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Atomically engineered electron spin lifetimes of 30 s in silicon

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Introduction

Motivation

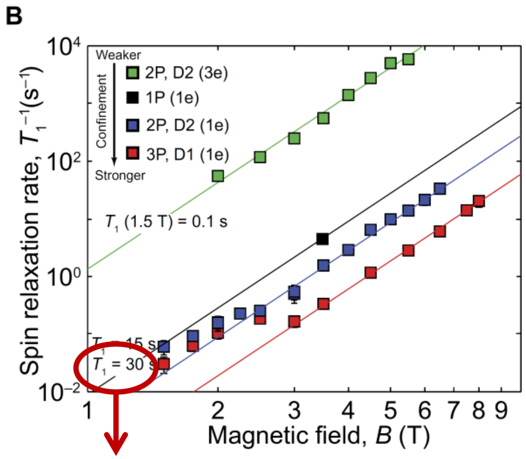
Long T1 times:

- **of interest for single shot readout fidelity**
- **Intrinsic upper limit to spin qubit coherence time T2 ($T_2 \leq 2T_1$)**

Why silicon?

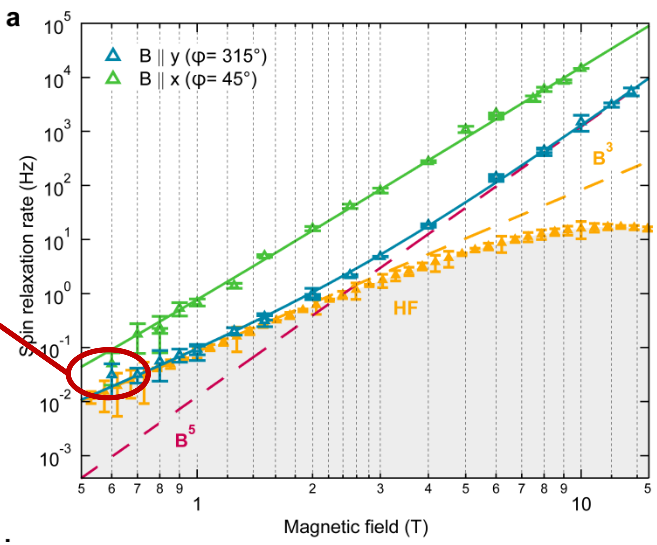
weak spin orbit coupling

lack of piezoelectric phonons



$T_1 = 57 \pm 15\ s$

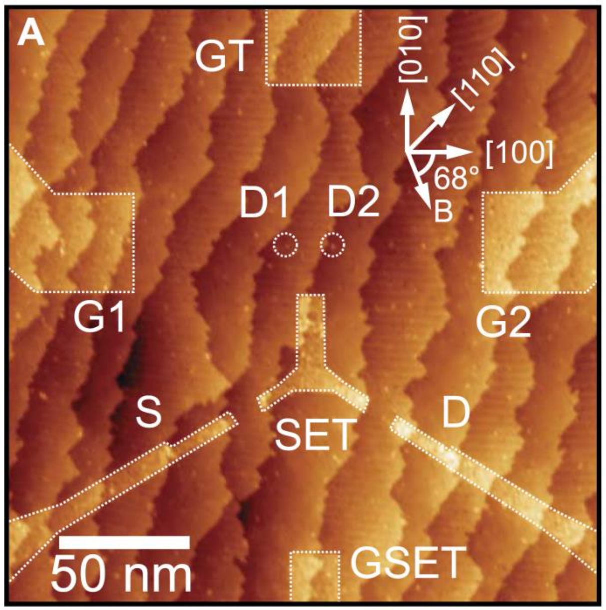
$T_1 = 30\ s$



the longest reported spin relaxation times for any single electron spin qubit in a nanoelectronic device.

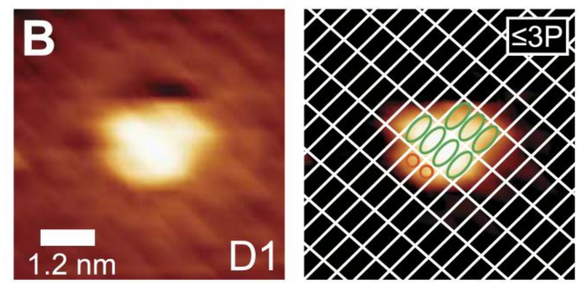
Device and characterization

Scanning tunneling microscope (STM) hydrogen lithography

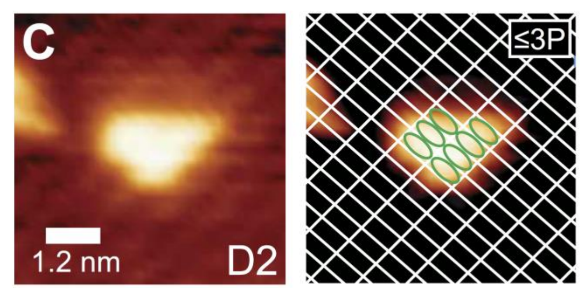


~ 20 nm center-to-center distance of D1 and D2
~ 19 nm to the SET charge sensor

GT, G1,G2, GSET are used to tune the electrochemical potentials of the dots and SET island

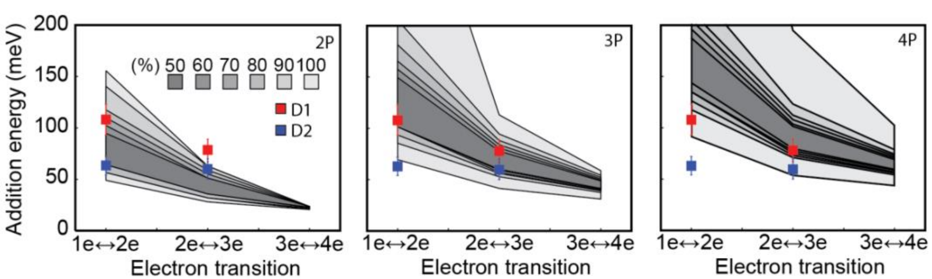


D1 : 3P



D2 : 2P

atomistic tight binding model



Spin relaxation measurements

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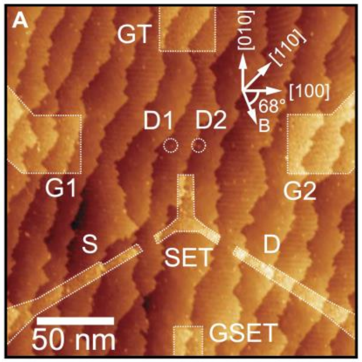
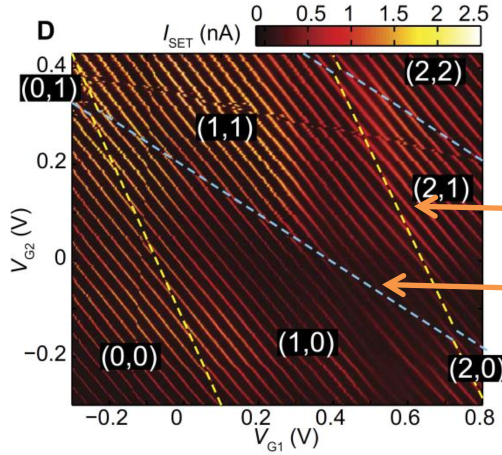




$V_{SD} = 300\mu V; V_{GT} = 100\ mV; V_{GSET} = 0\ V$

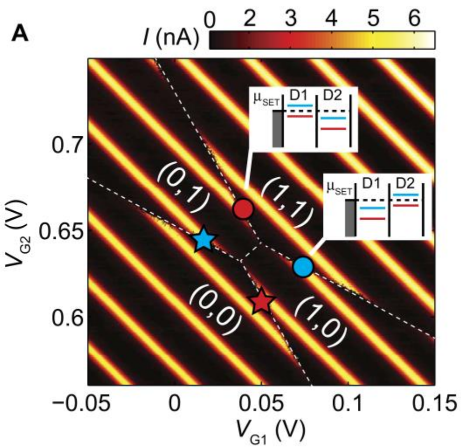
D1 : 3P

D2 : 2P

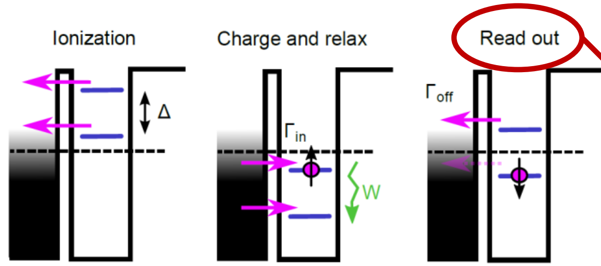
Larger charging energy for D1

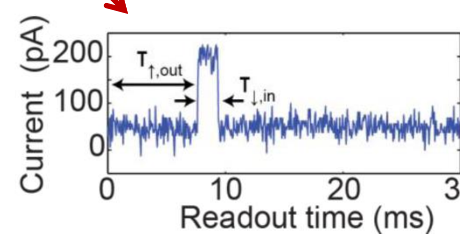
→ tighter confinement

$(\mathbf{0},\mathbf{0}) \leftrightarrow (\mathbf{1},\mathbf{1})$



Three step pulse sequence





No change in the spin relaxation times if an extra electron is added to the other dot.

Spin relaxation for donors

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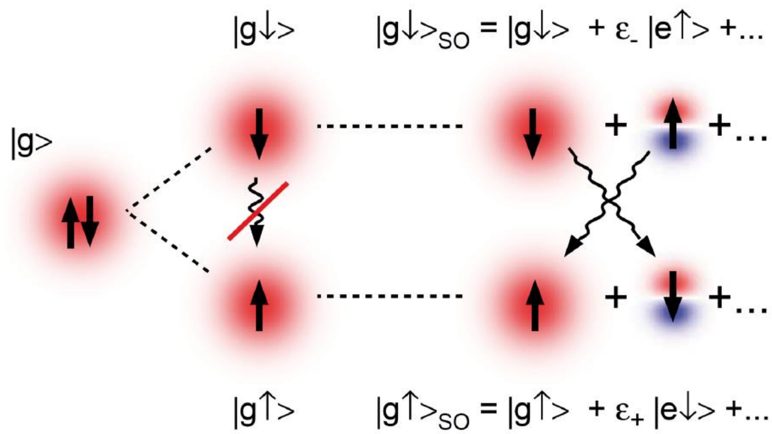
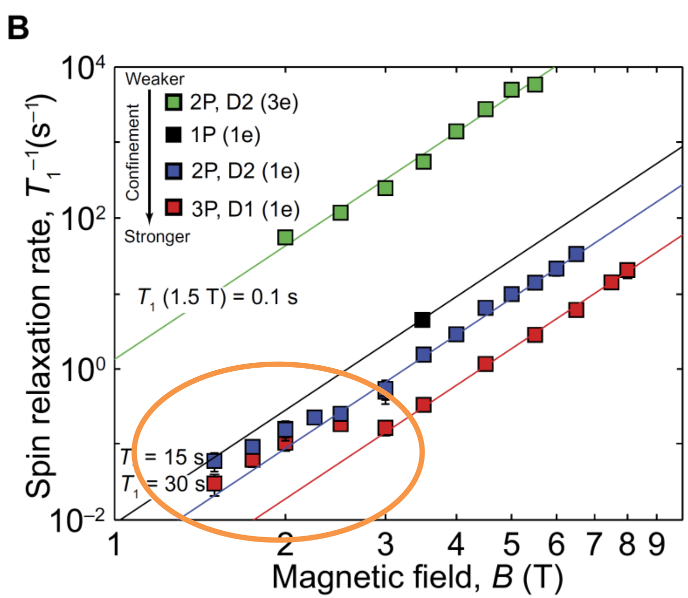


Spin orbit interaction acts as perturbation and **mixes the orbitals and spin states**, which leads to spin relaxation via emission of phonons

S. Amasha *et al.,* Phys. Rev. Lett. **100** (2008).



Spin relaxation mechanisms in silicon

single-phonon mechanisms of valley repopulation and the single-valley mechanism

--- valley-orbit splitting

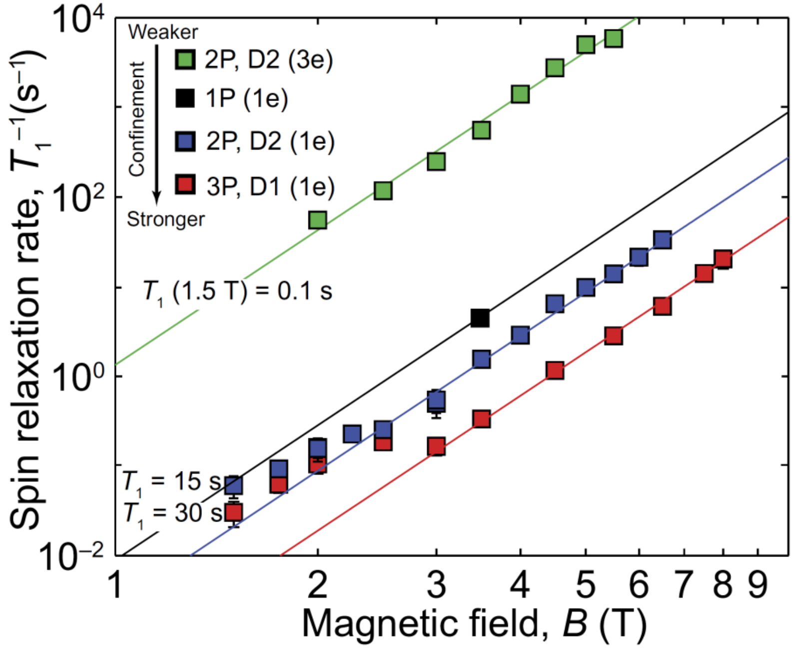
$$W \sim B^5$$

Johnson noise from reservoirs or gates, causing relaxation via Rashba spin-orbit coupling.

$$W \sim B^3$$

Spin relaxation vs confinement

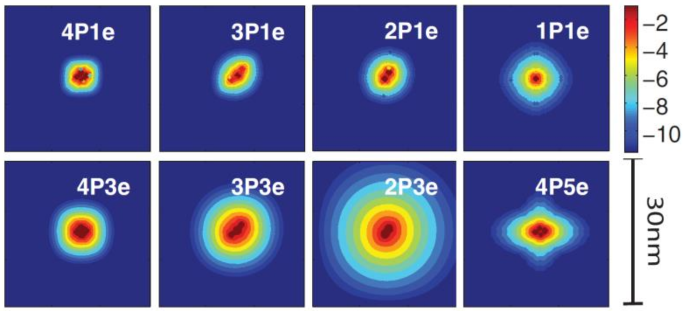
B



Confinement:

Number of donors

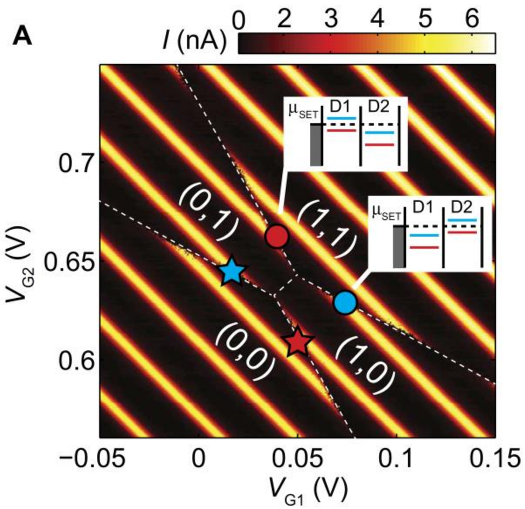
Number of electrons

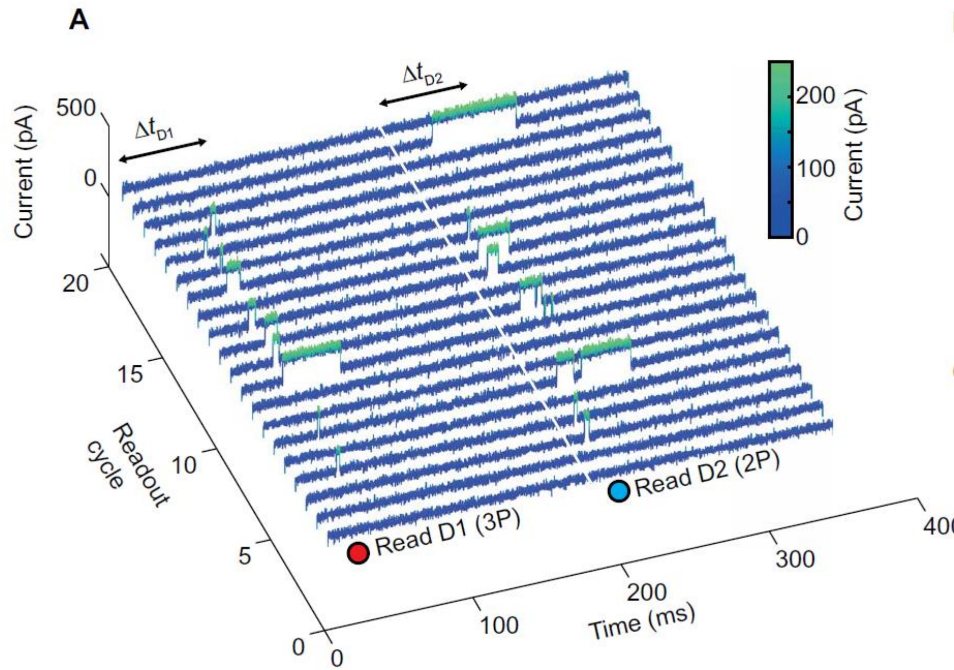


Yu-Ling Hsueh et al., PRL 113, 246406 (2014)

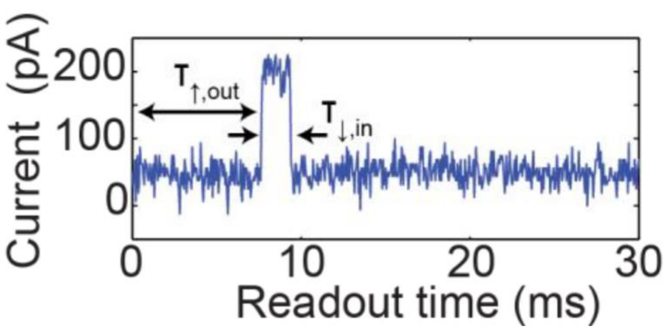
This tighter confinement potential reduces the electron wave function overlap with the lattice and results in a larger valley-orbit energy gap, combining to reduce the phonon-induced relaxation.

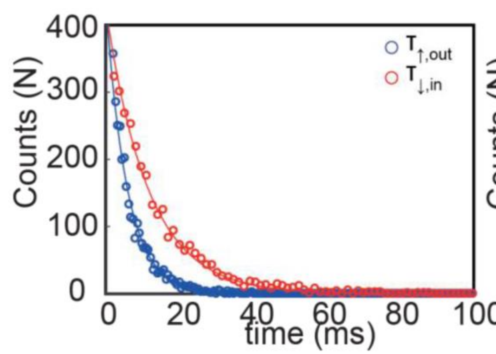
Sequential Readout Fidelity

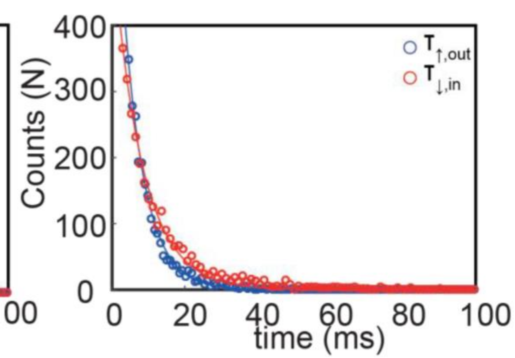




The measured spin states of D1 and D2 are uncorrelated







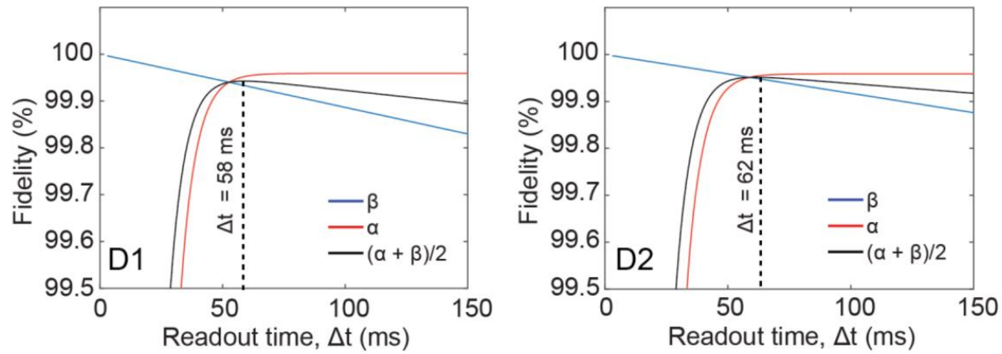
Sequential Readout Fidelity

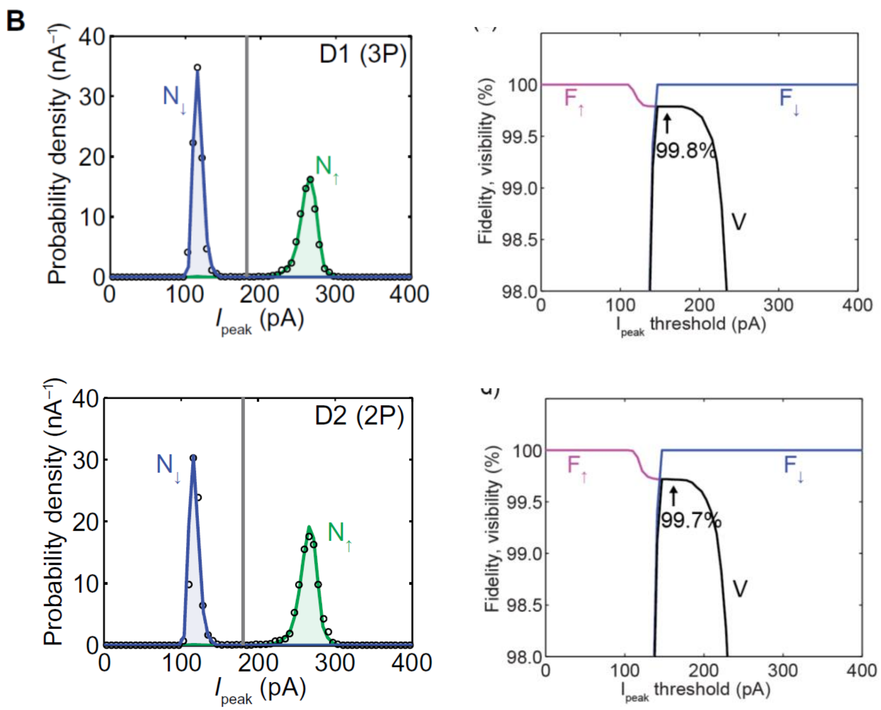
Spin-to-charge conversion error sources:

1. spin-down electron tunnels out of the ground state.
2. spin-up electron relaxes before it tunnels out.

Spin-to-charge conversion fidelities:

Spin down (β) and spin-up (α) $> 99.9\%$





Electrical detection error sources:

1. Spin-up state is missed being accounted due to bandwidth.
2. spin-down state is mistakenly accounted due to noise.

Electrical detection error fidelities:

$F_{\downarrow} = 100\%$ and $F_{\uparrow} = 99.7\%$

Total fidelity: $\boldsymbol{F_m = \frac{\beta F_{\downarrow} + \alpha F_{\uparrow}}{2} = 99.8\%}$

Fidelity of sequential readout of the nth electron

$$F_m(n) = (\beta F_{\downarrow} + \alpha F_{\uparrow} \exp[-\Delta t * (n-1)/T_1])/2$$

Summary

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Spin relaxation of STM patterned phosphorus donors in silicon has been investigated.

- T1 time as long as 30 s has been achieved.
- Different spin relaxation mechanisms are discussed.
- High fidelity sequential readout has been demonstrated.

Outlook

- Spin relaxation anisotropy measurements
- Measurements and universal control of two qubit system with proper exchange coupling

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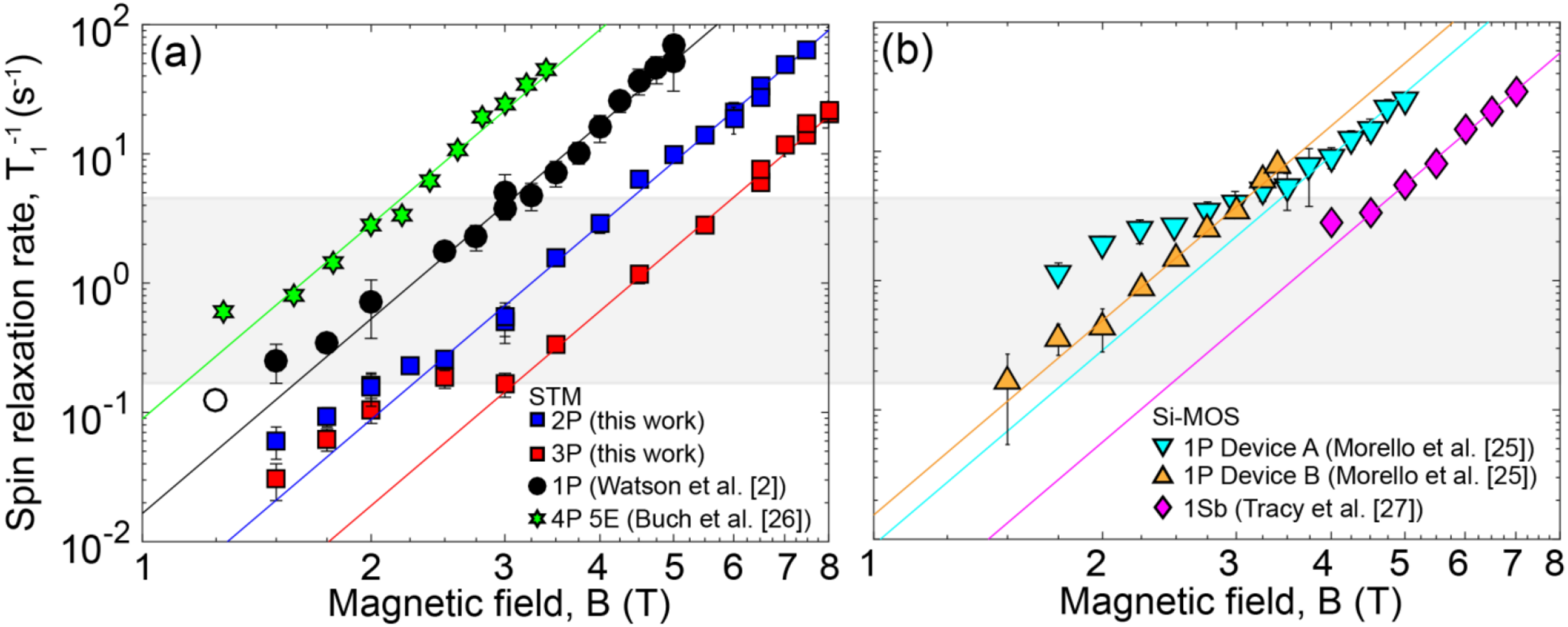
Thank you



(a)
(b)
Spin relaxation rate, T_1^{-1} (s^{-1})
Magnetic field, B (T)
Magnetic field, B (T)
STM
2P (this work)
3P (this work)
1P (Watson et al. [2])
4P 5E (Buch et al. [26])
Si-MOS
1P Device A (Morello et al. [25])
1P Device B (Morello et al. [25])
1Sb (Tracy et al. [27])