CENTRE FOR QUANTUM COMPUTATION
& COMMUNICATION TECHNOLOGY

AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

The Development of a Quantum Computer in Silicon

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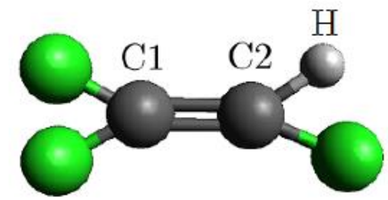
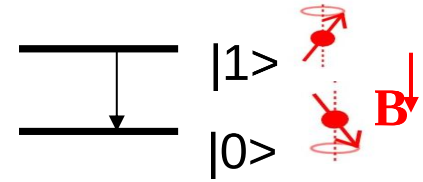
Outline

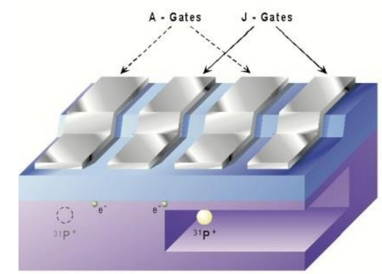
Short history of development of quantum computing



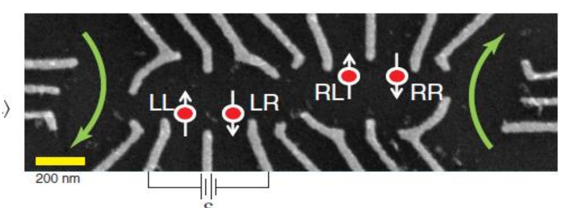
Comparison of classical and quantum computing



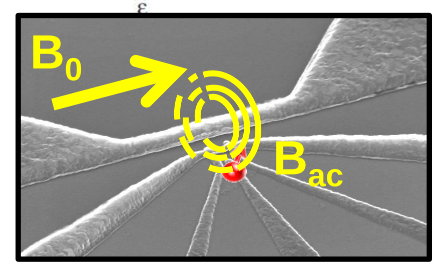
Experimental requirements for the practical realisation of a quantum computer: the 7 DiVincenzo criteria



Leading contenders in the solid state



Current status of silicon based quantum computing



A Brief History of Quantum Computing

1982: Richard Feynman, at the First Conference on the Physics of Computation held at MIT, proposed a basic model for a quantum computer that would exploit the potential of massive quantum parallelism.

1994: Peter Shor discovers the factorisation algorithm for large numbers theoretically capable of breaking today's public key cryptosystems.

1995: Peter Shor and Andrew Steane simultaneously proposed the first schemes for quantum error correction.

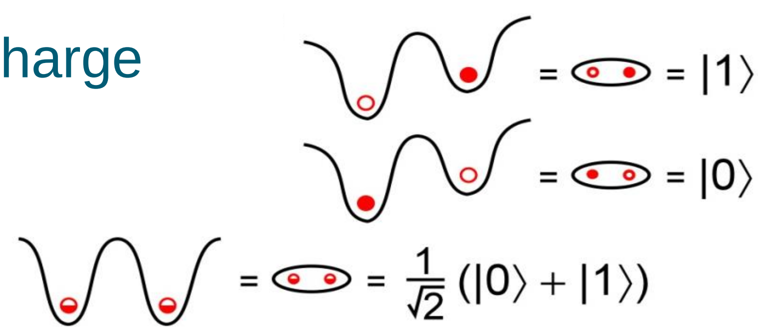
1996 Lou Grover propose an exhaustive search algorithm that showed for a system of *n* possibilities you can find the answer in $\sqrt{n}$ look-ups quantum mechanically compared with *n/2* classically.

1998 Ray LaFlamme experimentally demonstrates error correction in a trichoroethylene molecule using liquid state NMR

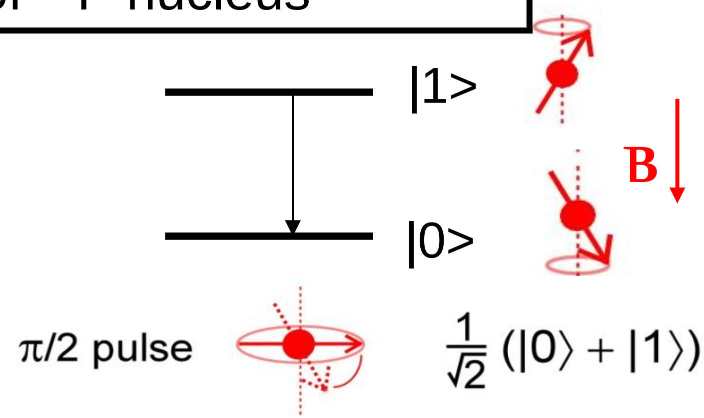
Classical versus quantum bits

Conventional Computer	Quantum Computer
0, 1	$\vert 0\rangle$, $\vert 1\rangle$
bits information is stored in “bits”. A bit can be either 0 ***or*** 1.	qubits information is stored in “quantum bits” or qubits, which can be *a combination* of 0 ***and*** 1. Quantum state of a two-level system such as spin or charge of ^{31}P nucleus

charge



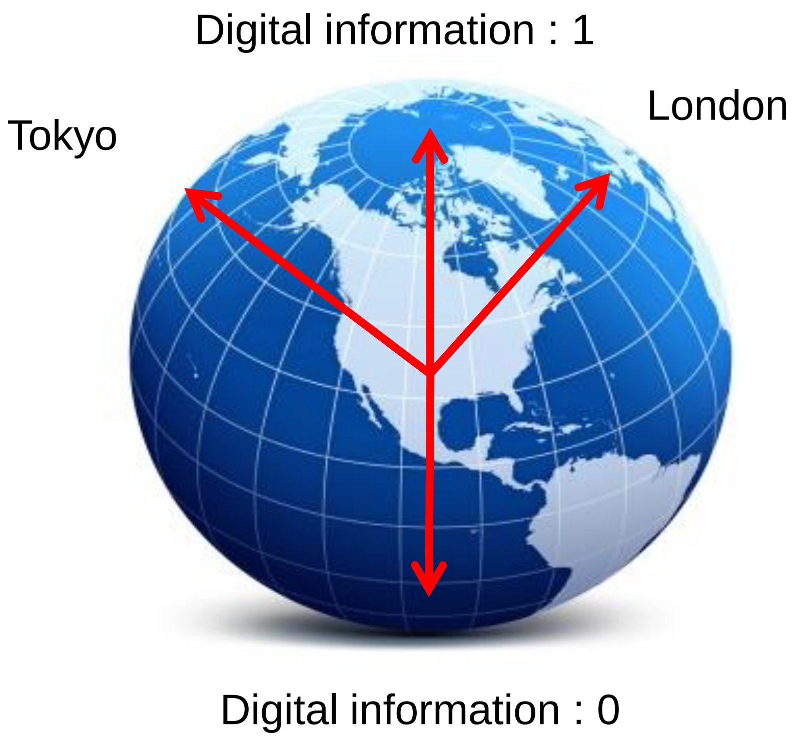
spin



Classical versus quantum computation

Classical computer - can check many different possibilities in *rapid succession*

Quantum computer - can check many different possibilities *in parallel*



Superposition, 1 spin:

$\Psi = \alpha_1|0> + \alpha_2|1>$

Entanglement, 2 spins:

$\Psi=\alpha_1|00> + \alpha_2|01> + \alpha_3|10> + \alpha_4|11>$

# qubits	classical possibilities	power
1/0	0 or 1	2
1/0 1/0	00, 01, 10, 11	4
1/0 1/0 1/0	000, 001, 010, 011 100, 101, 110, 111	8
N		**2^N**

Quantum computer's power ***doubles*** every time another qubit is added

A 30-qubit quantum computer would be more powerful than a supercomputer..

As for 300 qubits….

Difficult problems: the travelling salesman

Problem: A salesman has to travel to many cities and wants to work out the shortest possible route

14 cities: 10^{11} routes

for a classical 1GHz computer (10^9 operations/sec) it would take 100 seconds

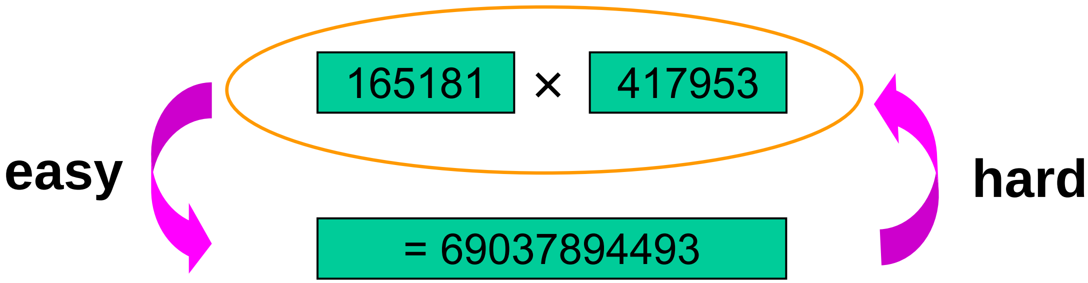
22 cities: 10^{19} routes

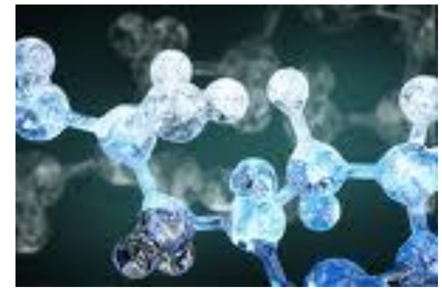
it would take 1600 years

28 cities

What can quantum computers do?

Quantum computers will not necessarily outperform classical computers but need to use algorithms that exploit quantum parallelism.





Applications: physical modelling (climate, engineering); simulations (chemistry, materials), database searching (bioinformatics); factorisation (data security)

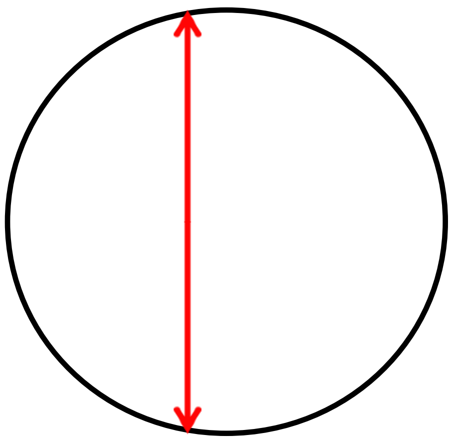
Algebraic and Number Theoretic Algorithms (11 algorithms); e.g. factorising

Oracular Algorithms (29 algorithms); e.g. searching, linear differential equations

Approximation and Simulation Algorithms (10 algorithms); e.g. simulation, adiabatic algorithms

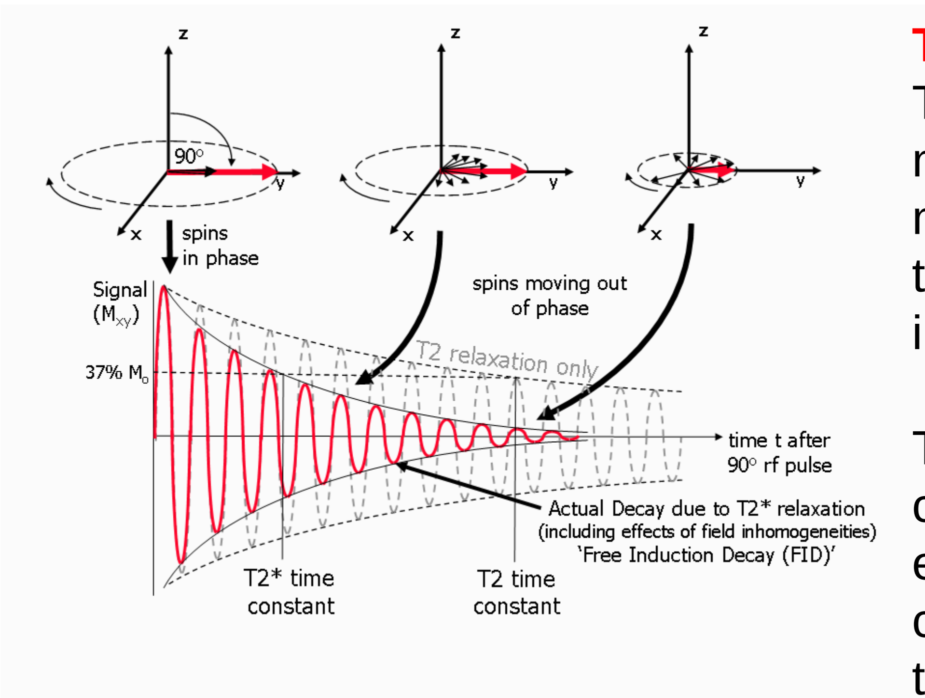
Experimental Requirements
for
Quantum Computing Devices

Relaxation and coherence times



The longitudinal relaxation time, T_1 is the time-scale for the exponential decay of a non-equilibrium polarization of spins to give up its Zeeman energy to the lattice.

→ it represents the maximum time available for a quantum computation



The transverse relaxation time, T_2

The amplitude of the net transverse magnetisation decays as the magnetic moments move out of phase with one another (shown by the small black arrows). Arise from spin-spin interactions.

The overall term for the observed loss of phase coherence is **T_2* relaxation**, which combines the effect of T_2 relaxation and additional de-phasing caused by local variations (inhomogeneities) in the applied magnetic field, e.g. by the presence of other nuclear spins.

Overview: Qubits in the Solid State

TABLE I. Comparison between different systems used as qubits.

	Atom, molecule, ion	Electron spin	Nuclear spin	Superconducting qubit
Size	$\sim 10^{-10}$ m	$\sim 10^{-10}$ m (impurities) $\sim 10^{-8}$ m (quantum dot)[a]	$< 10^{-10}$ m[a]	$\sim 10^{-6}$ m
Energy gap	10^5–10^6 GHz, $\sim$GHz (Rydberg atoms)	1–10 GHz	1–10 MHz	1–20 GHz
Frequency range	Optical, microwave	Microwave	Microwave	Microwave
Operating temperature	nK to μK	~ 100 mK (quantum dot), room temperature (NV center)	$\sim$mK	~ 10 mK
Single-qubit gate operation time τ_1	$\sim \mu$s (atom) ~ 50 ps (ion)	~ 10 ns	> 10 μs	~ 1 ns
Two-qubit gate operation time τ_2	$\sim \mu$s (atom) ~ 100 μs (ion)	~ 0.2 ns	~ 10 ms	~ 10–50 ns
Coherence time T_2	ms to s	ms to s	$\sim$s	~ 10–100 μs
T_2/τ_1	10–10^4	10^5–10^8	10^6	10^4–10^5
Coupling type	Electric or magnetic	Magnetic or electric	Magnetic	Electric or magnetic
Coupling strength with the cavity	$<$kHz (B field), ~ 10 kHz (E field), ~ 10 MHz (Rydberg atoms)	$>$MHz (quantum dot) ~ 100 Hz (impurities)	~ 0.1 Hz	~ 0.1–1 GHz

- Superconducting qubits offer flexibility and strong coupling to external fields BUT have relatively short coherence times (<0.1ms)
- Microscopic systems are given by nature and can easily be made identical with long coherence times (>1ms) BUT they operate slowly due to weak coupling to external fields.

Z.L. Xiang, Rev. Mod. Phys. 85, 623 (2013).

DiVincenzo Criteria for a scalable system

1. A scalable physical system of well-characterized qubits

A quantum register of multiple qubits must be prepared in an addressable form and isolated from environmental influences, which cause the delicate quantum states to decohere.

Although weakly coupled to the outside world, the qubits must nevertheless be strongly coupled together to perform logic-gate operations

There must be a readout method to determine the state of each qubit at the end of the computation.

[1] D. DiVincenzo, Fortschritte der Physik-Progress of Physics 48, 771 (2000)

Well defined two level quantum system

Physical system	Name	Information support	|0>	|1>
Photon	Polarisation encoding	Polarisation of light	Horizontal	Vertical
	Number of photons	Fock state	Vacuum	Single photon of light
	Time-bin encoding	Time of arrival	Early	Late

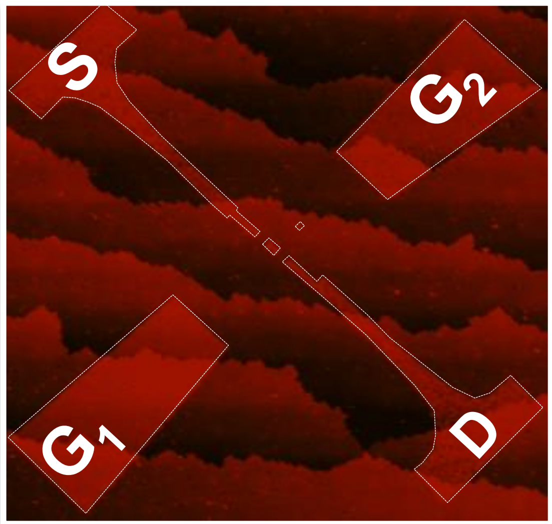
DiVincenzo Criteria for a scalable system

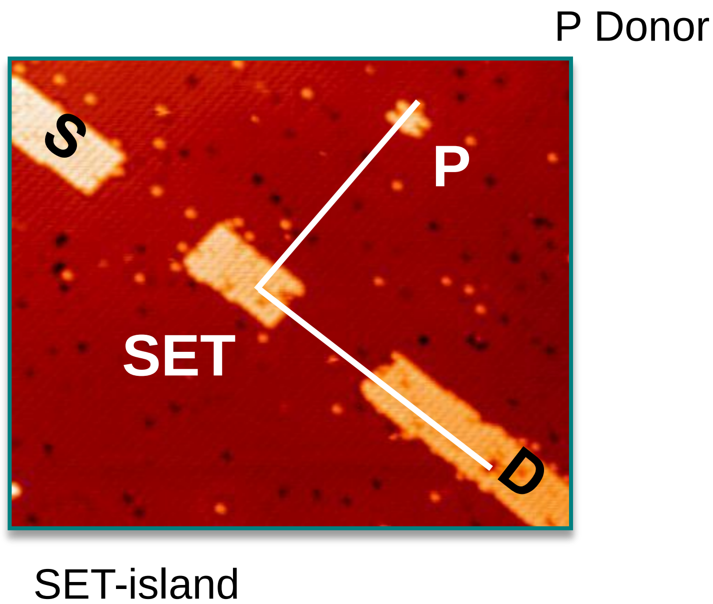
2. The ability to initialize the state of the qubits to a simple state

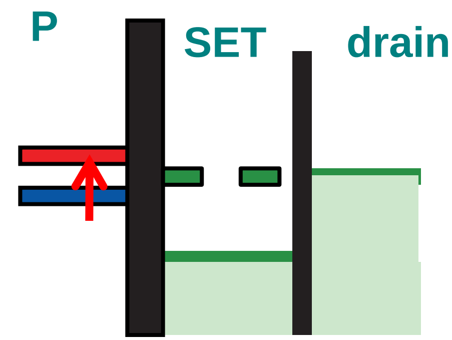
1. A scalable physical system of well-characterized qubits

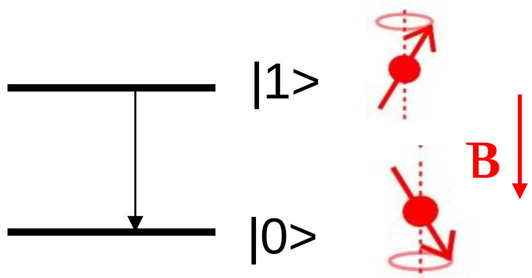
[1] D. DiVincenzo, Fortschritte der Physik-Progress of Physics 48, 771 (2000)

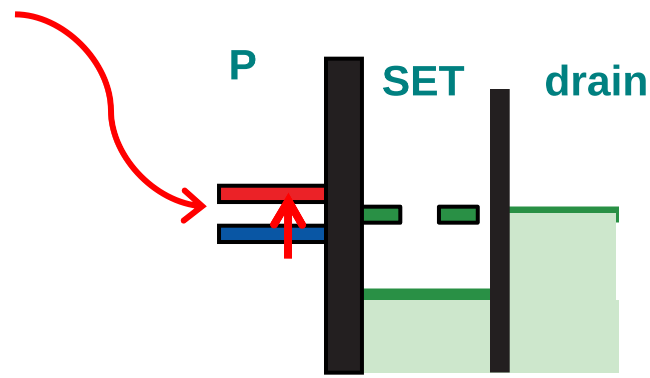
Initialisation of electron spin











DiVincenzo Criteria for a scalable system

3. Coherence times >> gate-operation times

2. The ability to initialize the state of the qubits to a simple state

1. A scalable physical system of well-characterized qubits

[1] D. DiVincenzo, Fortschritte der Physik-Progress of Physics 48, 771 (2000)

Promising proposals for qubits

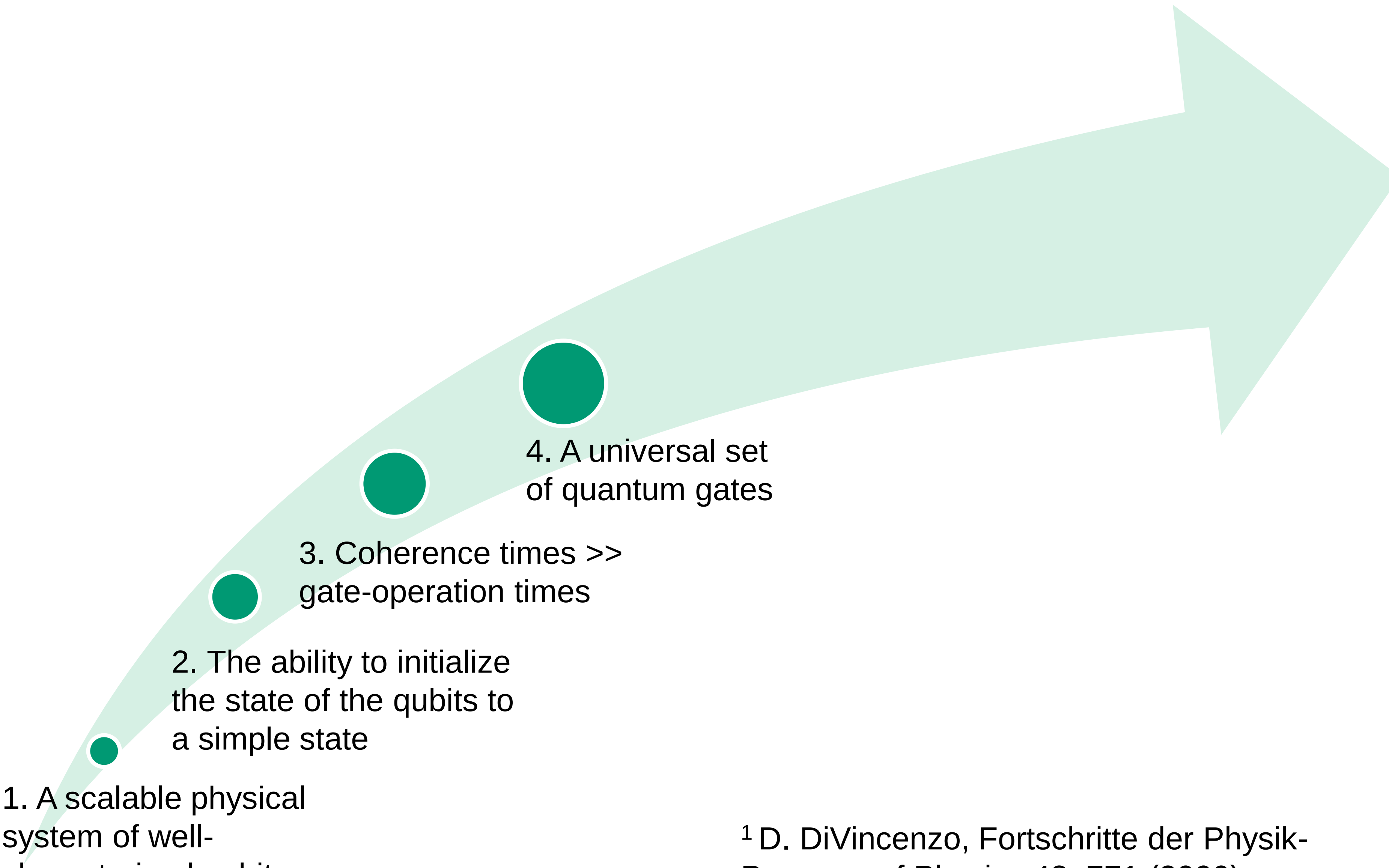
Table 1 | Current performance of various qubits

Type of qubit	T_2	Benchmarking (%)		References
		One qubit	Two qubits	
Infrared photon	0.1 ms	0.016	1	20
Trapped ion	15 s	0.48†	0.7*	104–106
Trapped neutral atom	3 s	5		107
Liquid molecule nuclear spins	2 s	0.01†	0.47†	108
e^- spin in GaAs quantum dot	3 μs	5		43, 57
e^- spins bound to ^{31}P:^{28}Si	0.6 s	5		49
^{29}Si nuclear spins in ^{28}Si	25 s	5		50
NV centre in diamond	2 ms	2	5	60, 61, 65
Superconducting circuit	4 μs	0.7†	10*	73, 79, 81, 109

Measured T_2 times are shown, except for photons where T_2 is replaced by twice the hold-time (comparable to T_1) of a telecommunication-wavelength photon in fibre. Benchmarking values show approximate error rates for single or multi-qubit gates. Values marked with asterisks are found by quantum process or state tomography, and give the departure of the fidelity from 100%. Values marked with daggers are found with randomized benchmarking[110]. Other values are rough experimental gate error estimates. In the case of photons, two-qubit gates fail frequently but success is heralded; error rates shown are conditional on a heralded success. NV, nitrogen vacancy.

T.D. Ladd, Nature 464, 45 (2010)

DiVincenzo Criteria for a scalable system



[1] D. DiVincenzo, Fortschritte der Physik- Progress of Physics 48, 771 (2000)

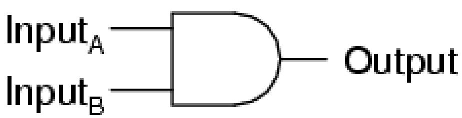
Universal quantum gates

Universal: one single computer for different computational tasks

In quantum computation all operations must be reversible.

An example of a non-reversible gate is an **AND** gate where two inputs only give one output $\rightarrow$ therefore information is lost.

2-input AND gate



A	B	Output
0	0	0
0	1	0
1	0	0
1	1	1

The quantum states of a qubit are a vector in 2D complex vector space.

$$\Psi = \alpha|0> + \beta|1>$$

A superposition is a linear combination of the 0 and 1 state amplitude with coefficients α and β. The constraints are that:

$$|\alpha|^2 + |\beta|^2 = 1$$

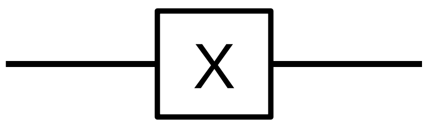
Single quantum NOT gate

Quantum NOT gate: $|0\rangle \rightarrow |1\rangle$ and $|1\rangle \rightarrow |0\rangle$

But we also have a superposition so

$$\alpha|0\rangle + \beta|1\rangle \rightarrow \alpha|1\rangle + \beta|0\rangle$$

Logic gate



$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$X|0\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} = |1\rangle$$

$$X|1\rangle = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = |0\rangle$$

2 qubit controlled NOT gate (CNOT)

4 computational basis states:

$\alpha|00\rangle$ $\beta|01\rangle$ $\gamma|10\rangle + \delta|11\rangle$ $\alpha^2 + \beta^2 + \gamma^2 + \delta^2 = 1$

If the control is 1, flip the target qubit; otherwise do nothing.

$|00\rangle \rightarrow |00\rangle$

$|01\rangle \rightarrow |01\rangle$

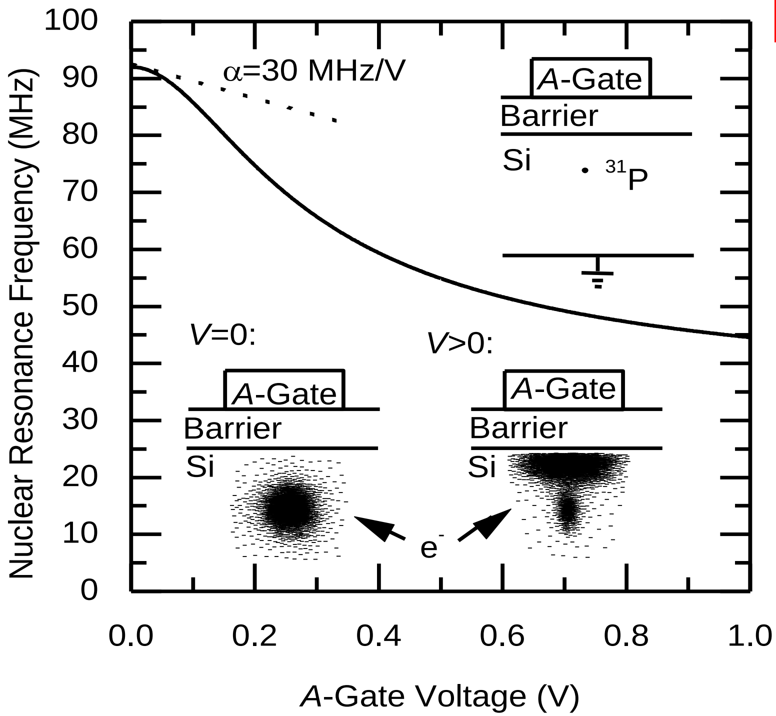
$|10\rangle \rightarrow |11\rangle$

$|11\rangle \rightarrow |10\rangle$

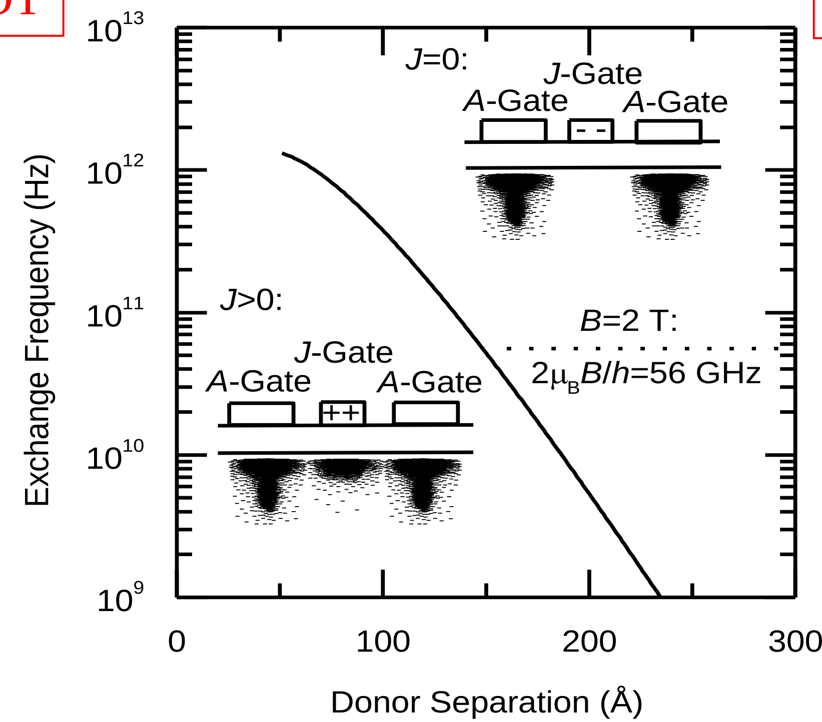
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 0 \\ 1 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} 0 & 0 \\ 0 & 1 \\ 1 & 1 \\ 1 & 0 \end{bmatrix}$$

A universal set of gate operations

QNOT

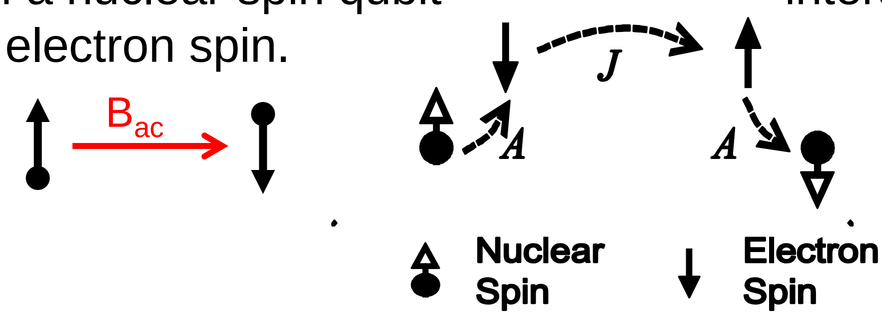


CNOT



A-gates control the interaction between a nuclear spin qubit and the electron spin.

J-gates control the exchange interaction between electron spins.



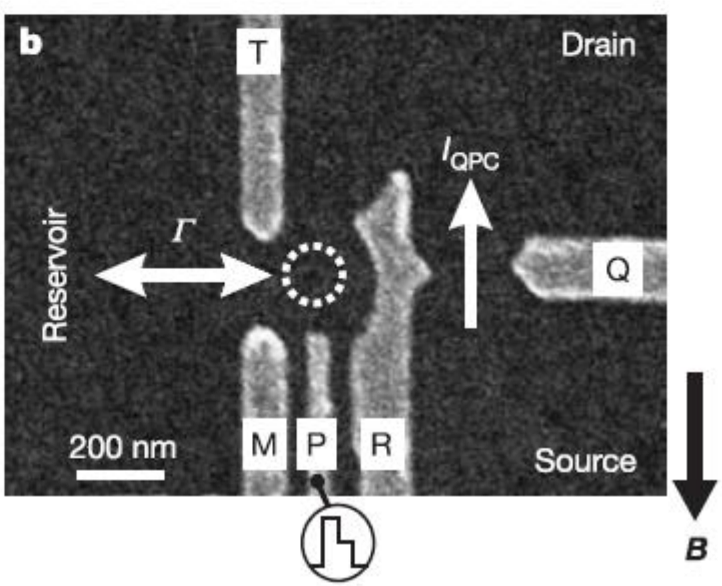
⇒ effectively using an electron spin mediated nuclear spin – nuclear spin interaction.

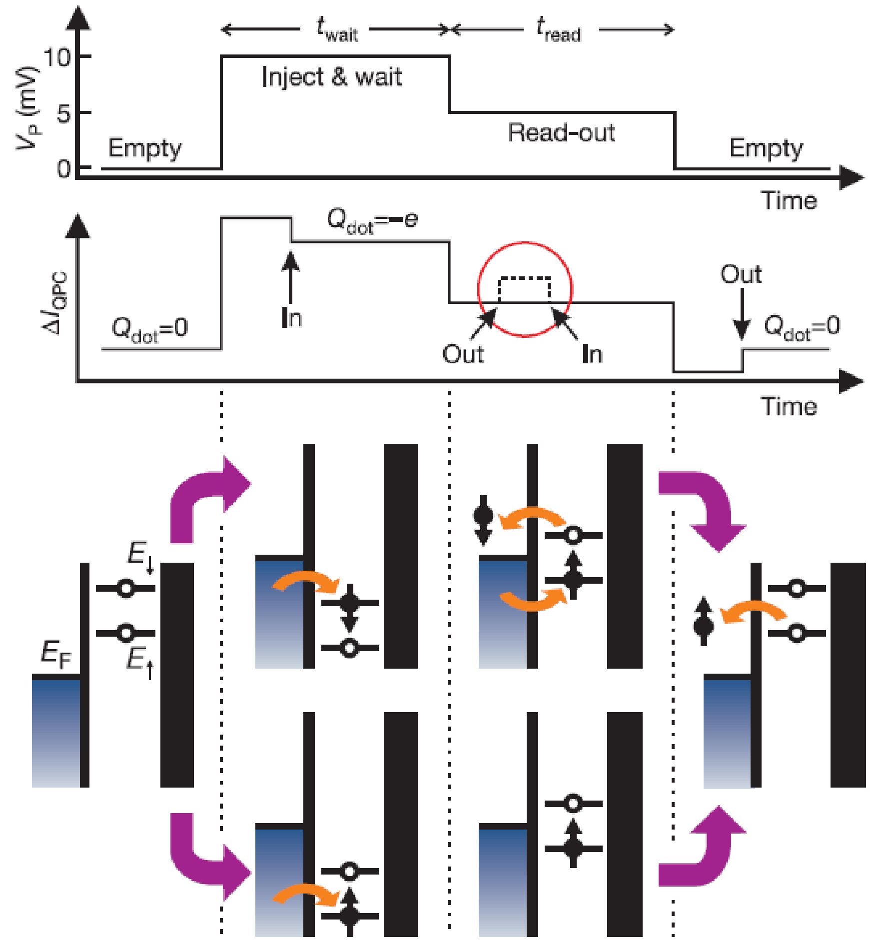
DiVincenzo Criteria for a scalable system

1. A scalable physical system of well-characterized qubits
2. The ability to initialize the state of the qubits to a simple state
3. Coherence times >> gate-operation times
4. A universal set of quantum gates
5. A qubit-specific measurement capability

[1] D. DiVincenzo, Fortschritte der Physik-Progress of Physics 48, 771 (2000)

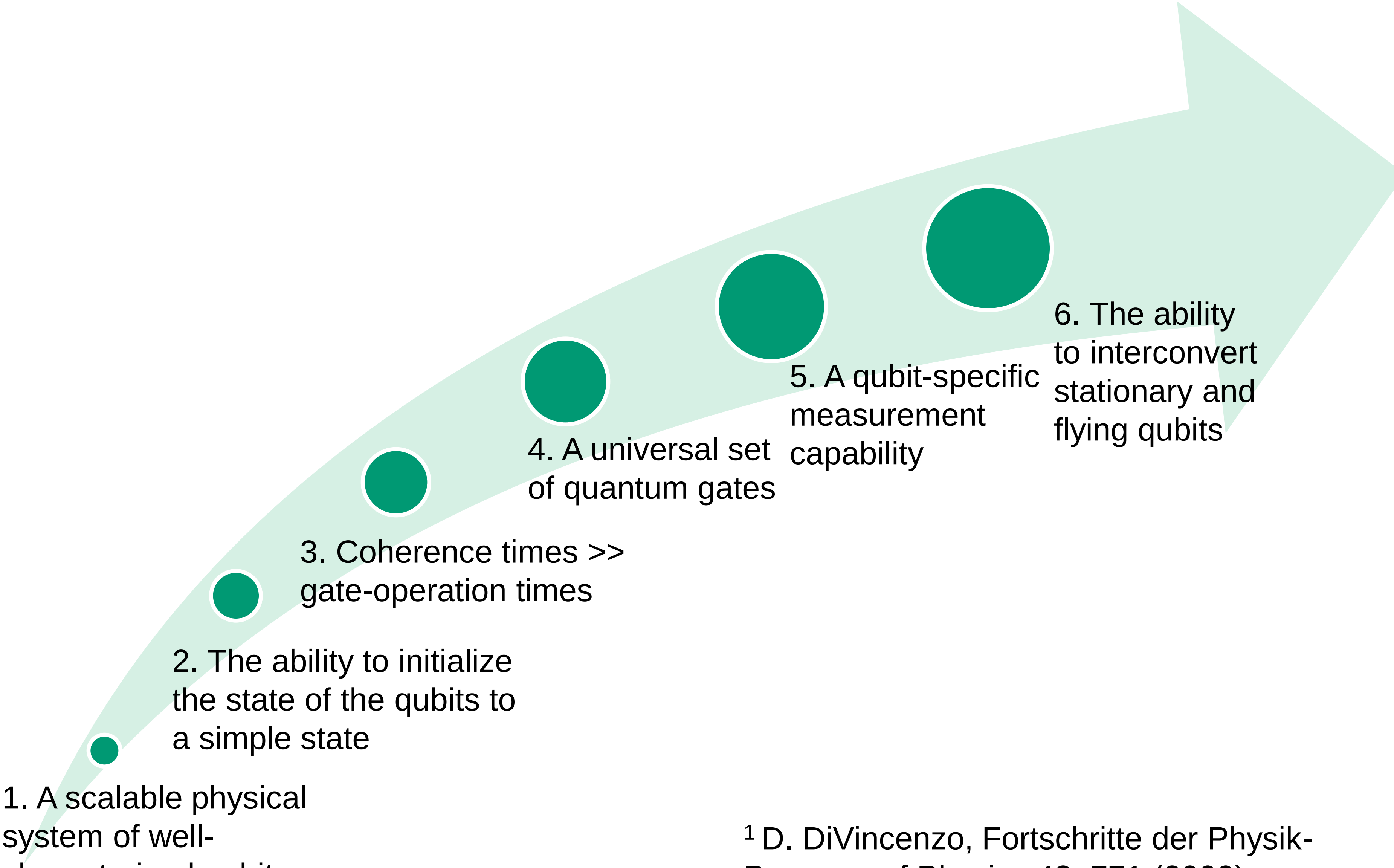
Single shot spin read out





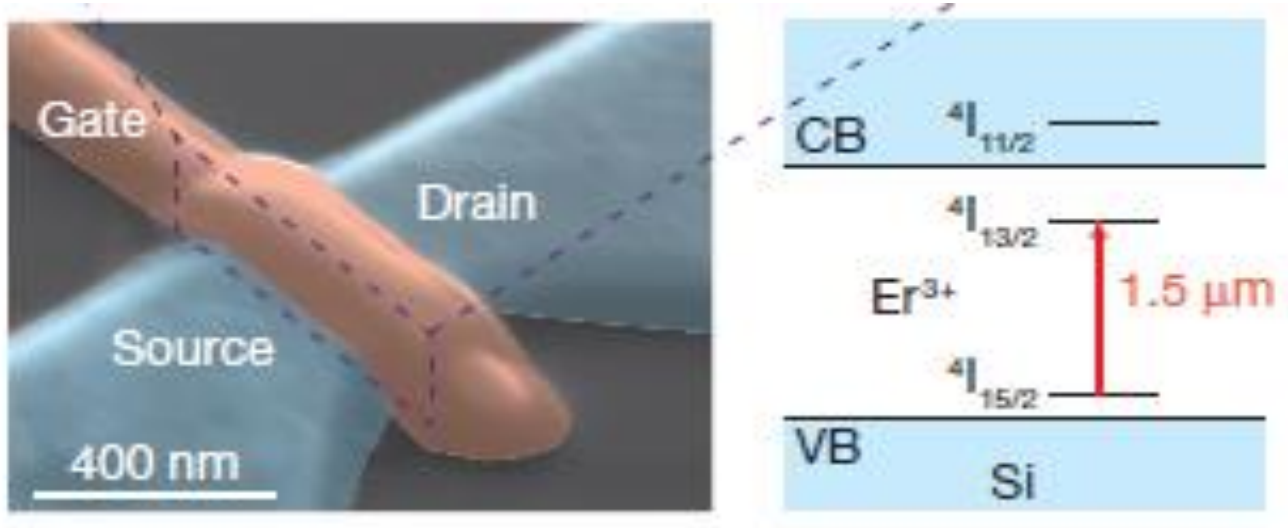
J. Elzerman *et al.*, Nature 430, 431–435 (2004).

DiVincenzo Criteria for a scalable system



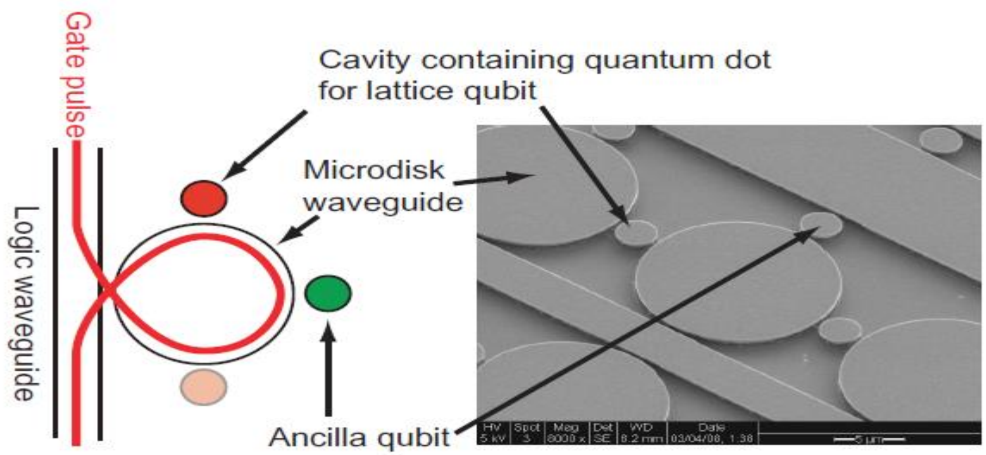
[1] D. DiVincenzo, Fortschritte der Physik-Progress of Physics 48, 771 (2000)

The ability to interconvert stationary and flying qubits



Optically addressing dopant atoms in silicon

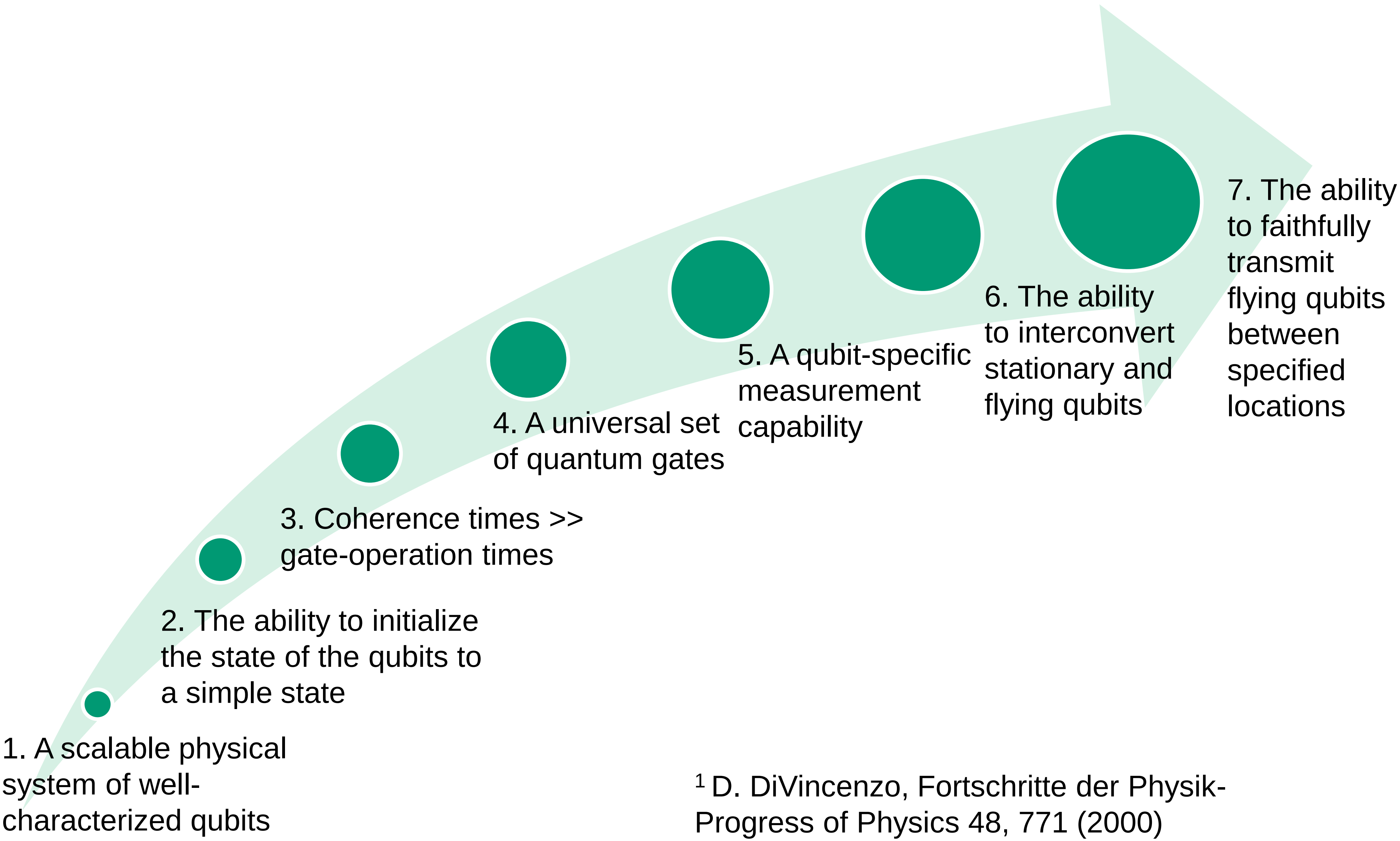
C. Yin *et al.*, Nature 497, 91 (2013).



Semiconductor nanophotonics

R. Van Meter et al., Int. J QC 1, 295 (2010).

DiVincenzo Criteria for scalable system

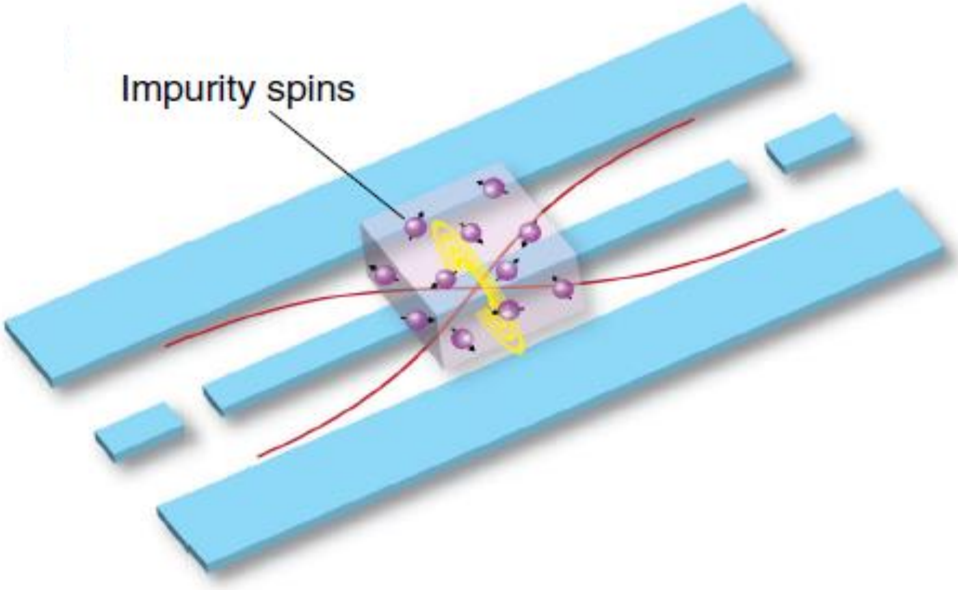


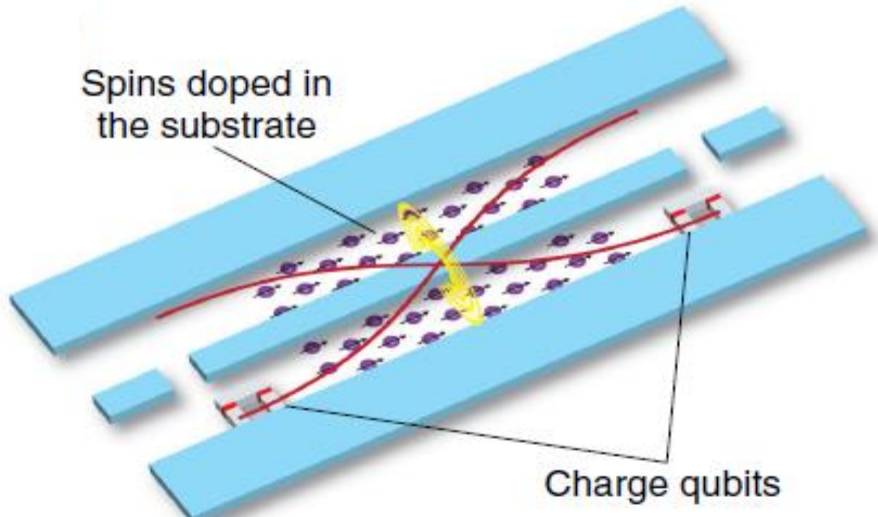
[1] D. DiVincenzo, Fortschritte der Physik- Progress of Physics 48, 771 (2000)

Faithfully transmit flying qubits

Z.L. Xiang, Rev. Mod. Phys. 85, 623 (2013).

Hybrid proposals

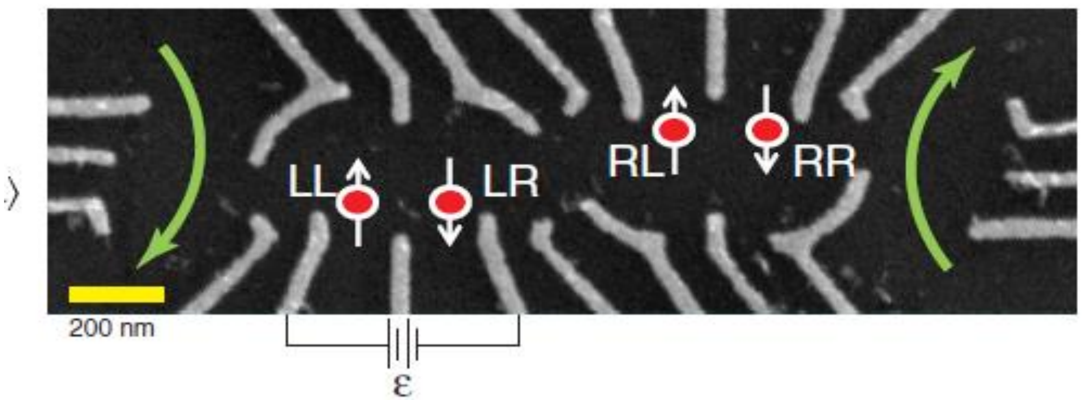




Spin hybrid quantum circuits
with spin and superconducting qubits

Leading Contenders in the Solid State

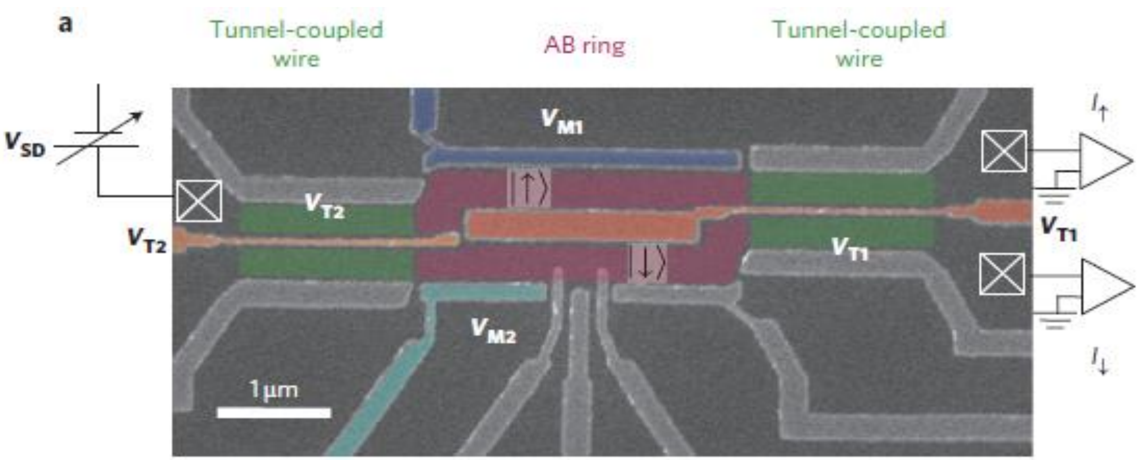
Electron spins in GaAs



Demonstration of two qubit gate in singlet-triplet basis
T_2~200μs

Bell state fidelity ~0.72

M.D. Shulman *et al.*,,
Science 336, 202 (2012).

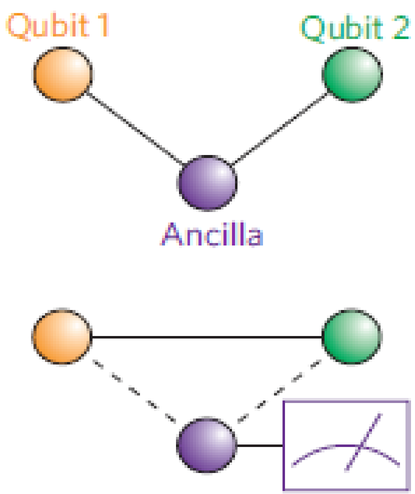


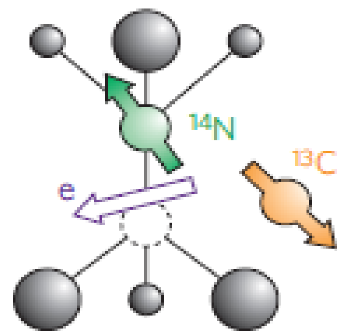
Demonstration of flying qubits:
Transport and manipulation of qubits over 6 microns in 40ps using Aharonov-Bohm rings connected to channel wires

M. Yamamoto *et al.*,
Nature Nanotechnology 7, 247 (2012)

Main limitation is coherence times ~hundreds of microseconds or less

Diamond based qubits

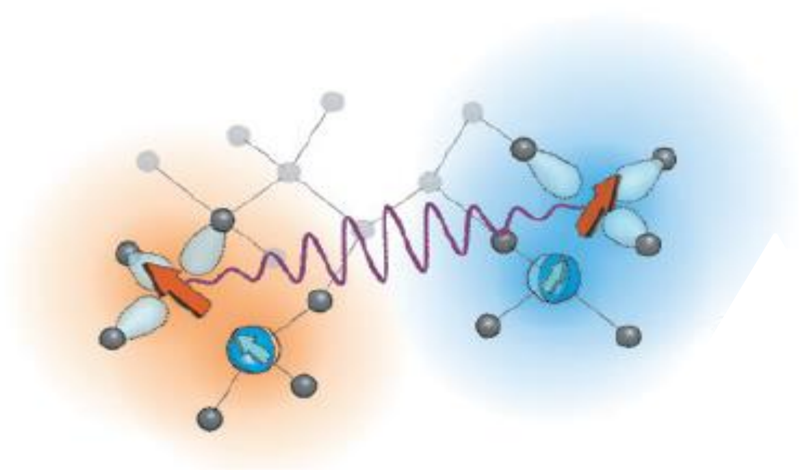




T_2~400μs (PRB 2011)

Two qubit parity measurement on nuclear spins in NV centres exploiting electron spin as a read-out ancilla

W. Pfaff *et al.*,
Nature Physics 9, 29 (2013).



Demonstration of room temperature entanglement of 2 NV centres

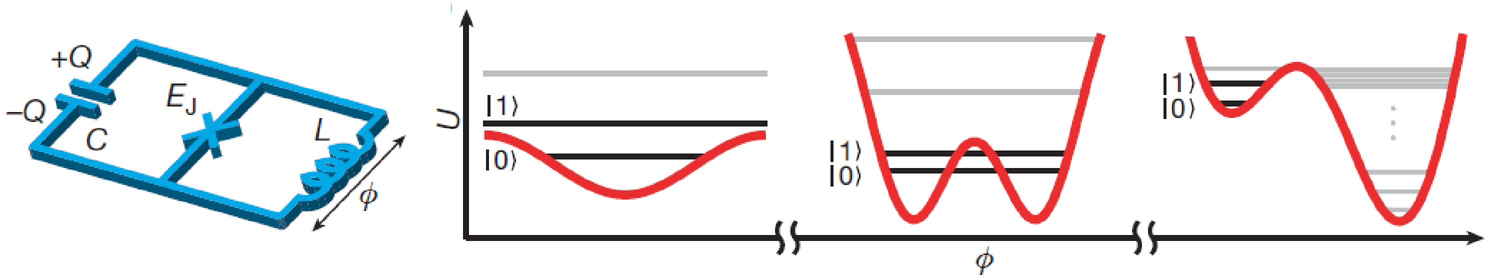
Entanglement fidelity ~0.67

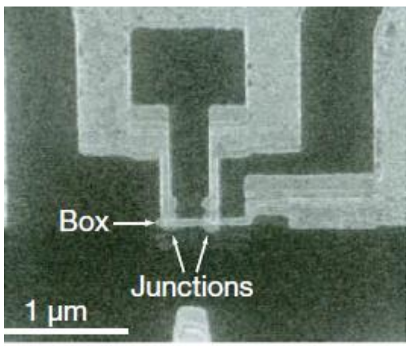
F. Dolde *et al.*,
Nature Physics 9, 139 (2013).

Scalable architectures:
L. Childress et al., PRL 96, 070504 (2006)
P. Rabl et al., Nat Phys 6, 602 (2010)
N.Y. Yao et al., Nat. Comms 3 (2012).

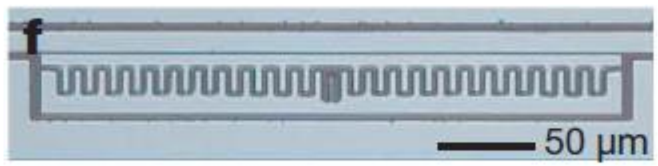
Main limitation is difficulty of reproducible fabrication

Superconducting qubits

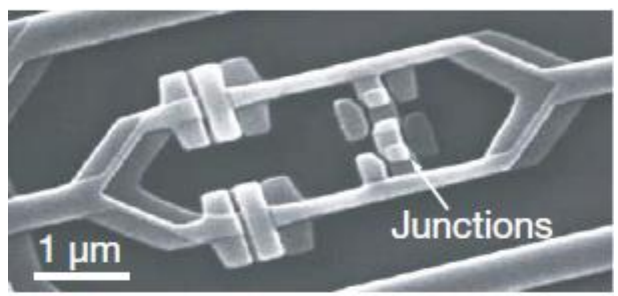




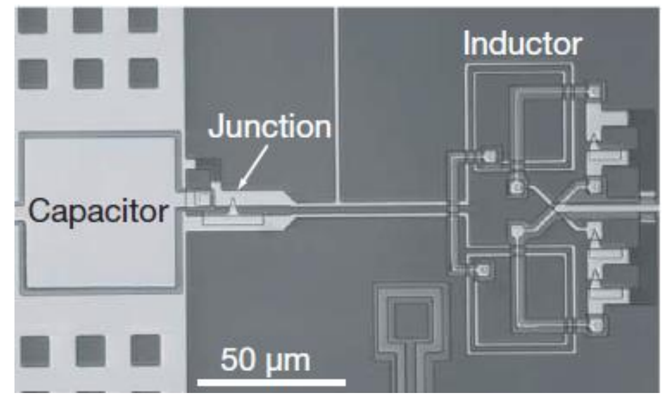
Charge qubit



Transmon qubit (Schoelkopf group)



Flux qubit (Mooij group)

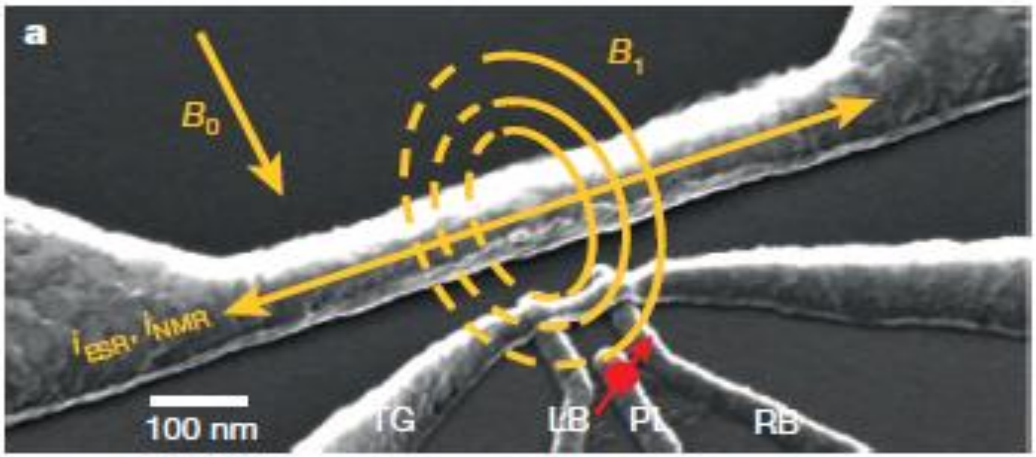


Phase qubit (Martinis group)

$T_2 \sim 100\ \mu s$
single qubit gate time ~ 1ns
Two qubit gate times ~ 10-50ns

Current Status of Silicon Quantum Computing

Silicon based qubits

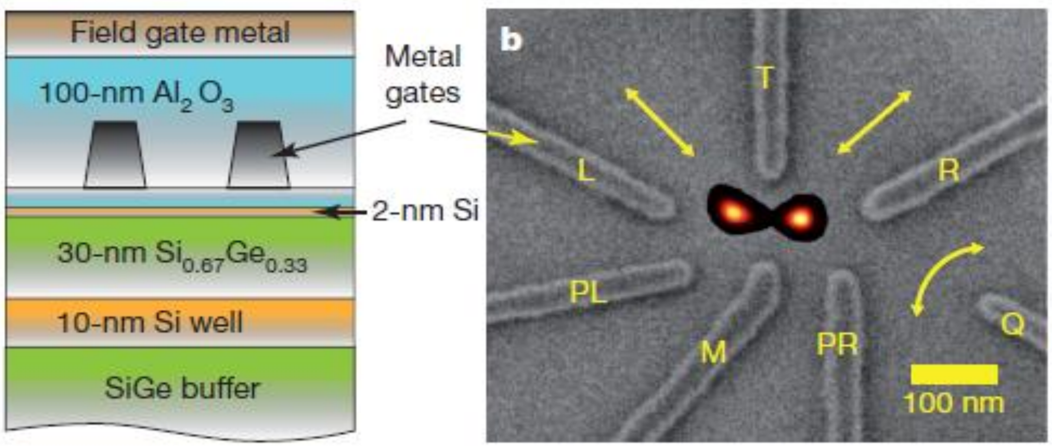


P nuclear spin qubit

^{nat}Si T_2 (n) > 60 ms (ionised donor)

Nuclear spin read-out fidelity 99.8%

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



Electron spin qubit in Si/SiGe

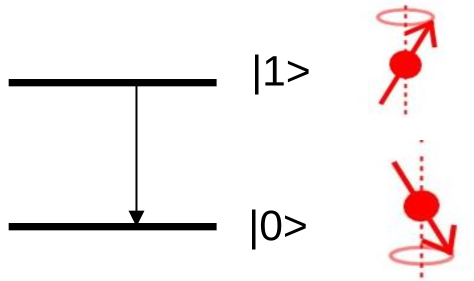
Singlet-triplet basis

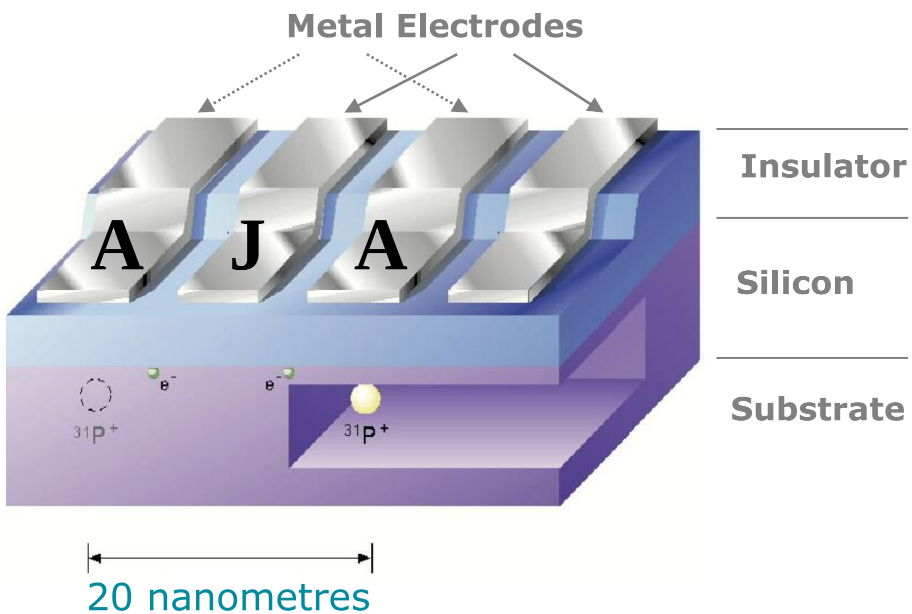
^{nat}Si T_2 (e) > 360ns

B.M. Maune *et al.*, Nature 481, 344 (2012)

Main limitation is difficulty of fabrication at such small scales

First proposal for a silicon quantum computer





Kane, Nature **393**, 133 (1998)

Qubits are the nuclear spins of ^{31}P donor atoms in ^{28}Si

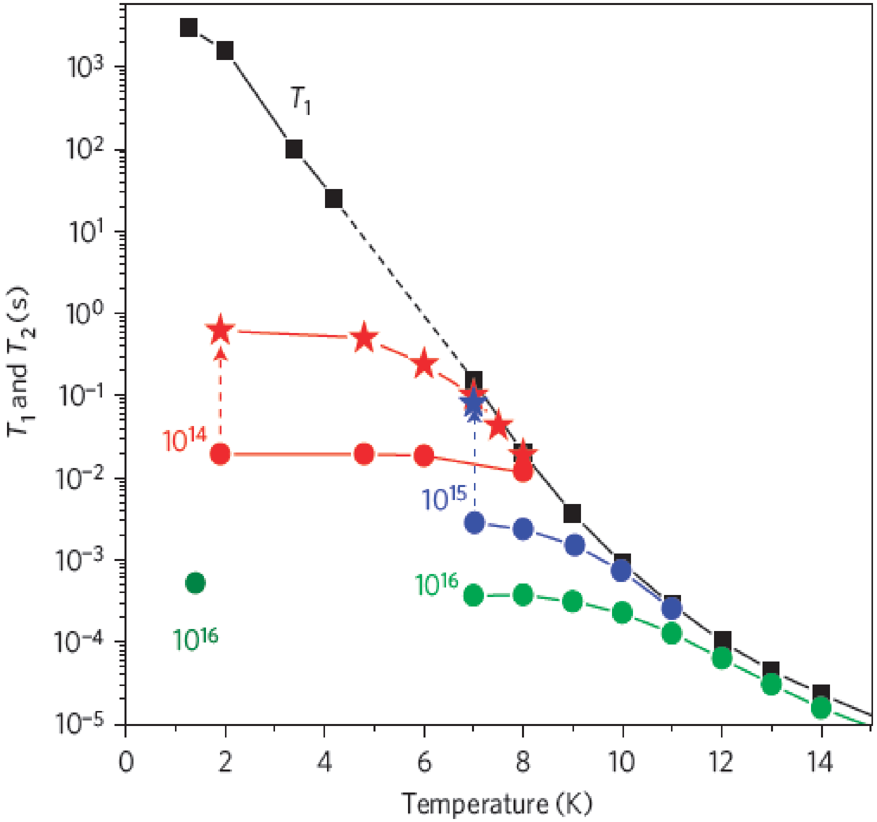
Advantages:

- relaxation T_1 long (10^{18} s)
- Low spin-orbit coupling
- Spin free host with low abundance of ^{29}Si (~5%)
- compatible with existing multi-billion dollar silicon microelectronics industry and scaleable

Disadvantages:

- require the ability to dope Si with atomic precision aligned to nanometer sized surface gates

Spin Coherence of P donors



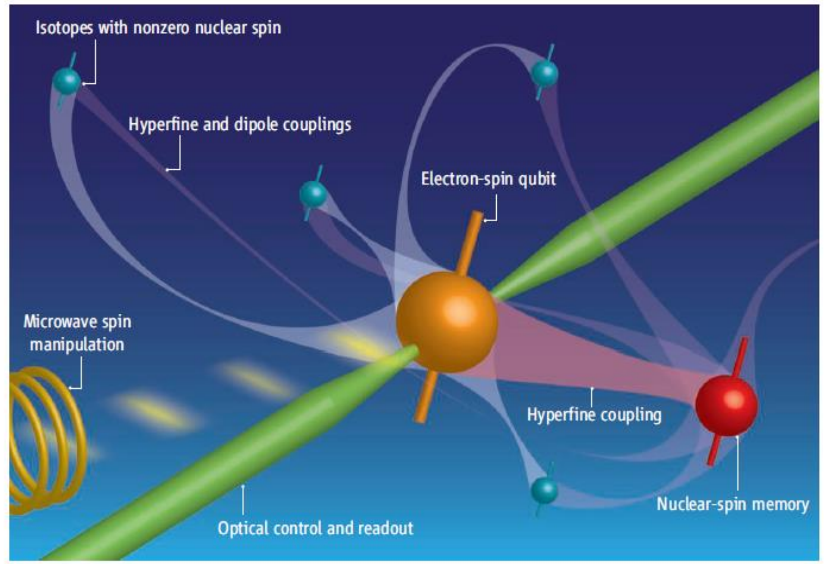
Bulk measurements:

^{28}Si $T_1(e)$ ~ 1 hour (1.2K; 0.35T)

^{28}Si $T_2(e)$ ~ secs (^{28}Si, 1.2K)

A.M. Tyryshkin et al.,
Nature Materials 11, 143 (2012)

^{31}P nuclear memory: $T_2(n)$ ~180 seconds



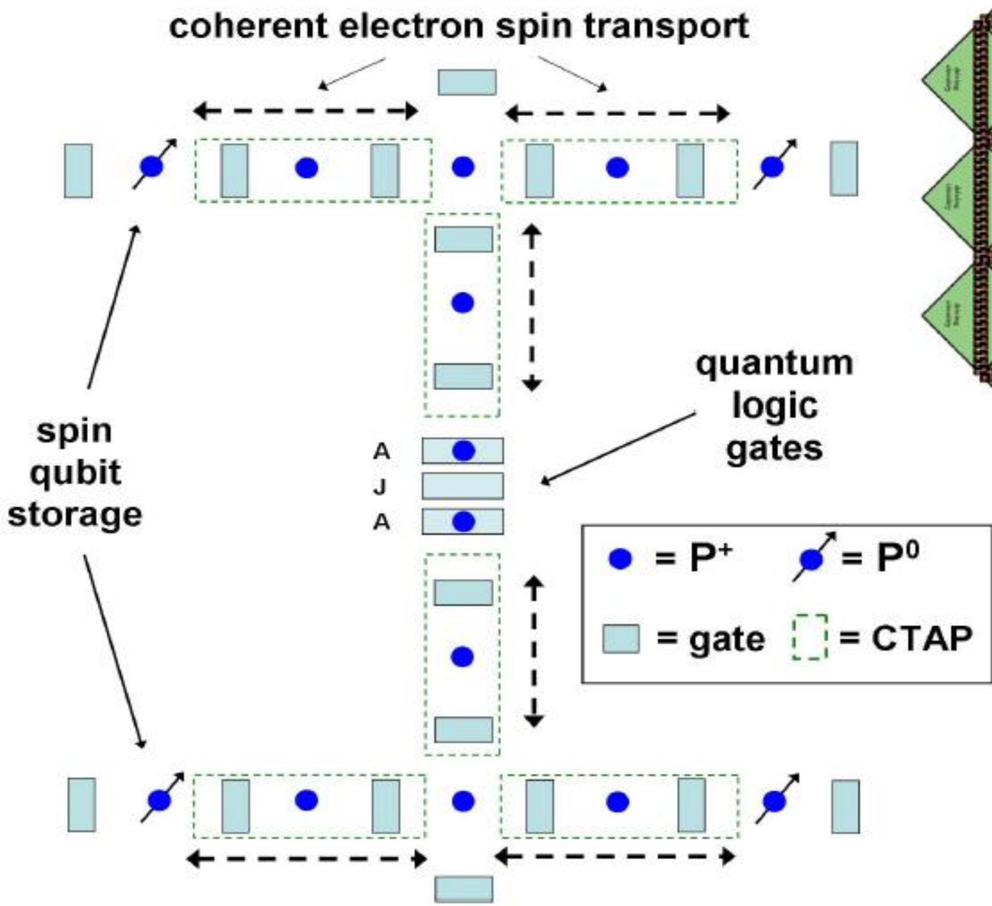
^{28}Si: "Semiconductor Vacuum"

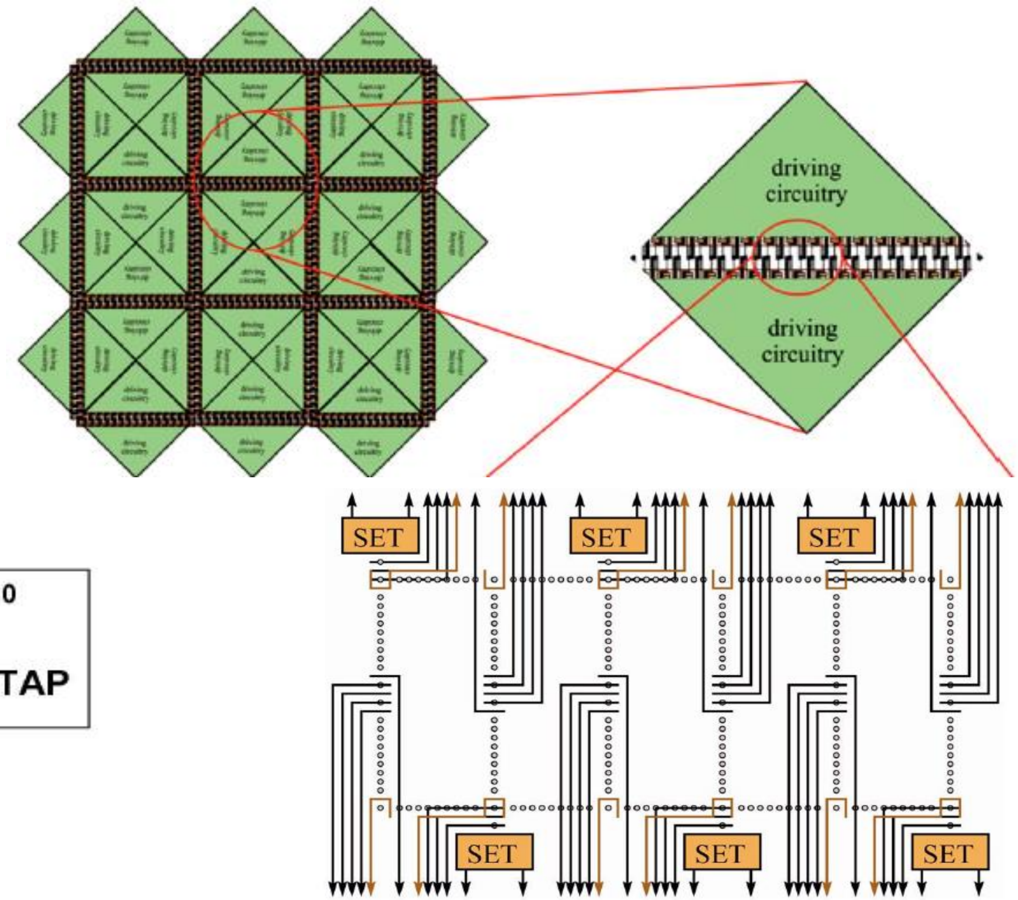
M. Steger et al., Science 336, 1280 (2012)
D. McCamey et al., Science 330, 6011 (2010)
J.L. Morton et al., Nature 455, 7216 (2008)

Ionised donor ~ 39 mins (RT)

M. Saeedi et al., Science 342, 130 (2013)

Scalable 2D architecture

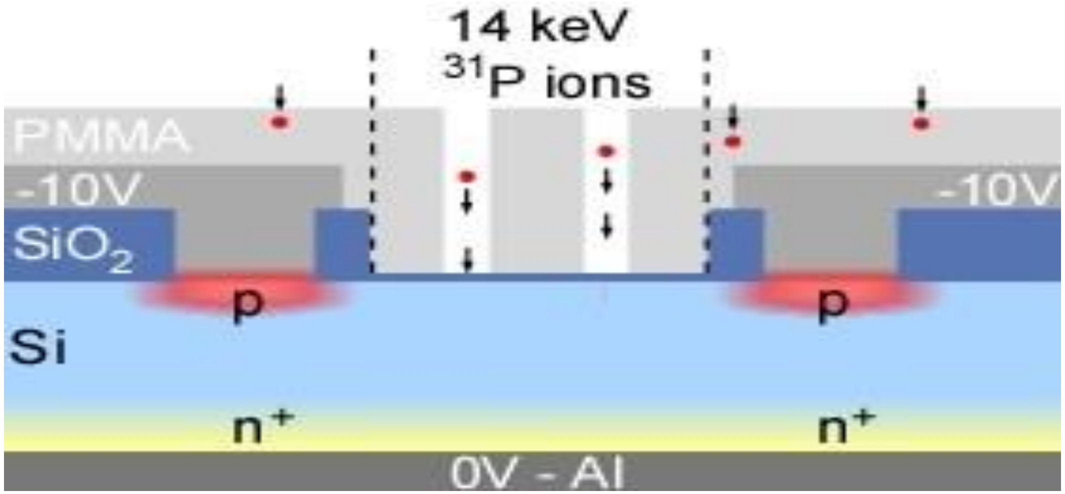


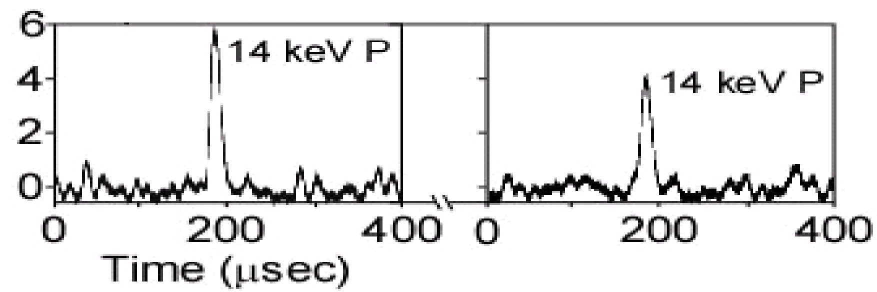


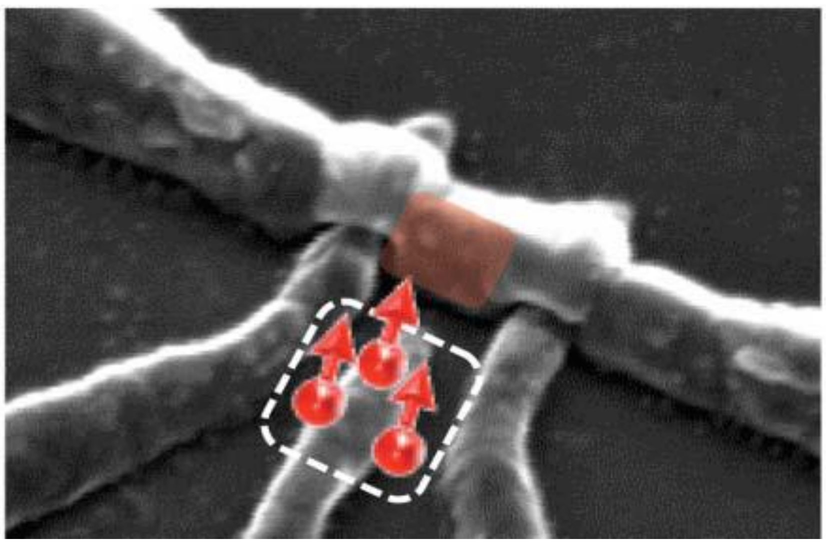
Shuttling time ~ns

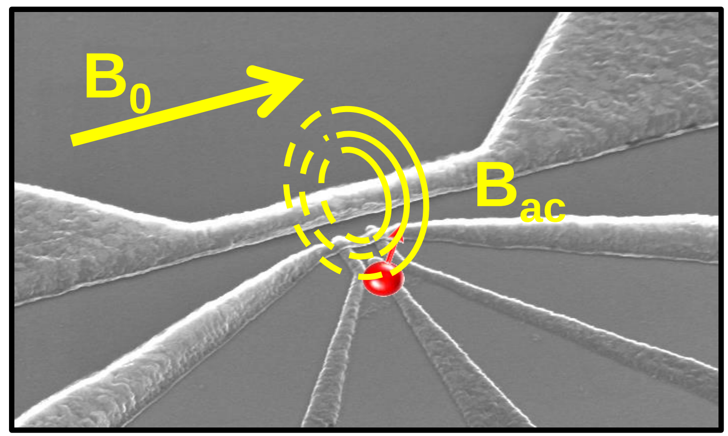
L.C.L. Hollenberg, Phys. Rev. B 74, 045311 (2006)

Donor based qubits by ion implantation



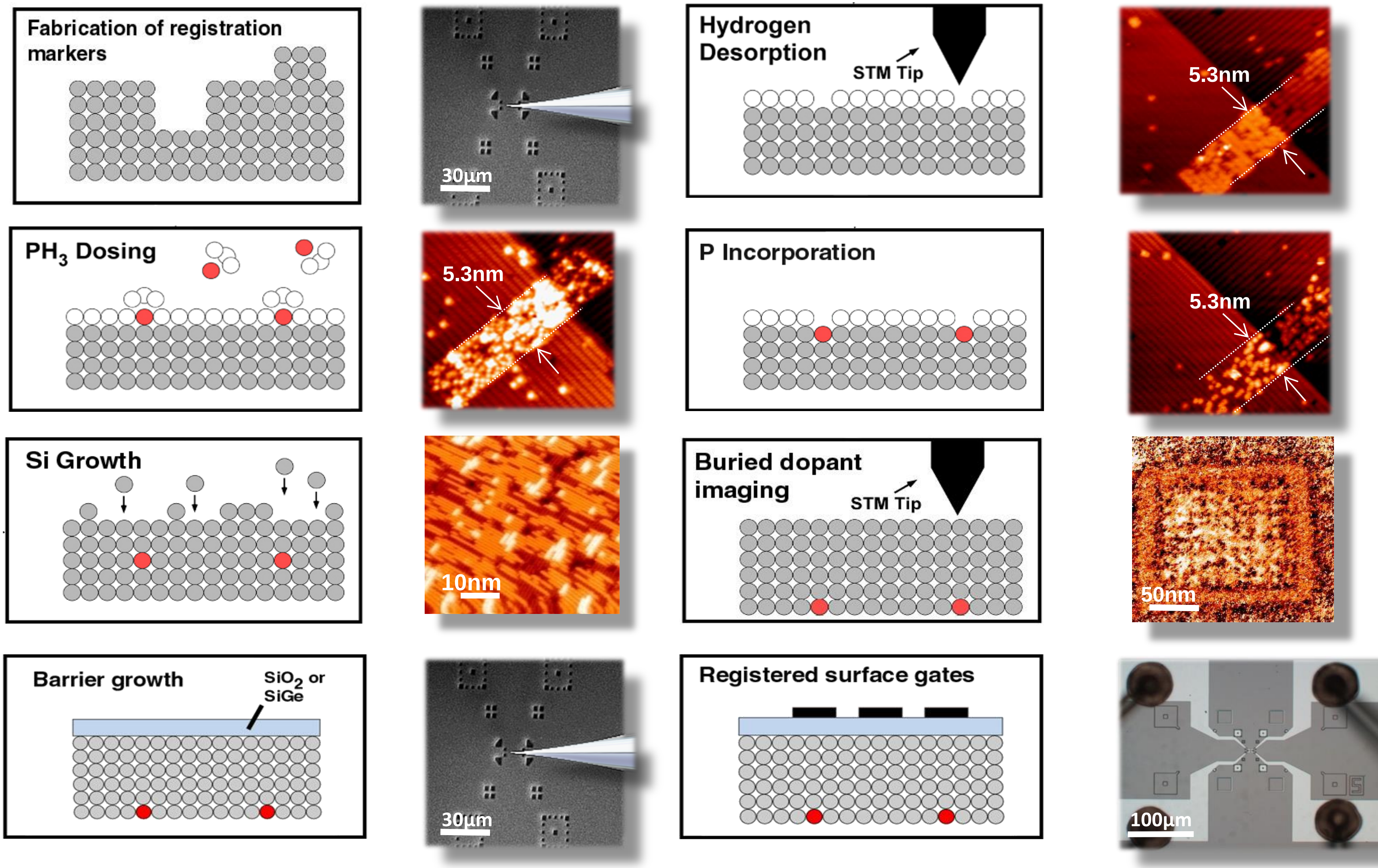






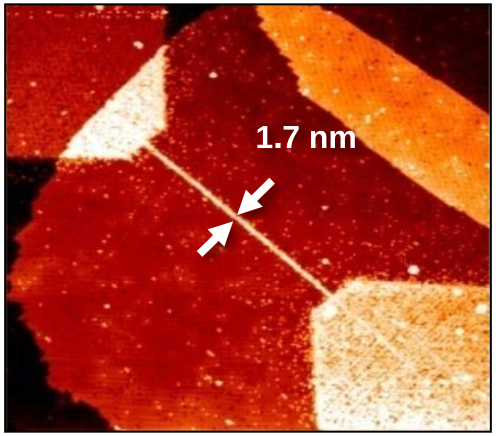
Andrew Dzurak, Andrea Morello and David Jamieson

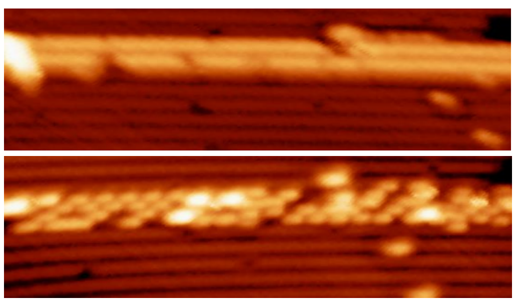
Atomic Fabrication Strategy in Silicon

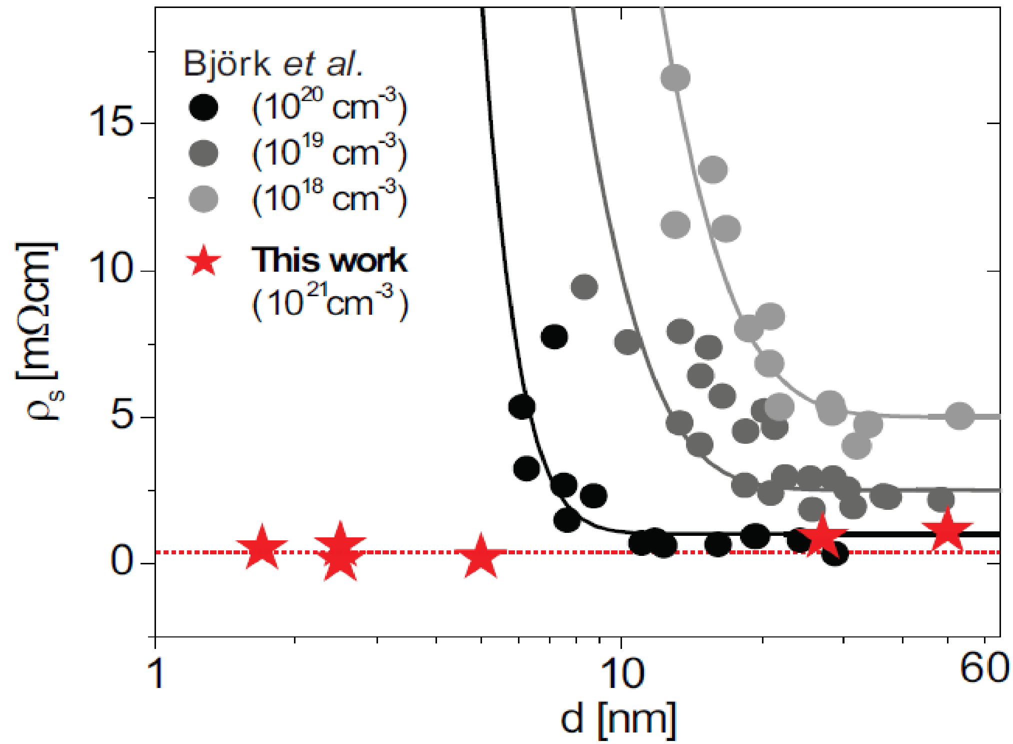


Narrowest, lowest resistance conducting Si nanowires

M.T. Bjork et al., Nature Nano 4, 103 (2009).







- Lowest resistivity doped silicon wires
- Constant resistivity down to ~1.7nm
- Resistivity comparable to bulk doping of similar density, ρ~0.3×10^{-3} Ωcm (4.2K)

*B.Weber et al., Science **335** 64(2012).*

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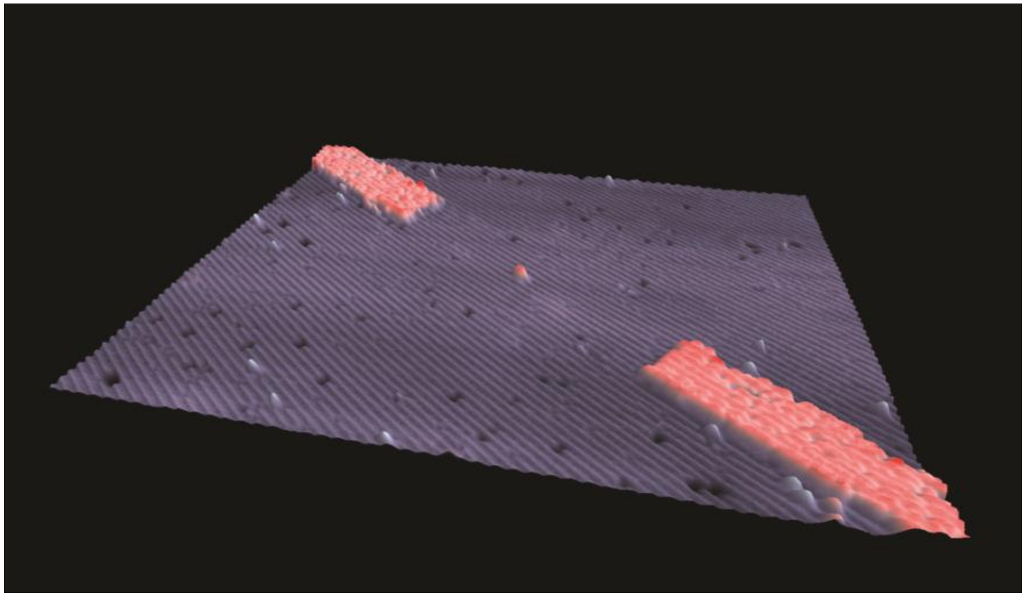
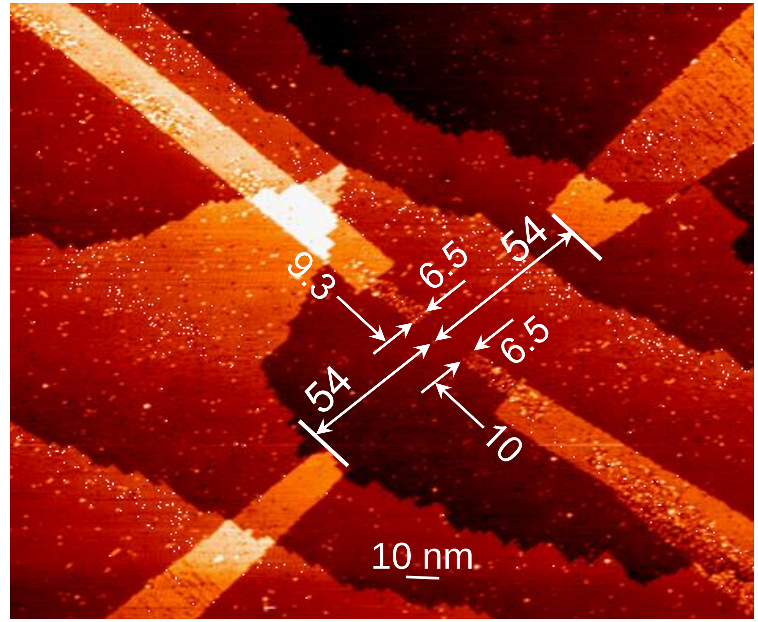
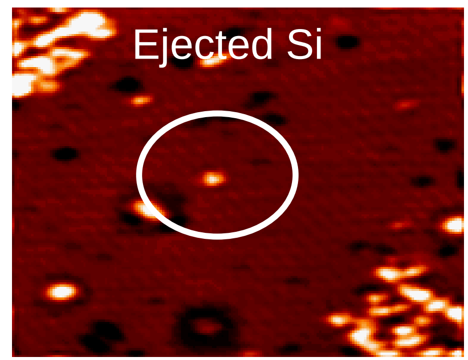
First deterministic, precision single donor device



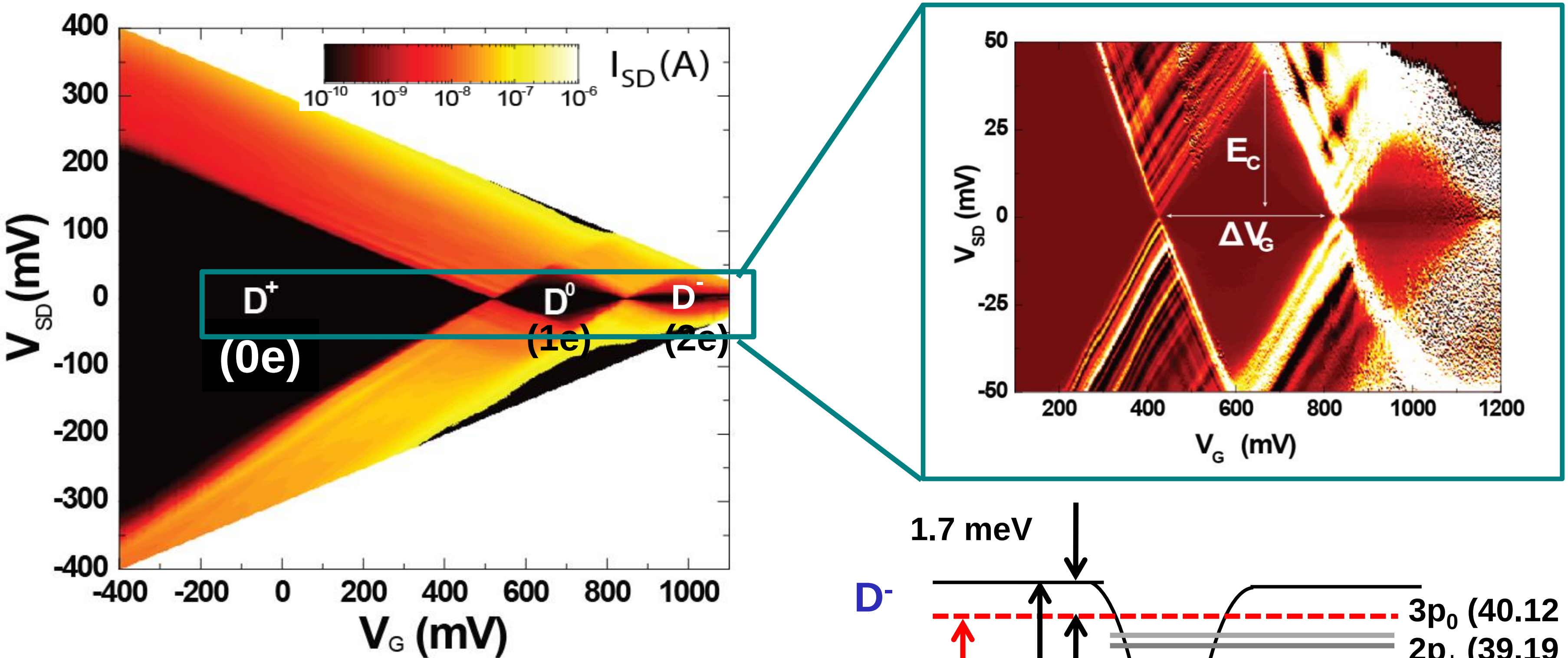




Ejected Si at the same site after incorporation

M. Fuecshle *et al.*,
Nature Nanotechnology, 7, 242 (2012)

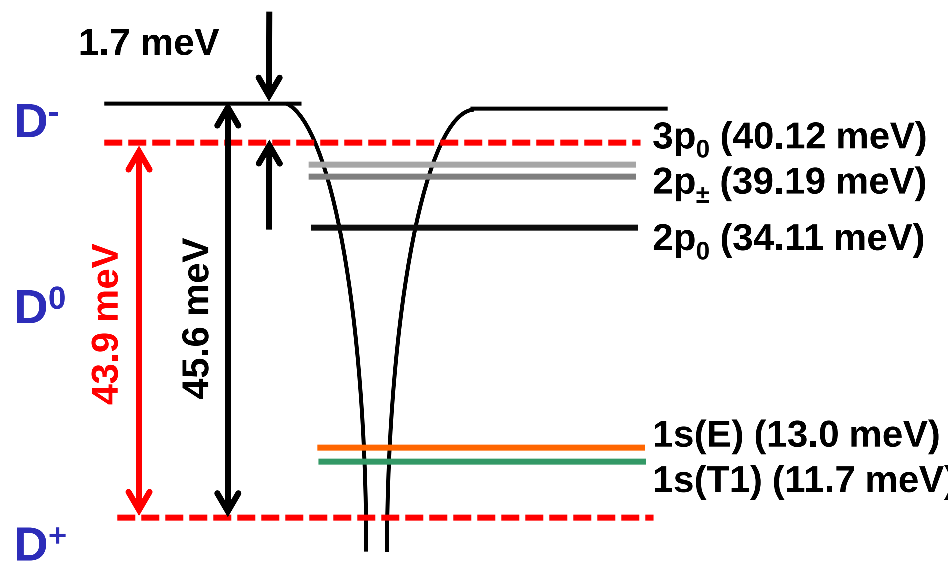
First deterministic, precision single donor device



E_C=47±2meV

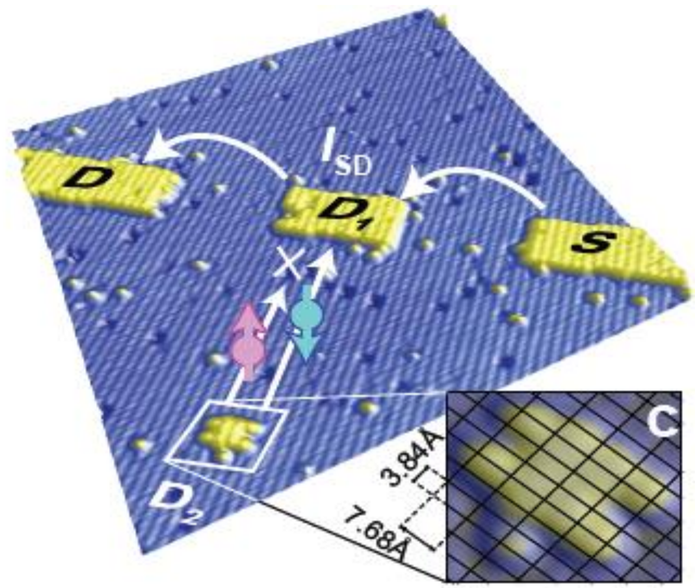
$1_S(T_1)$= 11.4±1
$1_s(E)$= 15±2

Compares well with: $1_S(T_1)$ = 11.7
$1_S(E)$ = 13.1

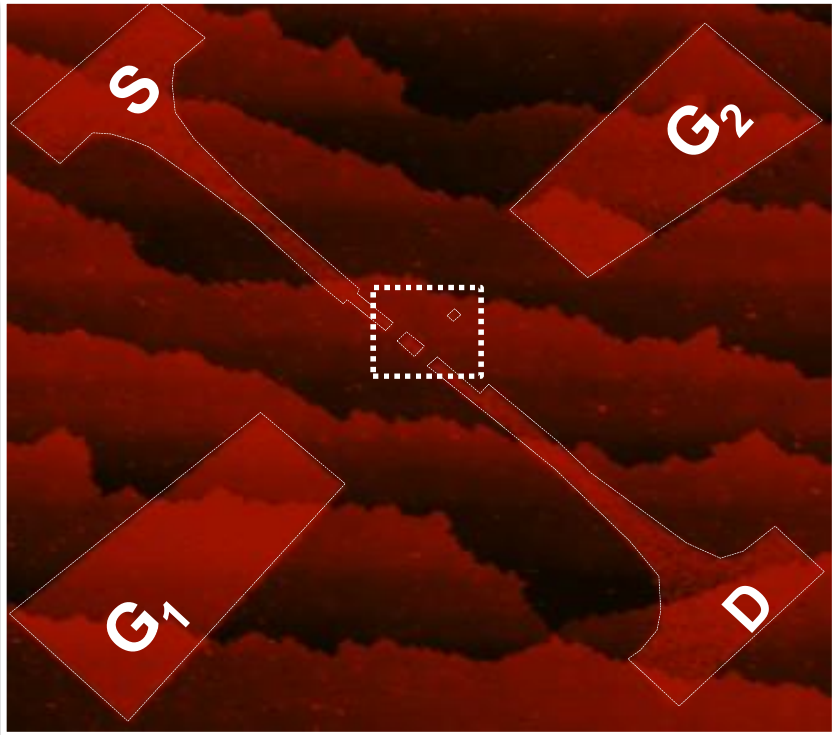


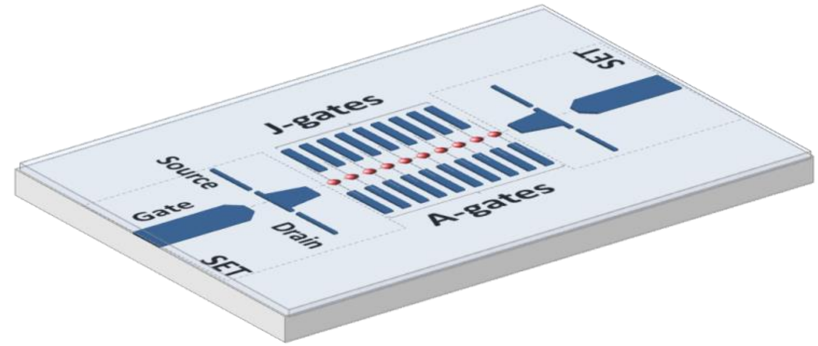
A.K. Ramadasa, Rep. Prog. Phys. 44 (12), 1297 (1981).

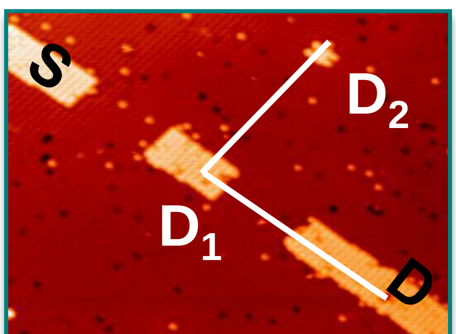
Single shot spin read-out using all epitaxial SETs



Integration of an in-plane detector for spin read-out

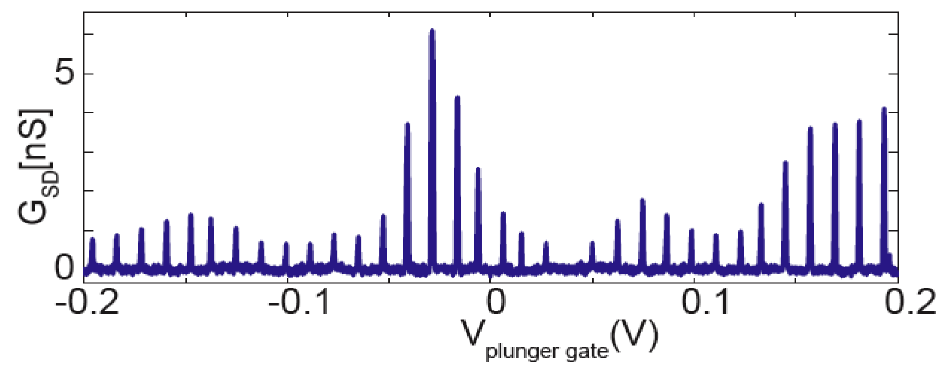






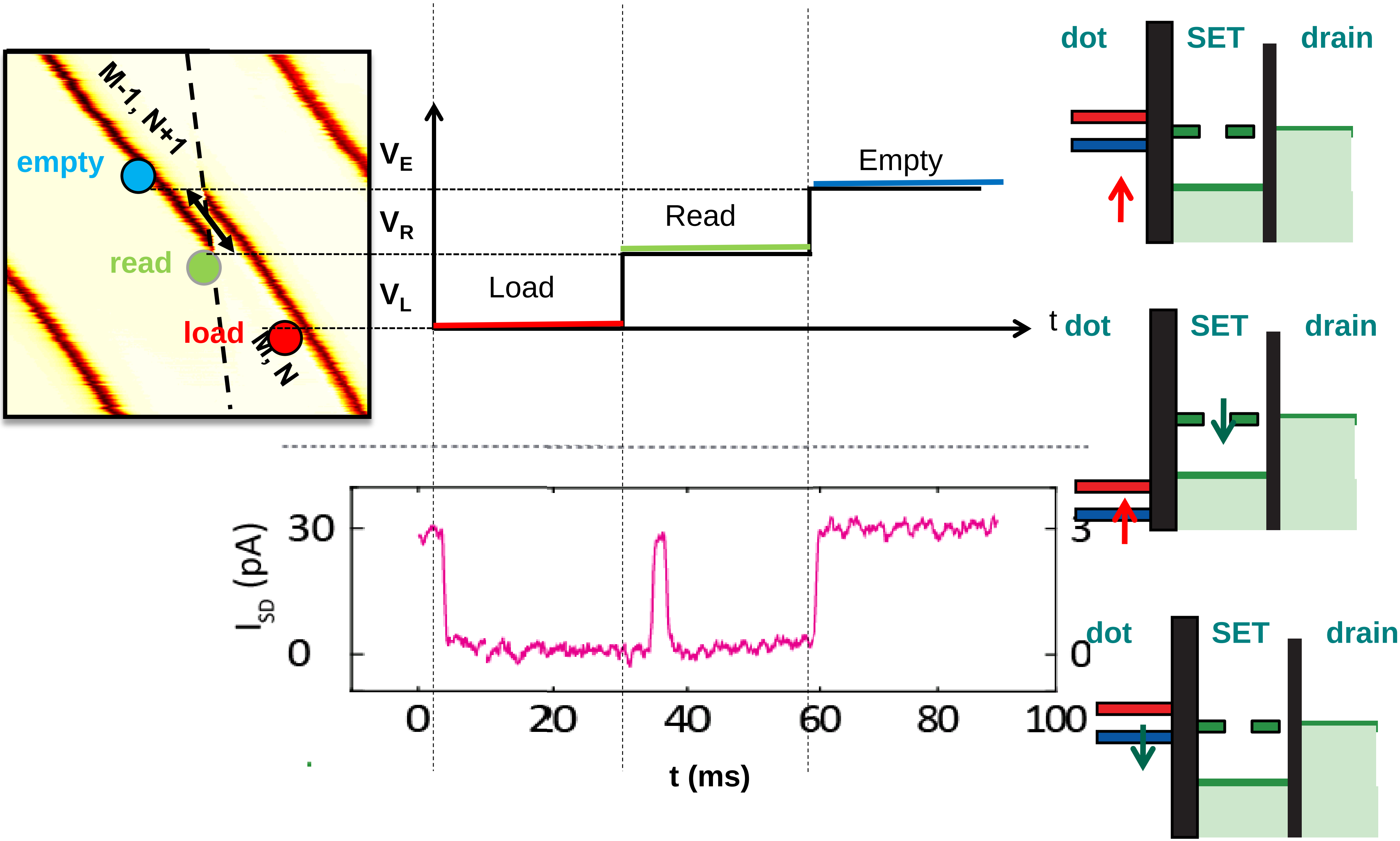
SET-island (D_1)
120 P donors

Quantum dot (D_2)
< 4 P donors



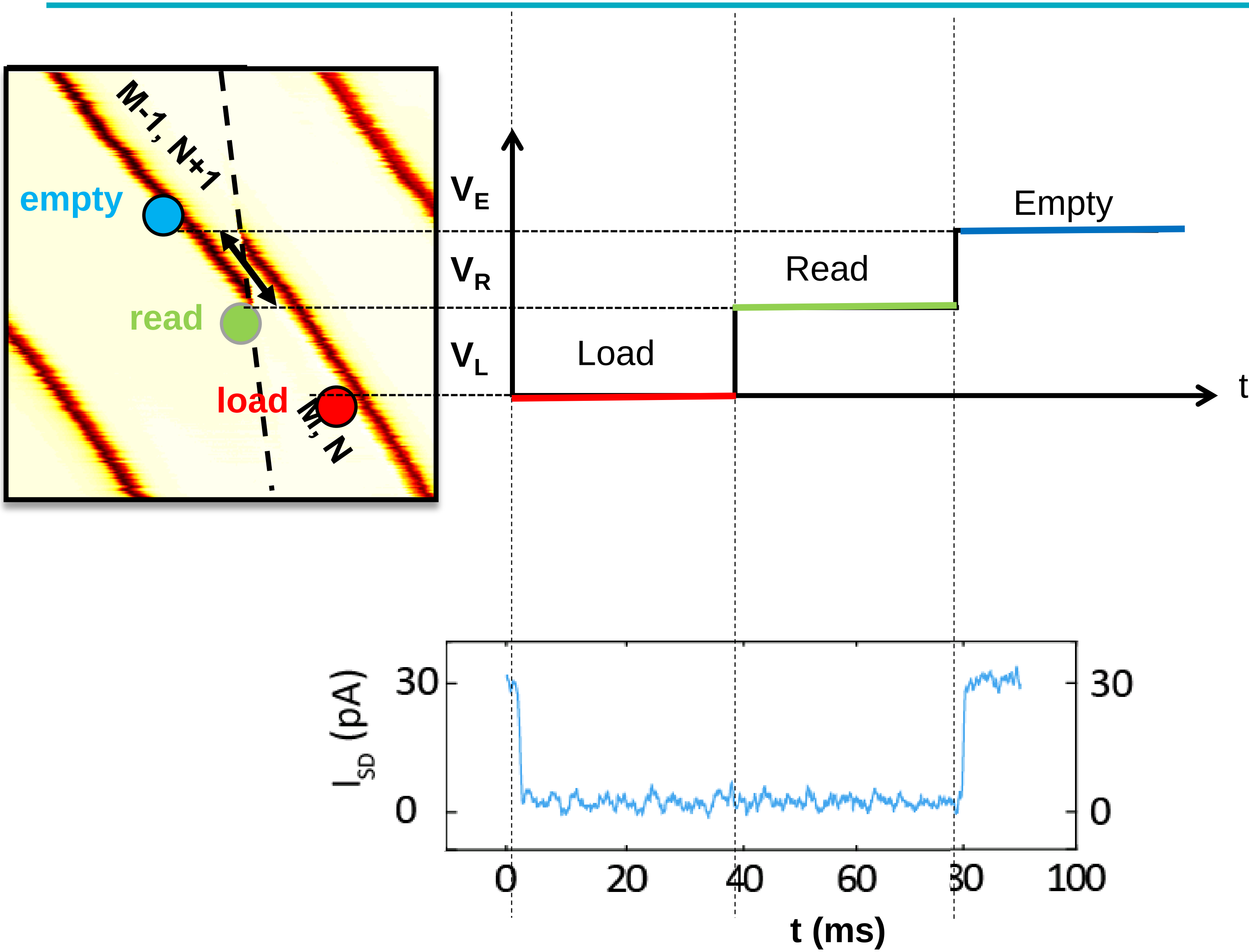
S. Mahapatra *et al.*, Nano Letters11, 4376 (2011).

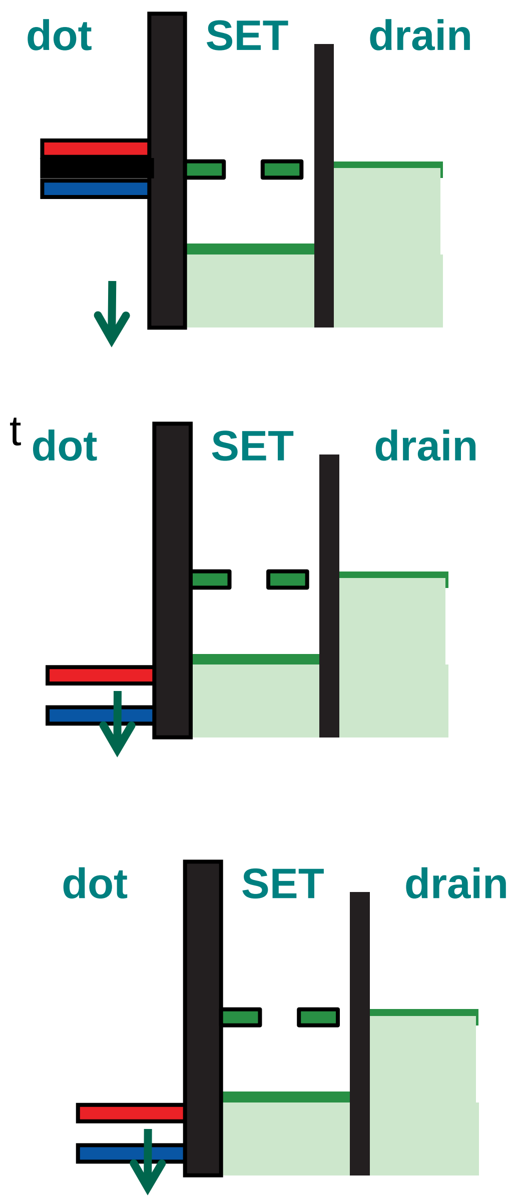
Single shot spin read-out: spin-up



J. Elzerman *et al.*, Nature 430, 431–435 (2004).

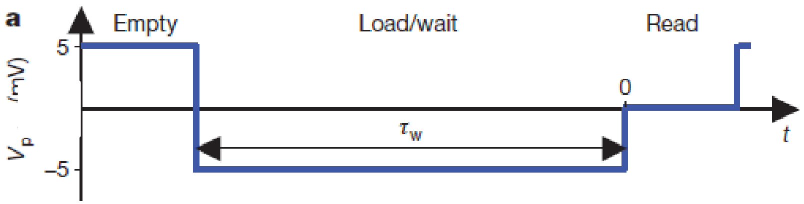
Single shot spin read-out: spin down

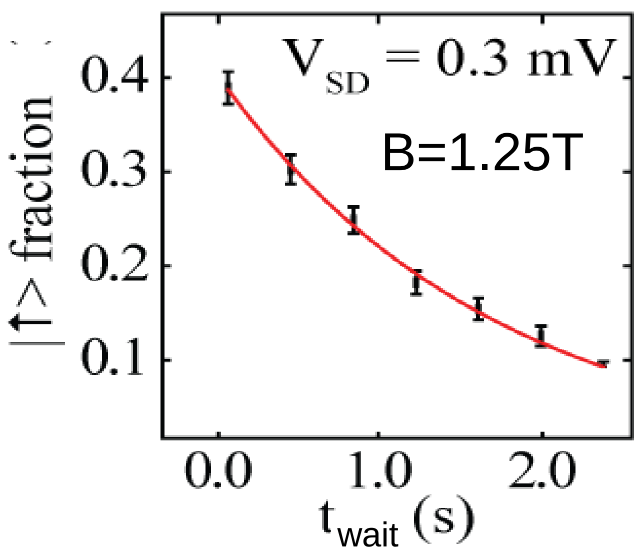


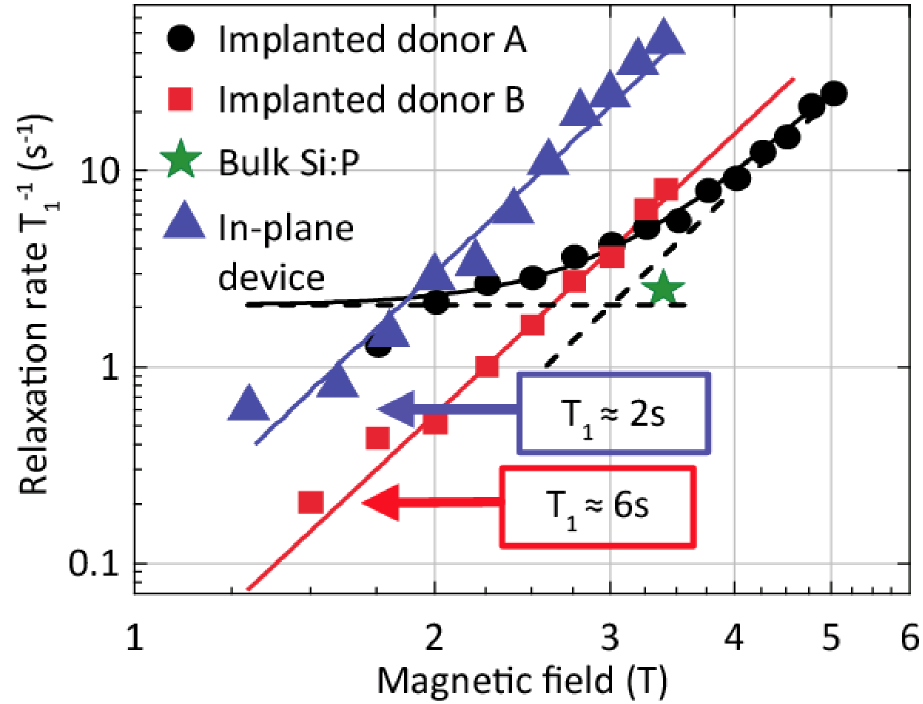


H. Büch *et al.*, Nature Communications **4**, 2017 (2013).

Spin relaxation rates, T_1





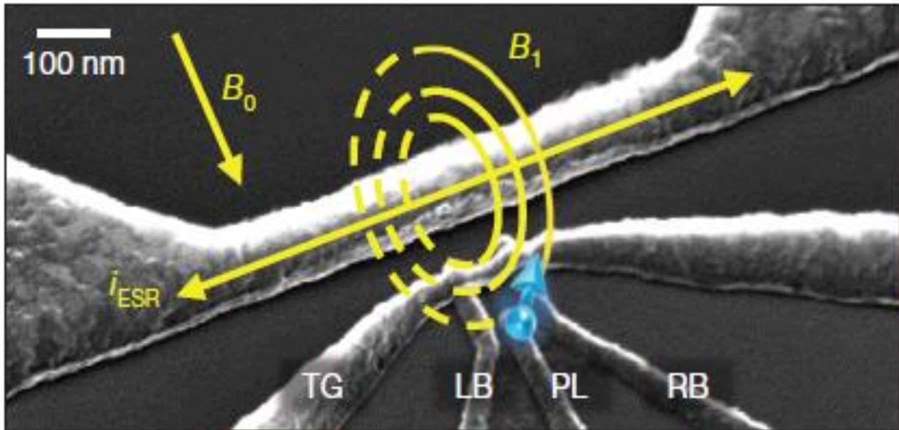


$T_1^{-1}(B) \approx B^5$ agrees with spin-lattice relaxation mechanism from valley depopulation

H. Hasegawa, Phys. Rev 118, 1523 (1960)

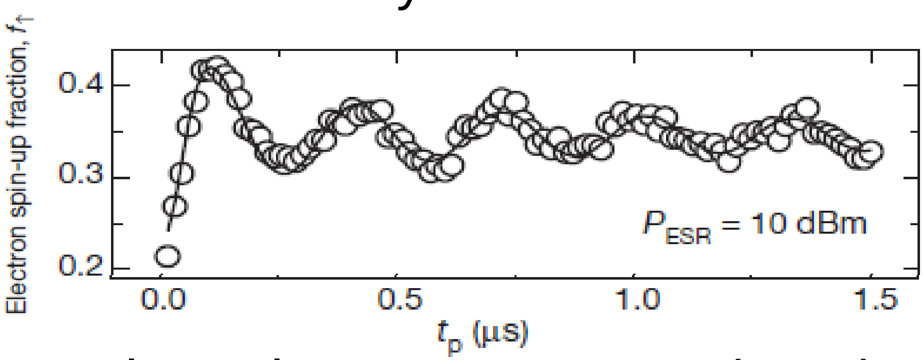
A. Morello et al, Nature 467, 687 (2010).

P donor single atom qubit

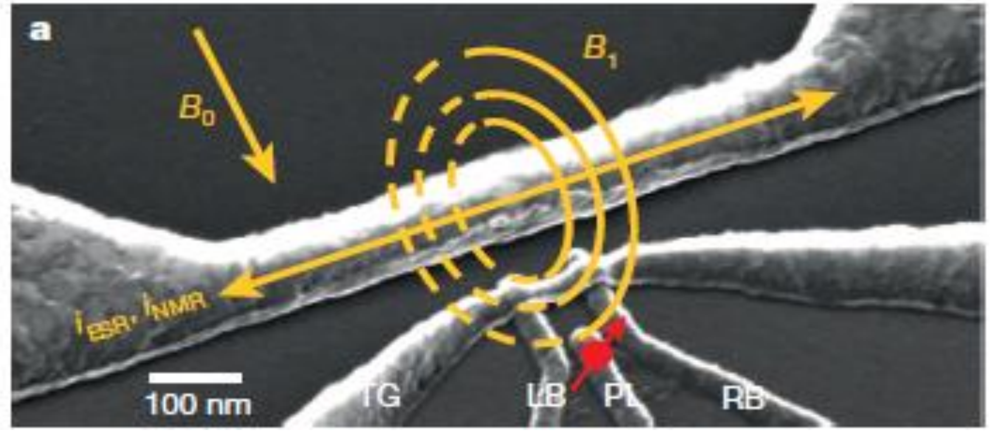


^{nat}Si T_2 (e) > 200 μs
(Hahn echo)

Electron spin read-out
fidelity ~ 57%

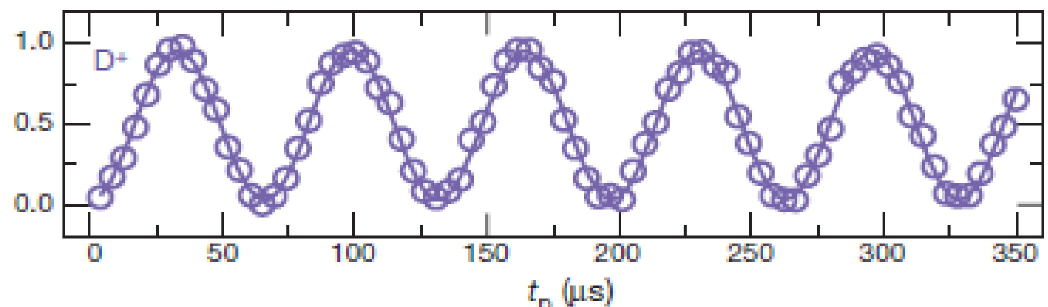


J. Pla et al., Nature 489, 541 (2012)



^{nat}Si T_2 (n) > 60 ms
(ionised donor)

Nuclear spin read-out
fidelity ~ 99.8%



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

Summary

- Quantum computing is a rapidly developing field with several implementations now reaching the integrated circuit state

- Hybrid proposals should allow the transition from stationary to flying qubits for scalable architectures

- There are over 50 different quantum algorithms with more being developed all the time

- In time I am confident that quantum computing will become a practical reality