High fidelity state preparation, quantum control, and readout of an isotopically enriched silicon spin qubit

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# Summary

## 1. Introduction
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## 2. System overview and optimizing operation parameters
- Measurement circuit for readout
- Charge sensor and spin-to-charge conversion
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Requirements for 99% visibility

- For a LD spin qubit that uses Elzerman readout, the minimum requirements for achieving 99% visibility are [1]:

1. large Zeeman splitting $E_z$ relative to the electron temperature $T_e$, $E_z \gtrsim 13k_B T_e$

2. fast tunnel out time $t_{\text{out}}^\uparrow$ for a spin-up electron relative to the spin relaxation time $T_1$, $T_1 \gtrsim 100t_{\text{out}}^\uparrow$

3. fast sampling rate $\Gamma_S$ relative to the reload rate $1/t_{\text{in}}^\downarrow$, $\Gamma_S \gtrsim 12/t_{\text{in}}^\downarrow$.

If any of these requirements are not met, 99% visibility Elzerman spin readout is not possible.

[1] D. Keith, S. K. Gorman, L. Kranz, Y. He, J. G. Keizer, M. A. Broome, and M. Y. Simmons, Benchmarking high fidelity single-shot readout of semiconductor qubits, New J. Phys. 21, 063011 (2019).
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The device [0]:

- Si/SiGe heterostructure with an isotopically purified $^{28}\text{Si}$ (800 ppm residual $^{29}\text{Si}$) quantum well
- Lithographically defined overlapping aluminum gate electrodes
- 6 quantum dots with 2 proximal charge sensors

[0] D. M. Zajac, T. M. Hazard, X. Mi, K. Wang, and J. R. Petta, A reconfigurable gate architecture for Si/SiGe quantum dots, Appl. Phys. Lett. 106, 223507 (2015)
Optimization of charge state readout:

- $V_{exc}$ @ 1 MHz is applied to S1 and the drain current flows to ground through a 20 kΩ resistor

- The voltage drop across the 20 kΩ resistor is amplified by 2 high-electron mobility transistors (HEMT) @ 1K and 4K before a RT amplifier

- $c_p \sim 8$ pF which limits the circuit bandwidth to $\sim 1$ MHz
• Coulomb blockade peak in the charge sensor conductance $g_{S1}$ as the sensor dot plunger gate voltage $V_{PS1}$ is swept

• Changing $N_2 = 0$ to $N_2 = 1$ shifts the Coulomb blockade peak by $\sim$ its FWHM

• When biased on the side of a Coulomb blockade peak the sensor dot can easily detect real-time tunneling events
Charge sensor – Coulomb blockade

- Real-time $g_{S1}$ sampled at 1 MS/s with chemical potential $\mu_2 \sim E_{F,Res}$

- The switching rate between $N_2 = 0$ and $N_2 = 1$ is set by the tunnel coupling $\Gamma$ between the $D_2$ and Res. to be slower than measurement bandwidth.

- The charge readout SNR is set by the separation of the two Gaussians relative to their spread: $SNR = (m_0 - m_1)/\bar{\sigma}$ with $\bar{\sigma} = (\sigma_1 + \sigma_0)/2$.
SNR and electron temperature $T_e$ as a function of the peak-to-peak excitation voltage $V_{exc}$ from the charge sensor.

- **Operation voltage:** $V_{exc} = 85 \, \mu V_{pp}$, where the $SNR \approx 12.5$ and $T_e \approx 45 \, mK$.
- The electron temperature is estimated by the broadening of the tunneling line width for the first electron dot-reservoir transition.
- Values of $T_e \ll 200 \, mK$ [2,3].

[2] D. Keith et al, Single-shot spin readout in semiconductors near the shot-noise sensitivity limit, Phys. Rev. X 9, 041003 (2019).
[3] A. Morello et al, Single-shot read-out of an electron spin in silicon, Nature (London) 467, 687 (2010).
Charge sensor – SNR and $T_e$

- SNR and electron temperature $T_e$ as a function of the peak-to-peak excitation voltage $V_{exc}$ from the charge sensor.

- In theory a $SNR = 12.5$ yields a lower bound estimate of the charge state infidelity $1 - F_c \geq 3e^{-10}$ [4].

- The negligible charge state infidelity implies that the overall readout performance will be limited by the spin-to-charge conversion process.

[4] J. Z. Blumoff et al., Fast and high-fidelity state preparation and measurement in triple-quantum-dot spin qubits, arXiv:2112.09801 (2021).
Process of spin-to-charge conversion for a spin-up electron:

- The $|\uparrow\rangle$ e$^-$ tunnels off the dot in $\sim 1/\Gamma_{out}^{\uparrow}$ and is replaced by $|\downarrow\rangle$ e$^-$ that tunnels into the dot in $\sim 1/\Gamma_{in}^{\downarrow}$.

- $1/\Gamma_{out}^{\uparrow} < T_1$ and $\Gamma_{in}^{\downarrow}$ must be slow enough to be detectable, given the finite bandwidth of the measurement circuit.

- The overall tunnel rate $\Gamma$ is set by $V_{B3}$.

- $\Gamma_{out}^{\uparrow}/\Gamma_{in}^{\downarrow}$ is adjusted by $\Delta (E_{F,Res} - E_{|\downarrow\rangle})$.

- $B_{ext} = 410$ mT, with $E_Z = 19.105$ GHz (79 $\mu$eV) and $T_1 = 31.5$ ms
Spin-to-charge conversion

- Process of spin-to-charge conversion for a spin-up electron:
  - The optimal $\Delta$ is large enough to suppress thermal errors and small enough to maximize the ratio $\Gamma_{\text{out}}^\uparrow/\Gamma_{\text{in}}^\downarrow$
  - The rates $\Gamma_{\text{out}}^\uparrow$ and $\Gamma_{\text{in}}^\downarrow$ are extracted by the tunneling times from many single shot traces Fig. (b) and fitting to an exponential decay
  - Fig. (c) shows the visibility $V = F^\uparrow + F^\downarrow - 1$ (preparing 10000 states and measuring) in function of $\Delta$
  - The optimal values: $\Delta^* \approx 30 \mu\text{eV}$ resulting in $\Gamma_{\text{out}}^\uparrow \approx \Gamma_{\text{in}}^\downarrow \approx 20 \text{ kHz}$
Data acquisition parameters

- Optimization of data acquisition parameters:
  - Conductance threshold $g_{thr}$ and duration of the readout window $t_R$
  - $|\uparrow\rangle$ state is registered when $g_{S1} > g_{thr}$ within the time window $t_R$, Fig. (a)
  - If $g_{thr}$ is set too low $\Rightarrow$ noise can lead to false positives ($F_{\downarrow}$ $\searrow$)
  - If $g_{thr}$ is set too high $\Rightarrow$ we miss the short events that don’t reach full amplitude ($F_{\uparrow}$ $\swarrow$)
Optimization of data acquisition parameters:

- Conductance threshold $g_{thr}$ and duration of the readout window $t_R$

  - if $t_R$ is too low ⇒ not able to catch all hopping events from spin-to-charge conversion ($F_↑ \downarrow$)
  - if $t_R \gg t_{out}^\uparrow$ ⇒ more thermal errors ($F_\downarrow \uparrow$)
Optimization of data acquisition parameters:

- Conductance threshold $g_{thr}$ and duration of the readout window $t_R$
- Optimization of $g_{thr}$ and $t_R$ preparing 10000 states and measuring, using the optimized $\Delta^*$
- Fidelity $F$ as a function of $g_{thr}$:
  $\Rightarrow$ Optimal $g_{thr}^* = 0.22$ e²/h, Fig. (b)

- If $g_{thr} \downarrow \Rightarrow F \downarrow \downarrow$
- If $g_{thr} \uparrow \Rightarrow F \uparrow \downarrow$
Data acquisition parameters

- Optimization of data acquisition parameters:
  - Conductance threshold $g_{thr}$ and duration of the readout window $t_R$
  - Optimization of $g_{thr}$ and $t_R$ preparing 10000 states and measuring, using the optimized $\Delta^*$
  - Measurement infidelities $1 - F$ as a function of $t_R$:
    $\Rightarrow$ Optimal $t_R^* = 670 \mu s$, Fig. (c)
    - If $t_R \searrow \Rightarrow F_{\uparrow} \searrow$
    - If $t_R \nearrow \Rightarrow F_{\downarrow} \nearrow
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Fidelities with optimized parameters

- Reached fidelities with optimized parameters ($V_{PS1}^*, V_{exc}^*, \Delta^*, g_{thr}^*$ and $t_R^*$):
  
  $F_\downarrow = 99.86\% \pm 0.05\%$, $F_\uparrow = 99.26\% \pm 0.12\%$

  $\Rightarrow$ average measurement fidelity $F_M = 99.56\%$

- The probability of missing a spin bump

  $P_{miss} = 1 - \frac{(1-e^{(R_S^\uparrow-R_S^\downarrow)/2})R_S}{(1-e^{R_S^\uparrow/2})(R_S^\uparrow-R_S^\downarrow)}$ with $R_S^\uparrow = t_S/t_{out}^\uparrow$, $R_S^\downarrow = t_S/t_{in}^\downarrow$ and $t_S = 1 \mu s$ (sampling rate)
Rabi oscillations

- Spin-up probability $P_{\uparrow}$ as a function of the frequency detuning $\Delta f$ from resonance (19.105 GHz) and the microwave burst length $\tau_R$, Fig. (a).

- Rabi oscillations at resonance, Fig. (b).
Gate and SPAM fidelities - GST

- High gate and SPAM fidelities verified using Gate Set Tomography (GST) protocols for single qubit gates ($I, X, Y$) [5]

- GST yields to:
  - $\rho_{0,GST} = 99.76\% \pm 0.04\%$
  - $M_{GST} = 99.35\% \pm 0.1\%$
  - $SQG_{GST} = 99.956\% \pm 0.002\%$

- The gate fidelity is limited by incoherent noise ($T_2^* = 3.2 \, \mu s$, $T_2^H = 139 \, \mu s$ measured using Ramsey and Hahn echo pulse sequences)

[5] E. Nielsen, J. K. Gamble, K. Rudinger, T. Scholten, K. Young, and R. Blume-Kohout, Gate Set Tomography, Quantum 5, 557 (2021).
Gate and SPAM fidelities - IRB

- \((X, X^2, -X, Y, Y^2, -Y)\) fidelities with Interleaved Randomized Benchmarking (IRB) [6]:
  - \(k = 200\) unique sequences per point, with 100 averages
  - Sequence lengths of up to \(N_{C1} = 4096\) Clifford operations are employed to achieve full saturation of the sequence fidelity curves, Fig. (c).

[6] E. Magesan, J. M. Gambetta, and J. Emerson, Scalable and robust randomized benchmarking of quantum processes, Phys. Rev. Lett. 106, 180504 (2011).

• traces shifted by 0.25
Gate and SPAM fidelities – GST & IRB

- Average gate fidelities, Table 1:
  - Retuning routines every ~ 30 mins during long measurements (~ 14 hrs.) to correct for readout and qubit frequency drifts
  - The charge sensor excitation is turned off during qubit manipulation to reduce heating at the device

| Gate | Fidelity          | Operation | Fidelity          |
|------|-------------------|-----------|-------------------|
| X    | $99.969\% \pm 0.004\%$ | $\rho_0$  | $99.76\% \pm 0.04\%$ |
| $X^2$| $99.964\% \pm 0.003\%$ | $M$       | $99.35\% \pm 0.1\%$  |
| $-X$ | $99.949\% \pm 0.005\%$ | $I$       | $99.43\% \pm 0.036\%$ |
| Y    | $99.973\% \pm 0.004\%$ | $X$       | $99.958\% \pm 0.002\%$ |
| $Y^2$| $99.961\% \pm 0.004\%$ | $Y$       | $99.954\% \pm 0.002\%$ |
| $-Y$ | $99.937\% \pm 0.005\%$ |           |                   |
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Si spin qubits can be operated reliably with all-around high performance metrics:

- Optimal SPAM requires careful tuning of operation parameters to minimize the loss of spin information due to relaxation and a finite 1 MHz measurement bandwidth.
- Measurement fidelities > 99%
- GST and IRB are implemented to demonstrate average $SQG$ fidelities > 99.95% under the same operating conditions.