Bell-state tomography in a silicon many-electron artificial molecule

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An error-corrected quantum processor will require millions of qubits, accentuating the advantage of nanoscale devices with small footprints, such as silicon quantum dots. However, as for every device with nanoscale dimensions, disorder at the atomic level is detrimental to quantum dot uniformity. Here we investigate two spin qubits confined in a silicon double quantum dot artificial molecule. Each quantum dot has a robust shell structure and, when operated at an occupancy of 5 or 13 electrons, has single spin-$\frac{1}{2}$ valence electron in its $p$- or $d$-orbital, respectively. These higher electron occupancies screen static electric fields arising from atomic-level disorder. The larger multielectron wavefunctions also enable significant overlap between neighbouring qubit electrons, while making space for an interstitial exchange-gate electrode. We implement a universal gate set using the magnetic field gradient of a micromagnet for electrically driven single qubit gates, and a gate-voltage-controlled inter-dot barrier to perform two-qubit gates by pulsed exchange coupling. We use this gate set to demonstrate a Bell state preparation between multielectron qubits with fidelity 90.3%, confirmed by two-qubit state tomography using spin parity measurements.
Semiconductor nanodevices, especially those incorporating oxide-insulating layers, suffer from variability due to various atomic-scale defects and morphological imprecision. This disorder degrades spin qubit performance due to the sub-nanometre wave properties of single electrons. The conflict between the benefits of densely packing many quantum dots within a chip and the exposure to disorder demands further research regarding improved systems for encoding solid-state qubits. We exploit here the operation of qubits in silicon metal-oxide-semiconductor (Si-MOS) quantum dots containing several electrons that form closed shells, leaving a single valence electron in the outer shell. The spin of a valence electron in a high-occupancy Si-MOS quantum dot was previously shown to form a high-fidelity single qubit, at least in part due to the improved screening of disorder provided by the raised electron density. However, it was not clear how well two-qubit logic could be performed using such systems, because of the complex molecular states present in a many-electron double quantum dot. We address this here using two multielectron qubits to operate an isolated quantum processing unit.

Results

This demonstration is performed with the device structure depicted in Fig. 1a and investigated in previous studies. Using the technique adopted from ref. 4, where the quantum dots are isolated from the electron reservoir, we load electrons into the two quantum dots formed under gates G1 and G2, and separated by gate J. We monitor inter-dot charge transitions by measuring the transconductance of a nearby single electron transistor (SET). An on-chip cobalt micromagnet is fabricated 120 nm away from the quantum dots. This micromagnet serves two purposes: to create an inhomogeneous magnetic field and an oscillatory electric field, for electrically driven spin resonance (EDSR)

To achieve an isolated mode of operation, the quantum dots are initialized with a desired number of electrons using the reservoir under RG, then the tunnel rate between the quantum dot under G2 and the reservoir is made negligible by lowering the voltage applied to gate BG, such that the double quantum dot becomes isolated. Figure 1c is a charge stability diagram with vertical lines indicating inter-dot charge transition. For the experiment discussed here, we load a total of 18 electrons. It is noteworthy that diagonal lines on the upper half of Fig. 1c (around $V_J = 1.9\, \text{V}$) mark transitions in which the J gate becomes too attractive for electrons and instead of forming a barrier it forms a quantum dot between G1 and G2. At very low voltages, the J gate creates a large barrier between the dots suppressing inter-dot tunnelling. Once the tunnel rate becomes less than the...
lock-in frequency (487 Hz), the transition lines fade, as observed for \( V_J < 1.6 \) V. In contrast to the experiment in ref. 4, which was performed using the same device as the present work, but at a lower charge occupancy of (3,3), the inter-dot charge transitions in Fig. 1c exhibits very high uniformity, showing the improved screening of disorder that is possible when many electrons are confined in the quantum dots. As the number of electrons in a quantum dot increases, the dot potential profile becomes more regular and is primarily defined by the gate electrodes structure, with limited impact from random charge disorder.

In a small two-dimensional circular quantum dot, full shells are formed at 4 and 12 electrons1,8–10. The fourfold degeneracy of the first shell has its origin in the spin and valley degrees of freedom for silicon conduction band electrons. The next shell is formed by two-dimensional \( p \)-like states, which means the \( p_x \) and \( p_y \) states are quasi-degenerate in the approximately circularly symmetric dot. This shell can fit a total of eight electrons. We control the voltage detuning \( \varepsilon \) between gates G1 and G2 voltages such that there are 13 and 5 electrons in Q1 and Q2, respectively, as shown in Fig. 1b, c. This means we have effectively a single valence electron in each quantum dot (\( d \)-shell and \( p \)-shell, respectively), whereas the electrons in the inner shells stay inert during spin operations1. Evidence supporting the \( p \)- and \( d \)-shell structures is demonstrated in the Supplementary Information. In choosing to focus here on the (13,5) charge configuration, we take into consideration the impact that various shell structures have on the qubit performance as identified in refs. 1,4. These include the impact of the excited state energies on a number of factors including the following: the creation of relaxation hotspots; the determination of a readout window for the Pauli spin blockades; the EDSR Rabi frequency; and the extent of the waveform and how it controls the exchange coupling between neighbouring dots. Early results from ref. 4 indicate that choosing the same shell occupancy for both dots does not necessarily imply consistent qubit characteristics, so there is no particular advantage to operating with the same number of electrons in each dot. Therefore, from a proof-of-principle perspective, it is beneficial to highlight the versatility of multielectron quantum dots as a qubit platform, by operating a \( p \)- and a \( d \)-shell electron in Q1 and Q2, respectively. In an earlier study, we demonstrated the improved performance of these shell configurations compared with \( s \)- or \( f \)-shell electrons for single-qubit operation1, but a systematic study of the optimal number of electrons for a two-qubit system is out of the scope of our present work.

In general, EDSR control of qubits is heavily influenced by the details of the quantum dot confinement potential9. By employing the voltage pulse sequence from ref. 4 for initialization, control, and readout, we investigate these parameters performing an adiabatic inversion of the spins with a variable frequency microwave excitation, with an external magnetic field \( B_0 = 1 \) T. First, a voltage ramp across the (12,6)–(13,5) transition over a period of 500 \( \mu \)s is applied, which is equivalent to the variation of the detuning \( \varepsilon \), such that a \( |\downarrow \downarrow \rangle \) spin state is initialized adiabatically. We note that (12,6) provides a good initialization, because it is a spin-0 configuration, as confirmed by magnetospectroscopy (see Supplementary Information). Moreover, a large anticrossing gap between this (12,6) singlet and the \(|\downarrow \downarrow \rangle \) state at (13,5) occupation is created by the difference in quantization axes between dots due to the micromagnet field gradient. We further improve the fidelity of this initialization by simultaneously lowering \( V_J \), to enhance the energy gap between this target state and the (14,4) singlet. Subsequently, a chirped pulse of microwave
Fig. 3 Bell state tomography. a Adiabatic inversion probability of both qubits as a function of detuned microwave frequency $\Delta f_{MW}$, where the carrier frequency is chosen to be the single-qubit operation frequency for Q2 and J gate voltage $\Delta V_J$, with qubits initialized in the $|\uparrow \downarrow\rangle$ state. Horizontal dashed lines represent J gate voltages applied for various single-qubit and two-qubit gates. Yellow dotted lines are a guide indicating the other resonance frequencies that would be observed at $\Delta V_J > 100$ mV if the spins were initialized randomly. b Schematic of an example microwave and voltage pulse sequence for state tomography. It initializes the qubits as $|\uparrow \downarrow\rangle$ by performing two $\pi/2 \times 1$ pulses (all calibration is performed for $\pi$ pulses, such that a high-fidelity $\pi$ pulse is obtained by composing it out of two $\pi/2$ gates, each starting and finishing at a common voltage $\Delta V_J = -70$ mV, which is shown as a blue dashed line in a), then perform I2 projection operation, by converting the parity readout into single-qubit readout via a CNOT gate. Horizontal lines align with $\Delta V_J$ from a. c Example qubit states and operations required to obtain projections along the indicated axes. The first, two columns of Bloch spheres represent the eigenstates of Q1 (red) and Q2 (blue) before state tomography, whereas the rest illustrates the logic gate operations required for state tomography, before parity readout. For IX and IZ, all possible initial eigenstates are displayed, with parity results shown on the last column. d-g Quantum-state tomography of Bell states $\Phi^+ = (|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle)/\sqrt{2}$, $\Phi^- = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$, $\Psi^+ = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$, $\Psi^- = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$. The height of the bars represents the absolute value of density matrix elements, whereas complex phase information is encoded in the colour map. Inset: bar graph of the ideal density matrix of the corresponding Bell state. The measured fidelities of each Bell state are $(87.1 \pm 2.8)^\%$, $(90.3 \pm 3.0)^\%$, $(90.3 \pm 2.4)^\%$, and $(90.2 \pm 2.9)^\%$, from d to g, respectively.

excitation with variable frequency adiabatically flips one of the spins into an antiparallel configuration, creating either a $| \downarrow \uparrow \rangle$ or a $| \uparrow \downarrow \rangle$ state, if the frequency sweep matches the resonance frequency of the qubit. This spin flip is then read out by quickly changing $\epsilon$ back to a (12,6) ground state, which will be blockedade by the Pauli principle unless the spin flip to the antiparallel configuration was successful.

Figure 1d shows the nonlinear dependency of the qubit resonance frequencies with electric potentials (Stark shift). Moreover, the efficiency of the adiabatic inversion of the spins depends on the intensity of the effective oscillatory field that drives Rabi oscillations. This is indicated by the colours in Fig. 1d and shows that each qubit has a different optimal gate configuration, such that a sufficiently fast Rabi oscillation frequency is obtained to ensure good control fidelity. This dependence of the Rabi frequency on the gate-voltage configurations was observed previously and associated with the electron position shifting under the micromagnet field. For more information on the method of choosing the optimal operation point, analysis of the Rabi efficiencies, and coherence times of the qubits, refer to Supplementary Information.

The geometry of the MOS device studied here is known to lead to single electron wavefunctions that extend laterally ~10 nm, which is consistent with the large charging energy previously measured in this device when a second electron is added. As the nominal distance from the centre of G1 to the centre of G2 exceeds 60 nm, the inter-dot exchange coupling in the (1,1) charge configuration is predicted to be insufficient for quantum operations—indeed, previous measurements in the same device reveal that exchange is only observed when the $J$ gate is positive enough to form a dot under it. At the $p$- and $d$-shells, nonetheless, the Coulomb repulsion from the core electrons leads to a larger wavefunction for the valence electron. As a result, we are able to measure a sizeable interaction between distant qubits. The
ability to control the inter-dot interaction is crucial for high-fidelity two-qubit gate operations. High-fidelity single-qubit gates require low exchange coupling to ensure individual addressability, whereas two-qubit gates demand strong coupling for fast exchange oscillation with minimal exposure to noise. Previous literature indicates the possibility to control exchange coupling between two multielectron quantum dots. Here we explore two methods for controlling inter-dot interactions—by detuning the quantum dot potentials, as shown in Fig. 2a, or by directly controlling the inter-dot barrier potential via an exchange J gate, as in Fig. 2b.

For each method, the exchange intensity is measured by comparing the precession frequency of one qubit (target) depending on the state of the other qubit (control) with a Ramsey interferometry protocol. Due to the large difference in Larmor frequencies between quantum dots, only the z components of the spins couple to each other, while the x and y components oscillate at different rates for each qubit and their coupling is on average vanishingly small. The measured oscillations shown in Fig. 2c, d result from a combination of the exchange coupling and the Stark shift induced by the gate pulses, measured with regard to a reference frequency f_red, which can be conveniently chosen to optimize the accuracy of our measurements (see Supplementary Information). The exchange coupling may be obtained by taking the difference between the resulting frequencies for the two states of the control qubit Q2 and Q1.

Figure 2e, f show the extracted oscillation frequencies as controlled by either the detuning ε or the exchange-gate voltage V_J. The difference in oscillation frequencies corresponds to the exchange coupling and can be tuned over two orders of magnitude, as seen in the extracted exchange coupling intensities in Fig. 2g, h. We use this conditional control to implement the two-qubit CZ gate. The impact of exchange coupling on qubit coherence is quantified by extracting the decay time of the exchange oscillations T_CZ, shown in Fig. 2i as a function of the extracted exchange coupling for both CZ operation methods. We observe an improvement in the driven coherence times when the exchange control is performed by pulsing the J gate to control the inter-dot barrier, as compared to the detuning method. As both methods can reach similar exchange frequencies, this results in an improvement in the quality factor of the exchange oscillations Q = J × T_CZ as seen in Fig. 2j, similar to previously reported experiments. Throughout the rest of this work, we adopt the direct J gate-controlled exchange coupling method for the implementation of CZ logic gates.

As shown in Fig. 1d, both qubits possess a strongly nonlinear Stark shift and large variation in the efficiency of the EDSR drive. Single-qubit control fidelity in excess of 99% was only achieved when the gate-voltage configuration was tuned differently for each qubit, as indicated in the example gate sequence shown in Fig. 3a. This leads to a major limitation—single-qubit gates must be performed sequentially, whereas the other qubit is left idling, unable to be protected by refocusing techniques such as dynamical decoupling or pulse shaping. Together with the two-qubit CZ gate, these span the two-qubit Clifford space (see Fig. 3b for illustration).

The strong Stark shift between operating points leads to a phase accumulation with regard to a reference frequency, which must be accounted for in gate implementations (see Supplementary Information). To minimize the gate error introduced by resonance frequency shifts (due to electrical 1/f noise and nuclear spin flips), a number of feedback protocols are implemented. The following input parameters are monitored periodically and adjusted if necessary: SET bias voltage, readout voltage level, ESR frequencies of both qubits, phase accumulations at five different gate voltages for the logic gates, and exchange coupling. This results in a total of ten feedback calibrations in each experiment. Further information on phase and exchange coupling feedback is provided in the Supplementary Information.

Discussion
Our study highlights various advantages of multielectron qubits, which lead to efficient EDSR-based single-qubit gates and extended reach of the exchange coupling between neighbouring qubits. The protocol for logic gates developed here leads to promising fidelities for Bell state preparation, but its use in longer computations would be impacted by the inability to refocus the spin that is not being manipulated. This problem can be solved by designing a more efficient EDSR strategy without the need to optimize the gate configuration, or by using an antenna to produce microwave magnetic field-based electron spin resonance. The ability of additional core electrons to screen charge disorder at the Si/SiO2 interface, as demonstrated here, indicates that multielectron qubits offer a promising pathway for near term demonstrations of quantum processing in silicon.

Data availability
The data that support the findings of this study are available from the authors on reasonable request; see author contributions for specific data sets.

Code availability
The code that support the findings of this study are available from the authors on reasonable request; see author contributions for specific code sets.

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Author contributions

R.C.C.L. and C.H.Y. performed the experiments. J.C.L., R.C.C.L., J.C.C.H., C.H.Y. and M.P.-L. designed the micromagnet, which was then simulated by J.C.L. and M.P.-L. J.C.C.H. and F.E.H. fabricated the device with A.S.D.’s supervision. K.M.I. prepared and supplied the 28Si epilayer. J.C.C.H., W.H. and T.T. contributed to the preparation of experiments. R.C.C.L., C.H.Y., A.S. and A.S.D. designed the experiments, with J.C.L., M.P.-L., W.H., T.T. and A.L. contributing to results, discussion, and interpretation. R.C.C.L., A.S. and A.S.D. wrote the manuscript with input from all co-authors. R.C.C.L. and J.Y.H. contributed in device visualization of Fig. 1a, b, while R.C.C.L. created the rest of the figures in the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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