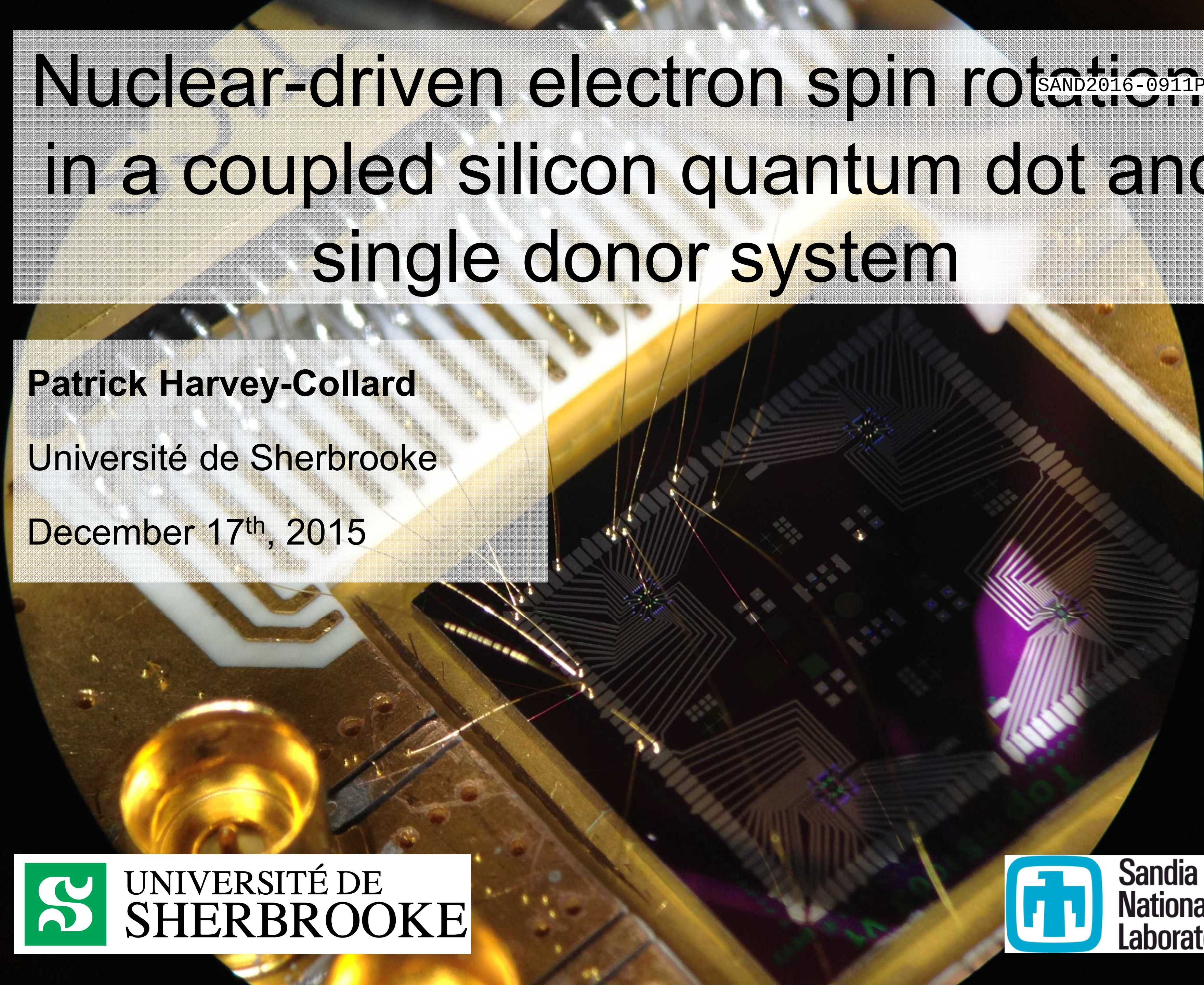
SAND2016-0911PE

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



Patrick Harvey-Collard

Université de Sherbrooke

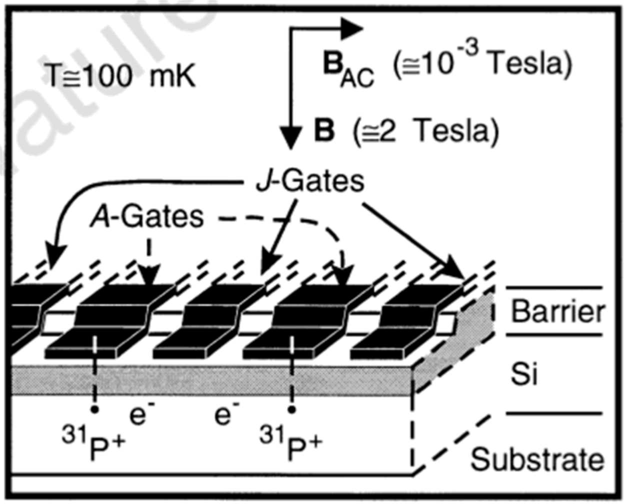
December 17th, 2015

UNIVERSITÉ DE SHERBROOKE

Sandia National Laboratories

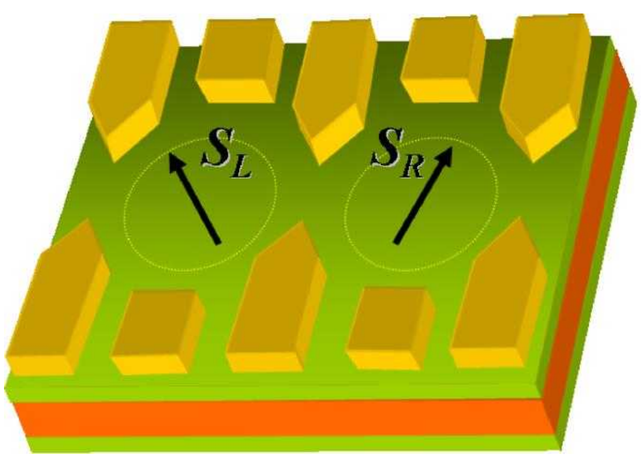
It all started with…

Kane-like architecture



[1] B. E. **Kane**, “A silicon-based nuclear spin quantum computer,” Nature, vol. 393, no. 6681, pp. 133–137, 1998.

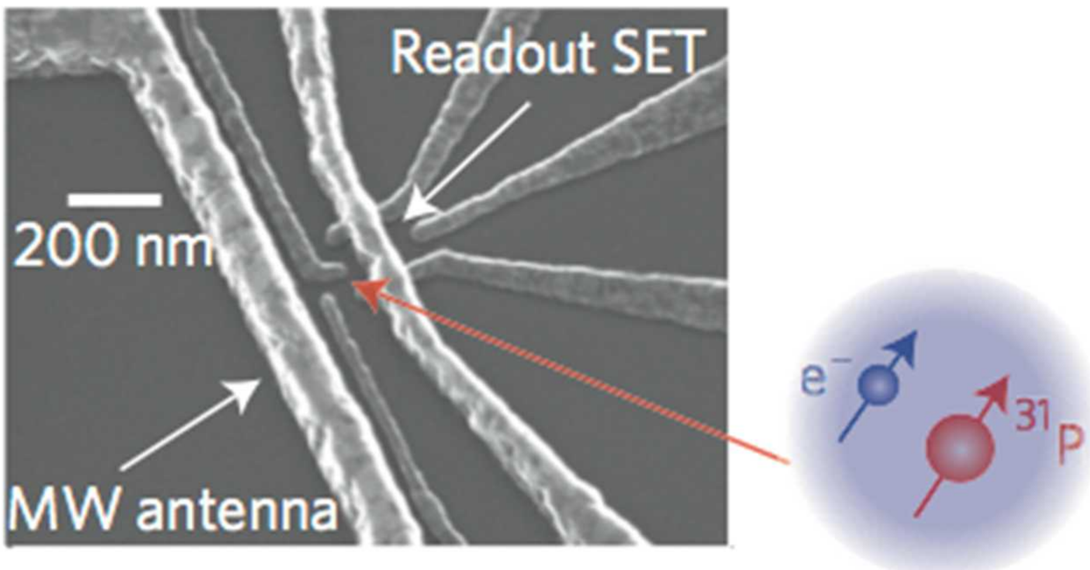
[1] D. **Loss** and D. P. **DiVincenzo**, “Quantum computation with quantum dots,” Phys. Rev. A, vol. 57, no. 1, pp. 120–126, Jan. 1998.
[2] www.wikipedia.org



Loss-DiVincenzo-like architecture

Yes, that’s 17 years ago!

Donors in isotopically-enriched silicon 28 have very good quantum coherence



Electron spin 1/2:

$T_2^* = 270\ \mu s$

$T_{2,\ CPMG} = 560\ ms$

$F_{prep/readout} = 97\%$

$F_{control} = 99.6\%$

Nuclear spin 1/2:

$T_2^* = 600\ ms$

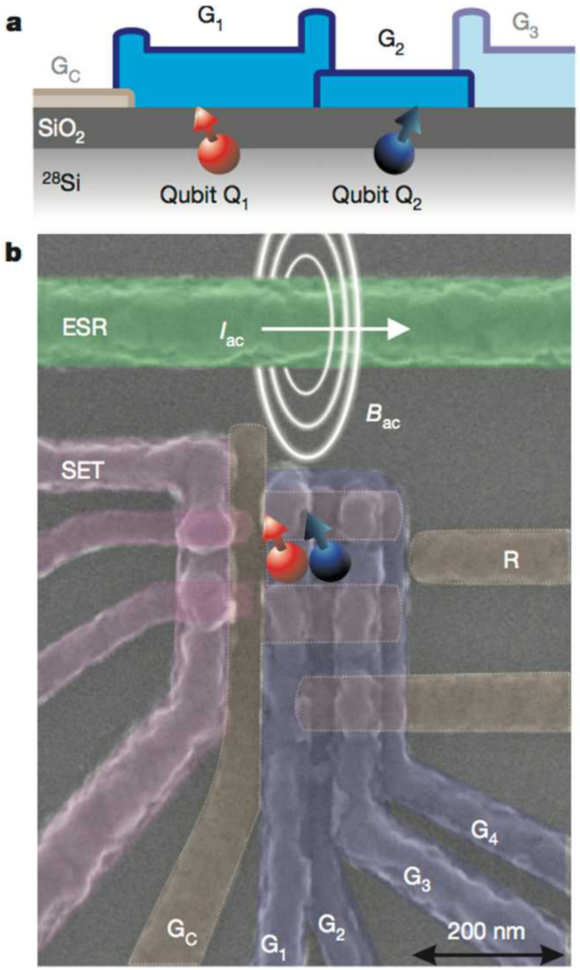
$T_{2,\ CPMG} = 36.5\ s$

$F_{prep/readout} = 99.995\%$

$F_{control} = 99.99\%$

[1] J. T. Muhonen, J. P. Dehollain, A. Laucht, F. E. Hudson, R. Kalra, T. Sekiguchi, K. M. Itoh, D. N. Jamieson, J. C. McCallum, A. S. Dzurak, and A. Morello, "Storing quantum information for 30 seconds in a nanoelectronic device," Nat Nano 9, 986 (2014).

Quantum dots in silicon are highly tunable



Electron spin 1/2:

$T_2^* = 120\ \mu s$

$T_{2,\ \mathrm{CPMG}} = 28\ \mathrm{ms}$

$F_{\mathrm{prep/readout}} = 92\%$

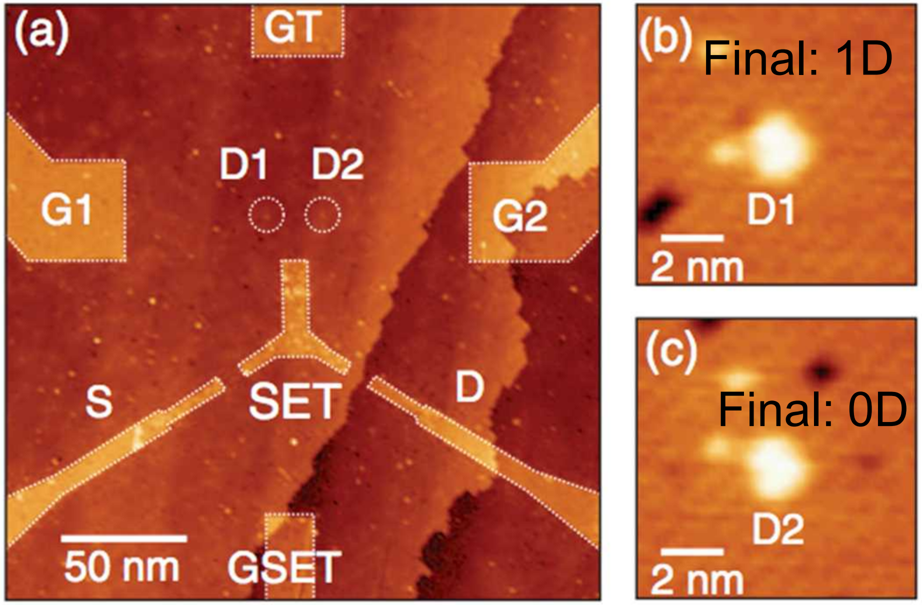
$F_{\mathrm{control}} = 99.59\%$

2-qubit gate:

$F \sim 96\%$

[1] M. Veldhorst, J. C. C. Hwang, C. H. Yang, A. W. Leenstra, B. de Ronde, J. P. Dehollain, J. T. Muhonen, F. E. Hudson, K. M. Itoh, A. Morello, and A. S. Dzurak, “An addressable quantum dot qubit with fault- tolerant control-fidelity,” Nat Nano 9, 981 (2014).
[2] M. Veldhorst, C. H. Yang, J. C. C. Hwang, W. Huang, J. P. Dehollain, J. T. Muhonen, S. Simmons, A. Laucht, F. E. Hudson, K. M. Itoh, A. Morello, and A. S. Dzurak, “A two-qubit logic gate in silicon,” Nature advance online publication, (2015).

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

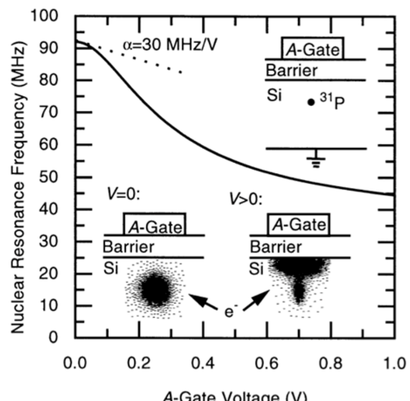


Not yet mature technology (fails stochastically)

[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).

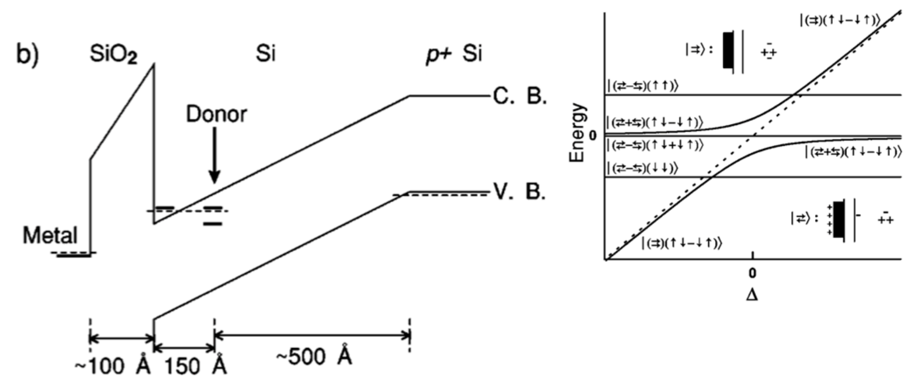
Coupling donor qubits involves quantum dots in many propositions…

Kane, 1998



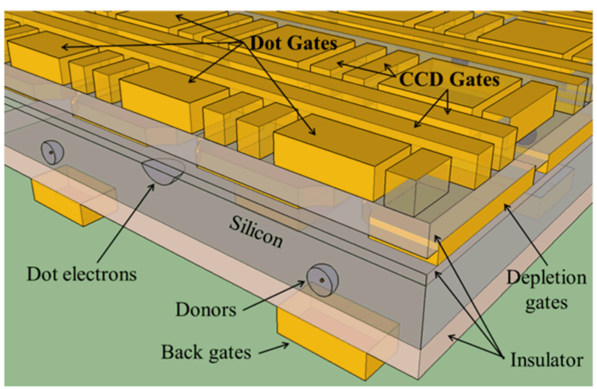
[1] B. E. Kane, “A silicon-based nuclear spin quantum computer,” Nature 393, 133 (1998).

Kane, 2000



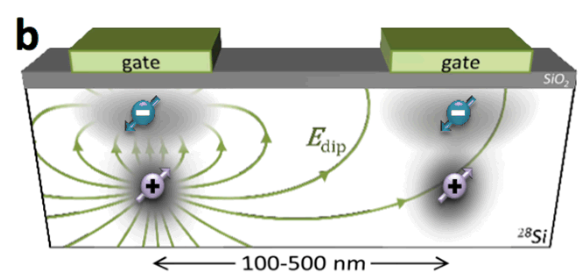
[1] B. E. Kane, N. S. McAlpine, A. S. Dzurak, R. G. Clark, G. J. Milburn, H. B. Sun, and H. Wiseman, Phys. Rev. B 61, 2961 (2000).

Pica, Lyon, 2015



[1] G. Pica, B. W. Lovett, R. N. Bhatt, T. Schenkel, and S. A. Lyon, “Surface code architecture for donors and dots in silicon with imprecise and non-uniform qubit couplings,” ArXiv e-prints (2015), arXiv:1506.04913 [cond-mat.mes-hall].

Tosi, Morello, 2015

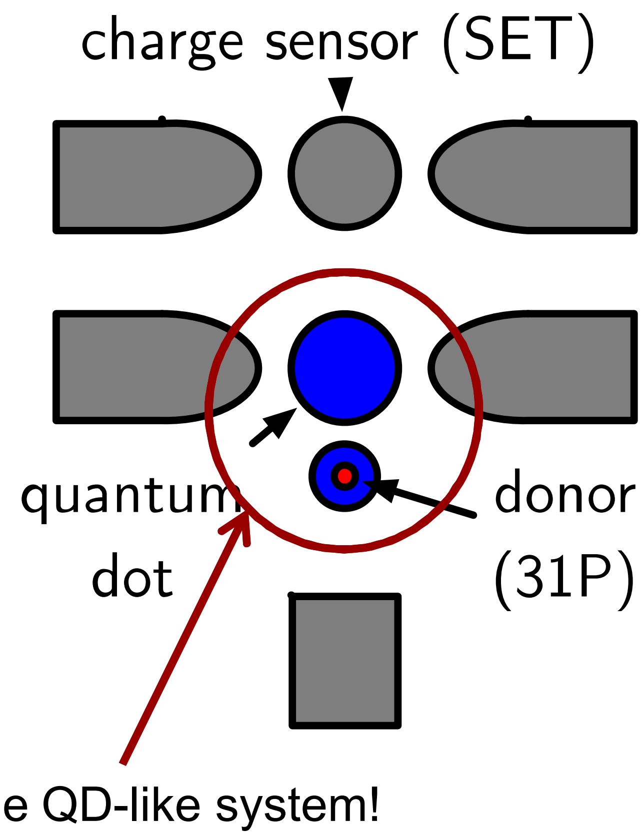


[1] G. Tosi, F. A. Mohiyaddin, S. B. Tenberg, R. Rahman, G. Klimeck, and A. Morello, “Silicon quantum processor with robust long-distance qubit couplings,” ArXiv e-prints (2015), arXiv:1509.08538 [cond- mat.mes-hall] .

New scheme: use donor contact hyperfine interaction to rotate the spin

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

Hybrid singlet-triplet qubit



For electron on donor:

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

S-T Hamiltonian:

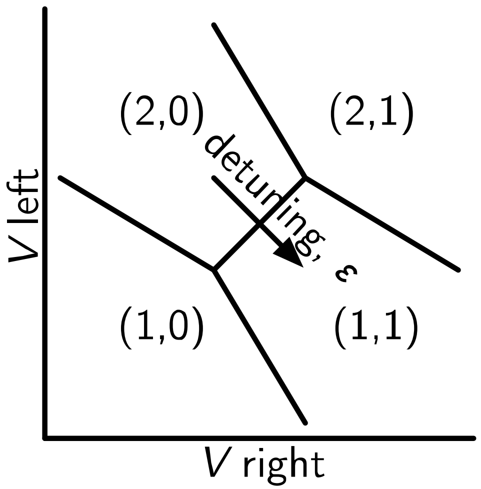
$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

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.** or **micromagnet**.
- Get a **nuclear spin** for free.

Singlet-triplet encoding

Charge stability diagram



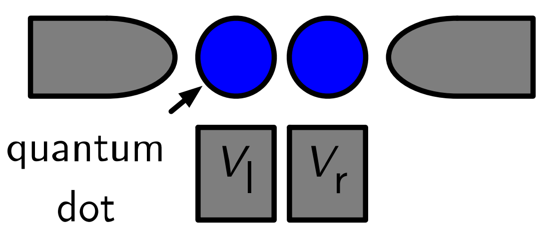
Spin states for two electrons

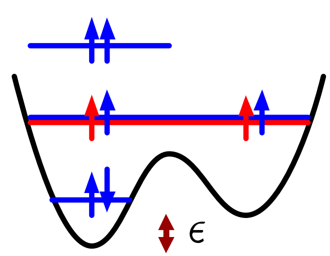
$$\left.\begin{aligned}|S\rangle &= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \\ |T_0\rangle &= |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\end{aligned}\right\} \quad m = 0$$

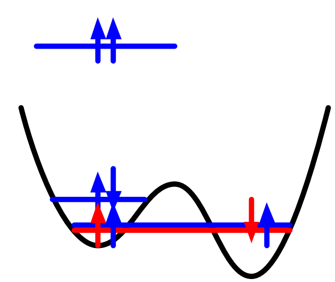
$$|T_-\rangle = |\downarrow\downarrow\rangle \qquad m = -1$$

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

Double QD

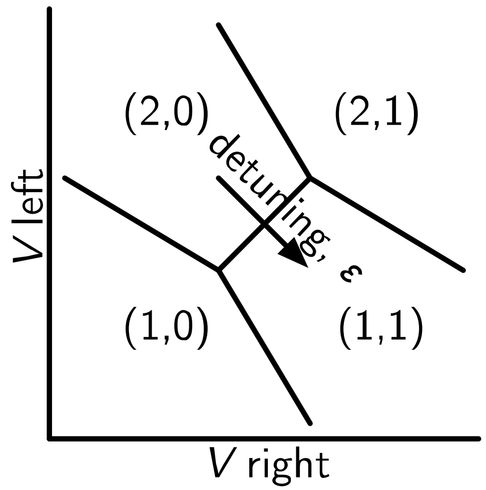


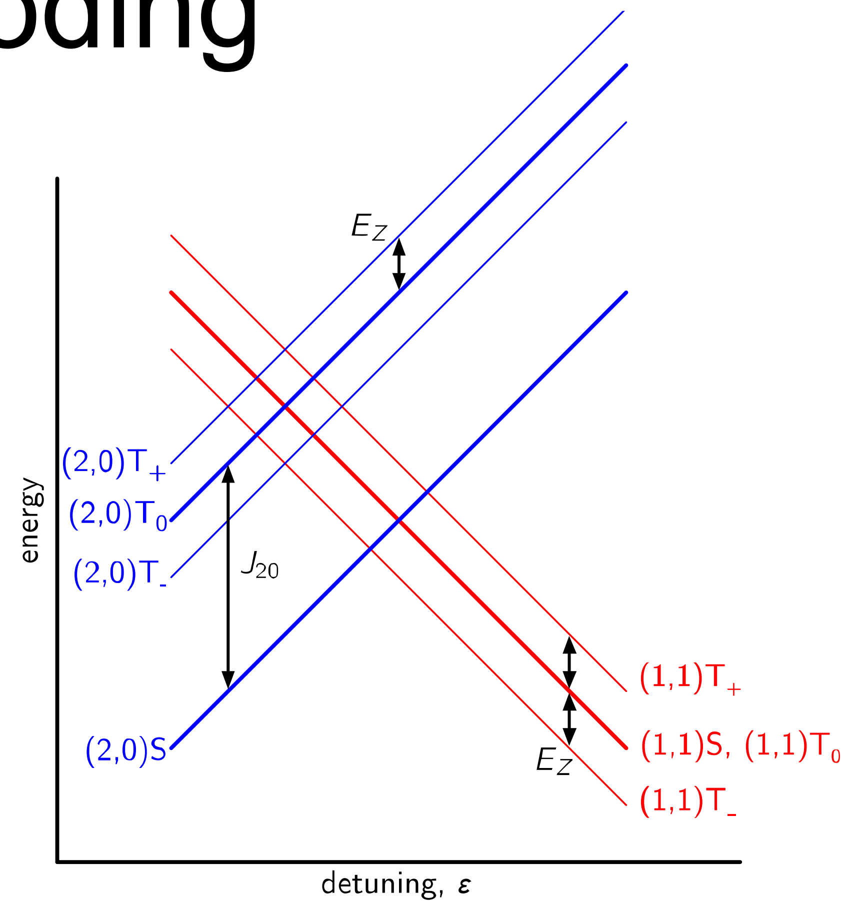




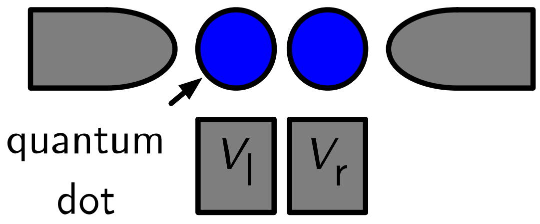
Singlet-triplet encoding

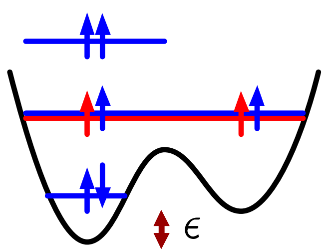
Charge stability diagram

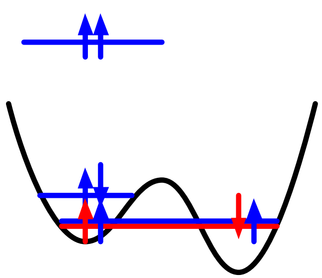




Double QD

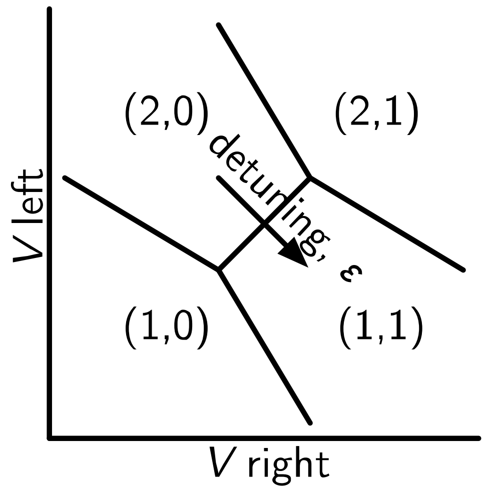


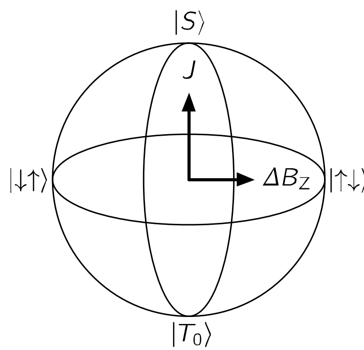


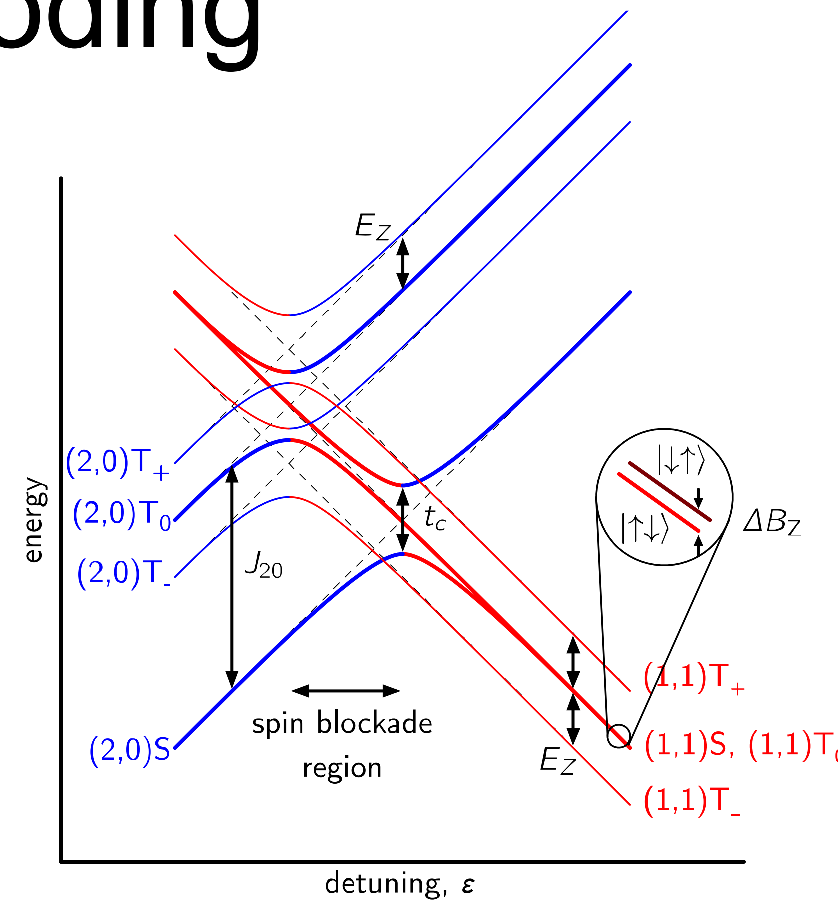


Singlet-triplet encoding

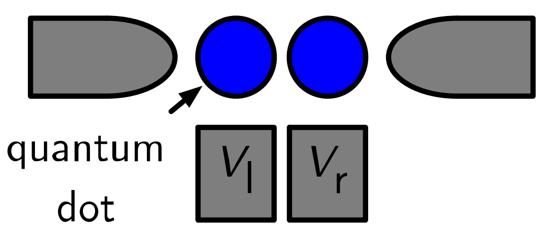
Charge stability diagram

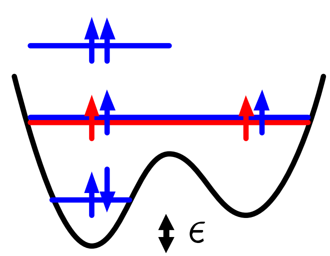


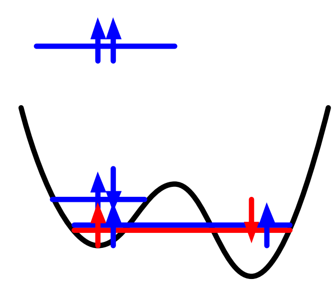




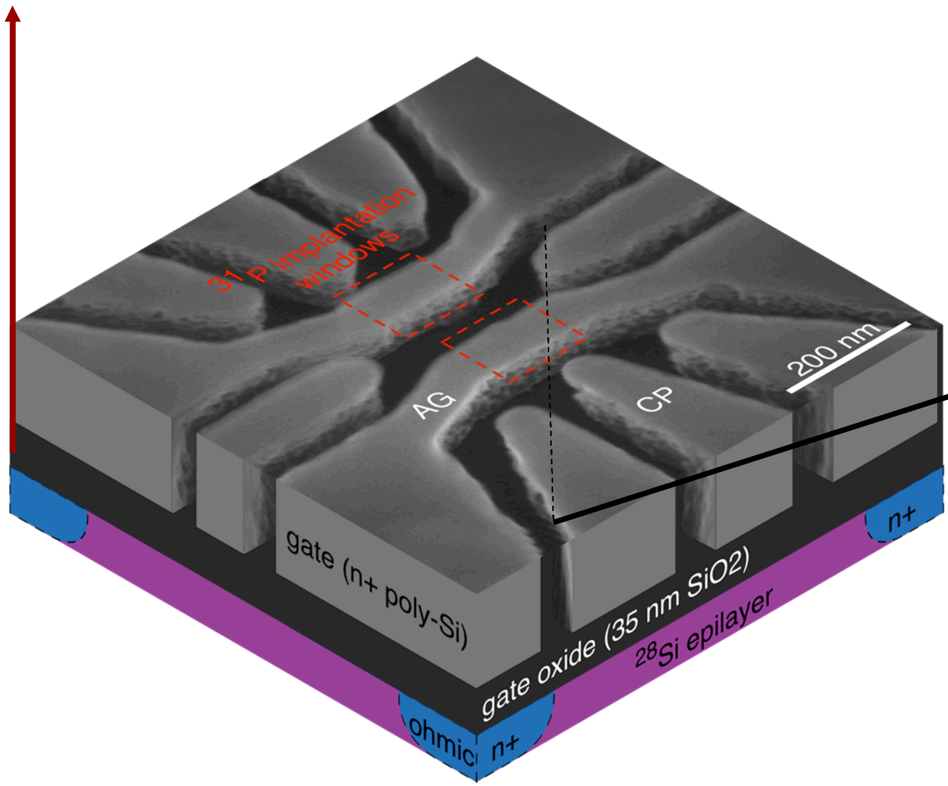
Double QD



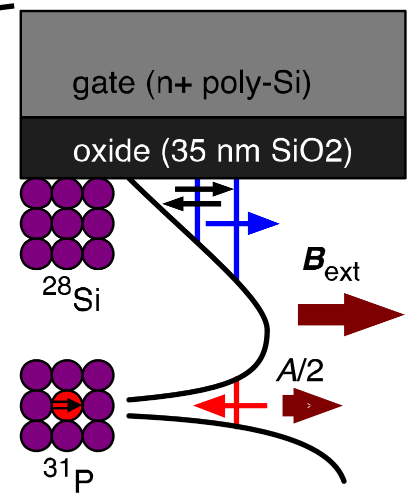




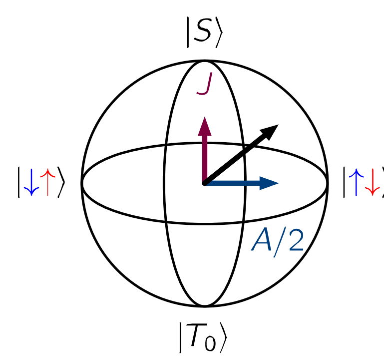
Our silicon MOS nanostructure



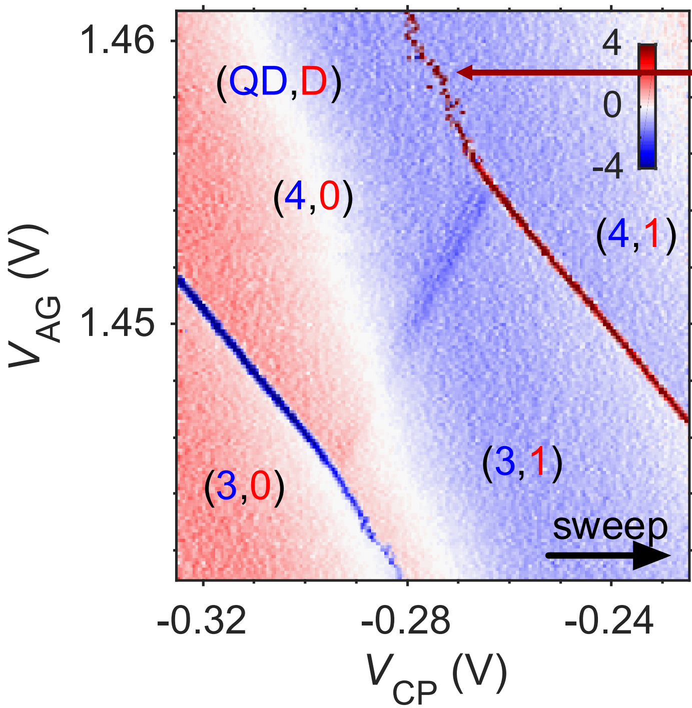
Filled-shell valley configuration

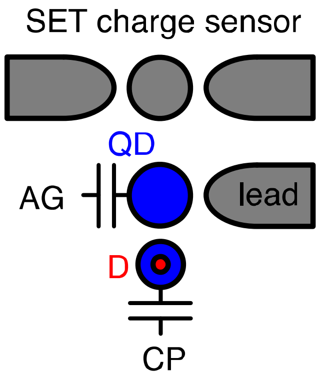


Bloch sphere

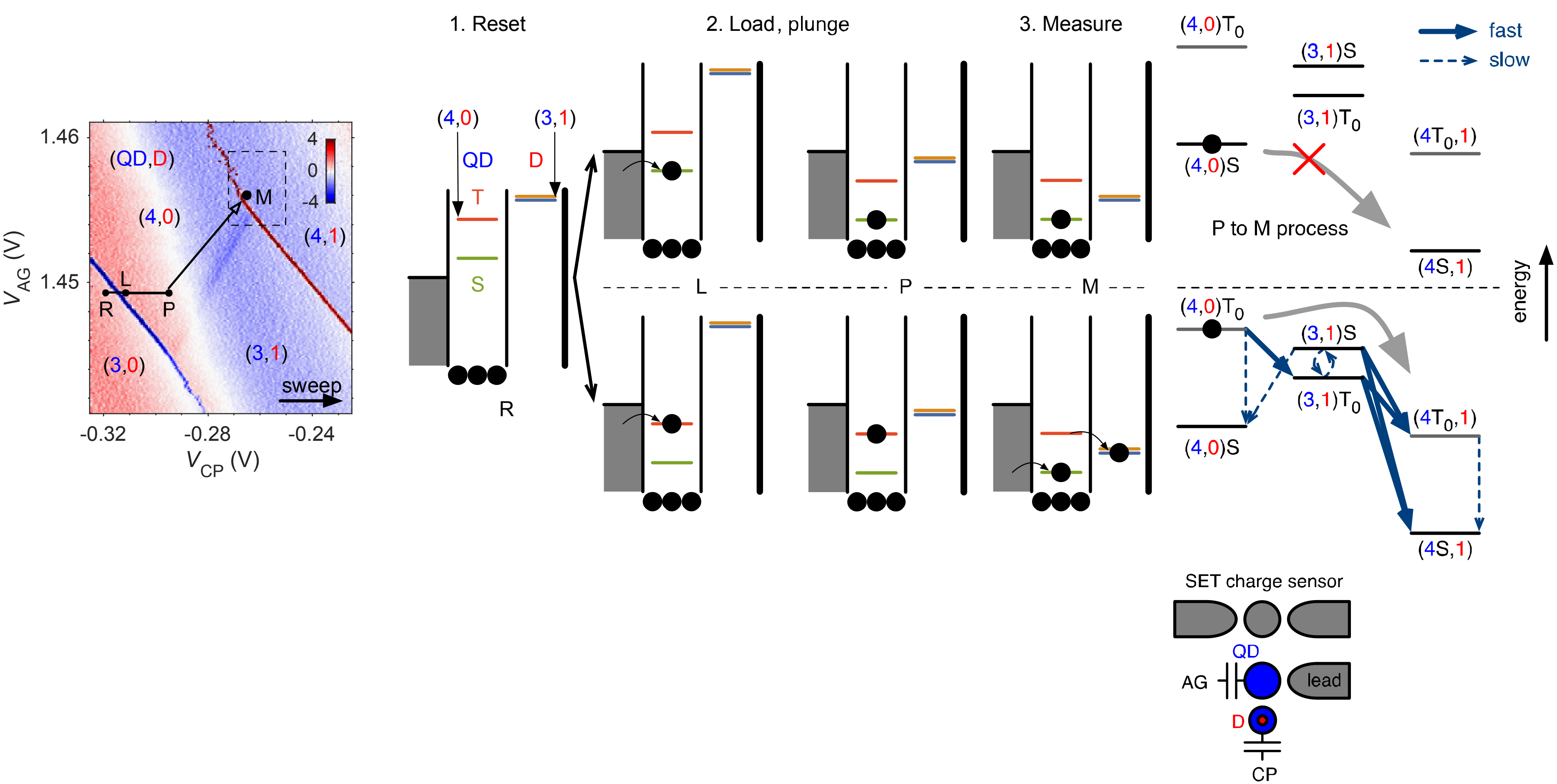


Quantum dot-donor anti-crossing

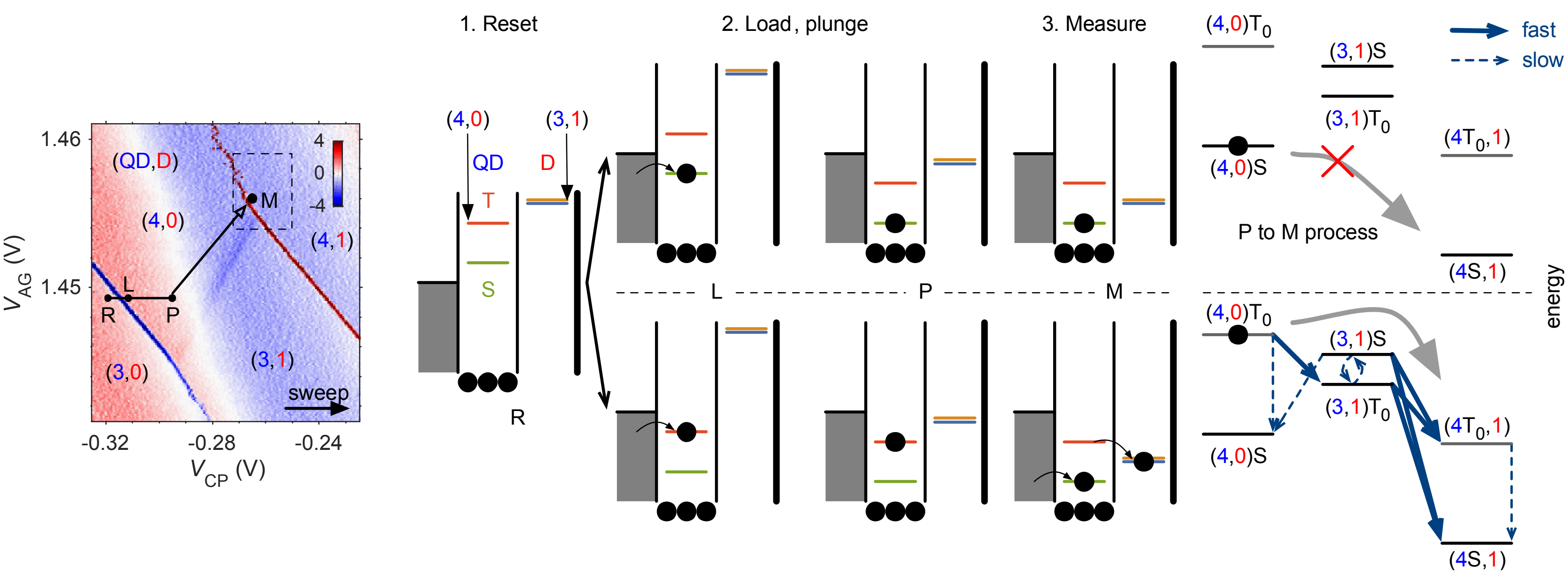


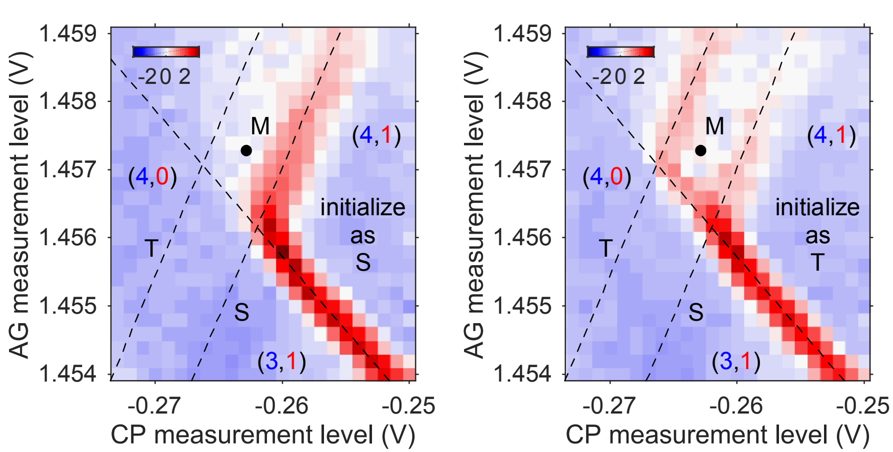


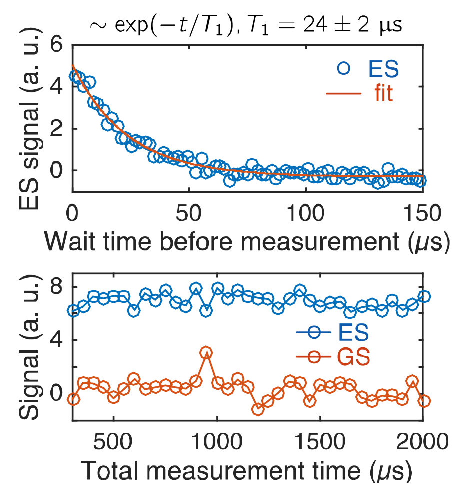
State preparation and readout



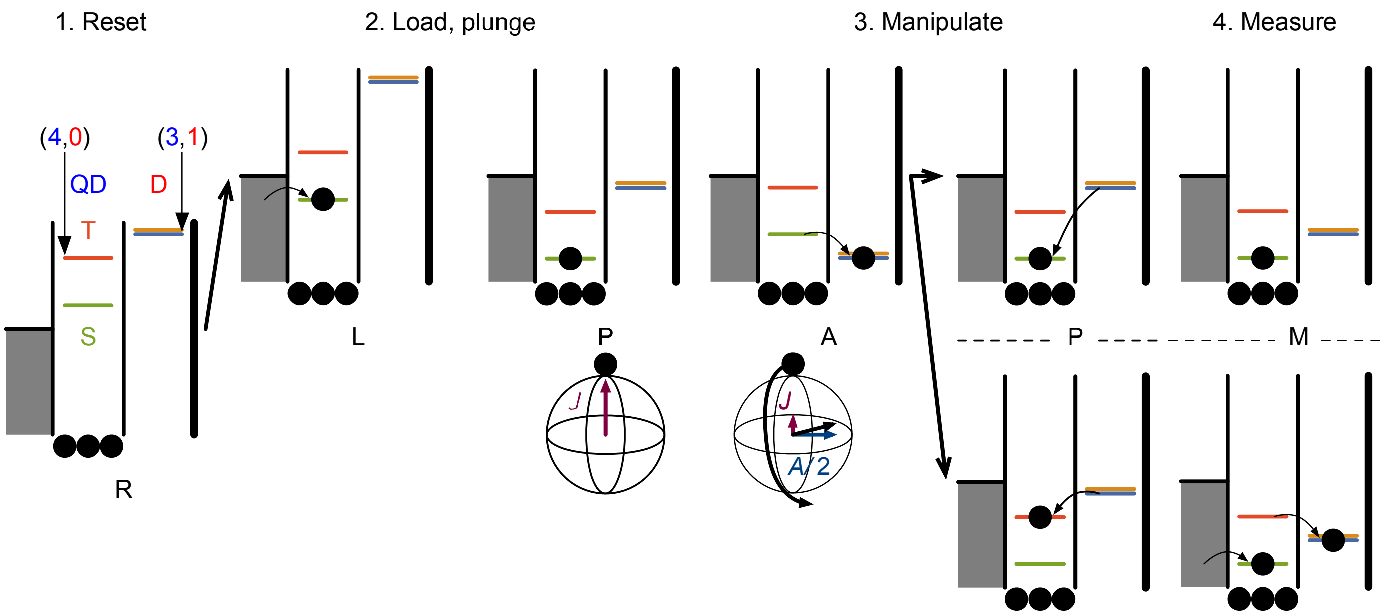
State preparation and readout

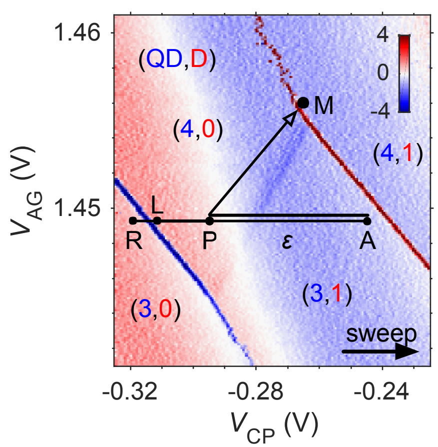


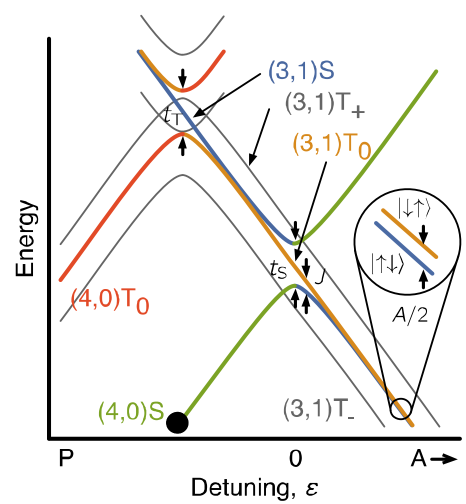


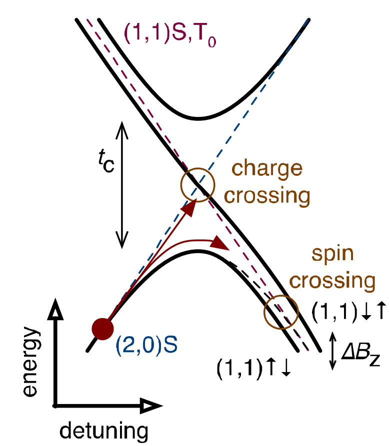


State manipulation



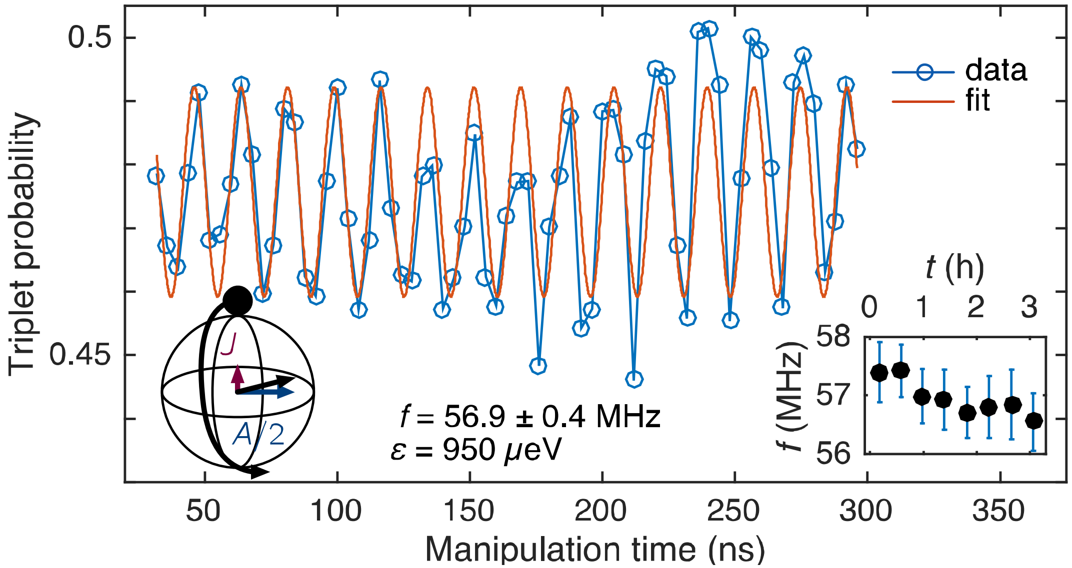




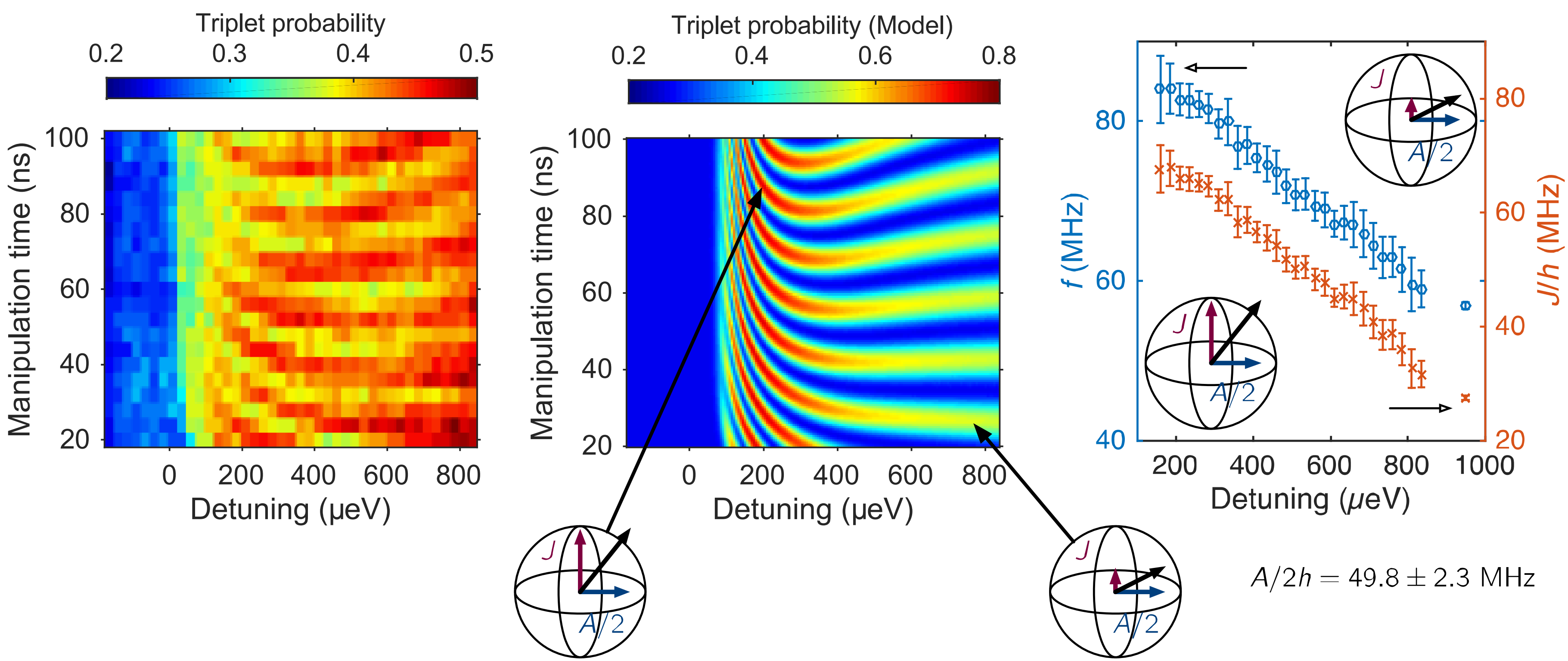


State manipulation

Singlet-triplet rotations driven by a single 31P nucleus

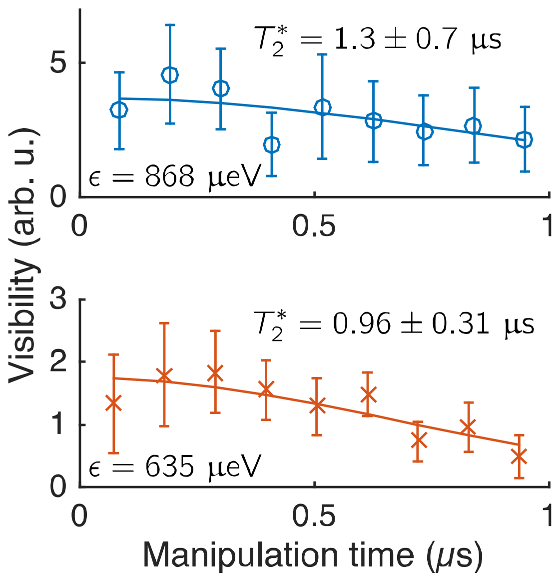


Detuning dependence of exchange interaction

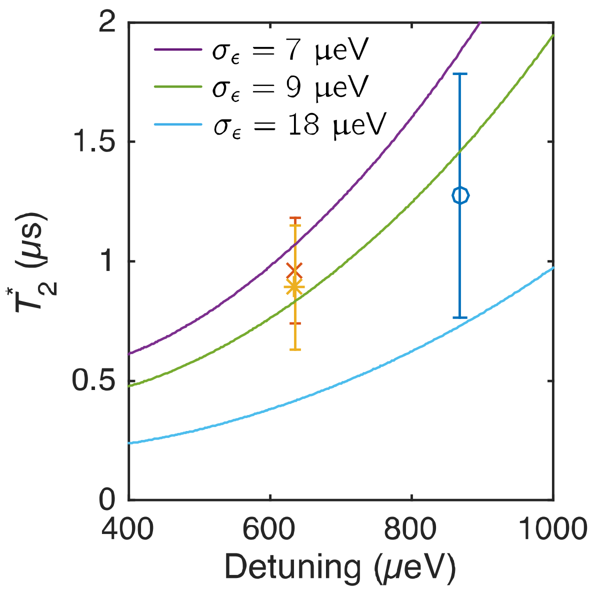


Coherence time and charge noise

Visibility decay

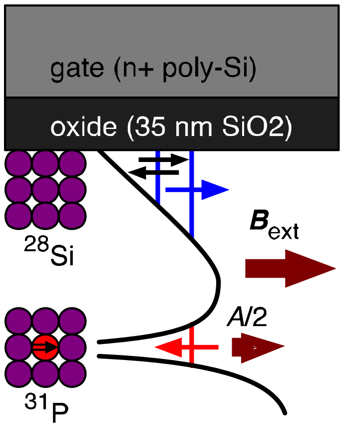


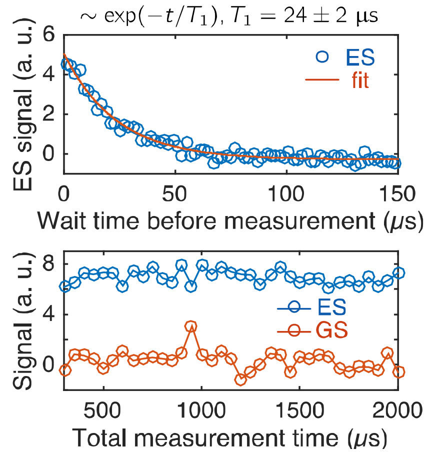
Coherence time vs detuning

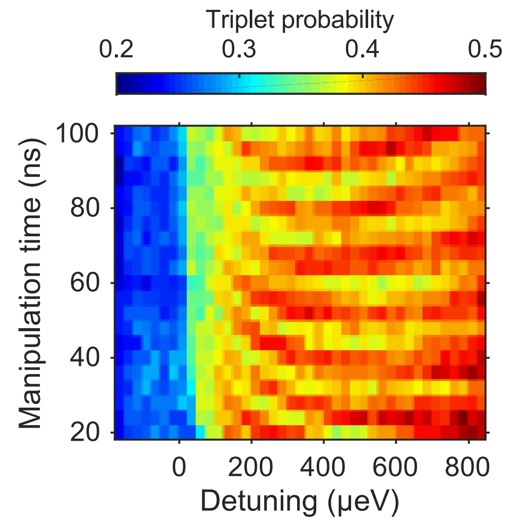


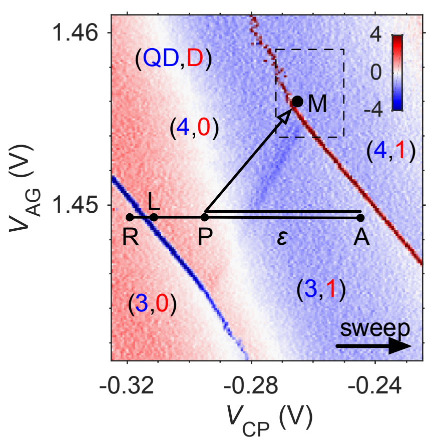
Charge-noise limited.
Possibly extended to > 10 μs

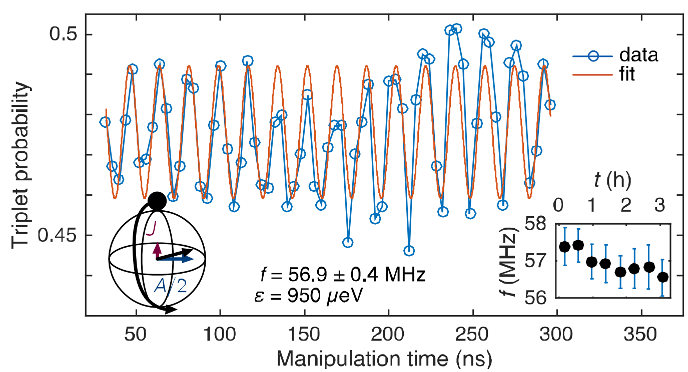
Summary

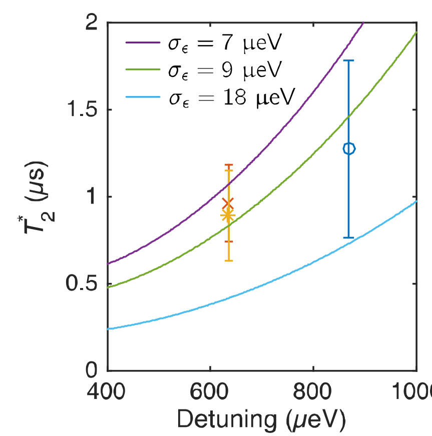

gate (n+ poly-Si)
oxide (35 nm SiO2)
28Si
31P
Bext
A/2


~ exp(−t/T1), T1 = 24 ± 2 µs
ES signal (a. u.)
ES
fit
Wait time before measurement (µs)
Signal (a. u.)
ES
GS
Total measurement time (µs)


Triplet probability
0.2
0.3
0.4
0.5
Manipulation time (ns)
Detuning (µeV)


(QD,D)
(4,0)
(4,1)
(3,0)
(3,1)
M
R
L
P
ε
A
sweep
VAG (V)
VCP (V)


Triplet probability
data
fit
J
A/2
f = 56.9 ± 0.4 MHz
ε = 950 µeV
t (h)
f (MHz)
Manipulation time (ns)


σϵ = 7 µeV
σϵ = 9 µeV
σϵ = 18 µeV
T2* (µs)
Detuning (µeV)

Future work

Singlet-triplet qubit

- AC control
- Single-shot readout
- Address visibility

Exciting possibilities

- Coupling of donor-based ST qubits
- Nuclear spin readout (without electron spin resonance)
- Nuclear spin qubit (with nuclear magnetic resonance)
- Coupling of donor qubits (original Kane proposal)

Acknowledgements & Team

And the rest of the QIST 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

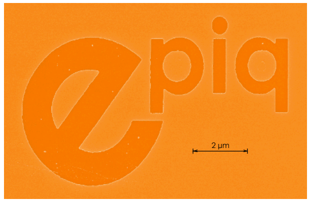
Theory

- N. Tobias Jacobson
- Erik Nielsen
- John K. Gamble
- Richard Muller

Université de Sherbrooke

- Michel Pioro-Ladrière (academic advisor)

Quantum Information S&T



National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY

CRSNG NSERC

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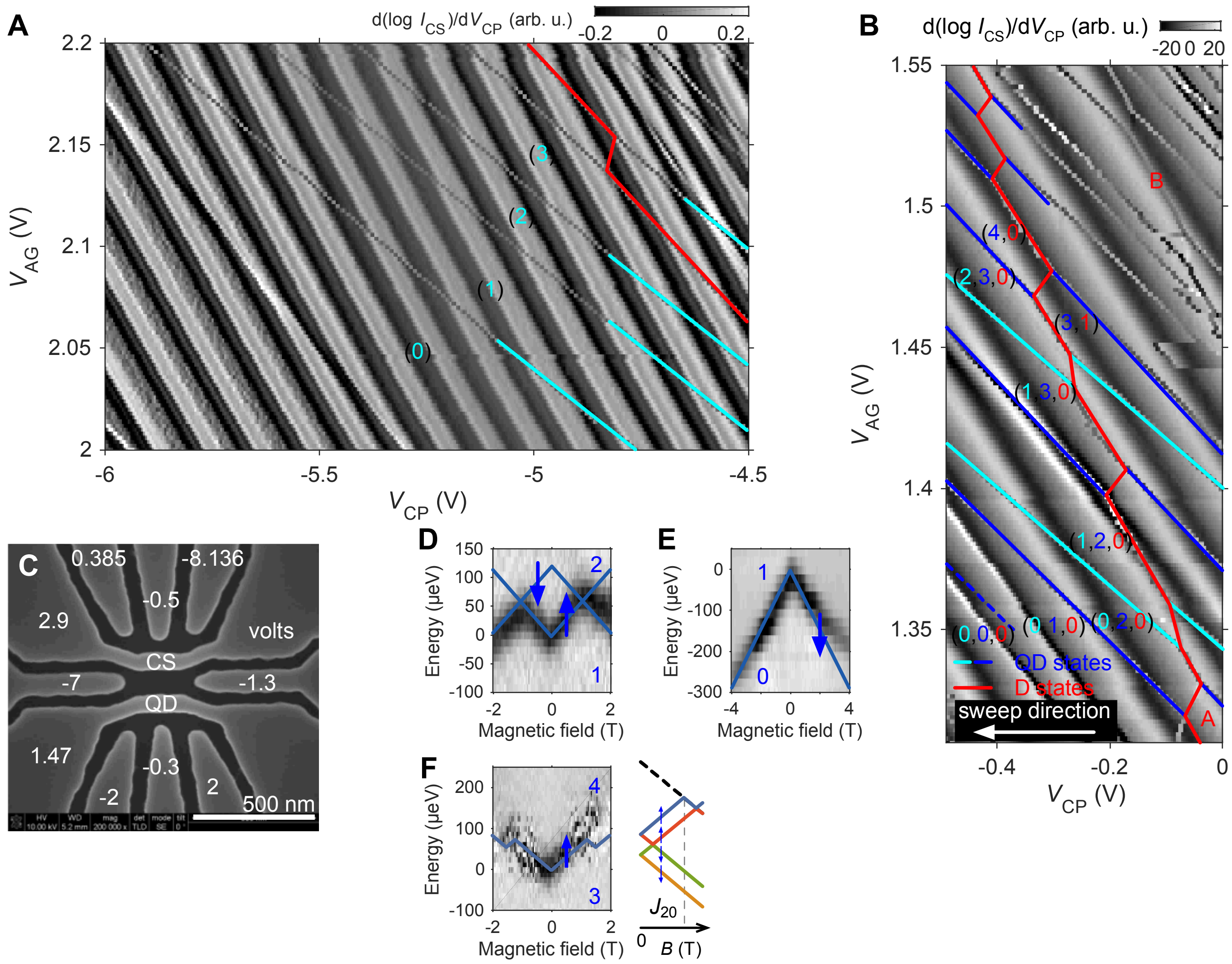
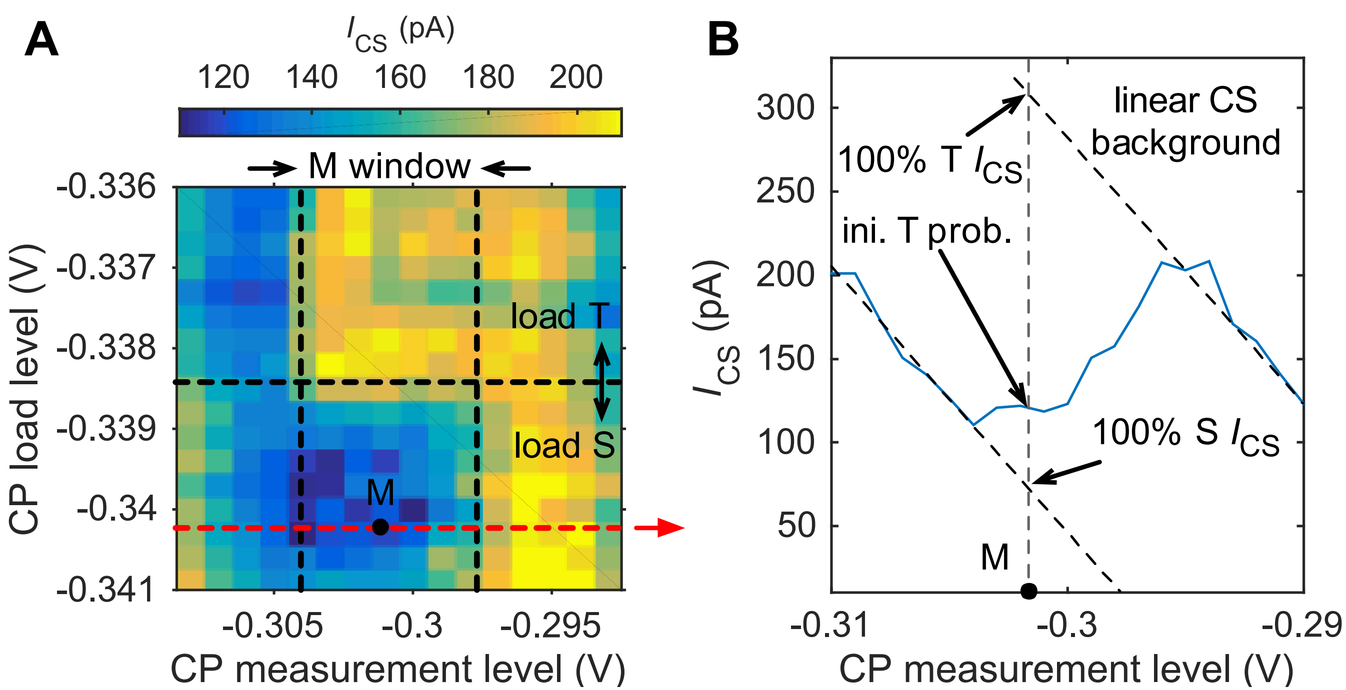
This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned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

Additional slides



Additional slides



Additional slides