ARTICLE

Probing two-qubit capacitive interactions beyond bilinear regime using dual Hamiltonian parameter estimations

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We report the simultaneous operation and two-qubit-coupling measurement of a pair of two-electron spin qubits, actively decoupled from quasi-static nuclear noise in a GaAs quadruple quantum dot array. Coherent Rabi oscillations of both qubits (decay time ≈ 2 μs; frequency few MHz) are achieved by continuously tuning their drive frequency using rapidly converging real-time Hamiltonian estimators. We observe strong two-qubit capacitive interaction (>190 MHz), combined with detuning pulses, inducing a state-conditioned frequency shift. The two-qubit capacitive interaction is beyond the bilinear regime, consistent with recent theoretical predictions. We observe a high ratio (>16) between coherence and conditional phase-flip time, which supports the possibility of generating high-fidelity and fast quantum entanglement between encoded spin qubits using a simple capacitive interaction.

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INTRODUCTION

Spins in semiconductor quantum dot (QD) nanostructures offer a promising platform for realizing scalable quantum information-processing units with high-fidelity universal quantum control1–3. Recent progress in III–V and IV semiconducting materials demonstrated several achievements including the demonstration of single- and two-qubit gate fidelities exceeding 99% in NaTa5Si and 28Si (ref. 22), simultaneous qubit operations in GaAs with a coherence time over 2 μs (refs. 43), a few qubit entanglements in Ge and 28Si (refs. 6–8), high-temperature operations of spin qubits9–12, and long-range coupling of spin qubits using superconducting cavity structures12,13. The field is currently moving towards the high-fidelity control of multiple qubits and the generation of controlled entanglement.

However, low-frequency noise, including quasi-static nuclear fluctuation and slow charge noise, is one of the main factors reducing coherence times below the intrinsic limit of a given host material14–20. For example, the spin coherence time is often affected by charge noise coupled through the inhomogeneous magnetic field generated by micromagnets18,19. In addition, exchange- or capacitive-coupling-based two-qubit control is inherently susceptible to charge noise14,16,20–22. Thus, eliminating or mitigating slow magnetic and electric noises is an important task in semiconductor QD platforms.

Real-time Hamiltonian parameter estimation and measurement-based feedback23,24 are two complementary techniques to coherent quantum feedback25 capable of error mitigation, which is compatible — albeit sequentially—with general qubit controls. Previously, the Hamiltonian parameter estimation applied to GaAs has shown that the effect of quasi-static nuclear spin fluctuations can be strongly suppressed for single-spin23 and singlet–triplet (ST0) qubits26. Nevertheless, extending the technique to a multi-qubit system is desirable. While this has not been demonstrated to date, the simultaneous Hamiltonian estimation is also crucial for the accurate measurement of inter-qubit coupling strength. This is particularly important in the case of GaAs, for which the application of real-time calibrated single-qubit rotations on each qubit is a prerequisite.

In this study, we demonstrate the simultaneous drive of a pair of ST0 qubits in GaAs. The quasi-static nuclear noise for each qubit is actively decoupled using a Bayesian inference-based real-time Hamiltonian estimation circuit. We show high-quality Rabi oscillations for both qubits with an oscillation quality factor above 10. We further exploit this result to demonstrate the measurement of the electrostatic coupling of two ST0 qubits, which grows beyond an empirically assumed bilinear form26,27 for large intra-qubit exchange energies. Combining this with the spin-echo sequence, we assess the potential to generate a high-fidelity and fast conditional phase gate using capacitive interactions in a linear QD array.

RESULTS

Simultaneous Hamiltonian parameter estimation

Figure 1a shows a quadruple QD device on top of a GaAs/AlGaAs heterostructure, hosting a pair of ST0 qubits with singlet |S⟩ and triplet-zero |T0⟩ basis states (See methods section and ref. 28 for details of the material structure and device fabrication). High-frequency and synchronous voltage pulses, combined with DC voltages through bias-tees, were input to gates V1–V6. Fast dual RF reflectometry was performed by injecting a carrier signal having a frequency ≈ 125 MHz (153 MHz) and power of ~100 dBm at the Ohmic contacts of the left (right) RF single-electron transistors (see Fig. 1a). The reflected power was monitored through a frequency-multiplexed homodyne detection. The device was operated in a dilution refrigerator with a base temperature ≈ 7 mK, where an external magnetic field (0.7 T) was applied in the direction shown in Fig. 1a. The measured electron temperature is ≈ 72 mK (ref. 29).
The Hamiltonian of the two-qubit system is given (up to a constant term) by
\[
H = \frac{\Delta J_z}{2} \sigma_z \otimes I + \frac{\Delta B_{\text{fl}}}{2} \sigma_z \otimes I + \frac{\Delta J_x}{2} \sigma_+ \otimes \sigma_- + \frac{\Delta J_y}{2} \sigma_- \otimes \sigma_+ + \frac{\Delta J_z}{2} (\sigma_+ - I) \otimes (\sigma_- - I)
\] (1)

where \(J_z(\epsilon_i)\) is the exchange splitting between states \(|5\rangle\) and \(|T_0\rangle\), controlled by potential detuning \(\epsilon_i\) of the left (right) qubit (QL, QR). \(\sigma_{+ \text{z+}}\) is the Pauli matrix for QL (QR), \(I\) is the identity matrix, and \(\Delta B_{\text{fl}}\) is the magnetic field difference between the constituent QDs of each qubit, set by the local hyperfine interaction with the host GaAs and As nuclei. Here, we adopted \(g^* \mu_B/\hbar = 1\) for units, where \(g^* \approx -0.44\) is the effective gyromagnetic ratio in GaAs, \(\mu_B\) is the Bohr magneton, and \(\hbar\) is Planck’s constant.

For the real-time Hamiltonian estimation of the quasi-static fluctuations of the nucle \(\Delta B_{\text{fl}}\) and \(\Delta B_{\text{fr}}\), according to the following rule (up to a normalization constant)\(^4\)
\[
P(\Delta B_{\text{fl}}|m_{\alpha}, m_{\beta}; \Delta B_{\text{fl}}; \Delta B_{\text{fr}}) = \mathcal{P}_J(\Delta B_{\text{fl}}) \prod_{i=1}^N \mathcal{P}_{\alpha}(\Delta B_{\text{fl}}; \alpha) |1 + r_k(\alpha + \cos(2 \pi \Delta B_{\text{fr}}))\rangle, \text{ for } i = L, R.
\] (2)

where \(N\) is the number of single-shot measurements per Hamiltonian estimation, \(P_J(\Delta B_{\text{fl}})\) is the uniform initial distribution, \(r_k = 1(-1)\) for \(m_{\alpha} = \{\pm \} |T_0\rangle\), and \(\alpha = 0.1(\beta = 0.8)\) is the parameter determined by the axis of rotation on the Bloch sphere (oscillation visibility). After the \(N\)th round, the value of \(\Delta B_{\text{fl}}\) is estimated, where the posterior distribution \(P(\Delta B_{\text{fl}}|m_{\alpha}, m_{N-1}\text{...} m_{1})\) reaches its maximum. The Bayesian circuit was implemented using a commercial field-programmable gate array (FPGA)\(^6\) (see Supplementary Note 2).

Figure 1c shows a typical time trace of the estimated \(\Delta B_{\text{fl}}\) and \(\Delta B_{\text{fr}}\). The time resolution of these estimations is \(\sim 1.8\) ms, which consists of \((N = \pi) \times 26\) \(\mu\)s, where a single Bayesian update takes \(16\) \(\mu\)s and \(10\) \(\mu\)s for a single-shot measurement and calculation according to Eq. (2), respectively. We found that both \(\Delta B_{\text{fl}}\) exhibit nonzero average values, likely arising from unintentional nuclear polarization, as reported previously for similarly prepared GaAs devices.\(^{17,33}\)

When ensemble-averaged, this fluctuation leads to a nuclear fluctuation-limited coherence time \(T_2^\ast\) of the order of \(20\) ns. Moreover, the difference between the mean values of \(\Delta B_{\text{fl}}\) and \(\Delta B_{\text{fr}}\) is at least twice the standard deviation. While the microscopic origin of this phenomenon is not well known yet, we used this difference to set the range of qubit frequencies to \(< 5 \times \Delta B_{\text{fl}} < 200\) MHz for simultaneous qubit drive and active frequency feedback.

As shown in the inset of Fig. 2a, we concatenate the Bayesian estimators, acting as probe and operation steps, to control the two qubits in the frequency feedback mode. The controller triggers the operation step when the estimated \(\Delta B_{\text{fl}}\) in the probe step is in the range described above; otherwise, the cases are discarded. However, the preset range of allowed \(\Delta B_{\text{fl}}\) covers almost the entire distribution (Fig. 1c), so heralding does not significantly increase the total experimental time. When triggered, each qubit is first adiabatically initialized near the x axis on the Bloch sphere.

The controller also adjusts the RF drive frequency using the performed \(\Delta B_{\text{fl}}\) for each qubit. Then, an RF pulse, with a varied pulse length, is applied to gate \(V_2\) (\(V_3\)) to resonantly modulate \(J_z(\epsilon_i)\) and

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**Fig. 1 Experimental setup.** a A schematic of the experimental setup. Yellow circles indicate the RF single-electron transistors for dual RF reflectometry. Orange (green) circles indicate QDs for the left (right) ST0 qubit (QL and QR). The plunger and barrier gates are connected to the arbitrary waveform generator for the application of detuning and RF pulses. The white scale bar corresponds to 500 nm. b Schematic diagram of the dual Hamiltonian estimation of the field gradient \(\Delta B_{\text{fl}}\) and \(\Delta B_{\text{fr}}\). See main text for the estimation procedure. The green box shows the energy selective tunneling-based single-shot readout method. c The example traces of the simultaneously estimated field gradient \(\Delta B_{\text{fl}}\) of each qubit as a function of time.
Fig. 2 Simultaneous driving of two ST$_0$ qubits. a Individually driven Rabi oscillation of the triplet return probability $P_T$ of Q$_L$ and Q$_R$ as a function of controlled detuning $\delta f$ and RF pulse duration $t_{RF}$. b The representative $P_T$ oscillation of each qubit as a function of RF pulse duration for an individual and simultaneous operation. Solid curves are a fit to sinusoidal functions with a Gaussian envelope. c Ramsey fringe of $P_T$ as a function of controlled detuning $\delta f$ and Ramsey delay $t_{W}$, showing a typical Ramsey interference pattern. Inset: the line cut at the resonance condition. The solid curve is a fit to a Gaussian decay function $P_T(t_{W}) = A \exp\left(-\left(t_{W}/T^*_2\right)^2\right) + B$ with the best fit parameter $T^*_2 = 151$ (183) ns for Q$_L$ (Q$_R$).
induce Rabi oscillation. In all experiments, ~50 shots of operations were performed after one probe step.

The main panel of Fig. 2a shows the coherent Rabi oscillation for each qubit measured as a function of the RF pulse duration $t_{RF}$ and the controlled detuning $\delta f$ with respect to the actively adjusted resonant frequency. The chevron pattern of QR shows a resonance frequency shift, most likely caused by the AC stark effect. Figure 2b compares the Rabi oscillations for individual and simultaneous qubit operations under resonant conditions. For the former (latter), both the probe and RF pulses were applied to only one qubit (simultaneously on both qubits). For individual operations, QL (QR) shows a Rabi decay time $T_{Rabi} = 1.75 \mu s$ ($1.88 \mu s$) at the Rabi frequency $f_{Rabi} = 3.09$ MHz (5.69 MHz) and oscillation visibility of 90.8% (93.6%), yielding the oscillation quality factor $Q = f_{Rabi}T_{Rabi}/C^2$. For simultaneous operations, corresponding results are 1.68 $\mu s$ (1.59 $\mu s$), 3.12 MHz (5.68 MHz), and 88.4% (88.9%).

The comparison reveals that the Rabi frequency remains virtually unchanged regardless of the operation scheme. For individual operations, QL (QR) shows a Rabi decay time $T_{Rabi} = 1.75 \mu s$ ($1.88 \mu s$) at the Rabi frequency $f_{Rabi} = 3.09$ MHz (5.69 MHz) and oscillation visibility of 90.8% (93.6%), yielding the oscillation quality factor $Q = f_{Rabi}T_{Rabi}/C^2$. For simultaneous operations, corresponding results are 1.68 $\mu s$ (1.59 $\mu s$), 3.12 MHz (5.68 MHz), and 88.4% (88.9%).

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nates from the different electric dipole moments of states the target qubit by the RF crosstalk.

We now discuss the two-qubit capacitive-coupling measurements using the dual Hamiltonian estimation circuit discussed in the previous section. Specifically, throughout the experiment, a resonant RF pulse is applied to the control qubit to observe the state-dependent frequency shift of the target qubit, whose frequency is estimated by the Hamiltonian estimator. In addition, using the simultaneous Hamiltonian estimation circuit, the control qubit is operated when the separation between the qubit frequency is larger than 50 MHz to prevent the unwanted flip of the target qubit by the RF crosstalk.

The capacitive coupling between single-triplet qubits originates from the different electric dipole moments of states $|S\rangle$ and $|T_0\rangle$ (ref. 36). It has been considered to be a simple method to generate leakage-free two-qubit gates22,26,27,37 unlike the inter-qubit exchange coupling-based method, in which the inter-qubit magnetic field difference should be sizable to prevent leakage of the qubits outside the computational space22. Nevertheless, the weak coupling dependent on the intra-qubit exchange energies constitutes the main disadvantage of the capacitive-coupling method. For example, the pioneering demonstration of entanglement in GaAs26 used a coupling strength on the order of a few MHz, whereas individual exchange energies were approximately 300 MHz. Moreover, it has been assumed that capacitive coupling follows a bilinear form $J_{RL} \propto \Delta_{RL}$. In this bilinear form, the entanglement fidelity is expected to remain constant since the fidelity is limited by the dephasing of an individual qubit in $J_{RL} \ll \Delta_{RL}$ giving a constant quality factor for $T_1(\Delta_{RL}) \propto \frac{1}{\Delta_{RL}}$ (ref. 26). This constant entanglement fidelity is experimentally confirmed in previous research, indicating that the bilinear form seems to hold, at least for the experiment in which the inter-qubit distance is larger than the distance between dots within a qubit26,36.

The validity of the previously assumed scaling of $J_{RL}$ was experimentally tested in a regularly and compactly spaced linear QD array. Motivated by theoretical works showing that $J_{RL}$ can actually be a stronger function of $J_L$ and $J_R$ (ref. 37), we measured $J_{RL}$ by performing state-dependent exchange oscillation in combination with the dual Hamiltonian estimator. Figure 3a shows the pulse sequence for the target and control qubits. After the probe step, the control qubit is initialized to the $x$ axis of a Bloch sphere, followed by an optional $\pi$ pulse. $J_{RL}$ is then adiabatically switched on by slowly adjusting the detuning of the control qubit while the target qubit is initialized to the $x$ axis of a Bloch sphere. The exchange oscillation of the target qubit is then performed by diabatically changing the detuning of the target qubit for a time $t_{echo}$ to induce exchange oscillations, whose frequency depends on the control qubit state as $f = \frac{1}{2\pi} \frac{g}{\hbar} (J_L + J_R) \left( \frac{\hbar}{2 \Delta B} \right)$ according to Eq. (1), where $J'$ is the intra-qubit exchange energy of the target qubit and $r_L = 0 (1)$ when the state of the control qubit is $|S\rangle (|T_0\rangle)$.

Figure 3b (Fig. 3c) shows the resultant state-conditional frequency shift of $Q_L$ ($Q_R$) as a function of $t_{echo}$ with $J_{RL} \sim -3.61$ (4.13) GHz. The precession frequency of the qubit is lower when the control qubit is in the $|S\rangle$ state for both cases, which is consistent with the charge configuration of the QD array38. The observed frequency shifts of 34.9 (40.6) MHz for $Q_L$ ($Q_R$) is a direct measure of $J_{RL}$ which is significantly larger than the value...
reported in (ref. 39). As predicted in recent theoretical works, we hypothesize that the different relative orientations and the shorter distance between the qubits are related to this enhancement39. In addition, we observe the beating of the target qubit oscillation when the control qubit is prepared as a superposition of $|S\rangle$ and $|T_0\rangle$ (see Supplementary Note 4).

We also measured $T_2^*$ and spin–echo coherence time, $T_{\text{echo}}$, for each qubit to quantify the quality factor of the conditional phase-flip operation. Figure 4a, b shows $T_2^*$ and $T_{\text{echo}}$ for each qubit, where $T_2^*$ is extracted from the exponentially decaying exchange oscillation and $T_{\text{echo}}$ is measured by fitting the data to the echo envelope using calibrated n and p pulses. Along with the form $J \propto \exp(-t)$ (inset of Fig. 4a, b), we observe charge noise–limited coherence time, where $T_2^*$ and $T_{\text{echo}}$ are close to the form ($d/d\epsilon$)$^{-1}$ (ref. 29). This essentially explains why previously demonstrated entanglement quality showed no improvement when increasing $J_1$ and $J_0$ if $J_{\text{RL}} \ll J_{\text{RL}}$ (ref. 29).

Next, we perform the experiment in Fig. 3 with varying $J_1$ and $J_0$ near $J_0 = J_1$ to investigate the super-linearity of $J_{\text{RL}}$ when both qubits show reasonable coherence. Figure 4c shows the nonlinearity of $J_{\text{RL}}$ as $J_1$ and $J_0$ increase, manifesting the deviation from the bilinear proportionality26,27 in our device. Here, the error bar of the estimated $J_{\text{RL}}$ is determined by the fitting uncertainty limited by the sampling rate of the arbitrary waveform generator (see Supplementary Note 5). By fitting the measured $J_{\text{RL}}$ to $(J_1 J_0)^n$, the agreement with experimental data is found for $n = 2.14$, which is close to the theoretically expected form $J_{\text{RL}} = (J_1 J_0)^2$ using the effective Hamiltonian obtained from a Hund–Mulliken model independent of the details of the confinement potential in the regime where intra-qubit tunnel coupling overwhelms the intra-qubit exchange energy37 (see Supplementary Note 6). Moreover, we estimated the dipolar energy $D \approx 46$ GHz, the order of which is consistent with the recent experimental work using a similar interdot spacing10. With this super-linear proportionality, we observe $J_{\text{RL}} \approx 190$ MHz when $J_1$ and $J_0 \approx 900$ MHz, showing that more than 20% of the state-conditional qubit frequency shift can be obtained in a closely spaced QD array.

**DISCUSSION**

The nonlinear $J_{\text{RL}}(J_1 J_0)$ form implies that the two-qubit gate quality should increase at larger $J_1$ and $J_0$. We calculated $Q_{\text{echo}}(T_{\text{echo}}) = 2 (J_1 J_0)/(T_{\text{echo}})$, which quantifies the number of conditional phase flips within $T_{\text{echo}}$, as shown in Fig. 4d. We observed $Q_{\text{echo}}$ as high as $16 \approx 7$ for $Q_1$ ($Q_0$), predicting that the fidelity of a conditional phase-flip operation of $Q_1$ ($Q_0$) with $Q_1$ ($Q_0$) in the $\sigma_z$ eigenstate reaches as high as $e^{-1/(Q_{\text{echo}})} \approx 94.0\% (86.7\%)$ and also monotonically increases as a function of $J_1$ and $J_0$. In addition, the simulation based on the measured values predicts that the maximum attainable Bell state fidelity $F_{\text{Bell}}$ reaches $\approx 95\%$ and increases at larger $J_1$ and $J_0$, where the Bell state is prepared by the echo-like pulse implemented in ref. 26 in which $F_{\text{Bell}}$ maximizes at $\approx 72\%$ with $J_{\text{RL}} \approx 1$ MHz (see Supplementary Note 7).

Previously, a Bell state fidelity with a capacitive coupling has enhanced to $\approx 93\%$ with simultaneous rotary echo and rapid dynamic nuclear polarization (DNP), which enabled an approximately tenfold increase of a coherence time with $\Delta B = 900$ MHz, but $J_{\text{RL}}$ on the order of a few MHz was rather exploited27. Thus we expect that $F_{\text{Bell}}$ could be enhanced more by applying simultaneous rotary echo to the closely spaced QD array at a large $J_{\text{RL}}$, although the application is not currently viable in our device due to the insufficient DNP rate. In addition, the minimum time step and pulse rise times are currently limited by the sample rate of the waveform generator (2.4 Gsa/s), which also prevents performing full two-qubit gate operations and entanglement demonstration. Therefore further optimization with a faster signal source is still required. Note also that the pulse sequence in Fig. 3a is proper only for a two-qubit interaction measurement since the control qubit is likely to decohere while adiabatically turning on the interaction. Thus, a different qubit driving strategy (for example, using a non-adiabatic pulse) should be devised for entanglement demonstration, which will be considered in future work. Nonetheless, as our Hamiltonian estimation technique and readout method are compatible with large $\Delta B$, we anticipate that performing a full two-qubit experiment in a regularly and closely spaced linear QD array, with increased $\Delta B$ by micromagnets or dynamic nuclear polarization, may show an even higher two-qubit gate fidelity that is also fast, exploiting large $J_{\text{RL}}$.

In conclusion, we demonstrated the simultaneous Hamiltonian parameter estimation and active suppression of the quasi-static noise of two ST0 qubits in a GaAs quadruple QD array. Using fast qubit calibration routines, we also showed that both the magnitude and scaling of the capacitive coupling in a closely spaced QD array can be stronger than the previously measured bilinear form, leading to a state-conditional frequency shift of over 20% and a quality factor of conditional phase flip of over 16. Our measurement confirms recent theoretical calculations and supports the possibility of realizing a high-fidelity and fast entanglement of encoded spin qubits in both GaAs and Si using a simple capacitive interaction.

**METHODS**

**Device fabrication**

The quadruple QD device shown in Fig. 1a was fabricated on a GaAs/AlGaAs heterostructure where two-dimensional electronic gas (2DEG) is located 70 nm below the surface. Mesa was defined by a wet etching technique to eliminate 2DEG outside the region of interest to suppress unwanted leakage. Five ohmic contacts were formed by metal diffusion with thermal annealing. Nanogates were fabricated by e-beam lithography and metal evaporation.

**Measurement**

The device was placed on the 7 mK plate in a commercial dilution refrigerator (Oxford Instruments, Triton-500). The battery-operated voltage sources (Stanford Research Systems, SIM928) supplied by stable DC voltages rapid voltage pulses generated by the arbitrary waveform generator with the maximum sampling rate of 2.4 Gsa/s (Zurich Instruments, HDAWG) were applied to metallic gates through on-board bias-tees. A detailed description of the experimental setup and FPGA implementation can be found in Supplementary Note 2.

**DATA AVAILABILITY**

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

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**AUTHOR CONTRIBUTIONS**

D.K. and J.Y. conceived the project. J.Y. performed the measurements and analyzed the data. J.K. and H.J. fabricated the device. J.P., H.J., W.J., Y.S., M.C., and H.S. built the experimental setup and configured the measurement software. V.U. synthesized and provided the GaAs heterostructure. All the authors contributed to the preparation of the manuscript.

**COMPETING INTERESTS**

The authors declare no competing interests.

**ADDITIONAL INFORMATION**

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