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

Summary

1. Introduction
   - Requirements for 99% visibility

2. System overview and optimizing operation parameters
   - Measurement circuit for readout
   - Charge sensor and spin-to-charge conversion
   - Data acquisition parameters

3. SPAM and Single Qubit Gates fidelities
   - GST and IRB fidelities

4. Conclusions
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 $T_e$, $E_z \simeq 13k_BT_e$

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

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

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

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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

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 ~ its FWHM.

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

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.

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 $\Delta (E_{F,\text{Res}} - E_{|\downarrow\rangle})$

- $B_{ext} = 410$ mT, with $E_Z = 19.105$ GHz (79 $\mu$eV) and $T_1 = 31.5$ ms
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 $\Gamma_{out}^{\uparrow}/\Gamma_{in}^{\downarrow}$

- The rates $\Gamma_{out}^{\uparrow}$ and $\Gamma_{in}^{\downarrow}$ 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: $\Delta^* \approx 30\mu eV$ resulting in $\Gamma_{out}^{\uparrow} \approx \Gamma_{in}^{\downarrow} \approx 20\ kHz$
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 ⇒ noise can lead to false positives ($F_{\downarrow} \searrow$)
- If $g_{thr}$ is set too high ⇒ we miss the short events that don’t reach full amplitude ($F_{\uparrow} \searrow$)
Optimization of data acquisition parameters:

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

  - if $t_R$ is too low $\Rightarrow$ not able to catch all hopping events from spin-to-charge conversion ($F_{↑} \searrow$)
  - if $t_R \gg t_{out}^\uparrow$ $\Rightarrow$ more thermal errors ($F_{↓} \searrow$)
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 $g_{thr}$:
  - Optimal $g_{thr}^* = 0.22 \text{ e}^2/\text{h}$, Fig. (b)
  - If $g_{thr} \downarrow \Rightarrow F \downarrow \downarrow$
  - If $g_{thr} \uparrow \Rightarrow F \uparrow \downarrow$
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 $t^*_R = 670$ µs, 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 $t^*_R$):
  - $F_\downarrow = 99.86\% \pm 0.05\%$, $F_\uparrow = 99.26\% \pm 0.12\%$
    \[ \Rightarrow \text{average measurement fidelity } F_M = 99.56\% \]
  - The probability of missing a spin bump
    \[ P_{\text{miss}} = 1 - \frac{(1-e^{(R^\uparrow_S-R^\downarrow_S)/2})R_S}{(1-e^{R^\uparrow_S/2})(R^\uparrow_S-R^\downarrow_S)} \]
    with $R^\uparrow_S = t_S/t^\uparrow_{out}$, $R^\downarrow_S = t_S/t^\downarrow_{in}$ 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 State Preparation And Measurement (SPAM) fidelities

- 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)

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).


- traces shifted by 0.25
 Average gate fidelities, Table 1:
• Retuning routines every $\sim 30$ mins during long measurements ($\sim 14$ 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

<table>
<thead>
<tr>
<th>Gate</th>
<th>IRB Fidelity</th>
<th>GST Fidelity</th>
<th>Operation</th>
<th>Fidelity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>99.969% ±0.004%</td>
<td>$\rho_0$</td>
<td>99.76% ±0.04%</td>
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<tr>
<td>$X^2$</td>
<td>99.964% ±0.003%</td>
<td>$M$</td>
<td>99.35% ±0.1%</td>
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<tr>
<td>$-X$</td>
<td>99.949% ±0.005%</td>
<td>$I$</td>
<td>99.43% ±0.036%</td>
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<tr>
<td>$Y$</td>
<td>99.973% ±0.004%</td>
<td>$X$</td>
<td>99.958% ±0.002%</td>
<td></td>
</tr>
<tr>
<td>$Y^2$</td>
<td>99.961% ±0.004%</td>
<td>$Y$</td>
<td>99.954% ±0.002%</td>
<td></td>
</tr>
<tr>
<td>$-Y$</td>
<td>99.937% ±0.005%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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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