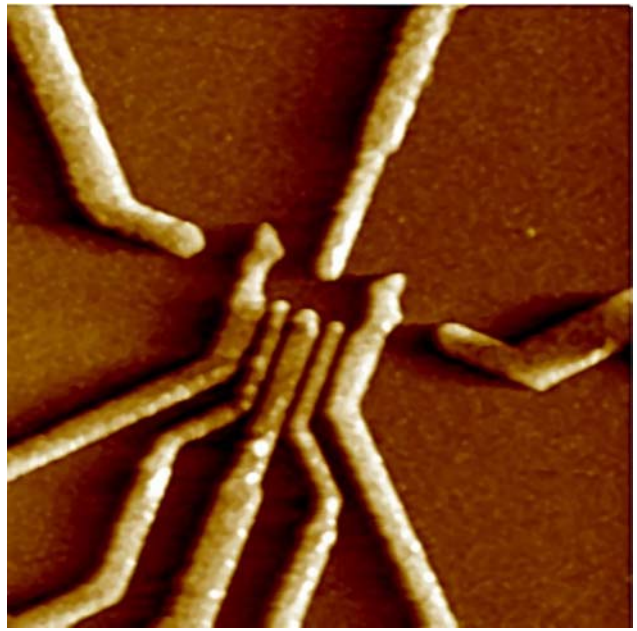
Electron Spin Qubits in Quantum Dots



Lancaster 2003

Lieven Vandersypen

Jeroen Elzerman
Ronald Hanson
Laurens Willems van Beveren
Jacob Greidanus
Jort Wever
Benoit Witkamp
Leo Kouwenhoven

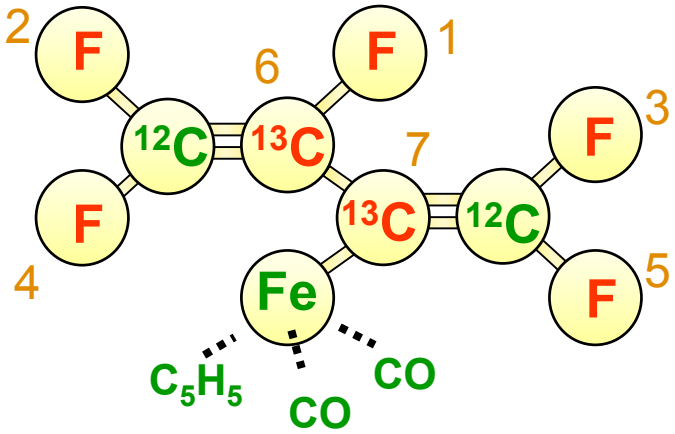
TU Delft
Technische Universiteit Delft

DARPA

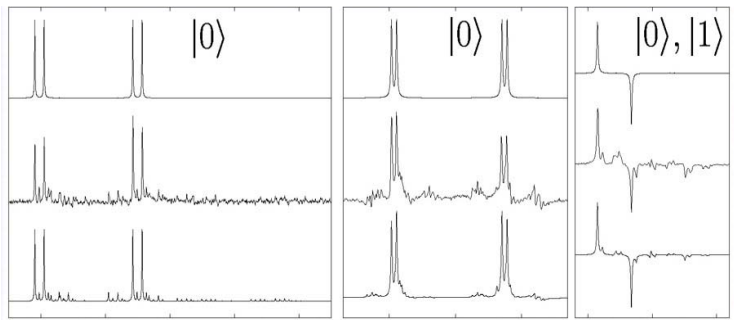
DIMES
Delft Institute of Microelectronics and Submicron Technology

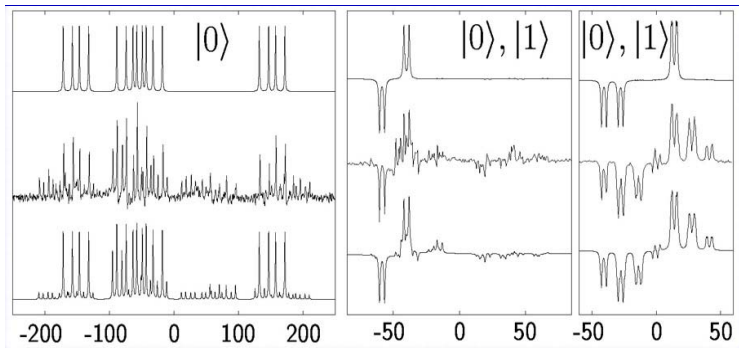
ERATO

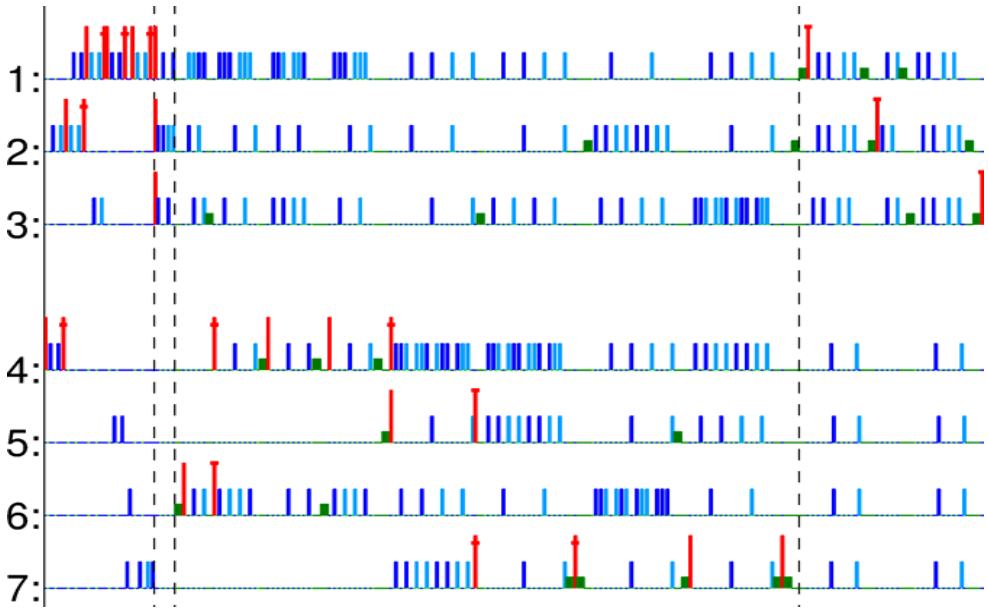
Factoring 15 with nuclear spins



Vandersypen et al., *Nature* **414**, 883 (2001)







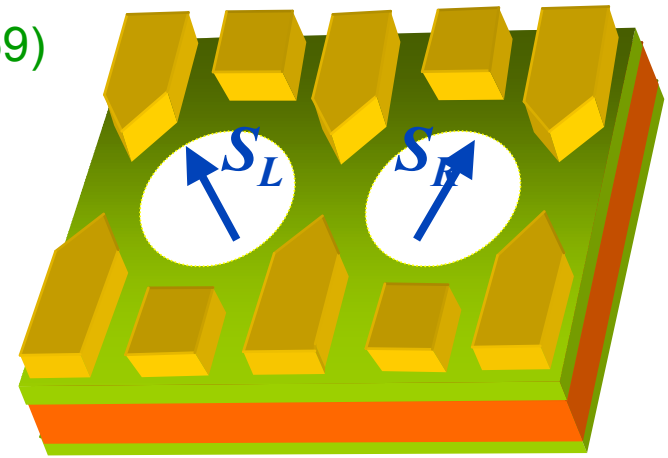
Spins are natural, beautiful qubits!

But: no practical path for scaling liquid NMR to many more qubits

Find scalable spin system
with access to *individual* spins

Key features

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



Courtesy D. Loss

Initialization 1-electron dot $H_0 \sim \Sigma\, \omega_i \sigma_{zi}$

equilibrate at low T, high B_0

Read-out convert spin to charge

then measure charge

ESR pulsed microwave magnetic field $H_{RF} \sim \Sigma\, A_i(t) \cos(\omega_i t) \sigma_{xi}$

microfabricated wire nearby dot

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

control via DC pulses on dot-dot tunnel barrier

Coherence spins have long coherence times

in 2DEG: T_2 > 100 ns (Kikkawa&Awschalom, 1998)

Experimental progress

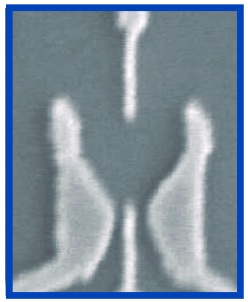
1. **A tunable few-electron quantum dot circuit**

2. **Zeeman splitting for a 1-electron dot**

3. **T_1 measurement for a single electron spin in a dot**

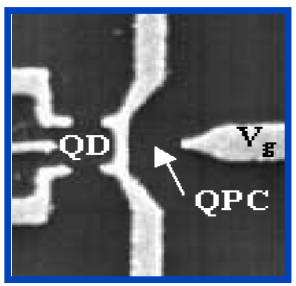
Double dot design (Gundam TM)

Ciorga '99

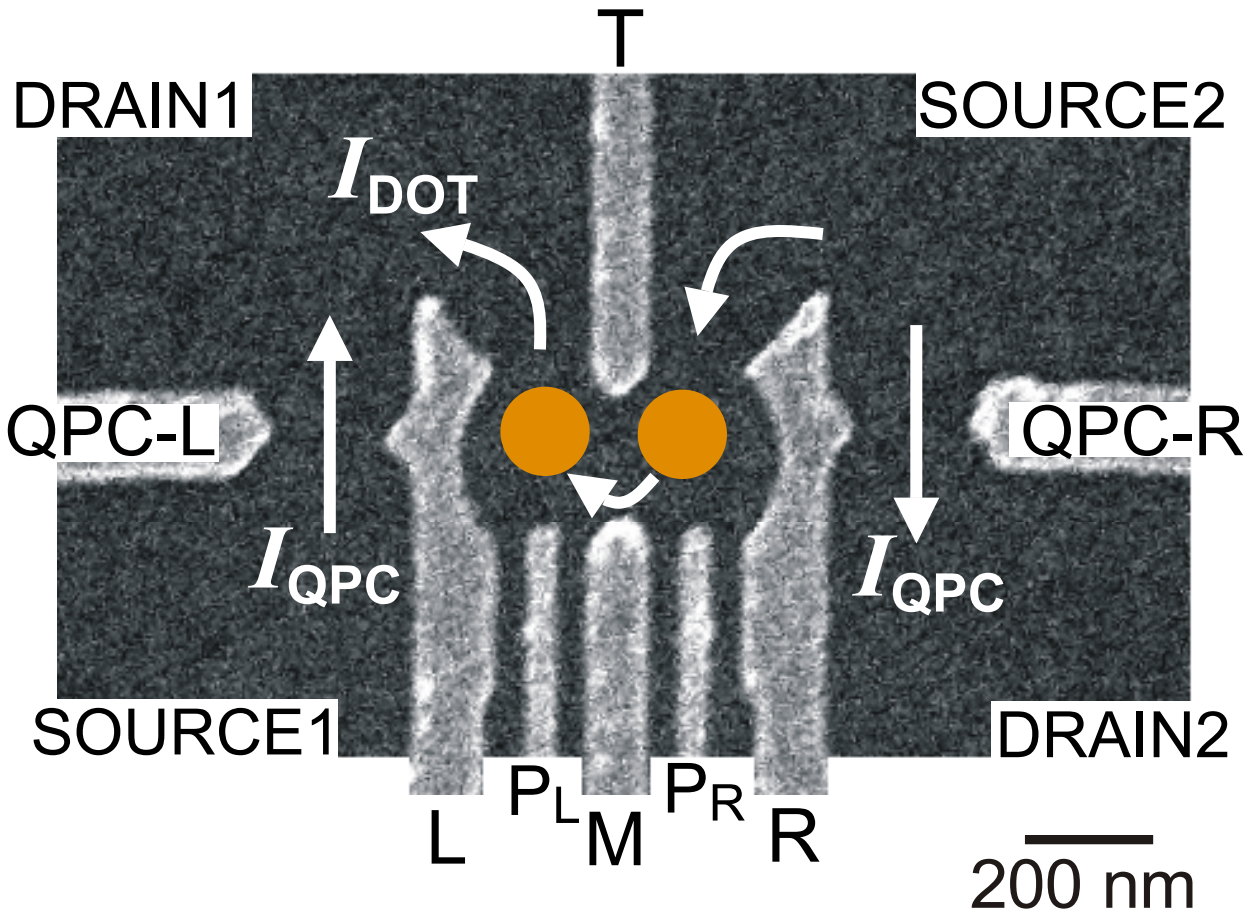


Open design

Field '93
Sprinzak '01



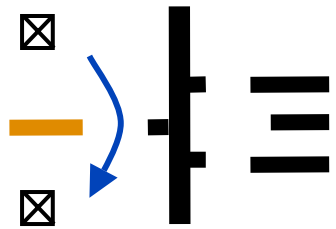
QPC for charge detection

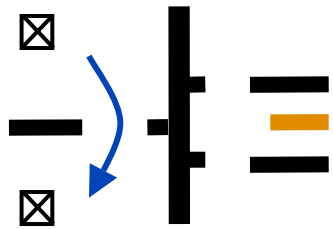


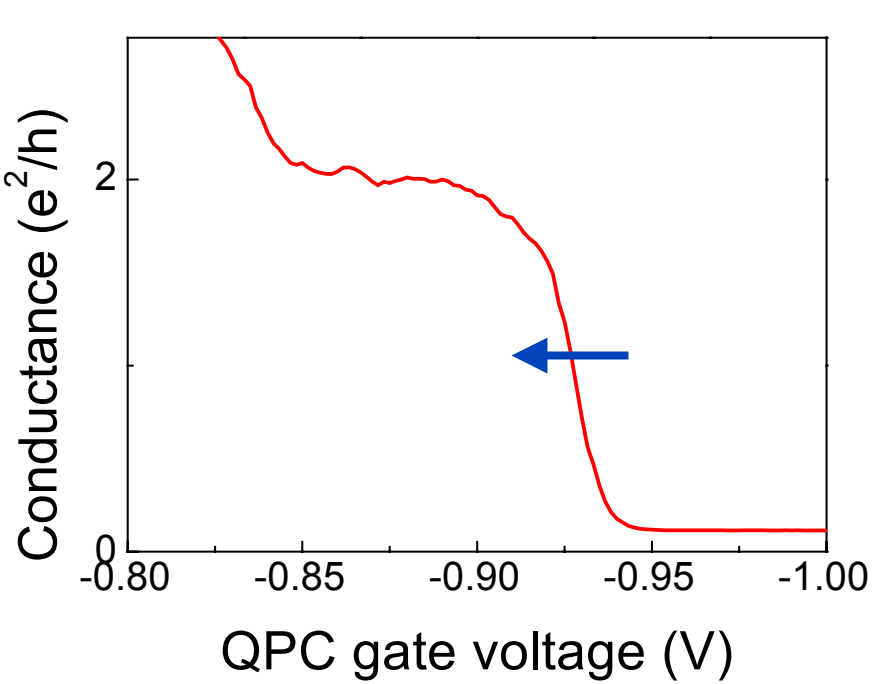
Fabrication at NTT by
L.H. Willems van Beveren

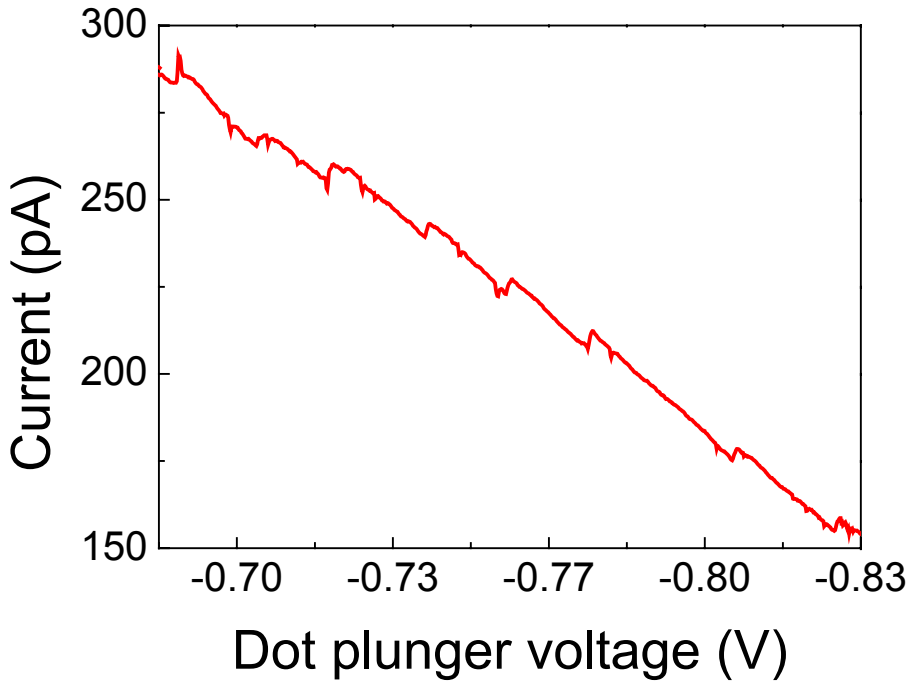
GaAs/AlGaAs heterostructure
2DEG 90 nm deep
$n_s = 2.9 \times 10^{11}$ cm^{-2}

Charge read-out with a quantum point contact (QPC)



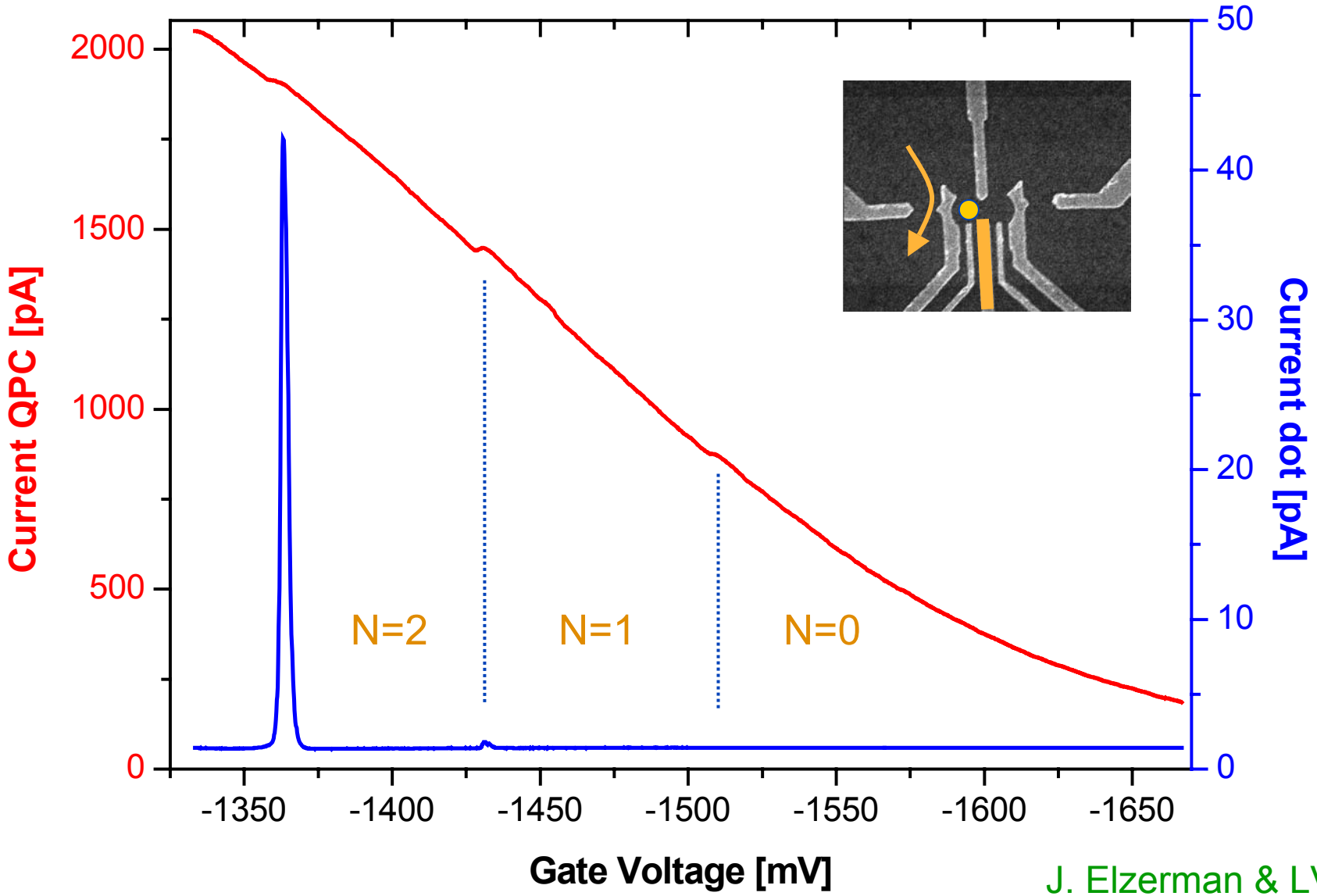






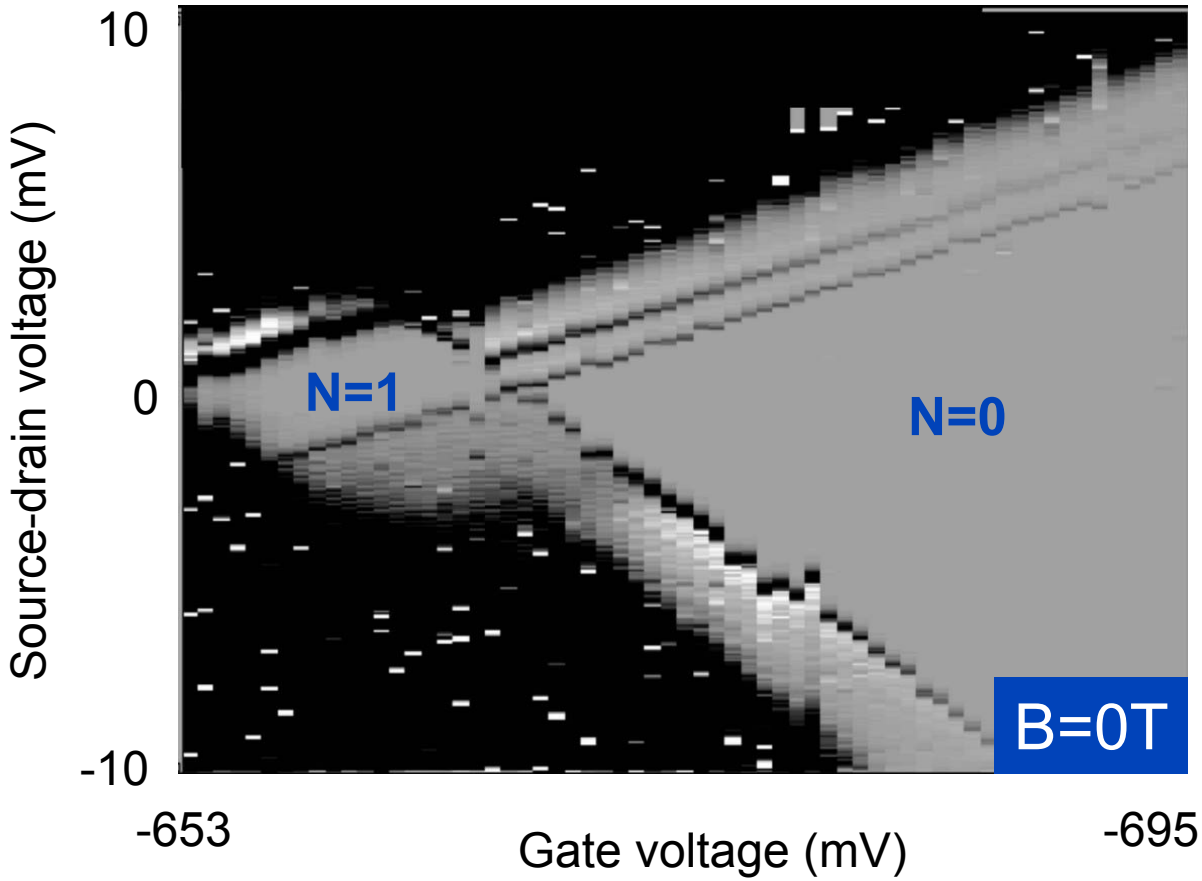
Field *et al*, PRL 1993

Is this really the last electron?



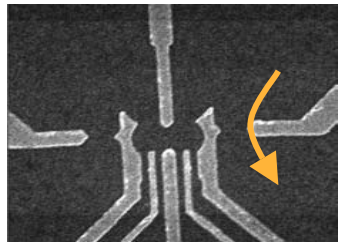
J. Elzerman & LV

Few-electron Coulomb diamond

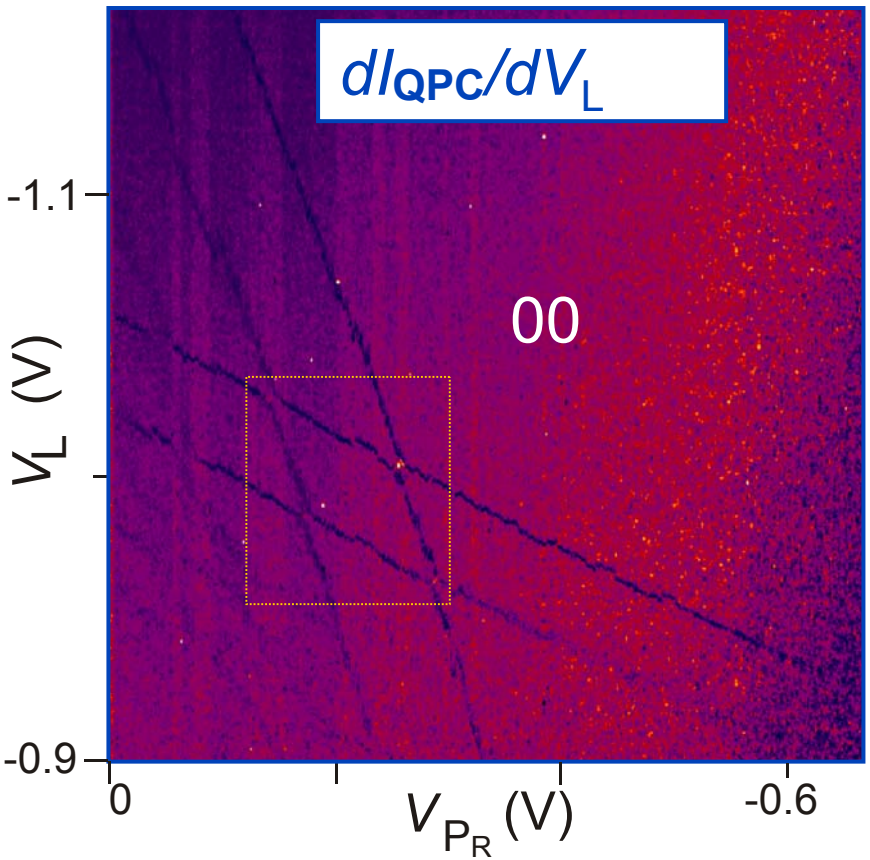


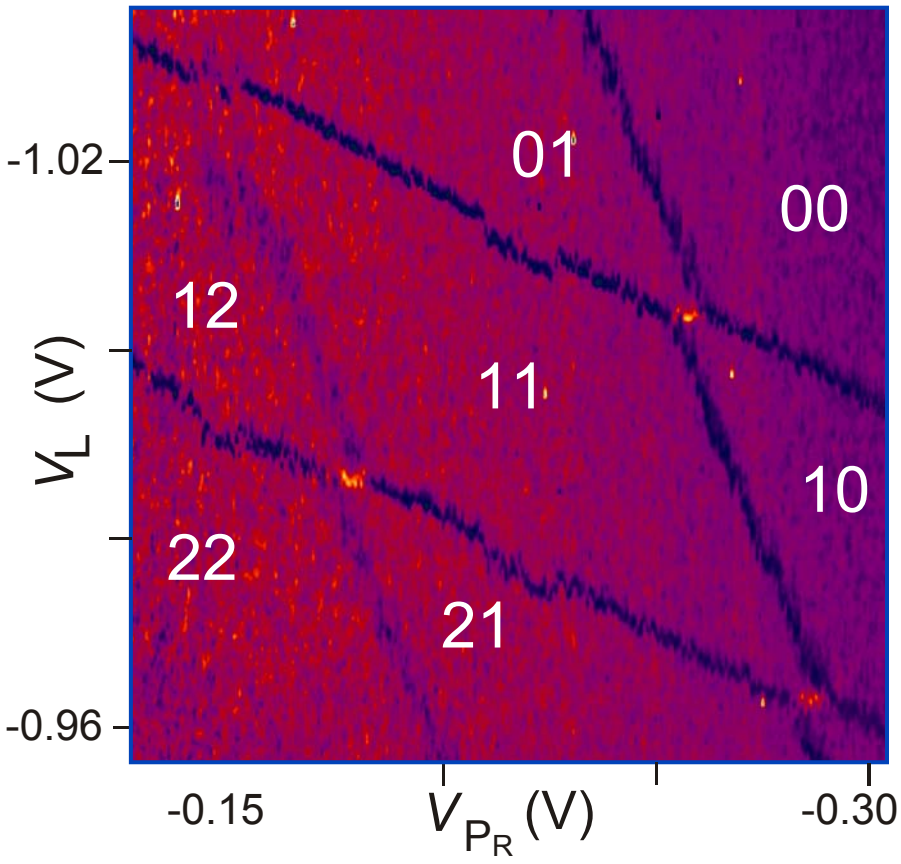
Few-electron double dot

Transport through QPC



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

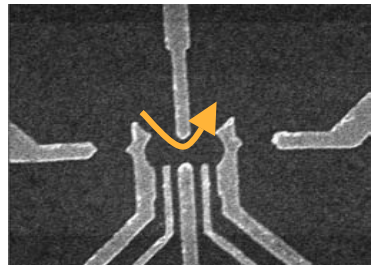


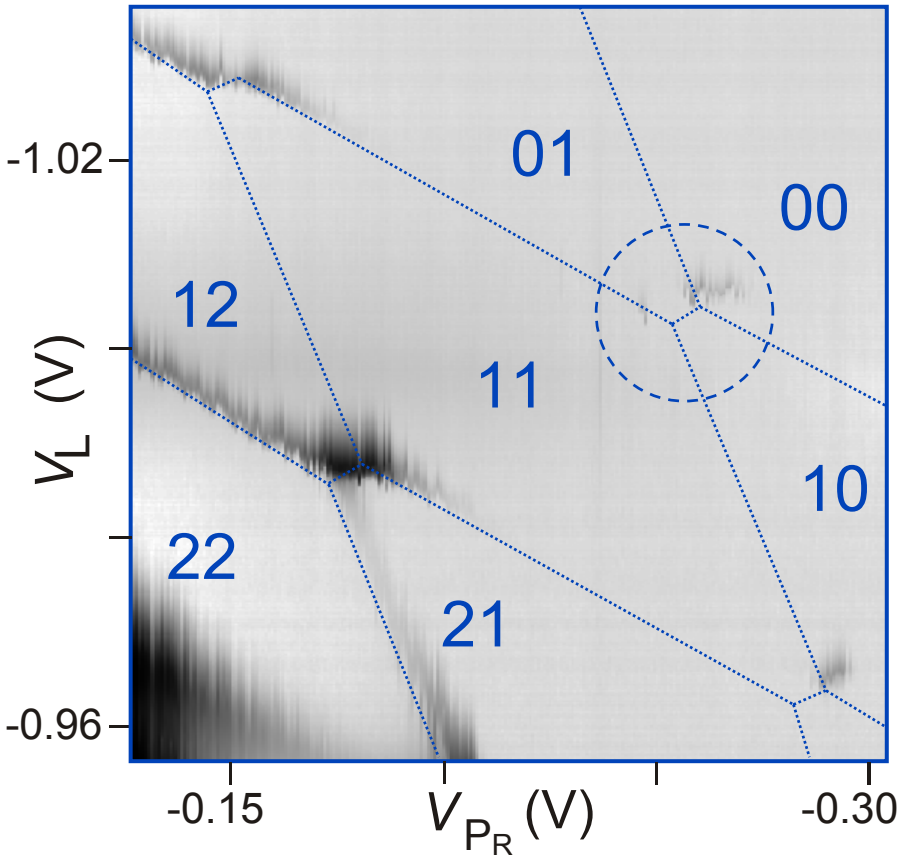


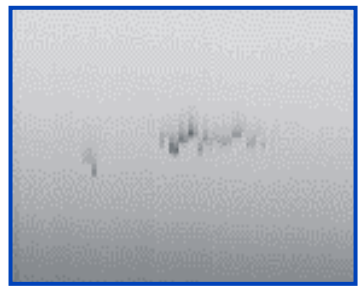
- Double dot can be emptied
- QPC can detect all charge transitions, also between dots

Few-electron double dot

Transport through dots

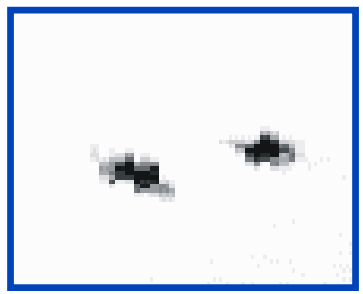




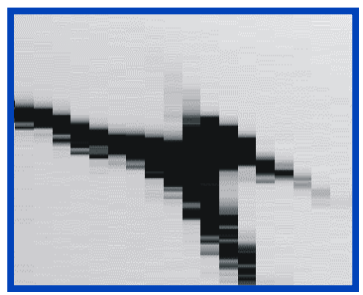


Peak height

< 1 pA



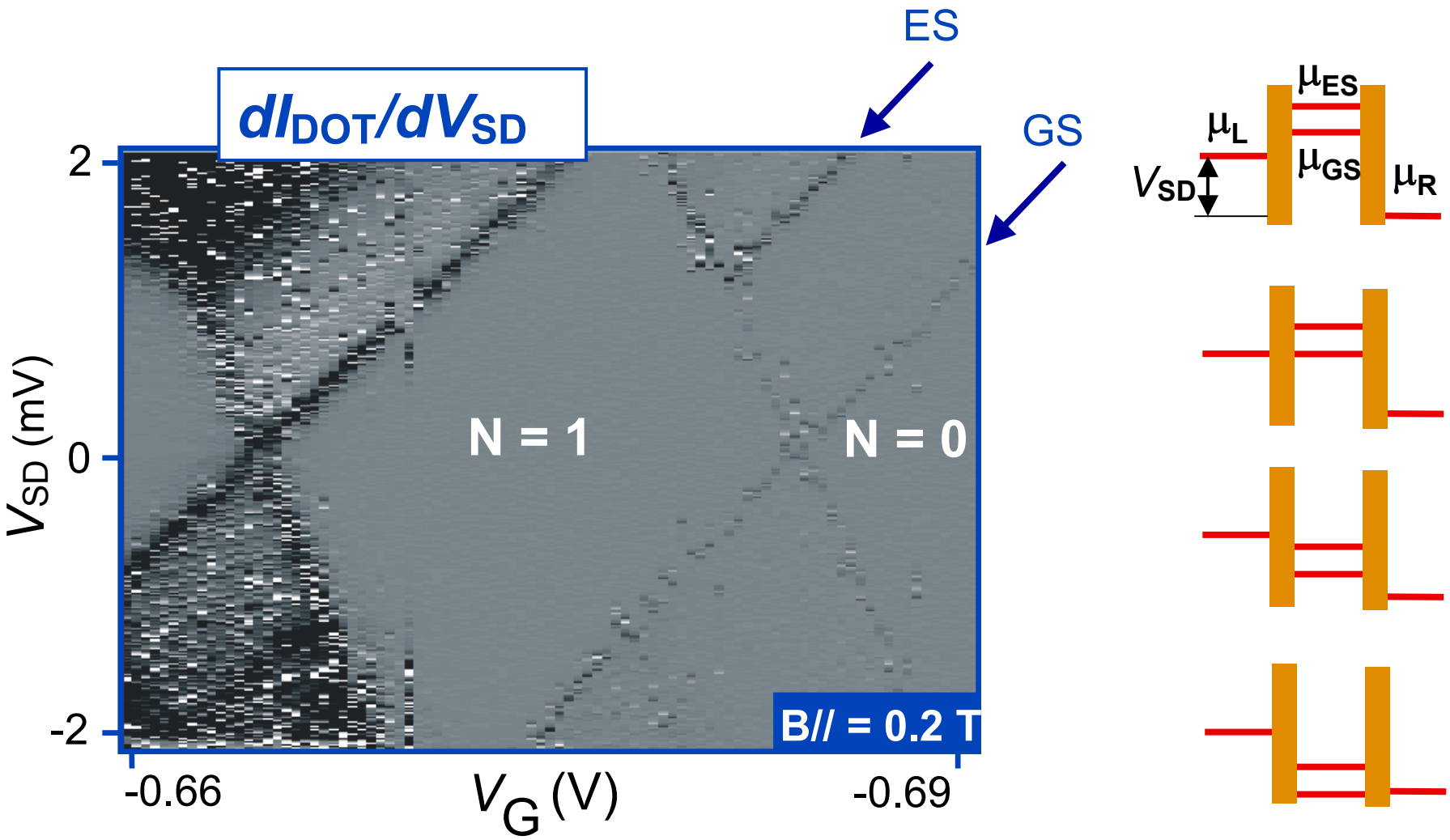
2 pA



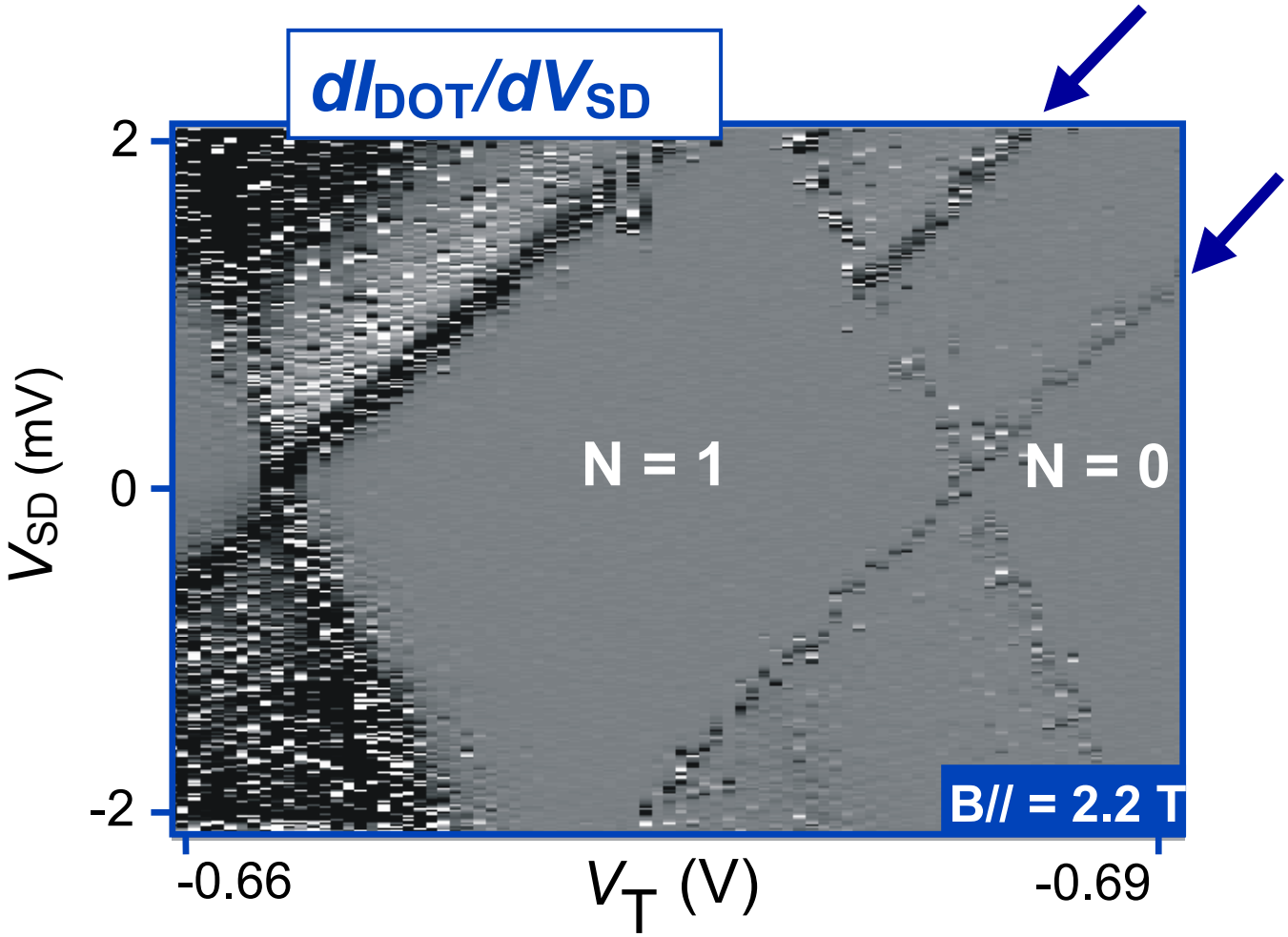
70 pA

Zeeman splitting for a single electron in a dot ?

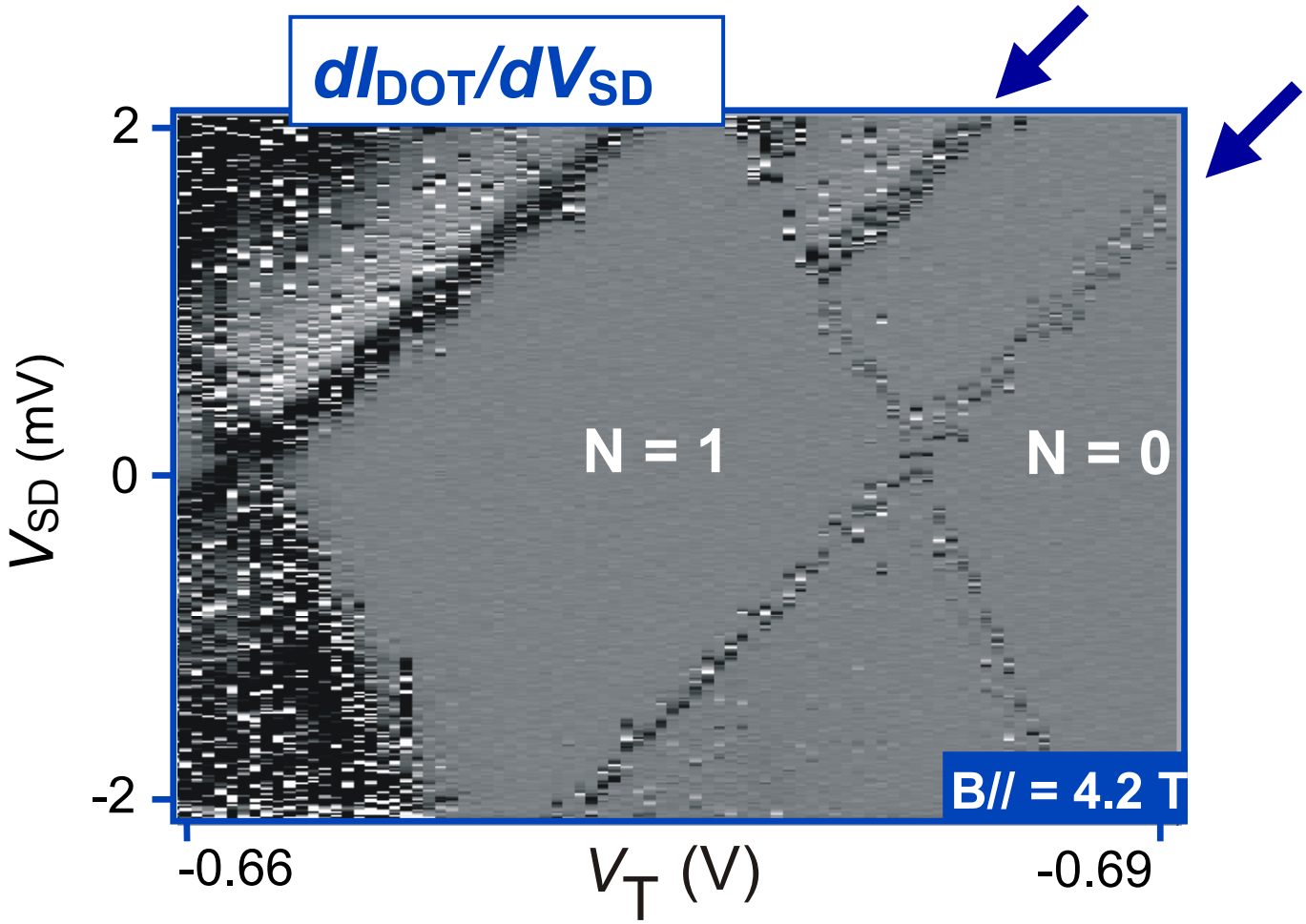
Non-linear spectroscopy



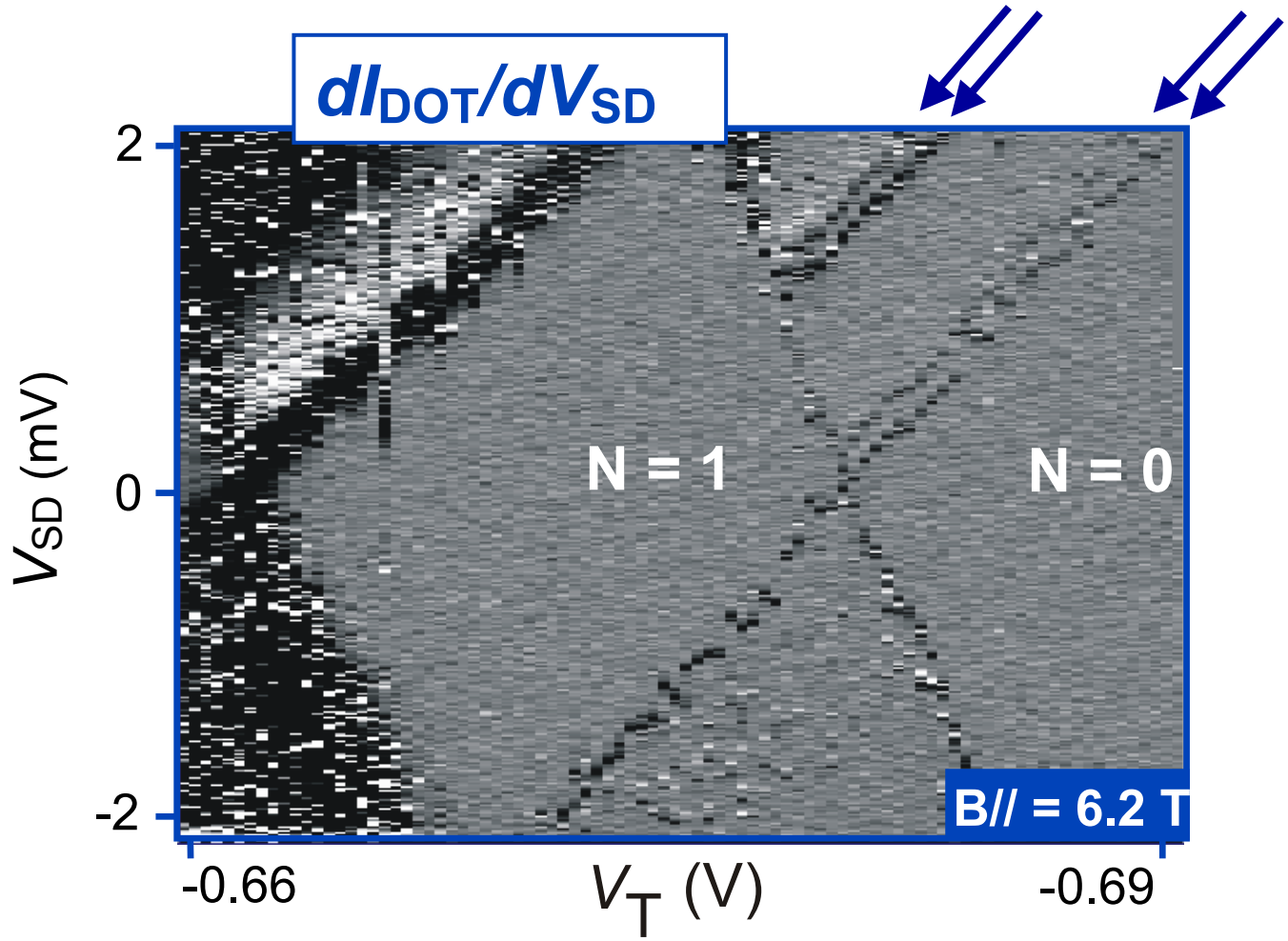
Zeeman splitting of a single electron



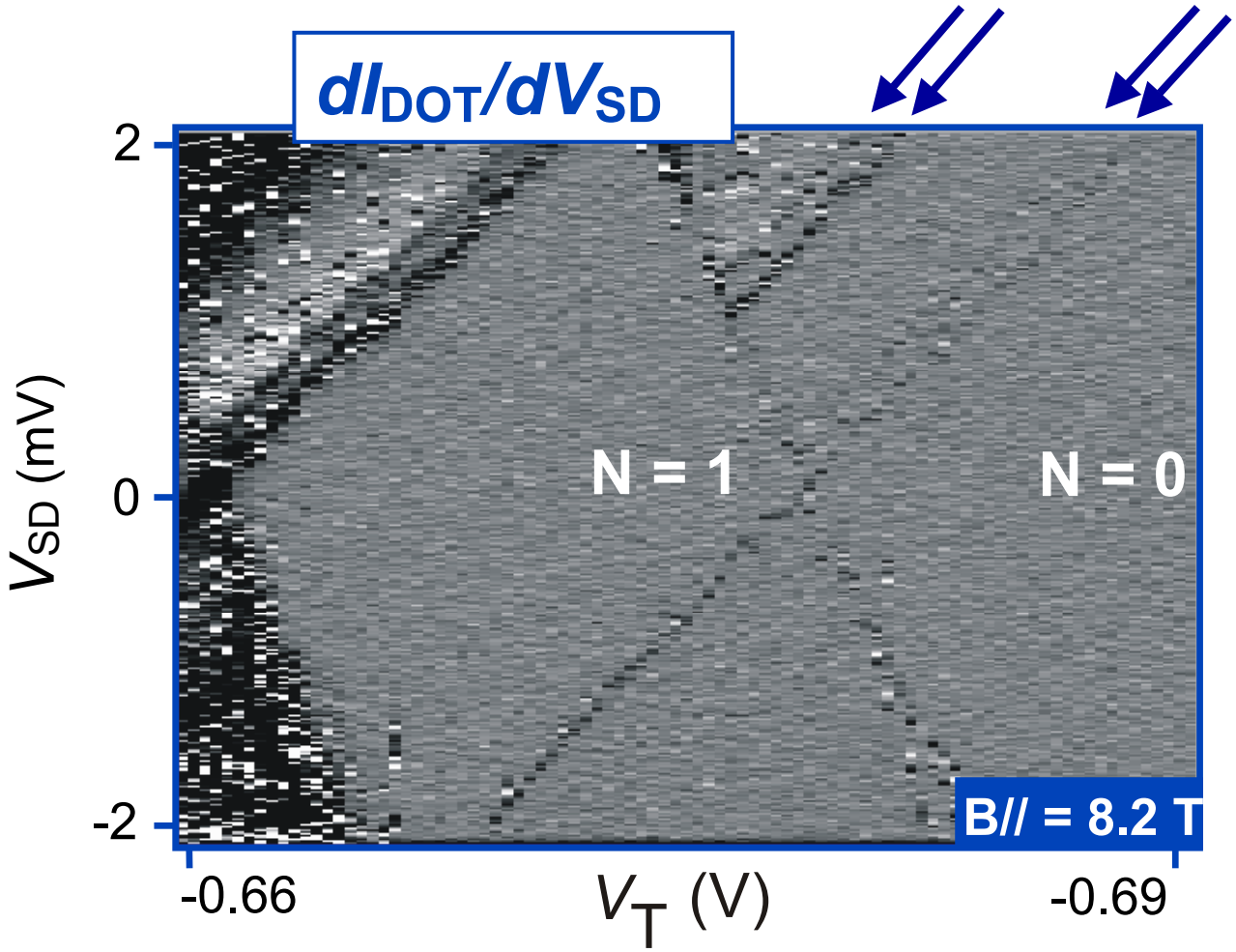
Zeeman splitting of a single electron



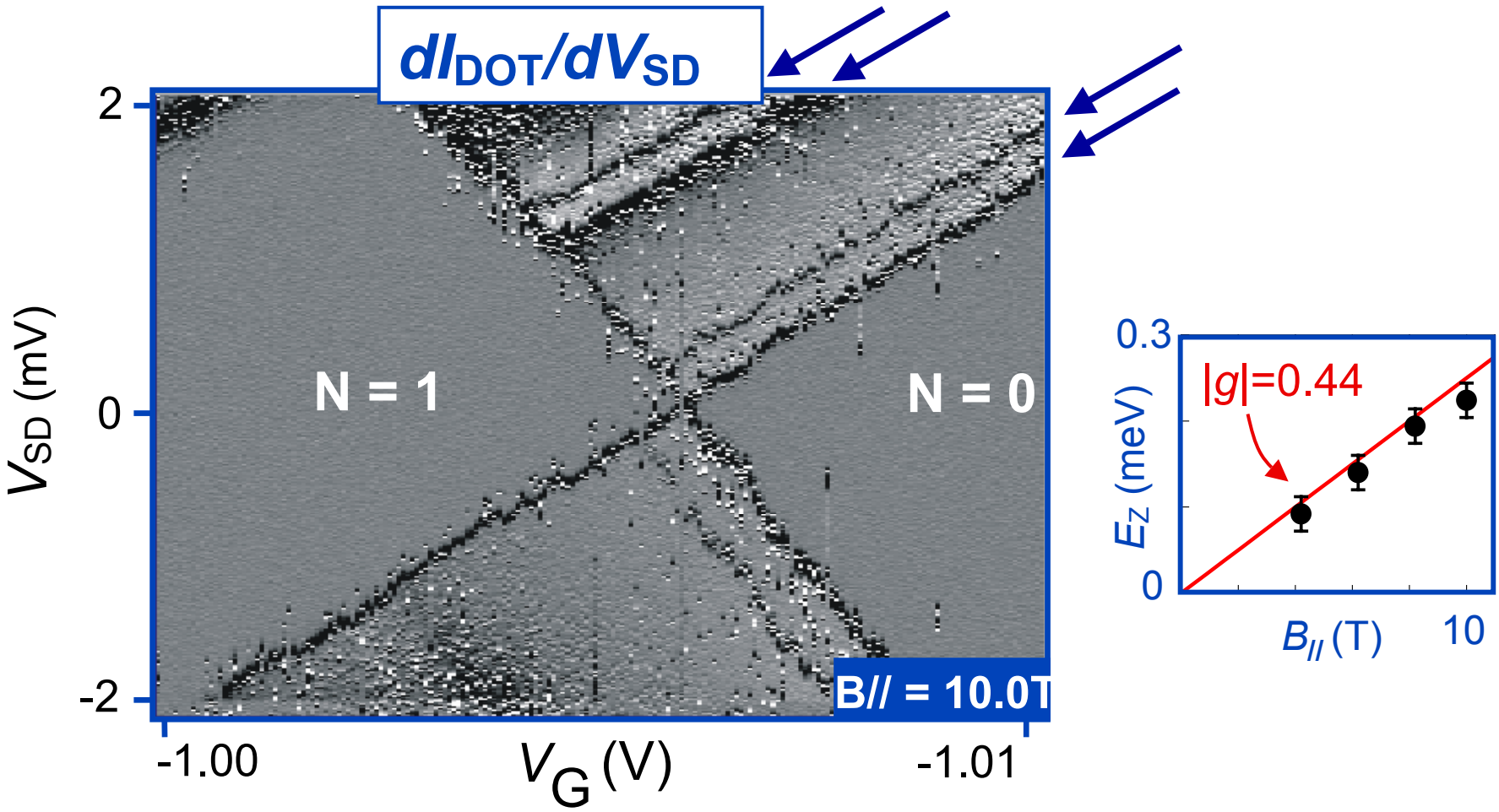
Zeeman splitting of a single electron



Zeeman splitting of a single electron



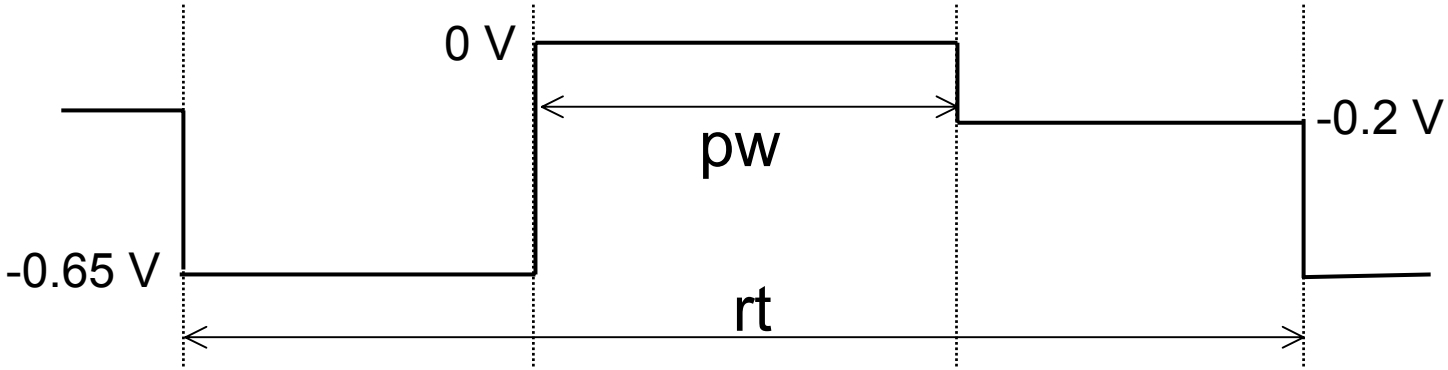
Zeeman splitting of a single electron

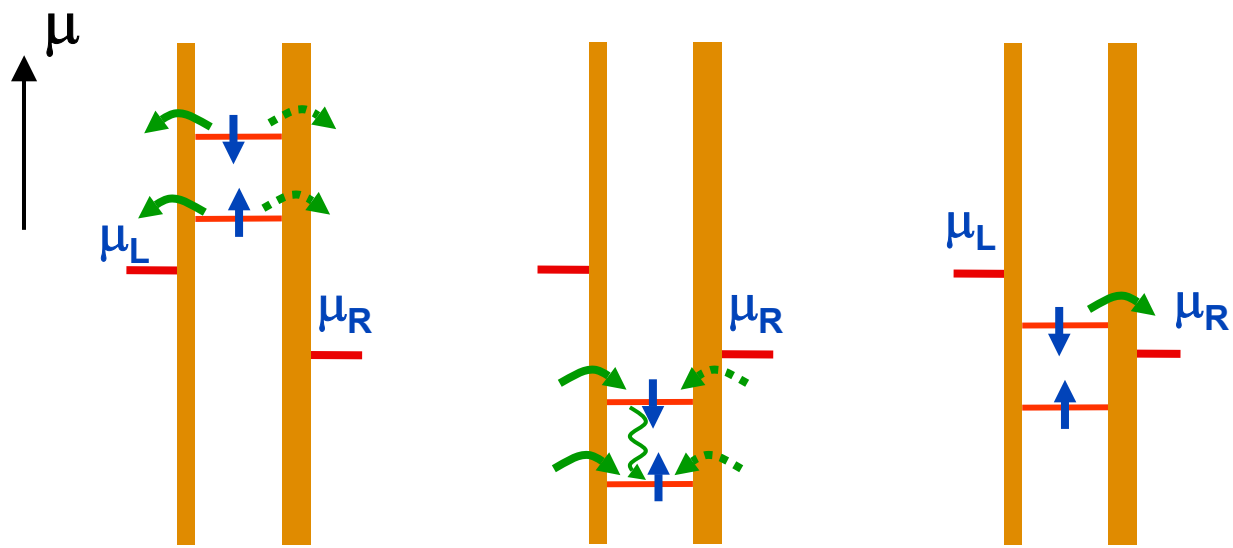


R. Hanson et al, unpublished

T_1 for the spin of a
single electron in a dot ?

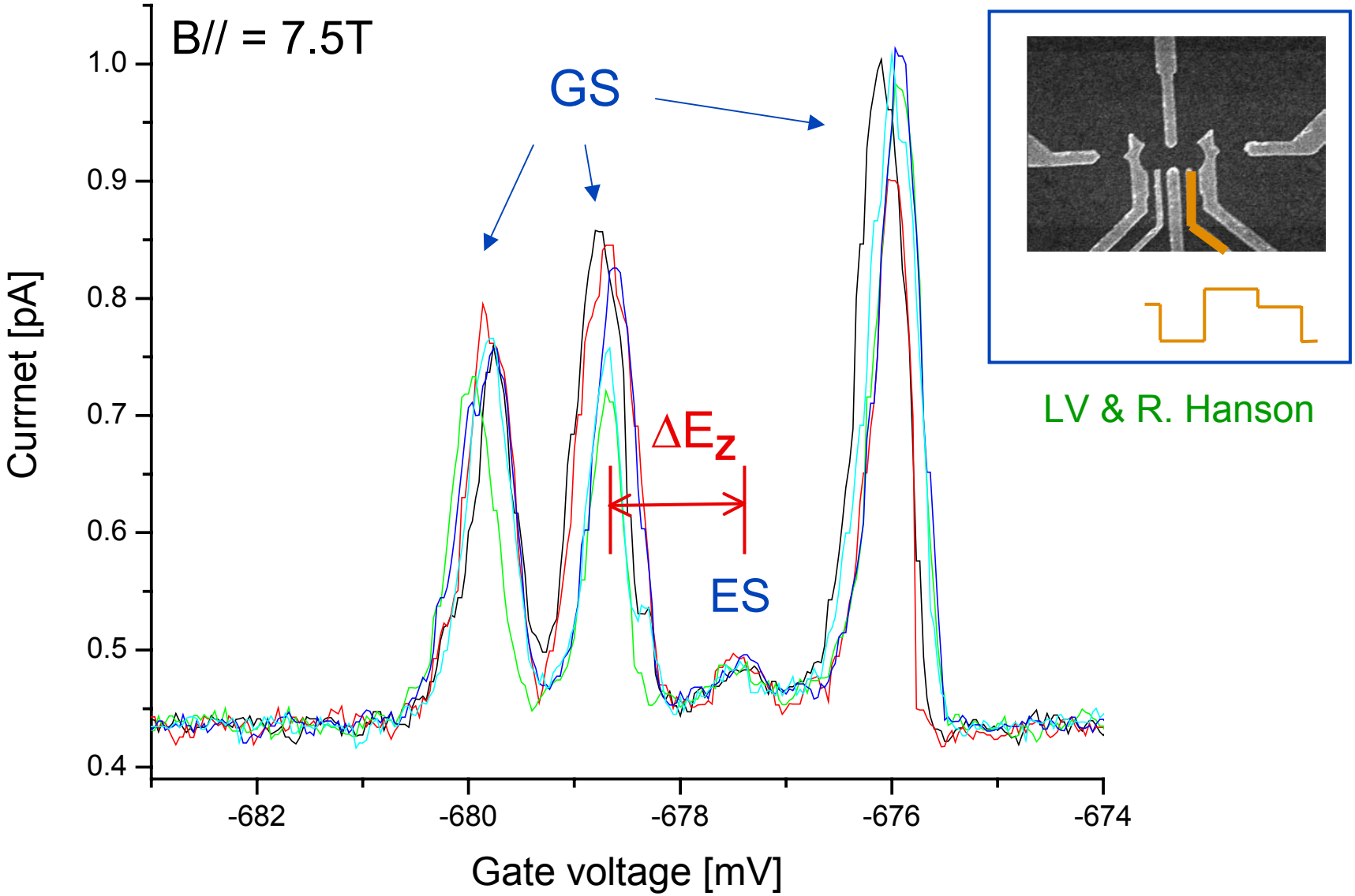
3-Level pulsed relaxation measurement



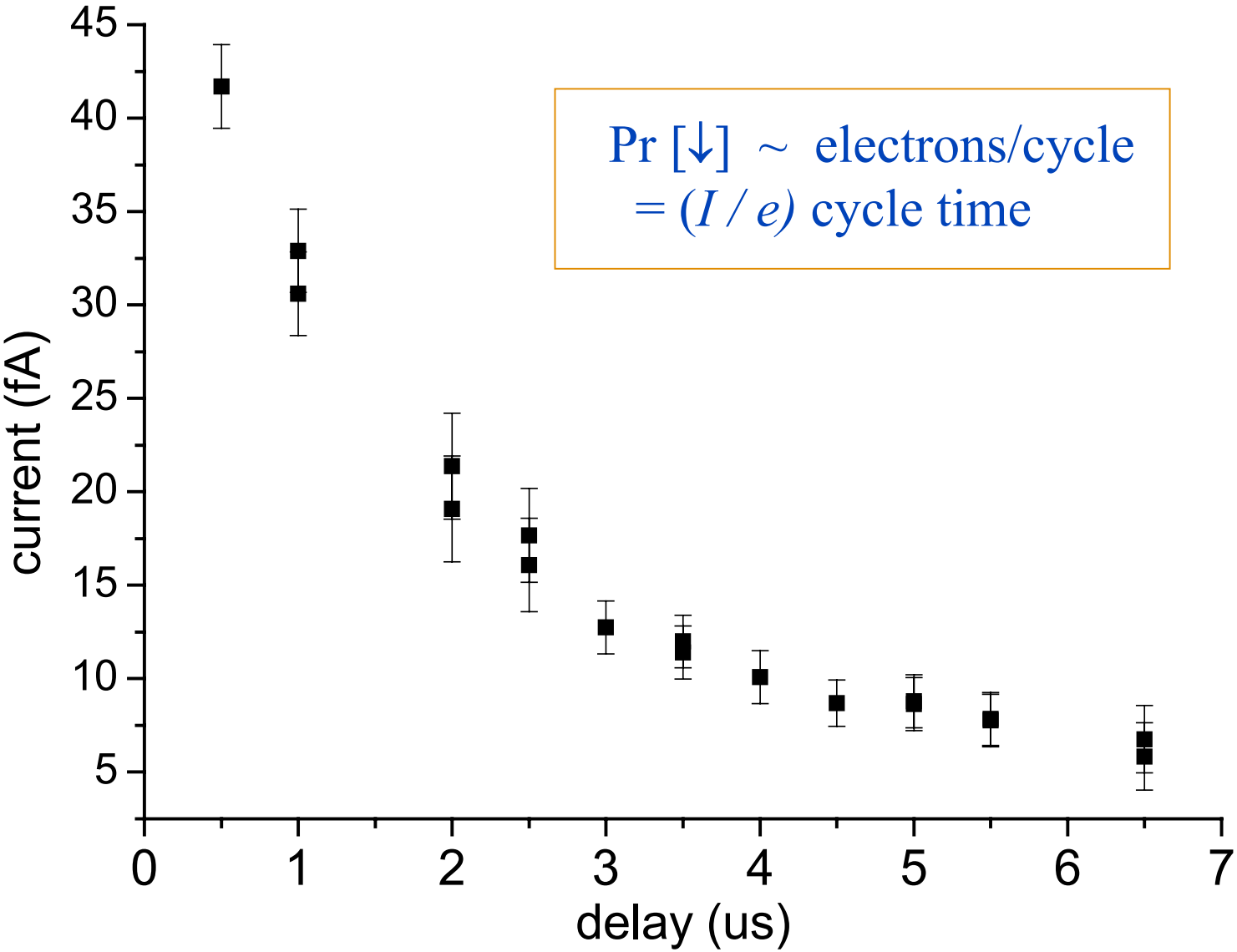


Fujisawa et al, *Nature* '02

Split Coulomb peak

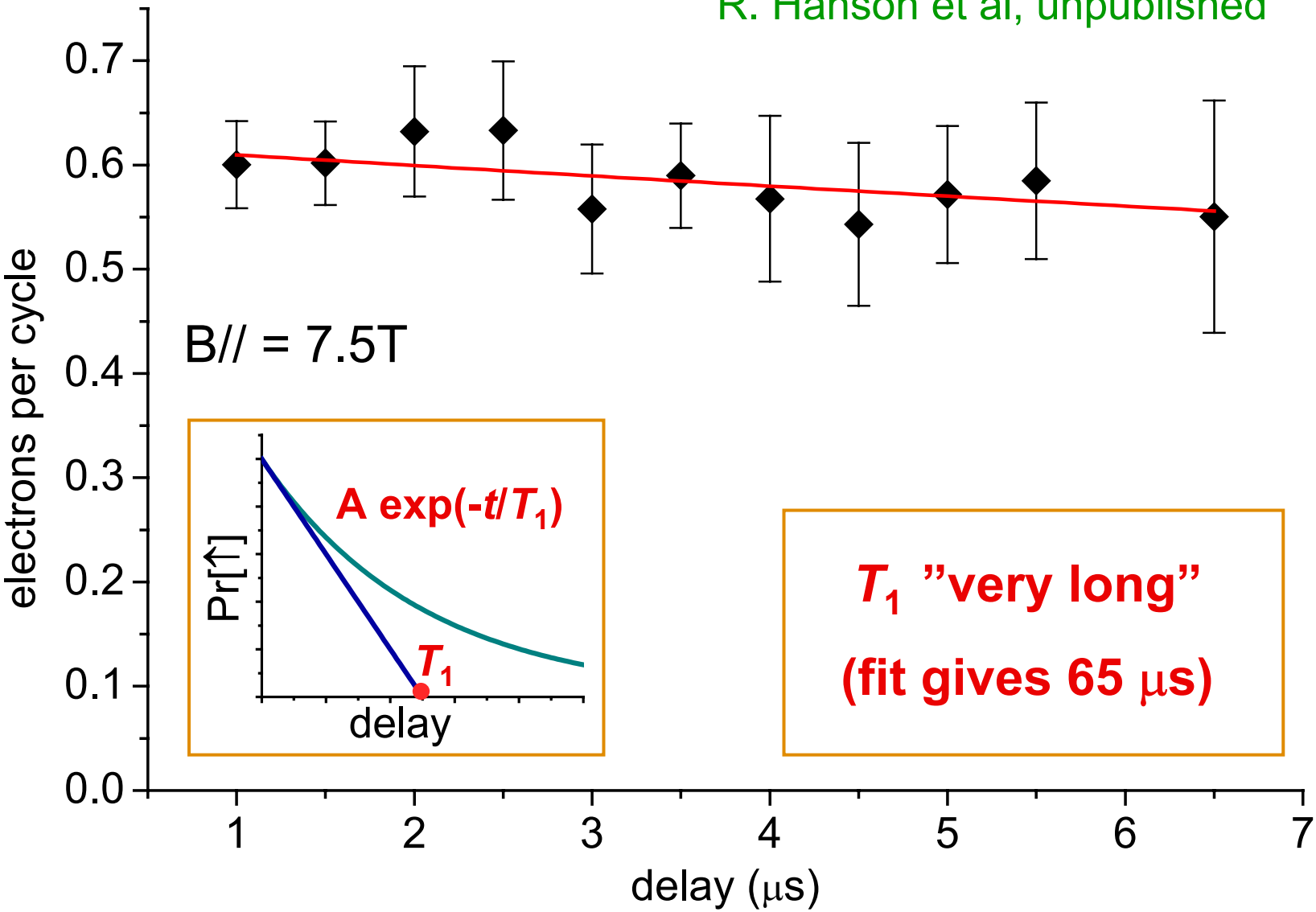


Zeeman T_1 measurement (1)



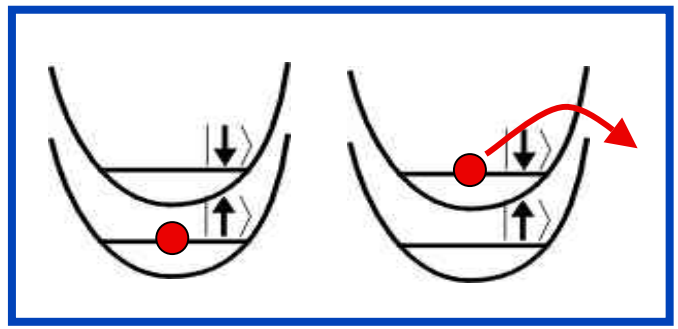
Zeeman T_1 measurement (2)

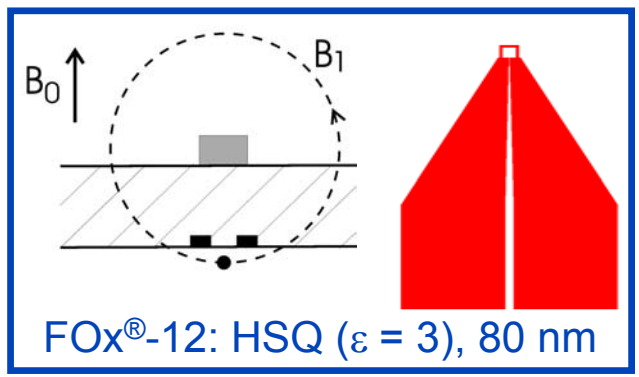
R. Hanson et al, unpublished



Work in preparation

- Spin-to-charge conversion
- 10 μs charge read-out (QPC)
- Single-shot spin read-out
- Electron spin resonance
- Swap spin states in double dot
- Entangle spins in double dot





Summary

http://qt.tn.tudelft.nl/research/spinqubits

Ideas for electron spin qubits

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

Few-electron tunable double dot

Elzerman et al (cond-mat/0212489)

Zeeman single electron in dot

Hanson et al (unpublished)

Long T_1 single electron in dot

Hanson et al (unpublished)