On-demand electrical control of spin qubits

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Once called a “classically non-describable two-valuedness” by Pauli, the electron spin forms a qubit that is naturally robust to electric fluctuations. Paradoxically, a common control strategy is the integration of micromagnets to enhance the coupling between spins and electric fields, which in turn hampers its noise immunity and adds architectural complexity. Here we exploit a switchable interaction between spins and orbital motion of electrons in silicon quantum dots, without a micromagnet. The weak effects of the relativistic spin-orbit interaction in silicon are enhanced, leading to a speed-up in Rabi frequency by a factor of up to 650 by controlling the energy quantisation of electrons in the nanostructure. Fast electrical control is demonstrated in multiple devices and electronic configurations. Using the electrical drive, we achieve a coherence time $T_{2,\text{Hahn}} \approx 50 \mu$s, fast single-qubit gates with $T_{\pi/2} = 3$ ns, and gate fidelities of 99.93%, probed by randomised benchmarking. High-performance all-electrical control improves the prospects for scalable silicon quantum computing.

The density of quantum dots in an array is set by the size of the electron wave functions and the consequent size and pitch of gate electrodes [1], but individualised high-fidelity control of electron spin qubits in silicon typically requires on-chip integration of much larger devices, such as micromagnets [2, 3] or stripline antennae [4]. Other spin qubit implementations, such as electrons in InAs nanowires [5] and holes in silicon [6] and germanium [7–9], have sufficient intrinsic spin-orbit coupling to enable localised, all-electrical control employing only the gate electrodes that are already used to define the quantum dots. Spin-orbit effects can also be intensified in the presence of orbital degeneracy [9–13]. However, the same spin-orbit coupling that enables direct electrical control also exposes the qubits to decoherence from electrical noise [14]. Furthermore, while some semiconductor fabrication plants have the capability to integrate non-silicon materials, electrostatic quantum dots using silicon CMOS technology offer the strongest prospect of leveraging the full potential for integration and miniaturisation of the most advanced transistor fabrication nodes [15].

Controlling the electron energy spectrum

Spin-orbit effects for electrons in silicon quantum dots are typically small, meaning that direct electric driving is weak, however, these effects can become significant if the electron is allowed to move between orbital configurations within the quantum dot [16]. These configurations are generally immutable due to the well quantised orbital energies of few-electron quantum dots. However, a dense arrangement of electrodes such as in Fig. 1a and b (nominally identical to all devices studied here) gives access to a level of control over the potential landscape that can be used to consistently form quantum dots that possess an energy spectrum with flexible controllability. Further technical details on strategies to achieve this controllability are discussed in Extended Data Fig. 1. We accumulate two quantum dots, each configured as single spin qubits. Fig. 1c shows how excited state spectroscopy may be used to infer the presence of electronic states within a dot that have a differential lever arm $\alpha_{\text{rel}}$, and correspond to different charge density distributions and which therefore couple differently to the various electrostatic gates. We rule out parasitic charge states due to the small $\alpha_{\text{rel}}$ (see Supp. Info.). We denote these orbital configurations A and B, and their energies $E_A$ and $E_B$, respectively.

We instigate internal movement of the electron within the dot by biasing the gate voltages to reconfigure the quantum dot to a point where the two states have approximately the same energy. At this point, the quantum dot becomes highly polarisable, which leads to fast electrically-driven spin resonance (EDSR). This quasi-degeneracy point can be found by extracting the excitation energy (separation of fitted orange and green dotted lines in Fig. 1c) extrapolating the trend against the side gate voltage ($J_{\text{gate}}$) to the point where it reaches zero.
Fig. 1 | Electrostatic quantum dots with tunable energy spectrum. a, Scanning electron micrograph of a quantum dot device nominally identical to the devices investigated here. Quantum dots are formed under metallic gates P1, P2, and confined with the assistance of barrier gates J, B1-B3, CB1-CB2, and SETB. A charge reservoir is accumulated under RES, and Single-Electron Transistor under SET. b, Simulated cross section of the device geometry overlaid with a schematic of the electron wavefunctions and spins. c, Excited state spectroscopy at zero $B_0$ field of an isolated double quantum dot containing 4 electrons, measured in device A as a function of $V_J$ and the interdot bias $\Delta V_P$ (static biases $V_{P1} = 2.08\,V$, $V_{P2} = 2.4\,V$), with $f_{\text{probe}} = 477\,\text{Hz}$, see Methods for details. Energies $E_A$ (green dashed line) and $E_B$ (orange dashed line) are fitted to step increases in interdot tunnel rate, indicating occurrence of ground and first excited states. d, Extrapolation of the $E_A - E_B$ separation reveals a convergence near $V_J = 1.6\,V$. e, Control sequence illustrating how to deform the quantum dot to turn on a controllable orbital degeneracy using the lateral J gate and use it for qubit control. The idling state is purely spin-only, while some of the qubits are being controlled in a spin-orbit mixed state.

(See Fig. 1d). At that point, the A and B states hybridize, and the electron enters a superposition state $\alpha|A\rangle + \beta|B\rangle$. The exact values of $\alpha$ and $\beta$ depend on the particular nature of the two states A and B, but they are controllable by exploiting the differential lever arm $\alpha_{\text{rel}}$.

This controllability over the wavefunction hybridization is the key to on-demand exploitation of spin-orbit effects. In Fig. 1e we present a typical series of control steps, starting from an idling qubit (i) that is set to have minimal spin-orbit effects by setting the quantisation energy to be large ($\alpha \approx 1$ and $\beta \approx 0$). The dot is then deformed to create the hybrid state (ii) for a short amount of time, sufficient for the application of a microwave pulse (iii) that creates the spin rotation. The quantum dot is then reconfigured to the idling mode (iv), which restores the qubit resilience against spurious electric field fluctuations. This strategy allows for idling qubits to be protected for prolonged times while active qubits are being manipulated. The vision of a scalable qubit arrangement presented in Fig. 1f is based on a dense array of spins in a grid of quantum dots. Individualised control of a subset of the qubits can be performed by reconfiguring the electrostatic potential and applying microwave excitations, both achieved directly by the top gate that defines the quantum dot. This on-demand activation of spin-orbit effects would significantly simplify the design and operation of large scale quantum processors by removing the need for additional complex nanomagnet or antennae arrays [17, 18].

**Pulsed electron spin-orbital spectroscopy**

While the orbital spectroscopy technique presented in Fig. 1c is useful in narrowing the search range for a degeneracy point, ultimately it is the change in spin dynamics that will be the most reliable signature of the successful formation of a hybrid wavefunction. We show as a dashed black line in Fig. 1c the trend of points that are identified as having maximum spin-orbit driving. This identification is obtained by a technique we call pulsed electron spin-orbital spectroscopy (PESOS). It consists of applying a microwave pulse of fixed duration and power and measuring its effect on the spins as a function of the microwave frequency and gate voltages. Optimal visibility of the spin resonant frequency is obtained when the
Fig. 2 | Pulsed Electron Spin Orbit Spectroscopy (PESOS). a, PESOS map, consisting of the probability of measuring a spin flip after a burst of microwave of fixed power and duration, while varying the microwave frequency $f_{\text{mw}}$ and a gate electrode voltage bias $\Delta V_F$ (voltage detuning between $V_{\text{G1}}$ and $V_{\text{G2}}$). The power and duration of the burst are roughly calibrated to correspond to a $\pi$-rotation for a pure spin state. Fringes appear as a function of $\Delta V_F$ as the spin-photon coupling becomes more intense, and the spin being rotated by several $\pi$. Measured in device A with a (1,3) charge configuration under $(P1, P2)$. b-e, Additional PESOS maps measured in different devices, varying materials, charge configurations, magnetic fields and others (see details in Extended Data 2). f-j, Four-level models that best reproduce the data from a-e, showing the variety of intradot level-crossing regimes between the orbital states $|A>$ and $|B>$ and their impact on the spin dynamics (see Supp. Info.). $V_0$ indicates the fitted orbital crossing location.

The colours correspond to the angle of spin rotations. k, Rabi frequencies extracted from the fitted simulations. m, Measured Rabi oscillations over time as a function of $\Delta V_F$, confirming the interpretation of the Rabi speed-up.

By measuring PESOS maps for different biases $V_J$ and $\Delta V_F$, we can extract the bias configuration that provides the largest speed-up in Rabi frequency, as shown in Fig. 2l. This allows us to completely reconstruct the line in the charge stability diagram in Fig. 1c that corresponds to a hybrid ground state. Fig. 2m shows the complete Rabi oscillations of the spin, confirming our interpretation of the PESOS maps. We also use this interpretation to guide the experimental search for the degeneracy point shown in Fig. 2b (see also Extended Data Fig. 1). The regularity with which we find these hybridisation points is encouraging for the prospects of scalability of this technology. Fig. 2a and b were taken using different charge configurations in the same device. Fig. 2c-e are three other devices, with different operation modes, material stacks and microwave excitation strategies, measured in two different cryogenic setups. Details of the differences between devices A, B, C and D are given in the Extended Data Fig. 2.

The taxonomy of the spin-orbit effects in Fig. 2a-e is related to the particularities of the orbital states A and B in each of the devices and dot configurations. The intradot state hybridization may involve states with different valley configurations (under a rough interface) [21–25],
in-plane orbitals [26] or even with interaction-induced charge transitions such as in Wigner molecules [27, 28].

For each of these transitions, the hybridization energy gap compares differently to the spin splitting energy, leading to significant qualitative differences as can be seen in the eigenvalues of the fitted four-level models, shown in Fig. 2f-j. We confirm this interpretation and the ability to recover different regimes by scanning the magnetic field applied to Device D until we obtain the same qualitative features as in Device A. Our model indicates that this is possible by setting the spin splitting to be comparable to the orbital splitting. In Device D, this occurs for a magnetic field around \( B_0 = 610 \text{ mT} \) (see Extended Data Fig. 3).

We note that device D is driven all-electrically by applying a microwave field directly to the CB1 gate (see Fig. 1a), while devices A to C are driven by the coplanar waveguide antenna, which creates both electric and magnetic fields [29].

Qubit performance

We turn our attention to the tunability of the hybridization characteristics, focusing on the device from Fig. 2c (namely, device D). This is the device with the most marked effects of the orbital degeneracy on spins among the devices studied here. We measure additional PESOS maps at two different magnetic fields, \( B_0 = 400 \text{ mT} \) in Fig. 3a and \( B_0 = 700 \text{ mT} \) in Fig. 3c (the latter is the same field as Fig. 2c, but adopting Gaussian pulses and focused near the degeneracy point). At 400 mT, we observe the largest enhancement in spin-orbit effects and the resulting Rabi frequency across all experiments (see Fig. 3a). Reaching \( f_{\text{Rabi}} = 81 \text{ MHz} \) close to the degeneracy point, we achieve the fastest \( \pi/2 \) qubit rotation in 3 ns (Fig. 3b, lower curve). The spin-orbit interaction continues to decrease for increasing \( V_J \), leading to Rabi frequencies < 125 kHz at \( V_J > 1.65 \text{ V} \) (see Extended Data Fig. 5), recovering the regime of vanishingly small spin-orbit interactions. For comparison, we also show the measurement at the point where the Larmor frequency is in first order insensitive to noise in the J gate voltage (\( V_J = 1.62 \text{ V} \)), in which the Rabi frequency is \( f_{\text{Rabi}} = 7 \text{ MHz} \) (Fig. 3b, upper curve).

At 700 mT the qubit states become more convoluted, with poorer initialisation fidelity and the appearance of additional transitions, which pollute the two-level nature of the system. Indeed, the small hybridization gap extracted in Fig. 2 is indicative of susceptibility to the appearance of undesirable diabatic transitions and leakage to the excited orbital. However, with careful initialisation strategies and using Gaussian pulses to avoid the leakage of the qubit into undesired excited states, it is possible to achieve PESOS maps with good visibility (Fig. 3c) and coherent driving (Fig. 3d).

In Fig. 3d we characterise the impact of the orbital hybridization on the coherent spin driving. Near the degeneracy point \( \Delta V_J = 0 \text{ V} \), the Stark shift \( df/dV_J \) becomes very large, leading to a faster damping rate of the Rabi oscillations \( \Gamma_2,\text{Rabi} \). However, the Rabi frequency improvement outpaces the decoherence amplification, resulting in a higher Q-factor \( = 2 \times f_{\text{Rabi}}/\Gamma_2,\text{Rabi} \) close to the degeneracy point.

For the remaining experiment, we tune device D to an alternative bias point in the (1,3) charge configuration and apply the microwave drive to the J gate to probe spin-orbit effect in line with the array of dots. This configuration yields a degeneracy point with strong spin-orbit effect in a region with only a weak voltage dependence on the qubit Larmor and Rabi frequencies (see Extended Data Fig. 4), making the qubit substantially more resistant to noise. The single qubit gate fidelity is

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**Fig. 3 | Impact of Zeeman energy and detuning on qubit dynamics.** a, PESOS map of device D at an external magnetic field of \( B_0 = 400 \text{ mT} \) measured with square microwave pulses at a frequency \( f_{\text{low}} \) and J-gate voltage \( V_J \). At 400 mT the resonance can be tracked until very near the degeneracy point, resulting in an increase in Rabi frequency of almost three orders of magnitude. b, Rabi measurements at \( V_J = 1.62 \text{ V} \) resulting in 7 MHz oscillations (offset for clarity) and \( V_J = 1.58 \text{ V} \) resulting in 81 MHz oscillations. (The Rabi frequency becomes immeasurably low for \( V_J > 1.65 \text{ V} \)). c, PESOS map of device D at 700 mT measured with Gaussian pulses. At 700 mT the Rabi speed-up is more modest, but the qubit frequency is also less strikingly affected by electric field fluctuations, resulting in an overall more precise qubit operation compared to 400 mT. d, Rabi frequency \( f_{\text{Rabi}} \) (red squares), Rabi decay rate \( \Gamma_2,\text{Rabi} \) (blue triangles), and quality-factor \( Q \) (orange diamonds) increase with proximity to the degeneracy point, with Q-factor reaching an optimal value at \( \Delta V_J = 13.6 \text{ mV} \).
assessed in this configuration via randomised benchmarking on the Clifford set, achieving a 99.93% elementary gate fidelity as shown in Fig. 4a, well above the threshold for error corrected fault tolerance [30]. Additionally we assess the fidelity of the individual elementary gates using Gate Set Tomography [31] shown in Fig. 4b resulting in average fidelities of 99.64%, 99.79% and 99.80% for the I, X, and Y gate, respectively.

Single qubit randomised benchmarking underestimates the importance of identity gates for quantum computation because identity is only one of the possible Clifford gates. However, in multi-qubit protocols it is most often necessary for qubits to remain idle for higher proportions of operation time (such as during the readout of ancillas in an error correction protocol), leading to significant dephasing errors [32–34]. Coherence times $T_2^\text{Hahn}$ and $T_2^*$ decrease with enhanced spin-orbit effect close to a degeneracy point (as shown in Figure 4c). This can be mitigated by detuning the qubit far from the degeneracy to reduce dephasing errors when qubits must idle for extended periods. The error from switching the spin-orbit interaction on and off again (round-trip) is measured to be 0.65% in Figure 4d, of which the main contributor is expected to be the increased dephasing in the on-state. In this experiment the total proportion of the time spent at the rapidly dephasing on-state is not kept constant with the number of round trips, but increases linearly (see details of the pulse format and error analysis with fixed total time in the on-state in Extended Data Fig. 6).

**Conclusions**

The demonstrated method for ultra-fast spin control raises several questions on the physics of such systems and their applications. For example, the dominant source of control errors for this resonance method are unknown. Pulse engineering for magnetically driven spin qubits in similar devices have led to significant improvements in control fidelity, achieving error rates below 0.05% [19]. However, these strategies can only be translated to the electric driving approach discussed here once the sources of error are well understood and characterised.

Another question left open in our analysis is in regard to the controllability of the hybridization gap. Comparison of the spin-orbit effect in all four devices investigated here creates confidence on the ubiquity of this phenomenon. Hence, its applicability as the main control strategy for qubit devices depends on the regularity of the resulting EDSR speed-up and dependability on being able to shape the orbital hybridization gap in accordance with one’s needs.

Switchability of the spin-orbit effect allows us to tackle one of the most cumbersome aspects of quantum infor-
nformation, which is that the addressability of a qubit often must be traded off against its noise resilience. We can turn on the degeneracy for control and turn it off to harvest the long intrinsic coherence of Si qubits while idling. This capability comes with the cost of an additional characterisation step for the quantum processor to achieve this degeneracy. Hence, from the scalability perspective it is crucial to further understand how to achieve this degeneracy in a consistent way in a given dot. We believe that the consistency of achieving this degeneracy in four different devices already in this first demonstration gives confidence that a consistent method is achievable and we anticipate more experiments and theoretical work in this direction in future.

We emphasise that enhanced electric driving of the spin is merely one consequence of the ability to controlably create hybridised wavefunctions with coherent spin states. Extensions of this result could lead to strategies to couple spins to photons [35, 36], as well as lead to long-range two-qubit gates via spin-dependent electric dipolar coupling, similar to strategies such as the Rydberg gates [37, 38] and Mølmer-Sørensen gates [39], previously demonstrated in atomic qubits, or predicted for electron-nuclear flip-flop qubits in silicon [40].

**METHODS**

**Measurement Setup**

Devices A & C were measured in an Oxford Kelvinox 400HA dilution refrigerator. DC bias voltages are generated from Stanford Research Systems SIM928 Isolated Voltage Sources. Gate pulse waveforms are generated from a Tektronix AWG5208 Arbitrary Waveform Generator (AWG) and combined with DC biases using custom linear bias-tees.

Devices B & D were measured in a Bluefors XLD400 dilution refrigerator. DC bias voltages are generated from Basel Precision Instruments SP927 DACs. Gate pulse waveforms are generated from a Quantum Machines OPX and combined with DC biases using custom linear bias-tees.

The SET current of devices A, B, & C are amplified using a room temperature I/V converter (Basel SP983c) and sampled by a digitiser (Gage Octopus CS8389 for devices A & B, QM OPX for device C). The SET of device D is connected to a tank circuit and measured via reflectometry, where the source tone is generated from the QM OPX, and the return signal amplified with a Cosmic Microwave Technology CITFL1 LNA at the 4K stage, and a Mini-circuits ZX60-P33ULN+ and Mini-circuits ZFL-1000LN+ at room temperature, before being digitised and demodulated with the QM OPX.

For all devices, microwave pulses are generated from a Keysight PSG8267D Vector Signal Generator, with I/Q and pulse modulation waveforms generated from the AWGs.

**Double Lock-in Charge Sensing**

In order to measure clear charge stability maps with high signal-to-noise ratio, a scheme involving two Stanford Research Systems SRI830 lock-in amplifiers is used [41]. A first lock-in amplifier (Sensor Lock-in) measures the source-drain current of the SET charge sensor under application of an excitation to the source-drain bias at 233 Hz, with an amplitude of 100 µV. The SET current passes through a transimpedance amplifier to convert it to a voltage so that it can be easily split, however it will continue to be referred to as a voltage. The Sensor Lock-in demodulates the current at 277 Hz, applies a low-pass filter, and the resulting value is used in a closed-feedback loop to keep the SET biased to a sensitive point. A second lock-in amplifier (Dot Lock-in) is used to probe the quantum dots accumulated under the P-gates, by measuring resonant changes to the SET current in-phase with the probe frequency. For this purpose a square-wave excitation at 477 Hz with rise/fall times of 20 ns, is generated by the AWG and applied to P1 and P2 in combination with a DC bias via custom linear bias-tees. It is applied with opposite phase on each gate to elicit an excitation in the interdot detuning. A trigger at the same frequency is provided to the Dot Lock-in for demodulation, along with an amplified copy of the SET current. The DC bias voltages on the dot-gates P1 and P2 are then swept and the Dot Lock-in signal measured. A low-current background is in the demodulated Dot Lock-in signal due to capacitive coupling between dot-gates and the SET. As the DC bias crosses an interdot charge transition, the detuning excitation applied to P1 and P2 will cause interdot charge movement in phase with the excitation, which in-turn modulates the SET current.

**Tunnel-rate-based Excited State Spectroscopy**

Using the double lock-in technique described above, changes in tunnel rate can be probed if the tunnel rate is comparable to $\approx 2 \times f_{\text{probe}}$, as the charge sensing signal will be modulated by the change in tunnel rate. This enables a technique for excited state spectroscopy, where excited state splittings can be measured if they have a different tunnel coupling to the ground state. The interdot barrier gate voltage $V_b$ is swept (as shown in Fig. 1c) to tune the interdot tunnel rate so that it crosses the probe frequency for all excited states probed. The excitation of excited states can be observed as step changes in the charge sensing signal. This technique provides an efficient estimation of excited state energies, however if
needed they must be confirmed with other techniques, as not all excited states will elicit a change in the tunnel rate.

**Parity Readout Based On Pauli Spin-Blockade**

The spin-state of both spins in the double quantum dots in this study are read out by first performing a spin-charge conversion based on Pauli spin-blockade [42], then reading out the resulting charge state with a nearby SET. Due to the time-scales and interdot couplings employed, there is no discrimination between singlet and unpolarised triplet $T_0$ states, leaving them both unblocked [20]. Readout is then in the parity basis, providing odd/even state discrimination. As only one spin is targeted throughout this study, the second spin is used solely as a readout ancilla, providing deterministic readout of the target spin.

**Theoretical Modeling and Fits**

Here, we summarise the theoretical method involved in obtaining the four-level energy diagrams shown in Fig. 2f-j. The goal of this method is to obtain a description of our system based on the PESOS maps using an effective four-level model, consisting of two spin-$\frac{1}{2}$ systems, A and B. These quantum states can be either valley or orbital states, depending on the specific system, and are represented by $|A\rangle$ and $|B\rangle$. The spin states are split by the Zeeman splitting in the presence of a magnetic field and thus, forming a total of four non-degenerate states. A full description of the Hamiltonian is contained in Supplementary Information Section B.

The four-level model is fitted to two different sets of information, one is the qubit frequency $f_0$, and the other is the Rabi frequency given by $f_{Rabi}$. To obtain these information from the PESOS maps as shown in Fig. 2a-e, we extract vertical line traces of $P_{\text{even}}$ as a function of the driving frequency $f_{\text{mw}}$ at each voltage value. We can then fit these traces to the Rabi equation given by:

$$P_{\text{even}} = \frac{A f_{\text{Rabi}}^2}{f_{\text{Rabi}}^2 + (f_{\text{mw}} - f_0)^2} + \delta A$$

where $A$ is the amplitude of the oscillations, $f_{\text{Rabi}}$ is the Rabi frequency, $f_{\text{mw}}$ is the driving frequency, $f_0$ is the resonant qubit frequency, $\tau$ is the total time of the driving pulse, and $\delta A$ is amplitude offset of the oscillations. From this fit, we can extract both the Rabi frequency $f_{\text{Rabi}}$, and the qubit frequency, given by $f_0$, as a function of the gate voltage (either $V_g$ or $\Delta V_P$). With these information, we are also able to obtain the simulated PESOS maps as shown in Fig. 2k by plotting the Rabi equation for each voltage value with the fitted parameters.

These extracted values of $f_{\text{Rabi}}$ and $f_0$ as a function of gate voltage will be the target fit values of the four-level model. By varying the parameters of the four-level model Hamiltonian, we perform a non-linear least squares fit of both the Rabi frequencies $f_{\text{Rabi}}$ and the qubit frequency $f_0$ simultaneously, minimizing the difference between the calculated values from the four-level model and target values obtained from fitting to the Rabi equation. The output of this least squares fit are the Hamiltonian parameters describing the system. More details on the fitting procedure and fitted values are contained in Supplementary Information Sections C & F. Finally, these fitted parameters will enable us to calculate the eigen-energies of the Hamiltonian and obtain the energy diagrams as shown in Fig. 2f-j.

**Randomised Benchmarking**

The benchmarking sequences used in Fig. 4a are constructed from elementary $\pi/2$ gates X, Y, -X, -Y, $\pi$ gates [X,X], [Y,Y], and an I-gate which is implemented as a sequence of [X,X,-X,-X,-X,X]. Each Clifford gate contains on average 1.875 elementary gates.

For each data point, an average probability is taken from 20 randomised sequences, each averaged over 100 shots. Due to a hardware memory limit, sequences longer than 1420 Cliffords are executed as repetitions of half, quarter, or eighth-length sequences as necessary. Repeated sections have a minimum length of 710 Cliffords.

**DATA AVAILABILITY**

The datasets used in this study are available at https://doi.org/10.5281/zenodo.7223114.

**CODE AVAILABILITY**

The analysis codes that support the findings of the study are available from the corresponding authors on reasonable request.

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AUTHOR INFORMATION

Author Contributions

T.T. measured devices A and C first observing the enhanced SOI Rabi in A. W.G. measured devices B and D demonstrating the EDSR without a micromagnet in D. J.Y.H participated in qubit benchmarking in D, with M.F & W.G. participating in the analysis. W.H.L participated in the measurements with all devices. Experiments were done under A.L., A.S., A.S.D., and C.H.Y.’s supervision. W.H.L and F.E.H. fabricated the devices, with A.S.D.’s supervision on enriched Si wafers supplied by K.M.I., N.V.A., H.-J.P., and M.L.W.T. S.S. designed the RF setup for devices B and D. A.S., C.H.Y., and R.C.C.L. developed control strategies for enhanced EDSR. P.Y.M., M.F., and J.D.C. developed models of spin-orbital degeneracy, with A.S. and C.E.’s supervision. W.G., A.S., M.F., T.T., W.H.L, J.Y.H, F.E.H., A.L., C.H.Y., A.M., and A.S.D. wrote the manuscript, with input from all co-authors.

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COMPETING INTERESTS

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Extended Data Fig. 1 | Obtaining degeneracy on demand via excited state spectroscopy

This is a protocol for tuning the energy spectrum of a new charge configuration to create a level degeneracy, resulting in a speed-up of the qubit Rabi frequency. The protocol utilises tunnel-rate-based excited state spectroscopy (see Methods). The voltage detuning between dots, $\Delta V_P$, is swept across an interdot charge transition to observe changes in the interdot tunnel rate associated with the resonant tunneling into excited states [43].

**a**, Top-view schematic layout of the device gates. **b**, Excited state spectroscopy where $V_{\text{offset}}$ is stepped. The two right-most features are designated as states A and B, representing the ground and first excited states of the P1 dot, which we observe to be converging for decreasing $V_{\text{offset}}$. The relevant gate voltages are shown in the table. In **c**, $V_J$ is swept to re-adjust the interdot tunnel rate so that the excited state transition is visible at the probe frequency of 477 Hz. In **d**, we again try to measure movement in the excited state energy, this time at a lower $V_{\text{offset}}$. In **e** we sweep $V_J$ to adjust the tunnel rate, and to get an indication of the effect on the excited state energy. We observe that the excited state energy appears to be decreasing for increasing $V_J$. Finally, we take a PESOS map in this configuration, and observe a speed up of the Rabi frequency at the location of the red triangle marked in **e**. This PESOS map is shown in main text Figure 2b.
Extended Data Fig. 2 | Devices details

Device A was fabricated on an isotopically enriched silicon-28 substrate (50 ppm residual $^{29}\text{Si}$) [44]. Devices B, C & D were fabricated on an epitaxially grown, isotopically purified $^{28}\text{Si}$ epilayer with a residual $^{29}\text{Si}$ concentration of 800 ppm [45].

| Device | $^{29}\text{Si}$ concentration | Gate Materials | Electron Occupancy | $B_0$-Field (T) | Microwave Carrier Frequency (GHz) | Mode of Driving |
|--------|-------------------------------|----------------|--------------------|-----------------|-------------------------------|----------------|
| A      | 50 ppm                        | TiPd           | (1,3) & (3,1)      | 0.827           | 22.3                          | antenna-based  |
| B      | 800 ppm                       | TiPd           | (3,1)              | 0.55            | 15.4                          | antenna-based  |
| C      | 800 ppm                       | Al             | (1,3)              | 0.827           | 22.3                          | antenna-based  |
| D      | 800 ppm                       | Al             | (3,1)              | 0.1 - 1.0       | 2.8 - 28                      | gate-based     |
Extended Data Fig. 3 | Variation of a degeneracy with applied magnetic field

a-h, PESOS maps taken at various values of $B_0$ field in Device D, with a (1,1) charge configuration, indicating that the characteristic of a degeneracy point may be tuned. Techniques using gate-bias voltages (such as in Ext Data Fig. 1) may prove more scalable however, and are an avenue for future research.
Extended Data Fig. 4 | PESOS and Rabi oscillations at the high-fidelity point

a, PESOS map acquired with microwave drive applied to the CB1 gate. b, A PESOS map acquired using the same configuration as for Fig. 4, with microwave drive applied to the J-gate. Both a and b use the same source power of 20 dBm, however variation in line losses due to different electronics may result in differences in electric field amplitude applied to the CB1- and J-gates. c, Rabi oscillations in the same configuration as Fig. 4a,b with an oscillation frequency of $f_{\text{Rabi}} = 4.6$ MHz, and a quality factor of 58.

Extended Data Fig. 5 | Slow rabi oscillation

a, PESOS map taken for a large range in $V_j$ in the same configuration as Fig. 3a,b. The microwave burst is applied for 8 μs. b, Rabi oscillation taken at $V_j = 1.642$ V, with the same power as the fast Rabi oscillation in Fig. 3b. A fitted decaying sinusoid gives $f_{\text{Rabi}} = 124$ kHz. It can be seen that the resonance vanishes in a at higher $V_j$, indicating that spin-orbit coupling and driving efficiency continue to decrease past the point at which coherent oscillations can be measured.
Extended Data Fig. 6 | Pulse sequences and additional data for coherence and switchability measurements

a, Altered Ramsey pulse sequence used for Fig. 4c in which during the wait time $T_{\text{wait}}$ a bias $\Delta V_J$ is applied to J. b, Coherent Ramsey oscillations for the sequence in a, and processed to produce Fig. 4c. A virtual phase is added to the second X/2 pulse to aid data processing and fitting. c, Altered Hahn echo pulse sequence with offset wait times (as in a) used for Fig. 4c. d, Measured data for the pulse sequence in c, and processed to produce the data in Fig. 4c. e, Coherent switching pulse sequence. The qubit is switched $N_{\text{cycles}}$ times between two bias points $\Delta_1$ and $\Delta_2$, being close to and far from the degeneracy point respectively. A virtual Z-phase is added before the final X/2 pulse. In addition to this, a variable time $T_{\text{wait}}$ is added in order to keep the total time between the two X/2 pulses the same for all values of $N_{\text{cycles}}$. The wait time is only added in the off-state, $\Delta_2$. Each switching cycle uses 20 ns on/off ramps, with a 20 ns pulse settling time at each level. f, Measured data using the pulse sequence in e, with $T_{\text{wait}} = 30$ μs. This data is used to calculate the return amplitudes for sequence e in h, also shown in Fig. 4d. g, Coherence switching pulse sequence in which the amount of time spent in each of the states $\Delta_1$ and $\Delta_2$ is kept constant in order to cancel out the effect of fast decoherence near the degeneracy from the switching fidelity calculation. h, Measurement of the return amplitudes for varying $N_{\text{cycles}}$ for sequences e with $T_{\text{wait}} = 30$ μs (also shown in Fig. 4d), and g with $T_{\text{wait}} = 4.8$ μs. We see that for sequence g the baseline return amplitude is reduced, due to the short coherence time at the $\Delta_1$ point, however there is no observable coherence decay associated with increasing $N_{\text{cycles}}$. 
**Extended Data Fig. 7 | Calibration of the microwave excitation amplitude**

The microwave signal applied to the CB1 gate of Device D is delivered through a transmission line that is poorly characterised for frequencies above 6 GHz. **a**, Here the line transmission is calibrated by first measuring the slope of Coulomb oscillations relative to the voltages on the sensor top gate and the CB1 gate, which gives a relative lever arm of 14.8. Then, in **b** the width of a single Coulomb peak is measured against the microwave amplitude, scaled from a reference level of 0 dBm from the source. The fitted peak width trend in **c** gives a maximum amplitude at the CB1 gate of 50 ± 2 mV when multiplied by the relative lever arm. Due to the possibility for a Coulomb peak to also be broadened by local heating effects, or microwave induced charge traps, this calculated amplitude represents an upper bound.

**Extended Data Fig. 8 | Enhanced relaxation rate near level degeneracy**

The spin relaxation time $T_1$ measuring across the full target charge configurations for Device A (**a**) and Device D (**b**) in $V_J$ and $\Delta V_P$ gate space. The locations of level crossings are indicated as red dashed lines. This shows an enhanced spin relaxation rate near the point of level degeneracy in the respective systems. Interestingly, there are two visible transitions in Device D, between which the spin relaxation is faster than the background, potentially indicating the population of an alternative ground state.
Extended Data Fig. 9 | Diabatic orbital excitation

**a**, PESOS map in which the ramp time of the J-gate voltage is 80 ns. The resonance frequency continues on a linear trend, indicating that the orbital state is maintained when crossing the point of degeneracy at \( V_J = 1.638 \) V. **b**, PESOS map in which the J-gate ramp time is increased to 2 \( \mu \)s. The resonance frequency jumps after the degeneracy point, indicating population of a new orbital state via adiabatic passage across the level-crossing.

Extended Data Fig. 10 | Rabi Frequency Compensation

**a** and **b** show Rabi oscillations discretised into \( \pi/2 \) rotations and repeated 10 times to observe instability, with Rabi frequency feedback on, and off, respectively. The feedback protocol measures \( P_{\text{flip}} \) for 5, 7, 9, and 11 \( \pi/2 \) pulses, each of which should result in a 0.5 flip proportion in the ideal case. It then applies a correction to the microwave amplitude of \( \delta A_{\text{MW}} = -\text{gain} \times [P_5 - P_7 + P_9 - P_{11}] \), where \( P_n \) is the measured spin flip proportion after \( n \) \( \pi/2 \) rotations.