A single–atom electron spin qubit in silicon

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A single atom is the prototypical quantum system, and a natural candidate for a quantum bit, or qubit—the elementary unit of a quantum computer. Atoms have been successfully used to store and process quantum information in electromagnetic traps, as well as in diamond through the use of the nitrogen–vacancy-centre point defect2. Solid-state electrical devices possess great potential to scale up such demonstrations from few-qubit control to larger-scale quantum processors. Coherent control of spin qubits has been achieved in lithographically defined double quantum dots in both GaAs (refs 3–5) and Si (ref. 6). However, it is a formidable challenge to combine the electrical measurement capabilities of engineered nanostructures with the benefits inherent in atomic spin qubits. Here we demonstrate the coherent manipulation of an individual electron spin qubit bound to a phosphorus donor atom in natural silicon, measured electrically via single-shot readout7–9. We use electron spin resonance to drive Rabi oscillations, and a Hahn echo pulse sequence reveals a spin coherence time exceeding 200 μs. This time should be even longer in isotopically enriched^{28}Si samples10,11. Combined with a device architecture12 that is compatible with modern integrated circuit technology, the electron spin of a single phosphorus atom in silicon should be an excellent platform on which to build a scalable quantum computer.

There have been a number of proposals for the implementation of a spin-based qubit in silicon13, though none have been studied in as much detail as the phosphorus atom qubit14. This interest has been motivated by the knowledge, developed over half a century from electron spin resonance experiments on bulk-doped phosphorus in silicon15, that spin coherence times can be exceptionally long, exceeding seconds11. This is due to the availability of silicon in an enriched nuclear spin-zero (^{28}Si) form, as well as the low spin-orbit coupling in silicon15. The use of donor electron spins has further advantages of consistency (because each atom is identical) and tuneability (for example, through the Stark shift16), and the donor atom’s nuclear spin can be employed as a quantum memory for longer term storage17.

Using methods compatible with existing complementary metal-oxide-semiconductor (CMOS) technology, we fabricated a nanostructure device on the SiO2 surface to enable read-out and control of an electron spin18 (Fig. 1a). In this work, the donor is intentionally implanted into the silicon substrate, with future options including the use of deterministic ion implantation18 or atomic precision in donor placement through scanning probe lithography19. The device is placed in a magnetic field of approximately 1 T, yielding well-defined electron spin–down and spin–up states (|胱⟩ and |＃⟩).

Transitions between the electron |胱⟩ and |＃⟩ states are driven by an oscillating magnetic field generated by applying microwaves to an on-chip broadband transmission line20. By operating at a high magnetic field and low temperature (T_{\text{electronic}} \approx 300 \text{mK}), we can detect these transitions through single-shot projective measurements on the electron spin with a process known as spin-to-charge conversion7,8. Here the donor electron is both electrostatically coupled and tunnel-coupled to the island of a single electron transistor (SET), with the SET serving as both a sensitive charge detector and an electron reservoir for the donor. Using gates PL and TG (Fig. 1a) to tune the electrochemical potentials of the donor electron spin states (μ_e and μ_n for states |胱⟩ and |＃⟩) and the Fermi level in the SET island (μ_{SET}), we can discriminate between a |胱⟩ or |＃⟩ electron as well as perform electrochemical initialization of the qubit, following the procedure introduced in ref. 8.

Our experiments use a two-step cyclical sequence of the donor potential, alternating between spin read-out/initialization phase and a coherent control phase (see Supplementary Video). The qubit is first initialized in the |胱⟩ state through spin-dependent loading by satisfying the condition μ_e < μ_{SET} < μ_n (Fig. 1b). After this, the system is brought into a regime where the spin is a stable qubit (μ_e, μ_n < μ_{SET}) and manipulated with various microwave pulse schemes resonant with the spin transition (Fig. 1c). The spin is then read out electrically via spin-to-charge conversion (Fig. 1b), a process which produces a pulse in the current through the SET (that is, I_{SET}) if the electron was |＃⟩, and leaves the qubit initialized |胱⟩ for the next cycle.

The electron spin resonance frequency can be extracted from the spin Hamiltonian describing this system (see also Fig. 1d):

\[ H = γ_e B_0 S_z - γ_n B_0 I_z + AS · I \]

where γ_e (or γ_n) is the gyromagnetic ratio of the electron (or nucleus), B_0 is the externally applied magnetic field, S (or I) is the electron (or nuclear) spin operator with z-component S_z (or I_z) and A is the hyperfine constant. If γ_e B_0 ≫ A, the states shown in Fig. 1d are good approximations for the eigenstates of equation (1). Allowed transitions involving flips of the electron spin only (identified by arrows in Fig. 1d) exhibit resonance frequencies that depend on the state of the ^{31}P nuclear spin: v_{e1} = γ_e B_0 - A/2 for nuclear spin–down; and v_{e2} = γ_e B_0 + A/2 for nuclear spin–up. The transition frequencies v_{e1} and v_{e2} are found by conducting an electron spin resonance (ESR) experiment21, which is described in the Supplementary Information.

To demonstrate coherent control, we apply a single microwave pulse of varying duration t_p to perform Rabi oscillations of the electron spin. For each t_p, the cyclic pulse sequence (Fig. 1e, f) is repeated 20,000 times, first with a microwave frequency v_{e1}, and immediately after at v_{e2}. It is necessary to pulse on both ESR transitions as the ^{31}P nuclear spin can flip several times during acquisition of the data in Fig. 2a. Figure 1g displays single-shot traces of the SET output current I_{SET} for four consecutive repetitions of the measurement sequence, for an arbitrary pulse length. A threshold detection method8 is used to determine the fraction of shots that contain a |＃⟩ electron for the measurements at both frequencies. Figure 2a shows the electron spin-up fraction f_{B1} as a function of the microwave pulse duration for different applied powers P_{ESR}. The fits through the data are derived from simulations assuming Gaussian fluctuations of the local field (see Supplementary Information). Confirmation that these are Rabi oscillations comes from the linear dependence of the Rabi frequency with the applied microwave amplitude (P_{ESR}^{1/2}), that is, f_{Rabi} = γ_e B_1. Here B_1 is taken as half of the total linear oscillating magnetic field amplitude generated by the transmission line at the site of the donor.
assumed the rotating-wave approximation. Figure 2b shows the expected linear behaviour with microwave amplitude of the Rabi frequency extracted from the data in Fig. 2a. The largest Rabi frequency attained was 3.3 MHz ($B_1 \approx 0.12$ mT), corresponding to a $\pi/2$ rotation in about 75 ns.

The qubit manipulation time should be contrasted with the coherence lifetime of the qubit, termed $T_2$. Possible sources of decoherence include spectral diffusion of the $^{29}$Si bath spins, noise in the external magnetic field, and paramagnetic defects and charge traps at the Si/SiO$_2$ interface. These mechanisms can, to a degree, be compensated for by using spin echo techniques (Fig. 3a), as long as the fluctuations are slow compared with the electron spin manipulation time (typically around 100 ns).

Figure 3a presents the gate voltage and microwave pulsing scheme for a Hahn echo measurement. Dephasing resulting from static local contributions to the total effective field during an initial period $\tau_1$ is (partially or fully) refocused by a $\pi$ rotation followed by a second period $\tau_2$ (see Fig. 3c for a Bloch sphere state evolution). A spin echo is observed by varying the delay $\tau_2$ and recording the spin–up fraction. In Fig. 3e we plot the difference in delay times ($\tau_2 - \tau_1$) against $f_1$. For $\tau_1 = \tau_2$, we expect to recover a $|\uparrow\rangle$ electron at the end of the sequence if little dephasing occurs (that is, for short $\tau$), and hence observe a minimum in $f_1$. When $\tau_2 - \tau_1 \neq 0$, imperfect refocusing results in an increase in the recovered spin-up fraction. The echo shape is approximated as being Gaussian and the half-width at half-maximum implies a pure dephasing time of $T_2^\ast = 55 \pm 5$ ns.

We now set $\tau = \tau_1 = \tau_2$ and monitor the spin–up fraction as a function of $\tau$, to obtain the spin echo decay curve of Fig. 3f. A fit of the form
\[ y = \exp\left(-\frac{2t}{T_2}\right) \]

where \( T_2 \) and \( b \) are free parameters, yields \( T_2 = 206 \pm 12 \mu s \) and \( b = 2.1 \pm 0.4 \). The coherence time \( T_2 \) is almost a factor of 2,000 times longer than \( T_2^* \), and is remarkably close to the value (300 \( \mu s \)) measured in bulk-doped natural silicon samples\(^{25}\).

Variations in \( T_2 \) can be expected, depending on the exact distribution of \(^{29}\)Si nuclei within the extent of the donor electron wavefunction. This indicates that the presence of a nearby SET and the close proximity of the Si/SiO\(_2\) interface have little, if any, effect on the electron spin coherence. This is not entirely surprising, because paramagnetic centres at the Si/SiO\(_2\) interface are expected to be fully spin-polarized under our experimental conditions \( g_{\text{eff}}B_0 \gg k_BT \) (where \( g \) is the donor electron Landé \( g \)-factor, \( \mu_B \) is the Bohr magneton and \( k_B \) is the Boltzmann constant), leading to an exponential suppression of their spin fluctuations\(^{29}\). Direct flip-flop transitions between the donor qubit and nearby interface traps are suppressed by the difference in \( g \)-factor (\( g = 1.9985 \) for the donor, \( g > 2 \) for the traps\(^{21}\)), whereas dipolar flip-flops with nearby donors\(^{27}\) can appear as a \( T_2^* \) process\(^8\) on a much longer timescale. We measured \( T_2^* = 0.7 \pm 0.05 \) \( \mu s \) at \( B_0 = 2.5 \)T (data not shown), implying that this process has no bearing on \( T_2 \). The echo decay is Gaussian in shape \((b = 2.1 \pm 0.4)\), consistent with decoherence dominated by \(^{29}\)Si spectral diffusion\(^{22}\).

We have extended the coherence time by applying an XXYY dynamical decoupling ESR pulse sequence\(^{28}\) (Fig. 3b and d). This sequence substitutes the single \( \pi \) rotation of the Hahn echo with a series of four \( \pi \) rotations alternating about the X and Y axes, achieved by applying adjacent \( \pi \) pulses that are 90° out of phase. The resulting echo decay is shown in Fig. 3f, with a fit to the data yielding \( T_2 = 410 \pm 20 \mu s \) and \( b = 2.1 \pm 0.4 \). As well as representing a factor-of-two improvement in \( T_2 \), the XXYY sequence demonstrates the ability to perform controlled rotations about two orthogonal axes on the Bloch sphere (X and Y), permitting arbitrary one-qubit gates for universal quantum computing\(^{29}\).

Next we consider the fidelity of our electron spin qubit, broken down into three components: measurement, initialization and control. The measurement fidelity \( F_M \) comprises errors resulting from detection limitations of the experimental set-up as well as thermally induced read-out events. The electrical spin-down and spin-up read errors \((\gamma_+ \text{ and } \gamma_- \text{ respectively})\) arise from a finite measurement bandwidth and signal-to-noise ratio. They depend on the threshold current \( I_T \) used for detecting the spin-up pulses. Figure 4a shows the results of a numerical model based on our experimental data (see Supplementary Information for details), where \( \gamma_+ \) and \( \gamma_- \) are plotted as a function of \( I_T \).

At \( I_T = 370 \) pA we achieve a best-case error of \( \gamma = \gamma_+ + \gamma_- = 18\% \).

Thermal broadening of the Fermi distribution in the SET island produces the read/load errors, as depicted in Fig. 4b. The process of a spin-down electron tunnelling into an empty state in the SET occurs with a probability \( z \), whereas \( \beta \) denotes the probability of incorrectly initializing the qubit in the spin-up state. The parameters \( z \) and \( \beta \) are sensitive to the device tuning and can vary slightly between measurements. We have extracted \( z \) and \( \beta \) from simulations of the Rabi oscillations in Fig. 2a, and for \( P_{\text{SET}} = 10 \)dBm we find \( z = 28 \pm 1\% \) and \( \beta = 1.5 \pm 0.2\% \). This gives an average measurement fidelity for the electron spin-up and spin-down states of \( F_M = 1 - (\gamma + \beta + \sqrt{\gamma \beta}) \approx 0.77 \pm 2\% \) and an initialization fidelity \( F_I \) of at least 90\% (see Supplementary Information for full details).

The qubit control fidelity \( F_C \) is reduced by random field fluctuations from the \(^{29}\)Si nuclear bath spins. These produce an effective field \( B_{\text{eff}} \) in the rotating frame that is tilted out of the X–Y plane (Fig. 4d), and lead to imperfect pulses. We now estimate the strength of these fluctuations. Figure 4c presents a series of ESR spectra, where the electron spin-up fraction is monitored as a function of the microwave frequency. The top three traces of Fig. 4c contain individual sweeps with each point obtained over a timescale of around 250 ms. We attribute the shift in peak position between sweeps to slow fluctuations of a few strongly coupled \(^{29}\)Si nuclei, with hyperfine coupling strengths of the order of 1 MHz. The width of the peaks is most probably the result of

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**Figure 3 | Coherence time and dynamical decoupling.** a and b, Pulse protocols for the Hahn echo (a) and XXYY dynamical decoupling (b) sequences with accompanying PL gate voltage waveforms, as described in the main text. The rotation angles are displayed above each pulse in brackets, with the subscript \((X\) or \( Y\)) denoting the axis on the Bloch sphere about which the rotation is applied. The read initialization time is 1 ms. All measurements were performed at \( B_0 = 1.07 \) T and with \( P_{\text{SET}} = 10 \)dBm, where a \( \pi/2 \) rotation takes around 75 ns. c and d, Bloch sphere representation of the evolution in the rotating frame for the Hahn echo (c) and XXYY (d) sequences. The green arrow represents the initial spin state \(|\uparrow\rangle\), while the grey arrow represents the final state for the case when the second \( \pi/2 \) pulse is about \( X \) (\( Y \) is not shown). The purple path represents dephasing in between pulses, the orange path represents a rotation about \( X \), and the blue path is a rotation about \( Y \). We have included rotation angle errors of \( 5^\circ \) and \( 15^\circ \) for the \( \pi/2 \) and \( \pi \) pulses respectively. e, An echo curve, obtained by applying the depicted pulse sequence with a fixed \( t_1 \) (= 10 ms) and varying \( t_2 \). Each point represents the electron spin-up fraction \( f_e \), calculated from 50,000 single shots acquired at both ESR frequencies \( f_{\text{r1}} = 29.886 \text{ GHz} \) and \( f_{\text{r2}} = 30.000 \text{ GHz} \) and summed. The fit in red is Gaussian and of the form \( f_e = \exp((-t/T_2)*f) \). F, Hahn echo (or XXYY dynamical decoupling) decay in red circles (or blue squares), measured via simulated quadrature detection (the Methods for details). A fit through the data is given by \( y = \exp((-N/t/T_2^*)f) \), where \( N = 2 \) (or \( N = 8 \)) for the Hahn echo (or XXYY dynamical decoupling) experiment. Parameter values are discussed in the main text.
now demonstrated in silicon, the advances reported here open the way for a spin-based quantum computer using single atoms, as first envisaged by Kane\(^\text{14}\) more than a decade ago.

**METHODS SUMMARY**

Device fabrication and experimental set-up. For information relating to the device fabrication and experimental set-up, see the Supplementary Information.

Simulated quadrature detection for \(T_\text{e}\) measurements. For each \(t = t_1 = t_2\) (the Hahn echo), the sequence of Fig. 3a (or Fig. 3b) is repeated 30,000 times (or 75,000 times) for the Hahn echo (or XXXY dynamical decoupling) measurement at both \(t_1\) and \(t_2\), and for \(X\) and \(Y\) phases of the final \(\pi/2\) rotation. The resulting signal amplitude is given by \(f(t_{\text{SET}}) - f(t_{\text{SET}} + t) + f(t_{\text{SET}}) - f(t_{\text{SET}} + t)\), where \(f(t_{\text{SET}} + t)\) represents the electron spin-up fraction of the single-shot traces taken at \(t_{\text{SET}}\) with a final \(\pi/2\) pulse about the \(Y\)-axis, and so on.

Received 16 May; accepted 27 July 2012.

Published online 19 September 2012.

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**Figure 4**  Qubit fidelity analysis. a, Electrical read-out errors generated from a numerical model. The red curve gives the error \(\gamma\) involved in identifying a \(|\uparrow\rangle\) electron as a function of the threshold current \(I_t\), caused by noise in \(I_{\text{SET}}\) exceeding \(I_t\). The blue curve represents the error \(\gamma\) for detecting a \(|\downarrow\rangle\) electron, which occurs as a result of detection bandwidth limitations and a finite \(|\downarrow\rangle\) \(I_{\text{SET}}\) pulse height. The dashed curve depicts the combined electrical error, \(\gamma = \gamma_\uparrow + \gamma_\downarrow\). b, Mechanisms by which read (top) and load (bottom) errors are produced as a result of thermal broadening in the SET island (discussed in the main text). The solid circles represent full electron states with spin indicated by the arrow, while the empty circles signify unoccupied states. c, Sweeps of the frequency \(\nu_{\text{ESR}}\) in the vicinity of the nuclear spin-up ESR transition \(\nu_{\text{ESR}}\). The top three traces are individual sweeps where \(f_i\) at each \(I_{\text{SET}}\) is calculated from 250 single-shot measurements. The bottom trace is an average of 100 sweeps. d, Illustration of the rotation errors created by hyperfine field fluctuations of the \(\text{^{29}Si}\) nuclear bath. For simplicity, only the Z-component of the hyperfine field has been shown. The bath nuclear spins produce an offset from resonance, \(\Delta B\), which causes rotations around a new axis aligned with \(\Delta B\).

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\(^{28}\text{Si}\) nuclear spins that fluctuate on the single-shot timescale (see Supplementary Information for further discussion). The bottom trace of Fig. 4c contains an average of 100 sweeps, representing many nuclear spin configurations. From this we extract a full-width at half-maximum \(\Delta \nu = 7.5 \pm 0.5\) MHz. This is consistent with the observed \(T_{\text{e}}^\text{a}\), where \(\Delta \nu = 1/4(\pi T_{\text{e}}^\text{a}) = 6 \pm 1\) MHz. To calculate the rotation angle error, we simulate a Rabi experiment assuming the largest \(B_0\) achieved (0.12 mT) and Gaussian fluctuations of the nuclear bath with a standard deviation of \(\sigma = \Delta \nu / (2 \sqrt{2 \ln (2)}) = 3.2 \pm 0.2\) MHz (see Supplementary Information). From this we infer an average tip angle of \(102 \pm 3\)° for an intended \(\pi\) rotation, corresponding to an average control fidelity of \(F_c = 57 \pm 2\%\).

The processes that contribute to the measurement, initialization and control fidelity degradation can be mitigated with foreseeable adjustments to the device architecture and experimental set-up. Significant improvements in the read/load errors would follow from enhanced electrical filtering to lower the electron temperature, thus enabling the high read-out fidelities (>90%) already achieved\(^8\). Moving to an enriched \(^{28}\text{Si}\) (nuclear spin-zero) substrate\(^9\) would remove the primary source of rotation angle error, and allow for the exceptional coherence times already demonstrated in bulk-doped samples\(^11\).

Future experiments will focus on the coupling of two donor electron spin qubits through the exchange interaction\(^14\), a key requirement in proposals for scalable quantum computing architectures in this system\(^10\). Taken together with the single-atom doping technologies\(^18,19\),
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Supplementary Information is available in the online version of the paper.

Acknowledgements We thank R. P. Starrett, D. Barber, C. Y. Yang and R. Szymanski for technical assistance. We also thank A. Laucht for the Bloch sphere artwork and D. Reilly for comments on the manuscript. This research was funded by the Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology (project number CE11E0096) and the US Army Research Office (W911NF-08-1-0527). We acknowledge support from the Australian National Fabrication Facility.

Author Contributions K.Y.T. and W.H.L. fabricated the device; D.N.J. designed the phosphorus implantation experiments; J.J.P., K.Y.T., J.J.L.M. and J.P.D. performed the measurements; J.J.P., A.M., A.S.D. and J.J.L.M. designed the experiments and discussed the results; J.J.P. analysed the data; J.J.P. wrote the manuscript with input from all co-authors.

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