High-Fidelity Rapid Initialization and Read-Out of an Electron Spin via the Single Donor D^- Charge State

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We demonstrate high-fidelity electron spin read-out of a precision placed single donor in silicon via spin selective tunneling to either the D^+ or D^- charge state of the donor. By performing read-out at the stable two electron $D^0 \leftrightarrow D^-$ charge transition we can increase the tunnel rates to a nearby single electron transistor charge sensor by nearly 2 orders of magnitude, allowing faster qubit read-out (1 ms) with minimum loss in read-out fidelity (98.4%) compared to read-out at the $D^+ \leftrightarrow D^0$ transition (99.6%). Furthermore, we show that read-out via the D^- charge state can be used to rapidly initialize the electron spin qubit in its ground state with a fidelity of $F_I = 99.8\%$.

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Electron spins confined in solids are attractive qubits due to long coherence times [1,2], fast gate operations [3,4], and the potential for scalability [5,6]. Particularly donor-bound spins in silicon show coherence times of milliseconds with the ability to store quantum information in the donor nuclei [1,7,8]. Initialization and read-out has been achieved via spin selective tunneling to an electron reservoir [9,10] with fidelities as high as 97% [1,2,11,12]. However, robust quantum error correction protocols such as the surface code require fidelities of ∼99% with the measurement of parity operators to detect and correct errors faster than qubit coherence times [13,14]. Read-out times and fidelity can be optimized by tuning electron tunnel rates to the reservoir [9]. This can, however, be challenging in donors [15–17] due to their close proximity to the reservoir and the stochastic nature of doping in many device architectures [10,18,19]. Here we demonstrate that we can decrease the read-out times of a single phosphorus donor by nearly 2 orders of magnitude to 1 ms by selecting the two-electron D^- state in a novel pulse sequence. Importantly, we observe no significant loss in qubit read-out fidelity (98.4%), compared to a record fidelity of 99.6% obtained using conventional read-out, giving the highest fidelity for such rapid spin read-out [1,2]. Both read-out schemes can be used to rapidly initialize spins with fidelities $F_I \geq 99.8\%$.

An overview of the device after STM hydrogen lithography [20] is shown in Fig. 1(a). Details of the device fabrication process have been published previously [16,21,22]. The device hosts two donor sites, $D1$ and $D2$, placed 25 nm apart at a distance ∼20 nm from a single electron transistor (SET) [11] which acts as charge sensor and electron reservoir [10]. Following lithography, this device template was selectively doped with PH_3 followed by annealing (350° C) providing an atomically abrupt planar doping profile with density $N_{2D} \approx 2 \times 10^{18}$ m^{-2} [23]. We

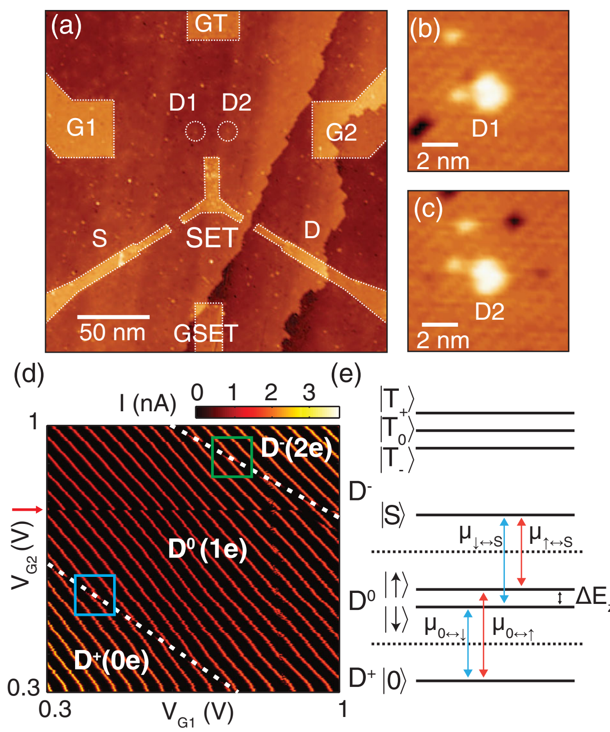

FIG. 1 (color). Stability diagram and energy levels of a single donor read-out device. (a) Overview STM image of the device architecture after lithography. (b),(c) Two incorporation sites for donors, $D1$ and $D2$, were patterned 20 nm from the SET. (d) SET current, I_{SET}, as a function of gate voltages V_{G1} and V_{G2} for fixed $V_{GT} = V_{GSET} = 1$ V and $V_{SD} = 0.75$ mV and $B = 0.1$ T. Two parallel offset lines in the SET current (white dashed lines) are due to the charging of the donor in $D2$ from the D^+ to D^0 and D^0 to D^- charge states. (e) Energy levels of the D^+, D^0, and D^- charge states. Conventional read-out is performed at the $D^+ \leftrightarrow D^0$ transition while fast read-out is performed at the $D^0 \leftrightarrow D^-$ transition.

estimate a maximum of two donors to be incorporated in $D1$ and $D2$ from the STM images in Figs. 1(b) and 1(c), respectively [16,24]. Charge sensing measurements show that a single donor was incorporated in $D2$ while no donor was incorporated in $D1$ (see Supplemental Material S1 [25]). Four in-plane gates, G1, G2, GSET, and GT are used to tune the electrochemical potentials of the donor and SET island. All experiments were performed at low temperature with a measured electron temperature of $T_e \sim 160$ mK (see Supplemental Material S2 [25]).

The charge stability diagram, recorded at $V_{\mathrm{SD}} = 0.75$ mV and $V_{\mathrm{GT}} = V_{\mathrm{GSET}} = 1$ V, is plotted in Fig. 1(d), showing the SET current as a function of the gate voltages V_{G1} and V_{G2}. Lines of current running at ~45° correspond to the Coulomb blockade (CB) peaks of the SET whenever its electrochemical potential is aligned between the Fermi level of the source and drain electrodes. Charge transitions on the donor are detected by shifts of the electrochemical potential of the SET [10,27], resulting in two parallel lines of charge offsets in the CB pattern (white dotted lines). The presence of two sets of charge transitions is consistent with a single P donor which can bind up to two electrons [28] within three stable charge states, D^+ ($0e$), D^0 ($1e$), and D^- ($2e$). From the separation of the $D^+ \leftrightarrow D^0$ and $D^0 \leftrightarrow D^-$ transitions in gate space we extract a charging energy, $E_C = 50 \pm 7$ meV, in good agreement with that of bulk P donors [28] and an STM-patterned single-atom transistor [24]. The horizontal offset marked by the red arrow in Fig. 1(d) is due to a trapped charge rearrangement.

The energy level diagram of a single donor with ground and excited states for both the D^0 and D^- charge states is shown in Fig. 1(e) [29]. A static magnetic field B splits the spin-degenerate D^0 ground state into spin-up $|\uparrow\rangle$ and spin-down $|\downarrow\rangle$, separated by the Zeeman energy, $\Delta E_Z = g\mu_B B$. The resulting electrochemical potentials $\mu_{0\leftrightarrow\downarrow}$ and $\mu_{0\leftrightarrow\uparrow}$ (colored arrows) allow spin read-out at the $D^+ \leftrightarrow D^0$ charge transition [blue box in Fig. 1(d)] [10,11] by applying a three level pulse sequence as shown in the left-hand panel of Fig. 2. For read-out both electrochemical potentials are aligned such that $\mu_{0\leftrightarrow\downarrow}$ is below and $\mu_{0\leftrightarrow\uparrow}$ is above the electrochemical potential of the SET allowing spin-selective tunneling to the SET island. If the electron spin is in the $|\uparrow\rangle$ state then it will tunnel onto the SET island, followed by a $|\downarrow\rangle$ returning to the donor resulting in a single pulse in the SET current [blue trace in Fig. 2(b)]. The time scale for read-out at this transition can be extracted from histograms of the start and duration of such events using 6250 read-out cycles, giving tunnel times $\tau_{\uparrow,\mathrm{out}} = 6.5 \pm 0.8$ ms and $\tau_{\downarrow,\mathrm{in}} = 5.1 \pm 0.3$ ms, respectively [Fig. 2(d)].

In this device these tunnel times were tailored to maximize the read-out fidelity by positioning the donor with respect to the SET with the atomic precision of the STM. However, it is beneficial while performing quantum error correction and nuclear spin read-out [8] to be able to tune these tunnel times to decrease the read-out time. As the location of the read-out position in gate space [blue circle in Fig. 2(a)] is determined by the alignment of donor and SET electrochemical potentials there is limited electrostatic

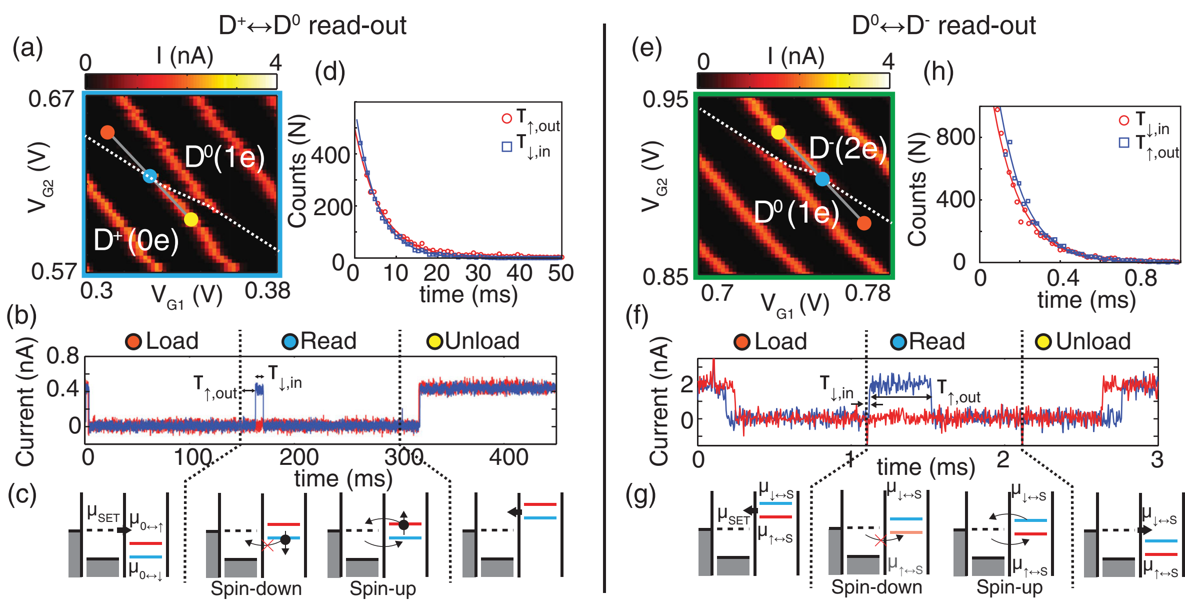

FIG. 2 (color). $D^+ \leftrightarrow D^0$ and $D^0 \leftrightarrow D^-$ single-shot spin read-out. (a),(e) Close-ups of the stability diagram at the (a) $D^+ \leftrightarrow D^0$ and the (e) $D^0 \leftrightarrow D^-$ charge transitions show the position of the three level gate pulses for single-shot spin read-out. (b),(f) SET current response for $|\uparrow\rangle$ (blue trace) and $|\downarrow\rangle$ (red trace) during read-out performed at $B = 1.6$ T and $V_{\mathrm{SD}} = 300$ μV. (c),(g) Electrochemical potentials of donor and SET during load, read, and unload phases. (d) From histograms of the start and duration of single current pulses using 6250 $D^+ \leftrightarrow D^0$ read-out cycles we extract tunnel times $\tau_{\uparrow,\mathrm{out}} = 6.5 \pm 0.8$ ms and $\tau_{\downarrow,\mathrm{in}} = 5.1 \pm 0.3$ ms, respectively. (h) Similarly, using 22 000 $D^0 \leftrightarrow D^-$ read-out cycles we extract tunnel times $\tau_{\downarrow,\mathrm{in}} = 140 \pm 10$ μs and $\tau_{\uparrow,\mathrm{out}} = 130 \pm 20$ μs.

control over the tunnel rates. For more rapid spin read-out and initialization, we can employ a novel pulse sequence at the two-electron $D^0 \leftrightarrow D^-$ transition [Fig. 2(e) and green box in Fig. 1(d)]. Different from the D^0 charge state, the D^- is only weakly bound below the silicon conduction band edge with both electrons effectively screening the donor nucleus. Consequently, the wave function overlap between the D^- state and the SET island is larger resulting in faster tunnel times by nearly 2 orders of magnitude.

The ground state of the two-electron D^- state is a spin singlet ($|S\rangle$) with the electrochemical potentials $\mu_{\uparrow\leftrightarrow S}$ and $\mu_{\downarrow\leftrightarrow S}$, as shown in Fig. 1(e) [30]. The modified pulse sequence at this charge transition is shown in the right-hand panels of Fig. 2. The sequence is applied such that the SET current is off (on) when 1 (2) electron(s) is (are) bound to the donor [Fig. 2(e)]. Starting with two electrons bound to the donor, we first raise both electrochemical potentials above that of the SET [Fig. 2(g)]. This allows a single electron to tunnel to the SET island, leaving behind an electron of arbitrary spin orientation. This spin can subsequently be read out by aligning the electrochemical potential of the SET such that it lies between $\mu_{\uparrow\leftrightarrow S}$ and $\mu_{\downarrow\leftrightarrow S}$. If the donor-bound electron is in its $|\downarrow\rangle$ ground state then its electrochemical potential for a $|\downarrow\rangle \rightarrow |S\rangle$ transition is above that of the SET and tunneling to the donor is prohibited [red trace in Fig. 2(f)]. However, if the electron is in its $|\uparrow\rangle$ excited state, transitions $|\uparrow\rangle \rightarrow |S\rangle$ are permitted and a second electron tunnels onto the donor, forming a spin singlet. The result is a single current pulse at the start of the read phase [blue trace in Fig. 2(f)] with an electron remaining in the $|\downarrow\rangle$ ground state at the end of the pulse sequence. The current during the $D^0 \leftrightarrow D^-$ read-out is greater than at the $D^+ \leftrightarrow D^0$ read-out due to a decrease in the tunnel barriers towards more positive gate voltages and from a background undulation of the current through the SET from a modulated density of states in the leads (see Supplemental Material S1 [25]). Again, we estimate the read-out time scale from histograms of the start and duration of the single current pulses using 22 000 read-out cycles and find tunnel times $\tau_{\downarrow,\mathrm{in}} = 140 \pm 10$ μs and $\tau_{\uparrow,\mathrm{out}} = 130 \pm 20$ μs [Fig. 2(h)]. The enhancement of qubit read-out time scales by nearly 2 orders of magnitude highlights the advantage of read-out via the D^- state.

Spin relaxation rates $1/T_1$ have been measured using both the above pulse sequences (Fig. 2) and are determined by fitting the exponential decay of the $|\uparrow\rangle$ probability $P_\uparrow$ as a function of wait time after loading. Values for $1/T_1$, obtained by utilizing the D^- charge state, are shown as red squares in Fig. 3 and agree perfectly with values obtained via conventional spin read-out at the $D^+ \leftrightarrow D^0$ transition (black squares). However, the faster $D^0 \leftrightarrow D^-$ read-out allows the spin to be measured at higher magnetic fields ($B > 5$ T) compared to the $D^+ \leftrightarrow D^0$ read-out where the spin relaxes before the electron can tunnel out ($T_1 > \tau_{\uparrow,\mathrm{out}}$).

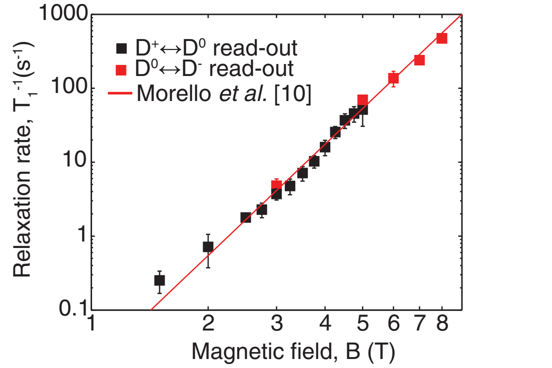

FIG. 3 (color). Magnetic field dependence of T_1. Comparison of spin relaxation rates $T_1^{-1}(B)$ measured both using conventional read-out (black squares) and read-out via the D^- charge state (red squares). The solid red line shows a fit ($\propto B^5$) in agreement with Morello *et al.* for an individual P donor [10].

We find $1/T_1 \propto B^5$ as expected for individual P donors in silicon as spin lifetimes are limited by the valley repopulation mechanism [31–33]. Indeed, a fit obtained by Morello *et al.* [10] using a proportionality constant $K_5 = 0.015$ in a previous spin read-out experiment shows excellent agreement with our data (red line in Fig. 3), independently confirming the presence of a single P donor in the device.

With faster qubit read-out established, we finally need to confirm that the read-out fidelity—the probability of the correct assignment of a $|\uparrow\rangle$ or $|\downarrow\rangle$ electron state after read-out—is not compromised as a result of an increased measurement bandwidth and its associated noise. Using both methods, the detection of current above a threshold I_T results in the assignment of a $|\uparrow\rangle$ electron. The fidelity of this detection scheme can be estimated by numerical modeling of the distribution of the peak current, I_{peak}, during the read-out phase [10] (see Supplemental Material S3 [25]). For the calculation we use 6250 (22 000) current traces, measured during the $D^+ \leftrightarrow D^0$ ($D^0 \leftrightarrow D^-$) read-out, respectively, at $B = 1.6$ T and a measurement bandwidth of 10 kHz (100 kHz). A higher bandwidth was required for the $D^0 \leftrightarrow D^-$ read-out due to the faster tunnel times resulting in a lower signal to noise ratio. This magnetic field was chosen as it is a typical field used in electron and nuclear spin resonance experiments in donor-based devices [1,34]. From the model, the electrical fidelities of the $|\uparrow\rangle$ and $|\downarrow\rangle$ spin states, $F_\uparrow$ and $F_\downarrow$, as well as the visibility, defined as $V = 1 - F_\uparrow - F_\downarrow$, can be determined as a function of threshold current and are shown in Figs. 4(a) and 4(b) for both the D^+ and D^- read-out. For the values for I_T that give the maximum visibility we find $F_\uparrow = 99.6\%$ and $F_\downarrow = 100\%$ for the $D^+ \leftrightarrow D^0$ read-out and $F_\uparrow = 97.6\%$ and $F_\downarrow = 99.8\%$ for the $D^0 \leftrightarrow D^-$ read-out.

Importantly, a potential source of error in the measurement fidelity is the thermal broadening of the Fermi distribution in the SET ($T_e \sim 160$ mK). For the $D^+ \leftrightarrow D^0$

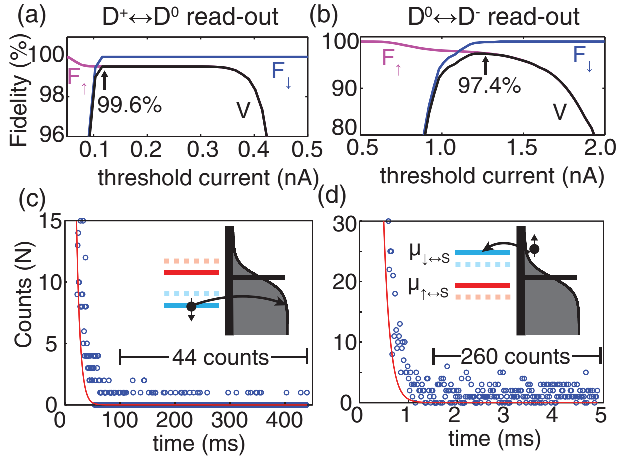

FIG. 4 (color). Measurement fidelities of the $D^+ \leftrightarrow D^0$ and $D^0 \leftrightarrow D^-$ read-out. Electrical fidelities ($F_\uparrow$ and $F_\downarrow$) and visibility (V) as a function of threshold current for the (a) $D^+ \leftrightarrow D^0$ and (b) $D^0 \leftrightarrow D^-$ read-out. The optimal threshold current results in a visibility of $V = 99.6\%$ for the $D^+ \leftrightarrow D^0$ read-out and $V = 97.4\%$ for the $D^0 \leftrightarrow D^-$ read-out. (c) Histogram of the start time of the single current pulse during the $D^+ \leftrightarrow D^0$ read-out. From the counts after a time $t_1 = 100$ ms where all $|\uparrow\rangle$ electrons have tunneled from the donor we estimate the $|\downarrow\rangle$ tunnel out time to be $\tau_{\downarrow,\mathrm{out}} = 24 \pm 4$ s. (d) From a similar histogram for the $D^0 \leftrightarrow D^-$ read-out we find $\tau_{\uparrow,\mathrm{in}} = 145 \pm 9$ ms.

read-out this results in a finite probability, α, for a $|\downarrow\rangle$ electron to tunnel from the donor to the SET and to be incorrectly assigned as $|\uparrow\rangle$. This can be estimated by counting tunneling events after a time t_1 where all the $|\uparrow\rangle$ electrons have tunnelled from the donor, $t_1 \gg \tau_{\uparrow,\mathrm{out}}$ [Fig. 4(c)]. During the read-out, 44 out of the 3125 ($50\% \times 6250$) $|\downarrow\rangle$ electrons tunnel from the donor between the times $t_1 = 100$ ms and $t_2 = 450$ ms. Therefore, an estimate of the tunnel time $\tau_{\downarrow,\mathrm{out}}$ can be found by solving $\exp(-t_1/\tau_{\downarrow,\mathrm{out}}) - \exp(-t_2/\tau_{\downarrow,\mathrm{out}}) = (44 \pm \sqrt{44})/3125$, which gives $\tau_{\downarrow,\mathrm{out}} = 24 \pm 4$ s. For an optimized read-out time $\Delta t = 55$ ms we find $\alpha = 1 - \exp[-(\Delta t/\tau_{\downarrow,\mathrm{out}})] = 0.3\%$. In the experiment we significantly reduced α from $\sim 2\%$ to 0.3% by increasing $\tau_{\downarrow,\mathrm{out}}$ through positioning the $|\downarrow\rangle$ electrochemical potential of the donor the maximum energy below the thermally broadened Fermi level of the SET while still maintaining read-out [see inset of Fig. 4(c)].

This analysis is repeated for the $D^0 \leftrightarrow D^-$ read-out. Here, tunneling of a $|\uparrow\rangle$ electron to the donor now results in the incorrect assignment of a $|\downarrow\rangle$ electron. From the histogram shown in Fig. 4(d) we find $\tau_{\uparrow,\mathrm{in}} = 145 \pm 9$ ms giving $\alpha = 0.7\%$ for an optimized read-out time of $\Delta t = 1$ ms. Together with the above electrical fidelities this gives an average measurement fidelity [35] for the $D^+ \leftrightarrow D^0$ and $D^0 \leftrightarrow D^-$ spin read-out of $F_M = [(1-\alpha)F_\downarrow + F_\uparrow]/2 = 99.6\%$ and $F_M = 98.4\%$, respectively. This demonstrates extremely high measurement fidelities in read-out with two significantly different tunnel rates.

In addition to being able to rapidly measure the spin state of the qubit with high fidelity, the rapid initialization of a qubit into a defined state is a further key requirement for scalable quantum computing as quantum error correction requires a continuous supply of ancilla qubits which can be initialized much faster than the qubit coherence time [36]. For electron spin qubits, one method to initialize spins is to perform spin read-out as described above as it naturally leaves electron spins in their $|\downarrow\rangle$ ground state. The initialization fidelity F_I of the $D^+ \leftrightarrow D^0$ read-out can be determined by modeling the occupation probability of the donor with the following rate equations,

$$\dot{p}_\downarrow(t) = -\frac{1}{\tau_{\downarrow,\mathrm{out}}} p_\downarrow(t) + \frac{1}{\tau_{\downarrow,\mathrm{in}}} p_0(t) + \frac{1}{T_1} p_\uparrow(t), \quad (1)$$

$$\dot{p}_\uparrow(t) = -\frac{1}{\tau_{\uparrow,\mathrm{out}}} p_\uparrow(t) + \frac{1}{\tau_{\uparrow,\mathrm{in}}} p_0(t) - \frac{1}{T_1} p_\uparrow(t), \quad (2)$$

where p_0 is the probability that the donor is unoccupied and $p_\downarrow(t)$ [$p_\uparrow(t)$] is the probability of the donor being occupied with a $|\downarrow\rangle$ ($|\uparrow\rangle$) spin. The sum of these probabilities is $p_0 + p_\downarrow + p_\uparrow = 1$. The $|\uparrow\rangle$ tunnel in time $\tau_{\uparrow,\mathrm{in}} = 5.4 \pm 0.6$ ms was extracted from a histogram of the duration of the first current pulse in read-out traces with multiple current pulses. Multiple pulses in the current signal are a result of a $|\uparrow\rangle$ electron tunneling back onto the donor after a $|\uparrow\rangle$ spin has tunneled from the donor due to thermal broadening in the SET. Solving this system of coupled differential equation with initial conditions $p_0(0) = 0\%$, $p_\downarrow(0) = 50\%$, and $p_\uparrow(0) = 50\%$, we find the $|\downarrow\rangle$ probability saturates to $F_I = p_\downarrow = 99.9\%$ after a time $t = 100$ ms. From similar rate equations for the $D^0 \leftrightarrow D^-$ read-out we find $F_I = 99.8\%$ after a time $t = 3$ ms, demonstrating a method for high-fidelity rapid initialization of spin qubits.

In conclusion, we have demonstrated single-shot spin read-out via the D^- charge state of a precision placed single donor. With faster qubit read out by nearly 2 orders of magnitude, we achieve read-out fidelities, $F_M = 98.4\%$, which are only marginally reduced from the measured record fidelity, $F_M = 99.6\%$, using conventional spin read-out. Furthermore, the D^- read-out is a fast method for high-fidelity ($F_I = 99.8\%$) qubit initialization. This number is above the threshold of error correction protocols such as the surface code and may further be improved through efforts to lower the electron temperature and reduce measurement noise.

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