was $|GS\rangle$. By combining this scheme with a fast (40 kHz bandwidth) measurement of the charge dynamics, we have recently performed read-out of the spin orientation of a single electron, with a single-shot visibility up to 65% [13]. (A conceptionally similar scheme has also allowed single-shot read-out of a superconducting charge qubit [14].) However, this energy-selective readout (E-RO) has three drawbacks: (i) E-RO requires an energy splitting of the spin states larger than the thermal energy of the electrons in the reservoir. Thus, for a single spin the readout is only effective at very low electron temperature and high magnetic fields (8 T and higher in Ref. [13]). Also, interesting effects occurring close to degeneracy, e.g. near the singlet–triplet crossing for two electrons [23], cannot be probed. (ii) Since the E-RO relies on precise positioning of the spin levels with respect to the reservoir, it is very sensitive to fluctuations in the electrostatic potential. Background charge fluctuations [15], active even in today's most stable devices, can easily push the levels out of the readout configuration. (iii) High-frequency noise can spoil the E-RO by inducing photon-assisted tunneling from the spin ground state to the reservoir. Since the QPC is a source of shot noise, this limits the current through the QPC and thereby the bandwidth of the charge detection [8].

Alternatively, spin-to-charge conversion can be achieved by exploiting the difference in *tunnel rates* of the different spin states to the reservoir [16]. We outline the concept of this tunnel-rate-selective readout (TR-RO) in Fig. 1b. Assume that the tunnel rate from $|ES\rangle$ to the reservoir, Γ_{ES}, is much higher than the tunnel rate from $|GS\rangle$, Γ_{GS}, i.e. $\Gamma_{ES} \gg \Gamma_{GS}$. Then, the spin state can be read out as follows. At time $t = 0$, the levels of both $|ES\rangle$ and $|GS\rangle$ are positioned far above μ_{res}, so that one electron is energetically allowed to tunnel off the dot regardless of the spin state. Then, at a time $t = \tau$, where $\Gamma_{GS}^{-1} \gg \tau \gg \Gamma_{ES}^{-1}$, an electron will have tunneled off the dot with a very high probability if the state was $|ES\rangle$, but most likely no tunneling will have occurred if the state was $|GS\rangle$. Thus, the spin information is converted to charge information, and a measurement of the number of electrons on the dot reveals the original spin state.

A major advantage of the TR-RO scheme is that it does not rely on a large energy splitting between the spin states. Furthermore, it is robust against background charge fluctuations, since these cause only a small variation in the tunnel rates (of order 10^{-3} in Ref. [15]). Finally, photon-assisted tunneling due to high-frequency noise does not disturb the readout since in the TR-RO scheme tunneling is energetically allowed regardless of the initial spin state. Thus, we see that TR-RO can overcome several constraints of E-RO.

We will discuss experiments aimed at spin measurements using TR-RO in single-shot mode. This requires a high fidelity of the readout, since no averaging is possible: there is only one copy of the spin state available. Note that although an ideal single-shot measurement yields the spin state with a 100% fidelity, the fidelity in real measurements will be reduced by imperfections and noise in the readout setup.

Fig. 1c shows the device used in these experiments [17]. Negative voltages applied to metallic gates on top of a GaAs/AlGaAs heterostructure define a quantum dot (white dotted circle) and a QPC in the two-dimensional electron gas (2DEG), which is 60 nm below the surface. The crossed boxes depict ohmic connections to the measurement wires. The electron density of the 2DEG is $4.0 \times 10^{15}\,\mathrm{m}^{-2}$.

In the experiments, the tunnel barrier between gates *L* and *T* is completely pinched off, so that the dot is only coupled to one reservoir. Gate *P* is used to apply fast voltage pulses to the device, with a typical pulse rise time of about 1 ns. The conductance of the QPC is tuned to about e^2/h, making it very sensitive to the number of electrons on the dot. A voltage bias of about 0.8 mV induces a current through the QPC, I_{QPC}, of about 30 nA. The number of electrons on the dot is then determined from pulse spectroscopy measurements [6].

3. Fidelity of the readout

We first analyze the fidelity of the TR-RO theoretically using the error rates α and β as defined in the diagram of Fig. 2 (inset). Here, α is the probability that one electron has tunneled even though the initial state was $|GS\rangle$, and β

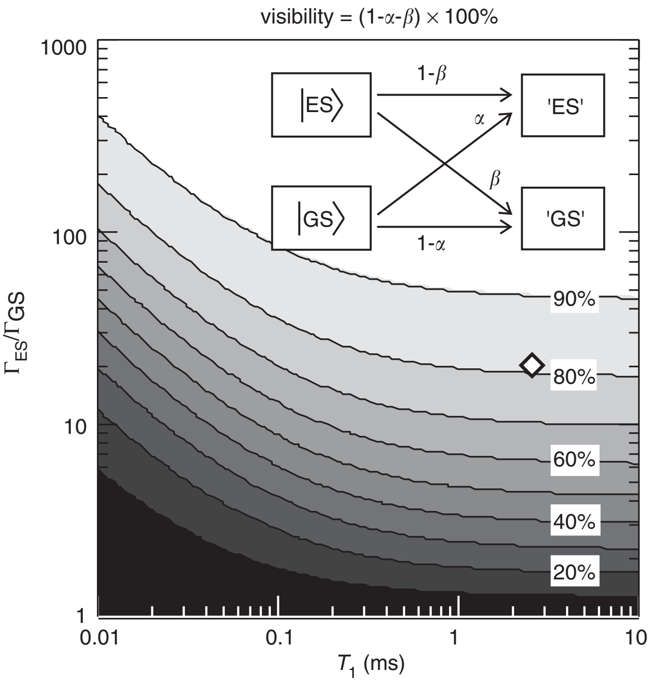

Fig. 2. Gray-scale plot of the maximum visibility of the TR-RO as a function of the relaxation time T_1 and the ratio of the tunnel rates between the states Γ_{ES}/Γ_{GS}. The diamond corresponds to the readout parameters in Fig. 4a,b.

the probability that no tunneling has occurred even though the initial state was $|ES\rangle$. The charge measurement itself is assumed to be perfect, and spin relaxation from $|ES\rangle$ to $|GS\rangle$ is modeled by a rate $1/T_1$. We find analytically

$$\alpha = 1 - e^{-\Gamma_{GS}\cdot\tau}, \quad (1)$$

$$\beta = \frac{(1/T_1)e^{-\Gamma_{GS}\cdot\tau} + (\Gamma_{ES} - \Gamma_{GS})e^{-(\Gamma_{ES}+1/T_1)\cdot\tau}}{\Gamma_{ES} + 1/T_1 - \Gamma_{GS}}, \quad (2)$$

where τ is the time at which we measure the number of electrons N [18]. The visibility of the readout is $1-\alpha-\beta$.

The optimal value for the readout time for given values of T_1 and the ratio Γ_T/Γ_S, τ_{max}, is found by solving $d(\text{visibility})/d\tau = 0$ for τ. We find

$$\tau_{max} = \frac{1}{\Gamma_{ES} + 1/T_1 - \Gamma_{GS}} \ln\left(\frac{\Gamma_{ES} + 1/T_1}{\Gamma_{GS}}\right). \quad (3)$$

Inserting this expression into Eqs. (1) and (2) yields the maximum visibility.

In Fig. 2 we plot the visibility for $\tau = \tau_{max}$ as a function of T_1 and the ratio of the tunnel rates Γ_{ES}/Γ_{GS}. (Here, Γ_{GS} is chosen to be 2.5 kHz, which is well within the bandwidth of our charge detection setup [8].) We see that for $\Gamma_{ES}/\Gamma_{GS} = 10$ and $T_1 = 0.5$ ms, the visibility is 65%, equal to the visibility obtained with E-RO for the same T_1. For $\Gamma_{ES}/\Gamma_{GS} > 60$ and $T_1 = 0.5$ ms, the visibility of TR-RO exceeds 90%.

The TR-RO can be used in a similar way if Γ_{ES} is much *lower* than Γ_{GS}. The visibility for this case can be calculated simply by replacing α and β in Eqs. (1)–(2) with $1-\alpha$ and $1-\beta$, respectively. Significant differences with the values in Fig. 2 arise only in the limit $T_1 \ll \Gamma_{ES}^{-1}$.

The main ingredient necessary for TR-RO is a spin dependence in the tunnel rates. For a single electron, this spin dependence can be obtained in the Quantum Hall regime, where a high spin-selectivity is induced by the spatial separation of spin-resolved edge channels [4,19]. TR-RO can also be used for readout of the spin states of a two-electron dot, where the electrons are either in the spin-singlet ground state, denoted by $|S\rangle$, or in a spin-triplet state, denoted by $|T\rangle$. In $|S\rangle$, the two electrons both occupy the lowest orbital, but in $|T\rangle$ one electron is in the first excited orbital. Since the wave function in this excited orbital has more weight near the edge of the dot [20], the coupling to the reservoir is stronger than for the lowest orbital. Therefore, the tunnel rate from a triplet state to the reservoir Γ_T is much larger than the rate from the singlet state Γ_S, i.e. $\Gamma_T \gg \Gamma_S$ [21]. This spin dependence is used to experimentally demonstrate the TR-RO for two electrons using the device shown in Fig. 1c.

4. Experimental results

We tune the dot to the $N = 1 \leftrightarrow 2$ transition in a small parallel field $B_\parallel$ of 0.02 T. Here, the energy difference between $|T\rangle$ and the ground state $|S\rangle$, E_{ST}, is about 1 meV. From measurements of the tunnel rates [6], we estimate the ratio Γ_T/Γ_S to be on the order of 20. A similar ratio was found previously in transport measurements on a different device [21]. As can be seen in Fig. 2 , for $T_1 > 1$ ms this permits a readout visibility $> 80\%$.

We test the TR-RO by applying voltage pulses as depicted in Fig. 3a to gate P. Fig. 3b shows the expected response of I_{QPC} to the pulse, and Fig. 3c gives the level diagrams in the three different stages. Before the pulse starts, there is one electron on the dot. Then, the pulse pulls the levels down so that a second electron can tunnel onto the dot ($N = 1 \to 2$), forming either a singlet or a triplet state with the first electron. The probability that a triplet state is formed is given by $3\Gamma_T/(\Gamma_S + 3\Gamma_T)$, where the factor of 3 is due to the degeneracy of the triplets. After a variable waiting time t_{wait}, the pulse ends and the readout process is initiated, during which one electron can leave the dot again. The rate for tunneling off depends on the two-electron state, resulting in the desired spin-to-charge conversion. The QPC is used to detect the number of electrons on the dot. Due to the direct capacitive coupling of gate P to the QPC channel, ΔI_{QPC} follows the pulse shape. Tunneling of an electron on or off the dot gives an additional step in ΔI_{QPC} [7,8,13], as indicated by the arrows in Fig. 3b.

Now, Γ_S is tuned to 2.5 kHz, and Γ_T is therefore ≈ 50 kHz. In order to achieve a good signal-to-noise ratio in I_{QPC}, the signal is sent through an external 20 kHz low-pass filter. As a result, many of the tunnel events from $|T\rangle$

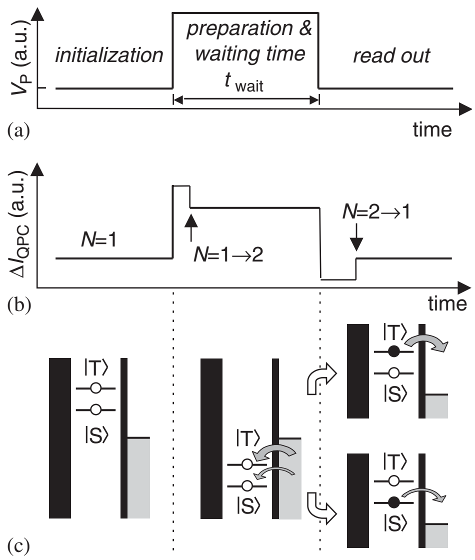

Fig. 3. Single-shot readout of two-electron spin states. (a) Voltage pulse waveform applied to one of the gate electrodes. (b) Response of the QPC current to the waveform of (a). (c) Energy diagrams indicating the positions of the levels during the three stages. In the final stage, spin is converted to charge information due to the difference in tunnel rates for states $|S\rangle$ and $|T\rangle$.

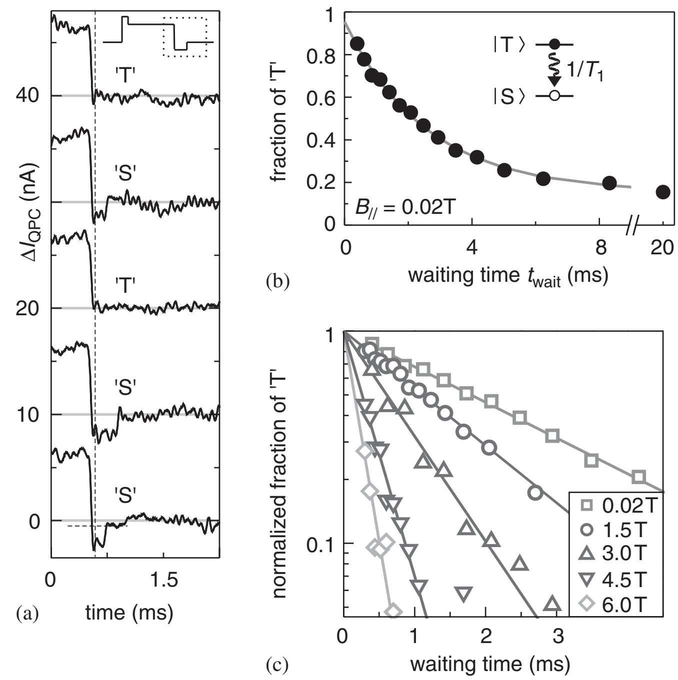

Fig. 4. (a) Real-time traces of ΔI_{QPC} during the last part of the waveform (dashed box in the inset), for $t_{wait} = 0.8$ ms. At the vertical dashed line, N is determined by comparison with a threshold (horizontal dashed line in bottom trace) and the spin state is declared $'T'$ or $'S'$ accordingly. (b) Fraction of $'T'$ as a function of waiting time at $B_{\parallel} = 0.02$ T, showing a single-exponential decay with a time constant T_1 of 2.58 ms. (c) Normalized fraction of $'T'$ vs. t_{wait} for different values of $B_{\parallel}$.

will not be resolved, but the tunneling from $|S\rangle$ should be clearly visible.

Fig. 4a shows several traces of ΔI_{QPC}, from the last part (300 μs) of the pulse to the end of the readout stage (see inset), for a waiting time of 0.8 ms. In some traces, there are clear steps in ΔI_{QPC}, due to an electron tunneling off the dot. In other traces, the tunneling occurs faster than the filter bandwidth. In order to discriminate between $|S\rangle$ and $|T\rangle$, we first choose a readout time τ (indicated by a vertical dashed line in Fig. 4a) and measure the number of electrons on the dot at that time by comparing ΔI_{QPC} to a threshold value (as indicated by the horizontal dashed line in the bottom trace of Fig. 4a). If ΔI_{QPC} is below the threshold, it means $N = 2$ and we declare the state $'S'$. If ΔI_{QPC} is above the threshold, it follows that $N = 1$ and the state is declared $'T'$. Our method for determining the optimal threshold value and τ is explained below.

To verify that $'T'$ and $'S'$ indeed correspond to the spin states $|T\rangle$ and $|S\rangle$, we change the relative occupation probabilities by varying the waiting time. The probability that the electrons are in $|T\rangle$, P_T, decays exponentially with the waiting time: $P_T(t) = P_T(0)e^{-t_{wait}/T_1}$. Therefore, as we make the waiting time longer, we should observe an exponential decay of the fraction of traces that are declared $'T'$.

We take 625 traces similar to those in Fig. 4a for each of 15 different waiting times. Note that the two-electron state is formed on a timescale (of order $1/\Gamma_T$) much shorter than the shortest t_{wait} used (400 μs). To find the optimal readout parameters, we scan a wide range of readout times and threshold values using a computer program. For each combination of these two parameters, the program determines the fraction of traces declared $'T'$ for each of the waiting times, and fits the resulting data with a single exponential decay $Ae^{-t_{wait}/T_1} + \alpha$. The prefactor A is given by $3\Gamma_T/(\Gamma_S + 3\Gamma_T) \times (1 - \alpha - \beta)$. We see that A is proportional to the readout visibility, and therefore the optimal readout parameters can be determined simply by searching for the highest value of A. Here, we find the optimal values to be -0.4 nA for the threshold and 70 μs for τ (corresponding to $t = 370$ μs in Fig. 4a), and use these in the following.

In Fig. 4b, we plot the fraction of traces declared $'T'$ as a function of t_{wait}. We see that the fraction of $'T'$ decays exponentially, showing that we can indeed read out the two-electron spin states. A fit to the data yields a triplet-to-singlet relaxation time $T_1 = (2.58 \pm 0.09)$ ms, which is more than an order of magnitude longer than the lower bound found in Ref. [22]. We can also extract α and β from the data. We find $\alpha = 0.15$ and $\beta = 0.04$ (taking $\Gamma_T/\Gamma_S = 20$). The single-shot visibility is thus 81%. These numbers agree well with the values predicted by the model ($\alpha = 0.14$, $\beta = 0.05$, visibility= 81%), as indicated by the diamond in Fig. 2. Note that, since the visibility is insensitive to τ near the optimal value, it is not significantly reduced by the finite bandwidth of the charge measurement.

As an extra check of the readout, we have also applied a modified pulse where during the preparation only the singlet state is energetically accessible. Here, the readout should ideally always yield $'S'$, and therefore the measured probability for finding $'T'$ directly gives us α. We find a fraction of $'T'$ of 0.16, consistent with the value of α obtained from the fit. This again confirms the validity of the readout method.

We further study the relaxation between triplet and singlet states by repeating the measurement of Fig. 4b at different magnetic fields $B_{\parallel}$. Fig. 4c shows the decay of the fraction of $'T'$, normalized to the fraction of $'T'$ at $t_{\mathrm{wait}} = 0$, on a logarithmic scale. The data follow a single-exponential decay at all fields. The dominant relaxation mechanisms for large values of E_{ST} are believed to originate from the spin–orbit interaction [23,24], but to our knowledge the case of an in-plane magnetic field has not been treated yet. A second-order polynomial fit to the data yields $1/T_1\,(\mathrm{kHz}) = (0.39 \pm 0.03) + (0.10 \pm 0.02) \cdot B_{\parallel}^2\,(\mathrm{T})$, with a negligible linear term.

Finally, we show that the TR-RO can still be used when $|S\rangle$ and $|T\rangle$ are almost degenerate. By mounting the device under a 45° angle with respect to the magnetic field axis, we can tune E_{ST} through zero [20]. In these devices, transitions are broadened both by the electron temperature in the reservoir and by fluctuations in the dot potential. We model these two effects by one effective electron temperature T_{eff}. For E_{ST} smaller than about $3.5kT_{\mathrm{eff}}$, the energy splitting cannot be resolved. As in previous transport and pulse spectroscopy measurements, we find here $3.5kT_{\mathrm{eff}} \approx 60\,\mu\mathrm{eV}$, making it impossible to use the E-RO method beyond $B \approx 3.9\,\mathrm{T}$. From extrapolation of the data, we find that the singlet–triplet ground state transition occurs at $(4.25 \pm 0.05)\,\mathrm{T}$.

We tune B to 4.15 T, so that we are very close to the degeneracy point, but still certain that $|S\rangle$ is the ground state. Here, we perform a readout measurement as in Fig. 4 (data not shown). Again, an exponential decay of the fraction of $'T'$ is observed, with a T_1 of $(0.31 \pm 0.07)\,\mathrm{ms}$. This demonstrates that even when the energy splitting E_{ST} is too small to resolve, we can still read out the spin states using TR-RO.

We have shown that the TR-RO scheme can be used to perform a highly efficient readout, and that it can overcome several constraints of the E-RO. However, readout of a single electron spin using TR-RO has not yet been demonstrated. In future measurements, we plan to apply the tunnel-rate-selective readout to detect relaxation and coherent manipulation of a single electron spin.

Acknowledgments

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References

[1] S.A. Wolf, et al., Science 294 (2001) 1488.
[2] D. Loss, D.P. DiVincenzo, Phys. Rev. A 57 (1998) 120.
[3] L.P. Kouwenhoven, et al., in: L.L. Sohn, L.P. Kouwenhoven, G. Schön (Eds.), Mesoscopic Electron Transport, NATO Advanced Study Institutes, Series E, vol. 345, Kluwer, Dordrecht, Boston, 1997, pp. 105–214.
[4] M. Ciorga, et al., Phys. Rev. B 61 (2000) R16315.
[5] J.M. Elzerman, et al., Phys. Rev. B 67 (2003) 161308.
[6] J.M. Elzerman, et al., Appl. Phys. Lett. 84 (2004) 4617.
[7] R. Schleser, et al., Appl. Phys. Lett. 85 (2004) 2005.
[8] L.M.K. Vandersypen, et al., Appl. Phys. Lett. 85 (2004) 4394.
[9] W. Lu, et al., Nature 423 (2003) 422.
[10] T. Fujisawa, et al., Appl. Phys. Lett. 84 (2004) 2343.
[11] R. Hanson, et al., Phys. Rev. Lett. 91 (2003) 196802.
[12] R.M. Potok, et al., Phys. Rev. Lett. 91 (2003) 016802.
[13] J.M. Elzerman, R. Hanson, L.H. Willems van Beveren, B. Witkamp, L.M.K. Vandersypen, L.P. Kouwenhoven, Nature 430 (2004) 431.
[14] O. Astafiev, et al., Phys. Rev. B 69 (2004) 180507.
[15] S.W. Jung, T. Fujisawa, Y. Hirayama, Y.H. Jeong, Appl. Phys. Lett. 85 (2004) 768.
[16] Similarly, spin-dependent tunneling to a second dot can be used, see H.A. Engel et al., Phys. Rev. Lett. 93 (2004) 106804.
[17] R. Hanson, L.H. Willems van Beveren, I.T. Vink, J.M. Elzerman, W.J.M. Naber, F.H.L. Koppens, L.P. Kouwenhoven, L.M.K. Vandersypen, Phys. Rev. Lett. 94 (2005) 196802.
[18] The probability β that no tunnel event has occurred at $t = \tau$, even though the initial state was $|ES\rangle$, is the sum of β_1, the probability that the state is $|ES\rangle$, and β_2, the probability that the state is $|GS\rangle$. These are given by

$$\beta_1 = \mathrm{e}^{-(\Gamma_{ES}+1/T_1)\cdot\tau},$$

$$\beta_2 = \int_0^{\tau} P_{\mathrm{rel}}(t) \cdot P_{GS}(\tau - t)\,\mathrm{d}t.$$

Here, $P_{\mathrm{rel}}(t)\,\mathrm{d}t$ is the probability that $|ES\rangle$ relaxes to $|GS\rangle$ within the time interval $[t, t+\mathrm{d}t]$, and $P_{GS}(\tau - t)$ is the probability that no tunneling has taken place from $|GS\rangle$ during a time $\tau - t$:

$$P_{\mathrm{rel}}(t) = 1/T_1 \mathrm{e}^{-(\Gamma_{ES}+1/T_1)\cdot t},$$

$$P_{GS}(\tau - t) = \mathrm{e}^{-\Gamma_{GS}\cdot(\tau - t)}.$$

[19] M. Ciorga, et al., Appl. Phys. Lett. 80 (2002) 2177.
[20] L.P. Kouwenhoven, D.G. Austing, S. Tarucha, Rep. Prog. Phys. 64 (6) (2001) 701.
[21] R. Hanson, et al., Proceedings of the 39th Rencontres de Moriond, see also cond-mat/0407793.
[22] T. Fujisawa, D.G. Austing, Y. Tokura, Y. Hirayama, S. Tarucha, Nature 419 (2002) 278.
[23] V. Golovach, et al., in preparation.
[24] A.V. Khaetskii, Y.V. Nazarov, Phys. Rev. B 61 (2000) 12639.