Silicon-based Quantum Computing: From laboratory to industrial manufacture

Andrew Dzurak

UNSW - Sydney

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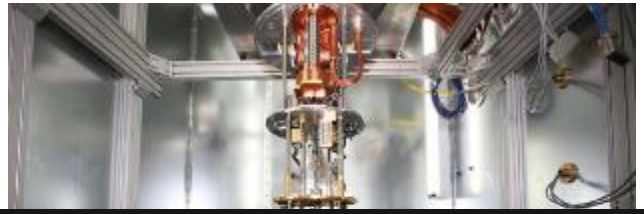
Australian National Fabrication Facility

The New York Times

Google Buys a Quantum Computer

By Quentin Hardy | May 16, 2013 5:00 am



Google and a corporation associated with NASA are forming a laboratory to study artificial intelligence by means of computers quantum physics. Their quantum computer, whicl thousands of times faster than existing supercomp use in the third quarter of this year.

A quantum computer deve
Credit Kim Stallknech

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TECHNOLOGY

IBM's quantum computer gets powerful upgrade

Friday, May 19, 2017 - 01:55

The New York Times | https://nyti.ms/2ferL3u

TECHNOLOGY

Microsoft Spends Big to Build a Computer Out of Science Fiction

By JOHN MARKOFF NOV. 20, 2016

SAN FRANCISCO — Microsoft is putting its considerable financial and engineering muscle into the experimental field of quantum computing as it works to build a machine that could tackle problems beyond the reach of today's digital computers.

Todd Holmdahl will direct Microsoft's quantum computing efforts.
Credit Ian C. Bates for The New York Times

Commercial Investments in QC

Superconducting QC

Google IBM D-Wave The Quantum Computing Company™

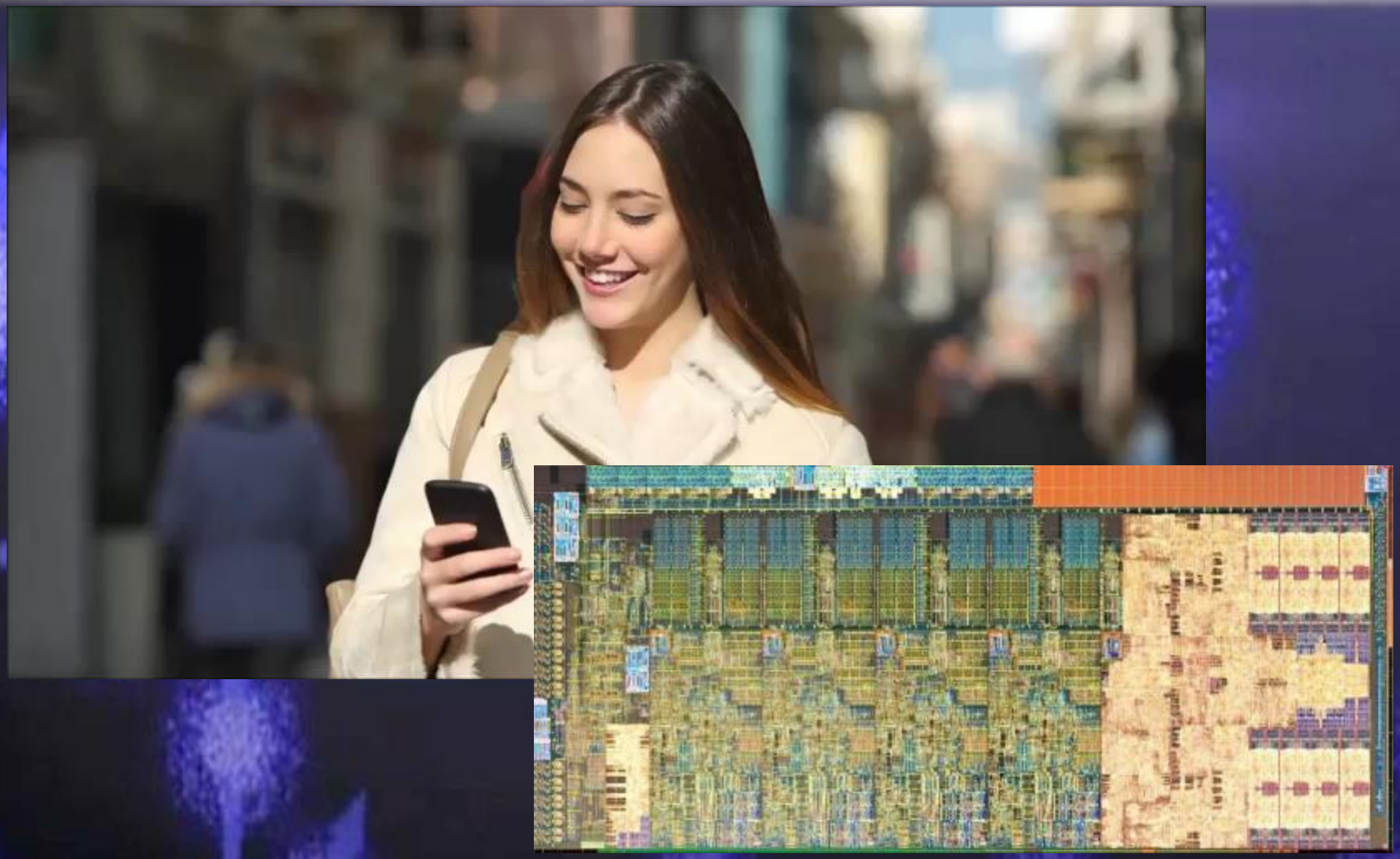
Microsoft ***Topological QC***

intel ***Superconducting QC & Silicon QC***

Silicon QC

SILICON QUANTUM COMPUTING UNSW AUSTRALIA Australian Government NSW GOVERNMENT TELSTRA CommonwealthBank

Silicon Quantum Computing



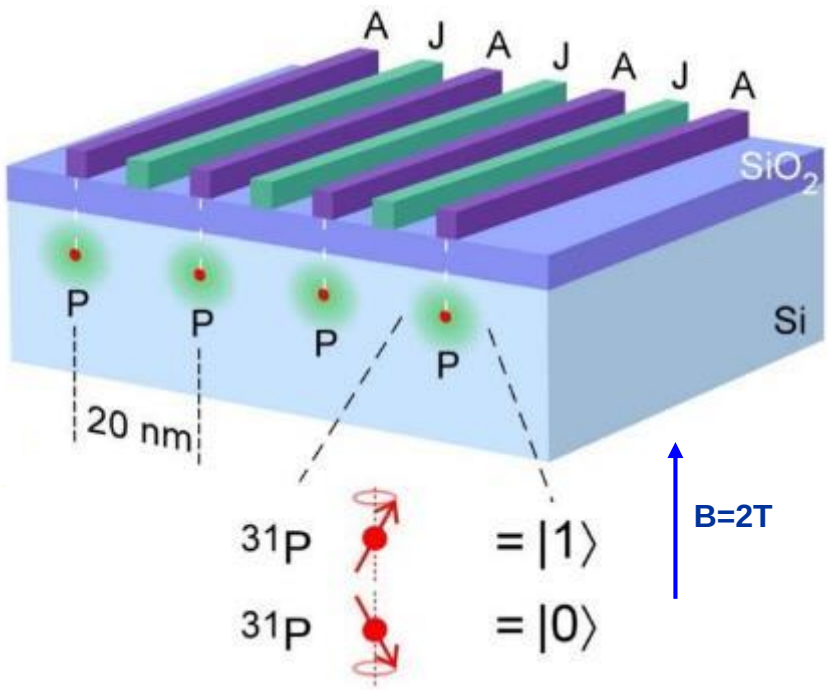
Spin Qubits in Silicon

NATURE | VOL 393 | 14 MAY 1998 133

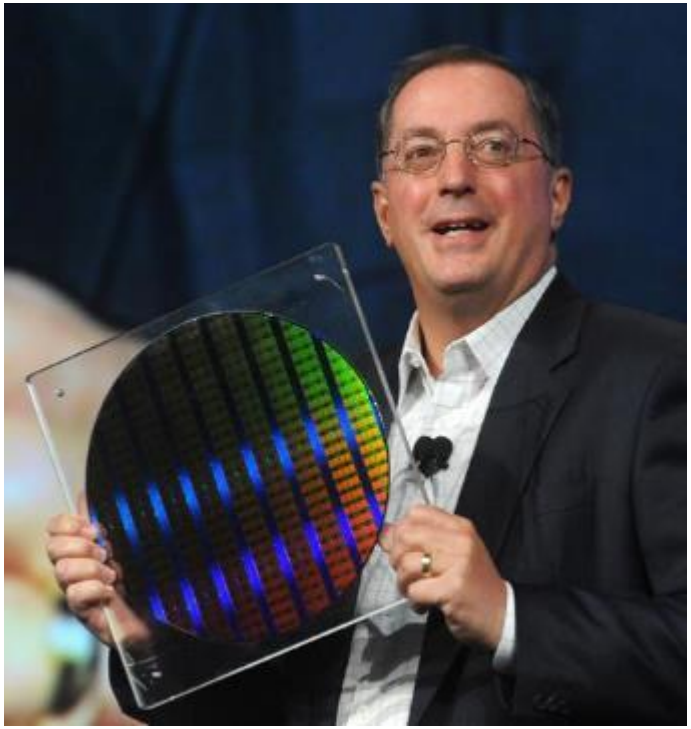
A silicon-based nuclear spin quantum computer

B. E. Kane

Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Australia



- **Long Coherence Times in Silicon at 1K:**
  - → **Nuclear – mins**
  - → **Electron – ms-s**
- **Scalable**
- **Industry "Compatible"**



B.E. Kane, *Nature* 393, 133 (1998)

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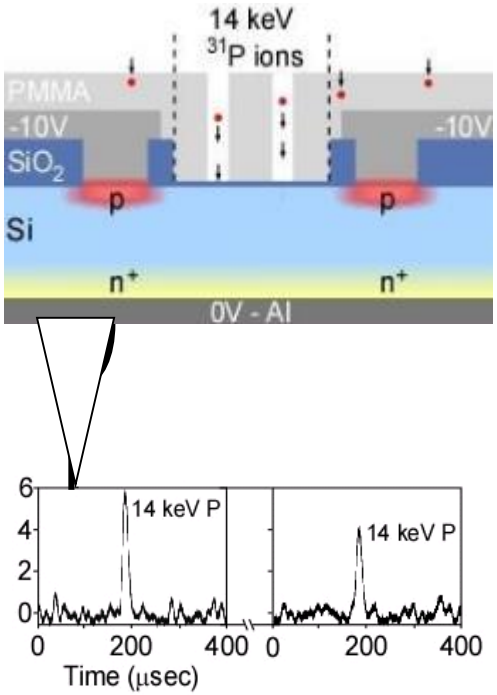
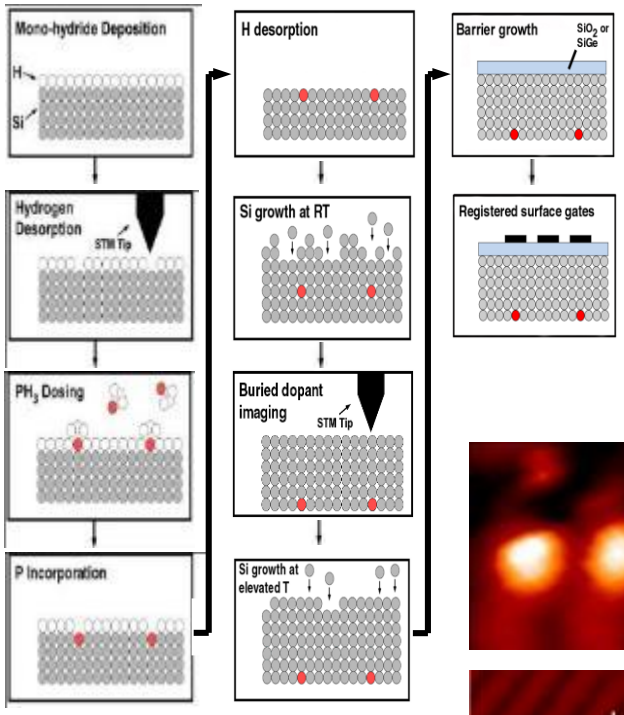
Silicon Qubits: *Single-Atom* Nanotechnologies

Top-Down

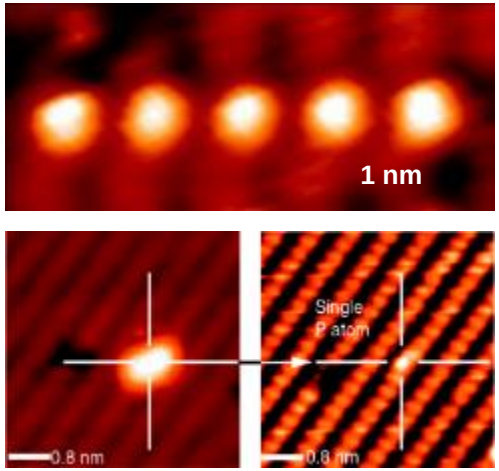
Jamieson, Yang, Hopf, Hearne, Pakes, Prawer, Mitic, Gauja, Andresen, Hudson, Dzurak and Clark, **Appl. Phys. Lett. 86, 202101 (2005)**



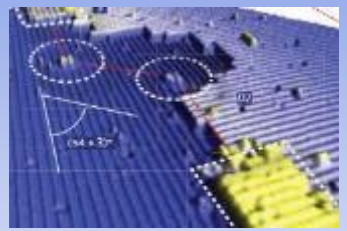
Bottom-Up



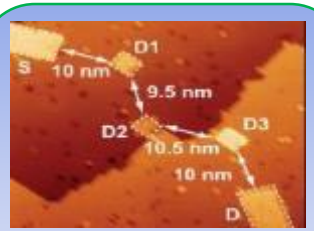
O'Brien, Schofield, Simmons, Clark, Dzurak, Curson, Kane, McAlpine, Hawley and Brown, **Phys.Rev. B 64, R161401 (2001)**



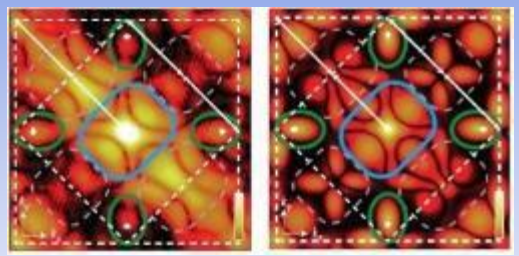
Atomically Precise *STM-fabricated* Devices



Nature Nanotechnology
9, 430 (2014)

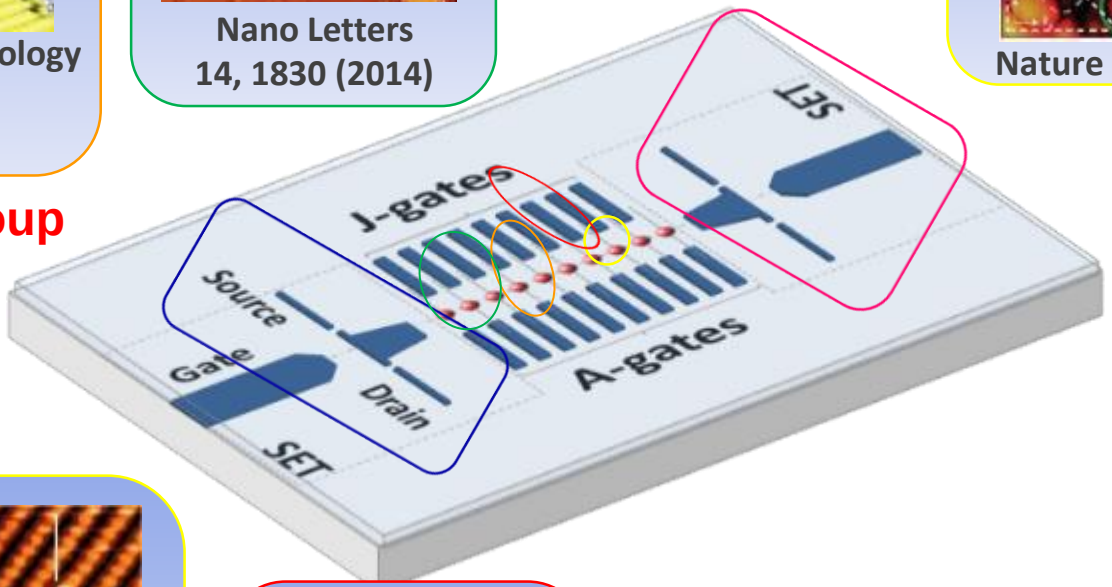


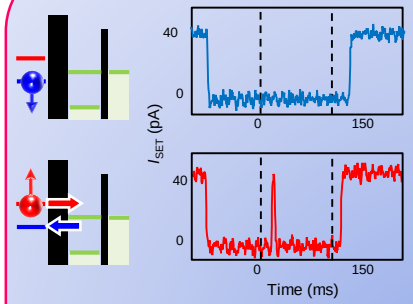
Nano Letters
14, 1830 (2014)



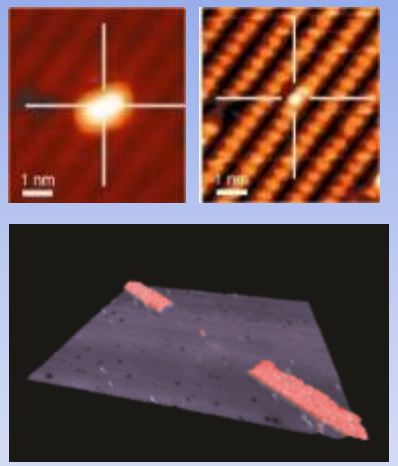
Nature Materials 13, 605 (2014)

Simmons Group
UNSW

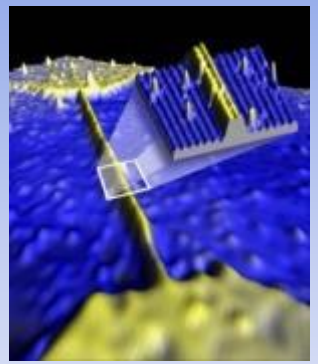




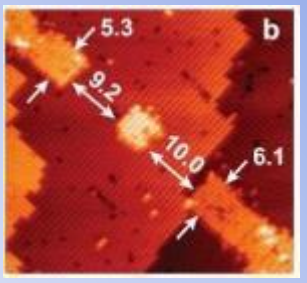
Nature Communications
4, 2017 (2013)



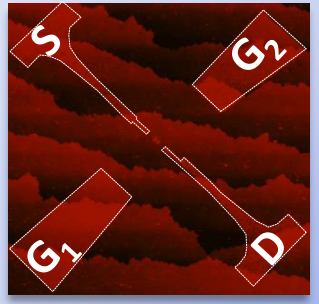
Nature Nanotechnology
7, 242 (2012)



Science
335 64 (2012)



Nature
Nanotechnology
5, 502 (2010)



Nano Letters
11, 4376 (2011)

Ion-Implanted Single-Atom Qubits

Ion Implantation:

Prof. David Jamieson

U. Melbourne

Si Device Engineering:

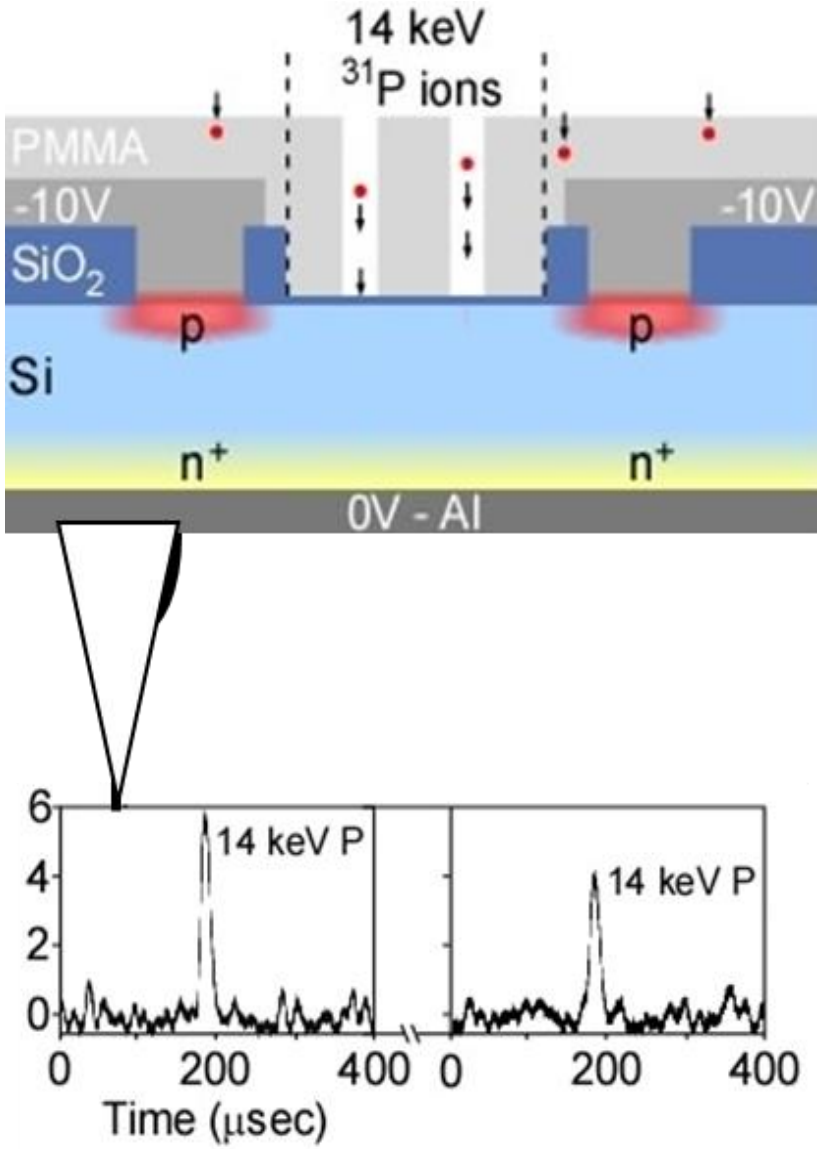
Prof. Andrew Dzurak

UNSW

Quantum Operations:

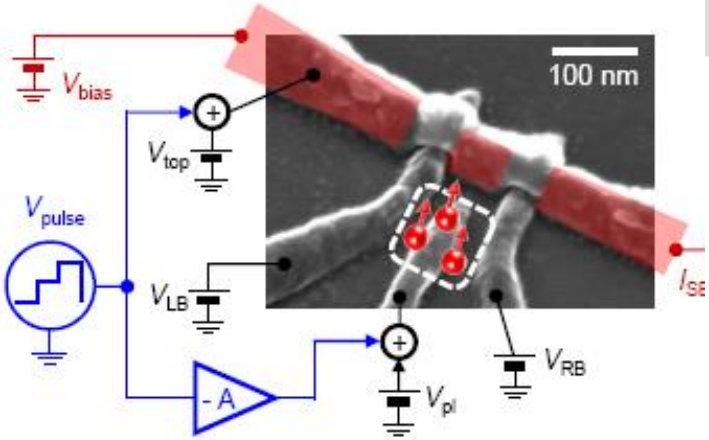
Prof. Andrea Morello

UNSW



Jamieson et al., *Appl. Phys. Lett.* 86, 202101 (2005)

Si:P e-Spin Qubit: *Single-Shot Readout*



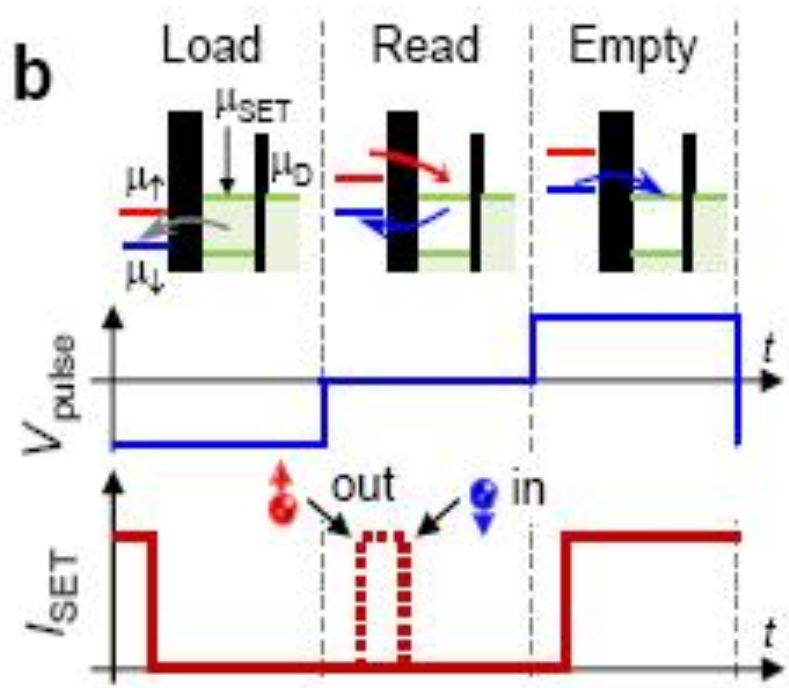
A. Morello et al., *Nature* 467, 687 (2010)

nature

LETTERS

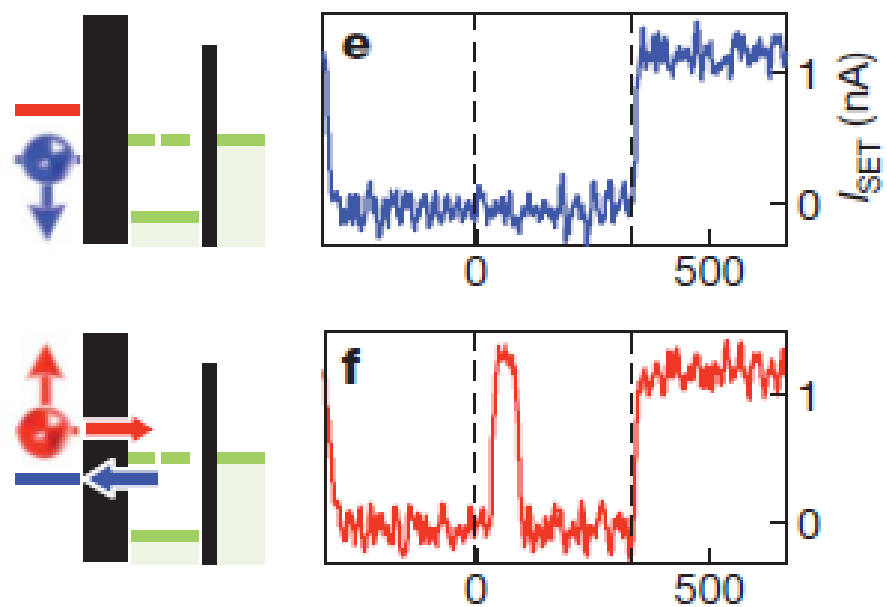
Single-shot readout of an electron spin in silicon

Andrea Morello[1], Jarryd J. Pla[1], Floris A. Zwanenburg[1], Kok W. Chan[1], Kuan Y. Tan[1], Hans Huebl[1]†, Mikko Möttönen[1,3,4], Christopher D. Nugroho[1]†, Changyi Yang[2], Jessica A. van Donkelaar[2], Andrew D. C. Alves[2], David N. Jamieson[2], Christopher C. Escott[1], Lloyd C. L. Hollenberg[2], Robert G. Clark[1]† & Andrew S. Dzurak[1]



T_{1e} = 6s (at 1.5T)

Fidelity > 90%

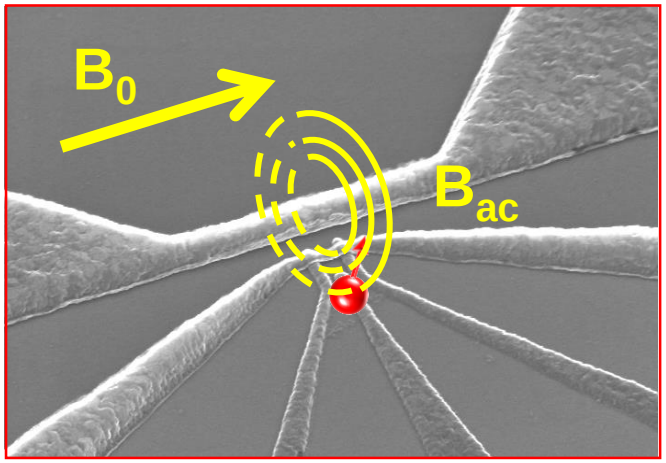


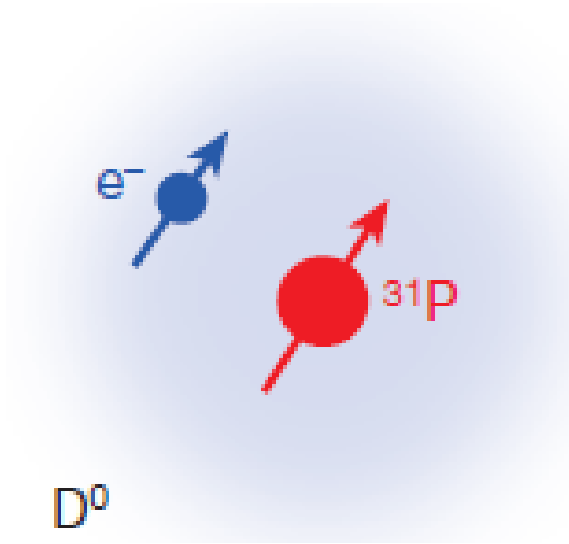
Qubit Gate Operations: P-Donor ESR & NMR

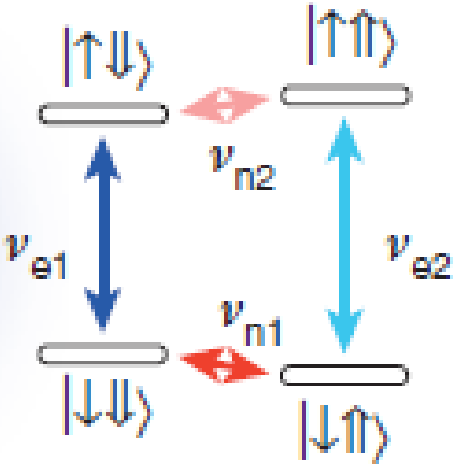
On-chip microwave transmission line:

J.P. Dehollain *et al*., *Nanotechnology* 24, 015202 (2013)

^{31}P:Si
P-Donor
Electron/Nuclear
Spin Levels







$$H = g\mu_B B_0 S_z - \gamma_n B_0 I_z + A\,\mathbf{I}\cdot\mathbf{S}$$

↓ = **Electron Spin, S**

⇓ = **Nuclear Spin, I**

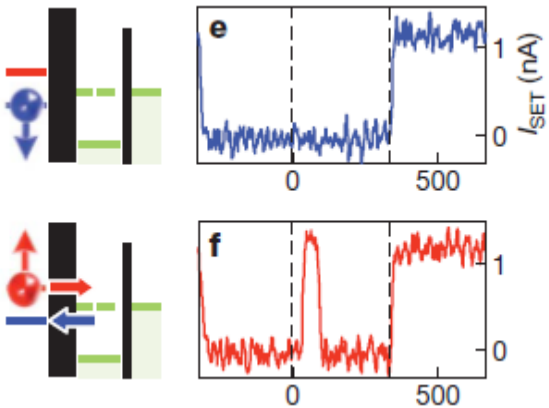
Si:P Donor Electron & Nuclear Spin Qubits

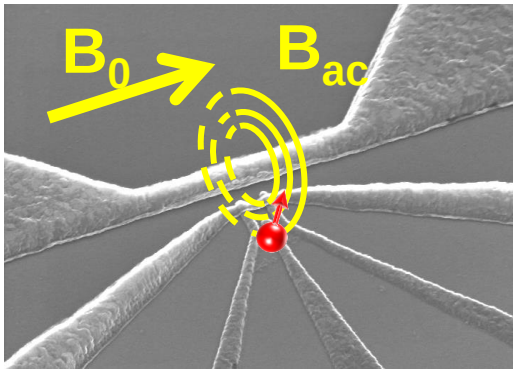
A. Morello et al., *Nature* 467, 687 (2010)

T_{1e} = 6s (at 1.5T)

Single-shot readout of an electron spin in silicon

Andrea Morello[1], Jarryd J. Pla[1], Floris A. Zwanenburg[1], Kok W. Chan[1], Kuan Y. Tan[1], Hans Huebl[1]†, Mikko Möttönen[1,3,4], Christopher D. Nugroho[1]†, Changyi Yang[2], Jessica A. van Donkelaar[2], Andrew D. C. Alves[2], David N. Jamieson[2], Christopher C. Escott[1], Lloyd C. L. Hollenberg[2], Robert G. Clark[1]† & Andrew S. Dzurak[1]





LETTER

J.J. Pla *et al.*, *Nature* 489, 541 (2012)

doi:10.1038/nature11449

A single-atom electron spin qubit in silicon

Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1], John J. L. Morton[2]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]

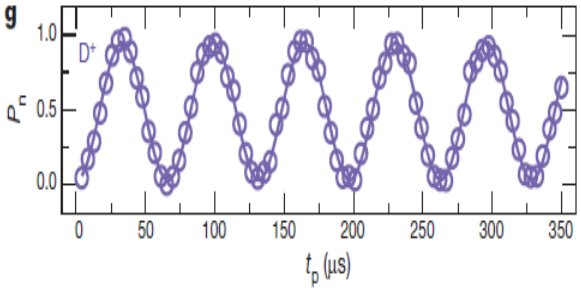
LETTER

J.J. Pla *et al.*, *Nature* 496, 334 (2013)

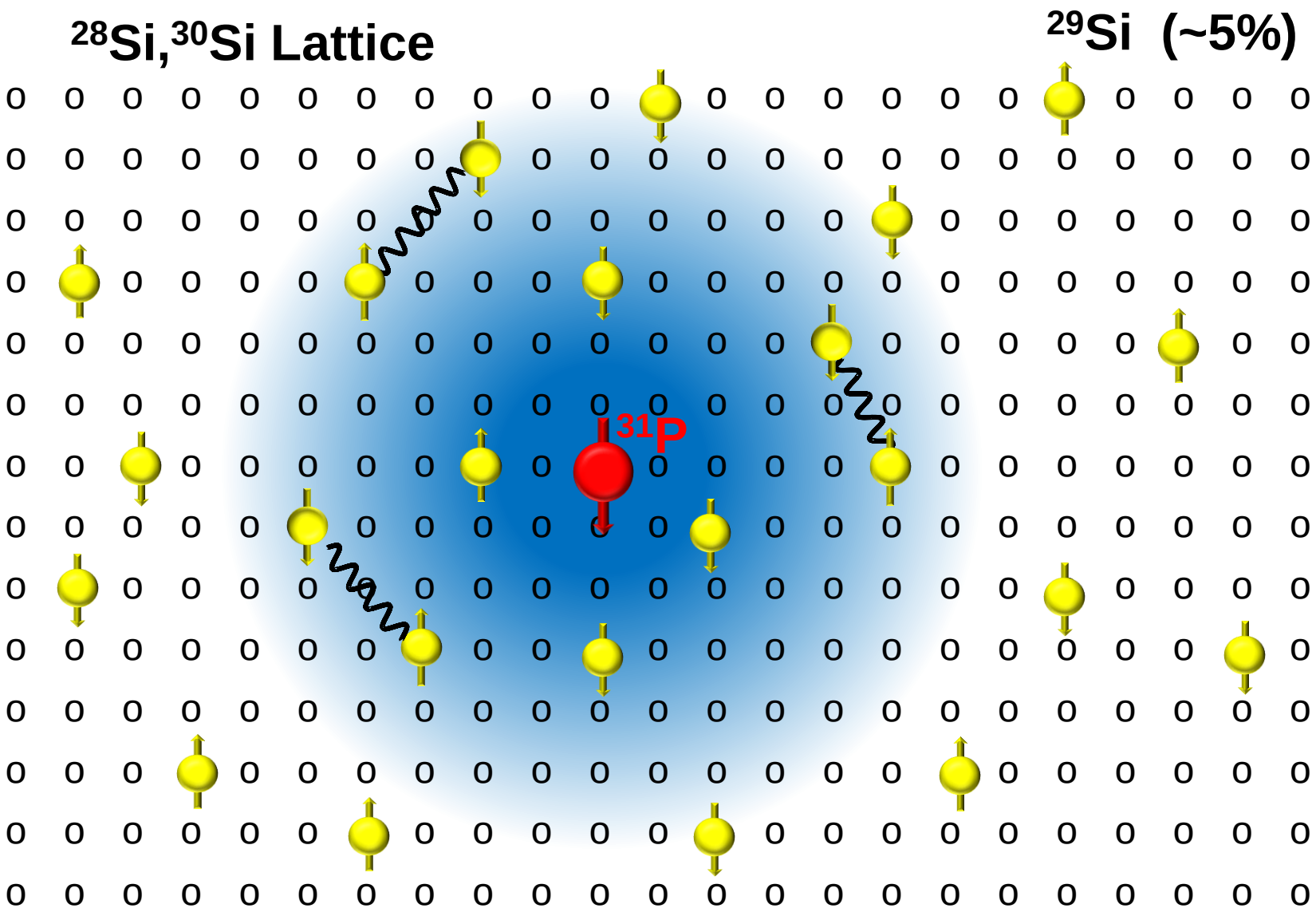
doi:10.1038/nature12011

High-fidelity readout and control of a nuclear spin qubit in silicon

Jarryd J. Pla[1], Kuan Y. Tan[1]†, Juan P. Dehollain[1], Wee H. Lim[1]†, John J. L. Morton[2], Floris A. Zwanenburg[1]†, David N. Jamieson[3], Andrew S. Dzurak[1] & Andrea Morello[1]



Lattice Nuclear Spin Noise in ^{nat}Si

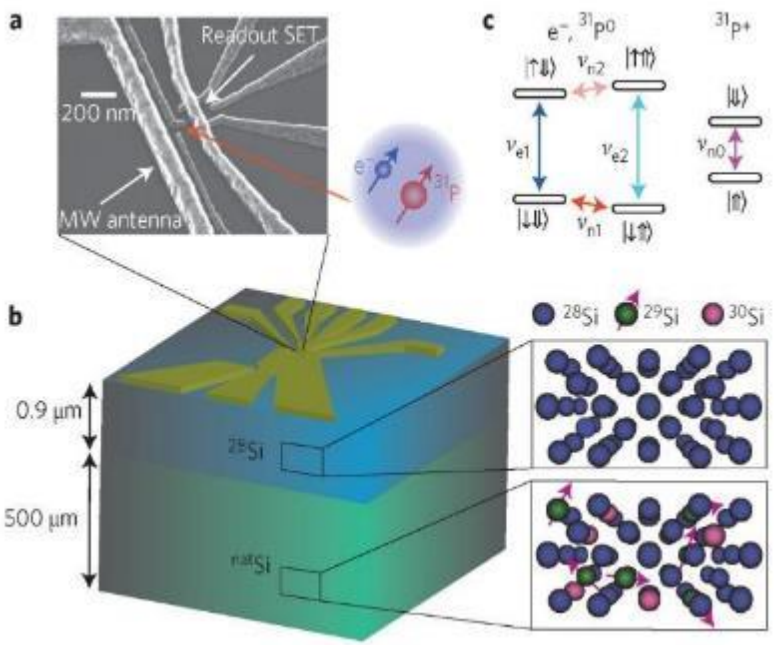


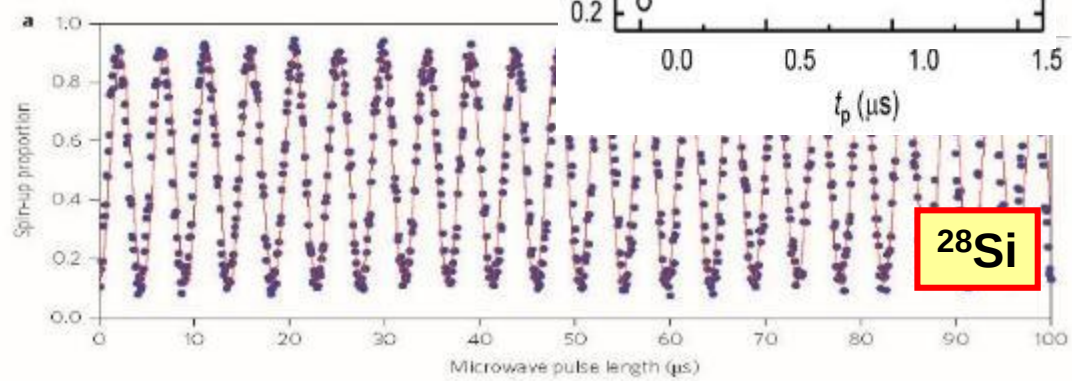
Si:P Donors: Electron & Nuclear Spin Qubits in ^{28}Si

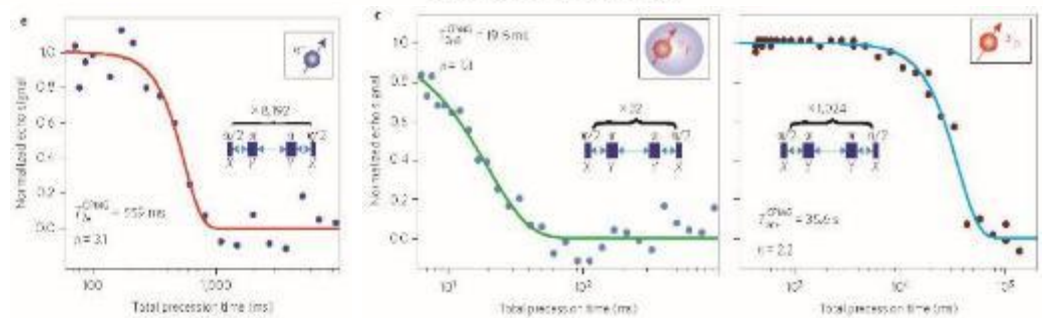
LETTERS
PUBLISHED ONLINE: 12 OCTOBER 2014 | DOI: 10.1038/NNANO.2014.211
nature nanotechnology

Storing quantum information for 30 seconds in a nanoelectronic device

Juha T. Muhonen[1]*, Juan P. Dehollain[1], Arne Laucht[1], Fay E. Hudson[1], Rachpon Kalra[1], Takeharu Sekiguchi[2], Kohei M. Itoh[2], David N. Jamieson[3], Jeffrey C. McCallum[3], Andrew S. Dzurak[1] and Andrea Morello[1]*







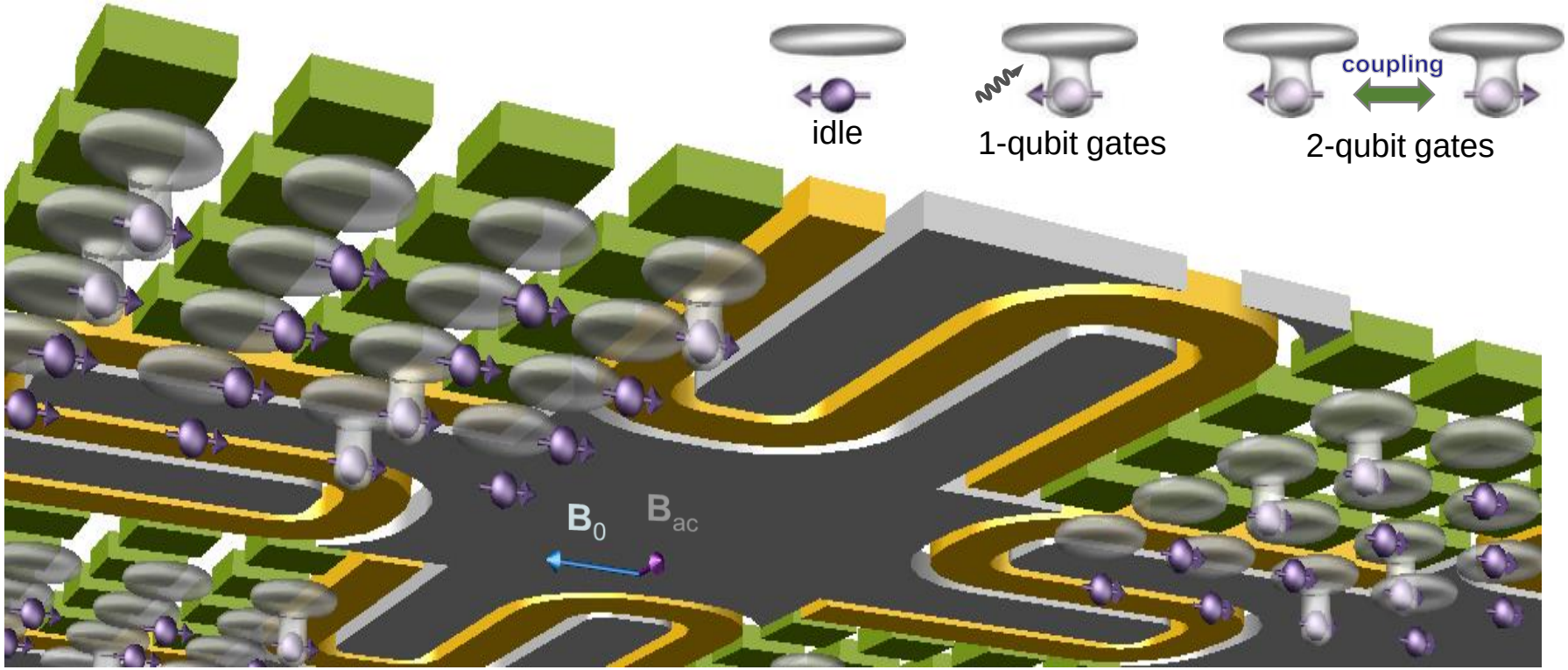
J. Muhonen et al., *Nature Nanotechnol.* 9, 986 (2014)

UNSW SYDNEY

Implanted P-atom Qubits: Scalability Pathways

Morello Group

"Flip-Flop Qubits"



G. Tosi et al., *Nature Communications* (2017)

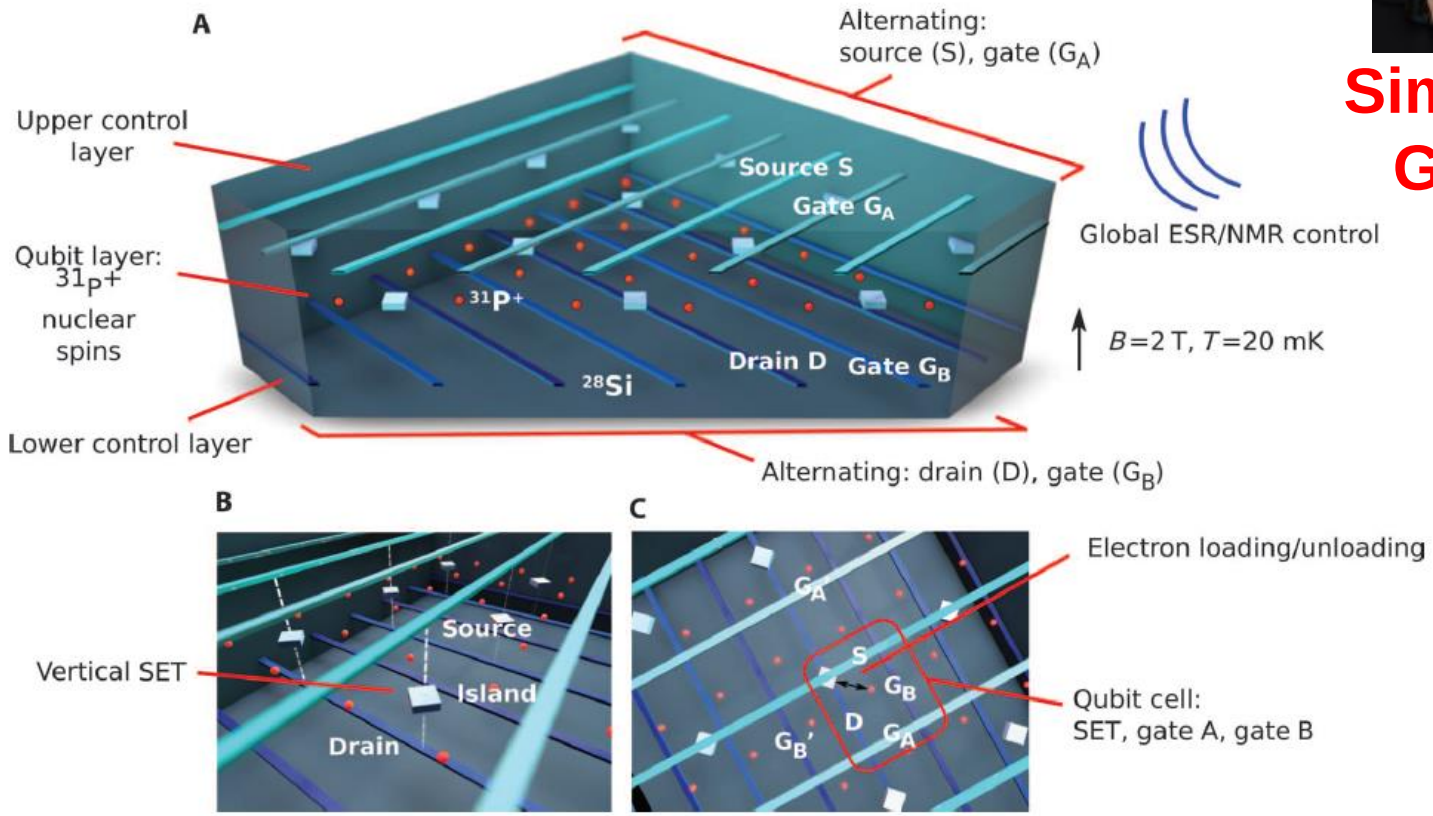
UNSW SYDNEY

STM-positioned P-atom Qubits: Scalability Pathways

A surface code quantum computer in silicon

Charles D. Hill,[1] Eldad Peretz,[2] Samuel J. Hile,[2] Matthew G. House,[2] Martin Fuechsle,[2] Sven Rogge,[2] Michelle Y. Simmons,[2] Lloyd C. L. Hollenberg[1]*

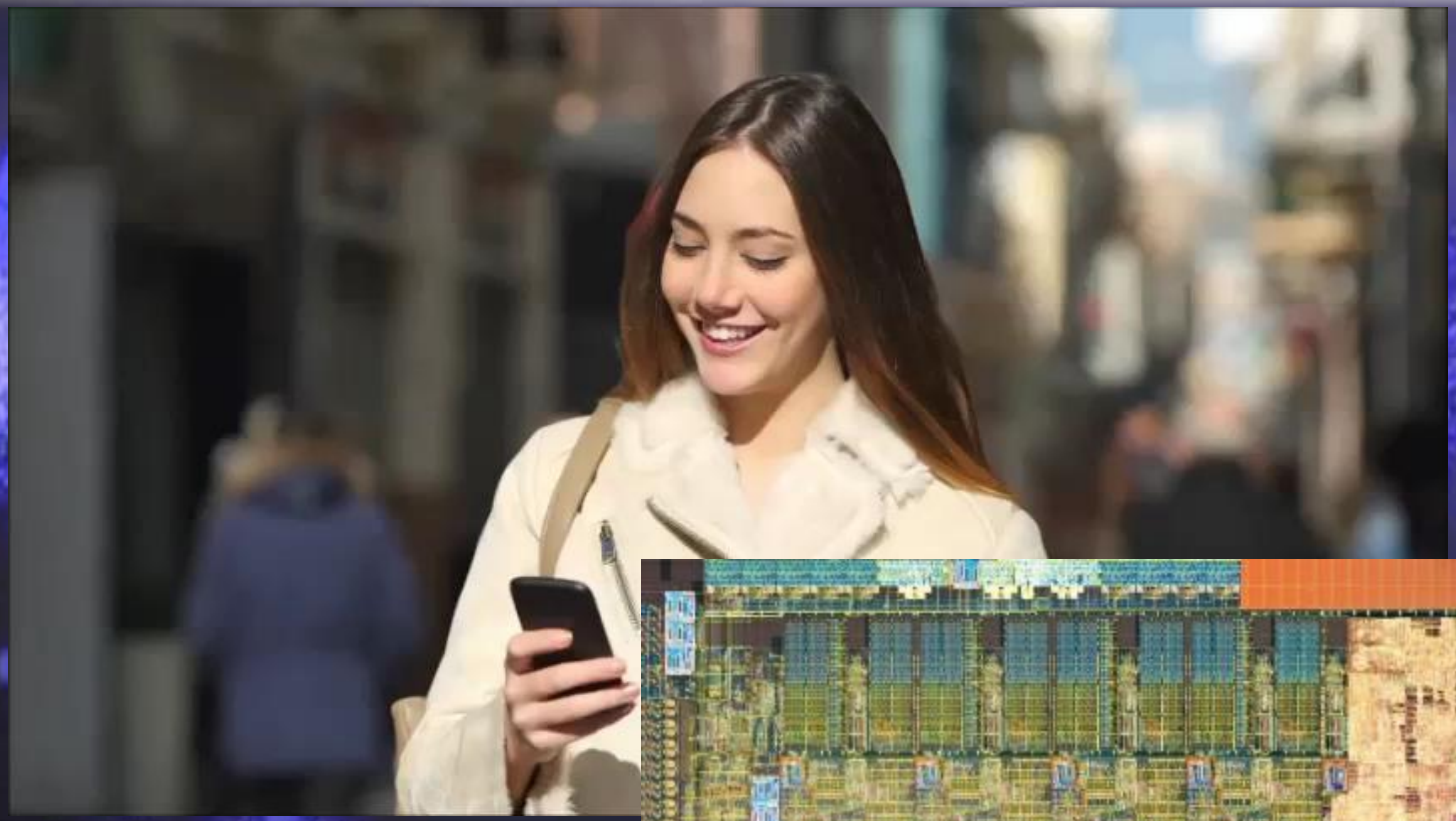
Simmons Group

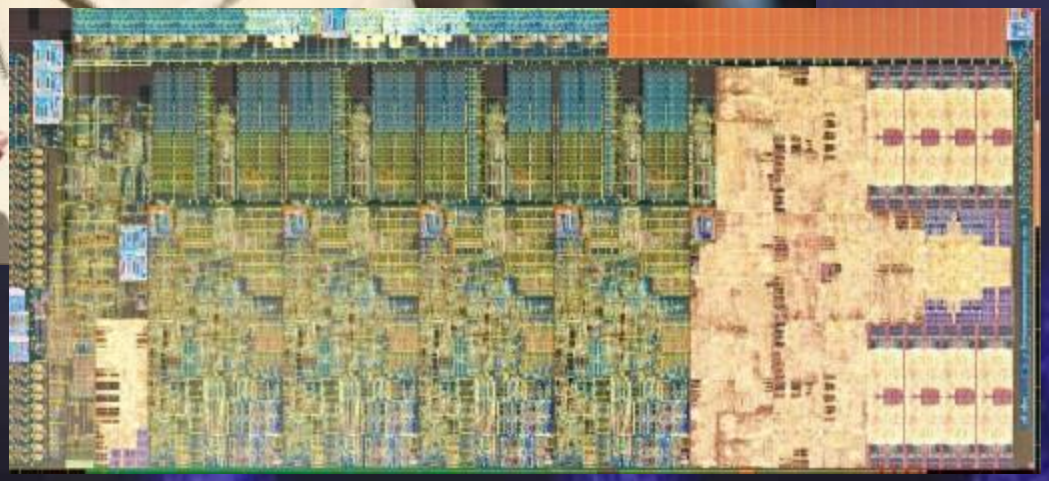


C.D. Hill et al., *Science Advances* 1, e1500707 (2015)

UNSW SYDNEY

Silicon CMOS mass production?





1998: *An important year for spin qubits …*

NATURE | VOL 393 | 14 MAY 1998 133

A silicon-based nuclear spin quantum computer

B. E. Kane

Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Australia

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]

Electron Spin *Qubits* based on *Quantum Dots*

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

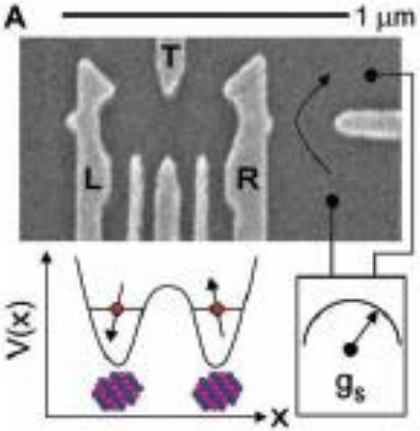
Quantum computation with quantum dots

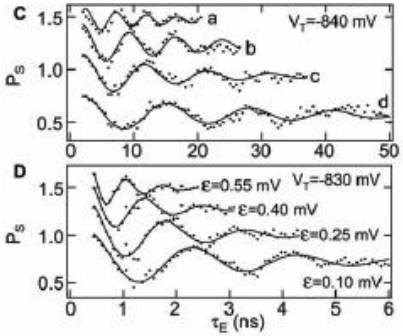
Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]

Coherence times in GaAs limited by nuclear spin bath

Coherent
Coupled E
Semiconductor Quantum Dots

J. R. Petta,[1] A. C. Johnson,[1] J. M. Taylor,[1] E. A. Laird,[1] A. Yacoby,[2] M. D. Lukin,[1] C. M. Marcus,[1] M. P. Hanson,[3] A. C. Gossard[3]



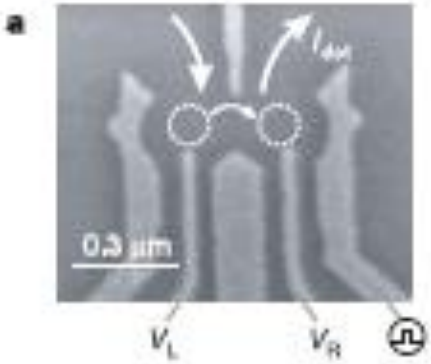


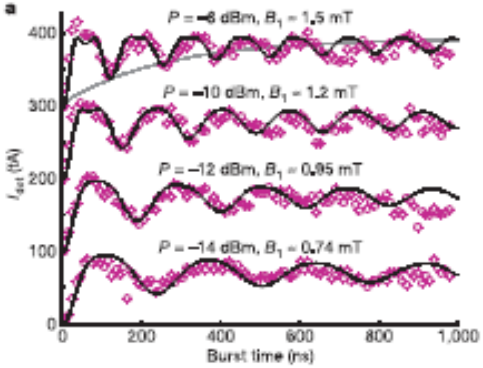
30 SEPTEMBER 2005 VOL 309 SCIENCE www.sciencemag.org

Vol 442 | 17 August 2006 | doi:10.1038/nature05065

Driven coherent oscillations of a single electron spin in a quantum dot

F. H. L. Koppens[1], C. Buizert[1], K. J. Tielrooij[1], I. T. Vink[1], K. C. Nowack[1], T. Meunier[1], L. P. Kouwenhoven[1] & L. M. K. Vandersypen[1]





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Si Q-Dot Qubits: Si/SiGe Heterostructures - I

LETTER

344 | NATURE | VOL 481 | 19 JANUARY 2012

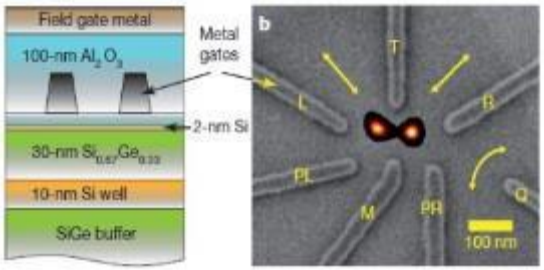
doi:10.1038/nature10707

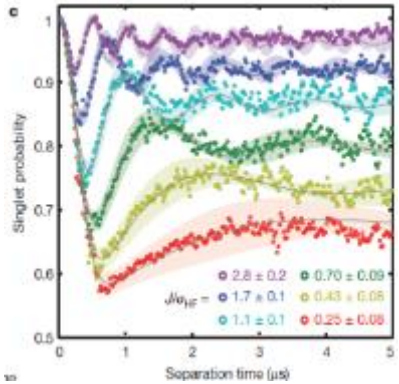
natSi

$T_2^* = 360$ ns

Coherent singlet–triplet oscillations in a silicon-based double quantum dot

B. M. Maune[1], M. G. Borselli[1], B. Huang[1], T. D. Ladd[1], P. W. Deelman[1], K. S. Holabird[1], A. A. Kiselev[1], I. R. S. Ross[1], A. E. Schmitz[1], M. Sokolich[1], C. A. Watson[1], M. F. Gyure[1] & A. T. Hunter[1]





RESEARCH ARTICLE

Eng *et al.* Sci. Adv. 2015;1:e1500214 29 May 2015

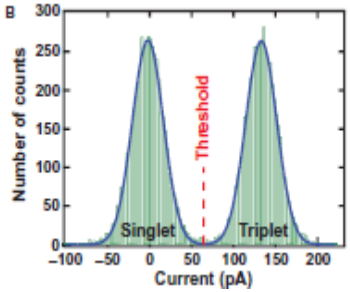
^{28}Si

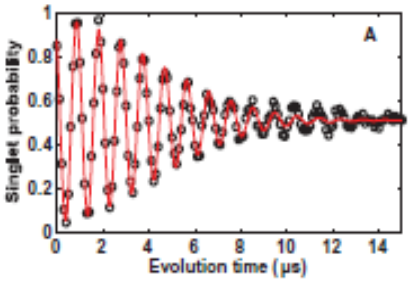
$T_2^* = 6$ μs

CONDENSED MATTER PHYSICS

Isotopically enhanced triple-quantum-dot qubit

Kevin Eng, Thaddeus D. Ladd, Aaron Smith, Matthew G. Borselli, Andrey A. Kiselev, Bryan H. Fong, Kevin S. Holabird, Thomas M. Hazard, Biqin Huang, Peter W. Deelman, Ivan Milosavljevic, Adele E. Schmitz, Richard S. Ross, Mark F. Gyure, Andrew T. Hunter*



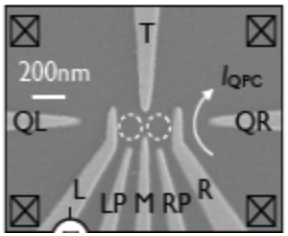


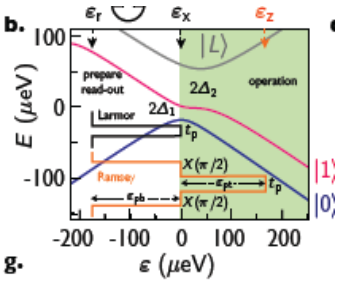
Quantum control and process tomography of a semiconductor quantum dot hybrid qubit

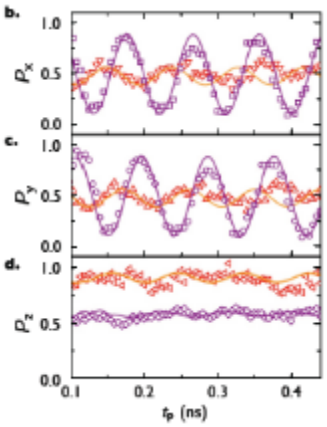
Dohun Kim,[1] Zhan Shi,[1] C. B. Simmons,[1] D. R. Ward,[1] J. R. Prance,[1] Teck Seng Koh,[1] John King Gamble,[2] D. E. Savage,[3] M. G. Lagally,[3] Mark Friesen,[1] S. N. Coppersmith,[1] and M. A. Eriksson[1]

Nature 511, 70 (2014)

natSi







$T_2^* = 2$-10 ns; $T_\pi \sim 50$ ps; $F_C = 85$-94%

Si Q-Dot Qubits: Si/SiGe Heterostructures - II

Nature Nanotechnology 9, 666 (2014)

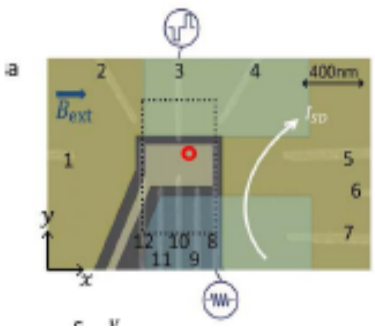
Electrical control of a long-lived spin qubit in a Si/SiGe quantum dot

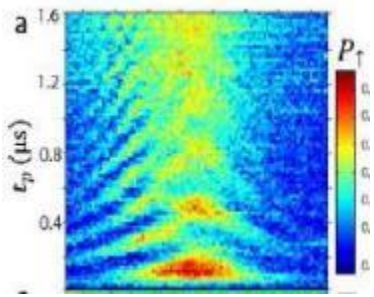
E. Kawakami[1†], P. Scarlino[1†], D. R. Ward[2], F. R. Braakman[1,3], D. E. Savage[2], M. G. Lagally[2], Mark Friesen[2], S. N. Coppersmith[2], M. A. Eriksson[2], and L. M. K. Vandersypen[1*]

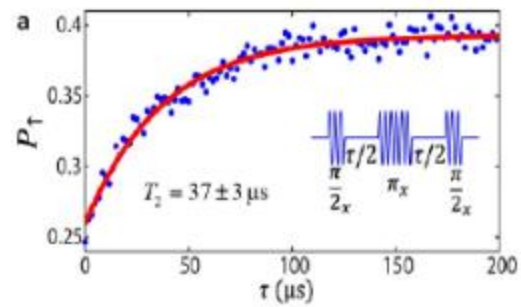
^{nat}Si

EDSR - μMagnet

$T_2^* = 1\ \mu s$; $T_2 = 37\ \mu s$







F_C = 99% via RBM - *PNAS* 113, 11738 (2016)

Science Advances 2, e1600694 (2016)

A fault-tolerant addressable spin qubit in a natural silicon quantum dot

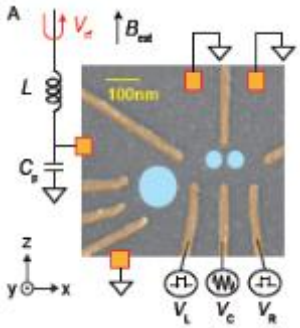
K. Takeda,[1] J. Kamioka,[2] T. Otsuka,[1] J. Yoneda,[1] T. Nakajima,[1]
M.R. Delbecq,[1] S. Amaha,[1] G. Allison,[1] T. Kodera,[2] S. Oda,[2] and S. Tarucha[1,3]

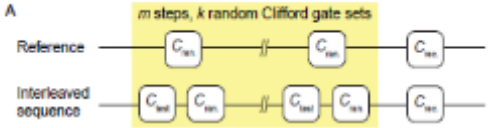
^{nat}Si

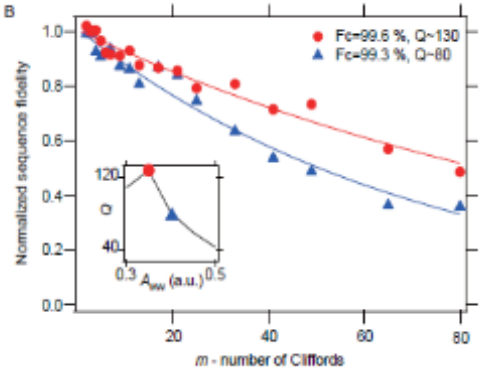
EDSR - μMagnet

$T_2^* \sim 2\ \mu s$

F_C = 99.6% via RBM







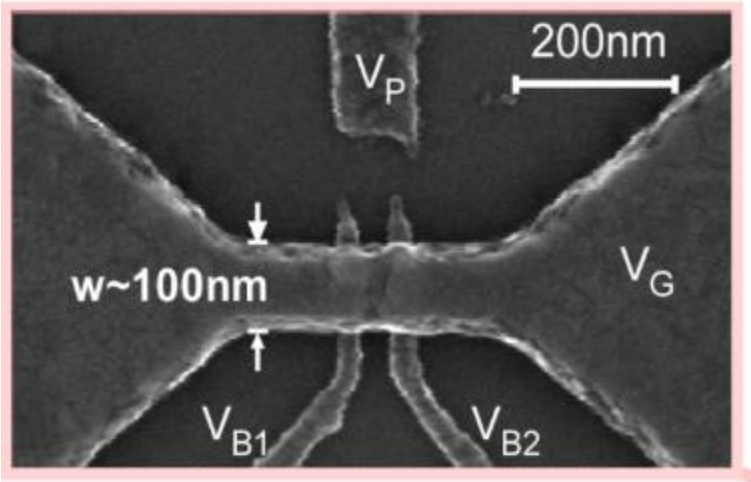
Silicon-MOS Quantum Dots

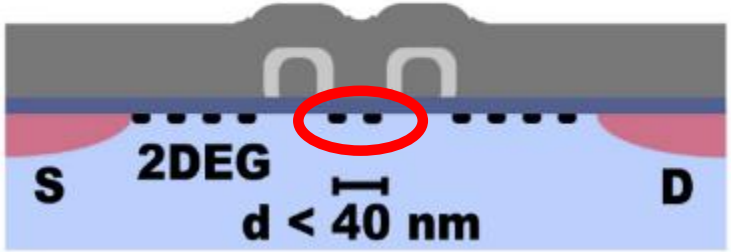
NANO LETTERS

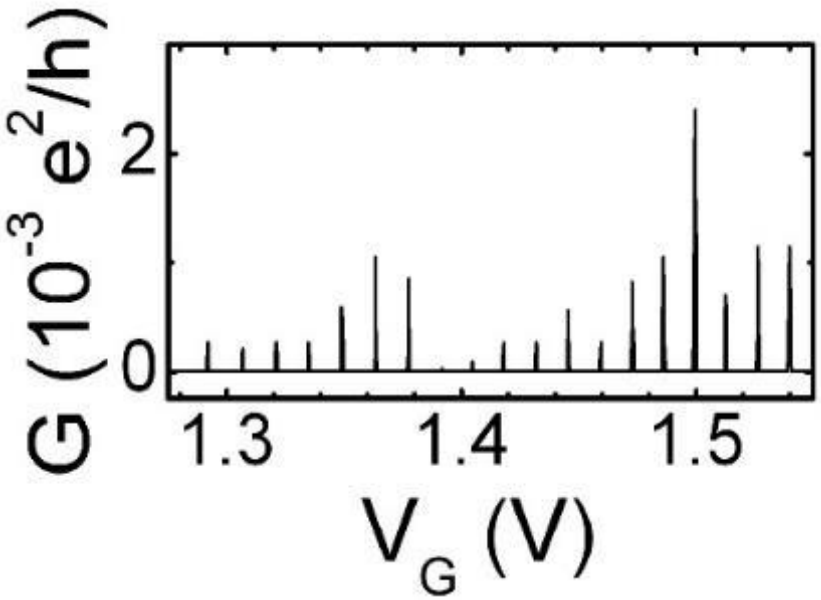
2007
Vol. 7, No. 7
2051−2055

Gate-Defined Quantum Dots in Intrinsic Silicon

Susan J. Angus,* Andrew J. Ferguson, Andrew S. Dzurak, and Robert G. Clark







S.J. Angus et al., *Nano Letters* 7, 2051 (2007)

^{28}SiMOS Q-Dots: 1-Qubit Gate, Fidelity > 99%

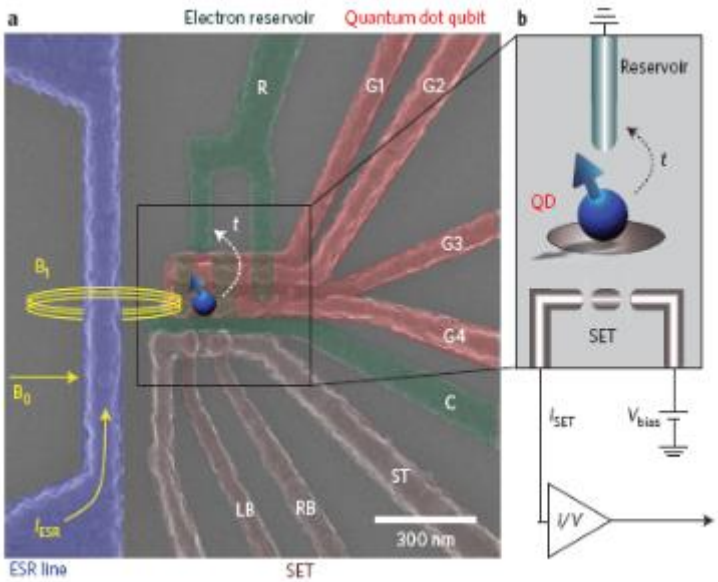
nature nanotechnology

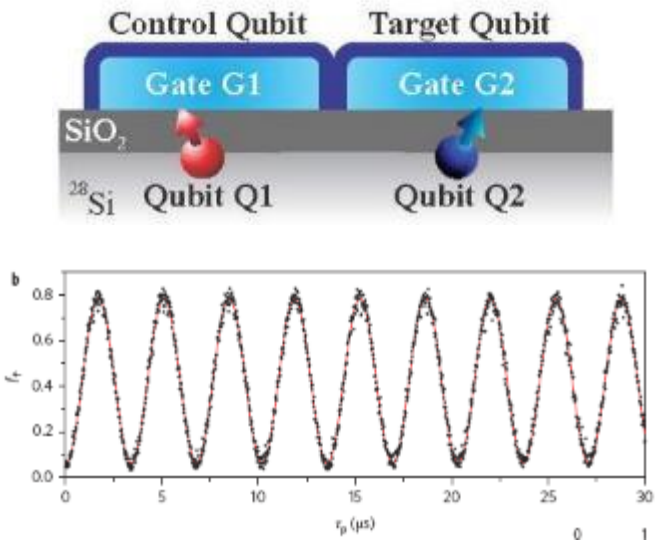
LETTERS

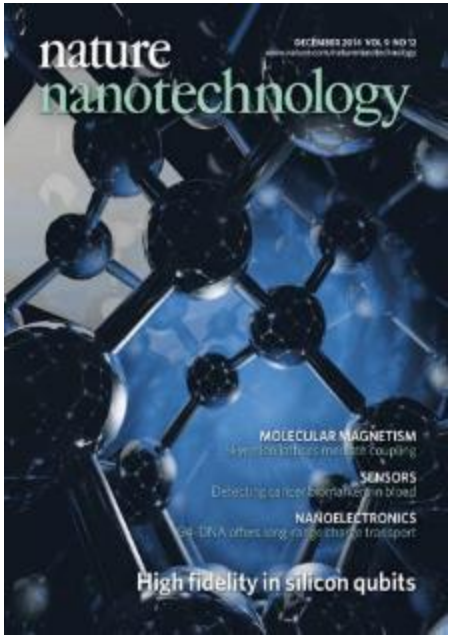
PUBLISHED ONLINE: 12 OCTOBER 2014 | DOI: 10.1038/NNANO.2014.216

An addressable quantum dot qubit with fault-tolerant control-fidelity

M. Veldhorst[1*], J. C. C. Hwang[1], C. H. Yang[1], A. W. Leenstra[2], B. de Ronde[2], J. P. Dehollain[1], J. T. Muhonen[1], F. E. Hudson[1], K. M. Itoh[3], A. Morello[1] and A. S. Dzurak[1*]







M. Veldhorst et al., *Nature Nanotechnol.* 9, 981 (2014)

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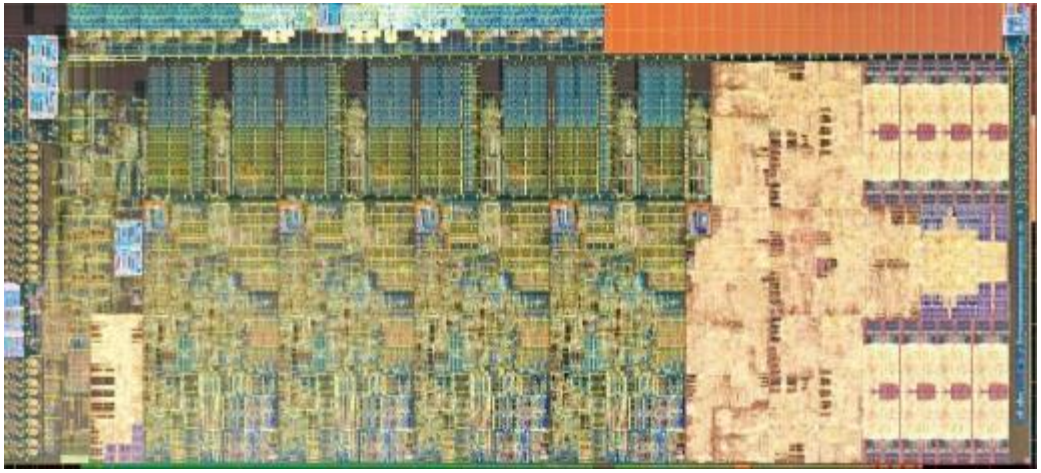
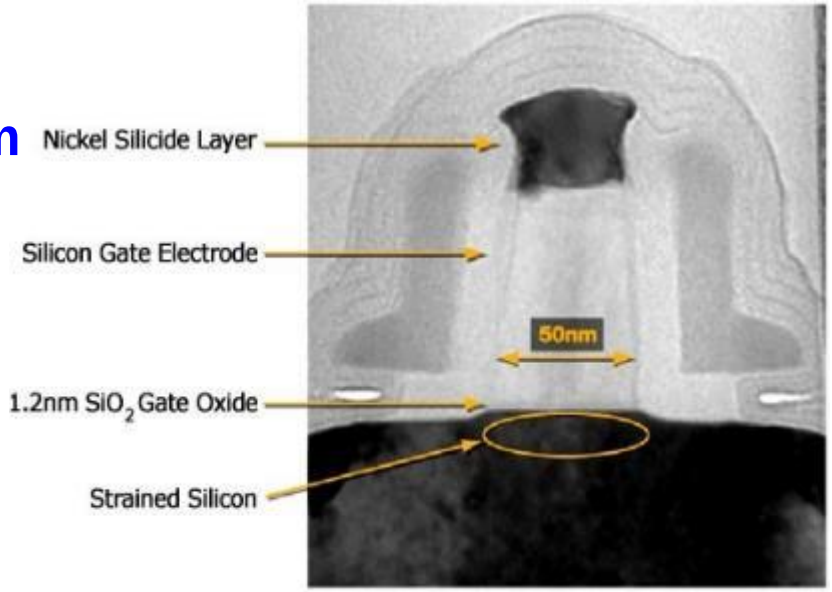
SiMOS Q-Dot Qubits: *CMOS Compatibilty*



Intel Pentium Silicon MOSFET Transistor 65nm Node (2005)



Silicon MOS Single-electron Qubit (2014)

SiMOS Q-Dot: *Large* & *Tuneable* Valley Splitting, ΔE_V

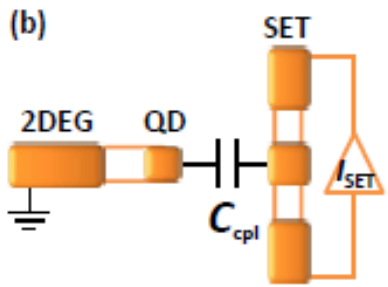
ARTICLE

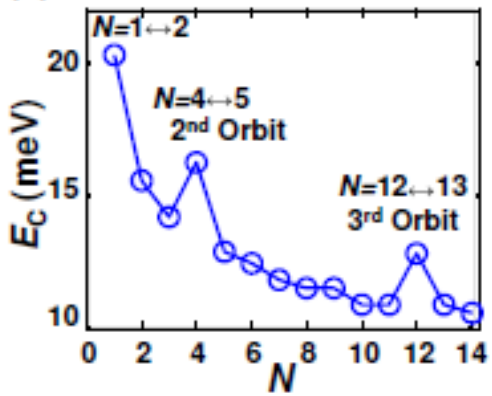
Received 11 Jan 2013 | Accepted 27 May 2013 | Published 27 Jun 2013

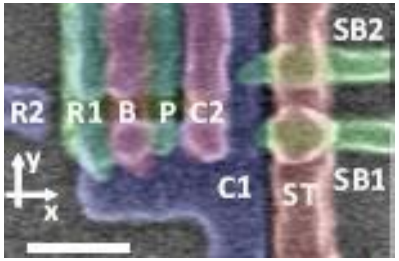
nature COMMUNICATIONS

Spin-valley lifetimes in a silicon quantum dot with tunable valley splitting

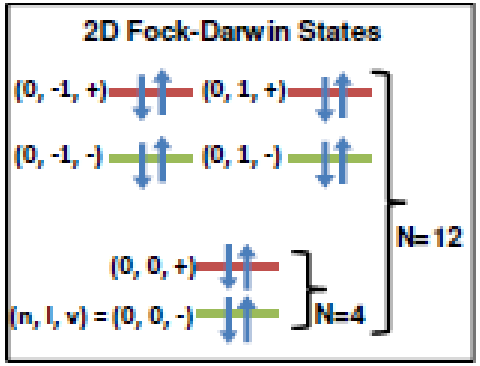
C.H. Yang[1], A. Rossi[1], R. Ruskov[2], N.S. Lai[1], F.A. Mohiyaddin[1], S. Lee[3], C. Tahan[2], G. Klimeck[3], A. Morello[1] & A.S. Dzurak[1]

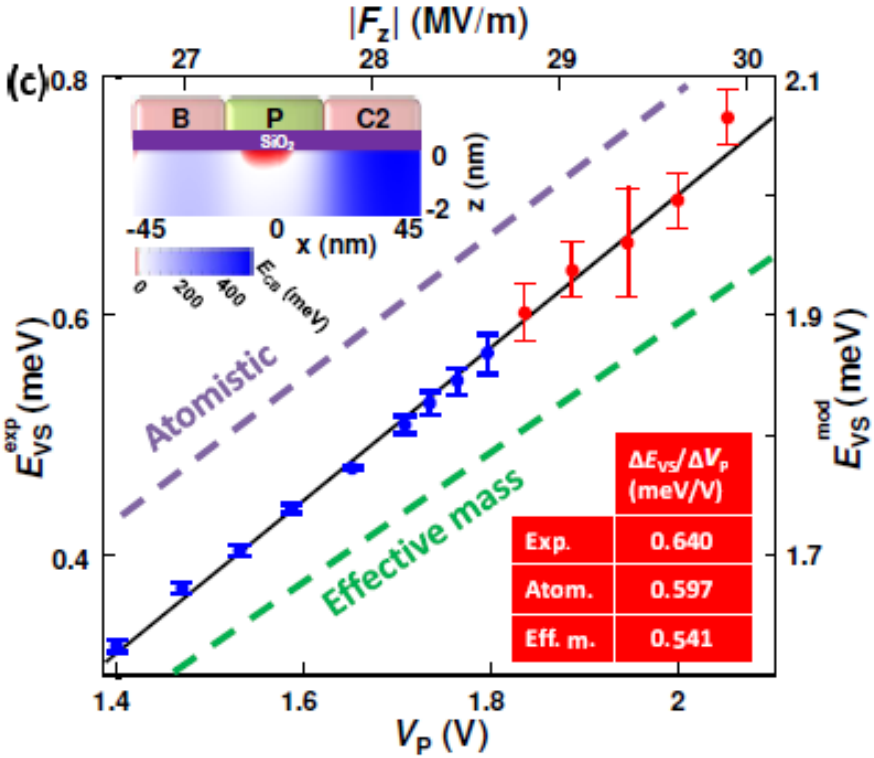






100 nm

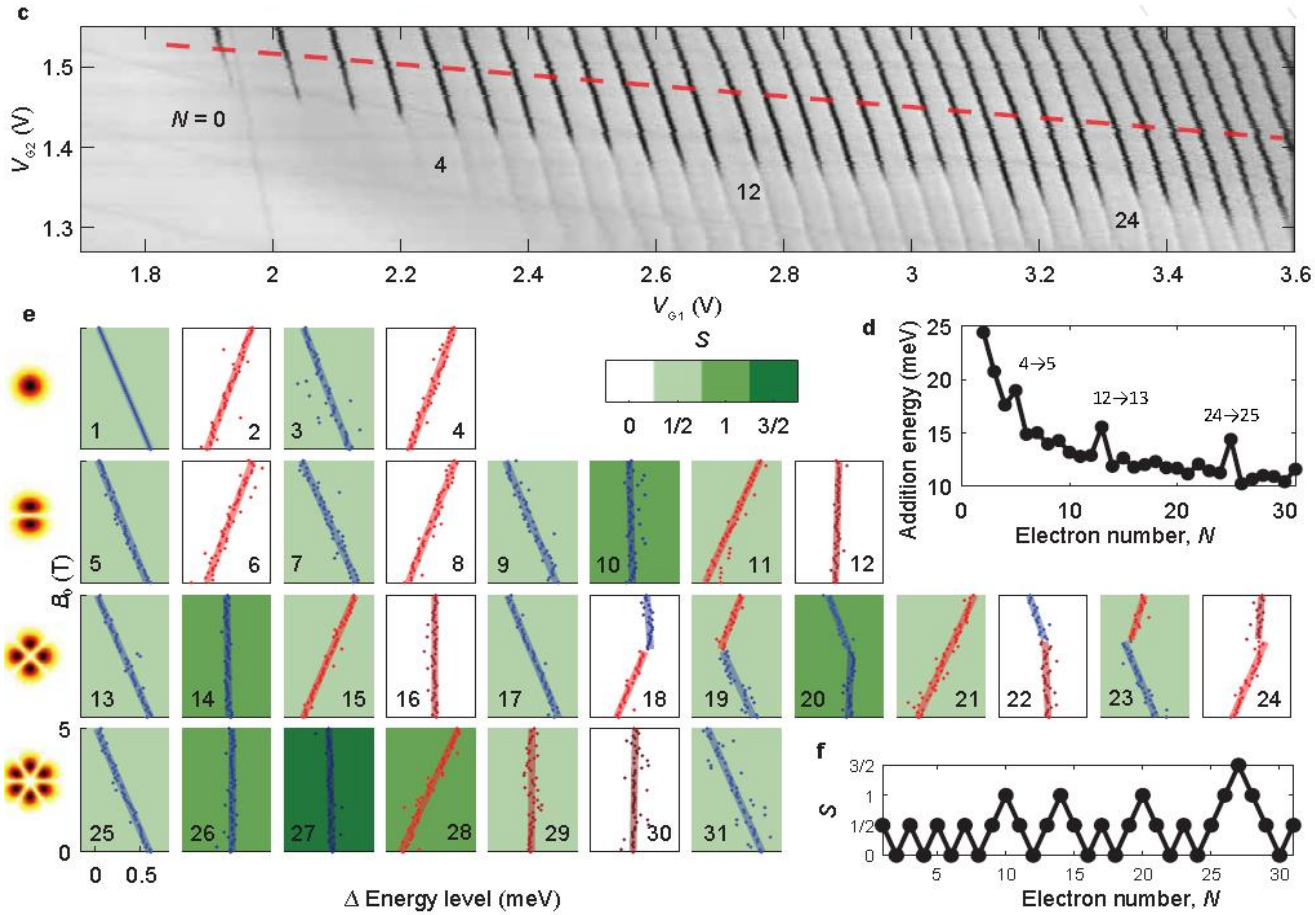


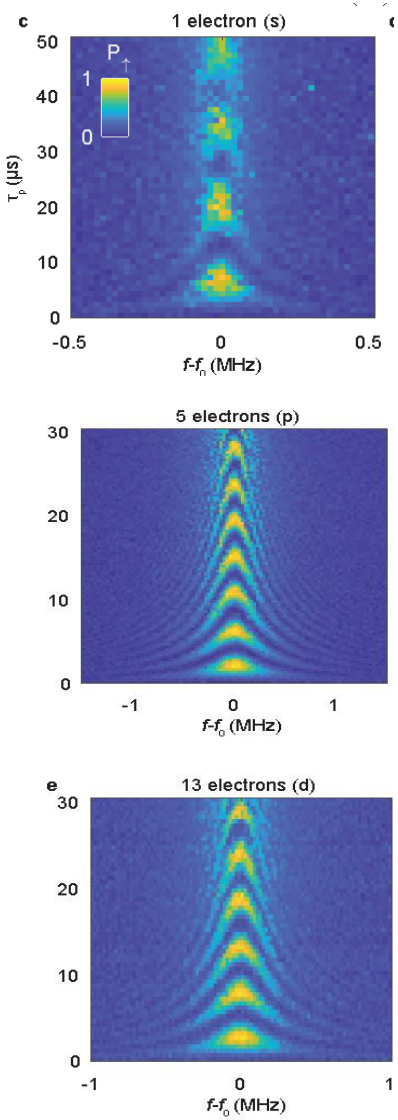


SiMOS Q-Dot = *Artificial Atom*: Monovalent Qubits

Coherent spin control of s-, p-, d- and f-electrons in a silicon quantum dot

R. C. C. Leon,[1,*] C. H. Yang,[1] J. C. C. Hwang,[1,†] J. Camirand Lemyre,[2] T. Tanttu,[1] W. Huang,[1] K. W. Chan,[1] K. Y. Tan,[3] F. E. Hudson,[1] K. M. Itoh,[4] A. Morello,[1] A. Laucht,[1] M. Pioro-Ladrière,[2,5] A. Saraiva,[1,‡] and A. S. Dzurak[1,§]





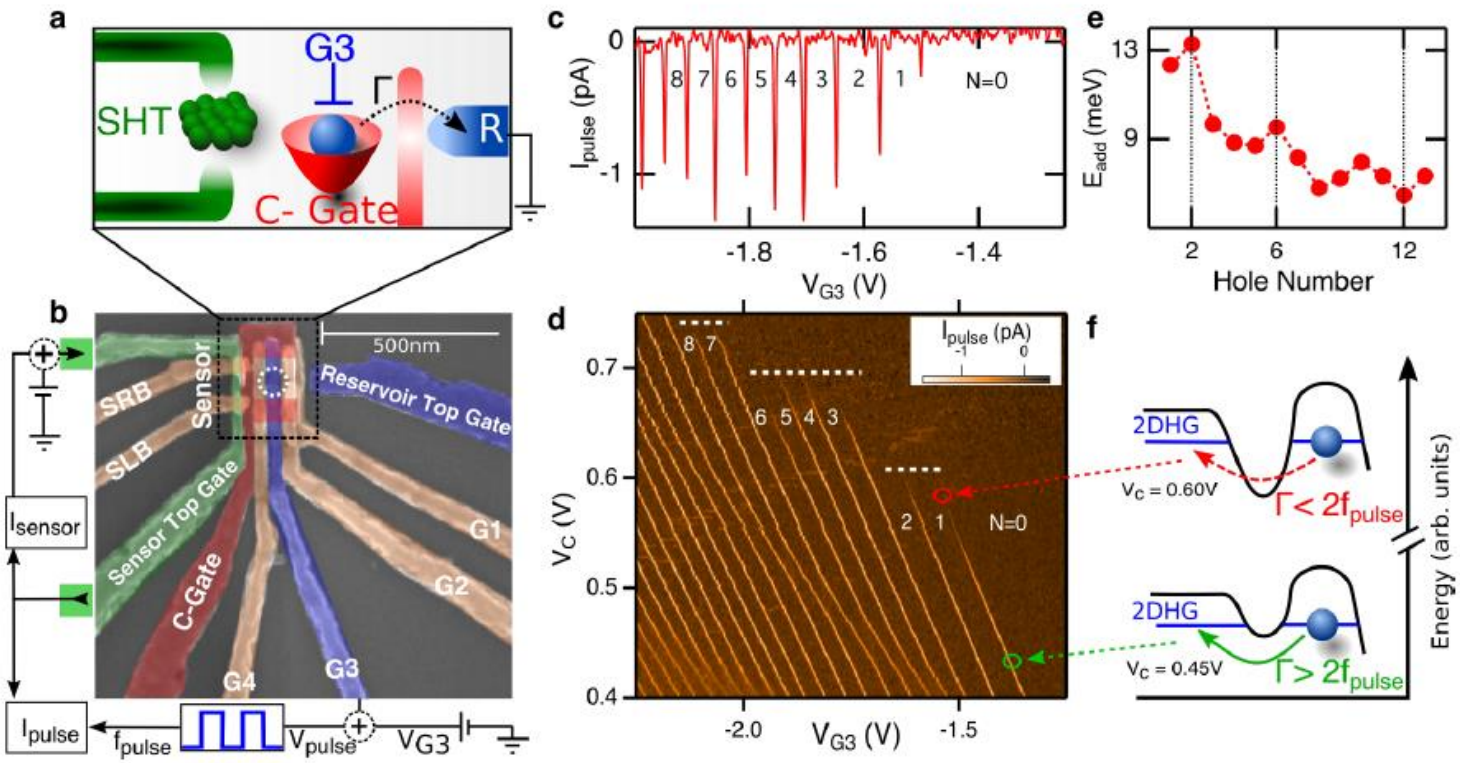
Leon et al., arXiv:1902.01550

SiMOS: pMOS Hole QDs

Spin filling and orbital structure of the first six holes in a silicon metal-oxide-semiconductor quantum dot

S. D. Liles[1], R. Li[1,3], C. H. Yang[2], F. E. Hudson[2], M. Veldhorst[2,3], A. S. Dzurak[2], A. R. Hamilton[1]

[1] *School of Physics, University of New South Wales, Sydney NSW 2052, Australia*
[2] *Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney NSW 2052, Australia*
[3] *QuTech and Kavli Institute of Nanoscience, TU Delft, 2600 GA Delft, The Netherlands*

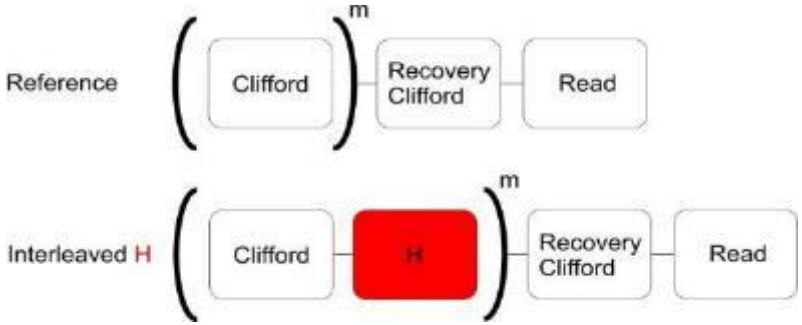


S.D. Liles *et al.*, *Nature Communications* (2018)

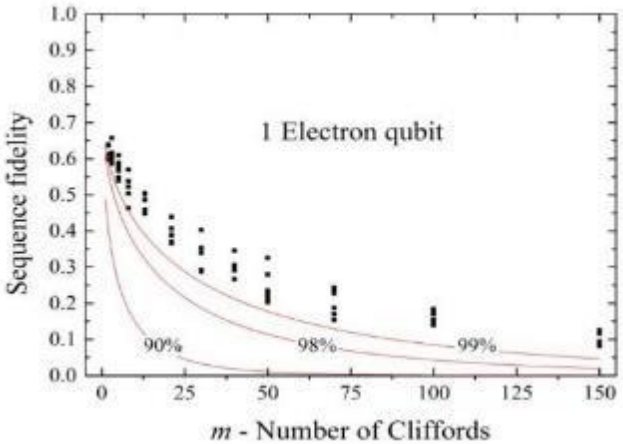
SiMOS Dot Qubits in ^{28}Si: *1-Qubit Randomized Benchmarking*

Gate	*1 electron qubit* Fidelity (%)	σ	*3 electron qubit* Fidelity (%)	σ
Reference	99.57	0.03	98.12	0.15
Average	99.59		98.15	
I	99.83	0.09	97.9	0.5
X	99.83	0.09	98.97	0.4
Y	99.99	0.07	99.34	0.3
X/2	99.57	0.09	98.15	0.4
-X/2	99.53	0.09	97.76	0.3
Y/2	99.67	0.09	98.71	0.5
-Y/2	99.23	0.1	96.90	0.5
α	0.61		0.67	
g^*-g_0	-2.5E-3	7E-5	-8.8E-3	4E-5
f_{ESR}	39.141	1E-3	39.016	1E-3
T_2^* (ms)	0.12		0.07	
T_2 (ms)	28		2.8	

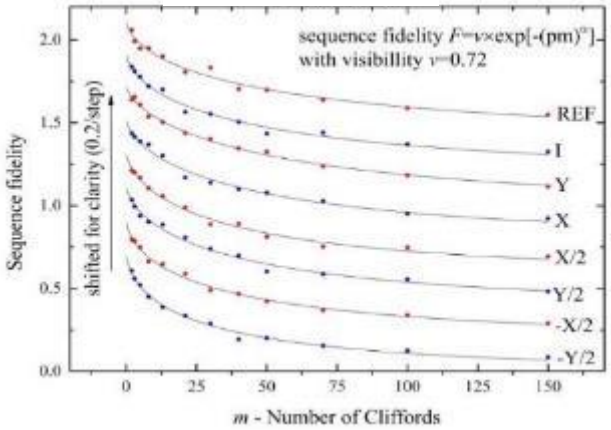
- **<u>ALL</u> 1e 1-qubit gate fidelities > 99%**
- **<u>Average</u> 1e 1-qubit gate fidelity = 99.6%**



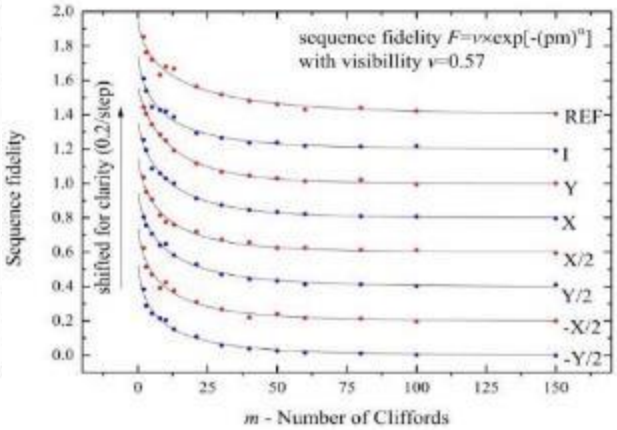
1-Electron Qubit



1-Electron Qubit



3-Electron Qubit



Veldhorst et al., *Nature Nanotechnology* <u>9</u>, 981 (2014)

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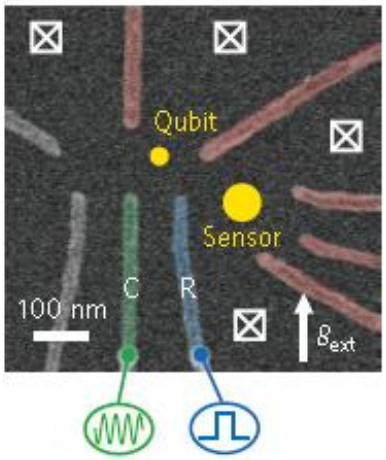
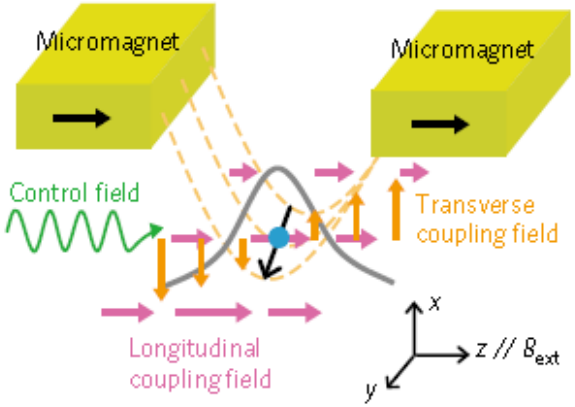
Si/SiGe Dot Qubits in ^{28}Si: *1-Qubit Randomized Benchmarking*

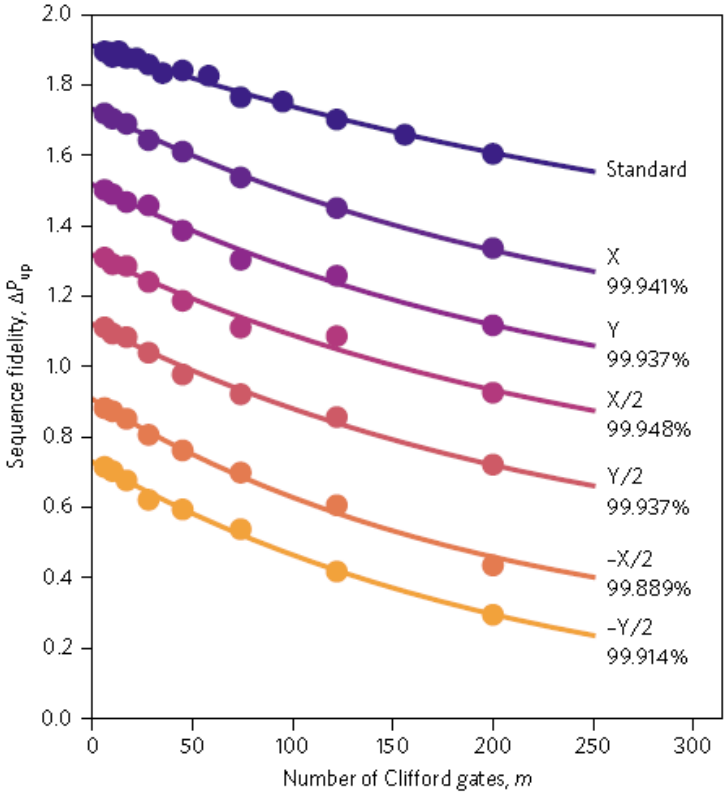
A quantum-dot spin qubit with coherence limited by charge noise and fidelity higher than 99.9%

EDSR | ^{28}Si

Jun Yoneda[1,2*], Kenta Takeda[1,2], Tomohiro Otsuka[1,2,3], Takashi Nakajima[1,2], Matthieu R. Delbecq[1,2], Giles Allison[1], Takumu Honda[4], Tetsuo Kodera[4], Shunri Oda[4], Yusuke Hoshi[5], Noritaka Usami[6], Kohei M. Itoh[7] and Seigo Tarucha[1,2*]







J. Yoneda et al., *Nature Nanotechnol.* 13, 102 (2018)

1-Qubit Gate: GRAPE Optimized Pulses, F_{1Q} = 99.96%

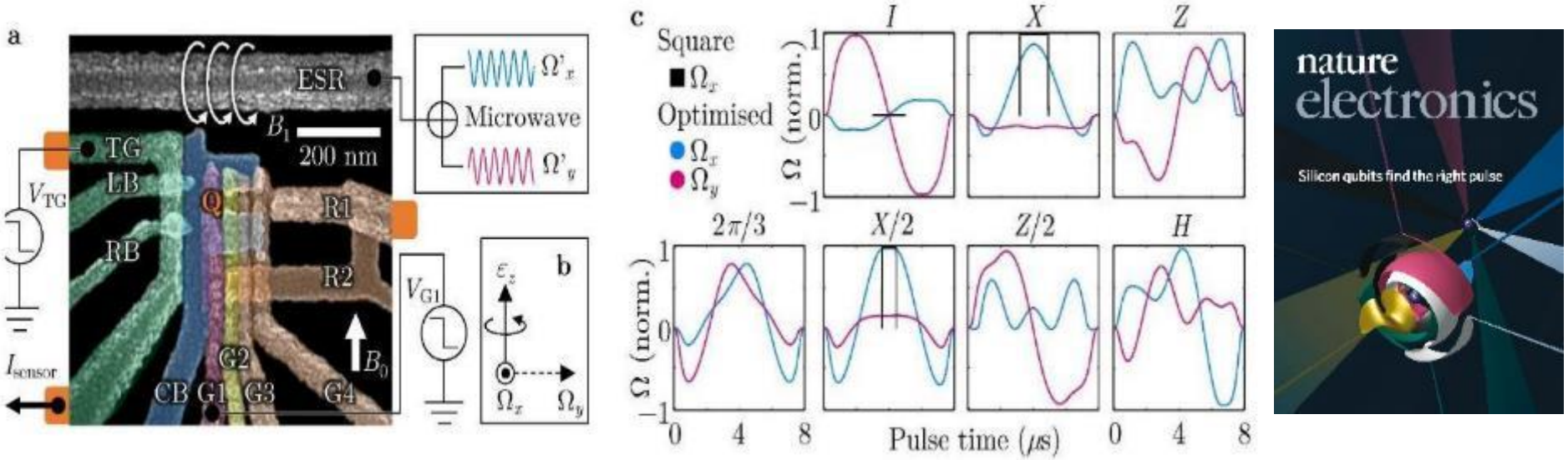
nature electronics

ARTICLES

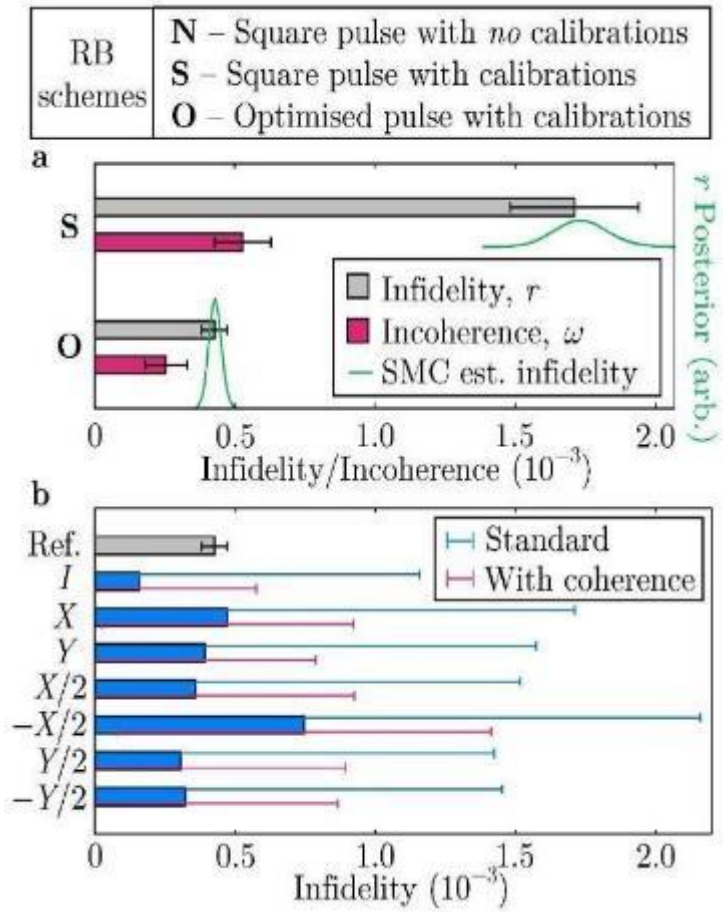
https://doi.org/10.1038/s41928-019-0234-1

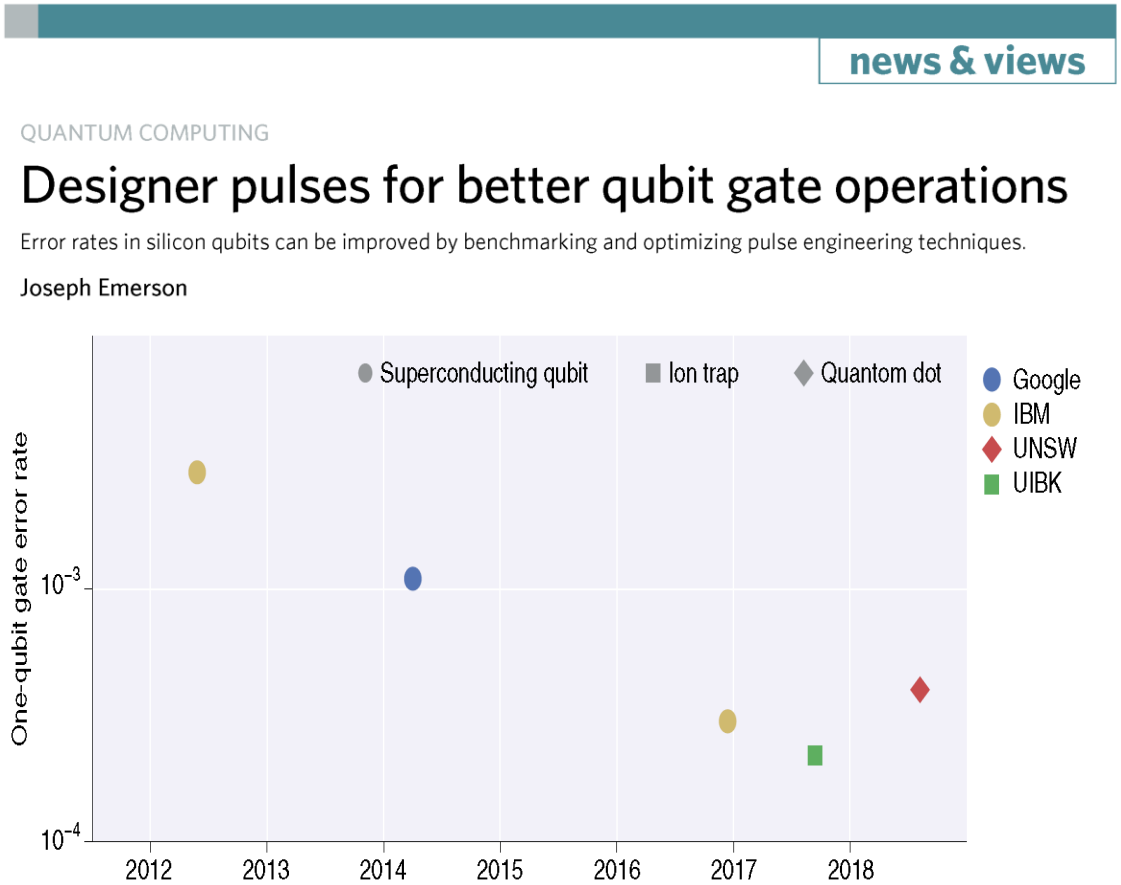
Silicon qubit fidelities approaching incoherent noise limits via pulse engineering

C. H. Yang[1*], K. W. Chan[1], R. Harper[2], W. Huang[1], T. Evans[2], J. C. C. Hwang[1], B. Hensen[1], A. Laucht[1], T. Tanttu[1], F. E. Hudson[1], S. T. Flammia[2], K. M. Itoh[3], A. Morello[1], S. D. Bartlett[2*] and A. S. Dzurak[1*]



Silicon-MOS Q-Dot 1-Qubit Gate: F_{1Q} = 99.96%



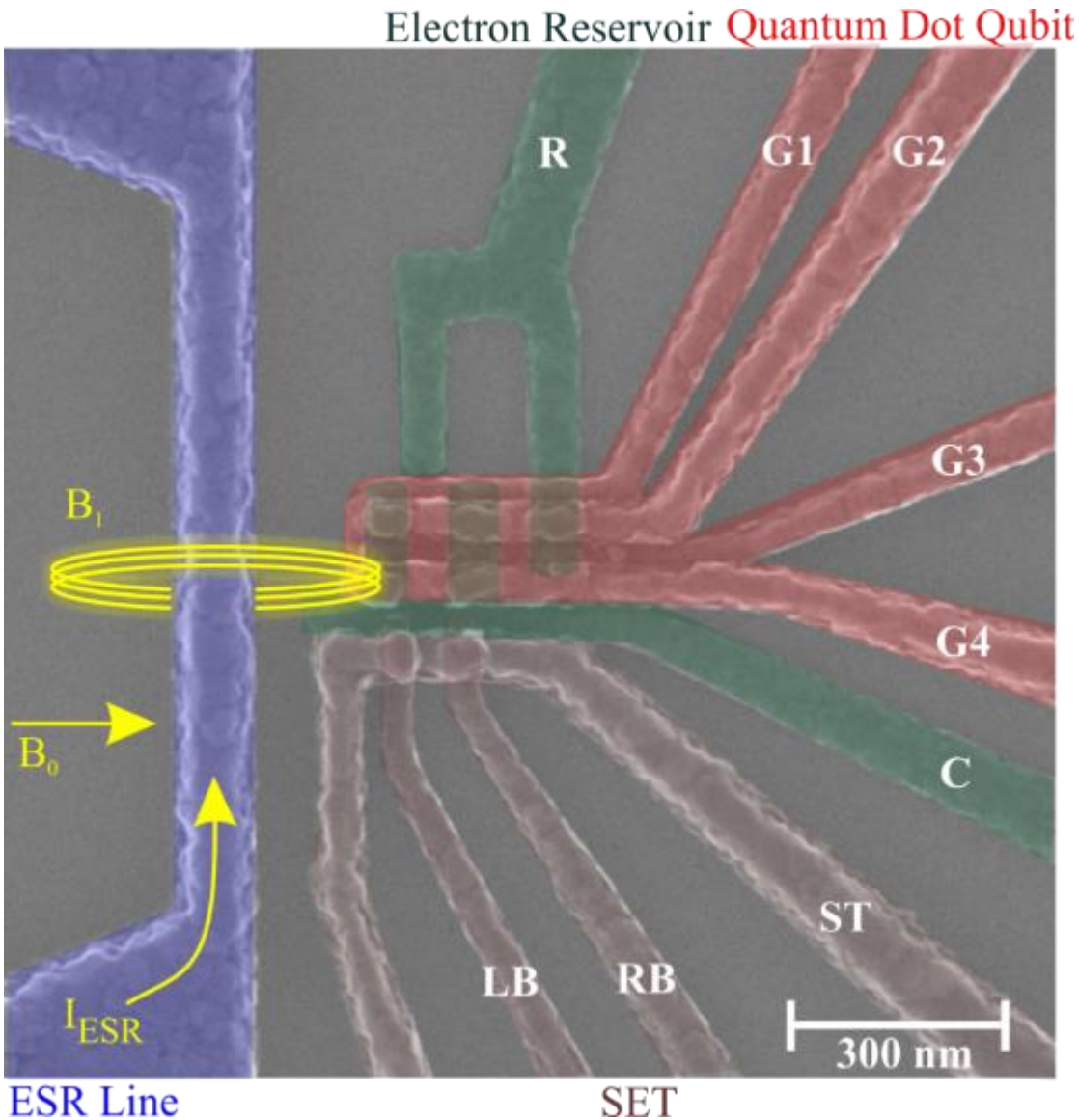


THE UNIVERSITY OF SYDNEY

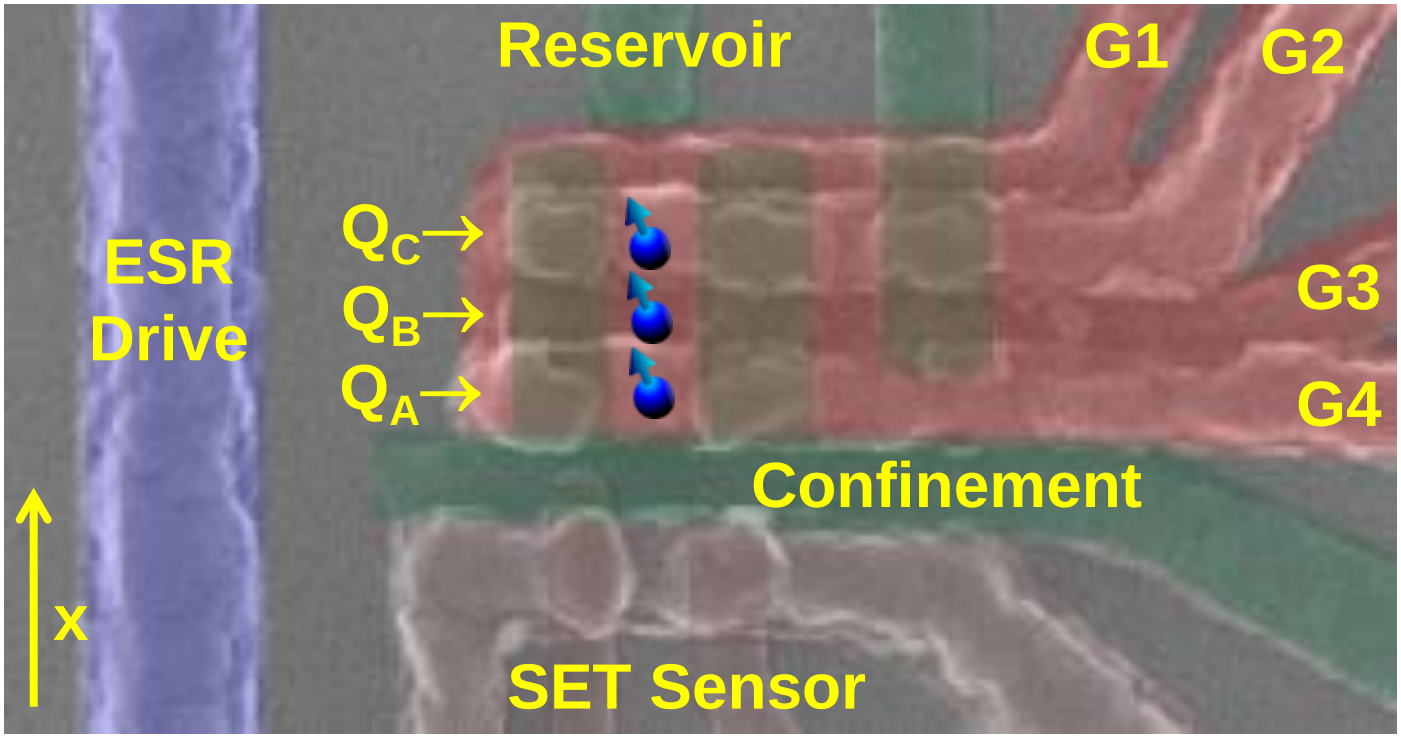
Yang *et al., Nature Electron.* 2, 151 (2019)

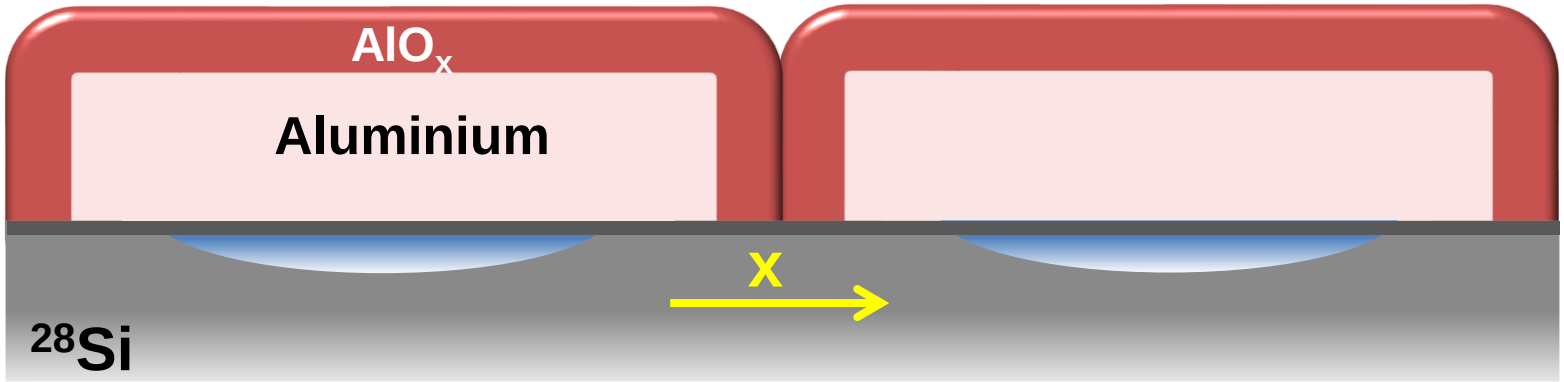
UNSW SYDNEY

^{28}Si-MOS Dots: *Multi-Qubit Devices*



^{28}Si-MOS Dots: *Multi-Qubit Devices*





1 Gate ⇒ 1 Qubit

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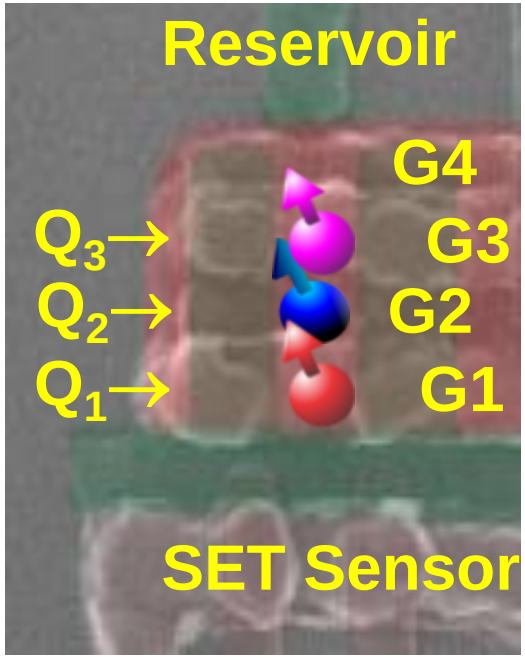
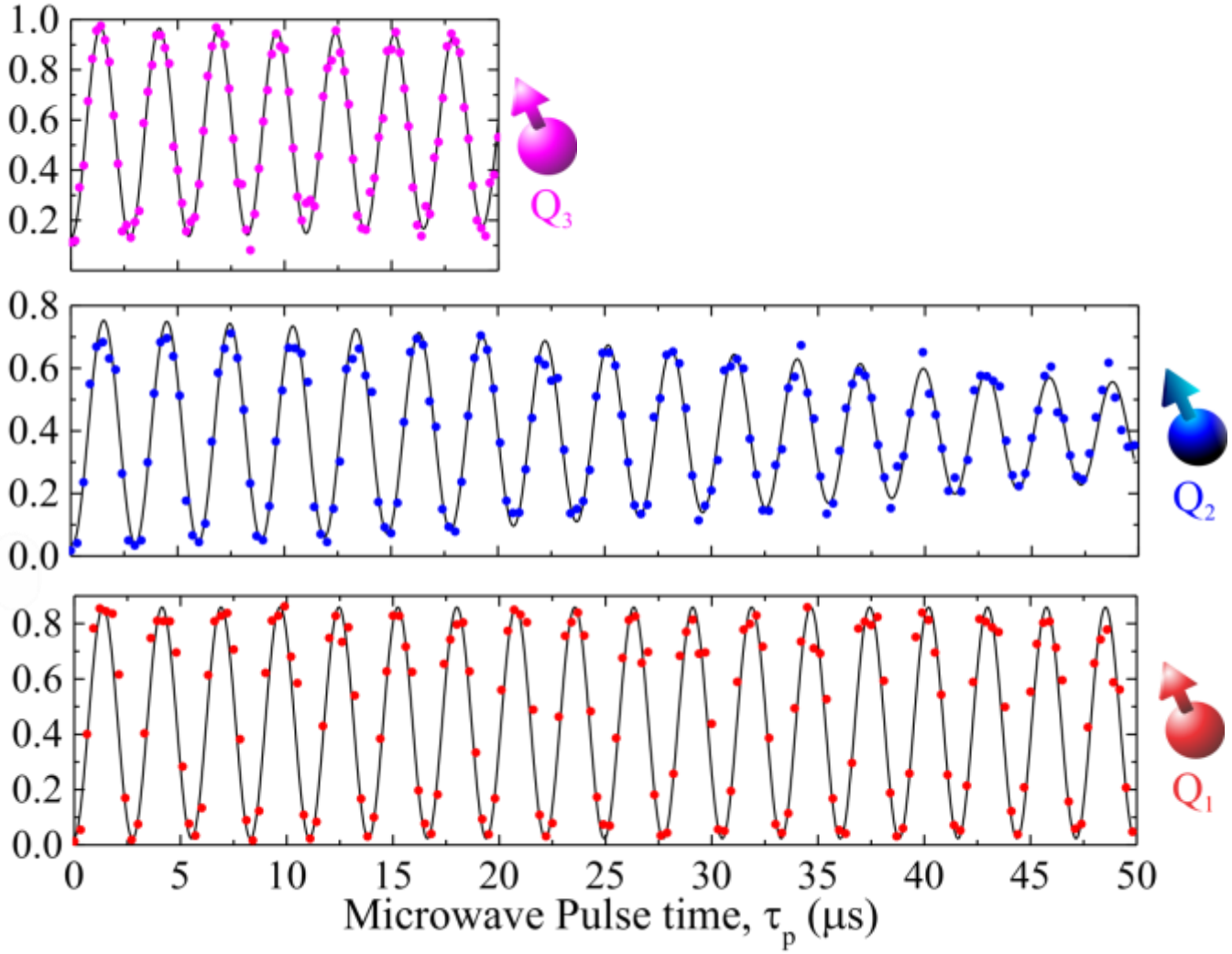
^{28}Si-MOS Dots: *Operation of 3 Independent Qubits*





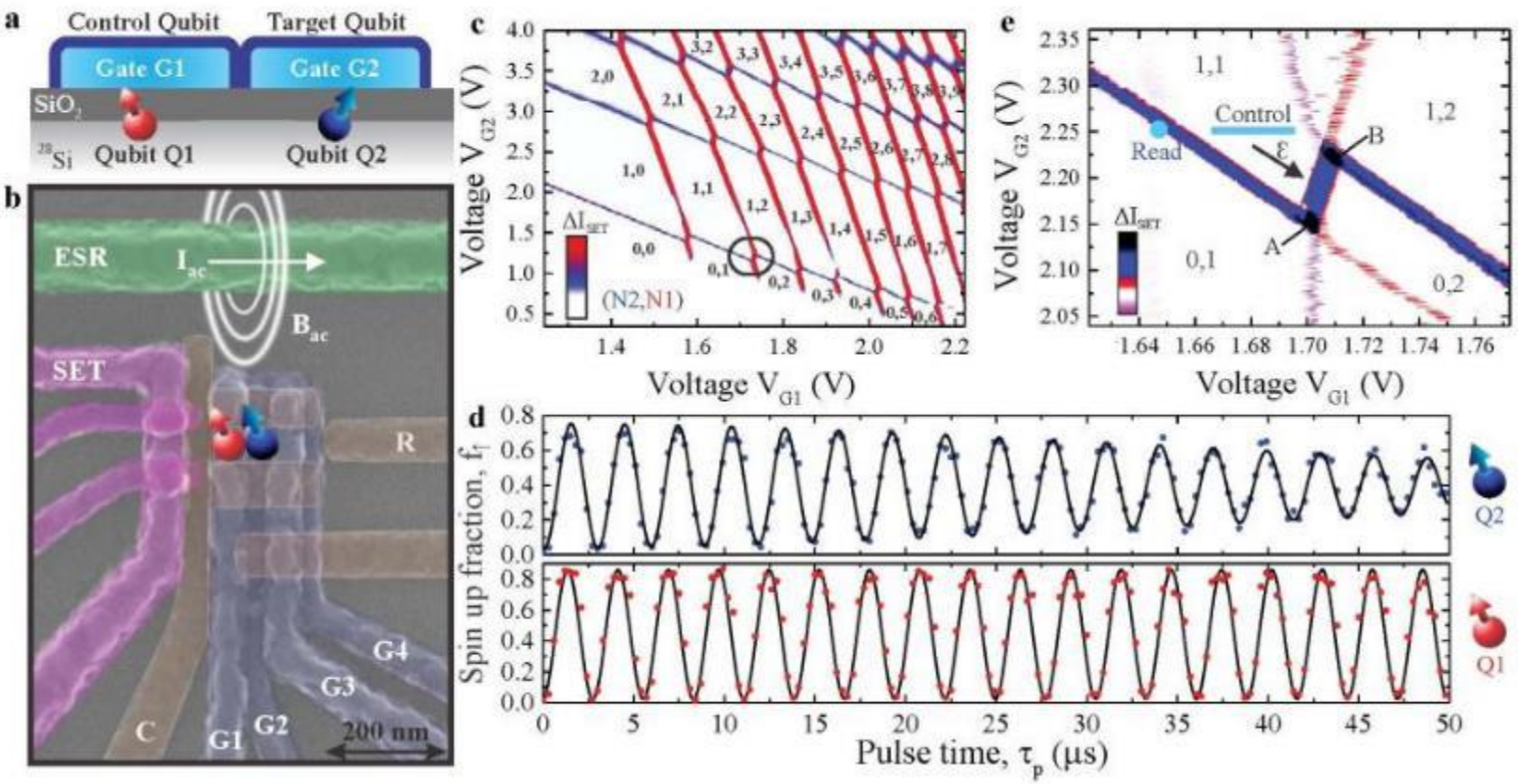
CMOS Qubits: *First 2-Qubit Logic in Silicon*

LETTER

doi:10.1038/nature15263

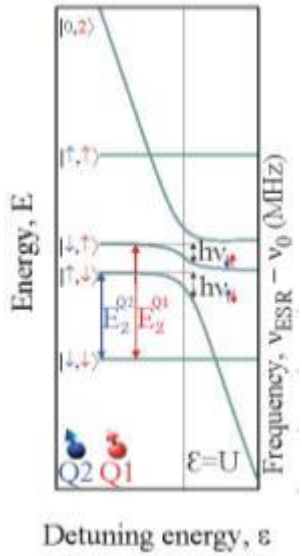
A two-qubit logic gate in silicon

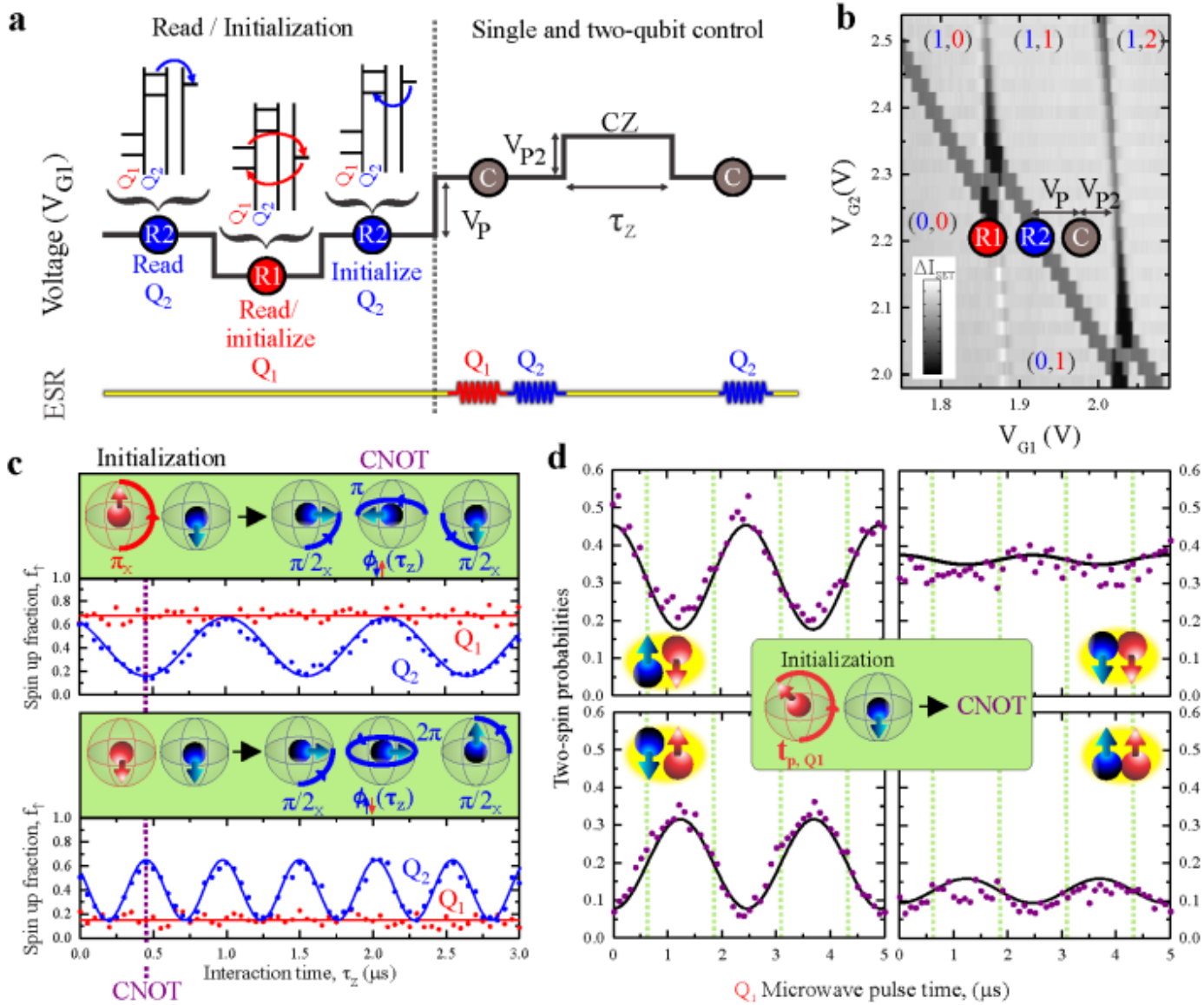
M. Veldhorst[1], C. H. Yang[1], J. C. C. Hwang[1], W. Huang[1], J. P. Dehollain[1], J. T. Muhonen[1], S. Simmons[1], A. Laucht[1], F. E. Hudson[1], K. M. Itoh[2], A. Morello[1] & A. S. Dzurak[1]



M. Veldhorst et al., *Nature* 526, 410 (2015)

SiMOS Q-Dots: CNOT via CZ & 2-Spin Correlations





M. Veldhorst et al., *Nature* 526, 410 (2015)

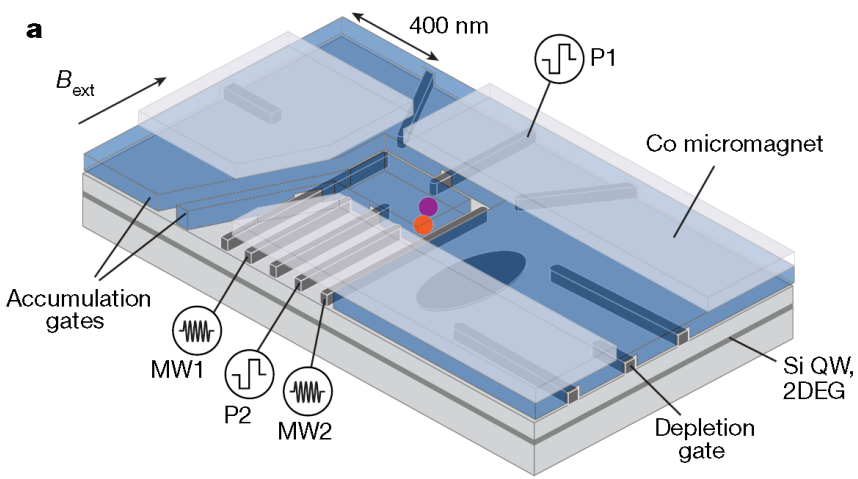
2-Qubit Algorithms: Si/SiGe Double-QD

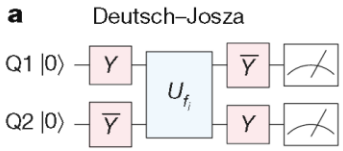
A programmable two-qubit quantum processor in silicon

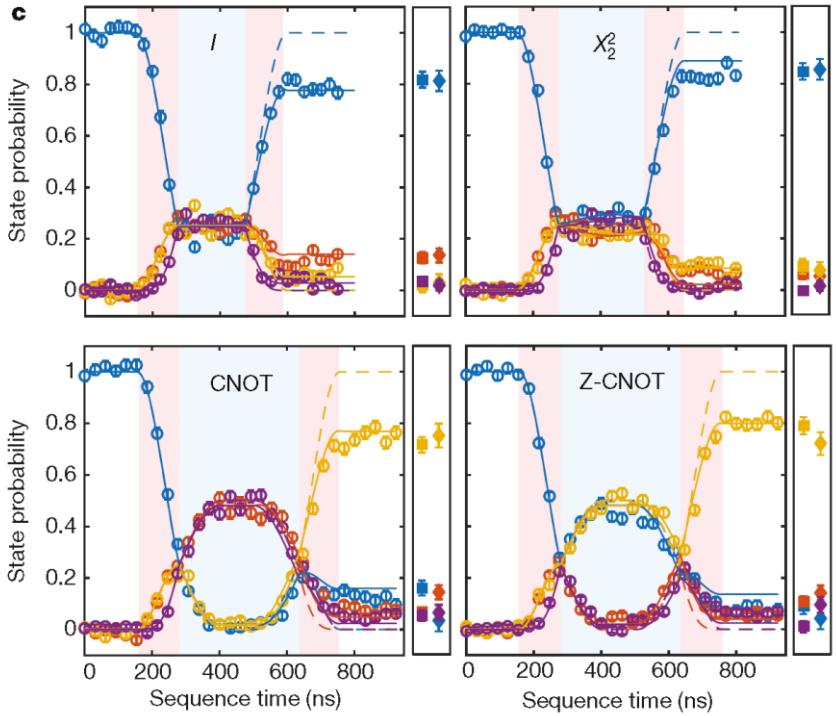
T. F. Watson[1], S. G. J. Philips[1], E. Kawakami[1], D. R. Ward[2], P. Scarlino[1], M. Veldhorst[1], D. E. Savage[2], M. G. Lagally[2], Mark Friesen[2], S. N. Coppersmith[2], M. A. Eriksson[2] & L. M. K. Vandersypen[1]

EDSR - μMagnet | **^{nat}Si**

Bell State F = 89%





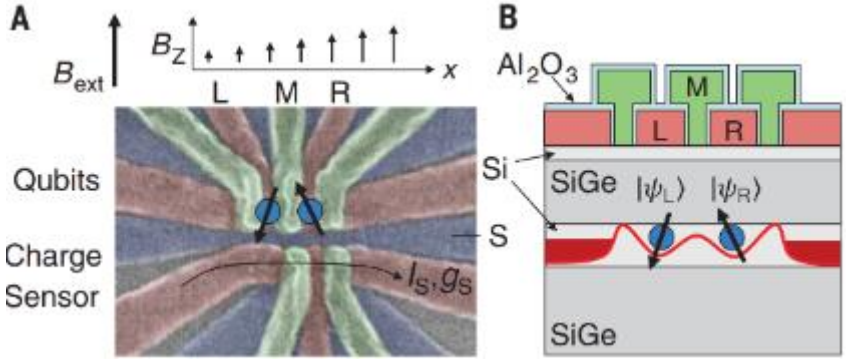


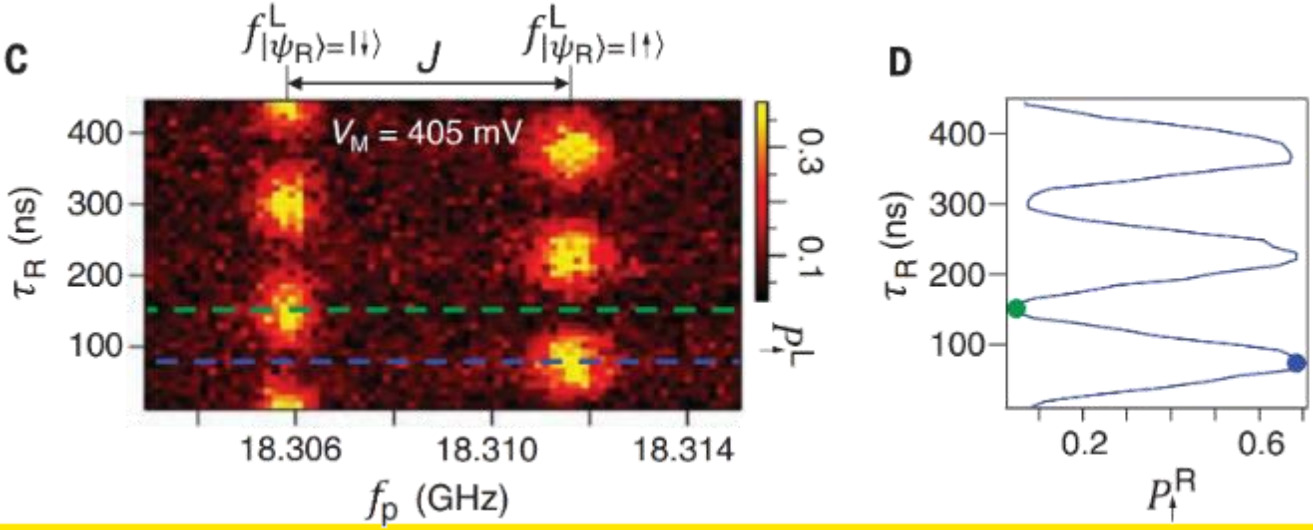
T.F. Watson et al., *Nature* (2018) - doi:10.1038/nature25766

Si/SiGe two-qubit gates: Resonant CNOT

Petta group (Princeton) – Si/SiGe QDs:

- Resonantly driven rather than waiting for phase accumulation
- Exchange gate to manipulate exchange coupling
- Measured Bell states (F = 78 %) and demonstrated entanglement





Zajac et al., Science 359, 439 (2018)

^{28}SiMOS QDs: Two-Qubit Fidelity via RB

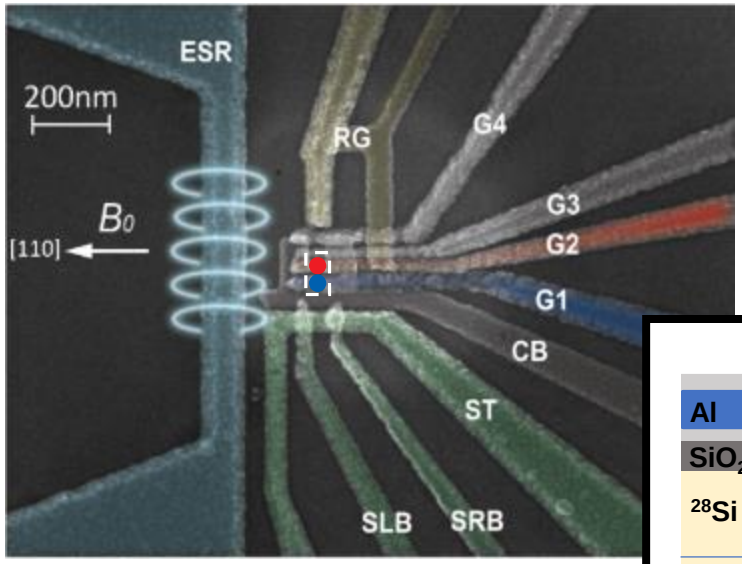
LETTER

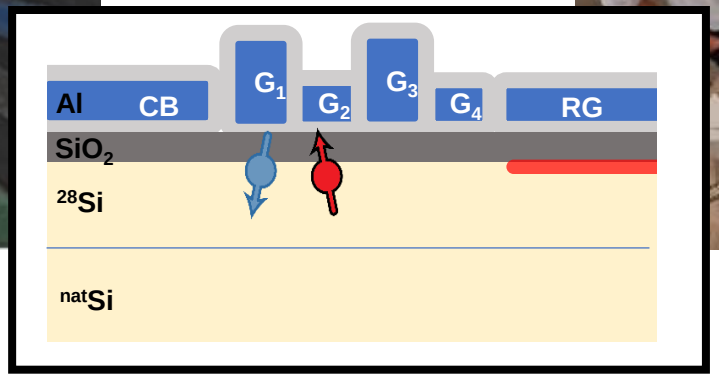
nature
International journal of science

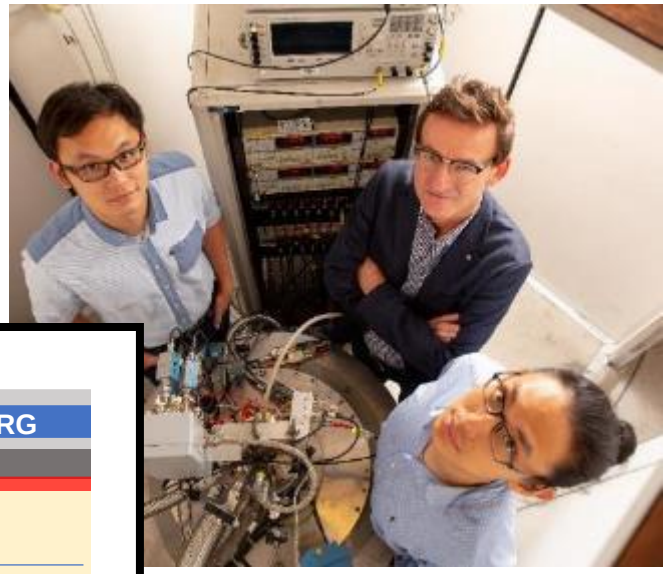
https://doi.org/10.1038/s41586-019-1197-0

Fidelity benchmarks for two-qubit gates in silicon

W. Huang[1]*, C. H. Yang[1], K. W. Chan[1], T. Tanttu[1], B. Hensen[1], R. C. C. Leon[1], M. A. Fogarty[1,2], J. C. C. Hwang[1], F. E. Hudson[1], K. M. Itoh[3], A. Morello[1], A. Laucht[1] & A. S. Dzurak[1]*

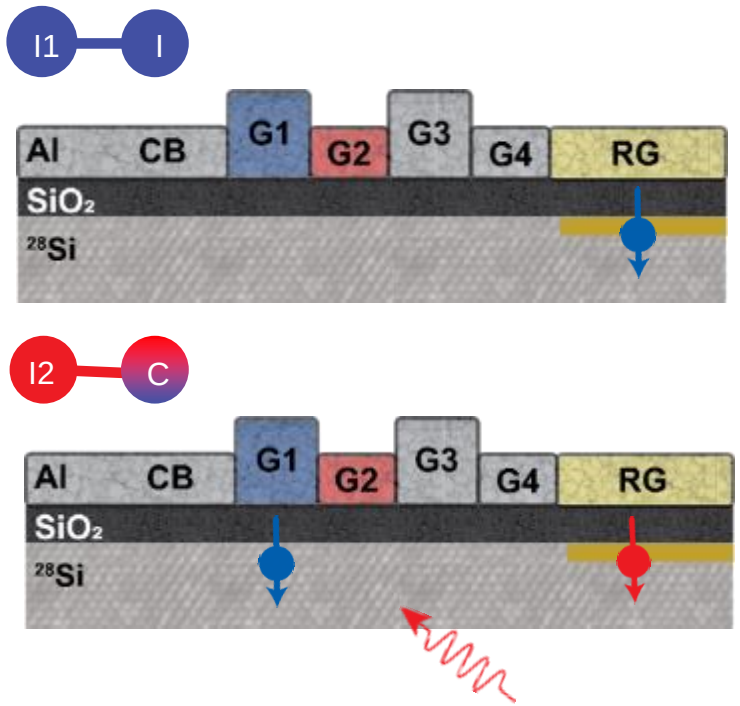


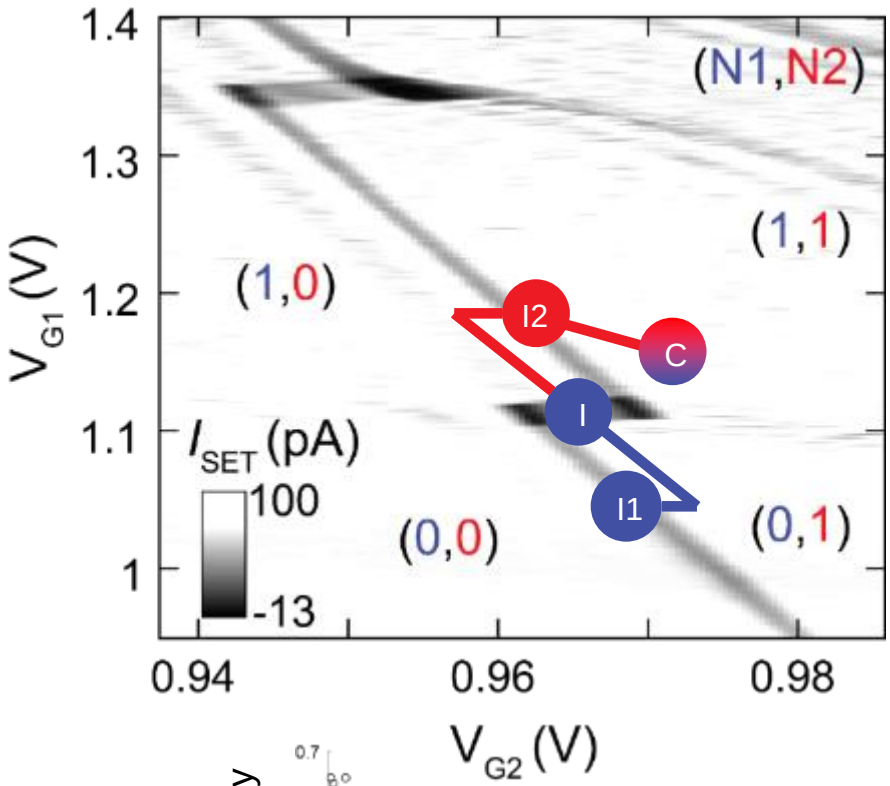




Huang et al., *Nature* 569, 532 (2019)

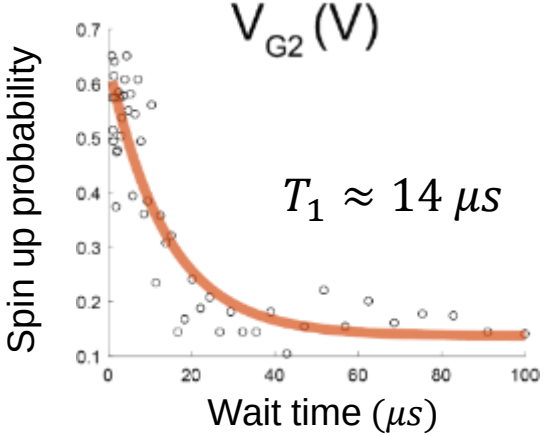
Initialization process for two qubits





- **Hot-spot relaxation close to (0,1)-(1,0) improves initialization fidelity of Q1**

Watson et al., Nature **555**, 633 (2018)
Zhao et al., arXiv:1707.05217



Huang et al., *Nature* 569, 532 (2019)

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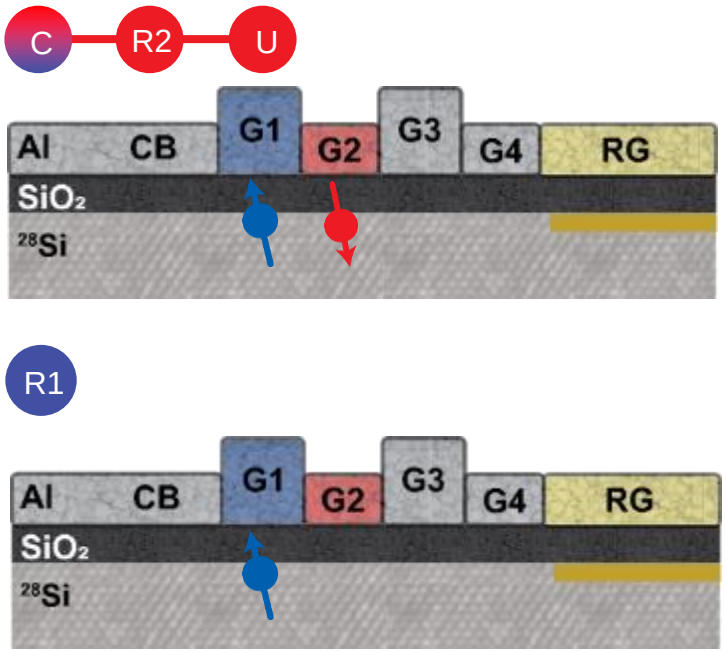
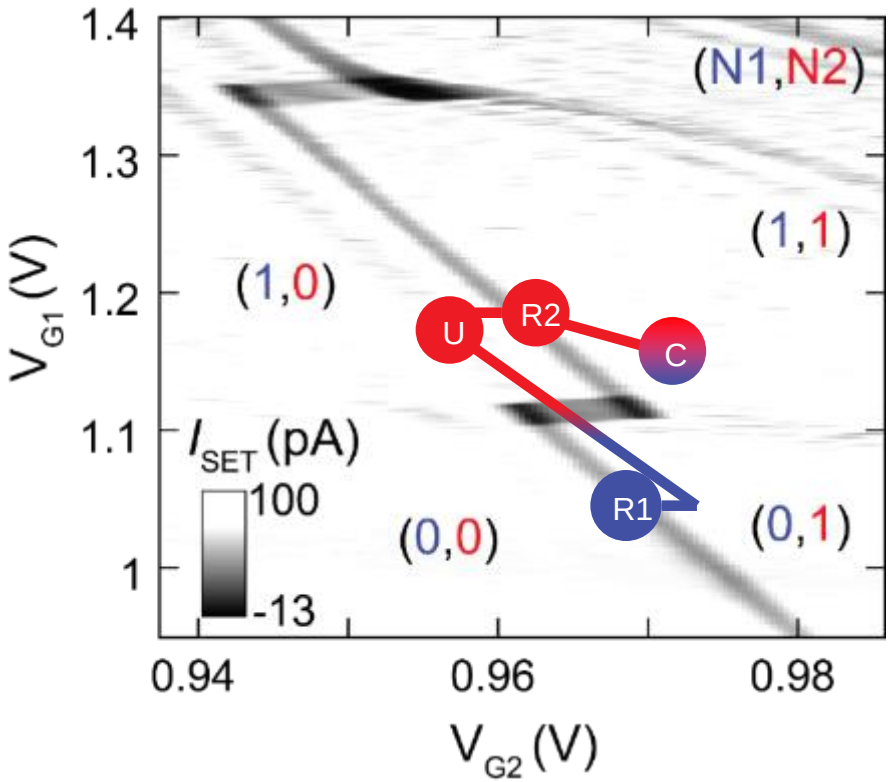
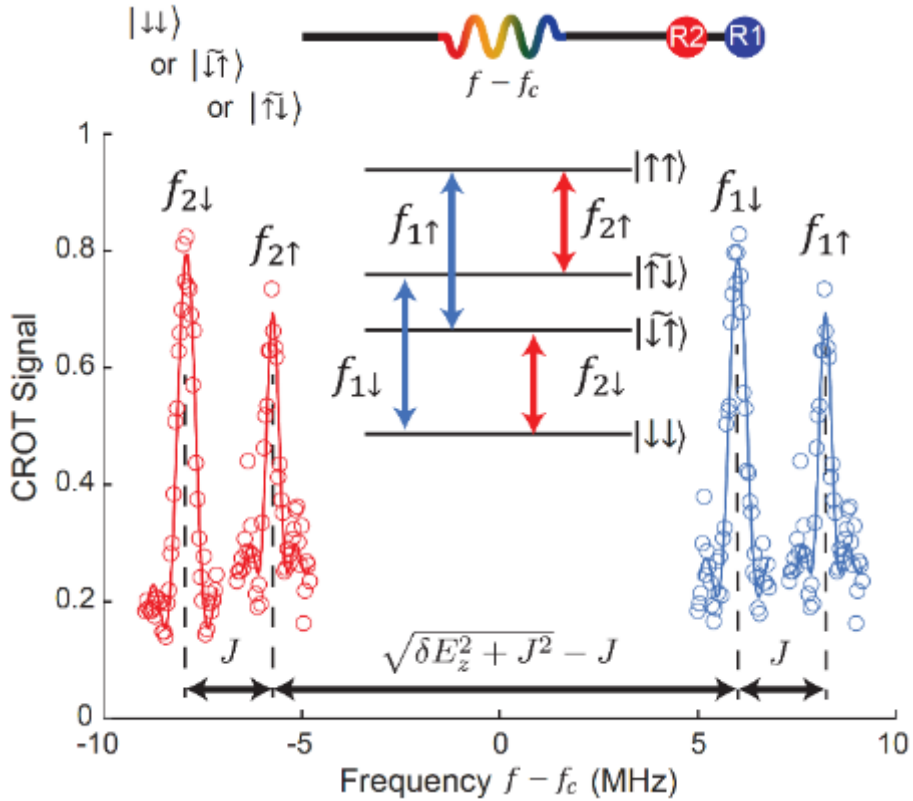
Readout process for two qubits

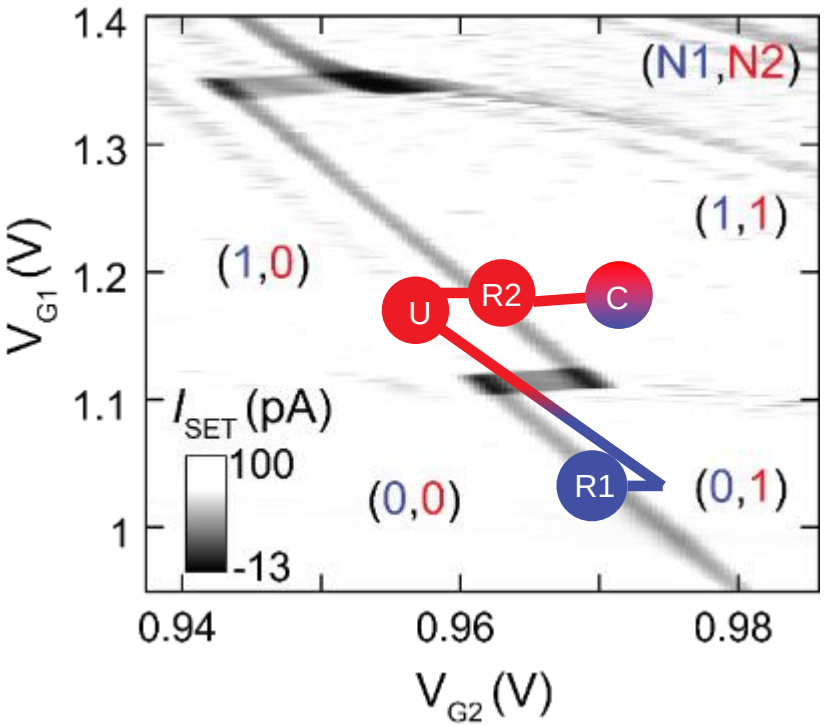




- **Shuttling Q1 from D1 to D2 is advantageous over reading out Q1 at the (1,0)-(0,0) transition directly, due to the slow tunneling rate from D1 to the reservoir.**

Conditional control





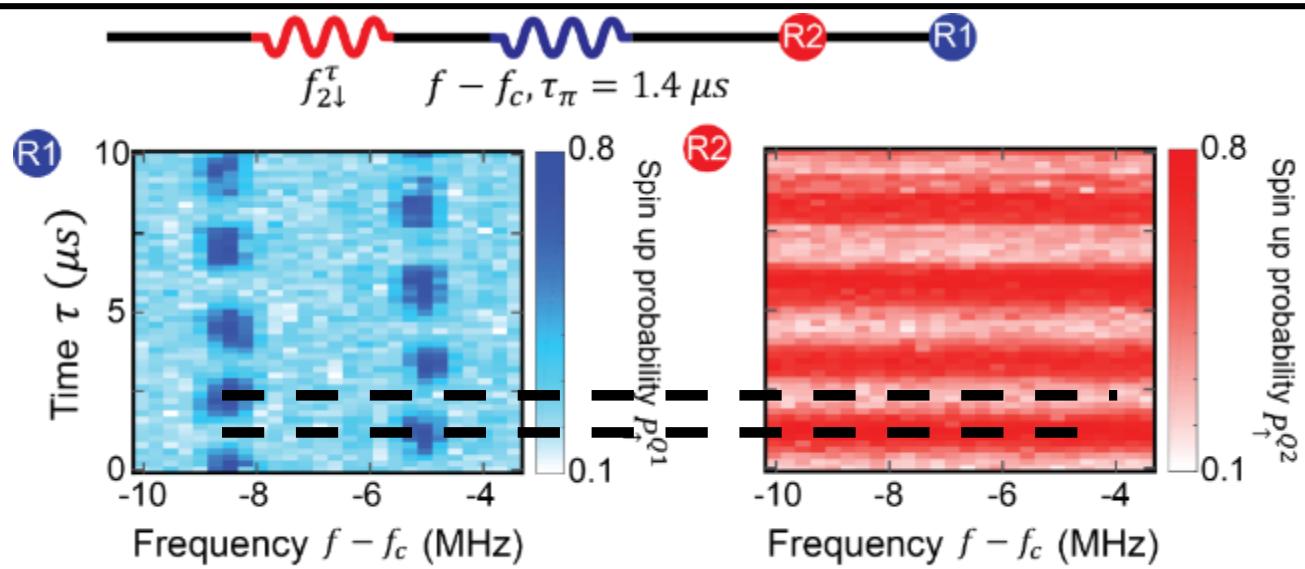
- **Lines clearly split by δE_Z and J → conditional and selective addressing**

$\overline{E_z}$	39.17 GHz
δE_z	13.72 MHz
J	2.51 MHz
Ω_R	0.35-0.55 MHz

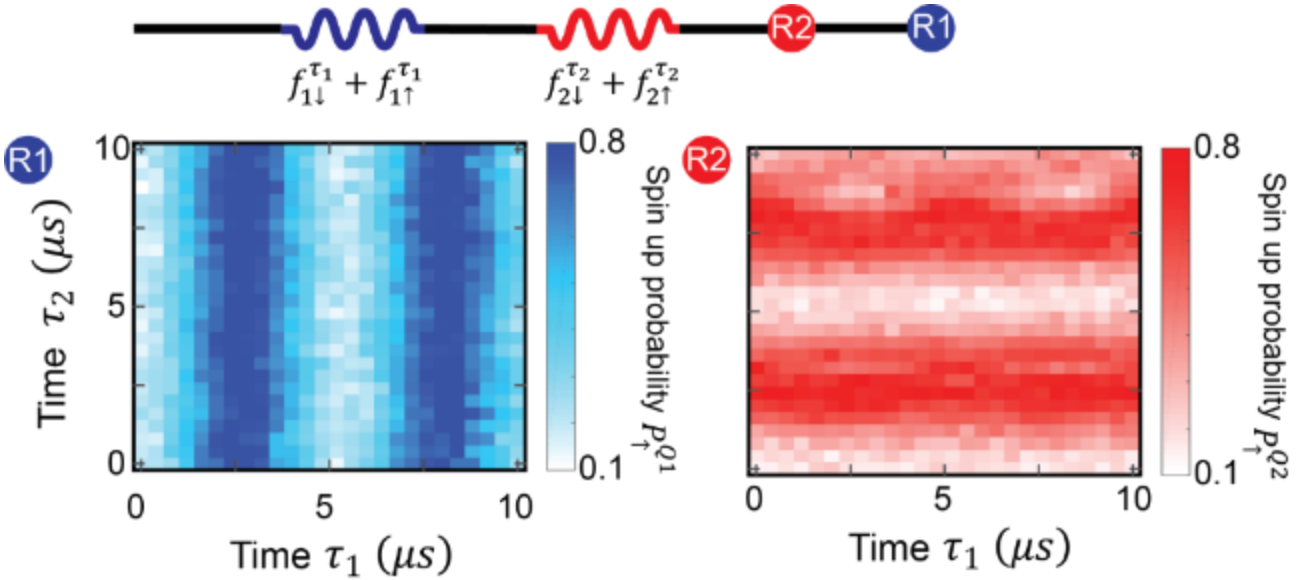
Huang et al., *Nature* 569, 532 (2019)

Conditional rotations

- **Every MW pulse is a conditional qubit gate**

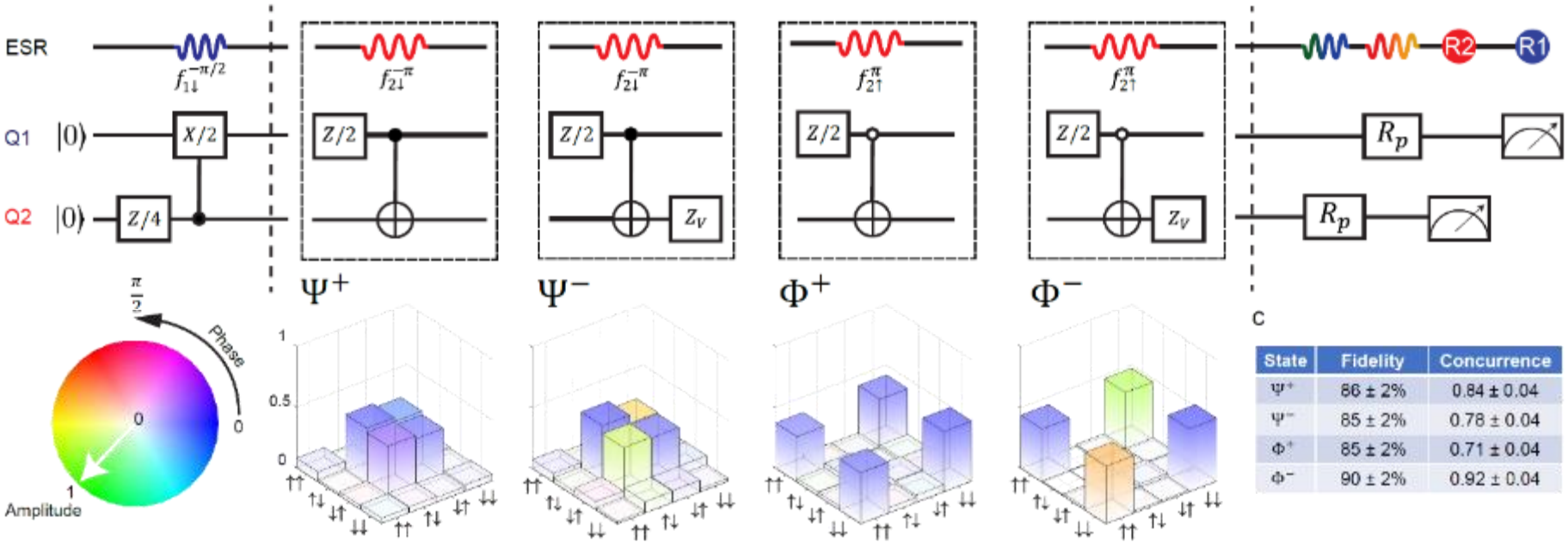


- **Single qubit gates require 2 MW pulses (either serial or parallel)**



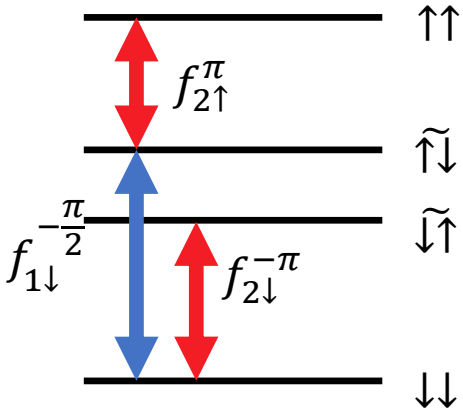
Huang et al., *Nature* 569, 532 (2019)

Bell state tomography



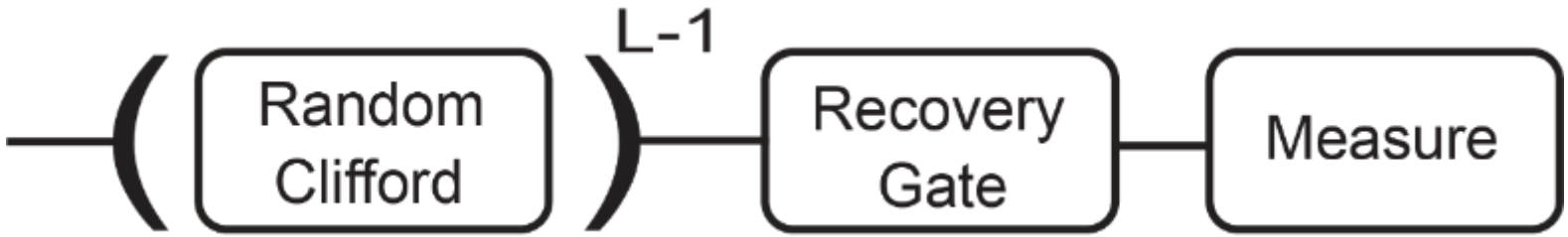
State	Fidelity	Concurrence
Ψ^+	86 ± 2%	0.84 ± 0.04
Ψ^-	85 ± 2%	0.78 ± 0.04
Φ^+	85 ± 2%	0.71 ± 0.04
Φ^-	90 ± 2%	0.92 ± 0.04

- **Projected to $X, -X, Y, Z$ axis**
- **8960 single shots**
- **Corrected for readout error**



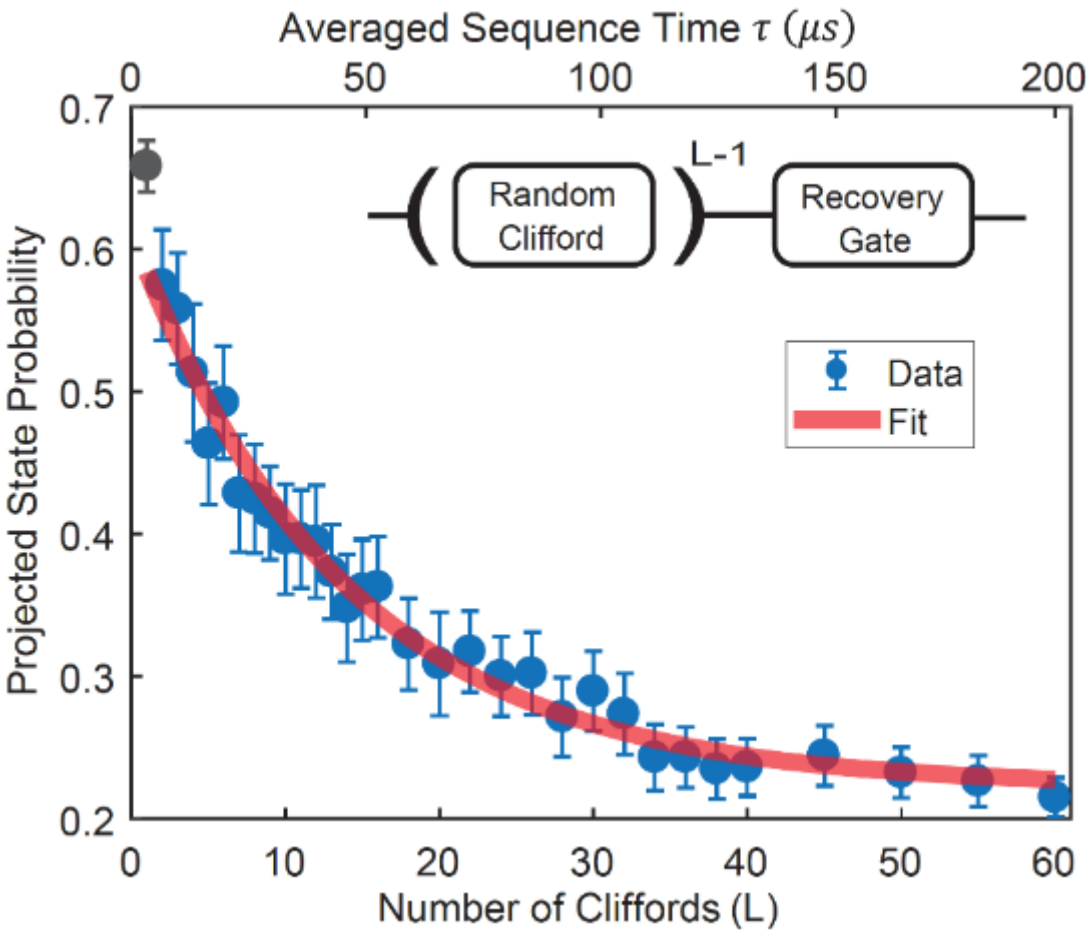
Huang et al., *Nature* 569, 532 (2019)

Two-qubit randomized benchmarking



- **Single qubit : 24 Clifford gates**
- **Two qubit : 11520 Clifford gates**
- **Project to $|\uparrow\uparrow\rangle$ final state.**
- $\mathbf{P} = \boldsymbol{A}\left(\frac{\mathbf{1}}{\mathbf{4}} + \frac{\mathbf{4}}{\mathbf{3}}\boldsymbol{F}_{Clifford}\right)^{\boldsymbol{L}} + \boldsymbol{B}$
- **SPAM errors absorbed by parameters $\boldsymbol{A}$ and $\boldsymbol{B}$**

2-Qubit Randomized Benchmarking in Silicon



- 51 random Clifford sequences per L data point
- $P = A\left(\frac{1}{4} + \frac{4}{3}F_{Clifford}\right)^L + B$
- Gate fidelities:

$$F_{\mathbf{Clifford}} = \mathbf{94.7 \pm 0.8}\ \%$$

$$F_{\mathbf{primitive}} = \mathbf{98.0 \pm 0.3}\ \%$$

$$F_{\pi/2}^{\mathbf{cond}} = \mathbf{99.0 \pm 0.2}\ \%$$

Huang et al., *Nature* 569, 532 (2019)

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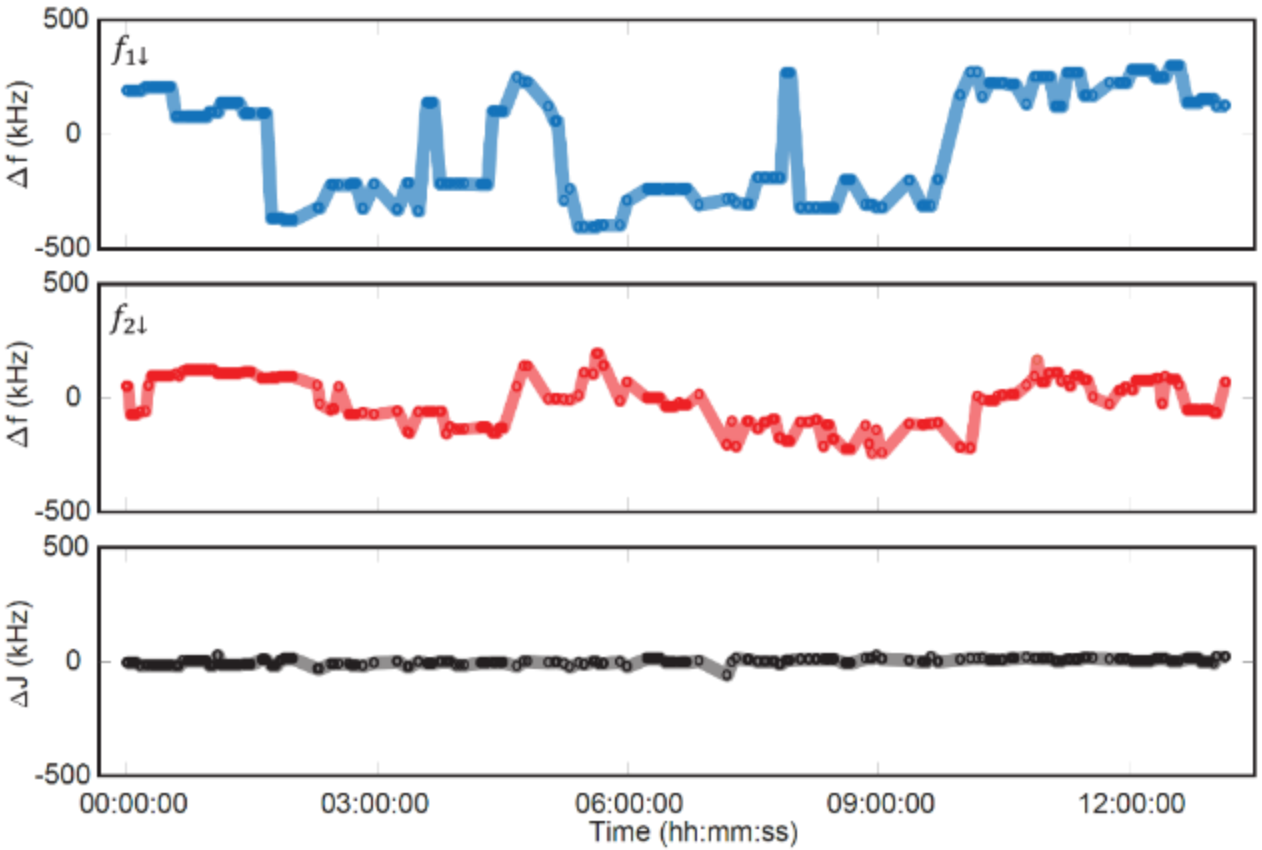
ESR Frequency Tracking: *12 hours*



- Frequency jumps of up to 600 kHz for Q1
- Much smaller jumps for Q2
- Q1 and Q2 jumps are uncorrelated
  → No B_0 or MW source noise
- *J* very stable + SET charge sensor stable
  → <u>Not</u> charge noise

➔ Residual ^{29}Si nuclei couple locally to the qubits

Huang et al., *Nature* <u>569</u>, 532 (2019)

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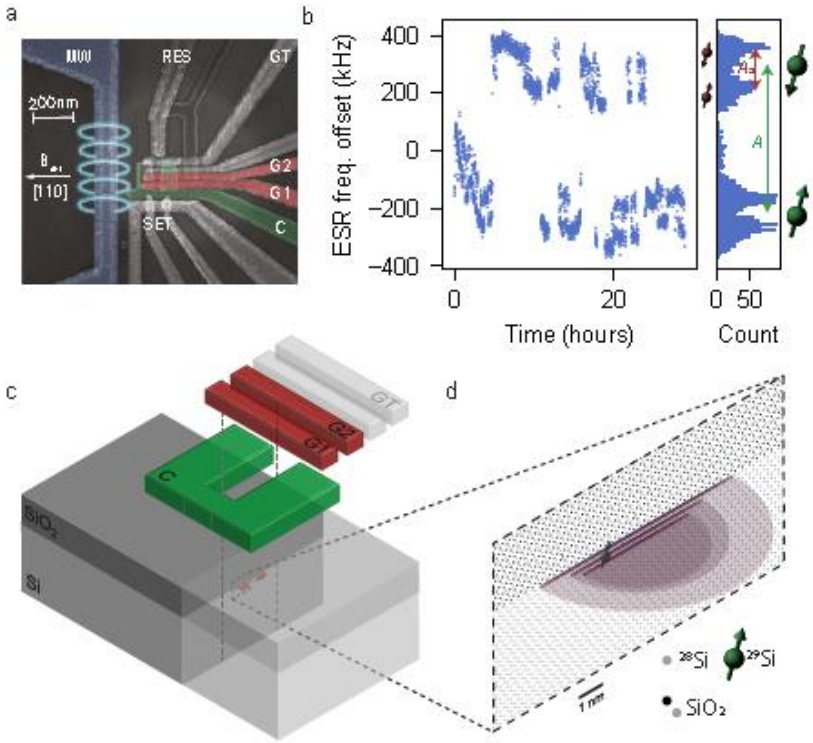
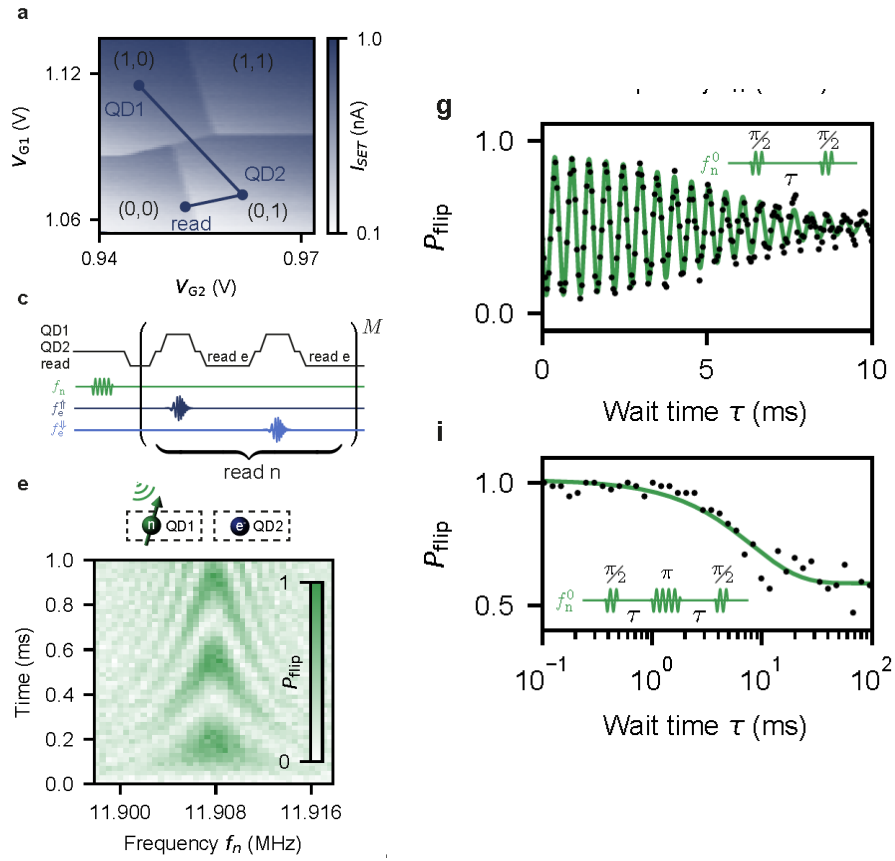
^{29}Si Nuclear Spin Qubit: *Possible Quantum Memory*

A silicon quantum-dot-coupled nuclear spin qubit

Bas Hensen[*,1], Wister Huang[*,1], Chih-Hwan Yang[1], Kok Wai Chan[1], Jun Yoneda[1], Tuomo Tanttu[1], Fay E. Hudson[1], Arne Laucht[1], Kohei M. Itoh[2], Andrea Morello[1], Andrew S. Dzurak[1]





B. Hensen et al., arXiv:1904.08260

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Scalability of Silicon Spin Qubits

Medium-term Vision: Error-corrected 1D Architecture

HRL LABORATORIES

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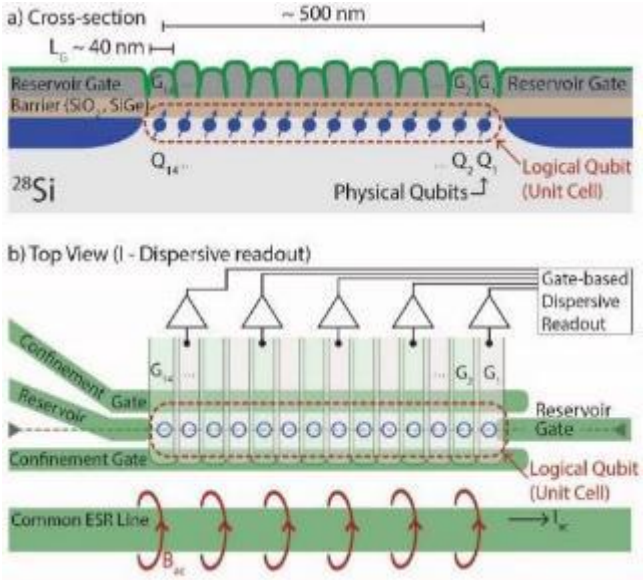
PHYSICAL REVIEW X **8,** 021058 (2018)

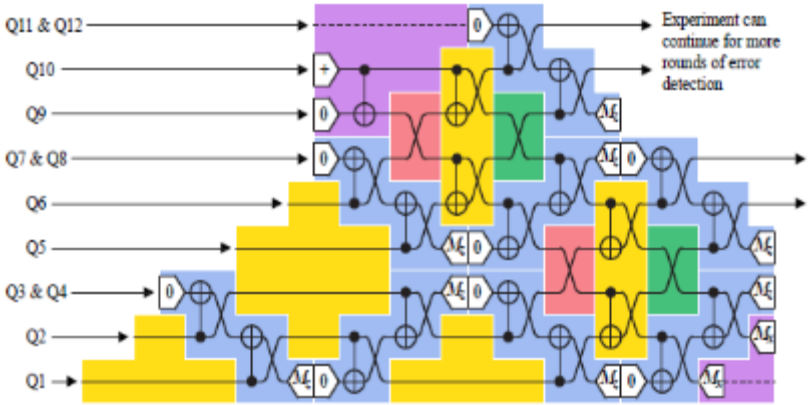
Logical Qubit in a Linear Array of Semiconductor Quantum Dots

Cody Jones,[1,*] Michael A. Fogarty,[2] Andrea Morello,[2] Mark F. Gyure,[1] Andrew S. Dzurak,[2] and Thaddeus D. Ladd[1]

[1]*HRL Laboratories, LLC, 3011 Malibu Canyon Road, Malibu, California 90265, USA*

[2]*Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, New South Wales 2052, Australia*





PRX - June 2018

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Key Components for *Parity Readout* in SiMOS QDs

nature COMMUNICATIONS

Article | OPEN | Published: 30 October 2018

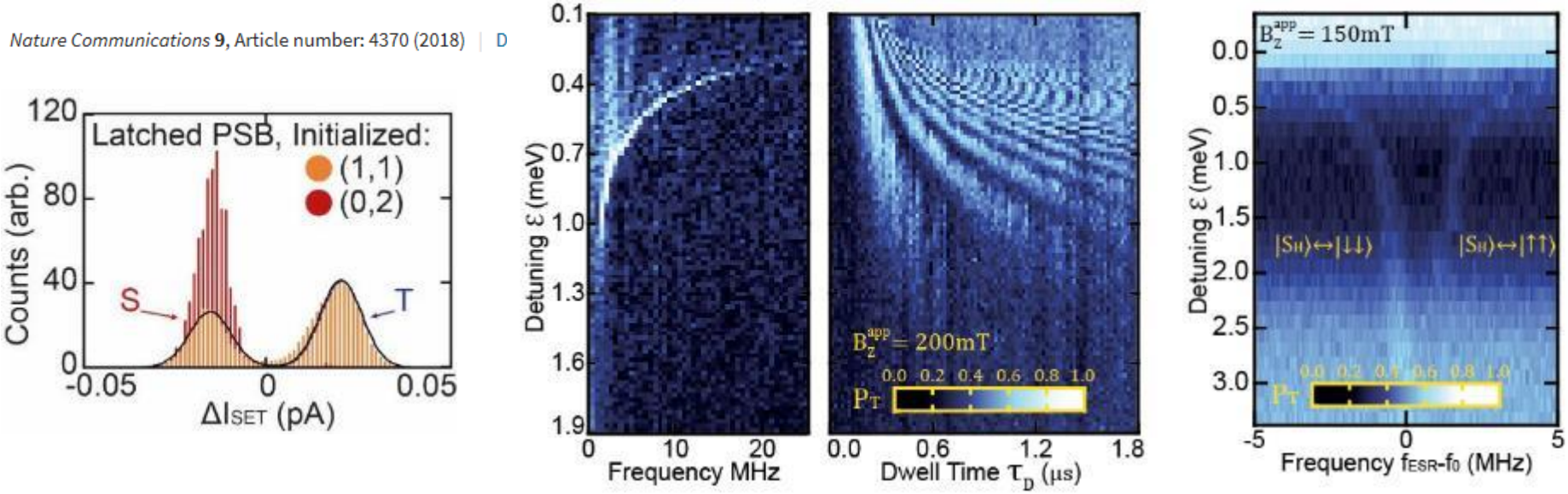
Integrated silicon qubit platform with single-spin addressability, exchange control and single-shot singlet-triplet readout

M. A. Fogarty, K. W. Chan, B. Hensen, W. Huang, T. Tanttu, C. H. Yang, A. Laucht, M. Veldhorst, F. E. Hudson, K. M. Itoh, D. Culcer, T. D. Ladd, A. Morello & A. S. Dzurak

Nature Communications **9**, Article number: 4370 (2018) | D

Requirements achieved:

- ✓ **Single-shot spin-blockade readout**
- ✓ **Coherent control of spin-pairs in singlet-triplet basis**
- ✓ **Individual ESR spin addressability**



M. Fogarty *et al.*, *Nature Communications* 9, 4370 (2018)

UNSW SYDNEY

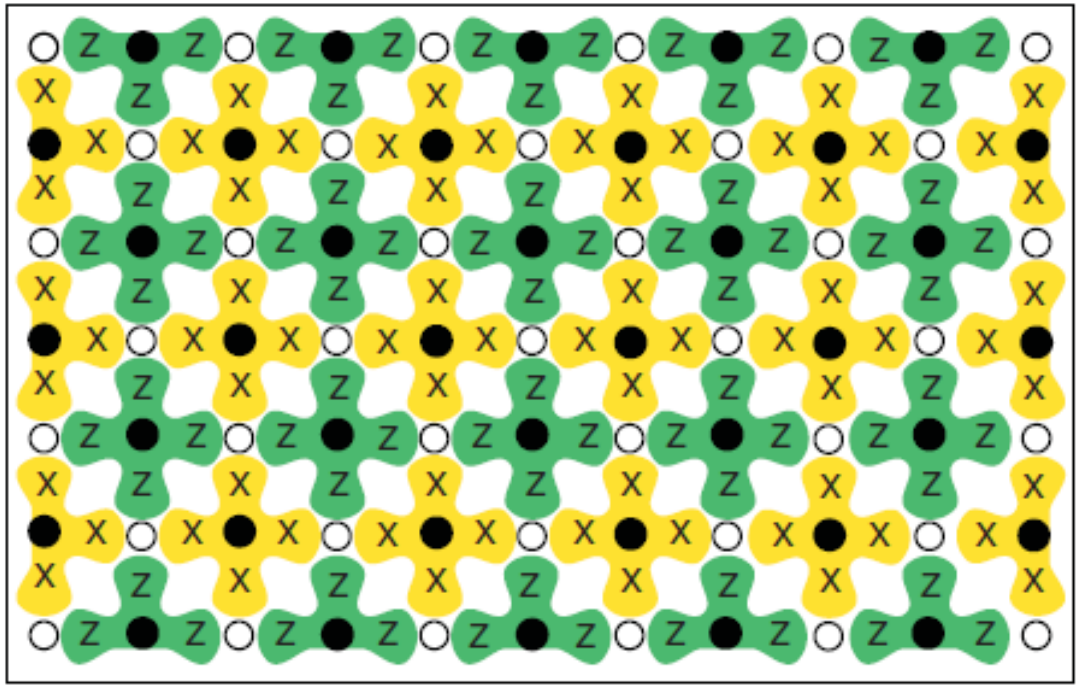
Fault-tolerant Scalibility: Surface Codes

PHYSICAL REVIEW A **86**, 032324 (2012)

Surface codes: Towards practical large-scale quantum computation

Austin G. Fowler
Centre for Quantum Computation and Communication Technology, School of Physics, The University of Melbourne, Victoria 3010, Australia

Matteo Mariantoni, John M. Martinis, and Andrew N. Cleland
Department of Physics, University of California, Santa Barbara, California 93106-9530, USA
and California Nanosystems Institute, University of California, Santa Barbara, California 93106-9530, USA
(Received 2 August 2012; published 18 September 2012)



A.G. Fowler et al., *PRA* 86, 032324 (2012)

QD Qubits: Scalability Concepts

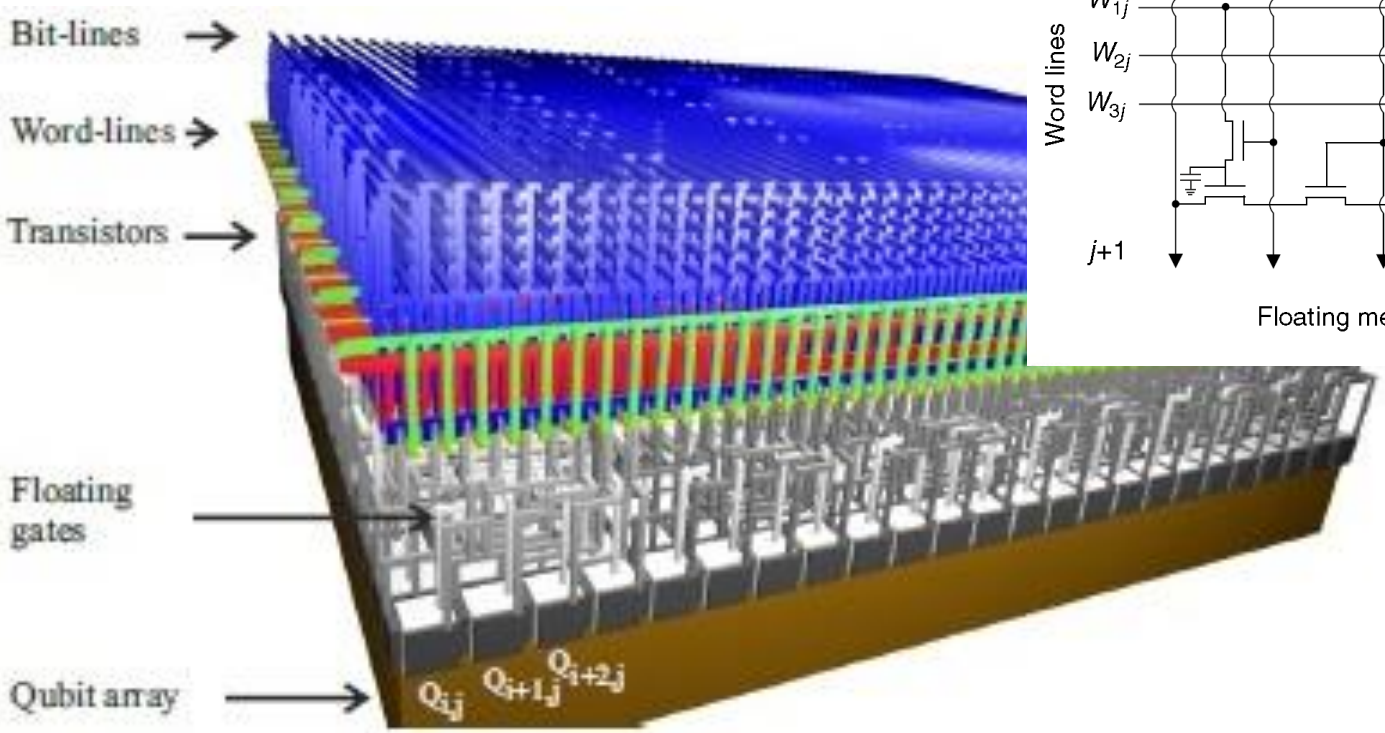
ARTICLE

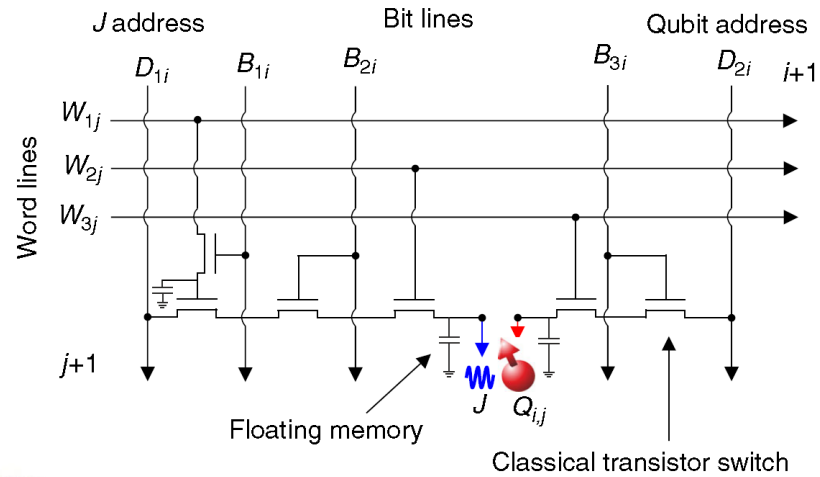
DOI: 10.1038/s41467-017-01905-6 OPEN

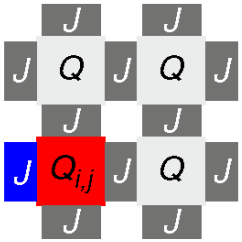
nature COMMUNICATIONS

Silicon CMOS architecture for a spin-based quantum computer

M. Veldhorst[1,2], H.G.J. Eenink[1,2], C.H. Yang[2] & A.S. Dzurak[2]







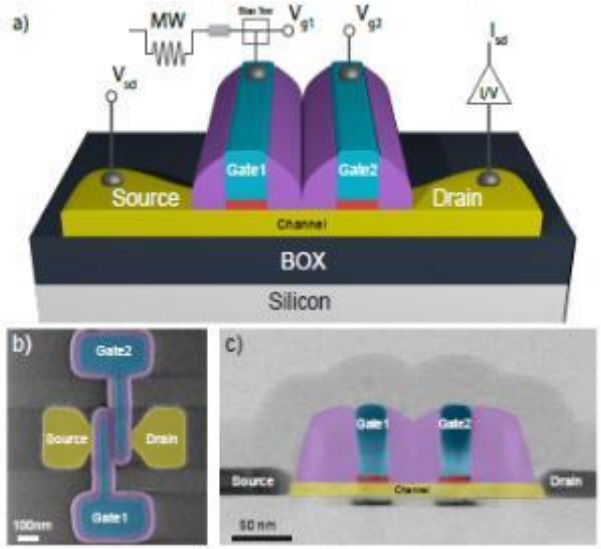
Industrial Manufacture: *Uniformity, Integration*

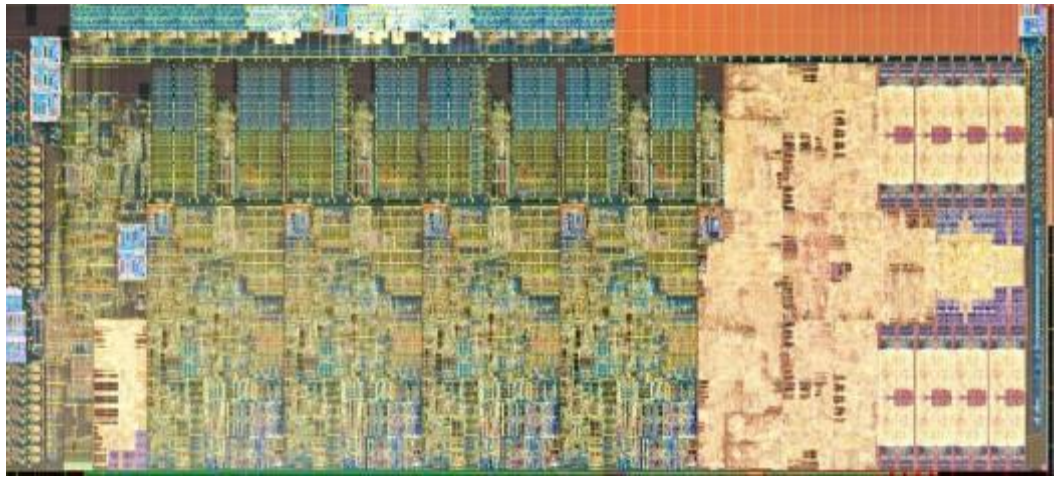
ARTICLE

Received 28 Jul 2016 | Accepted 14 Oct 2016 | Published 24 Nov 2016

A CMOS silicon spin qubit

R. Maurand[1,2], X. Jehl[1,2], D. Kotekar-Patil[1,2], A. Corna[1,2], H. Bohuslavskyi[1,2], R. Laviéville[1,3], L. Hutin[1,3], S. Barraud[1,3], M. Vinet[1,3], M. Sanquer[1,2] & S. De Franceschi[1,2]





Maurand et al., *Nature Communications* 7, 13575 (2016)

Scalability: Reducing wiring complexity

Dispersive Readout of a Few-Electron Double Quantum Dot with Fast rf Gate Sensors

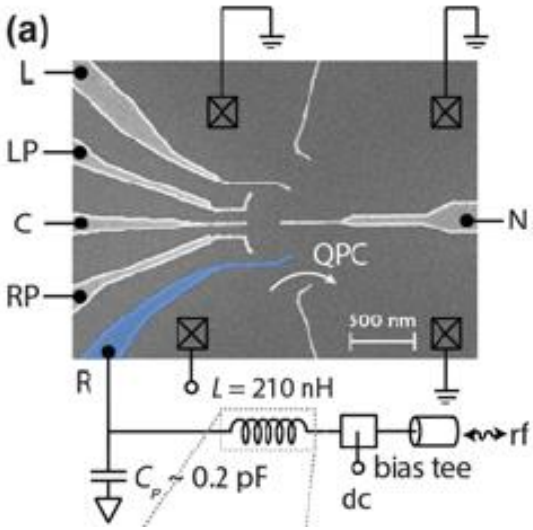
J. I. Colless,[1] A. C. Mahoney,[1] J. M. Hornibrook,[1] A. C. Doherty,[1] H. Lu,[2] A. C. Gossard,[2] and D. J. Reilly[1,*]

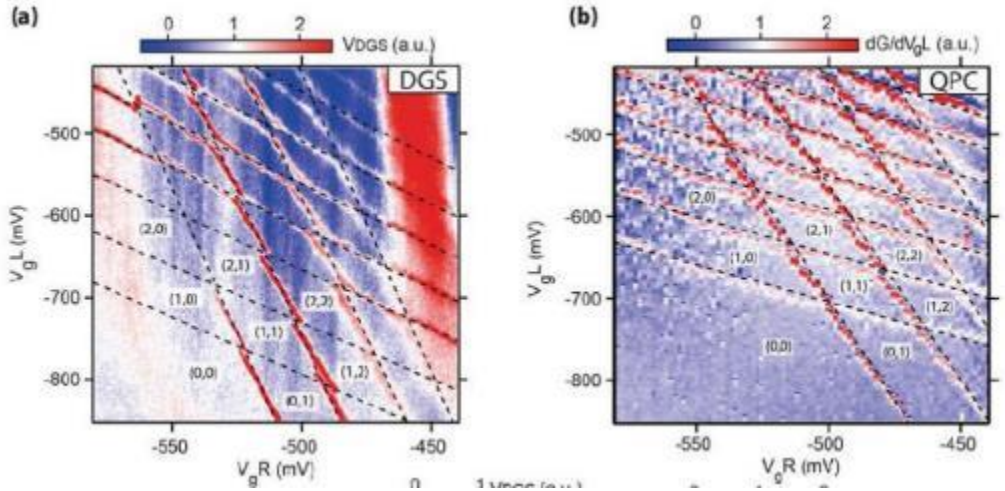
[1]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, New South Wales 2006, Australia*

[2]*Materials Department, University of California, Santa Barbara, California 93106, USA*

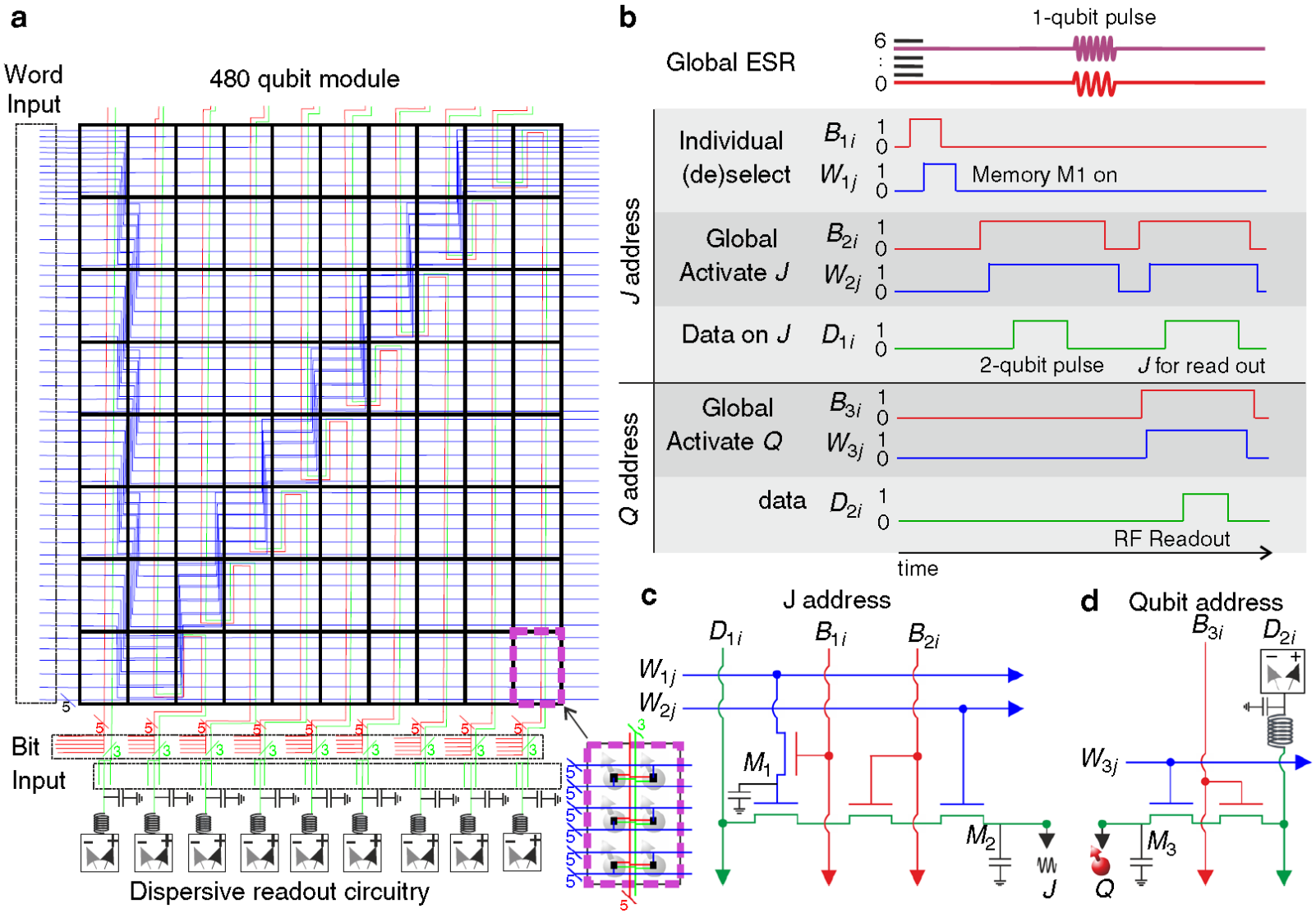
(Received 17 October 2012; published 25 January 2013)

We report the dispersive charge-state readout of a double quantum dot in the few-electron regime using the *in situ* gate electrodes as sensitive detectors. We benchmark this gate sensing technique against the well established quantum point contact charge detector and find comparable performance with a bandwidth of ~10 MHz and an equivalent charge sensitivity of $\sim 6.3 \times 10^{-3}\ e/\sqrt{\mathrm{Hz}}$. Dispersive gate sensing alleviates the burden of separate charge detectors for quantum dot systems and promises to enable readout of qubits in scaled-up arrays.



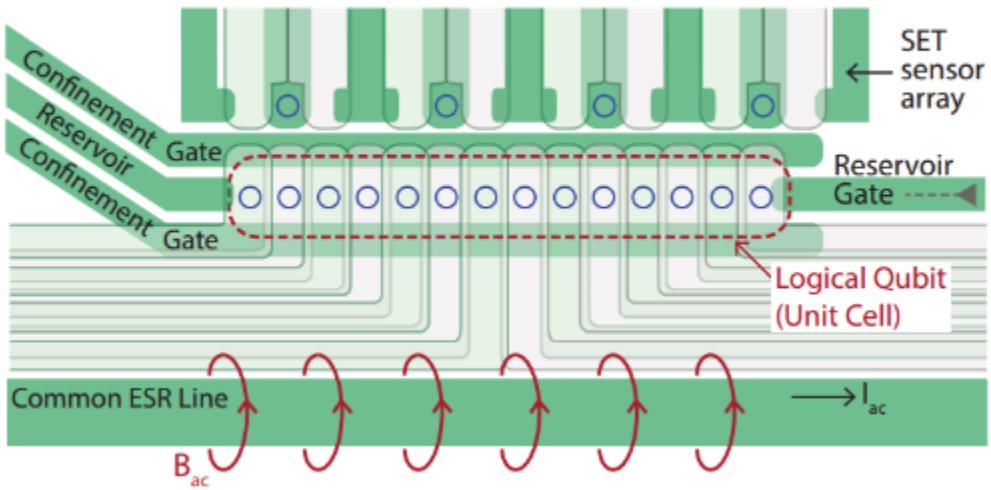


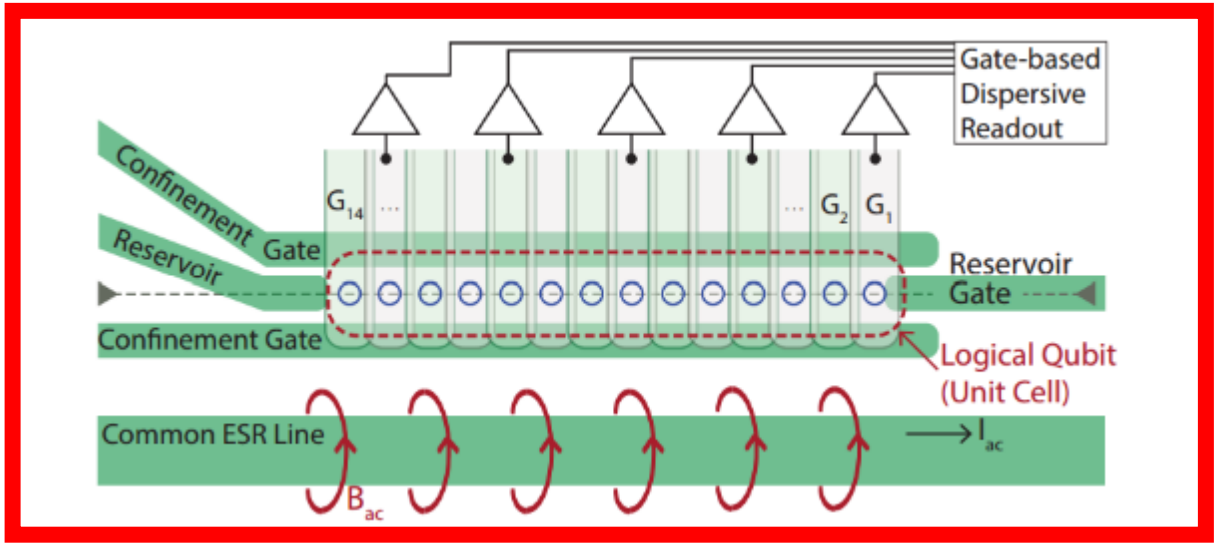
CMOS QD Qubit Processor: Dispersive Readout



M. Veldhorst et al., *Nature Comms.* 8, 1766 (2017)

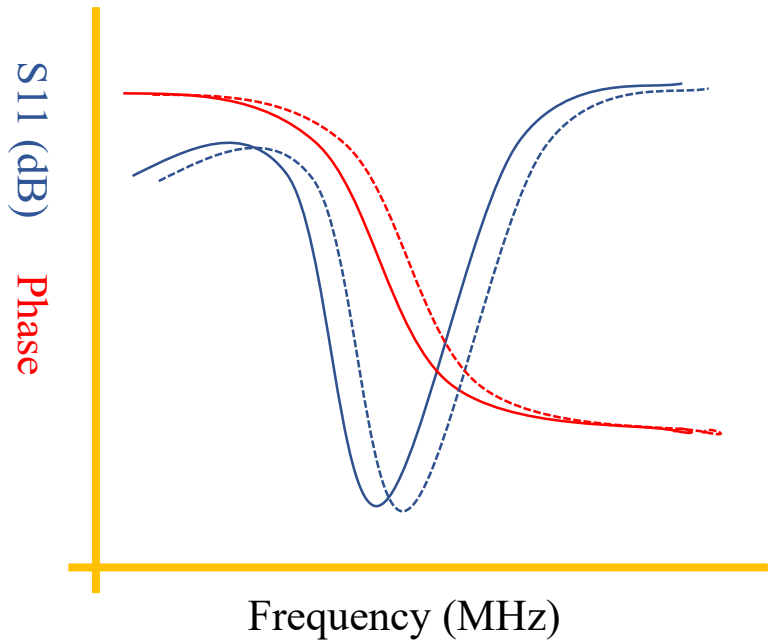
Dispersive Gate Sensing: Compact, Scalable

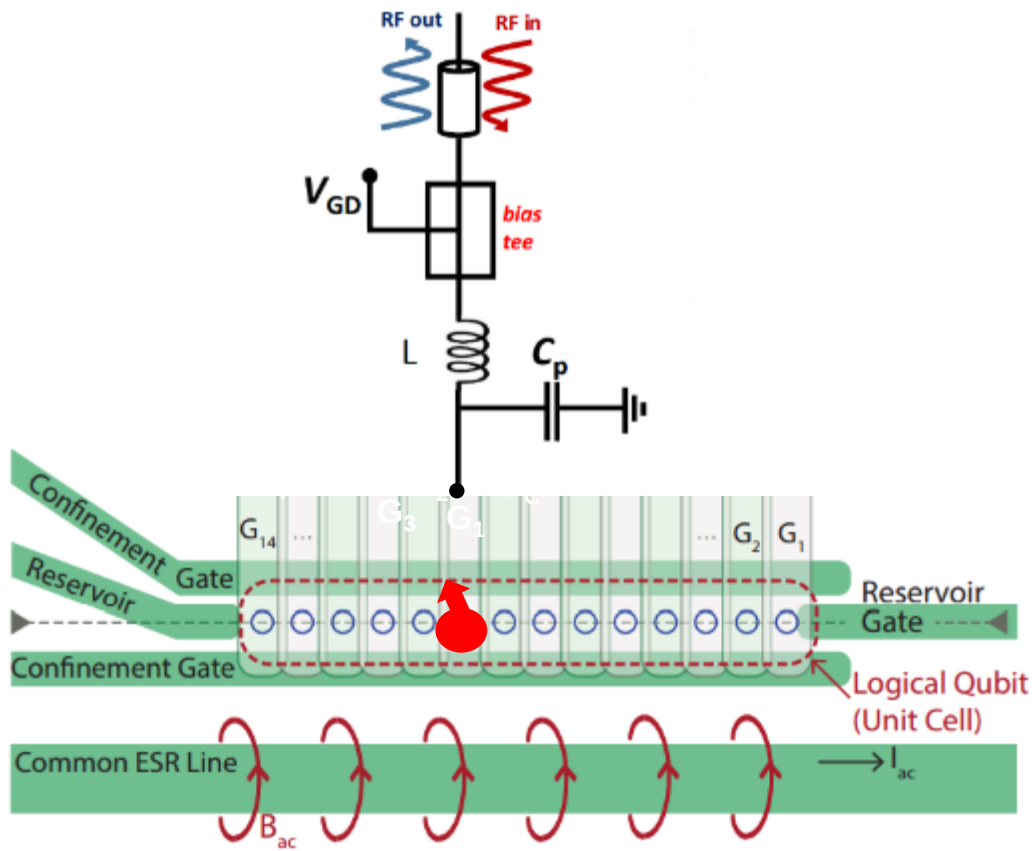




Jones *et al.*, *PRX* 8, 021058 (2018)

Electron tunnelling shifts resonant frequency





$$f = \frac{1}{2\pi(L(C_p + C_t))^{1/2}}$$

Single-Shot Dispersive-Gate Spin Readout

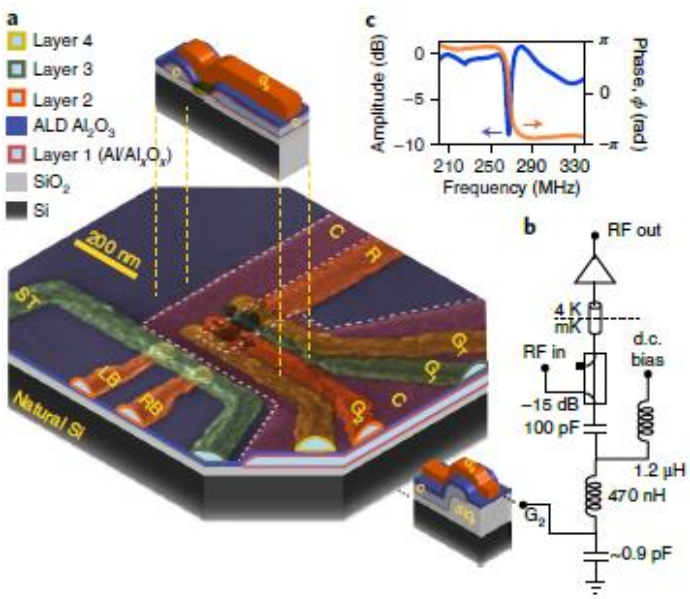
nature nanotechnology

LETTERS

https://doi.org/10.1038/s41565-019-0400-7

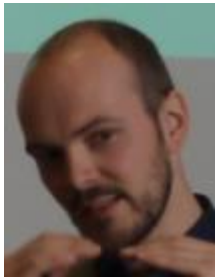
Gate-based single-shot readout of spins in silicon

Anderson West[1,6], Bas Hensen[1,6*], Alexis Jouan[2], Tuomo Tanttu[1], Chih-Hwan Yang[1], Alessandro Rossi[3], M. Fernando Gonzalez-Zalba[4], Fay Hudson[1], Andrea Morello[1], David J. Reilly[2,5] and Andrew S. Dzurak[1*]



Anderson West

Bas Hensen

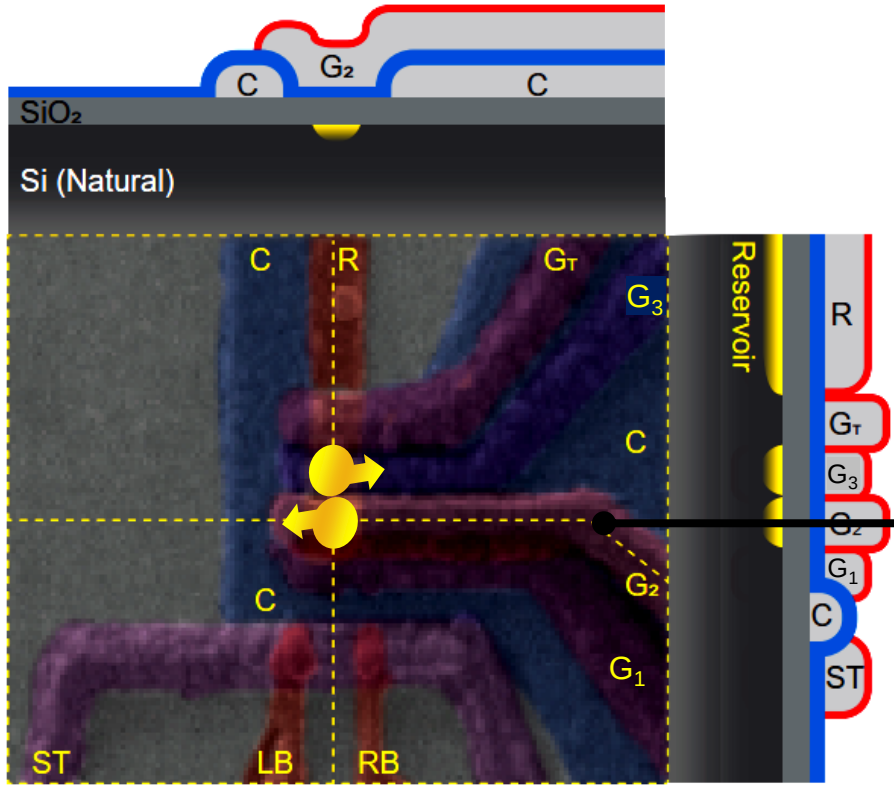


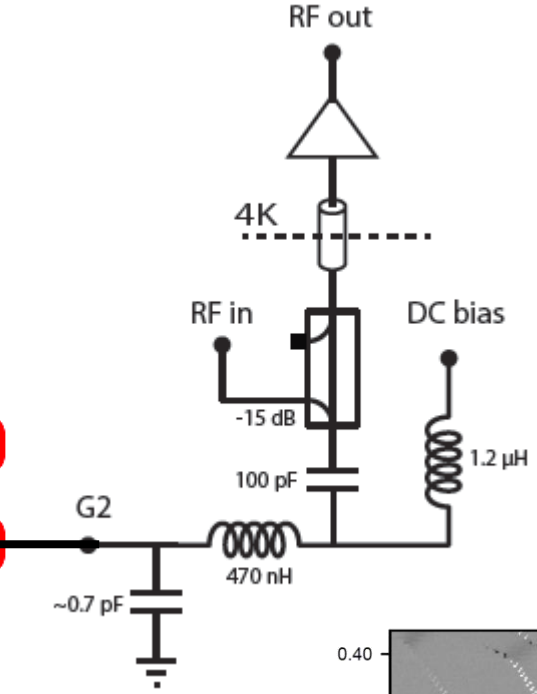
Alexis Jouan

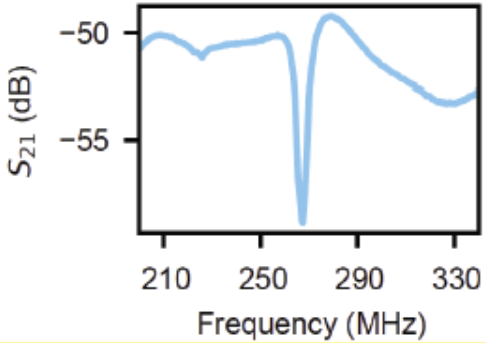
David Reilly

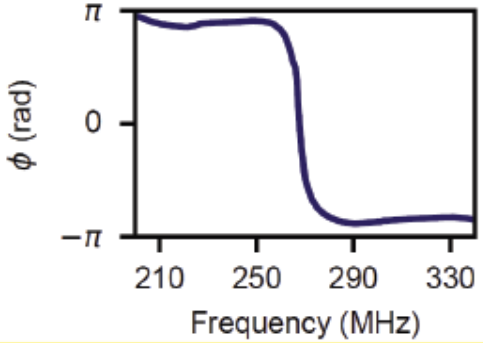
A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

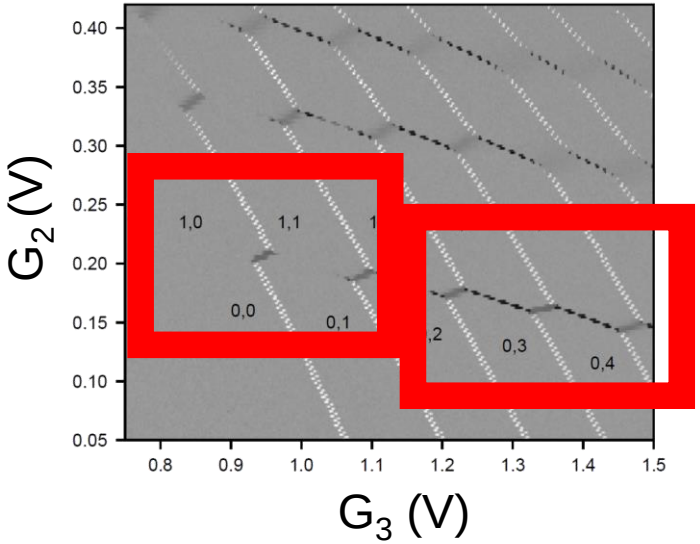
Optimized Device for *Dispersive Gate Readout*







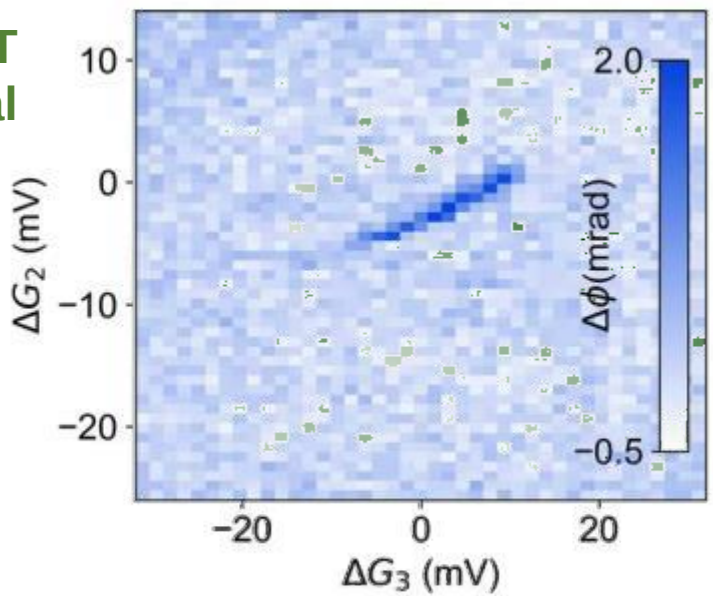




A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

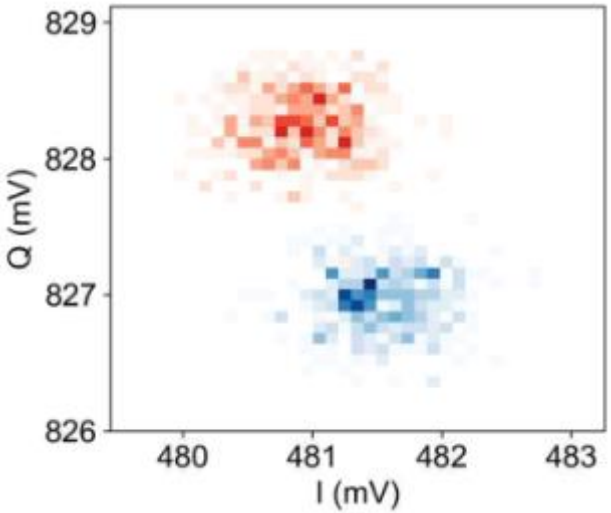
Dispersive Gate *Charge* Sensing: (0,1) – (1,0)

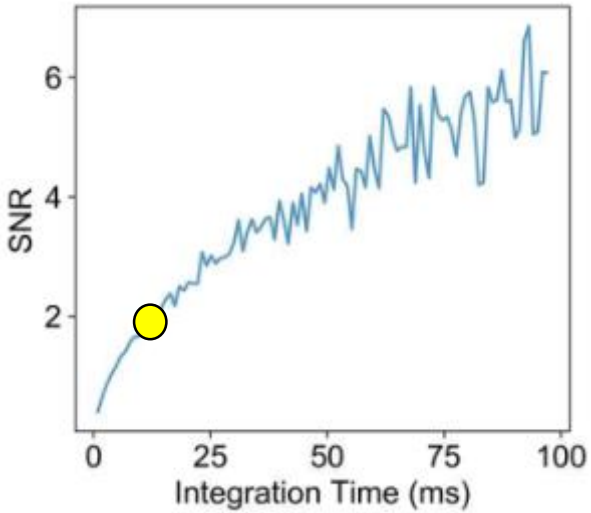
SET Signal



DGS Signal

In-phase (I) & Quadrature (Q) DGS Signal [for SNR = 2]



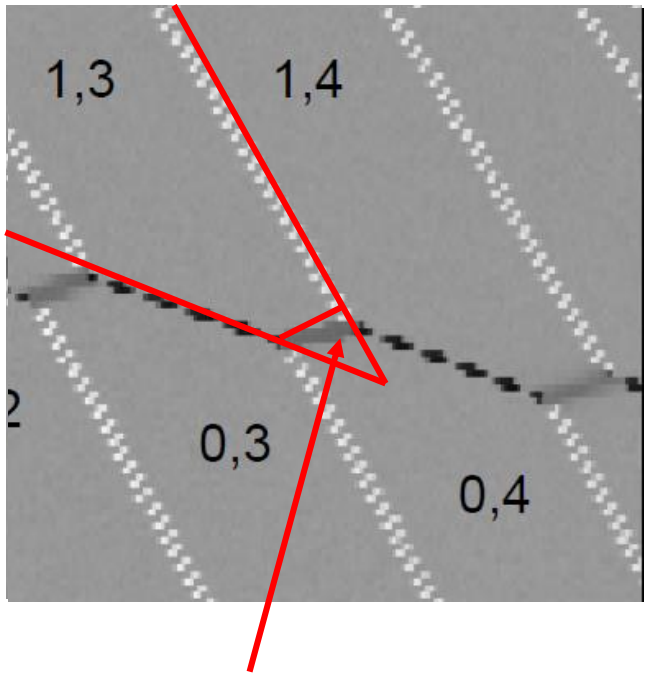


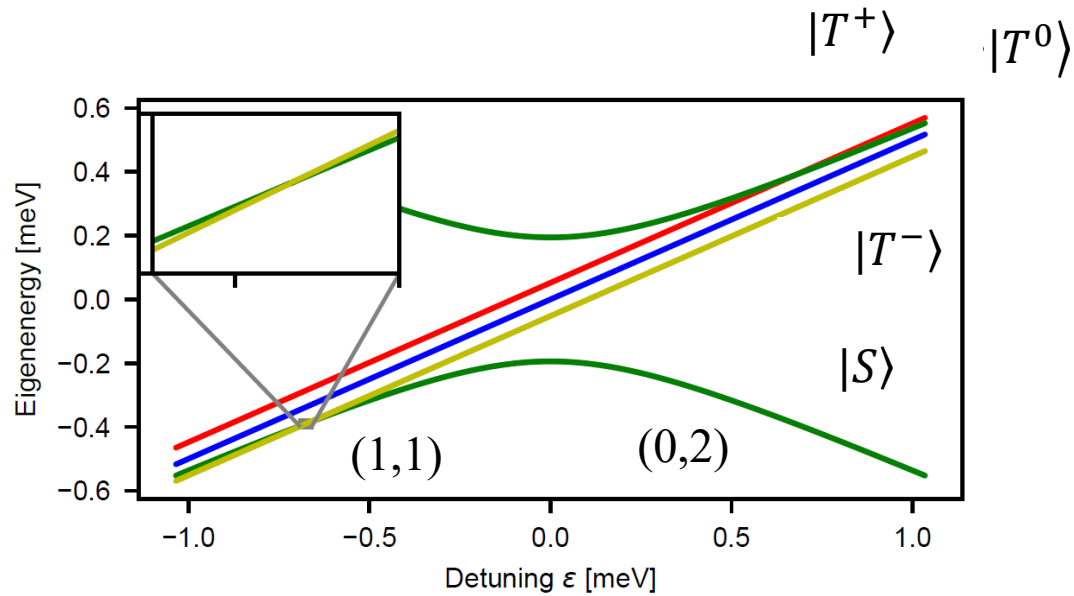
Signal-to-Noise Ratio (SNR)

A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

Pauli Spin Blockade (PSB)

- We do not observe PSB at (1,1)-(0,2) transition ⇒ $\Delta E_v < kT_e$, or noise level
- We do observe PSB at (1,3)-(0,4) transition ⇒ $\Delta E_{orb} > \Delta E_v$



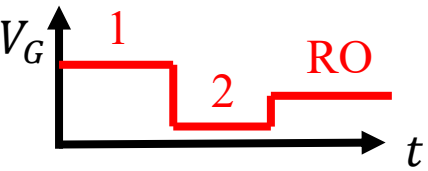


Spin blockade region:

- Spin triplet states are blocked from tunnelling from (1,1) to (0,2)
- No tunnelling → No dispersive shift
  → Enables gate-based dispersive spin readout

A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

Spin Blockade at (4,0) – (3,1)

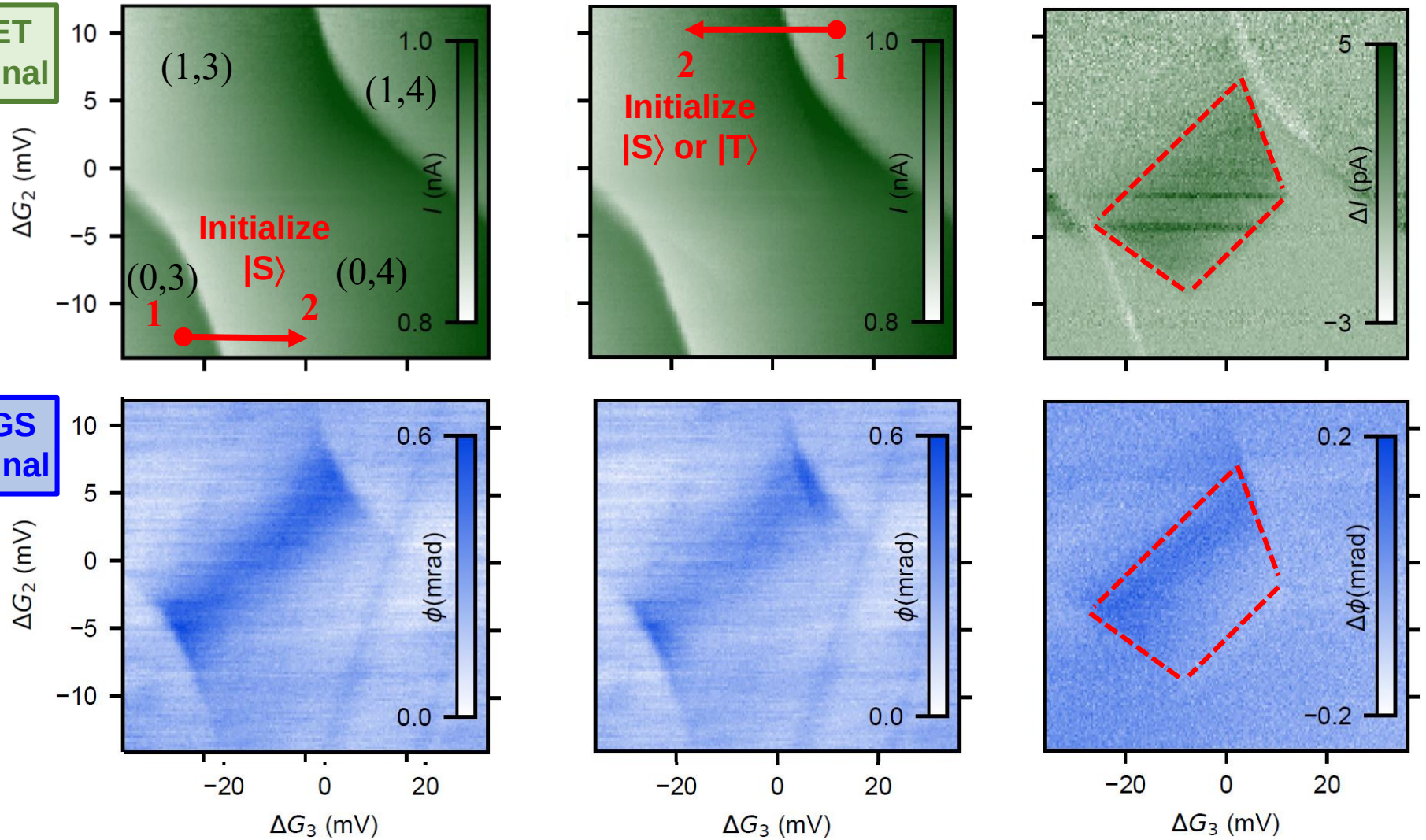


Acquisition time per plot ~ few mins

Differential Signal

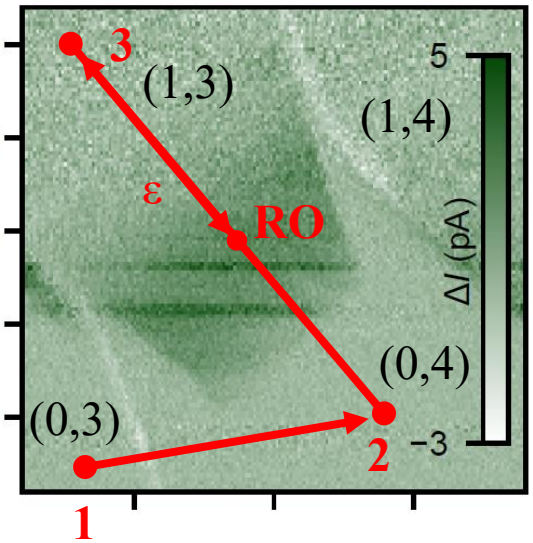
SET Signal

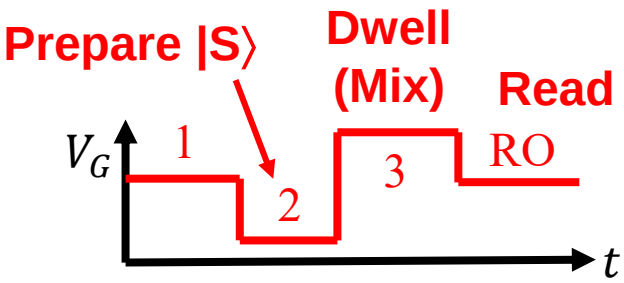
DGS Signal

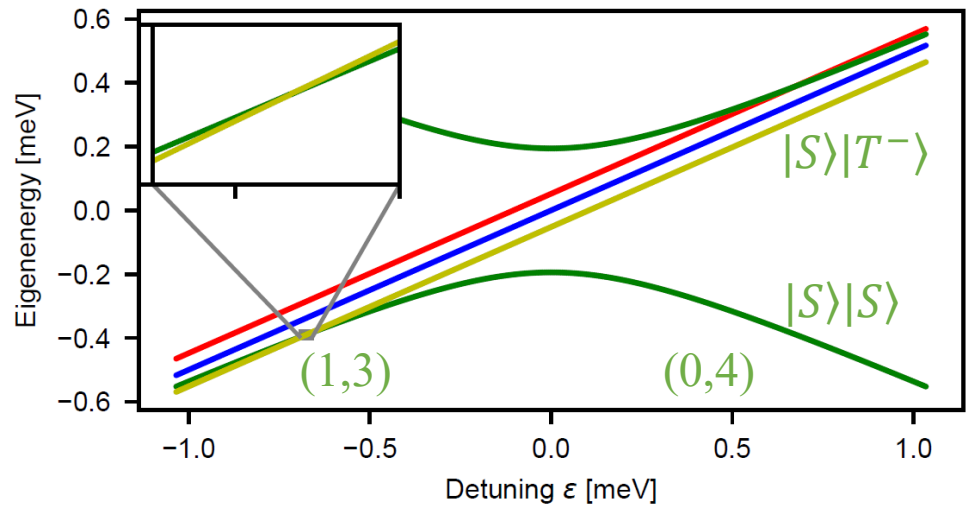


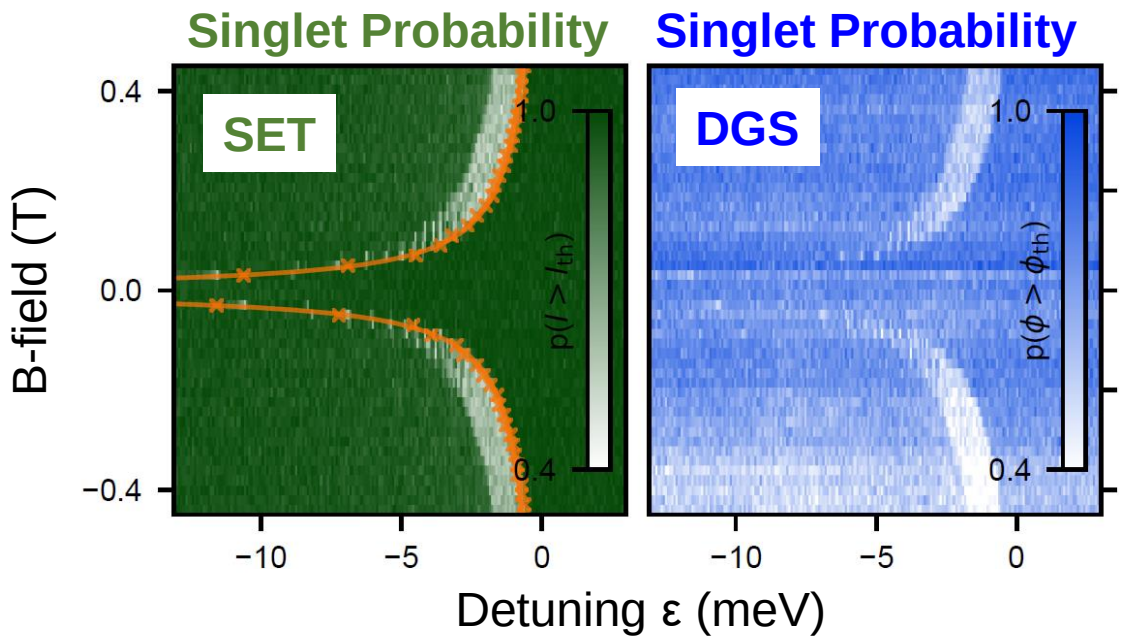
A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

$|S\rangle - |T^-\rangle$ Mixing: *Spin Funnel via DGS*









^{nat}Si sample

→ $|S\rangle - |T^-\rangle$ mixing is hyperfine

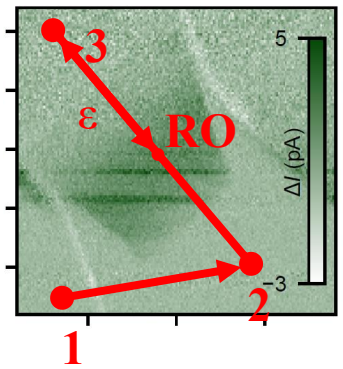
Fit → Large t_c ~ 50 GHz

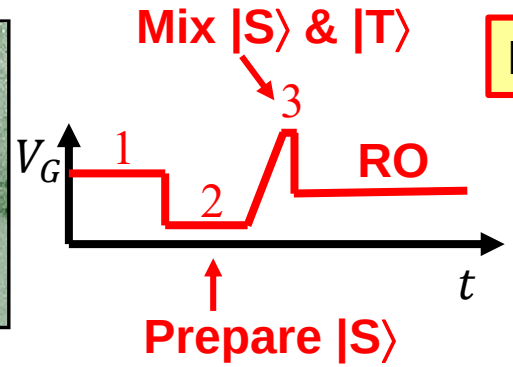
A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

UNSW SYDNEY

S-T *Single-Shot* Spin Readout via *DGS*

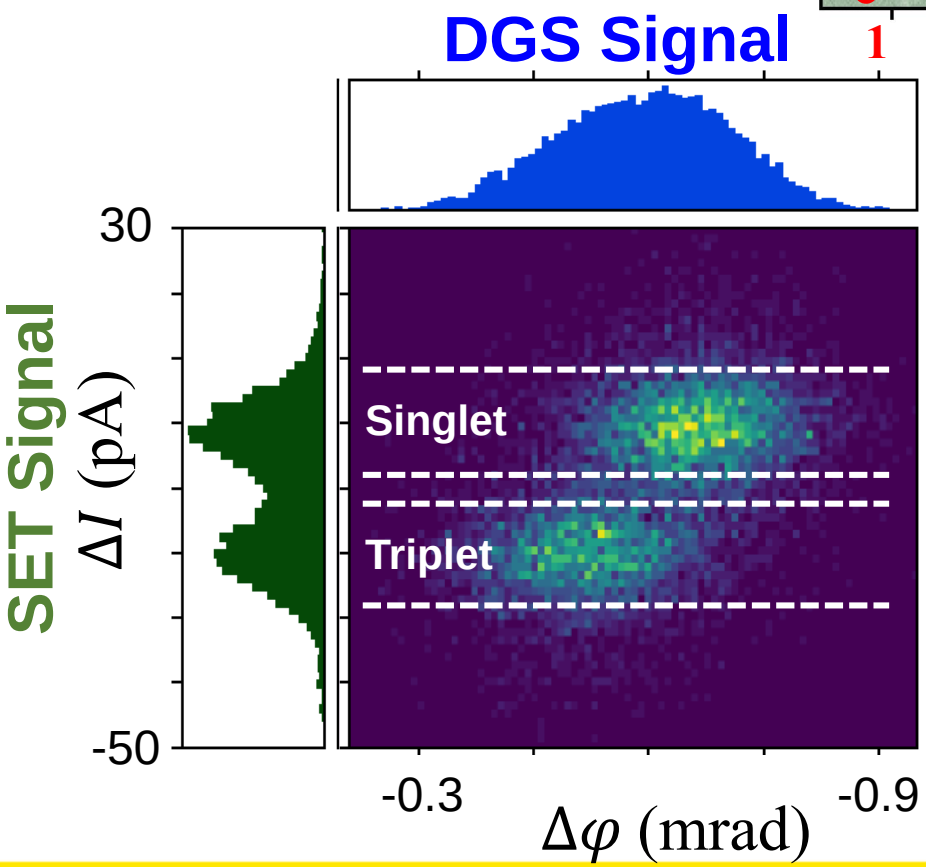
Calibrating signal levels with SET sensor to set DGS threshold:
→ DGS RO Fidelity = 70%

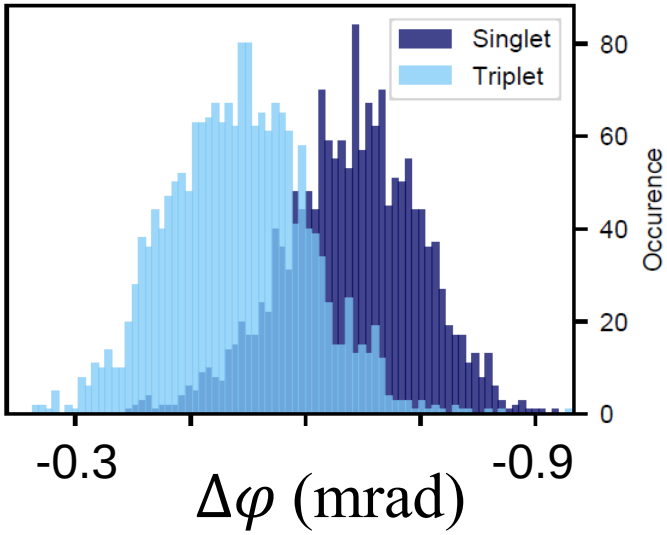




B=250mT

3 ms readout time per single-shot data point





A. West *et al.*, *Nature Nanotechnol.* 14, 437 (2019)

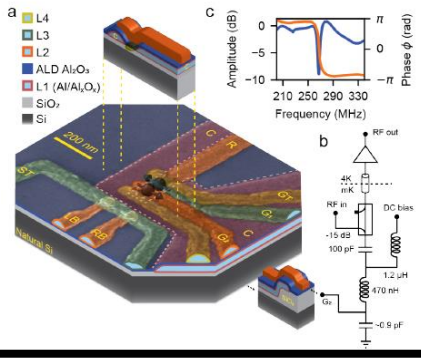
Single-Shot Gate-based Spin Readout in Silicon

arXiv:1809.01864

SiMOS QDs

Gate-based single-shot readout of spins in silicon

A. West,[1,*] B. Hensen,[1,*] A. Jouan,[2] T. Tanttu,[1] H. Yang,[1] A. Rossi,[3]
M.F. Gonzalez-Zalba,[4] F.E. Hudson,[1] A. Morello,[1] D.J. Reilly,[2,5] and A.S. Dzurak[1]
[1]*Centre for Quantum Computation and Communication Technology, School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney, New South Wales 2052, Australia*
[2]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Sydney, Sydney, NSW 2006, Australia*

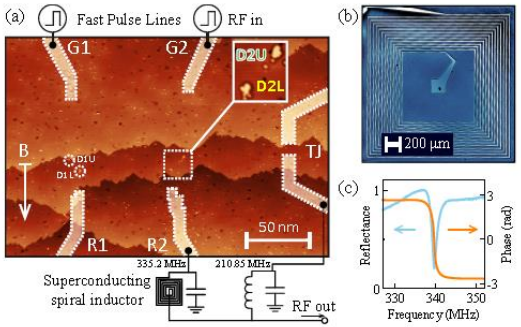


arXiv:1809.01802; *PRX* (2018)

STM P-donor QDs

Single-shot single-gate RF spin readout in silicon

P. Pakkiam, A. V. Timofeev, M.G. House, M.R. Hogg, T. Kobayashi, M. Koch, S. Rogge, and M.Y. Simmons
CQC2T, UNSW, Sydney, Australia
(Dated: September 7, 2018)

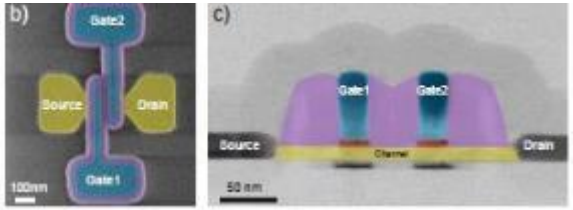


arXiv:1809.04584

Si CMOS QDs

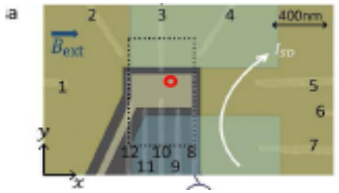
Gate-Based High Fidelity Spin Readout in a CMOS Device

Matias Urdampilleta,[1,*] David J. Niegemann,[1] Emmanuel Chanrion,[1] Baptiste Jadot,[1] Cameron Spence,[1]
Pierre-André Mortemousque,[1] Christopher Bäuerle,[1] Louis Hutin,[2] Benoit Bertrand,[2] Sylvain Barraud,[2] Romain Maurand,[3] Marc Sanquer,[3] Xavier Jehl,[3] Silvano De Franceschi,[3] Maud Vinet,[2] and Tristan Meunier[1,†]



Si/SiGe QDs

Zheng, Vandersypen et al. – TU Delft



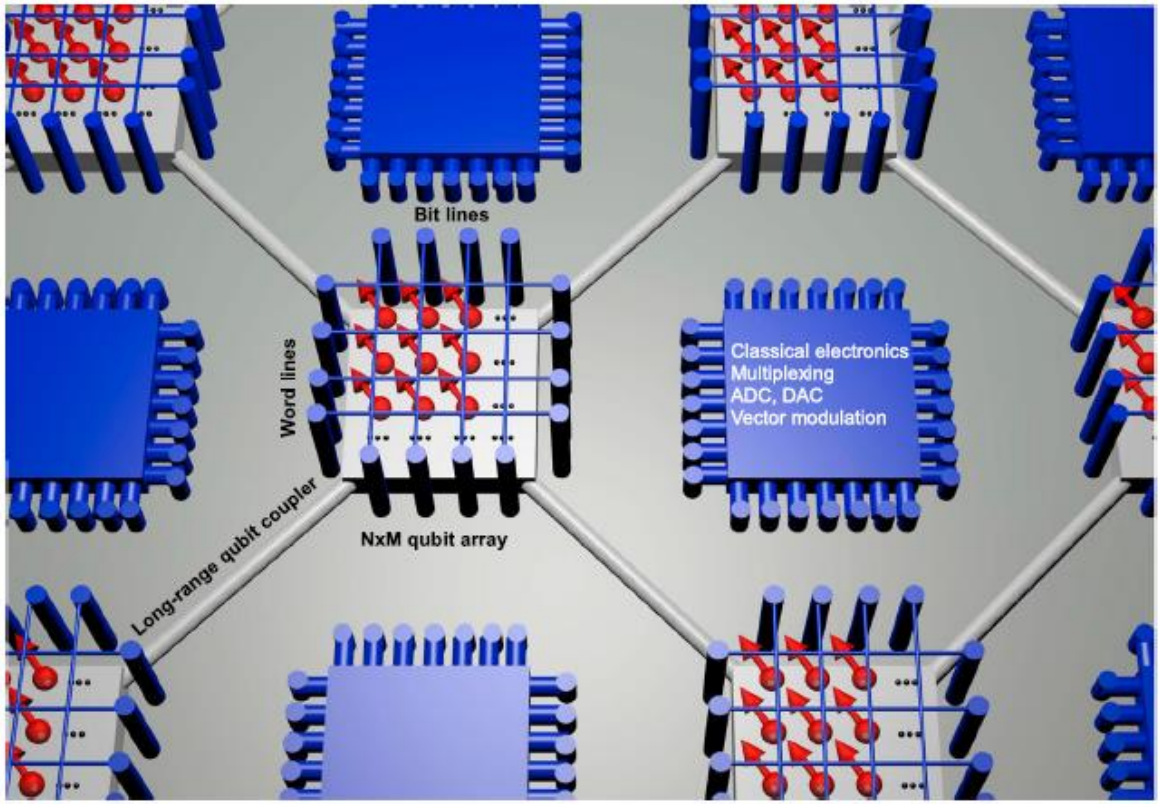
UNSW SYDNEY

Scalability – Wiring Fan-out: *Problems & Solutions*

REVIEW ARTICLE **OPEN**

Interfacing spin qubits in quantum dots and donors—hot, dense, and coherent

L. M. K. Vandersypen[1,2], H. Bluhm[3], J. S. Clarke[2], A. S. Dzurak[4], R. Ishihara[1], A. Morello[4], D. J. Reilly[5], L. R. Schreiber[3] and M. Veldhorst[1]



L.M.K. Vandersypen et al., *npj Quantum Information* 3, 34 (2017)

Scalability: *Coupling Spin to Microwave Photons*

Strong coupling of a spin qubit to a superconducting stripline cavity

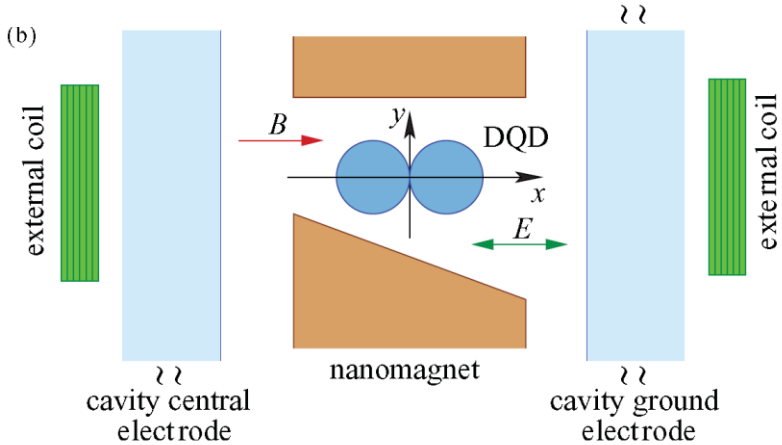
Xuedong Hu
Department of Physics, University at Buffalo, SUNY, Buffalo, New York 14260-1500, USA

Yu-xi Liu
Institute of Microelectronics, Tsinghua University, Beijing 100084, China,
Tsinghua National Laboratory for Information Science and Technology (TNList), Tsinghua University, Beijing 100084, China,
and Advanced Science Institute, RIKEN, Wako, Saitama 351-0918, Japan

Franco Nori
Advanced Science Institute, RIKEN, Saitama 351-0918, Japan and Department of Physics, University of Michigan, Ann Arbor, Michigan 48109-1040, USA

(Received 2 May 2012; revised manuscript received 27 June 2012; published 16 July 2012)

We study electron-spin-photon coupling in a single-spin double quantum dot embedded in a superconducting stripline cavity. With an external magnetic field, we show that either a spin-orbit interaction (for InAs) or an inhomogeneous magnetic field (for Si and GaAs) could produce a strong spin-photon coupling, with a coupling strength of the order of 1 MHz. With an isotopically purified Si double dot, which has a very long spin coherence time for the electron, it is possible to reach the strong-coupling limit between the spin and the cavity photon, as in cavity quantum electrodynamics. The coupling strength and relaxation rates are calculated based on parameters of existing devices, making this proposal experimentally feasible.

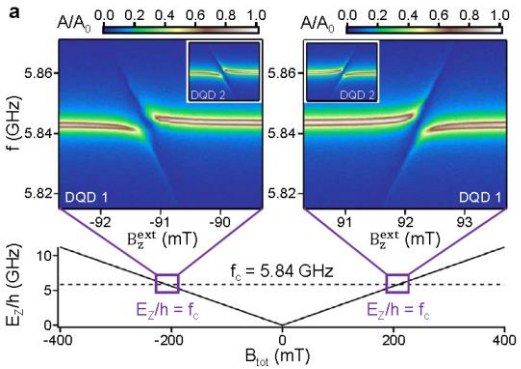


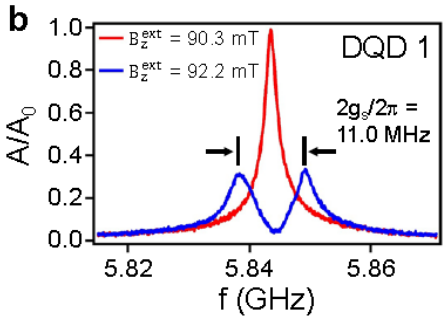
X. Hu, Y. Liu, F. Nori, *Phys. Rev. B* 86, 035314 (2012)

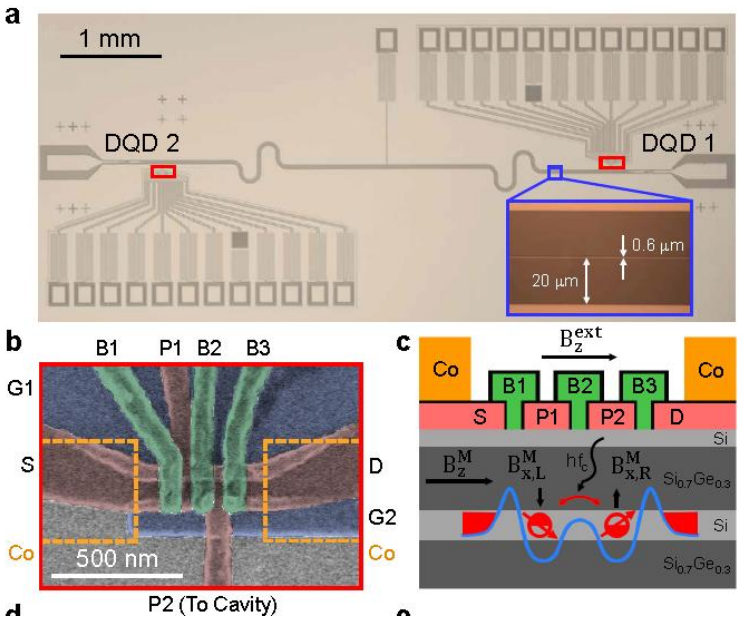
Scalability: *Coupling Spin to Microwave Photons*

A Coherent Spin-Photon Interface in Silicon

X. Mi,[1] M. Benito,[2] S. Putz,[1] D. M. Zajac,[1]
J. M. Taylor,[3] Guido Burkard,[2] and J. R. Petta[1,*]



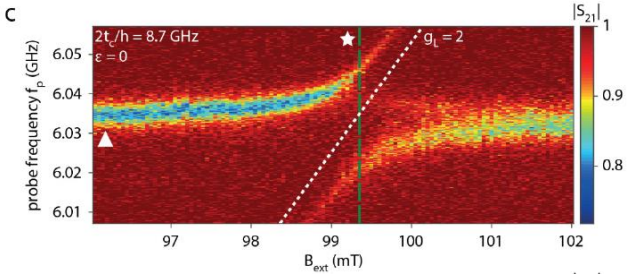


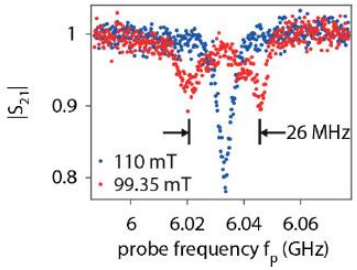


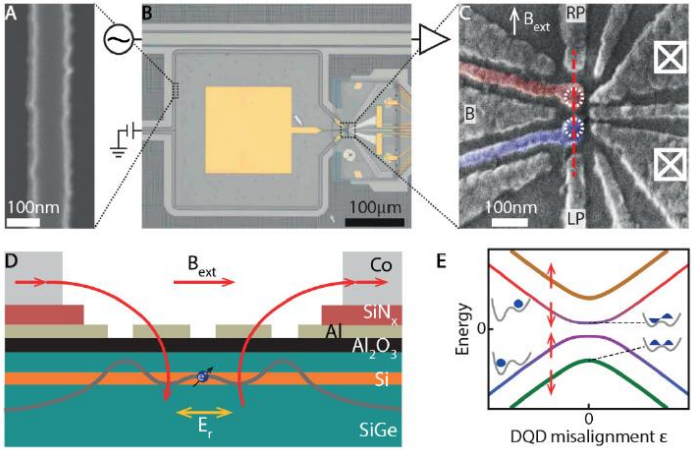
Strong spin-photon coupling in silicon

N. Samkharadze,[1*] G. Zheng,[1*] N. Kalhor,[1] D. Brousse,[2] A. Sammak,[2] U. C. Mendes,[2] A. Blais,[3,4] G. Scappucci,[1] L. M. K. Vandersypen[1†]

[1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology Lorentzweg 1, 2628 CJ Delft, Netherlands. [2]QuTech and Netherlands Organization for Applied Scientific Research (TNO), Stieltjesweg 1 2628 CK Delft, Netherlands. [3]Institut Quantique and Département de Physique, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada. [4]Canadian Institute for Advanced Research, Toronto, Ontario, Canada.







X. Mi et al., arXiv:1710.03265; N. Samkharadze et al., *Science* (2018)

What about power dissipation?

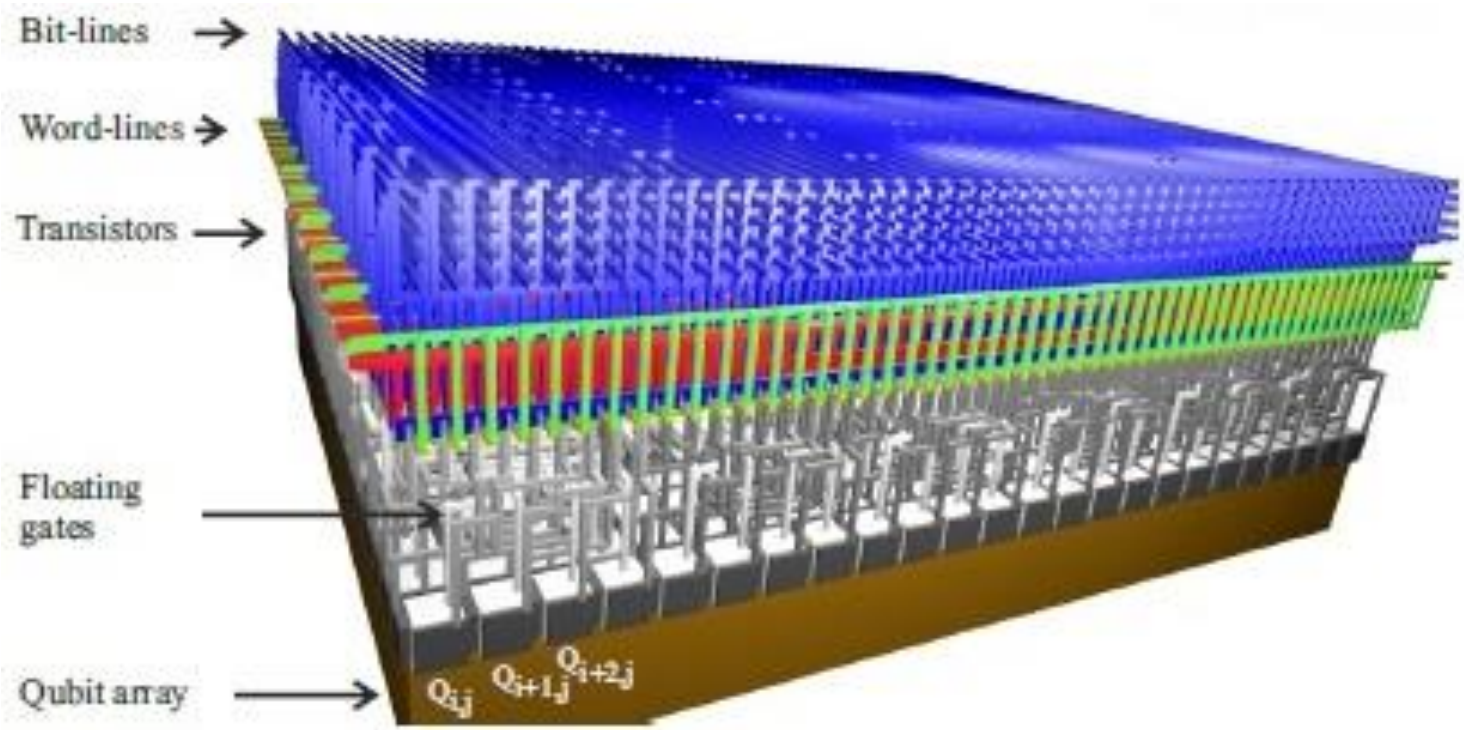
ARTICLE

DOI: 10.1038/s41467-017-01905-6 OPEN

nature COMMUNICATIONS

Silicon CMOS architecture for a spin-based quantum computer

M. Veldhorst[1,2], H.G.J. Eenink[1,2], C.H. Yang[2] & A.S. Dzurak[2]



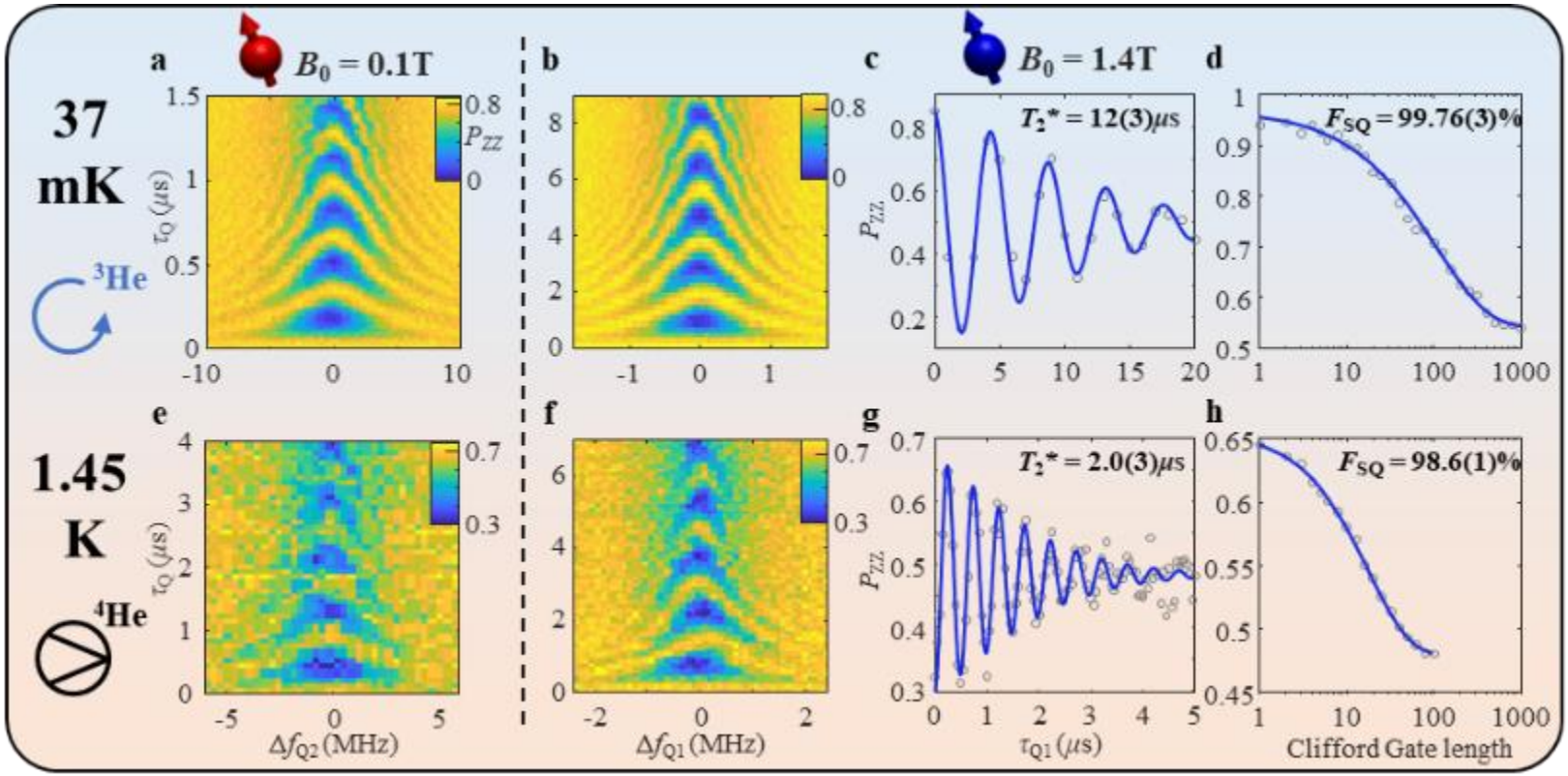
M. Veldhorst et al., *Nature Comms.* 8, 1766 (2017)

UNSW SYDNEY

SiMOS QD Qubit Operation at 1.5 Kelvin

Silicon quantum processor unit cell operation above one Kelvin

C. H. Yang,[1,*] R. C. C. Leon,[1] J. C. C. Hwang,[1,†] A. Saraiva,[1] T. Tanttu,[1] W. Huang,[1] J. Camirand Lemyre,[2] K. W. Chan,[1,‡] K. Y. Tan,[1,‡] F. E. Hudson,[1] K. M. Itoh,[3] A. Morello,[1] M. Pioro-Ladrière,[2,4] A. Laucht,[1] and A. S. Dzurak[1,§]

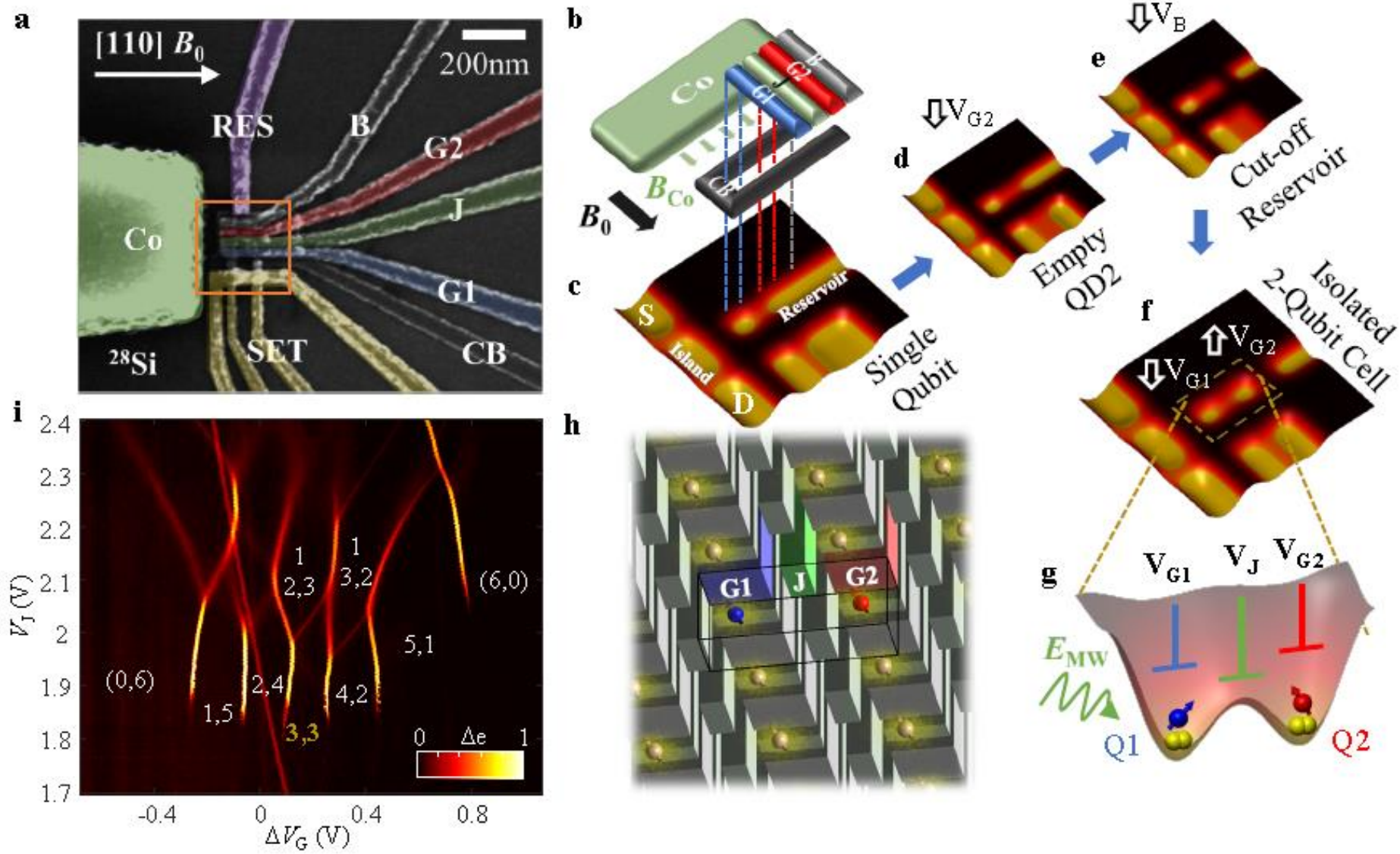


⇒ 1.5 K performance comparable to ^{nat}Si at 100 mK !

H. Yang *et al.*, arXiv:1902.09126

UNSW SYDNEY

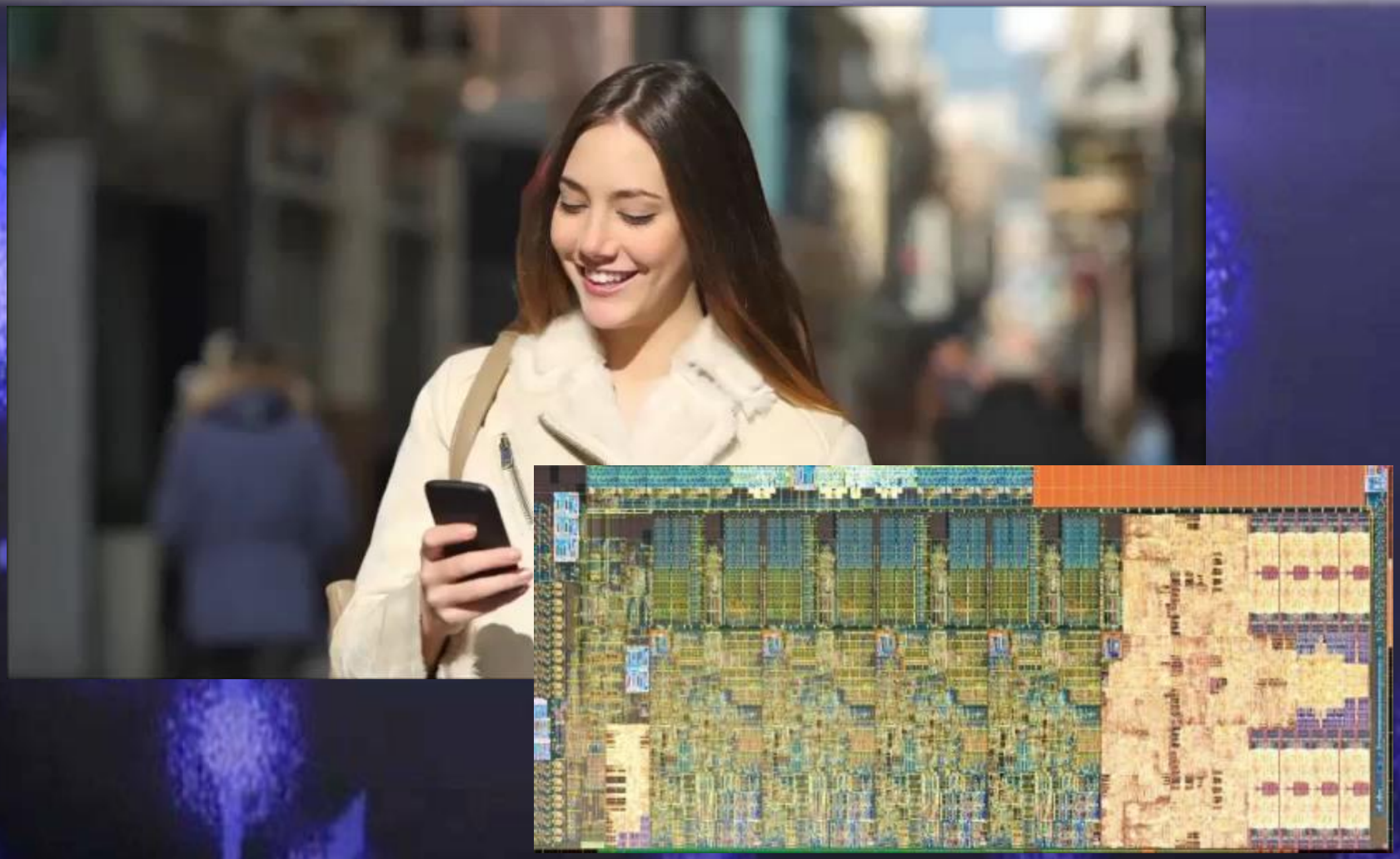
SiMOS QD Qubit Operation at 1.5 Kelvin



H. Yang *et al.*, arXiv:1902.09126

UNSW SYDNEY

Silicon Quantum Computing



Dzurak Research Group (UNSW)

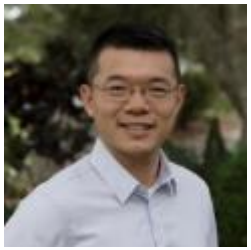
Postdoctoral Researchers


Henry Yang


Chris Escott


Tuomo Tanttu


Bas Hensen


Ruichen Zhao


Fay Hudson

Graduate Students


Wister Huang


Ross Leon

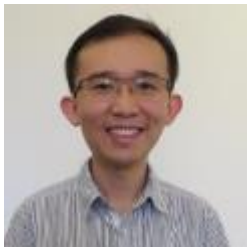

Anderson West


Will Gilbert


Alexis Shaw

Former Team Members (2017-18)


Michael Fogarty (now UCL)


Kok Wai Chan (now Aalto U)


Jason Hwang (now ANFF-Sydney)

Collaborators

Morello

Laucht

Culcer

UNSW SYDNEY

Hamilton

Bartlett

Flammia

Reilly

THE UNIVERSITY OF SYDNEY

Gyure

Ladd

HRL

Rossi

UNIVERSITY OF CAMBRIDGE

Poiro-Ladriere

UNIVERSITÉ DE SHERBROOKE

Veldhorst

TU Delft

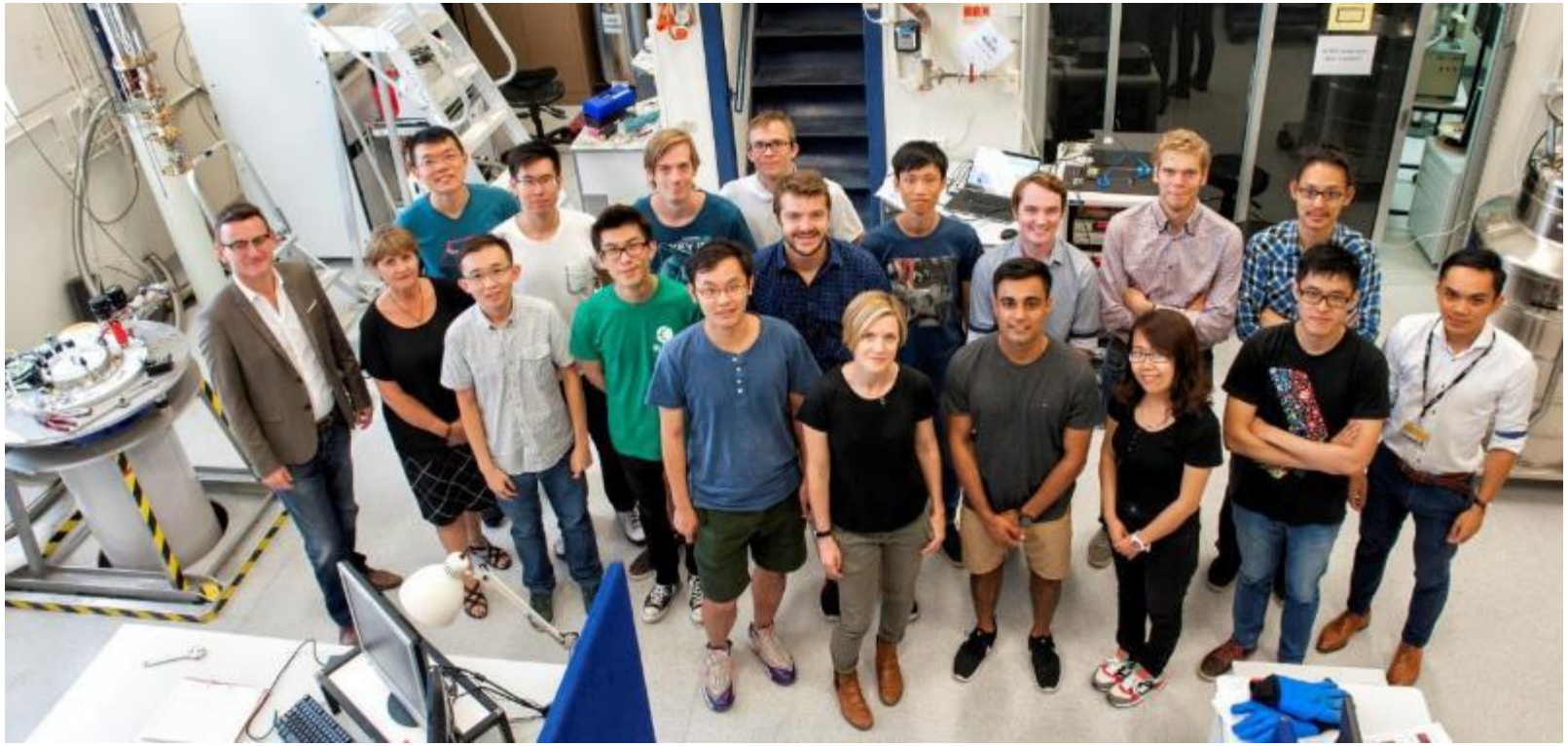
Ruskov & Tahan

LPS The Laboratory for Physical Sciences

Itoh

Keio University

Acknowledgments



ANFF

CQC²T

Australian Government

Australian Research Council

NSW GOVERNMENT

NCRIS
National Research Infrastructure for Australia
An Australian Government Initiative

SILICON QUANTUM COMPUTING