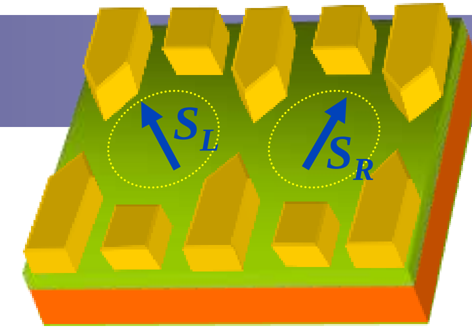
SPIN Qubits
in Quantum dots

Covering: basic concepts, measurement techniques,
implementations, qubit approaches, current trends

With figures and slides borrowed from
L. Vandersypen, J. Elzerman, R. Hanson, L. Kouwenhoven, M. Veldhorst (TU Delft)

Spin qubits in quantum dots



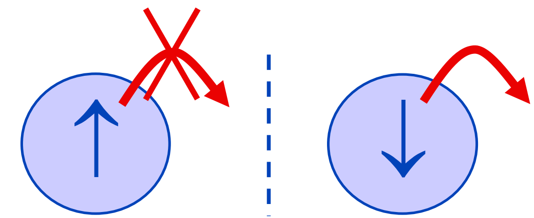
Loss & DiVincenzo, PRA 1998
Vandersypen et al., Proc. MQC02 (quant-ph/0207059)

Initialization 1-electron, low T, high B_0

$$H_0 \sim \Sigma\, \omega_i\ \sigma_{zi}$$

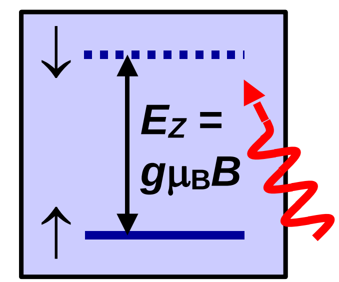
Read-out convert spin to charge

then measure charge



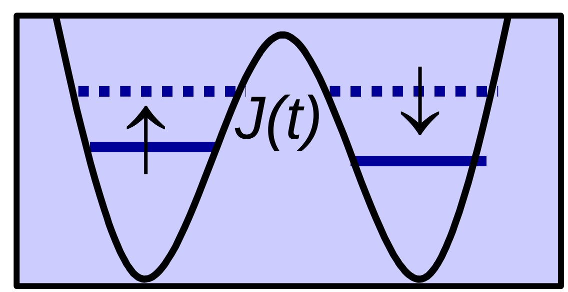
ESR pulsed microwave magnetic field

$$H_{RF} \sim \Sigma\, A_i(t) \cos(\omega_i\, t)\ \ \sigma_{xi}$$



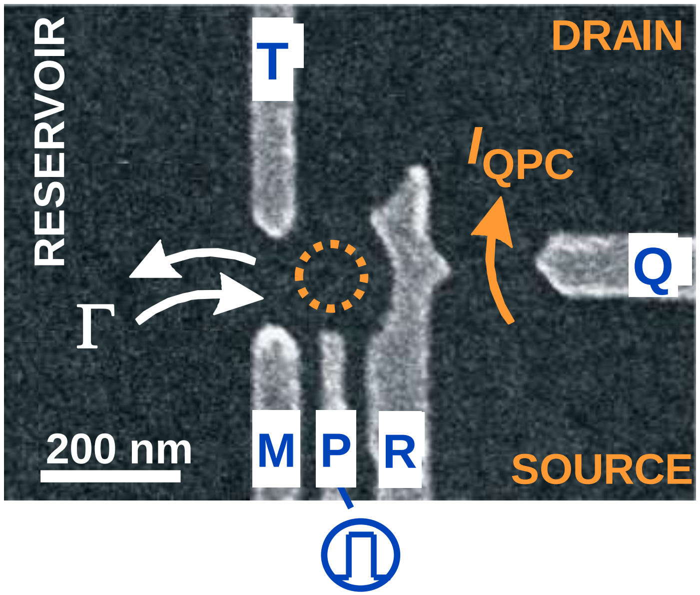
SWAP exchange interaction

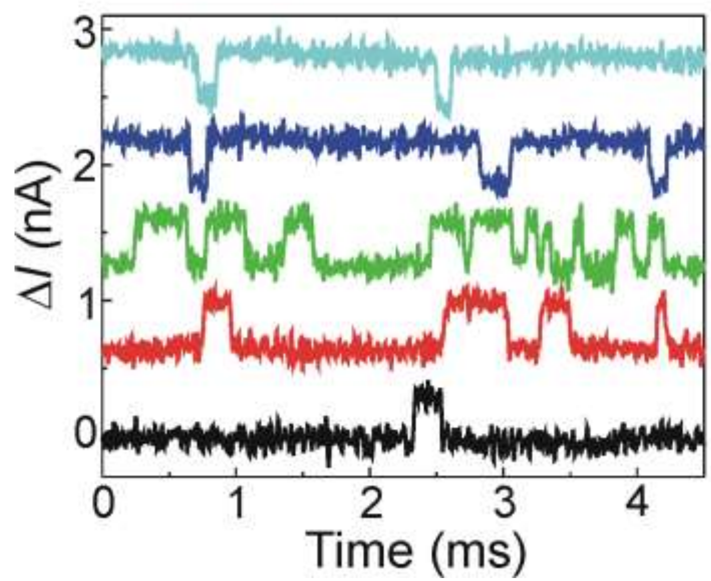
$$H_J \sim \Sigma\, J_{ij}\,(t)\ \ \sigma_i \cdot \sigma_j$$

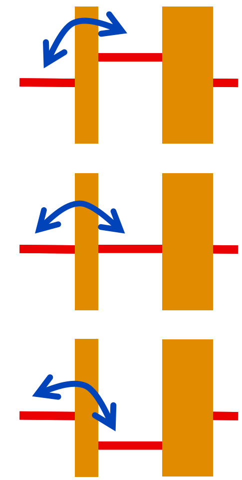


Coherence long relaxation time T_1
long coherence time T_2

Real-time single-electron detection

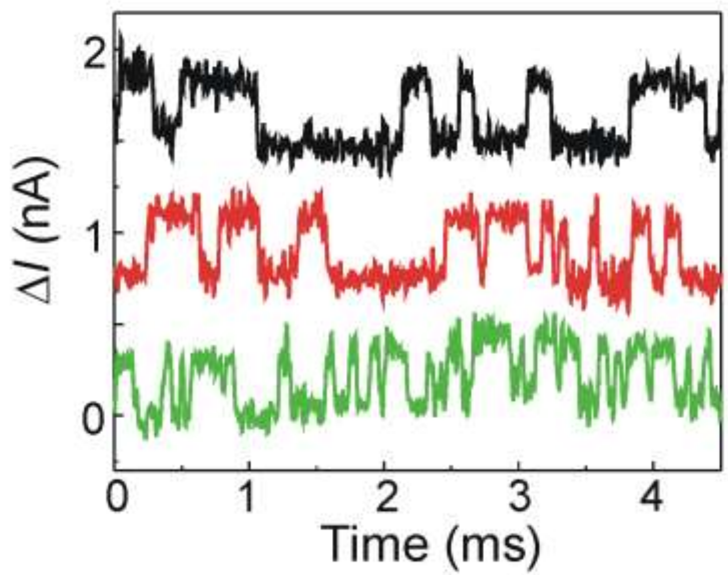


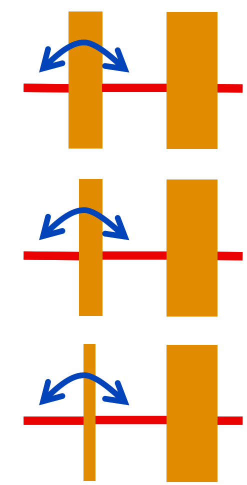




- V_{SD} = 1 mV
- I_{QPC} ~ 30 nA
- ΔI_{QPC} ~ 0.3 nA
- Shortest steps ~ 8 μs

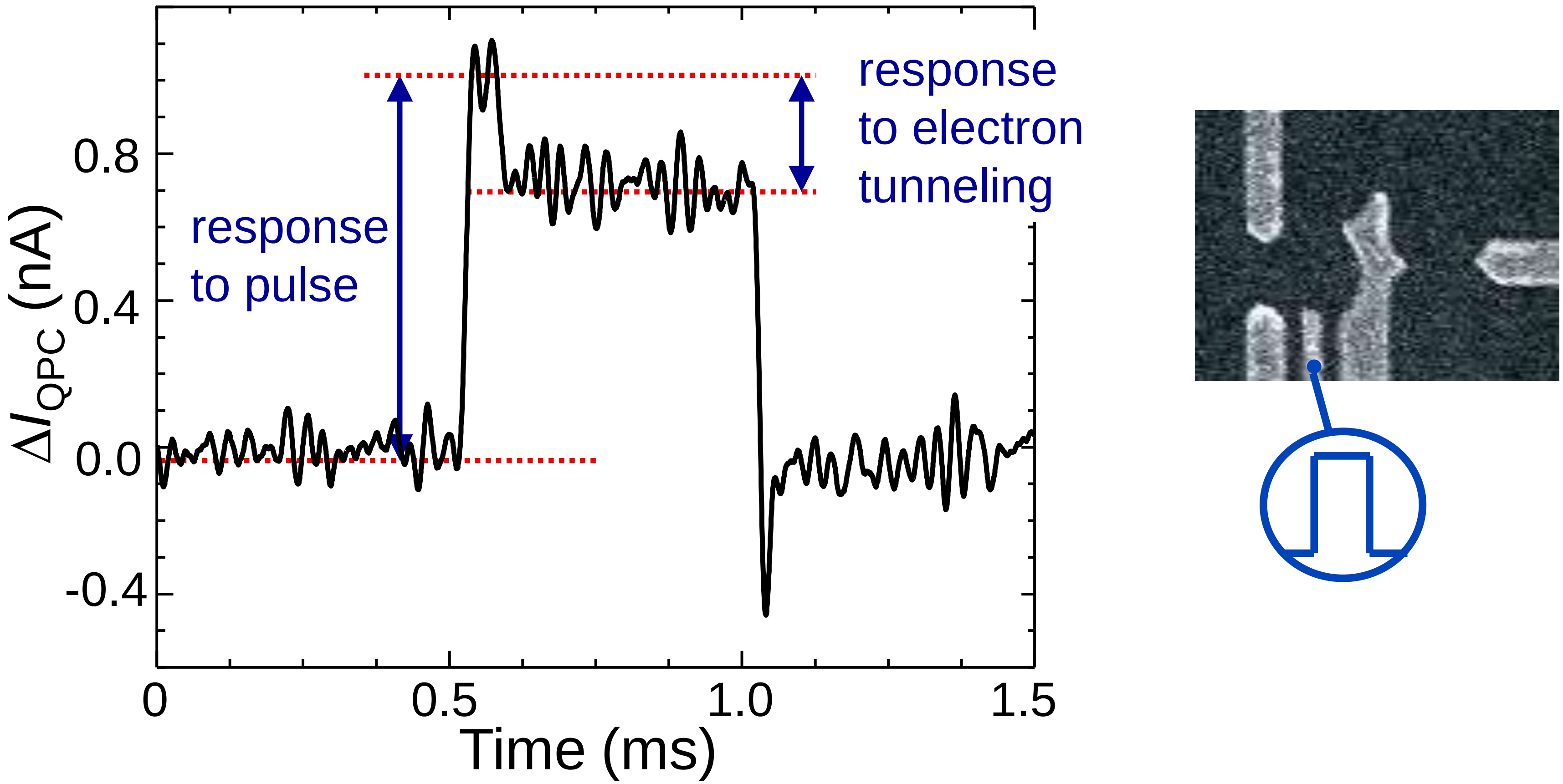
See single electrons jump on/off the dot in real-time

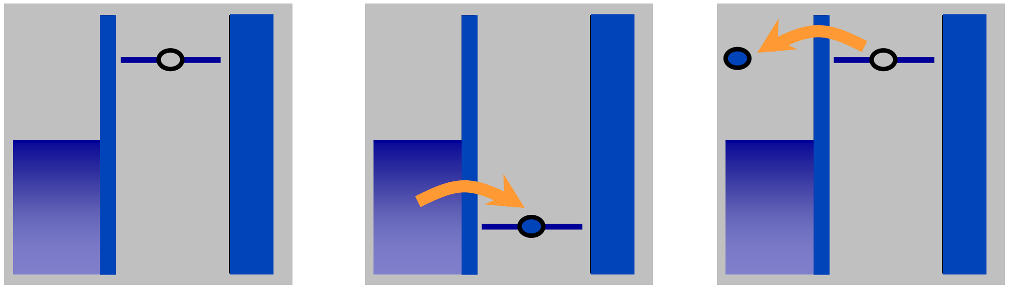




Vandersypen et al, APL 2004

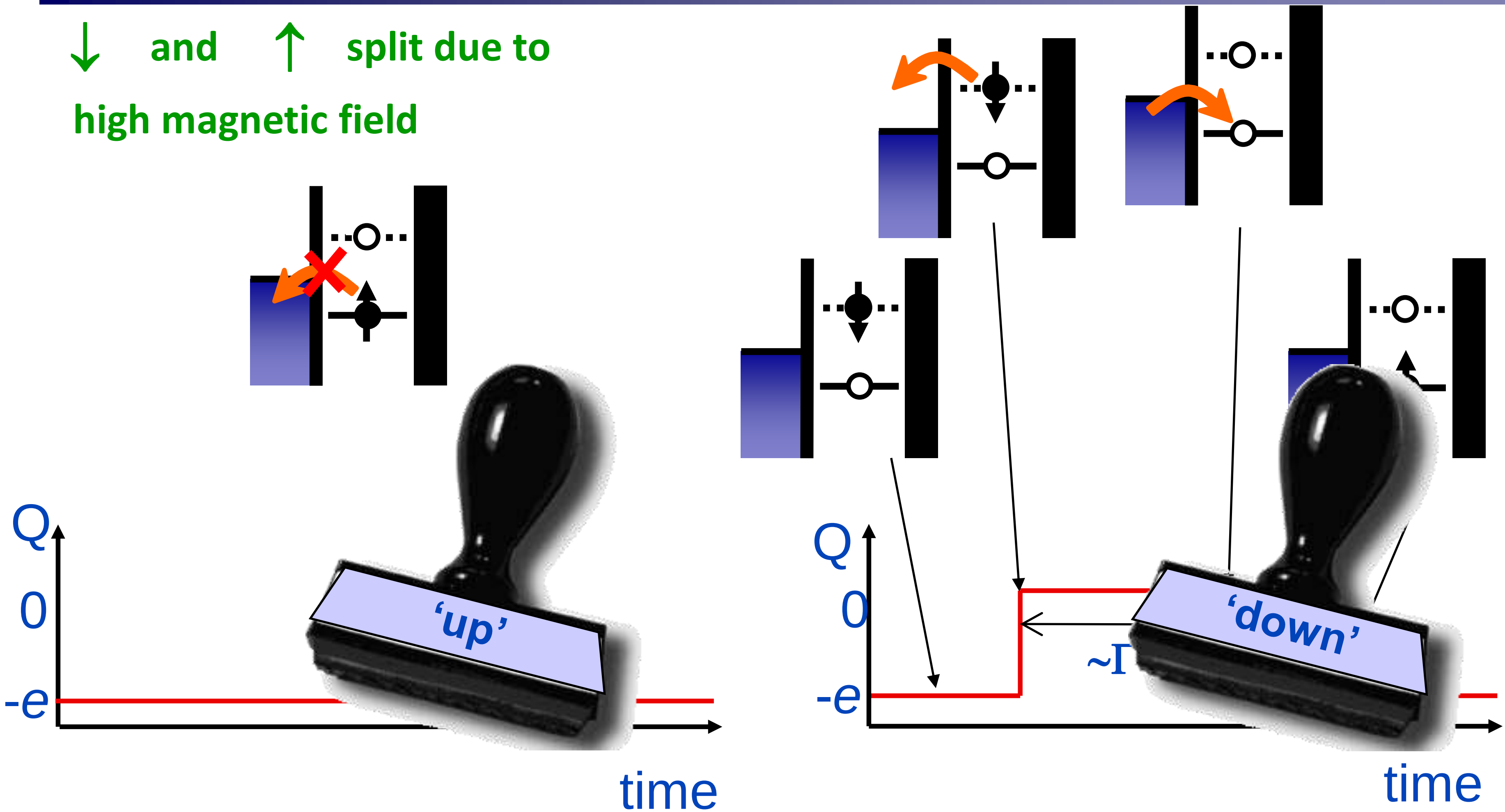
Pulse-induced tunneling





Energy-selective readout

↓ and ↑ split due to high magnetic field



Elzermann et al., *Nature* ('04)

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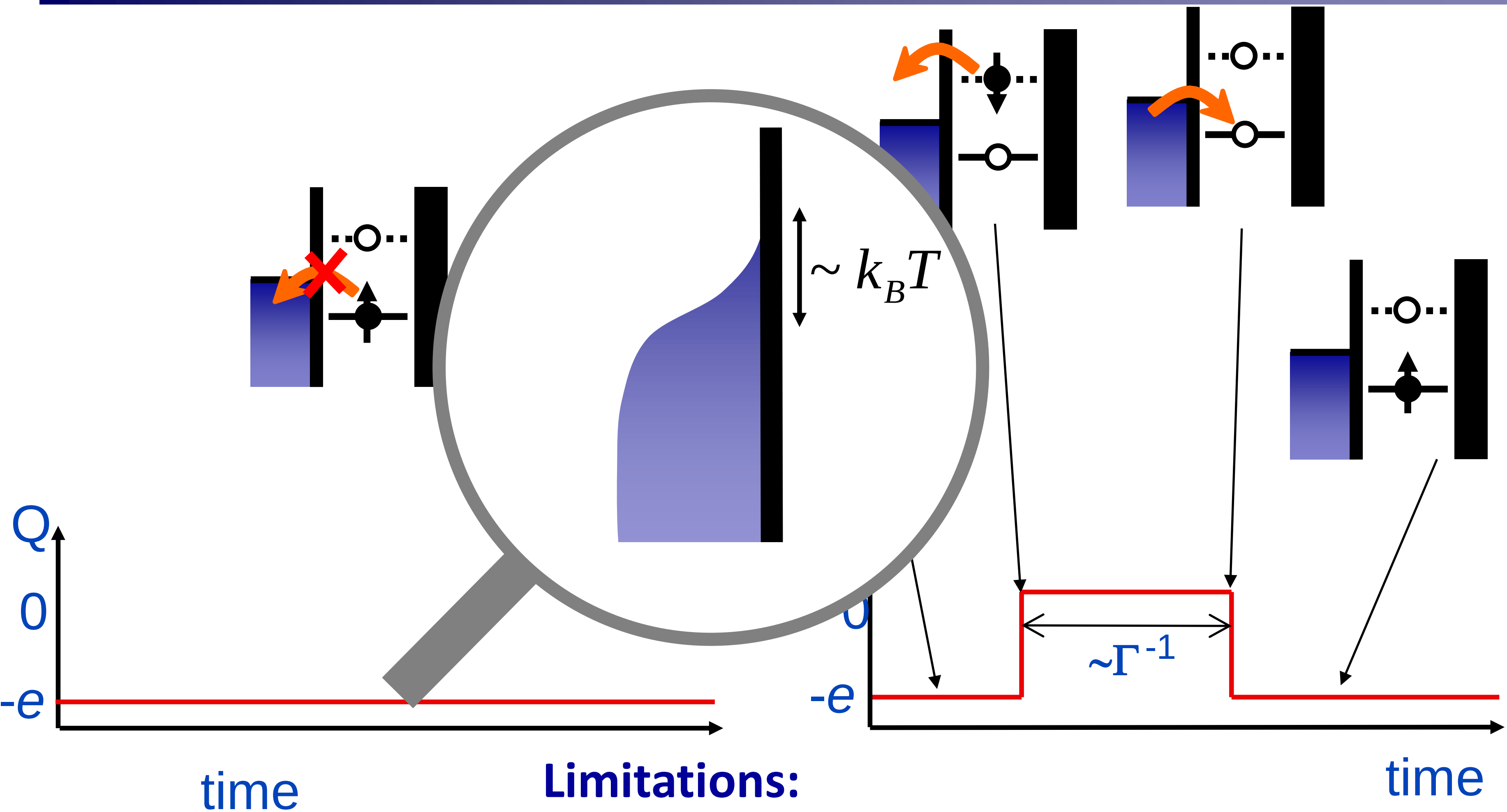


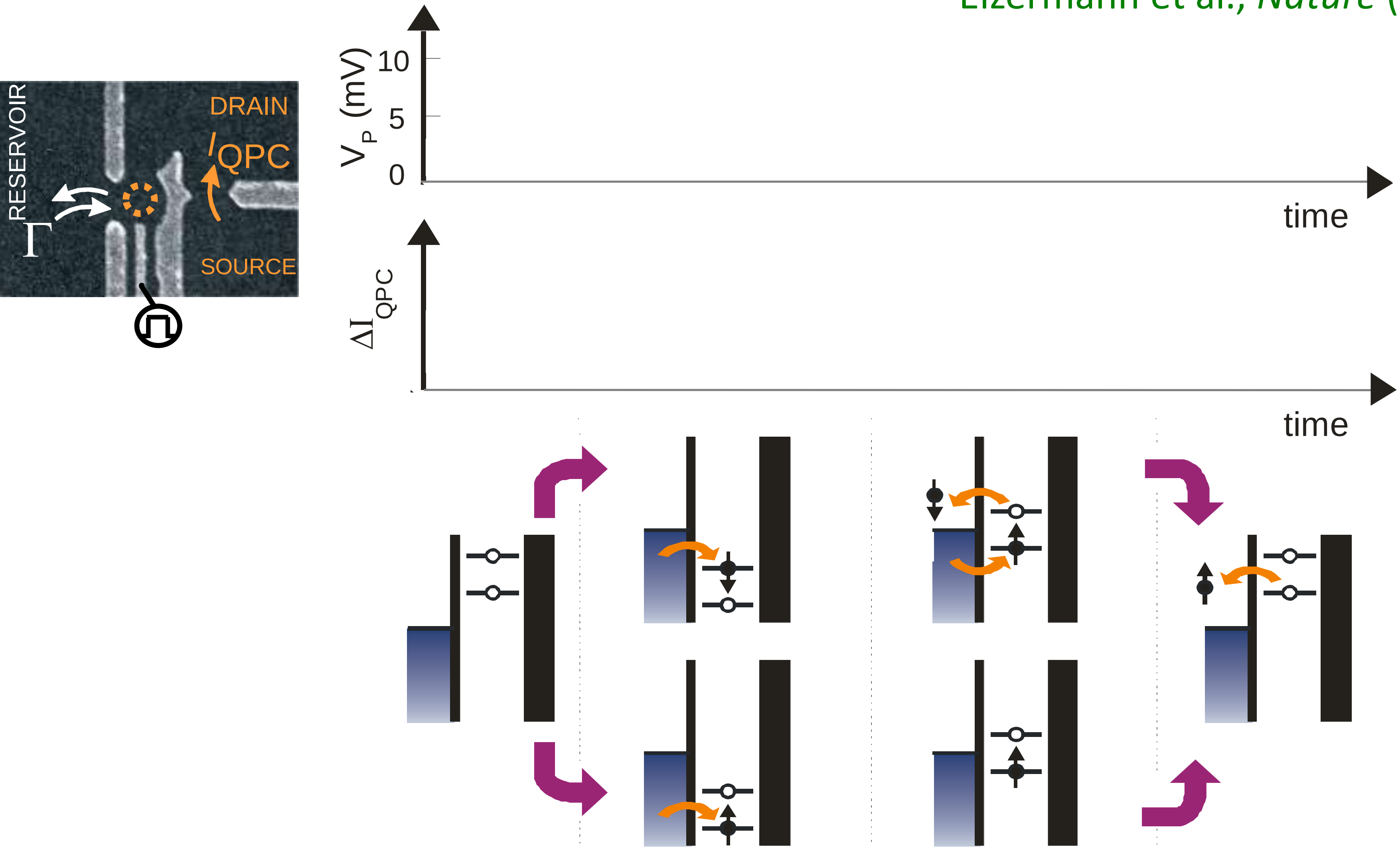
Elzermann et al., *Nature* (‘04)

Limitations:

- Requires $\Delta E_Z >> k_B T$
- Sensitive to background charge fluctuations (“switching”)
- Sensitive to HF noise (photon-assisted tunneling)

Readout pulse scheme

Elzermann et al., *Nature* ('04)



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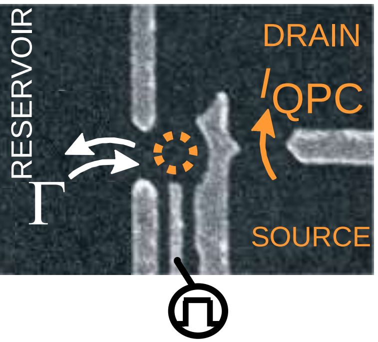
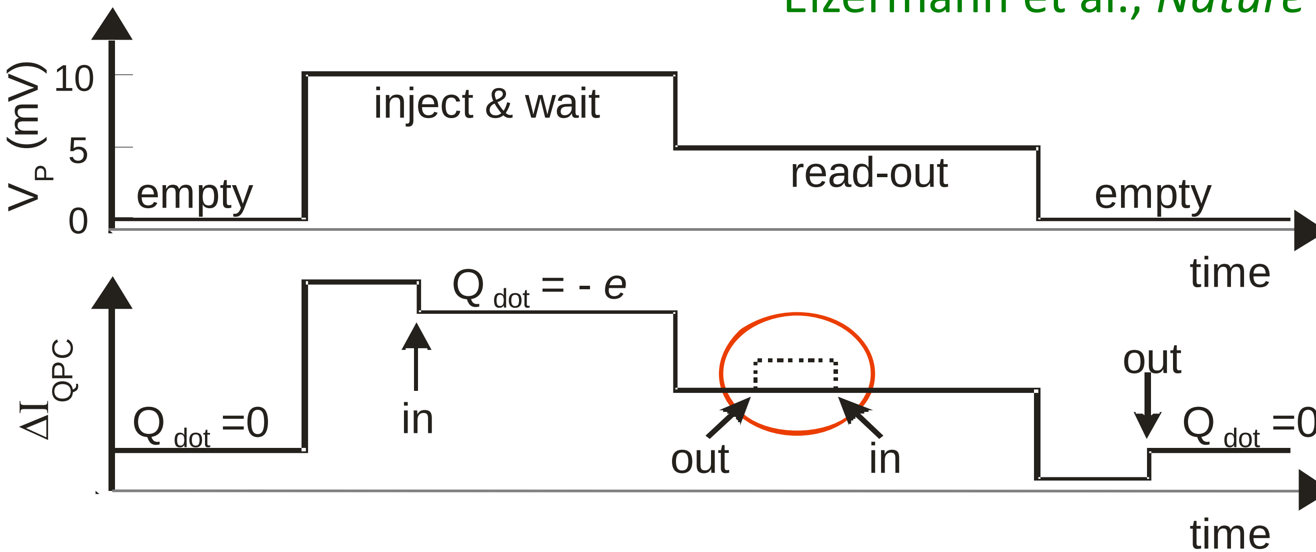
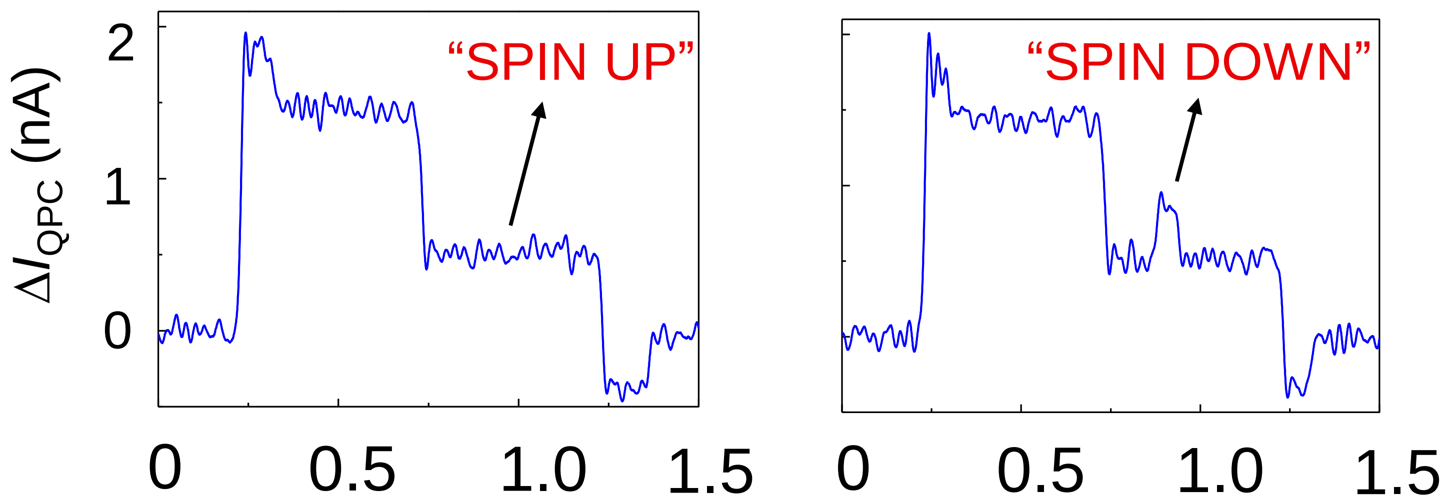


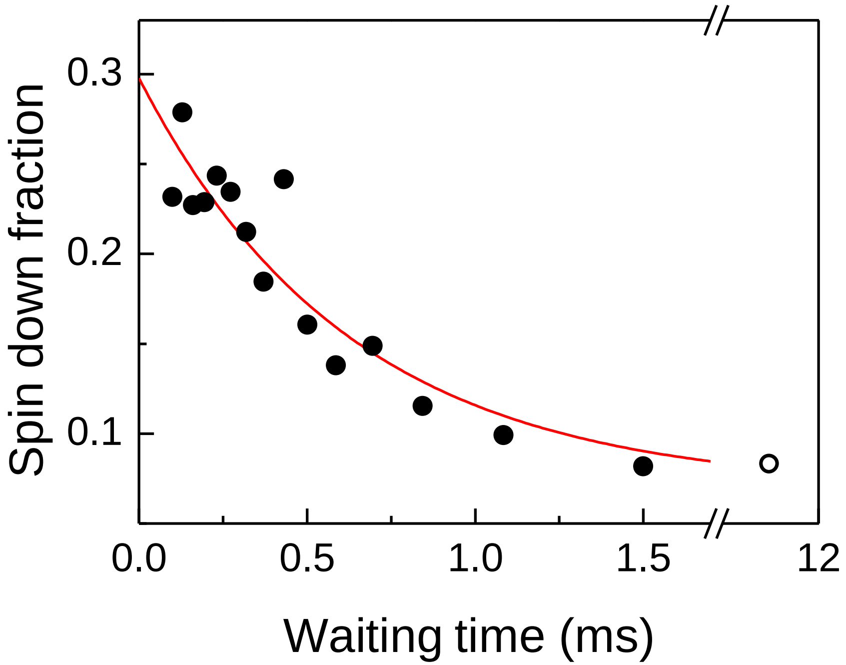


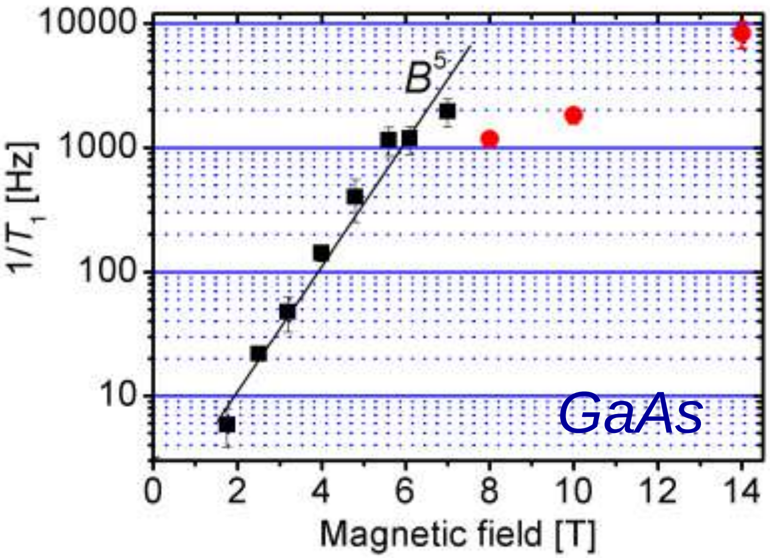


Spin relaxation in quantum dots

Energy dissipated in phonon bath

Electric field from phonons couples to spin via spin-orbit coupling

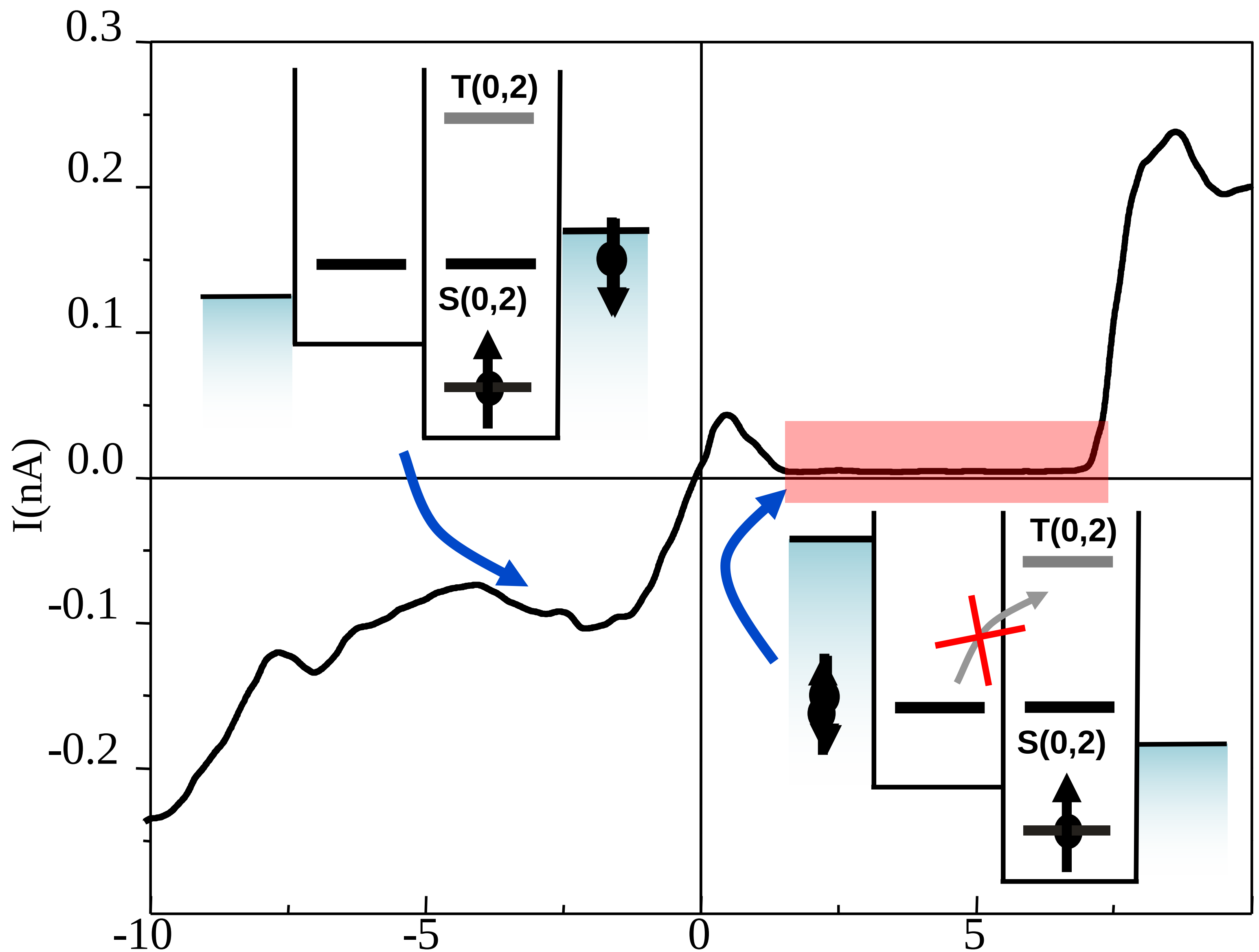




● *Elzerman et al., Nature 2004*
■ *Amasha et al., PRL 2008*

T_1's are over 1 sec at low B

Probe: spin blockade due to Pauli exclusion



Ono, Austing, Tokura, Tarucha, *Science* ('02)

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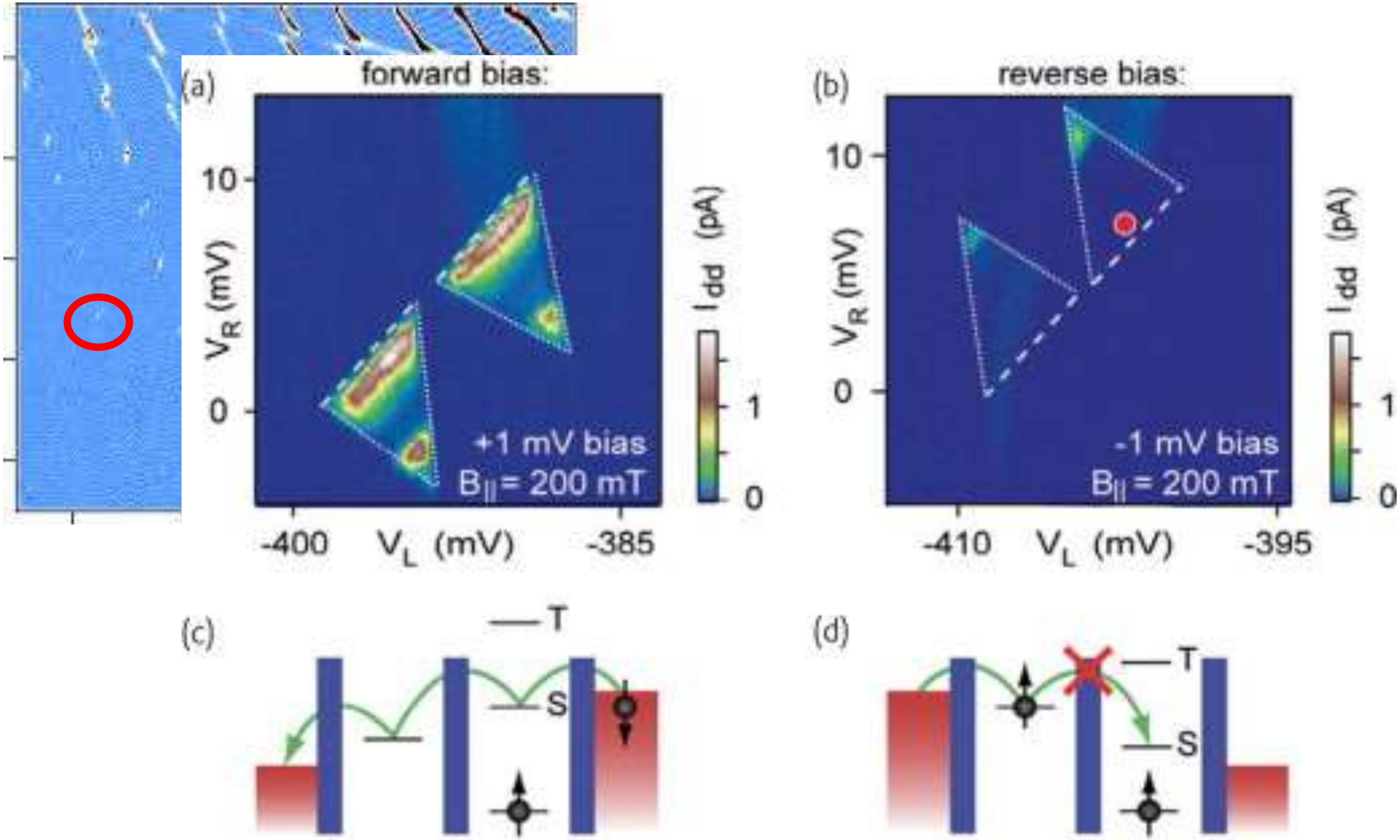

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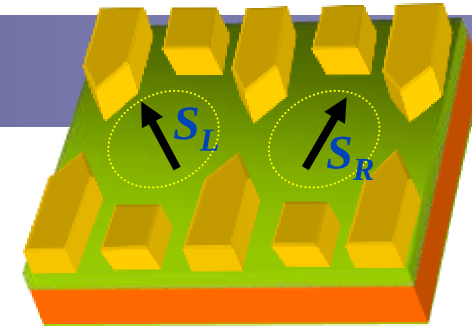

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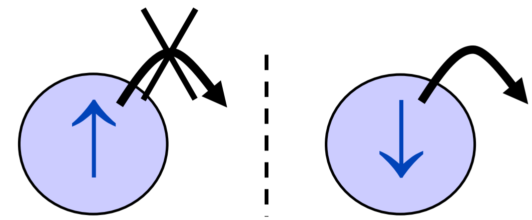

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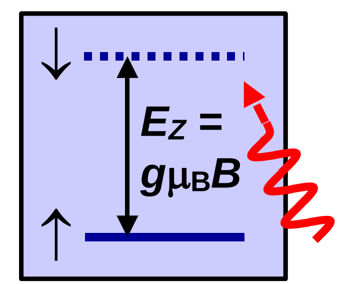

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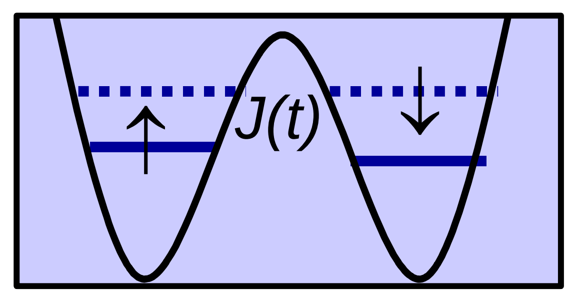

Coherence long relaxation time T_1
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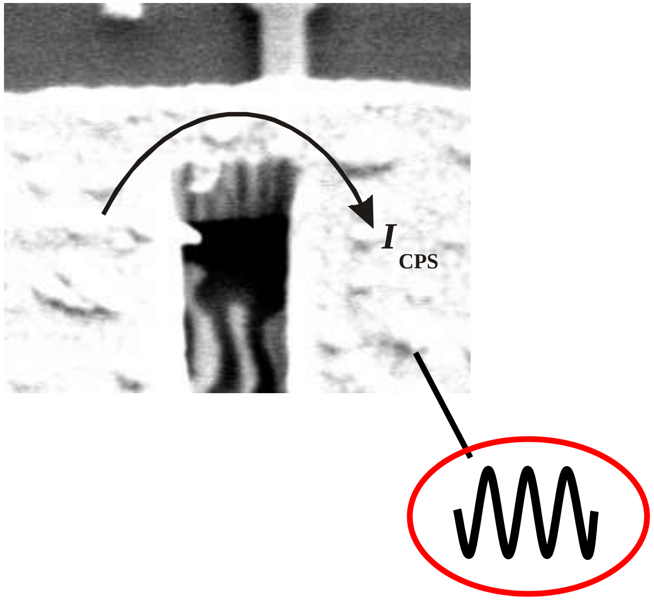
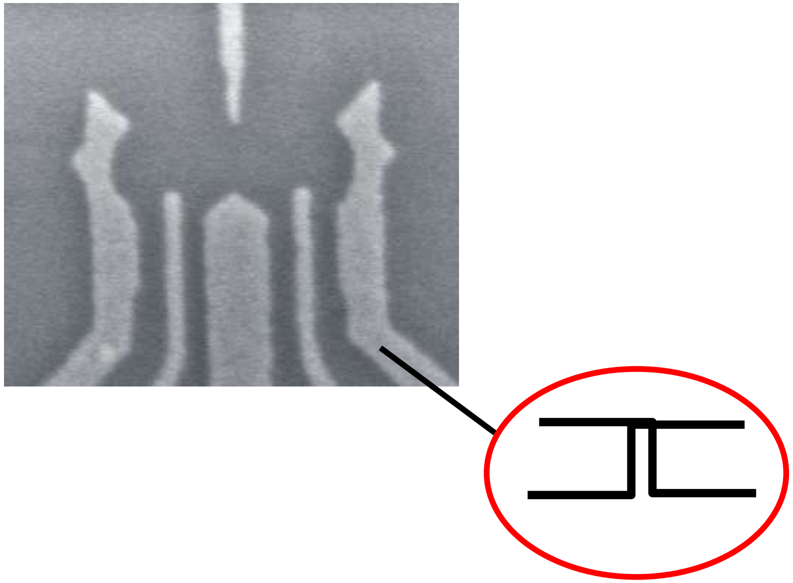
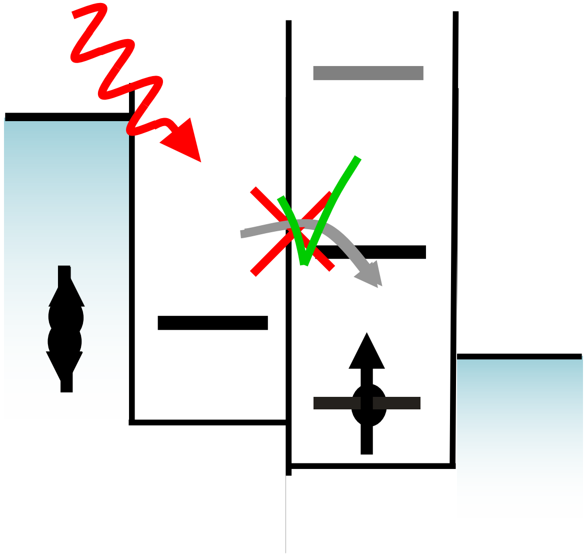
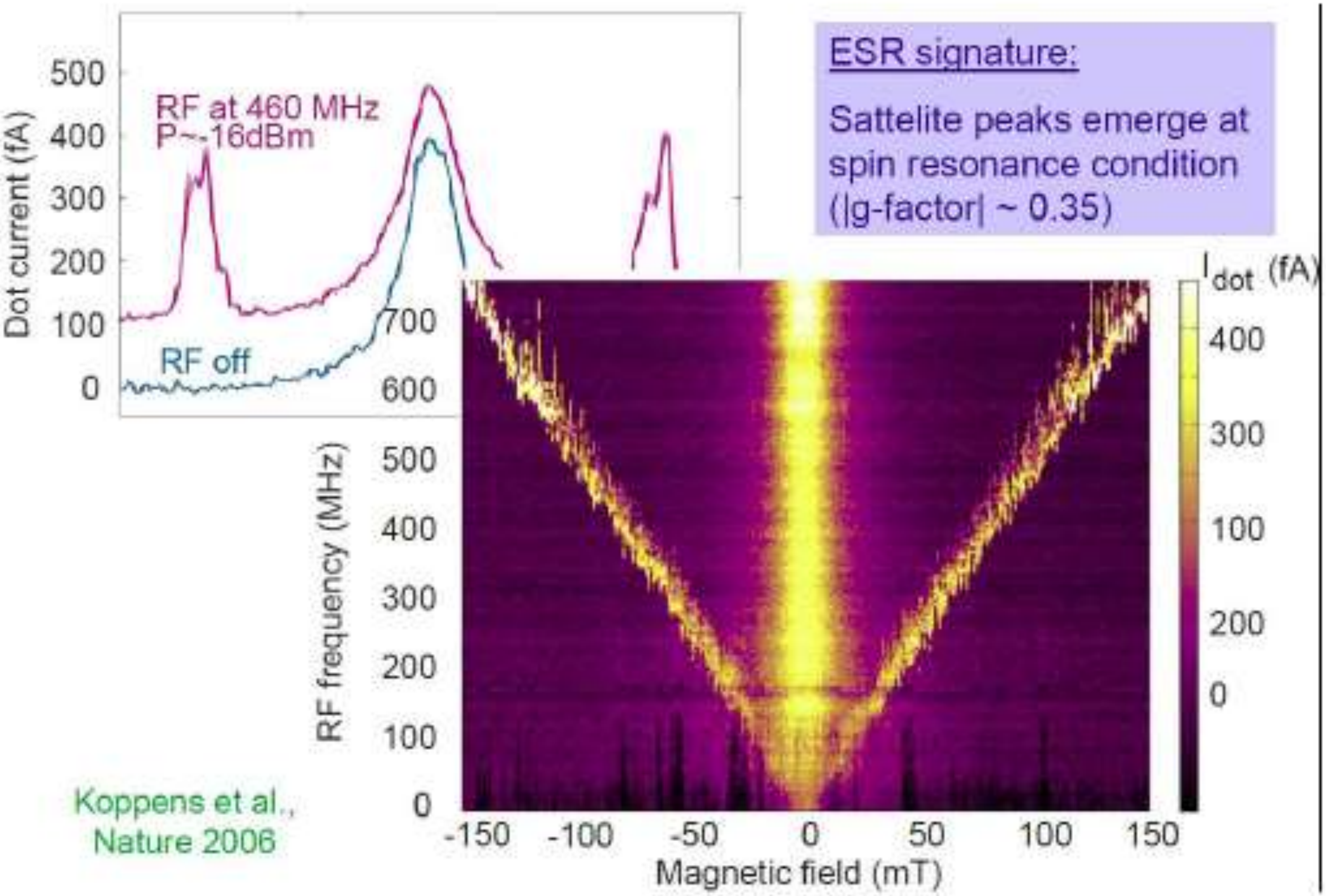
Detection and pulse scheme





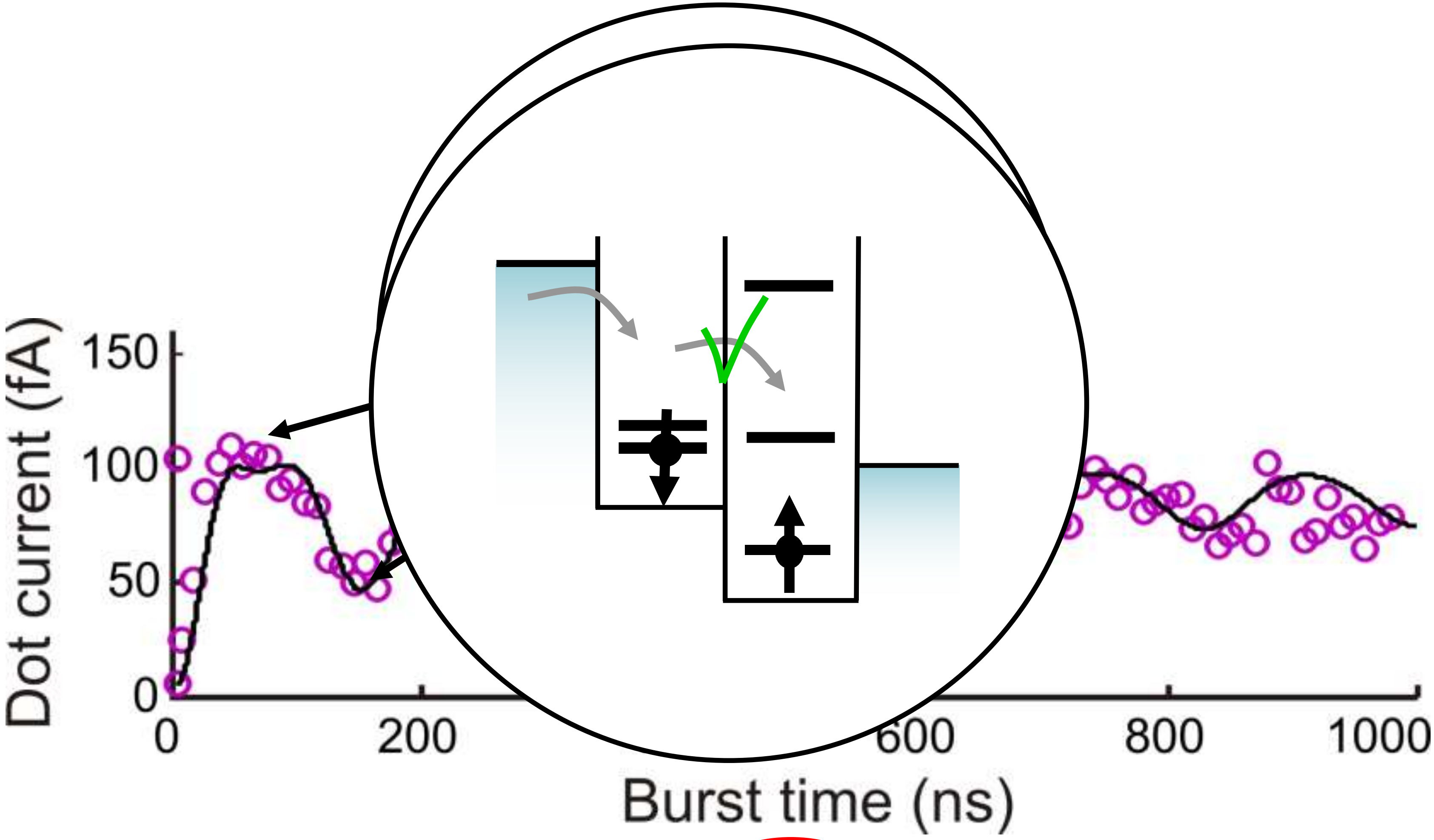


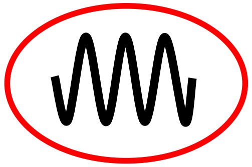
Electron Spin Resonance Spectroscopy



Koppens *et al.*, *Nature* 442, 766 (2006)

Coherent control of a single electron spin





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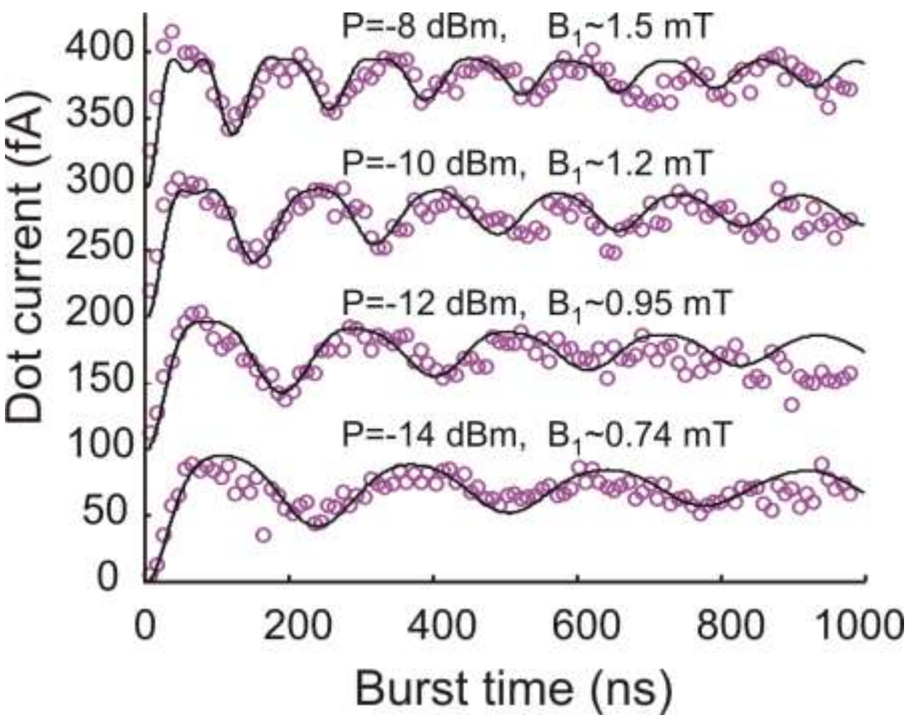
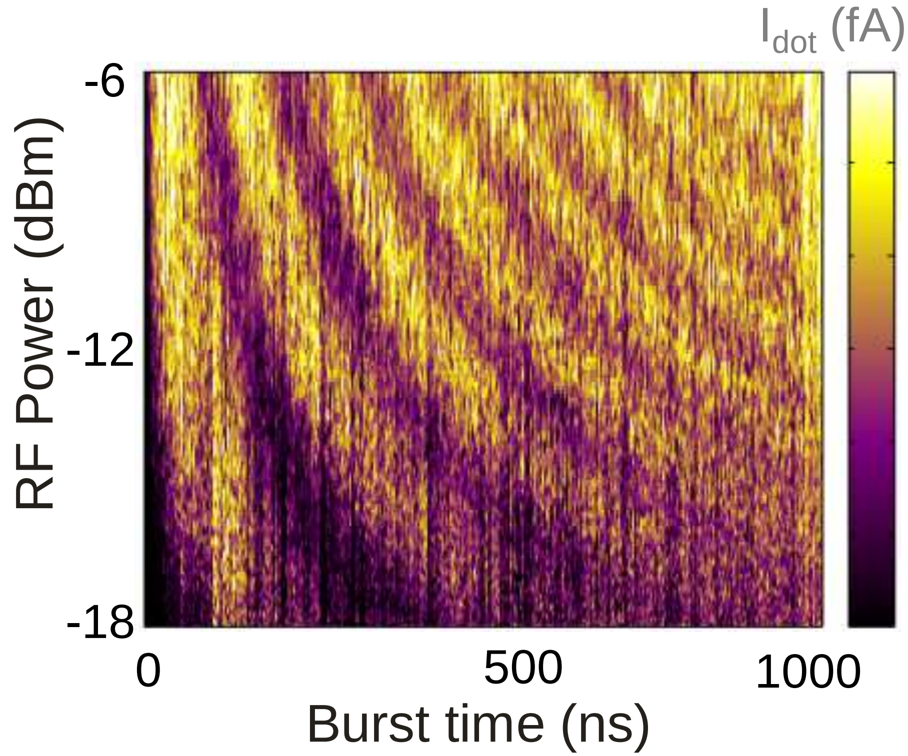
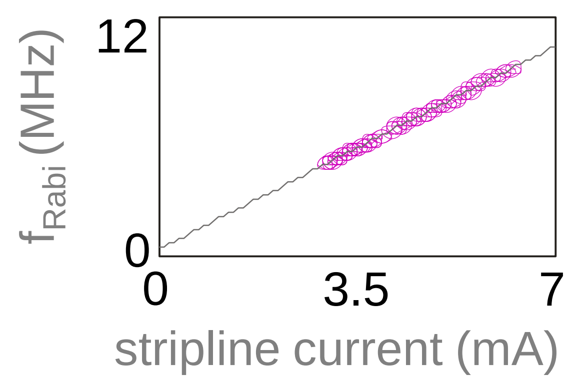




up to 8 periods observed

$\pi/2$ rotation in 25ns

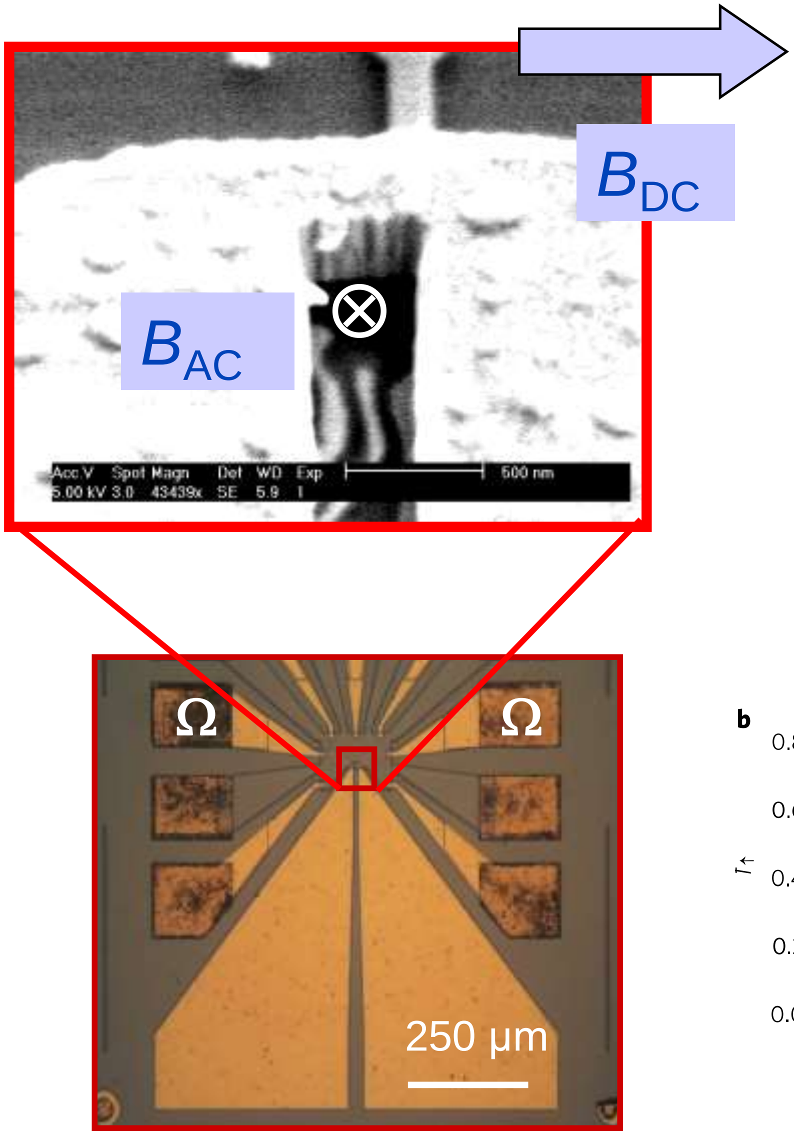


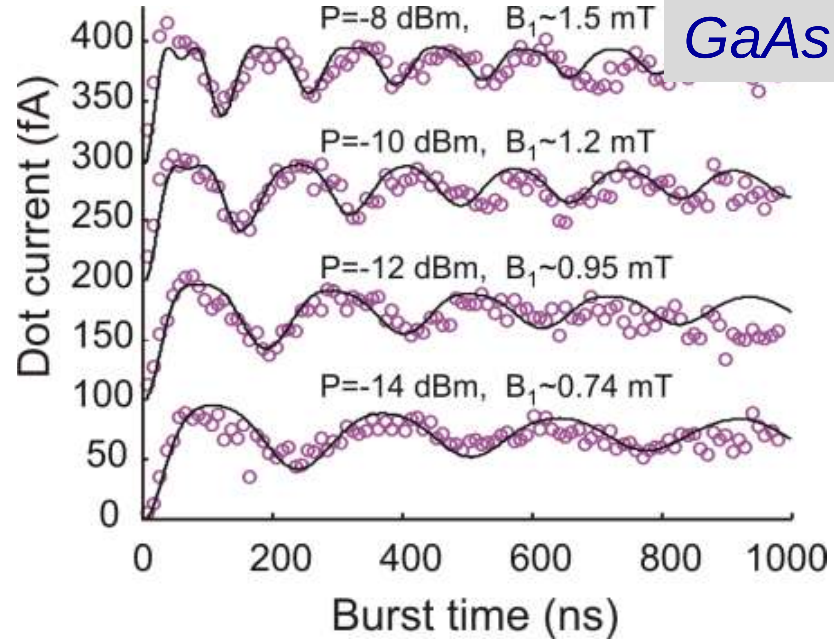
max $B_1 \sim 1.9$ mT, compare $B_{N,z} \sim 1.3$ mT

Analysis: Koppens, Klauser, et al, *PRL* 2007

Koppens et al. *Nature* ('06)

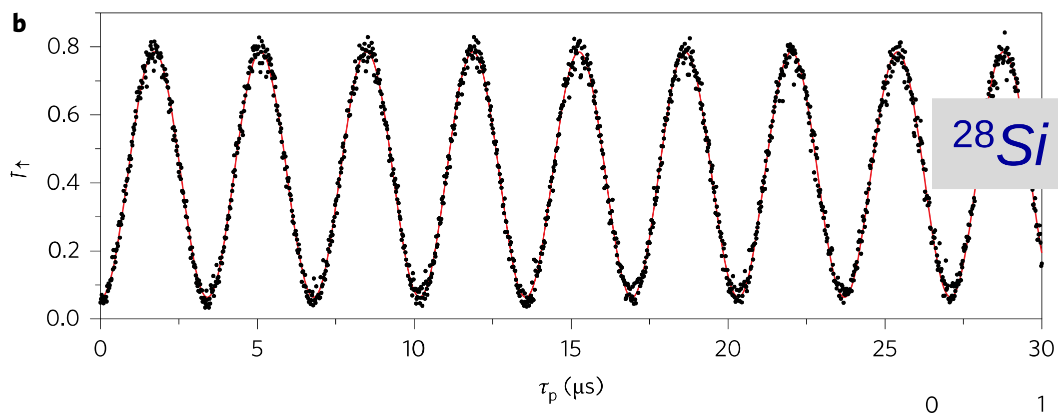
Coherent control of a single electron spin





GaAs

Koppens et al. Nature 2006



^{28}Si

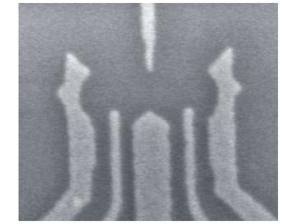
Veldhorst et al, Nature Nano 2014

Mechanism: spin-orbit interaction

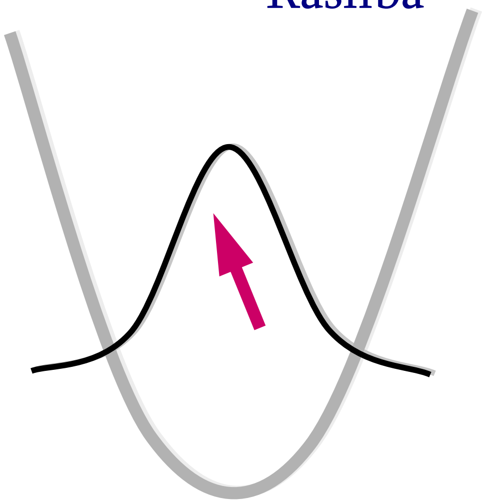
$$H_R = \alpha(\sigma_x p_y - \sigma_y p_x) + \beta(\sigma_x p_x - \sigma_y p_y)$$

Rashba

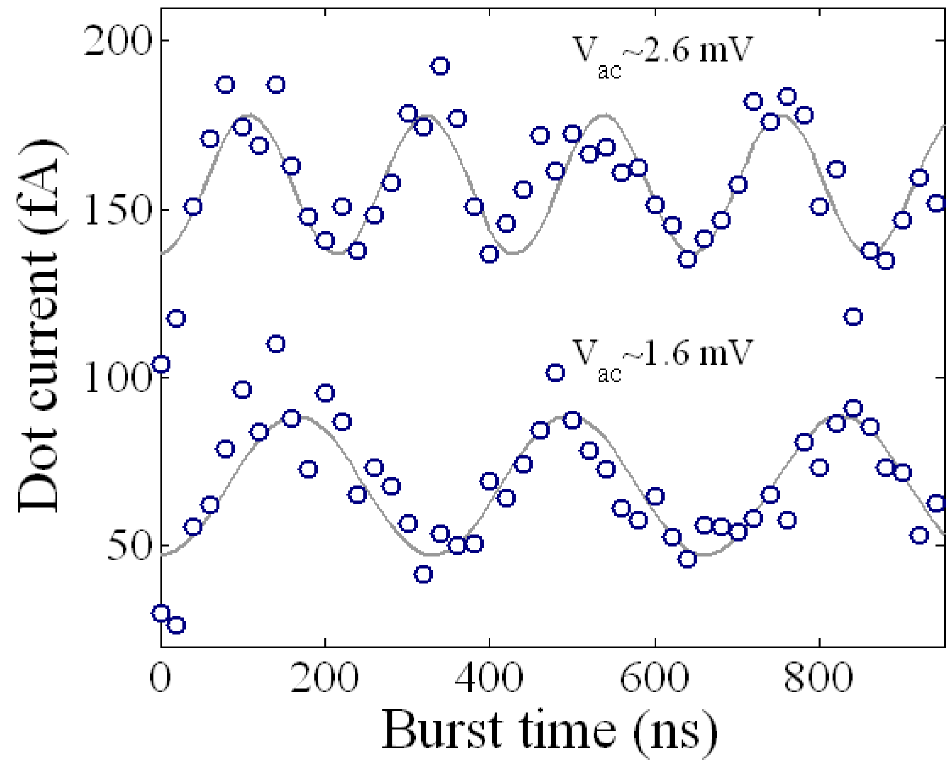
Dresselhaus



B_{ext} // $E(t)$ // $[1\bar{1}0]$



Nowack et al., Science ('07)



$$B_{eff}, f_{Rabi} \sim \frac{1}{l_{SO}} \left|\vec{B}_{ext}\right| \left|\vec{E}\right|$$

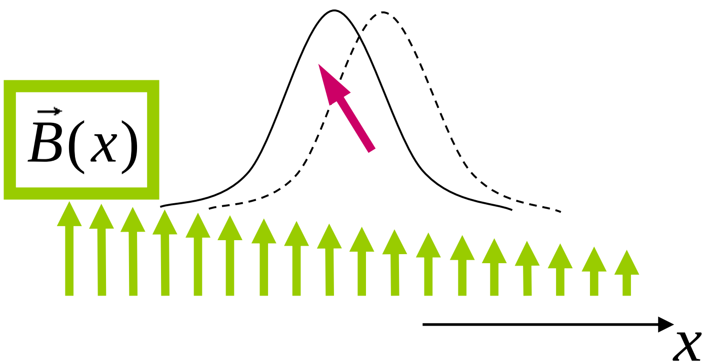
$$l_{SO} = \frac{\hbar}{m(\beta - \alpha)}$$

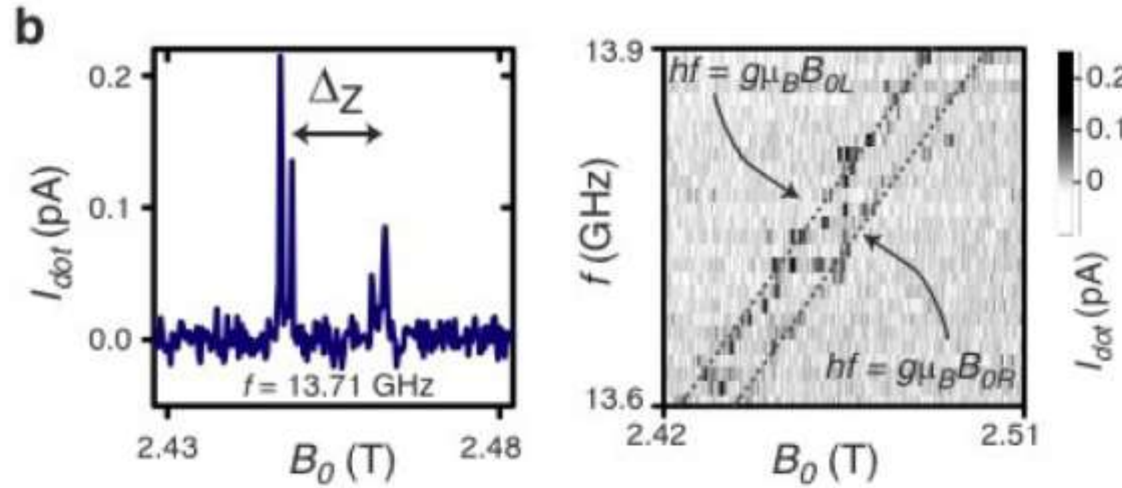
Theory: Golovach et al., *PRB* ('06)

Other mechanisms for electrical driving

Magnetic field gradient
(microfabricated ferromagnet)

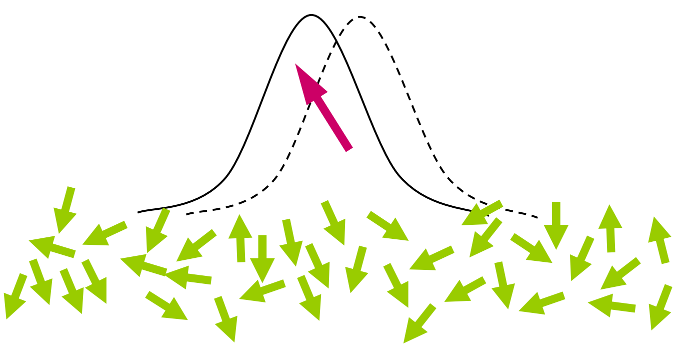
Pioro-Ladriere et al, arXiv:0805.1083

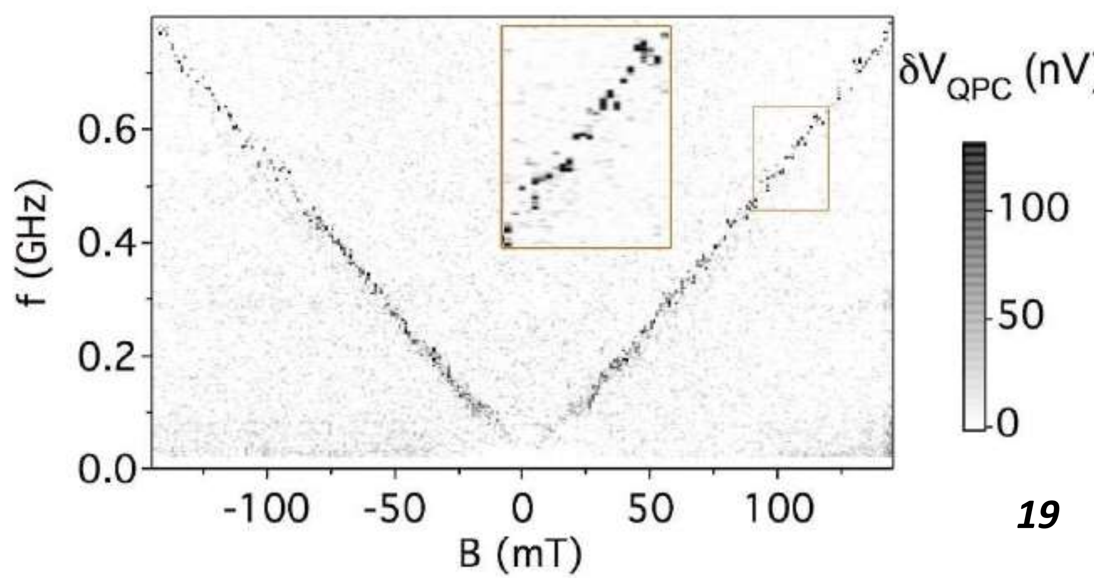




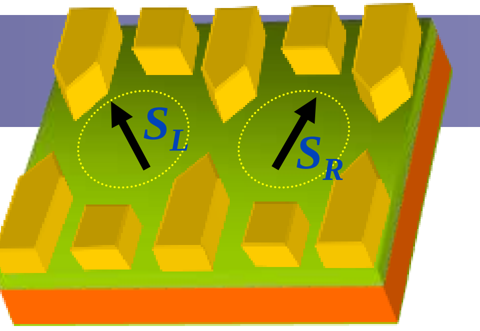
Nuclear field gradient
(incoherent only)

Laird et al., *PRL* ('07)





Spin qubits in quantum dots



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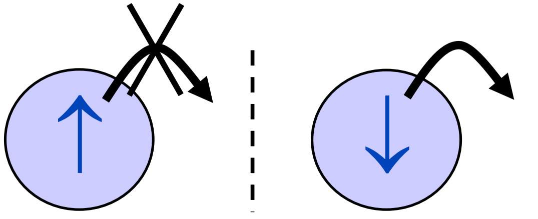

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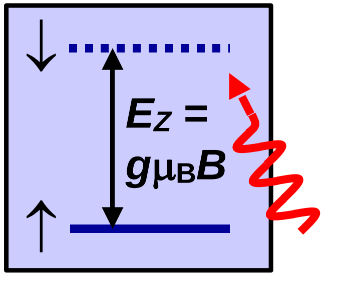

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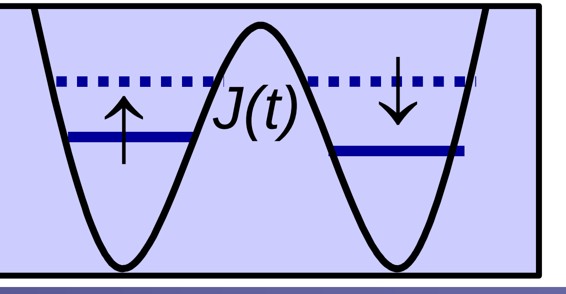

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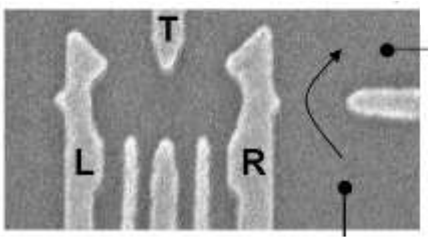
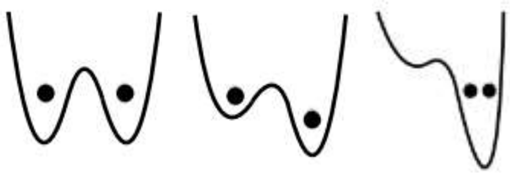
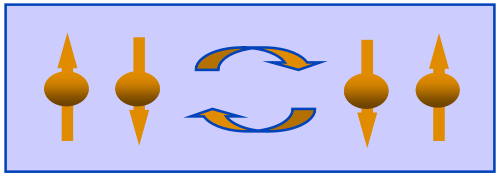
Coherent exchange of two spins

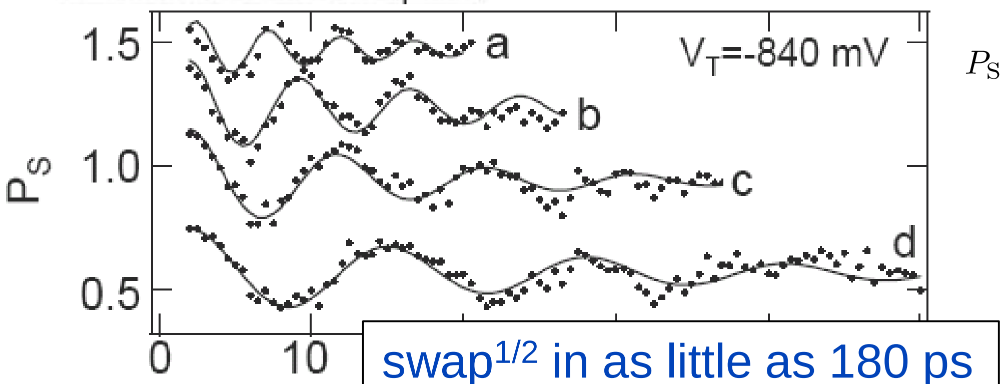




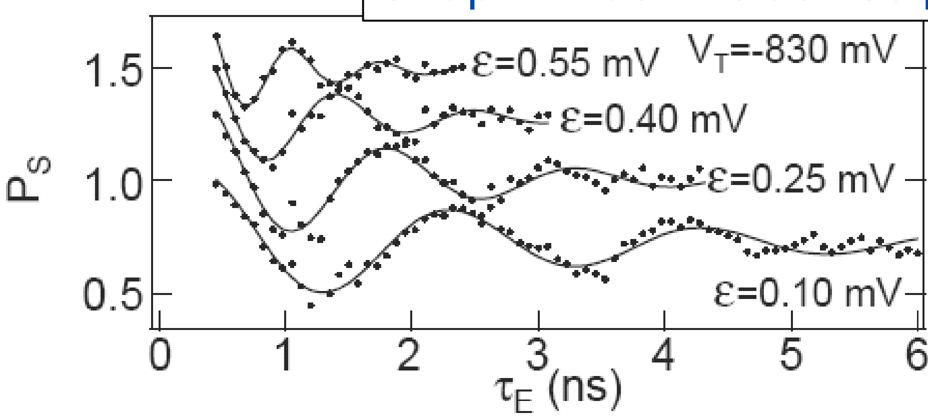


Gate voltage pulse controls spin exchange

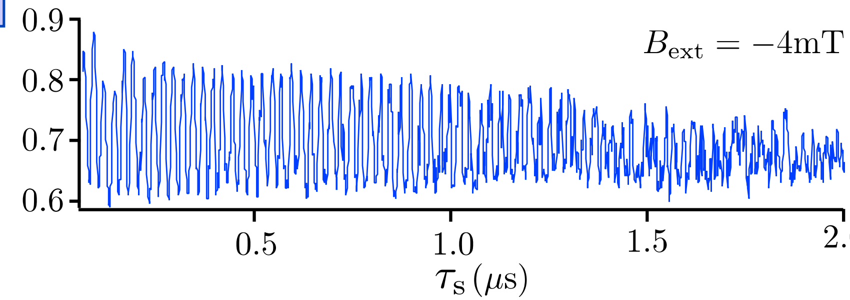
Decay from charge noise



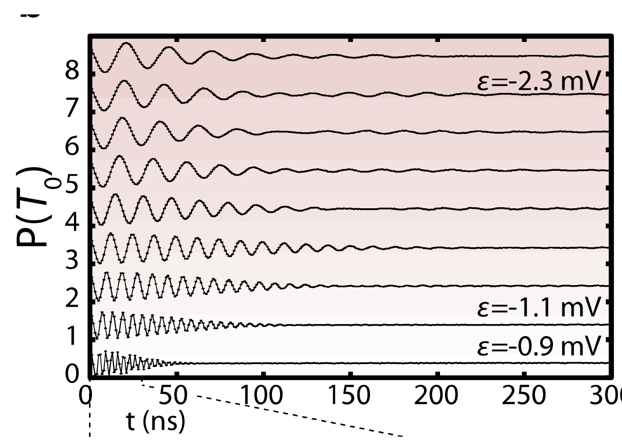
swap$^{1/2}$ in as little as 180 ps



Petta *et al.*, Science 2005

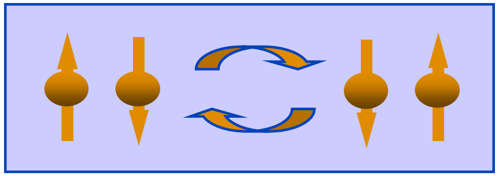


Wu *et al.*, PNAS 2014



Dial *et al.*, PRL 2013

Coherent exchange of two spins



$$H_s(t) = J(t)\vec{S}_1 \cdot \vec{S}_2 ;$$

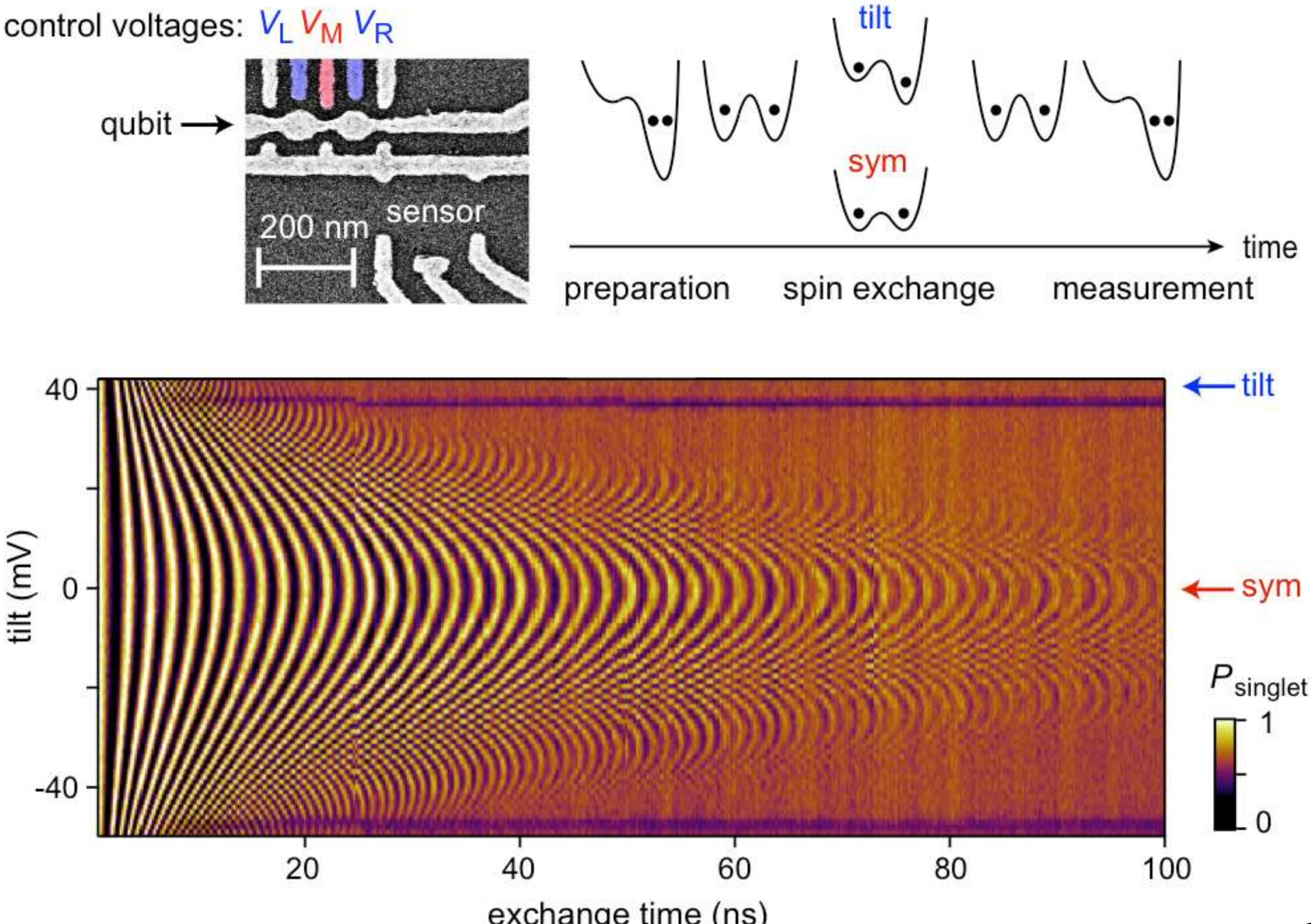
where $J(t) = 4t_0^2(t)/u$ is the time-dependent exchange constant [10] that is produced by the turning on and off of the tunneling matrix element $t_0(t)$. Here u is the charging energy of a single dot and $\vec{S}_i$ is the spin-1/2 operator for dot i.

If Γ^{-1} is long, then the ideal of quantum computing may be achieved, wherein the effect of the pulsed Hamiltonian is to apply a particular unitary time evolution operator $U_s(t) = T\exp\{-i\int_0^t H_s(t')dt'\}$ to the initial state of the two spins: $|\Psi(t)\rangle = U_s|\Psi(0)\rangle$. The pulsed Heisenberg coupling leads to a special form for U_s: For a specific duration τ_s of the spin-spin coupling such that $\int dt J(t) = J_0\tau_s = \pi(\mathrm{mod}\, 2\pi)$ [12], $U_s(J_0\tau_s = \pi) = U_{sw}$ is the "swap" operator: If $|ij\rangle$ labels the basis states of two spins in the S_z basis with $i,j = 0,1$, then $U_{sw}|ij\rangle = |ji\rangle$.

D. Loss and D. P. DiVincenzo

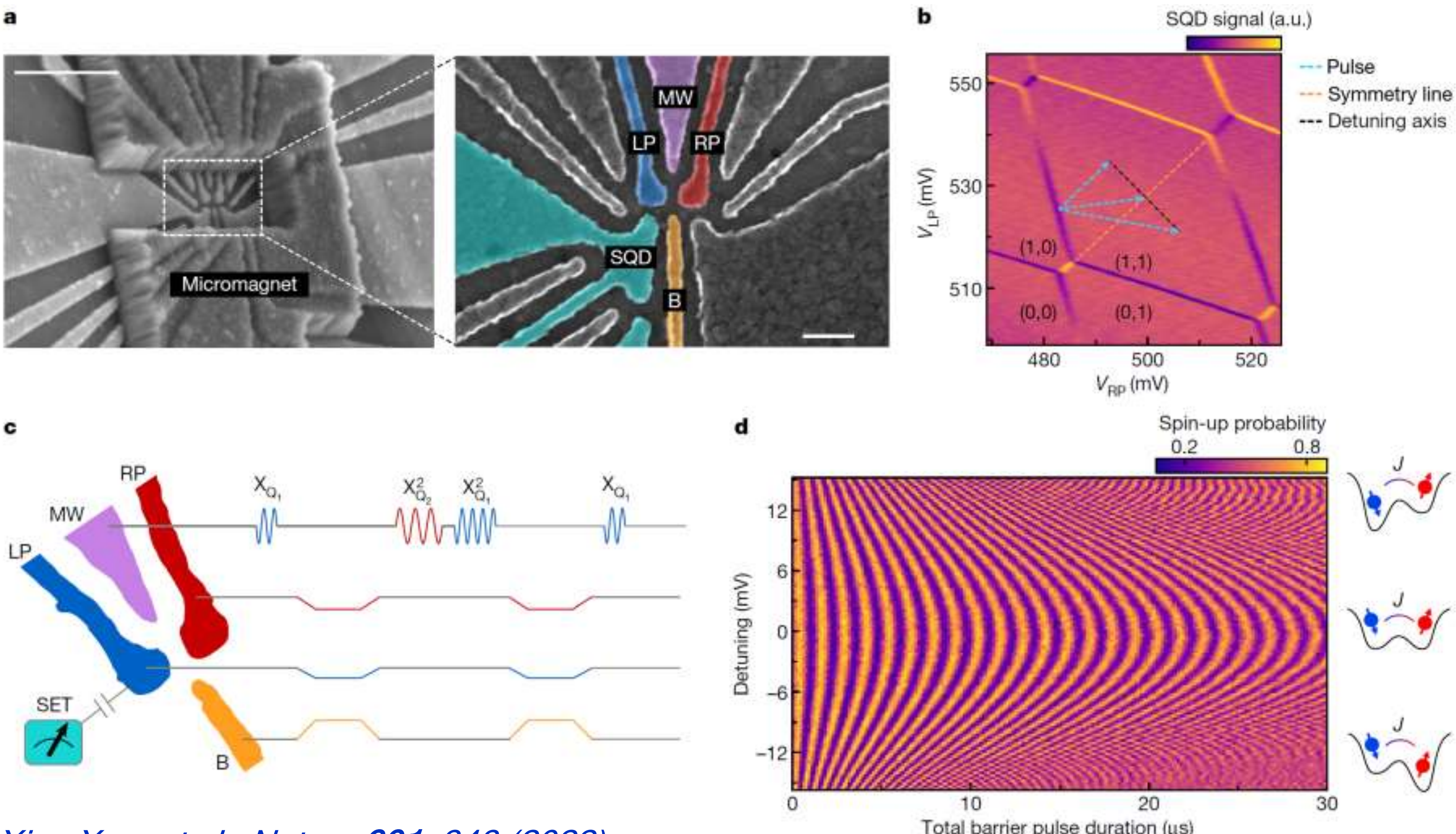
Phys. Rev. A **57**, 120 (1998)

Operation at the symmetry point



Martins et al, PRL 2016, see also Reed et al, PRL 2016

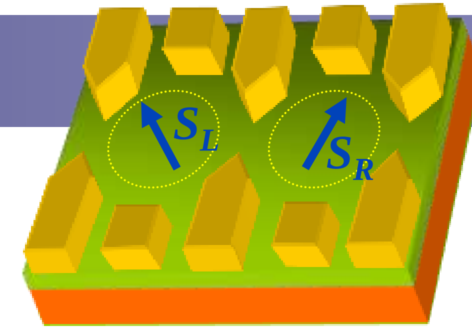
Computing with spin qubits at the surface code error threshold



*Xiao Xue, et al., Nature **601**, 343 (2022)*

'Now that the 99% barrier for the two-qubit gate fidelity has been surpassed, semiconductor qubits have gained credibility as a leading platform, not only for scaling but also for high-fidelity control.'

Spin qubits in quantum dots



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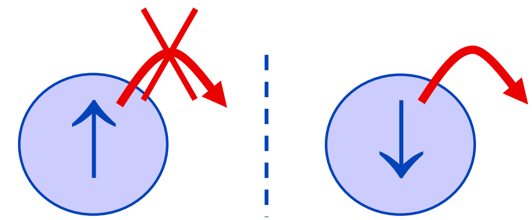
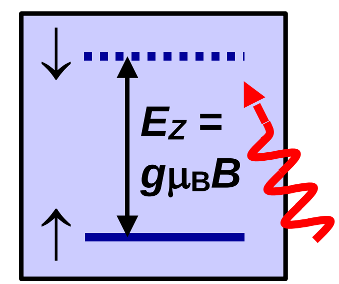
Read-out convert spin to charge

then measure charge



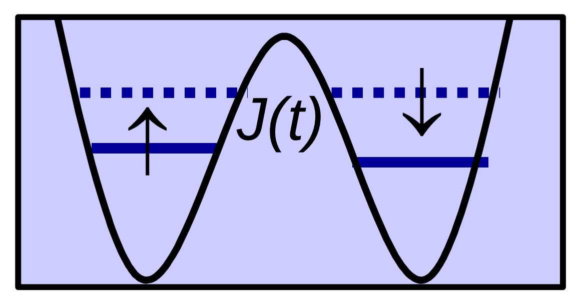
ESR pulsed microwave magnetic field

$$H_{RF} \sim \sum A_i(t) \cos(\omega_i \, t) \;\; \sigma_{xi}$$



SWAP exchange interaction

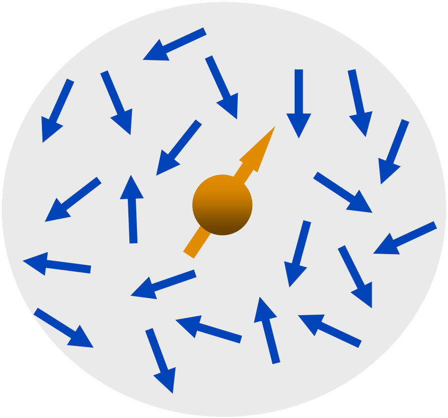
$$H_J \sim \sum J_{ij}(t) \;\; \sigma_i \cdot \sigma_j$$



Coherence long relaxation time T_1
long coherence time T_2

Hyperfine interaction with the nuclear spins

$$\mathcal{H} = g\mu_B \vec{S}\,\vec{B} + \underbrace{\vec{S}\sum_i A_i \vec{I}_i}_{\textbf{Overhauser field } B_N}$$



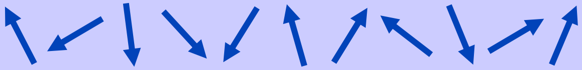
Full polarization

$$A = \sum_i A_i$$

GaAs: A ~ 5.5 T

Paget, 1977

Statistical polarization



$$A/\sqrt{N}$$

GaAs dot: $N \sim 10^6$

$B_N = A\,/\,N^{1/2} \sim 5$ mT

Merkulov, Efros, Rosen, PRB 2002

Khaetskii, Loss, Glazman, PRL 2002

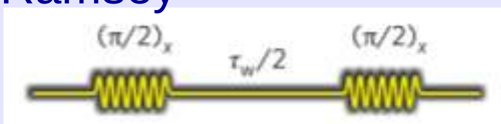
Nuclear correlation time

GaAs: ~ 100 μs - few sec.

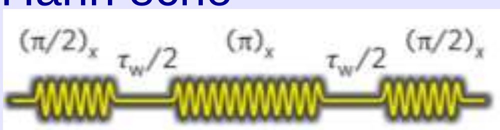
Trend 1: Eliminate nuclear spins

Pulse toolbox
Dynamical decoupling

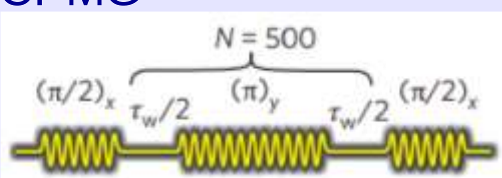
Ramsey



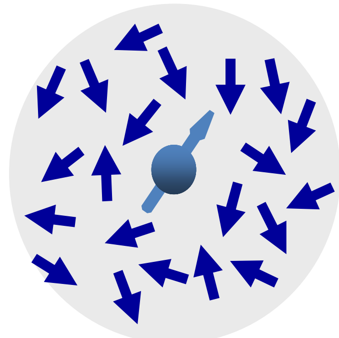
Hahn echo



CPMG



GaAs

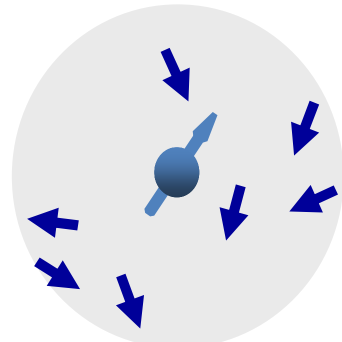


$T_2^* \sim 10$ ns

$T_2^{CPMG} \sim 0.2$ ms

Petta et al, Science 2005
Bluhm et al., Nat Phys 2008

Si

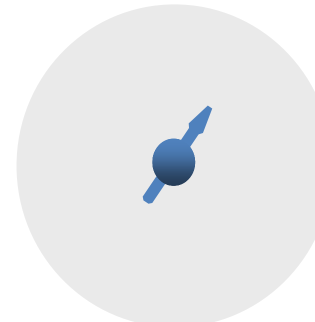


$T_2^* \sim 1$ μs

$T_2^{CPMG} \sim 0.5$ ms

Kawakami, Scarlino, et al, Nature Nano 2014

^{28}Si



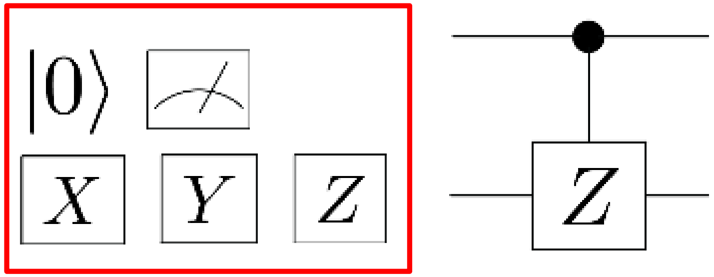
$T_2^* \sim 100\text{-}250$ μs

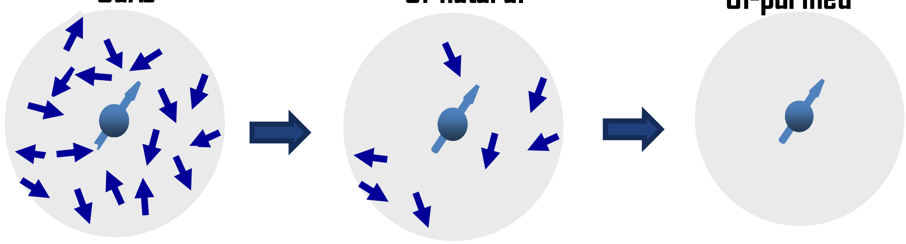
$T_2^{CPMG} \sim 28\text{-}500$ ms

Veldhorst, et al, Nature Nano 2014
Muhonen et al, Nature Nano 2014

Trend 1: Eliminate nuclear spins

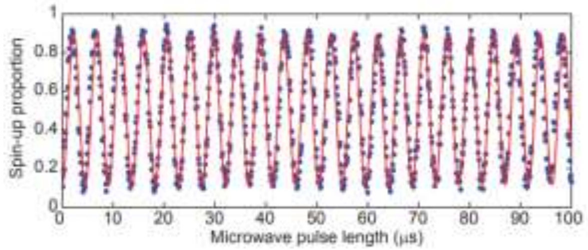
Coherent spins in isotopically purified silicon





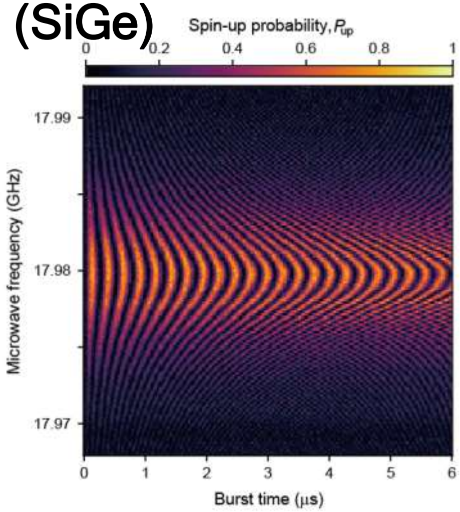
In Si28 epilayer (Si-SiOx)

For electron spin:
T_2^*= 200us
T_2 = 28ms
F_C = 99.9%



Veldhorst, et al. *Nat. Nanotech* **9**, 981 (2014)

In Si28 quantum well (SiGe)

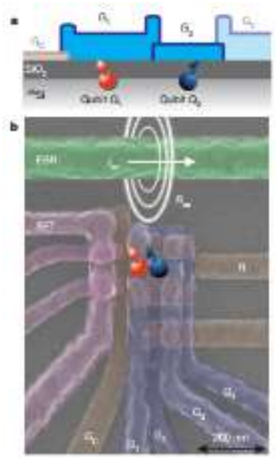


Yoneda, et al. *Nat. Nanotech* **13**, 102 (2018)

Trend 1: Eliminate nuclear spins

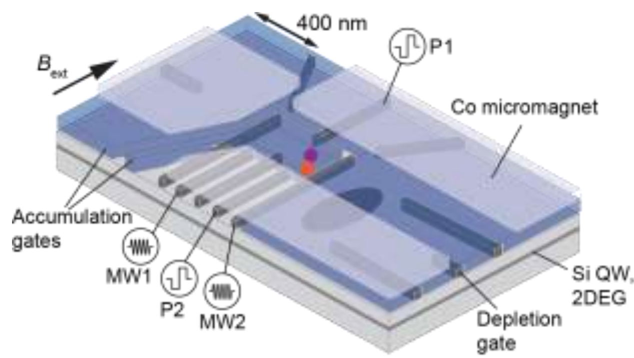
Two-qubit devices for electrons in silicon

^{28}SiMOS



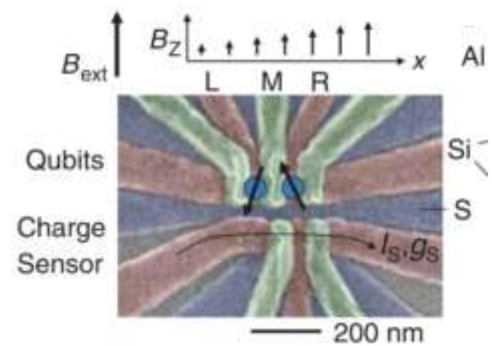
Veldhorst et al., *Nature* **526,** 410 (2015)

SiGe



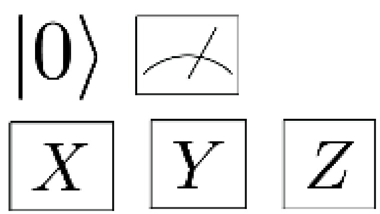
Watson et al., *Nature* **555**, 633 (2018)

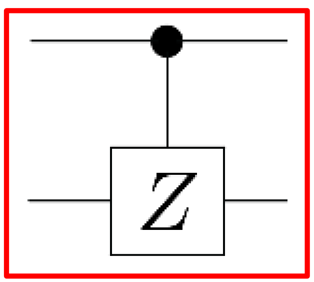
SiGe



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

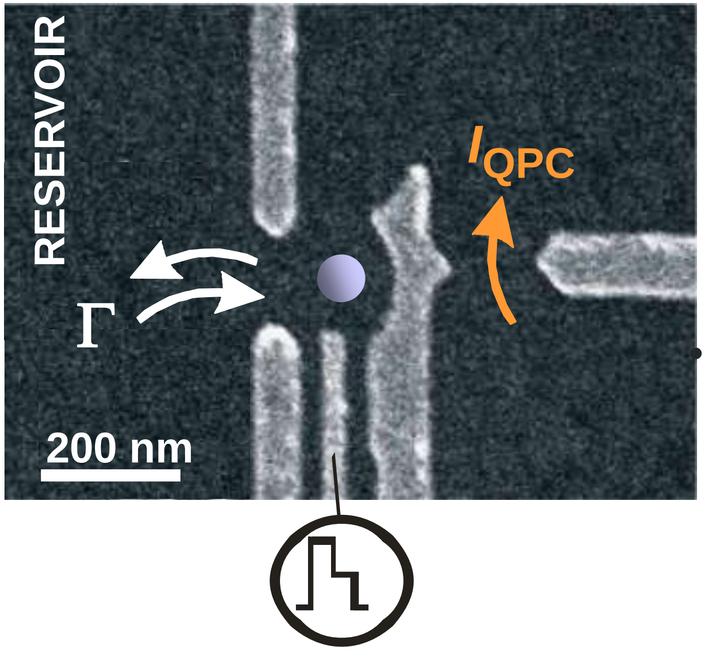
Xiao Xue, et al., *Nature* **601**, 343 (2022)
Y. Noiri, et al. *Nature* **601**, 338 (2022)

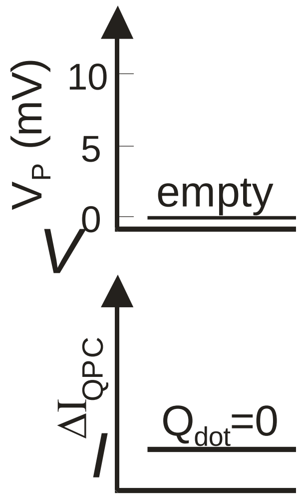


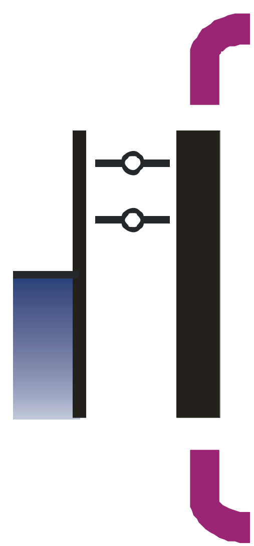


Computing with spin qubits at the surface code error threshold
*'Now that the **99%** barrier for the two-qubit gate fidelity has been surpassed, semiconductor qubits have gained credibility as a leading platform, not only for scaling but also for high-fidelity control.'*

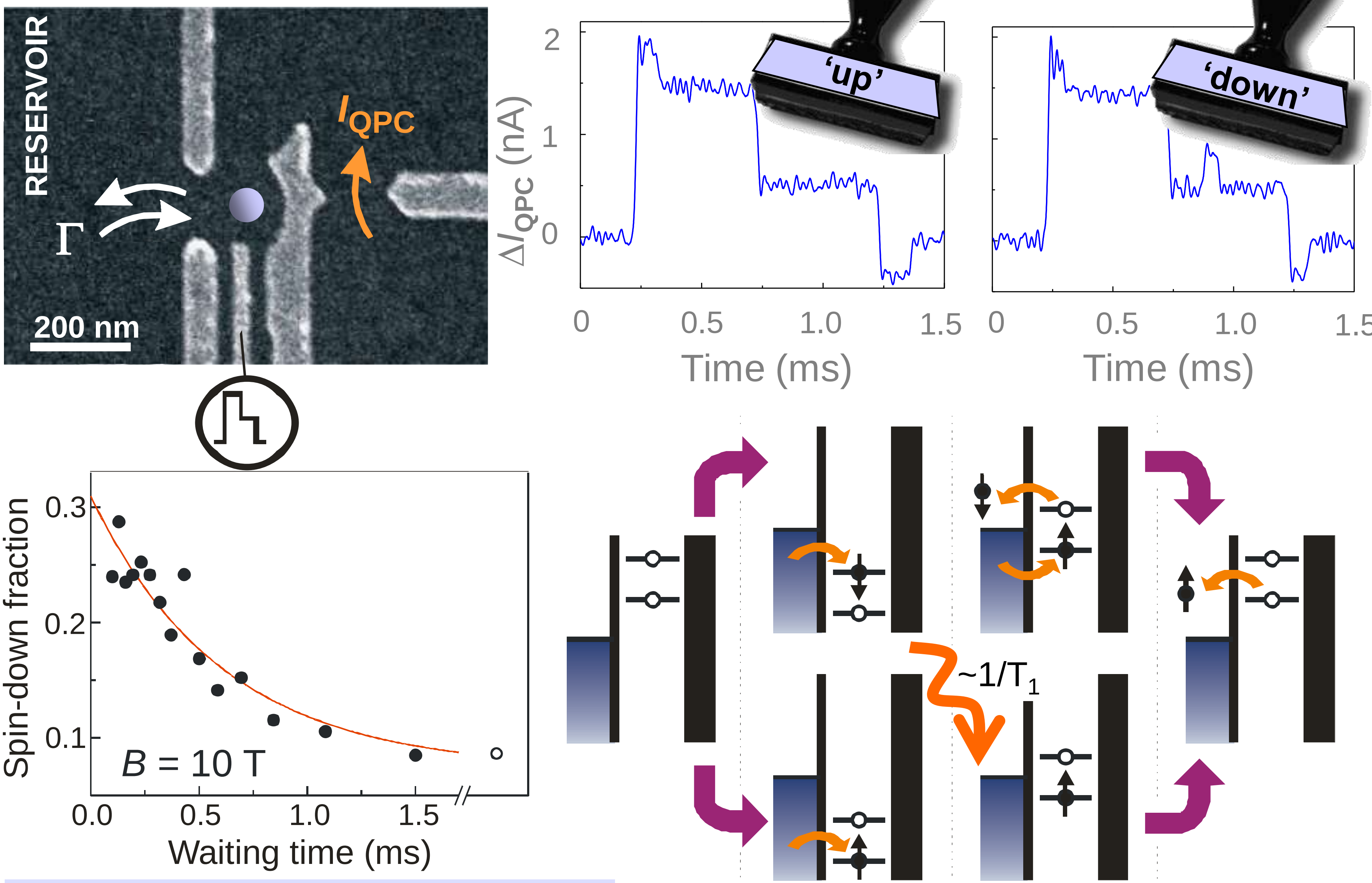
Pulse scheme to measure T_1







Pulse scheme to measure T_1

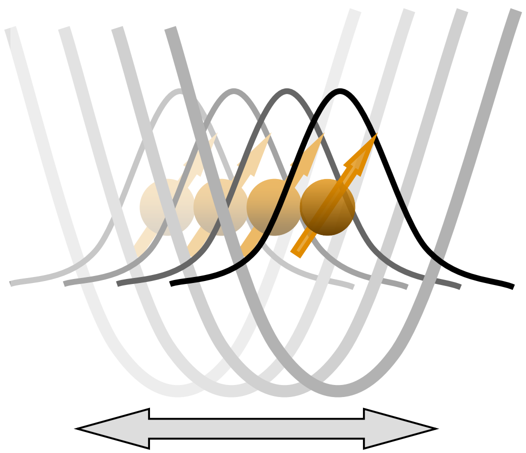


timescale: 100 µs up to > 1 s (!)

Elzermann et al., *Nature* ('04)

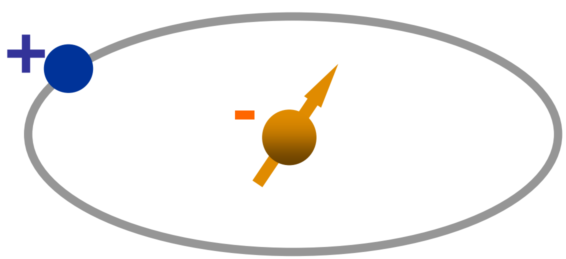
Environment and interactions in GaAs

Uncontrolled electric fields
- phonons



Absorb the energy, but conserve spin.

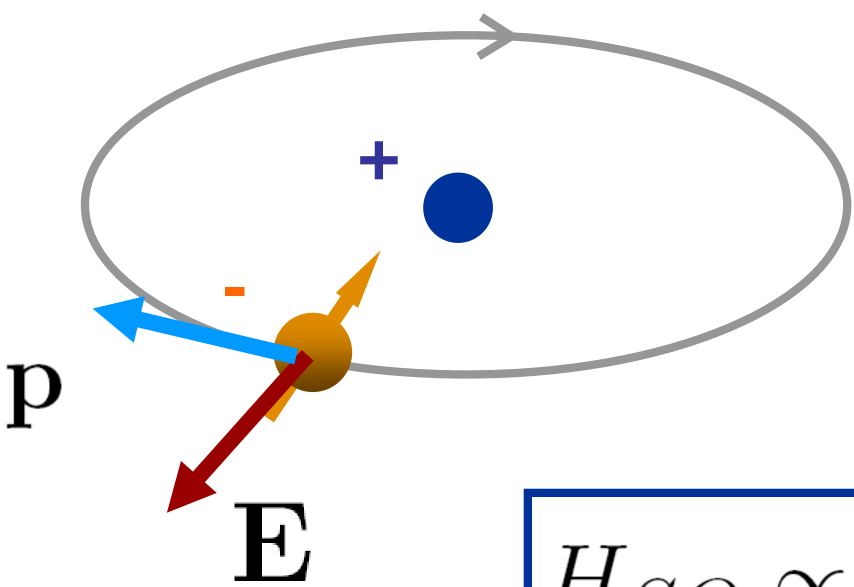
Spin-orbit coupling



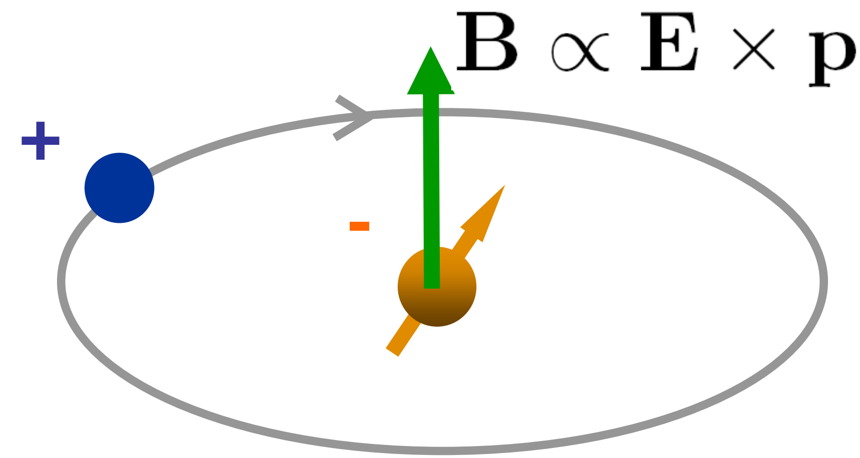
Admixes pure spin states.

Spin-orbit coupling in hydrogen

Hydrogen atom



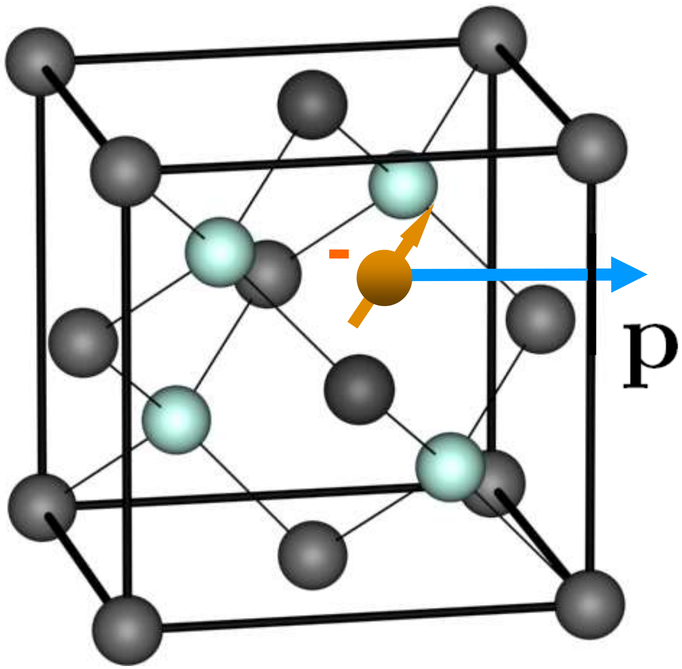
Rest frame electron



$$\boxed{H_{SO} \propto \mathbf{S} \cdot (\mathbf{E} \times \mathbf{p})}$$

In hydrogen: $\mathbf{E} \propto \dfrac{\mathbf{r}}{r^3} \Rightarrow H_{SO} \propto \mathbf{L} \cdot \mathbf{S}$

Spin-Orbit coupling in a crystal



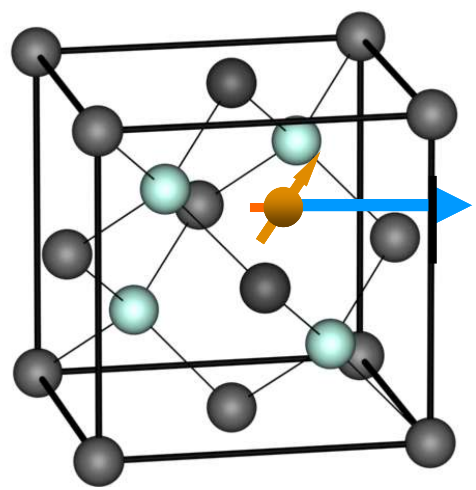
- Crystal symmetry determines the geometry of the electric field the electron ‘sees’
- Zincblende structure has no inversion symmetry (Bulk Inversion Asymmetry)
- Due to low symmetry electric fields don’t cancel out

Spin-Orbit coupling in a two-dimensional electron gas

x| | [100]
y| |[010]

Dresselhaus

$$H_{SO} = \beta(-p_x\sigma_x + p_y\sigma_y)$$

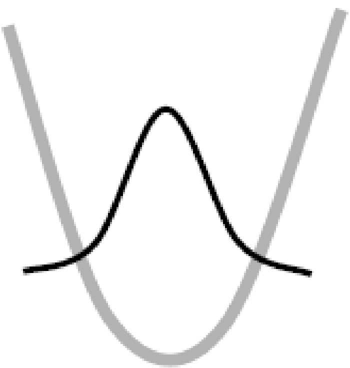


Structure given by symmetry, microscopic details of the atomic structure hidden in the coupling strength

Experiments in 2D: e.g. Kato et al., Nature ('03),
Meier et al., Nature Physics ('08)

Spin-orbit coupling in a quantum dot

electron is confined ⇒ **spin states are not directly coupled:**



$$\langle n,l\downarrow|H_{SO}|n,l\uparrow\rangle \propto \underbrace{\langle n,l|p_{x,y}|n,l\rangle}_{=0}\langle\downarrow|\sigma_{x,y}|\uparrow\rangle = 0$$

x|| [100]
y||[010]

perturbative treatment yields:

$$H = \frac{1}{2} g\mu_B \left(\vec{n}\times\vec{B}_{ext} + \vec{B}_{ext}\right)\vec{\sigma}$$

with

$$n_x = \frac{2m^*}{\hbar}\left(-\alpha y - \beta x\right)$$

$$n_y = \frac{2m^*}{\hbar}\left(\alpha x + \beta y\right)$$

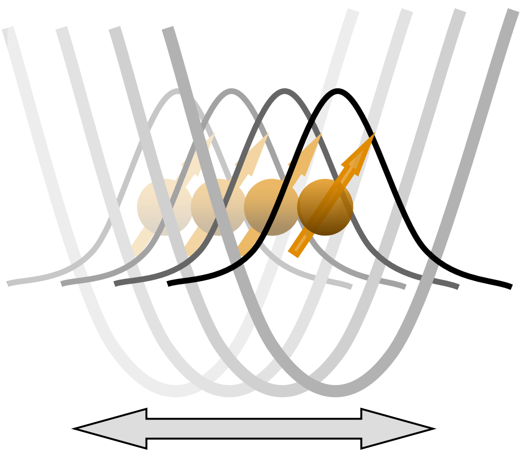
$$n_z = 0$$

Khaetskii, Nazarov, PRB(2001)
Levitov, Rashba, PRB (2003)
Golovach *et al.*, PRL ('04), PRB ('06)

Spin-orbit coupling and uncontrolled electric fields

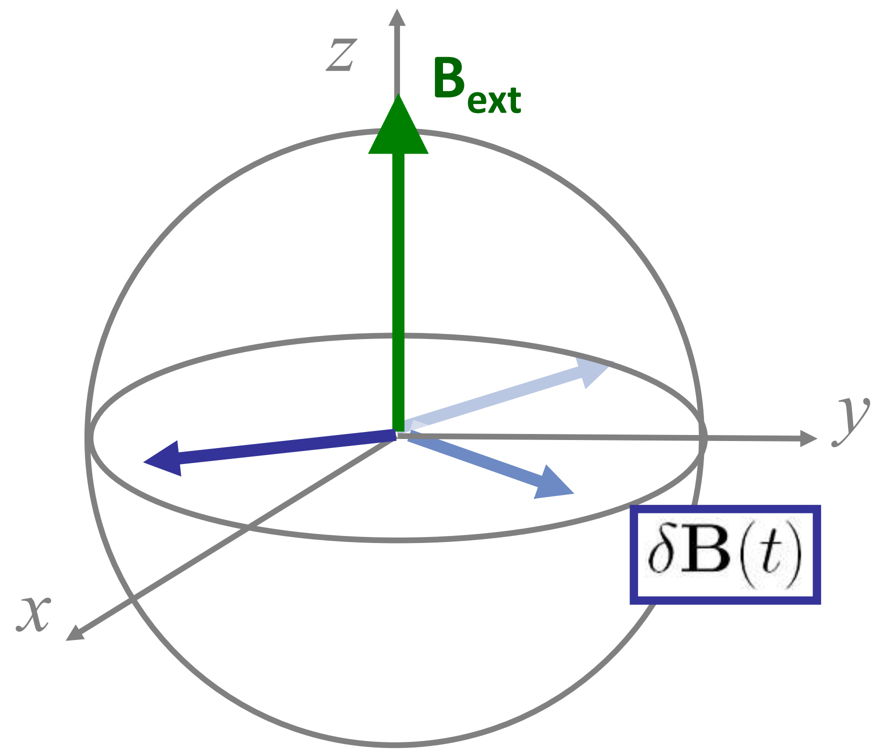
$$H = \frac{1}{2} g \mu_{\mathrm{B}} \left(\underbrace{\mathbf{n} \times \mathbf{B}_{\mathrm{ext}}}_{\delta \mathbf{B}(t)} + \mathbf{B}_{\mathrm{ext}} \right) \boldsymbol{\sigma}$$

$$n_{x,y} \propto x, y$$



electric fields couple to the electron position:

$$x(t), y(t) \propto E_{x,y}(t)$$

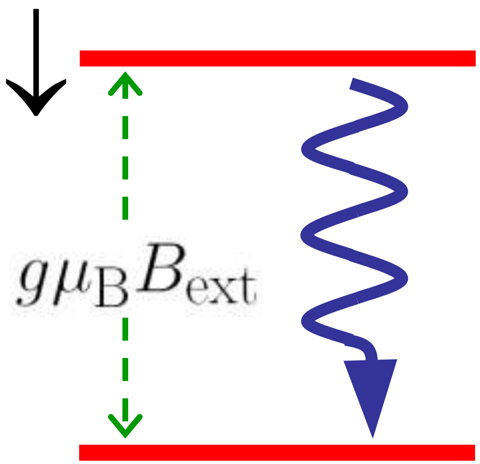


Spin-orbit coupling and uncontrolled electric fields

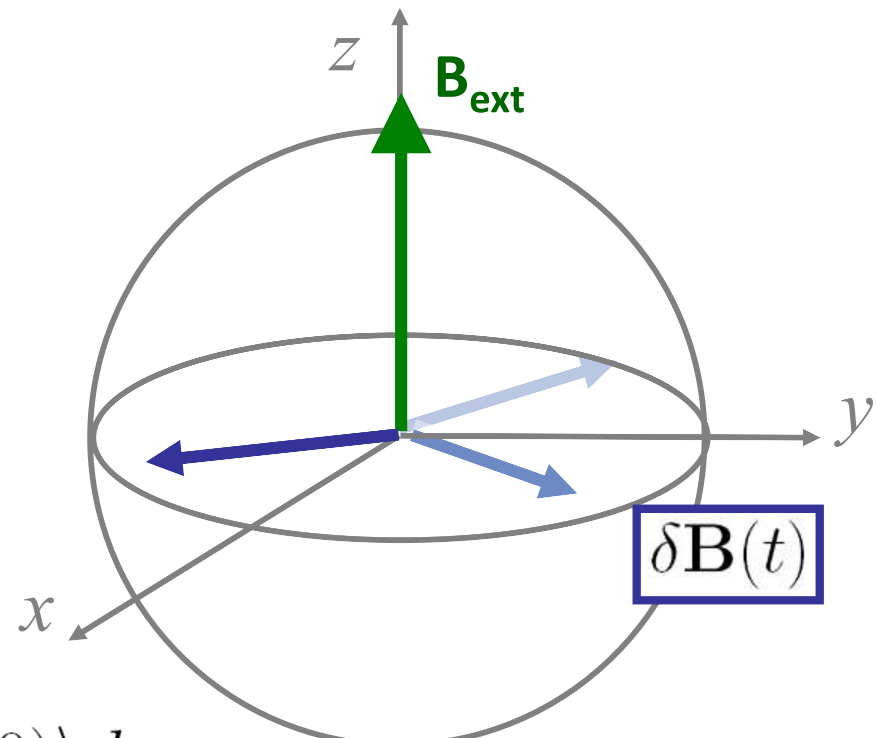
$$H = \frac{1}{2} g \mu_{\mathrm{B}} \left(\underbrace{\mathbf{n} \times \mathbf{B}_{\mathrm{ext}}}_{\delta\mathbf{B}(t)} + \mathbf{B}_{\mathrm{ext}} \right) \boldsymbol{\sigma}$$

$$n_{x,y} \propto x, y$$

$$\boxed{\Gamma_{relax} \propto S(E_Z)}$$



$$E_Z = g \mu_{\mathrm{B}} B_{\mathrm{ext}}$$



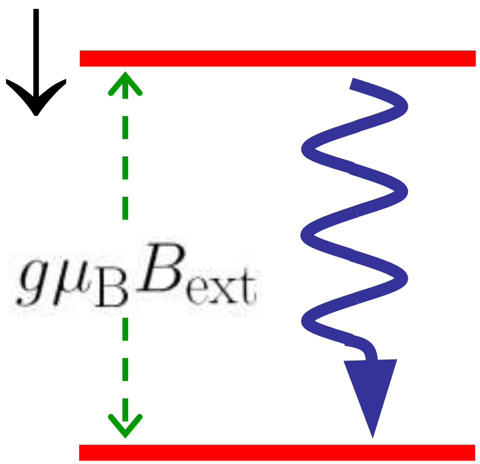
$$S(E) = \int_{-\infty}^{+\infty} e^{iEt/\hbar} \langle \delta\mathbf{B}(\tau) \mathbf{B}(0) \rangle d\tau$$

Spin-orbit coupling and uncontrolled electric fields

$$H = \frac{1}{2} g\mu_{\mathrm{B}} \left(\underbrace{\mathbf{n} \times \mathbf{B}_{\mathrm{ext}}}_{\delta\mathbf{B}(t)} + \mathbf{B}_{\mathrm{ext}} \right) \boldsymbol{\sigma}$$

$$n_{x,y} \propto x, y$$

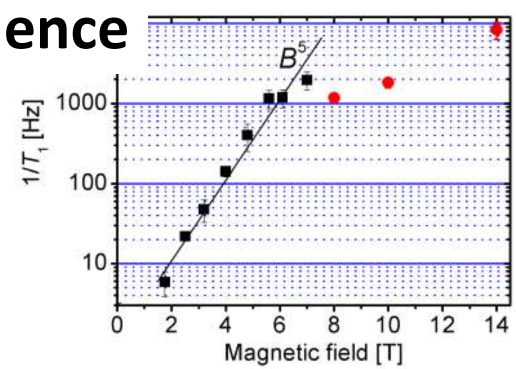
$$\boxed{\Gamma_{relax} \propto S(E_Z)}$$



$$E_Z = g\mu_{\mathrm{B}} B_{\mathrm{ext}}$$

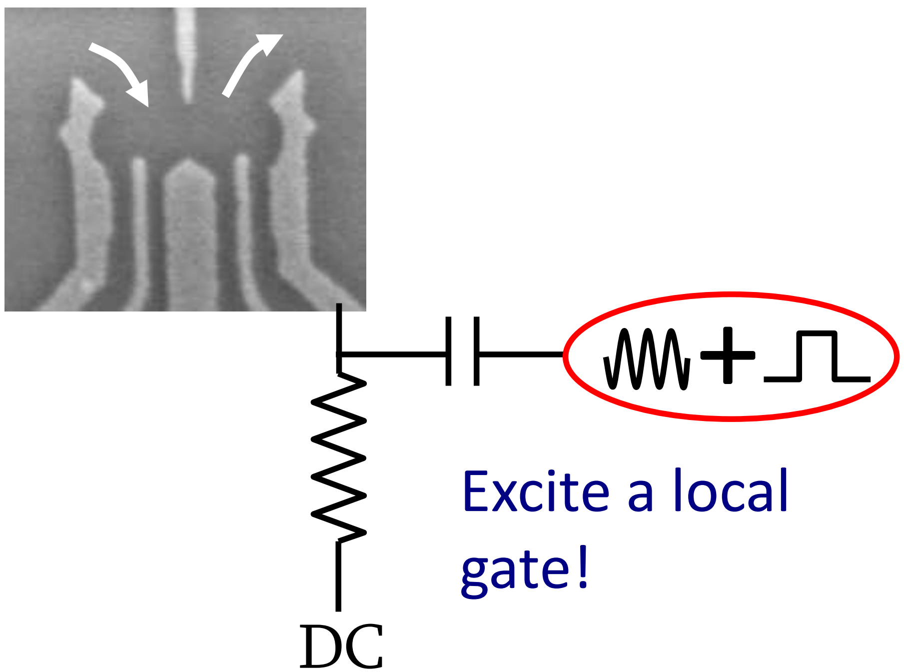
- $\delta\mathbf{B}(t)$ depends linearly on external field
- phonon density of states at Zeeman splitting
- dot – phonon coupling
- electric field amplitude

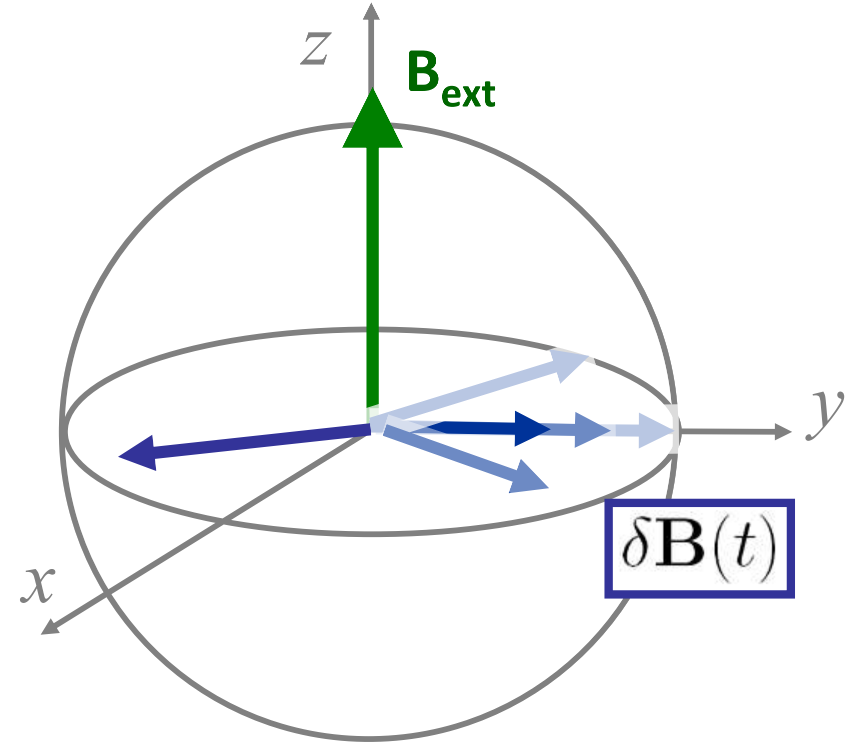
$\mathbf{B}^5$ dependence

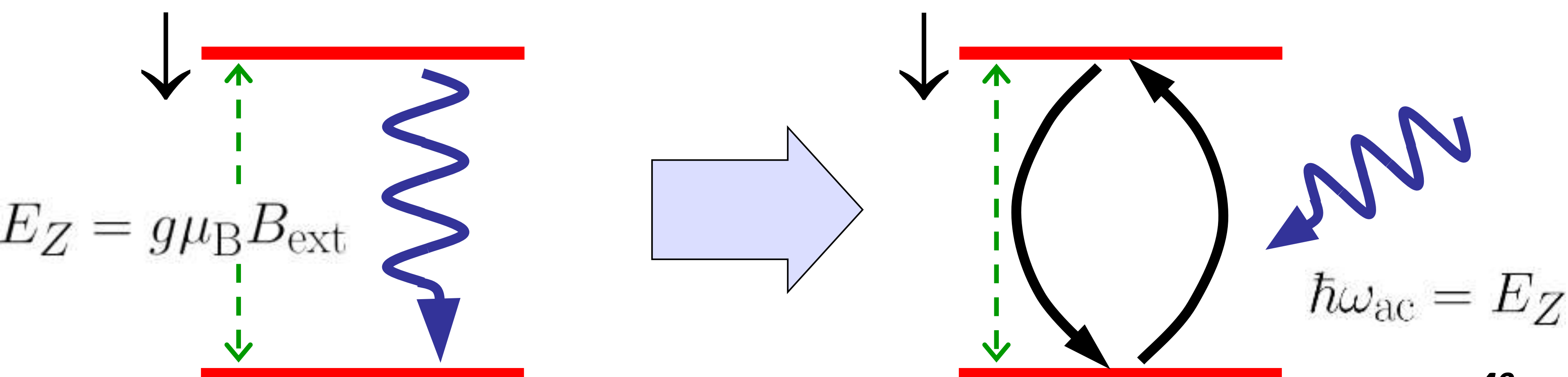


$$S(E) = \int_{-\infty}^{+\infty} e^{iEt/\hbar} \langle \delta\mathbf{B}(\tau)\mathbf{B}(0) \rangle d\tau$$

Spin-orbit coupling combined with *controlled* electric fields

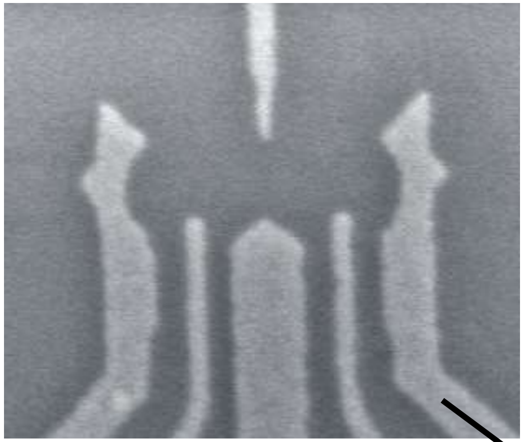


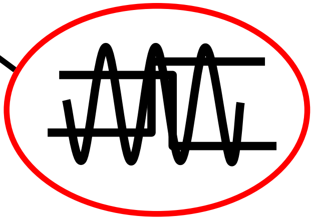


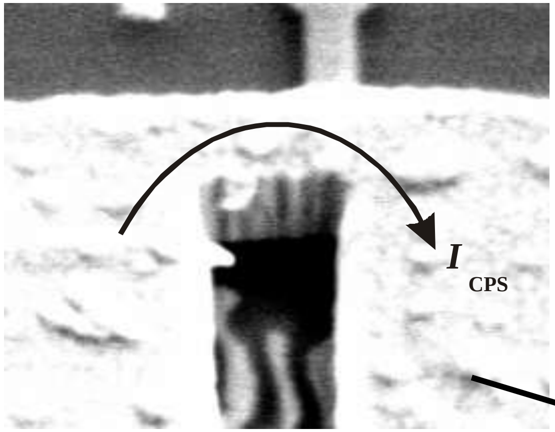


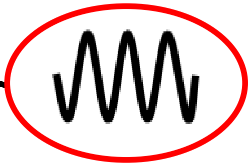
Reminder

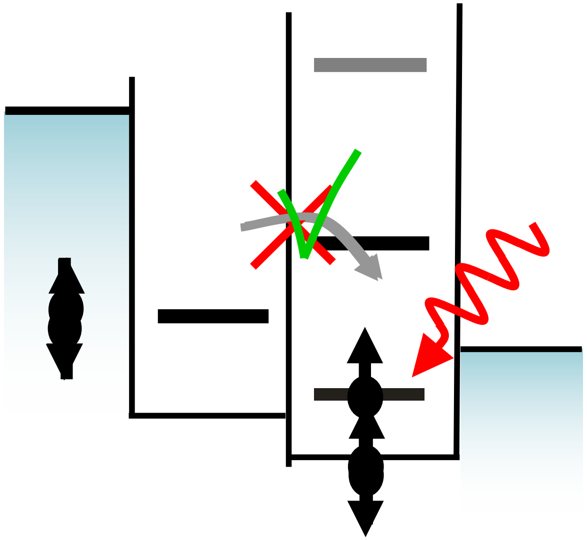
Detection and pulse scheme





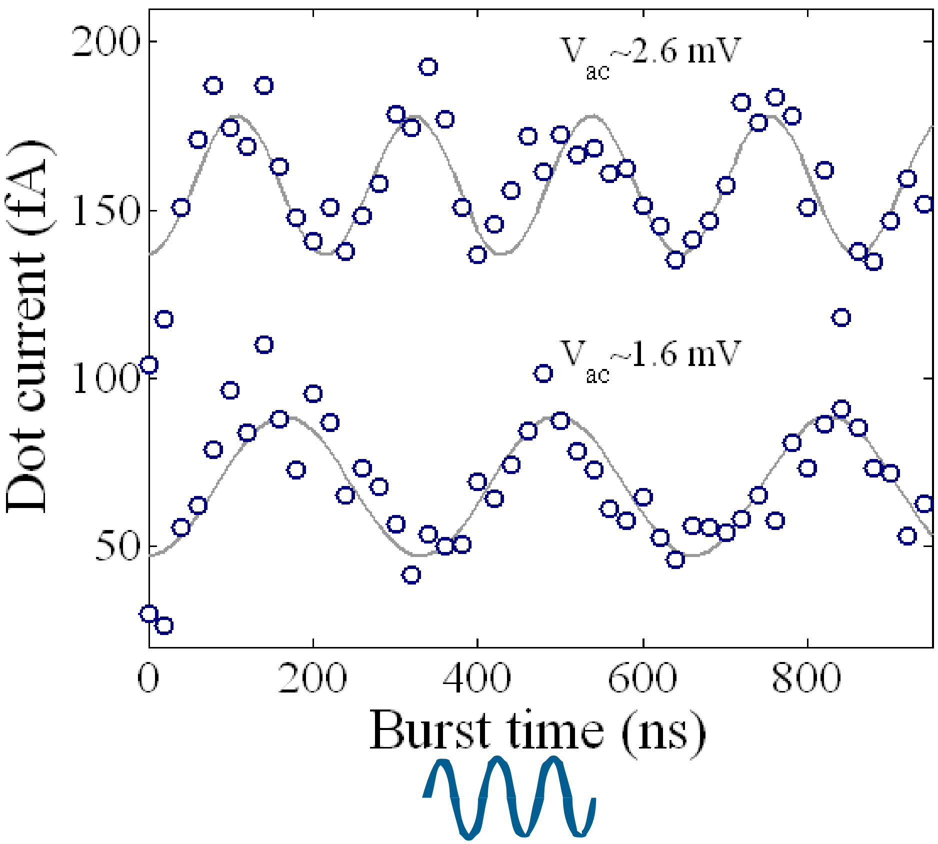




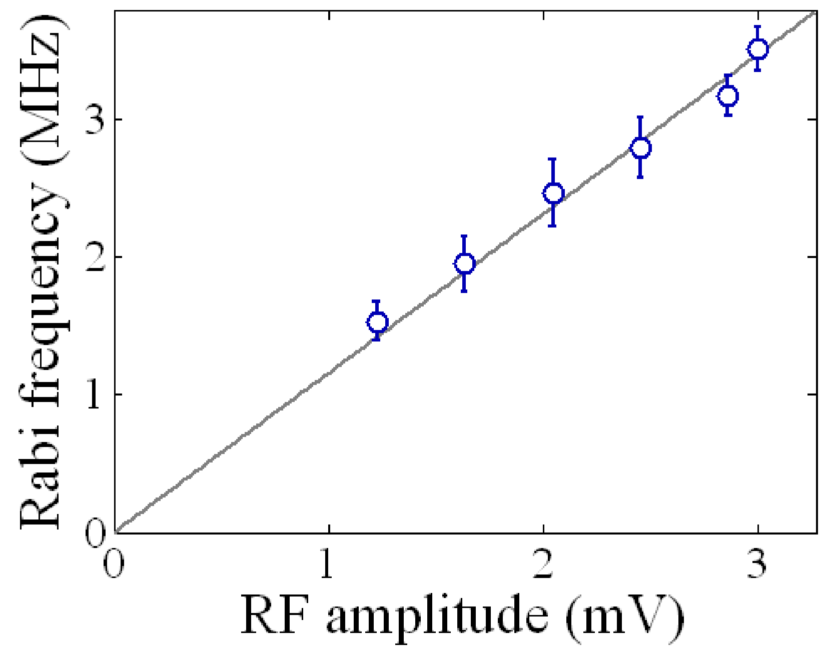


Electrically driven Rabi oscillations

f_{AC}=15.2GHz



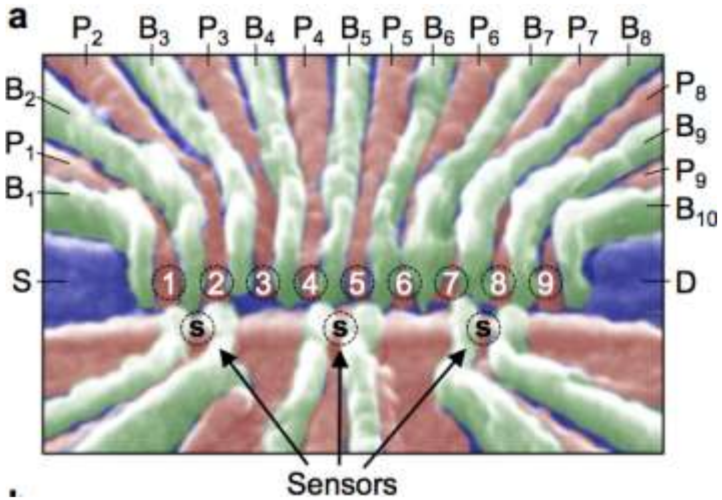
f_{AC}=14GHz



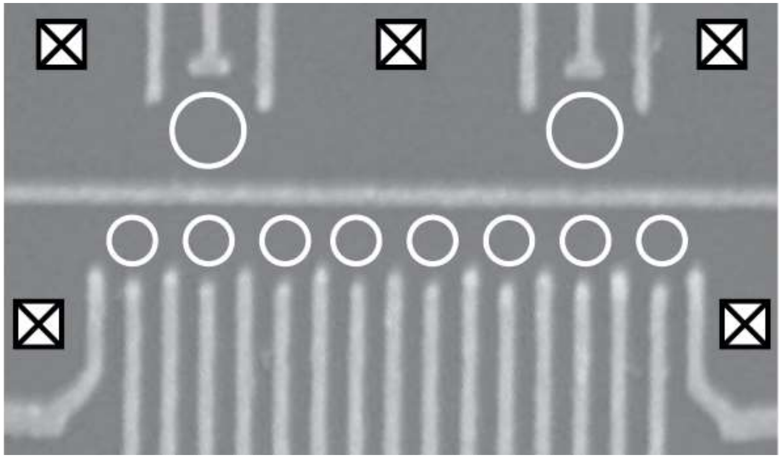
Rabi frequency depends linear on electric field amplitude

Nowack et al., *Science* ('07)

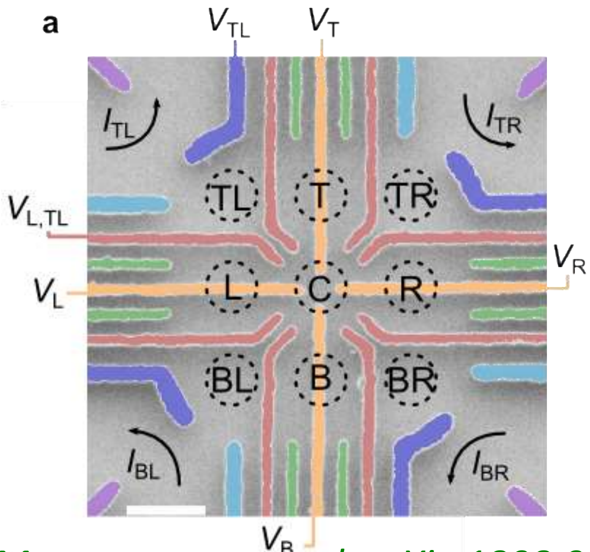
Trend 2: Scaling up tunnel coupled arrays



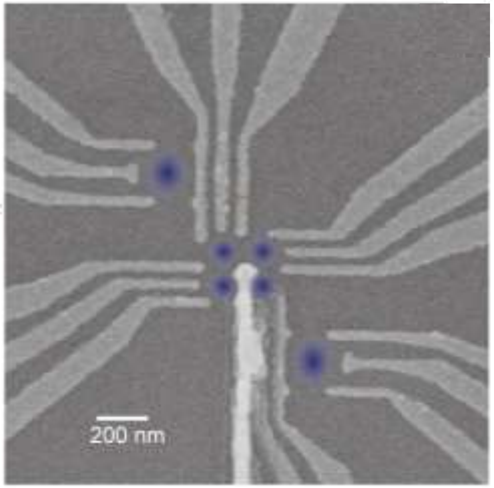
A.R. Mills et al, Nature Comm 2019



C. Volk, A-M. Zwerver et al, npj Q Info 2019

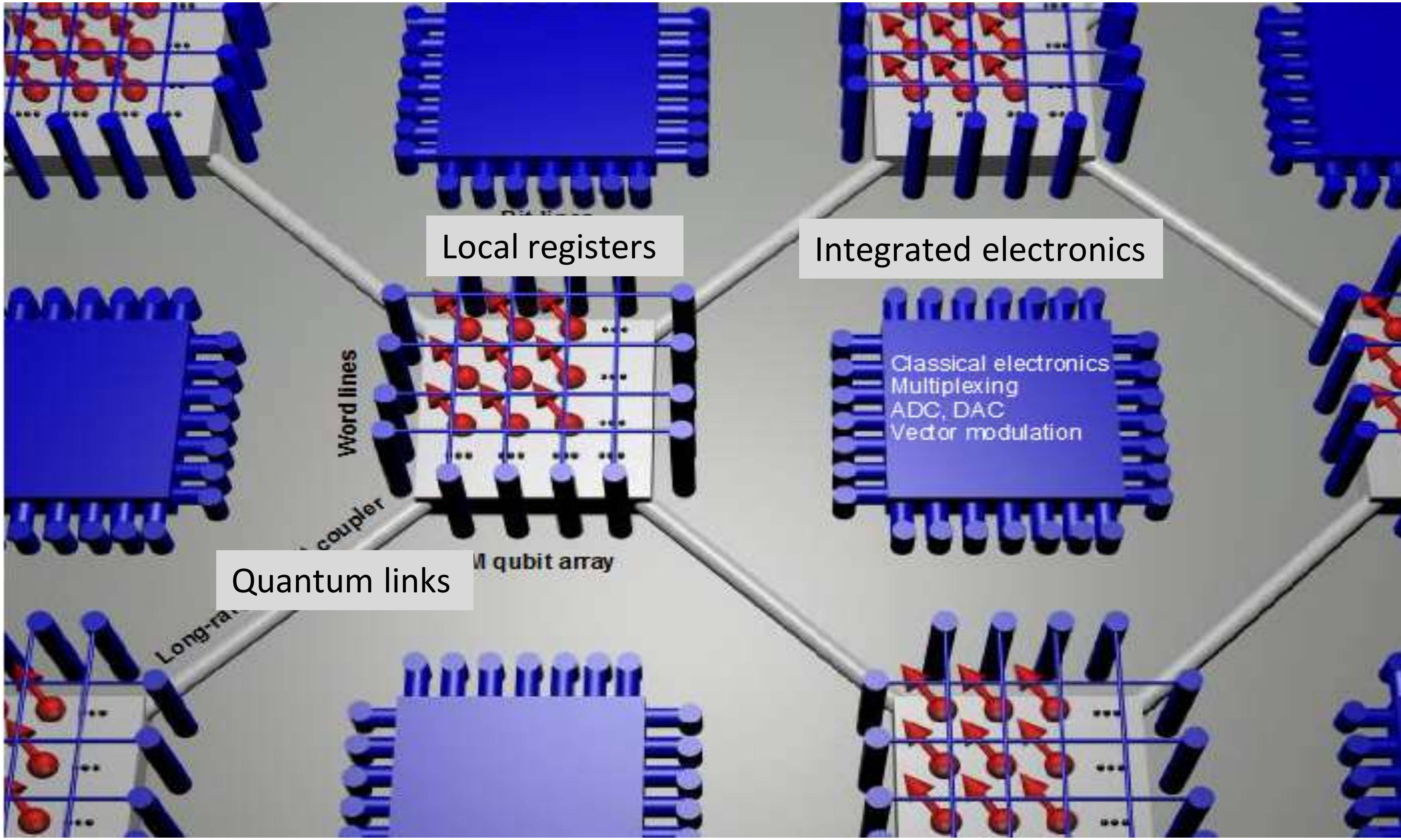


Mortemousque et al, arXiv:1808.06180



Mukhopadhyay, Dehollain et al. APL 2018

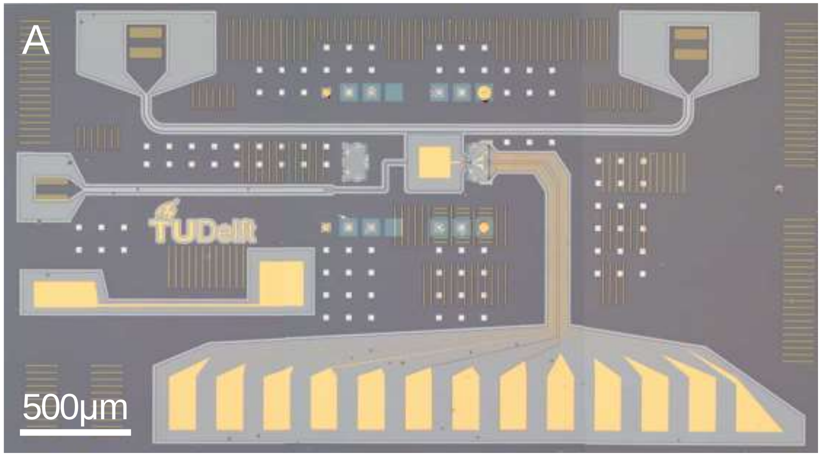
Vision of a scalable spin qubit architecture



Using the strengths of spin qubits: "Hot, dense and coherent"

Vandersypen et al., npj Q Info 2017

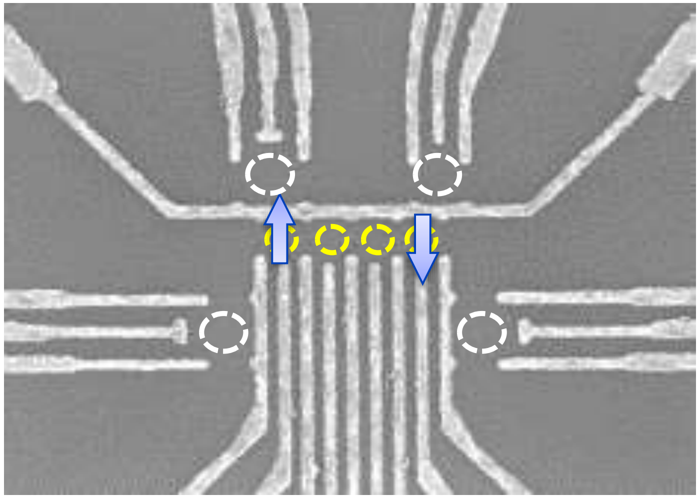
Trend 3: Distant coupling of spin qubits



Strong spin-photon coupling

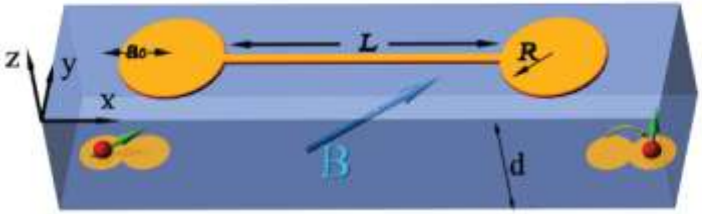
Samkharadze, Zheng, et al., Science 2018
X. Mi et al., Nature 2018
Landig, Koski, et al., Nature 2018

Spin shuttles



Fujita et al, npj Q Info 2017
Flentje et al, Nature Comm 2017

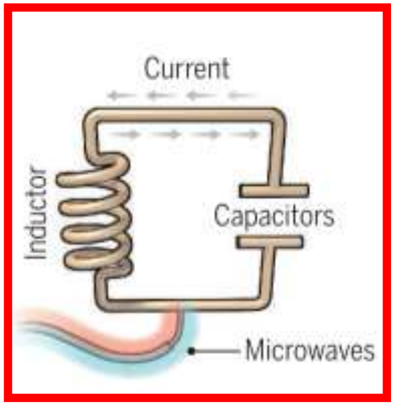
Capacitive coupling



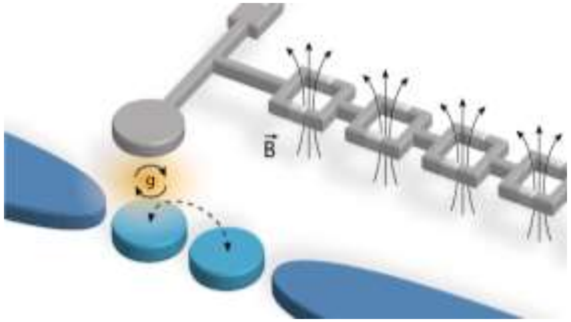
Trifunovic et al, PRX 2012
Shulman et al, Science 2015

Quantum Dot - Cavity Hybrid Technology

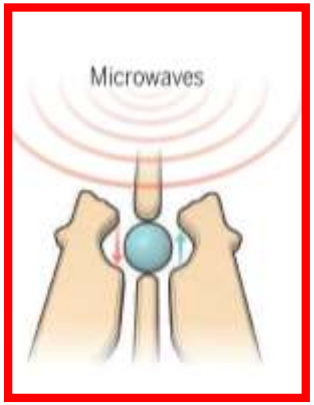
Building a coherent interface for hybrid technology via high impedance resonators



Superconducting circuits platform



Hybrid QD-resonator devices



Semiconductor QDs platform

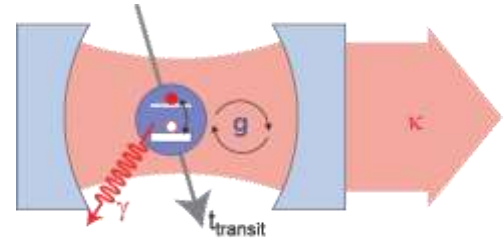
While both superconducting and semiconducting platforms have strong potential for **quantum technology** on their own, we will explore novel opportunities emerging at the interface between the two hardware.

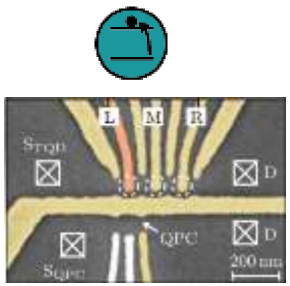
For investigating light-matter interaction **at the fundamental level** and implementing a rich set of novel applications **in quantum information technology**

Quantum Dot - Cavity Hybrid Technology

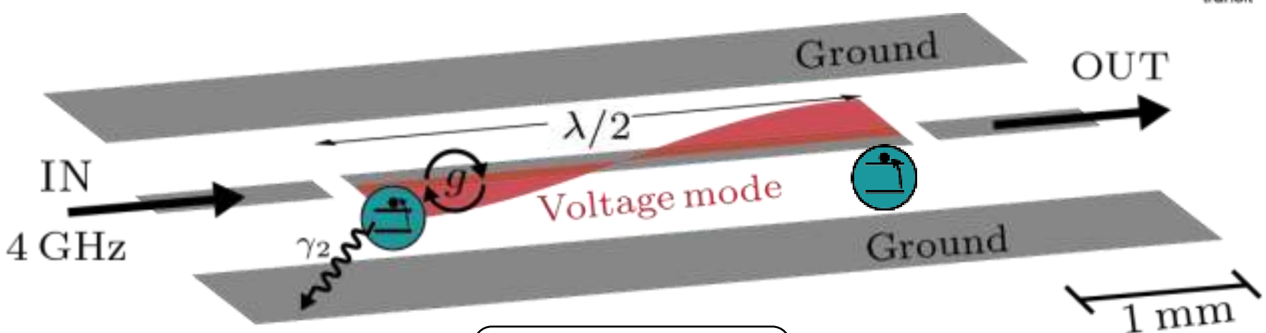
Circuit QED architecture: coherent link

t Quantum Electrodynamics





electron spin



Interaction of distant qubits

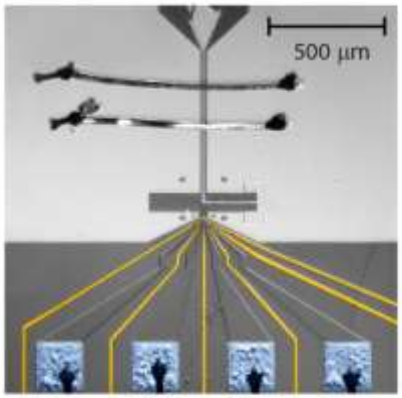
Blais *et al.*, *Phys Rev A* **69**, 062320 (2004)
Wallraff *et al.*, *Nature* **431**, 162 (2004)
Schoelkopf & Girvin, *Nature* **451**, 664 (2008)

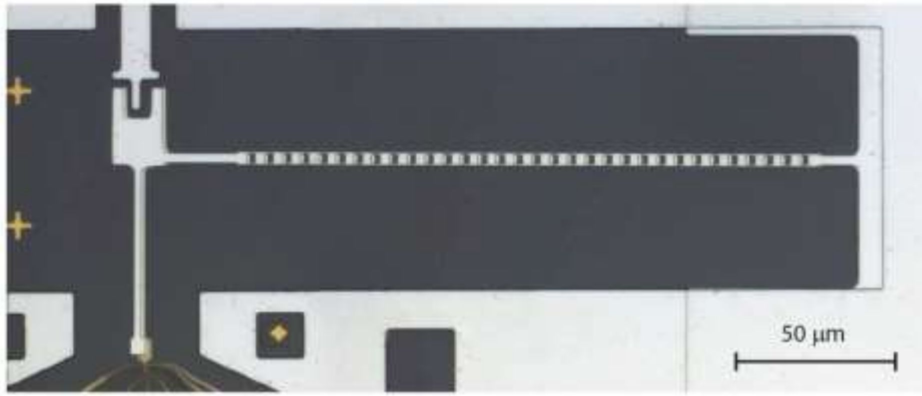
Raimond *et al.*, *Rev Mod Phys* **73**, 565 (2001)
Haroche & Raimond, OUP Oxford (2006)
Ye *et al.*, *Science* **320**, 1734 (2008)

Strong coupling of the qubit to a quantum information mediator (photon)

Quantum Dot - Cavity Hybrid Technology

Integrated GaAs DQD with SQUID Array Resonator in Hybrid Device





32 SQUID array resonator

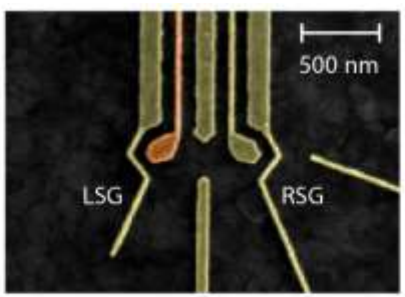
- $200\ \mu\mathrm{m}$ long
- Al based
- Dolan bridge technique

$L_\mathrm{r} \sim 40\ nH$

$C_\mathrm{r} \sim 15\ fF$

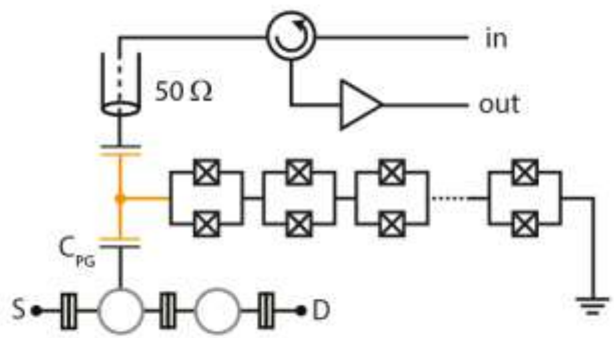
$Z_\mathrm{r} \sim 1.5\ k\Omega$

$f_\mathrm{r} \sim 6\ GHz$



Gate defined GaAs DQD

- On small mesa
- Resonator coupling gate not DC biased

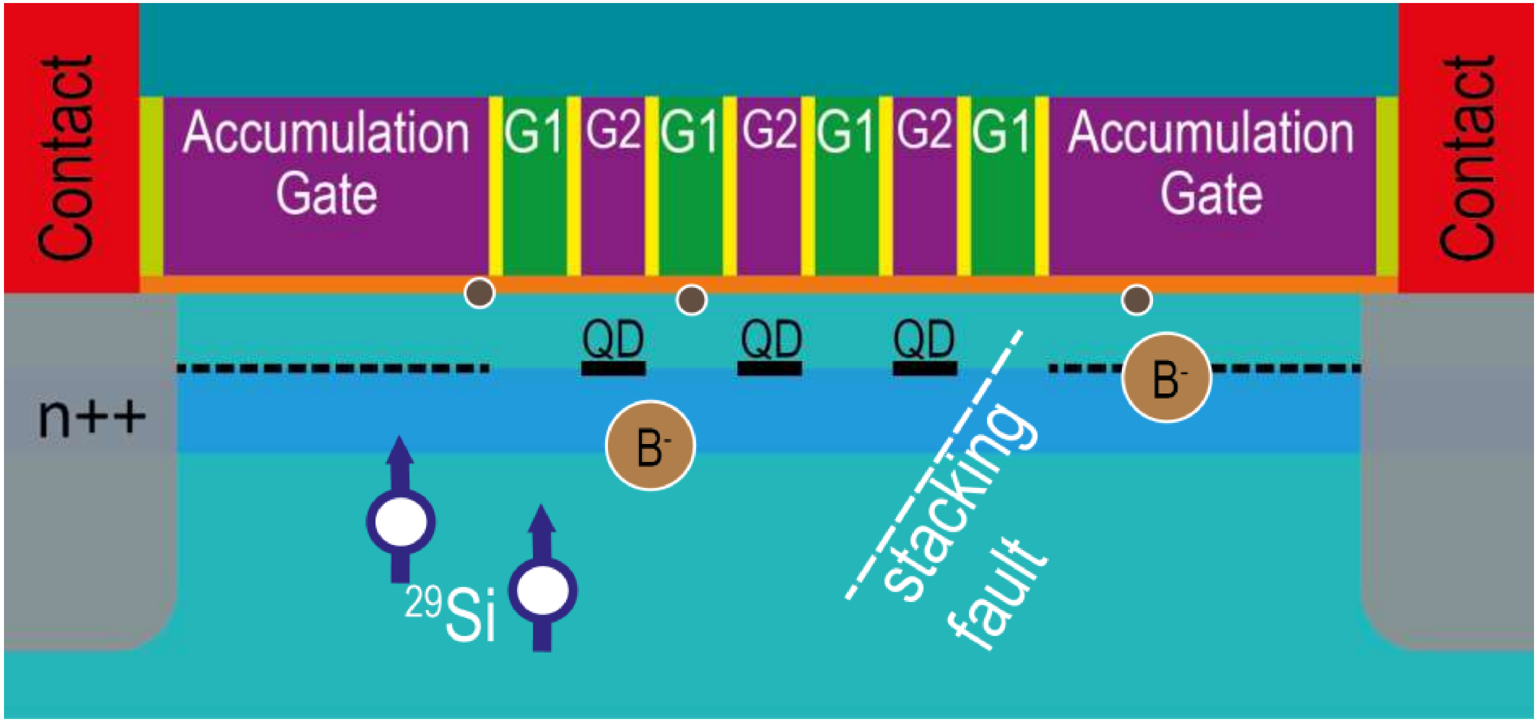


Microwave reflectometry measurement

- Josephson parametric amplifier
- Custom FPGA electronics

Stockklauser*, Scarlino* *et al., PRX* **7**, 011030 (2017)

Challenge: Qubits have personalities



Qubit is very sensitive to litho variations, scattering, defects, charge noise and even nuclear spins

Trend 4: Qubits made by advanced semiconductor manufacturing

QuTech-Intel collaboration

10 years, 50 M$

Silicon spin qubits

Transmon qubits

Architecture, Cryo-CMOS,

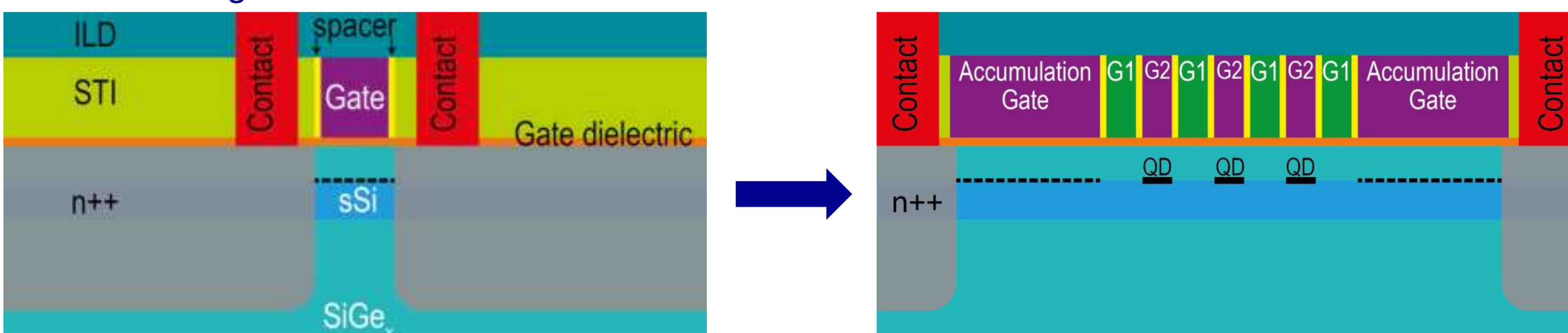
Interconnects

arXiv:2101.12650

Quantum dots made @ Intel 300 mm cleanroom

Transistor: 1 gate / 1 device

QDots: 2N+3 gates / N devices

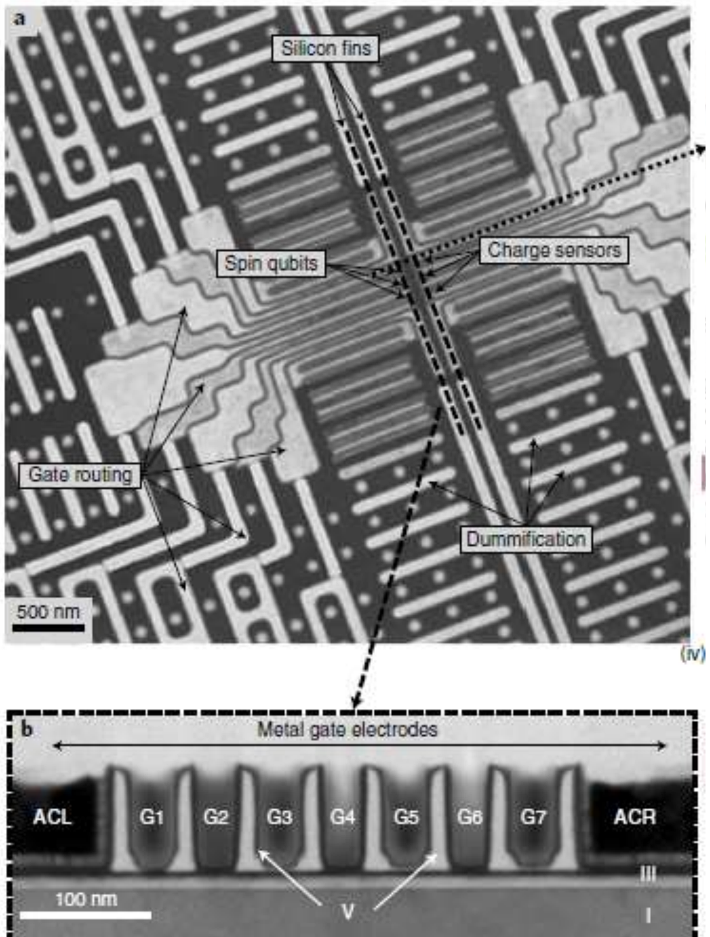


ARTICLES
https://doi.org/10.1038/s41928-022-00727-9
nature electronics

Check for updates

OPEN

Qubits made by advanced semiconductor manufacturing



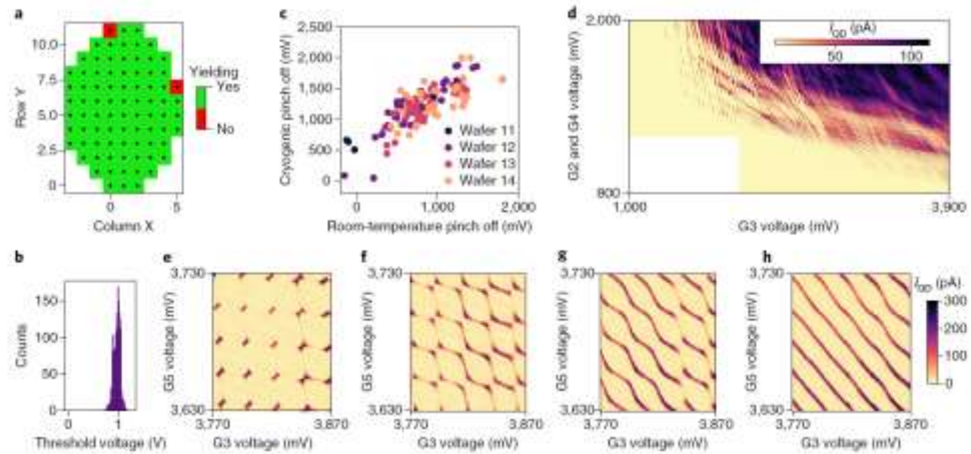
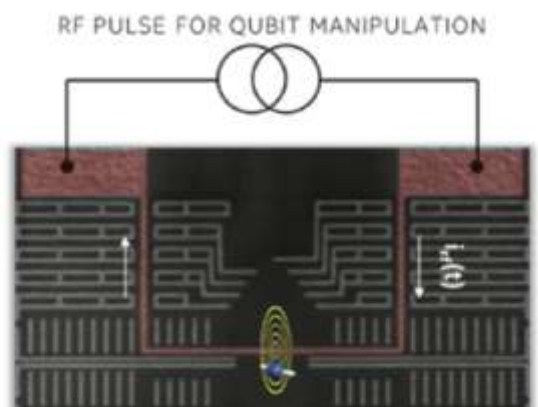


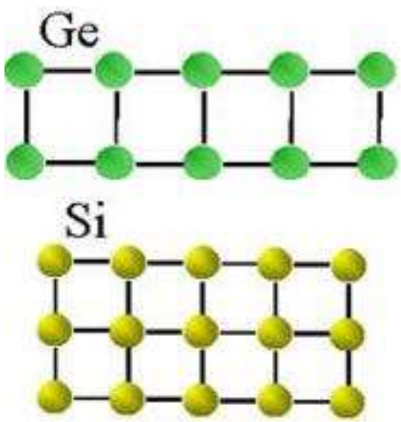
Fig. 2 | Tuneable single and double (
the main text. b, Histogram of room-
wafers 11–14 (2,288 gates from 286
voltages at room temperature and lo
for a single QD measured via electro
gradually increased (G4 is 1,245 mV,



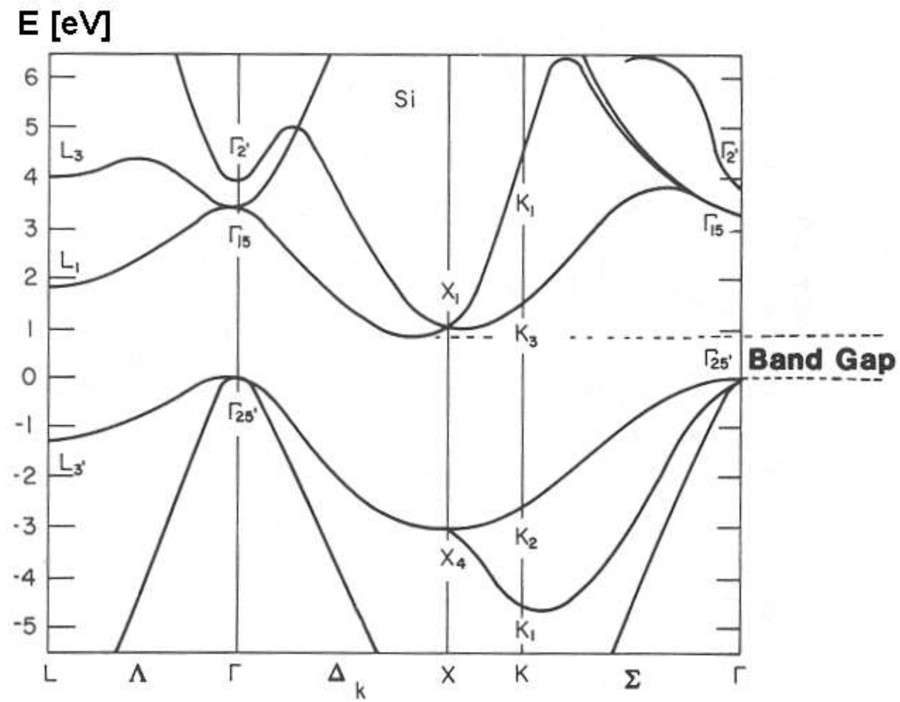
SR striplines. The yield is defined in
G5 and G7) from yielding devices of
s 70 mV. c, Correlation map for threshold
been cooled. d, Charge stability diagram
3 and G5. The gate voltage on G4 is
rol over the interdot tunnel coupling.

Why did it take 10 years for Silicon?

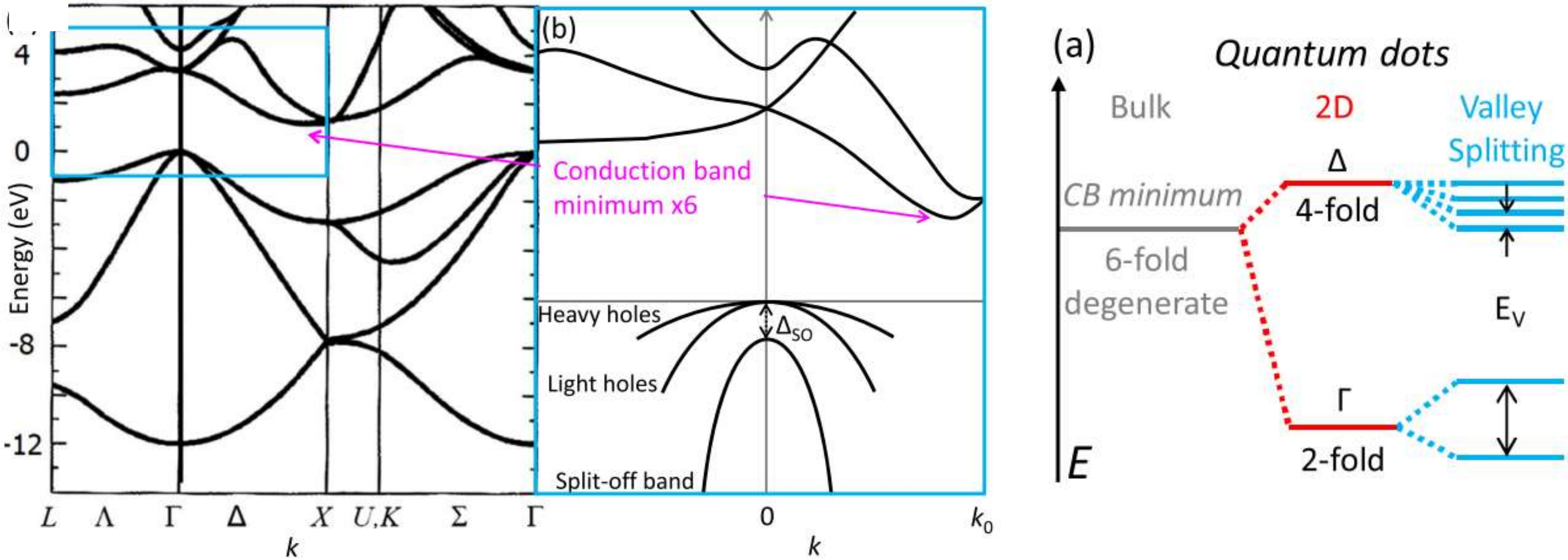
- *(Effective mass)* *$m^*_{//}$=0.2 for Si, m^*=0.067 in GaAs*
- *Fabrication issues* *lattice mismatch, defects, failing contacts, leaky gates*
- *Noisy substrates*
- *Valley degree of freedom*



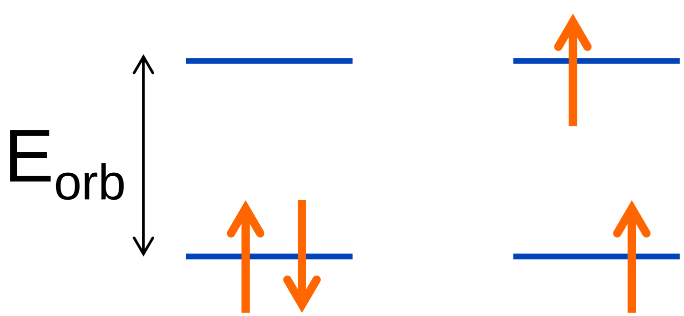
4.2% mismatch

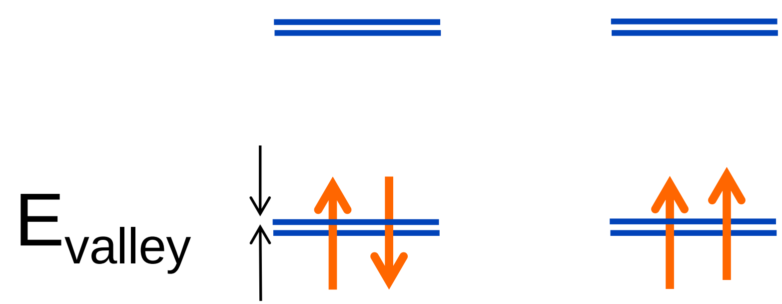


Valley splitting in silicon



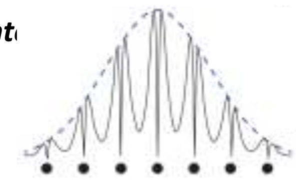
Zwanenburg et al, Rev. Mod. Phys. **85**, 961 (2013)



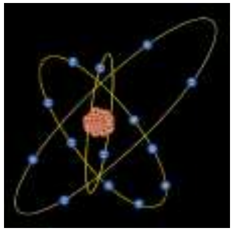


Trend 5: Holes' spins in Germanium

- ***Suppressed Hyperfine int***

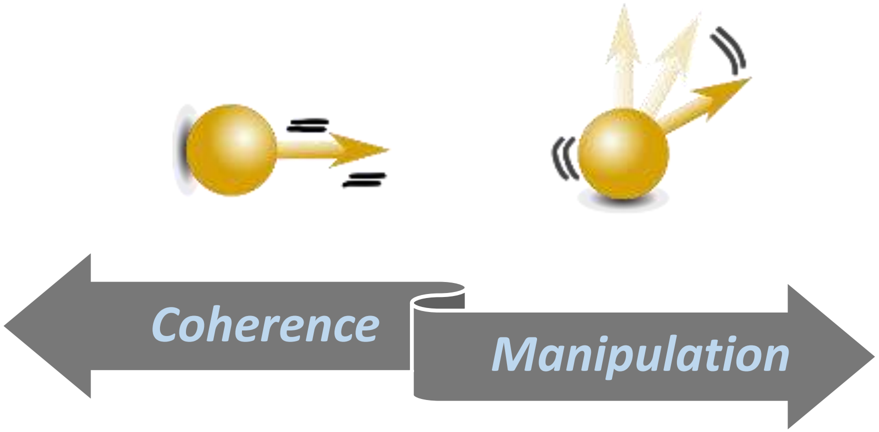


- ***Mostly nuclear spin zero***



Ge: 92.2 % **Si:** 95.3 %

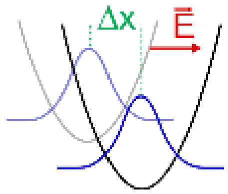
- ***More advantages:***
  - High mobility
  - No valley degeneracy



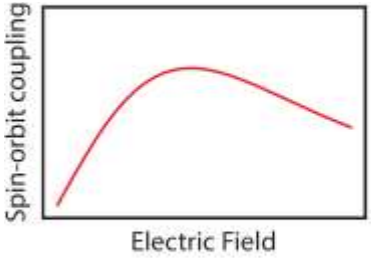
Relaxation (T_1)	*Single- and two-qubit gates*
Decoherence (T_2)	*Long-distance coupling*
	Individual addressability

⇨ ***Spin-orbit switch***

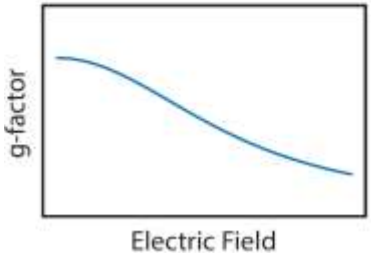
- ***Strong spin-orbit interaction***



- ***Tunable strength***



- ***Tunable g-factor/qubit***



Review articles

- **Introduction to spin qubits:**
  - **Vandersypen and Eriksson, *Physics Today* 72, 8, 38 (2019)**
- Single dots:
  - Kouwenhoven *et al*, *Rep. Progr. Phys.* **64** (6), 701 (2001)
- Double dots:
  - van der Wiel *et al*., *Rev. Mod. Phys.* **75**, 1 (2003)
- Spins in dots
  - Hanson et al, Rev. Mod. Phys. **79,** 1217 (2007)
- Spin qubits in silicon
  - Zwanenburg et al, Rev. Mod. Phys. **85**, 961 (2013)
- Scaling spin qubits
  - Vandersypen et al, npj Q Info **3**, 34 (2017)