A fast quantum interface between different spin qubit encodings

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Single-spin qubits in semiconductor quantum dots hold promise for universal quantum computation with demonstrations of a high single-qubit gate fidelity above 99.9% and two-qubit gates in conjunction with a long coherence time. However, initialization and readout of a qubit is orders of magnitude slower than control, which is detrimental for implementing measurement-based protocols such as error-correcting codes. In contrast, a singlet-triplet qubit, encoded in a two-spin subspace, has the virtue of fast readout with high fidelity. Here, we present a hybrid system which benefits from the different advantages of these two distinct spin-qubit implementations. A quantum interface between the two codes is realized by electrically tunable inter-qubit exchange coupling. We demonstrate a controlled-phase gate that acts within 5.5 ns, much faster than the measured dephasing time of 211 ns. The presented hybrid architecture will be useful to settle remaining key problems with building scalable spin-based quantum computers.
initialization, single-qubit and two-qubit gate operations, and measurements are fundamental elements for universal quantum computation. Generally, they should all be fast and with high fidelity to reach the fault-tolerance thresholds. So far, various encodings of spin qubits into one to three-spin subspaces have been developed in semiconductor quantum dots. In particular, recent experiments demonstrated all of these elements including two-qubit logic gates for single-spin qubits proposed by Loss and DiVincenzo (LD qubits) and singlet-triplet (ST) qubits. These qubits have different advantages depending on the gate operations, and combinations thereof can increase the performance of spin-based quantum computing. In LD qubits, the two-qubit gate is fast as it relies on the exchange interaction between neighboring spins. In contrast, the two-qubit gate in ST qubits is much slower as it is mediated by a weak dipole coupling. Concerning initialization and readout, however, the situation is the opposite: it is slow for LD qubits, relying on spin-selective tunneling to a lead, while it is orders of magnitude faster in ST qubits relying on Pauli spin blockade. Therefore, a fast and reliable interface between LD and ST qubits would allow for merging the advantages of both realizations.

Here we present such an interface implementing a controlled-phase (CPHASE) gate between a LD qubit and a ST qubit in a quantum dot array. The gate is based on the nearest neighbor exchange coupling and is performed in 5.5 ns. Even though we do not pursue benchmarking protocols here, the gate time being much shorter than the corresponding dephasing time indicates that the fidelity of this type of gates can be very high. Our results demonstrate that controlled coherent coupling of different types of gated spin qubits is feasible, and one can proceed to combining their advantages. Overall, our work pushes further the demonstrated scalability of spin qubits in quantum dot arrays.

Results

A LD qubit and a ST qubit formed in a triple quantum dot (TQD). A hybrid system comprising a LD qubit and a ST qubit is implemented in a linearly-coupled gate-defined TQD shown in Fig. 1a. The LD qubit (QLD) is formed in the left dot while the ST qubit (QST) is hosted in the other two dots. We place a micromagnet near the TQD to coherently and resonantly control QLD via electric dipole spin resonance (EDSR) at the same time it makes the Zeeman energy difference between the center and right dots, much larger than their exchange coupling. At this energy, the Zeeman energy difference between the center and right dots, $E_{ST}$, much larger than their exchange coupling $f_{ST}$, such that the eigenstates of QST become $|↑⟩$ and $|↓⟩$ rather than singlet $|S⟩$ and triplet $|T⟩$. We apply an external in-plane magnetic field $B_{ext} = 3.166$ T to split the QLD states by the Zeeman energy $E_{Z}$ as well as to separate polarized triplet states $|↑⟩$ and $|↓⟩$ from the QST computational states. The experiment is conducted in a dilution refrigerator with an electron temperature of approximately 120 mK. The qubits are manipulated in the $(N_1, N_2, N_3) = (1,1,1)$ charge state while the $(1,0,1)$ and $(1,0,2)$ charge states are also used for initialization and readout (see Fig. 1b). Here, $N_{L(C,R)}$ denotes the number of electrons inside the left (center, right) dot.

We first independently measure the coherent time evolution of each qubit to calibrate the initialization, control, and readout. We quench the inter-qubit exchange coupling by largely detuning the energies of the $(1,1,1)$ and $(2,0,1)$ charge states. For QLD, we observe Rabi oscillations with a frequency $f_{Rab}$ of up to 10 MHz (Fig. 1d) as a function of the microwave (MW) burst time $t_{MW}$, using the pulse sequence in Fig. 1e. For QST, we observe the precession between $|S⟩$ and $|T⟩$ (ST precession) (Fig. 1f) as a function of the evolution time $t_{e}$, using the pulse sequence in Fig. 1g (see Supplementary Note 2 for full control of QST). We use a metastable state to measure QST with high fidelity (projecting to $|S⟩$ or $|T⟩$) in the presence of large $ΔE_{Z}^2$ with which the lifetime of $|T⟩$ is short.

Calibration of the two-qubit coupling. The two qubits are interfaced by exchange coupling $f_{QQ}$ between the left and center dots as illustrated in Fig. 1c. We operate the two-qubit system under the conditions of $E_{Z} ≫ ΔE_{ST}^2, ΔE_{ST} ≫ 0$ for $f_{QQ} ≫ f_{ST}$ where $ΔE_{Z}^3$ is the Zeeman energy difference between the left and center dots. Then, the Hamiltonian of the system is

$$\mathcal{H} = -E_{Z}^L ⟨z⟩ - ΔE_{ST}^2 ⟨z⟩/2 + f_{QQ} (\hat{a}_{L}^z ⟨z⟩^L - 1)/4$$

where $\hat{a}_{L}^z$ and $\hat{a}_{ST}^z$ are the Pauli z-operators of QLD and QST, respectively (Supplementary Note 3). The last term in Eq. (1) reflects the effect of the inter-qubit coupling $f_{QQ}$ for states in which the spins in the left and center dots are antiparallel, the energy decreases by $f_{QQ}/2$ (see Fig. 2a).

We observe the precession frequency $f_{ST}$ depends on the state of QLD, $f_{ST}^{QD} = (ΔE_{ST}^z - ΔE_{ST}^L - f_{QQ} / 2) / h$. Here $\sigma_{L}^z$ represents $|↑⟩$ or $|↓⟩$ and $+1$ or $-1$ interchangeably. This means that while $f_{QQ}$ is turned on for the interaction time $t_{int}$, QST accumulates the controlled-phase $ϕ_{z} = 2π f_{QQ} t_{int}/h$, which provides the CPHASE gate (up to single-qubit phase gates; see Supplementary Note 7) in $t_{int} = h/2f_{QQ}$. An important feature of this two-qubit gate is that it is intrinsically fast, scaling with $f_{QQ}/h$ which can be tuned up to $\sim 100$ MHz, and is limited only by the requirement $f_{QQ}/h ≪ ΔE_{Z}^2 / h ≈ 500$ MHz in our device.

Before testing the two-qubit gate operations, we calibrate the inter-qubit coupling strength $f_{QQ}$ and its tunability by gate voltages. The inter-qubit coupling in pulse stage F (Fig. 2b) is controlled by the detuning energy between $(2,0,1)$ and $(1,1,1)$ charge states (one of the points indicated in Fig. 1b). To prevent leakage from the QST computational states, we switch $f_{QQ}$ on and off adiabatically with respect to $ΔE_{Z}$ by inserting voltage ramps to stage F with a total ramp time of $t_{amp} = 24$ ns (Fig. 2b). The coherence precession of QST is measured by repeating the pulse stages from D to H without initializing, controlling and measuring QLD, which makes QLD a random mixture of $|↑⟩$ and $|↓⟩$. Figure 2c shows the FFT spectra of the precession measured for various interaction points indicated in Fig. 1b. As we bring the interaction point closer to the boundary of $(1,1,1)$ and $(2,0,1)$, $f_{QQ}$ becomes larger and we start to see splitting of the spectral peaks into two. The separation of the two peaks is given by $f_{QQ}/h$ which can be controlled by the gate voltage as shown in Fig. 2d.

We now demonstrate the controllability of the ST precession frequency by the input state of QLD, the essence of a CPHASE gate. We use the quantum circuit shown in Fig. 2b, which combines the pulse sequences for independent characterization of QLD and QST. Here we choose the interaction point such that $f_{QQ} = 90$ MHz. By using either $|↑⟩$ or $|↓⟩$ as the QLD initial state (the latter prepared by an EDSR π pulse), we observe the ST precessions as shown in Fig. 2e. The data fit well to Gaussian-decaying oscillations giving $f_{ST}^{QD} = 434 ± 0.5$ MHz and $f_{ST}^{QST} = 524 ± 0.4$ MHz [These are consistent with the values determined by Bayesian estimation discussed in Methods]. This demonstrates the control of the precession rate of QST by $f_{QQ}$ depending on the state of QLD.

Demonstration of a CPHASE gate. To characterize the controlled-phase accumulated during the pulse stage F, we separate the phase of QST into controlled and single-qubit contributions as $ϕ_{z} = -π \sigma_{L}^z f_{QQ} (t_{int} + t_{p}) / h$ and...
**Fig. 1** Hybrid system of a LD qubit and a ST qubit realized in a TQD. 

_**a**_ False color scanning electron microscope image of a device identical to the one used in this study. The TQD is defined in a two-dimensional electron gas at the GaAs/AlGaAs heterointerface 100 nm below the surface. The upper single electron transistor is used for radiofrequency-detected charge sensing24,25. A MW with a frequency of 17.26 GHz is applied to the S gate to drive EDSR. 

_**b**_ Stability diagram of the TQD obtained by differentiating the charge sensing signal $V_{rf}$. 

_**c**_ Hybrid system of a LD qubit and a ST qubit coupled by the exchange coupling $J_{QQ}$. 

_**d**_ Rabi oscillation of QLD (rotation around x-axis) driven by EDSR with $J_{QQ} \approx 0$ at point RL in Fig. 1b. The data is fitted to oscillations with a Gaussian decay of $T_{Rabi}^2 = 199$ ns. 

_**e**_ Pulse sequence used to produce Fig. 1d showing gate voltages $V_{PL}$ and $V_{PR}$ applied to the PL and PR gates and a MW burst $V_{MW}$. 

_**f**_ Precession of QST (rotation around z-axis) with a frequency of $f_{ST} = 280$ MHz due to $\Delta E_{ST}^Z$ taken at point E marked by the white circle in (1,1,1) in Fig. 1b, where $J_{QQ}$ and $J_{ST} \approx 0$. The data follow the Gaussian decay with a decay time of 207 ns (see Supplementary Fig. 2a) induced by the nuclear field fluctuations29. 

_**g**_ Pulse sequence used to produce Fig. 1f.
\[ \phi^{ST} = 2\pi \Delta E_{Z}^{ST} (t_{int} + t_{ramp}) / h + \phi_{0} \]

where \( \phi_{0} \) represents the effective time for switching on and off \( J_{QQ} \) (Supplementary Note 5). A phase offset \( \phi_{0} \) denotes the correction accounting for nonuniform \( \Delta E_{Z}^{ST} \) during the ramp (Supplementary Note 5). Then the probability of finding the final state of \( Q_{ST} \) in singlet is modeled as

\[ P_{S,\text{model}} = \cos \left( \phi_{obj} + \phi^{ST} \right) \exp \left( -\left( t_{int} / T_{2} \right) ^{2} \right) + b \]

where \( a, b, T_{2} \) represent the values of amplitude, mean and the dephasing time of the ST precession, respectively. We use maximum likelihood estimation (MLE) combined with Bayesian estimation\(^{29,30}\) to fit all variables in Eq. 2, that are \( a, b, t_{0}, J_{QQ}, T_{2}, \phi_{0}, \) and \( \Delta E_{Z}^{ST} \), from the data (Methods). This allows us to extract the \( t_{int} \) dependence of \( \phi_{obj} \) (Fig. 3a) (Methods) and consequently \( \phi_{C} = \phi_{obj} - \phi_{1} \) (Fig. 3b). It evolves with \( t_{int} \) in the frequency of \( j_{QQ} / h = 90 \) MHz, indicating that the CPHASE gate time can be as short as \( h / 2j_{QQ} = 5.5 \) ns (up to single-qubit phase). On the other hand, \( T_{2}^{*} \) obtained in the MLE is \( 211 \) ns, much longer than what is observed in Fig. 2c, f because the shorter data acquisition time used here cuts off the low-frequency component of the noise spectrum\(^{29}\). We note that this \( T_{2}^{*} \) is that for the two-qubit gate while \( j_{QQ} \) is turned on\(^8\), and therefore it is likely to be dominated by charge noise rather than the nuclear field fluctuation (Supplementary Note 6). The ratio \( 2j_{QQ} / h \) suggests that 38 CPHASE operations would be possible within the two-qubit dephasing time. We anticipate that this ratio can be further enhanced by adopting approaches used to reduce
the sensitivity to charge noise in exchange gates such as symmetric operation \(^{31,32}\) and operation in an enhanced field gradient \(^{33}\).

Finally we show that the CPHASE gate operates correctly for arbitrary QLD input states. We implement the circuit shown in Fig. 4a in which \(t_{\text{int}}\) is fixed to yield \(\phi_C = \pi\), while a coherent initial QLD state with an arbitrary \(\sigma^{LD}_{z}\) is prepared by EDSR. We extract the averaged \(\phi_{\sigma^{LD}}\) by Bayesian estimation \(^{29,30}\), which shows an oscillation as a function of \(t_{\text{MW}}\) in agreement with the Rabi oscillation measured independently by reading out QLD state. The oscillation visibility of \(\phi_{\sigma^{LD}}\) is most probably limited by low preparation fidelity of the input QLD state as the visibility of the oscillation in \(P_1\) is also low (see Methods).

**Discussion**

In summary, we have realized a fast quantum interface between a LD qubit and a ST qubit using a TQD. The CPHASE gate between these qubits is performed in 5.5 ns, much faster than its dephasing time of 211 ns and those ratio (~38) would be high enough to provide a high-fidelity CPHASE gate (Supplementary Note 8). Optimizing the magnet design to enhance the field gradient would allow even faster gate time beyond GHz with larger \(f^2\). At the same time, this technique is directly applicable to Si-based devices with much better single-qubit coherence \(^{5,9}\).

Our results suggest that the performance of certain quantum computational tasks can be enhanced by adopting different kinds of qubits for different roles. For instance, LD qubits can be used for high-fidelity control and long memory and the ST qubit for fast initialization and readout. This combination is ideal for example, the surface code quantum error correction where a data qubit must maintain the coherence while a syndrome qubit must be measured quickly \(^{34}\). Furthermore, the fast (~100 ns \(^{25}\)) ST qubit readout will allow the read out of a LD qubit in a quantum-demolition manner \(^{35}\) with a speed three orders of magnitude faster than a typical energy-selective tunneling measurement \(^{16,17}\). Viewed from the opposite side, we envisage coupling two ST qubits through an intermediate LD qubit, which would boost the two ST qubit gate speed by orders of magnitude compared to the demonstrated capacitive coupling scheme \(^{14}\). In addition, our results experimentally support the concept of the theoretical proposal of a fast two-qubit gate between two ST qubits based on direct exchange \(^{36}\) which shares the same working principle as our two-qubit gate. Our approach will further push the demonstrated scalability of spin qubits in quantum dot arrays beyond the conventional framework based on a unique spin-qubit encoding.

**Methods**

**Device design.** Our device was fabricated on a GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As heterostructure wafer having a two-dimensional electron gas 100 nm below the surface, grown by molecular beam epitaxy on a semi-insulating (100) GaAs substrate. The electron density \(n\) and mobility \(\mu\) at a temperature of 4.2 K are \(n = 3.21 \times 10^{15} \text{m}^{-2}\) and \(\mu = 86.5 \text{m}^2 \text{V}^{-1} \text{s}^{-1}\) in the dark, respectively. We deposited Ti/Au gate electrodes to define the TQD and the charge sensing single electron transistor. A piece of Co metal (micro-magnet, MM) is directly placed on the surface of the wafer to provide a local magnetic field gradient in addition to the external magnetic field applied in-plane (along \(z\)). The MM geometry is designed based on the numerical simulations of the local magnetic field \(^{31}\). The field property is essentially characterized by the two parameters \(^{25}\): \(B_B/dz\) at the position of each dot and the difference in \(B_z\) between the neighboring dots, \(B_B\) (see Fig. 1a for the definition of the \(x\) and \(z\) axes). \(B_B/dz\) determines the spin rotation speed by EDSR and is as large as ~1 mT nm\(^{-1}\) at the left dot (Supplementary Fig. 5a) allowing fast control of \(Q_{LD}(t_{\text{MW}} > 10 \text{MHz})\)\(^{20,23}\). At the same time \(\Delta B_B\) between the left and center dots, \(\Delta B^{LD}_{c1}\) is designed to be ~60 mT (Supplementary Fig. 5b) to guarantee the selective EDSR.

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**Fig. 3** Controlled-phase evolution. **a** Interaction time \(t_{\text{int}}\) dependence of \(\phi_{\sigma^{LD}}\) controlled by \(Q_{LD}\). The blue and red data are for \(Q_{LD} = |\uparrow\rangle\) and \(|\downarrow\rangle\), respectively. The solid curves are \(\sin(\phi_{\sigma^{LD}} \pm t_{\text{int}}/\hbar)\) (red) and \(\sin(-\phi_{\sigma^{LD}} \pm t_{\text{int}}/\hbar)\) (blue) where the values of \(\phi_{\sigma^{LD}}\) and \(t_{\text{int}}\) are obtained in the MLE. The curves are consistent with the data as expected. **b** Controlled-phase \(\phi_C = \phi_{\sigma^{LD}} - \phi_{\sigma^Z}\) extracted from Fig. 3a. Including the initial phase accumulated during gate voltage ramps at stage F, \(\phi_C\) reaches \(\pi\) at 4.0 ns and increases by \(\pi\) in every 5.5 ns afterwards.

**Fig. 4** Demonstration of the controlled-phase gate for arbitrary control qubit states. **a** The circuit for CPHASE gate demonstration. Here \(t_{\text{int}}\) is fixed at 4.2 ns where \(\phi_C \approx \pi\) (Fig. 3b). **b** \(t_{\text{MW}}\) dependence of the spin-down probability of \(Q_{LD}\), \(P_2\) (yellow) and the averaged \(\phi_{\sigma^{LD}}\) (purple) obtained by the circuit shown in Fig. 4a. \(\langle \phi_{\sigma^{LD}} \rangle = -\pi(\phi_C/2)\) is expected to be proportional to \(P_1\). We see \(\langle \phi_{\sigma^{LD}} \rangle\) oscillates depending on the input \(Q_{LD}\) state. The oscillation visibility of \(\phi_{\sigma^{LD}}\) is most probably limited by low preparation fidelity of the input QLD state as the visibility of the oscillation in \(P_1\) is also low (see Methods).
control of QLD without rotating the spin in the center dot.20,23 Furthermore, \( \Delta R_{\text{f}} \) between the center and right dots, \( \Delta R_{\text{f}}^{\text{LD}} \), is designed to be \(-40 \text{ mT} \) (Supplementary Fig. 5b) to make the eigenstates of QLD at \( |1\rangle \) and \( |\uparrow\rangle \) rather than \( |\downarrow\rangle \) and \( |\uparrow\rangle \) by satisfying \( \Delta E_{\text{f}}^{\text{LD}} \gg \omega_{\text{f}} \). Note that \( \Delta E_{\text{f}}^{\text{LD}} = \left| \mu_B \Delta R_{\text{f}}^{\text{LD}} \right| g \approx -0.4 \) and \( \mu_B \) are the electron g-factor and Bohr magneton, respectively. From the design we expect a large variation of \( \Delta E_{\text{f}}^{\text{LD}} \) when the electron in the center dot is displaced by the electric field. Indeed, we observe a strong influence of the gate voltages on \( \Delta E_{\text{f}}^{\text{LD}} \), which reaches \(-100 \text{ mT} \) at \( \Delta E_{\text{f}}^{\text{LD}} / h \approx 500 \text{ MHz} \) in the configuration chosen for the two-qubit gate experiment.

**Estimation of the ST precession parameters.** We here describe the estimation of the ST precession parameters in Eq. 2 under the influence of a fluctuating single-qubit phase of QLD. Out of the parameters involved, \( \phi_{\text{LD}} \) is the only parameter assumed to be QLD state-dependent, and the rest is classified into two types. One is the pulse-cycle-independent parameters, \( a, b, f_{\text{QD}}, T_{z}, \) and \( \theta_{0} \) which is constant during the experiment, and the other is the pulse-cycle-dependent parameters, \( \Delta E_{\text{f}}^{\text{LD}} \) and \( \phi_{0} \), which can change cycle by cycle. Each pulse cycle consists of pulse stages from A to C as shown in Fig. 2b. We run the pulse cycle consecutively with a fixed \( \Delta E_{\text{f}}^{\text{LD}} \) and \( \phi_{0} \) which reach \( \approx 100 \text{ mT} \). Then, we take the average of the estimated values for 800 pulse cycles. The oscillation visibility of \( \phi_{\text{LD}} \) in Fig. 4b is limited by three factors, low preparation fidelity of the input QLD state, estimation error of \( \phi_{\text{LD}} \) and CPHASE gate error. The first contribution is likely to be dominant as the visibility of the oscillation in \( P_{\text{m}} \) is correspondingly low. Note that the effect of those errors is not visible in Fig. 3 because the most likely values of \( \phi_{\text{LD}} \) are plotted.

**Data availability**

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions

A.N. and J.Y. conceived the experiment. A.N. and T.N. performed the measurement with the assistance of K.K., Y.K., M.R.D., T.O., K.T., S.A., and G.A.N. and T.N. conducted data analysis with the inputs from J.Y., P.S., and D.L. A.N. and T.N. fabricated the device on the heterostructure grown by A.L. and A.D.W. A.N. and T.N. wrote the manuscript with inputs from other authors. All authors discussed the results. The project was supervised by S.T.

Additional information

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