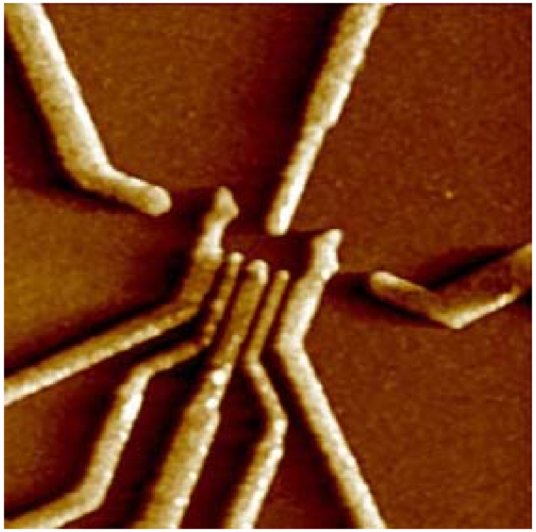
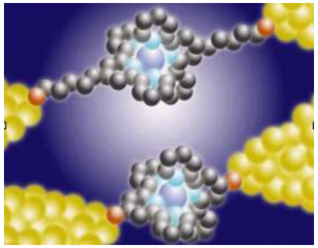
Quantum Information Processing with Semiconductor Quantum Dots



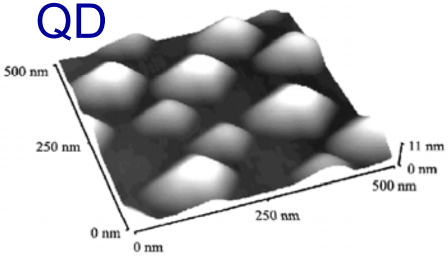
slides courtesy of Lieven Vandersypen, TU Delft

Examples of quantum dots

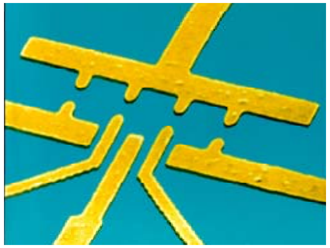
single molecule



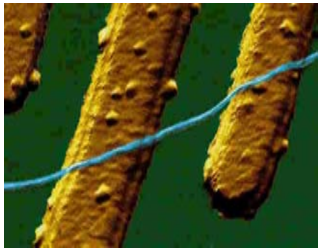
self-assembled QD



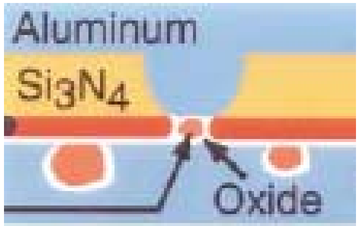
lateral QD



nanotube

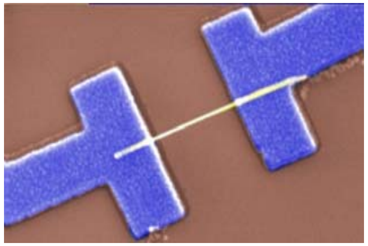


1 nm 10 nm 100 nm 1μm



metallic nanoparticle

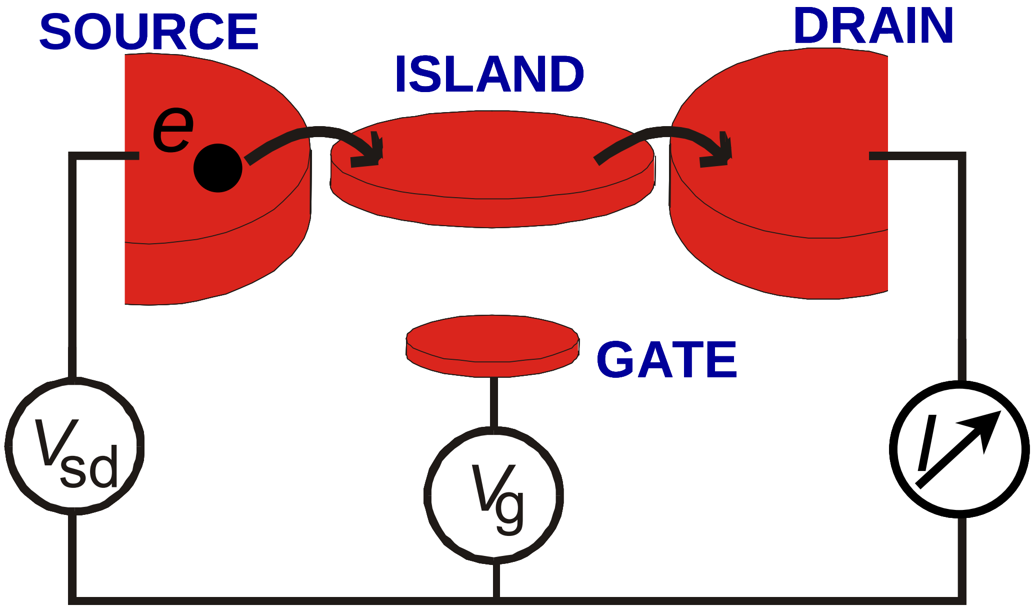
vertical QD



nanowire

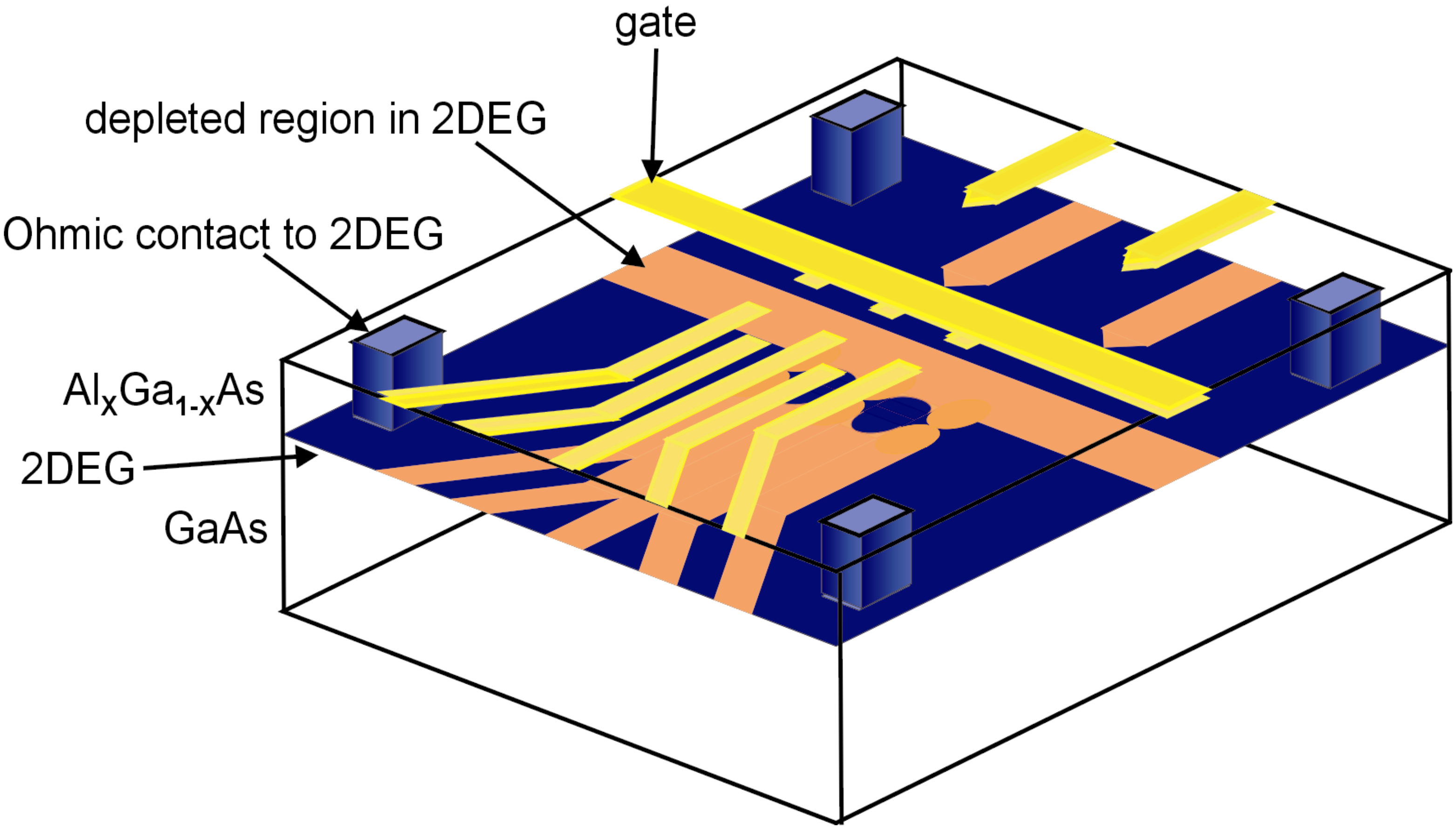
Electrically controlled and measured quantum dots

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

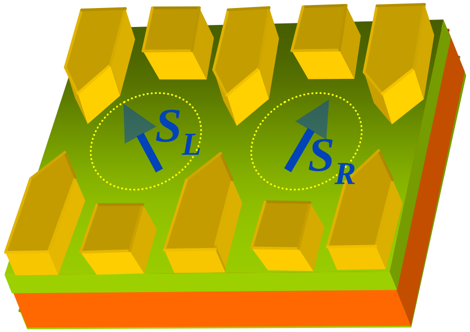
Electrostatically defined quantum dots



- 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)

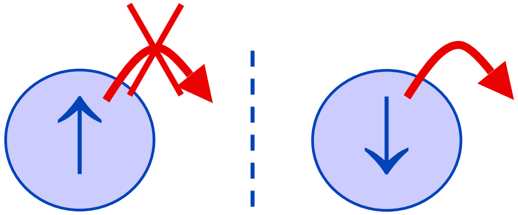


Initialization 1-electron, low T, high B_0

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

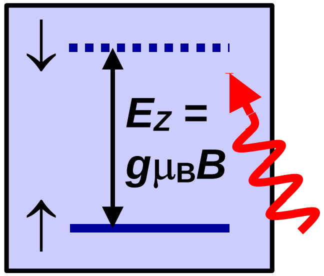
Read-out convert spin to charge

then measure charge



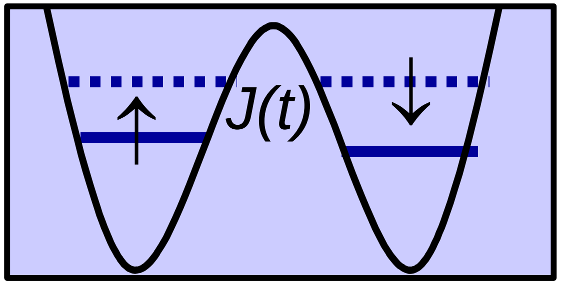
ESR pulsed microwave magnetic field

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



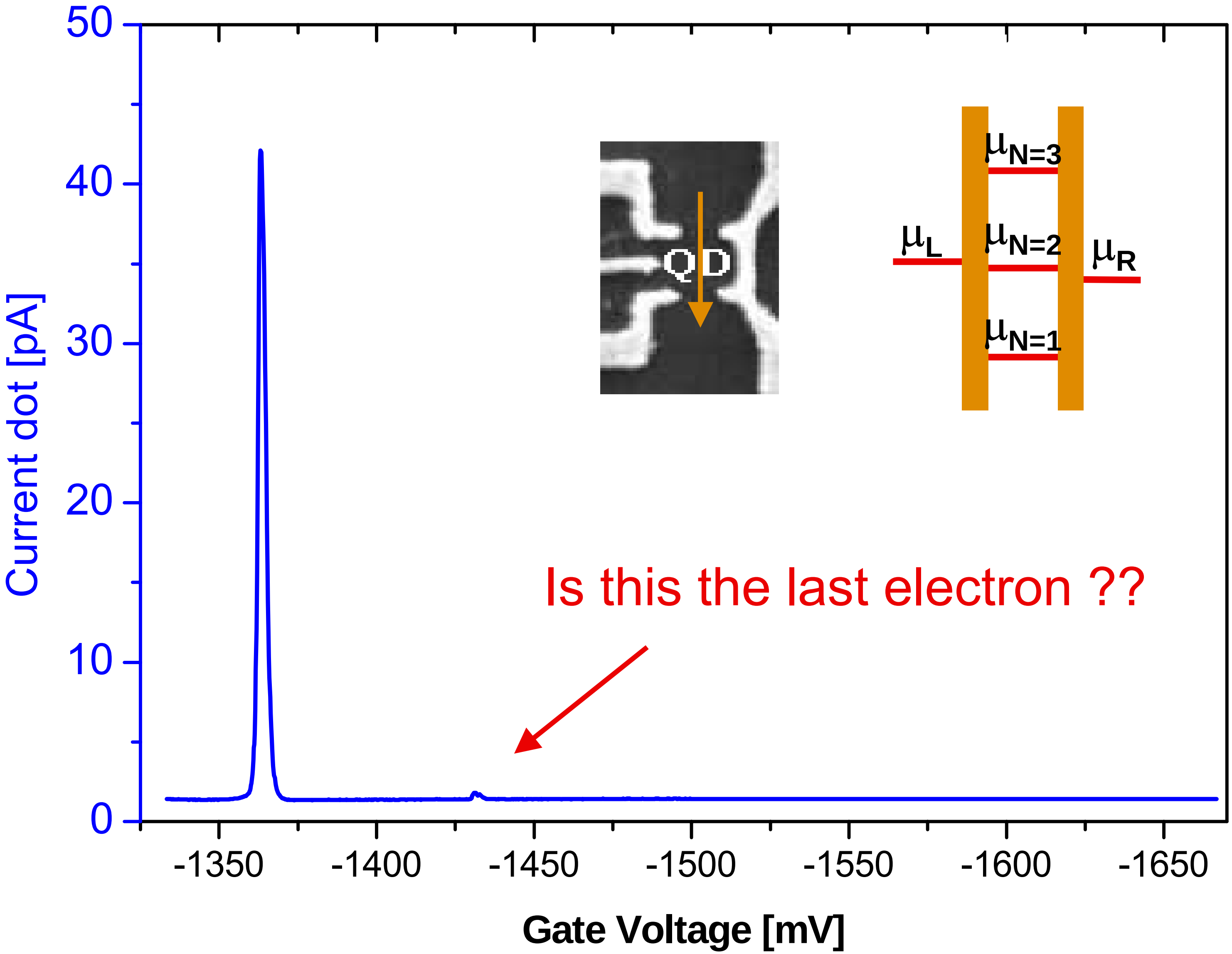
SWAP exchange interaction

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



Coherence long relaxation time T_1
long coherence time T_2

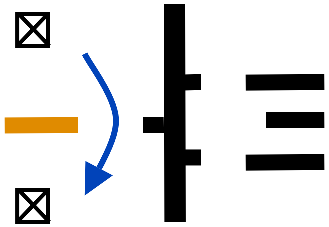
Transport through quantum dot - Coulomb blockade

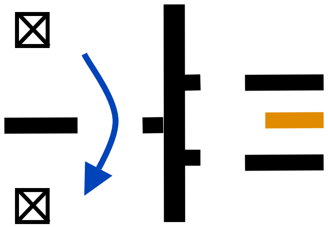


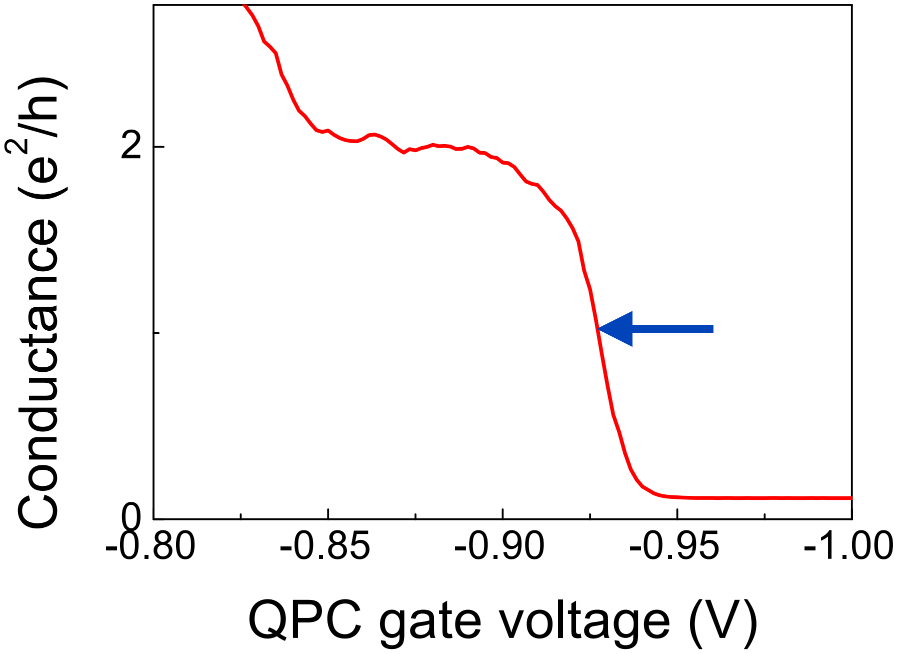
Is this the last electron ??

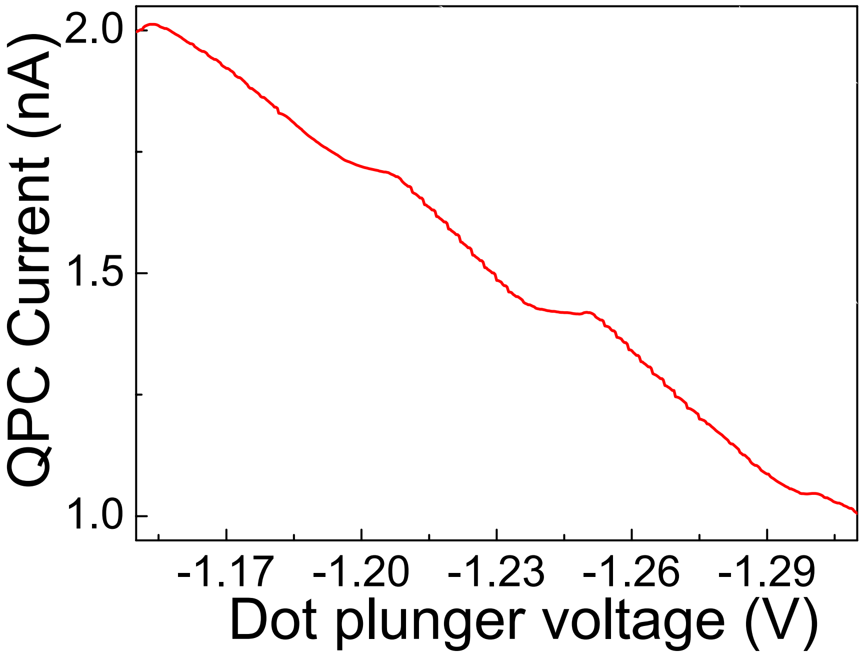
A quantum point contact (QPC) as a charge detector

Field *et al*, PRL 1993

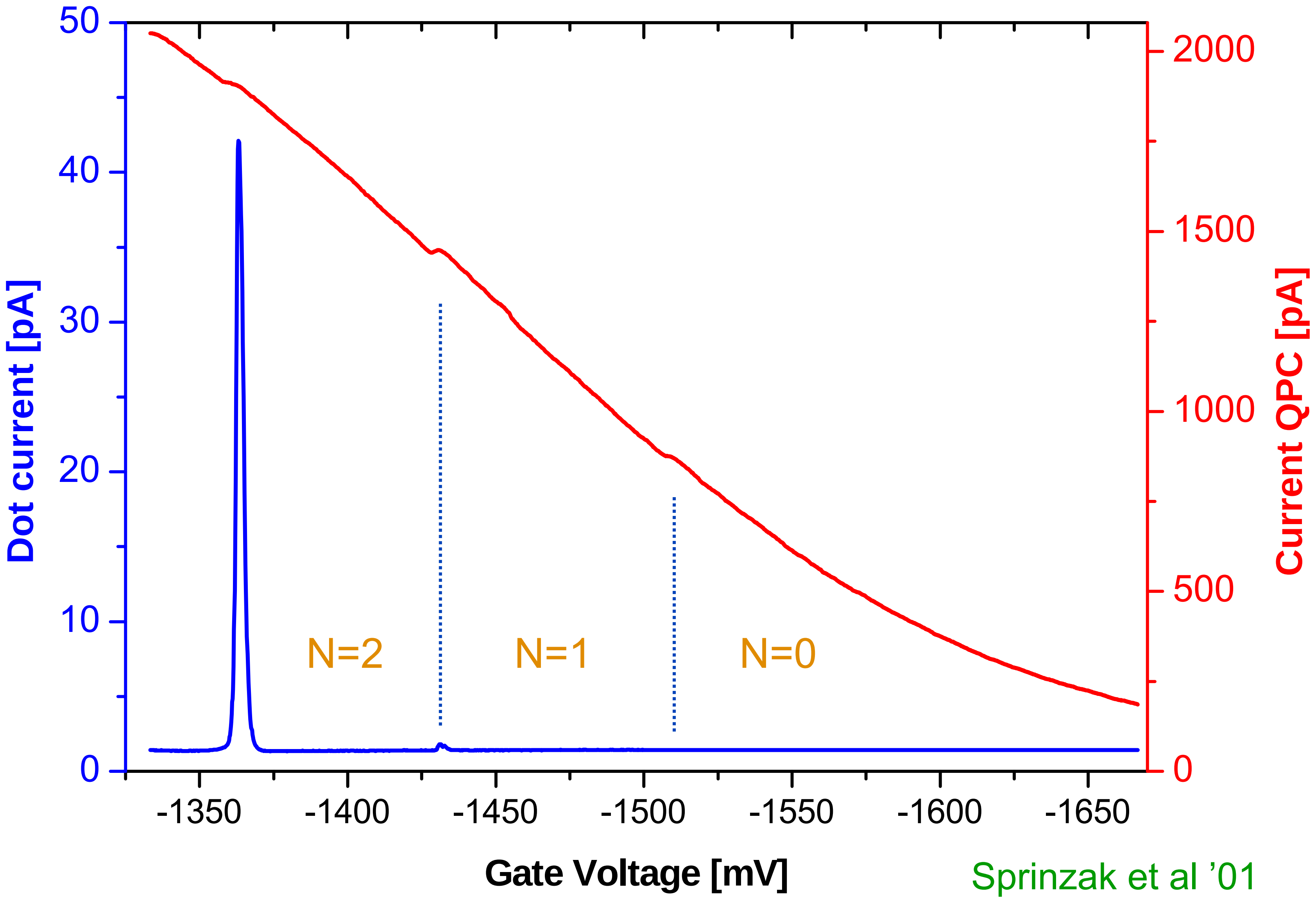






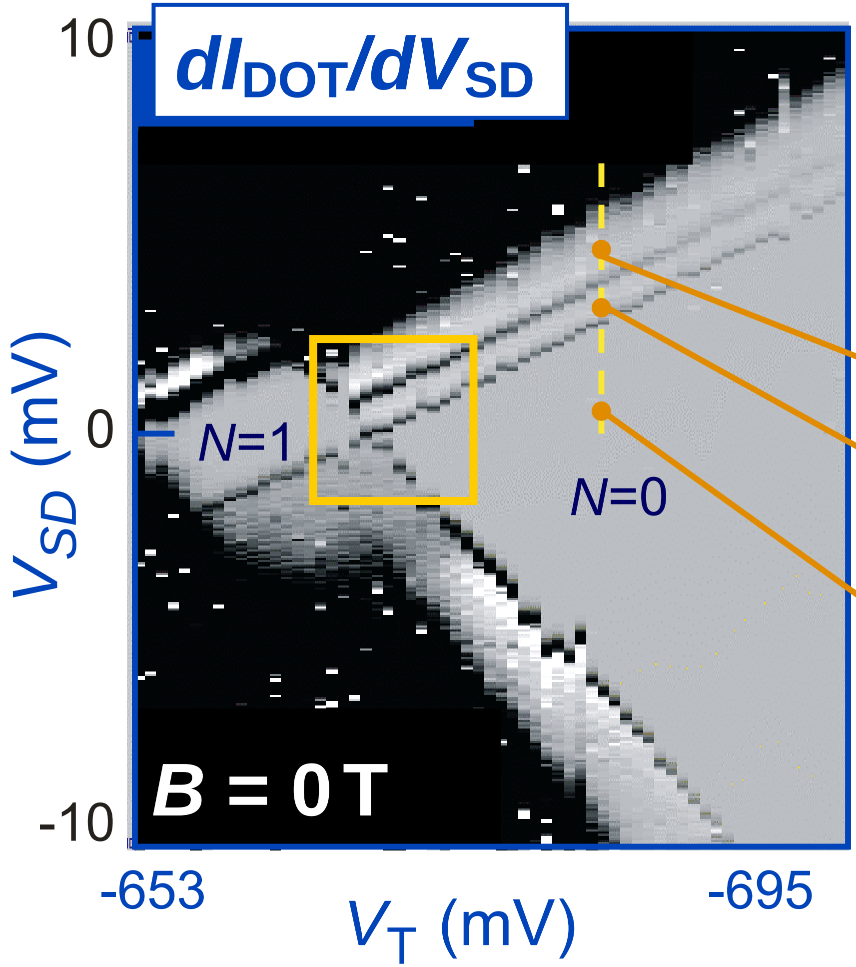


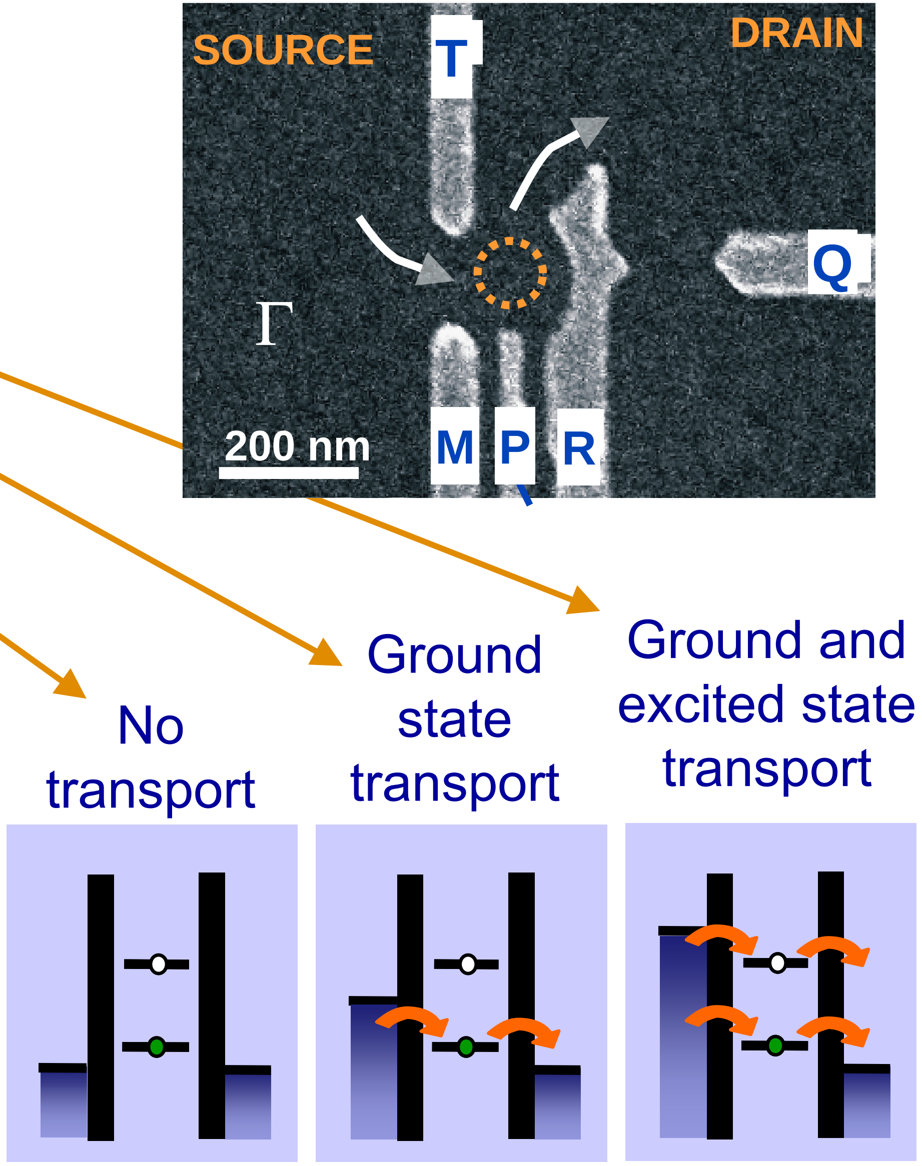
The last electron!



Sprinzak et al ’01

Energy level spectroscopy at $B = 0$





No transport

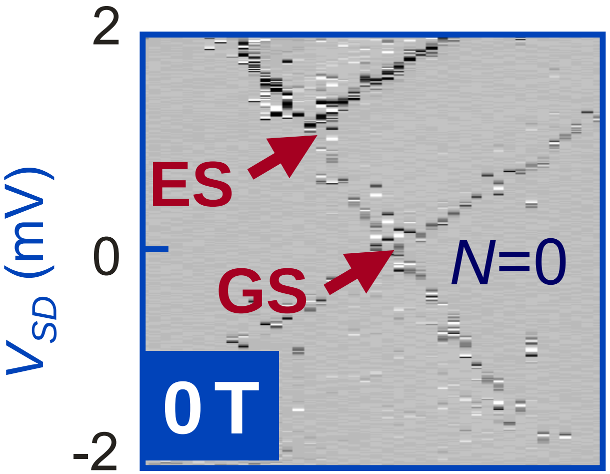
Ground state transport

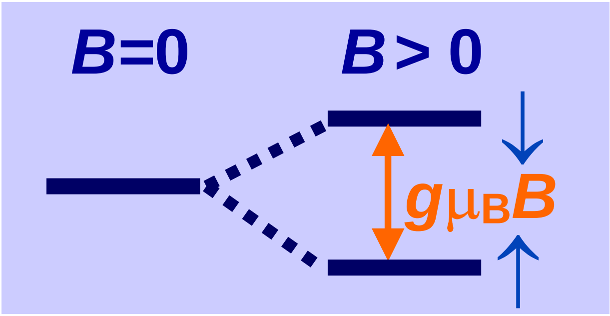
Ground and excited state transport

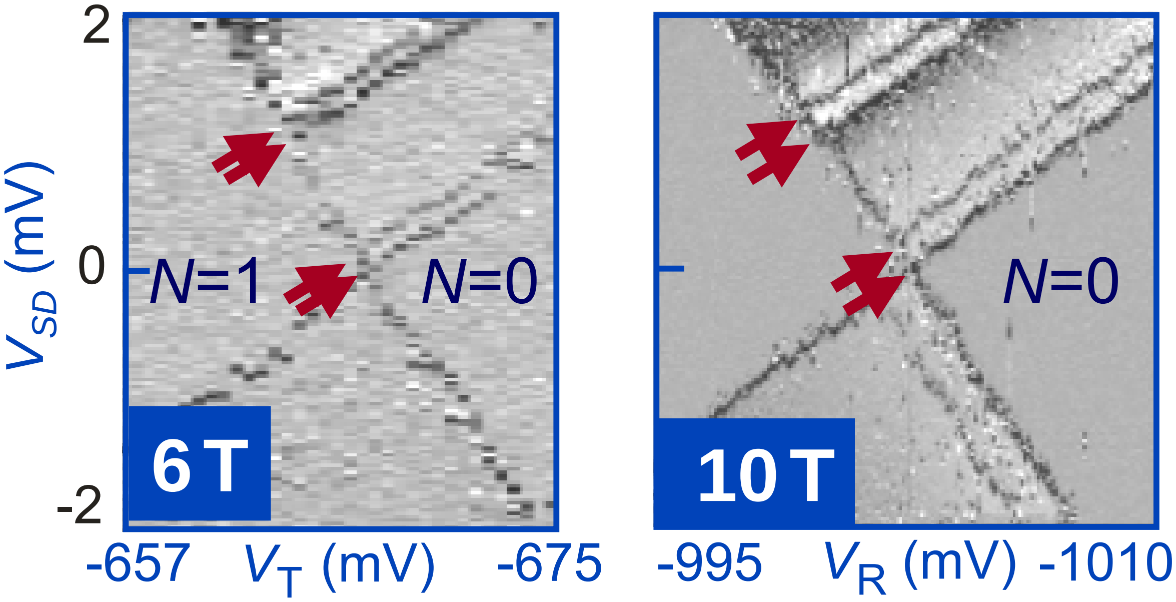
- $\Delta E \sim 1.1$meV
- $E_C \sim 2.5$meV

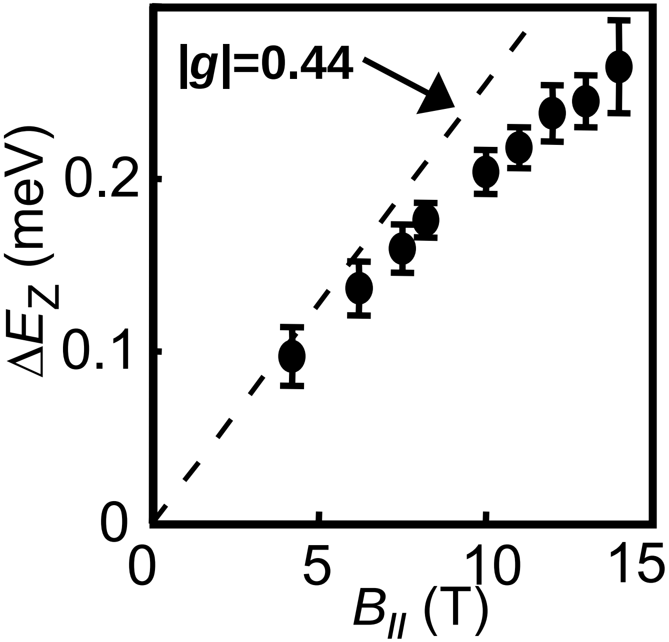
Single electron Zeeman splitting in $B_{//}$

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



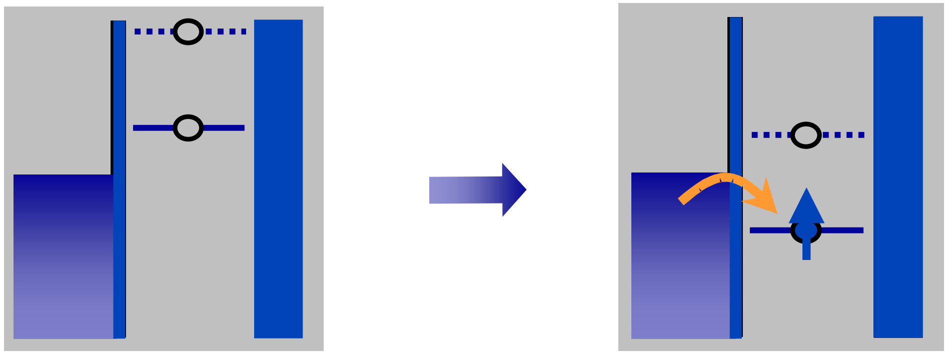




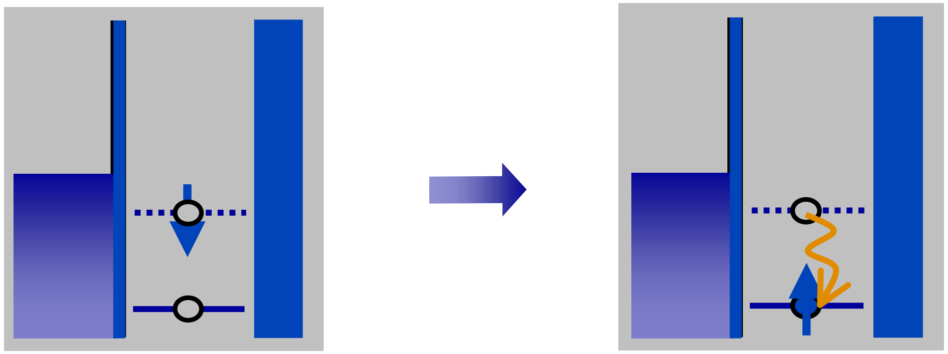


Initialization of a single electron spin

Method 1:
spin-selective
tunneling

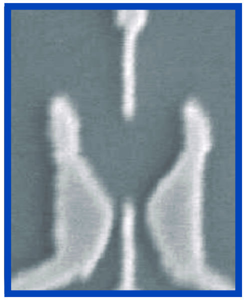


Method 2:
relaxation to
ground state



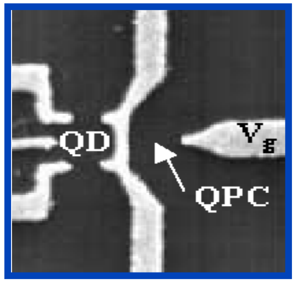
Few-electron double dot design

Ciorga et al '99



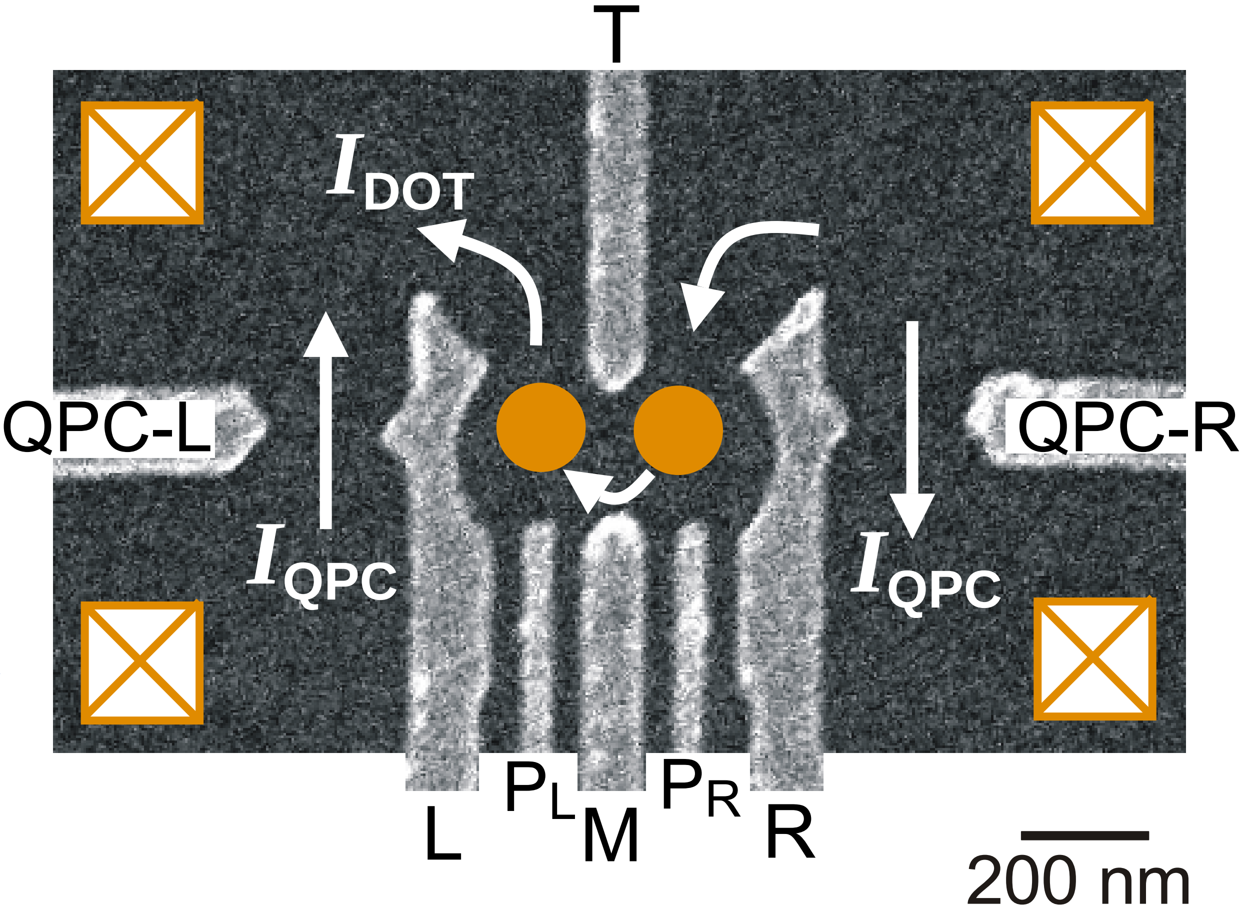
Open design

Field et al'93
Sprinzak et al '01



QPC for charge detection

Elzerman et al., PRB 2003

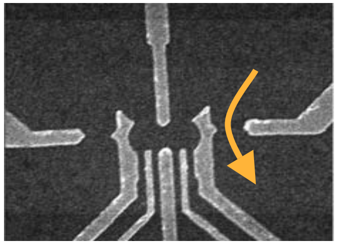


GaAs/AlGaAs wafers:

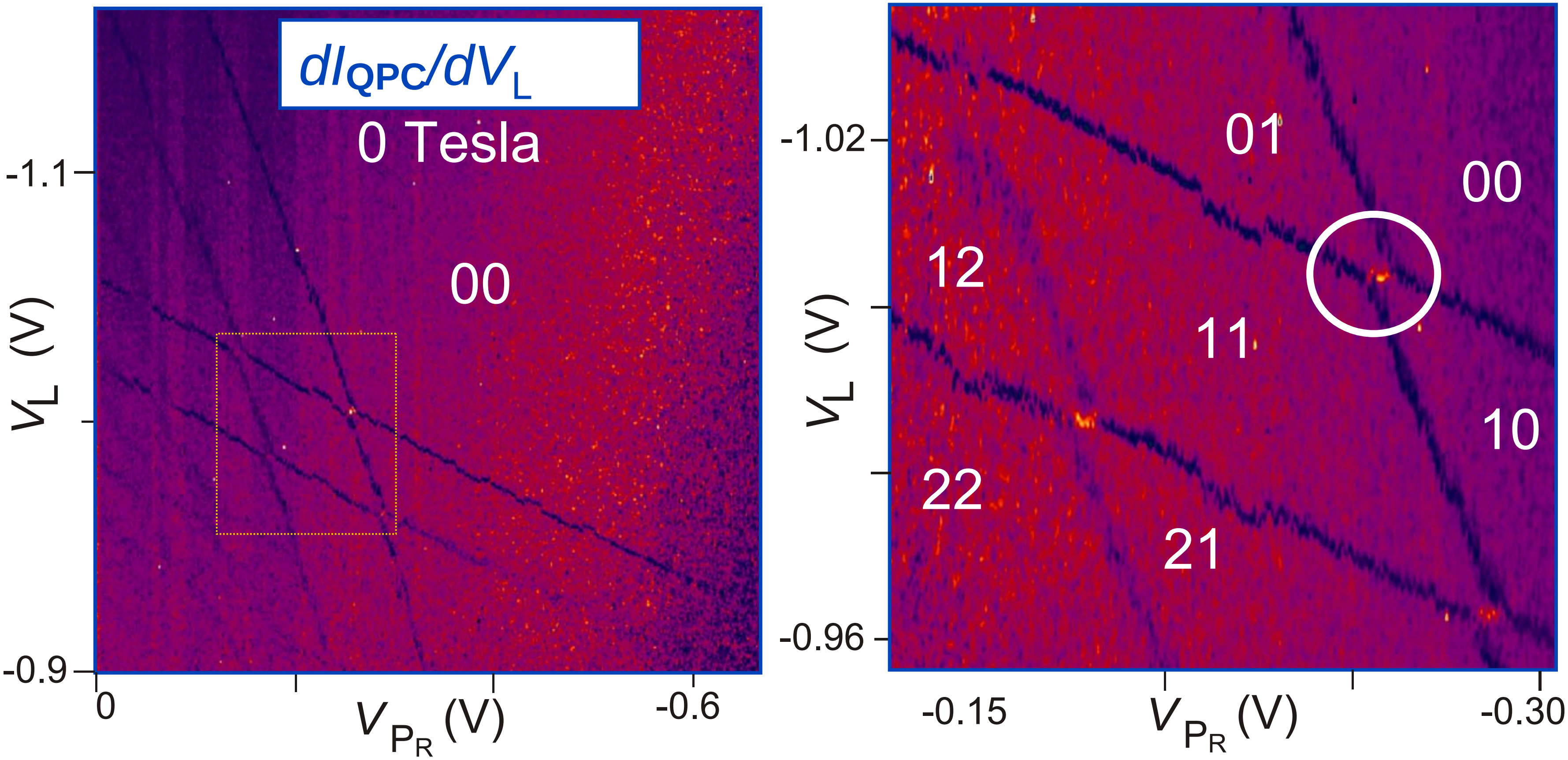
NTT (T. Saku, Y. Hirayama)
Sumitomo Electric
Universität Regensburg (W. Wegscheider)

Few-electron double dot

Measured via QPC



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

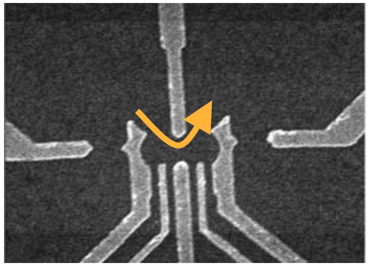


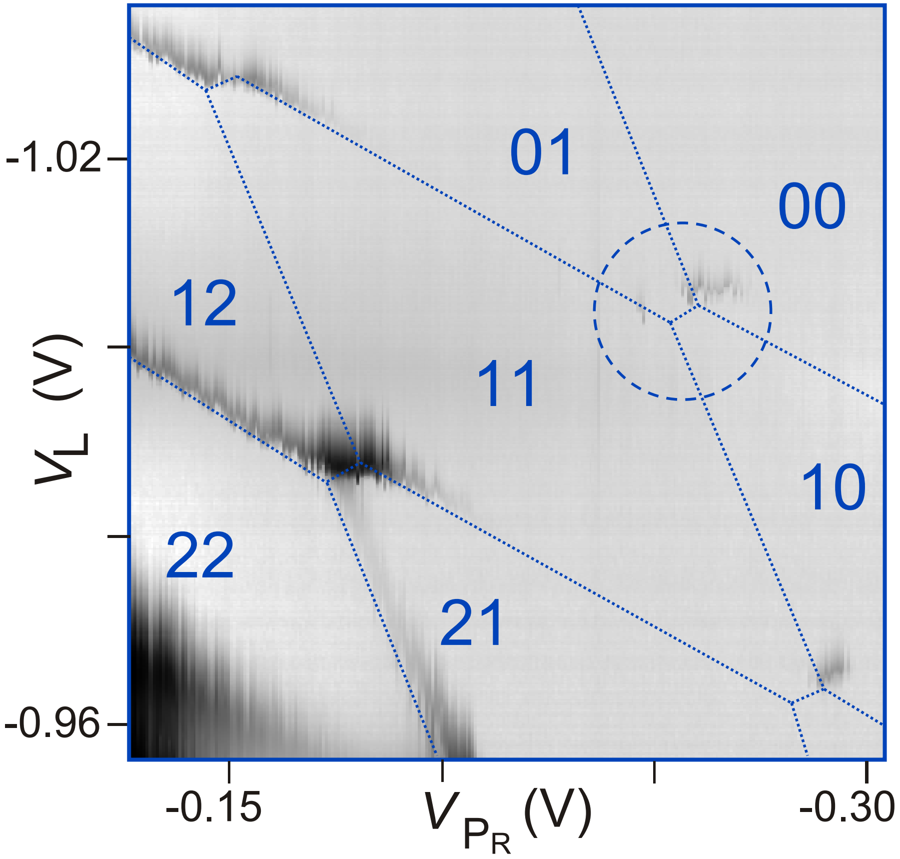
- Double dot can be emptied
- QPC can detect all charge transitions

Few-electron double dot

Transport through dots

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





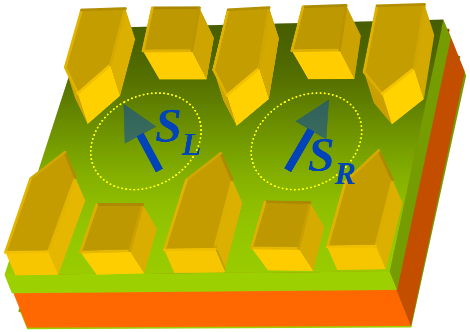
Peak height

< 1 pA

2 pA

70 pA

Spin qubits in quantum dots



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

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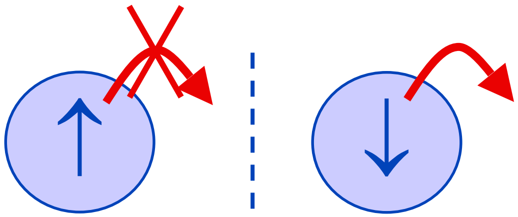
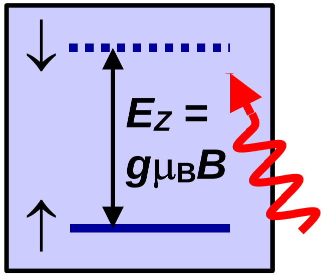
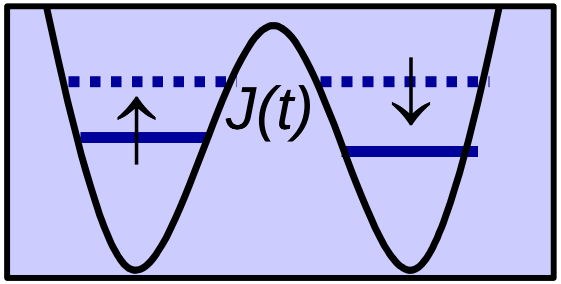
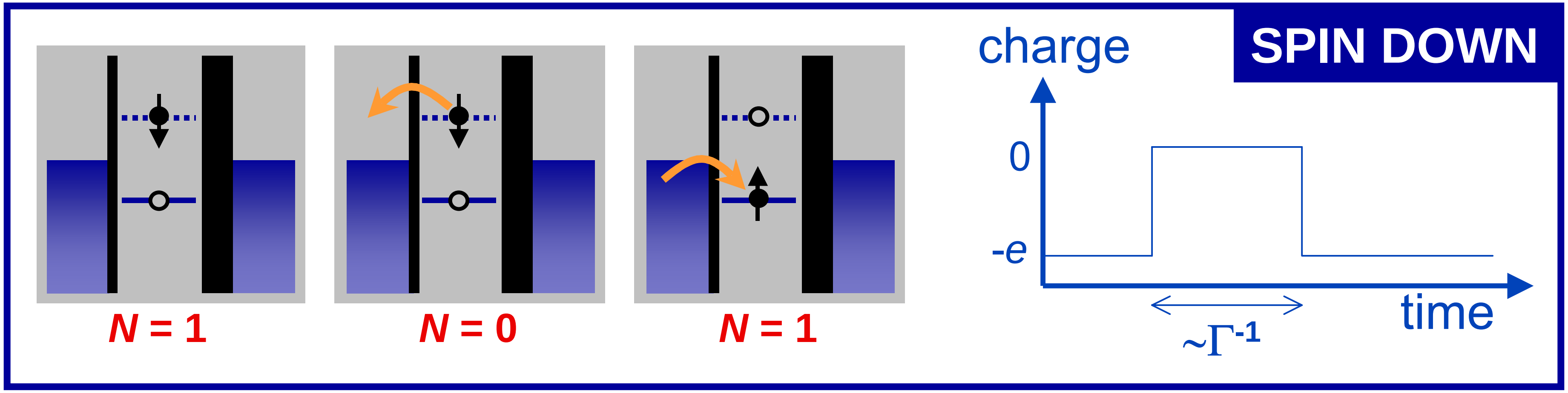




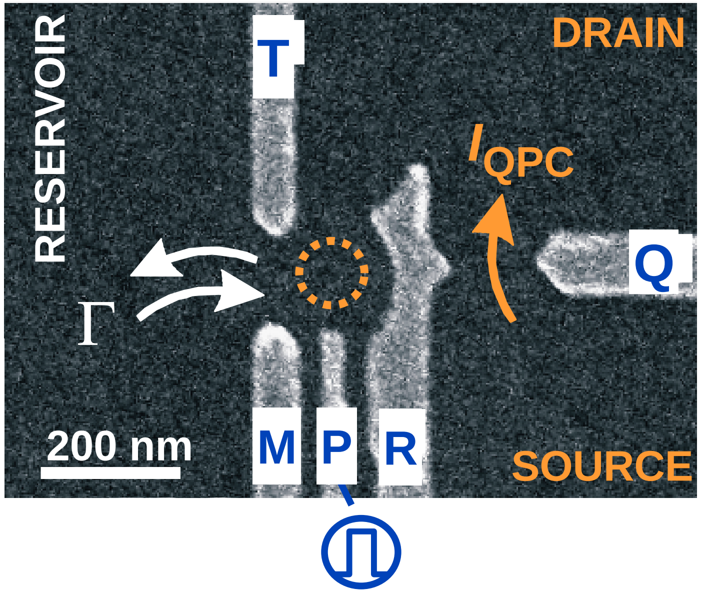


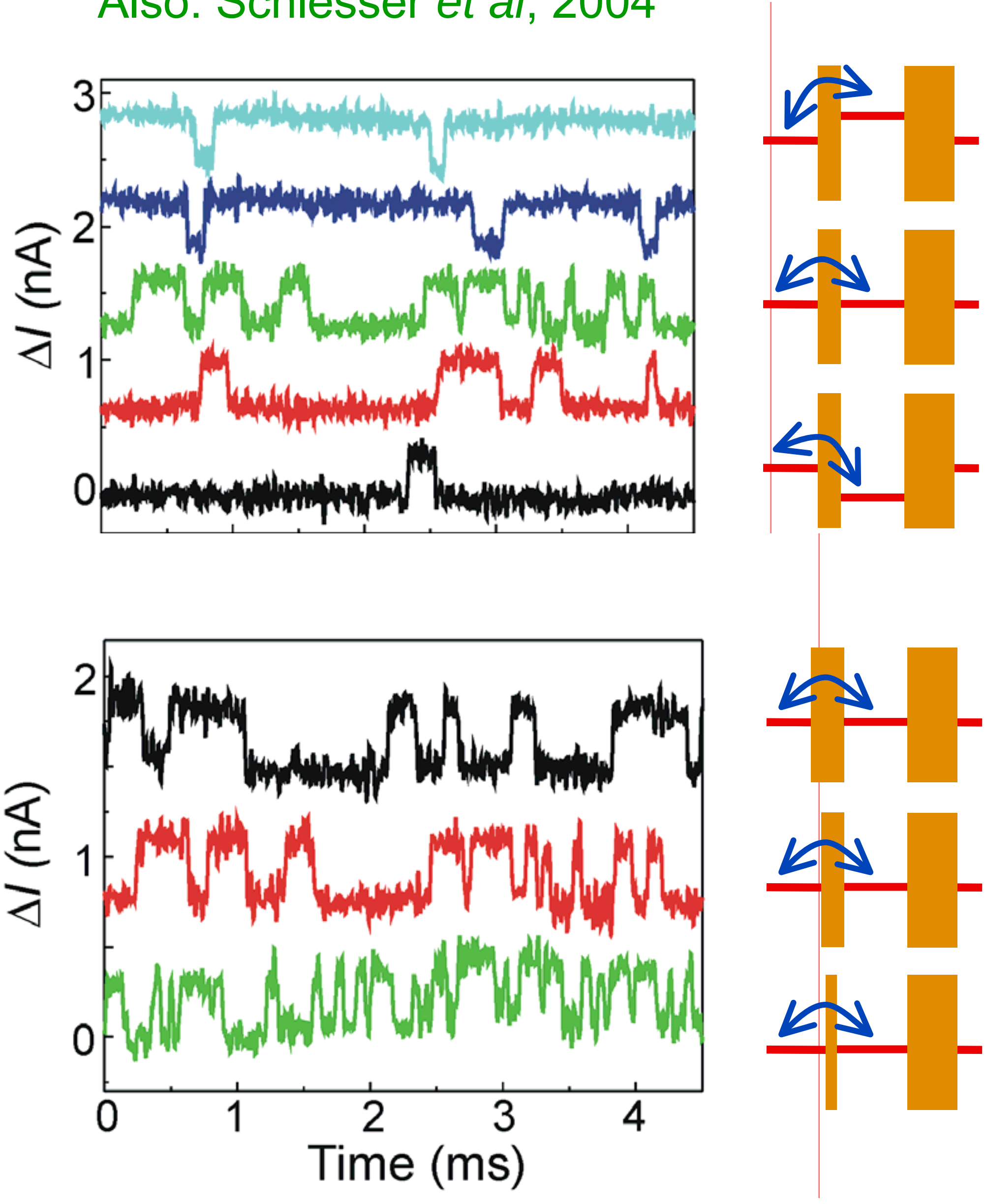
Spin read-out principle:
convert spin to charge



Observation of individual tunnel events

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



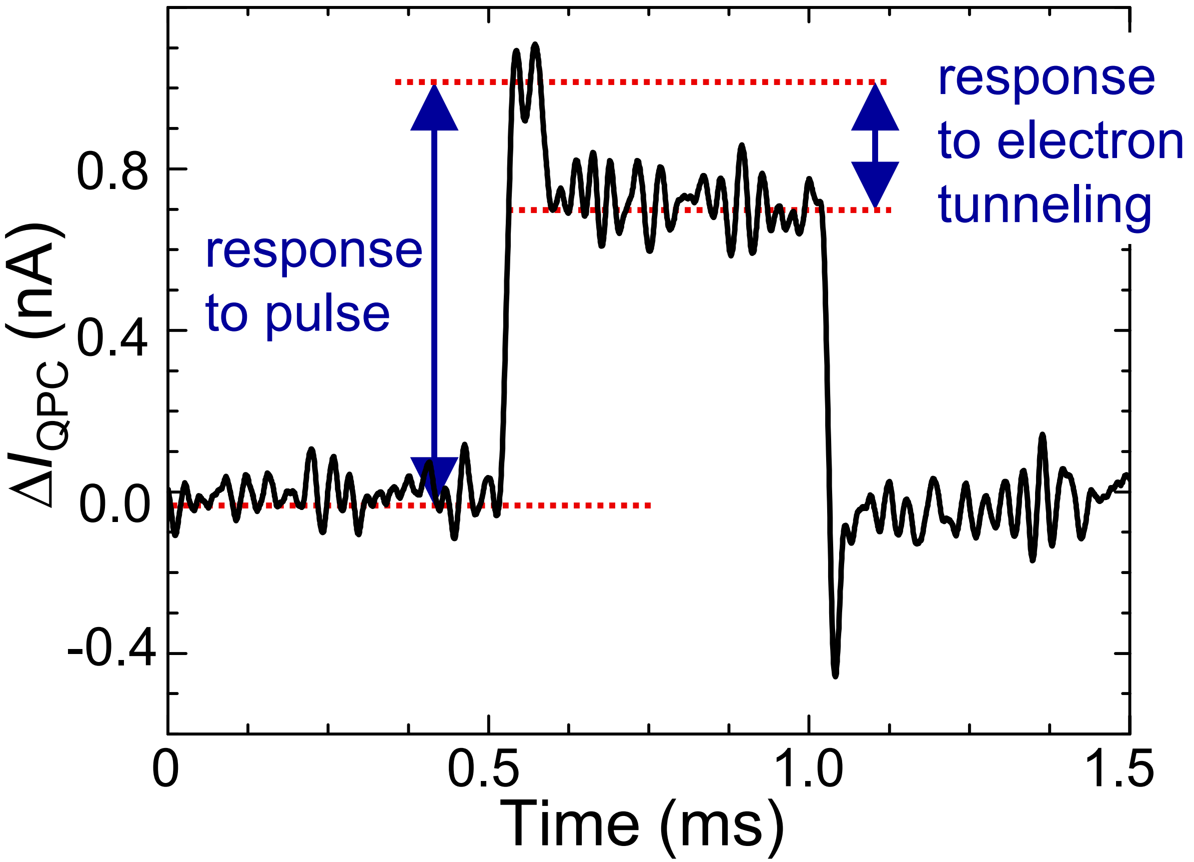


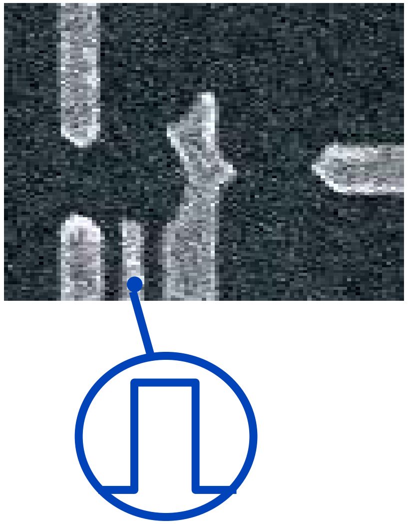
- V_{SD} = 1 mV

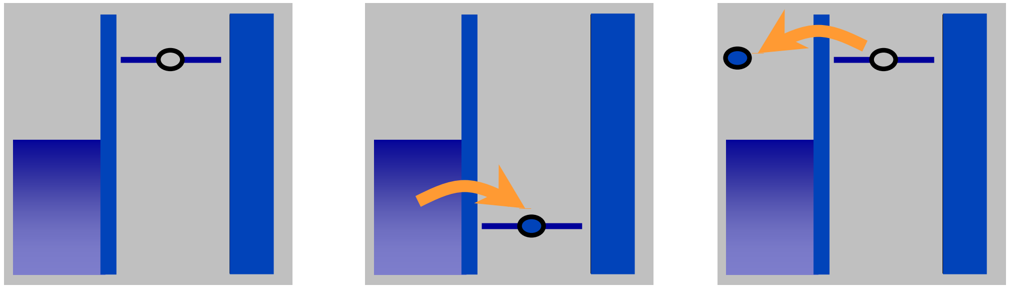
- I_{QPC} ~ 30 nA
- ΔI_{QPC} ~ 0.3 nA

- Shortest steps ~ 8 μs

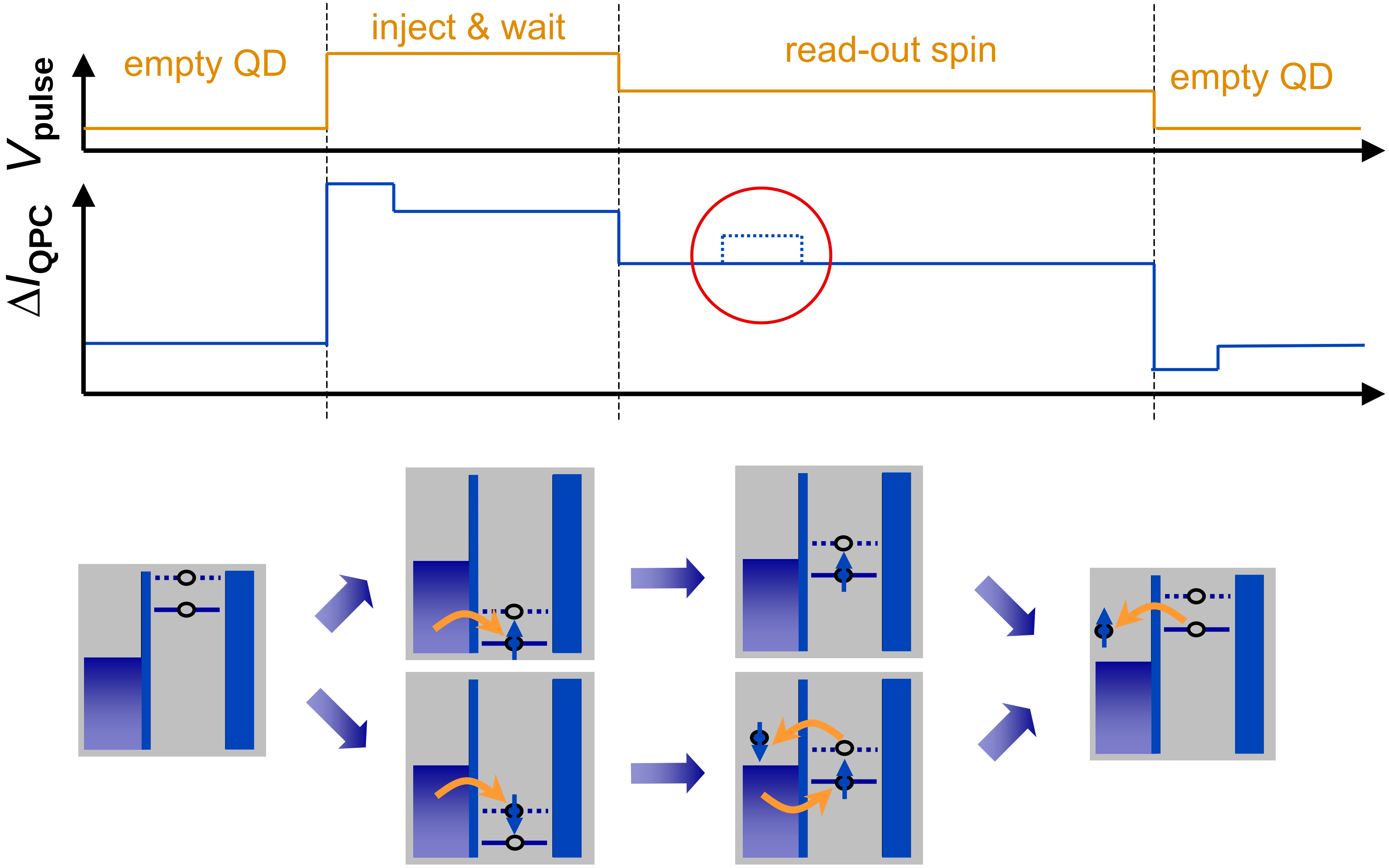
Pulse-induced tunneling







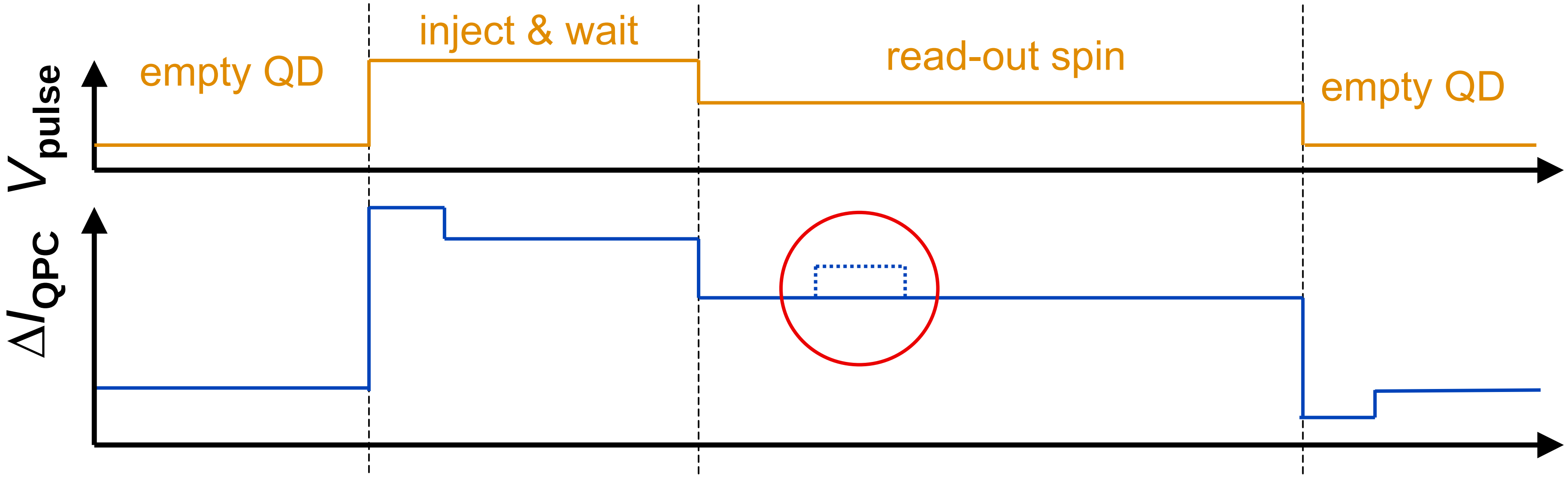
Spin read-out procedure

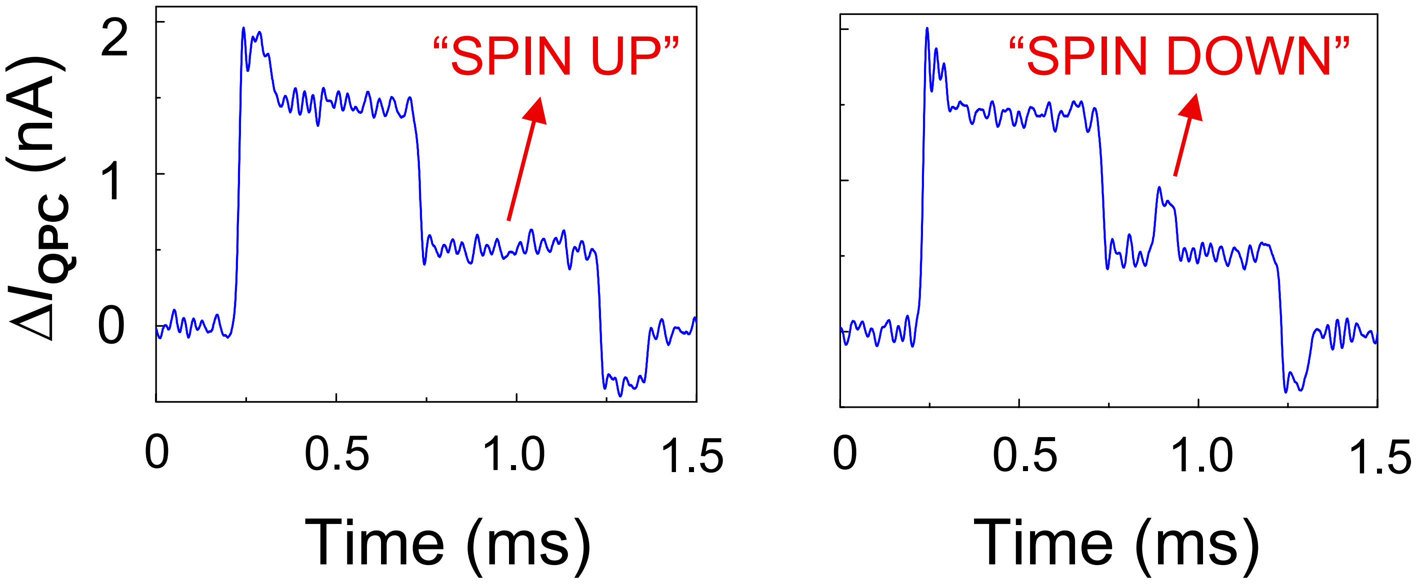


Inspiration: Fujisawa *et al.*, Nature **419**, 279, 2002

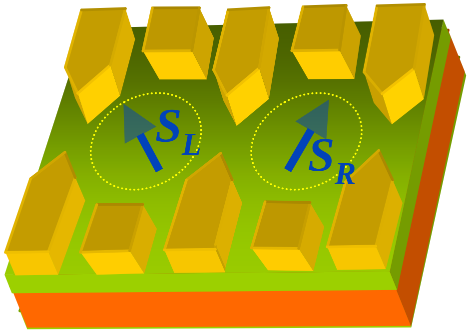
Spin read-out results

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





Spin qubits in quantum dots



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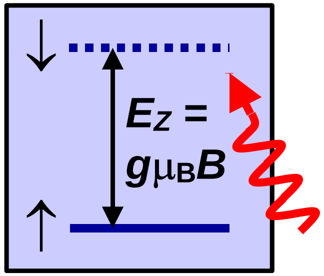
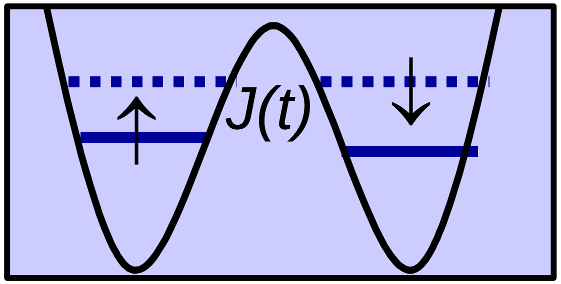
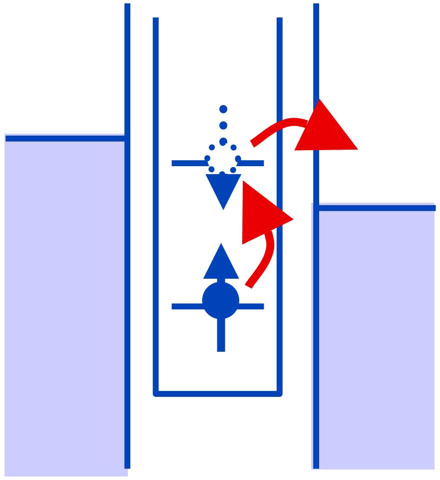




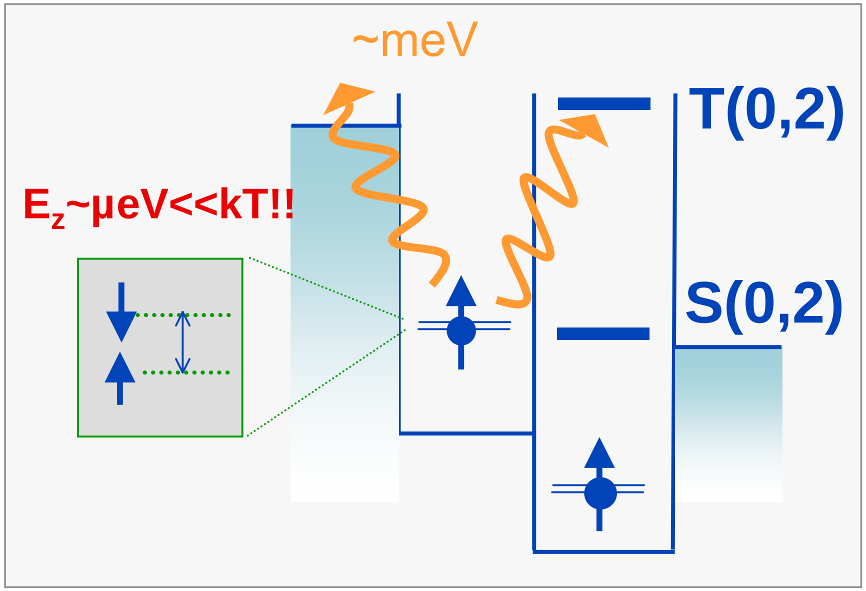
ESR detection in a single dot



ESR lifts Coulomb
blockade

Engel & Loss, PRL 2001

Double dot in spin blockade for ESR detection



Advantage: ***interdot transition instead of dot-lead transition***

- Insensitive to temperature

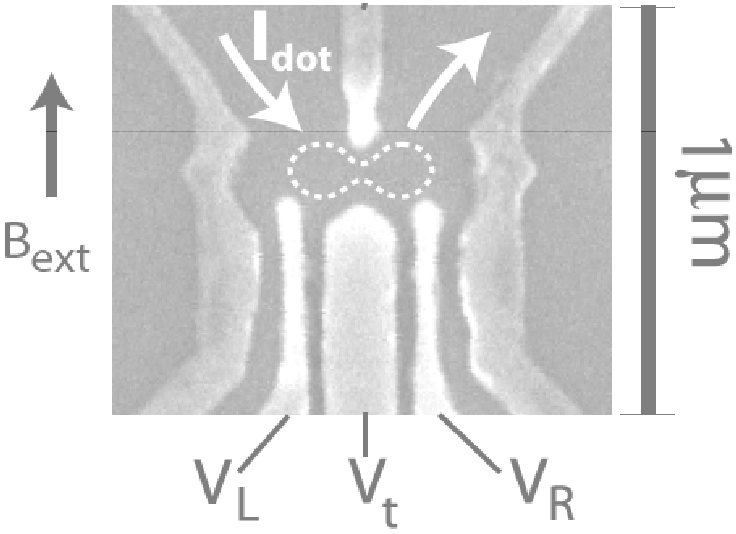
  ⇒ can use $B < 100$ mT, $f < 500$ MHz

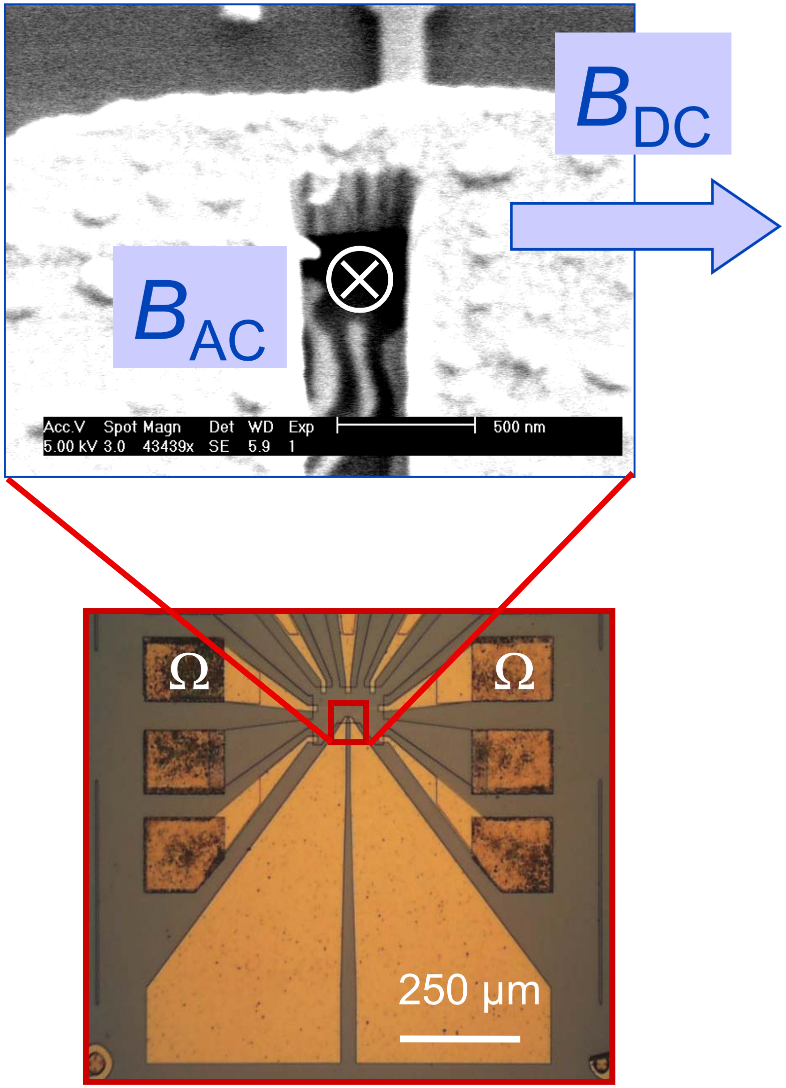
- Insensitive to electric fields

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

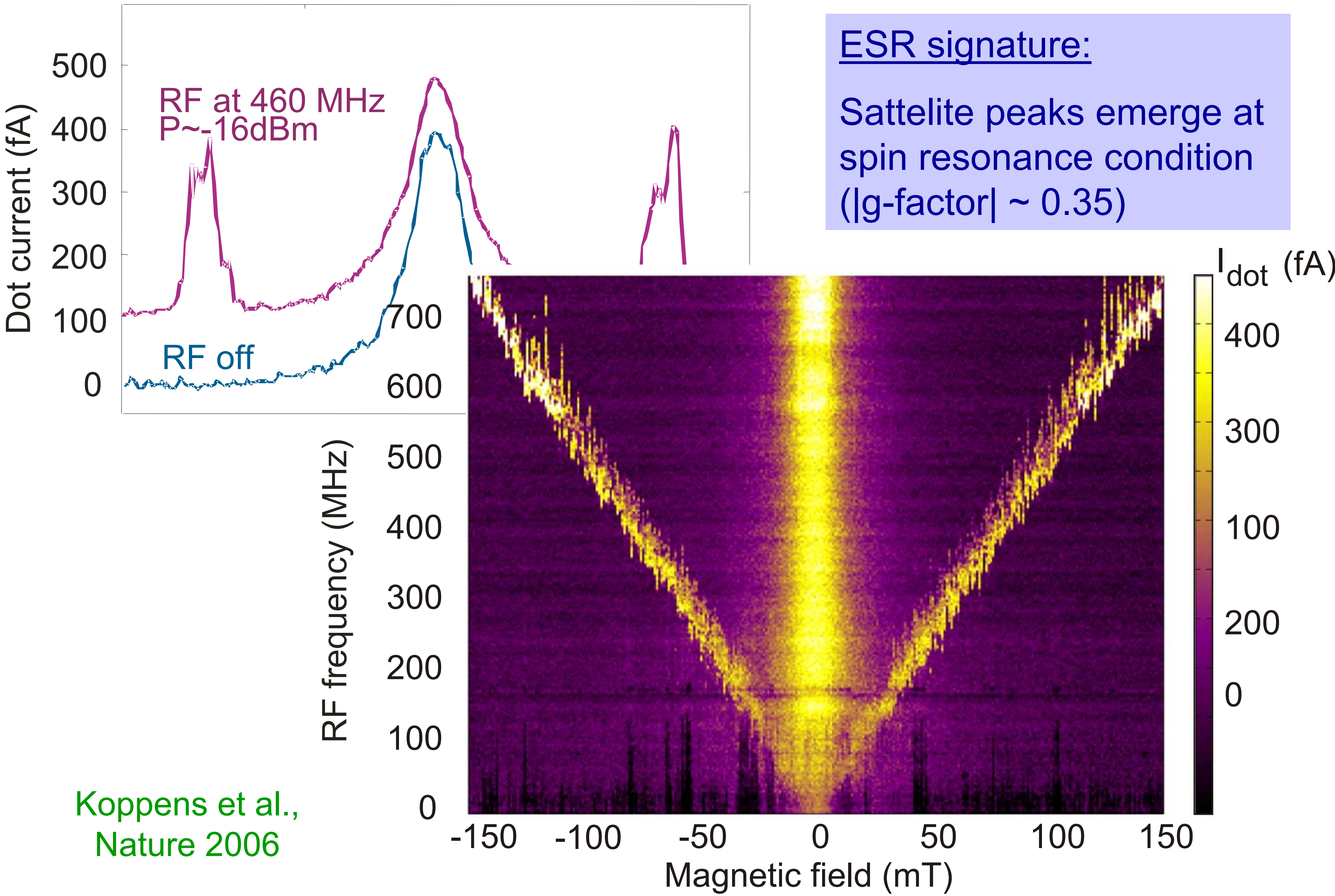
Dielectric ~ 100nm calixerene

Stripline ~ 400nm thick gold

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

Maximize B_1, minimize E_1

ESR spin state spectroscopy

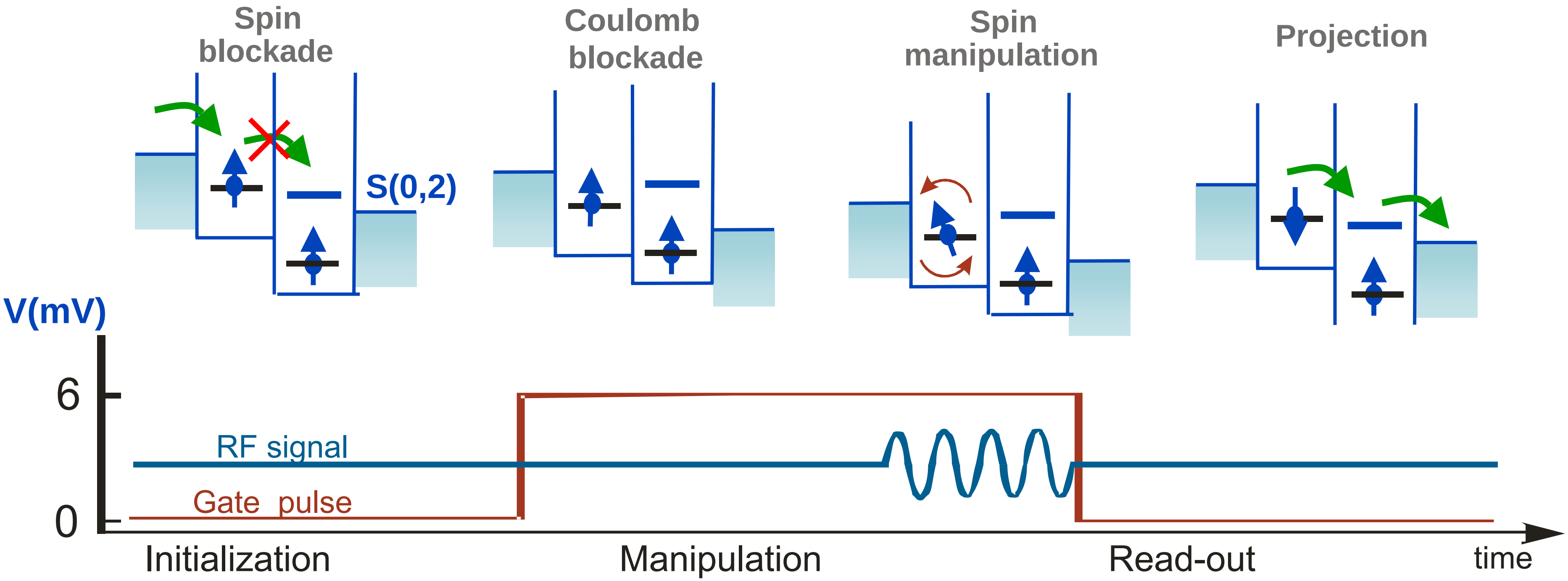


ESR signature:

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

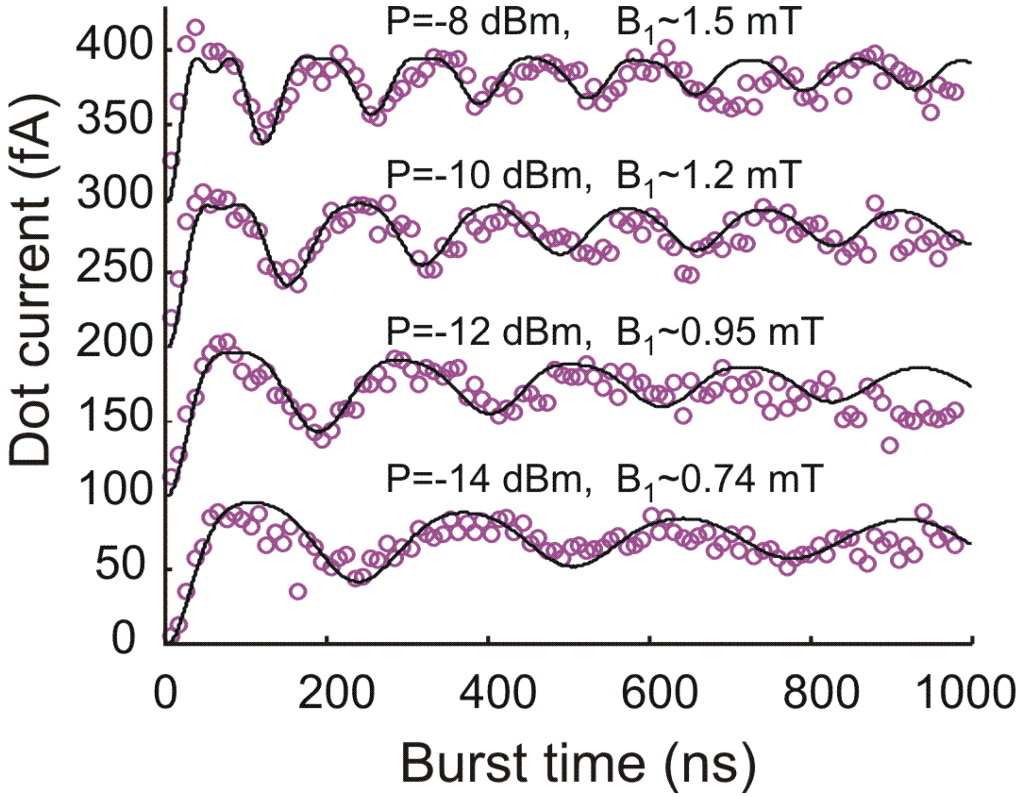
Koppens et al., Nature 2006

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!

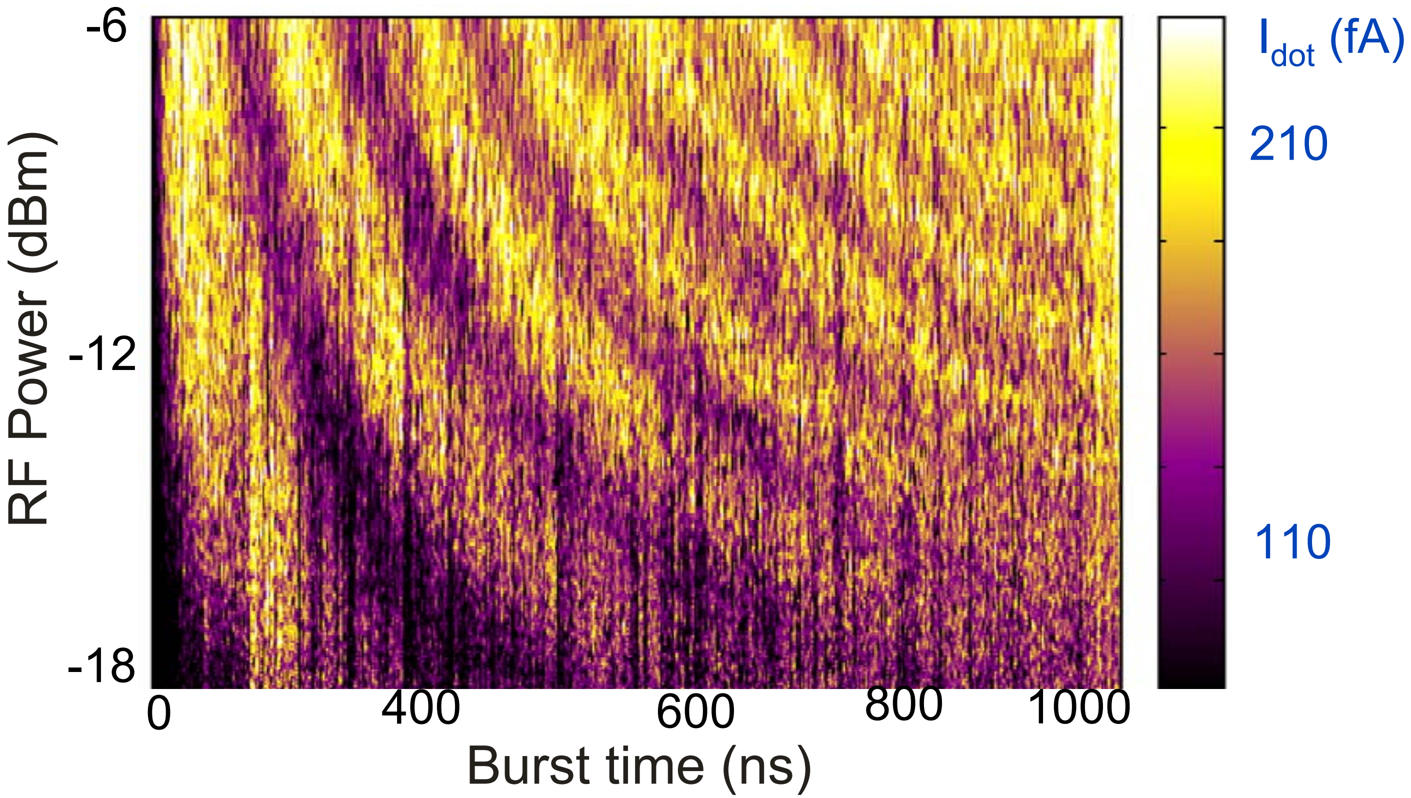


Koppens et al.
Nature 2006

- 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

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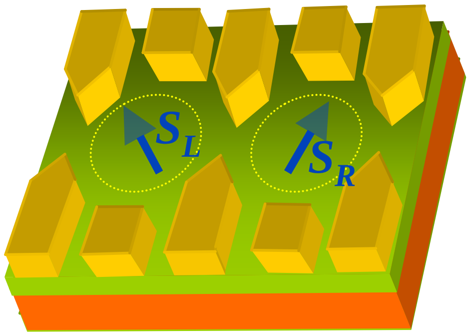
Vandersypen et al., Proc. MQC02 (quant-ph/0207059)



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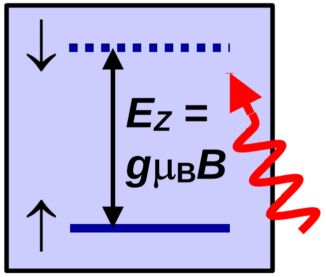
then measure charge

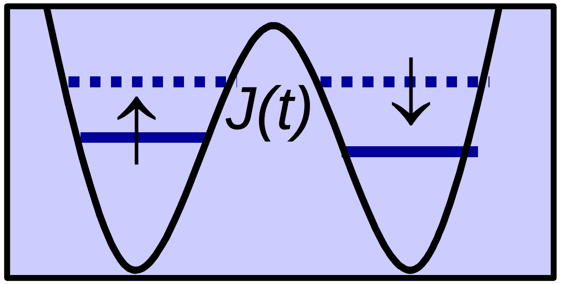
ESR pulsed microwave magnetic field

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



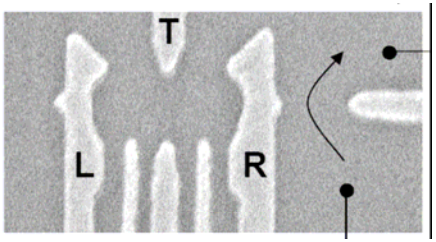
SWAP exchange interaction

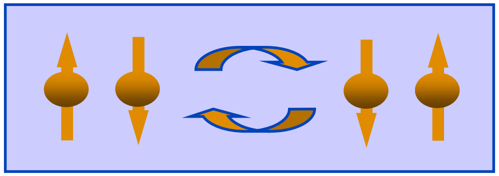
$$H_J \sim \Sigma\, J_{ij}(t)\;\; \sigma_i \cdot \sigma_j$$



Coherence long relaxation time T_1
long coherence time T_2

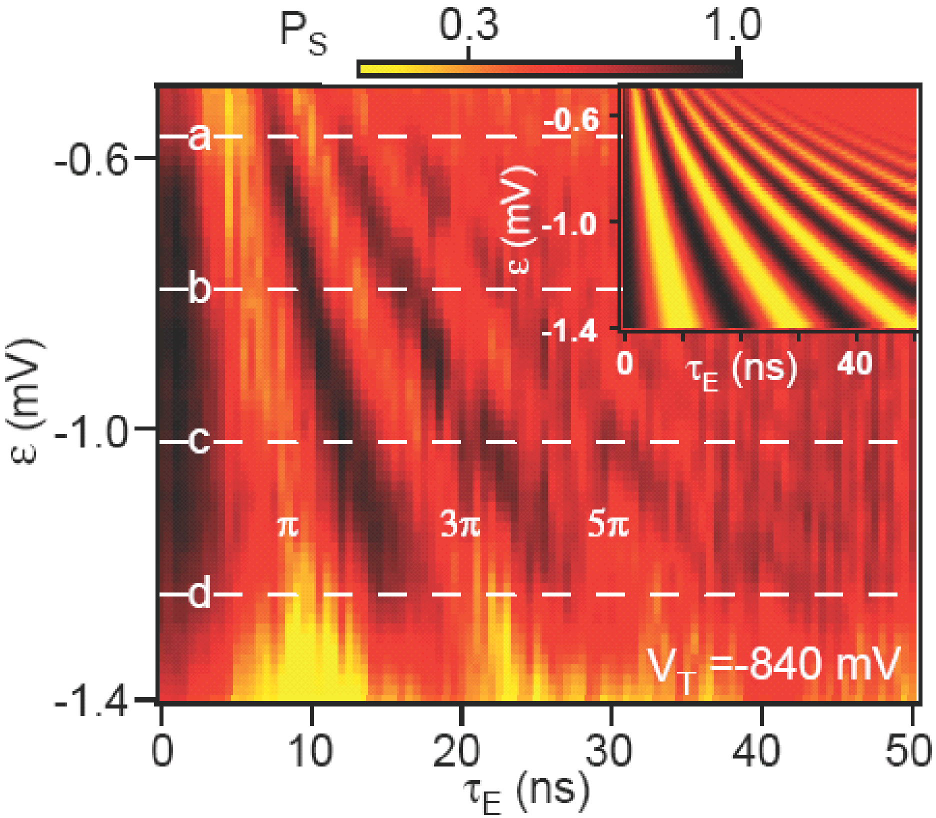
Coherent exchange of two spins

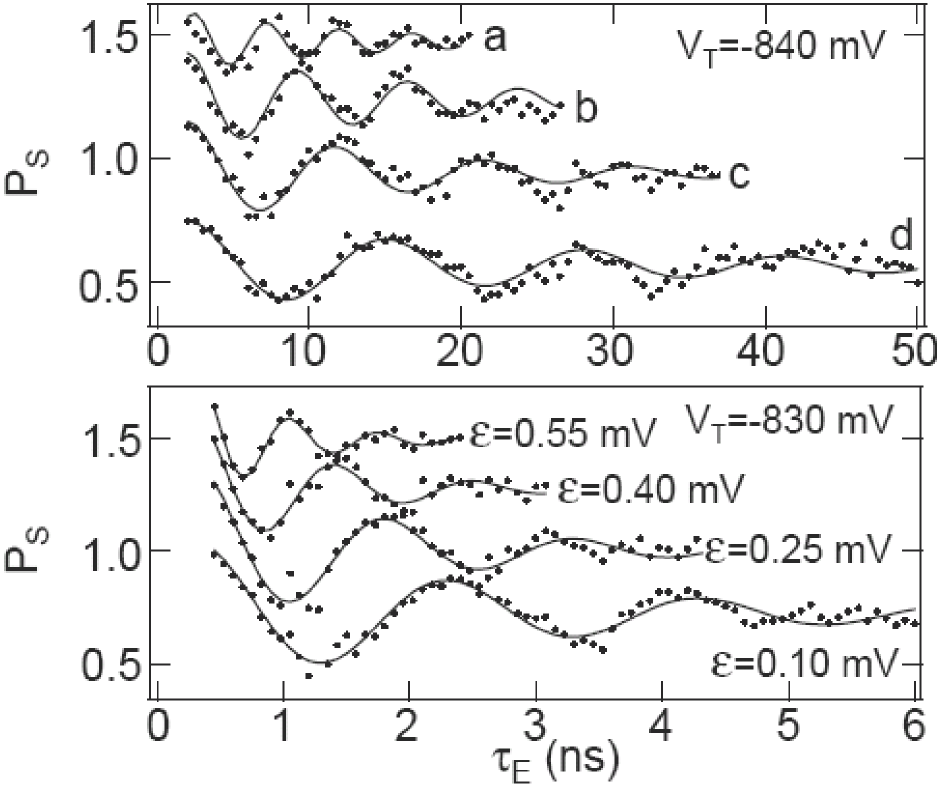




Petta *et al.*, Science 2005

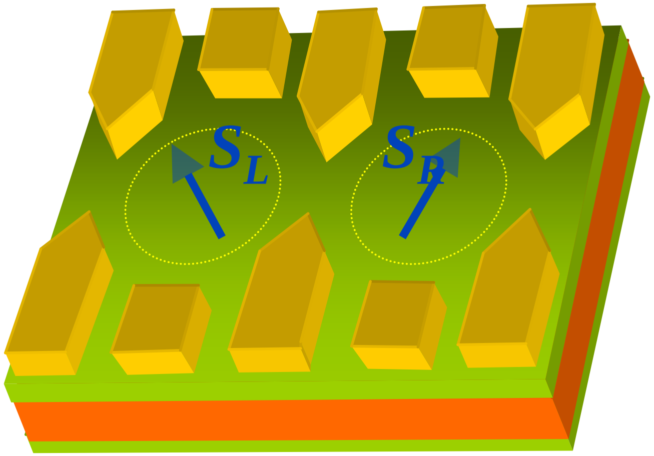
- free evolution under exchange Hamiltonian
- swap$^{1/2}$ in as little as 180 ps
- three oscillations visible, independent of *J*

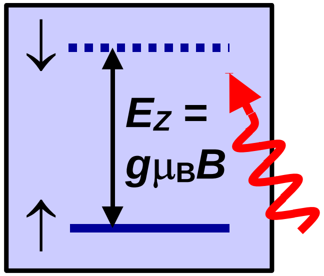


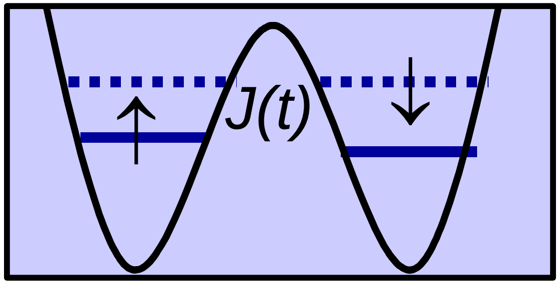


Spin qubits in quantum dots - present status

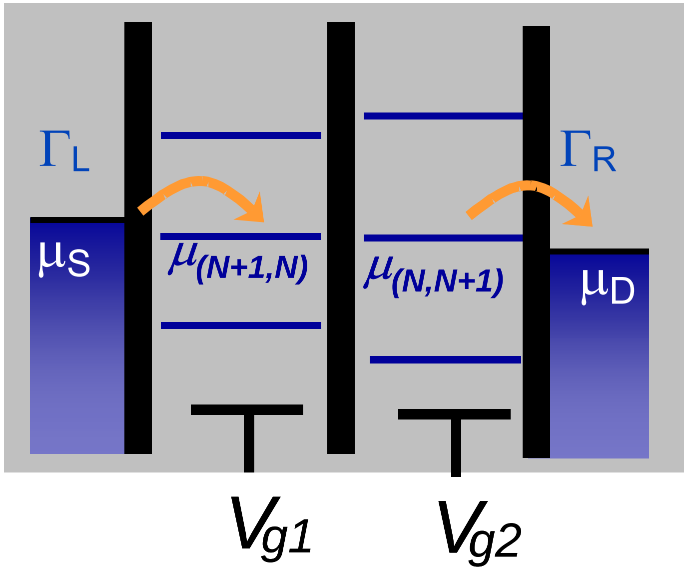
Initialization	☑	1 electron, low T, high B_0 $H_0 \sim \Sigma\ \omega_i\ \sigma_{zi}$
Read-out	☑	convert spin to charge then measure charge
ESR	☑	pulsed microwave magnetic field $H_{RF} \sim \Sigma\ A_i(t) \cos(\omega_i t)\ \sigma_{xi}$
SWAP	☑	exchange interaction $H_J \sim \Sigma\ J_{ij}(t)\ \sigma_i \cdot \sigma_j$
Coherence	☑	measure coherence time $T_1 \sim 1$ ms; $T_2 > 1$ μs



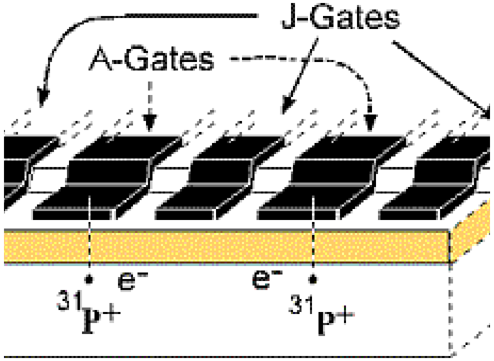




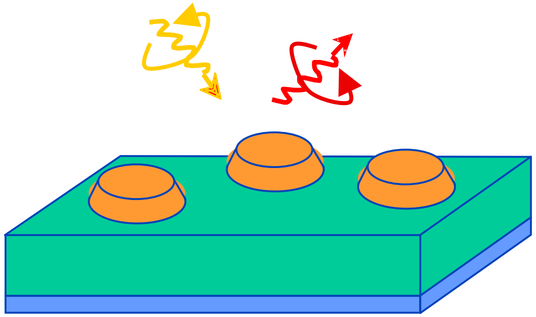
Single electron tunneling through two dots in series



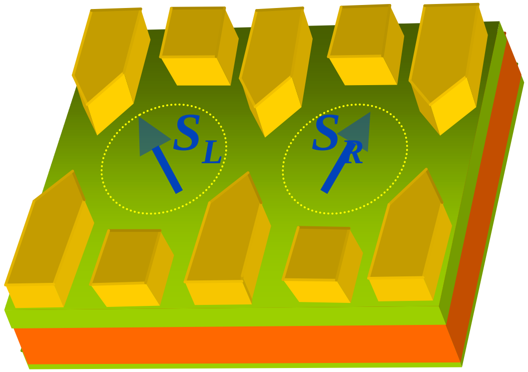
Can we access the quantum world at the level of single-particles? in a solid state environment?



Kane, Nature 1998



Imamoglu *et al*, PRL 1999



Loss & DiVincenzo
PRA 1998