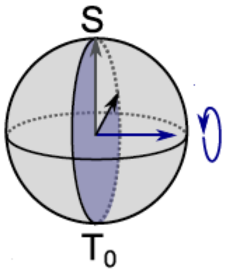
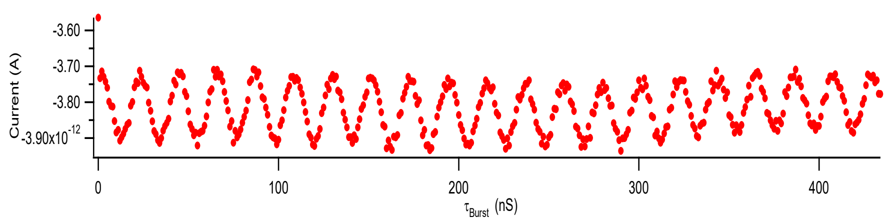
Experimental techniques for spin qubits manipulation and readout

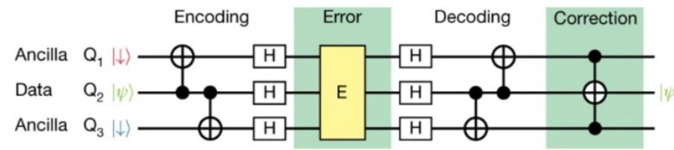
Alessandro Crippa

NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore

alessandro.crippa@nano.cnr.it







About me

Universita' Bicocca (Milano)
Condensed Matter Physics

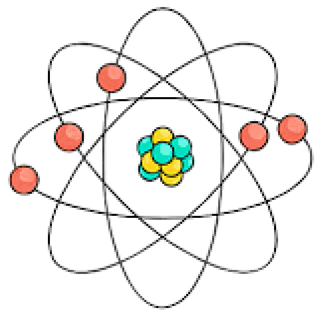
PhD Nanoscience & Nanotechnologies (CNR Agrate Brianza) 2012 - 2015

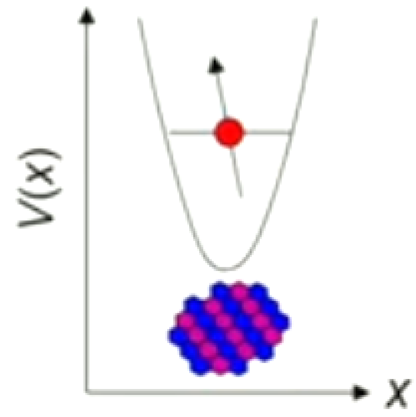
PostDoc
Silicon Spin Qubits (Grenoble, De Franceschi group)
2016 - 2019

PostDoc
cQED in Ge spin qubits (Vienna, Katsaros group)
2019 - 2020

Researcher
(Pisa, NEST)
2021 - …

Testbed for quantum physics: artificial atoms

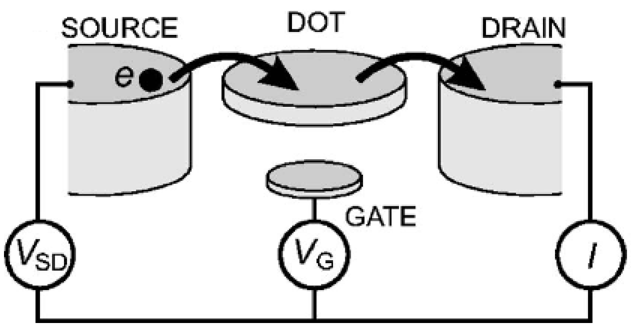


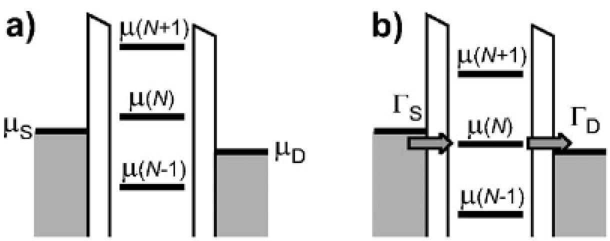


Size	d = 1 Å	d = 1000 Å
Level spacing	Δ ~ eV	$\Delta \sim 1/(d^2\ m^*)$ ~ 100s of μeV – meV
# of nuclei	$N_{nuc} = 1$	$N_{nuc} = 10^5 - 10^6$
Spin-orbit	$\vec{L} \cdot \vec{S}$	material dependent anisotropic structure dependent

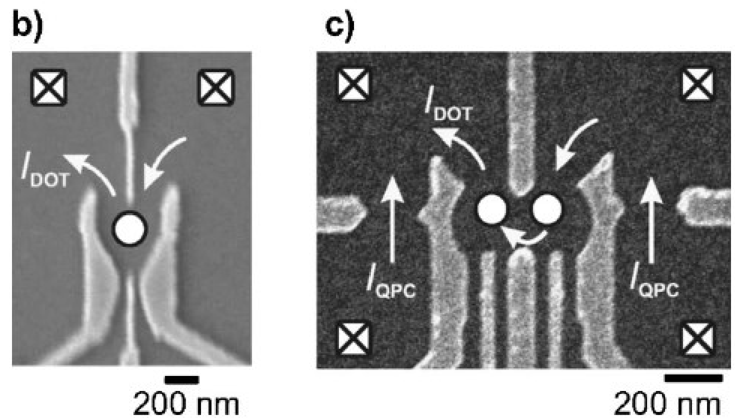
Semiconductor quantum dots

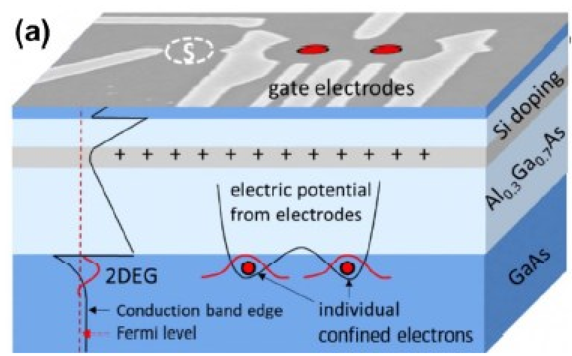
Principle



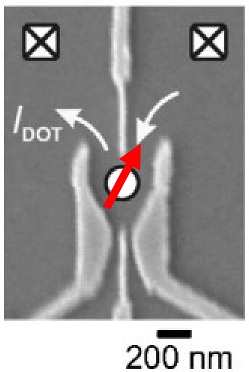


Experimental implementations





Single spin states

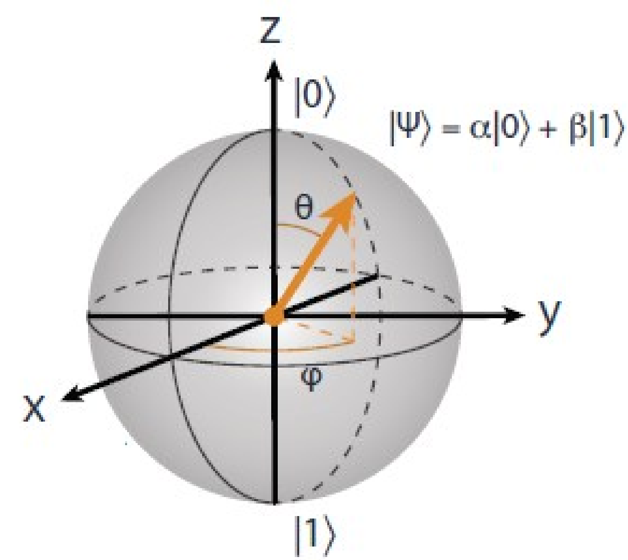


One confined charge carries a spin ½: that's a qubit

Ideal quantum two-level system: $|\downarrow\rangle$ $|\uparrow\rangle$,

$|\downarrow\rangle \equiv |0\rangle$

$|\uparrow\rangle \equiv |1\rangle$



Single spin states

Fact: weak magnetic moment of the electron
(μ_B is "small")

A single electron (i.e., ~1μ_B)
generates a B-field of 1μT at
a distance of 10 nm

Single spin states

Fact: weak magnetic moment of the electron (μ_B is "small") →

- ✓ Natural quantum two-level system of carriers
- ✗ Need of high-sensitive magnetic probes

A single electron (i.e., ~1μ_B) generates a B-field of 1μT at a distance of 10 nm

Single spin states

Fact: weak magnetic moment of the electron (μ_B is "small") →

A single electron (i.e., ~1μ_B) generates a B-field of 1μT at a distance of 10 nm

✓ Natural quantum two-level system of carriers

✗ Need of high-sensitive magnetic probes

✓ Protected against e.m. noise

✗ Hard to manipulate by e.m. fields

Single spin states

<u>Fact:</u> weak magnetic moment of the electron (μ_B is "small") →

A single electron (i.e., ~1μ_B) generates a B-field of 1μT at a distance of 10 nm

- ✓ Natural quantum two-level system of carriers
- ✗ Need of high-sensitive magnetic probes

- ✓ Protected against e.m. noise
- ✗ Hard to manipulate by e.m. fields

- ✓ Long coherence times
- ✗ Difficult spin-spin coupling

Single spin states – detection

Fact: weak magnetic moment of the electron
(μ_B is "small")

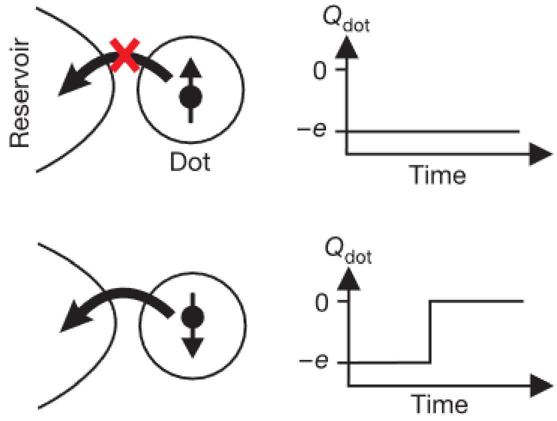
A single electron (i.e., ~1μ_B)
generates a B-field of 1μT at
a distance of 10 nm

- ✓ Natural quantum two-level system of carriers
- ✗ Need of high-sensitive magnetic probes

- ✓ Protected against e.m. noise
- ✗ Hard to manipulate by e.m. fields

- ✓ Long coherence times
- ✗ Difficult spin-spin coupling

Charge sensing to perform spin readout

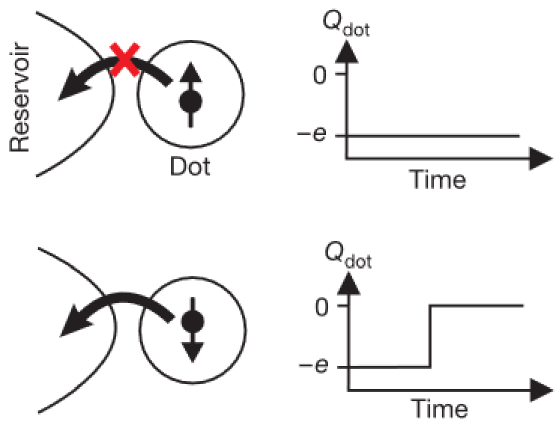


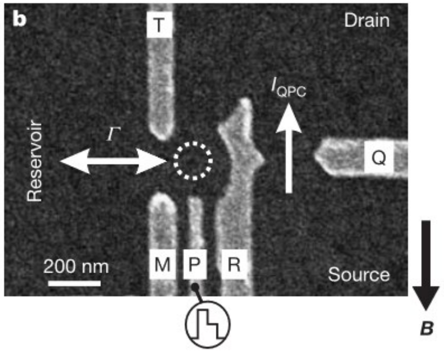

Single-shot read-out of an individual electron spin in a quantum dot

J. M. Elzerman, R. Hanson, L. H. Willems van Beveren, B. Witkamp, L. M. K. Vandersypen & L. P. Kouwenhoven

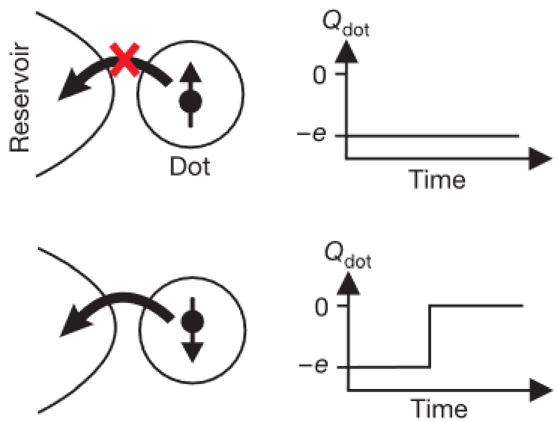
Kavli Institute of Nanoscience Delft and ERATO Mesoscopic Correlation Project, Delft University of Technology, PO Box 5046, 2600 GA Delft, The Netherlands

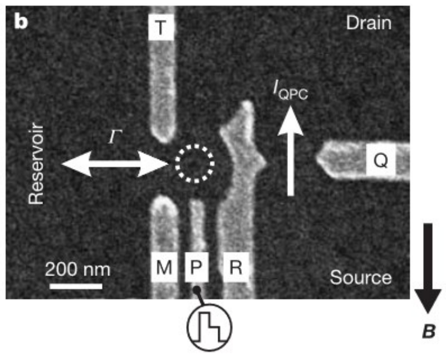
Charge sensing to perform spin readout

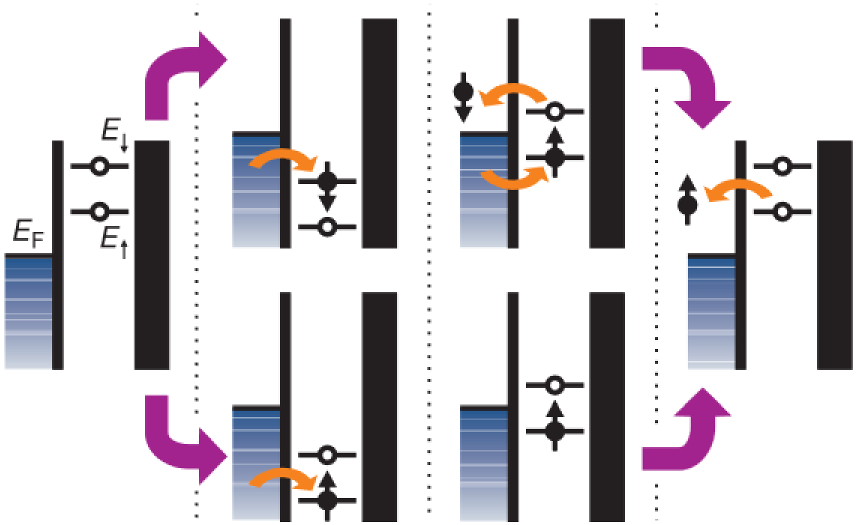




Charge sensing to perform spin readout



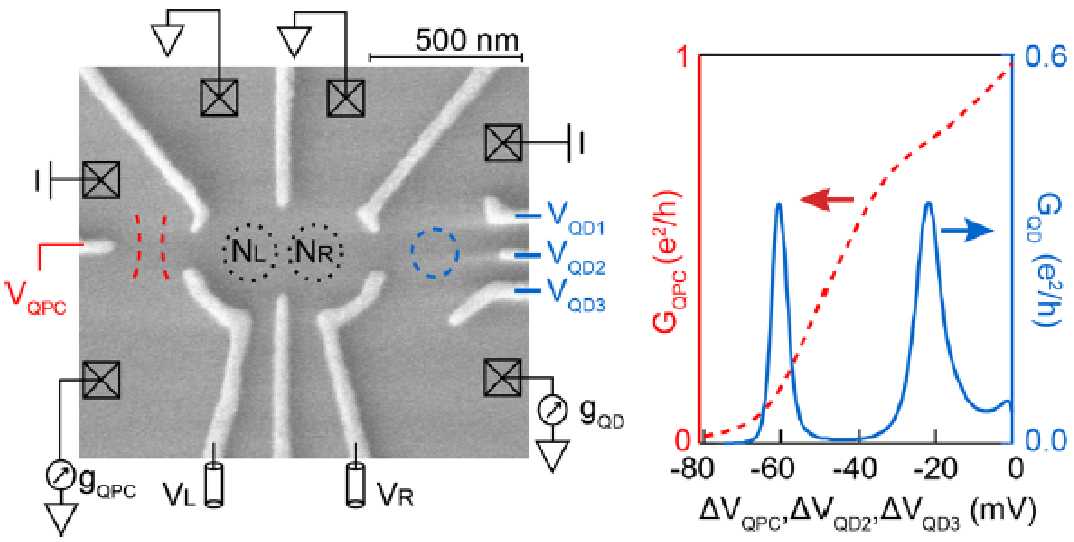




Spin-to-charge conversion

QPC vs SET

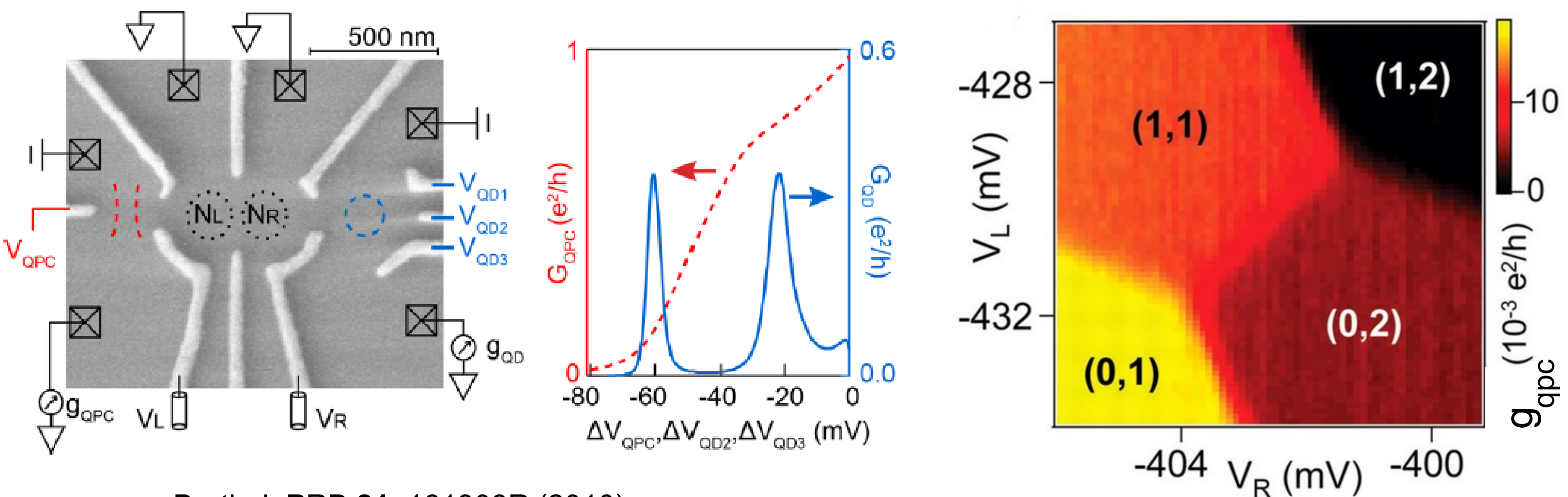
- QPC (quantum point contact): quantized conductance ($2e^2/h$)
- SET (single electron transistor): conductance dictated by Coulomb blockade



Barthel, PRB 81, 161308R (2010)

QPC vs SET

- QPC (quantum point contact): quantized conductance ($2e^2/h$)
- SET (single electron transistor): conductance dictated by Coulomb blockade

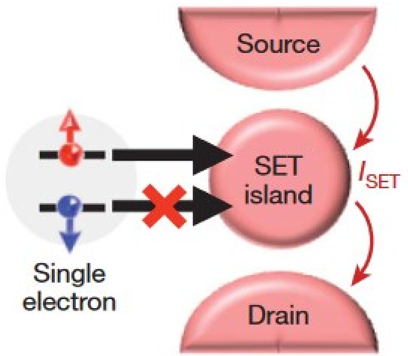


Barthel, PRB **81**, 161308R (2010)

Single shot spin readout

"Single-shot": each experimental trial (i.e. qubit gate) is followed by a measurement of the outcome

- No averages
- Fidelity estimation
- Scalable

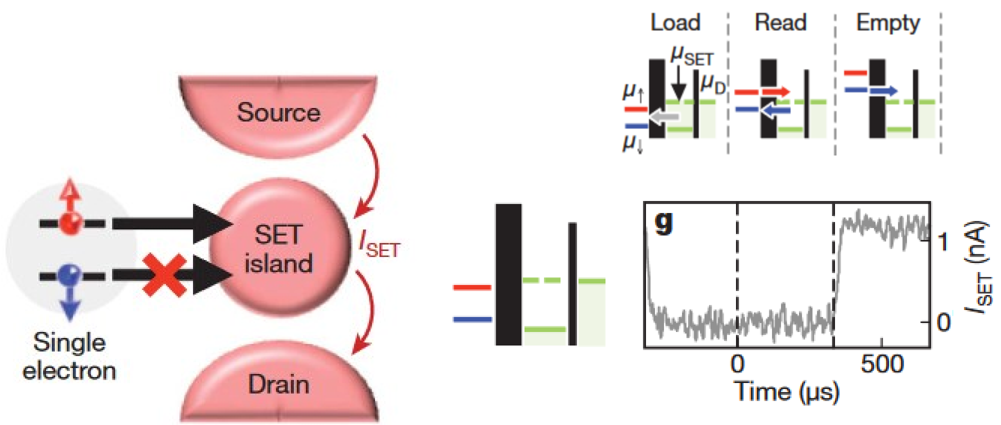


Morello, Nature **467**, 687–691 (2010)

Single shot spin readout

"Single-shot": each experimental trial (i.e. qubit gate) is followed by a measurement of the outcome

- No averages
- Fidelity estimation
- Scalable

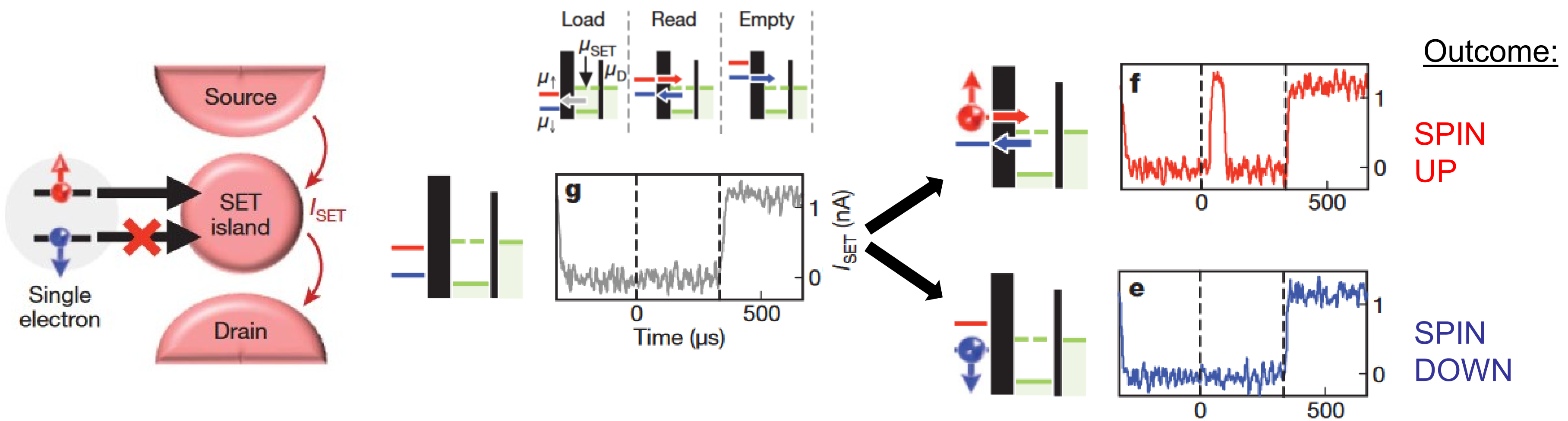


Morello, Nature **467**, 687–691 (2010)

Single shot spin readout

“Single-shot”: each experimental trial (i.e. qubit gate) is followed by a measurement of the outcome

- No averages
- Fidelity estimation
- Scalable

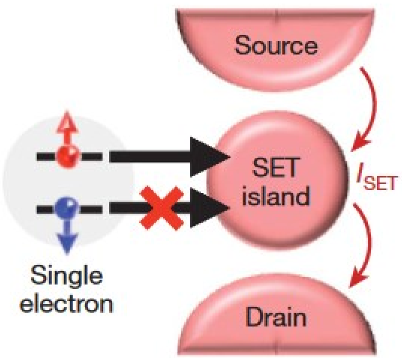


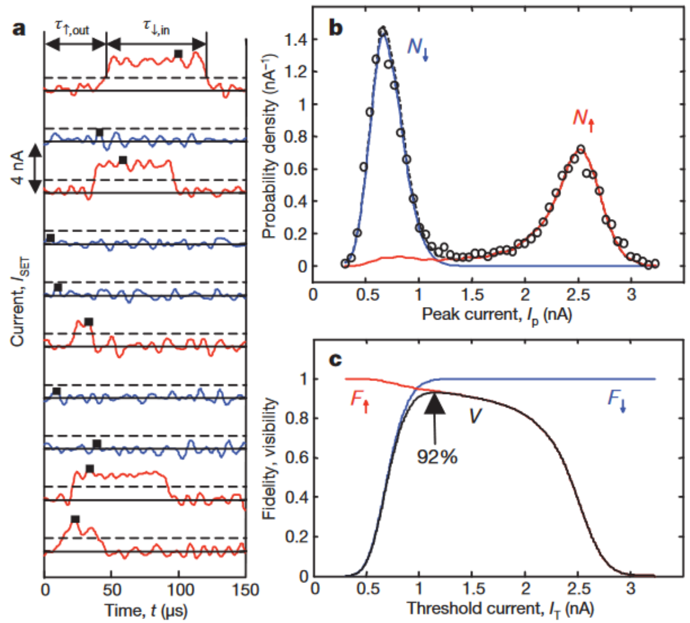
Morello, Nature **467**, 687–691 (2010)

Single shot spin readout

"Single-shot": each experimental trial (i.e. qubit gate) is followed by a measurement of the outcome

- No averages
- Fidelity estimation
- Scalable





$$F_\downarrow = 1 - \int_{I_T}^{\infty} N_\downarrow(I)\,\mathrm{d}I$$

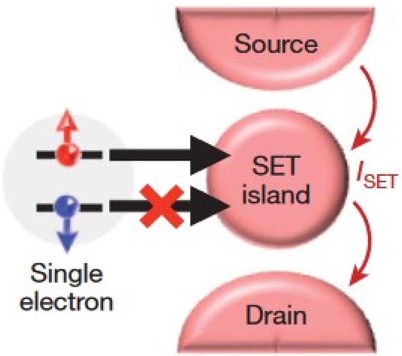
$$F_\uparrow = 1 - \int_{-\infty}^{I_T} N_\uparrow(I)\,\mathrm{d}I$$

Morello, Nature **467**, 687–691 (2010)

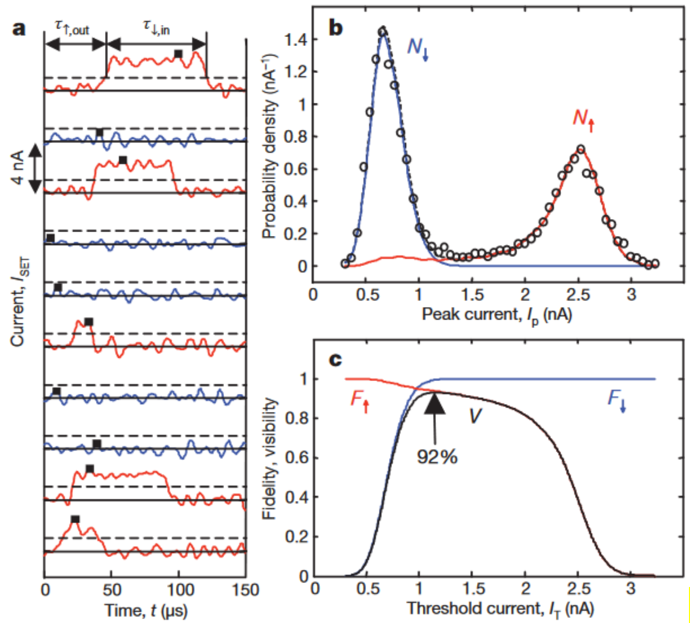
Single shot spin readout – fidelity

"Single-shot": each experimental trial (i.e. qubit gate) is followed by a measurement of the outcome

- No averages
- Fidelity estimation
- Scalable



Morello, Nature **467**, 687–691 (2010)



$$F_{\downarrow} = 1 - \int_{I_T}^{\infty} N_{\downarrow}(I)\mathrm{d}I$$

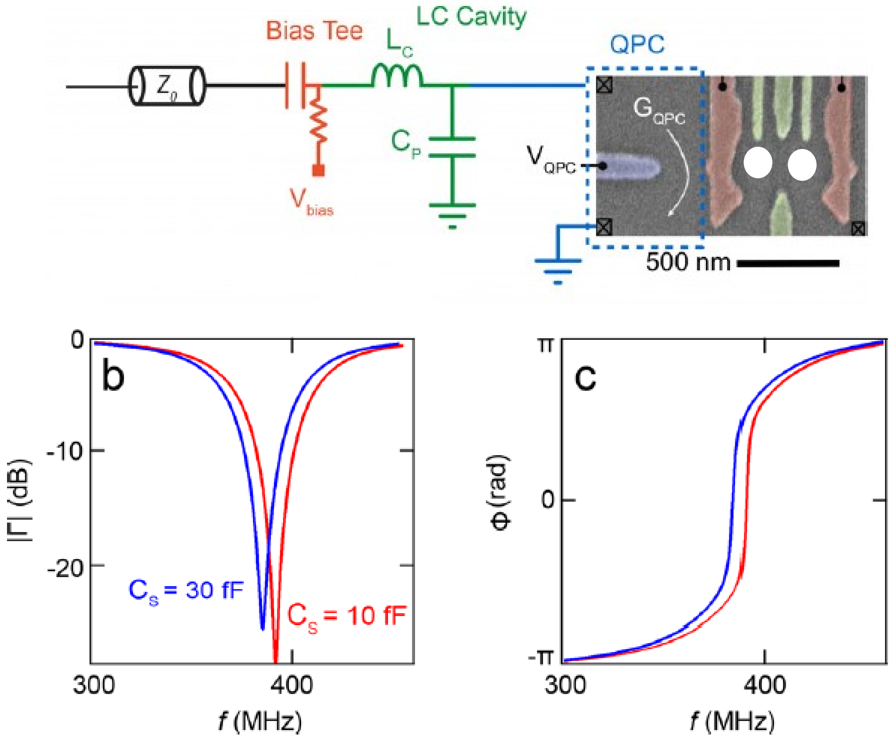
$$F_{\uparrow} = 1 - \int_{-\infty}^{I_T} N_{\uparrow}(I)\mathrm{d}I$$

Where are we now?

single-qubit control fidelities $> 99.95\%$.

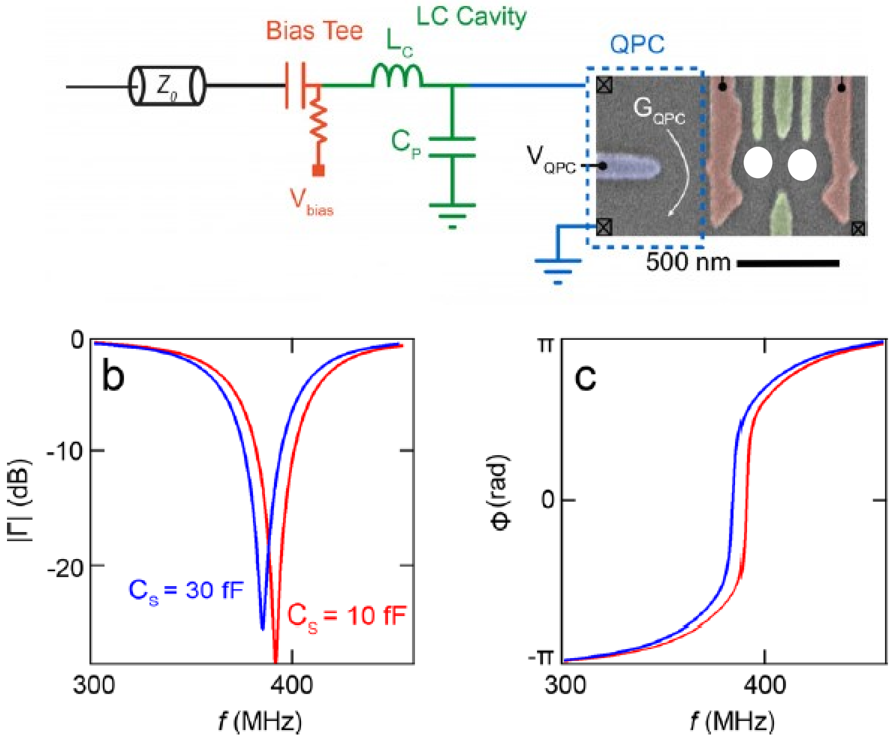
Radio-frequency charge sensing

Reilly, APL **91**, 162101 (2007)

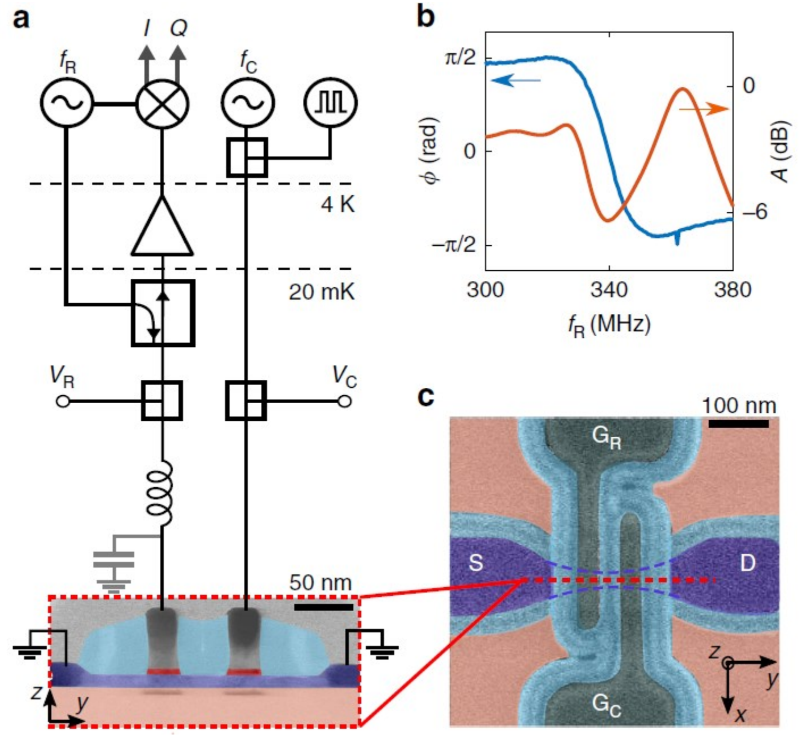


Radio-frequency charge sensing

Reilly, APL **91**, 162101 (2007)



Crippa, Nat. Com. **10**, 2776 (2019)



Take-home messages – detection

- Sensitivity of spin resonance is poor, i.e. single spin state hardly readable
- Through spin-to-charge conversion, charge sensing can allow single spin readout
- Single-shot readout is a key element for qubits
- Radio-frequency charge sensing increases speed readout and sensitivity

Other kinds of qubit measurements include:

- Quantum non-demolition measurements
- Weak measurements
- Parity measurements
- ….

Single spin states – manipulation

<u>Fact:</u> weak magnetic moment of the electron (μ_B is "small") →

A single electron (i.e., ~1μ_B) generates a B-field of 1μT at a distance of 10 nm

- ✓ Natural quantum two-level system of carriers
- ✗ Need of high-sensitive magnetic probes

- ✓ Protected against e.m. noise
- ✗ Hard to manipulate by e.m. fields

- ✓ Long coherence times
- ✗ Difficult spin-spin coupling

Electron spin resonance (ESR or EPR)

$$\vec{B}_0 = \vec{b}_0 B_0$$
$$\vec{B}_1(t) = \vec{b}_1 B_1 \cos \omega t$$

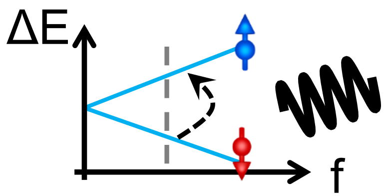
$$hf_R = \frac{1}{2} \frac{\mu_B B_1 \left| g \cdot \vec{b}_1 \times g \cdot \vec{b}_0 \right|}{\left| g \cdot \vec{b}_0 \right|}$$

$$\vec{B}_0 = \vec{z} B$$
$$\vec{B}_1(t) = \vec{x} B_1 \cos \omega t$$

$$hf_R = \frac{1}{2} g \mu_B B_1$$

$$H = \frac{1}{2} g \mu_B B \sigma_z + B \sigma_x = \begin{pmatrix} \frac{1}{2} g \mu_B B & B_1 \\ B_1 & -\frac{1}{2} g \mu_B B \end{pmatrix}$$

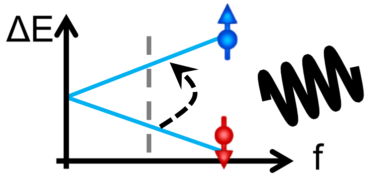
$$\Delta E = g \mu_B B$$



B sets the spin levels
B_1 promotes the transitions between levels

RWA and Bloch sphere

$\Delta E = g\mu_B B$

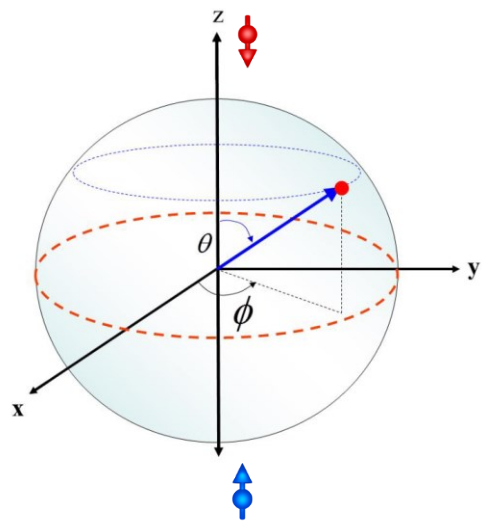


μ_B~ 57 μeV/T
g = 2
B = 0.5 T

ΔE ~ 57 μeV ~ 14 GHz

4 μeV ~ 1 GHz

Driving tone: $\cos(\omega t + \phi)e_x$

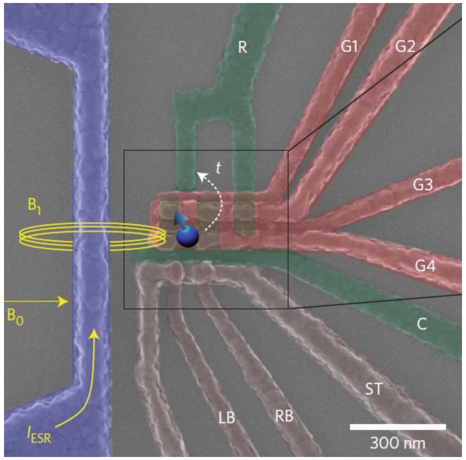


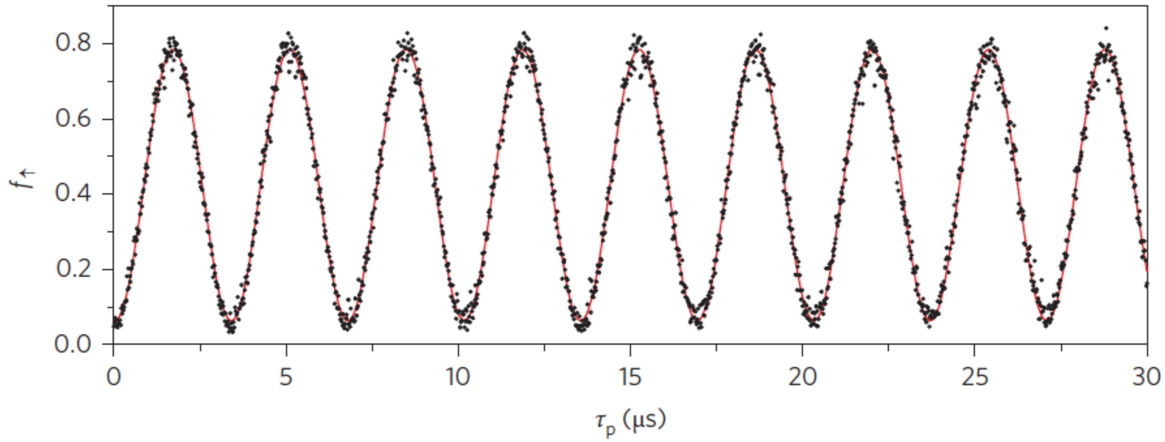
Rotating wave approx.:

$$H_{rot} = \frac{\omega_q - \omega}{2}\sigma_z + \frac{\Omega}{2}\underbrace{(\cos\phi\sigma_x + \sin\phi\sigma_y)}_{\text{Rotations in xy plane depend on } \phi}$$

Microwaves, with their amplitude, frequency and phase, provide an ideal tool to promote spin transitions!

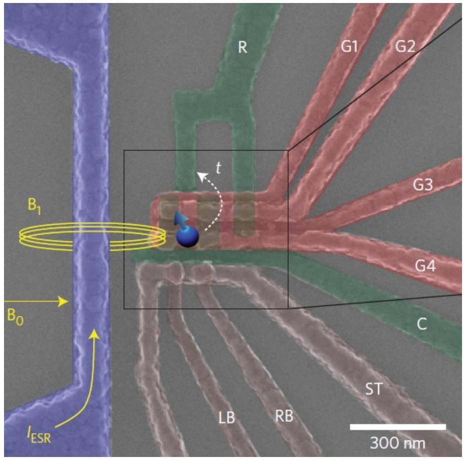
Rabi experiment

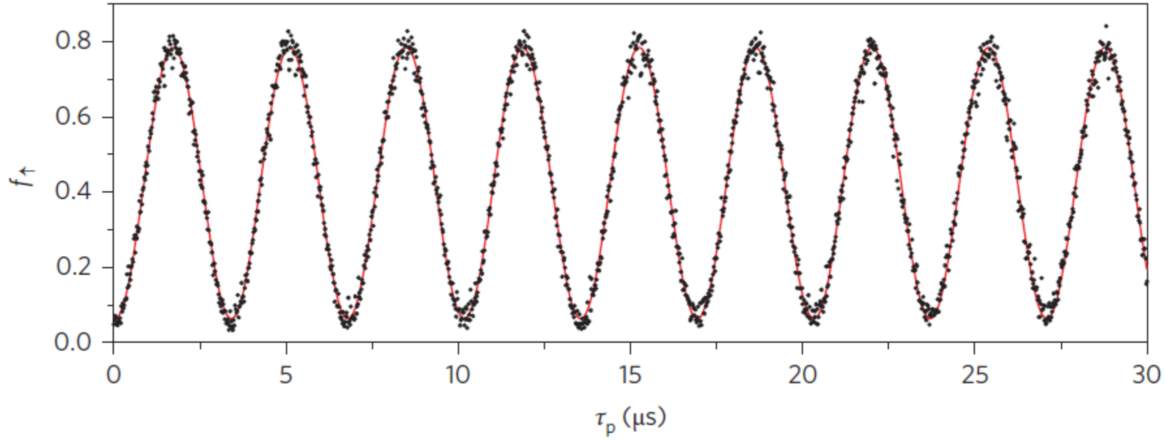




Veldhorst, Nat. Nano. **9**, 981 (2014)

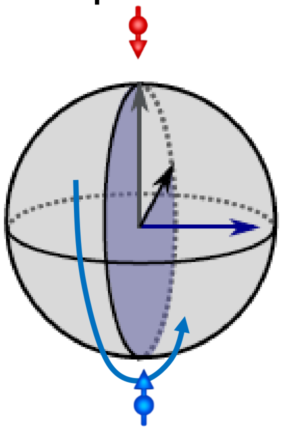
Rabi experiment

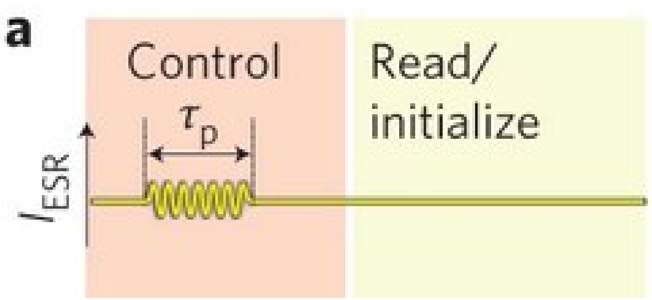




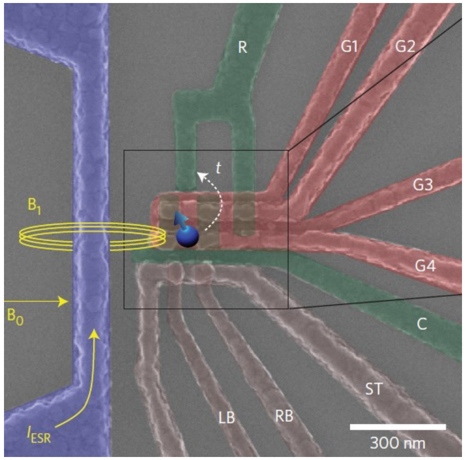
Veldhorst, Nat. Nano. **9**, 981 (2014)

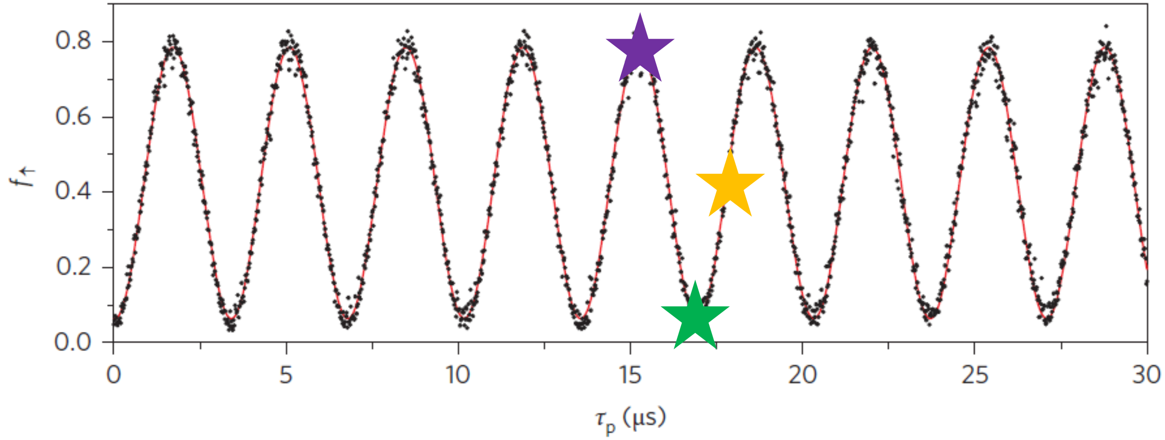
Manipulation:



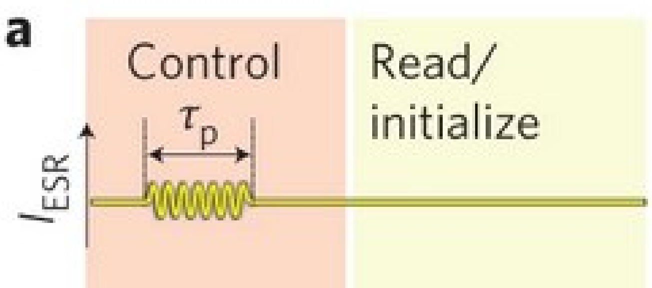


Rabi experiment

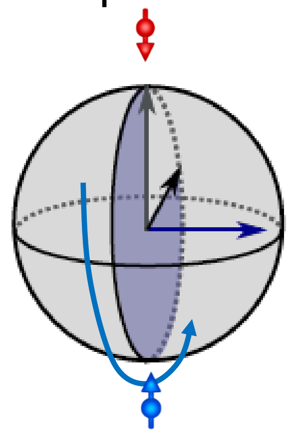




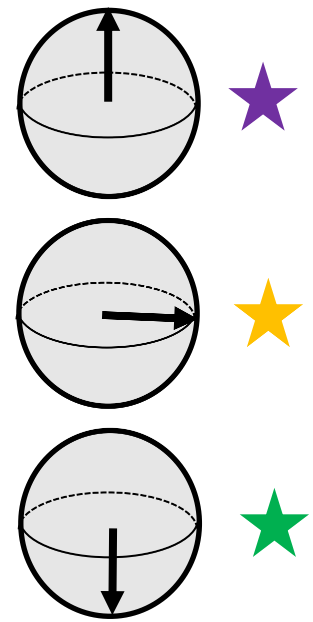
Veldhorst, Nat. Nano. **9**, 981 (2014)



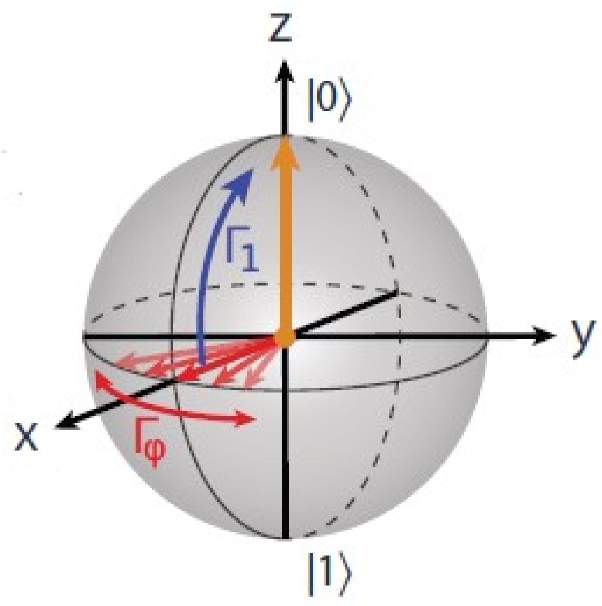
Manipulation:



Final state:



Decoherence, relaxation, dephasing



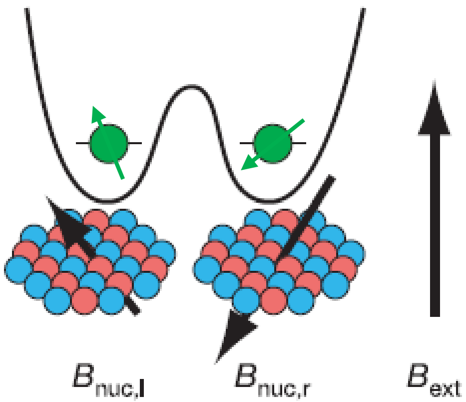
$$\boxed{\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}}$$

T_2 : decoherence
T_1 : relaxation
T_φ : dephasing

Each time is limited by a specific kind of interaction of the spin

Ex: spin nuclear noise

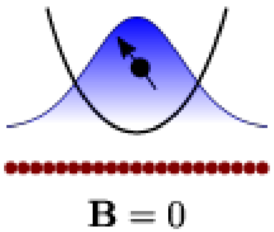
2000s



B_{nuc}= 1 – 5 mT

^{69}Ga, I=3/2, 60%
^{71}Ga, I=3/2, 40%
^{75}As, I=3/2, 100%

2010s



isotopically engineered silicon (800ppm ^{29}Si)

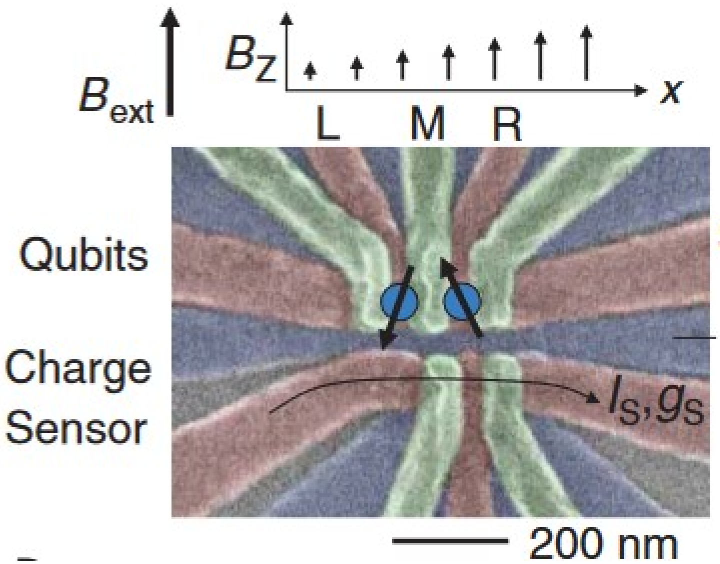
LETTERS
https://doi.org/10.1038/s41565-017-0014-x
nature nanotechnology

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

Electrical manipulation (EDSR)

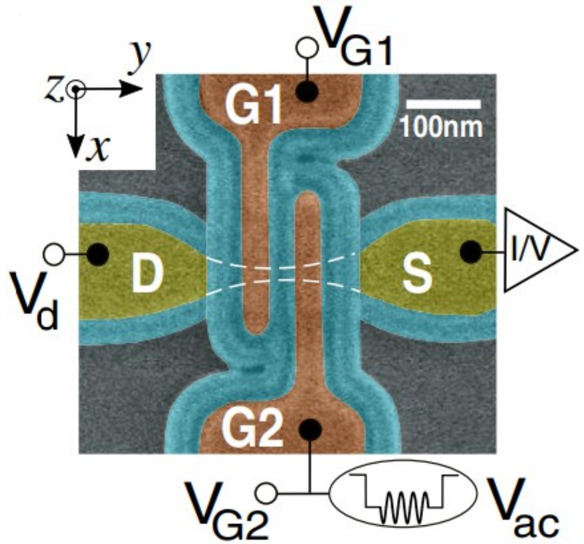
- Strong spin-orbit coupling → spin manipulation by electric fields
  EDSR: electric dipole spin resonance

Electrons



Zajac, Science **359**, 439–442 (2018

Holes

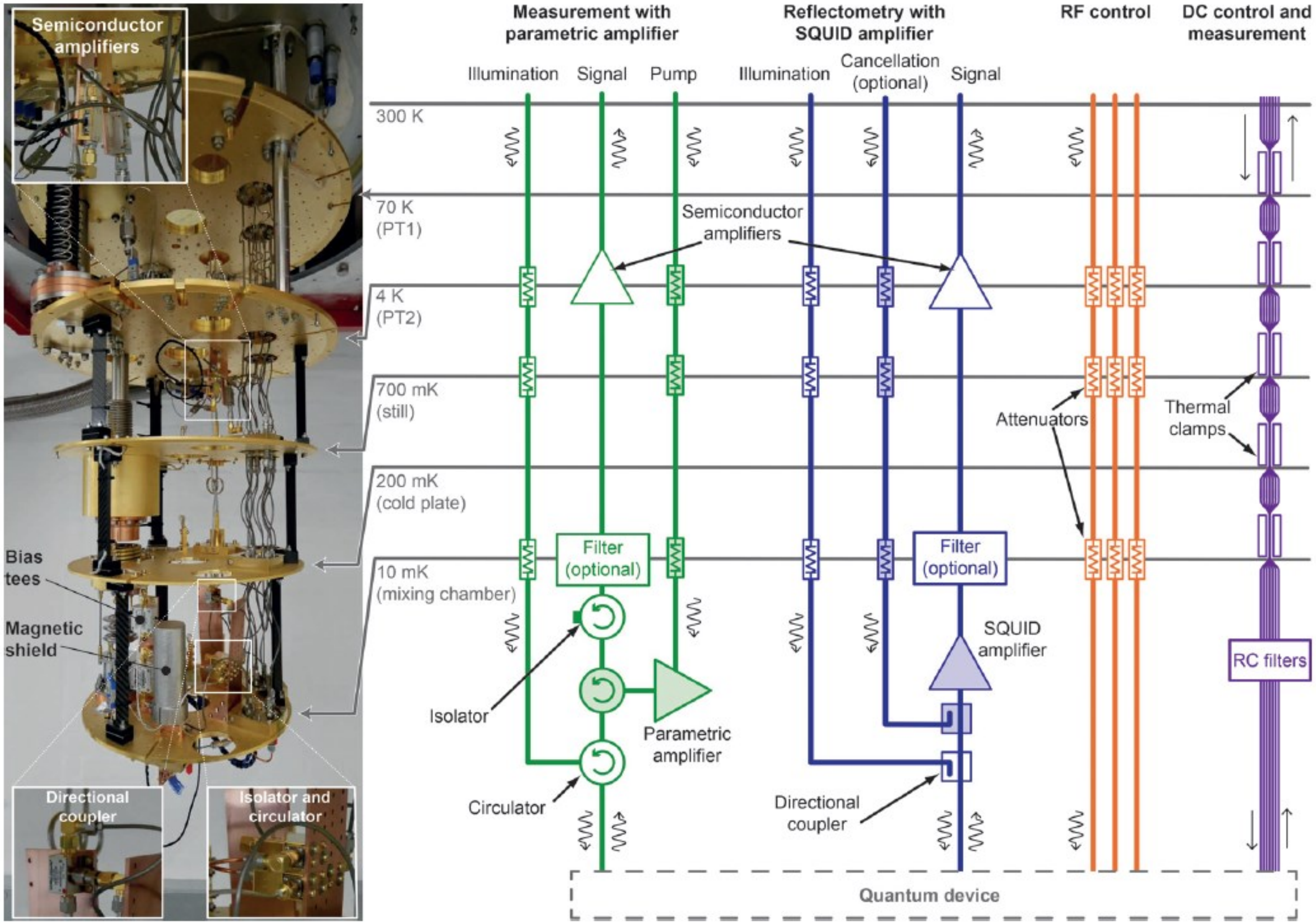


Crippa, Phys. Rev. Lett. **120**, 137702 (2018)

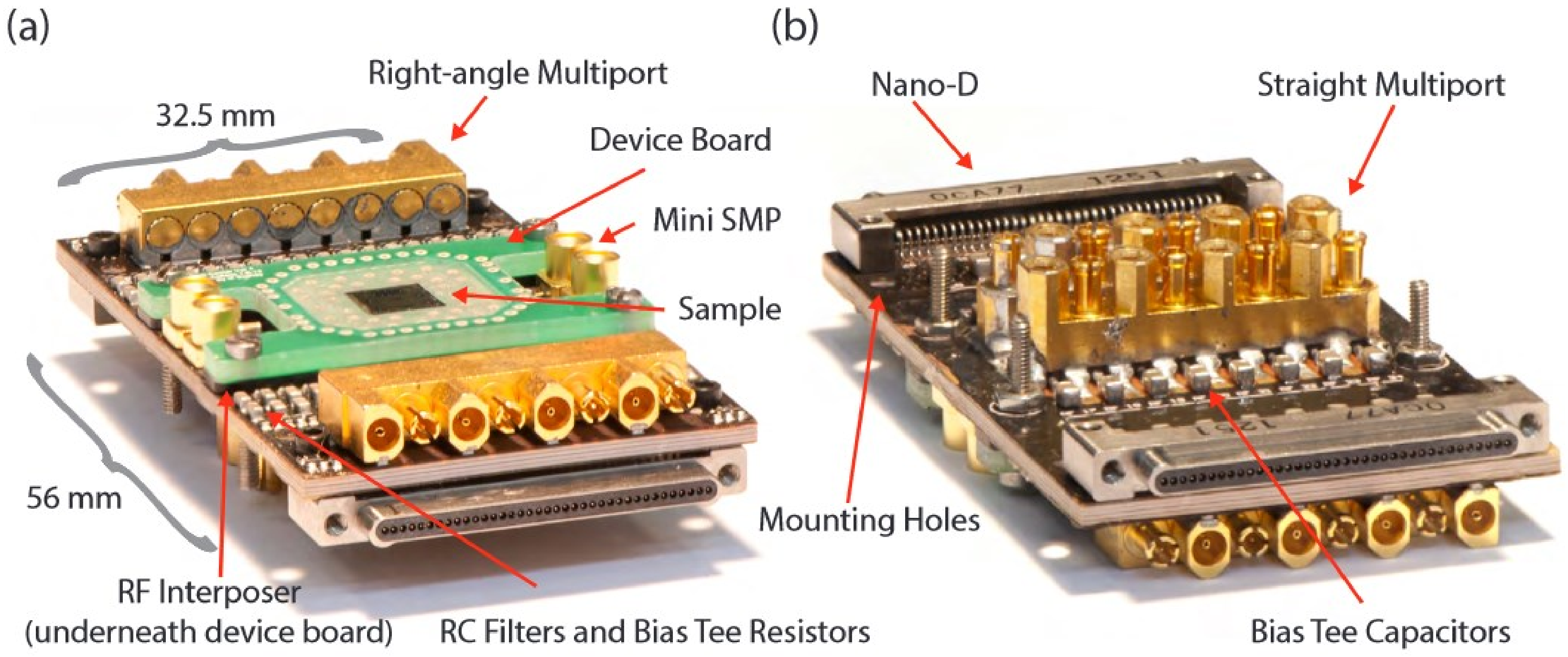
Take-home messages – manipulation

- Single spin manipulation requires a local oscillating B field
- Microwaves can manipulate the spin state over the surface of a Bloch sphere, realizing states of arbitrary superpositions of the eigenstates
- Decoherence, relaxation and dephasing are spurious, incoherent effects of the environment on the spin states
- There are specific tools and microwave sequences to mitigate the detrimental effects of the environment
- Spin manipulation can be performed electrically in presence of spin-orbit interaction: micromagnets (synthetic spin-orbit) or holes (intrinsic)

Hardware – detection

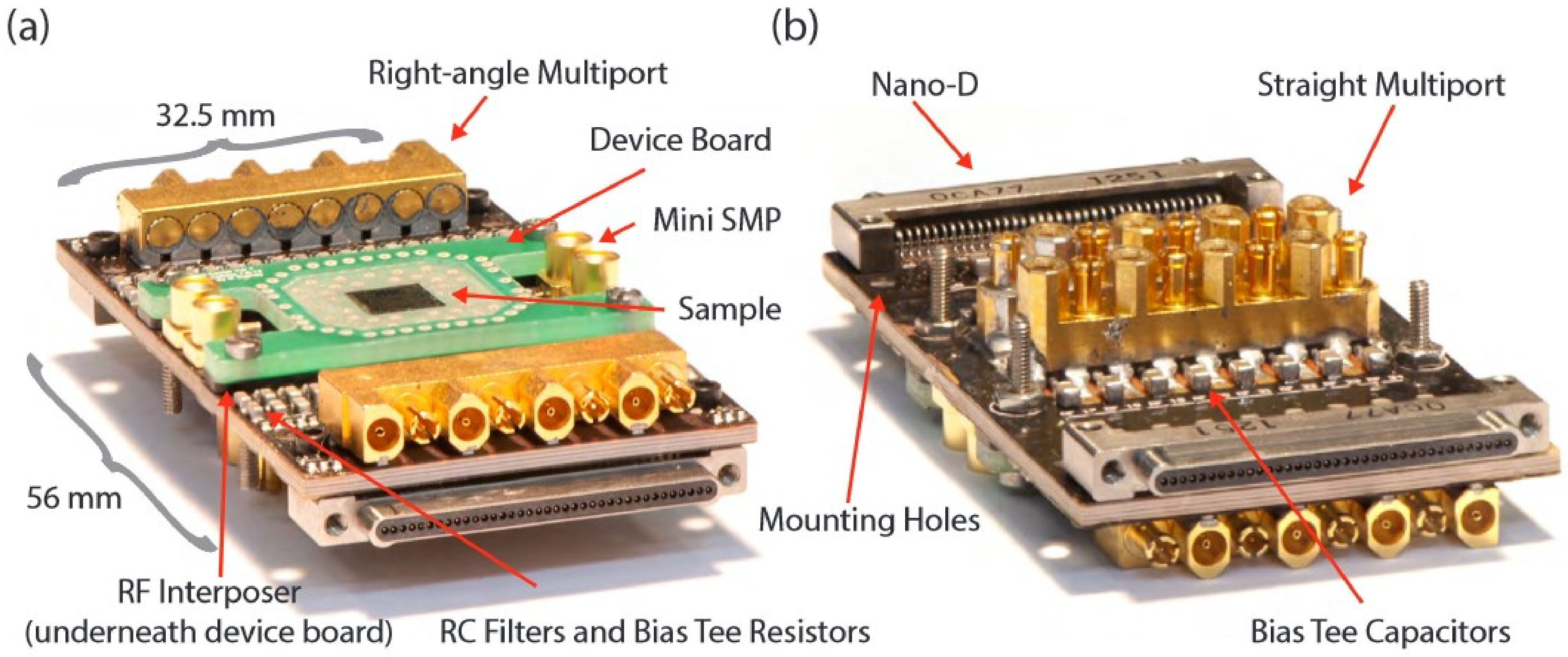


Hardware – manipulation



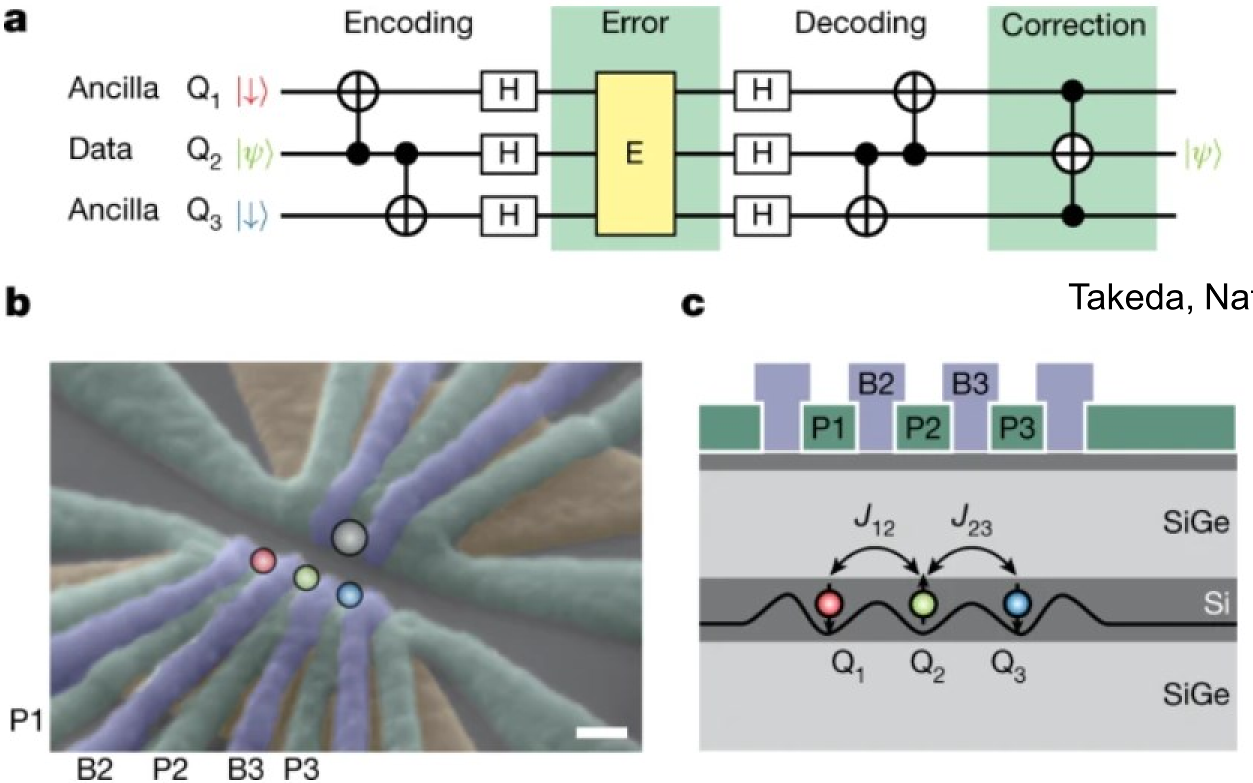
JI Colless, Rev. Sc. Instr. **85**, 114706 (2014)

Hardware – manipulation



JI Colless, Rev. Sc. Instr. **85**, 114706 (2014)

THANK YOU FOR THE ATTENTION



Takeda, Nature **608**, 682–686 (2022)

inverse of the encoding. Finally, the correction is performed by a three-qubit Toffoli gate