An electrically-driven single-atom ‘flip-flop’ qubit

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An electrically-driven single-atom ‘flip-flop’ qubit

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- Quantum information encoded in electron-nuclear states of P donor in Si
- Qubit controlled by local electric fields
- Electrical drive mediated by modulating the electron-nuclear hyperfine coupling
Flip-flop Qubit

\[ H = \gamma_e B_0 S_z + \gamma_n B_0 I_z + AS \cdot I \]

- Nucleus: \( I = \frac{1}{2} \), \( \gamma_n = 17.23 \text{ MHz/T} \) - basis states \( |\uparrow\rangle, |\downarrow\rangle \)
- Electron: \( S = \frac{1}{2} \), \( \gamma_e = 27.97 \text{ GHz/T} \) - basis states \( |\uparrow\rangle, |\downarrow\rangle \)
- At \( B_0 \gg A \): eigenstates are tensor-product states \( |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle, |\uparrow\uparrow\rangle, |\downarrow\downarrow\rangle \)
- Fermi contact hyperfine interaction: eigenstates are \( |S\rangle = (|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)/\sqrt{2} \) and \( |T_0\rangle = (|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)/\sqrt{2} \)
Flip-flop Qubit

\[ H = (\gamma_+)B_0 \sigma_z + A \sigma_x \]

- Flip-flop subspace: \( |0\rangle = |\downarrow\uparrow\rangle \), \( |1\rangle = |\uparrow\downarrow\rangle \) (z-operator eigenstates)

- \( |S\rangle = (|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)/\sqrt{2} \) and \( |T_0\rangle = (|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle)/\sqrt{2} \) are x-operator eigenstates

- Flip-flop resonance frequency:
  \[ \epsilon_{eff} = \sqrt{(\gamma_+ B_0)^2 + A(E_{dc})^2} \]

- Modulating hyperfine interaction by electric field drives qubit transitions
Device

- MOS device with ion-implanted $^{31}P$ donor
- Fast Donor (FD) gate for EDSR
- SET for electron spin readout (spin-dependent tunnelling)
- Microwave antenna for ESR and NMR
Resonant Transitions

- ESR1 and ESR2 separated by $A = 114.1$ MHz – close to 117.53 MHz found in bulk (bulk-like donor)

- Flip-flop transition: microwave tone applied to FD, then nuclear spin orientation is measured

- Nuclear spin readout:
  - adiabatic frequency sweep around ESR1 (adiabatic inversion) – aESR1
  - Readout electron spin
  - If $|\uparrow\rangle$, then nuclear spin was $|\downarrow\rangle$

- High probability $P_{flip}$ of the nuclear state changing from one shot to the next -> indicates flip-flop resonance being driven
Initialization

- Electron-Nuclear Double Resonance (ENDOR) pulse sequence to initialize in the flip-flop ground state $|\downarrow\uparrow\rangle$
- aESR2 pulse followed by aNMR1 pulse
- If system is in $|\downarrow\uparrow\rangle$:
  - aESR2 flips electron spin to $|\uparrow\uparrow\rangle$
  - aNMR pulse is off-resonant and electron readout will initialize back to $|\downarrow\uparrow\rangle$
- If system is in $|\downarrow\downarrow\rangle$:
  - aESR2 pulse is off-resonant
  - aNMR1 pulse will flip the nucleus to $|\downarrow\uparrow\rangle$
Coherent Electrical Control

- ENDOR initialization -> EDSR -> flip-flop readout
- Flip flop readout:
  - readout electron spin
  - reload electron onto donor
  - perform nuclear spin readout
Rabi Frequency, Hyperfine Modulation

- Maximum Rabi frequency of 118.5 kHz (5x typical NMR drive) – limited by bulk-like donor state (small dipole)
  \[ f_{\text{rabi}} = \left( \frac{\partial A(E)}{2 \partial E} \right) E_{ac} \]

- \[ \frac{\partial A}{\partial V_{FD}} = 512 \text{ kHz/V} \] with positive slope – expectation that this should be negative

- Limited control of hyperfine interaction due to charging of nearby donors

Relaxation

- $T_{1ff}$ found by saturating the ESR1 transition
  - Start from $|\downarrow\downarrow\rangle$
  - Calibrated slow frequency inversion sweep used to create $a|\downarrow\downarrow\rangle + b|\uparrow\downarrow\rangle$
  - $|a|^2 = |b|^2 = 0.5$

- aESR1 applied every 5 s to counteract $T_{1e}$ process

- Measure leakage out of flip-flop subspace

- $T_{1ff} = 173$ s
Decoherence

- Both $T_{2ff}^*$ and $T_{2ff}^H$ measured

- Decoherence Mechanisms:
  - EDSR pulse induced resonance shift (poorly understood)
  - Residual $^{29}Si$ in substrate (splitting of flip-flop ESR resonances – coupling to $^{29}Si$ nuclei)

<table>
<thead>
<tr>
<th></th>
<th>$T_1$ (s)</th>
<th>$T_2^*$ (μs)</th>
<th>$T_2^H$ (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>6.45(39)</td>
<td>14.6(9)</td>
<td>336(10)</td>
</tr>
<tr>
<td>$n$</td>
<td>–</td>
<td>240(42)</td>
<td>541(72)</td>
</tr>
<tr>
<td>$ff$</td>
<td>173(12)</td>
<td>4.08(88)</td>
<td>184(24)</td>
</tr>
</tbody>
</table>

\[ T_{2ff}^* \] and \[ T_{2ff}^H \] measured

\[ T_{2ff}^* = 4.09(88) \text{ μs} \]

\[ T_{2ff}^H = 184(24) \text{ μs} \]
Single Qubit Gate Fidelities

- Average $F_{1Q} = 97.5\% - 98.5\%$ from Gate Set Tomography
- $F_{1Q} = 98.4\%$ from Randomised Benchmarking
Conclusion

- This time:
  - large gate voltage swing necessary to move the electron away from the donor under study would unsettle the charge state of nearby donors (limits Rabi frequency)

- Next time:
  - large dipole regime where Rabi frequency would be maximum (30 ns for $\frac{\pi}{2}$ rotation)
  - deterministic single-ion implantation will help

- Future:
  - Different donors, e.g. $^{123}Sb$ with $I > 1/2$ for all-electrical control (electric quadrupole moment enables nuclear electric resonance)
Thanks for your attention!