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

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Paper

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

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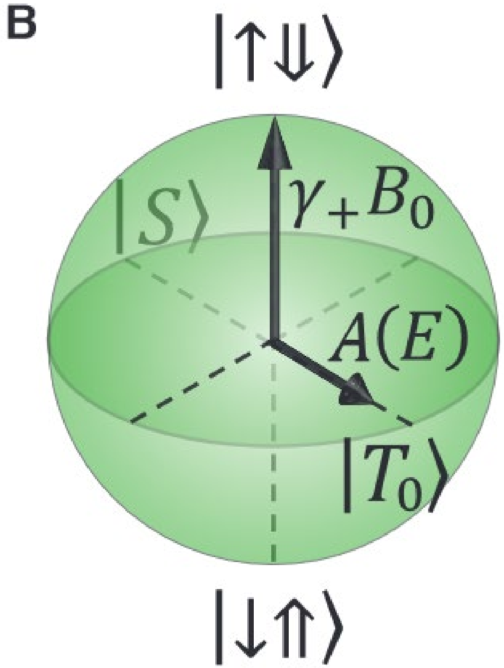
- Quantum information encoded in electron-nuclear states of P donor in Si
- Qubit controlled by local electric fields
- Electrical drive mediated by modulating the electron-nuclear hyperfine coupling

Flip-flop Qubit

$$H = \gamma_e \mathrm{B_0 S_z} + \gamma_n \mathrm{B_0 I_z} + A\boldsymbol{S} \cdot \boldsymbol{I}$$

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



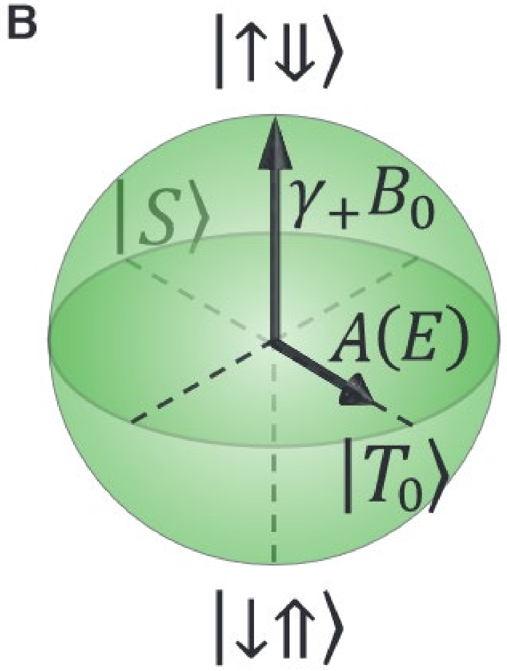
Flip-flop Qubit

$$H = (\gamma_+)\mathrm{B}_0\sigma_z + A\ \sigma_x$$

- 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 $|\mathrm{T}_0\rangle = (|{\downarrow}{\Uparrow}\rangle + |{\uparrow}{\Downarrow}\rangle)/\sqrt{2}$ are x-operator eigenstates
- Flip-flop resonance frequency:

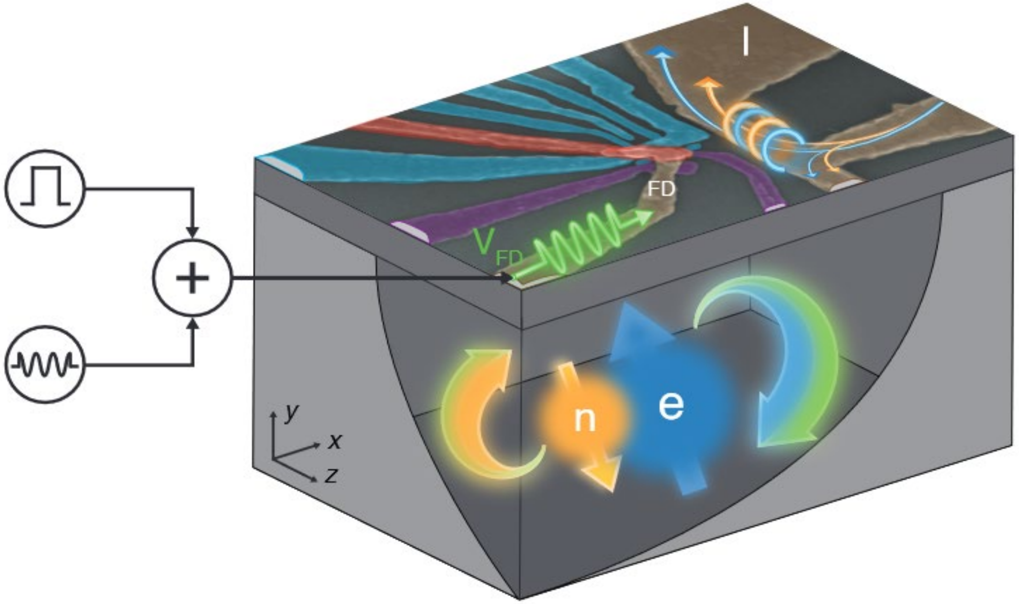
$$\epsilon_{eff} = \sqrt{(\gamma_+ B_0)^2 + A(E_{dc})^2}$$

- Modulating hyperfine interaction by electric field drives qubit transitions



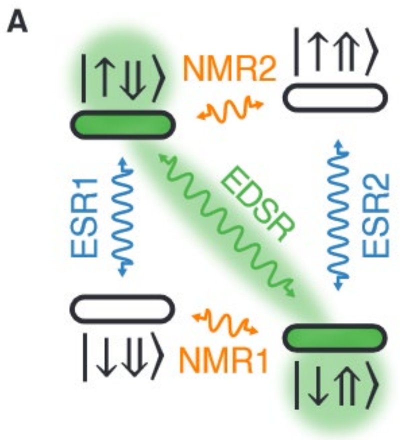
Device

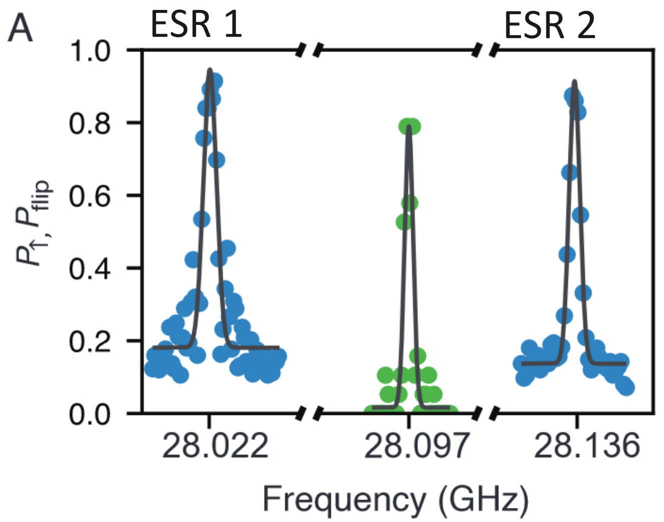
- MOS device with ion-implanted ^{31}P donor
- Fast Donor (FD) gate for EDSR
- SET for electron spin readout (spin-dependent tunnelling)
- Microwave antenna for ESR and NMR



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

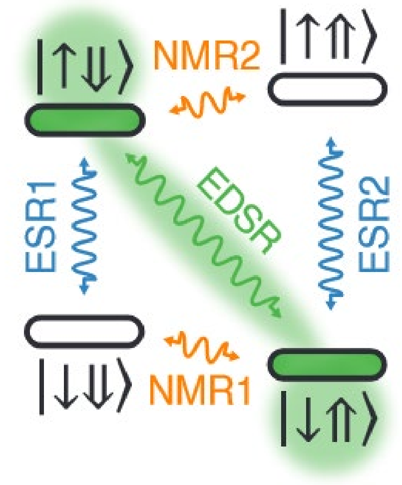




Initialization

- Electron-Nuclear Double Resonance (ENDOR) pulse sequence to initialize in the flip-flop ground state |↓⇑⟩
- aESR2 pulse followed by aNMR1 pulse
- If system is in |↓⇑⟩ :
  - aESR2 flips electron spin to |↑⇑⟩
  - aNMR pulse is off-resonant and electron readout will initialize back to |↓⇑⟩
- If system is in |↓⇓⟩:
  - aESR2 pulse is off-resonant
  - aNMR1 pulse will flip the nucleus to |↓⇑⟩

A



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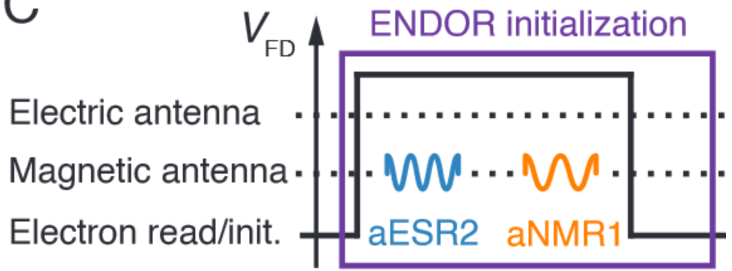
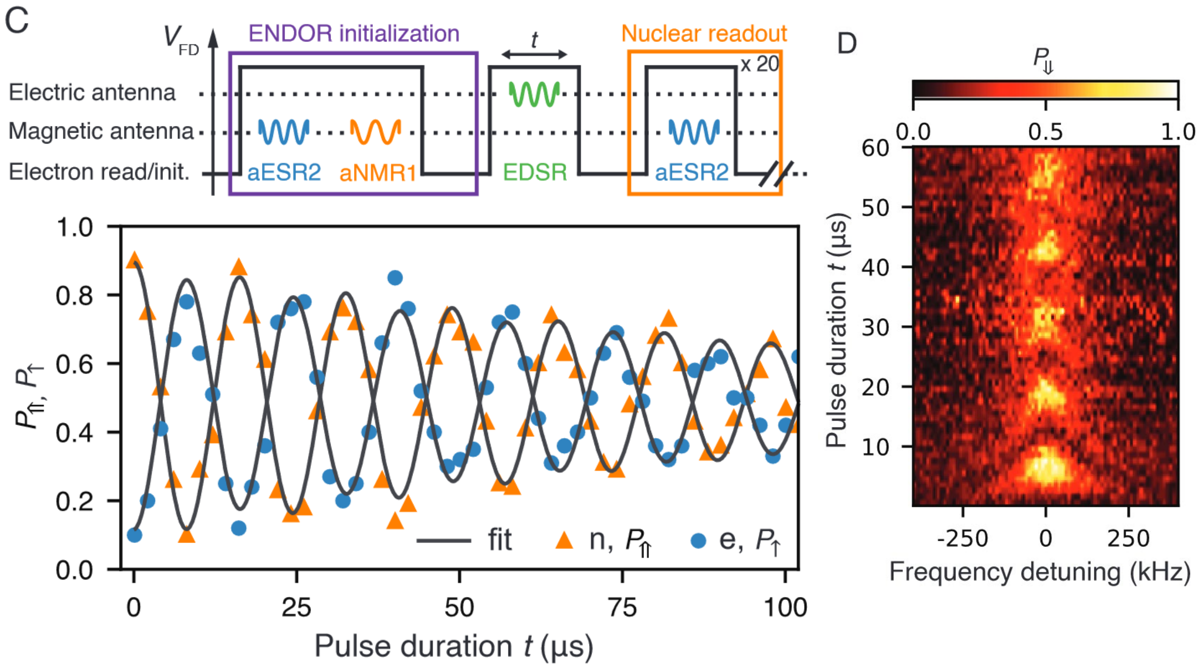


Coherent Electrical Control

- ENDOR initialization -> EDSR ->flip-flop readout
- Flip flop readout:
  - readout electron spin
  - reload electron onto donor
  - perform nuclear spin readout



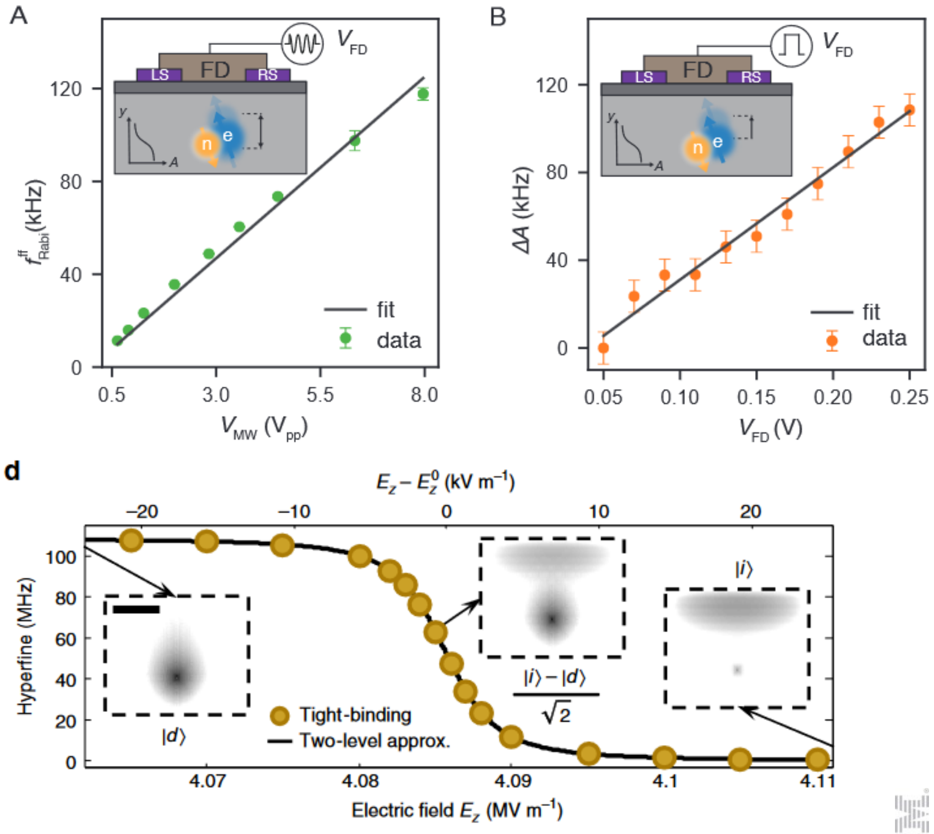
Rabi Frequency, Hyperfine Modulation

- Maximum Rabi frequency of 118.5 kHz (5x typical NMR drive) – limited by bulk-like donor state (small dipole)

$$f_{rabi} = \left(\frac{\partial A(E)}{2\partial E}\right) E_{ac}$$

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

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



Tosi, G. et. al., *Nat. Comm.* **8,** 450 (2017)

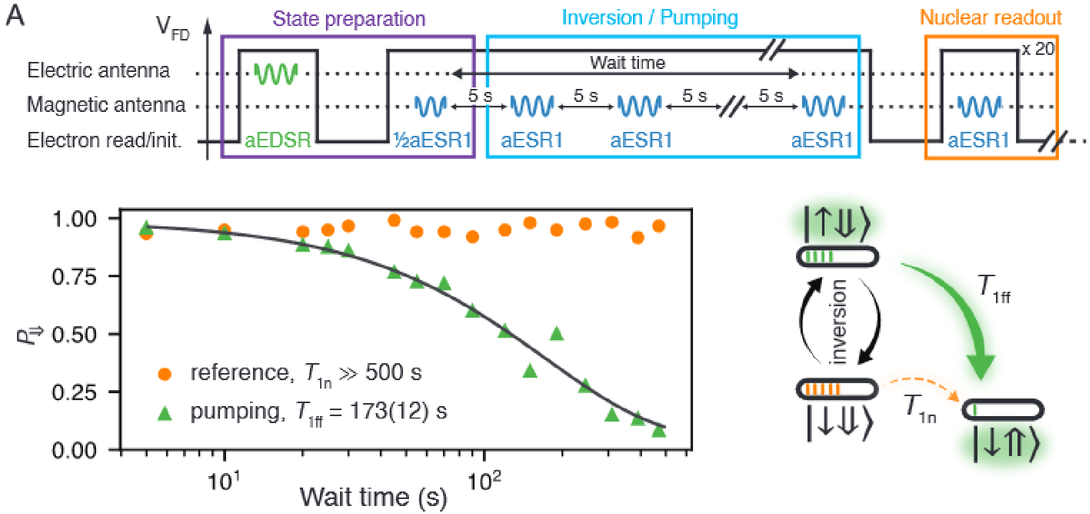
Relaxation

- 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

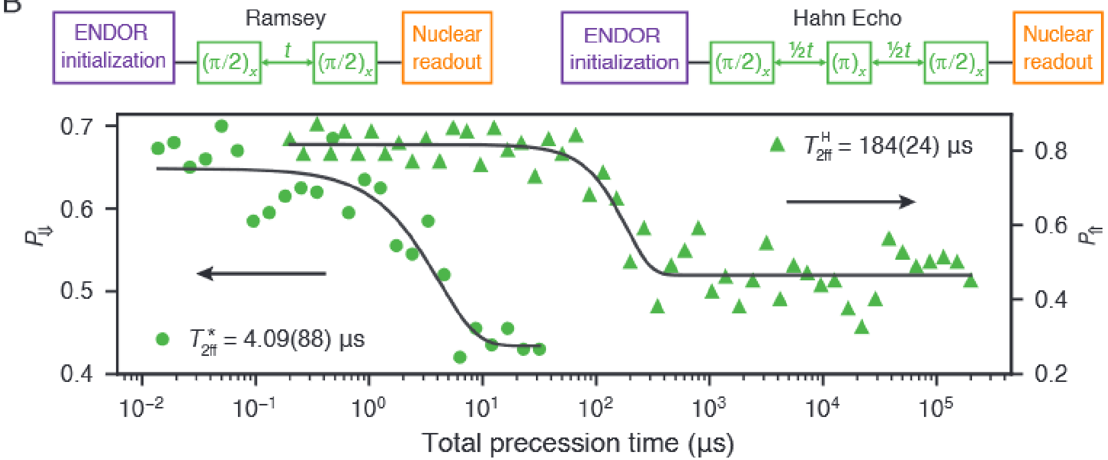
C

	T_1 (s)	T_2^* (μs)	T_2^H (μs)
e	6.45(39)	14.6(9)	336(10)
n	–	240(42)	541(72)
ff	173(12)	4.09(88)	184(24)

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

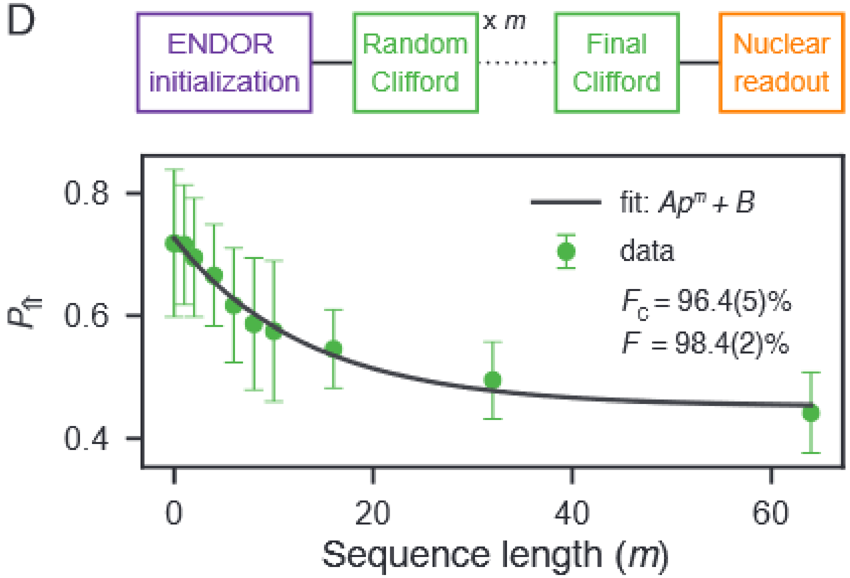
- Decoherence Mechanisms:
  - EDSR pulse induced resonance shift (poorly understood)
  - Residual ^{29}Si in substrate (splitting of flip-flop ESR resonances – coupling to ^{29}Si nuclei)

B



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 you attention!