Nuclear-driven electron spin rotations in a coupled silicon quantum dot and single donor system

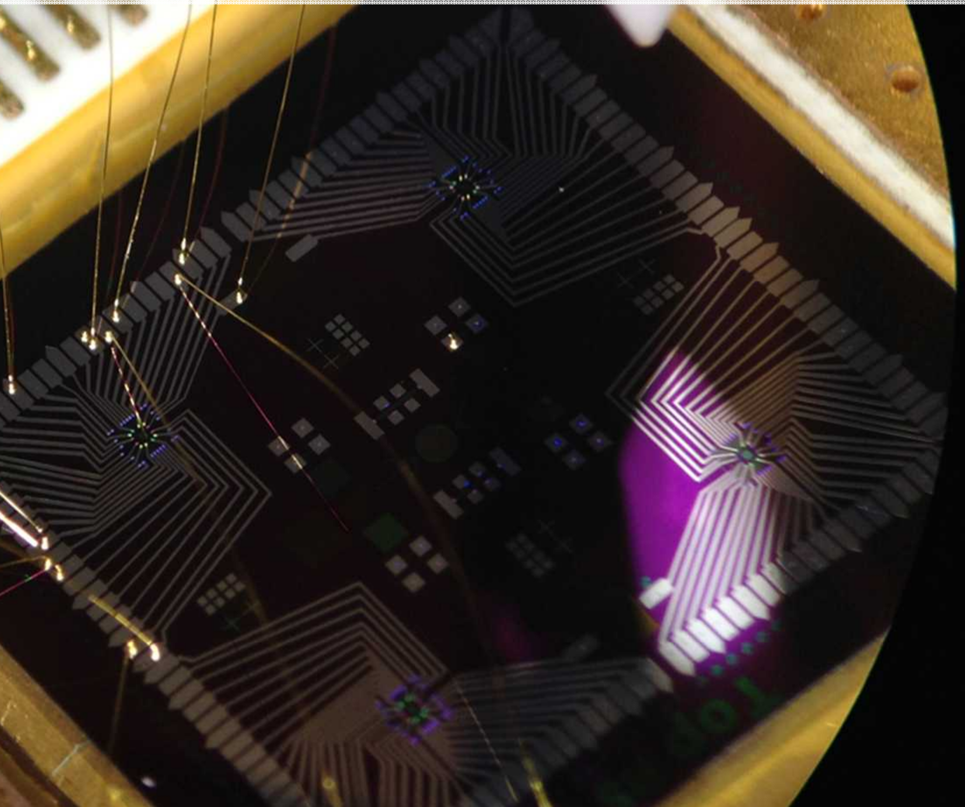
SAND2016-6183C

Patrick Harvey-Collard

Silicon Quantum Electronics Workshop

June 13th, 2016

Preprint: arXiv:1512.01606



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Outline

- Introduction
- Singlet-triplet encoding
- Device
- State preparation, manipulation and readout
- Summary and perspectives

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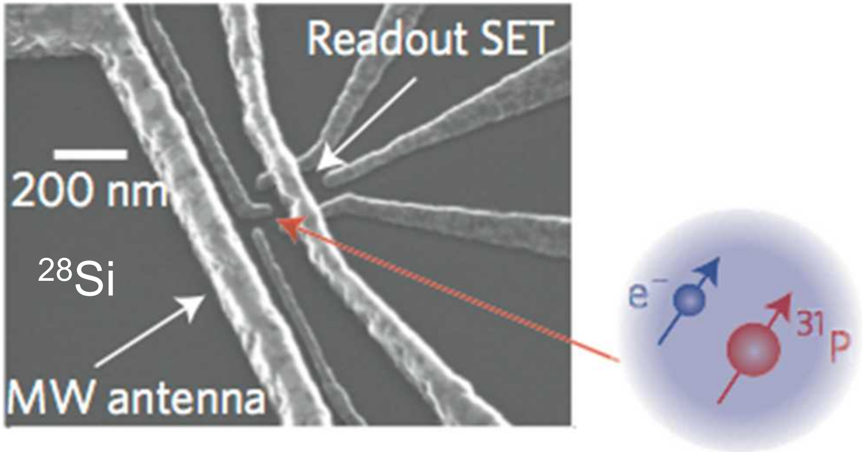
Can the best characteristics of qubit systems be combined?

Donor (D) qubits are high fidelity…



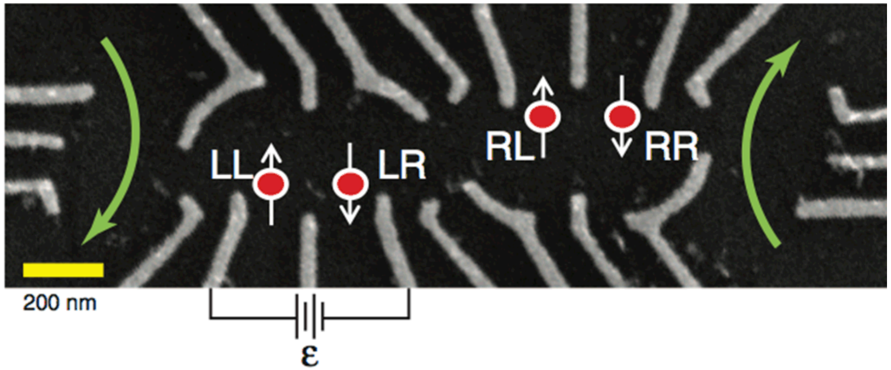
Electron spin 1/2:
$T_2^* = 270\ \mu s$
$T_{2,\ CPMG} = 560$ ms
$F_{prep/readout} = 97\%$
$F_{control} = 99.95\%$

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

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. Journal of Physics: Condensed Matter 27, 154205 (2015).

Quantum dot (QD) qubits are tunable…

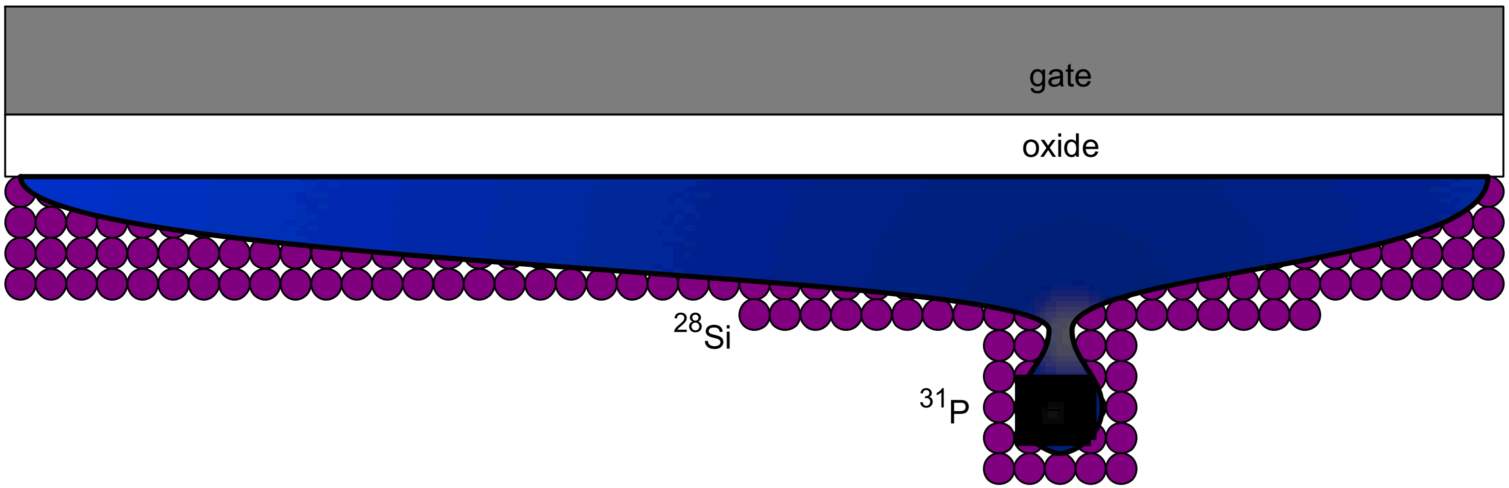


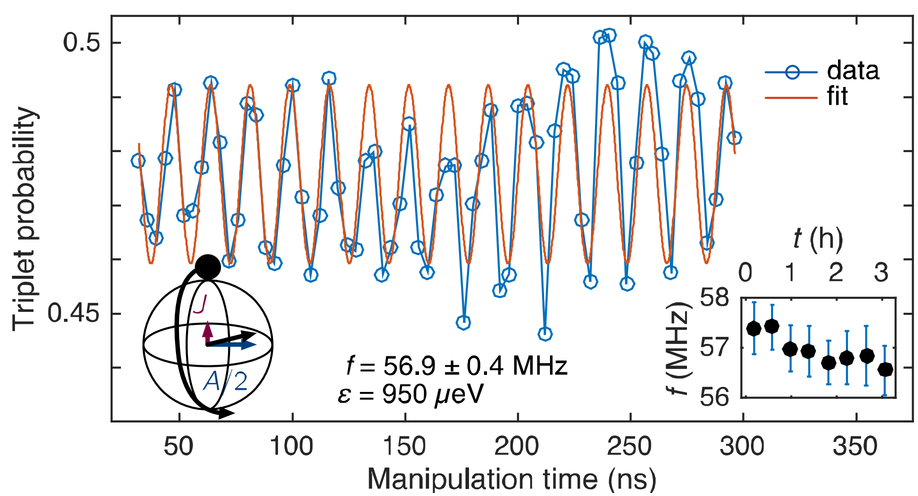
Singlet-triplet spin qubit in GaAs:
- All-electrical control
- Two-qubit gates possible

But they are not quite as high fidelity!

[1] Shulman, M. D. et al. Science 336, 202–205 (2012).
[2] Petta, J. R. et al. Science 309, 2180–2184 (2005).
[3] Veldhorst, M. et al. Nat Nano 9, 981–985 (2014).
[4] Veldhorst, M. et al. Nature 526, 410–414 (2015).

In this presentation:
First *coherent* coupling and control between a quantum dot (QD) and a donor (D)





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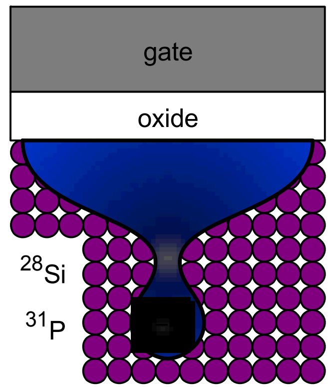
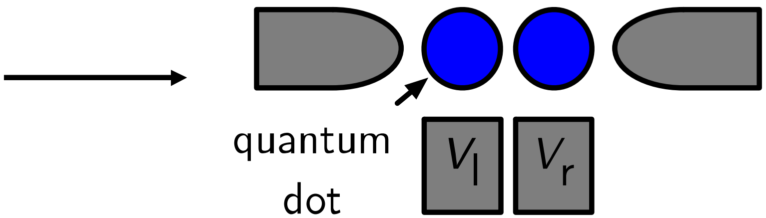
Singlet-triplet encoding

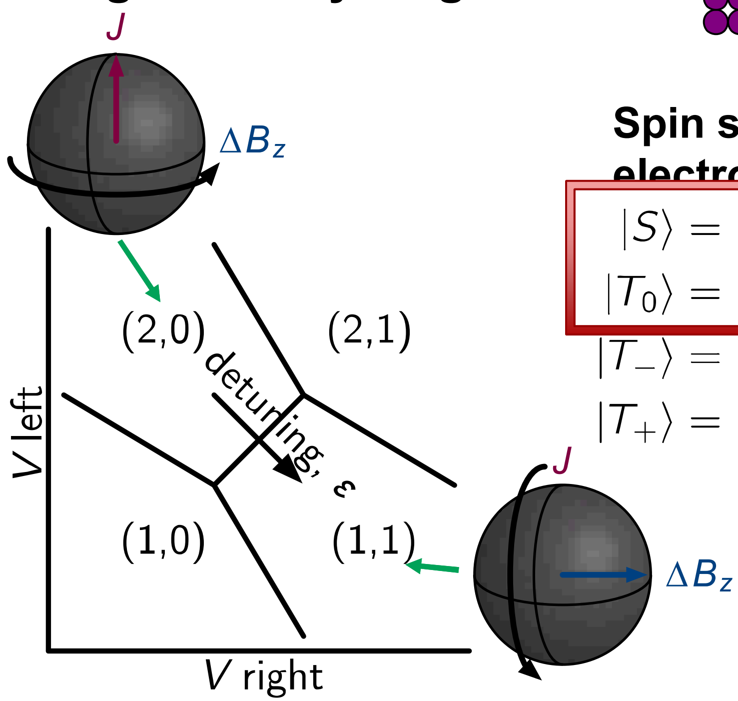
QD-D



Double QD



Charge stability diagram



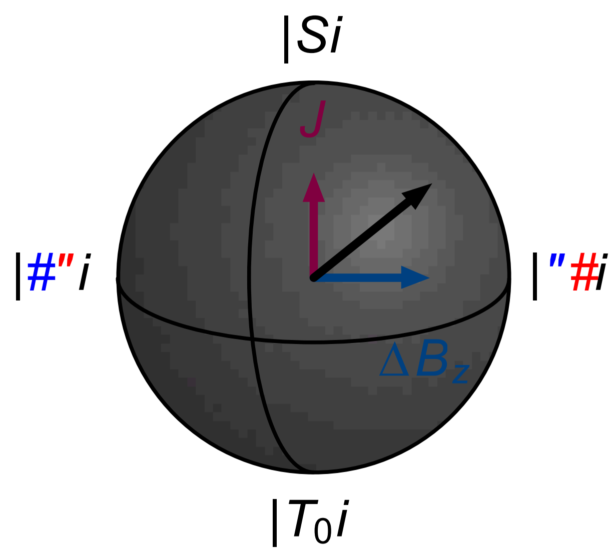
Spin states for two electrons

$$\left.\begin{aligned}|S\rangle &= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \\ |T_0\rangle &= |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\end{aligned}\right\} m = 0$$

$$|T_-\rangle = |\downarrow\downarrow\rangle \qquad m = -1$$

$$|T_+\rangle = |\uparrow\uparrow\rangle \qquad m = +1$$

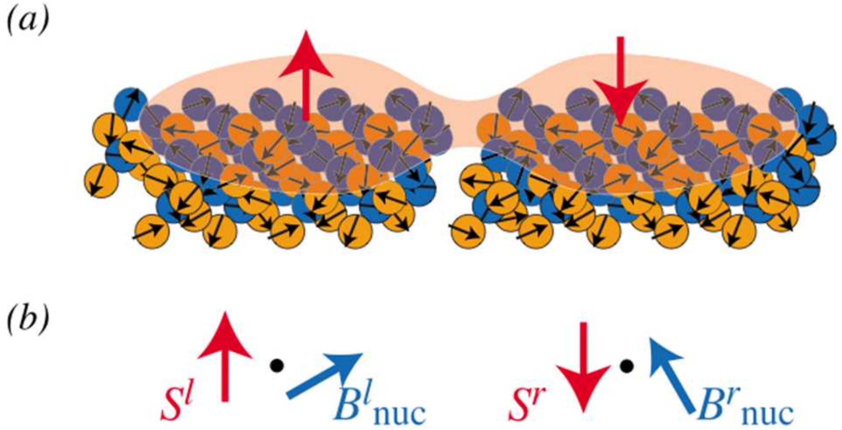
Qubit Bloch Sphere



ST qubit theory: J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, "Relaxation, dephasing, and quantum control of electron spins in double quantum dots," Phys. Rev. B 76, 035315 (2007).

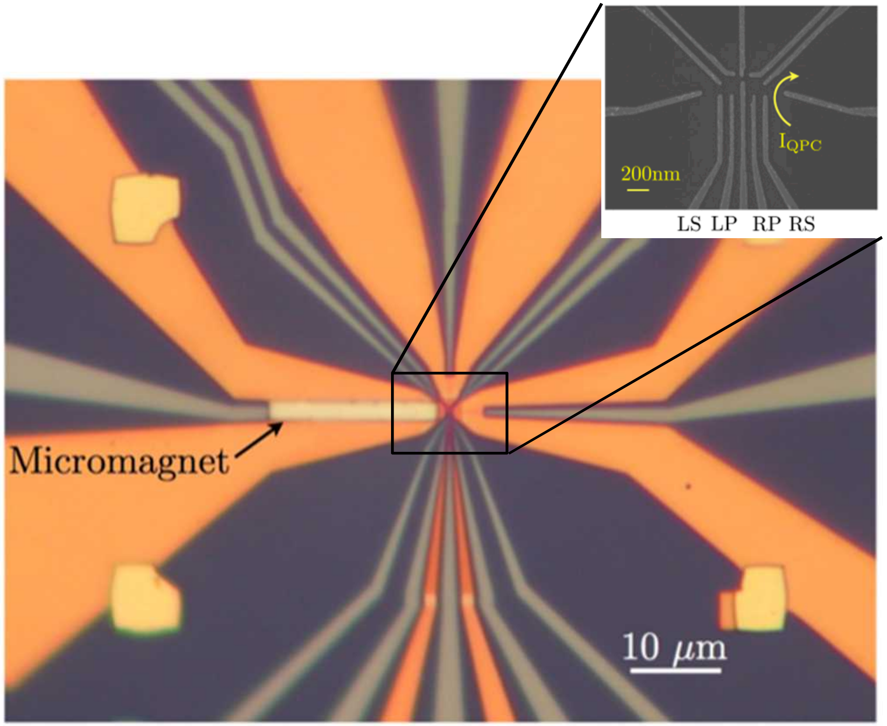
Driving ΔB_z rotations in the singlet-triplet qubit

GaAs: nuclear field gradient



[1] J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, “Relaxation, dephasing, and quantum control of electron spins in double quantum dots,” Phys. Rev. B 76, 035315 (2007).

Si: micromagnets

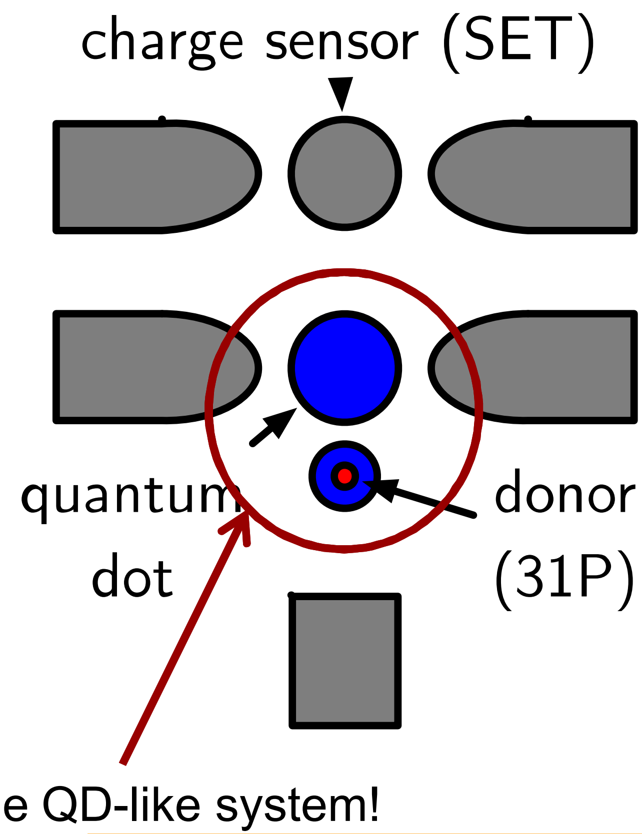


[1] X. Wu, D. R. Ward, J. R. Prance, D. Kim, J. K. Gamble, R. T. Mohr, Z. Shi, D. E. Savage, M. G. Lagally, M. Friesen, S. N. Coppersmith, and M. A. Eriksson, “Two-axis control of a singlet–triplet qubit with an integrated micromagnet,” Proceedings of the National Academy of Sciences 111, 11938 (2014).

New key idea: use contact hyperfine interaction with ***single donor*** to rotate the spin

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

Hybrid QD-D singlet-triplet qubit



For electron on donor:

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

Singlet-Triplet Hamiltonian:

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

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.

For details: N. Tobias Jacobson and Andrew D. Baczewski

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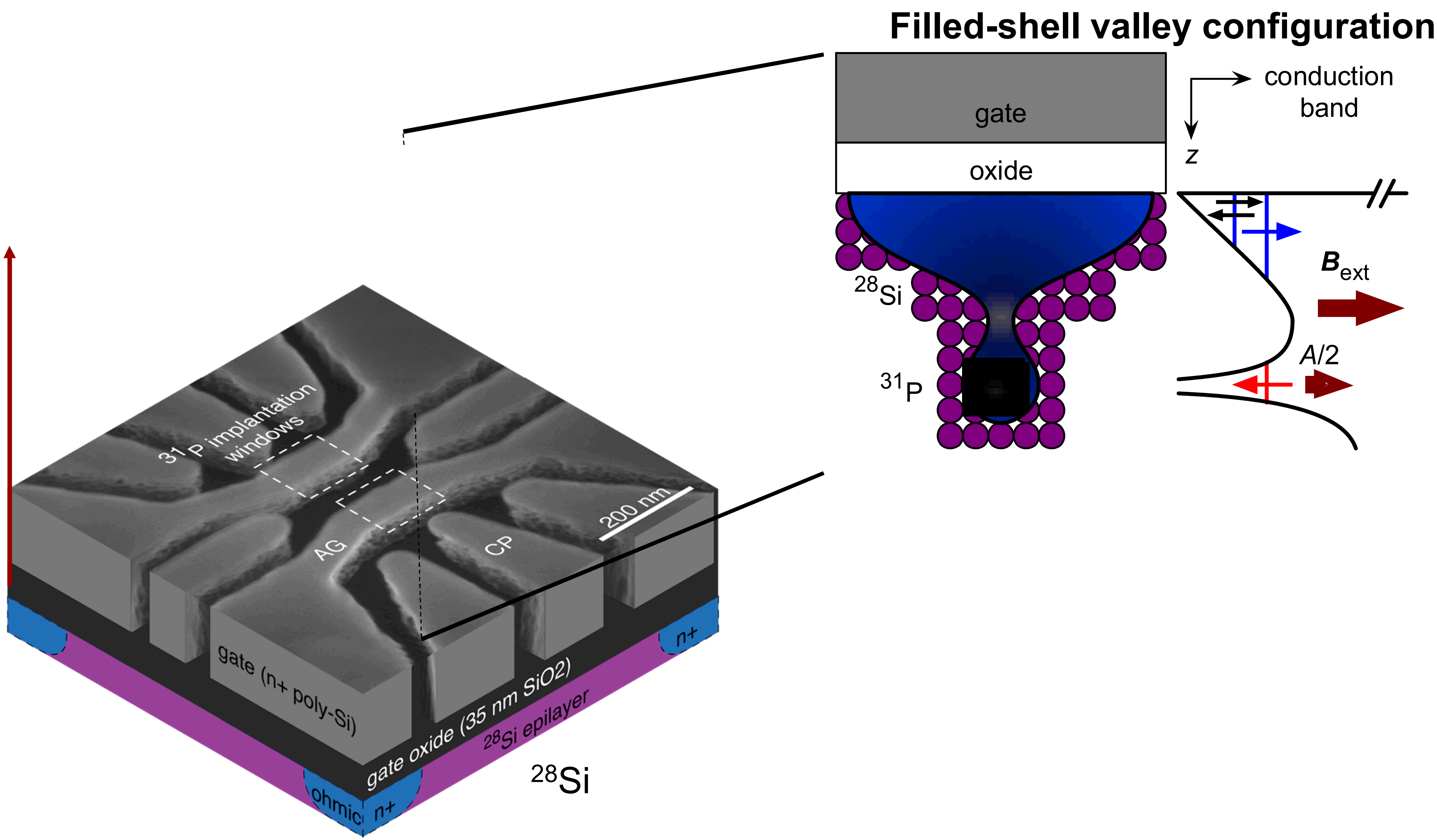
Our silicon MOS nanostructure



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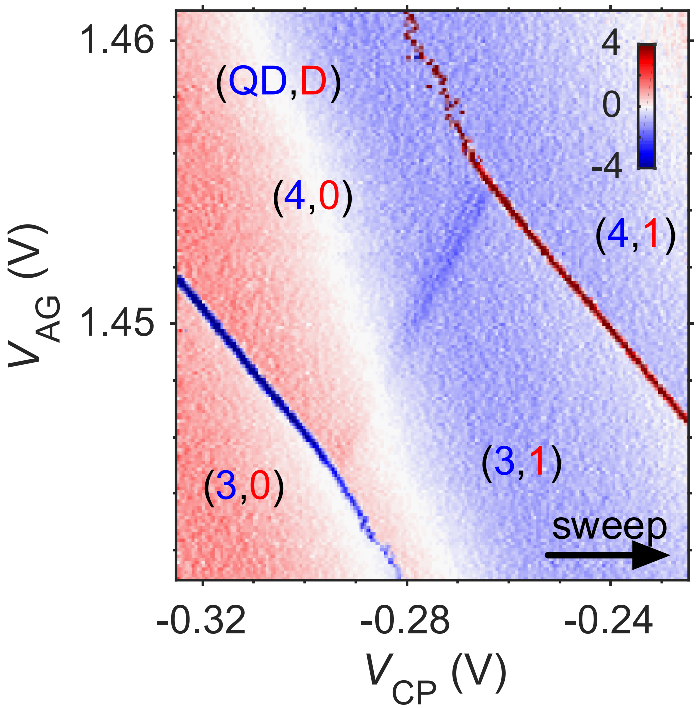
Quantum dot-donor anti-crossing

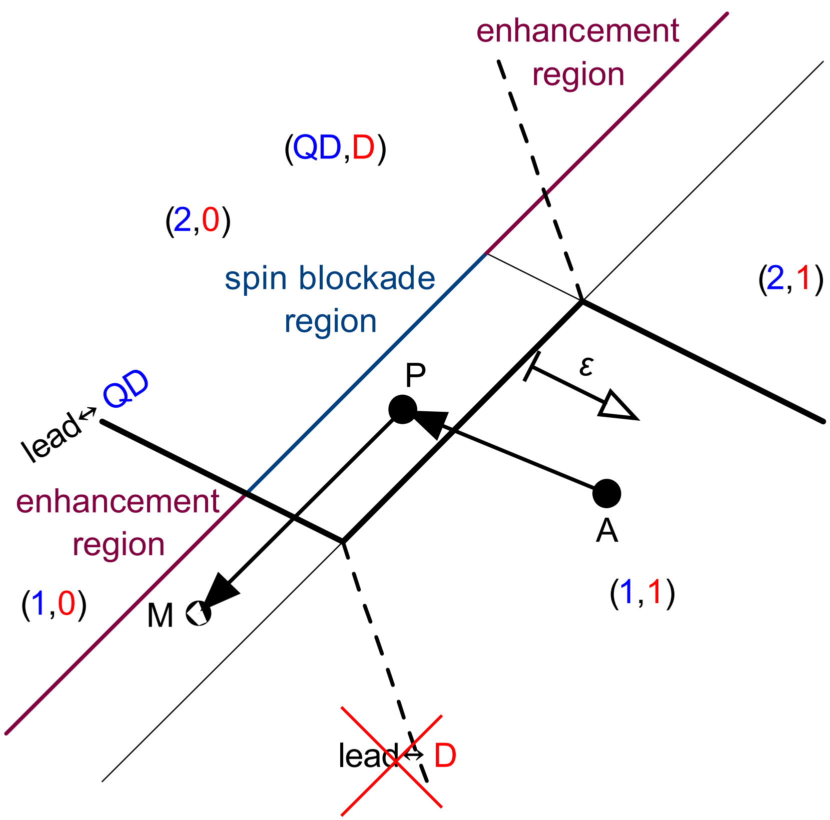
Forms an effective (2,0) ↔ (1,1) transition



Charge hysteresis: [1] Yang, C. H. et al. Applied Physics Letters 105, 183505 (2014).

Enhanced Latching Readout - How it works

Mechanism



Comparison of readouts

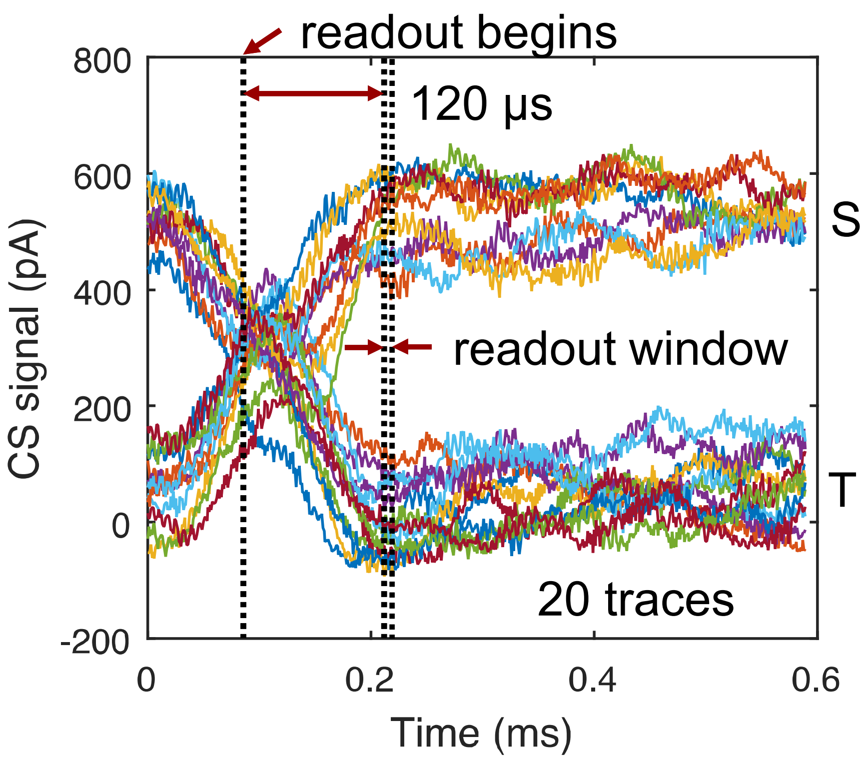
	Spin 1/2	Singlet-triplet	This work
Signal	1 e	~0.2 e	1 e
Lifetime	Good, but long waits	Ok (Si), Bad (GaAs)	Good
Fixed readout window	Poor	Good	Good

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

Inspired from: [1] Studenikin, S. A. et al. Applied Physics Letters 101, 233101 (2012).

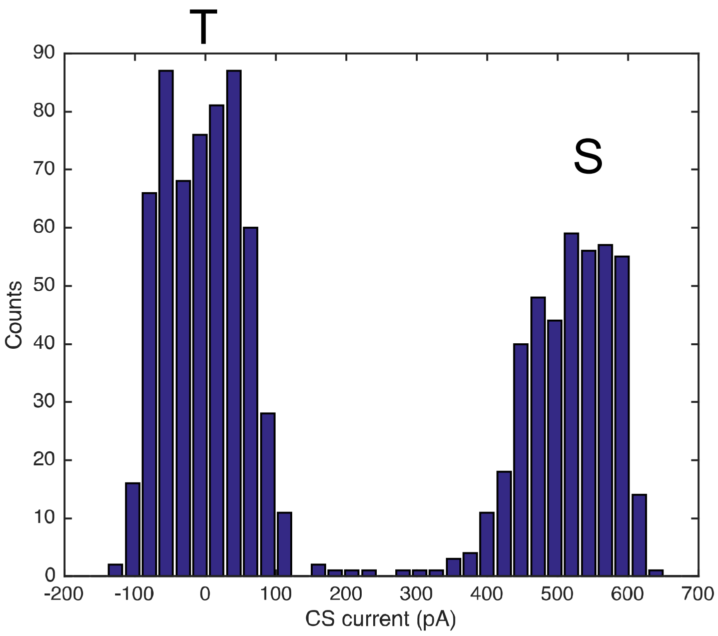
High fidelity enhanced latching readout

Single shot traces



Signal relaxation time: 38 ms

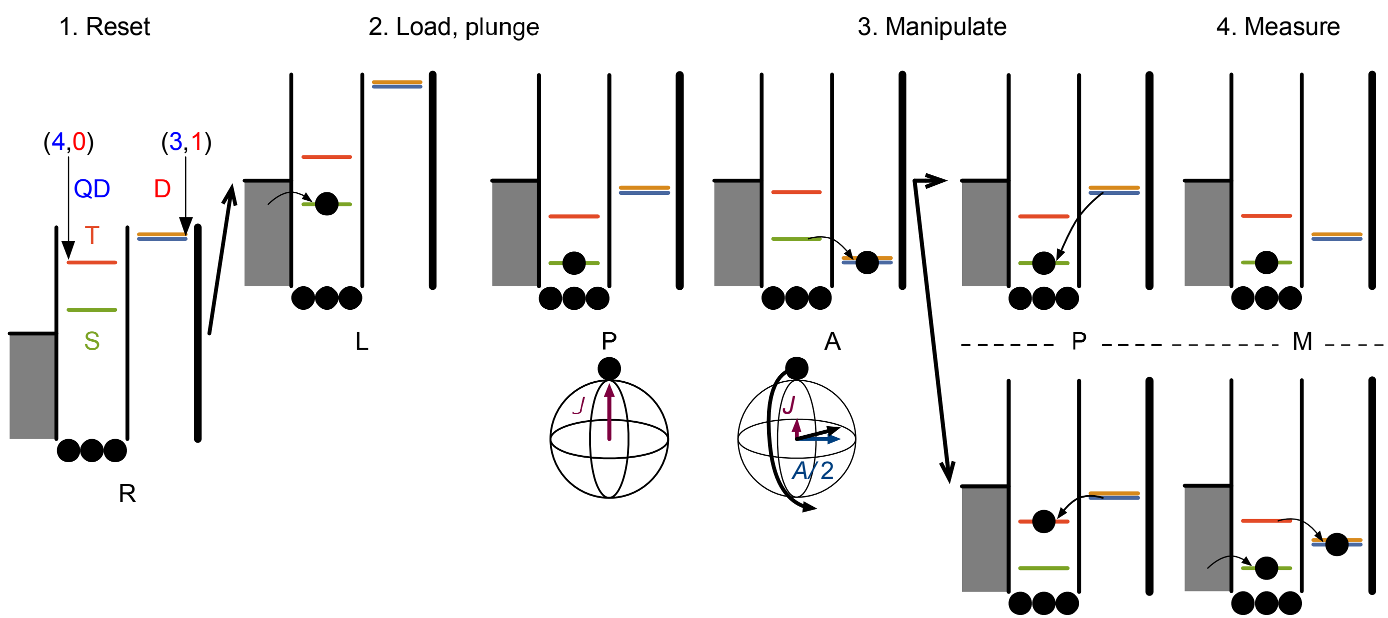
Readout window histogram

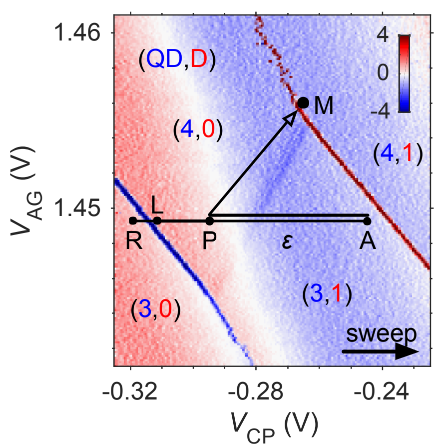


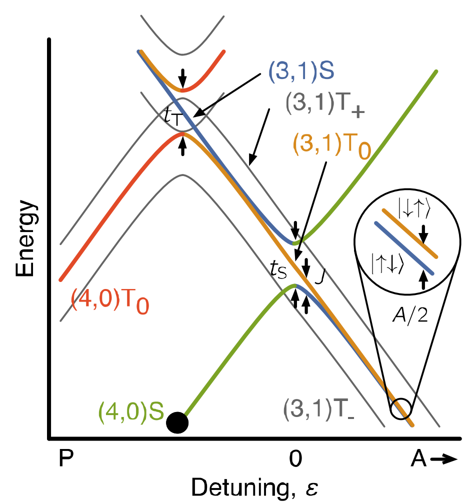
Singlet fidelity: >99.95 %
Triplet fidelity: 99.7±0.1 %
Avg. fidelity: 99.8±0.1 %

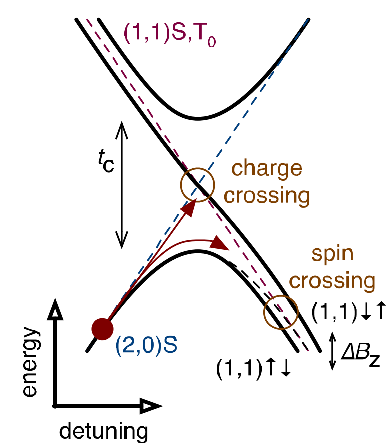
- Low bandwidth (DC filters)
- No cryo pre-amplification
- **Can get better! (Satellite workshop: Troy England)**

State manipulation



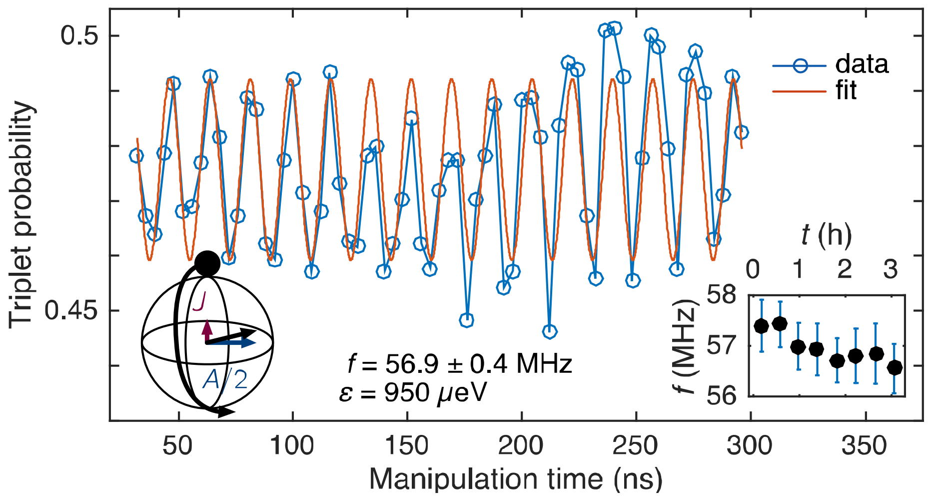


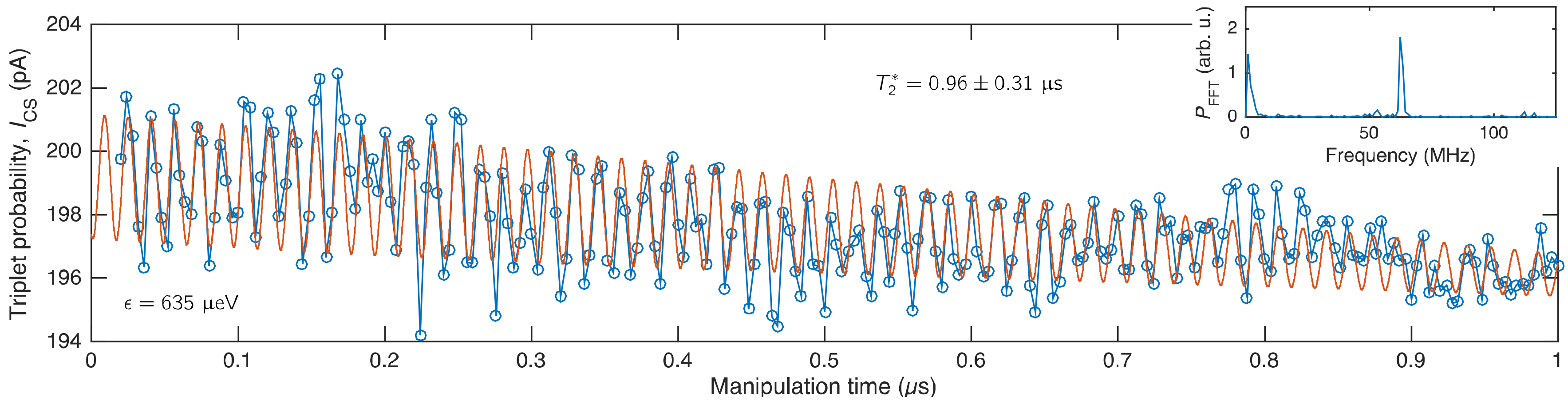




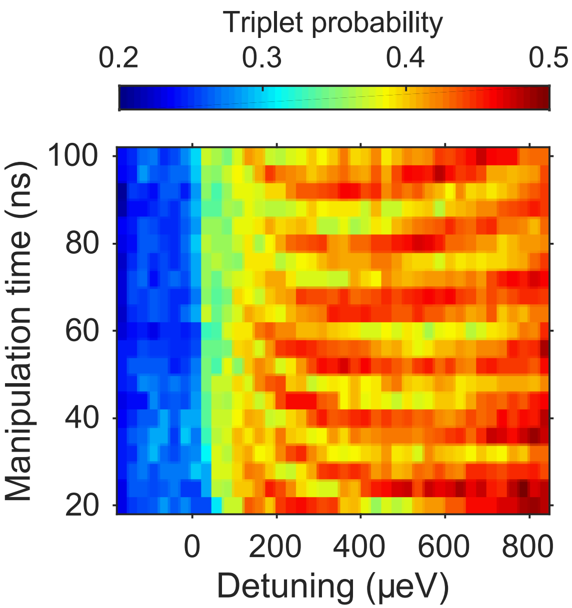
State manipulation

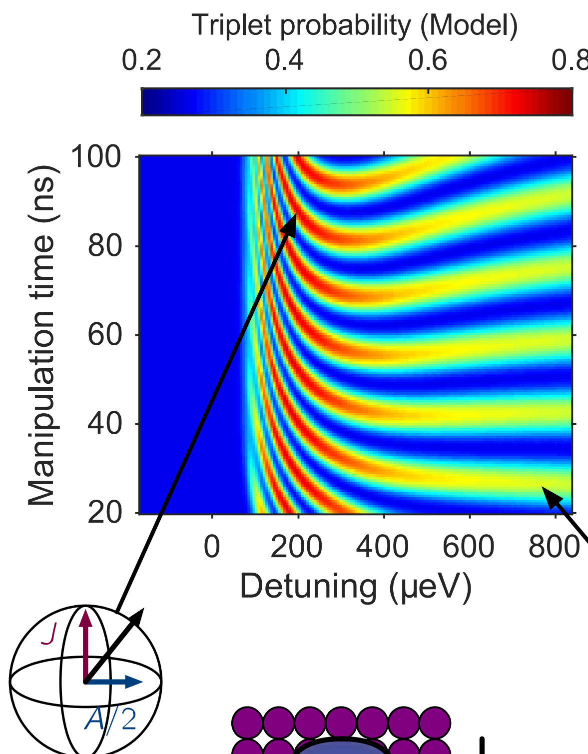
Singlet-triplet rotations driven by a single 31P nucleus

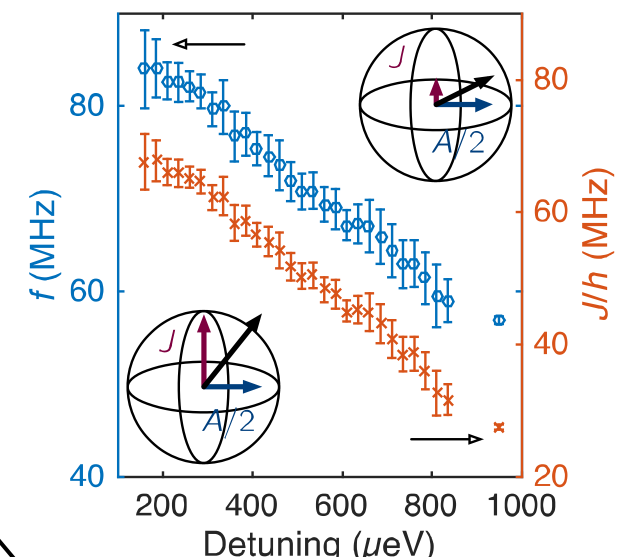




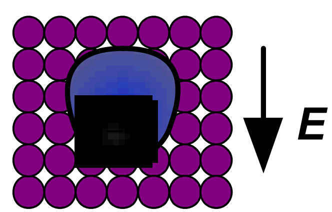
Detuning dependence of exchange interaction







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

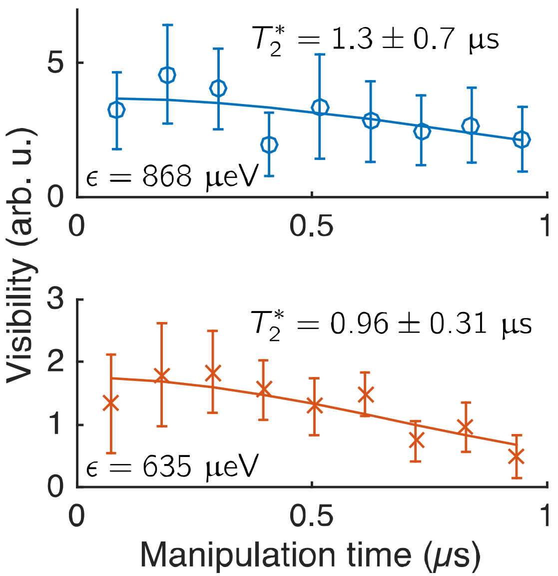


Bulk: A/h = 117 MHz

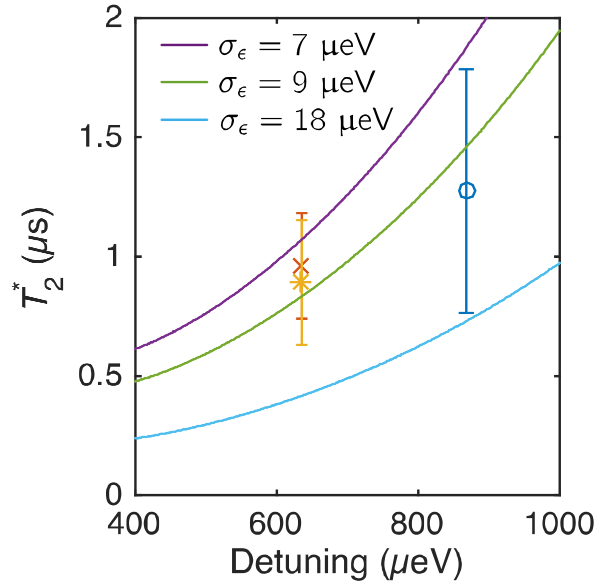
Our exp.: A/h = 100 MHz

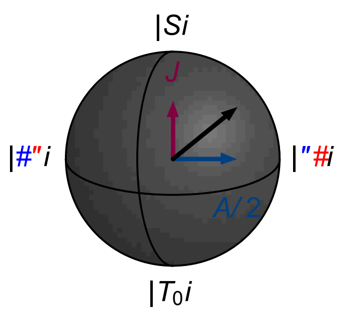
Coherence time and charge noise

Visibility decay



Coherence time vs detuning





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

Charge-noise limited.
Possibly extended to > 10 μs

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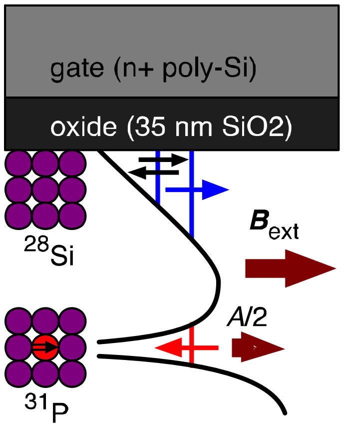
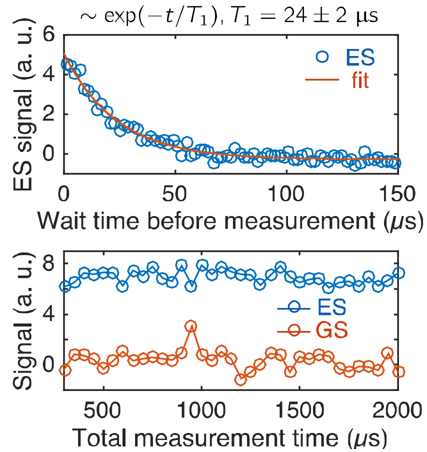
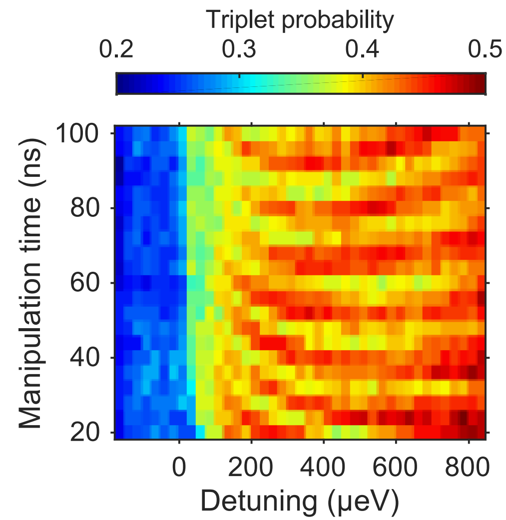
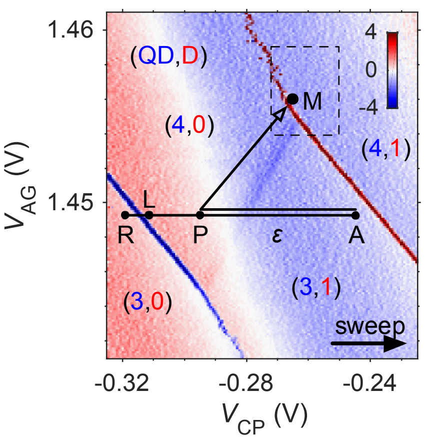
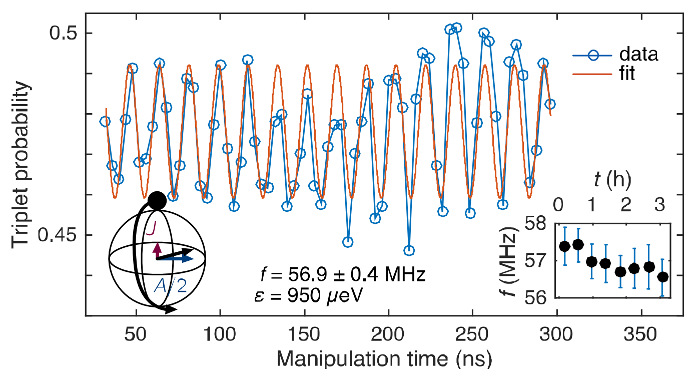
Summary

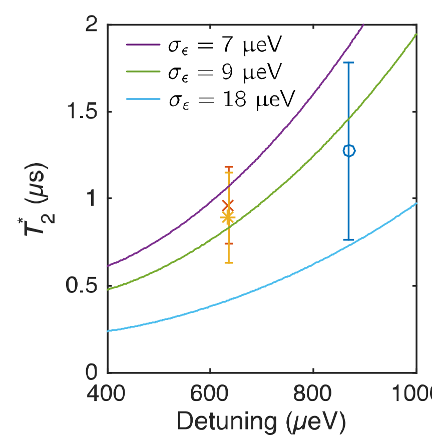








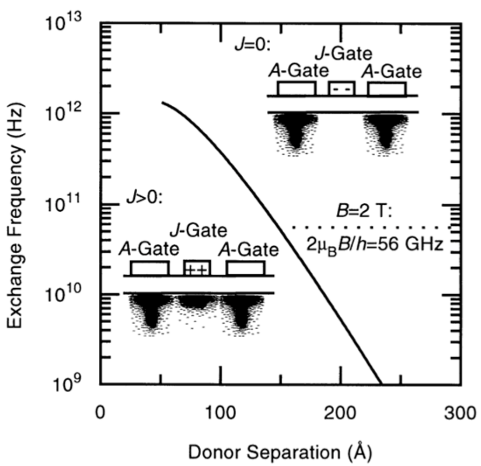




Preprint: Nuclear-driven electron spin rotations in a single donor coupled to a silicon quantum dot. arXiv:1512.01606

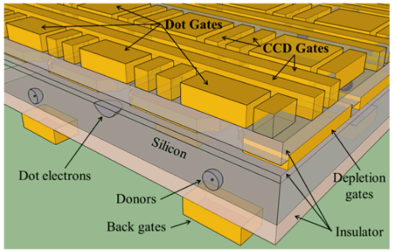
Perspectives

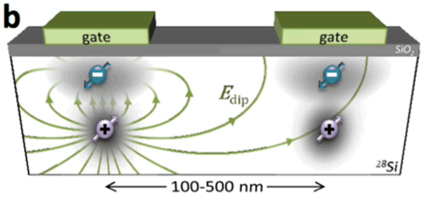
Kane's original exchange "*J*" gate



[1] Kane, B. E. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998).

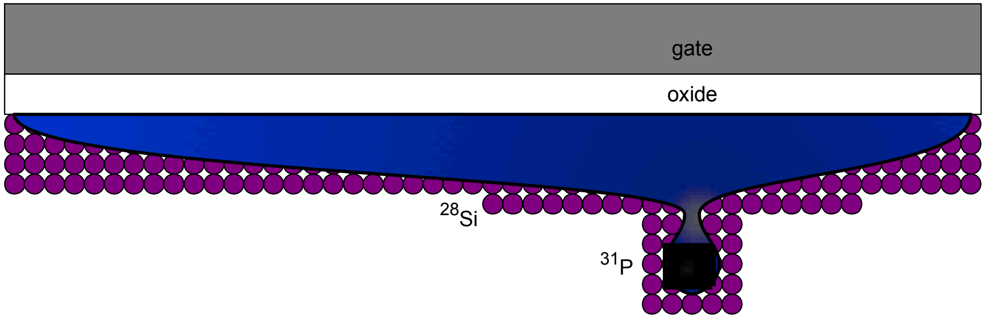
"Modern" proposals involve QDs



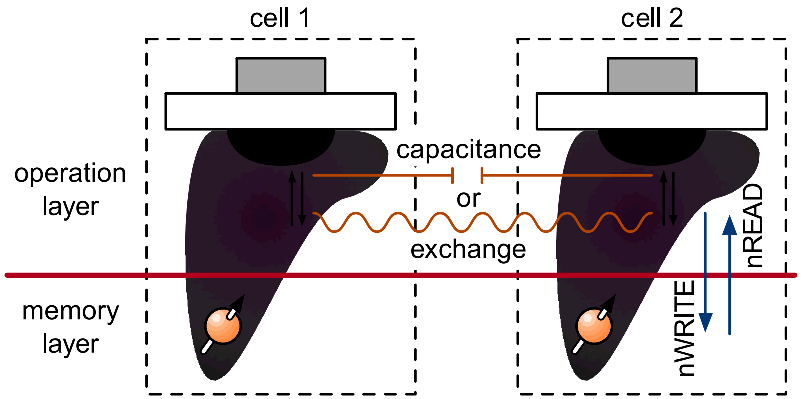


[1] Pica, G., Lovett, B. W., Bhatt, R. N., Schenkel, T. & Lyon, S. A. Phys. Rev. B 93, 035306 (2016).
[2] Tosi, G. et al. ArXiv e-prints (2015). 1509.08538.

This work: First coherent coupling between a quantum dot (QD) and a donor (D)



Future work



J.K. Gamble

John Gamble: "*Designing a flying qubit at a silicon interface*"
Andrew Baczewski: "*What can I do with a singlet-triplet qubit coupled to a nuclear spin qubit?*"
Toby Jacobson: "*A singlet-triplet qubit coupled to the nuclear spin of a single phosphorus donor*"

Acknowledgements & Team

And the rest of the QIST team!

Experiments

- Malcolm S. Carroll (SNL advisor)
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- Martin Rudolph (Staff, experiments)
- Lisa A. Tracy (Staff, fridge)
- Matthew J. Curry (PhD student)

Fabrication

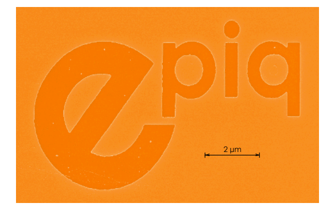
- Jason Dominguez
- Gregory A. Ten Eyck
- Joel R. Wendt
- Tammy Pluym

Theory

- N. Tobias Jacobson
- John King Gamble
- Andrew D. Baczewski
- Erik Nielsen
- Richard Muller

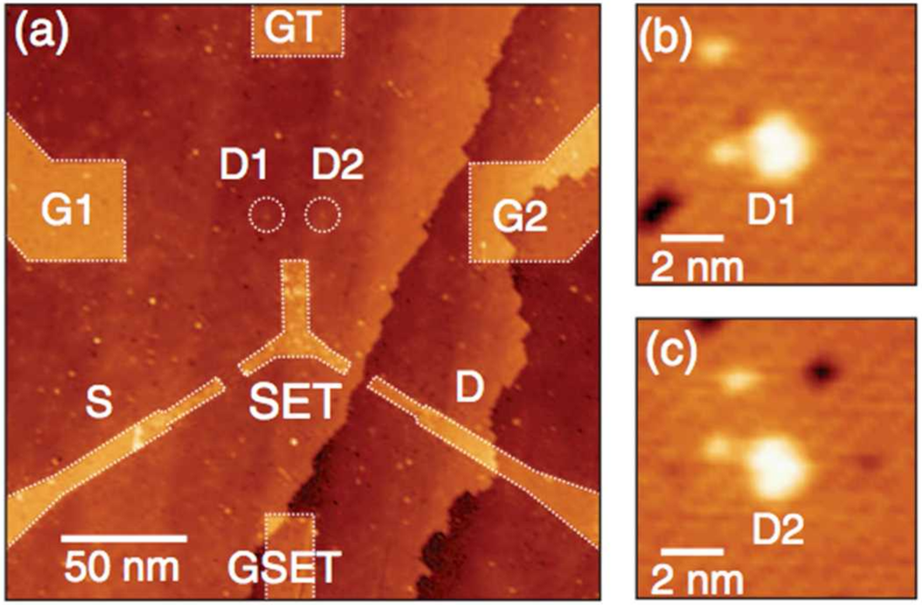
Université de Sherbrooke

- Michel Pioro-Ladrière (academic advisor)



This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. DOE's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Coupling donor qubits *directly* involves atomic-precision fabrication…



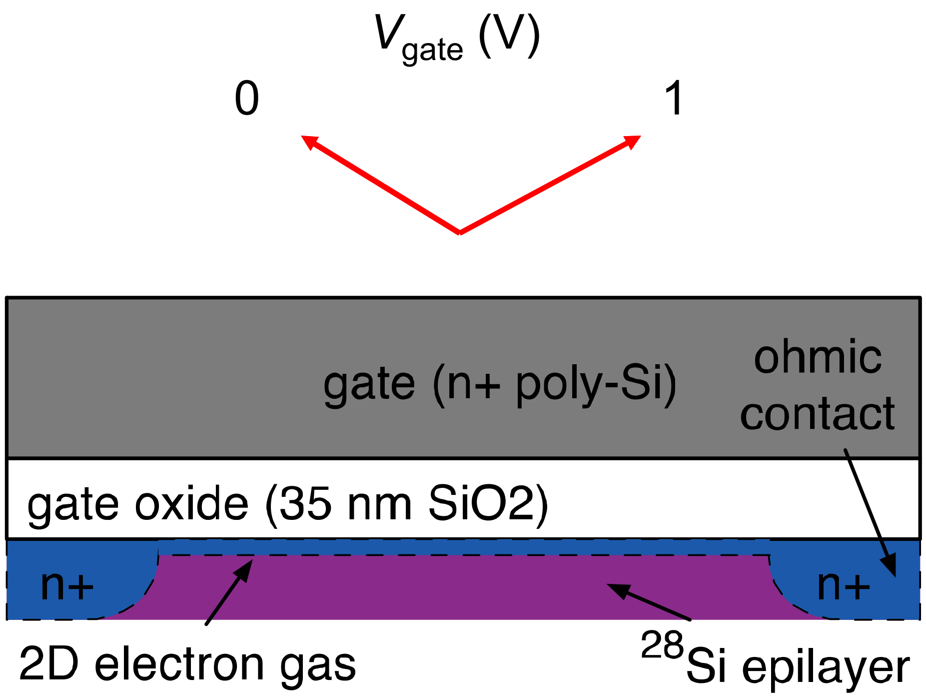
After incorporation:
1 donor

After incorporation:
0 donor

Not yet mature technology (fails stochastically)

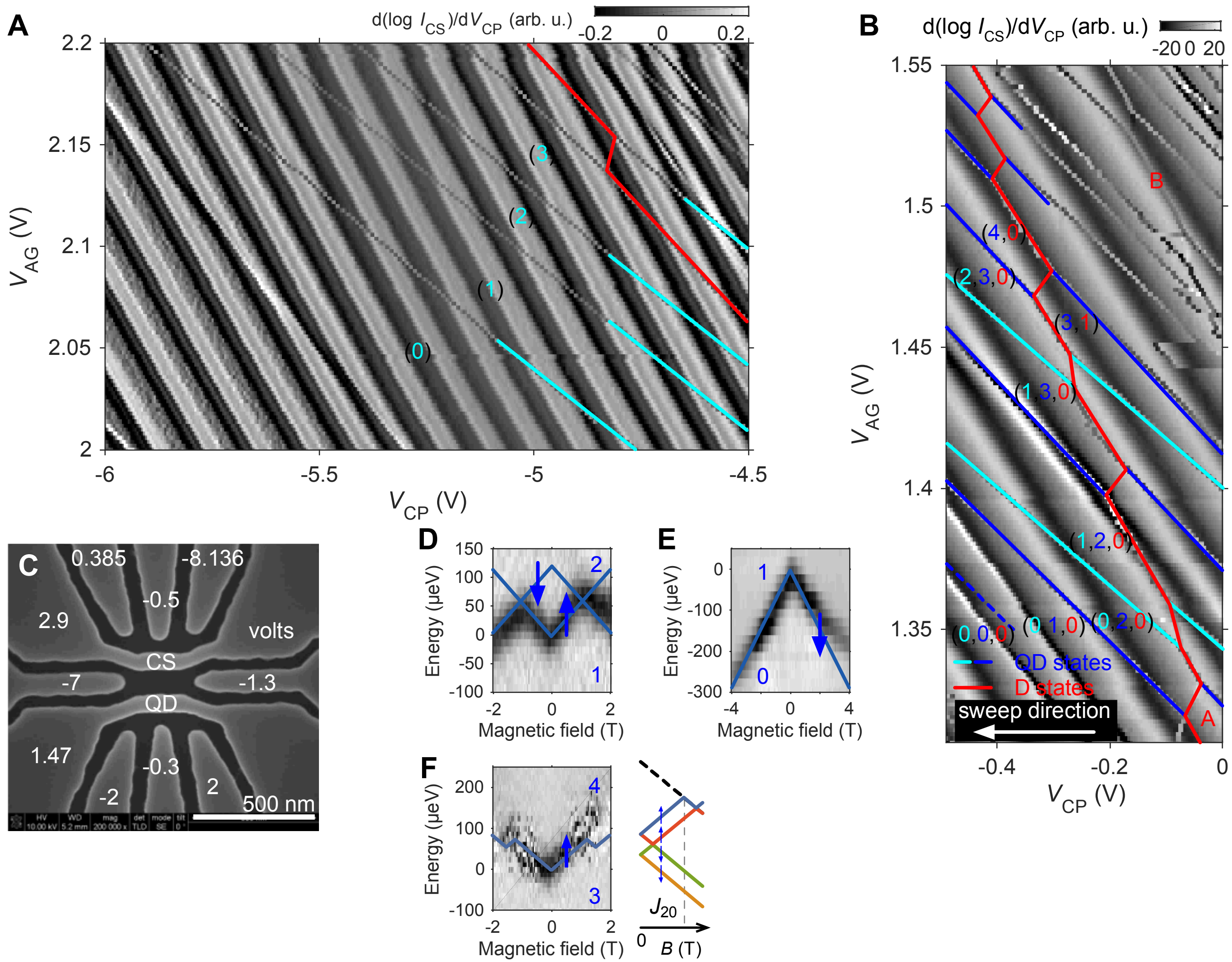
[1] T. F. Watson, B. Weber, M. G. House, H. Büch, and M. Y. Simmons, "High-fidelity rapid initialization and read-out of an electron spin via the single donor D− charge state," Phys. Rev. Lett. 115, 166806 (2015).

Our silicon MOS nanostructure



Based on
Complementary Metal-Oxide-Semiconductor (CMOS) technology

Additional slides



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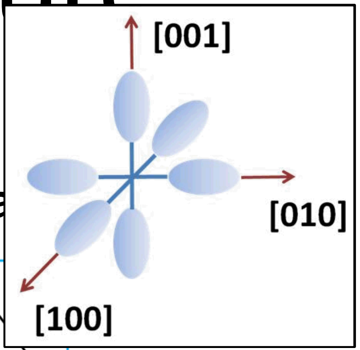
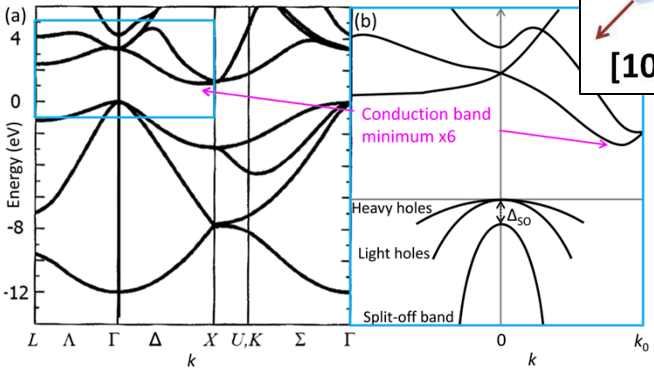
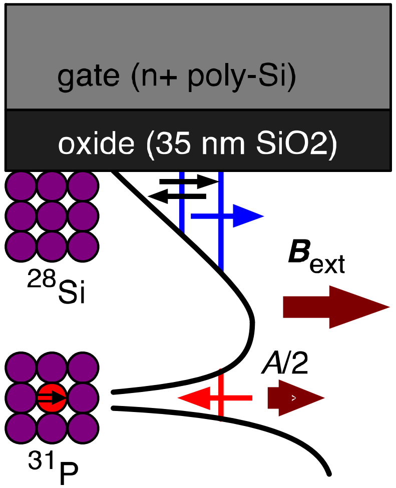


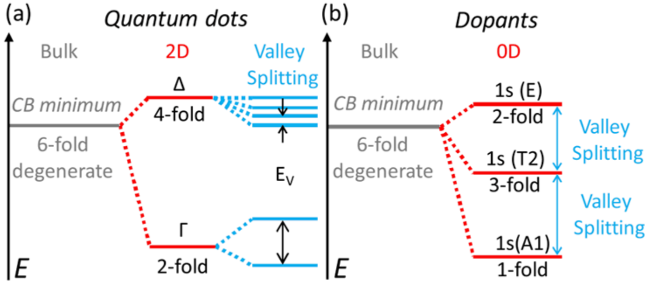
Silicon has 6 degenerate va



Filled-shell valley configuration

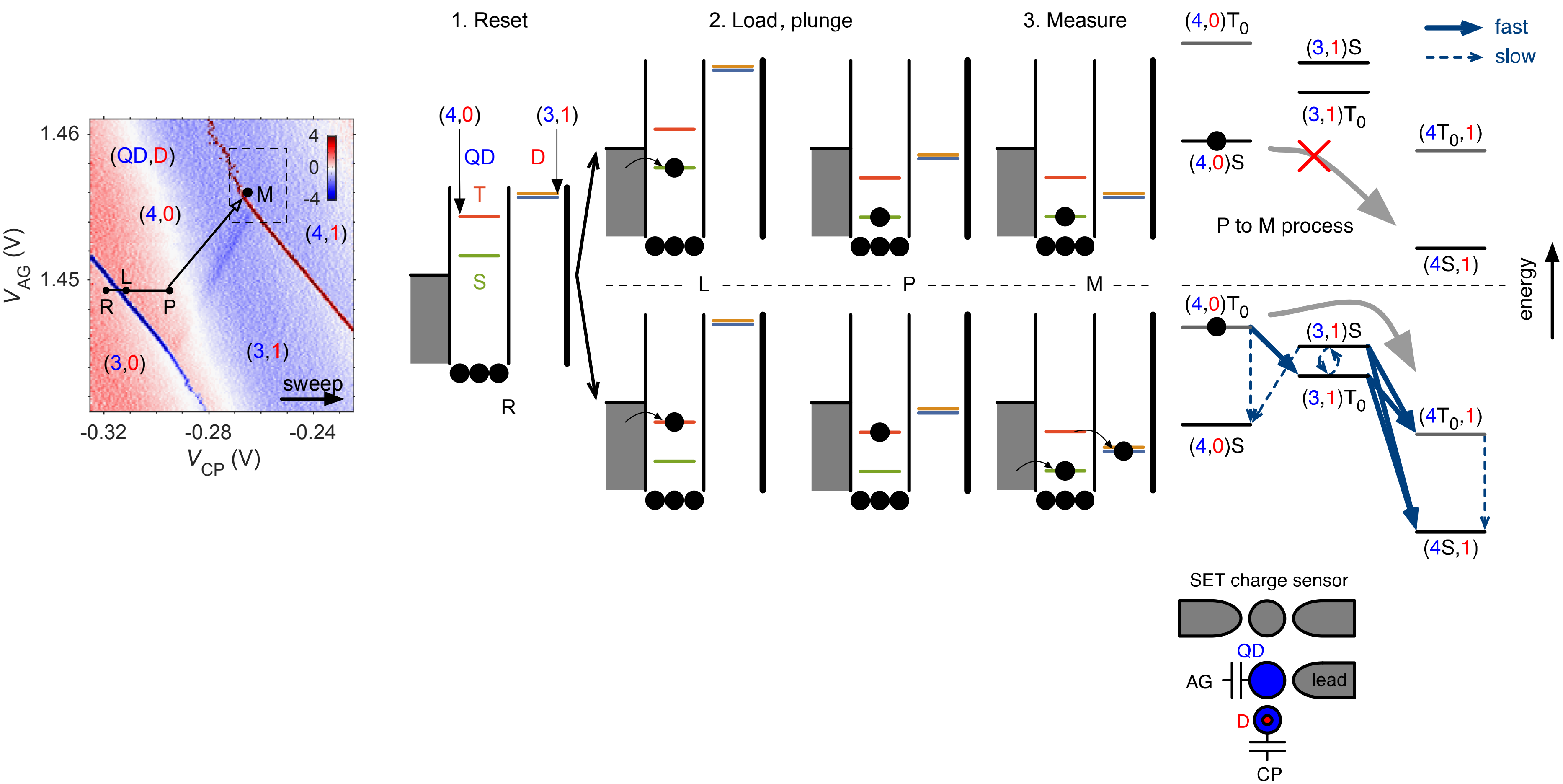


Valley degeneracy is lifted because of the strong confinement at the Si/SiO2 interface

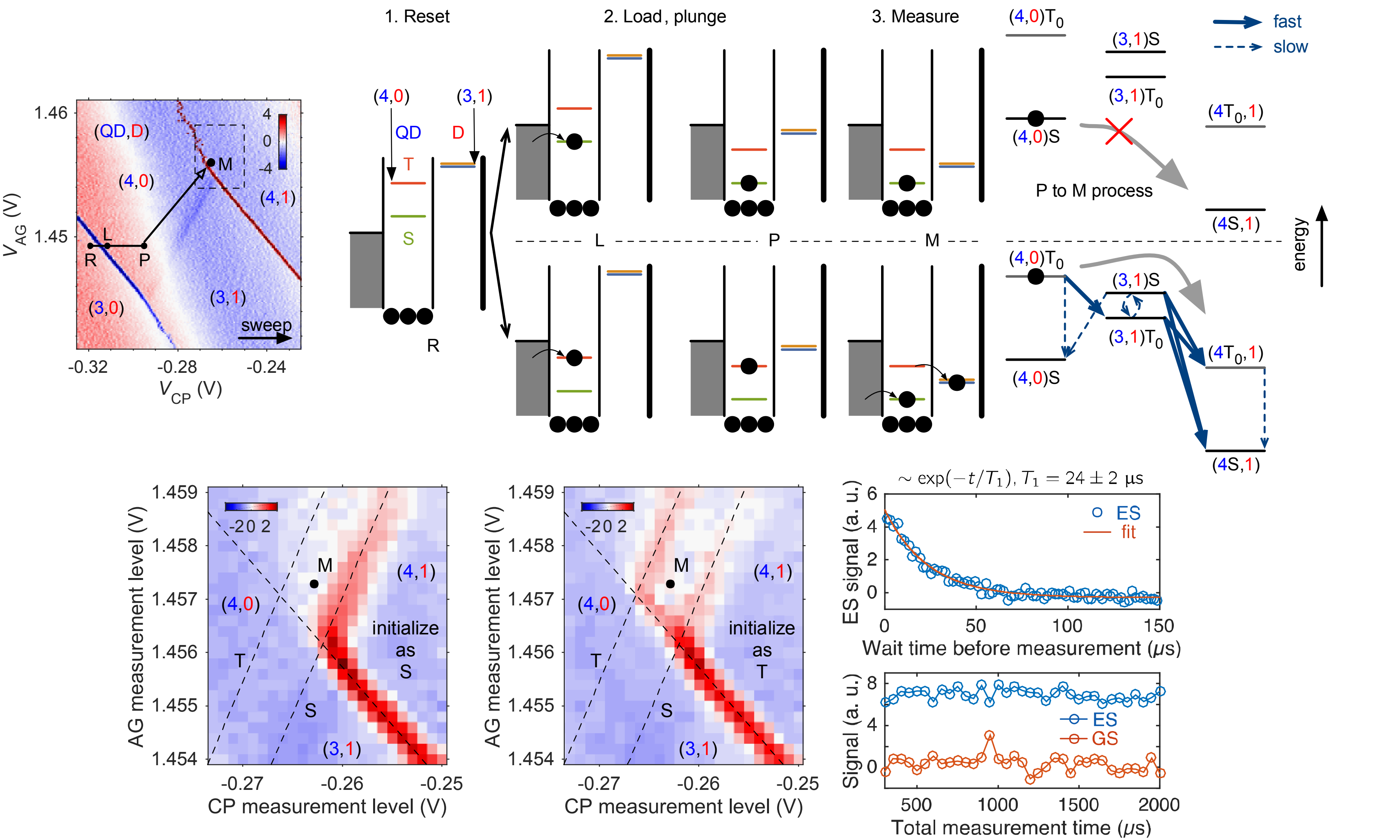


[1] F. A. Zwanenburg, A. S. Dzurak, A. Morello, M. Y. Simmons, L. C. L. Hollenberg, G. Klimeck, S. Rogge, S. N. Coppersmith, and M. A. Eriksson, “Silicon quantum electronics,” Rev. Mod. Phys. 85, 961 (2013).

State preparation and readout

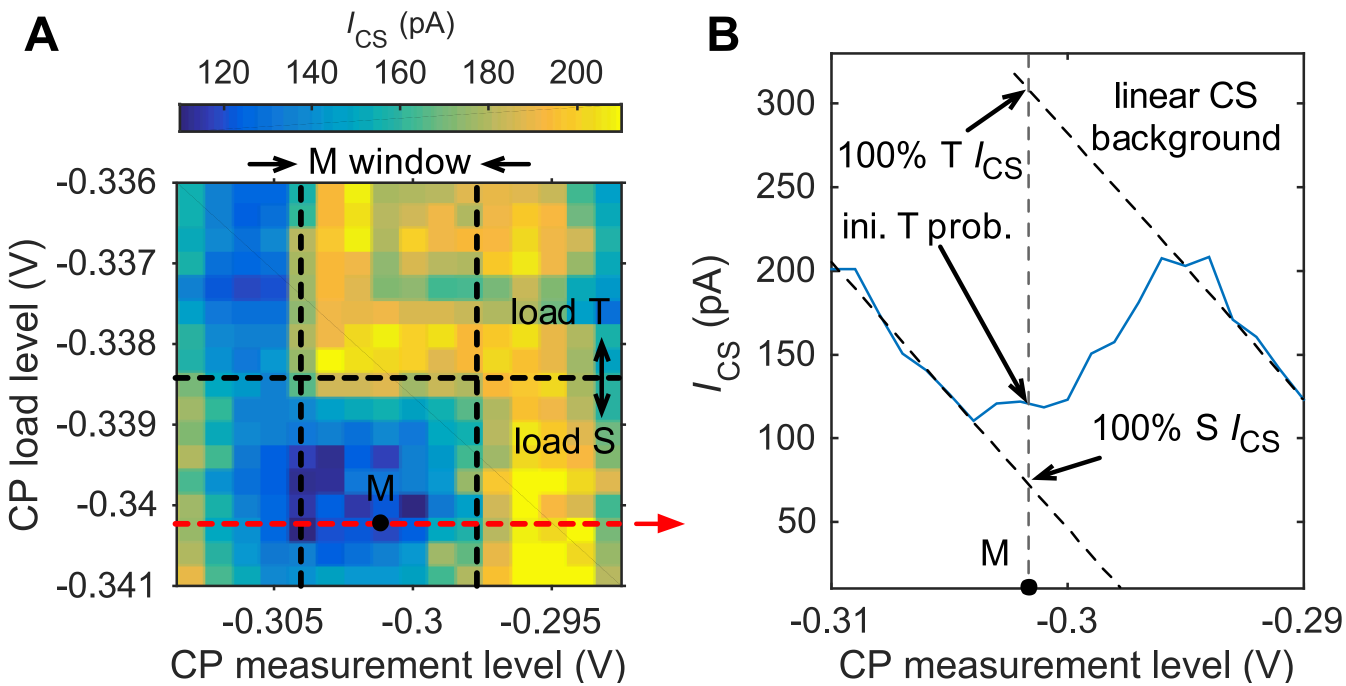


State preparation and readout

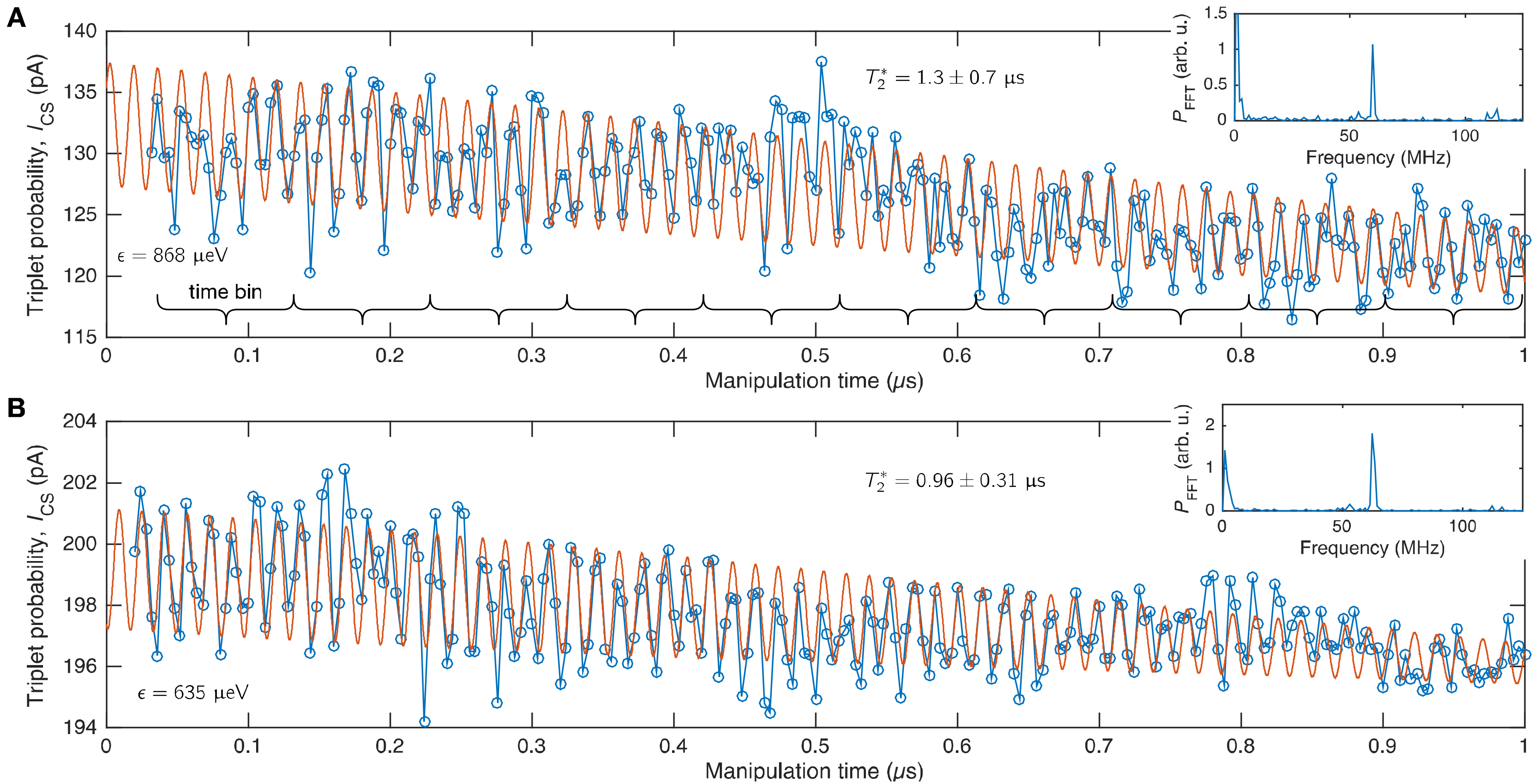


Building on ideas from: S. A. Studenikin, J. Thorgrimson, G. C. Aers, A. Kam, P. Zawadzki, Z. R. Wasilewski, A. Bogan, and A. S. Sachrajda, "Enhanced charge detection of spin qubit readout via an intermediate state," Applied Physics Letters 101, 233101 (2012).

Additional slides

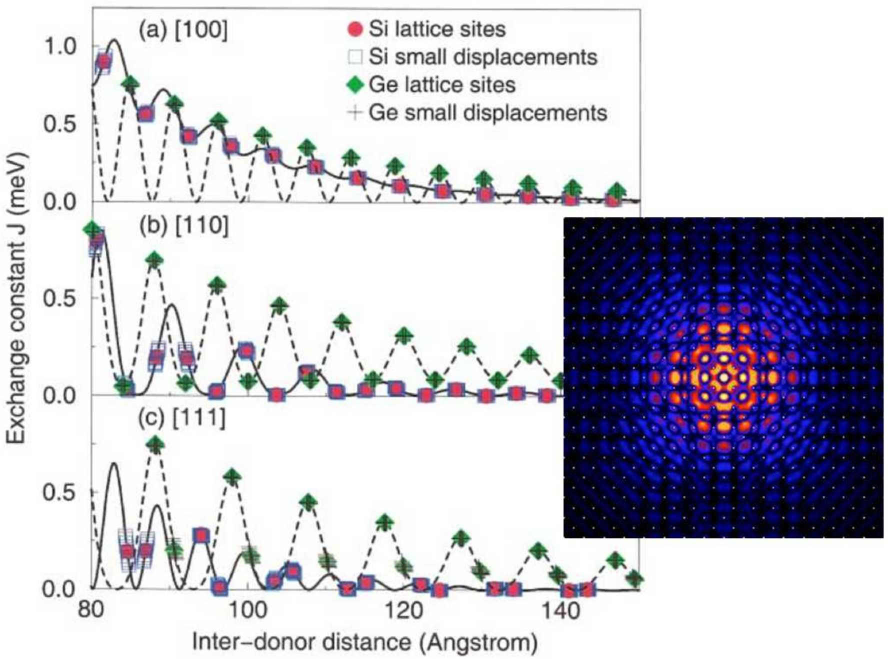


Additional slides



How to couple multiple donors?

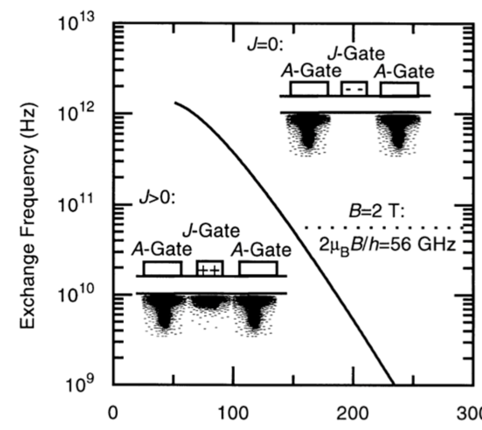
Direct coupling is challenging



Small wave functions!
Exchange oscillations are strong.
Near-atomic precision fab. required!

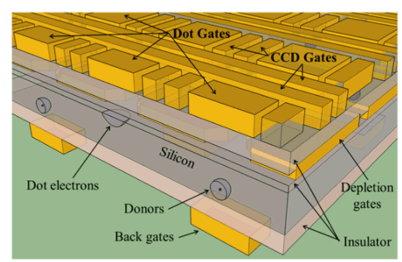
[1] Koiller, B., Hu, X. & Das Sarma, S. Exchange in silicon-based quantum computer architecture. Phys. Rev. Lett. 88, 027903 (2001).
[2] Wellard, C. J. & Hollenberg, L. C. L. Donor electron wave functions for phosphorus in silicon: Beyond effective-mass theory. Phys. Rev. B 72, 085202 (2005).

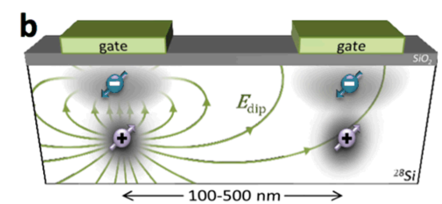
Kane's original exchange "*J* " gate



[1] Kane, B. E. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998).

"Modern" proposals involve QDs





[1] Pica, G., Lovett, B. W., Bhatt, R. N., Schenkel, T. & Lyon, S. A. Phys. Rev. B 93, 035306 (2016).
[2] Tosi, G. et al. ArXiv e-prints (2015). 1509.08538.