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Spin qubits made of quantum dots and donors in silicon

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APS March Meeting

March 4-8, 2019

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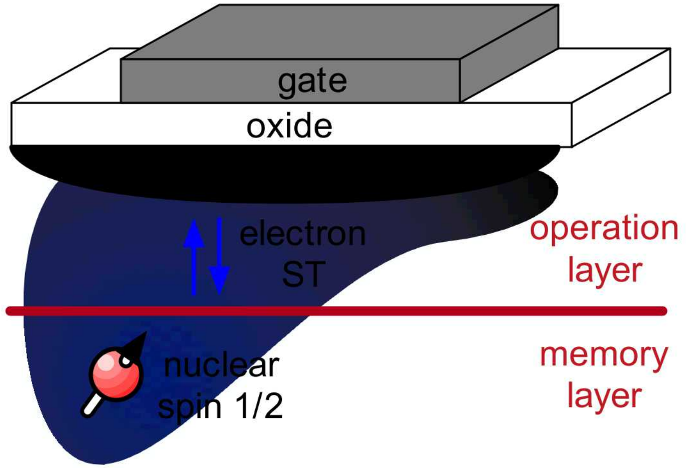
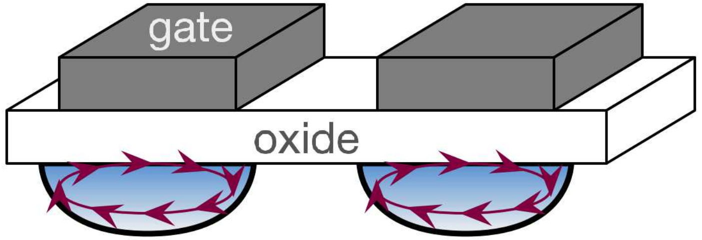
- Donor-Dot system
- Valley splitting, singlet-triplet splitting, coupling to donors, and 4-electron trick
- Enhanced latching readout
- Singlet-triplet qubit (hyperfine-driven rotations)

Part 1: Donor-dot system and related topics



- Universal control using spin-orbit interaction
- Implications of the spin-orbit interaction for singlet-triplet qubits in silicon

Part 2: Spin-orbit interaction in silicon dots



⊗ $\boldsymbol{B}_{\mathrm{ext}}$

$|\uparrow\rangle$

$E_Z = g_1 \mu_B B_{\mathrm{ext}}$

$|\downarrow\rangle$

$|\uparrow\rangle$

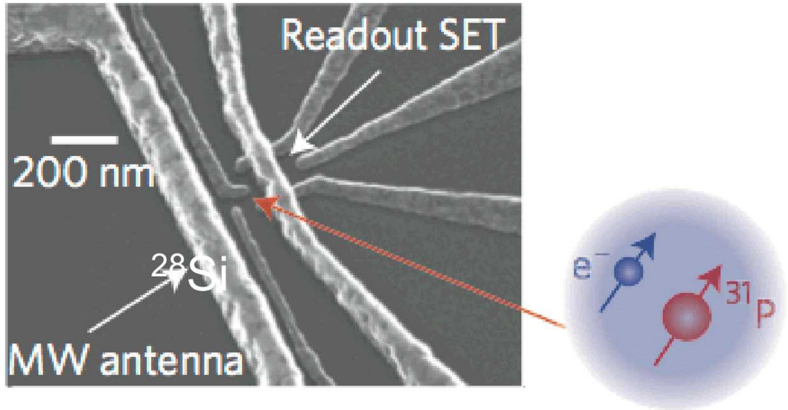
$E_Z = g_2 \mu_B B_{\mathrm{ext}}$

$|\downarrow\rangle$

$$\Delta E_z = (\Delta g) \mu_B B_{\mathrm{ext}}$$

Can the best characteristics of qubit systems be combined?

Donor (D) qubits are high fidelity…



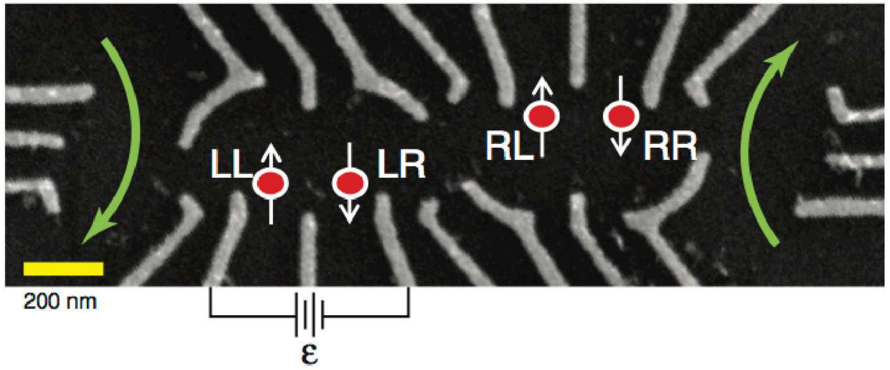
Electron spin 1/2:
T_2^* = 270 μs [1]
$T_{2,\ CPMG}$ = 0.98 s [3]
$F_{prep/read}$ = 97% [4,1]
$F_{control}$ = 99.95%

Nuclear spin 1/2:
T_2^* = 600 ms [3]
$T_{2,\ CPMG}$ = 36.5 s [3]
$F_{prep/read}$ = 99.995%
$F_{control}$ = 99.99%

But they are not easily coupled together!

[1] Muhonen, J. T. et al., Nat Nano 9, 986–991 (2014).
[2] Muhonen, J. T. et al., J. of Physics: Cond. Mat. 27, 154205 (2015).
[3] A. Morello, unpublished.
[4] L. A. Tracy et al, App. Phys. Lett. 108, 063101 (2016).

Quantum dot (QD) qubits are tunable…



Singlet-triplet spin qubit in GaAs:

- All-electrical control [6]
- Two-qubit gates realized [5,6,9]

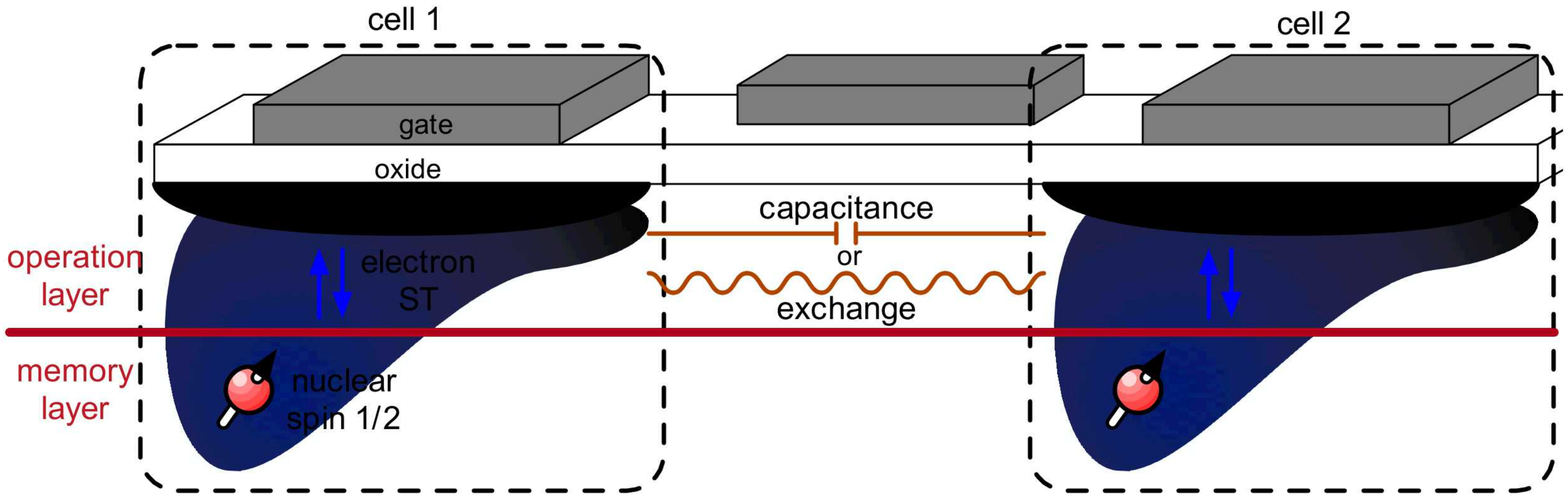
... many other GaAs and Si realizations now!

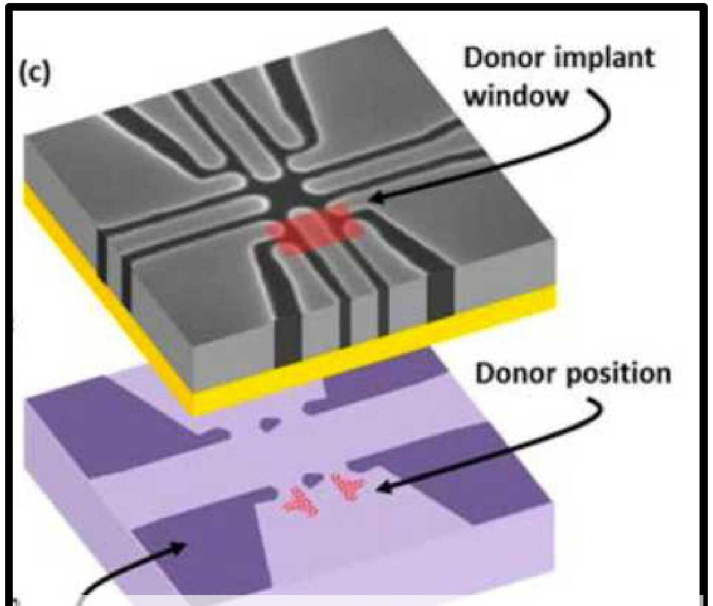
But they are not quite as high fidelity!

[5] Shulman, M. D. et al. Science 336, 202–205 (2012).
[6] Petta, J. R. et al. Science 309, 2180–2184 (2005).
[7] Veldhorst, M. et al. Nat Nano 9, 981–985 (2014).
[8] Veldhorst, M. et al. Nature 526, 410–414 (2015).
[9] Nichol, J. M. et al. npj Quantum Information 3, 3 (2017).

The MAJIQ system

MOS (M) hyperfine (A) exchange (J) nuclear spin (I) qubit (Q)





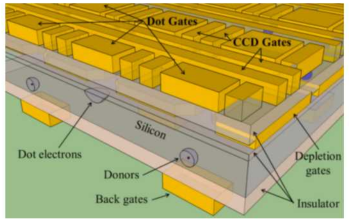
[M. Rudolph, P. Harvey-Collard ... In 2016 IEEE IEDM, 34.1.1–34.1.4 (2016)]

Advantages

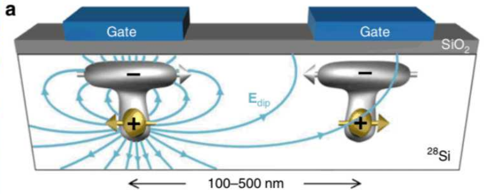
- **Fast** and **stable** rotation speed: Contact hyperfine interaction $A/2$ = 57 MHz gives **9 ns π rotation (potentially faster)**.
- Compact design: No need for **nuclear field bath**, **spin-orbit int.**, **micromagnet**. Just **one QD**.
- ST states: good probe of coherence between the QD and the D.
- Get a **nuclear spin** for free. Nuclear spin qubit is the **"best" single qubit** in solid state.

[P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)]

Other proposals



[G. Pica ... Phys. Rev. B 93, 035306 (2016)]



[G. Tosi ... Nat. Commun. 8, 450 (2017)]

Part 1: Outline

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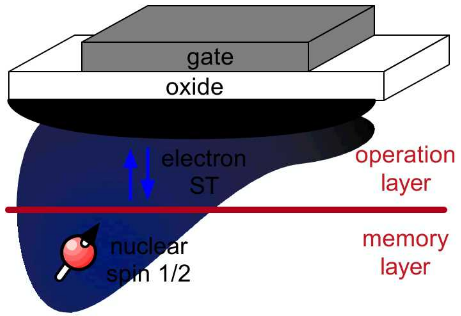
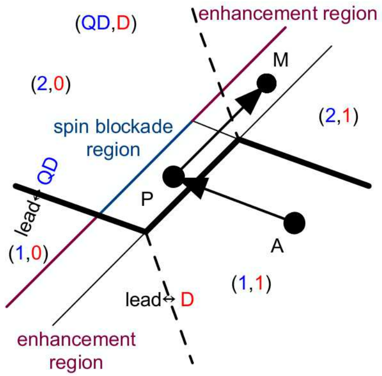
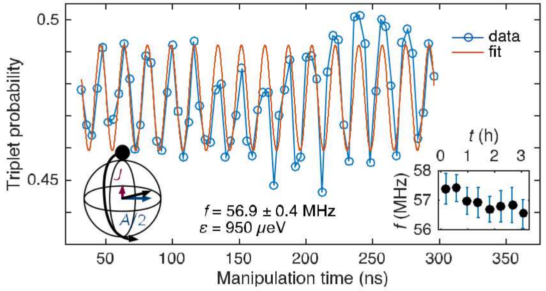
- Enhanced latching readout
- Singlet-triplet qubit (hyperfine-driven rotations)







References

1. Gamble, J. K., **Harvey-Collard, P.** et al. "Valley splitting of single-electron Si MOS quantum dots" App. Phys. Lett. 109, 253101 (2016).
2. **Harvey-Collard, P.** et al., "High-fidelity single-shot readout for a spin qubit via an enhanced latching mechanism," Phys. Rev. X 8, 021046 (2018).
3. **Harvey-Collard, P.** et al. "Coherent coupling between a quantum dot and a donor in silicon" Nat. Commun. 8, 1029 (2017).
4. M. Rudolph, **P. Harvey-Collard** et al. "Coupling MOS quantum dot and phosphorous donor qubit systems," in 2016 IEEE IEDM (2016) pp. 34.1.1–34.1.4.

- Donor-Dot system
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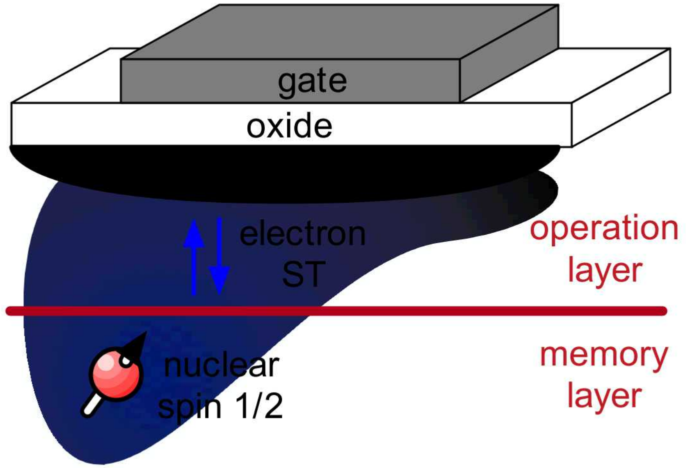
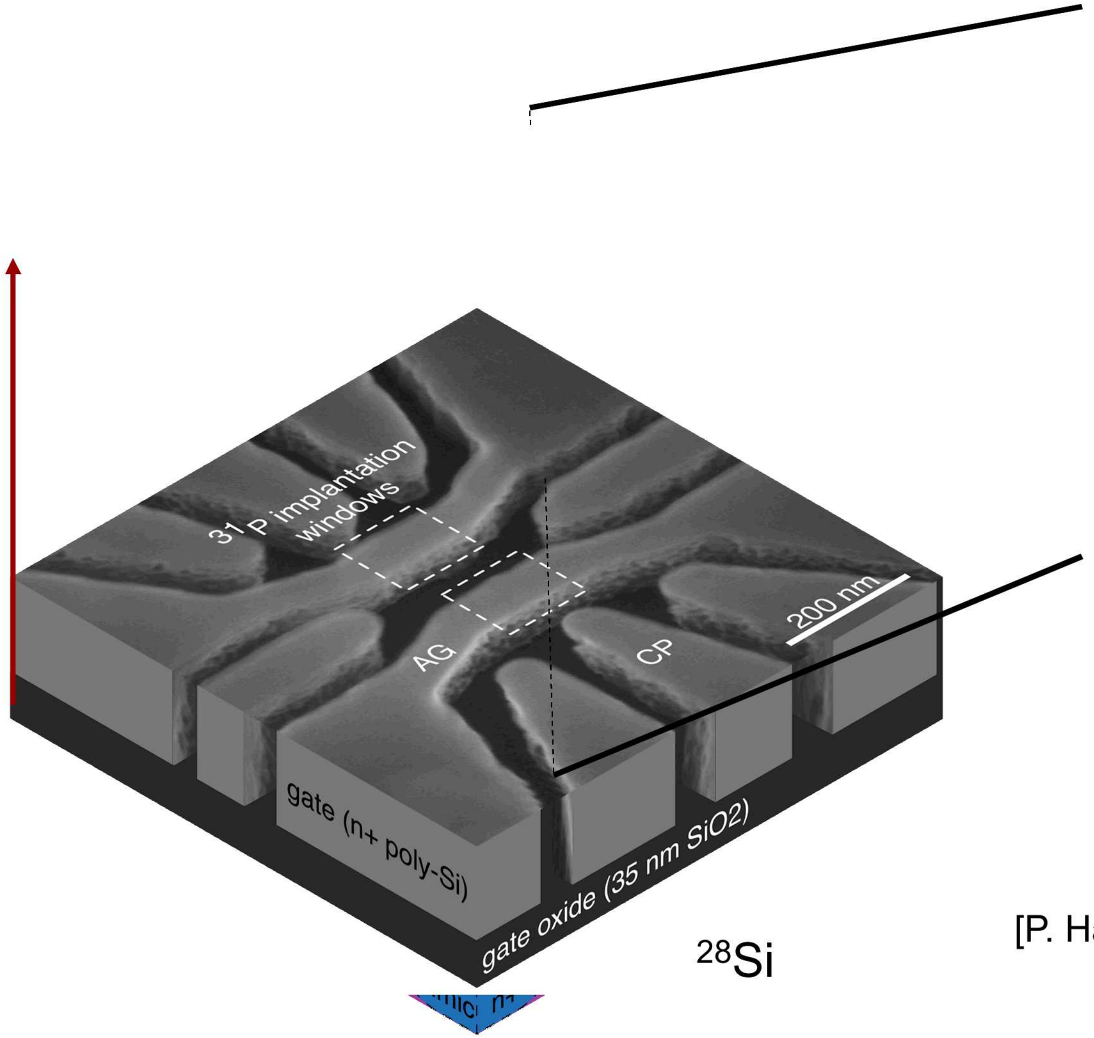
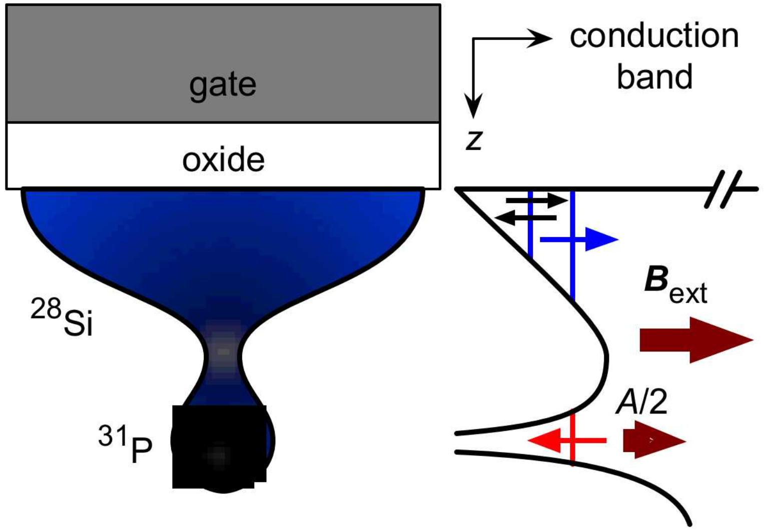
Part 1: Donor-dot system and related topics



The “gated wire” device



Filled-shell valley configuration

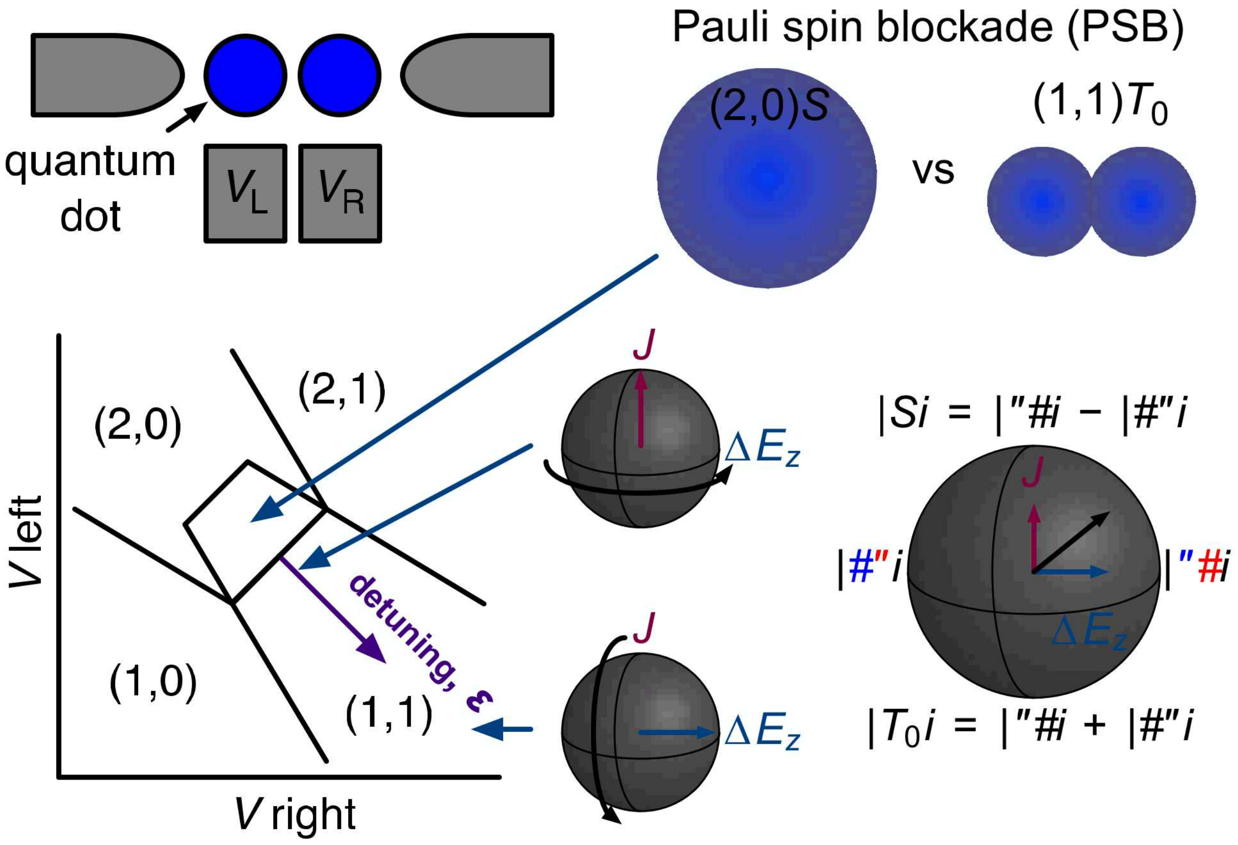


effective (2,0)-(1,1)

[P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)]

The singlet-triplet (ST) qubit

Readout and control



[ST qubit theory:] Taylor, J. M. ... Phys. Rev. B 76, 035315 (2007).

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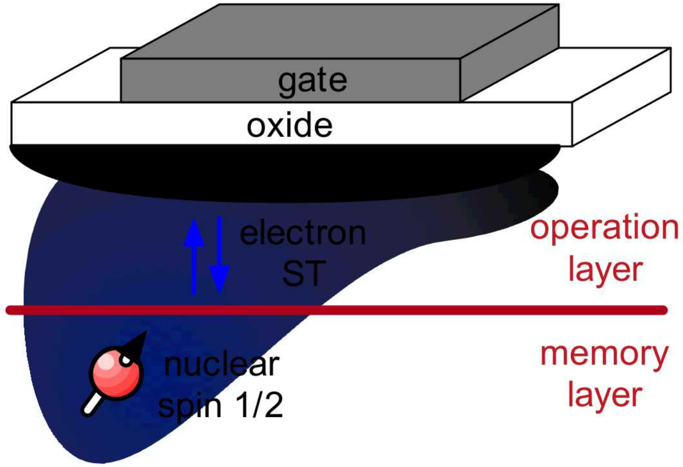
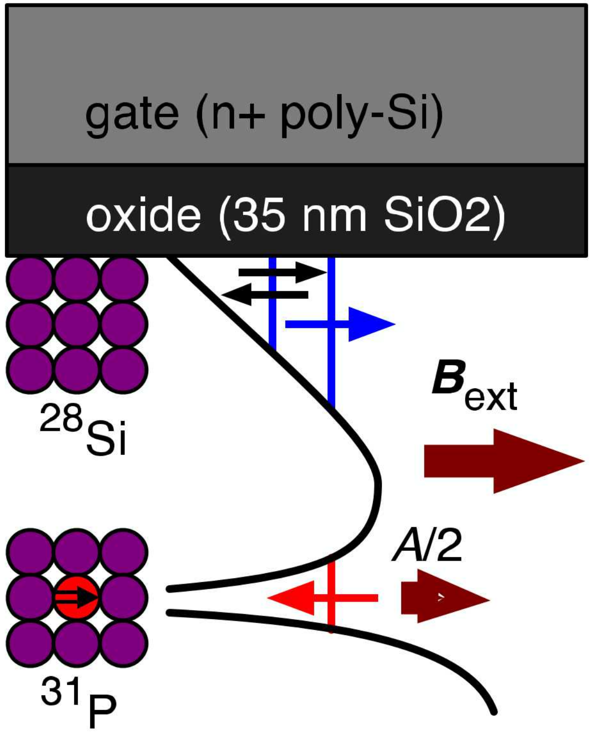
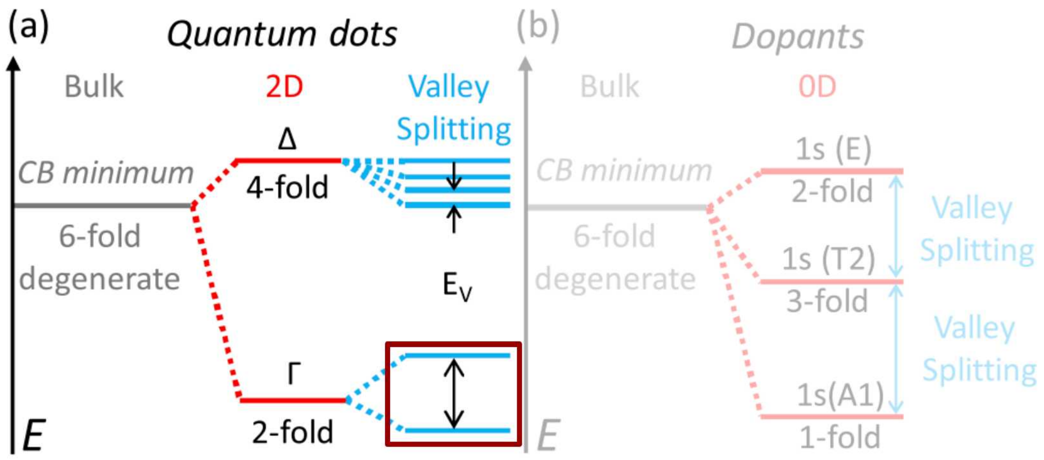


Valley splitting in Si

Filled-shell valley configuration



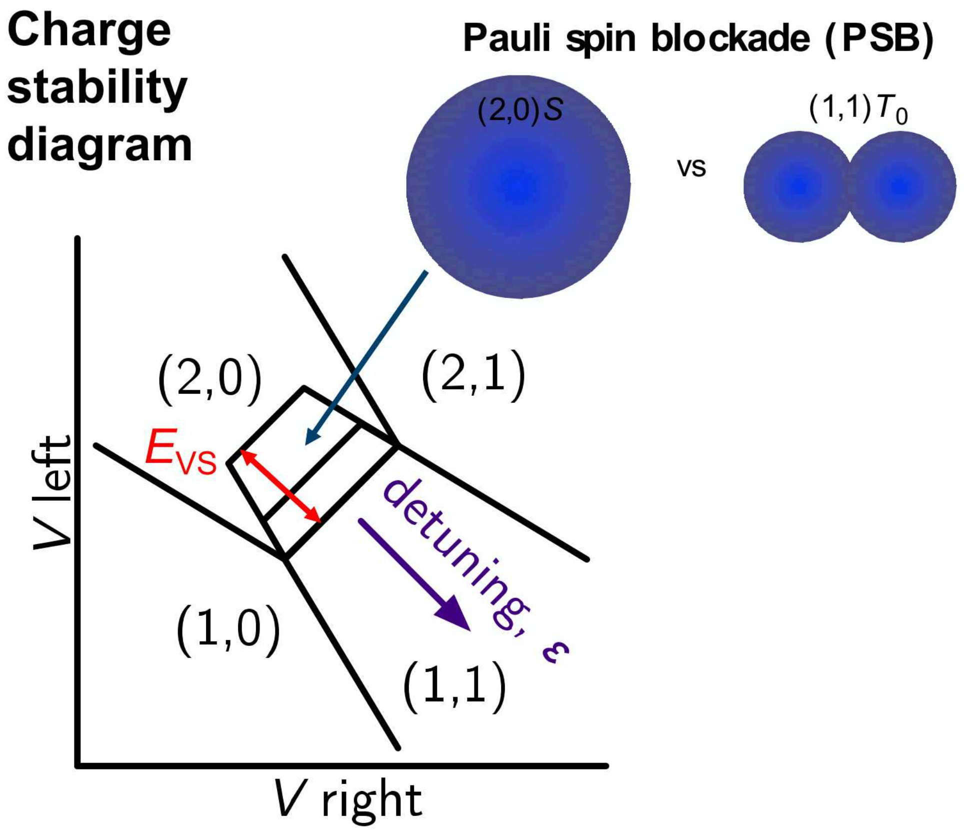
Valley degeneracy is lifted because of the strong confinement at the Si/SiO2 interface [1]



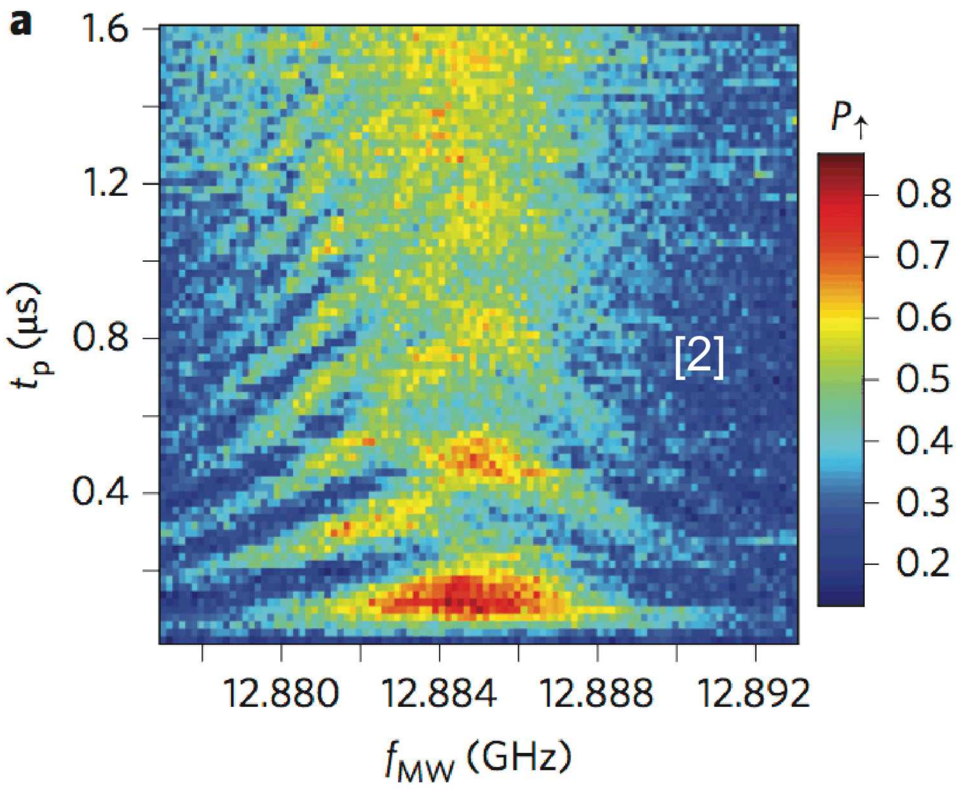
[1] Zwanenburg, F. A. ... Rev. Mod. Phys. 85, 961 (2013).

Small valley splitting is a problem

Spin blockade window can be unpractically small



Valleys can have different *g*-factors [1, 2]

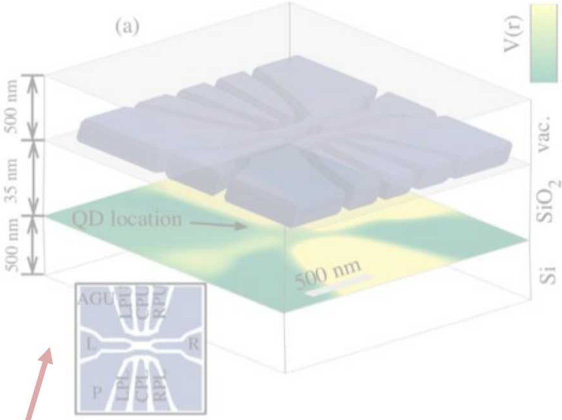


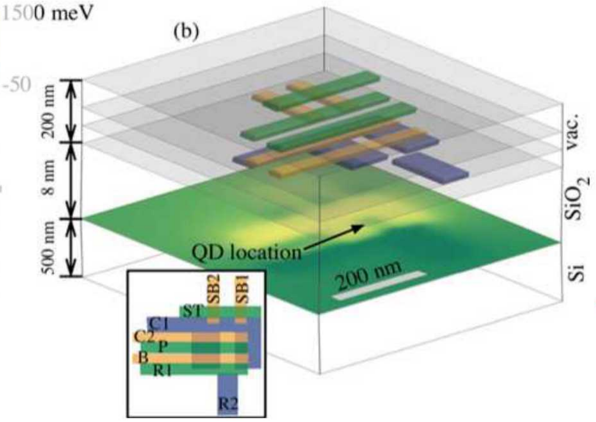
[1] Eng, K. ... Science Advances 1, e1500214 (2015).
[2] Kawakami, E. ... Nat Nano 9, 666–670 (2014).

Valley splitting is tunable in MOS

Reproduced in our devices [1].

Theoretical understanding [1].

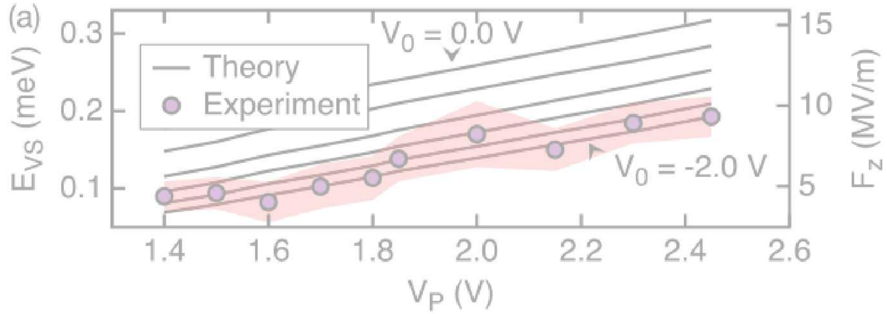


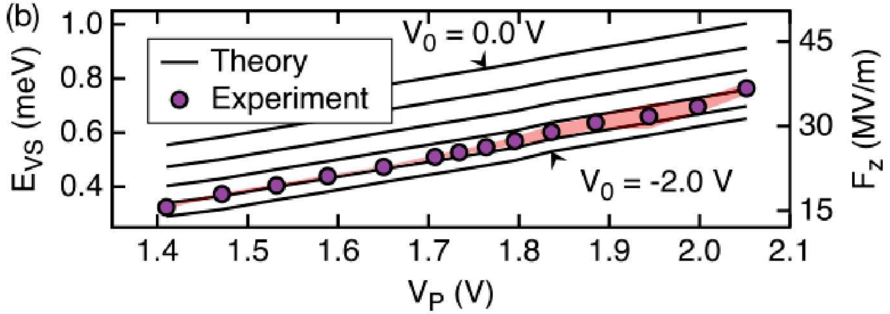


Our work (SNL)

Yang (UNSW)

[Original work:] Yang, C. H. ... Nat. Commun. 4, 2069 (2013).



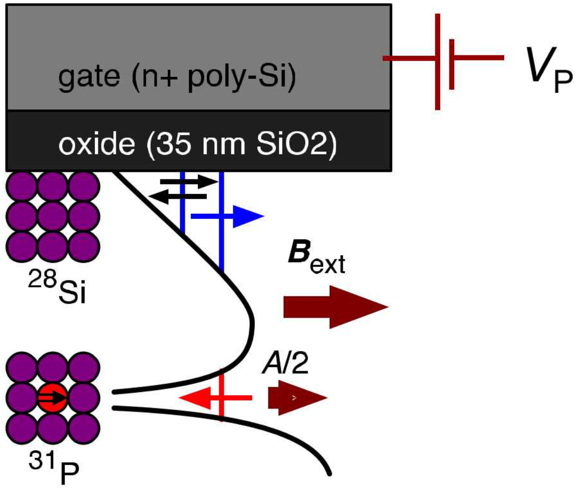


We find consistently large (>60 µeV) and tunable (60 to >250 µeV) valley splittings in our SNL devices.

[1] Gamble, J. K., Harvey-Collard, P. ... App. Phys. Lett. 109, 253101 (2016).

Valley splitting in Si — donors

Filled-shell valley configuration

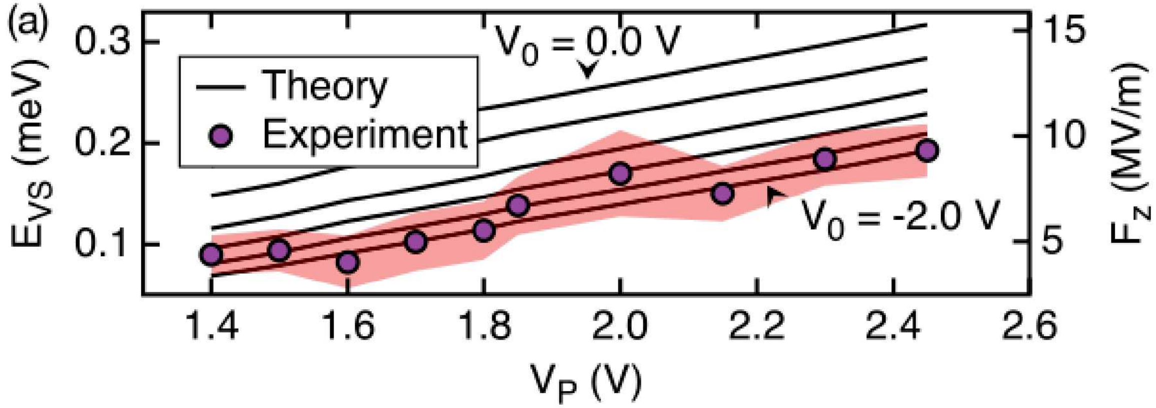


Strong tunnel coupling to donor

=

Low electric field (V_P)

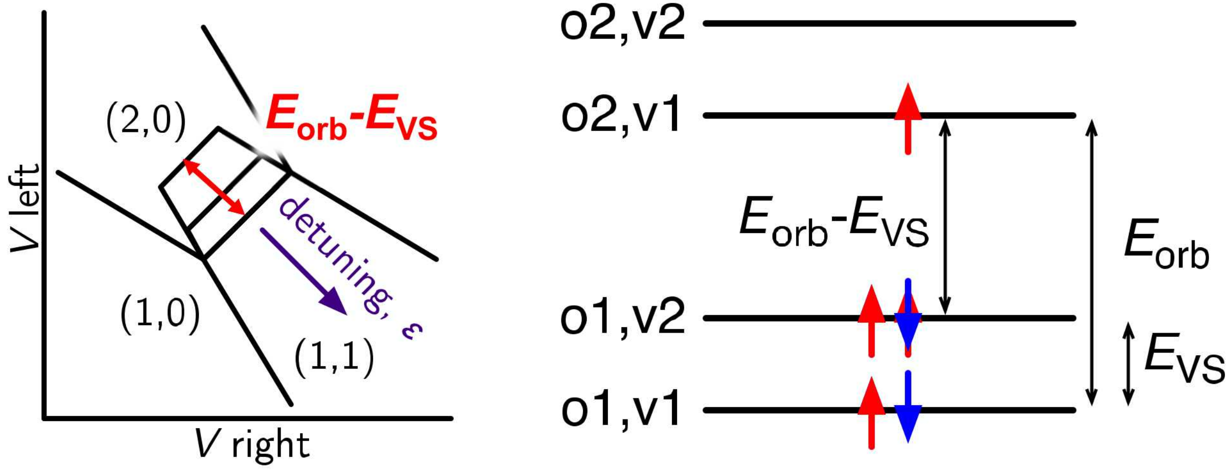
Limits the valley splitting!



Tuning the ST splitting via shell engineering

Give up? Or play some tricks!

- Spin singlets have a symmetric valley-orbit wavefunction.
- Trick: fill the lowest valley with a singlet. Then forget about it!



4-electron trick

- Proposed that this trick can
  - Circumvent small ST splitting
  - Change QD size to adjust tunnel coupling to donors
- Introduced in 2015 (arXiv) and [Harvey-Collard, P. ... Nat. Commun. 8, 1029 (2017).]
- Now used by other groups (HRL, U Wisc, ...)

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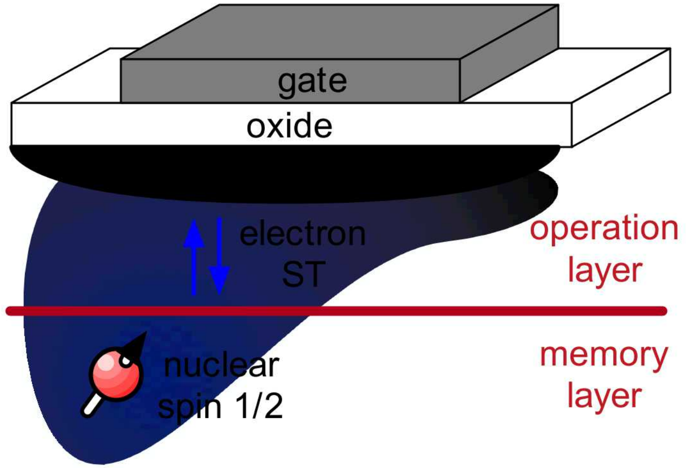
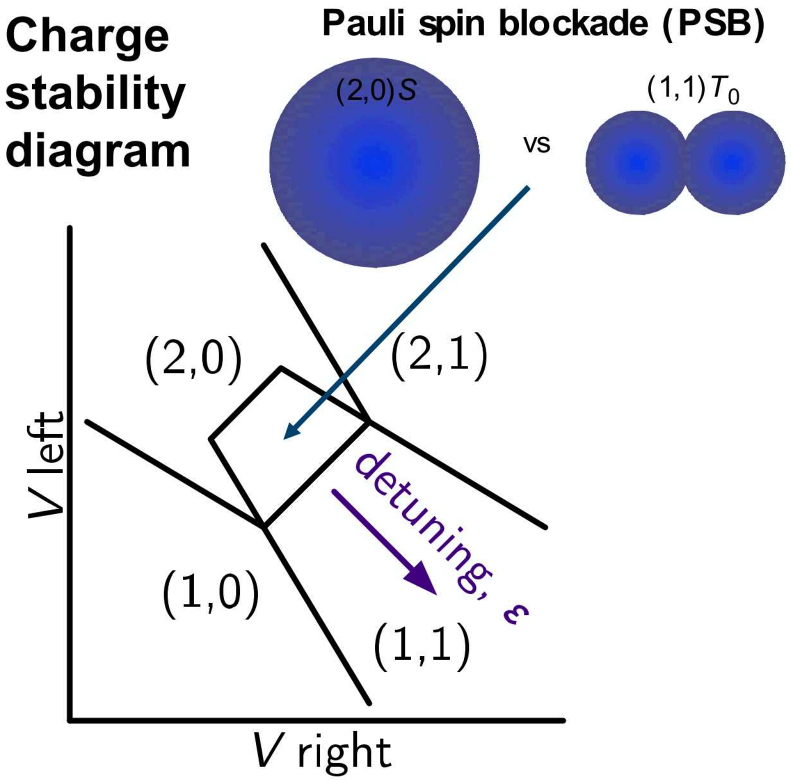
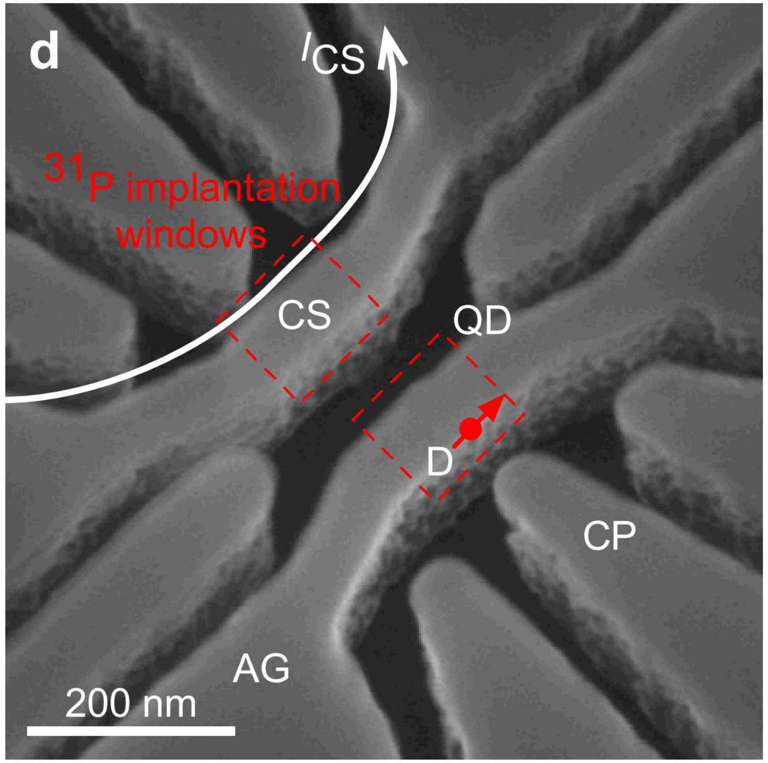


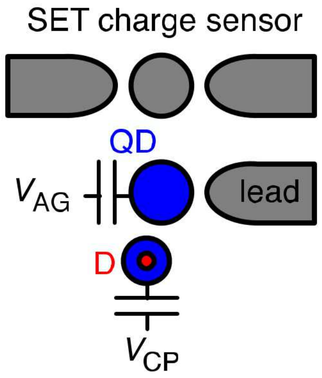
Issues with spin readouts

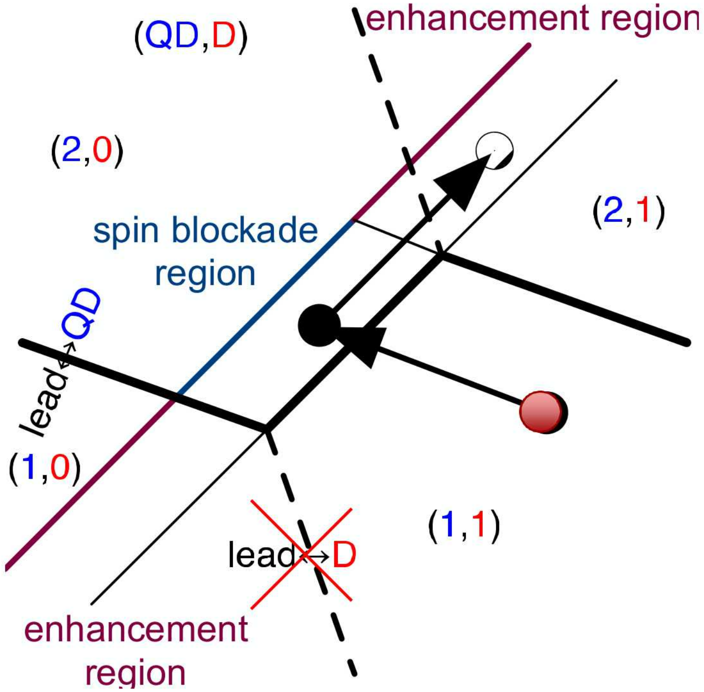
Example: Charge sensor not necessarily aligned with sensed dipole

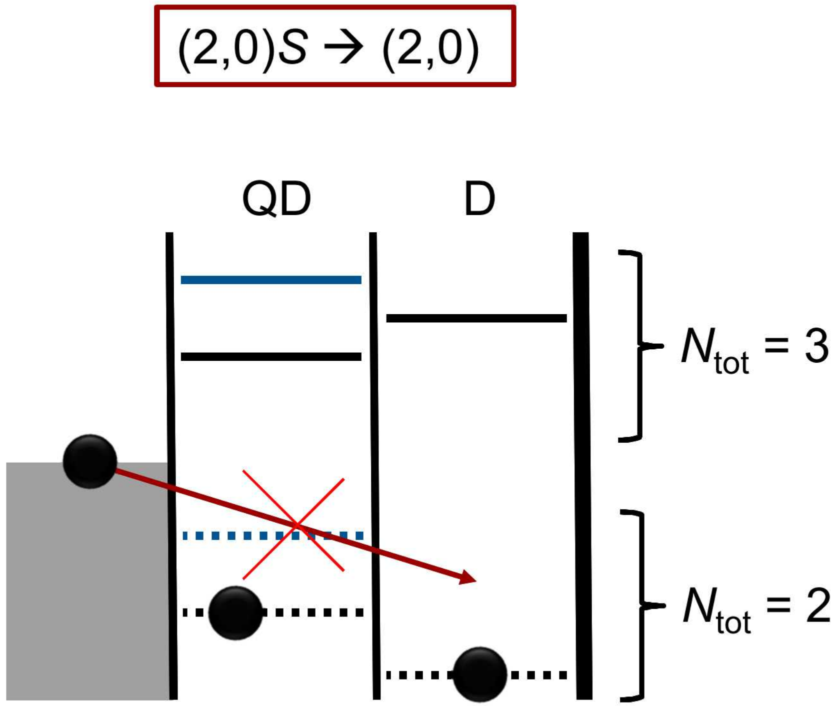




Readout concept (illustrated)



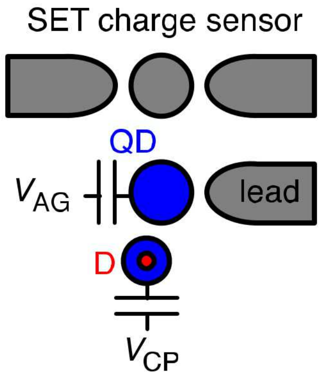


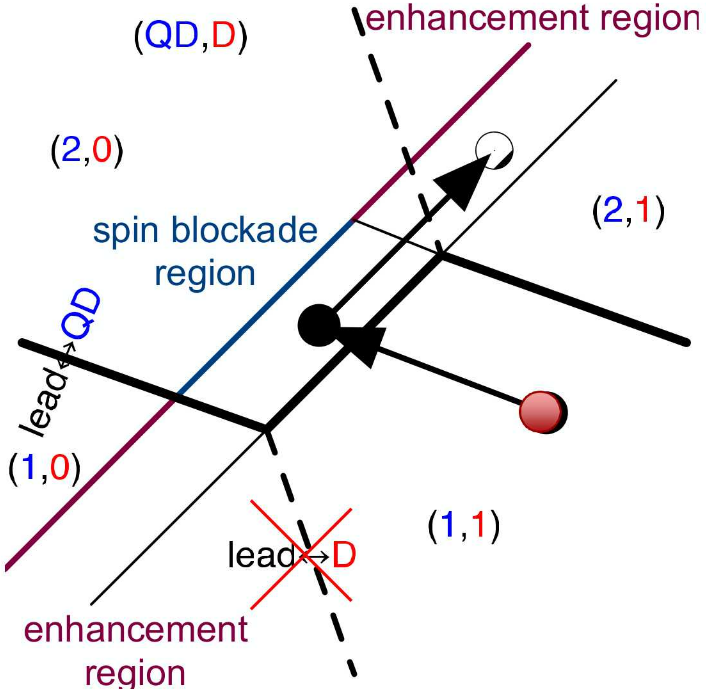


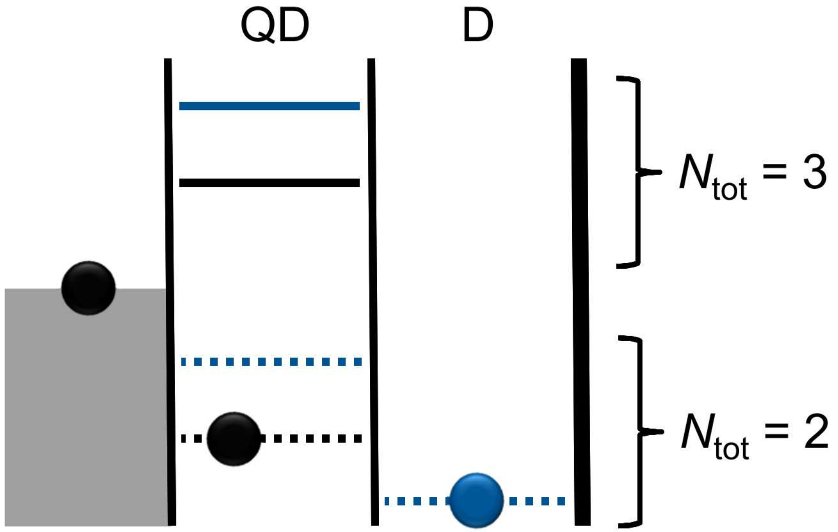
[P. Harvey-Collard ... Phys. Rev. X 8, 021046 (2018)]

Readout concept (illustrated)

$(1,1)T_0 \rightarrow (2,1)$
$(2,0)S \rightarrow (2,0)$

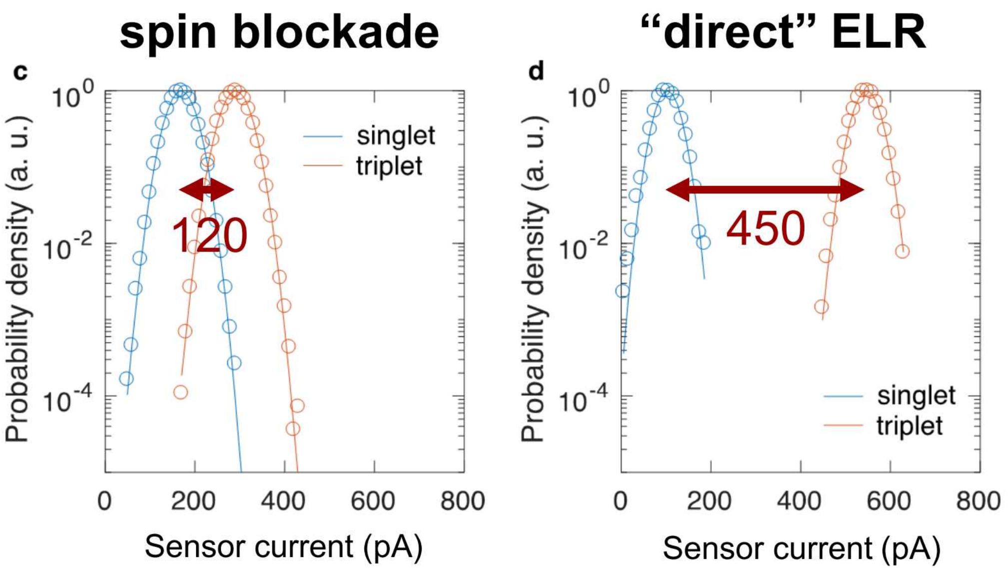






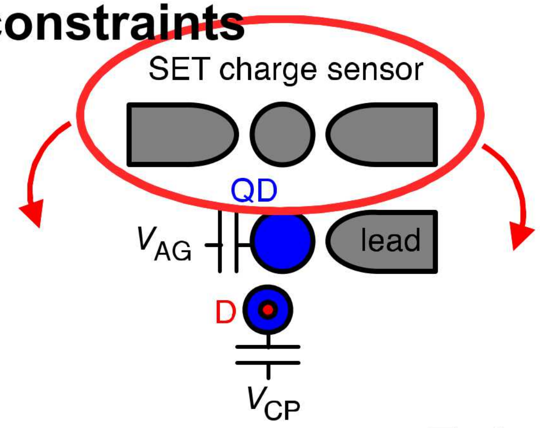
[P. Harvey-Collard ... Phys. Rev. X 8, 021046 (2018)]

Enhanced Latching Readout enhances the signal-to-noise ratio



Noise is the same.

Relaxes layout constraints

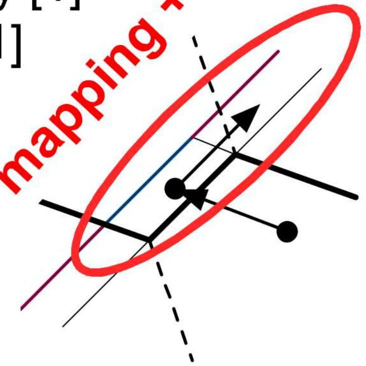


[1] P. Harvey-Collard ... Phys. Rev. X 8, 021046 (2018).

Enhances lifetime [1]

99.91% avg. charge readout fidelity [1]
99.86% avg. spin readout fidelity [1]

Still record to date?



[Inspired from:] S. A. Studenikin ... App. Phys. Lett. 101, 233101 (2012).
[Other work:] Mason, J. D. ... Phys. Rev. B 92, 125434 (2015).
Petersson, K. D. ... Phys. Rev. Lett. 105, 246804 (2010).

Enhanced Latching Readout (ELR) Comparison

Comparison of electron readouts

	Spin 1/2	Singlet-triplet	This work (ELR)
Mechanism	Tunneling (stochastic)	Spin blockade (deterministic)	Spin blockade (deterministic)
Speed	Slow	Fast	Fast
Signal	1 e	~0.2 e	1 e
Lifetime	Good, but long waits	~Ok (Si), Bad (GaAs)	Good

If you have ***any*** singlet-triplet system, this can work!

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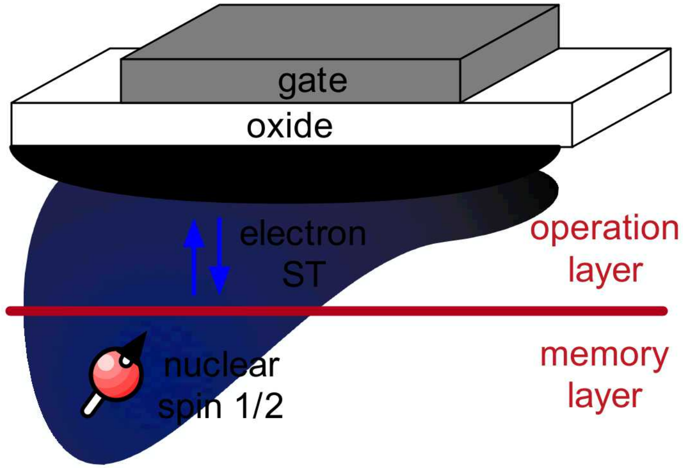

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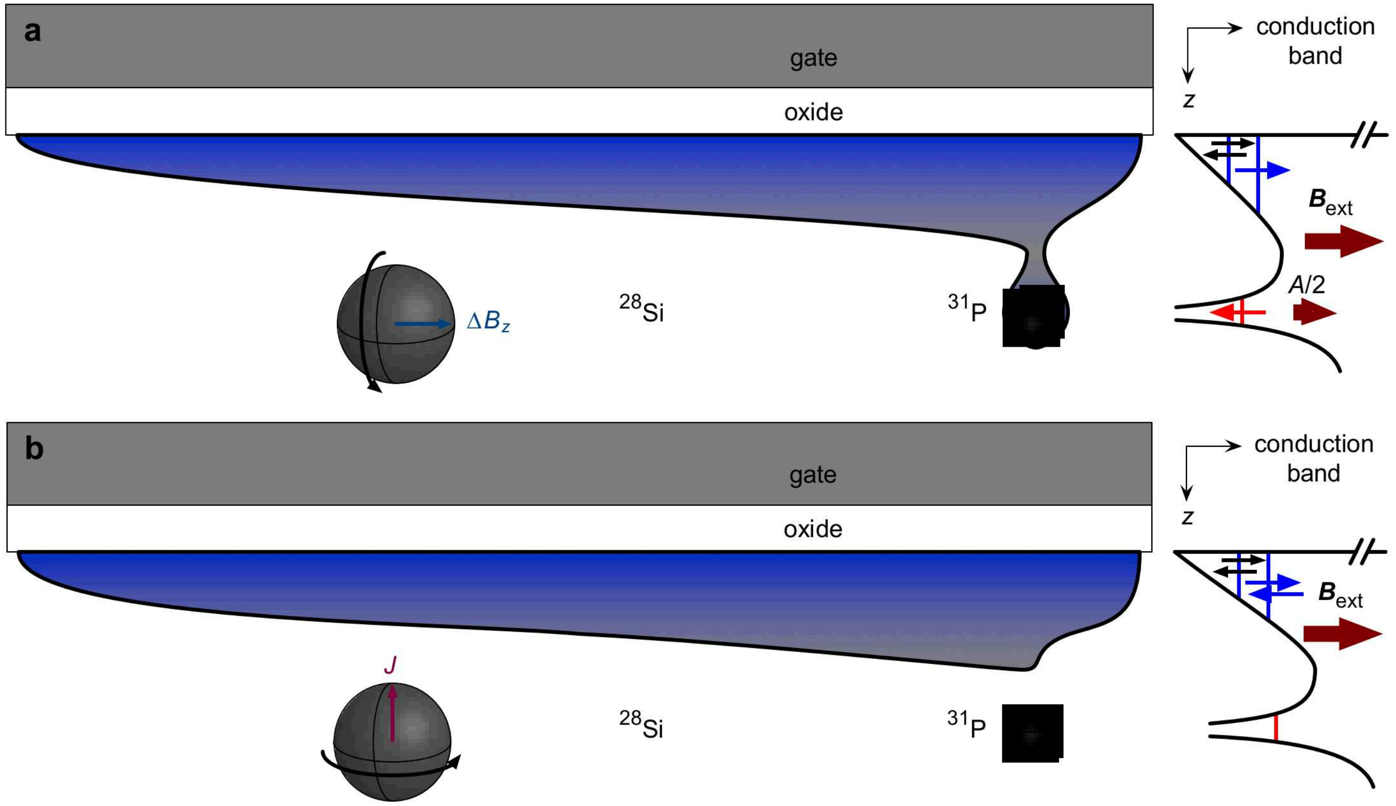
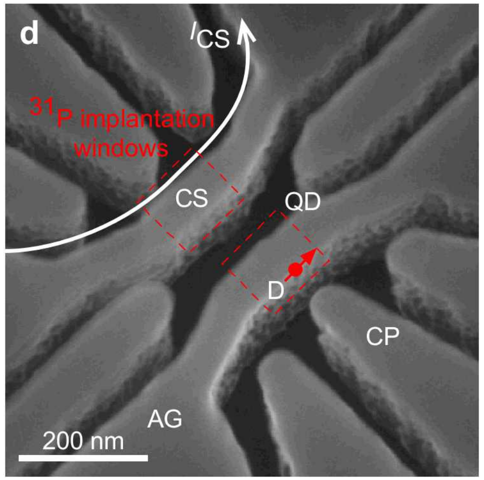




$$\langle \Downarrow | A\boldsymbol{S} \cdot \boldsymbol{I} | \Downarrow \rangle = \frac{A}{2}\boldsymbol{S}$$

For electron on donor:

$$\hat{H} = (g\mu_B/\hbar)\boldsymbol{S} \cdot \boldsymbol{B}_{ext} + A\boldsymbol{S} \cdot \boldsymbol{I}$$

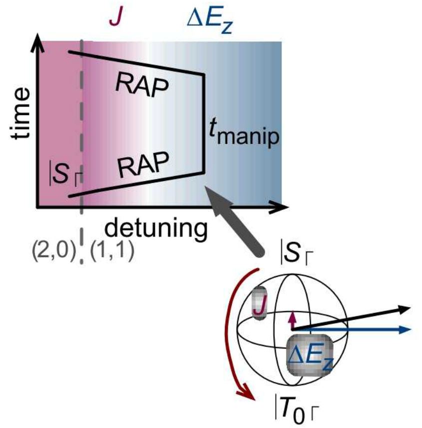
Singlet-Triplet Hamiltonian:

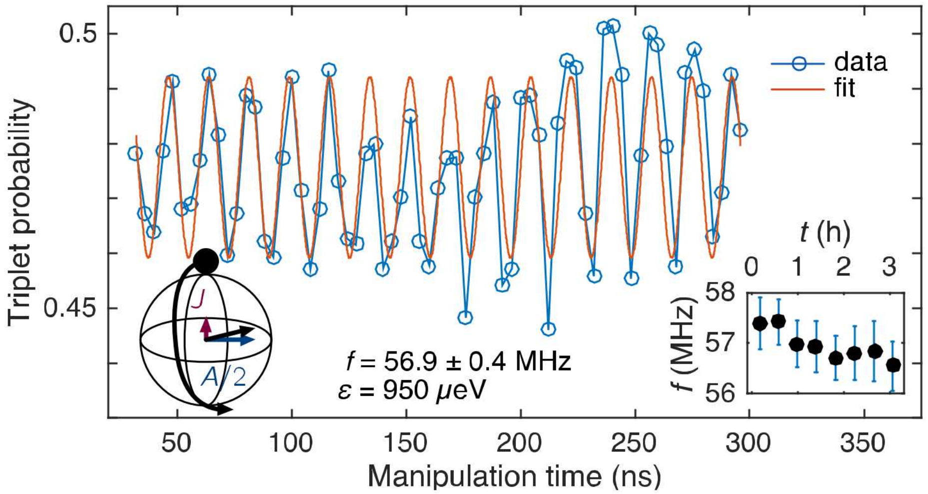
$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

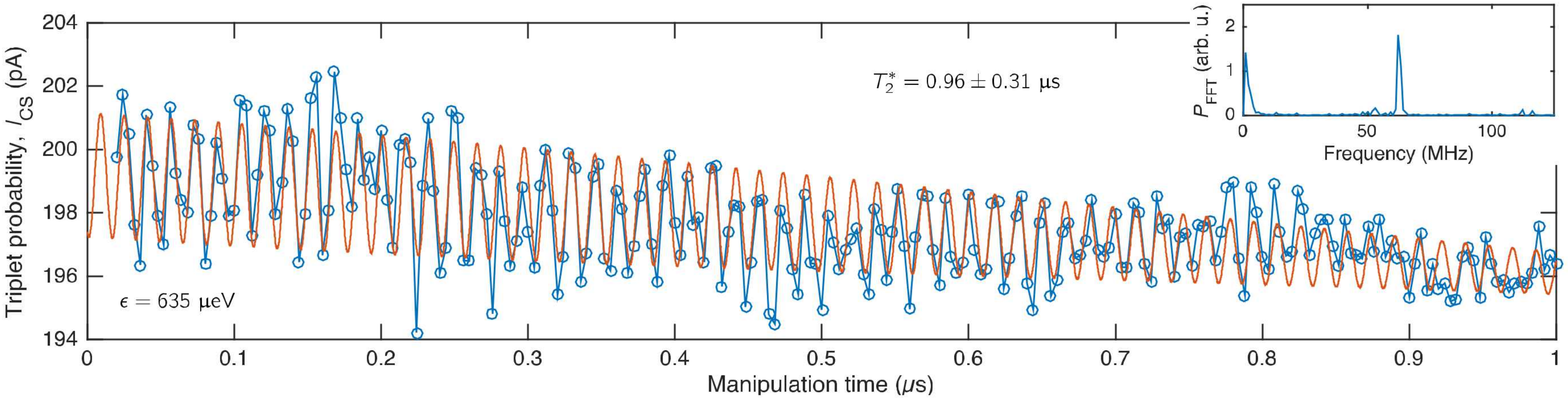
[P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)]

State manipulation

Singlet-triplet rotations driven by a single ^{31}P nucleus

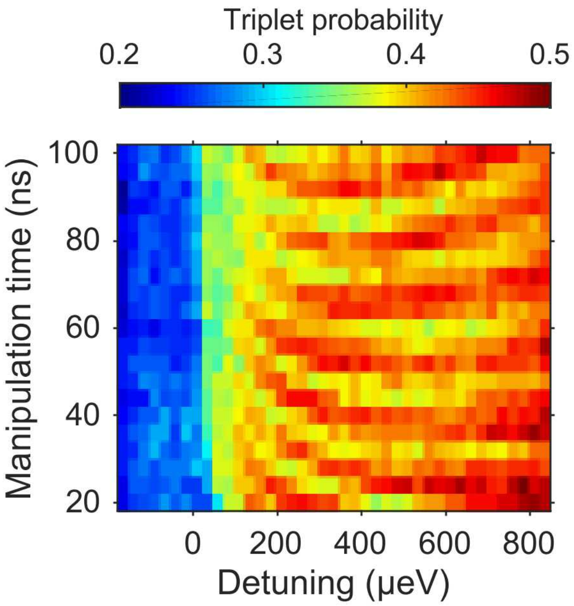


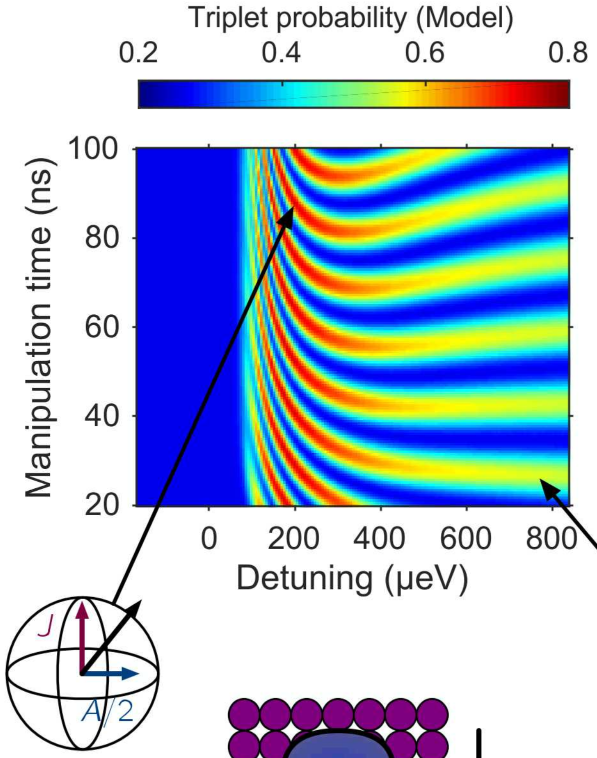


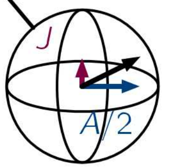


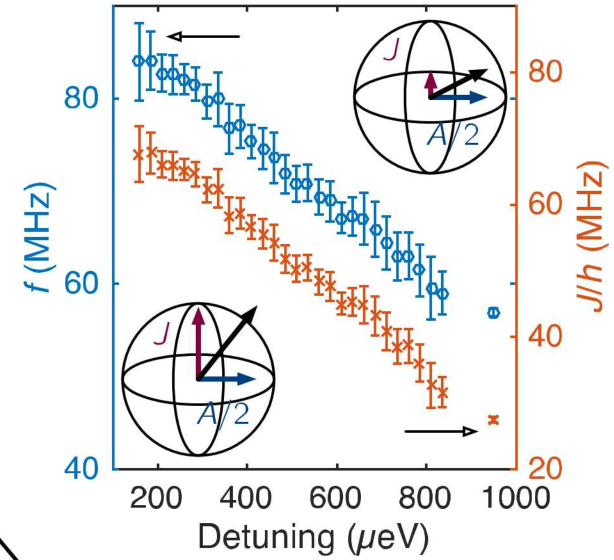
[P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)]

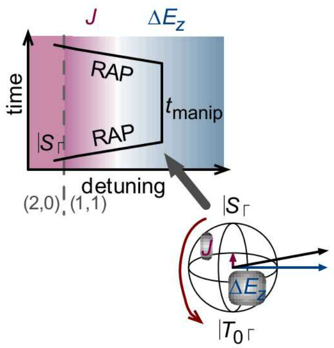
Detuning dependence of exchange interaction



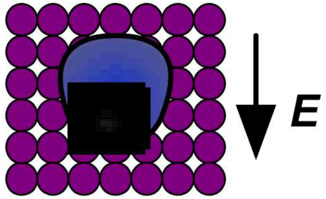








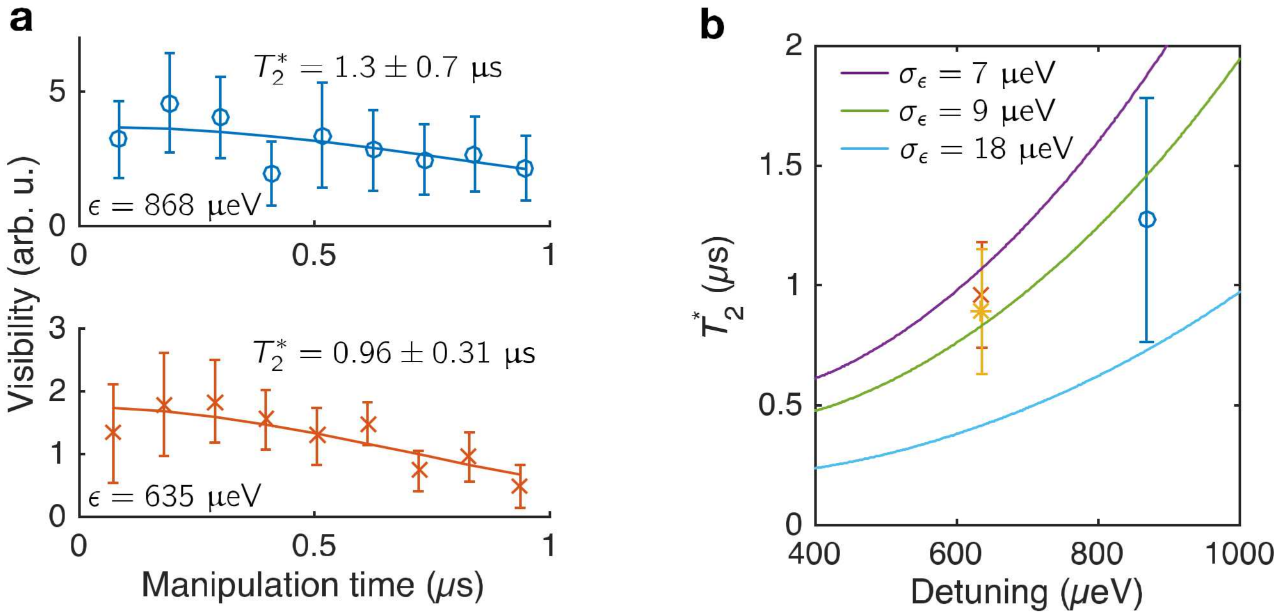
$A/2h = 49.8 \pm 2.3$ MHz

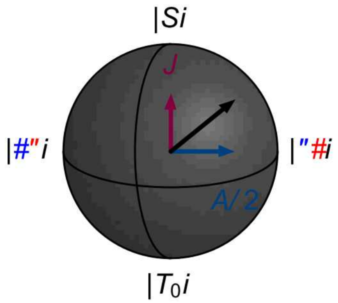


Bulk: A/h = 117 MHz
Our exp.: A/h = 100 MHz

[P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)]

Coherence time and charge noise





$$J \to J(\epsilon + \text{noise})$$

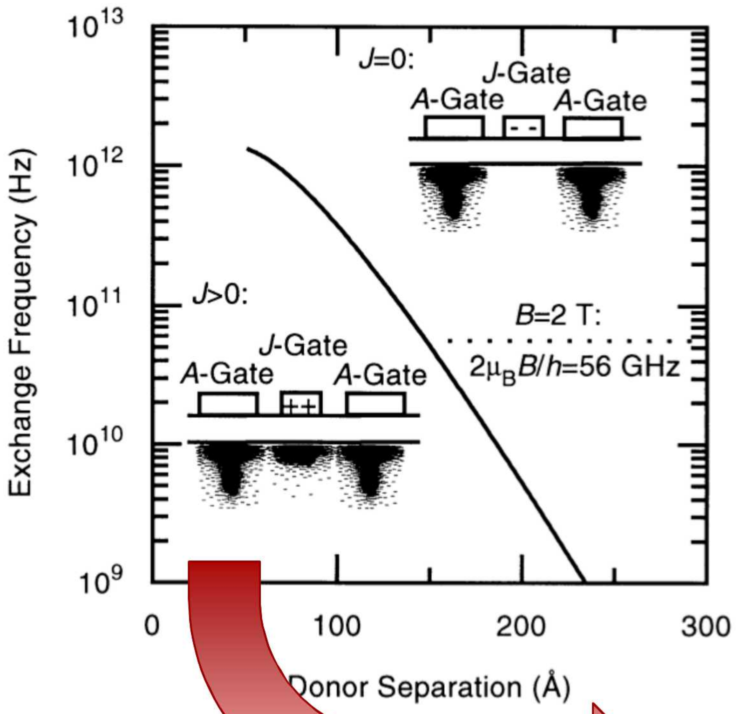
Quantitative measure of charge noise in Si-MOS

Reference	Petersson *et al.*	Shi *et al.*	Eng *et al.*	This work	Jock et al.
Material	GaAs/AlGaAs	Si/SiGe	Si/SiGe	Si (MOS)	Si (MOS)
$2\sigma_\varepsilon$ (µeV)	7.4	10	9.2	18	4
$k_B T_e$ (µeV)	6.9	12	6.9 — 8.6	18	13

[1] P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)
[See also:] Rudolph, M. ... 2016 IEEE IEDM, 34.1.1–34.1.4 (2016).
R. M. Jock ... Nat. Commun. 9, 1768 (2018).

Perspectives

Modern implementation of Kane's original vision

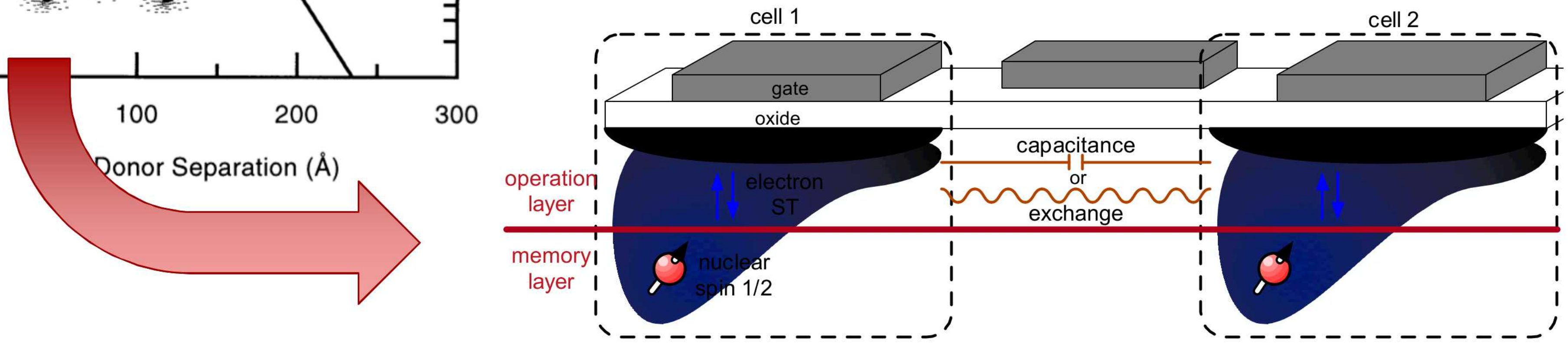


[B. Kane ... Nature 393, 133–137 (1998)]

Over 19 years of QD-D schemes!

Future work:

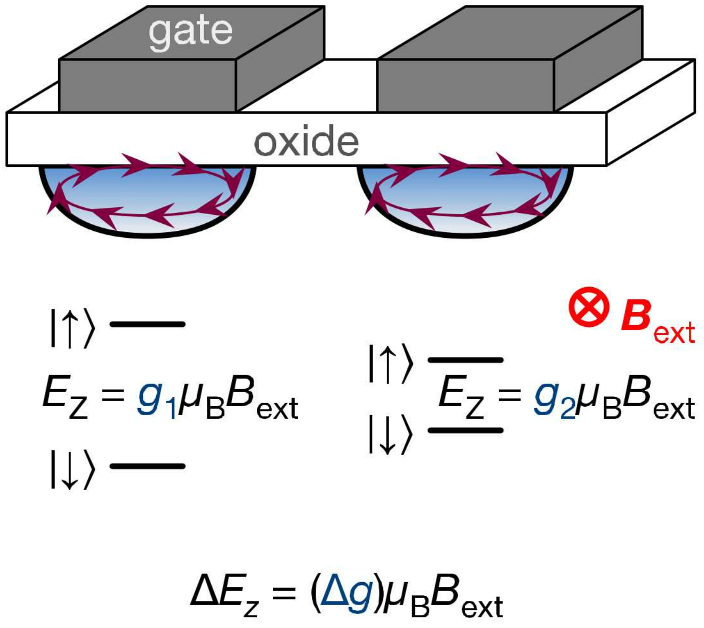
- High-fidelity qubit operation (AC, etc.)
- Strong hyperfine donors species
- Two-MAJIQ coupling
- Nuclear spin addressing



[P. Harvey-Collard ... Nat. Commun. 8, 1029 (2017)]

- Universal control using spin-orbit interaction
- Implications of the spin-orbit interaction for singlet-triplet qubits in silicon

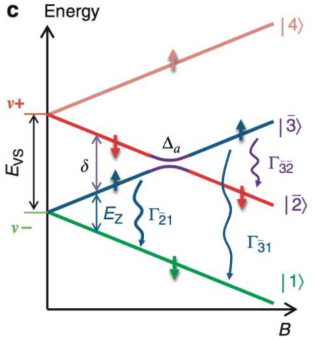
Part 2: Spin-orbit interaction in silicon dots



Spin-orbit interaction in silicon — Other work

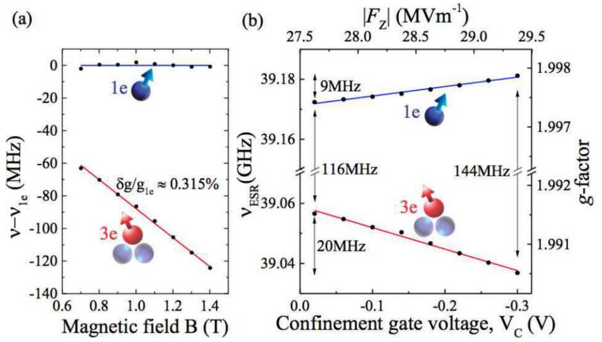
Broken symmetry at Si/material interface:
U. Rössler ... Solid State Comm. 121, 313 (2002).
L. E. Golub ... Phys. Rev. B 69, 115333 (2004).
M. Prada ... New J. of Phys. 13, 013009 (2011).

Spin relaxation hot-spot in MOS



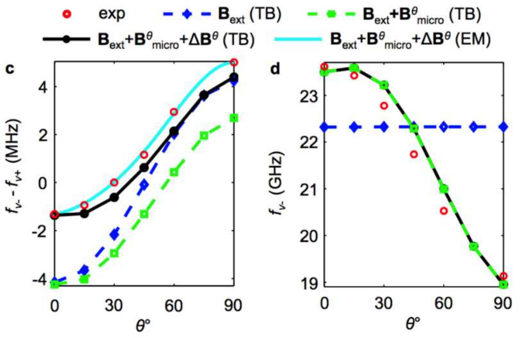
C. H. Yang ... Nat. Commun. 4, 2069 (2013).
X. Hao ... Nat. Commun. 5, 3860 (2014).

Spin resonance frequency in MOS



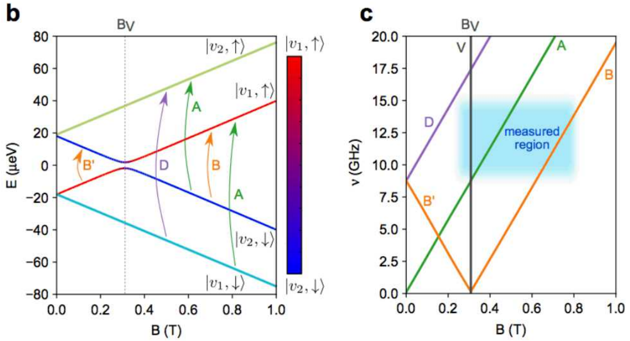
M. Veldhorst ... Phys. Rev. B 92, 201401 (2015).
R. Ferdous ... Phys. Rev. B 97, 241401 (2018).

Spin resonance frequency anisotropy in Si/SiGe



R. Ferdous ... npj Quantum Information 4, 26 (2018).

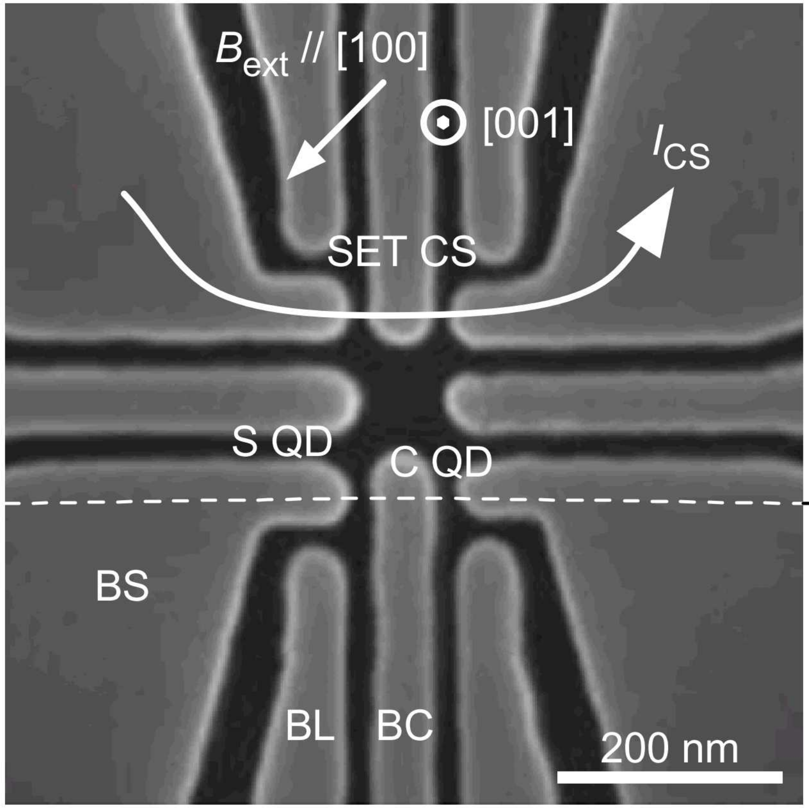
Spin-orbit-driven spin resonance in a MOS finFET

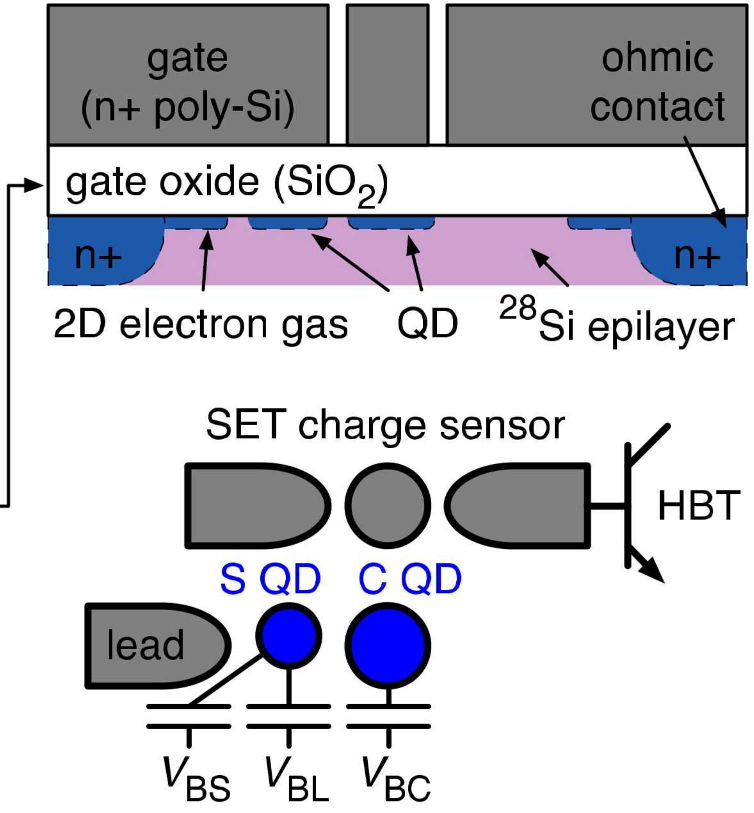


A. Corna ... npj Quantum Information 4, 6 (2018).

Simple CMOS-compatible qubit

Pure CMOS design [1, 2, 3]
Isotopically-enriched silicon 28





***Split Wire Accumulation Gate** (SWAG)*

First* spin-orbit-driven e^- qubit in silicon.**

*: See also [Corna et al. (2018)]

**: Excluding artificial spin-orbit.

[1] P. Harvey-Collard et al. All-electrical universal control of a double quantum dot qubit in silicon MOS. *In 2017 IEEE IEDM* (2017).

[2] R. M. Jock, N. T. Jacobson, P. Harvey-Collard et al. “A silicon metal-oxide-semiconductor electron spin-orbit qubit,” Nat. Commun. 9, 1768 (2018).

[3] P. Harvey-Collard et al., “Implications of the spin-orbit interaction for singlet-triplet qubits in silicon,” arXiv:1808.07378 (2018).

- Universal control using spin-orbit interaction
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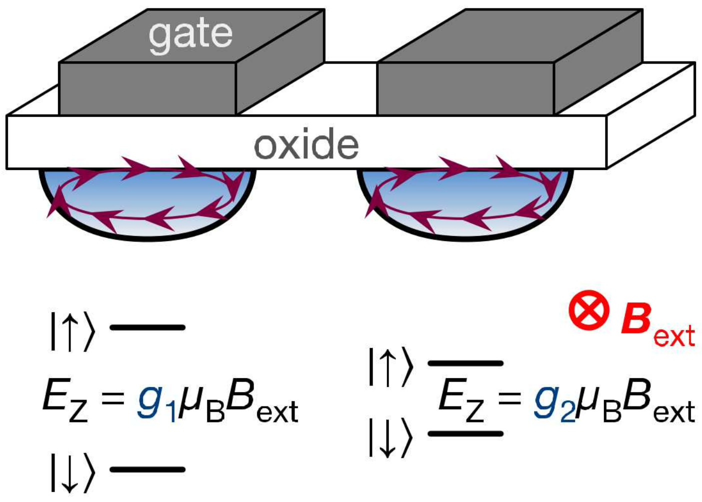


$\Delta E_z = (\Delta g)\mu_B B_{ext}$

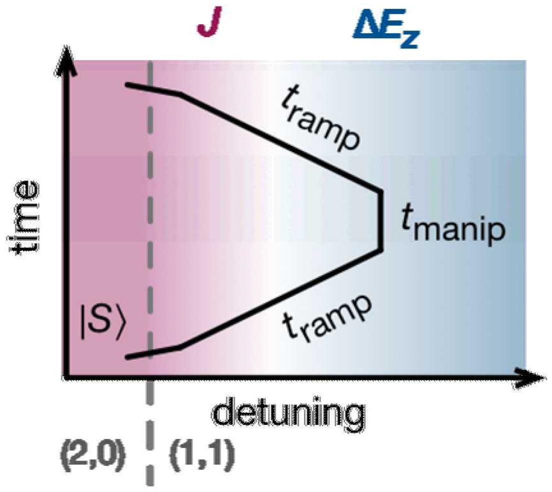
Initializing the qubit: Slow/Rapid Adiabatic Passage (SAP/RAP)

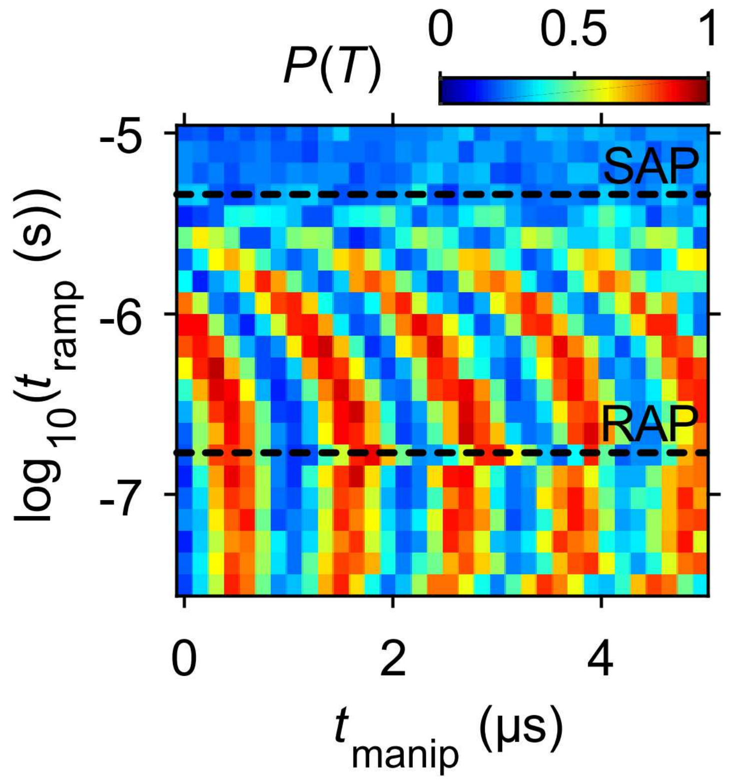
SAP: Slow Adiabatic Passage
Adiabatically with respect to both spin and charge.

$$|S\rangle \leftrightarrow |\uparrow\downarrow\rangle$$
$$|T_0\rangle \leftrightarrow |\downarrow\uparrow\rangle$$

RAP: Rapid Adiabatic Passage
Adiabatically with respect to charge.
Diabatically with respect to spin.

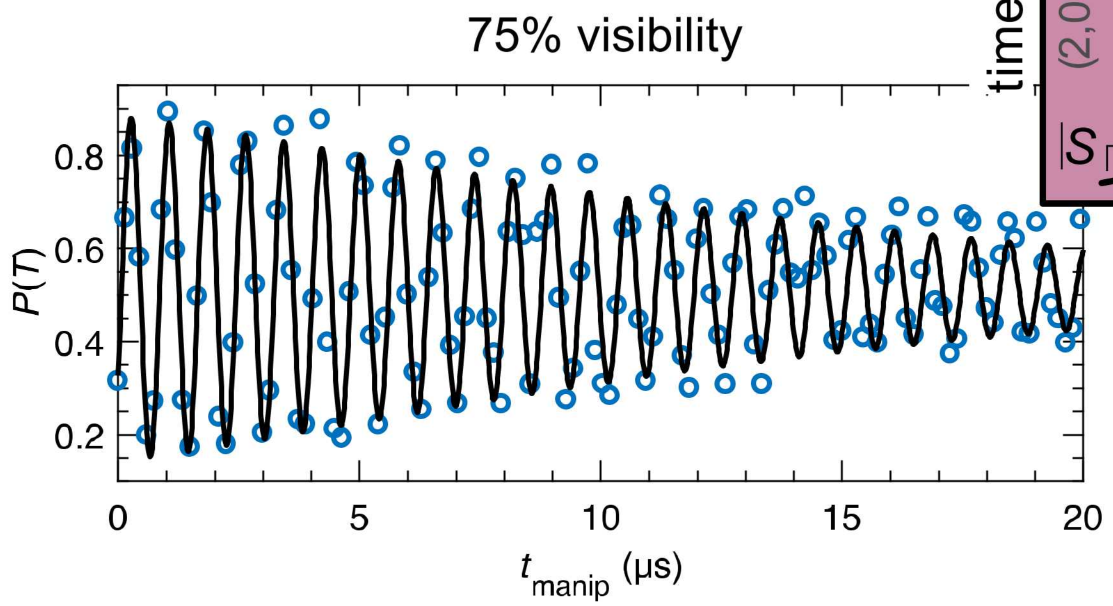
$$|S\rangle \leftrightarrow |S\rangle$$
$$|T_0\rangle \leftrightarrow |T_0\rangle$$



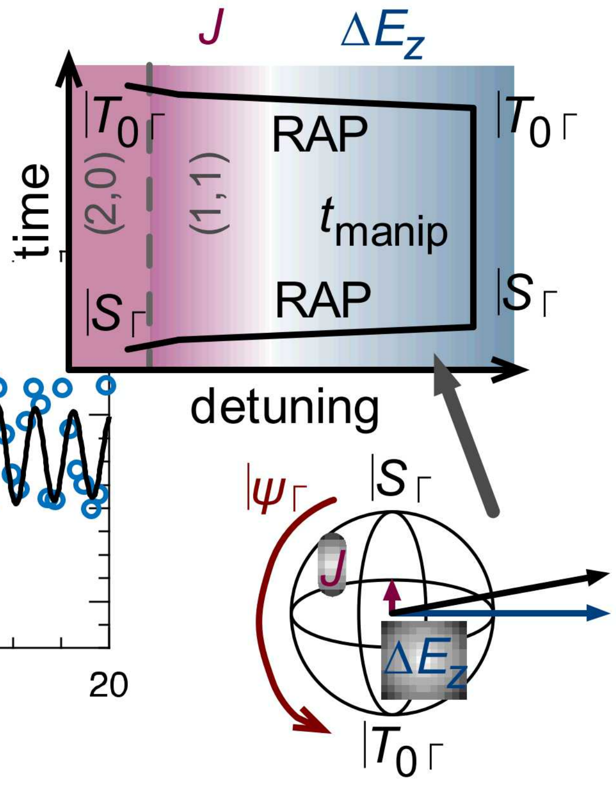


[P. Harvey-Collard ... In 2017 IEEE IEDM (2017)]

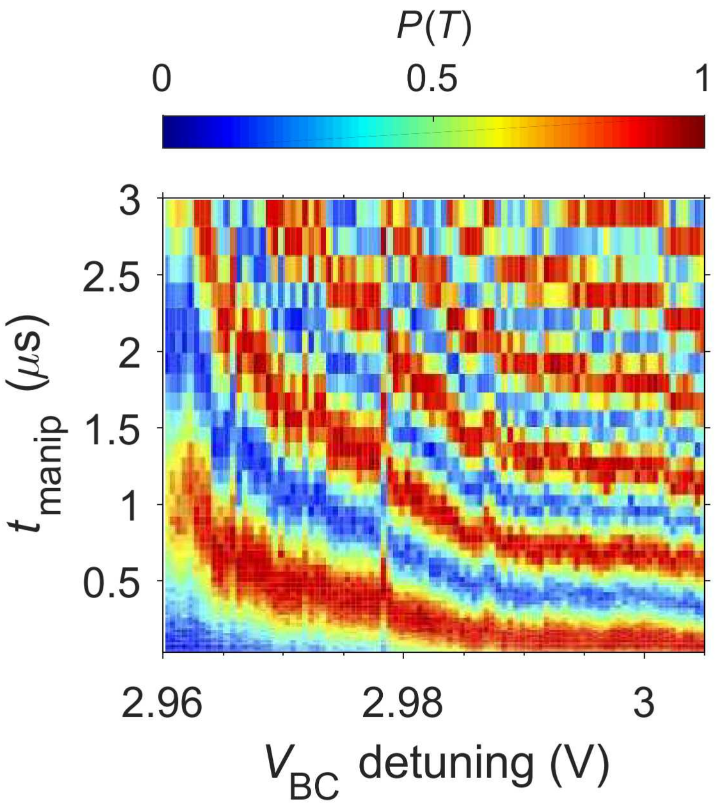
DC control — Zeeman rotations



Pulse



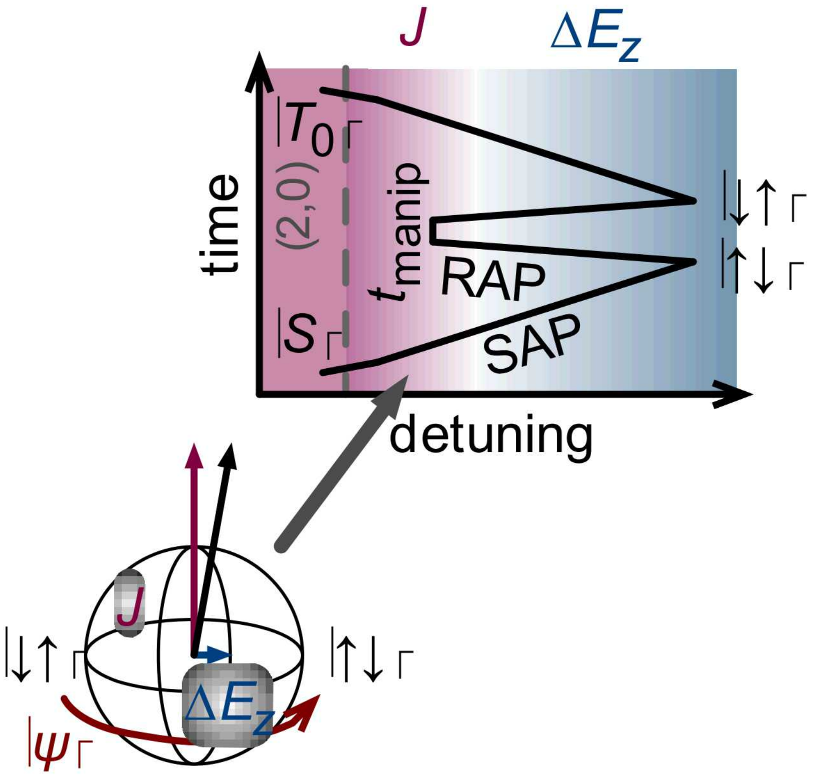
Detuning dependence



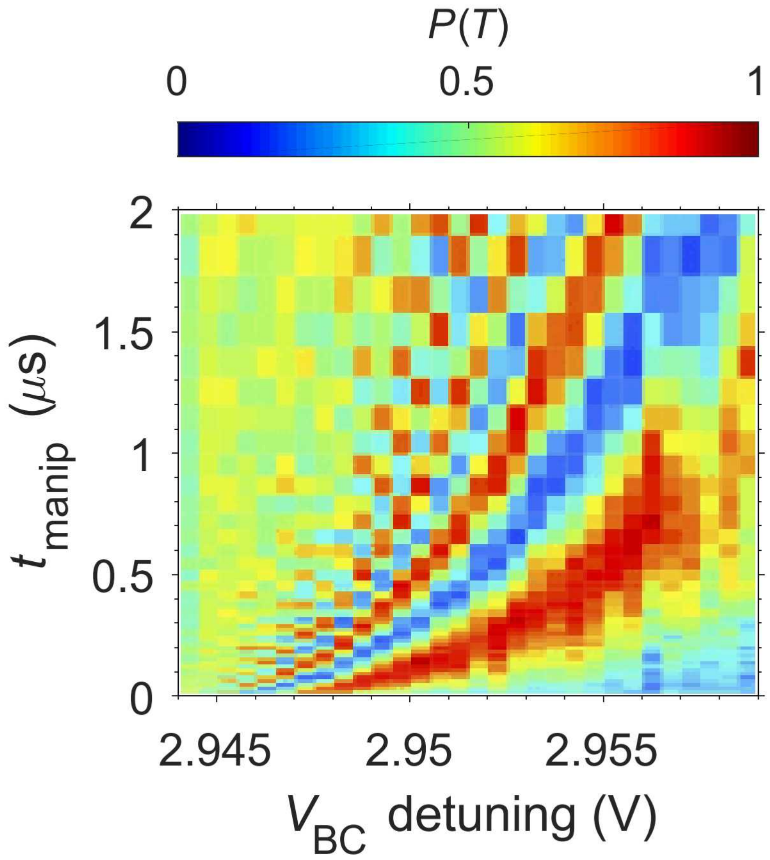
[P. Harvey-Collard ... In 2017 IEEE IEDM (2017)]

DC control — Exchange rotations

Pulse



Detuning dependence

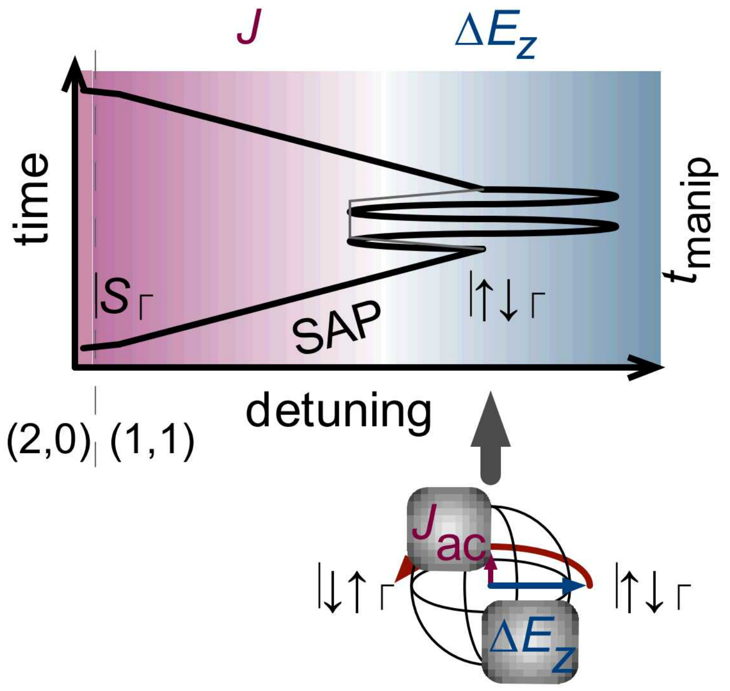


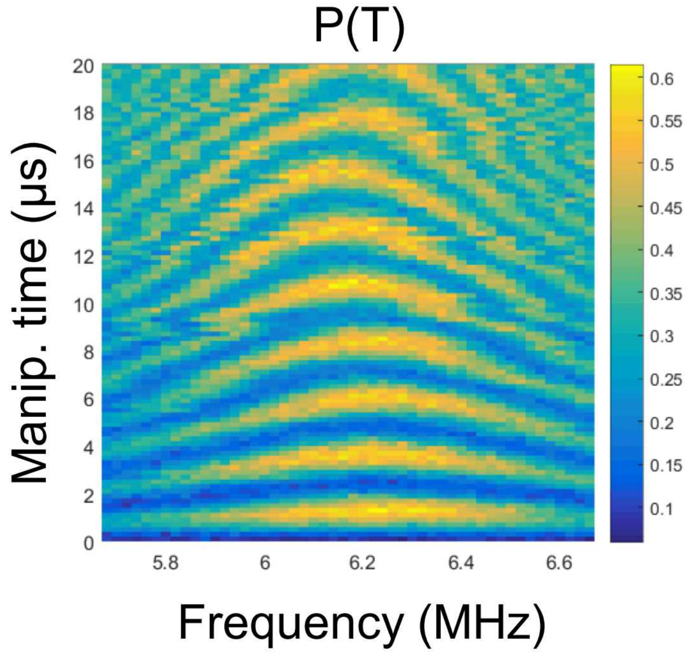
65% visibility

[P. Harvey-Collard ... In 2017 IEEE IEDM (2017)]

AC control of the singlet-triplet qubit

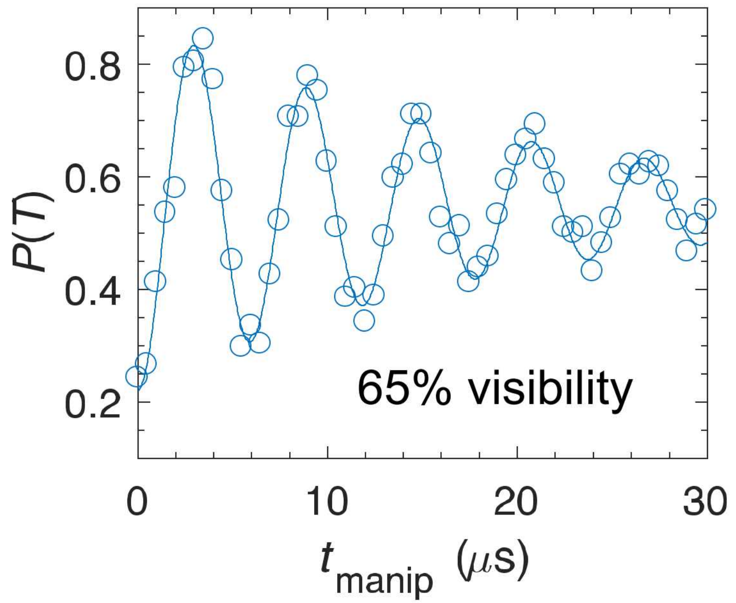
AC-controlled rotations [1, 2, 3]
Access any 1 qubit state





Data: C. Bureau-Oxton

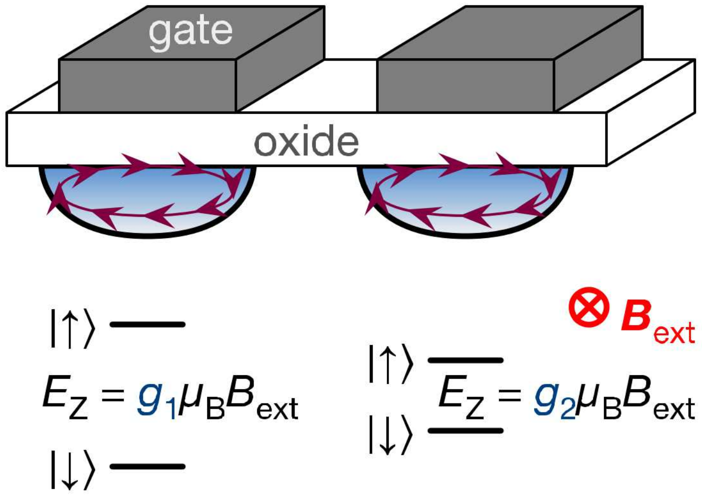
Rabi oscillations



[1] Klauser, D. ... Phys. Rev. B 73, 205302 (2006).
[2] Shulman, M. D. ... Nat Commun 5, 233101 (2014).
[3] P. Harvey-Collard ... In 2017 IEEE IEDM (2017).

- Universal control using spin-orbit interaction
- Implications of the spin-orbit interaction for singlet-triplet qubits in silicon

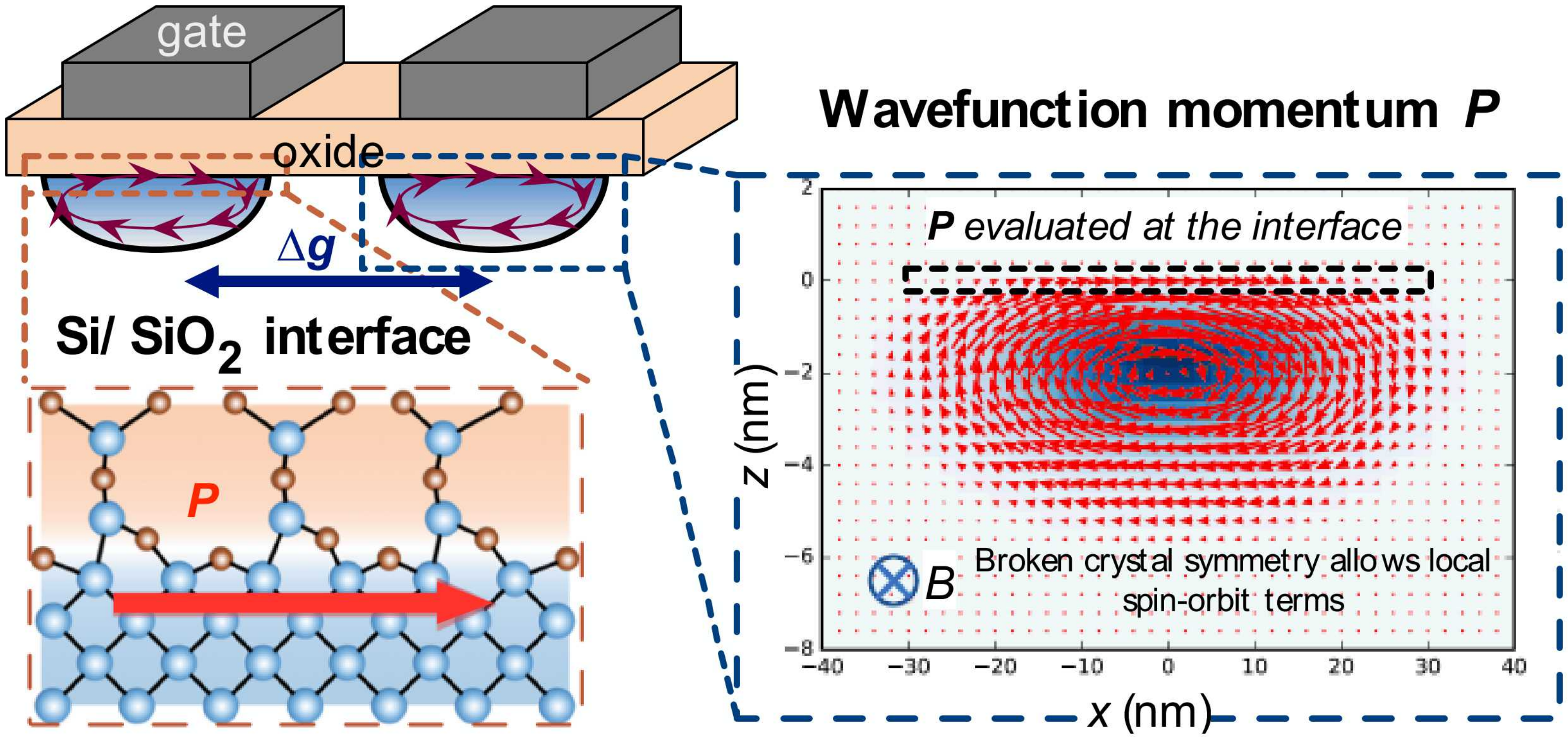
Part 2: Spin-orbit interaction in silicon dots



$$\Delta E_z = (\Delta g)\mu_B B_{ext}$$

Spin-orbit interaction in silicon MOS — Interface mechanism

Interface mechanism due to broken crystal symmetry*



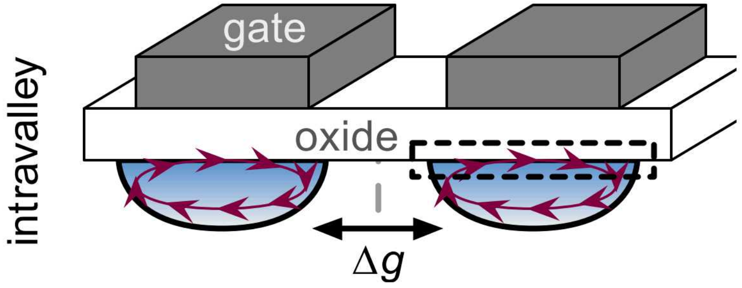
* Different from E-field-induced broken symmetry in 2DEGs [L. E. Golub ... Phys. Rev. B 69, 115333 (2004)]

-> First-order effect vs ***P***

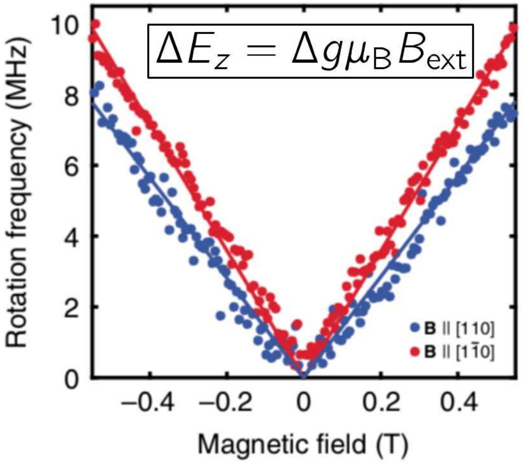
[R. M. Jock ... Nat. Commun. 9, 1768 (2018)]

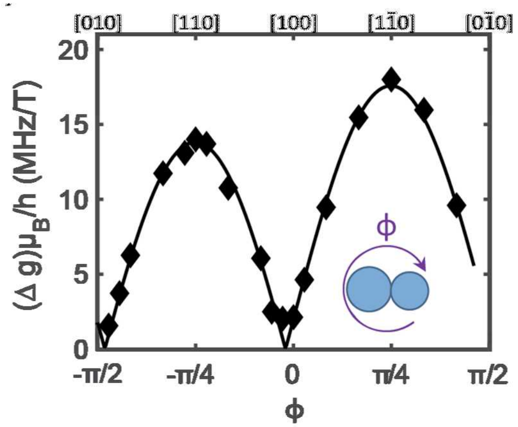
Spin-orbit interaction in silicon MOS — Intravalley effect

g is renormalized in each dot



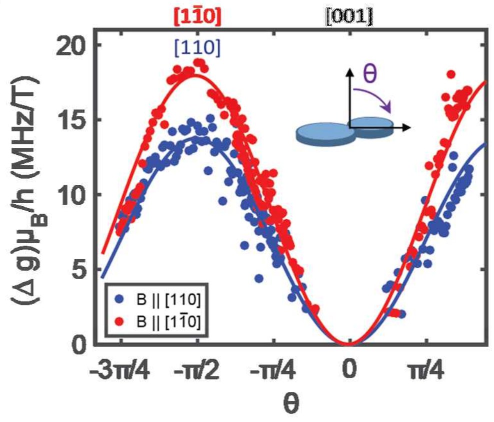
Anisotropy of Δg





Δg vanishes for out-of-plane B-field

e)



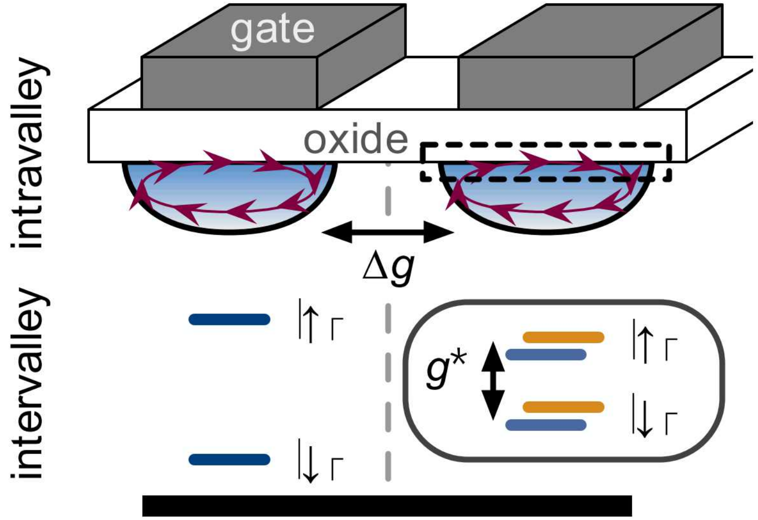
g-tensor

$$\boldsymbol{g} = \boldsymbol{g}_0 + \boldsymbol{g}_{SO} = \begin{pmatrix} g_\perp - \frac{2}{\mu_B}\alpha & \frac{2}{\mu_B}\beta & 0 \\ \frac{2}{\mu_B}\beta & g_\perp - \frac{2}{\mu_B}\alpha & 0 \\ 0 & 0 & g_\parallel \end{pmatrix}$$

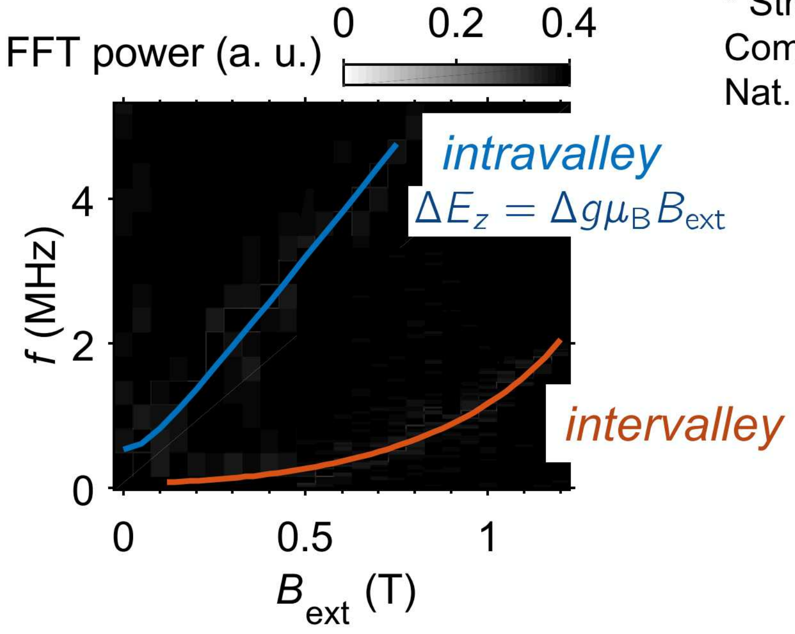
[R. M. Jock ... Nat. Commun. 9, 1768 (2018)]

Spin-orbit interaction in silicon MOS — Intervalley effect

Interaction with excited valley state



Non-linear effect

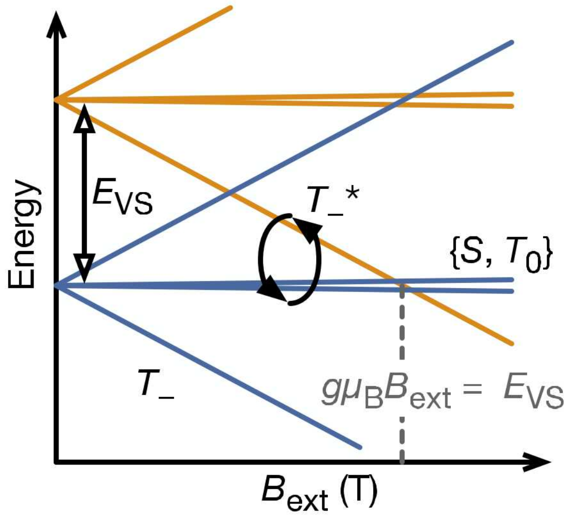


$$\Delta E_z = \frac{\bar{\beta}_C^2 B_{ext}^2}{2(E_{VS} - g\mu_B B_{ext})}$$

$$\bar{\beta}_C = 0.7\ \mu\text{eV}\ \text{T}^{-1}$$

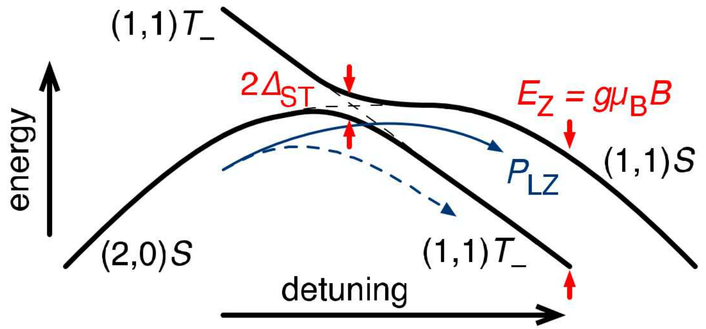
Second-order intervalley mechanism*

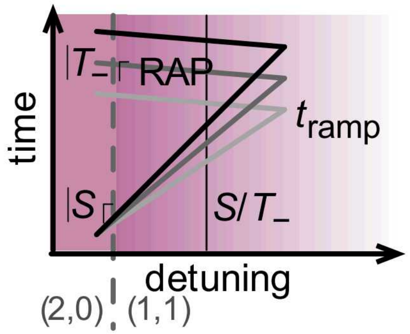
* Strength consistent with [C. H. Yang ... Nat. Commun. 4, 2069 (2013)] and [X. Hao ... Nat. Commun. 5, 3860 (2014)]

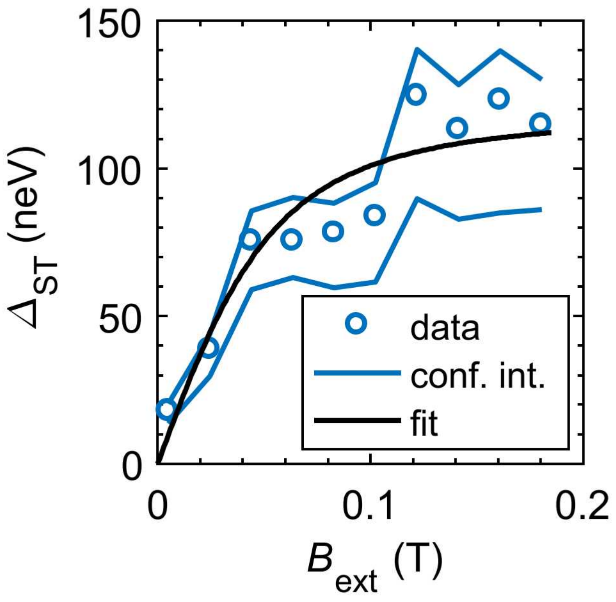


[P. Harvey-Collard ... arXiv:1808.07378 (2018)]

Spin-orbit interaction in silicon MOS — Tunneling + spin-flip mechanism







Spin-orbit length [1]:

Result: $\Omega_{SO} \sin\Phi$ = 113 ± 22 neV B_{ext} // [100]

$\lambda_{SO} = t_C d / \Omega_{SO} \sqrt{2} \sim 1$ μm

Bulk Si: 20 μm!

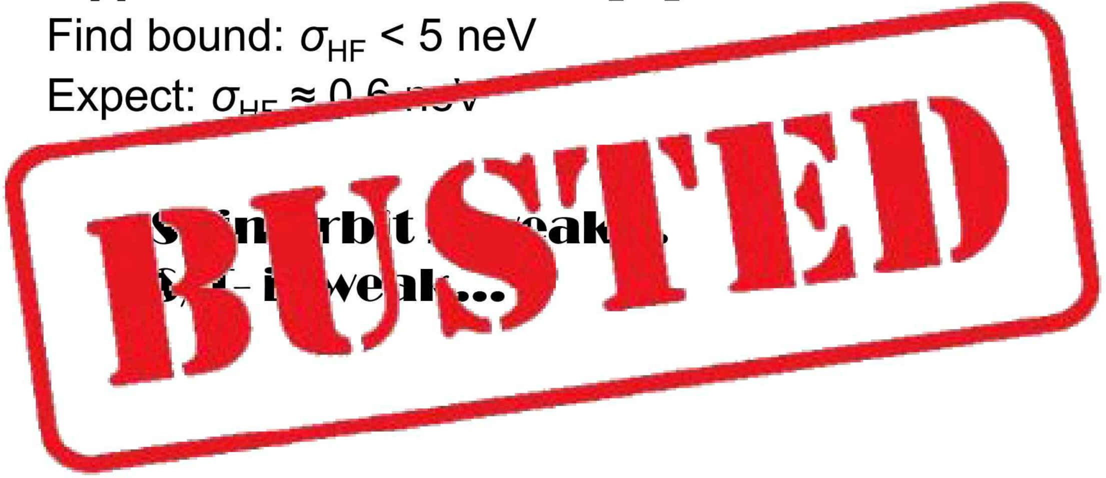
Bulk GaAs: 1.1 μm!

Affects dynamic nuclear polarization (DNP)

Hyperfine interaction [1]:

Find bound: $\sigma_{HF} < 5$ neV

Expect: $\sigma_{HF} \approx 0.6$ neV



Spin-orbit ... weak.

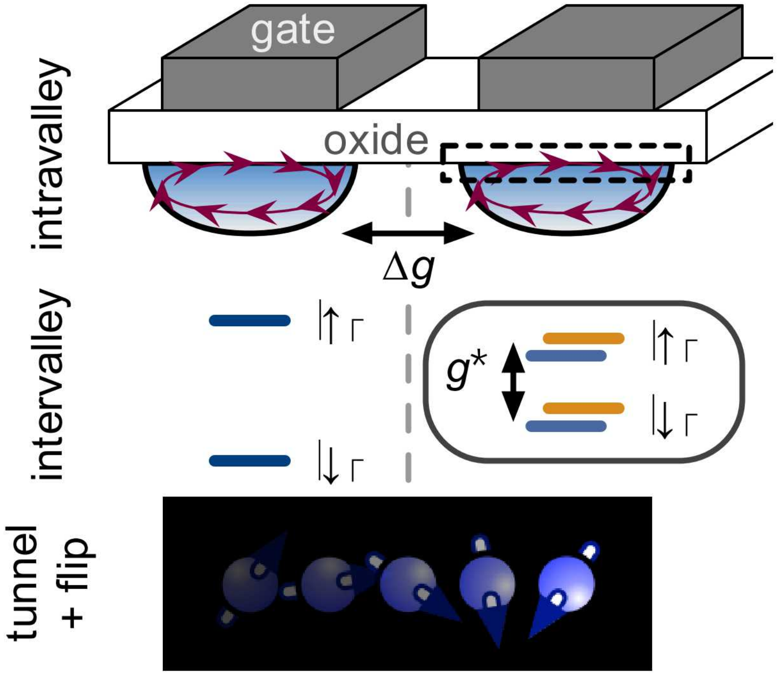
S,T- is weak...

[Method:] J. M. Nichol ... Nat Commun 6, 7682 (2015).

[1] P. Harvey-Collard ... arXiv:1808.07378 (2018).

How should I mount my device?

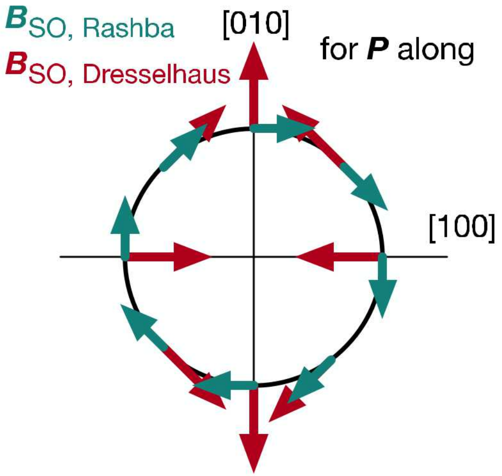
3 spin-orbit effects



S-T_0 effects caused by $\Delta B_{/\!/}$

- Static (1,1)
- intravalley, intervalley
- momentum ***P*** :
  B_{ext} via cyclotron orbit
- component of B_{SO} // B_{ext}

Δg vanishes for
out-of-plane B-field



S-T_- effect caused by $\Delta B_\perp$

- Dynamic (2,0) ↔ (1,1)
- tunneling + spin-flip
- momentum ***P*** :
  double quantum dot axis
- component of $B_{SO} \perp B_{ext}$

Δ_{ST} persists for
out-of-plane B-field

[P. Harvey-Collard ... arXiv:1808.07378 (2018)]

Conclusion & Summary

Acknowledgements & Team

Experiments

- Martin Rudolph
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- Chloé Bureau-Oxton
- Matthew J. Curry
- Andrew M. Mounce
- Michael P. Lilly
- Malcolm S. Carroll

Theory

- N. Tobias Jacobson
- Andrew D. Baczewski
- Vanita Srinivassa
- Wayne M. Witzel
- John King Gamble

Fabrication

- Daniel R. Ward
- John M. Anderson
- Ronald P. Manginell
- Joel R. Wendt
- Jason Dominguez
- Tammy Pluym

Université de Sherbrooke

- Michel Pioro-Ladrière

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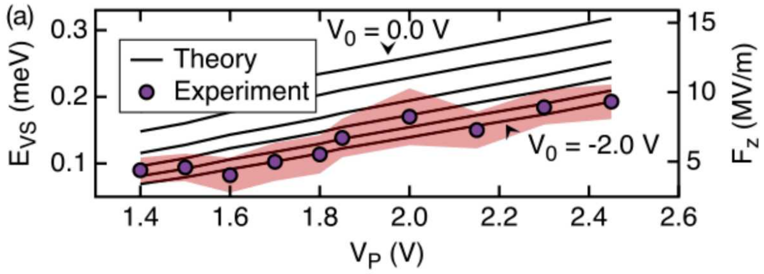
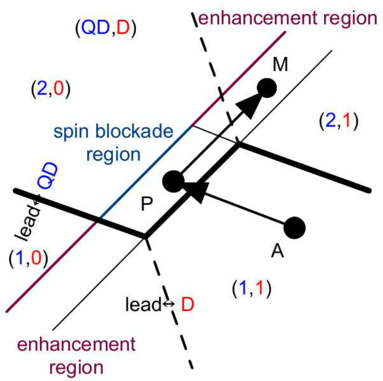
Valley splitting



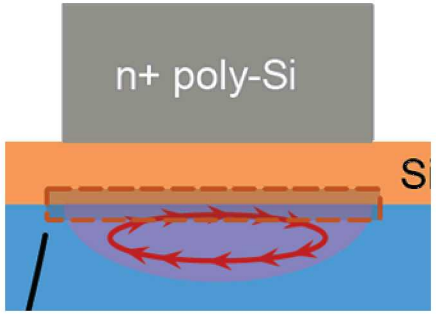
J. K. Gamble, P. Harvey-Collard et al., App. Phys. Lett. 109, 253101 (2016).

Enhanced latching readout



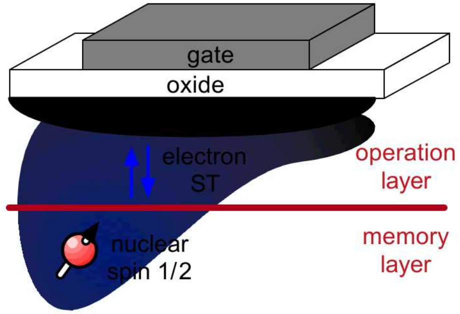
P. Harvey-Collard et al., Phys. Rev. X 8, 021046 (2018).

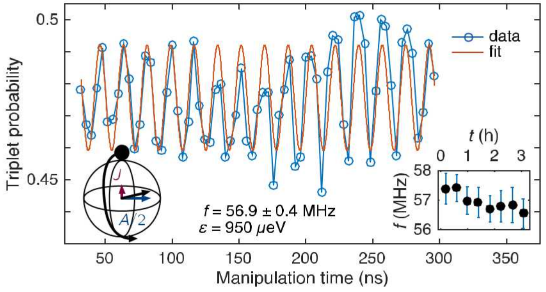
Spin-orbit



R. M. Jock, N. T. Jacobson,
P. Harvey-Collard et al., Nat. Commun. 9, 1768 (2018).

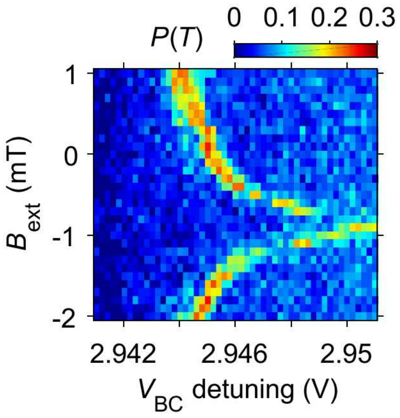
MAJIQ (donor-dot)

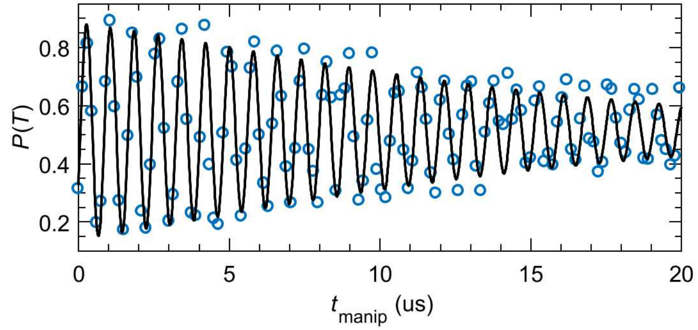




1. P. Harvey-Collard et al., Nat. Commun. 8, 1029 (2017).
2. M. Rudolph, P. Harvey-Collard et al. In 2016 IEEE IEDM (2016) pp. 34.1.1–34.1.4.

More spin-orbit





1. P. Harvey-Collard et al. *In 2017 IEEE IEDM* (2017).
2. P. Harvey-Collard et al., arXiv:1808.07378 (2018).