A silicon singlet-triplet qubit driven by spin-valley coupling

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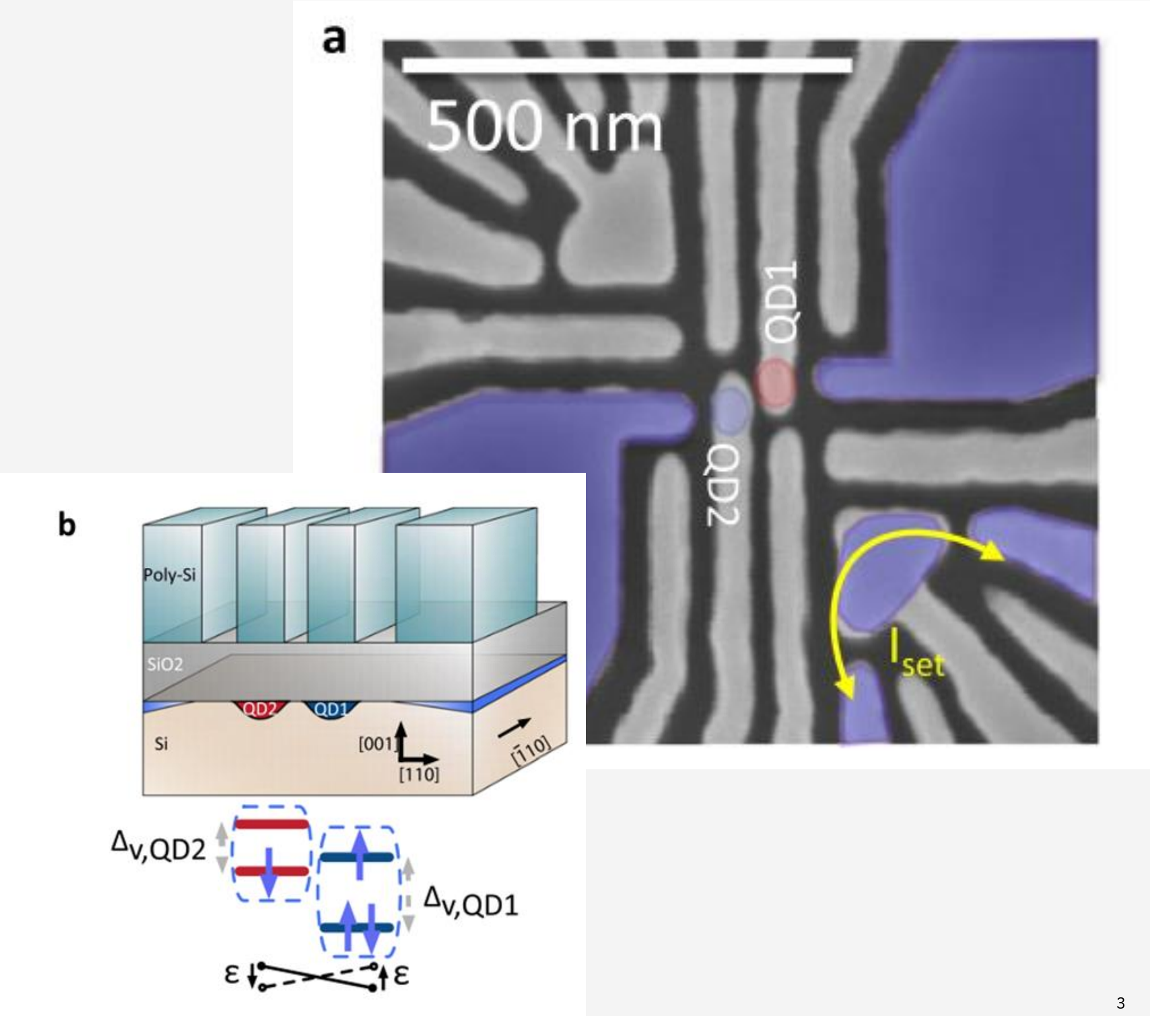
Abstract

Spin–orbit effects, inherent to electrons confined in quantum dots at a silicon heterointerface, provide a means to control electron spin qubits without the added complexity of on-chip, nanofabricated micromagnets or nearby coplanar striplines. Here, we demonstrate a singlet–triplet qubit operating mode that can drive qubit evolution at frequencies in excess of 200 MHz. This approach offers a means to electrically turn on and off fast control, while providing high logic gate orthogonality and long qubit dephasing times. We utilize this operational mode for dynamical decoupling experiments to probe the charge noise power spectrum in a silicon metal-oxide-semiconductor double quantum dot. In addition, we assess qubit frequency drift over longer timescales to capture low-frequency noise. We present the charge noise power spectral density up to 3 MHz, which exhibits a $1/f^{\alpha}$ dependence consistent with $\alpha \sim 0.7$, over 9 orders of magnitude in noise frequency.

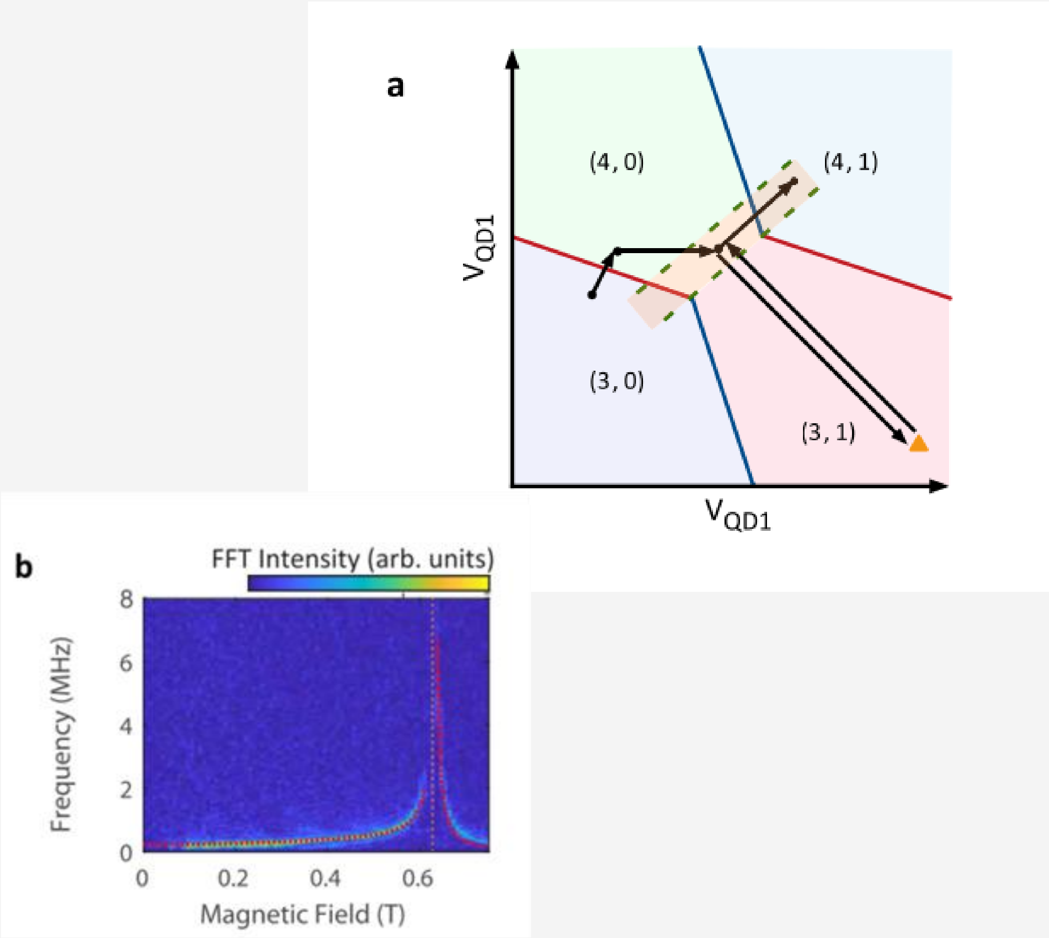
Device

- Fully foundry compatible
- MOS device with ^{28}Si
- Poly-Si single layer gates
- Singlet-triplet qubit



Device operation

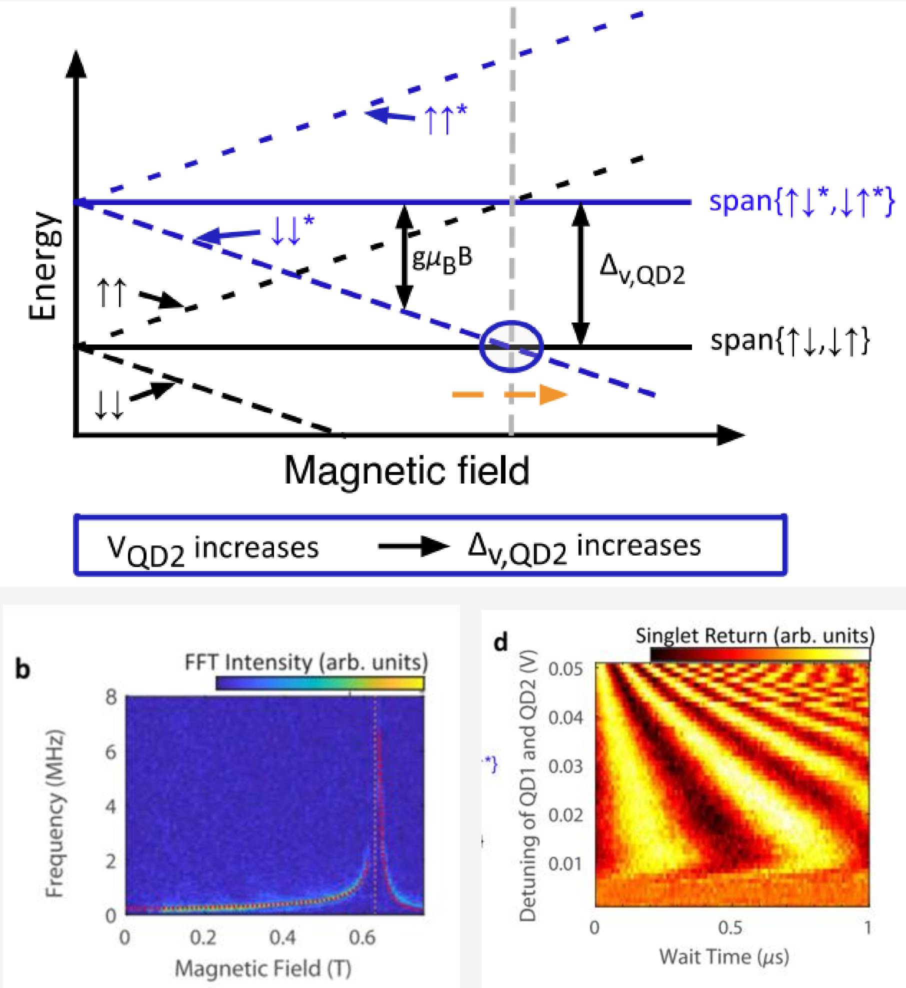
- Loading in (4,0) state
- Adiabatic passage to (3,1)
- SOC-driven rotations
- Readout back to (4,0) by PSB and enhanced latching mechanism



Singlet-triplet qubit

- The peak comes from the crossing of the excited state ↓↓* with the spin-valley hot-spot $span\{\uparrow\downarrow,\downarrow\uparrow\}$.

- This hot-spot is tunable by the QD-QD detuning



Intervalley hotspot

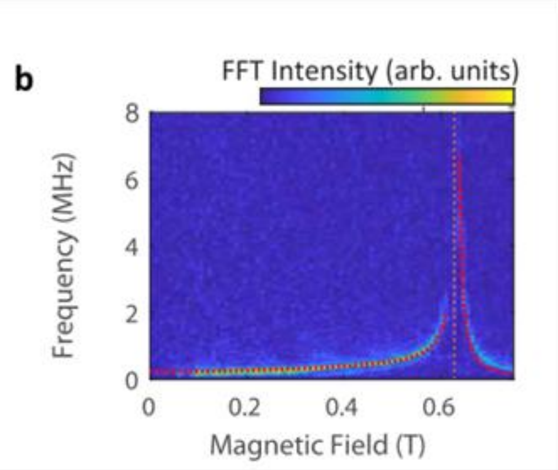
The hotspot corresponds to a distortion of the subspace $span\{\uparrow\downarrow, \downarrow\uparrow\}$, where $\downarrow\uparrow$ and $\downarrow\downarrow^*$ are hybridized. The interaction can be represented by:

$$H = \begin{pmatrix} B\delta & 0 & 0 \\ 0 & -B\delta & \gamma \\ 0 & \gamma^* & \Delta_{\mathrm{v,QD2}} - g_*\mu_B B \end{pmatrix}$$

$$\begin{aligned} |+\rangle &= w_-\left|\downarrow\uparrow\right\rangle + w_+\left|\downarrow\downarrow^{(1)}\right\rangle \\ &\left|\uparrow\downarrow\right\rangle \\ |-\rangle &= w_+\left|\downarrow\uparrow\right\rangle - w_-\left|\downarrow\downarrow^{(1)}\right\rangle \end{aligned}$$

So 3 peaks in frequency (corresponding to the 3 eigenvalues) are expected here

Why only one peak?



Suppose:

1) we start with the singlet state.

2) If valley splitting is changed to the hot-spot:

=> the ↓↑ deforms either to + or –

=> on the left side of the peak the measured frequencies are dominated by rotation within the subspace {(↑↓, +), (↑↓, -)}

=> We have a two qubit system

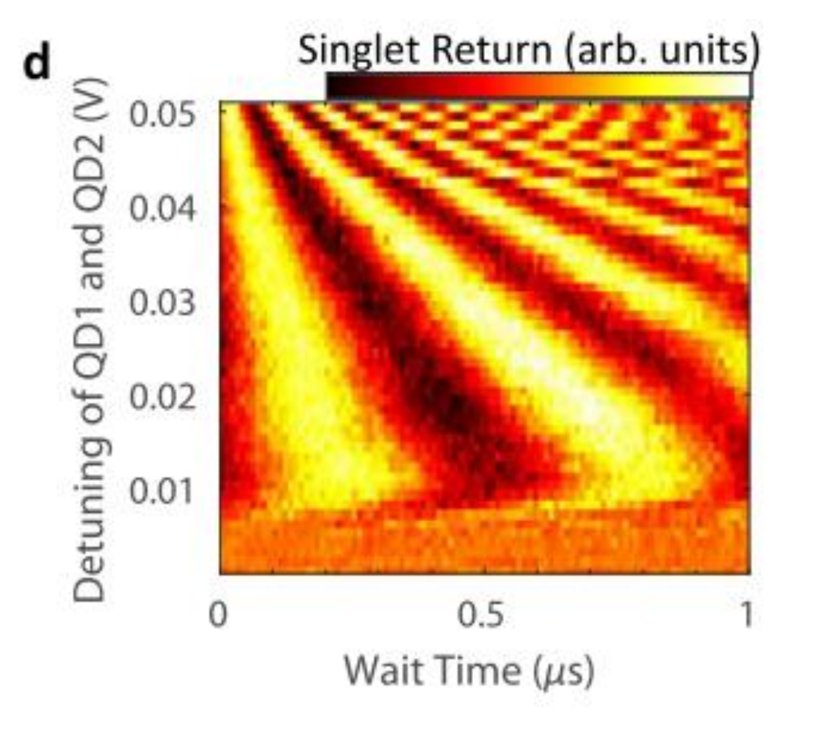
=> one frequency component

Singlet-triplet qubit with intervalley coupling

- Shallow detuning: no rotation

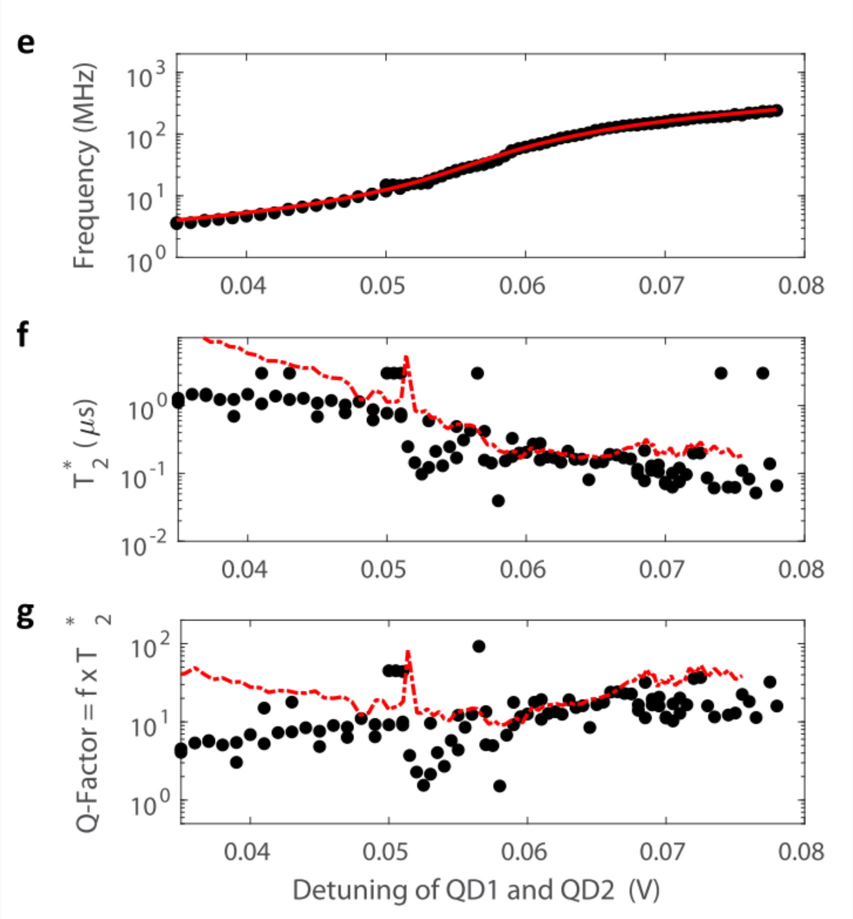
- Moderate detuning: slow rotations

- High detuning: fast rotations



Singlet-triplet qubit with intervalley coupling

- Control of rotation frequency by QD-QD detuning over 2 orders of magnitude
- Dephasing time decreases since better coupling to charge noise $T_2^* \propto |df/dV|^{-1}$
- Quality of rotation peaks above 100 MHz



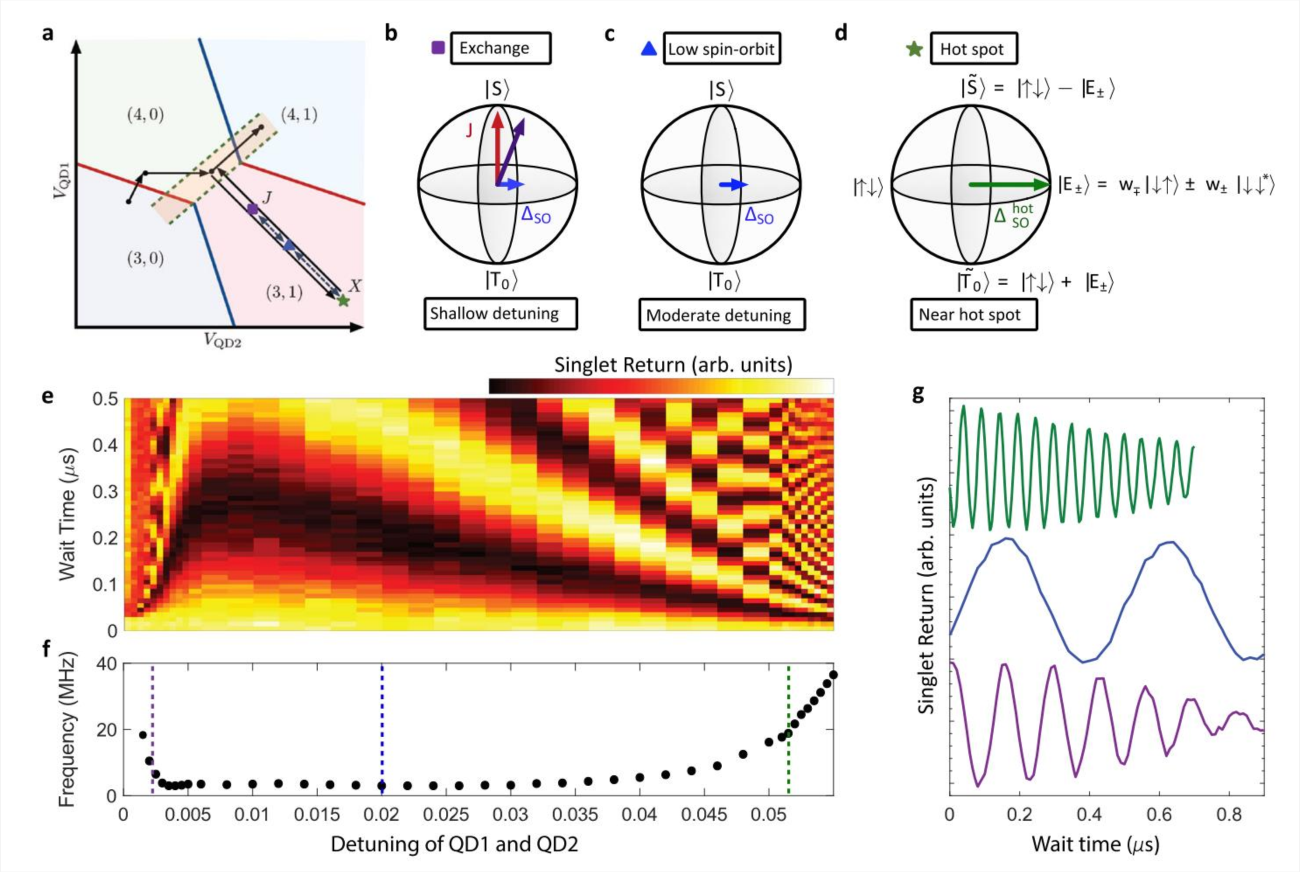
Singlet-triplet qubit with intervalley coupling

Z-axis:

- J

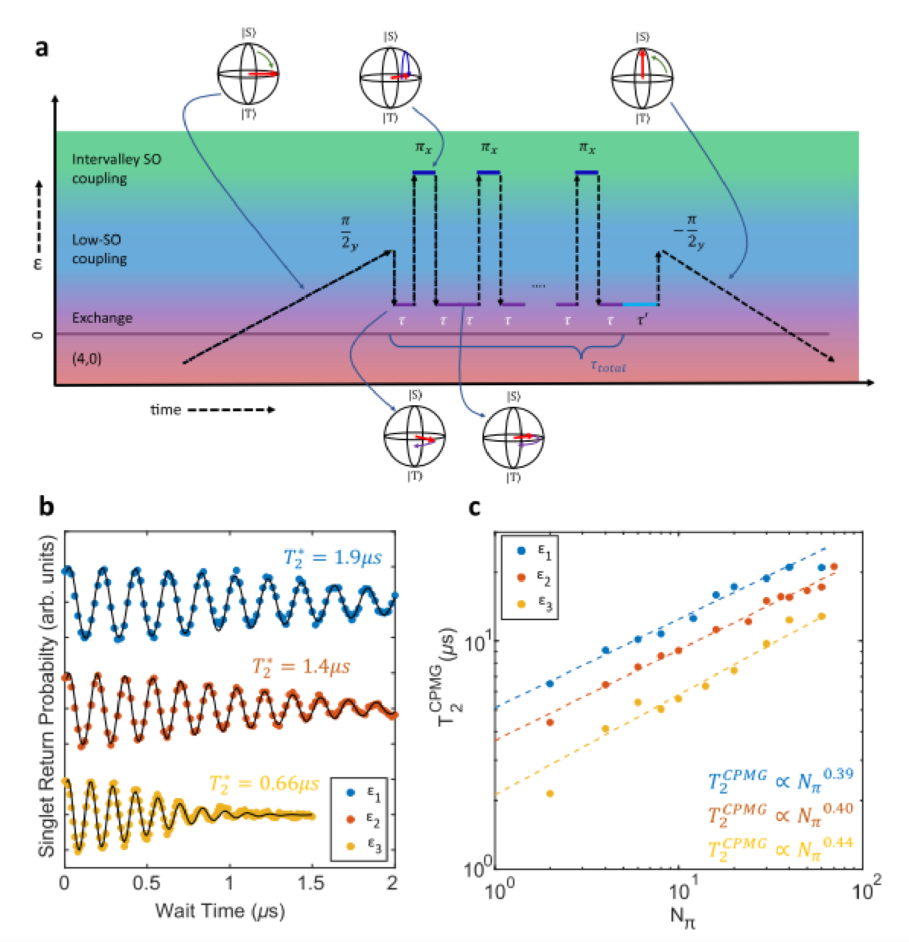
X-axis:

- moderate ϵ intravalley SO
- Deep ϵ intervalley SO



Decoupling from charge noise

- CPMG protocol at different detuning points
- Dephasing time is dependent on detuning point (faster exchange pulses leads to faster detuning)

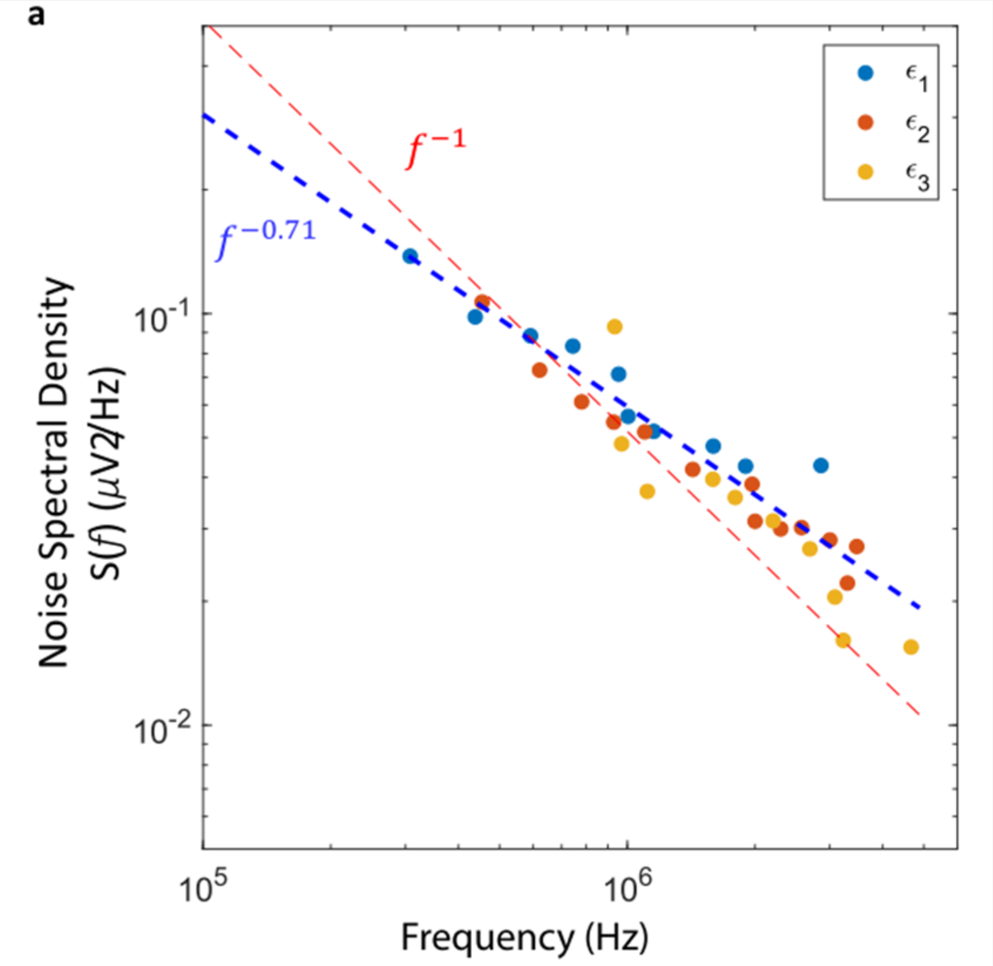


Charge noise measurements

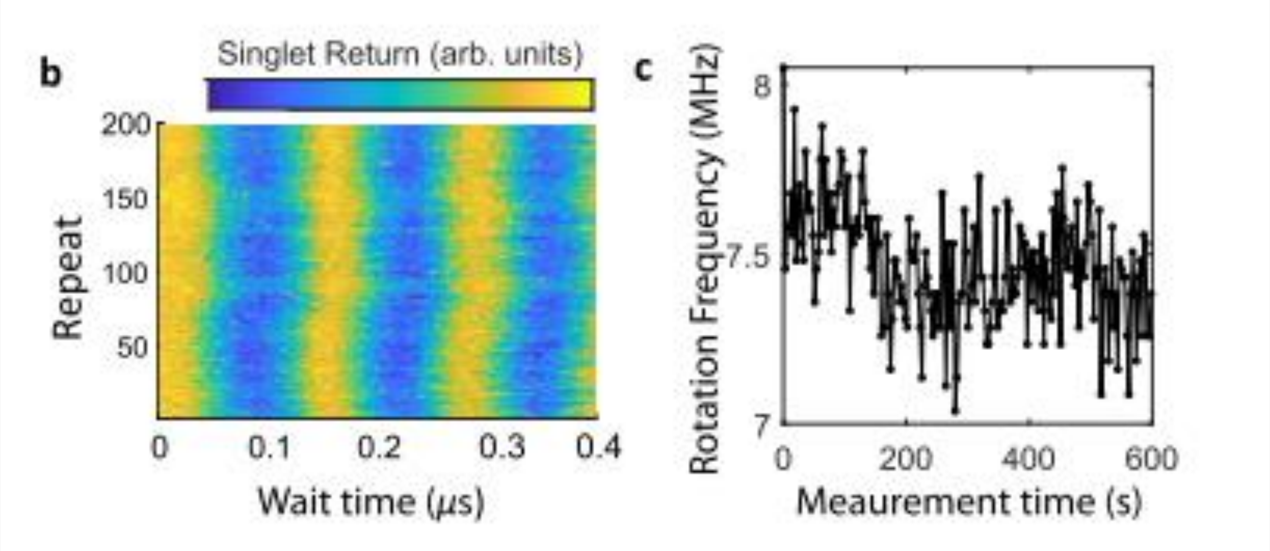
Charge noise (fluctuations in exchange rotation frequency) obtained by treating the CMPG sequence as a noise filter.

$$S(f_{N_\pi}) = \frac{\pi^2}{4 \cdot T_{2,N_\pi}^{\mathrm{CPMG}}}$$

$$f_{N_\pi} = \frac{N_\pi}{T_{2,N_\pi}^{\mathrm{CPMG}}}.$$

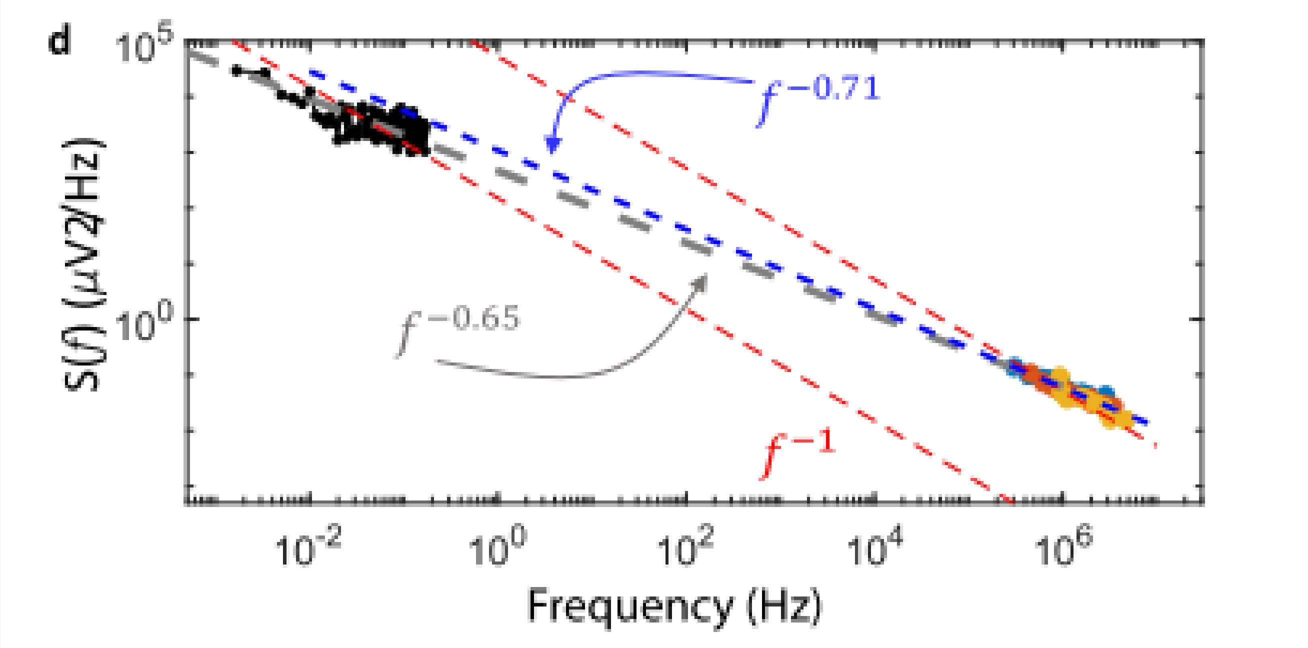


Charge noise measurements



Additional charge noise measurement (low frequency): shift of S return probability by exchange rotation

Charge noise measurements



Combining the two dataset, gives PSD with a $1/f^a$ spectrum (a ~ 0.7) between 3mHz and 3 MHz.

Conclusions

Main results

- First spin qubit driven by spin-valley coupling
- Can switch between 3 control regimes:

  1) large exchange interactions

  2) intervalley coupled qubit

  3) g-factor difference (intravalley coupling), sensitive to hyperfine interaction and decoupled from charge noise

- Investigation of charge noise for MOS qubit

Open issues

- Fast dephasing time
- No full control on valley uniformity yet

Operation of the device

The system is initialized by first unloading an electron from the DQD (point U).
An energy-selective pulse is applied to load a (4,0)S ground state (point L).
The system is then plunged (point P) near the charge anti-crossing.
The electrons are then separated (point C) and qubit manipulation pulse sequences are performed in the (3,1) charge region.
The system is then pulsed back to point P where, due to Pauli spin blockade, a singlet spin state is allowed to transfer to the (4,0) charge state but a triplet spin state is energetically blocked and remains in a (3,1) charge state.
An enhanced latching mechanism is then utilized for a spin-to-charge conversion (point M).