Spin Lifetime and Charge Noise in Hot Silicon Quantum Dot Qubits

L. Petit, J. M. Boter, H. G. J. Eenink, G. Droulers, M. L. V. Tagliaferri, R. Li, D. P. Franke, K. J. Singh,
J. S. Clarke, R. N. Schouten, V. V. Dobrovitski, L. M. K. Vandersypen and M. Veldhorst

arXiv:1803.01774v1 (2018)

Motivation

- 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)

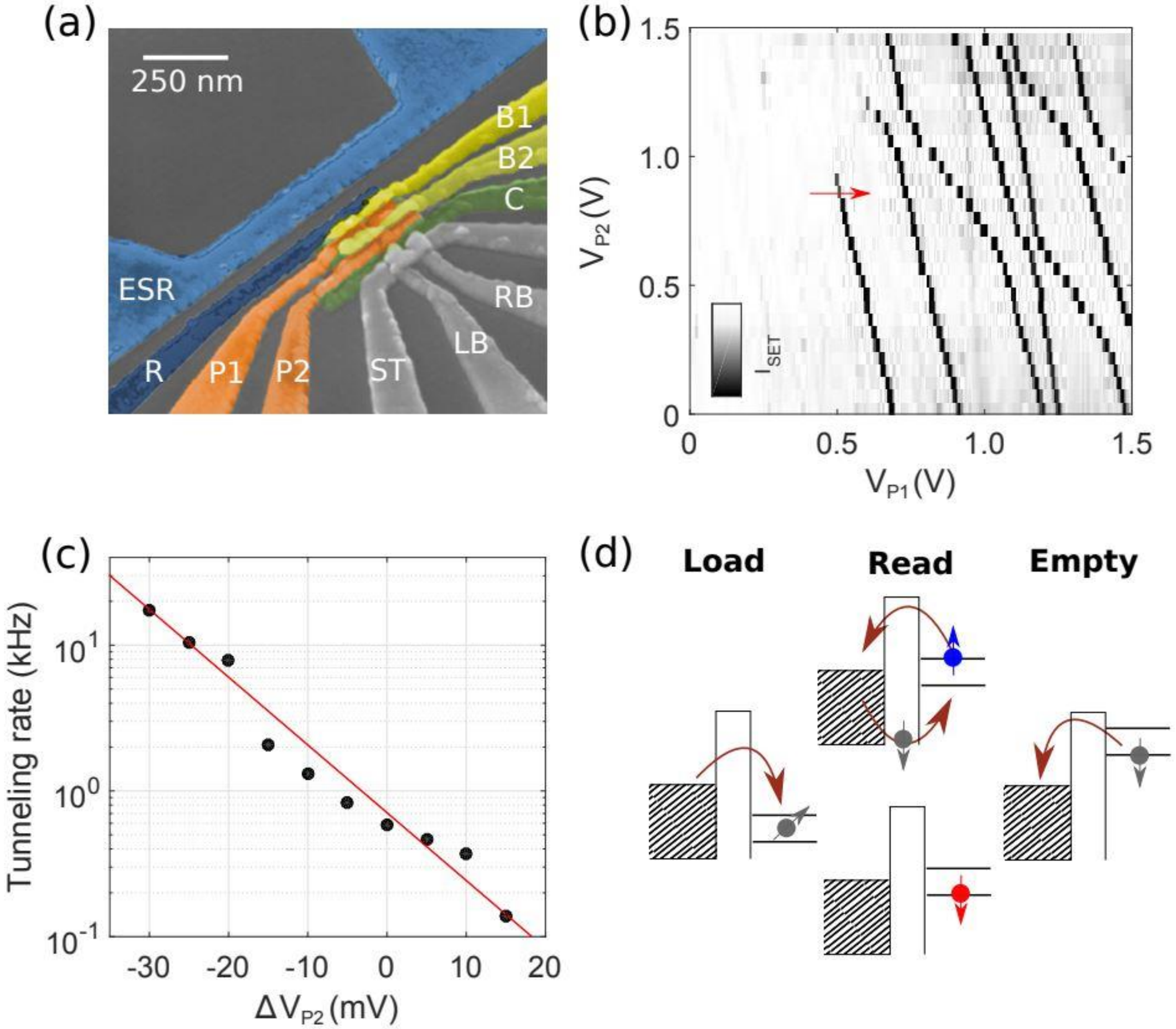
Device

- Si wafer with 100 nm epitaxial grown Si_{28} and 10 nm thermally grown SiO_2 plus 10 nm Al_2O_3 (ALD)

- Gates: Ti (3 nm) and Pd (37 nm)
- Sensor dot for spin-to-charge conversion

- Claim: tripple 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)

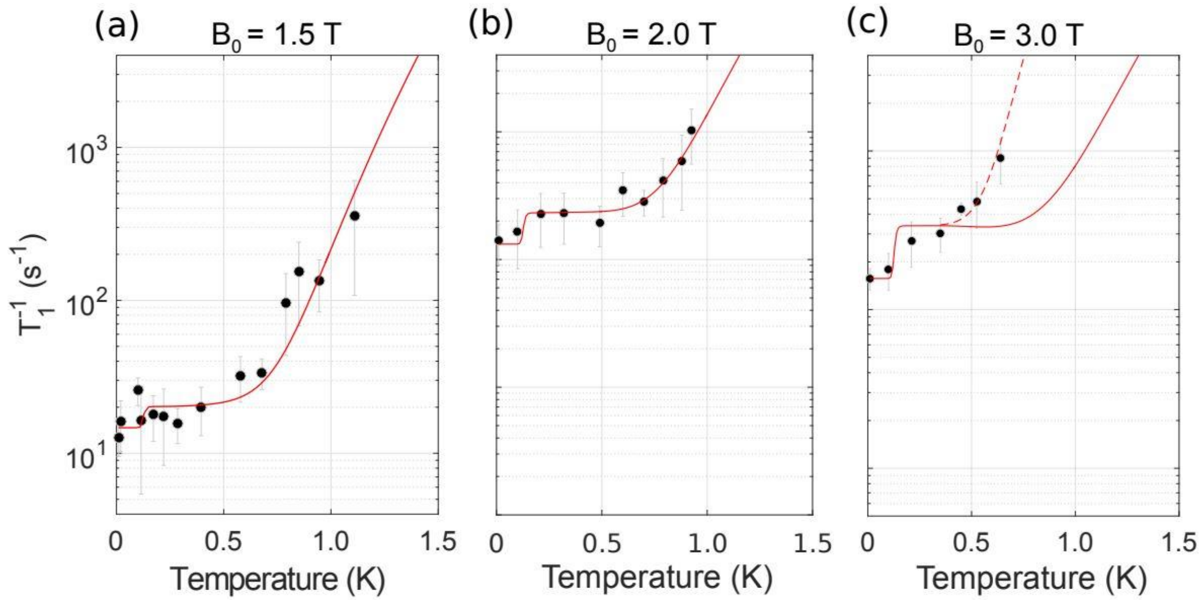


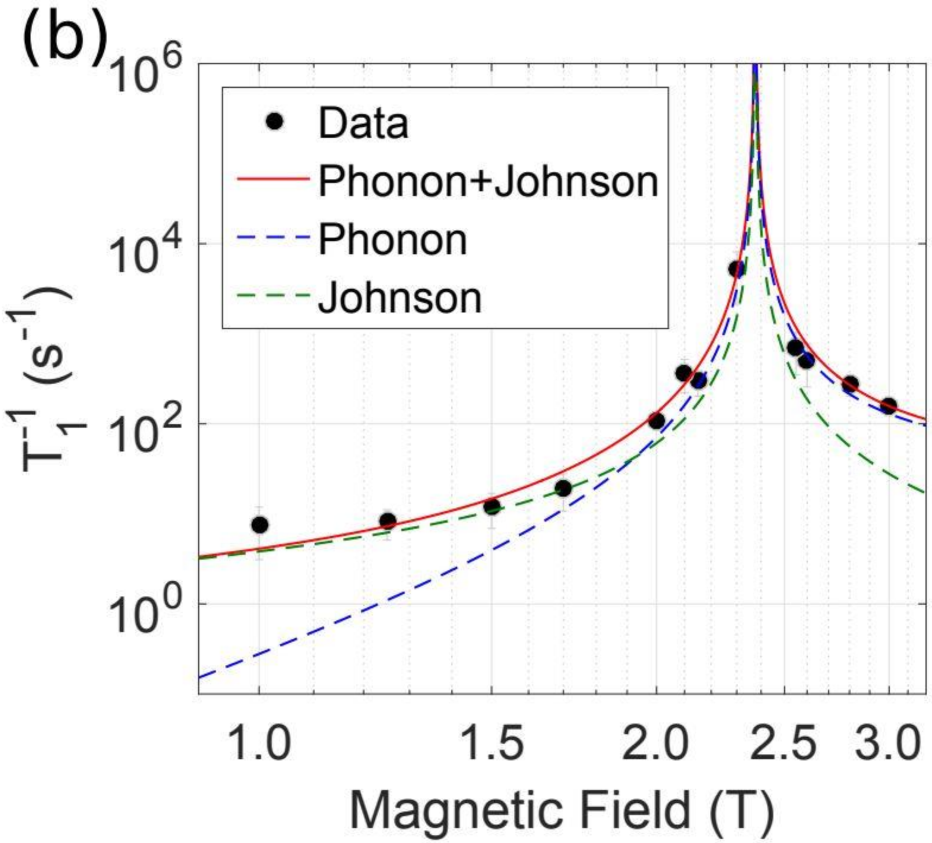
T_1 Measurements

- 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
  - ➢ $T_{1,base} = 145$ ms and $T_{1,1.1K} = 2.8$ ms at $B_0 = 1$ 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:

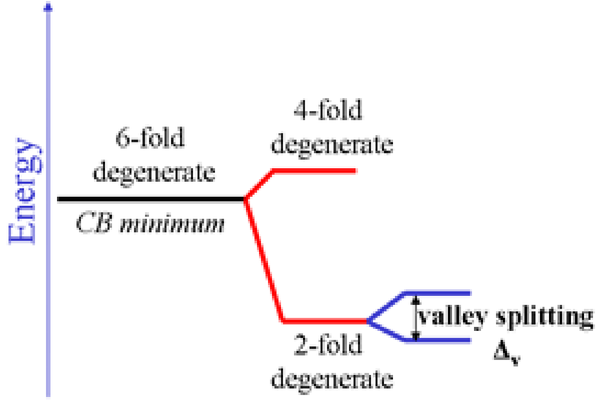
$$|1\rangle = |v_-,\downarrow\rangle,\ |2\rangle = |v_-,\uparrow\rangle,\ |3\rangle = |v_+,\downarrow\rangle,\ |4\rangle = |v_+,\uparrow\rangle$$

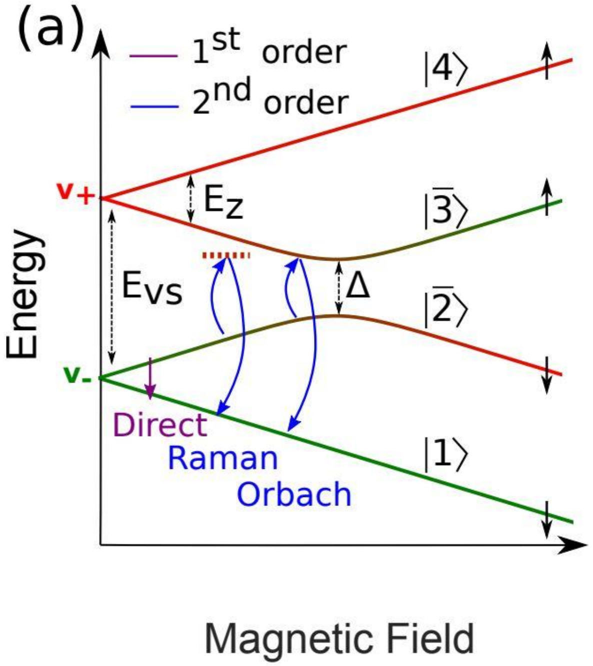
- In systems with interface disorder, spin-orbit interaction leads to coupling

$$|\bar{2}\rangle = \left(\frac{1-a}{2}\right)^{1/2}|2\rangle - \left(\frac{1+a}{2}\right)^{1/2}|3\rangle \quad \text{and} \quad |\bar{3}\rangle = \left(\frac{1+a}{2}\right)^{1/2}|2\rangle + \left(\frac{1-a}{2}\right)^{1/2}|3\rangle$$

$$\text{with } a = \frac{(E_{vs} - \hbar\omega_Z)}{\sqrt{(E_{vs} - \hbar\omega_Z)^2 + \Delta^2}}$$

- 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 $E_{vs} = 275$ µeV





[1] http://uw.physics.wisc.edu/~eriksson/si-valley-splitting.html
[2] Goswami, Slinker, Friesen *et al.*, Nature Physics 3 (2007)

Spin Relaxation

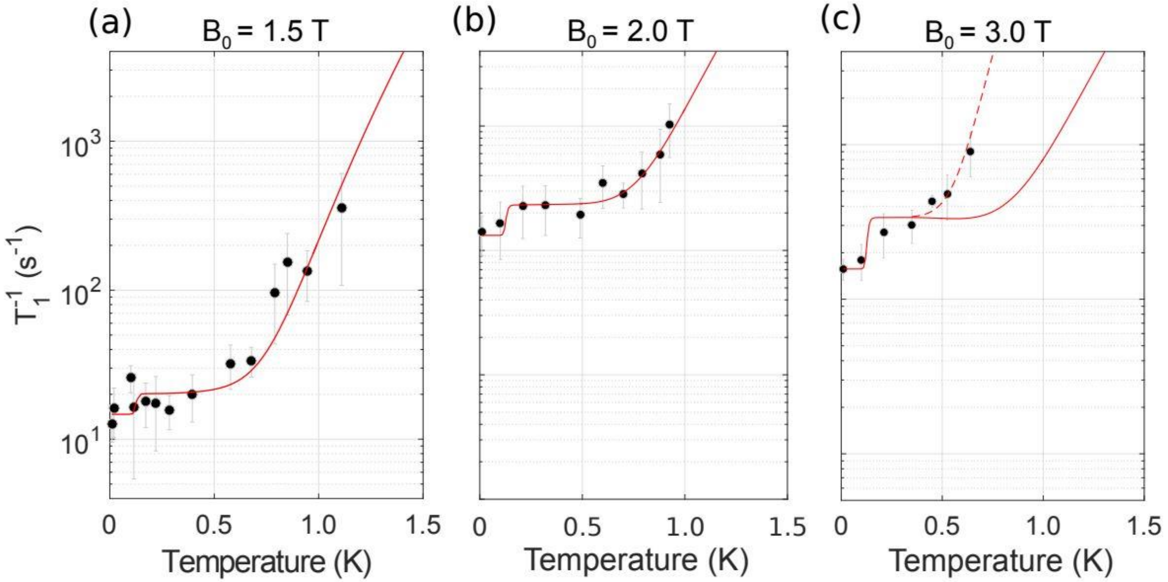
- *Reminder:* Phonon mediated relaxation and Johnson noise

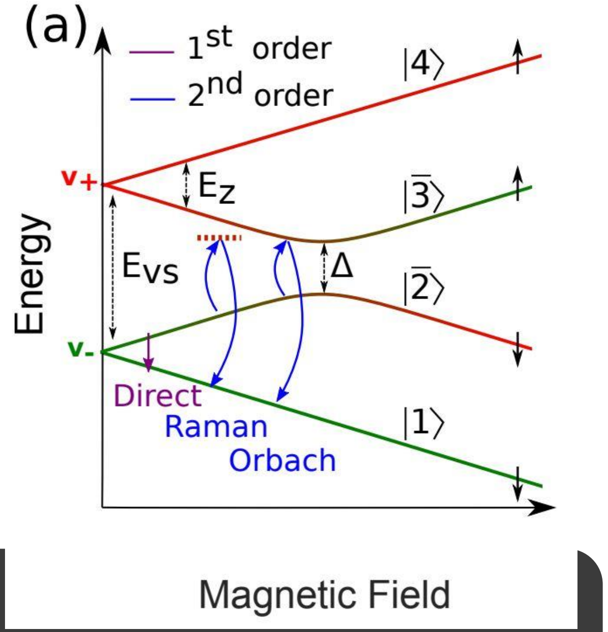
➢ $\Gamma_{v+v-}^{ph(J)}(\omega) = \Gamma_0^{ph(J)} \cdot \left(\frac{\omega}{\omega_{vs}}\right)^{5(1)} [1 + 2n_b(\hbar\omega, k_b T)]$

- 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 elevatet temperatures (0.5 – 1 K): absorbtion processes due to thermal energy comperable to splitting

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





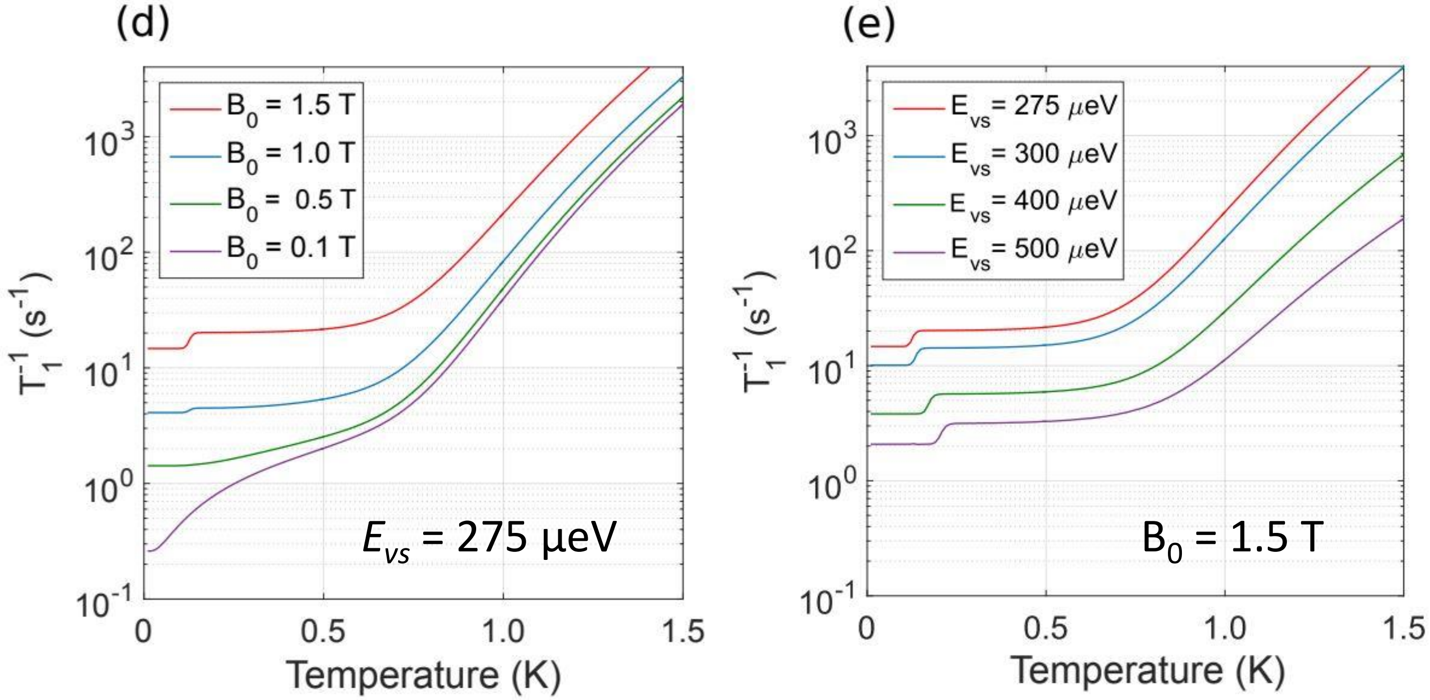
Temperature Dependence

$$|\bar{2}\rangle = \left(\frac{1-a}{2}\right)^{1/2} |2\rangle - \left(\frac{1+a}{2}\right)^{1/2} |3\rangle$$

with

$$a = \frac{(E_{vs} - \hbar\omega_Z)}{\sqrt{(E_{vs} - \hbar\omega_Z)^2 + \Delta^2}}$$

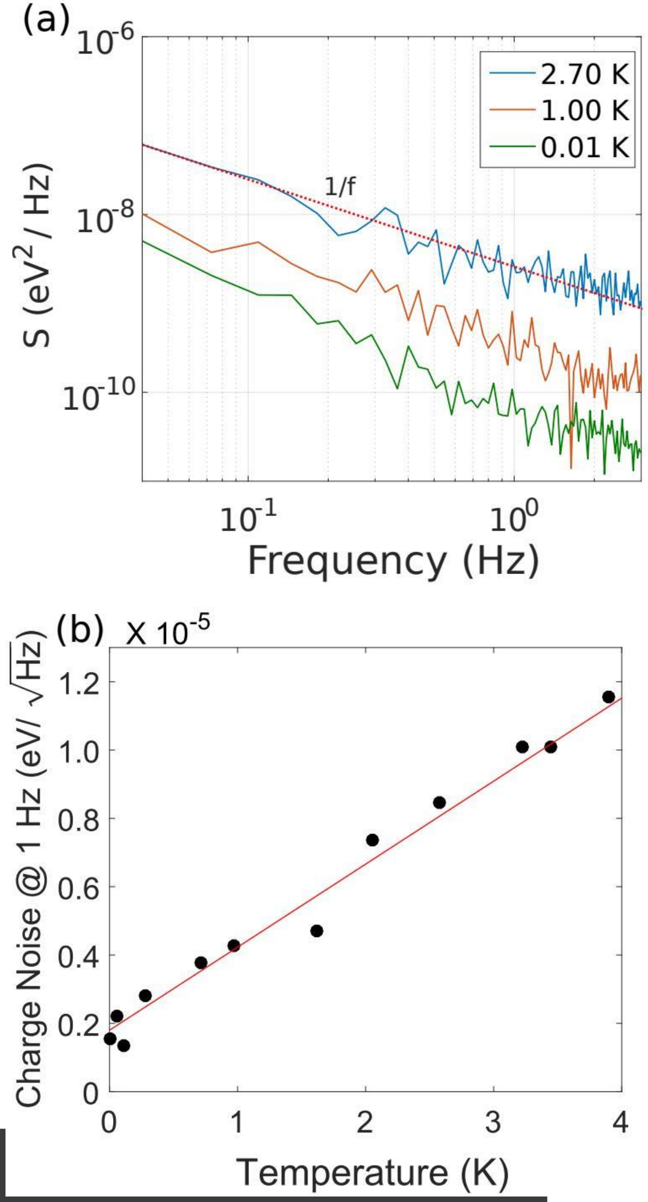
- *Reminder:* $|\bar{2}\rangle$ and $|\bar{3}\rangle$ are dependend on magnetic (Zeeman) and electric (valley splitting) field
  - Spin lifetime can be controlled (reducing B, increasing E)
- By using extracted parameters from fits -> spin lifetime at 1 K larger than 400 ms when $B_0 = 0.1$ T and $E_{vs} = 575$ μeV
- Relaxation at low magnetic fields predicted to be dominated by second order processes (stronger field dependence of first order processes)



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



Conclusion

- Investigation of temperature depence of spin relaxation and charge noise in a silicon quantum dot
- $T_{1,base} = 145$ ms and $T_{1,1.1K} = 2.8$ ms at $B_0 = 1$ 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

Additional Slide I