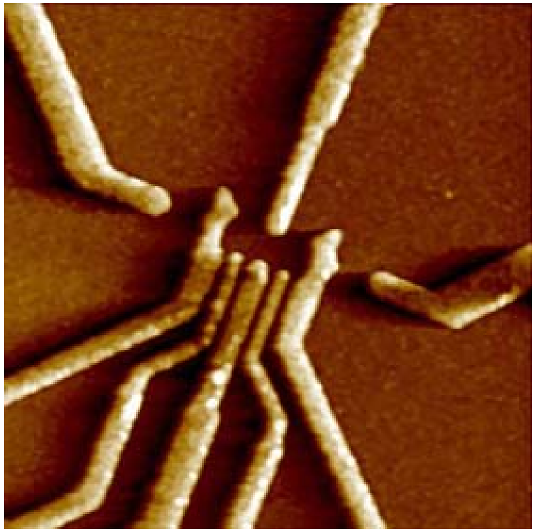
Quantum Information Processing with Semiconductor Quantum Dots



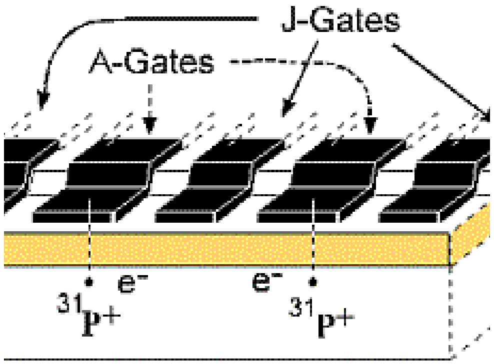
slides courtesy of Lieven Vandersypen, TU Delft

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

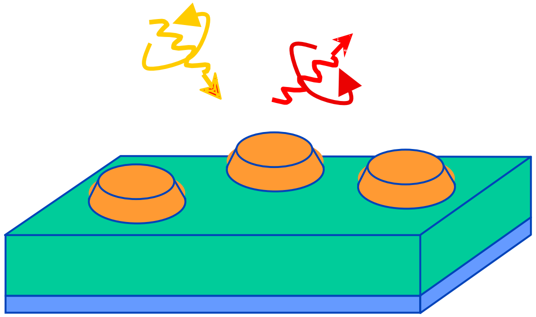
Can we access the quantum world

at the level of single-particles?

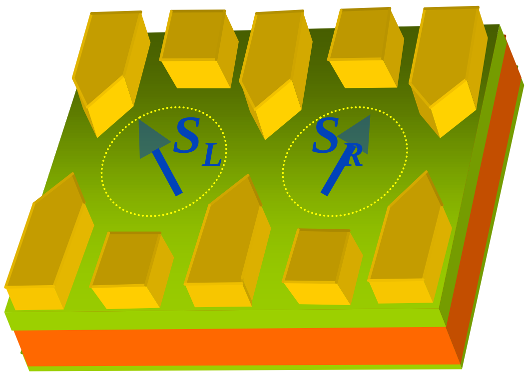
in a solid state environment?



Kane, Nature 1998



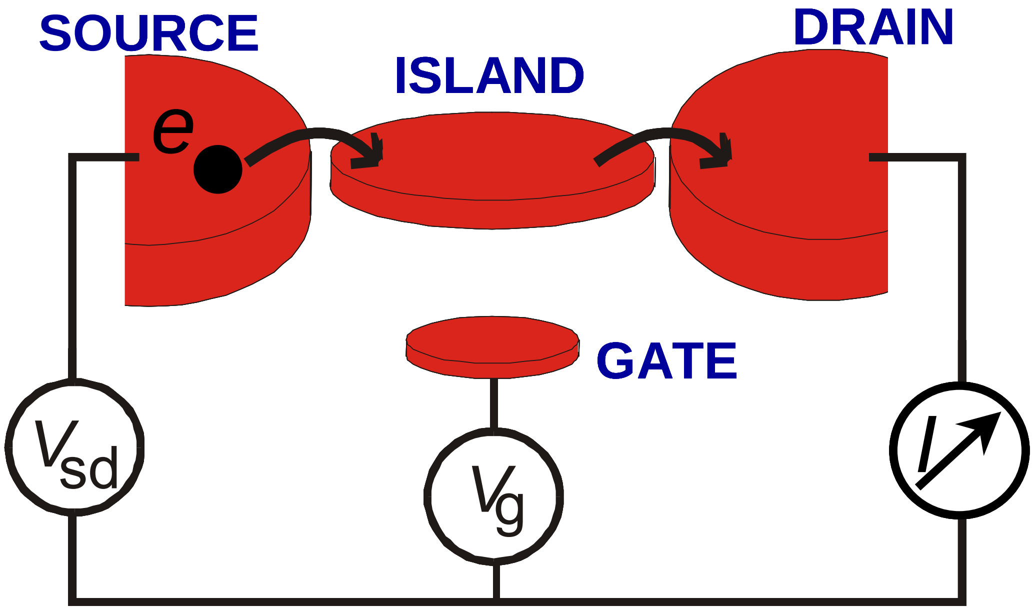
Imamoglu *et al*, PRL 1999



Loss & DiVincenzo PRA 1998

Electrically controlled and measured quantum dots

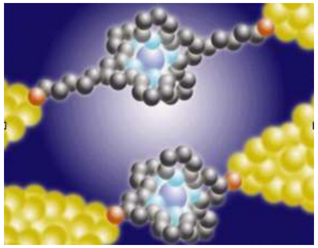
A small semiconducting (or metallic) island
where electrons are confined, giving a discrete level spectrum



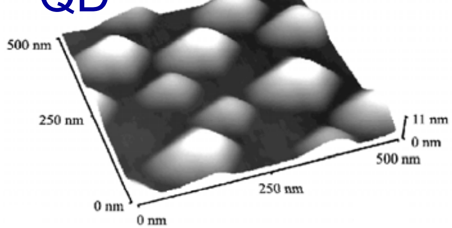
- Coupled via tunnel barriers to source and drain reservoirs
- Coupled capacitively to gate electrode, to control # of electrons

Examples of quantum dots

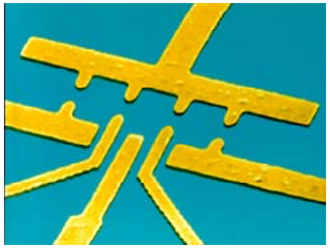
single molecule



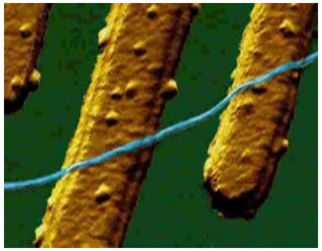
self-assembled QD



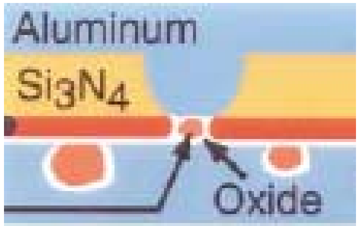
lateral QD



nanotube

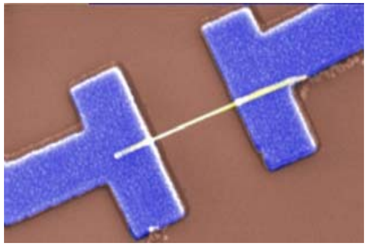


1 nm | 10 nm | 100 nm | 1μm



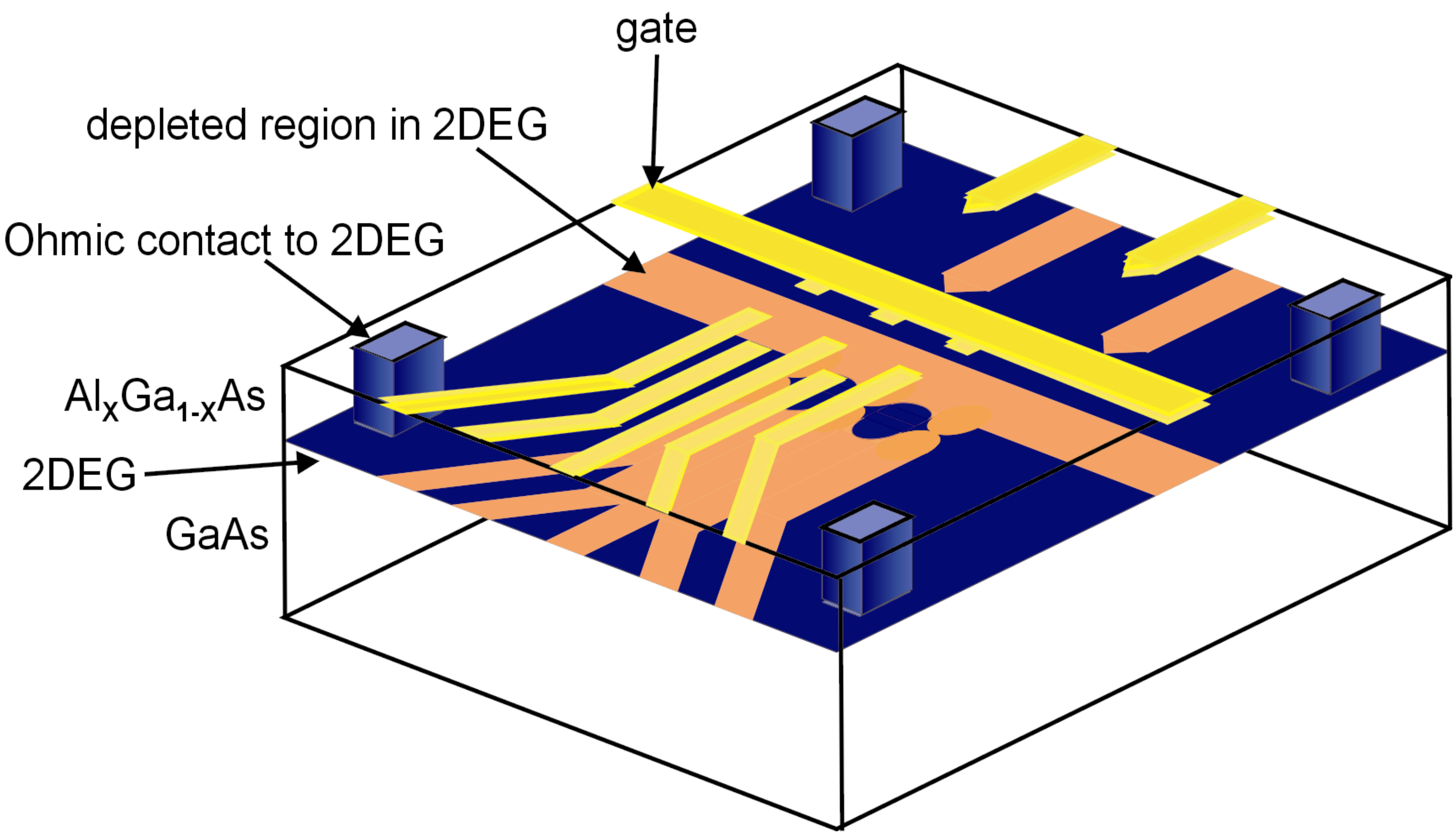
metallic nanoparticle

vertical QD



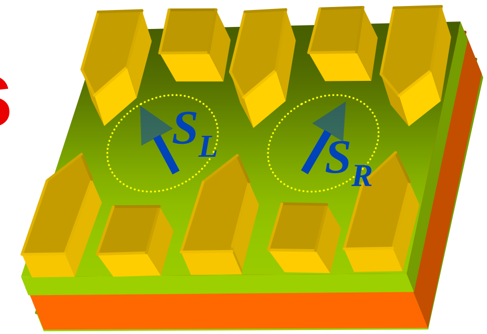
nanowire

Electrostatically defined quantum dots



- Electrically measured (contact to 2DEG)
- Electrically controlled number of electrons
- Electrically controlled tunnel barriers

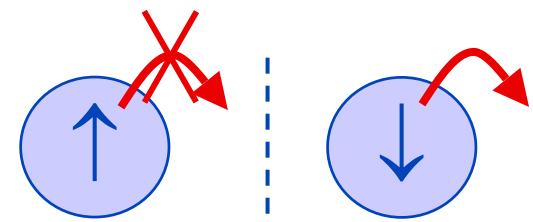
Spin qubits in quantum dots



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

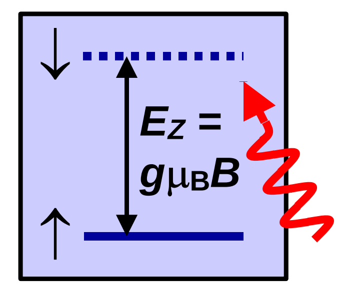
Initialization 1-electron, low T, high B_0

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



Read-out convert spin to charge

then measure charge

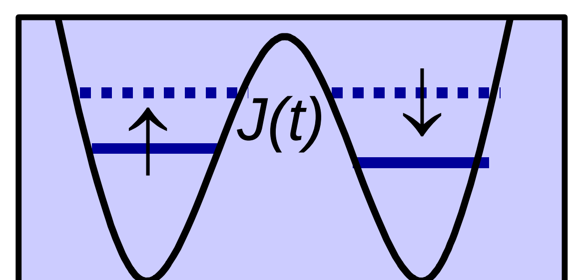


ESR pulsed microwave magnetic field

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

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

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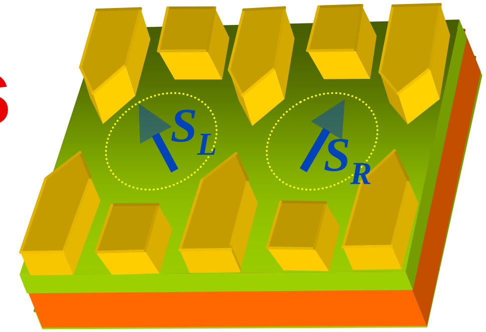

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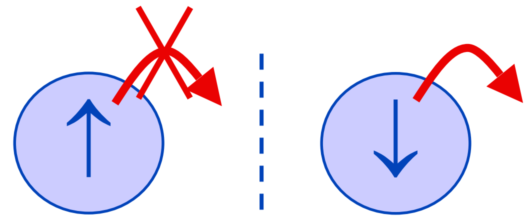

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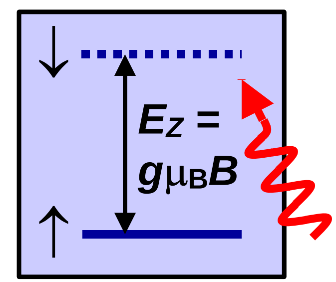

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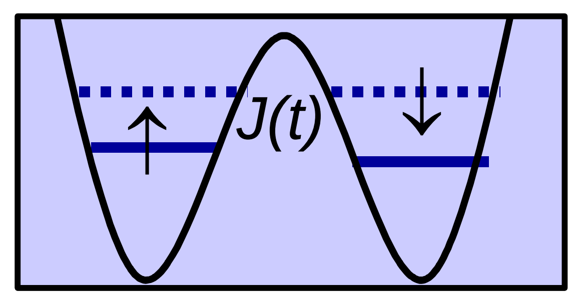
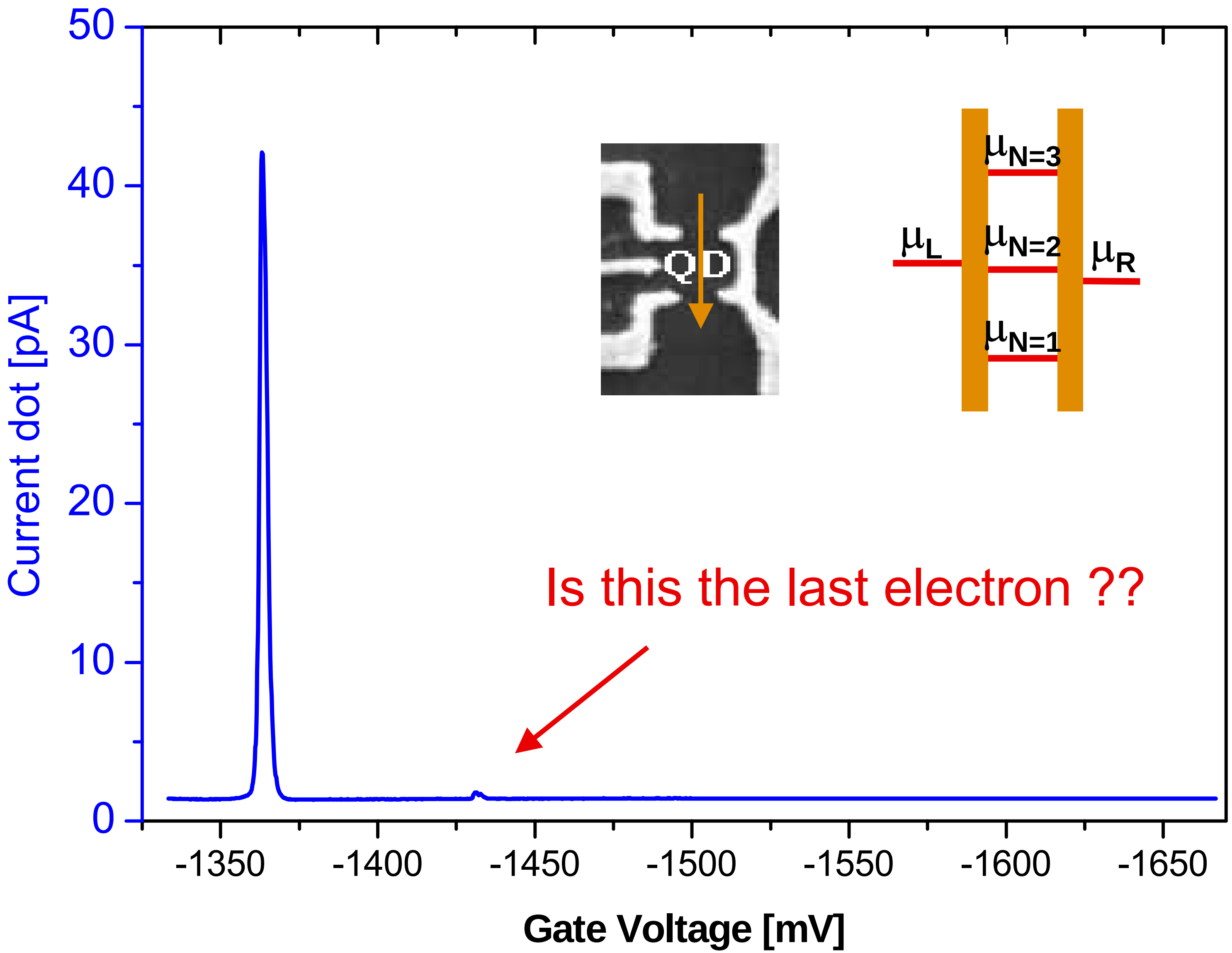


Coherence long relaxation time T_1

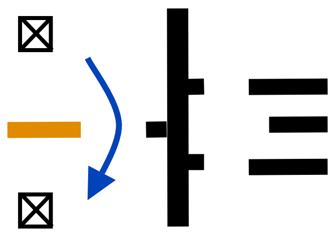
long coherence time T_2

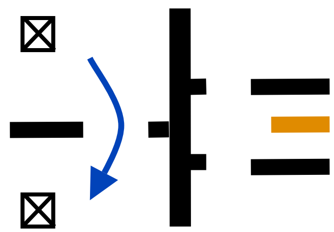
Transport through quantum dot - Coulomb blockade

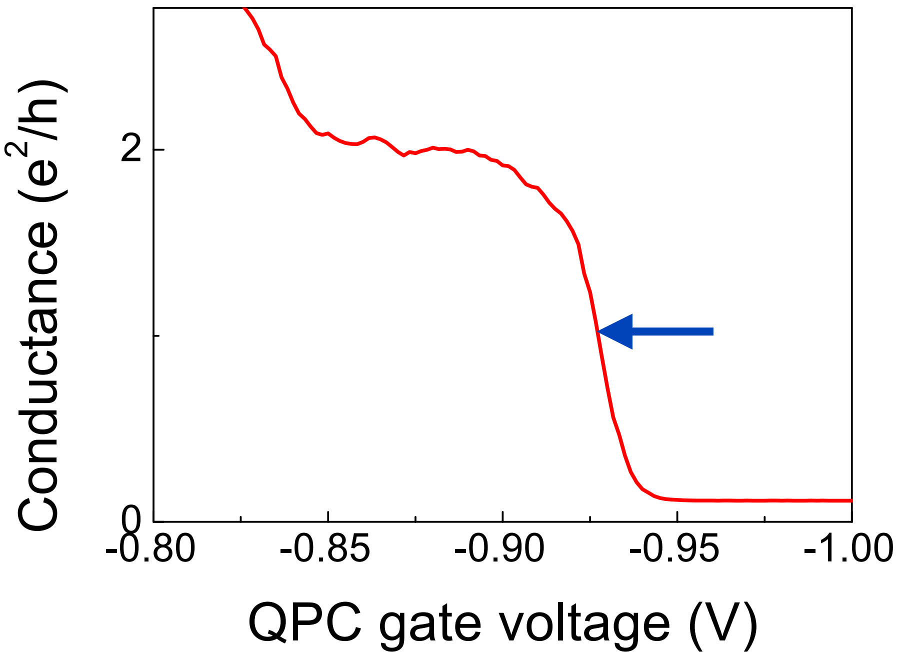


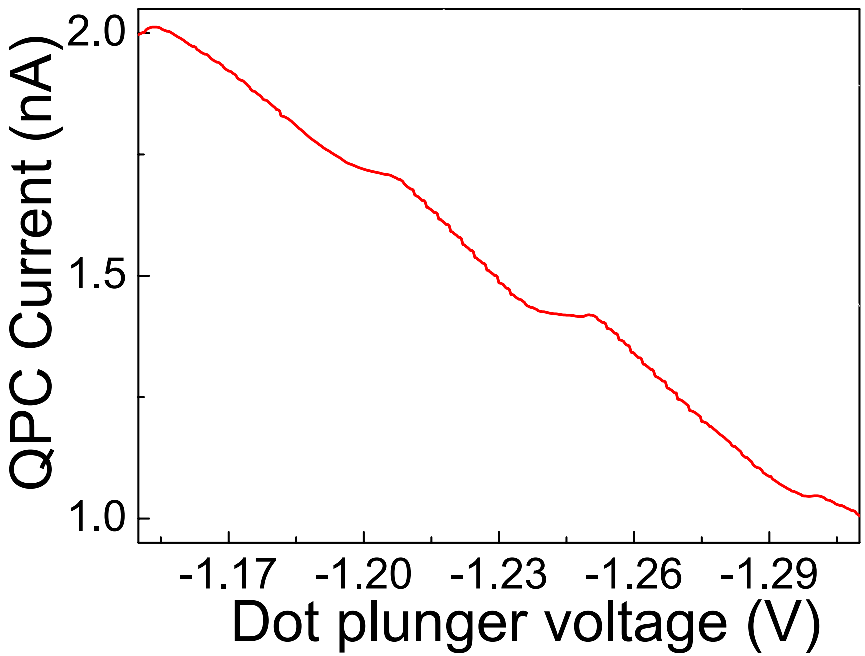
A quantum point contact (QPC) as a charge detector

Field *et al*, PRL 1993

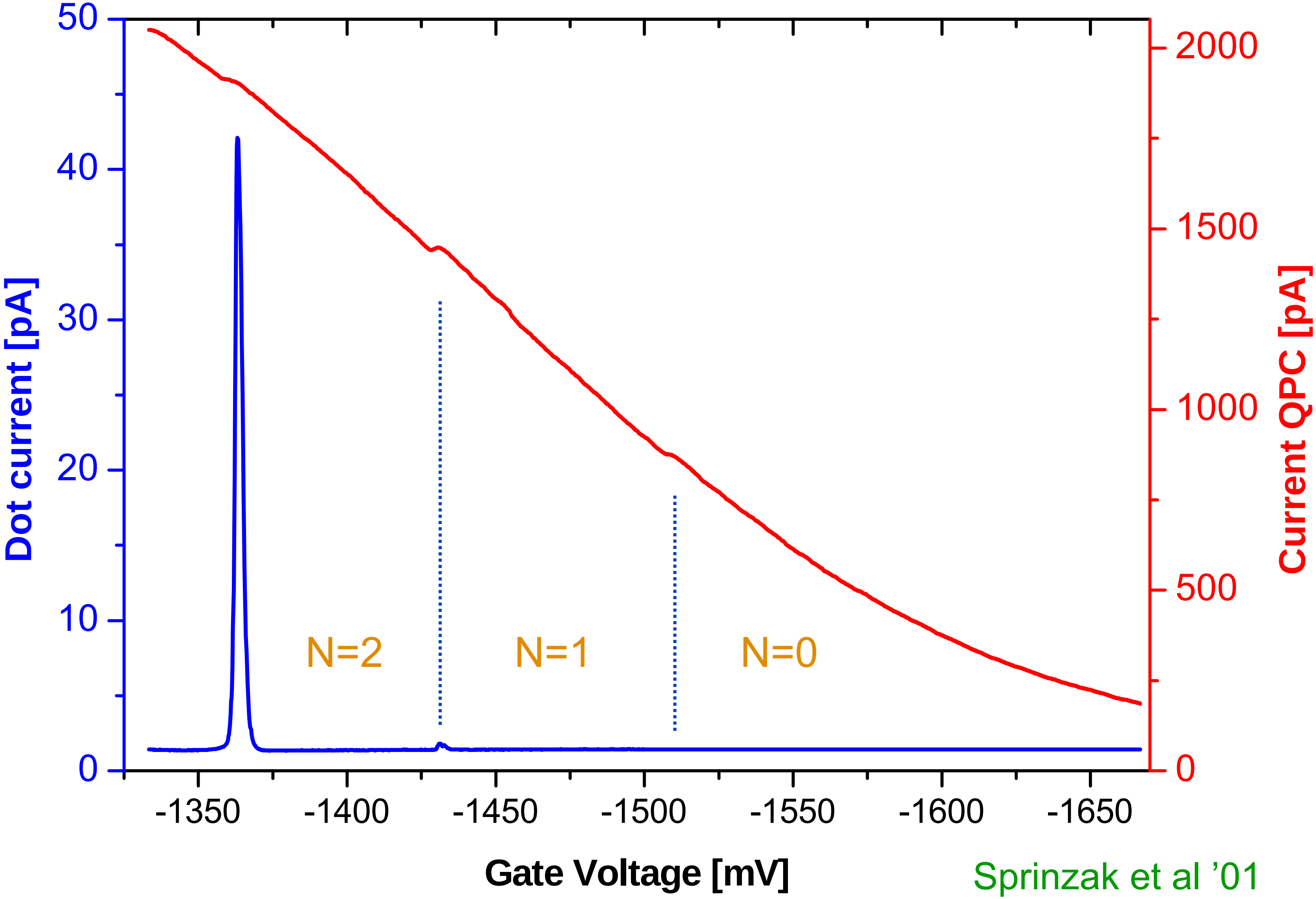








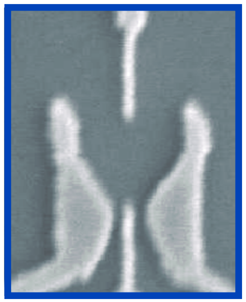
The last electron!



Sprinzak et al '01

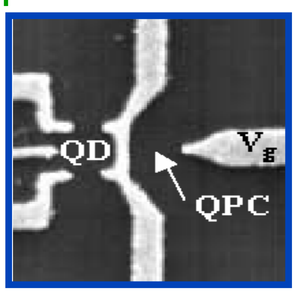
Few-electron double dot design

Ciorga et al '99



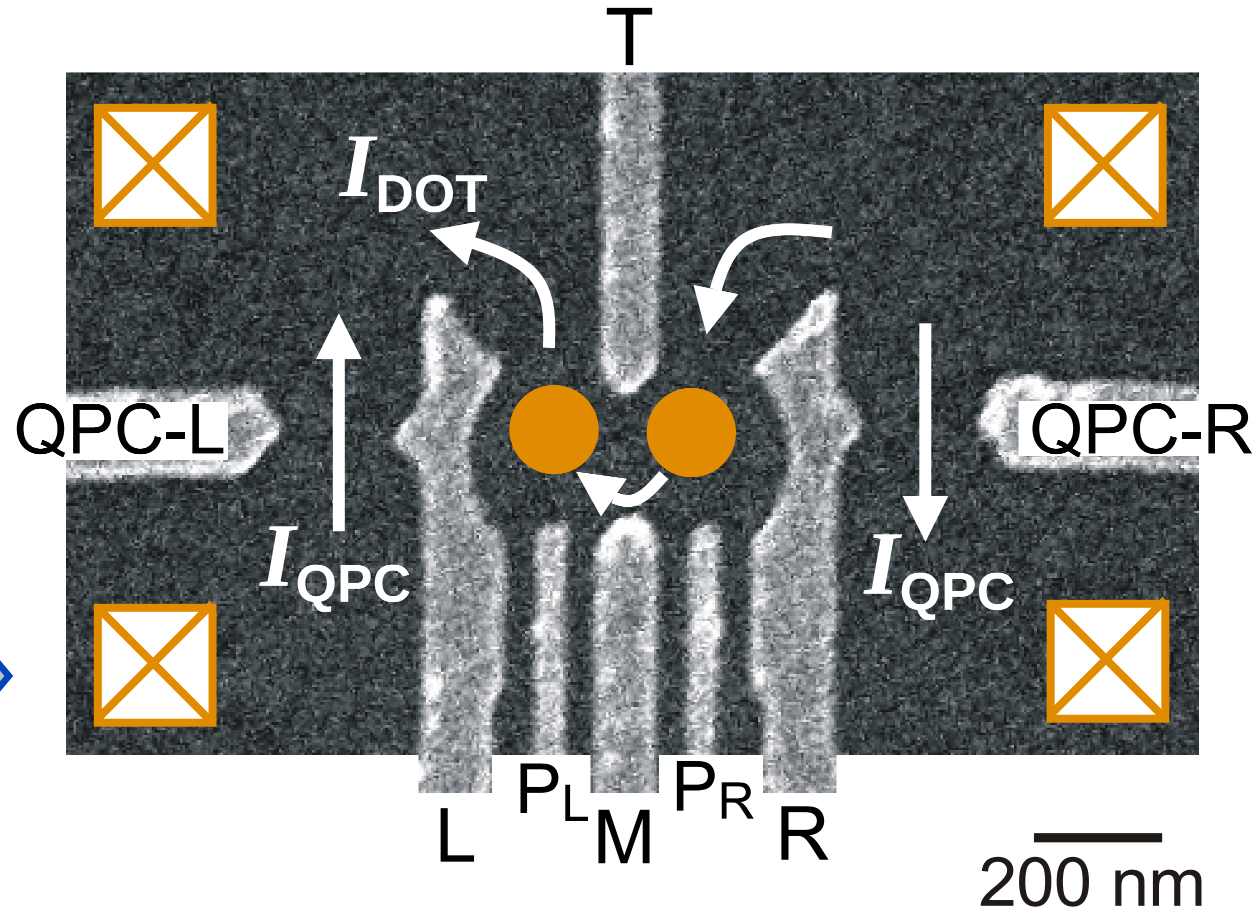
Open design

Field et al'93
Sprinzak et al '01



QPC for charge detection

Elzerman et al., PRB 2003

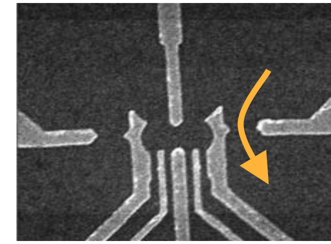


GaAs/AlGaAs wafers:

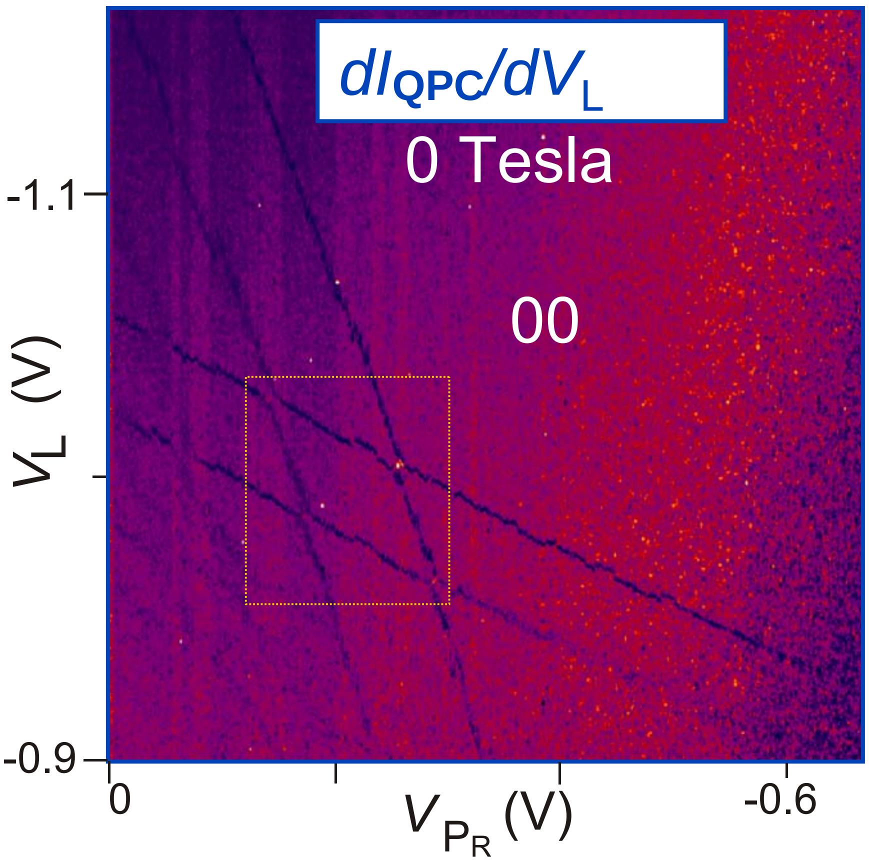
- NTT (T. Saku, Y. Hirayama)
- Sumitomo Electric
- Universität Regensburg (W. Wegscheider)

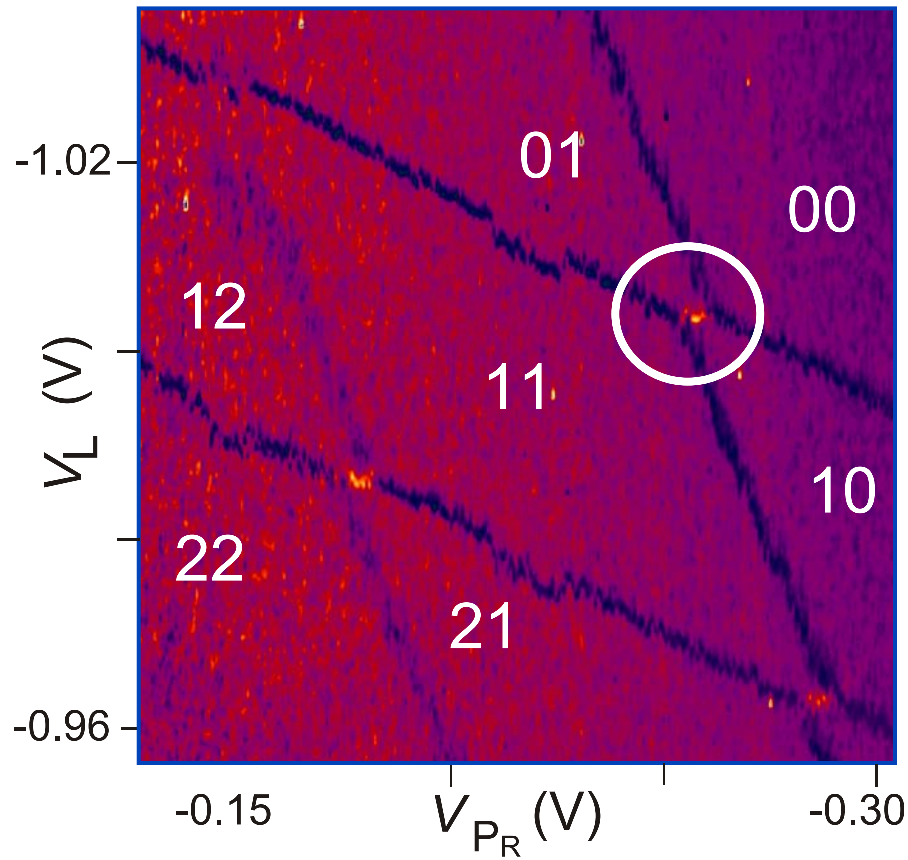
Few-electron double dot

Measured via QPC



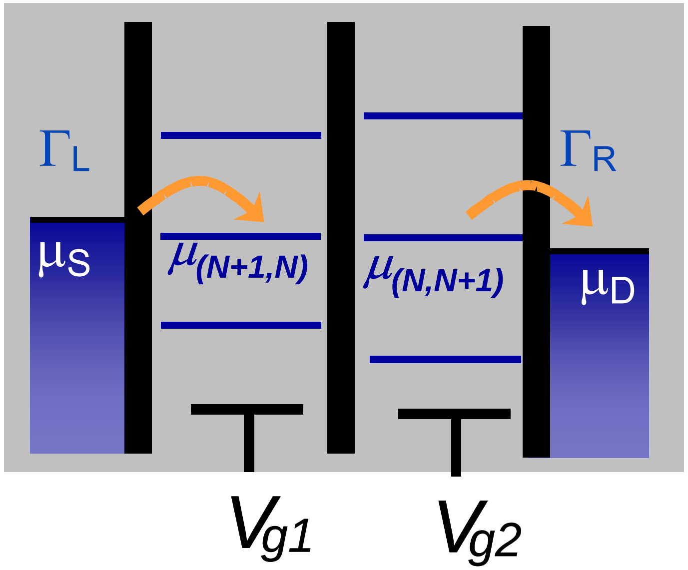
J.M. Elzerman et al., PRB **67**, R161308 (2003)





- Double dot can be emptied
- QPC can detect all charge transitions

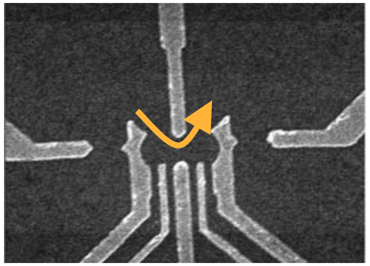
Single electron tunneling through two dots in series

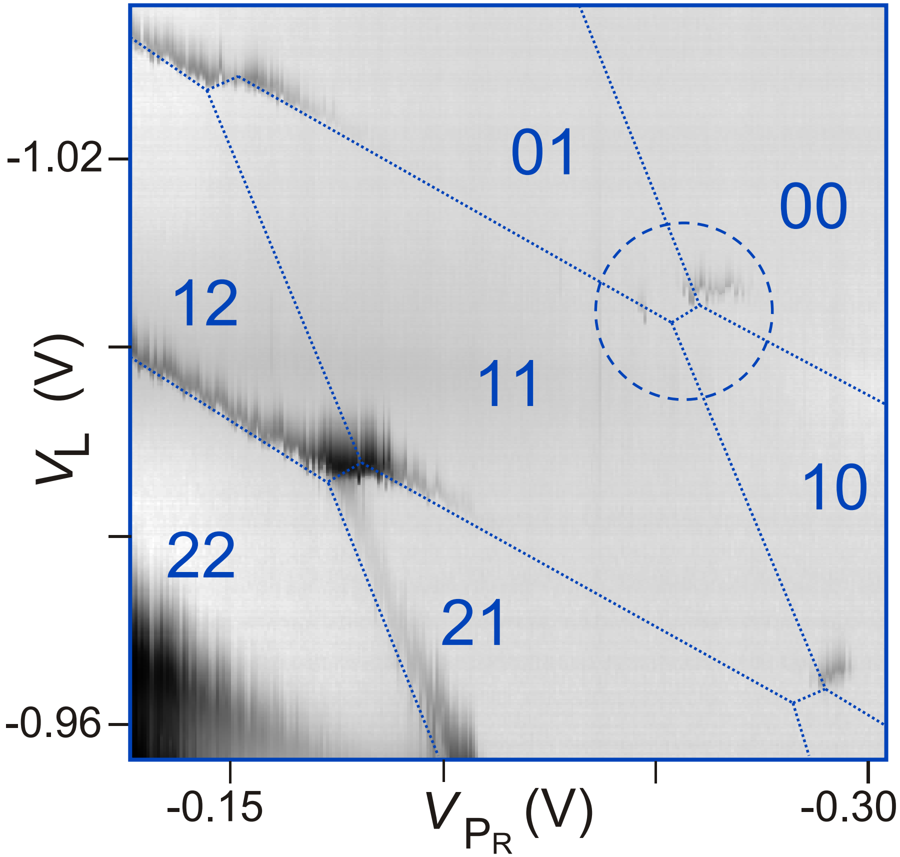


Few-electron double dot

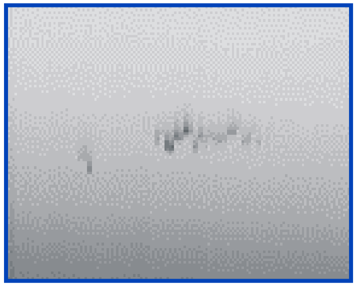
Transport through dots

J. Elzerman et al., cond-mat/0212489



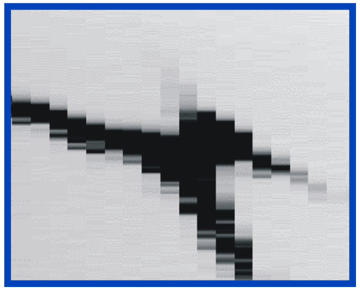


Peak height



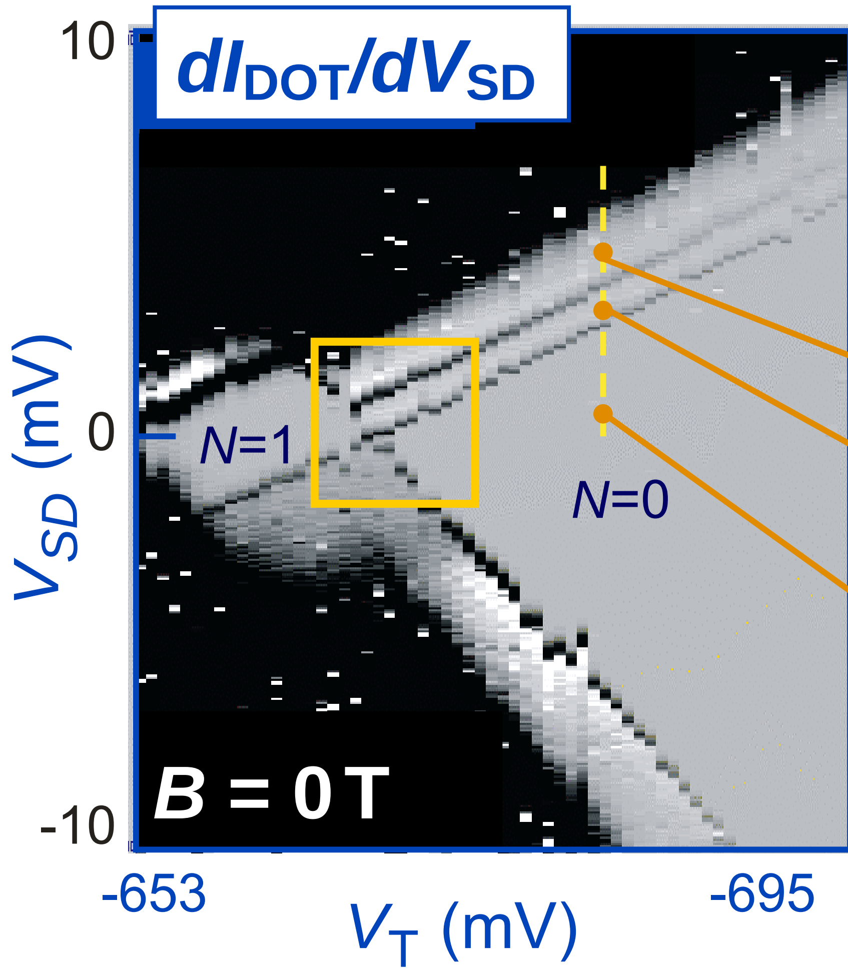
< 1 pA

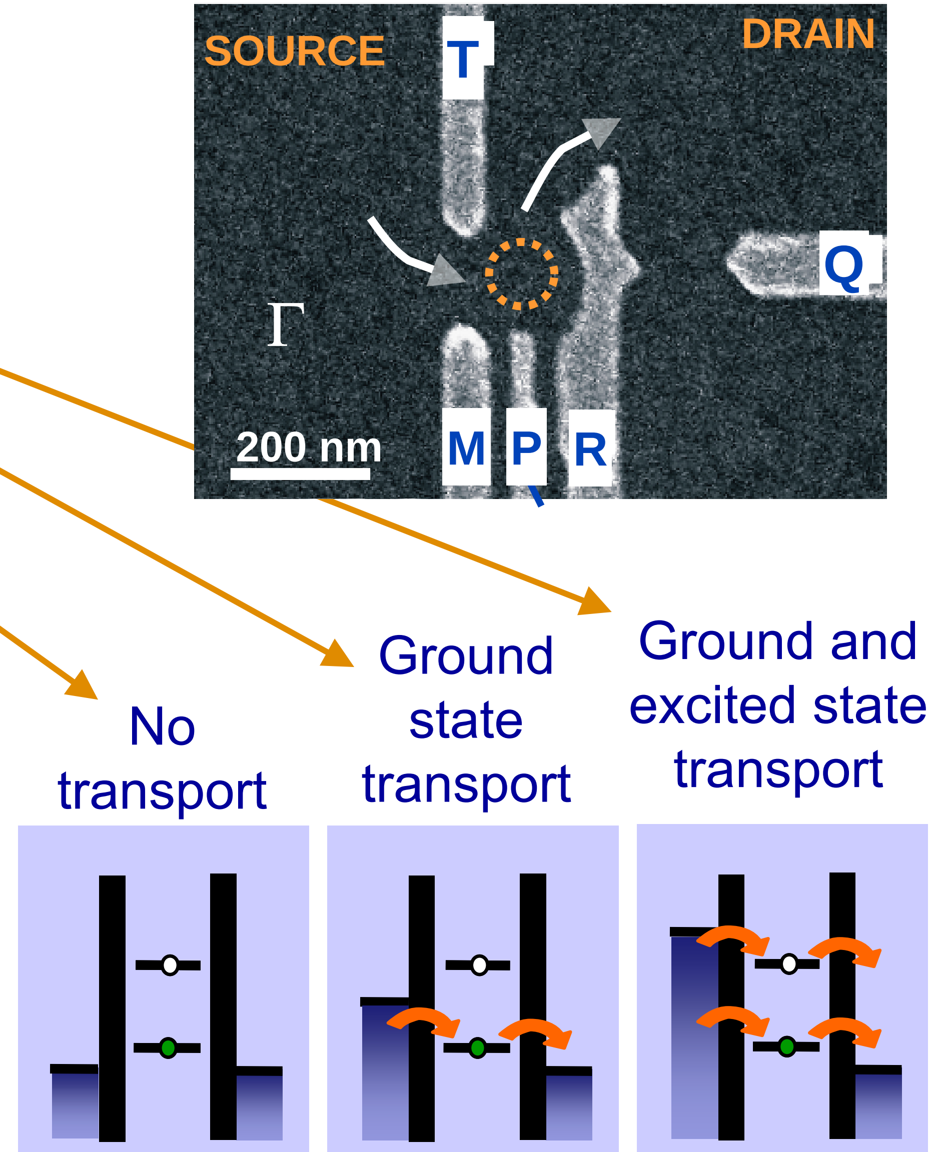
2 pA



70 pA

Energy level spectroscopy at $B = 0$

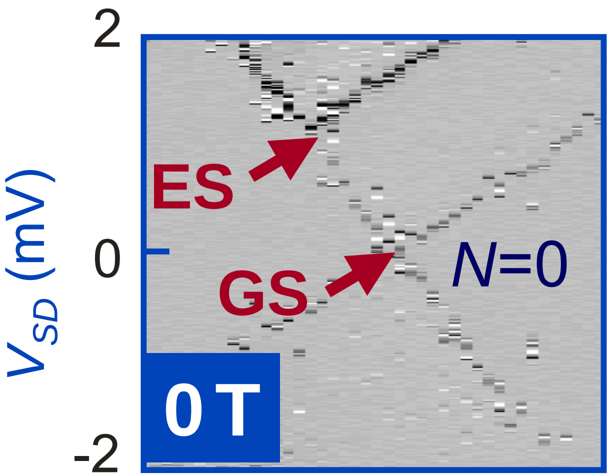


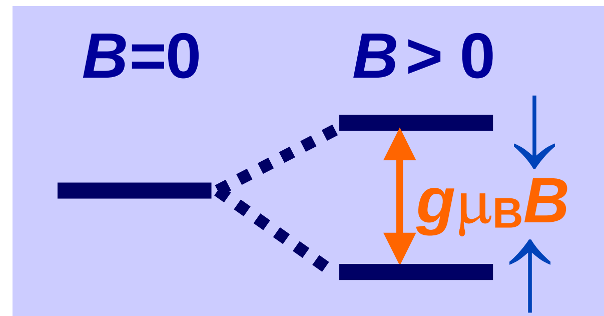


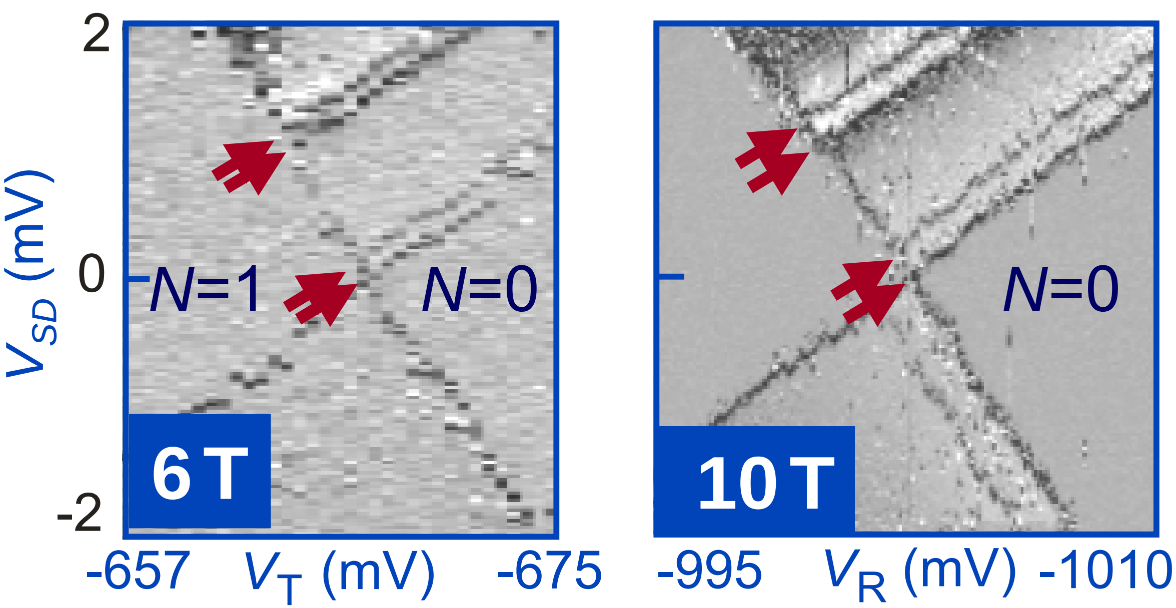
- $\Delta E \sim 1.1$meV
- $E_C \sim 2.5$meV

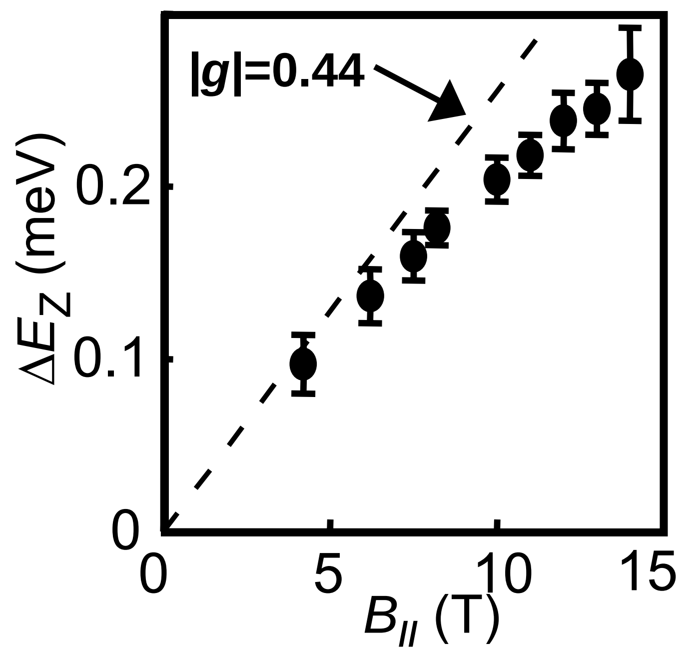
Single electron Zeeman splitting in $B_{//}$

Hanson et al, PRL 91, 196802 (2003)
Also: Potok et al, PRL 91, 016802 (2003)



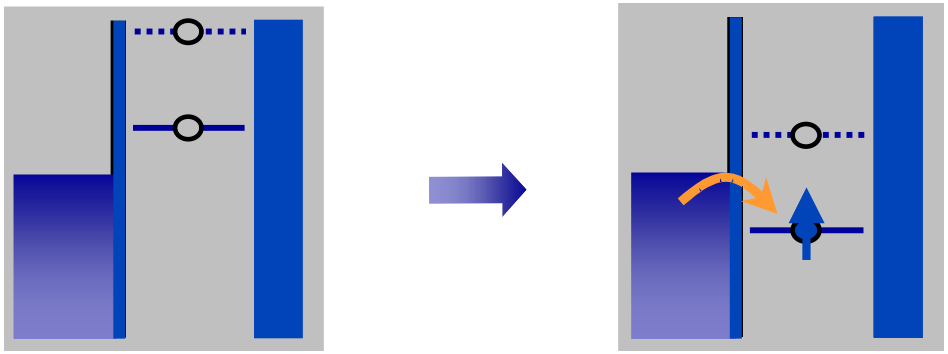




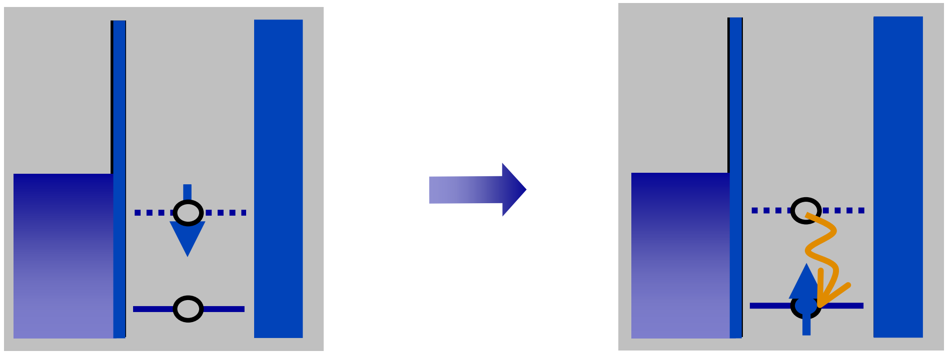


Initialization of a single electron spin

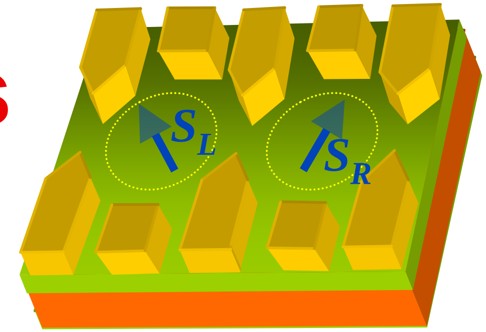
Method 1:
spin-selective
tunneling



Method 2:
relaxation to
ground state



Spin qubits in quantum dots



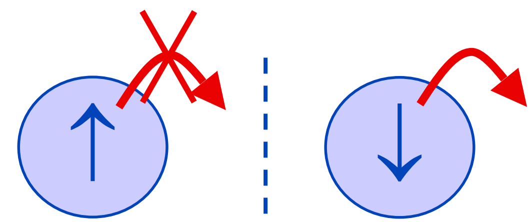
Loss & DiVincenzo, PRA 1998
Vandersypen et al., Proc. MQC02 (quant-ph/0207059)

Initialization 1-electron, low T, high B_0

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

Read-out convert spin to charge

then measure charge



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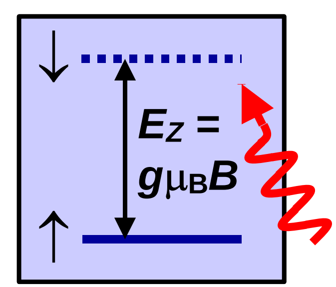

SWAP exchange interaction

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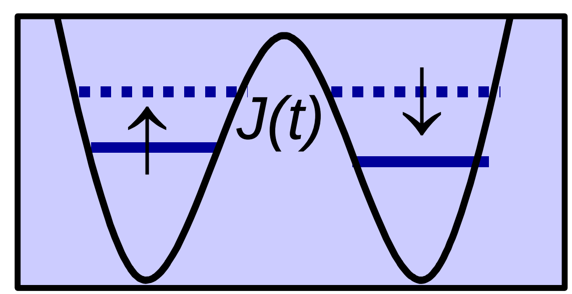
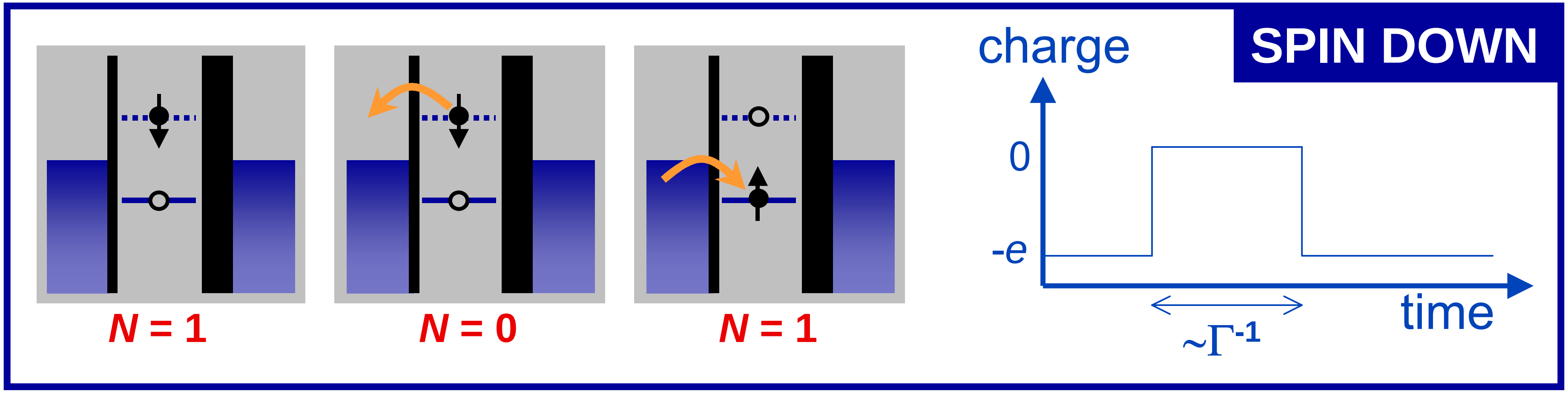


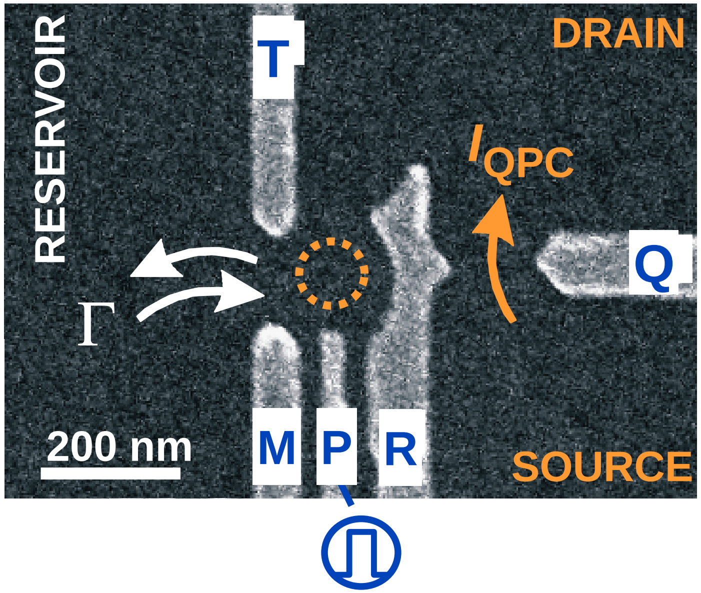
Coherence long relaxation time T_1
long coherence time T_2

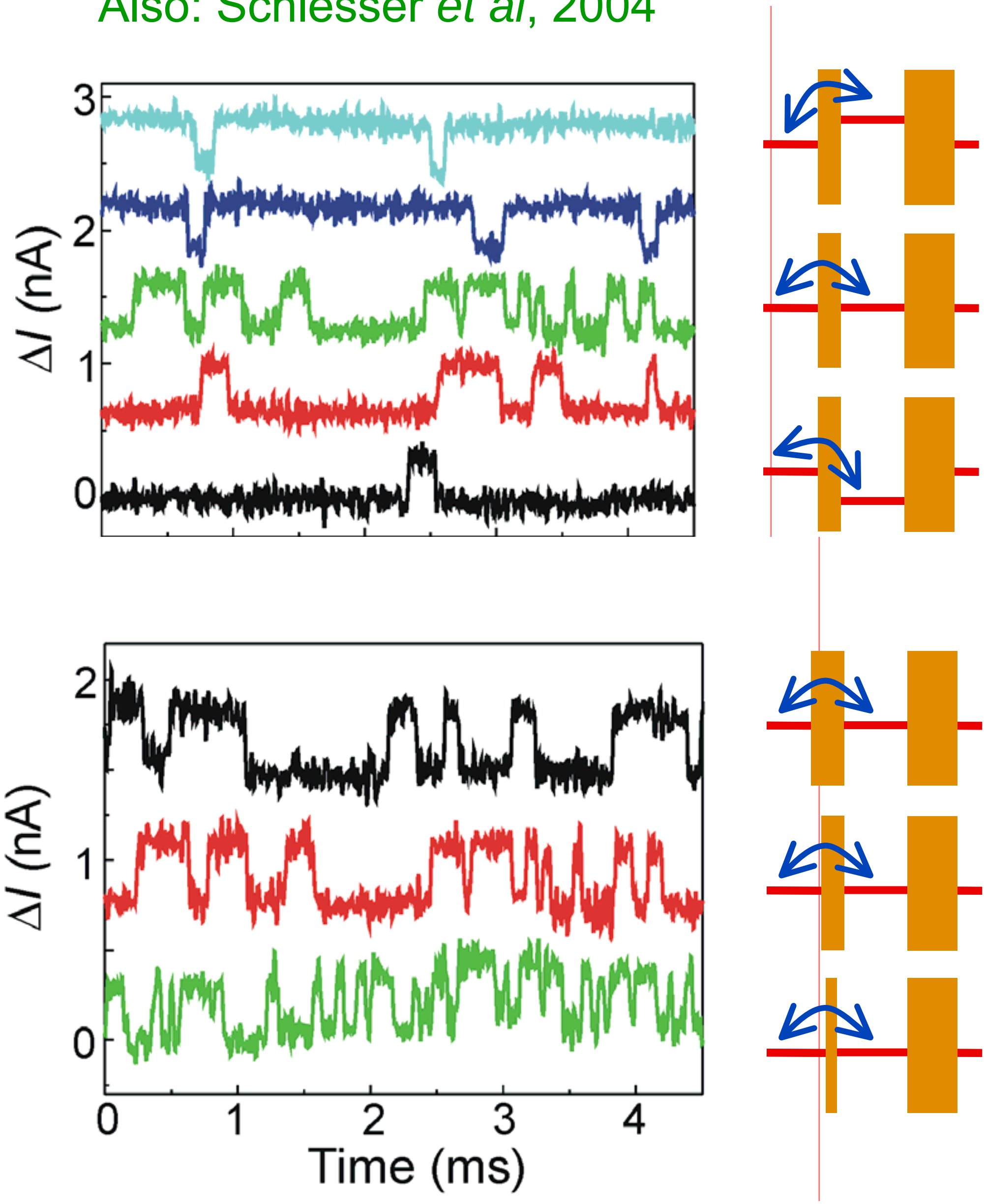
Spin read-out principle:
convert spin to charge



Observation of individual tunnel events

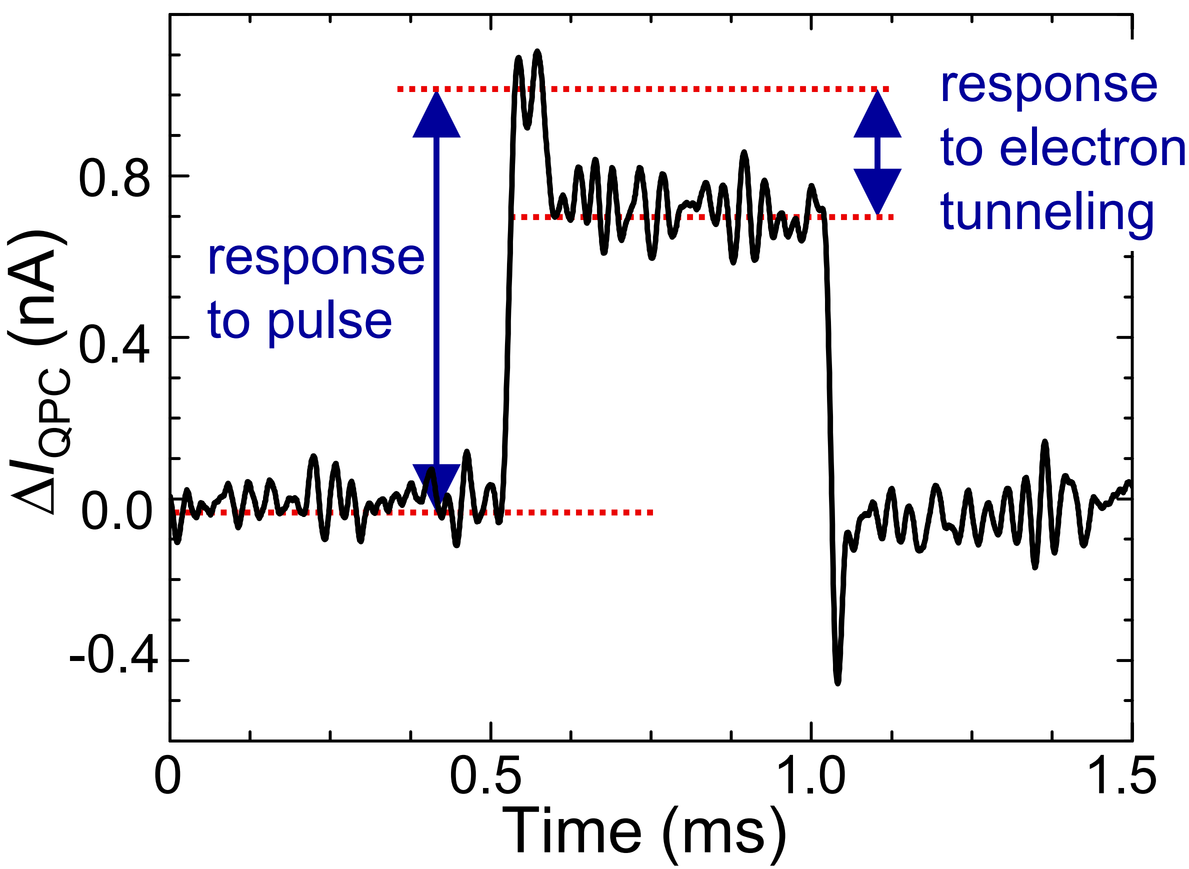
Vandersypen *et al*, APL 85, 4394, 2004
Also: Schlesser *et al*, 2004

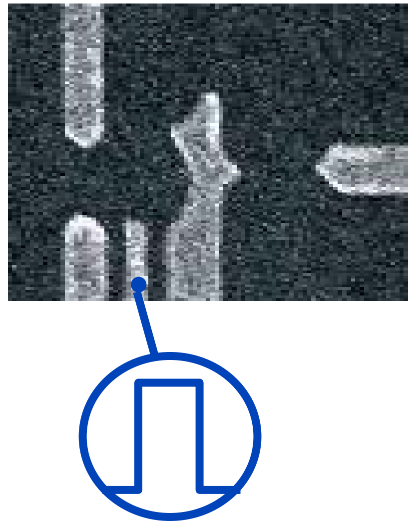


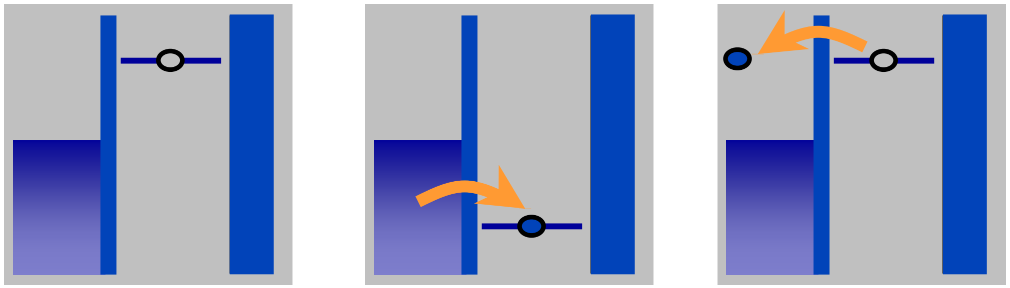


- V_{SD} = 1 mV
- I_{QPC} ~ 30 nA
- ΔI_{QPC} ~ 0.3 nA
- Shortest steps ~ 8 µs

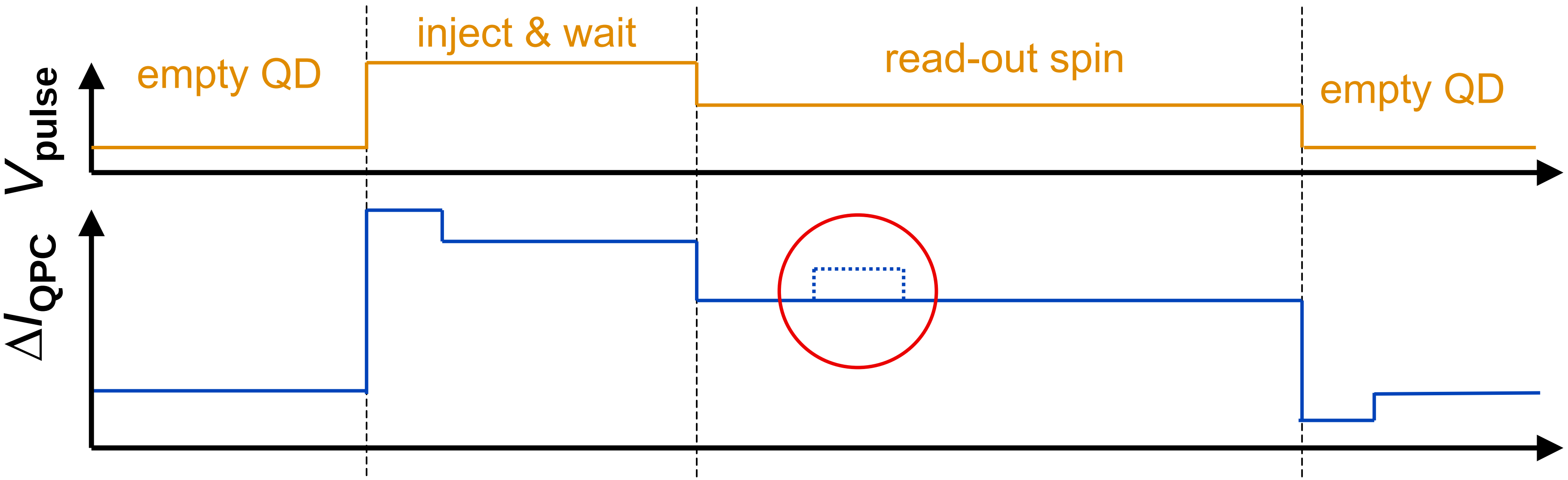
Pulse-induced tunneling

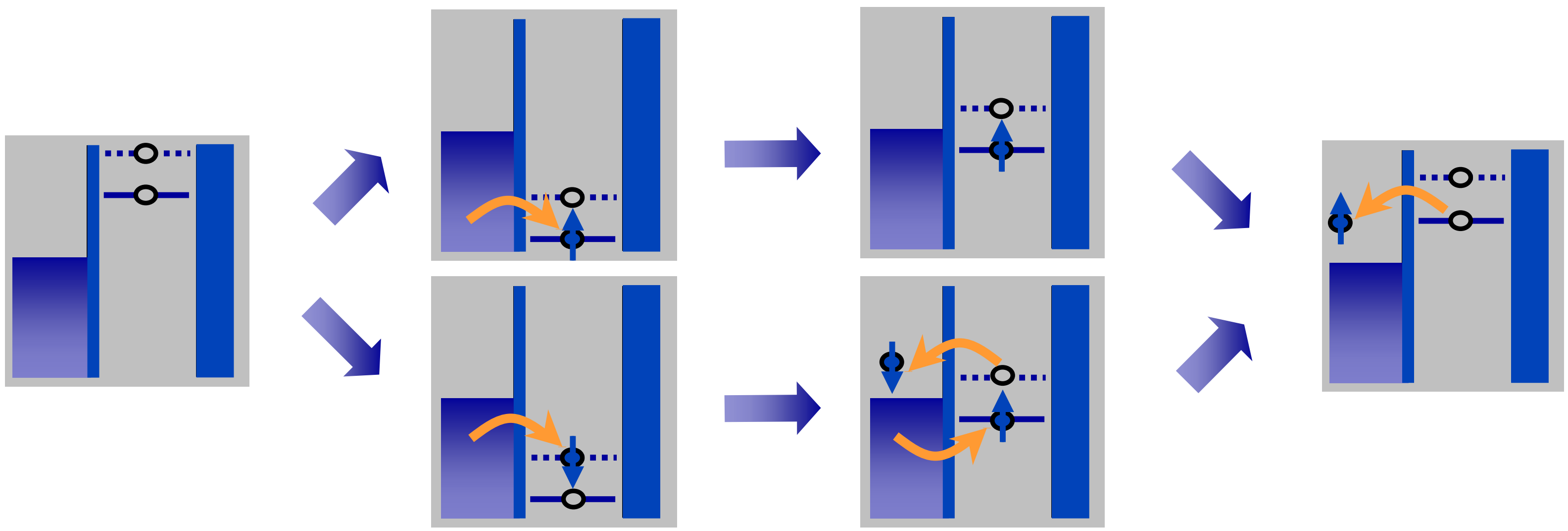






Spin read-out procedure

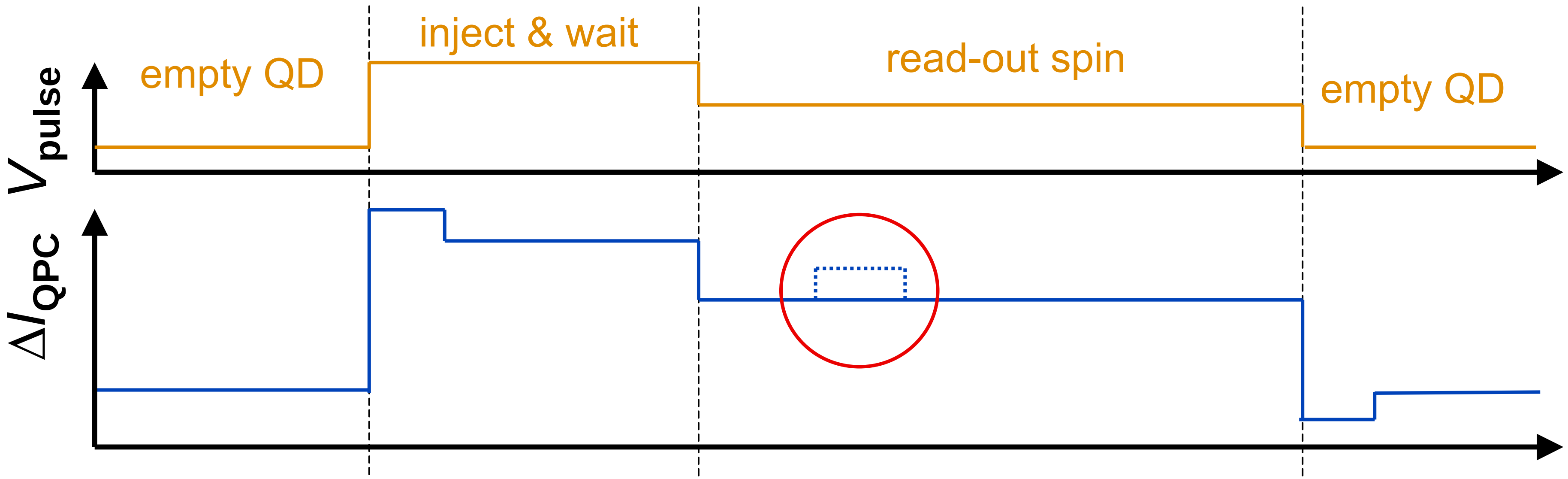


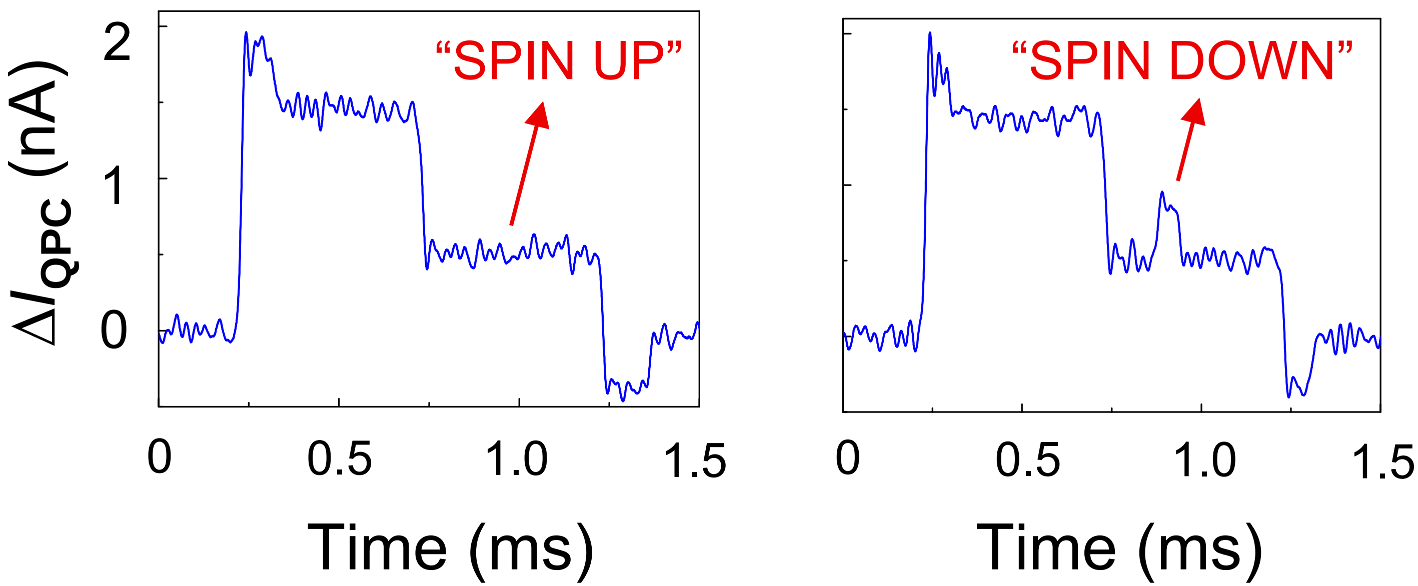


Inspiration: Fujisawa *et al.*, Nature **419**, 279, 2002

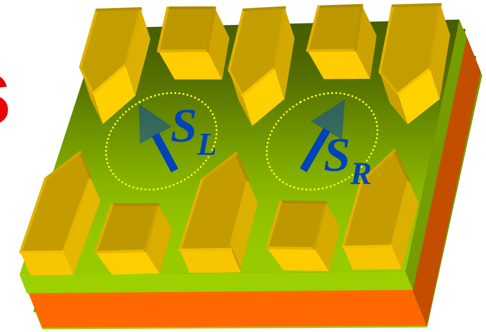
Spin read-out results

Elzerman *et al.*, Nature **430**, 431, 2004





Spin qubits in quantum dots



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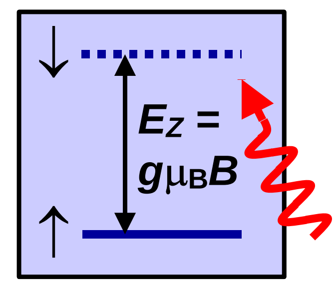

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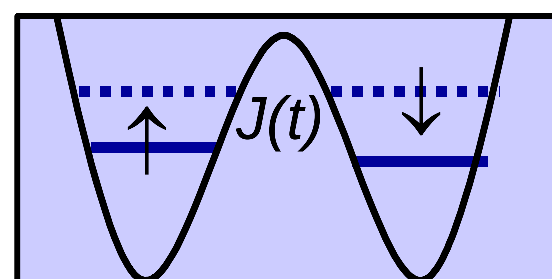
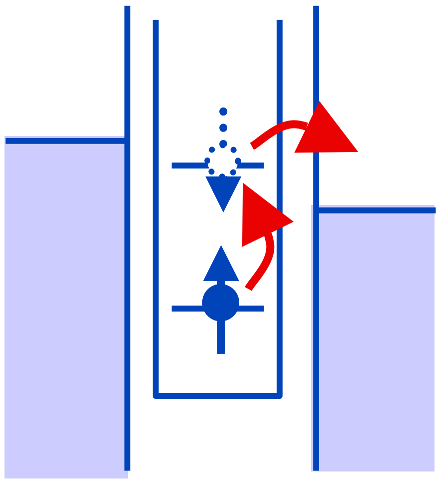


Coherence long relaxation time T_1
long coherence time T_2

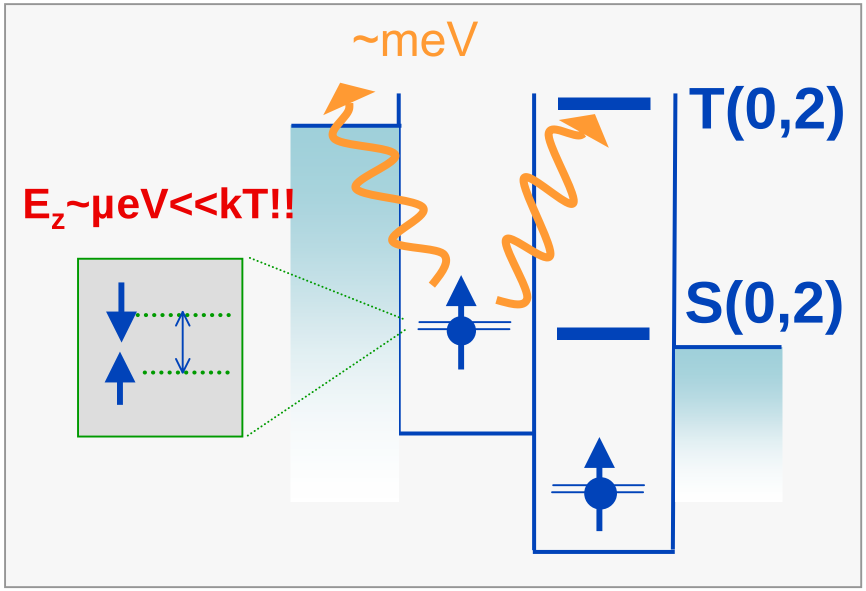
ESR detection in a single dot



ESR lifts Coulomb blockade

Engel & Loss, PRL 2001

Double dot in spin blockade for ESR detection



<u>Advantage</u>: ***interdot transition instead of dot-lead transition***

- Insensitive to temperature

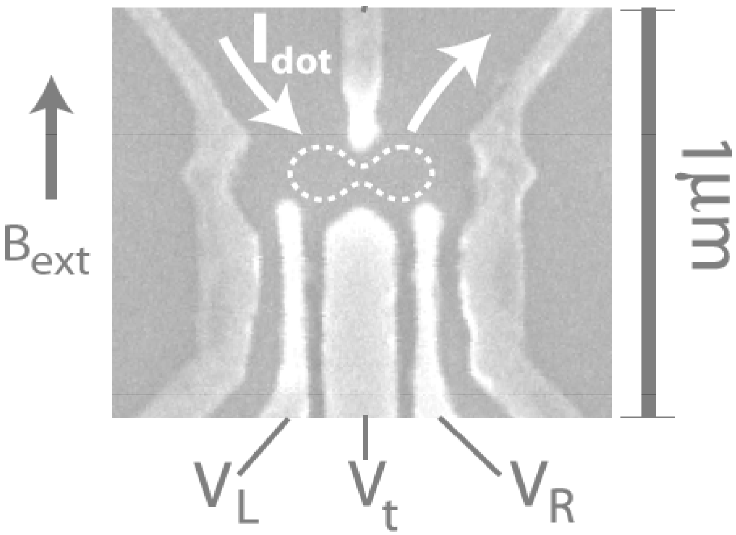
  ⇒ can use B < 100 mT, f < 500 MHz

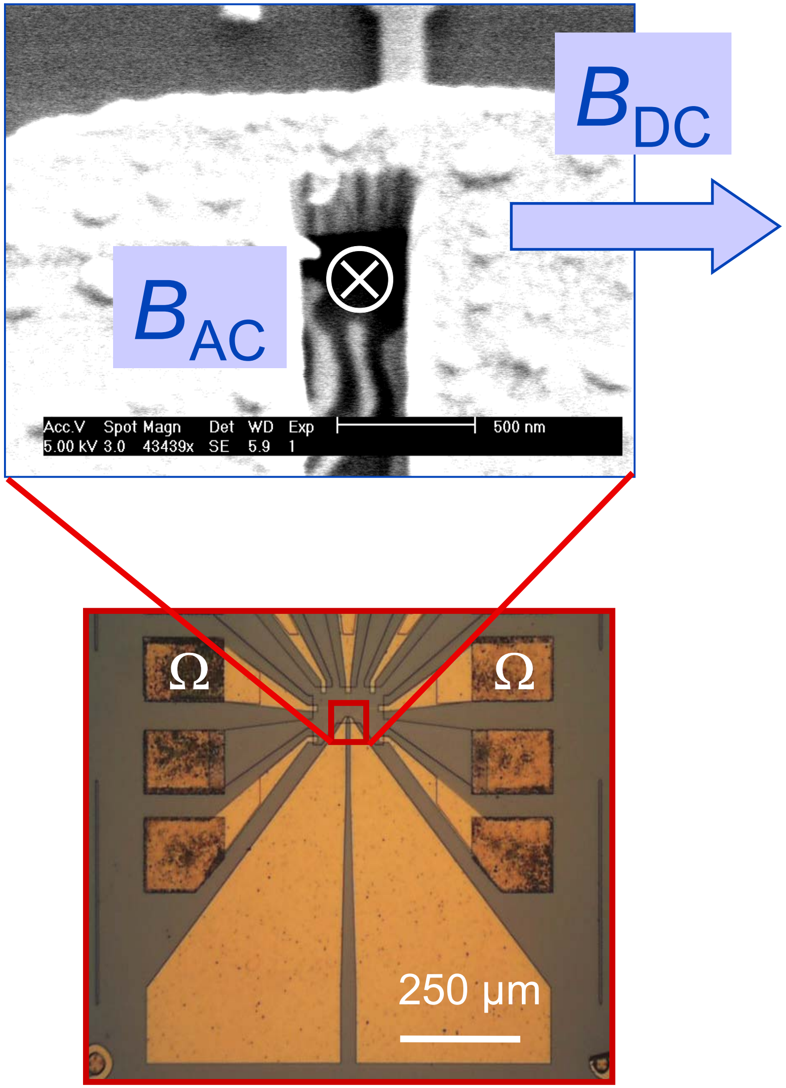
- Insensitive to electric fields

ESR flips spin, lifts spin blockade

Combine Engel & Loss (PRL 2001) ESR detection with
Ono & Tarucha (Science 2002) spin blockade

ESR device design





Gates ~ 30 nm thick gold

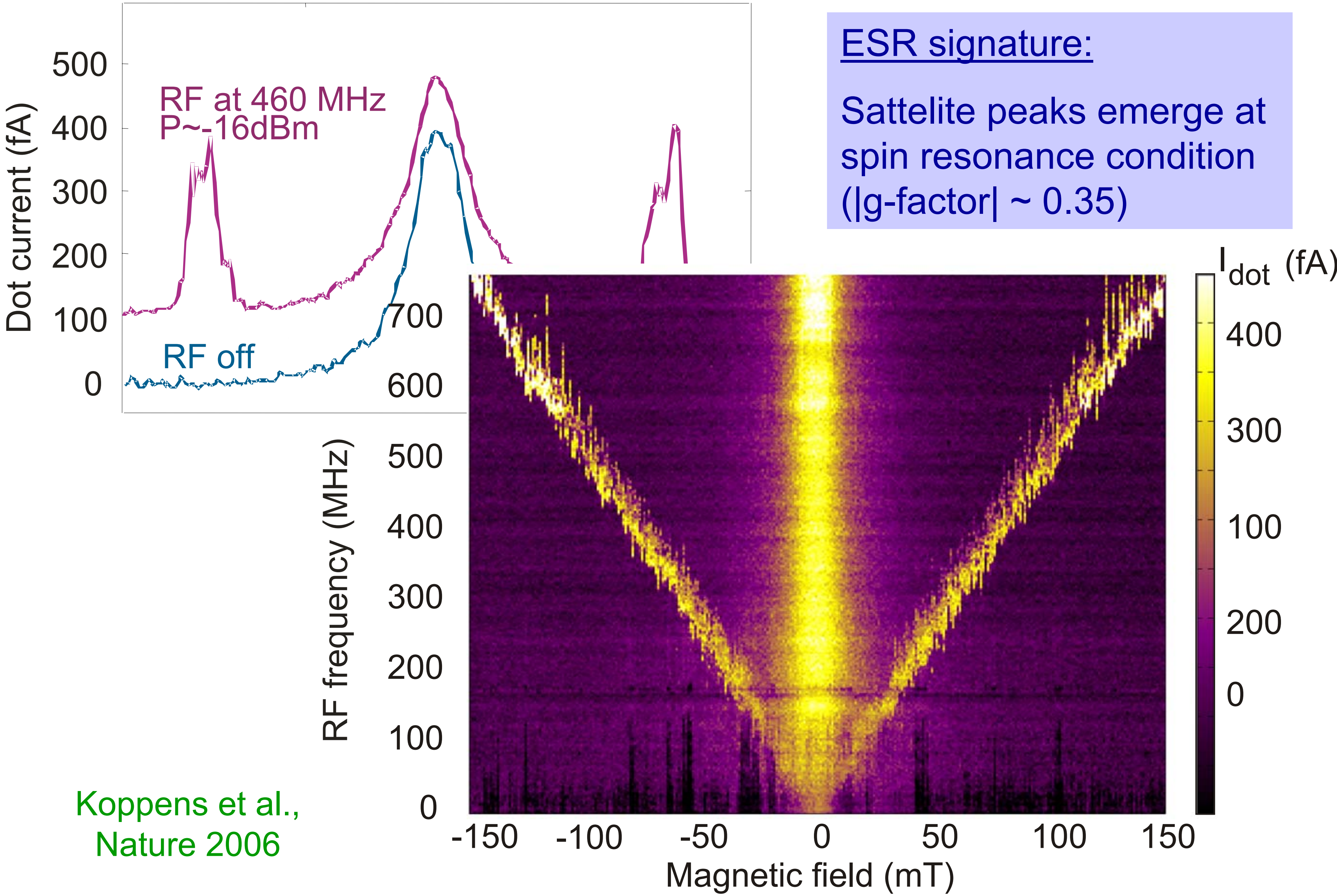
Dielectric ~ 100nm calixerene

Stripline ~ 400nm thick gold

Expected AC current ~ 1mA
Expected AC field ~ 1mT

Maximize B_1, minimize E_1

ESR spin state spectroscopy

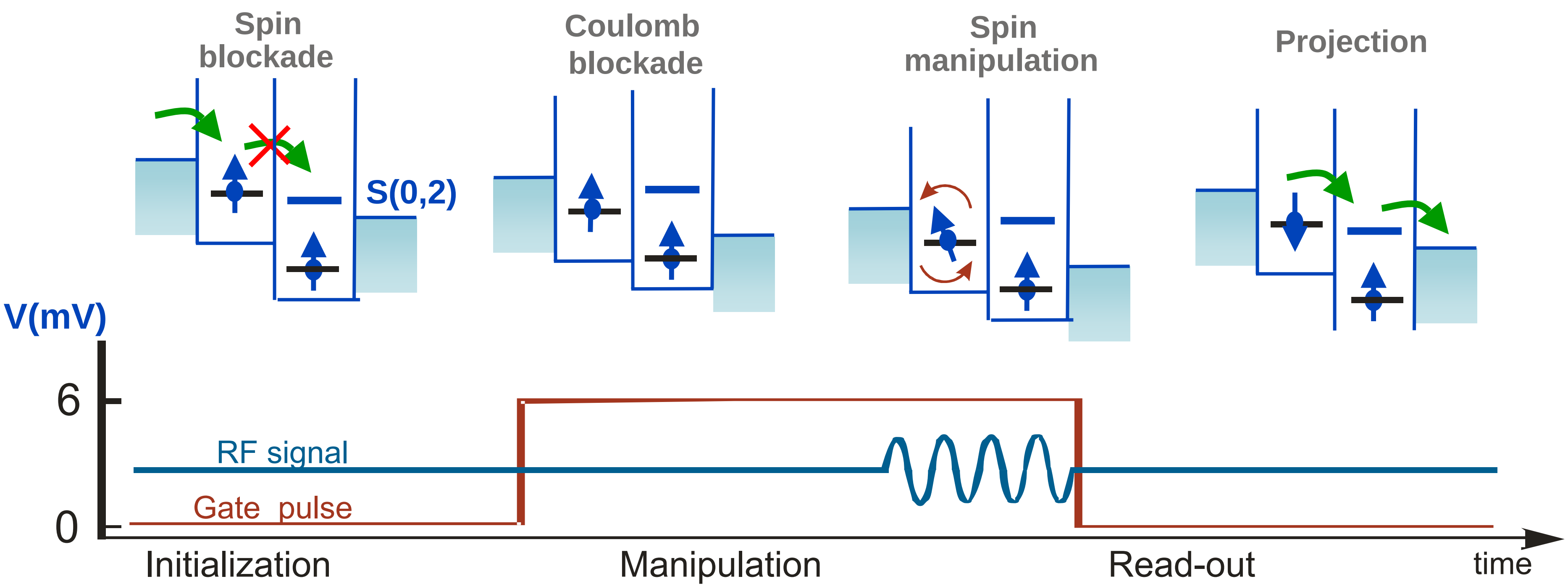


ESR signature:

Sattelite peaks emerge at spin resonance condition (|g-factor| ~ 0.35)

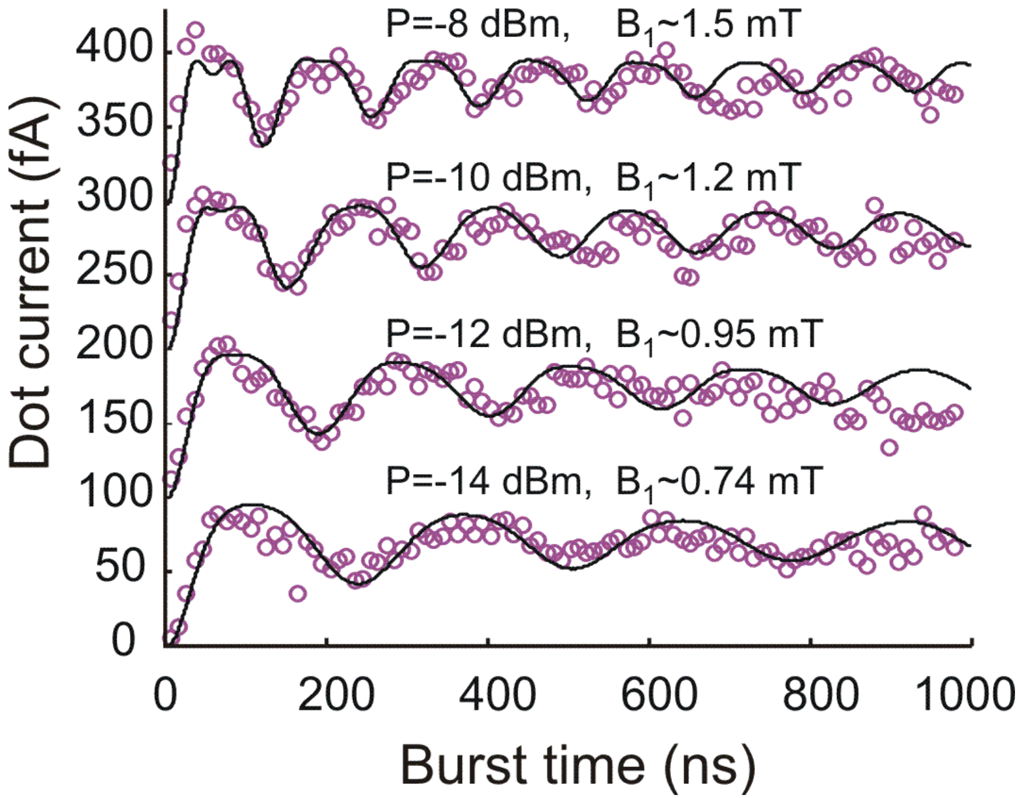
Koppens et al., Nature 2006

Coherent manipulation: pulse scheme



- Initialization in mixture of ↑↑ and ↓↓
- Measurement switched off (by pulsing to Coulomb blockade) during manipulation
- Read-out: projection on {↑↑,↓↓} vs. {↑↓,↓↑} basis

Coherent rotations of single electron spin!

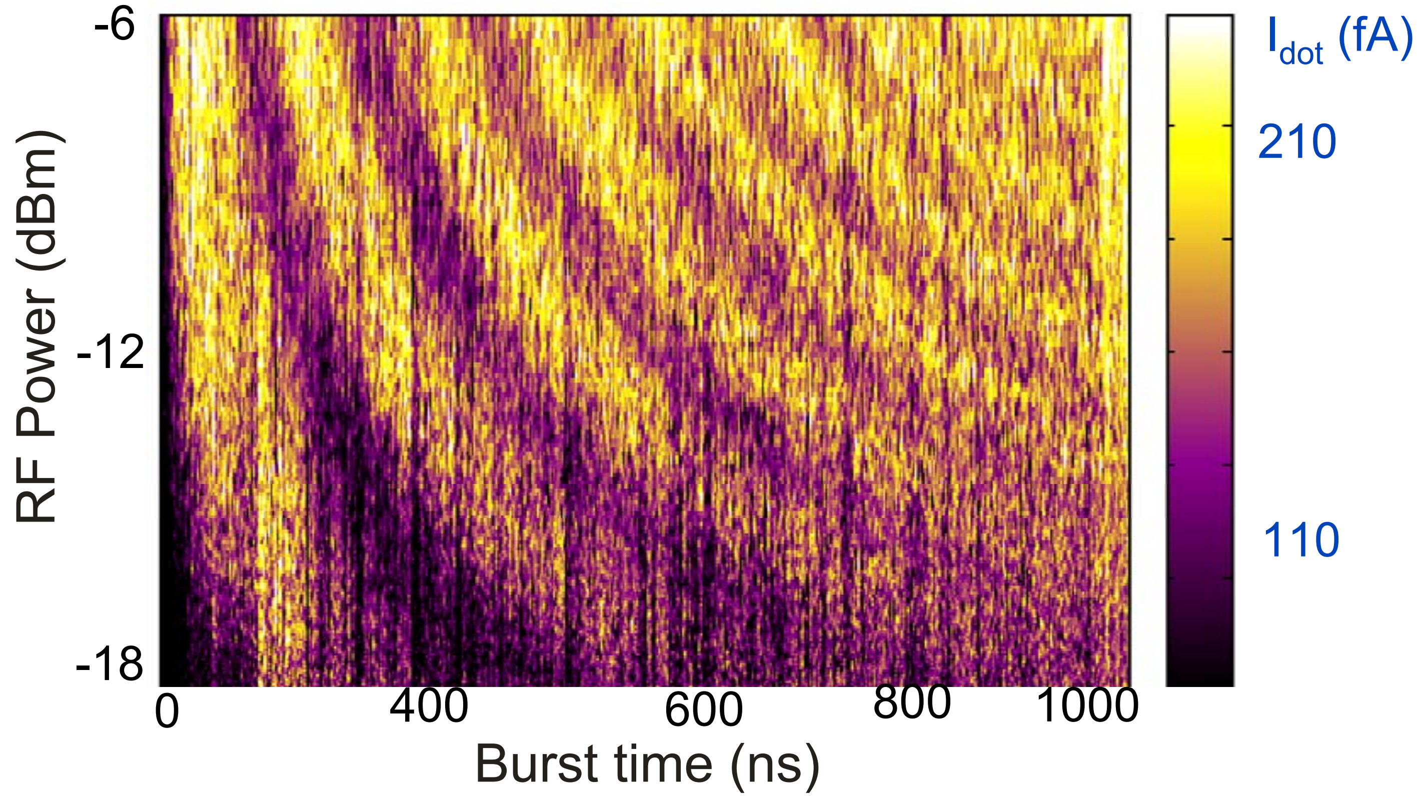


Koppens et al.
Nature 2006

- Oscillations visible up to 1μs
- Decay non exponential → slow nuclear dynamics (non-Markovian bath)
- Agreement with simple Hamiltonian

  taking into account different resonance conditions both dots

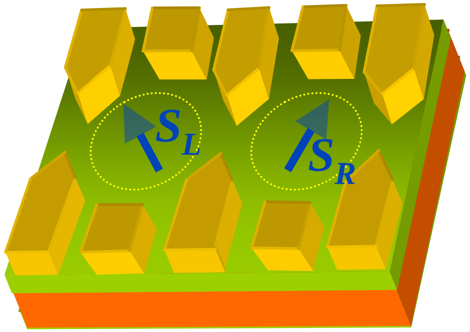
Driven coherent oscillations



- Oscillation frequency ~ B_{AC} → clear signature of Rabi oscillations
- π/2 pulse in 25ns
- max $B_1 = B_{AC}/2 = 1.9$ mT
  $B_{N,z} = 1.3$ mT } estimated fidelity ~73%

Koppens et al.
Nature 2006

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

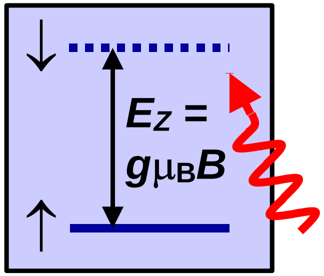
$$H_0 \sim \Sigma\, \omega_i\, \sigma_{zi}$$

Read-out convert spin to charge

then measure charge

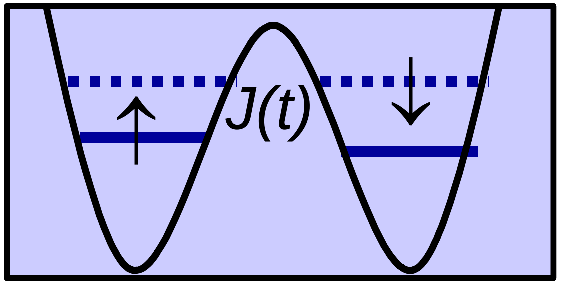
ESR pulsed microwave magnetic field

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



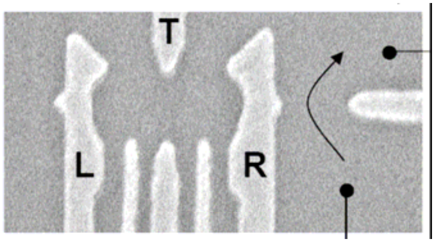
SWAP exchange interaction

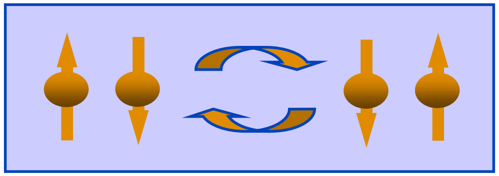
$$H_J \sim \Sigma\, J_{ij}(t)\ \sigma_i \cdot \sigma_j$$



Coherence long relaxation time T_1
long coherence time T_2

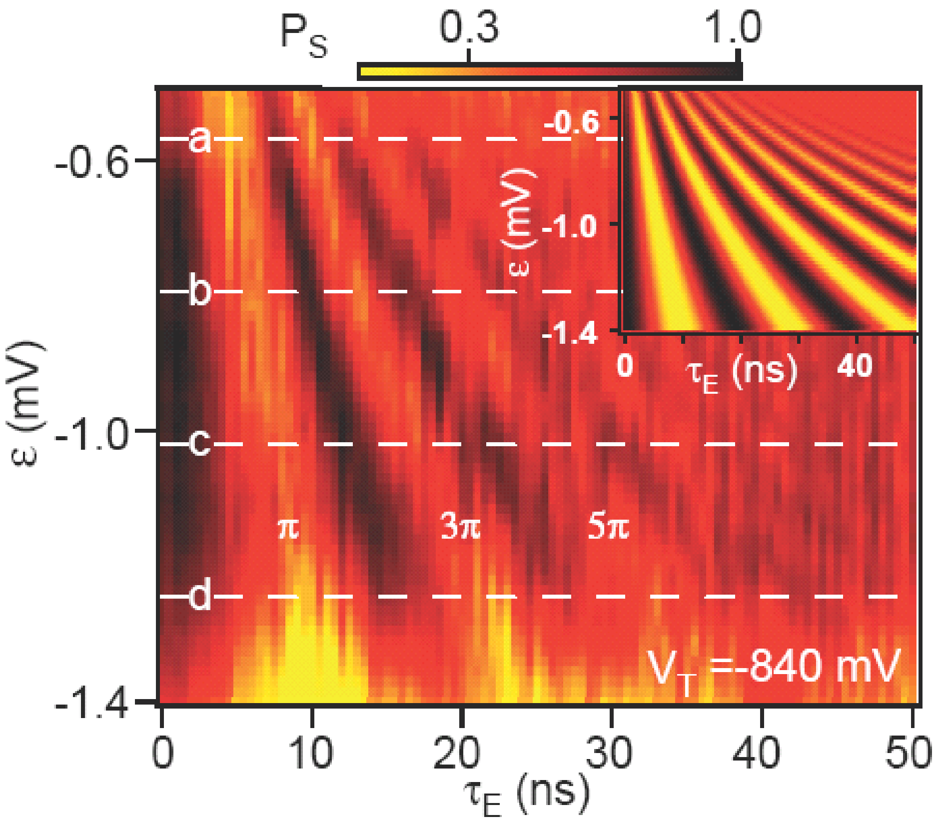
Coherent exchange of two spins

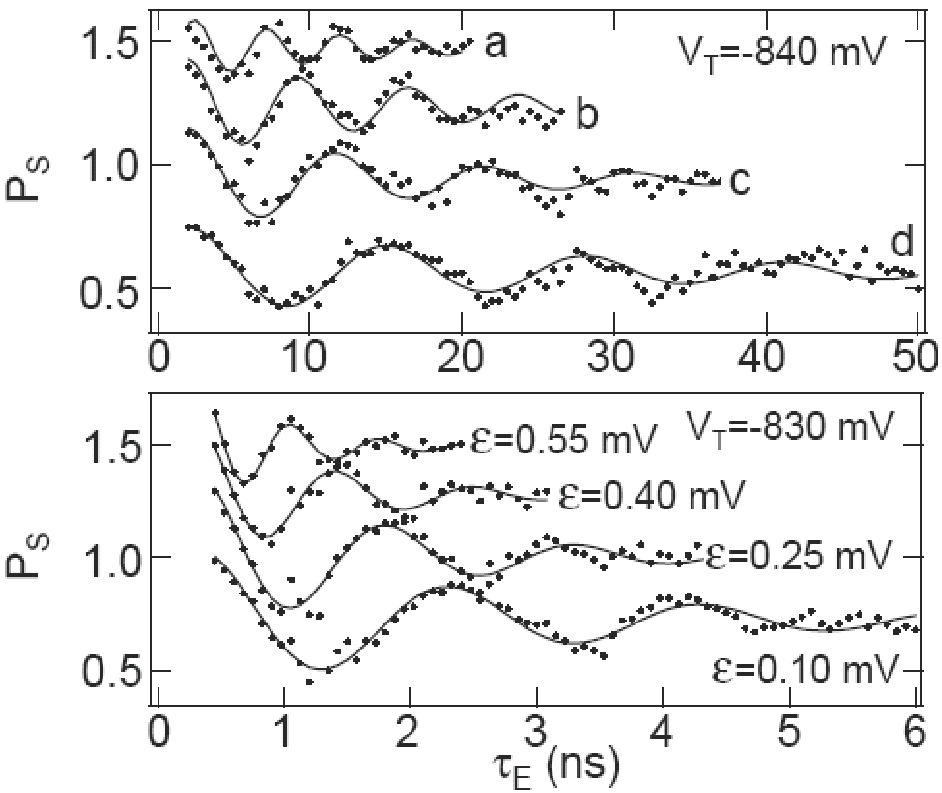




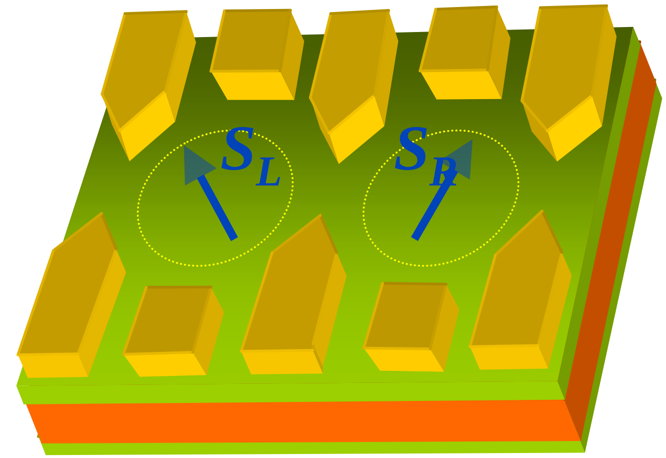
Petta *et al.*, Science 2005

- free evolution under exchange Hamiltonian
- swap$^{1/2}$ in as little as 180 ps
- three oscillations visible, independent of J





Spin qubits in quantum dots - present status



Initialization	1 electron, low T, high B_0 $H_0 \sim \sum \omega_i \, \sigma_{zi}$
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	measure coherence time $T_1 \sim 1$ ms; $T_2 > 1$ μs