High-visibility single-shot readout of singlet-triplet qubits in a micromagnet-integrated quadruple quantum dot array

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Abstract

Fast and high-fidelity quantum state detection is essential for building robust spin-based quantum information processing platforms in semiconductors. The Pauli spin blockade (PSB)-based spin-to-charge conversion and its variants are widely used for the spin state discrimination of two-electron singlet–triplet (ST\textsubscript{0}) qubits; however, the single-shot measurement fidelity is limited by either the low signal contrast, which depends on the charge sensor position, or the short lifetime of the triplet state at the PSB energy detuning, especially due to strong mixing with singlet states at large magnetic field gradients. Ultimately, the limited single-shot measurement fidelity leads to low visibility of quantum operations. Here, we demonstrate an alternative method to achieve spin-to-charge conversion of ST\textsubscript{0} qubit states using energy selective tunneling between doubly occupied quantum dots (QDs) and electron reservoirs, commonly called Elzerman type readout. We demonstrate a single-shot
measurement fidelity of 93% and an S–T₀ oscillation visibility of 81% at a field gradient of 100 mT without the necessity to convert to intermediate metastable states first; this allows single-shot readout with full electron charge signal contrast and, at the same time, long and tunable measurement time with negligible effect of relaxation even at strong magnetic field gradients. Using an rf-sensor positioned opposite to the QD array, we further apply this method to two ST₀ qubits and show that high-visibility readout of two individual single-qubit gate operations is possible with a single rf single-electron transistor sensor. We expect that our measurement scheme for two-electron spin states, analogous to single-electron spin-to-charge conversion, can be applied to various hosting materials and provides a simplified and unified route for multiple qubit state detection with high accuracy in QD-based quantum computing platforms.

Introduction

The assessment of general quantum information processing performance can be divided into that of state initialization, manipulation, and measurement. Rapid progress has been made in semiconductor quantum dot (QD) platforms, with independent demonstrations of, for example, high-fidelity state initialization of single and double QD spin qubits¹–³, high-fidelity quantum control with resonant microwaves⁴–⁷ and non-adiabatic pulses¹,⁸,⁹, and high-fidelity state measurements using spin-to-charge conversion¹⁰–¹⁶. However, the high visibility of a quantum operation requires high fidelity in all stages of the quantum algorithm execution, which has been demonstrated in only a few types of spin qubits so far⁴,⁶,⁹,¹⁷.

For double QD two-electron spin qubits, the Pauli spin blockade (PSB) phenomenon is typically used for discriminating spin-singlet (S) and -triplet (T₀) states where different spin
states are mapped according to the difference in the relative charge occupation of two electrons inside the double QD, which is detected by a nearby electrometer\textsuperscript{18–20}. However, depending on the device design, the signal contrast can be small compared to the signal of one electron, especially when the charge sensor position in the device is not aligned with the QD axis. This issue is particularly problematic in recent multiple QD designs\textsuperscript{21–23}, where the charge sensor positioned opposite to the qubit array increases the range of QDs detectable by one sensor, but renders sensitive measurement of the relative electron position between nearest-neighbor dots difficult.

Moreover, the magnetic field gradient along the QD axis $\Delta B_z$ provides relaxation pathways through $(1,1)T_0$–$(1,1)S$ mixing and rapid $(1,1)S$ to $(2,0)S$ tunneling in the PSB region, and normal PSB readout is difficult under large $\Delta B_z$, as shown in the solid green regions in Fig. 1a. As most QD spin qubit platforms utilize sizeable intrinsic\textsuperscript{2,24,25} or extrinsic\textsuperscript{26} $\Delta B_z$ to realize individual qubit addressing and high-fidelity single- and two-qubit operations\textsuperscript{4,6,27,28}, it is important to develop fast readout techniques that enable high-fidelity spin detection even at large $\Delta B_z$. So far, high visibility of approximately 90\% using PSB readout can be achieved only for small $\Delta B_z$\textsuperscript{12}.

These limitations of conventional PSB readout have been addressed in previous works, and several variants of the PSB readout have been developed for various QD systems\textsuperscript{13–16}. In the latched readout scheme\textsuperscript{13}, the lack of the reservoir on one side of the double QD enables spin conversion to the $(1,0)$ or $(2,1)$ charge state, enhancing the signal contrast. In Ref \textsuperscript{14}, singlet–triplet (ST\textsubscript{0}) qubit readout was performed in a triple QD to isolate the middle QD from the reservoirs, and the qubit state conversion to a metastable charge state enabled robust, high-
fidelity qubit readout. While these techniques enhance the signal contrast to the full electron charge, it is expected that the fast relaxation of the T_0 state at PSB detuning $\varepsilon$ can still affect the final quantum oscillation visibility. On the other hand, Orona, L. A. et al.\textsuperscript{15} reported the shelving readout technique, whereby one of the qubit states is first converted to the T_+ state through fast electron exchange with the reservoir to prevent mixing with the (1,1)S state, enabling high-visibility readout of the ST_0 spin qubit. They showed explicitly that single-shot readout is possible even for $\Delta B_{\mathrm{z}} \approx 180$ mT by optimizing the shelving pulse sequence. However, the technique relies on PSB for final spin-to-charge conversion and is expected to be effective only when the charge sensor is sensitive to the relative position of electrons in the double QD.

Here, we demonstrate the energy selective tunneling (EST) readout, commonly called Elzerman readout\textsuperscript{10}, of ST_0 qubits under large $\Delta B_{\mathrm{z}}$, accomplishing both signal enhancement, due to one electron tunneling, and long measurement time, enabling a robust single-shot readout. EST readout of the two electron spin states in a single QD was performed previously\textsuperscript{11}, but the explicit application of such readout with high-fidelity coherent operation at large $\Delta B_{\mathrm{z}}$ has not been reported to date. Unlike previous works, which demonstrated independent enhancement of the signal contrast and measurement time through intermediate spin or charge state conversion steps, our scheme does not require additional state conversion during the readout. Using large voltage modulation by rapid pulsing with $\varepsilon$ ranging from the PSB-lifted (2,0) to the deep (1,1) charge regions, where the exchange coupling $J(\varepsilon)$ is turned off, we explicitly demonstrate a single-shot measurement fidelity of 93% and an S–T_0 oscillation visibility of 81% at $\Delta B_{\mathrm{z}} \approx 100$ mT, corresponding to an oscillation frequency of 500 MHz. Furthermore, we demonstrate the detection of coherent operation of two individual ST_0 qubits.
in a quadruple QD array with a single rf-reflectometry line. In this paper, we describe the proposed EST readout method in detail, compare it with the conventional PSB readout, and suggest possible routes for its further optimization.

![Diagram](image)

**Fig. 1.**

**Results**

The blue rectangular regions in Fig. 1a show the position of $\varepsilon$ and the energy level configuration used for EST state initialization and readout. At this readout point, the PSB is lifted, and both S and T$_0$ levels can first occupy the (2,0) charge state, the energies of which are separated by ST$_0$ splitting typically in the order of $\sim$20–30 GHz$^{29}$ depending on the dot-confining potential. Near the (1,0) - (2,0) electron transition, the electrochemical potential of the reservoir resides between these states, which enables the EST of the ST$_0$ qubits. As discussed in detail below, we observe the single-shot spin-dependent tunneling signal where
one electron occupying an excited orbital state of the (2,0)T₀ state tunnels to the reservoir to form the (1,0) charge state, leading to an abrupt change in the sensor signal, and predominantly initializes back to the energetically favorable (2,0)S state. In contrast, no tunneling occurs for the (2,0)S state (see Fig. 1a, blue right panel).

We study a quadruple QD array with an rf single-electron transistor (rf-set) sensor consisting of Au/Ti metal gates on top of a GaAs/AlGaAs heterostructure, where a 2D electron gas (2DEG) is formed approximately 70 nm below the surface (Fig. 1b). A 250 nm-thick rectangular Co micromagnet with large shape anisotropy was deposited on top of the heterostructure to generate stable \( \Delta B_z \) for ST₀ qubit operation\(^{26,30-32} \) (see methods section for fabrication details). The device was placed on a plate in a dilution refrigerator at \( \sim 20 \) mK and an in-plane magnetic field \( B_{z,\text{ext}} \) of 225 mT was applied. To demonstrate the EST readout in the experiment, we independently operated and readout two ST₀ qubits (Qₐ and Qᵦ) in the non-interacting regime by blocking Qₐ–Qᵦ tunneling using appropriate gate voltages. We monitored the rf-reflectance of the rf-set sensor (Fig. 1b, yellow dot) for fast single-shot charge occupancy detection in the \( \mu s \) time scale\(^{33,34} \). The intra qubit tunnel couplings for both Qₐ and Qᵦ were tuned above 8 GHz to suppress unwanted Landau–Zener–Stuckelberg interference under fast \( \epsilon \) modulation, and we estimated the electron temperature to be approximately 230 mK (see also Supplementary Information S1).

We first locate appropriate EST readout points in the charge stability diagrams. Figure 1c (1d) shows the relevant region in the stability diagram for the Qₐ (Qᵦ) qubit operation as a function of two gate voltages \( V_1 \) (\( V_3 \)) and \( V_2 \) (\( V_4 \)). We superimpose the cyclic voltage pulse, sequentially reaching I – W – O – W – R points in the stability diagram (see Fig. 1c and 1d) with a pulse rise time of 200 ps. During the transition from the point W to point O stage, the
pulse brings the initialized (2,0)S state to the deep (1,1) region non-adiabatically, and the time evolution at point O results in coherent S-T0 mixing due to $\Delta B_z$. The resultant non-zero T0 probability is detected at the I/R point. For this initial measurement, the duration of each pulse stage was not strictly calibrated, but the repetition rate was set to 10 kHz. The resulting ‘mouse-bite’ pattern inside the (2,0) charge region (Fig. 1c, boundary marked by the red dashed line) implies the (1,0) charge occupancy within the measurement window, which arises from the EST of the ST0 qubit states averaged over 100 $\mu$s. For comparison, we note that the PSB readout signal with a similar pulse sequence is not clearly visible in the main panel of Fig. 1c in the time-averaged manner due to fast relaxation, as described above. The inset in Fig. 1c shows the PSB readout signal measured by gated (boxcar) integration (see Supplementary Information S2), where an approximately 100 ns gate window was applied immediately after the pulse sequence. This difference in the available range of measurement time scale clearly contrasts two distinct readout mechanisms for the spin-to-charge conversion of ST0 qubits.
Fig. 2

The PSB and EST readouts are systematically compared through time-resolved relaxation measurements, which also serve as calibration of the readout parameters for EST readout visibility optimization. Fig. 2a (2b) shows the relaxation of the sensor signal as a function of waiting time $\tau$ before reaching the measurement stage, using the pulse sequence shown in the inset of Fig. 2a (2b) near the PSB (EST) readout position for $Q_L$. The corresponding measurement results for $Q_R$ are described in Supplementary Information S3. As expected, the lifetime $T_1$ of the $T_0$ state at the PSB region is in the order of 200 ns, indicating strong spin state mixing and subsequent charge tunneling due to the large $\Delta B_z$ produced by the micromagnet (see Supplementary Information S4 for $\Delta B_z$ simulation). However, at large negative $\varepsilon$, the PSB is eventually lifted, and the absence of rapid spin mixing as well as the insensitivity of the $(2,0)T_0 - (2,0)S$ spin splitting to charge fluctuations ensures the long lifetime of the $T_0$ state. The evolution time at $O$ is varied in the EST relaxation time measurement in Fig. 2b, and the amplitude decay of the coherent oscillation is probed to
remove background signals typically present for long pulse repetition periods. The resultant $T_1$ of 156 $\mu$s is three orders of magnitude longer than that in PSB readout. Note that this $T_1$ is taken at $\varepsilon$ near $(1,1)T_0 - (2,0)T_0$ anti-crossing; thus, an even longer $T_1$ is expected at the actual $\varepsilon$ measurement position selected for EST readout, which is difficult to measure due to the limitation of the low frequency cut off of the bias tee in the order of 1 kHz. Without fast $\varepsilon$ modulation, a long $T_1$ exceeding 2.5 ms has been reported in GaAs QDs.

Next, we discuss the calibration of the tunnel rates for single-shot readout and the optimization of the readout fidelity and visibility with the given experimental parameters. While for time-averaged charge detection we use a minimum integration time of 30 ns in the signal demodulation setup, corresponding to a measurement bandwidth of 33 MHz, we set the integration time to 1 $\mu$s for single-shot detection to increase the signal to noise ratio, and we typically tune the tunneling rates to less than 1 MHz. Fig. 2c shows time-resolved tunnel out events triggered by the end of the pulse sequence from which we measure the tunneling out rate $\nu_{out} \sim \tau_{out}^{-1} = (16\mu s)^{-1}$, extracted from the fit to an exponentially decaying function. The rate is within our measurement bandwidth. Also note that the ratio $T_1 / \tau_{out}$ is at least 10, which is reasonable to perform high-fidelity measurements. Fig. 2d shows the resultant histogram showing a separation of the mean value of the S and T0 signal levels of more than 8 times the standard deviation, confirming the high fidelity of single-shot spin state detection with 1 $\mu$s integration time. We also find good agreement between the experimental and numerically simulated single-shot histograms generated using the measured tunneling rates and signal to noise ratio.
After the rf demodulation stage, we further apply correlated double sampling (CDS)\textsuperscript{14} to the single-shot traces to simplify the state discrimination and measurement automation. Using a fast boxcar integration with two gate windows that are 5 $\mu$s apart in the time domain, a dc background-removed pseudo-time derivative of the single-shot traces is generated, enabling separate detection of tunneling out/in events with an external pulse counter (Stanford Research Systems, SR400 dual gated photon counter) and time-correlated pulse counting with a multichannel scaler (Stanford Research Systems, SR430 multichannel scaler) without the need for customized field-programmable gate array (FPGA) programming\textsuperscript{36,37} (see Supplementary Information S2 for details of the CDS scheme). While this scheme was successful, the electronic measurement bandwidth was further reduced to 200 kHz for single-shot detection, which resulted in a relatively long readout time requiring relatively slow tunneling rates. To simulate realistic measurement conditions, we applied the numerical CDS filter to the simulated single-shot traces (Fig. 2e) and reproduced the measurement fidelity and visibility (see Supplementary Information S5 for measurement fidelity analysis). The resulting theoretical measurement fidelity of the left qubit is 93%, corresponding to a visibility of 86%, confirming that high-fidelity single-shot detection is possible at the given experimental conditions (see Supplementary Information S3 for right qubit analysis). Moreover, in Supplementary Information S6, we show through numerical simulation that FPGA-based single-shot detection, which we plan to perform in the future, will yield a measurement fidelity (visibility) of 97% (93%) at the same experimental condition through faster and more accurate peak detection. Thus, we conclude that the measurement fidelity and visibility obtained in this study, while showing the highest values for ST$_0$ qubit operation at large $\Delta B_z$, are mainly
limited by the CDS technique used and can be improved in a straightforward manner in the future.

Fig. 3.

We now demonstrate high-visibility coherent qubit operations with the EST single-shot readout. The panels in Fig. 3 show the high-visibility two-axis control of Q_L (Figs. 3a–c) and Q_R (Figs. 3d–f) under large $\Delta B_z$ recorded with a single rf-set. For the $\Delta B_z$ oscillations (Figs. 3a, 3d), the I – W – O – W – R with the period of 150 $\mu$s (Fig. 3a, top panel) was applied, and the evolution time at O was varied from 0 to 10 ns. Each trace in Figs. 3a and 3d is the average of 50 repeated measurements with 2000 shots per point, which takes over 5 min; thus, we expect an ensemble-averaged coherence time of ST$_0$ qubit oscillation $T_{2^*}$ in the order of 15 ns, limited by nuclear bath fluctuation. We clearly observe coherent oscillations of Q_L (Q_R) with $\sim$81% ($\sim$64%) visibility, which is consistent with the results of the numerical
simulation reported in Fig. 2e. Under the large $\Delta B_z$ of 100 (80) mT, corresponding to an oscillation frequency of 500 (400) MHz, we expect the control fidelity of the $\pi$ pulse to reach up to 99.63% (99.23%) for QL (QR) assuming gaussian decay, even with the ensemble-averaged $T_{2*} \sim 15$ ns; thus, one can neglect the effect of the limited control fidelity on the visibility. As discussed above, with the experimental conditions considered in this study, the visibility for both QL and QR is limited by the electronic bandwidth owing to the CDS technique used. For QR, tuning to an even longer $\tau_{out}$ of 25 $\mu$s was necessary to account for the reduced rf-set sensor’s signal contrast to farther QDs, for which the final visibility is approximately 64%. However, as shown in Supplementary Information S6, the visibility of the further QDs can be easily enhanced to more than 85% by simply improving the electronics of the measurement system, for example, with FPGA programming.

To acquire the 2D plots shown in Figs. 3b and 3e, the typical Ramsey pulse sequence of $I-W-O (\pi/2) - A_{ex}-O (\pi/2) - W - R$ (Fig. 3b, top panel) was applied, and the detuning amplitude $A_{ex}$ and evolution time $\tau_{ex}$ at the exchange step were varied. The figures show high-visibility quantum oscillation as well as continuous evolution of rotation axis on the Bloch sphere as $A_{ex}$ is varied over different regimes, where $T_{2*}$ is limited by the charge noise for $J(\epsilon) > \Delta B_z$ or by fluctuations in $\Delta B_z$ for $J(\epsilon) \sim 0$. The fast Fourier transform (FFT) of the exchange oscillations along the exchange detuning axis (Figs. 3c and 3f) confirms the control of the ST$_0$ qubit over the two axes on the Bloch sphere for both QL and QR, which is consistent with the expected qubit energy splitting (Fig. 3c, top panel). We emphasize that the measurement of two qubits is possible with one accompanied rf-set, which can be useful for the linear extension of the ST$_0$ qubits because the charge sensor does not need to be aligned.
with the QD array. In this work, we focused on independent two single-qubit gate operation; nevertheless, we expect that long $T_1$ at EST readout will allow the sequential measurement of two qubit states for a given quantum operation, which, in turn, will allow two qubit correlation measurement, enabling full two qubit state and process tomography in the future. Characterization of the two qubit interaction of $\text{ST}_0$ qubits in the current quadruple dot array, for example by dipole coupling\textsuperscript{6,9} or exchange interaction\textsuperscript{32}, is the subject of current investigations.

**Discussion**

High-visibility readout of the $\text{ST}_0$ qubit at large $\Delta B_z$ is necessary for high-fidelity $\text{ST}_0$ qubit operations\textsuperscript{6,36}. We performed high-visibility single-shot readout of two adjacent $\text{ST}_0$ qubits at $\Delta B_z$ of 100 mT by direct EST with one rf-set. No mixing between $T_0$ and (1,1)$\text{S}$ state was observed at the EST readout point, which would allow sequential readout of multiple arrays of qubits due to the long $T_1$. Full one-electron signal difference discriminates the $\text{S}$ and $T_0$ states compared to other readout methods where the dipolar charge difference is measured to readout the $\text{ST}_0$ qubit states\textsuperscript{12,15}. This feature can be especially useful for scaling up the $\text{ST}_0$ qubits for the following reasons: 1) the large signal contrast can result in high visibility and low measurement error, and 2) the sensor does not need to be aligned along the QD array. Especially for GaAs spin qubits, high-visibility $\text{ST}_0$ qubit readout allows fast nuclear-spin fluctuation measurements, which will enable accurate feedback/stabilization of the nuclear spin bath for high-fidelity qubit control\textsuperscript{2,25,36}. Furthermore, our method does not require additional metastable states\textsuperscript{14,16,38} or pulsing sequences for high-fidelity measurements at large $\Delta B_z$\textsuperscript{13,15},
showing that the experimental complexity is greatly reduced. EST readout of ST$_0$ qubits in nuclear spin-free systems, including Si, may also enhance the measurement fidelity by providing even longer $T_1$ for electron spins$^{7,39,40}$.

Because the highest bandwidth potential of rf-reflectometry cannot be fully exploited with the CDS technique used in this study, we expect that the use of FPGA to detect the peaks from the bare rf demodulated single-shot traces will enhance the visibility to at least 93% (86%) for $Q_L$ ($Q_R$). The use of FPGA programming will also allow faster nuclear environment Hamiltonian learning$^{36}$, which can be useful in, for example, studying the time-correlation of nuclear spin bath fluctuations at different QD sites. We roughly estimated the thermal excitation arising from the relatively high electron temperature of 230 mK (see Supplementary Information S1), and the colored low-frequency electronic noise present in the current setup$^{41}$ reduced the visibility by a few percent, which can explain the slight disagreement between the experimental and calculated visibility. In the future, we plan to improve the performance by adopting an FPGA-based customized measurement, reducing electron temperature, and further optimizing the electronic signal path. However, even with the current limitations, the achieved visibility of 81% for ST$_0$ qubits at large $\Delta B_z$ shows potential to realize high-fidelity quantum measurements in scalable and individually addressable multiple QD arrays in semiconductors.

Methods

**Device Fabrication.** The quadruple QD device was fabricated on a GaAs/AlGaAs heterostructure with a 2DEG formed 73 nm below the surface. The transport property of the 2DEG shows mobility $\mu = 2.6 \times 10^6 \, cm^2 V^{-1} s^{-1}$ with electron density $n = 4.6 \times 10^{11} \, cm^{-2}$ and
temperature $T = 4$ K. Mesa was defined by the wet etching technique to eliminate the 2DEG outside the region of interest. Ohmic contact was formed through metal diffusion to connect the 2DEG with the electrode on the surface. The depletion gates were fabricated on the surface using standard e-beam lithography and metal evaporation. The QD array axis was oriented parallel to the [011] crystallographic direction of GaAs. Subsequently, the micromagnet was patterned perpendicular to the QD array using standard e-beam lithography, and a Ni 10 nm/Co 200 nm/Au 5 nm was deposited using metal evaporation.

**Measurement.** The experiments were performed on a quadruple QD device placed on the 20 mK plate in a commercial dilution refrigerator (Oxford instruments, Triton-500). Rapid voltage pulses generated by Agilent M8195A arbitrary waveform generator (65 GSa/s sampling rate) and stable dc voltages generated by battery-operated voltage sources (Stanford Research Systems SIM928) were applied through bias-tees (picosecond Pulselabs 5546) in the dilution refrigerator before applying the metal gates. An LC-resonant tank circuit was attached to one of the ohmic contacts near the rf-set with a resonance frequency of ~110 MHz for homodyne detection. The reflected rf-signal was first amplified at 4 K with a commercial cryogenic amplifier (Caltech Microwave Research, CITLF2) and then further amplified at room temperature with home-made low-noise amplifiers. Signal demodulation was performed with an ultra-high-frequency lock-in amplifier (Zurich instrument UHFLI), and the demodulated amplitude was processed using a boxcar integrator built in the UHFLI for CDS. The CDS peaks were counted with an external photon counter (Stanford Research, SR400). The pulse parameters could be rapidly swept via a hardware looping technique, which enabled fast acquisition of the $\Delta B_z$ oscillations. In Supplementary Information S7, we show the details of
the measurement setup, CDS technique, and signal analysis.

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Figure captions

Figure 1. Energy levels and device platform a. Schematic of the singlet–triplet (ST₀) qubit energy levels as a function of detuning $\epsilon$ with energy selective tunneling (EST, blue boxes) and Pauli spin blockade (PSB, green boxes)-based readout schemes. Green panel: At the PSB readout point, the (1,1)S state tunnels into the (2,0) charge state while the tunneling from the (1,1)T₀ state is blocked. The relative charge position is observed to determine the spin state of the qubit. (1,1)T₀–(1,1)S mixing under the finite magnetic field gradient $\Delta B_z$ provides a relaxation pathway for the (1,1)T₀ state. Blue panel: Energy level configuration and a single-shot readout signal at the EST readout point. The Fermi level resides between the (2,0)S and (2,0)T₀ states, which enables EST. The triplet state (red) tunnels out to the (1,0) state and initializes to the (2,0)S state, while no tunneling occurs for the S state. b. Scanning electron microscopy image of the device. Green (orange) dots indicate the position of the left (right)
ST₀ qubit Qₐ (Qᵦ), and the yellow dot indicates the rf single-electron transistor (rf-set) position. The blue arrow indicates the external magnetic field direction. c. (d.) Double QD charge stability diagram for Qᵦ (Qᵦ) operation with the 100 μs-period pulse cycling I – W – O – W – R points superimposed with raster scanning gate voltages. The red dashed line shows the boundary of the (2,0) charge stability region inside which the EST readout is appropriate. The inset of c. shows the PSB readout signal for the same gate voltage area observed by gated (boxcar) integration. The yellow line in d. shows the electron transition signal of the QD coupled to V₂.

Figure 2. Time-resolved relaxation measurements and fidelity analysis of Qₐ. a. Relaxation time measurement at PSB readout. The time-averaged rf-demodulated signal Vᵣf is recorded as a function of the waiting time τ at the ε denoted in the inset. T₁ ~ 200 ns is extracted from the fitting data to the exponential decay curve. b. Relaxation time measurement near EST readout. The decay of the coherent oscillation is observed along the waiting time τ near the PSB-lifted (1,1)T₀–(2,0)T₀ excited anti-crossing position denoted in the inset. T₁ ~ 156 μs is extracted, while even longer T₁ in the actual EST readout ε is expected. c. Histogram of the tunneling out events triggered by the end of the manipulation pulse as a function of time. d. Histogram of the experimental and simulated rf-demodulated single-shot traces with the application of π pulses for EST readout showing a mean value separation of more than 8 times the standard deviation. e. Measurement fidelity and visibility calculated from the CDS peak amplitude histogram shown in the inset. Maximum visibility of ~86% and a corresponding measurement fidelity of 93% are estimated at the optimal threshold voltage Vₜₐᵦ.
**Figure 3. High-visibility two-axis control of two ST₀ qubits.**

a. (d.) Coherent ST₀ oscillation of Q_L (Q_R) under large $\Delta B$. Electronic bandwidth-limited 81% (64%) quantum oscillation visibility is defined by the oscillation amplitude. b. (e.) Coherent exchange oscillation and two-axis control of Q_L (Q_R) on the Bloch sphere. The top panel of b. shows the Ramsey pulse sequence where the first $\pi/2$ pulse induces equal superposition of S and T₀ spin states, and the phase evolution under non-zero $J(\epsilon)$ is probed by the second $\pi/2$ pulse. By varying the pulse amplitude $A_{ex}$ and the evolution time $\tau_{ex}$ at the exchange step, the high-resolution rotation axis evolution and an energy spectrum consistent with the expected functional form of $J(\epsilon)^{29}$, the schematic of which is shown in the top panel of c., are confirmed by the fast Fourier transform (FFT) plots in c. (f.).

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Author contributions

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

Competing interests

The authors declare no competing interests.

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**Supplementary Information**

**S1. Electron temperature and intra-qubit tunnel coupling calibration**

Electron temperature, and the tunnel coupling strength of the left double quantum dot are measured using the standard lock-in technique. $dV_{rf}/dV_2$ is observed by modulating $V_2$ gate voltage with 337Hz frequency. With proper adjustment of dot-reservoir tunnel rates less than 1 MHz and setting minimal modulation amplitude, the electron temperature $T_e \sim 230\text{mK}$ is determined by fitting the heterodyne detected single electron transition line to the equation

$$
\frac{dV_{rf}}{dV_2}(V_1) = A_{offset} - \frac{A\alpha}{k_BT} \frac{\exp(\alpha(V_1 - V_{offset})/k_BT)}{(1 + \exp(\alpha(V_1 - V_{offset})/k_BT))^2},
$$

which is the derivative of the typical Fermi-Dirac distribution (Fig. S1a). Here $\alpha = 0.035$ is the lever-arm of the $V_1$ gate obtained from the Coulomb diamond measurement, $k_B$ is the Boltzmann constant, and $A_{offset}$ and $V_{offset}$ are the $dV_{rf}/dV_2$ offset and the offset $V_1$ voltage in the $dV_{rf}/dV_2 - V_1$ plot, respectively. The intra-qubit tunnel coupling strength $t_c$ was obtained in the similar manner, by sweeping the gate voltage through the inter-dot transition line in the stability diagram for example shown in Fig. 1c of the main text. The broadening is fitted using the same equation described above, with the broadening width $2t_c$ instead of $k_BT$ where the $t_c$ represents the tunnel coupling strength. The resultant $2t_c/h$ is 16 GHz where $h$ is the Plank’s constant.

**Fig. S1. System parameter calibration.** a. Electron temperature measurement. b. tunnel coupling strength measurement using the heterodyne detection scheme. Typical lock-in measurement was performed to obtain the broadening of the single electron transition due to thermal broadening and the intra-qubit tunneling. Electron temperature $T_e \sim 230\text{mK}$, and tunnel coupling $t_c/h \sim 8\text{GHz}$ were obtained from the fitting. When obtaining b. both $V_1$, and $V_2$ were swept through the inter-dot transition line in Fig. 1c, but only the $V_1$ gate voltage is shown in the x-axis.
S2. Correlated double sampling (CDS)

By resampling the demodulated rf-signal with the boxcar integrator, we enable the real-time single-shot event counting without the use of field-programmable gate arrays (FPGA) programming. As shown in Fig. S2, the boxcar integrator subtracts the 100 ns-averaged baseline signal from the gate signal which are separated by $5 \mu s$ in the time domain to yield a pseudo-time derivative signal of the single-shot trace with 200 kHz sampling rate. CDS converts the falling (rising) edge to the positive (negative) peak and the peaks are detected by the external photon counter (Stanford Research Systems SR400) as shown in Fig. S2a. This allows the separate detection of tunneling in / out event in real-time without post-processing which may reduce the experimental overhead in the analysis step. By counting the tunneling out events, we have observed the coherent singlet-triplet qubit (ST$_0$ qubit) oscillations in the energy selective tunneling (EST) readout point in the main text. For single-shot readout, the boxcar integrator is operated with average number set to 1 (no averaging).

When averaged, however, the CDS technique can also be utilized to observe short-lived T$_0$ signal for Pauli Spin Blockade (PSB) readout, which enable measurement bandwidth of 33MHz in time averaged manner (see also the inset to Fig. 1c in the main text). By setting the ~ 0.1 $\mu s$ gate window right after the spin-mixing pulse comes back to the PSB region, and the ~ 0.1 $\mu s$ baseline gate window before the next pulse start as shown in Fig. S2b, the demodulated signal is effectively sampled for short time where the portion of the T$_0$ signal is sufficiently large to be observed with sufficient periodic average.

**Fig. S2. Correlated double sampling schematics.** a. Correlated double sampling for tunneling out / in event detection. Boxcar integrator resamples the bare demodulated rf signal by subtracting the ~ 100 ns averaged baseline (B) signal from the gate (G) signal every $5 \mu s$. This resampling process converts the falling edge signal of the rf signal to a positive peak with removing dc background and produces pulse signal robust to background drift. b. CDS scheme for short T$_0$ signal detection in PSB readout. Pulse mixes the S and T$_0$ states in the operation.
(O) sequence, and when returning to the readout (R) step, the $T_0$ quickly relaxes to (2,0) charge state under large magnetic field gradient. The boxcar integrator in this case is operated in averaging mode where sampled signal $G$ of the rf-signal for short period time after the pulse sequence are subtracted by the $B$ signal and averaged about 5000 times to increase signal to noise ratio.

**S3. Right qubit measurement fidelity**

**Fig. S3. Right qubit readout fidelity analysis.**  

**a.** Tunneling out rate of the right qubit $Q_R$ at the EST readout point. Tunneling out events were recorded as a function of the tunneling time, and the exponential fit to the curve yields $\tau_{out} \approx 25\mu s$.  

**b.** Experimental, and simulated rf single-shot traces of the $Q_R$ with the $\pi$ pulse applied.  

**c.** Histogram of the CDS amplitude of the S (red) and $T_0$ (blue) states. The histograms in b. and c. are normalized to generate the probability density plot.  

**d.** The measurement fidelity and visibility of the $Q_R$. The maximum fidelity / visibility is 83% / 65% which is in good agreement with the experimentally acquired visibility shown in Fig. 3 of the main text.
S4. Magnetic field gradient simulation

Fig. S4. Simulation of the magnetic field by the micromagnet. The z-component of the magnetic field around the quantum dots in our device (see Fig. S7) is simulated using the boundary integral method with RADIA¹,² package. Green dots indicate the quantum dot positions. The fast \( \Delta B_z \) oscillations shown in Fig. 3 in the main text is up to 500MHz corresponding to \( \Delta B_z \) of 100 mT, and we ascribe this higher-than-expected- \( \Delta B_z \) to the displacement of the electrons from the expected positions by the confining potential in the few electron regime.
S5. Measurement fidelity analysis

Single-shot traces were numerically simulated following the Morello, A. et al\textsuperscript{3}, using the experimentally acquired parameters including the tunneling out / in rates, and rf signal contrast. $T_1$ relaxation time is also taken into account by calculating the relaxation probability $P_{\text{relax}} = 1 - \exp(-t_{\text{out}}/T_1)$. By varying the amplitude of the numerical noise filter applied to the simulated single-shot traces the numerical simulation reproduce the experimental histogram as shown in Fig. 2d of the main text. As we have detected the events by thresholding CDS amplitude described above, for the readout fidelity analysis the simulated single-shot traces are further processed with the same CDS filter condition. To find the optimal threshold for maximum readout fidelity / visibility the single-shot traces corresponding to the singlet and triplet states were prepared respectively, and histograms were constructed with the peak values of the CDS traces (see inset to Fig. 2e in the main text). After normalizing the histogram to generate a histogram of probability density, the singlet, and triplet fidelities ($F_S$, and $F_T$) were acquired by the following integrations,

$$F_T = \int_{V_T}^{\infty} p_T(V) \, dV$$

$$F_S = \int_{-\infty}^{V_T} p_S(V) \, dV$$

and the visibility is defined by $V = F_T + F_S - 1$. $p_T(V)$ , and $p_S(V)$ are the probability density of the triplet and singlet outcomes at $V$ which can be obtained from the CDS histogram. By optimizing the threshold voltage $V_T$ we acquire the maximum measurement fidelity and visibility.
**S6. Expected fidelity with direct peak detection**

**Fig. S6 a.** (c.) Histogram constructed directly from the peak values of the Q_L (Q_R) single-shot traces without the CDS. The histograms are normalized to yield the probability density histogram. **b.** (d.) Fidelity and visibility acquired from the histogram a. (c.). The maximum measurement fidelity / visibility of the Q_L (Q_R) can reach 97% / 94% (93% / 86%), by optimizing the thresholding voltage.

The measurement fidelity and visibility are calculated for the direct peak detection scheme to explicitly show that the use of FPGA rather than CDS technique may extend the measurement fidelity and visibility with the same experimental parameters. Following the Morello et al\(^3\), single-shot traces were first simulated with the experimental parameters, and instead of passing through additional numerical CDS filter, the peak value (the minimum value) from each rf single-shot trace is sampled for 10,000 traces to construct the histogram shown in Fig. S6a. and S6c. Because the short peaks or the full signal contrast cannot be perfectly detected with the CDS due to its limited bandwidth, the histograms of the S and T_0 are more clearly separated in Fig. S6, which naturally leads to higher fidelity and visibility as in Fig. S6b, and S6d respectively for Q_L and Q_R. The measurement fidelities (97% for Q_L and 93% for Q_R) are limited by the T_1 relaxation time, which we claim to be a rather conservative calculation since we use the T_1 time measured at \( \epsilon \) near (1,1)T_0-(2,0)T_0 anti-crossing. The tunneling rates may be tuned faster in the case where the CDS is not utilized, and it will be less
likely for the relaxation to take place before tunneling events, which will extend the fidelity further. Experimentally, direct peak detection described above is possible with the usage of FPGA, where the peak value from a single-shot trace can be detected by setting appropriate threshold levels.

S7. Measurement setup

A rf-single electron transistor (rf-set) sensor is operated to detect the charge states of the ST₀ qubits in our device. For the rf-reflectometry, impedance matching tank circuit as shown in Fig. S7 is attached to the rf-ohmic contact of the device, and the 100 pF capacitor is connected in series to the other ohmic contact (depicted on the micromagnet) to serve as a rf-ground. With the inductor value L = 1500 nH and the parasitic capacitance Cₚ = 1.4 pF of the circuit board, the resonance frequency is about 110MHz, and the impedance matching occurs at rf-set sensor resistance approximately 0.5 h/e² where h is Plank’s constant and e is the electron charge. A commercial high frequency lock-in amplifier (Zurich Instrument, UHFLI) is used as the carrier generator, rf demodulator for the homodyne detection, and further signal processing such as gated integration and timing marker generation. Carrier power of -40dBm power is generated at room temperature and attenuated through the attenuators and the directional coupler by -50 dB in the input line. The reflected signal is first amplified by 25 dB with commercial cryogenic amplifier (Caltech Microwave Research Group, CITLF2), and further amplified by 50 dB at room temperature using a home-made low-noise rf amplifier. Demodulated signal is acquired with a data acquisition card (National Instruments, NI USB-9215A) for raster scanning and also boxcar-averaged with the gated integrator module in the UHFLI for the correlated double sampling described above. For single-shot readout, the CDS output is counted with a high-speed commercial photon counter (Stanford Research Systems, SR400 dual gated photon counter). A commercial multichannel scalar (Stanford Research Systems, SR430 multichannel scaler & average) is also used for time correlated pulse counting for tunneling rate calibration.
Fig. S7. The measurement setup for radio frequency (rf)-reflectometry, and the signal block diagram. Impedance matching tank-circuit ($L \sim 1500$ nH, $C_p \sim 1.4$ pF) is attached to the rf-set sensor Ohmic contact for homodyne detection. Orange (green) line indicates the input (reflected) signal. Reflected signal is demodulated and processed for single-shot event counting as shown in the block diagram.
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