Fidelity benchmarks for two-qubit gates in silicon

W. Huang1*, C. H. Yang1, K. W. Chan1, T. Tanttu1, B. Hensen1, R. C. C. Leon1, M. A. Fogarty1,2, J. C. C. Hwang1, F. E. Hudson1, K. M. Itoh3, A. Morello1, A. Laucht1 & A. S. Dzurak1*

Universal quantum computation will require qubit technology based on a scalable platform1, together with quantum error correction protocols that place strict limits on the maximum infidelities for one- and two-qubit gate operations1–3. Although various qubit systems have shown high fidelities at the one-qubit level4–10, the only solid-state qubits manufactured using standard lithographic techniques that have demonstrated two-qubit fidelities near the fault-tolerance threshold10 have been in superconductor systems. Silicon-based quantum dot qubits are also amenable to large-scale fabrication and can achieve high single-qubit gate fidelities (exceeding 99.9 per cent) using isotopically enriched silicon11,12. Two-qubit gates have now been demonstrated in a number of systems13–18, but as yet an accurate assessment of their fidelities using Clifford-based randomized benchmarking, which uses sequences of randomly chosen gates to measure the error, has not been achieved. Here, for qubits encoded on the electron spin states of gate-defined quantum dots, we demonstrate Bell state tomography with fidelities ranging from 80 to 89 per cent, and two-qubit randomized benchmarking with an average Clifford gate fidelity of 94.7 per cent and an average controlled-rotation fidelity of 98 per cent. These fidelities are found to be limited by the relatively long gate times used here compared with the decoherence times of the qubits. Silicon qubit designs employing fast gate operations with high Rabi frequencies16,17, together with advanced pulsing techniques18, should therefore enable much higher fidelities in the near future.

Silicon-based qubits are amenable to large-scale manufacture thanks to their compatibility with industrial manufacturing technologies. Furthermore, silicon (Si) provides an ideal environment for spin qubits in the near-perfect nuclear-spin vacuum that isotopically enriched 28Si provides11. Qubits can be encoded directly on the spins of individual nuclei, donor-bound electrons, or electrons confined in gate-defined quantum dots, or they can be encoded in subspace provided by two or more spins12. Electrostatic gate electrodes allow initialization, readout19 and, in some cases, manipulation of qubits20 to be implemented with local electrical pulses. For qubits encoded on single spins, single-qubit gates can be driven using an oscillating magnetic field to perform electron spin resonance (ESR) directly10,16,17, through an oscillating electric field produced by a gate electrode combined with the magnetic field gradient from an on-chip micro-magnet16,17,22, or with an alternating-current electric field acting on the spin–orbit field23–27. In enriched 28Si devices such single-qubit gates have attained high fidelities of 99.9% or above16,17,28.

Two-qubit gates, required to complete the universal gate set, are commonly implemented in spin systems such as the SWAP20,29, the controlled phase13,14 or the controlled rotation (CROT)13,15. While the SWAP and controlled-phase gates require fast temporal control of the exchange interaction J, accurately synchronized with spin resonance pulses, the CROT can be implemented30 with constant J, alleviating the need for high-bandwidth gate-electrode voltage pulses. However, although two-qubit gates have been demonstrated in silicon13–15, it has not yet been possible to rigorously assess their fidelities using randomized benchmarking, because this requires sequences of large numbers of qubit operations (exceeding 20) to be completed without non-vanishing fidelity. Here, in a silicon double-quantum-dot system, we show how the full two-qubit Clifford gate set can be constructed entirely using ESR pulses in the presence of constant exchange coupling, and we use this to perform both Bell state tomography and Clifford-based randomized benchmarking, providing a detailed analysis of two-qubit gate fidelities in a silicon-based system.

Figure 1a shows a scanning electron microscope image of a silicon-metal-oxide-semiconductor double-quantum-dot device, nominally identical to the one measured and similar to the one that we previously used to demonstrate a two-qubit logic gate17. The device was fabricated on a natural silicon substrate with a 900-nm thick isotopically enriched 28Si epi-layer (residual 29Si concentration of 800 parts per million11). Aluminium gate electrodes were fabricated using multi-layer gate stack technology. Quantum dots D1 and D2 are formed underneath gates G1 and G2; however, the exact dot centre positions can be influenced by local strain fields in the device. The tunnelling rate between the dots and the reservoir (yellow feature labelled RG in Fig. 1d) can be modified by adjusting the voltages on G3 and G4 (grey). An external magnetic field \( B_0 = 1.42 \, T \) creates a Zeeman splitting of \( E_Z = g_\mu_B B_0 \approx 16.1 \, \text{meV} \), corresponding to an ESR frequency \( f = E_Z / h = 39.33 \, \text{GHz} \), where \( g \) is the electron g-factor, \( \mu_B \) is the Bohr magneton and \( h \) is Planck’s constant. When operating the device in a dilution refrigerator at an electron temperature of \( T_e \approx 100 \, \text{mK} \), the energy gap between the spin-up and the spin-down states allows us to read the electron spin state via spin-dependent tunnelling19 and selectively load a spin-down electron for initialization. An on-chip ESR antenna (light blue) creates the oscillating magnetic field \( B_1 \) to perform qubit operations.

Figure 1b, c shows charge-stability diagrams of the double quantum dot system comprising dots D1 and D2, recorded by measuring the current through the single-electron transistor charge sensor with a double lock-in technique. The charge occupancies of D1 and D2 are labelled \( (N_1, N_2) \). Our two-qubit system operates in the sequence schematically depicted in Fig. 1d, e.

During microwave control, when operating the device deep in the (1, 1) charge stability region, the system can be described by a Hamiltonian in a diagonalized basis \( (\uparrow\uparrow, \uparrow\downarrow, \downarrow\uparrow, \downarrow\downarrow) \):

\[
H = \frac{1}{2} \begin{pmatrix}
2\tilde{E}_Z & \gamma_1 B_1 & \gamma_1 B_1 & 0 \\
\gamma_1 B_1 & 0 & -\delta E_Z - J & \gamma_2 B_1 \\
\gamma_1 B_1 & -\delta E_Z - J & 0 & \gamma_1 B_1 \\
0 & \gamma_2 B_1 & \gamma_2 B_1 & -2\tilde{E}_Z
\end{pmatrix}
\]

Here, \( \gamma_1 \) (or \( \gamma_2 \)) is the effective gyromagnetic ratio that couples qubit \( n \) to the oscillating magnetic field \( B_1 \) created by the ESR antenna when the other qubit is in the \( \downarrow \) (or \( \uparrow \)) state. \( J \) is the exchange coupling, \( \tilde{E}_Z \) is the average Zeeman energy, and \( \delta E_Z = \frac{1}{2} (E^{\uparrow\uparrow}_Z + E^{\down\down}_Z) \) is the normalized difference in Zeeman energies. The corresponding energy spectrum is shown in Fig. 2a. We extract a difference in Zeeman energy for...
Letter research

and measure the spin-up probability probed by the SET current. The energy level diagram (inset) maps each peak to the corresponding target qubit conditional on the state of the control qubit (CROT signal). Fig. 2 providing us with independent control over the two qubits. In addition, face roughness, mediated by spin–orbit coupling 25. This splitting is the two qubits of quantum dots. RG (yellow) is the reservoir gate that supplies electrons purple), G3 and G4 (grey) form confinement barriers that laterally define are formed underneath gates G1 (blue) and G2 (red). The gates CB (dark electron to a spin relaxation hotspot 33 (H) close to the (0, 1)-to-(1, 0) anti-biasing to the (0, 0)-to-(0, 1) transition (I1) for 2.75 ms. (ii) Move the readout. (i) Load a spin-down electron from the reservoir into D2 by frequency 1.1 MHz for Bell state tomography and f to improve the initialization fidelity 14. (vii) Transfer the qubit Q1 from dot D1 to D2 by adiabatically sweeping through the (1, 0)-to-(0, 1) anti-crossing within 5 μs, which is fast enough to avoid relaxation at the hotspot14. (vii) Read out Q1 at the (0, 0)-to-(0, 1) transition (R1) for 2.75 ms. This concludes the operational sequence. In our devices, performing readout by shuttling Q1 from D1 to D2 is advantageous over reading out Q1 at the (1, 0)-to-(0, 0) transition directly, owing to the slow tunnelling rate from D1 to the reservoir.

Fig. 1 | Two-qubit device layout and operation. a. False-colour scanning electron microscope image of the device. Two quantum dots, D1 and D2, are formed underneath gates G1 (blue) and G2 (red). The gates CB (dark purple), G3 and G4 (grey) form confinement barriers that laterally define the quantum dots. RG (yellow) is the reservoir gate that supplies electrons to the quantum dots. The gate electrodes ST, SLB and SRB (green) define a single-electron transistor (SET), designed to sense charge movement in the quantum dot region. An alternating current running through the SET line (light blue) generates an oscillating magnetic field to manipulate the electron spins. The direction of the external magnetic field B0 is indicated by the white arrow. b–e. Control path in the charge-stability diagram as a function of the G1 (G2) voltage Vg1 (Vg2) with charge state (N1, N2) probed by the SET current ISET, and schematic depicting initialization and readout. (i) Load a spin-down electron from the reservoir into D2 by biasing to the (0, 0)-to-(0, 1) transition (I1) for 2.75 ms. (ii) Move the electron to a spin relaxation hotspot 33 (H) close to the (0, 1)-to-(1, 0) anti-crossing and keep it there for 300 μs to improve the initialization fidelity 14. Then transfer the electron to D1 by moving it through the anti-crossing.

The two qubits of $\hbar \omega_J / \hbar = 13.26 \text{MHz}$ at $B_0 = 1.42 \text{T}$, which arises from $g$-factor variations due to local electric field gradients and Si/SiO2 interface roughness, mediated by spin–orbit coupling 25. This splitting is around 30 times greater than our typical Rabi frequency of 500 kHz, providing us with independent control over the two qubits. In addition, the exchange coupling $J$ further splits both resonance frequencies, providing us with conditional control of one qubit dependent on the state of the other qubit. $J$ is tunable via gates G1 and G2 (see Supplementary Figs. 1, 2), but we keep it constant during our control sequences $J / \hbar = 1.06 \text{MHz}$ for Bell state tomography and $J / \hbar = 1.59 \text{MHz}$ for

Fig. 2 | Independent and conditional two-qubit control. a. ESR spectra of the two-qubit system. Here the peaks are power-broadened and the linewidths are given by the respective Rabi frequencies. We prepare $|Q_1, Q_2\rangle$ in either $|\uparrow\uparrow\rangle$, $|\uparrow\downarrow\rangle$ or $|\downarrow\downarrow\rangle$ and measure the spin-up probability of Q1 and Q2 as a function of the applied microwave frequency. Four distinct ESR peaks arise owing to the presence of a finite exchange coupling $J$ and a Zeeman energy difference $\Delta E_z$, centred around $f = \Delta E_z / \hbar = 39.33 \text{GHz}$. Each resonance peak represents a rotation of the target qubit conditional on the state of the control qubit (CROT signal). The energy level diagram (inset) maps each peak to the corresponding transition between a pair of qubit eigenstates. B. Controlled qubit rotations are naturally implemented by pulsing at individual resonance frequencies. A first pulse $U_1$ performs Rabi rotations on Q2 that result in the resonance frequency of Q1 oscillating between $f_{g1}$ and $f_{g1}$. C. Independent qubit control can be achieved under the presence of constant exchange interaction $J$ by applying microwave pulses at the two conditional frequencies simultaneously. A first pulse at $U_1^\dagger U_1^\dagger$ defines the state Q1. A second pulse $U_2^\dagger U_2^\dagger$ then rotates Q2, independent of the state of Q1.
Letter

We note that the $Z/2$ gates in the quantum circuits compensate for the phase difference between the experimental CROT gate and the schematic CNOT gate. The Bell states are created by a single-qubit $X_{24}$ gate followed by a CROT gate ($|\psi^+\rangle$, $|\psi^-\rangle$) or Z-CROT gate ($|\psi^{+}\rangle$, $|\psi^{-}\rangle$) that includes a $Z_{2}$ gate for $|\psi^+\rangle$ and $|\psi^-\rangle$. One of four pre-measurement rotations $R_p = \{I, X/2, -X/2, Y/2\}$ is performed to project the state of each qubit into the $Z$, $Y$, $X$ and $X$ bases to reconstruct the density matrices.

Quantum state tomography of the Bell states. The heights of the bars represent the absolute values of the density matrix elements after readout error correction. The phase information in the state reconstruction is encoded in the colour of the bars according to the colour diagram on the left.

Table of Bell state fidelities and concurrences.

The fidelities reported here are comparable to the those reported (78% in ref. 13 and 85%–89% in ref. 14). Our Bell state fidelities are noticeably lower than those expected from the randomized benchmarking results (below), which we attribute in part to systematic sequence errors (see Methods).

Fig. 3b Quantum state tomography of the Bell states. The heights of the bars represent the absolute values of the density matrix elements after readout error correction. The phase information in the state reconstruction is encoded in the colour of the bars according to the colour diagram on the left.
leaving $r_C$ as the error per Clifford gate. We obtain a Clifford gate fidelity of $F_{\text{Clifford}} = 1 - r_C = 94.7\% \pm 0.8\%$, and a primitive gate fidelity of $F_{\text{primitive}} = 98.0\% \pm 0.3\%$. As all primitive gates are very similar in construction, we expect the fidelity of the entangling CROT gate to be very close to the average primitive fidelity.

Two-qubit randomized benchmarking is much more sensitive to decoherence than single-qubit randomized benchmarking (see Extended Data Fig. 1 and Extended Data Table 2). In single-qubit randomized benchmarking, the qubit is almost continuously driven around the Bloch sphere, which somewhat refocuses fluctuations in the relaxation process13, while the coherent drive also makes the qubit less sensitive to noise32. In our mode of operation with constant $\bar{J}$, the qubits sit idle for approximately 50% of the two-qubit randomized benchmarking sequence, making them susceptible to dephasing on the timescale of the dephasing time, $T_2^*$. As a consequence, the projected state probability decays on a comparable timescale (see top axis in Fig. 4b).

Faster gate operations would allow more gates to be completed within $T_2^*$, but the comparatively small value of $\bar{J}/\hbar = 1.59$ MHz limits our utilizable Rabi frequencies, because of the power-broadening of the excitation profile16,17. Possible remedies include higher $J$ coupling, optimized shaped pulses that reduce accidental excitation of neighbouring transitions18, dynamical decoupling of the qubits during the idle times, and samples with higher isotopic purification. Over the 13 h of data acquisition used to compile the data in Fig. 4b, we used frequency feedback to compensate for drifts and jumps of the ESR frequencies caused by magnetic field decay, local charge fluctuations and residual $^{29}$Si nuclear spins (see Extended Data Fig. 2). More sophisticated frequency tracking schemes could also contribute to higher fidelities. Although this technique utilizes a constant exchange coupling between qubits and provides a convenient way of benchmarking fidelities without the need for complex synchronization between exchange gate and spin resonance pulses, a scalable architecture will require tunability of exchange between qubits, for example by using a gate electrode placed between adjacent quantum dots, as demonstrated in recent two-qubit gate experiments in Si/SiGe devices15.

In conclusion, we have shown that the full two-qubit Clifford gate set can be constructed purely using magnetic resonance pulses acting on silicon spin qubits, and have used this to obtain the two-qubit gate fidelity using randomized benchmarking. The two qubits can be controllably entangled, as demonstrated by the generation of the four Bell states with fidelities of $F = 80\%–89\%$ and concurrences between 0.78 and 0.82. We measured a two-qubit gate fidelity of $F_{\text{Clifford}} = 94.7\% \pm 0.8\%$, which translates into $F_{\text{primitive}} = 98.0\% \pm 0.3\%$ for the primitive gates that include the CROT with a platform-independent protocol. We identify the main source of infidelity in our experiment to be dephasing, which occurs at a rate that is only one order of magnitude lower than our Rabi frequency (about 410 kHz). Higher Rabi frequencies can act as a remedy, and Rabi frequencies as high as 30 MHz have recently been demonstrated using electric-dipole spin resonance techniques in silicon devices, while barely affecting $T_2^*$ (ref. 17). Two-qubit fidelities reaching the required limits for fault-tolerance are therefore within reach and underpin silicon as a technology platform with good prospects for scalability to the large numbers of qubits needed for universal quantum computing.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-019-1197-0.

Received: 24 August 2018; Accepted: 28 February 2019; Published online 13 May 2019.

1. Loss, D. & DiVincenzo, D. P. Quantum computation with quantum dots. Phys. Rev. A 57, 120–126 (1998).
2. Knill, E. & Laflamme, R. Theory of quantum error-correcting codes. Phys. Rev. A 55, 900 (1997).
3. Fowler, A. G., Mariantoni, M., Martinis, J. M. & Cleland, A. N. Surface codes: towards practical large-scale quantum computation. Phys. Rev. A 86, 032324 (2012).
4. Kok, P. et al. Linear optical quantum computing with photonic qubits. Rev. Mod. Phys. 79, 135 (2007).
5. Haffner, H., Roos, C. & Blatt, R. Quantum computing with trapped ions. Phys. Rep. 469, 155–203 (2008).
6. Barends, R. et al. Superconducting quantum circuits at the surface code threshold for fault tolerance, Nature 508, 500–503 (2014).
7. Rong, X. et al. Experimental fault-tolerant universal quantum gates with solid-state spins under ambient conditions. Nat. Commun. 6, 8748 (2015).
8. Muhonen, J. T. et al. Quantifying the quantum gate fidelity of single-atom spin qubits in silicon by randomized benchmarking, J. Phys. Condens. Matter 27, 154205 (2015).
9. Veidtirthor, M. et al. An addressable quantum dot qubit with fault-tolerant control-fidelity, Nature Nanotechnol. 9, 981–985 (2014).
10. Nichol, J. M. et al. High-fidelity entangling gate for double-quantum-dot spin qubits. npj Quantum Inform. 3, 3 (2017).
11. Itoh, K. M. & Watanabe, H. Isotope engineering of silicon and diamond for quantum computing and sensing applications. MRS Commun. 4, 143–157 (2014).
12. Ladd, T. D. & Carroll, M. S. Silicon qubits. In Encyclopedia of Modern Optics 2nd edn, 467–477 (Elsevier, 2018).
13. Veidtirthor, M. et al. A two-qubit logic gate in silicon. Nature 526, 410–414 (2015).
14. Watson, T. F. et al. A programmable two-qubit quantum processor in silicon. Nature 555, 633–637 (2018).
15. Zajac, D. M. et al. Resonantly driven cnot gate for electron spins. Science 359, 439–442 (2018).
16. Kawakami, E. et al. Experimental control of a long-lived spin qubit in a Si/SiGe quantum dot. Nat. Nanotechnol. 9, 666–670 (2014).
17. Yoneda, J. et al. A quantum-dot spin qubit with coherence limited by charge noise and fidelity higher than 99.9%. Nat. Nanotechnol. 13, 102106 (2018).
18. Vandervos, L., M. K. & Chuang, I. L. NMR techniques for quantum control and computation. Rev. Mod. Phys. 76, 1037–1069 (2005).
19. Elzerman, J. M. et al. Single-shot read-out of an individual electron spin in a quantum dot. *Nature* **430**, 431 (2004).
20. Petta, J. R. et al. Coherent manipulation of coupled electron spins in semiconductor quantum dots. *Science* **309**, 2180–2184 (2005).
21. Koppens, F. H. L. et al. Driven coherent oscillations of a single electron spin in a quantum dot. *Nature* **422**, 766–771 (2006).
22. Pioro-Ladrière, M. et al. Electrically driven single-electron spin resonance in a slanting Zeeman field. *Nat. Phys.* **4**, 776–779 (2008).
23. Golovach, V. N., Borhani, M. & Loss, D. Electric-dipole-induced spin resonance in quantum dots. *Phys. Rev. B* **74**, 165319 (2006).
24. Maurand, R. et al. A CMOS silicon spin qubit. *Nat. Commun.* **7**, 13575 (2016).
25. Huang, W., Veldhorst, M., Zimmerman, N. M., Dzurak, A. S. & Culcer, D. Electrically driven spin qubit based on valley mixing. *Phys. Rev. B* **95**, 075403 (2017).
26. Corna, A. et al. Electrically driven electron spin resonance mediated by spin-valley-orbit coupling in a silicon quantum dot. *npj Quant. Inform.* **4**, 6 (2018).
27. Nowack, K. C., Koppens, F. H. L., Nazarov, Y. V. & Vandersypen, L. M. K. Coherent control of a single electron spin with electric fields. *Science* **318**, 1430–1433 (2007).
28. Yang, C. H. et al. Silicon qubit fidelities approaching incoherent noise limits via pulse engineering. *Nat. Electron.* **2**, 151–158 (2019).
29. Nowack, K. C. et al. Single-shot correlations and two-qubit gate of solid-state spins. *Science* **333**, 1269–1272 (2011).
30. Kaia, R., Laucht, A., Hill, C. D. & Morello, A. Robust two-qubit gates for donors in silicon controlled by hyperfine interactions. *Phys. Rev. X* **4**, 021044 (2014).
31. Ryan, C., Laforest, M. & Laflamme, R. Randomized benchmarking of single- and multi-qubit control in liquid-state NMR quantum information processing. *New J. Phys.* **11**, 013034 (2009).
32. Laucht, A. et al. A dressed spin qubit in silicon. *Nat. Nanotechnol.* **12**, 6166 (2017).
33. Yang, C. H. et al. Spin-valley lifetimes in a silicon quantum dot with tunable valley splitting. *Nat. Commun.* **4**, 2069 (2013).

**Acknowledgements** We thank S. Bartlett, R. Harper, L. M. K. Vandersypen, T. D. Ladd and N. C. Jones for discussions. We acknowledge support from the US Army Research Office (W911NF-13-1-0024 and W911NF-17-1-0198), the Australian Research Council (CE170100012), and the NSW Node of the Australian National Fabrication Facility. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Office or the US Government. The US Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation herein. B.H. acknowledges support from the Netherlands Organization for Scientific Research (NWO) through a Rubicon Grant. K.M.I. acknowledges support from a Grant-in-Aid for Scientific Research by MEXT, NanoQuine, FIRST, and the JSPS Core-to-Core Program.

**Reviewer information** Nature thanks Jason Petta and the other anonymous reviewer(s) for their contribution to the peer review of this work.

**Author contributions** W.H. and C.H.Y. performed the experiments. K.W.C. and F.E.H. fabricated the devices. K.M.I. prepared and supplied the 28Si wafer. T.T. and J.C.C.H. contributed to the preparation of the experiments. W.H., C.H.Y., M.A.F., A.L. and B.H. designed the experiment and discussed the results. R.C.C.L. assisted with the data analysis. W.H., A.L. and A.S.D. wrote the manuscript with input from all co-authors. A.M., A.L. and A.S.D. planned and supervised the experiment.

**Competing interests** The authors declare no competing interests.

**Additional information**

**Extended data** is available for this paper at https://doi.org/10.1038/s41586-019-1197-0.

**Supplementary information** is available for this paper at https://doi.org/10.1038/s41586-019-1197-0.

**Reprints and permissions information** is available at http://www.nature.com/reprints.

**Correspondence and requests for materials** should be addressed to W.H. or A.S.D.

**Publisher’s note:** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2019
METHODS

Experimental setup. The measurements were conducted in an Oxford Instruments wet dilution refrigerator with base temperature \( T_{\text{base}} \approx 30 \) mK and electron temperature \( T_{\text{electron}} \approx 100 \) mK. DC voltages were applied using battery-powered voltage sources (Stanford Research Systems, SIM928) and added to voltage pulses produced with an arbitrary waveform generator (LeCroy ArbStudio, 1104 AWG) through resistive voltage dividers/combiners. The voltages applied to the quantum device were attenuated 1:5 for D C voltages and 1:25 for voltage pulses. Low-pass filters were included for slow and fast lines (10 Hz to 80 MHz). ESR pulses were delivered to the on-chip microwave antenna by an Agilent E8257D microwave vector signal generator and attenuated at the 1.5 K stage (10 dB) and the 30 mK stage (3 dB). The internal arbitrary waveform generator of the vector signal generator is used to perform in-phase and quadrature modulation. The four different drive frequencies are generated by single side-band generation via mixing the in-phase and quadrature signal from the internal arbitrary waveform generator with the baseband signal. The stability diagrams are obtained using a double lock-in technique (Stanford Research Systems, SR830) with dynamic voltage compensation.

State tomography. To prepare the four Bell states \( |\psi^{\pm}\rangle = \frac{1}{\sqrt{2}} (|11\rangle \pm |00\rangle) \) and \( |\psi^{-}\rangle = \frac{1}{\sqrt{2}} (|11\rangle \pm |00\rangle) \), we start with the system initialized in the \( |11\rangle \) state. We then perform a zero-conditional-\( X/2 \) pulse on Q1 to bring the system into the \( |\pm\rangle \) state. A CROT or Z-CROT gate is applied to entangle the two qubits. By varying the phase of the underlying ESR pulse to perform either a \( \pi \) or \( -\pi \) rotation, we include the additional \( Z_{c} \) phase gate on Q2 that is needed to create \( |\phi^{-}\rangle \) and \( |\phi^{+}\rangle \). This results in the creation of the four Bell states. After this sequence we perform one of four pre-measurement rotations \( R_{\phi} = \{ I, X/2, -X/2, Y/2, -Y/2 \} \) to achieve projective measurements in the \( Z, Y, -Y, -X, \) and \( X \) bases, respectively. Although the projection outcome of the \( -X \) and \( Y \) bases contains redundant information, it is useful to cancel out offset errors. The two-qubit density matrix \( \rho \) is reconstructed from the combined 25 projection axes with 800 repetitions using maximum likelihood estimation. We further exclude readout errors by taking readout visibility into account.

The readout error for each probability set \( P = (P_{11}, P_{10}, P_{01}, P_{00}) \) is corrected by \( P = (F_{1} \otimes F_{2})^{-1} P_{\text{measured}} \) where

\[
F_{i} = \begin{pmatrix} F_{i1} & 1 - F_{i1} \\ 1 - F_{i1} & F_{i1} \end{pmatrix}
\]

In the experiment, we characterized the readout fidelity using the amplitude of the Rabi oscillations and obtained \( F_{11} = 0.83 \), \( F_{10} = 0.92 \), \( F_{01} = 0.84 \) and \( F_{00} = 0.94 \).

Maximum likelihood estimation is used to estimate the inversion of the matrix. The density matrix is first restricted to be non-negative Hermitian:

\[
\hat{\rho} = \frac{T^{\dagger}T}{\text{tr}(T^{\dagger}T)}
\]

where the division by \( \text{tr}(T^{\dagger}T) \) is to ensure normalization. Assuming the measurement error of each qubit state follows a Gaussian distribution, it is possible to estimate the closest density matrix to the measured state. The matrix \( T \) for the two qubit system can be parameterized by 15 independent parameters \( t_{1}, \ldots, t_{15} \).

The resulting matrix \( \rho \) is the closest estimation of the real density matrix by minimizing the following cost function:

\[
L(t_{1}, t_{2}, \ldots, t_{n}) = \sum_{i} \frac{\left| \langle \psi_{i} | \rho(t_{1}, t_{2}, \ldots, t_{n}) | \psi_{i} \rangle - n_{i} \right|^{2}}{2 \langle \psi_{i} | \rho(t_{1}, t_{2}, \ldots, t_{n}) | \psi_{i} \rangle}
\]

where \( n_{i} \) is the measured probability projected at \( |\psi_{i}\rangle \).

One of the main error sources in the state tomography experiment is the waveform generator in the vector source, which had a 3% probability of generating the incorrect waveform sequence. Since the measurement operators during state projection involve the application of gates that may have the same degree of error as the process being interrogated, the accumulated error will appear to be larger than the error in randomized benchmarking. This is corroborated by time evolution simulations taking into account the coherence times in the two-qubit system that suggest a Bell state fidelity of 90–95%.

Generation of Clifford gates. The Clifford group consists of all elements \( C \) that fulfill the condition \( C^{T}PC = \pm P \), where \( P \) are the Pauli matrices. The Clifford gates in our experiment are generated by different combinations of the primitive gates described in Fig. 4a and a virtual \( Z_{c}/2 \) gate on each qubit. All primitive gates consist of two conditional \( \pi/2 \)-pulses on the same qubit, and we adjusted the pulse amplitude to ensure that all conditional \( \pi/2 \)-pulses have the same length of 0.61 \( \mu \)s. We then generate the Clifford group by computer search. Comparing all possible combinations of primitive gates to the gates in the Clifford group, we find the combinations that require the minimal numbers of primitive gates \( I_{\text{primitive}} \). The number of Clifford gates that can be produced by sequencing \( L_{\text{primitive}} \) gates is summarized in Extended Data Table 1. All two-qubit Clifford gates can be built out of four primitive gates, and on average each Clifford gate is composed of 2.5694 primitive gates. In two-qubit randomized benchmarking experiments, the projected state probability is fitted to \( P = A - 4/3, B \), where \( A \) and \( B \) are free parameters that absorb SPAM errors. The average Clifford gate fidelity is calculated as \( F_{\text{Clifford}} = 1 - \gamma_{c} \) and the primitive gate fidelity is \( F_{\text{primitive}} = 1 - \gamma_{c}/2.5694 \).

Error analysis. All error bars through out the paper are defined as 95% confidence level of a least-squares fit of 1.96 times the standard deviation. The error analysis in quantum state tomography is obtained from Monte Carlo bootstrap re-sampling. The two-spin probability of each single shot readout is assumed to follow multinomial distribution with an average probability measured by experiment. The process is repeated 1,000 times until the variances of fidelity converge.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Source Data for Figs. 1, 2, 3, 4 and Extended Data Figs. 1, 2 are available with the online version of the paper.

34. Dehollain, J. P. et al. Nanoscale broadband transmission lines for spin qubit control, Nanotechnology 24, 015202 (2013).
35. Yang, C. H., Lim, W. H., Zwanenburg, F. A. & Dzurak, A. S. Dynamically controlled charge sensing of a few electron silicon quantum dot, Adv. Mater. 1, 042111 (2011).
36. McKay, D. C., Wood, C. J., Sheldon, S., Chow, J. M. & Gambetta, J. M. Efficient generation of Clifford gates. Phys. Rev. A 84, 052315 (2011).
37. Sergeevich, A., Chandran, A., Combes, J., Bartlett, S. D. & Wiseman, H. M. Characterization of a qubit Hamiltonian using adaptive measurements in a fixed basis, Phys. Rev. A 86, 022330 (2017).
38. Shulman, M. D. et al. Suppressing qubit dephasing using real-time hamiltonian estimation, Nat. Commun. 5, 5156 (2014).
39. Delbecq, M. R. et al. Quantum dephasing in a gated gaas triple quantum dot due to nongeneric noise. Phys. Rev. Lett. 116, 046802 (2016).
Extended Data Fig. 1 | Single-qubit coherence properties in the (1, 1) regime. Blue data corresponds to Q1 and red data corresponds to Q2. We have characterized the single-qubit coherence properties $T_1$ and $T_2^{\text{Hahn}}$, and measured their control fidelities via single-qubit randomized benchmarking. All data are acquired with the frequency feedback protocol described in Extended Data Fig. 2.

**a**, Spin-up probability as a function of wait time in the Ramsey sequence. $T_{2,\text{Q1}} = 10.5 \pm 1 \mu s$ is much shorter than $T_{2,\text{Q1}} = 24.3 \pm 2 \mu s$.

**b**, Spin-down probability as a function of wait time in the Hahn echo sequence. $T_{2,\text{Q2}}^{\text{Hahn}} = 33 \pm 5 \mu s$ is much shorter than $T_{2,\text{Q1}}^{\text{Hahn}} = 290 \pm 40 \mu s$.

**c**, Single-qubit randomized benchmarking with the other qubit initialized in the $|\downarrow\rangle$ state. Only the frequencies $f_1$ and $f_2$ are used for gate operations on Q1 and Q2 (single tone randomized benchmarking), respectively. The plot shows the projected state probability with increasing number of Clifford gates. The curve is fitted with $P = A(1 - 2r_c) + B$, and the Clifford gate fidelity is given by $F_{\text{Clifford}} = 1 - r_c$. The single-qubit Clifford gates are on average composed of 1.875 primitive $\pi/2$-pulses, so the $\pi/2$-pulse fidelity is extracted as $F_{\text{C}} = 1 - r_c/1.875$. The fidelity for all ESR pulses is in excess of 99%.
Extended Data Fig. 2 | Frequency tracking protocol.  

**Extended Data Fig. 2** (a) Frequency calibration of the ESR frequencies is implemented by interleaving calibration sequences with the randomized benchmarking experiment. After acquisition of three random sequences (one sequence is repeated 125 times), we check if the ESR frequency is still on-resonance by applying a low-power (26 dB lower than the typical operating power) \( \pi \) rotation. If the spin-up probability is above the threshold of 50% of the readout visibility, the experiment will continue. If the spin-up probability is below the threshold, the resonance frequency will be recalibrated until all ESR frequencies pass the check, and the measurement will continue. More sophisticated frequency tracking schemes could also contribute to higher gate fidelities\(^{37-39}\). 

(b, c) Resonance frequency fluctuations \( \Delta f = f_i - f_{\text{avg}} \) of \( f_{11} \) (b) and \( \Delta f = f_{21} - f_{\text{avg}} \) of \( f_{21} \) (c) during the measurement period. We subtracted the average values of the respective frequencies \( f_{\text{avg}} \) for better visibility. Over 13 h of data acquisition, Q1 experiences multiple jumps of about 600 kHz, while the fluctuations of Q2 remain within about 300 kHz. Since the resonance frequency fluctuations of Q1 and Q2 are uncorrelated, we exclude fluctuations of \( B_0 \) or the microwave reference clock as the cause of the frequency changes. 

(d) Variation of exchange coupling \( \Delta J = J - J_{\text{avg}} \) during the measurement period. We subtracted the average value \( J_{\text{avg}} \) for better visibility. The exchange coupling is relatively stable during the experiment. If the frequency fluctuations in b and c were to originate from charge noise, it is unlikely that \( J \) would remain unaffected. Furthermore, since the Stark shift of Q1 and Q2 is approximately 30 MHz \( V^{-1} \), a 600-kHz jump would require a change of the bias voltage applied to the D1 and D2 gates of about 20 mV. Such a change in the electrostatic environment would deteriorate qubit readout via the single-electron transistor charge sensor, but we noticed no substantial change of the readout level during the experiment. On this basis, we further exclude charge noise from being the cause of the frequency changes. We conclude that the frequency jumps are most probably caused by spin flips of residual \(^{29}\)Si nuclei that locally couple to the quantum dots.
Extended Data Table 1 | Number of Clifford gates built from each primitive gate length

| $L_{\text{primitive}}$ | Number of Clifford gates |
|------------------------|--------------------------|
| 0                      | 16                       |
| 1                      | 384                      |
| 2                      | 4176                     |
| 3                      | 6912                     |
| 4                      | 32                       |
| **Total**              | **11520**                |

Because the virtual gate $Z_v/2$ requires no pulse time, we do not include it in the primitive gate length $L_{\text{primitive}}$. When $L_{\text{primitive}} = 0$, there are four virtual $Z$ gates on each qubit.
Extended Data Table 2 | Single-qubit properties in different charge regimes

| Qubit | Charge Regime | $F_{\text{Clifford}}$ | $F_{\pi/2}$ |
|-------|---------------|-----------------------|-------------|
| Q1    | (1,0)         | 99.0 ± 0.38 %         | 99.5 ± 0.20 %|
|       | (1,1)         | 98.7 ± 0.23 %         | 99.3 ± 0.12 %|
| Q2    | (0,1)         | 99.1 ± 0.11 %         | 99.5 ± 0.06 %|
|       | (1,1)         | 98.9 ± 0.12 %         | 99.4 ± 0.06 %|

$F_{\text{Clifford}}$ and $F_{\pi/2}$ are similar in the single-electron and the (1, 1) charge regime, indicating that the dominant source of error is not noise in the exchange coupling $J$. 