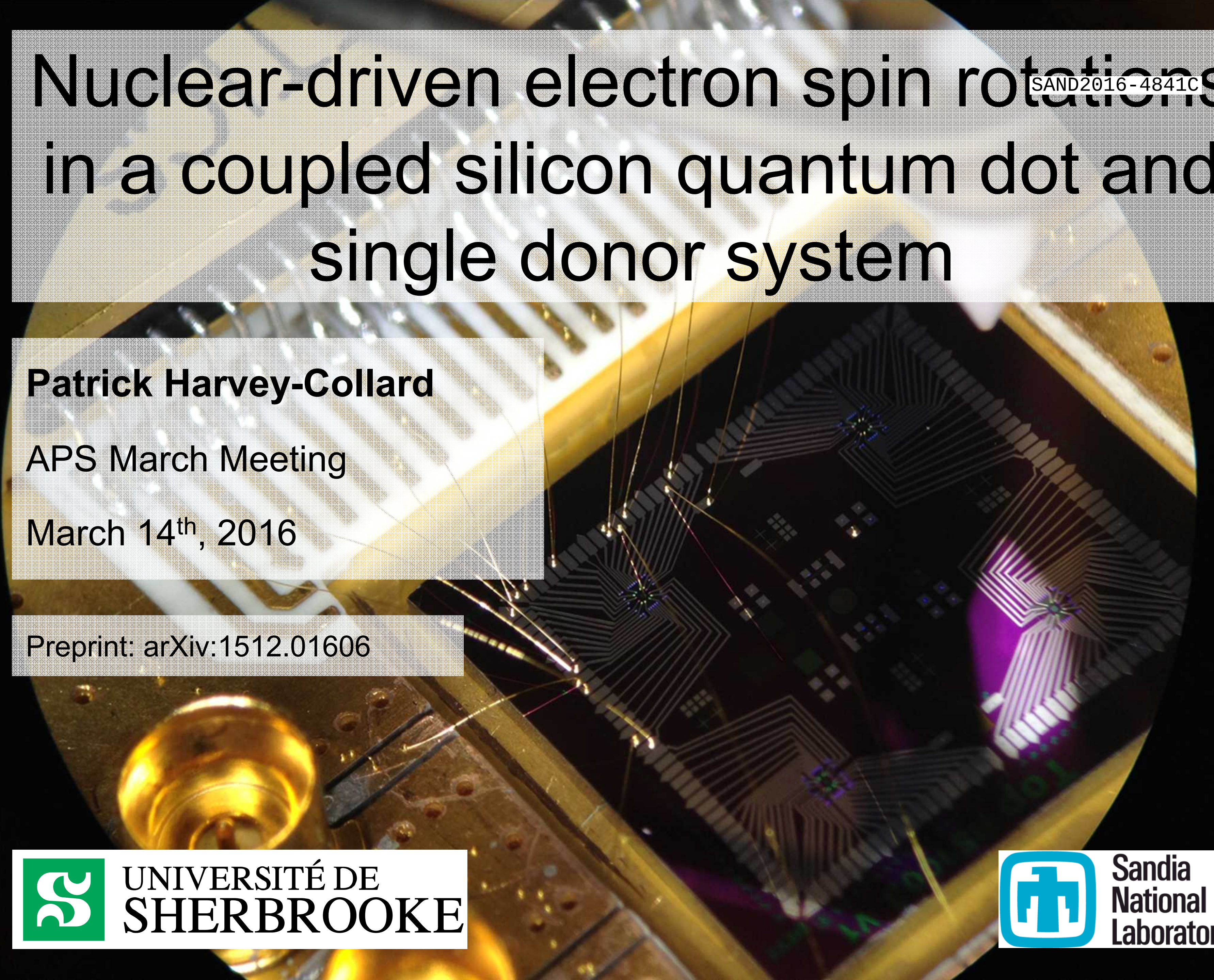

SAND2016-4841C

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

Patrick Harvey-Collard

APS March Meeting

March 14^{th}, 2016

Preprint: arXiv:1512.01606

UNIVERSITÉ DE SHERBROOKE

Sandia National Laboratories

Outline

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

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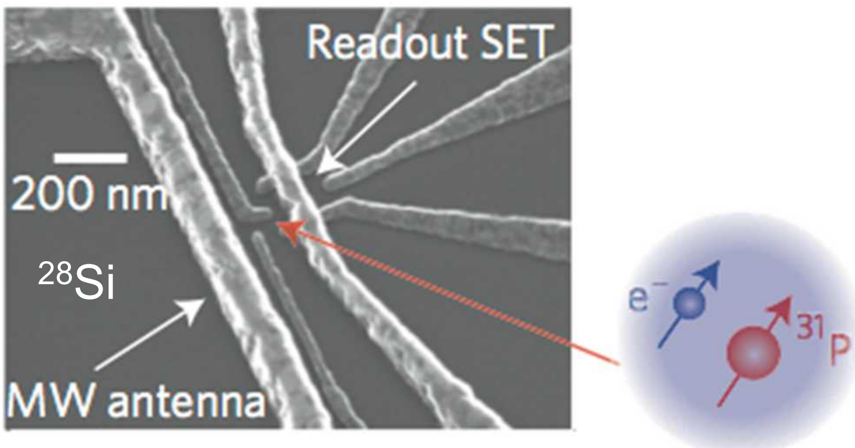
Why silicon spin qubits?

Donor (D) qubits are high fidelity…



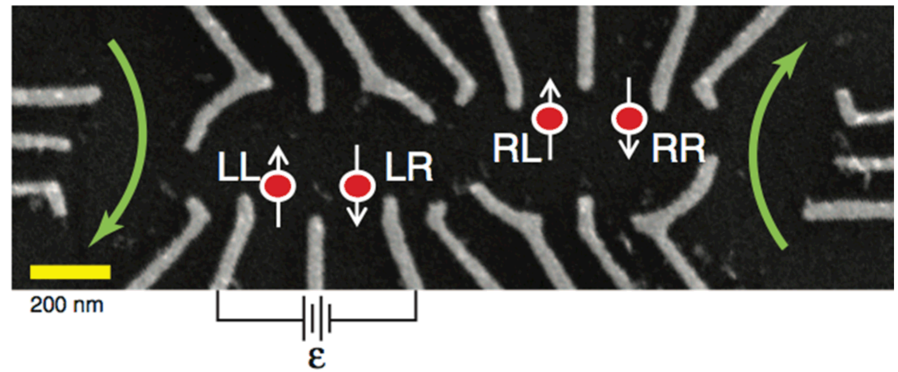
Electron spin 1/2:
$T_2^* = 270$ μs
$T_{2,\,\mathrm{CPMG}} = 560$ ms
$F_{\mathrm{prep/readout}} = 97\%$
$F_{\mathrm{control}} = 99.95\%$

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

But they are not easily coupled together!

[1] Muhonen, J. T. et al. Storing quantum information for 30 seconds in a nanoelectronic device. Nat Nano 9, 986–991 (2014).
[2] Muhonen, J. T. et al. Quantifying the quantum gate fidelity of single-atom spin qubits in silicon by randomized benchmarking. Journal of Physics: Condensed Matter 27, 154205 (2015).

Quantum dot (QD) qubits are tunable…



Singlet-triplet spin qubit in GaAs:

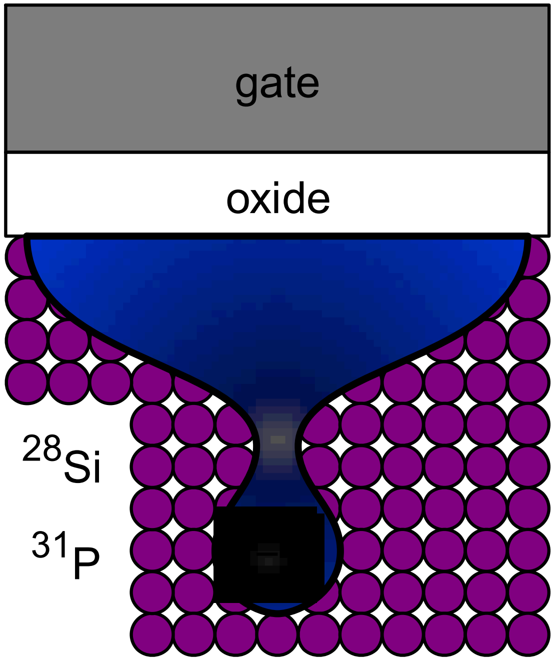
- All-electrical control
- Two-qubit gates possible

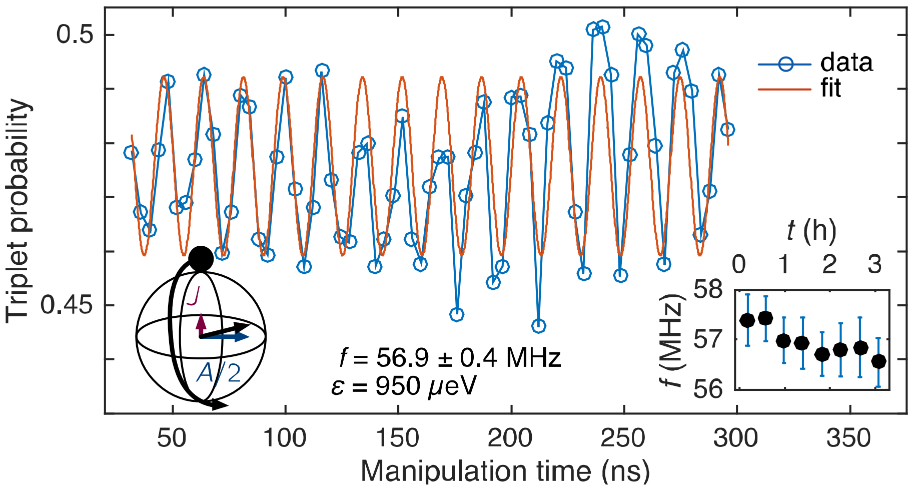
But they are not quite as high fidelity!

[1] Shulman, M. D. et al. Demonstration of entanglement of electrostatically coupled singlet-triplet qubits. Science 336, 202–205 (2012).
[2] Petta, J. R. et al. Coherent manipulation of coupled electron spins in semiconductor quantum dots. Science 309, 2180–2184 (2005).
[3] Veldhorst, M. et al. An addressable quantum dot qubit with fault-tolerant control-fidelity. Nat Nano 9, 981–985 (2014).
[4] Veldhorst, M. et al. A two-qubit logic gate in silicon. Nature 526, 410–414 (2015).

In this presentation:

First *coherent* coupling between a quantum dot (QD) and a donor (D)





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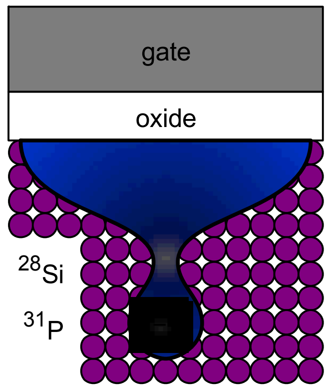
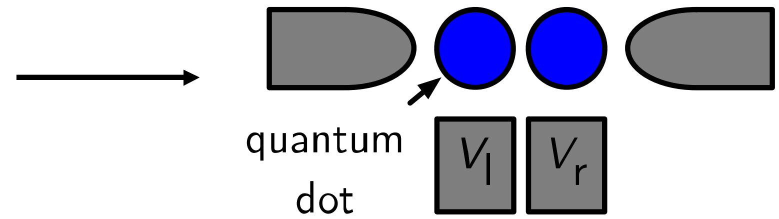
Singlet-triplet encoding

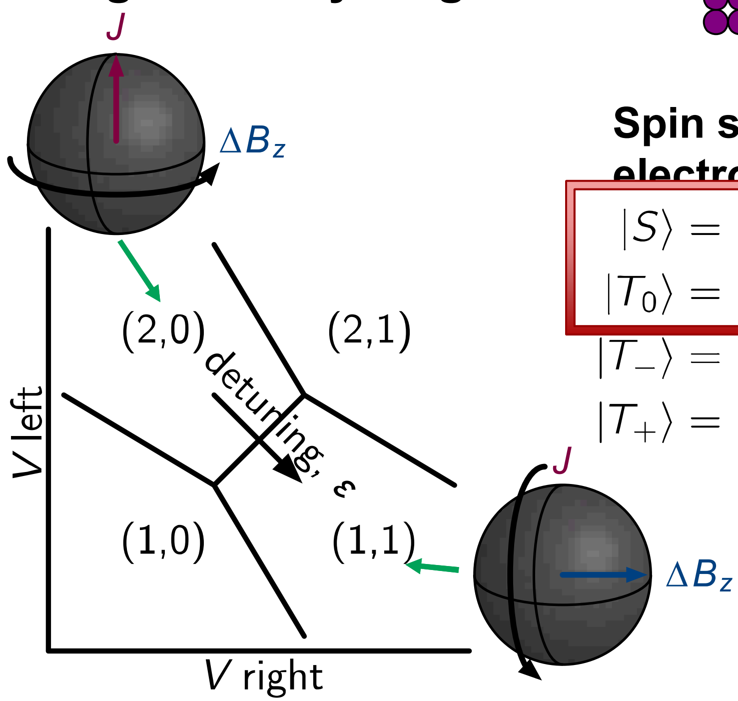
QD-D



Double QD



Charge stability diagram



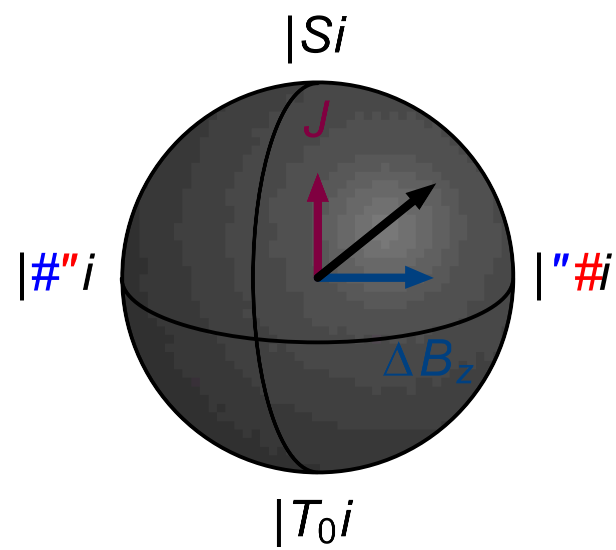
Spin states for two electrons

$$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$
$$|T_0\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$
m = 0

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

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

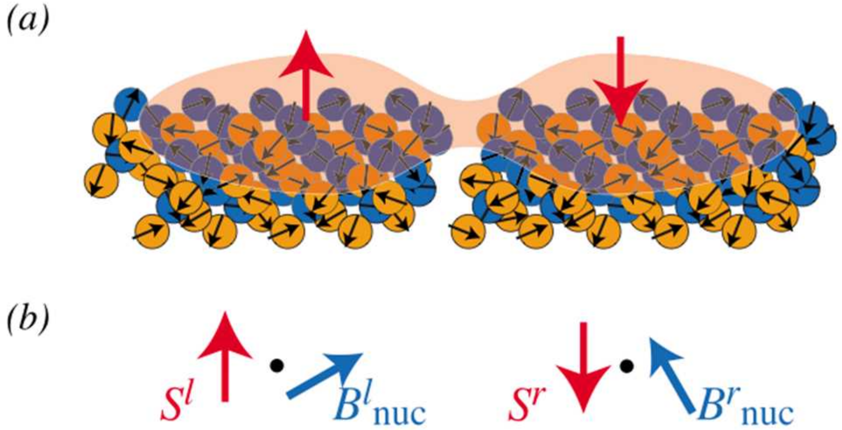
Qubit Bloch Sphere



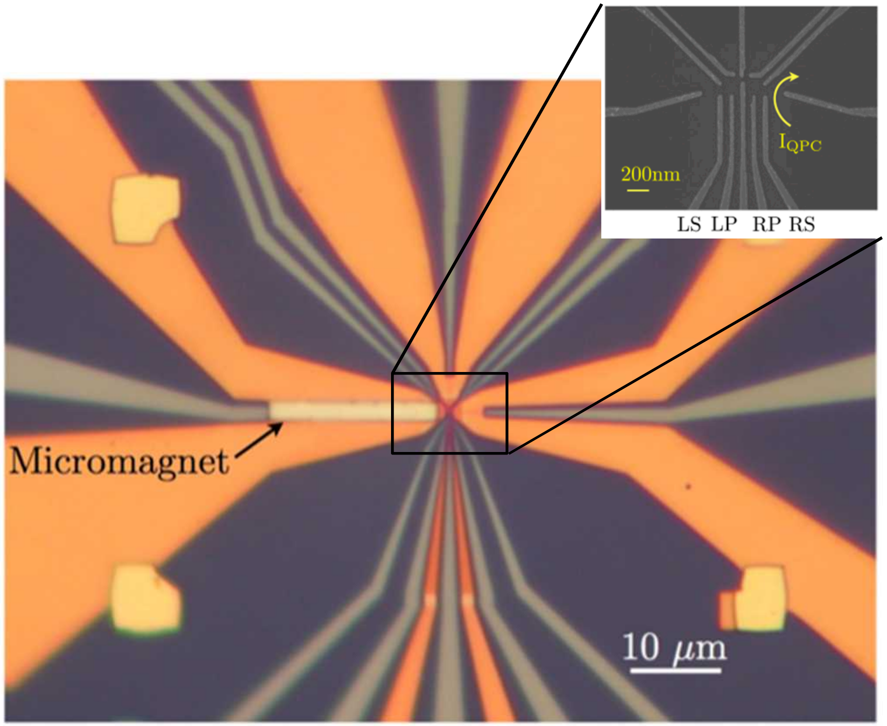
ST qubit theory: J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, “Relaxation, dephasing, and quantum control of electron spins in double quantum dots,” Phys. Rev. B 76, 035315 (2007).

Driving ΔB_z rotations in the singlet-triplet qubit

GaAs: nuclear field gradient



Si: micromagnets



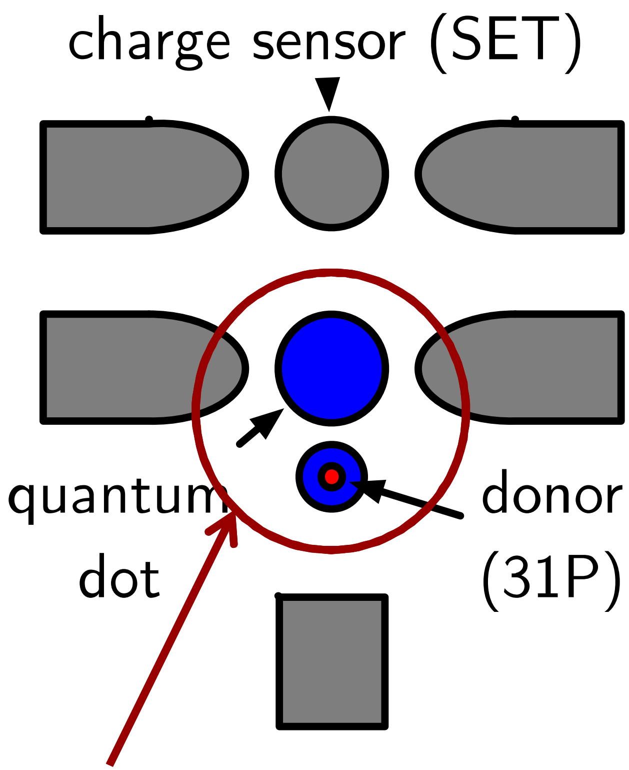
[1] J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, "Relaxation, dephasing, and quantum control of electron spins in double quantum dots," Phys. Rev. B 76, 035315 (2007).

[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

$\langle\Downarrow|AS\cdot I|\Uparrow\rangle = \frac{A}{2}s$

Hybrid QD-D singlet-triplet qubit



Double QD-like system!

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:

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

Advantages

- **Fast** and **stable** rotation speed: Contact hyperfine interaction $A/2$ = 57 MHz gives **9 ns π rotation**.
- 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 (next) and Andrew D. Baczewski (next-next)

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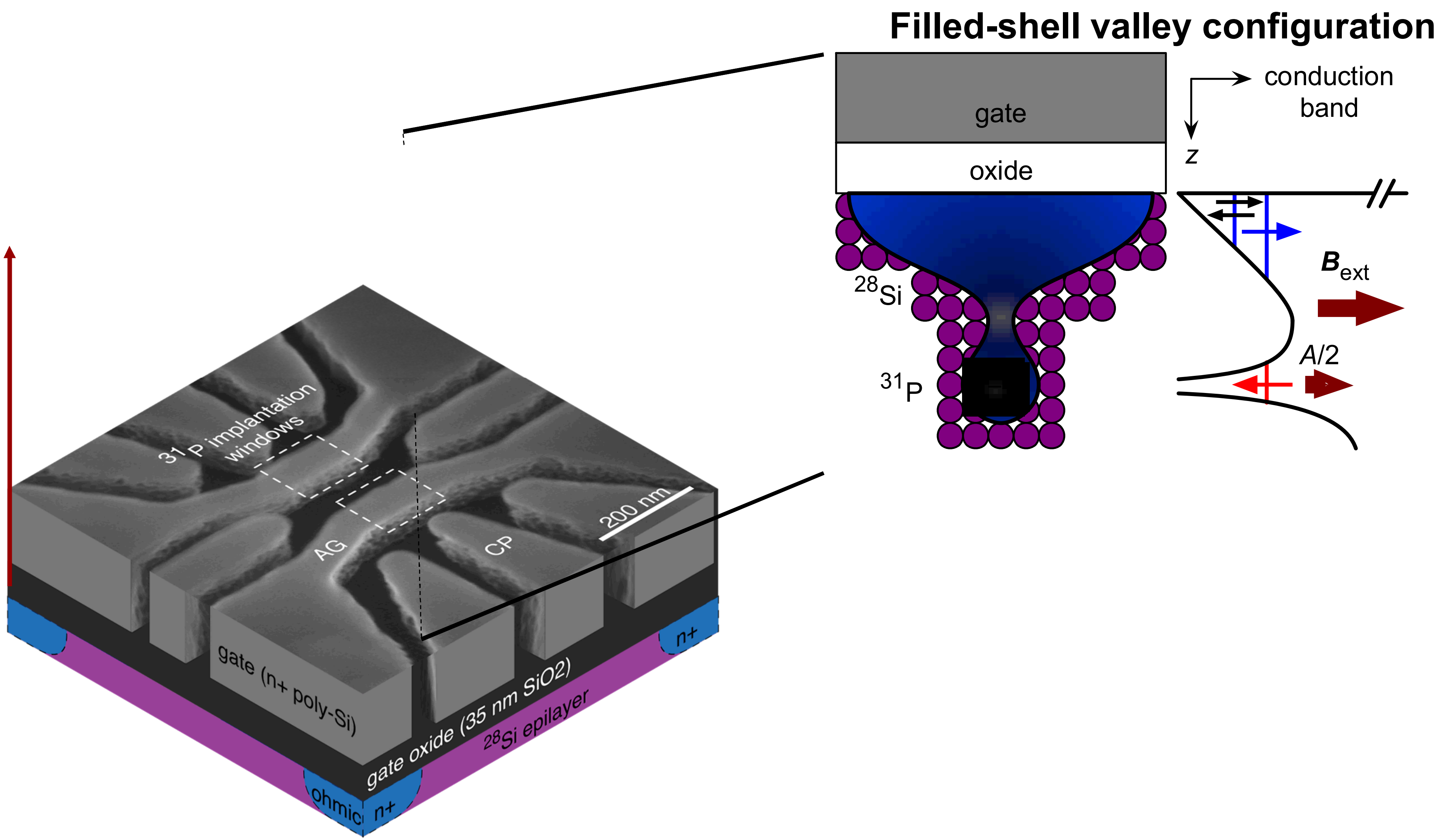
Our silicon MOS nanostructure



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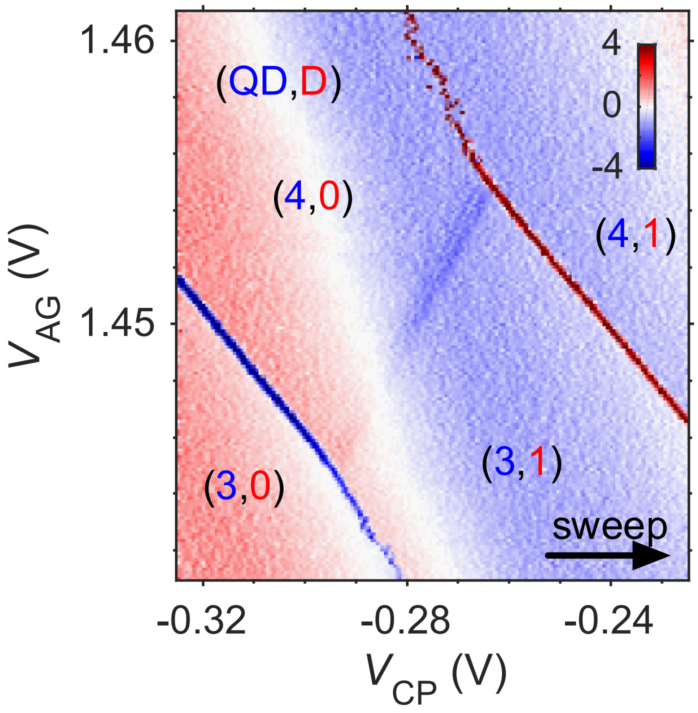
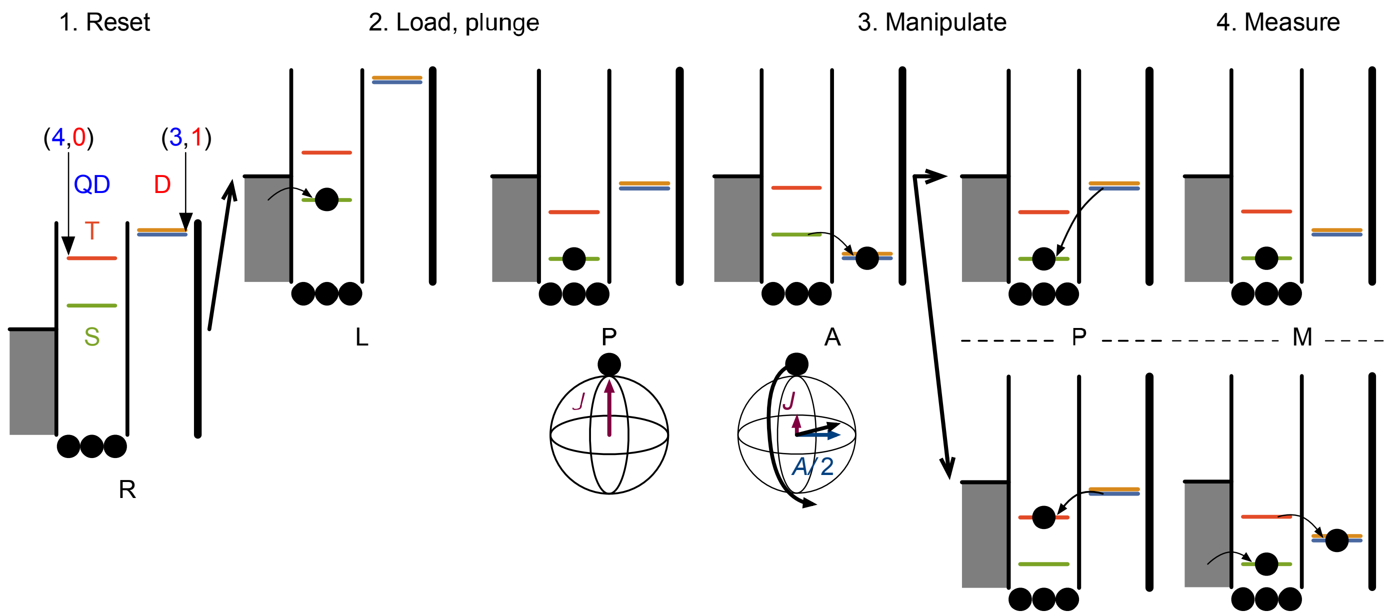
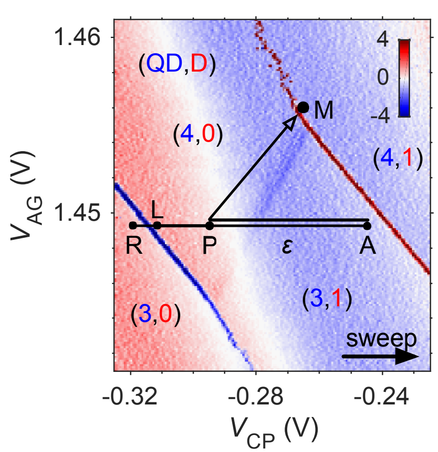
Quantum dot-donor anti-crossing

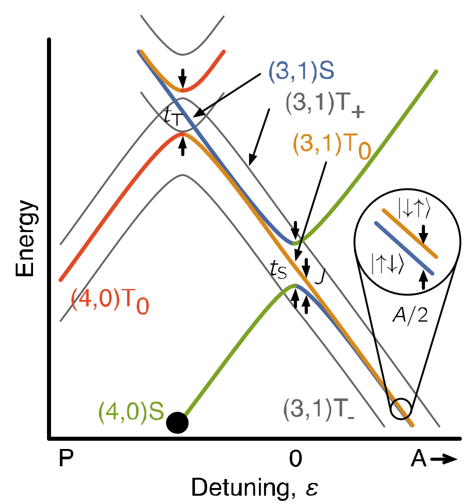
Forms an effective (2,0) ↔ (1,1) transition

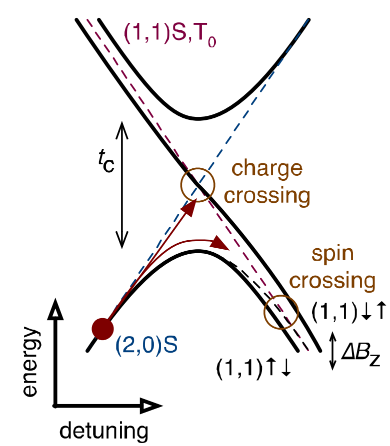


State manipulation



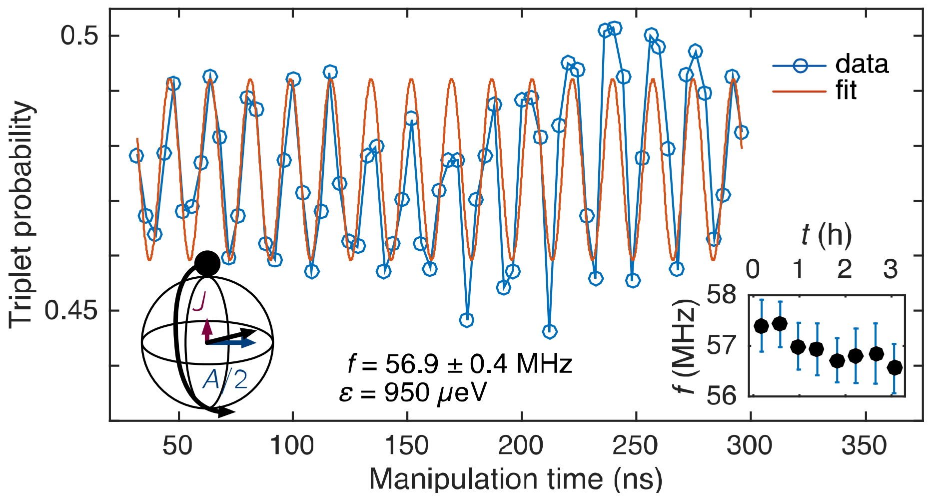


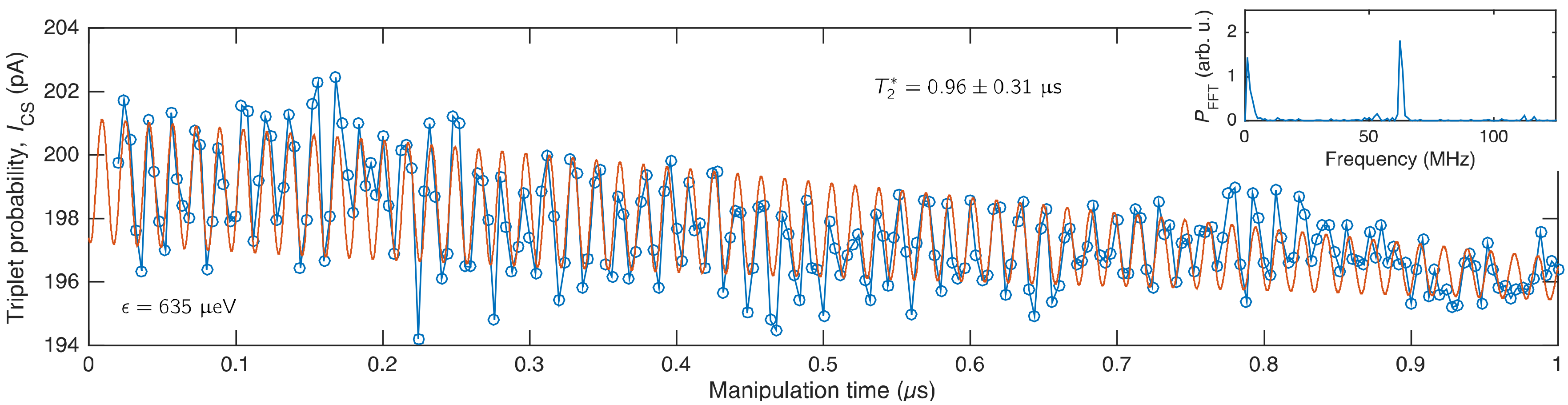




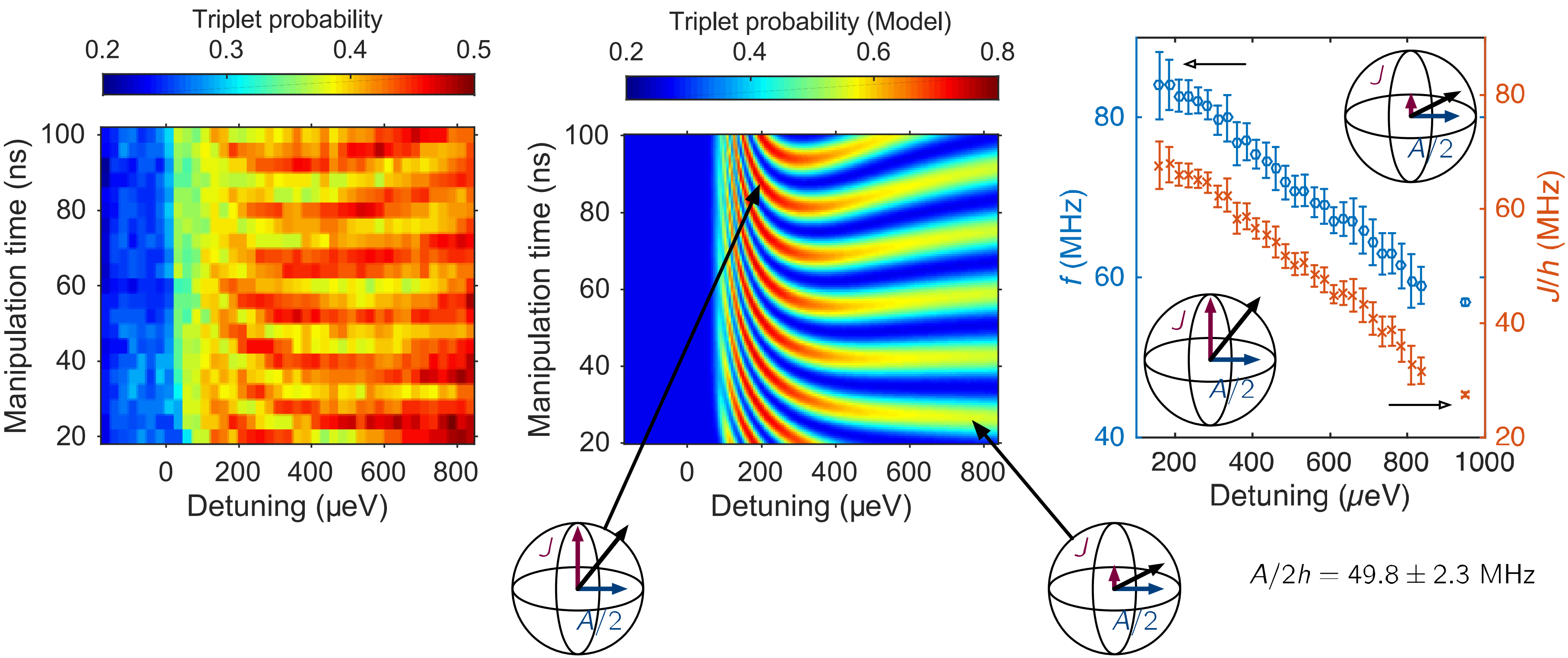
State manipulation

Singlet-triplet rotations driven by a single 31P nucleus





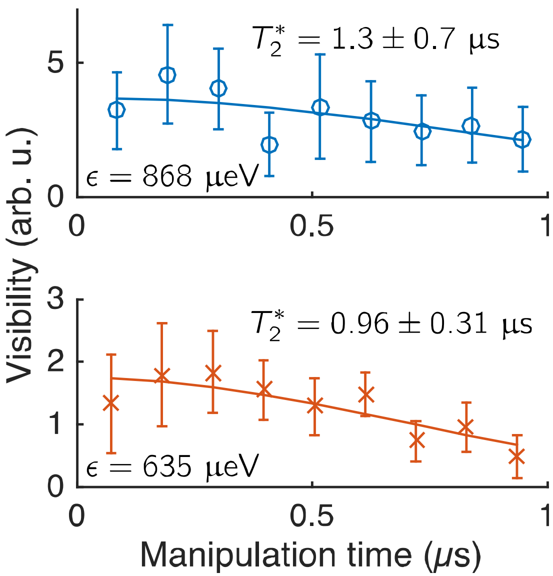
Detuning dependence of exchange interaction



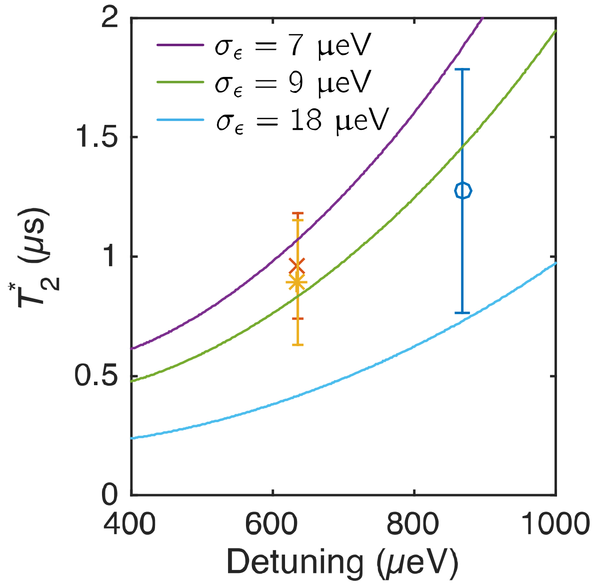
$A/2h = 49.8 \pm 2.3$ MHz

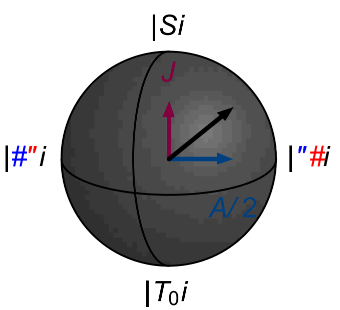
Coherence time and charge noise

Visibility decay



Coherence time vs detuning





$J \rightarrow J(\epsilon)$

Charge-noise limited.
Possibly extended to > 10 μs

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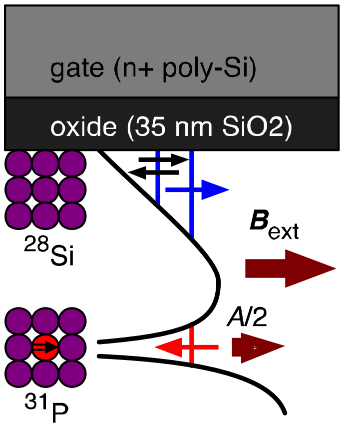
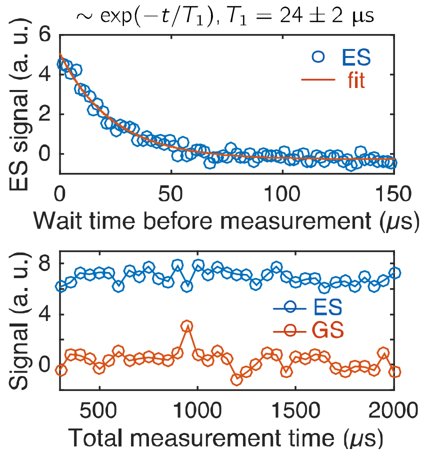
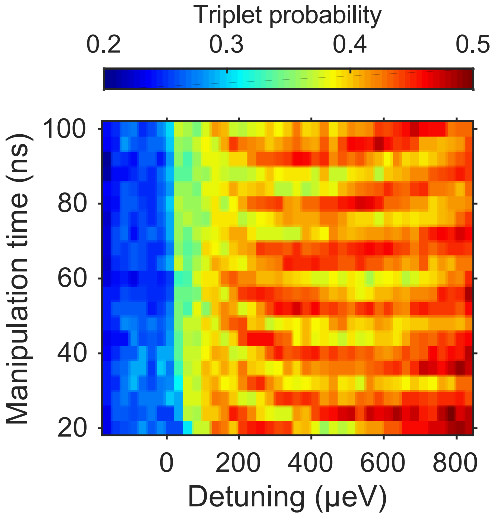
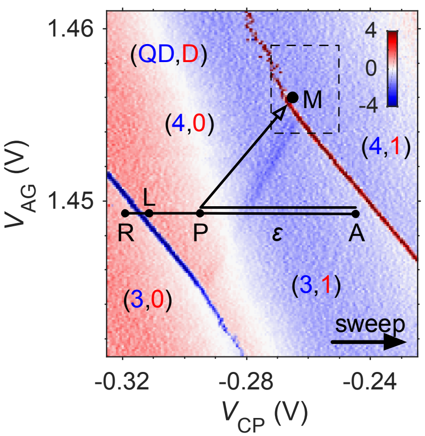
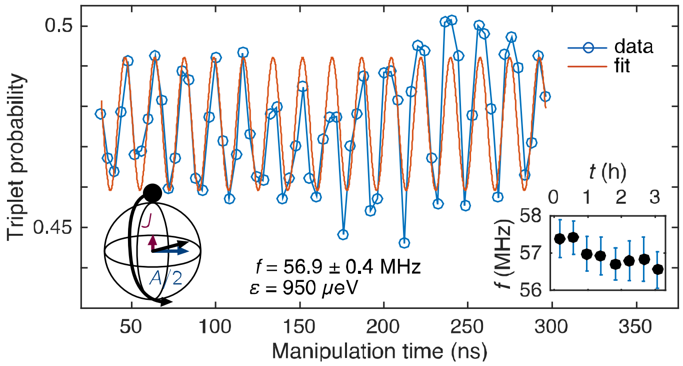
Summary

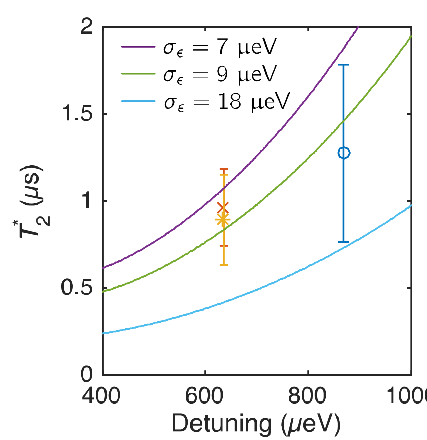








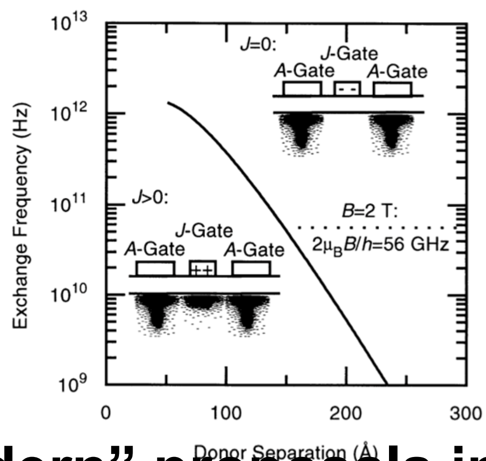




Preprint: Nuclear-driven electron spin rotations in a single donor coupled to a silicon quantum dot. arXiv:1512.01606

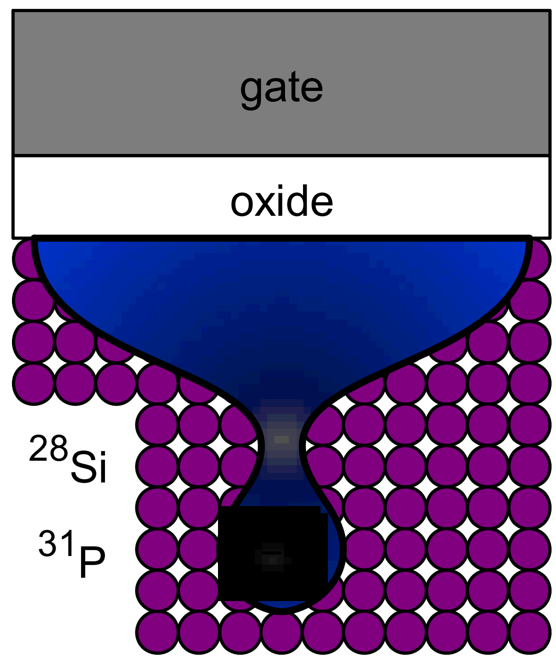
Perspectives

Kane's original exchange "*J*" gate

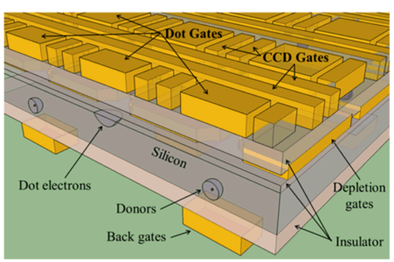


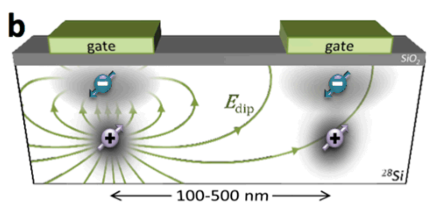
[1] Kane, B. E. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998).

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



"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.

Acknowledgements & Team

Experiments

- Malcolm S. Carroll (SNL advisor)
- Michael P. Lilly (Lab owner)
- 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)

And the rest of the QIST team!

Quantum Information S&T

National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

CRSNG NSERC

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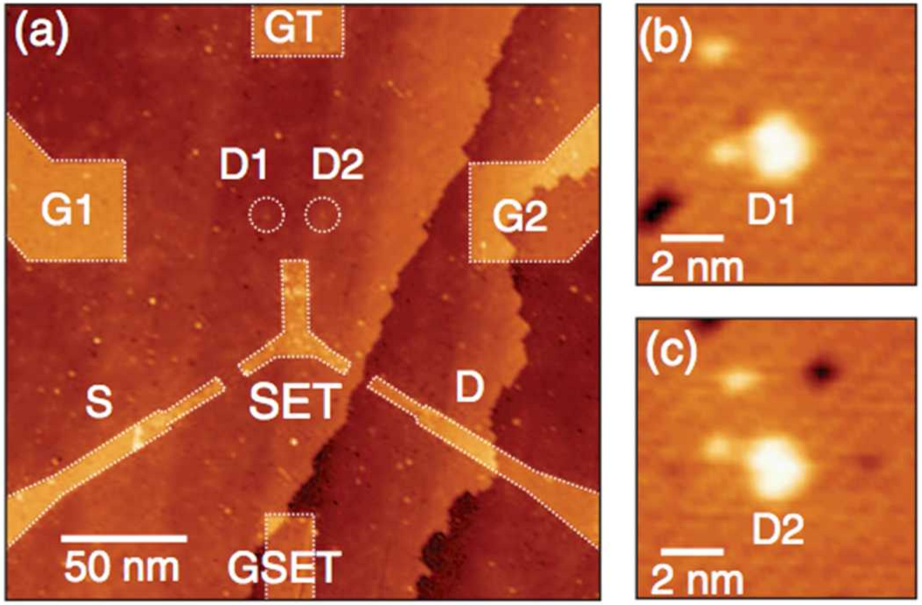
Coupling donor qubits *directly* involves atomic-precision fabrication…



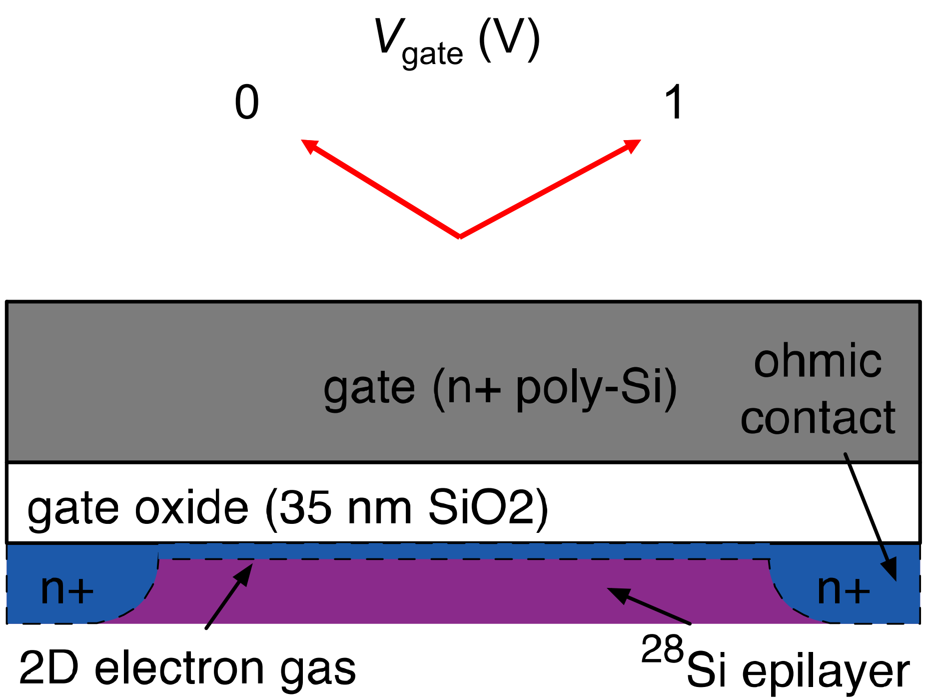
After incorporation: 1 donor

After incorporation: 0 donor

Not yet mature technology (fails stochastically)

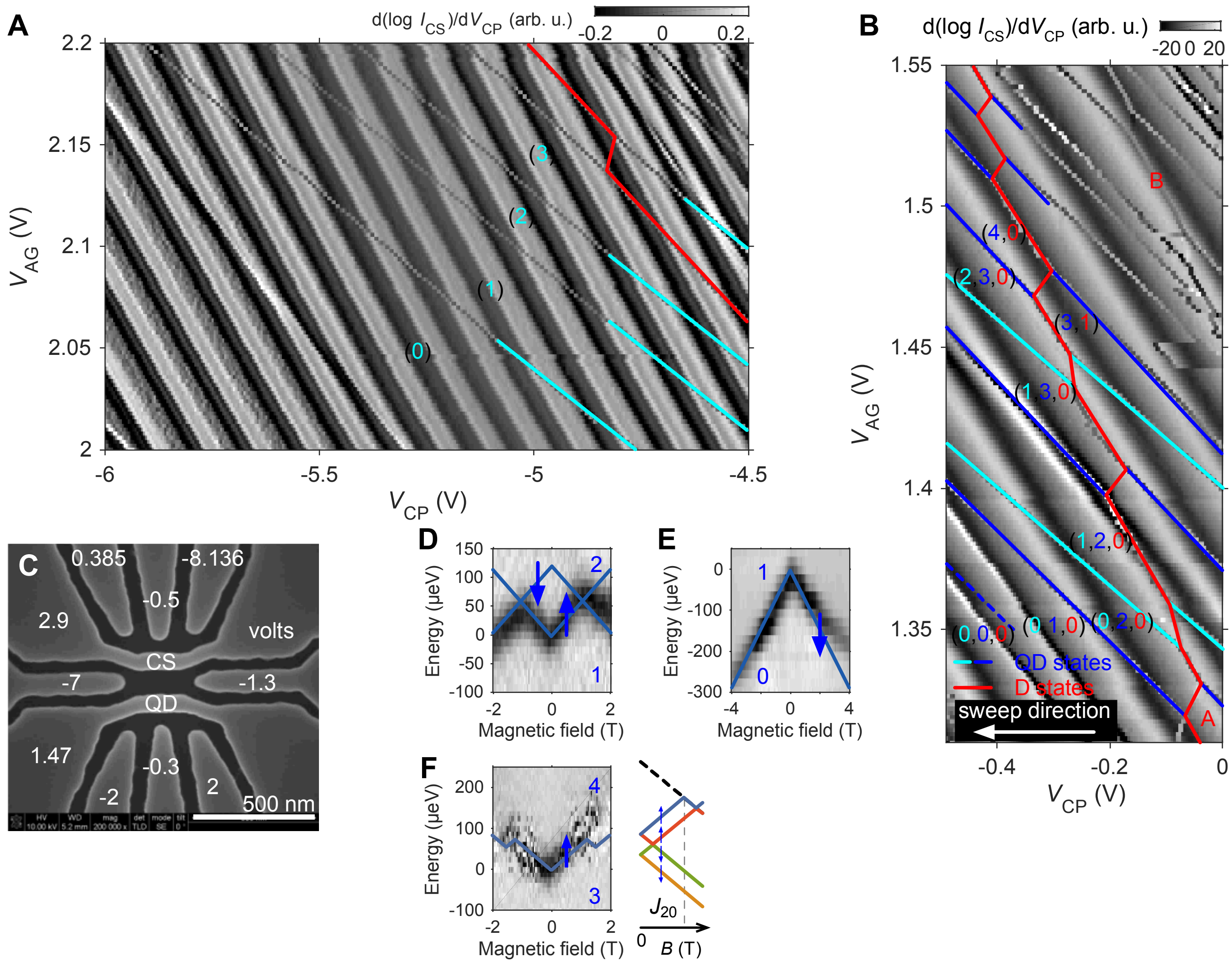
[1] T. F. Watson, B. Weber, M. G. House, H. Büch, and M. Y. Simmons, "High-fidelity rapid initialization and read-out of an electron spin via the single donor D− charge state," Phys. Rev. Lett. 115, 166806 (2015).

Our silicon MOS nanostructure



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

Additional slides



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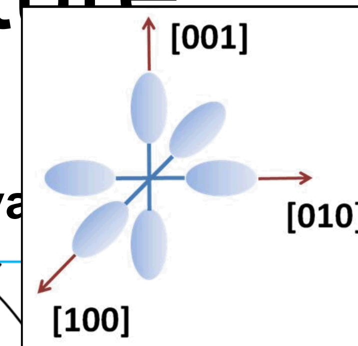
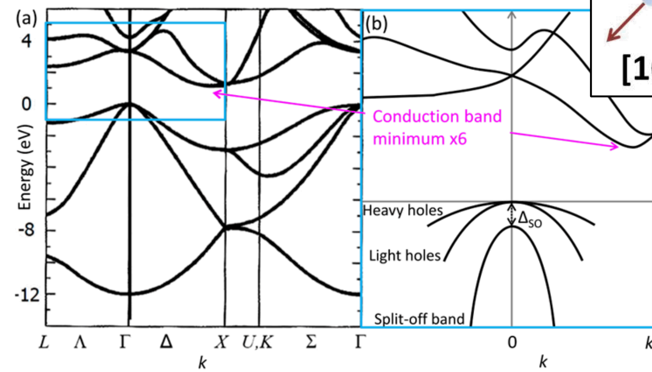
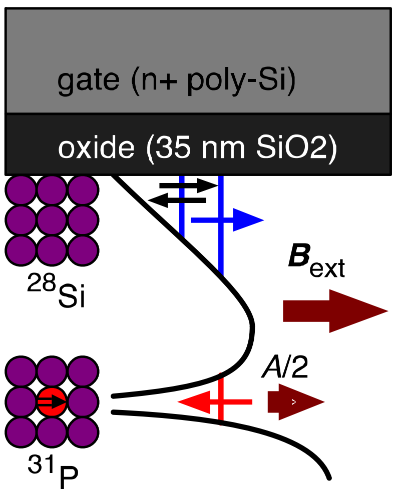


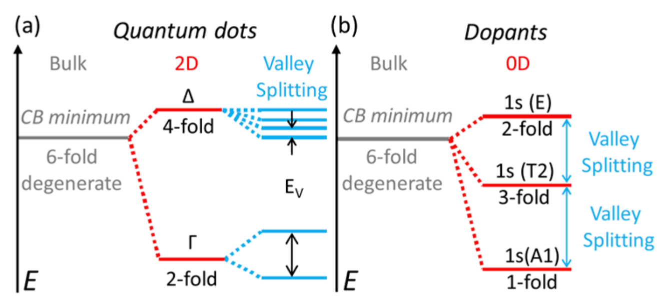
Silicon has 6 degenerate va



Filled-shell valley configuration

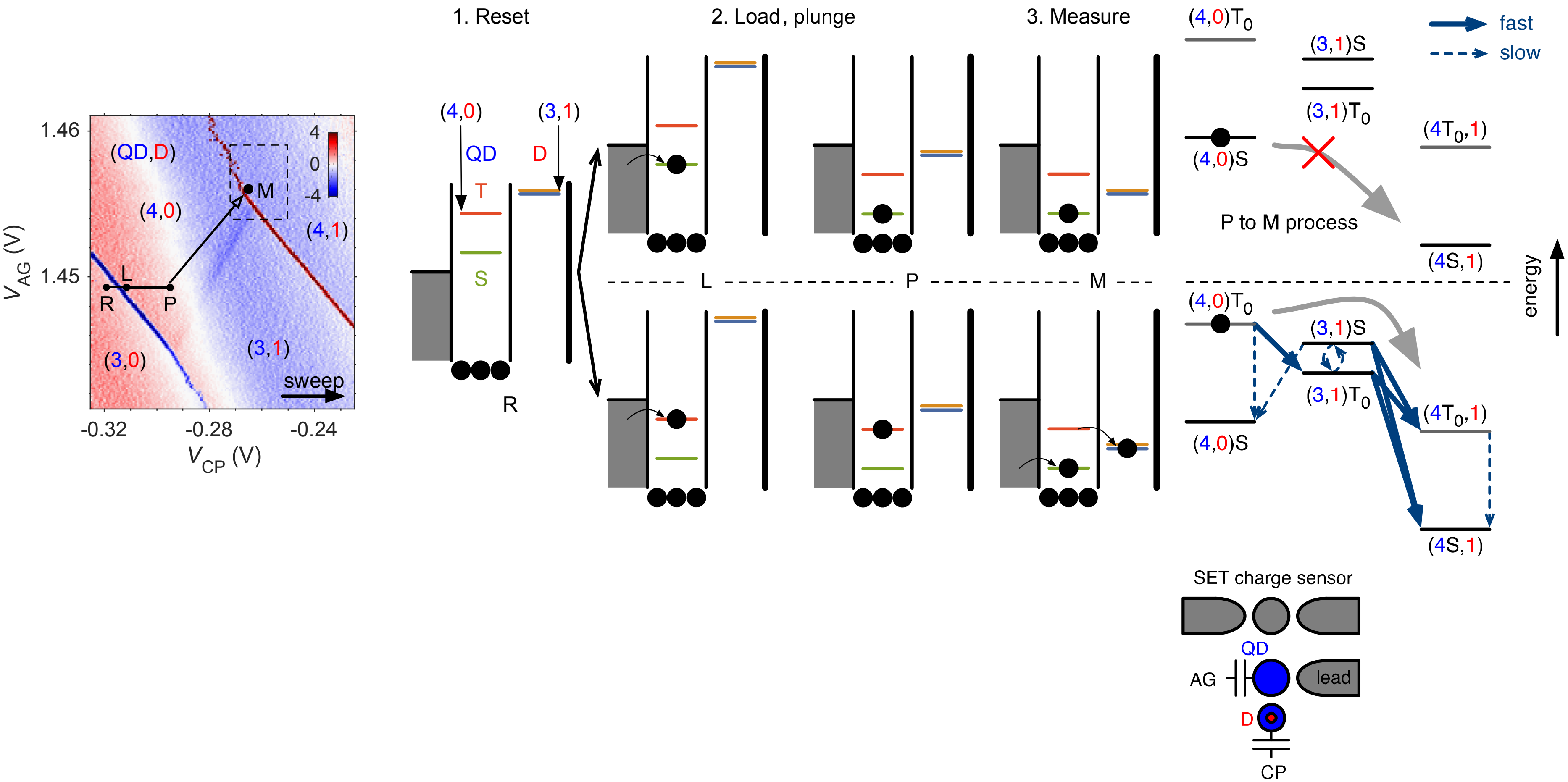


Valley degeneracy is lifted because of the strong confinement at the Si/SiO2 interface



[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



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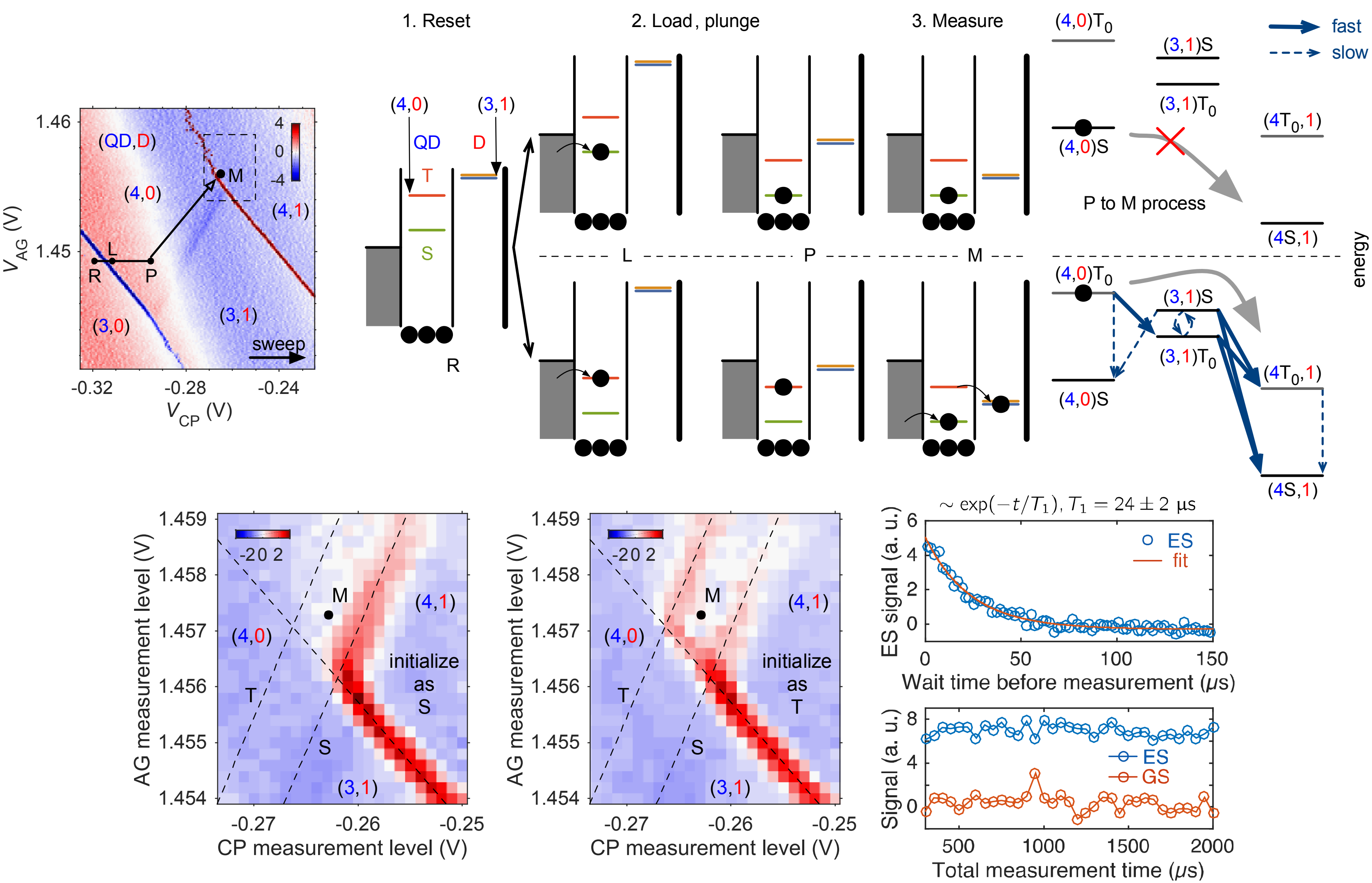
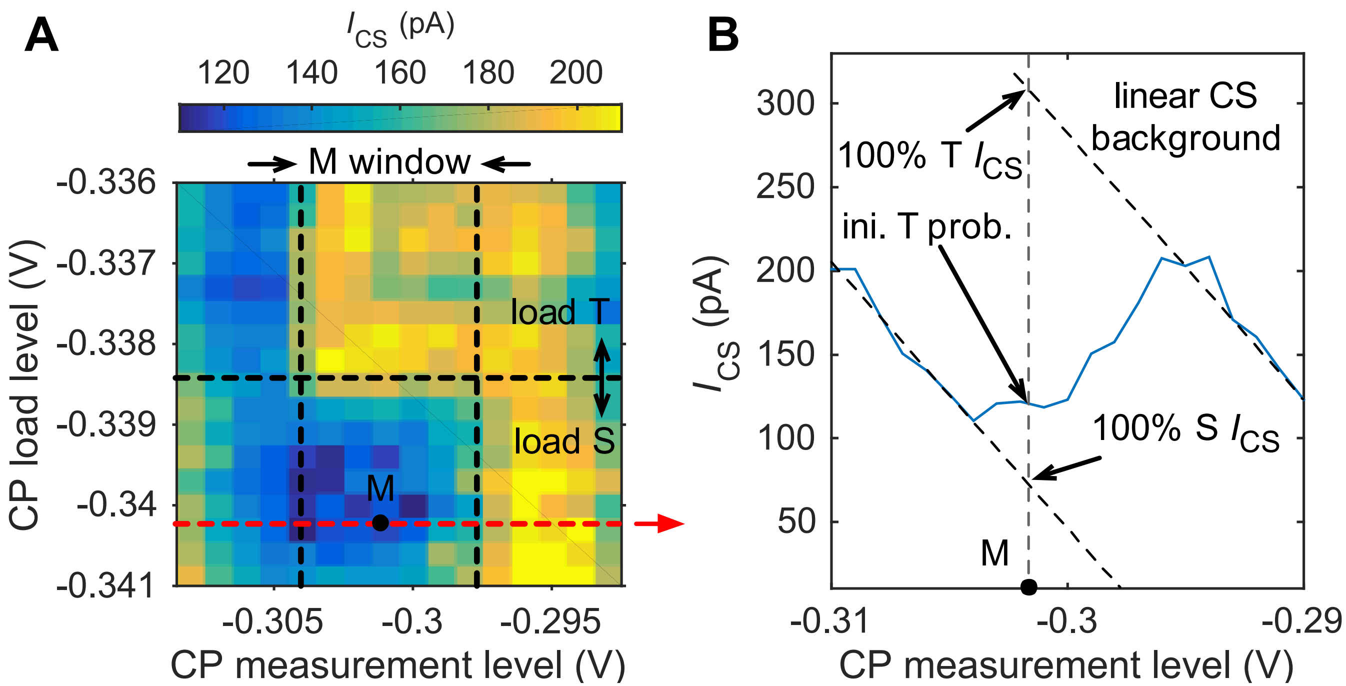


Building on ideas from: S. A. Studenikin, J. Thorgrimson, G. C. Aers, A. Kam, P. Zawadzki, Z. R. Wasilewski, A. Bogan, and A. S. Sachrajda, "Enhanced charge detection of spin qubit readout via an intermediate state," Applied Physics Letters 101, 233101 (2012).

Additional slides



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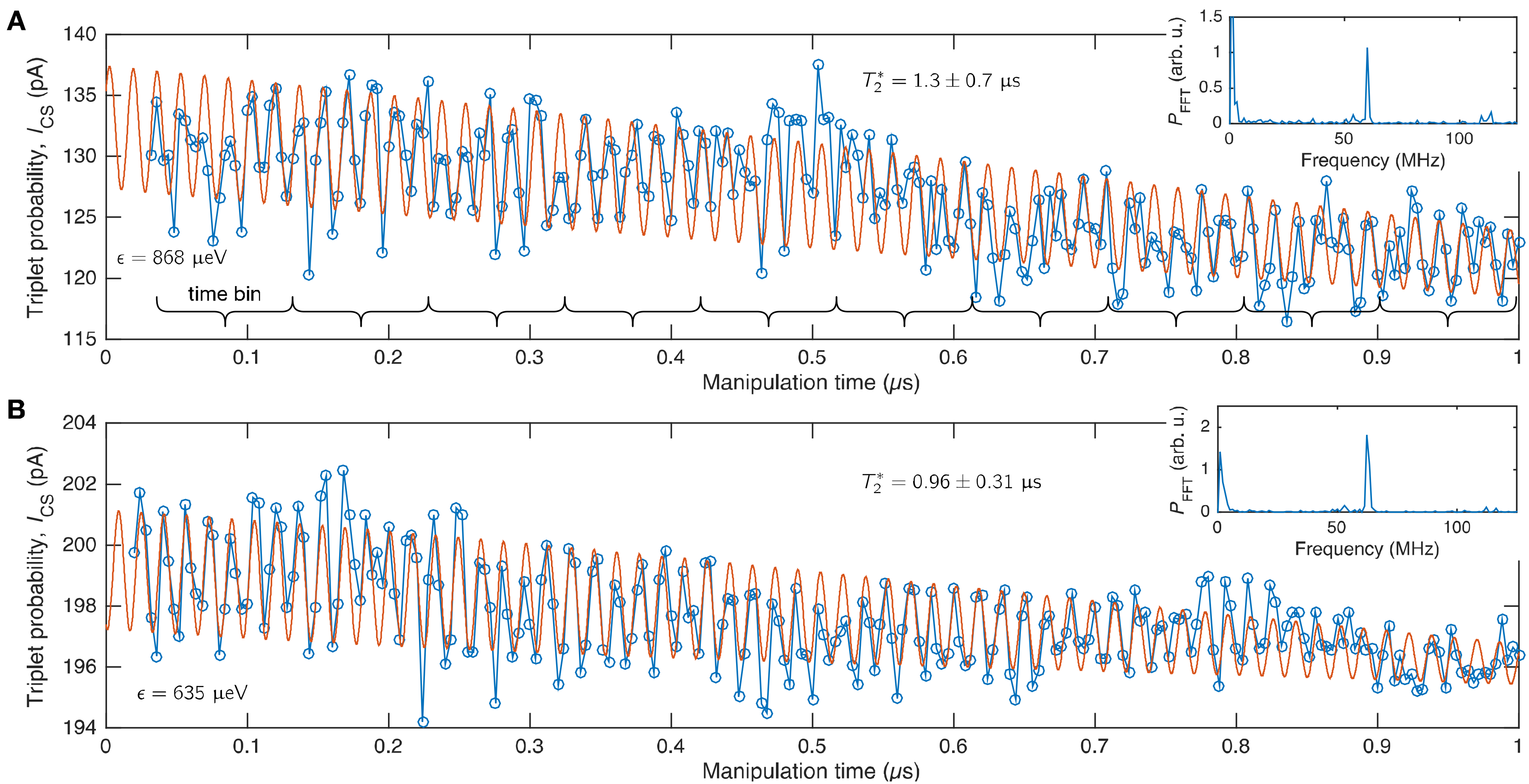
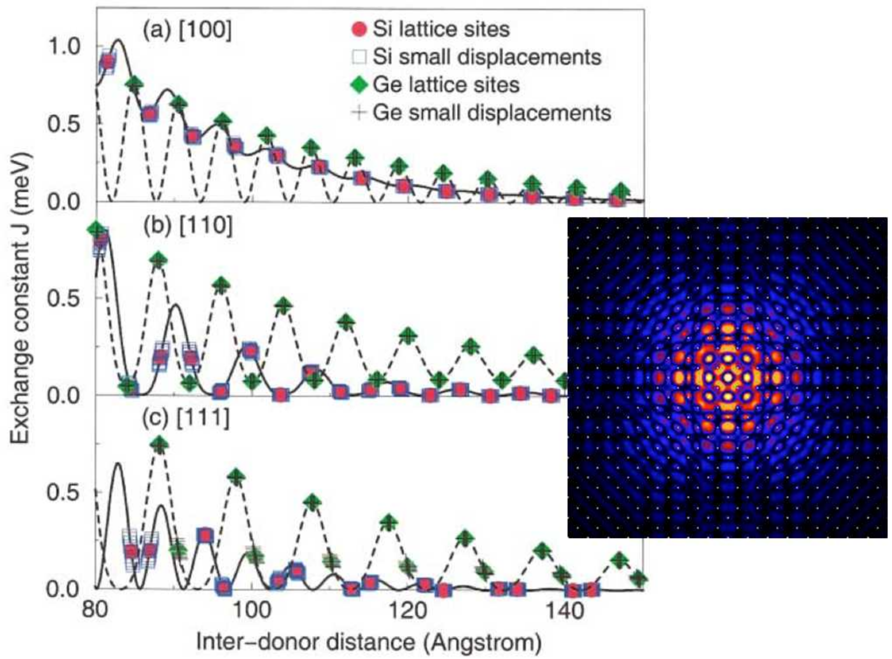


How to couple multiple donors?

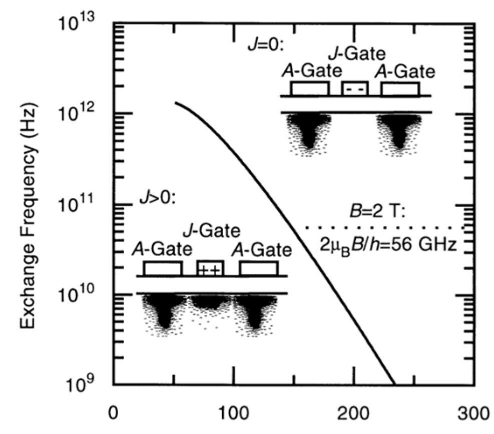
Direct coupling is challenging



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



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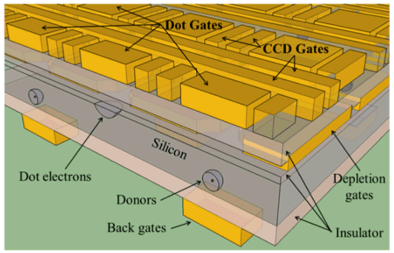

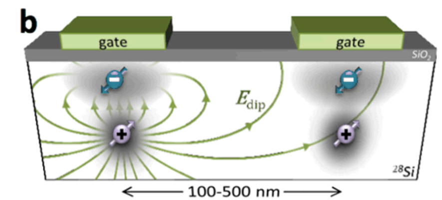

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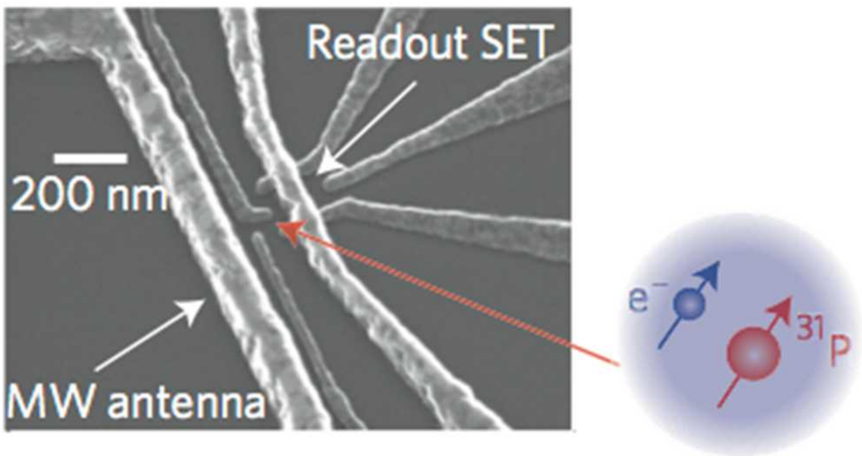

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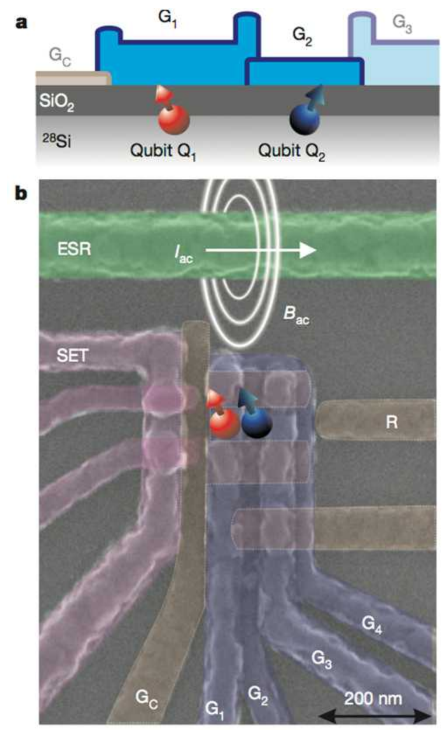
$F_{control} = 99.99\%$

But they are not easily coupled together!

[1] Muhonen, J. T. et al. Storing quantum information for 30 seconds in a nanoelectronic device. Nat Nano 9, 986–991 (2014).
[2] Muhonen, J. T. et al. Quantifying the quantum gate fidelity of single-atom spin qubits in silicon by randomized benchmarking. Journal of Physics: Condensed Matter 27, 154205 (2015).

Quantum dot (QD) qubits are tunable…



Electron spin 1/2:
$T_2^* = 120\ \mu s$
$T_{2,\ CPMG} = 28\ ms$
$F_{prep/readout} = 92\%$
$F_{control} = 99.59\%$

2-qubit gate!

But they are not quite as high fidelity!

[1] Veldhorst, M. et al. An addressable quantum dot qubit with fault-tolerant control-fidelity. Nat Nano 9, 981–985 (2014).
[2] Veldhorst, M. et al. A two-qubit logic gate in silicon. Nature 526, 410–414 (2015).