Spin Lifetime and Charge Noise in Hot Silicon Quantum Dot Qubits


Electron spins in quantum dots are a promising platform for large scale quantum computer.

Silicon: long coherence time, high fidelity single qubit rotation, compatible with conventional manufacturing technologies.

Control electronics dissipate heat -> limits operating temperature.

Investigation of the temperature dependence of two important metrics:

- Spin lifetime $T_1$ (determined by the spin relaxation)
- Charge noise (reduces readout and control fidelities)
- Si wafer with 100 nm epitaxial grown Si$_{28}$ and 10 nm thermally grown SiO$_2$ plus 10 nm Al$_2$O$_3$ (ALD)
- Gates: Ti (3 nm) and Pd (37 nm)
- Sensor dot for spin-to-charge conversion
- Claim: triple dot
- Red arrow: 0→1 transition relevant in this work
- Extract tunnel rate to reservoir by controlling P2 -> changes the position of the dot and its distance to the reservoir (in experiment ~700 Hz)
- Measurement of $T_1$ as a function of magnetic field and temperature

- When $k_B T \approx E_Z$, the visibility of the readout mechanism is reduced
  \[ T_{1,base} = 145 \text{ ms and } T_{1,1.1K} = 2.8 \text{ ms at } B_0 = 1 \text{ T} \]

- Two dominant relaxation mechanisms
  1. Phonon mediated relaxation ($\propto \omega^5$)
  2. Johnson noise ($\propto \omega$, mainly from 2DEG under reservoir gate)
Spin-Valley States

- Dependence of $T_1$ on temperature and magnetic field is coupled to the mixing of valley and spin

- Bulk silicon: 6 conduction band minima (valleys)
  - strain reduces the degeneracy to two, confinement results in non-degenerate valleys [1,2]

- Four lowest spin valley states:
  \[ |1\rangle = |v_-, \downarrow\rangle, |2\rangle = |v_-, \uparrow\rangle, |3\rangle = |v_+, \downarrow\rangle, |4\rangle = |v_+, \uparrow\rangle \]

- In systems with interface disorder, spin-orbit interaction leads to coupling
  \[ |\bar{2}\rangle = \left(\frac{1-a}{2}\right)^{1/2} |2\rangle - \left(\frac{1+a}{2}\right)^{1/2} |3\rangle \quad \text{and} \quad |\bar{3}\rangle = \left(\frac{1+a}{2}\right)^{1/2} |2\rangle + \left(\frac{1-a}{2}\right)^{1/2} |3\rangle \]
  with $a = \frac{E_{vs} - \hbar \omega_Z}{\sqrt{(E_{vs} - \hbar \omega_Z)^2 + \Delta^2}}$

- From relaxation rate $\Gamma_{sv} = \Gamma_{v+v-}(\omega_Z)F_{sv}(\omega_Z)$ when $E_{vs} = E_Z$ (maximum coupling, pure valley relaxation) one can determine $E_{vs} = 275 \, \mu\text{eV}$

**Reminder:** Phonon mediated relaxation and Johnson noise

\[ \Gamma^{ph(f)}_{v+v-}(\omega) = \Gamma^{ph(f)}_0 \cdot \left(\frac{\omega}{\omega_{VS}}\right)^{5(1)} \left[1 + 2n_b(\hbar\omega, k_b T)\right] \]

- If \( \hbar\omega \gg k_b T \): spontaneous phonon emission (T independent)
- If \( \hbar\omega \approx k_b T \): single phonon process (linear in T)
- If \( \hbar\omega \ll k_b T \): two-phonon processes

- At elevated temperatures (0.5 – 1 K): absorption processes due to thermal energy comparable to splitting

- Two main second order processes:
  1. Orbach (on resonance)
     - \( \Gamma \) at low T: exponential T dependence
     - \( \Gamma \) at high T: linear T dependence
  2. Raman (off resonance), dominant at \( T > 500 \text{ mK} \):
     - \( \Gamma \) scales polynomially with T (here \( T^9 \))
Temperature Dependence

- **Reminder:** $|\tilde{2}\rangle$ and $|\tilde{3}\rangle$ are dependend on magnetic (Zeeman) and electric (valley splitting) field
  - Spin lifetime can be controlled (reducing $B$, increasing $E$)

- By using extracted parameters from fits -> spin lifetime at 1 K larger than 400 ms when $B_0 = 0.1$ T and $E_{vs} = 575$ μeV

- Relaxation at low magnetic fields predicted to be dominated by second order processes (stronger field dependence of first order processes)

\[
|\tilde{2}\rangle = \left(\frac{1 - a}{2}\right)^{1/2} |2\rangle - \left(\frac{1 + a}{2}\right)^{1/2} |3\rangle
\]

\[
a = \frac{(E_{vs} - \hbar \omega_Z)}{\sqrt{(E_{vs} - \hbar \omega_Z)^2 + \Delta^2}}
\]
Charge Noise Measurements

- Charge noise attributed to defects -> 1/f spectral signature
- Measure charge noise as current fluctuations of the sensing dot
- Linear increase in charge noise over extended range of temperatures
  - Weak dependence -> qubit operation is only moderately affected upon temperature increase
Investigation of temperature dependence of spin relaxation and charge noise in a silicon quantum dot

- $T_{1,\text{base}} = 145 \text{ ms}$ and $T_{1,1.1K} = 2.8 \text{ ms}$ at $B_0 = 1 \text{ T}$

- Spin relaxation through electric field mediated spin-valley coupling

- Johnson noise dominates at low T, second order phonon processes at high T

- Noise is only moderately affected by temperature

- Spins in Si-MOS structures are robust against thermal noise

- Avenue for the demonstration of spin qubits at 1 - 4 K