Single-Shot Readout of a Driven Hybrid Qubit in a GaAs Double Quantum Dot

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ABSTRACT: We report a single-shot-based projective readout of a semiconductor hybrid qubit formed by three electrons in a GaAs double quantum dot. Voltage-controlled adiabatic transitions between the qubit operations and readout conditions allow high-fidelity mapping of quantum states. We show that a large ratio both in relaxation time vs tunneling time ($T_1/\tau\approx50$) and singlet–triplet splitting vs thermal energy ($\Delta E/T\approx20$) allows energy-selective tunneling-based spin-to-charge conversion with a readout visibility of $\approx92.6\%$. Combined with ac driving, we demonstrate high visibility coherent Rabi and Ramsey oscillations of a hybrid qubit in GaAs. Further, we discuss the generality of the method for use in other materials, including silicon.

KEYWORDS: Quantum dot, Hybrid qubit, Single-shot measurement, rf reflectometry, GaAs

Performing a high-fidelity projective readout of qubit states is an important requirement in many steps of quantum information processing protocols. In the semiconductor quantum dot (QD) qubit platform, state detection mainly uses sensors proximal to qubits, where the sensor is sensitive to either the number or the susceptibility of the charges inside a QD to external perturbations. Along with the progress in developing wide-bandwidth charge sensors, single-shot state detection methods have been employed in various spin qubits in semiconductors, including single-spin, singlet–triplet, and exchange-only qubits. The rapidly repeated single-shot readout performed in these systems is also used for nuclear feedback control and quantum nondemolition measurement.

The QD hybrid qubit (HQ) compromises the desirable features of charge (fast manipulation) and spin (long coherence time) qubits. Formed by a decoherence-free subspace of three-electron spin states in a double QD, recent experiments on both Si/SiGe and GaAs have demonstrated fast electrical control of HQ with a favorable ratio between the manipulation time and coherence time $T_2^*$. Moreover, the naturally formed exchange charge insensitive sweet spot is tunable, and $T_2^*$ exceeding 100 ns has been demonstrated in Si/SiGe. However, so far these experiments have been performed by time-averaged measurements, while more advanced protocols using HQ require a high-fidelity single-shot readout. Time-averaged measurements are also often susceptible to errors in relaxation time $T_1$ compensated probability normalization.

In this work, we demonstrate high-fidelity single-shot measurements of a three-electron HQ in GaAs. The logical states $|0\rangle$ and $|1\rangle$ are mapped to spin states that are energetically separated by more than 20 times the thermal energy, and the energy-selective tunneling (EST) events between one of the QDs and the reservoir is measured by a radio frequency single-electron transistor (rf-set). Similar to ref 37, we use resonant driving to coherently control the HQ states and demonstrate high-visibility, normalization-free two-axis control on the HQ Bloch sphere. Achieving a measurement fidelity $\approx96.4\%$, readout visibility $\approx92.6\%$, and quantum oscillation visibility $\approx75\%$, the result facilitates efficient HQ state detection with fidelity in line with the state-of-the-art EST single-shot detections achieved in various semiconductor gate-defined QB qubits.

Figure 1a shows a scanning electron microscope image of a QD device similar to the one we measured. The device is designed to form up to four QDs used for qubits, but we focus on the right double QD by grounding the irrelevant gate electrodes. Au/Ti gate electrodes are deposited on top of a GaAs/AlGaAs heterostructure, where a 2D electron gas...
(2DEG) is formed 70 nm below the surface. The device was operated in a dilution refrigerator with a base temperature $\approx 20$ mK and at zero external magnetic fields. The electron temperature is $\approx 234$ mK (see SI Section S3).

A previous study of HQ in GaAs double QD showed that operating the HQ near the $(2, 3) - (1, 4)$ charge occupation provides energy tunability stemming from asymmetric and anharmonic potentials. Instead, we operate our HQ with the same total number of electrons as proposed originally near the $(2, 1) - (1, 2)$ charge transition. We define the qubit states at the readout window as $|0\rangle = |\downarrow\rangle |S\rangle$ and $|1\rangle = \sqrt{1/3} |\downarrow\rangle |T\rangle - \sqrt{2/3} |\uparrow\rangle |T\rangle$ where $|\downarrow\rangle$ and $|\uparrow\rangle$ represent the spin configuration of the single electron in the left QD and $|S\rangle$, $|T_{0}\rangle$, and $|T_{-}\rangle$ represent the singlet ($S$) and triplet ($T_{0}$, $T_{-}$) spin configurations of the two electrons in the right QD as in the original HQ design. Note that the spin states comprise $S_{\text{tot}} = 1/2$, $S_z = -1/2$ subspace. We describe the detailed energy levels and toy-model Hamiltonian in the Supporting Information.

We perform ac-driven spectroscopy of the qubit frequency. As shown in the right panel of Figure 1b, we start with an initial qubit state at the $(1, 2)$ ground level at the initialization and measurement point I/M. After adiabatically ramping the detuning $\xi$ to the operation point O, the resonant ac modulation in the detuning induces the probability to be in the excited state, $P_{1}$, which is adiabatically mapped back to the point I/M. The point I/M is chosen so that the Fermi level of the right reservoir resides between the energies of $|0\rangle$ and $|1\rangle$ to enable EST. The same technique was used for HQ in Si/SiGe in the time-averaged probability measurement. Here, we monitor the charge difference using fast rf-reflectometry recording tunneling events at MHz bandwidth, which enables a single-shot projective readout. As we show below in detail, the double QD used in this work exhibits a highly asymmetric singlet–triplet splitting between the dots, where the splitting in the left (right) dot, $\delta L$ ($\delta R$) is $\sim 3$ (96) h. GHz. The exceptionally small $\delta L$ may be possible evidence for the non-negligible electron–electron interaction which is known to cause quenching of the excited orbital energy spectrum (see SI Section S2 for the preliminary theoretical calculation). From the magnetic field susceptibility measurement (see SI Section S2) we show that the $(2, 1)$ qubit states split by $\delta L$ have the same $S_{\text{tot}}$ and $S_z$ where the spin-conserving tunnel coupling ensures the $(2, 1)$ ground states with $S_{\text{tot}} = 1/2$, $S_z = -1/2$ can be prepared via the adiabatic passage discussed above. Thus, we interpret the $(2, 1)$ qubit states observed in
this work as the HQ states and use the toy-model Hamiltonian identical to the original HQ proposal\cite{35,42} to simulate the energy dispersion. The calculation agrees well with the measured energy dispersion (black dashed curve, Figure 1b). While further studies including the exact diagonalization calculation\cite{41,43} are required to reveal the actual origin of the asymmetry, we focus on the single-shot readout of the HQ in this work and leave the detailed investigation of the energy levels for the future works.

Figure 1c shows a double-dot charge stability diagram where the scanning gate voltage is superimposed with a voltage pulse with a rise time of 100 ps and width of 10 ns (schematic in Figure 1c, see the SI for zoomed-out version of the diagram and the high-frequency setup), which induces a nonadiabatic coherent Landau–Zener tunneling. The range of the gate voltage $V_g$ where these oscillations appear can be used for estimating singlet–triplet splitting at $\approx 0.39$ meV using the measured lever arm of 0.028. This is $\approx 20$ times larger than the thermal energy $\approx 20$ μeV. As shown in Figure 1d, the real-time traces of the rf-set signal at I/M show a clear distinction between $|0\rangle$ and $|1\rangle$. An electron occupying an excited orbital state of the $|1\rangle$ tunnels to the reservoir to form the $(1, 1)$ charge state, leading to an abrupt change in the sensor signal, and initializes back to the energetically favorable $|0\rangle$. In contrast, no tunneling occurs for the state $|0\rangle$.

We analyze the performance of the single-shot readout by optimizing various tunneling rates and signal integration times. Figure 2a depicts the time-resolved tunnel-out events, which predominantly involve triplet states, triggered at the end of the pulse sequence. We measure the tunneling-out time $\tau_{out} \approx 2 \mu$s extracted from the exponential fitting. Similar measurements for tunneling in events, which occurs mostly by singlet states, result in a tunneling-in time of $\tau_{in} \approx 32 \mu$s (Figure 2a, inset). Highly asymmetric tunneling times stem from different spatial distributions of the orbital wave functions of the singlet and triplet states that lead to different dot-to-reservoir coupling.\cite{23,25} We note that this large difference in state-dependent tunneling rates can, in principle, be used for tunneling rate-based single-shot measurement, which can be useful for reducing measurement times,\cite{23,25} but here we focus on the Elzerman-type readout\cite{21} and set the measurement window to 140 μs longer than $\tau_{in}$. Compared with these time scales, $T_1$ at the point I/M shown in Figure 2b, which is obtained by measuring the decay of the oscillation visibility as a function of the waiting time at point W (see inset to Figure 2b), is longer than 100 μs leading to $T_1/\tau_{out}$ of about 50. Figure 2c, which depicts the signal histogram with a 1 μs integration time, shows a separation of the mean value of the $|0\rangle$ and $|1\rangle$ signal levels by more than 5 times the standard deviation. Using these parameters, we estimate the measurement fidelities for the $|0\rangle$ and $|1\rangle$ and the readout visibility that accounts for measurement errors owing to relaxation and thermal tunneling events\cite{22,25} (see SI Section S4). As shown in Figure 2d, the measurement fidelity (visibility) reaches 96.4% (92.6%) at the optimum threshold, confirming the high-fidelity single-shot readout of the HQ states (see SI Section S5). Moreover, using master equation simulations and additional $T_1$ measurements, we estimate that the readout error due to leakage and state relaxation during the adiabatic ramp pulse is less than 2% (see SI Section S4).

We now discuss the application of the single-shot readout method to ac-driven coherent operations of the HQ. Applying bursts of ac detuning modulation at the point O yields Rabi oscillations corresponding to $x$-axis rotations on the Bloch sphere, as shown in Figure 3a,b. The typical Rabi frequency, which is of the order of 100 MHz, increases linearly as a function of the microwave amplitude $A_{mic}$ at the output port of the waveform generator. Although the readout visibility with

Figure 2. (a) Histogram of the tunnel-out time $\tau_{out}$. Inset: Histogram of the tunnel-in time $\tau_{in}$. Exponential fits yield $\tau_{out} = 2.04 \pm 0.03 \mu$s and $\tau_{in} = 32 \pm 3 \mu$s. (b) Relaxation time $T_1$ measurement at $\tau$ identical to point I/M. By observing the amplitude decay of the Larmor oscillation as a function of the waiting time at the point W indicated in the inset, $T_1 = 102 \pm 6 \mu$s is obtained. (c) Histogram of the detector signal with an integration time of 1 μs. The solid curves are the histograms for the states $|0\rangle$ and $|1\rangle$ simulated using the experimentally obtained $\tau_{out}$, $\tau_{in}$, $T_1$, and thermal tunneling probability. (d) Calculated fidelity and visibility as a function of the threshold level $V_{\text{threshold}}$ showing the readout fidelity for the state $|0\rangle$/$|1\rangle$ of 95.4% (97.3%). The readout visibility is 92.6% at the optimal threshold $V_{\text{opt}}$. \
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perfect gate control can be as high as 92.6%, the limited Rabi decay time due to decoherence and finite pulse length (see SI Section S4) leads to a maximum oscillation visibility of approximately 75% in this experiment.

Moreover, $T_2^\#$ is characterized by performing a Ramsey experiment (Figure 3c), which demonstrates $z$-axis rotations on the qubit Bloch sphere. Between the first and the second rotation pulses $X_{\pi/2}$, which initialize the superposition state and set the measurement axis, respectively, we apply a ramp-evolution pulse with detuning amplitude $\epsilon_p$. $Z$-axis rotation during the evolution time $\tau_e$, results from the development of a relative phase between $|0\rangle$ and $|1\rangle$, given by $\phi = \epsilon_p (2\pi f_{Qubit}) \tau_e$, where $f_{Qubit}$ is the qubit frequency. Typically, $T_2^\#$ is of the order of 7 ns, which is similar to earlier results (Figure 3c, inset).\(^{39}\)

While a recent theory provides coherence analysis of HQs in both GaAs and Si,\(^{44}\) more work is necessary for systematically identifying the dominant sources of noise in this system.

Furthermore, Figure 3d demonstrates two-axis controllability on the $x$−$y$ plane of the Bloch sphere. The $P_1$ oscillations of the states initially prepared along and opposite to the $y$-axis ($P(|Y\rangle)$ and $P(|\overline{Y}\rangle)$) are out-of-phase as a function of the phase $\phi$ of the measurement pulse $\Omega(\phi)$ that determines the angle between the $x$-axis and the measurement axis. Together with the Rabi ($x$-axis control) and Ramsey ($z$-axis control) oscillations, the result demonstrates the full control of the GaAs HQ with a single-shot readout capability.

In this experiment, the highly asymmetric singlet–triplet energy splitting, possibly originating from the electron–electron interaction,\(^{40,41}\) was exploited, which provided the $f_{Qubit} \approx 1.4$ GHz regime during operation in the (2, 1) configuration that facilitates electronic ac control. It also provided the $f_{Qubit} \approx 95.8$ GHz regime in the measurement configuration (1, 2), which is useful for high-fidelity EST. While the technique is general and can be used for GaAs HQ in other electron occupancies as well as silicon-based HQ,\(^{37,45}\) further investigations are required for determining a convenient regime for both ac control and high-fidelity measurement in Si/SiGe. $T_1$ at the I/M point is shown to exceed 100 ms,\(^{35}\) which facilitates a high-fidelity single-shot readout even with a room-temperature trans-impedance amplifier. Moreover, the current quantum oscillation visibility is limited by $T_2^\#$ for the given tuning. While the splitting in the energy level in the operation configuration is expected to be tunable, one cannot rule out that $T_2^\#$ of the HQ in GaAs in this tuning is limited by nuclear fluctuations that mix different logical states. In such a situation, reducing $df_{Qubit}/d\phi$ and, hence, reducing the susceptibility to charge noise by further tuning may not necessarily increase $T_2^\#$. We plan to investigate the dominant
source of noise by systematic tuning as well as the HQ regime for the left double QD (Figure 1a) in the same device.

In conclusion, we have demonstrated the high-fidelity EST-single-shot readout of a driven HQ in GaAs. Achieving a measurement fidelity $\approx 96.4\%$ and readout visibility $\approx 92.6\%$, which are comparable with state-of-the-art EST single-shot detections for other types of QD qubits, $^{32,25,46}$ the results set the benchmark for the HQ readout performance and provide a useful demonstration that can be adopted for HQ in a more general setting. With a single-shot readout on a microsecond time scale, experiments involving fast Hamiltonian learning $^{32,34}$ or detecting wide-band noise spectra $^{47}$ the benchmark for the HQ readout performance and provide a demonstration has so far been limited only to single-spin and singlet–triplet qubits, are also conceivable.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.nanolett.1c00783.

Zoomed-out version of the stability diagram, preliminary full configuration interaction calculation, magnetic field susceptibility measurement, numerical model for the hybrid qubit, experimental methods, and details of the readout fidelity analysis (PDF)

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