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Electrical Control of Spin Relaxation in a Quantum Dot

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Motivation

- quantum computation
- good qubit - long T_1, T_2, …
- control spin-environment interactions

Outline

- electrical control of T_1
- relaxation is mediated by spin-orbit interaction (SOI)
- manipulate orbitals $\rightarrow$ change T_1
- theory, spin-orbit length extraction
- SOI mediated coupling to phonons dominates relaxation for $B>1T$

Interactions

hyperfine interaction

- electron's spin ↔ effective magnetic field from nuclear spins
- electron spin state decoherence
- relaxation, suppressed for $B \gg B_n \sim 3mT$ nuclear and electron Zeeman energies are very different

spin-orbit interaction

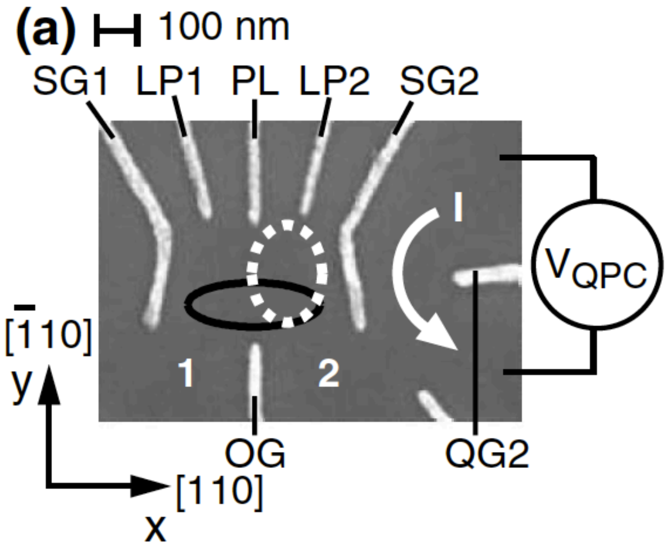
- mixing orbital and sin states
- couples spin to electrical environment
- primarily to piezoelectric phonons

- T_1 - energy relaxation time scale
- spin decoherence - $T_2 < 2*T_1$

  relaxation in singlet-triplet qubit

low B (still B>>Bn) HF interaction mediated coupling to phonons

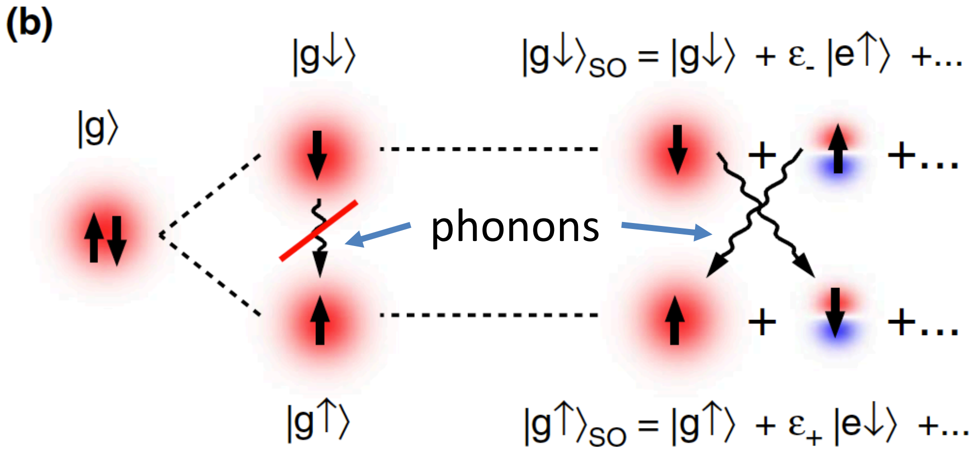
Device architecture



- AlGaAs/GaAs heterostructure
- single-electron dot
- QPC charge sensor
- real time electron tunneling to lead 2
  no tunneling to lead 1
- 120 mK = 10 ueV (1K = 86 ueV)

- all voltage pulses on LP2
- B || y

SOI mediated relaxation



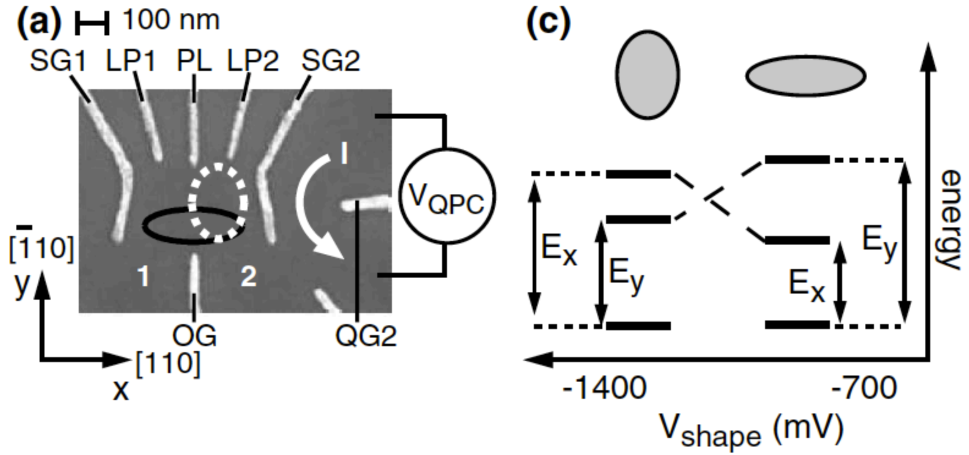
B = 0
SOI = 0

B ≠ 0
SOI = 0

B ≠ 0
SOI ≠ 0

- B = 0, no SOI: spins are degenerate in the ground orbital state |g>
- B ≠ 0, no SOI: Zeeman split spins in |g↑> and |g↓>, phonon coupling is prohibited
- SOI mixes orbital and spin states
- change excited state energies to control the amount of mixing and spin relaxation

Orbital excited state control



- gate voltages manipulate the dot shape → energy of the orbital states
- $V_{shape} = V_{SG1}$
- confinement potential:

$$U(x, y) = \frac{1}{2} m^* \omega_x^2 x^2 + \frac{1}{2} m^* \omega_y^2 y^2$$

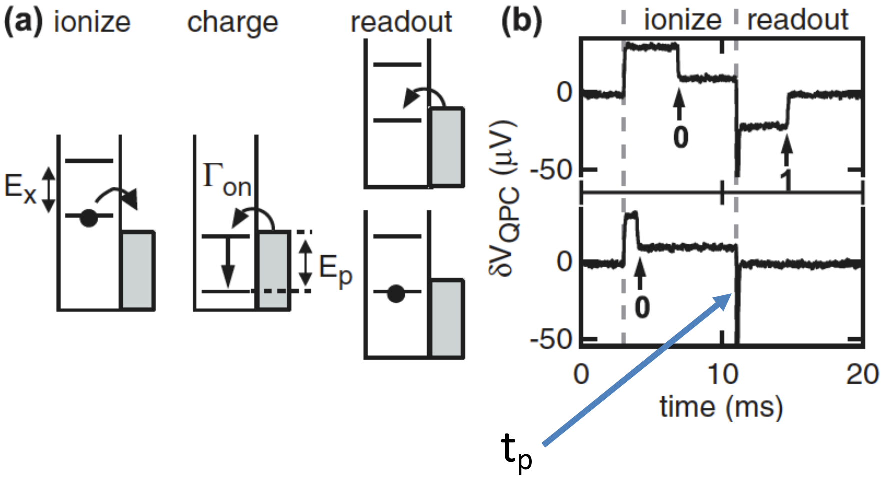
- dot shape = horizontal ellipse:

  $w_x < w_y$ $E_x < E_y$

- vertical ellipse:

  $w_x > w_y$ $E_x > E_y$

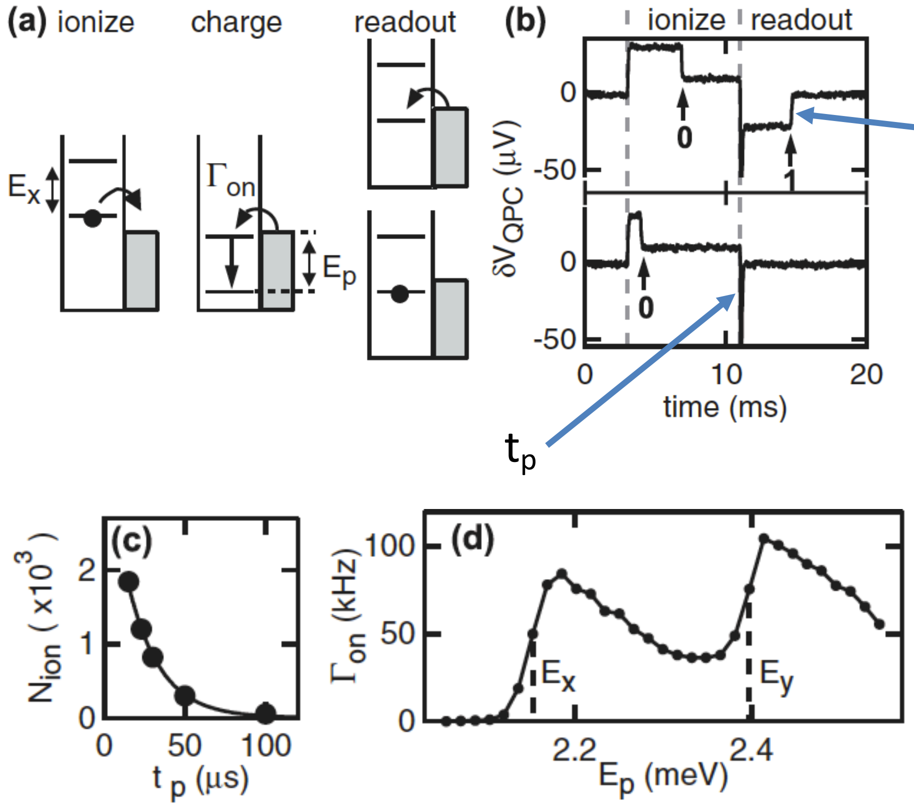
Energy of the excited orbital states



- three step pulse sequence for each V_{shape}
- B = 0
- ionize
- pulse V_p, $E_p = e\, a_{LP2}\, V_p$
- pulse duration t_p: 15 us < t_p < 400 us
- small amount of tunneling into |g>

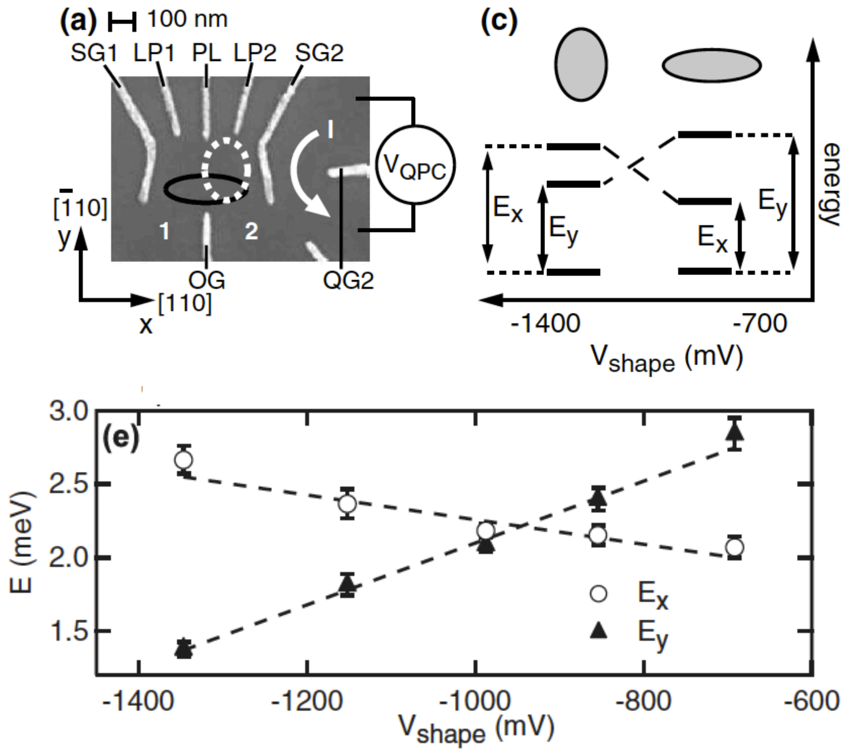
  averaged tunneling time 10 ms
- excited state more strongly coupled to the leads
- quick decay to |g>

Readout



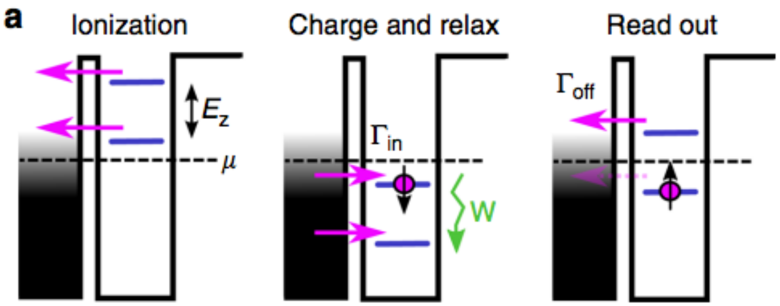
- position |g> just below the Fermi energy
- dot ionized - during the readout electron tunnels in, N_{ion}
- N_{ion} decays exponentially with t_p, rate Γ_{on}
- Γ_{on} depends on E_p
- excited state energies
- decrease of Γ_{on} due to the increase of the height of the tunnel barrier

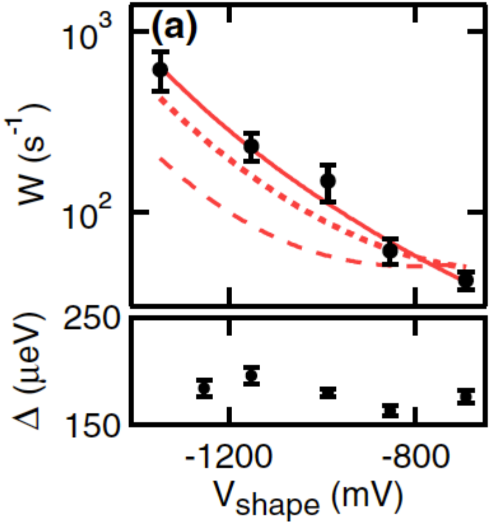
Excited states manipulation



- position |g> just below the Fermi energy
- dot ionized - during the readout electron tunnels in, N_{ion}
- N_{ion} decays exponentially with t_p, rate $\boldsymbol{\Gamma}_{on}$
- $\boldsymbol{\Gamma}_{on}$ depends on E_p
- excited state energies
- decrease of $\boldsymbol{\Gamma}_{on}$ due to the increase of the height of the tunnel barrier
- E_x and E_y evolve as a function of V_{shape}

T_1 measurements

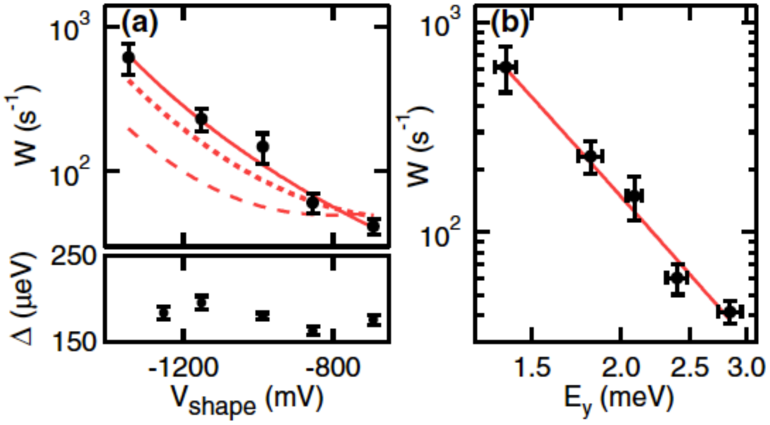


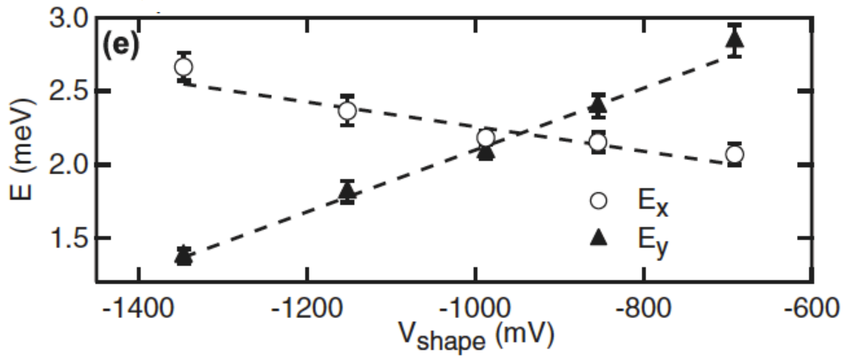


- B = 3 T
- ionize the dot
- pulse |g↑> and |g↓> below the Fermi level for the time t_w
- electrons can tunnel onto the dot
- relax from the spin excited state (|g↓>) to spin ground state (|g↑>)

- measure |g↓> probability decay as a function of t_w, obtain $W = 1/T_1$
- electrically control W

E - dependence



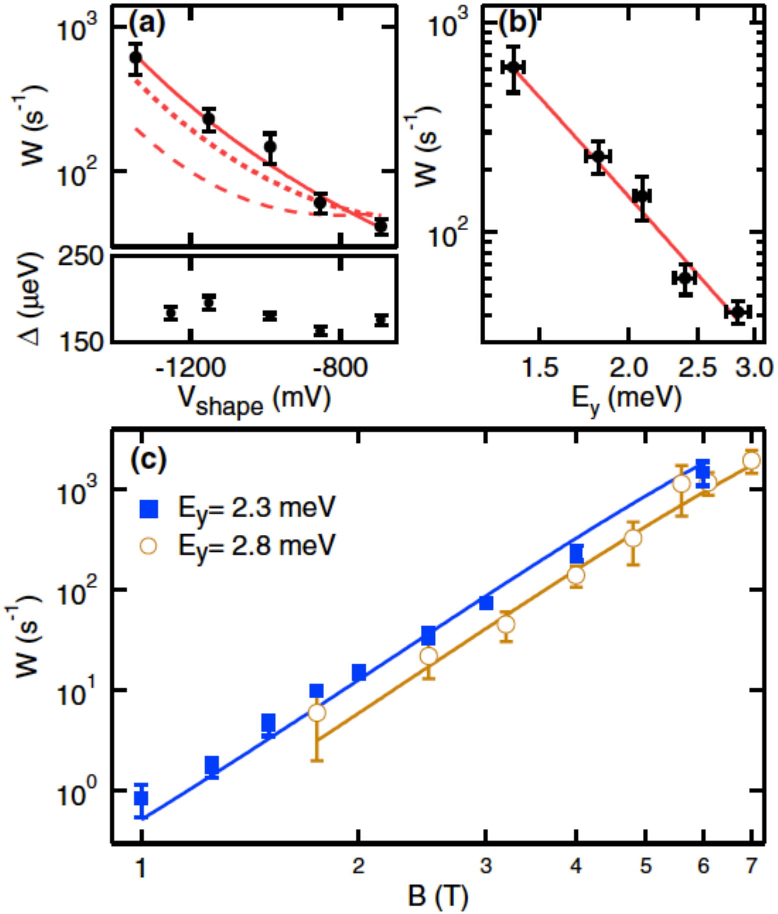


- smaller E_x, E_y - stronger coupling and relaxation, larger W
- theory: $W = A_x E_x^{-4} + A_y E_y^{-4}$
- fit: $A_x/A_y < 0.14$
- only y-orbital contributes to spin relaxation
- SOI Hamiltonian:

$$H_{SO} = \underline{(\beta - \alpha) p_y \sigma_x} + (\beta + \alpha) p_x \sigma_y$$

- B || y
- y-parity change required (term proportional to p_y)
- higher energy excited state dominates spin relaxation for V_{shape} > -1000 mV

B - dependence

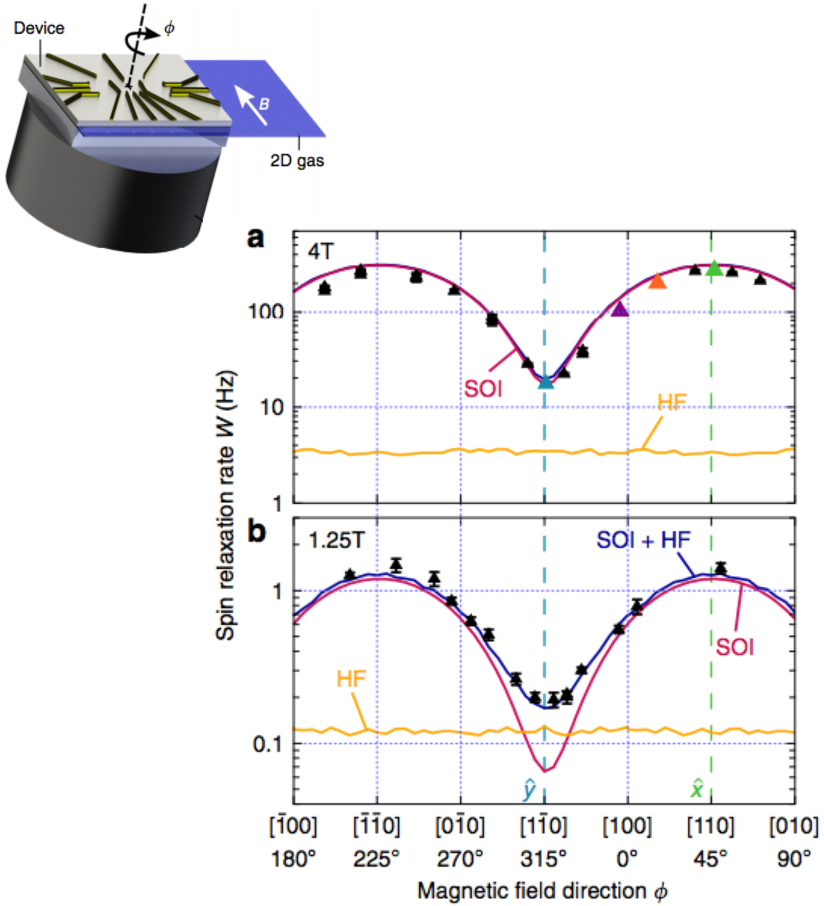


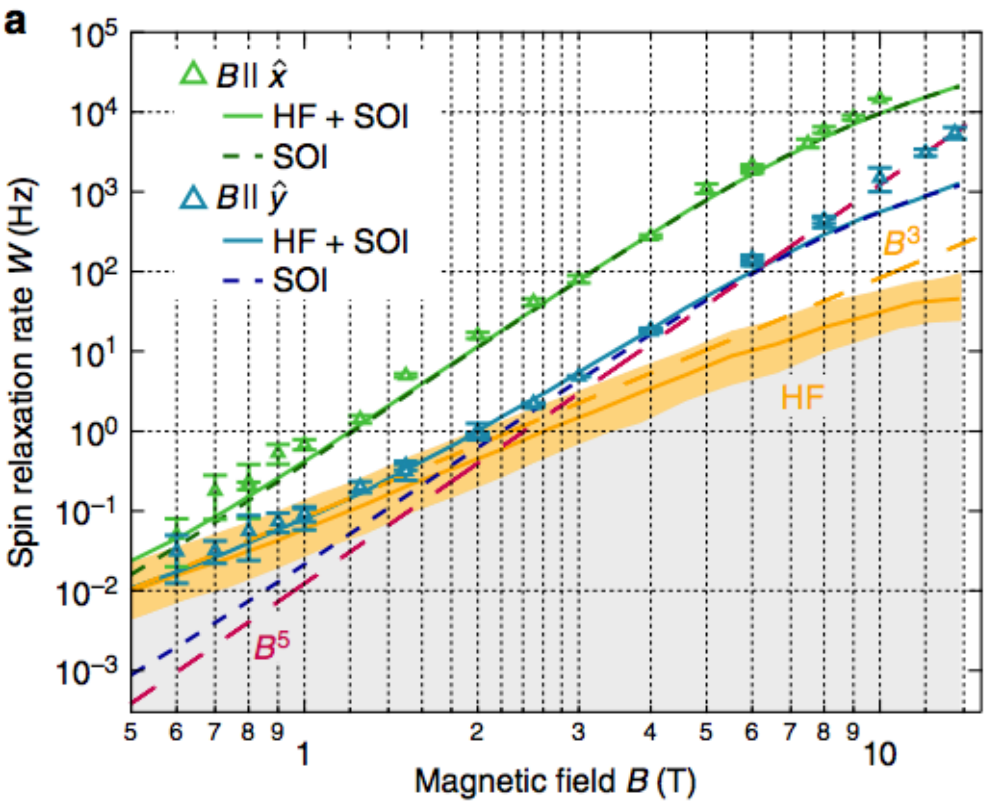
- $W \approx A B^5 E_y^{-4} \lambda_{\mathrm{SO}}^{-2}$
- fit $\lambda_{SO} = 1.7 \pm 0.2\ \mu m$
- SOI mediated coupling to phonons lead to spin relaxation rate: $W \propto B^5$

Conclusion

- electrical control of the spin relaxation rate
- Spin-orbit mediated coupling to phonons dominates spin relaxation

Hyperfine-phonon spin relaxation





Camenzind et al., Nat. Commun. **9**, 3454 (2018)