Coherent coupling between a quantum dot and a donor in silicon

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Individual donors in silicon chips are used as quantum bits with extremely low error rates. However, physical realizations have been limited to one donor because their atomic size causes fabrication challenges. Quantum dot qubits, in contrast, are highly adjustable using electrical gate voltages. This adjustability could be leveraged to deterministically couple donors to quantum dots in arrays of qubits. In this work, we demonstrate the coherent interaction of a 31P donor electron with the electron of a metal-oxide-semiconductor quantum dot. We form a logical qubit encoded in the spin singlet and triplet states of the two-electron system. We show that the donor nuclear spin drives coherent rotations between the electronic qubit states through the contact hyperfine interaction. This provides every key element for compact two-electron spin qubits requiring only a single dot and no additional magnetic field gradients, as well as a means to interact with the nuclear spin qubit.
The silicon industry’s fabrication capability promises to be a differentiating accelerator for the future development of quantum computers built with silicon quantum bits (qubits). Silicon is, furthermore, an appealing material for qubits because it provides an ultra low decoherence environment. In particular, extremely high fidelities have been demonstrated for both the electron and nuclear spins of a single dopant atom in isotopically-enriched silicon nanostructures. Assembling these exceptional solid-state qubits into a full quantum processor, as envisioned by Kane, will require coupling donor atoms to one another in a controllable way. This has proven extremely challenging, demanding near-atomic precision in the placement of the donors. In contrast, single electron spins confined in quantum dots (QDs) are routinely coupled to one another since quantum dots are highly tunable and fabricated in engineered locations, allowing for controllable and scalable two-qubit interactions. For this reason, QDs have been theoretically discussed as intermediates to couple donor qubits. Recently, spin blockade has been observed in a silicon QD-donor system. However, the coherent spin coupling between donor and quantum dot-based qubits has remained elusive. It is the cornerstone advance necessary for exploiting the advantages of these two complementary qubit systems.

Here, we advance silicon-based quantum information processing by coherently coupling a phosphorus donor’s electron spin to a metal-oxide-semiconductor (MOS) QD. In our system, the QD is tuned to few-electron occupancy while simultaneously keeping a nearby donor (D) tunnel-coupled to the QD. The combination of the QD and donor electron qubits gives rise to a joint singlet-triplet (ST) logical encoding analogous to those in double-QD schemes such as micromagnets, microwave striplines or engineered locations, allowing for controllable and scalable two-qubit interactions. For this reason, QDs have been theoretically discussed as intermediates to couple donor qubits. Recently, spin blockade has been observed in a silicon QD-donor system. However, the coherent spin coupling between donor and quantum dot-based qubits has remained elusive. It is the cornerstone advance necessary for exploiting the advantages of these two complementary qubit systems.

The electron qubit formed by the QD-D coupled system is analogous to other ST qubits, while introducing important advantages. It features full electrical control with a uniquely compact design requiring only one QD. The QD-ST qubit avoids the integration complexities of other Si spin control schemes such as micromagnets, microwave striplines, or additional QDs for full electrical control. The hyperfine coupling to the single nuclear spin introduces a nature-defined and potentially very stable (i.e. low noise) rotation axis for the ST qubit. Furthermore, the system has a natural access to the nuclear spin, which is one of the highest performing solid state qubits. Integration of a coil for nuclear magnetic resonance could enable full control over the nuclear spin qubit. Nuclear spin readout schemes based on ST interactions with the donor have already been proposed, making complete control of these two coupled qubits foreseeable in the near future. The engineered coupling of the QD and D spins constitutes a possible path to realize over nineteen years of different theoretical proposals of donor qubit architectures. For example, the large lithographic quantum dot can facilitate the coupling of neighboring QD-D cells using capacitive coupling or exchange interaction.  

**Results**  
**Device description.** The QD-D device is fabricated with isotopically-enriched $^{28}$Si and a foundry-compatible process (i.e. no lift-off processing). We use a poly-silicon gate stack, shown in Fig. 1a, that allows self-aligned ion implantation and subsequent activation annealing process. Phosphorus donors are implanted using the AG gate as a mask. This process maximizes the probability of placing a D in a suitable location next to the QD. It also facilitates future multi-qubit fabrication that could take advantage of single ion implantation and a planar QD geometry. Fabrication details are found in the Supplementary Note 1 and are similar to ref. 39. A channel of electrons is formed at the MOS interface underneath the wire-shaped accumulation gate (AG) by applying a positive voltage, depicted as a blue overlay in Fig. 1a. Next, a QD island is isolated by applying suitable negative voltages on neighboring gates. A single-electron transistor (SET) is formed in the upper wire to monitor the electron occupation N of the QD and the relevant donor, denoted $(N_{QD}, N_D)$. The SET charge sensor (CS) is also used for spin blockade via spin-to-charge conversion. An in-plane magnetic field of 300 mT is applied throughout the experiments and the electron temperature is measured to be 215 mK. Detailed information about fabrication, gate biasing and electron counting is provided in the Supplementary Note 2.

To investigate coherent coupling dynamics between the donor and the QD, we first identify an effective $(2, 0)\leftrightarrow(1, 1)$ QD-D charge transition with a total of four electrons, as shown in Fig. 1b–d. We use the spin filling structure, measured through magnetic fields, to engineer a sufficiently large energy difference $J_{QD,D}(4,0)$ between the singlet and triplet states, which we observe to be substantially larger for four electrons (~150 μeV) than for two electrons (~60 μeV). Details are available in the Supplementary Note 3. In Si MOS, the valley splitting can be tuned to large values by increasing the electric field perpendicular to the interface, which was verified in this device. Simultaneously keeping the donor in resonance with the few electron QD states, however, constrained the available range of voltage in this design leading to the relatively small two-electron valley splitting. We note two general benefits of using the four-electron configuration: (i) filled shells might be a general approach to circumvent the obstacle of low valley splitting in any material with conduction band degeneracy; and (ii) increased electron numbers can extend the size of the QD due to the increased filling of the potential well, which in turn allows more range in selecting a suitable tunnel coupling to remote donor sites.

**Hyperfine-driven spin rotations.** Rotations between $|S\rangle$ and $|T_0\rangle$ can be driven by an effective magnetic field gradient $\Delta B_z = \pm A/2$ between the QD and the donor (in the remainder of the text we will drop the ket notation). These rotations provide a signature of the single $^{31}$P donor. The source of the effective $\Delta B_z$ is the contact hyperfine interaction $A\vec{S}\cdot\vec{I}$ between the donor electron spin $\vec{S}$ and the nuclear spin $\vec{I}$. We expect the nuclear spin state to be projected onto a $\pm 1/2$ eigenstate by the repetitive experimental measurement. Rapidly separating a singlet state by pulling one electron onto the donor triggers coherent rotations between the $S$ and $T_0$ states. Reuniting the electrons onto the QD projects the state onto $S$ or $T_0$. We note that spin preparation, manipulations and readout act self-consistently with respect to a fixed but unknown state of the nuclear spin (i.e. the sign of $\Delta B_z$) in sufficiently large magnetic fields such that the interaction with the polarized triplets is suppressed (which is the case in this experiment). Moreover, nuclear states are known to be long lived (~seconds) compared to the timescale of electron manipulations, therefore, errors caused by random flips while an electron is on
Electrical voltages adjust the relative magnitudes of the exchange energy and the effective magnetic field. Note 4 to measure the triplet return probability.

The electron qubit (blue arrows) is well suited for fast operations and readout. The nuclear spin qubit has high coherence and fidelity. The donor electron can be moved to the QD using gate voltages. In this (4, 0) configuration at the Si-oxide interface in a large tunable QD and separated by a valley splitting, the hyperfine interaction with the \( ^{31}\text{P} \) nucleus makes the electrons precess at different rates, creating an effective magnetic field difference \( \Delta B_z = \pm A/2 \) between the QD and the D.

Characterization of exchange interaction. The detuning dependence of the ST rotations reveals additional information about this QD-D system. In Fig. 3a, we plot the triplet return probability against both detuning and manipulation time. As the detuning gets closer to zero, the frequency of the exchange rotations increases, as shown in Fig. 3c. This is consistent with a ST model where the exchange energy \( J \) between the S and T\(_0\) states is not negligible and drives rotations around a tilted axis in the qubit Bloch sphere. To better understand the exact shape of the oscillations of Fig. 3a, we simulate the quantum dynamics of
the system using a master equation approach and time-dependent controls. We describe the system using the basis states $\{(4, 0) S, (4, 0) T_0, (3, 1) S, (3, 1) T_0\}$, similarly to previous treatments such as Taylor et al.29. The details of the model are given in the Supplementary Note 7. The numerical simulation results are shown in Fig. 3c. Inset: Frequency of the oscillations for repeated measurements over 3 h. Each point represents data averaged over 22 min, and the error bar represents the 95% confidence interval.

Discussion
Decoherence of MOS QDs33 and single donors4 has been characterized in separate systems, but the charge noise and magnetic noise properties of strongly hybridized QD-D systems are not well established. Our system provides a unique platform to study these important properties in an effective two-electron case where entanglement is delocalized in the form of a spatially separated singlet or triplet. We measure long time traces and plot the visibility of the oscillations vs. manipulation time $t$ in Fig. 4a. The data and method are presented in the Supplementary Note 9. We then fit the decay using a slow detuning noise model that produces a Gaussian decay of the visibility $v = v_0 \exp\left[-(t/T_{2e})^2\right]$, where $v_0$ is an arbitrary initial visibility. We find that $T_{2e}$ depends on the detuning (Fig. 4b). To understand this dependence, we use a charge noise model represented by $n$ noise with a characteristic standard deviation $\sigma_n$ and producing decoherence through $J_n(e)$46. Details about the model are given in the Supplementary Note 10. We find that $\sigma_n = 9 \, \mu eV$ is consistent with the observed $T_{2e}$. In this model, we neglect magnetic noise that could be caused by residual $^{29}$Si or other sources. Our observations are consistent with $T_{2e}$ being limited by charge noise, a mechanism that is expected to play an important role when $J$ varies as a function of $e$46. We note that $\Delta\sigma$ is approximately the electronic temperature $k_B T_e$. The noise magnitude has previously been correlated with the electronic temperature46. We further tabulate noise magnitudes in a variety of material systems, like GaAs/AlGaAs heterostructures47, Si/Ge heterostructures48 and MOS (this work), and show the results in Fig. 4c.

In summary, we have demonstrated coherent coupling between the electrons of two very different qubit systems: a donor atom (natural atom) and a MOS quantum dot (artificial atom)49. The coherent rotations between the singlet and triplet are driven by a nuclear spin qubit through the contact hyperfine interaction, and produce $10$ ns $X(\pi)$ rotations with a $T_{2e}$ of $1.3 \pm 0.7$ $\mu s$, thus

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**Fig. 2** Hyperfine ST rotations. a Pulse sequence for the spin manipulations with schematic conduction band diagrams through the reservoir, QD and donor. The system is initialized as (4, 0)S and plunged to point P. Then, the detuning is pulsed rapidly to point A, which yields a separated (3, 1)S. After a given manipulation time in (3, 1), which rotates the spin between S and $T_0$, it is pulsed back to point P. The state is then either (4, 0)S or (4, 0)T_0, and is measured by going to point M, where an enhancement in CS signal occurs (see Supplementary Note 4). b QD-D charge stability diagram. Overlaid are the different points of the experiment’s pulse sequence. The detuning $\epsilon$ is defined along the black line with zero detuning at the center of the (4, 0) ↔ (3, 1) transition. c Triplet probability vs. manipulation time for $\epsilon = 950 \, \mu eV$. The oscillation frequency is $f = 56.9$ MHz. This is not the bare hyperfine frequency due to a residual exchange of $J/h = 27$ MHz, see Fig. 3c. Inset: Frequency of the oscillations for repeated measurements over 3 h. Each point represents data averaged over 22 min, and the error bar represents the 95% confidence interval.
allowing over 100 rotations within the coherence time. A charge noise magnitude of 9 μeV fits the stationary noise model and is a characterization of the MOS interface noise properties, which are found to be of similar magnitude to other common QD material systems. Assuming this model, the $T_2^*$ could possibly be improved by a factor 10 or more by operating at larger detunings where the exchange is negligible, hence taking full advantage of isotopically pure silicon. Our experiments demonstrate the feasibility of using the QD-D system as a compact ST qubit with no additional micromagnets or QDs (as in all-exchange qubits), and avoid the decoherence mechanisms associated with GaAs or Si host nuclear species.

More sophisticated ST qubit control approaches and optimized preparation/readout parameters will likely increase the visibility and reduce errors of future two-axis QD-0 qubit demonstrations. To further speed up the operations compared to the coherence time, it could be possible to use other donor species that have stronger contact hyperfine strengths. Beyond individual ST qubits, this work opens-up compelling possibilities. One such example is the coupling of donor-based qubits without atomic precision placement through, for example, electrostatic coupling between ST qubits. Another example is all-electrical nuclear spin readout and electric/nuclear magnetic resonance control without high magnetic fields or ESR, thus introducing a nuclear spin qubit as an additional resource.

Data availability. The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Additional data (e.g. source data for figures) are available from the corresponding author upon reasonable request.

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Author contributions
P.H.-C. and M.S.C. designed the experiments. P.H.-C. performed the central measurements and analysis presented in this work. M.R. performed supporting measurements on similar “control” samples that establish repeatability of many observations in this work. N.T.J., P.H.-C., M.R. and J.K.G. modelled key elements of the device structure providing insights. P.H.-C., M.S.C., N.T.J. and M.P.-L. analyzed and discussed central results throughout the project, including designing models for observations. J.D., T.P., G.A.T.E. and M.S.C. designed process flow, fabricated devices and designed/characterized the 28Si material growth for this work. I.R.W. provided critical nanolithography steps. M.L. supplied critical laboratory set-up for the work. M.S.C. supervised combined effort including coordinating fab and identifying modelling needs for experimental path. P.H.-C., M.S.C. and M.P.-L. wrote the manuscript with input from all co-authors.

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