Spin Qubits in Quantum dots I

Driven coherent oscillations of a single electron spin in a quantum dot

Coherent Control of a Single Electron Spin with Electric Fields

F.H. L. Koppens, K.C. Nowack et al.

Tobias Rosskopf, Felix Geldmacher

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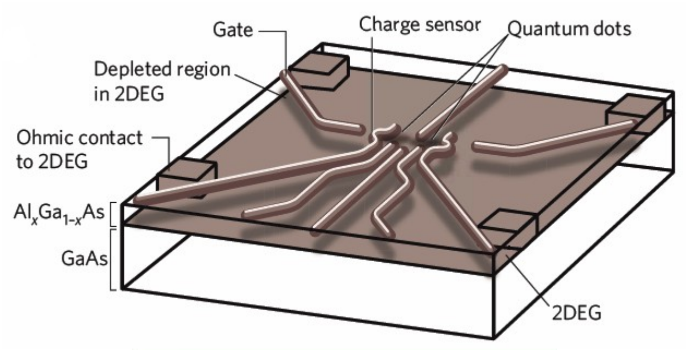
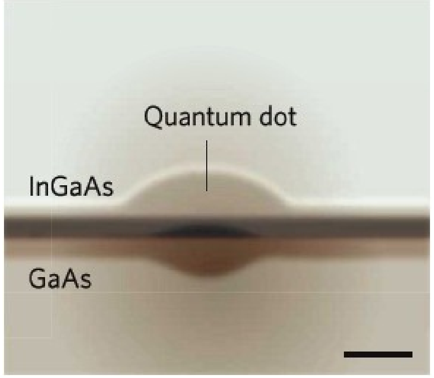
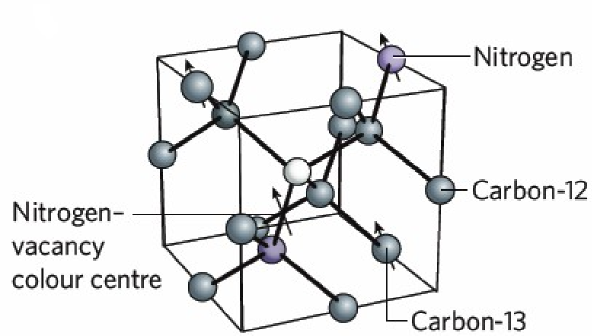
Introduction to quantum dots

- Definition: Charge carriers that are confined in all three dimensions by:
  - Electrical fields
  - Growth (islands)
  - Crystal lattice
- Quantised energy levels that can be engineered
- ± easy to fabricate

→ Good candidates for qubit implementation



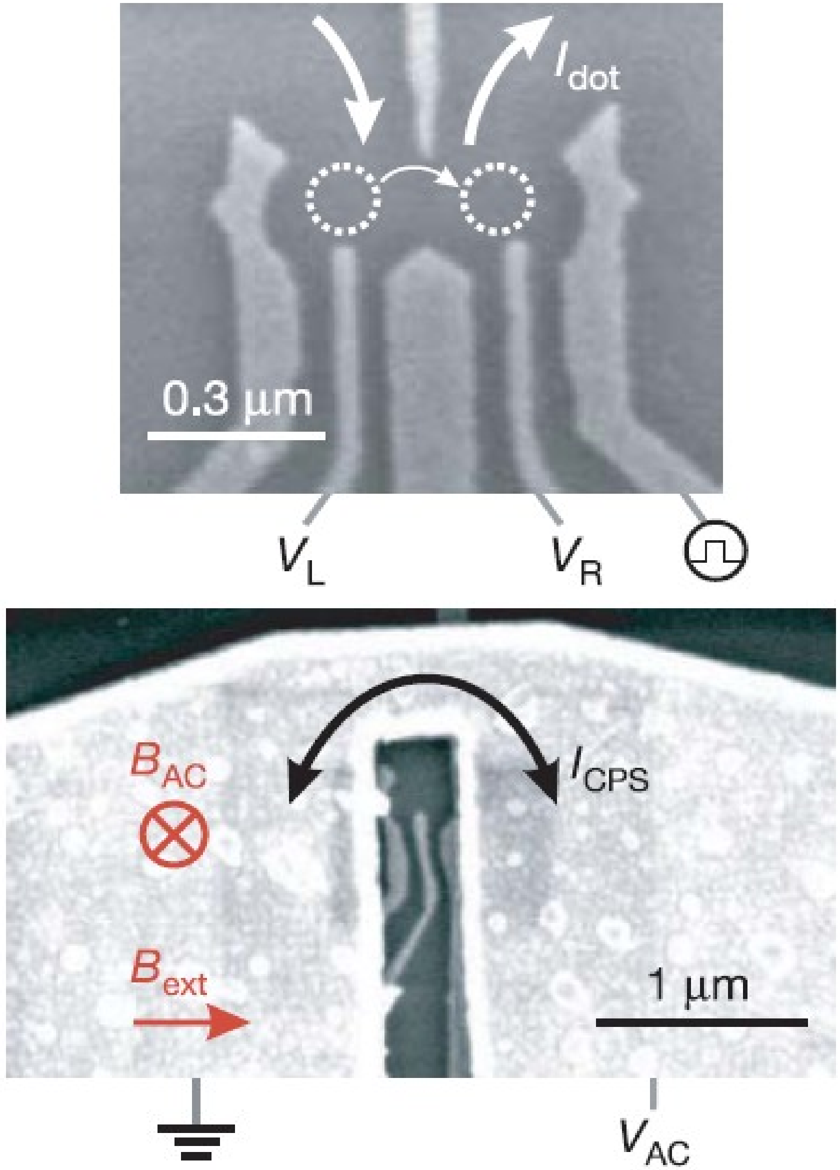




Hanson, R & Awschalom, DD
Coherent manipulation of single spins in semiconductors
Nature 453, 1043 (2008)

Experimental Setup

- Two coupled semiconductor quantum dots defined by surface gates
- B_{ext} establish Coulomb blockade
- Oscillating magnetic field B_{AC} (RF signal on coplanar stripline)
- → ESR induced spin rotation

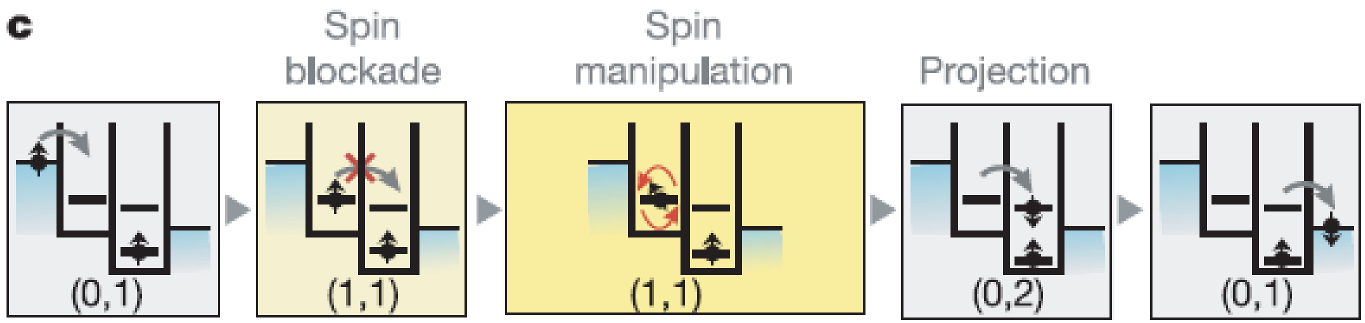


Experimental principle

- Detection by electrical transport measurement in Spin blockade regime
- Current flow depends on relative spin state
- For spin state S = ↑↓ - ↓↑ (singlet state S):

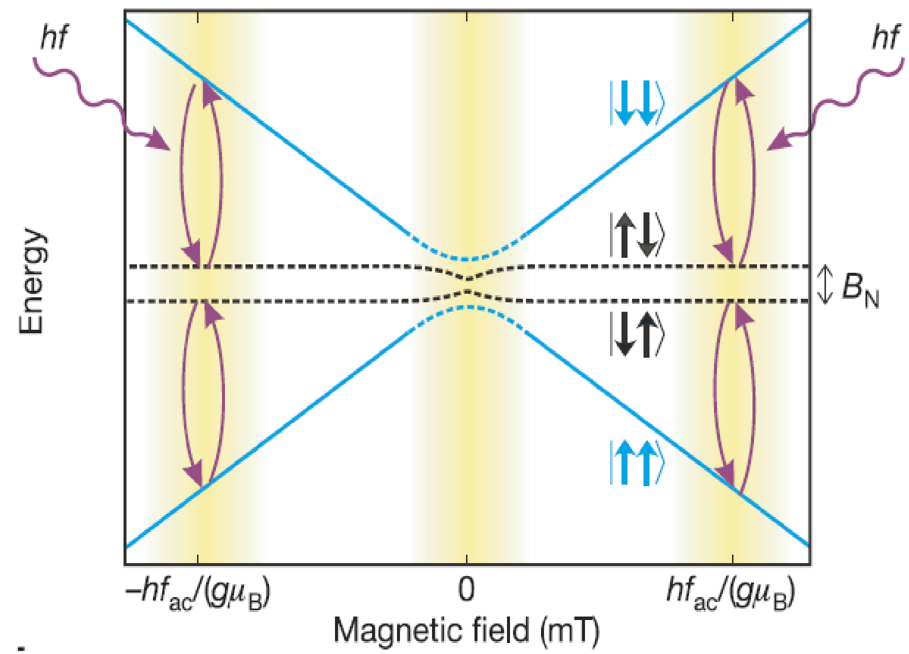
→ left electron tunnels to the right dot

→ current flow through the double dot



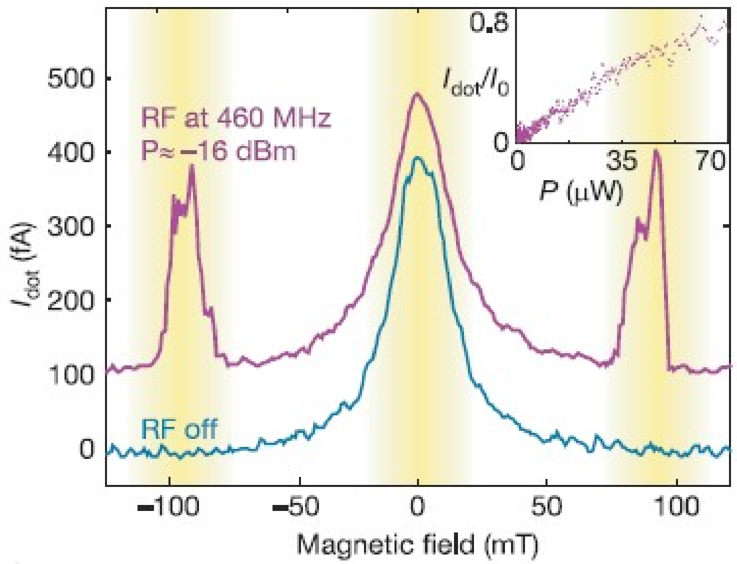
Principle of spin blockade

- Double dot singlet (S) and triplet states ($T_{0,\pm}$)
- B_{ext}>> 0,
  $T_{\pm}$ split of in energy
  → Spin blockade
  for ↑↑ and ↓↓
- T_0 and S still admixed

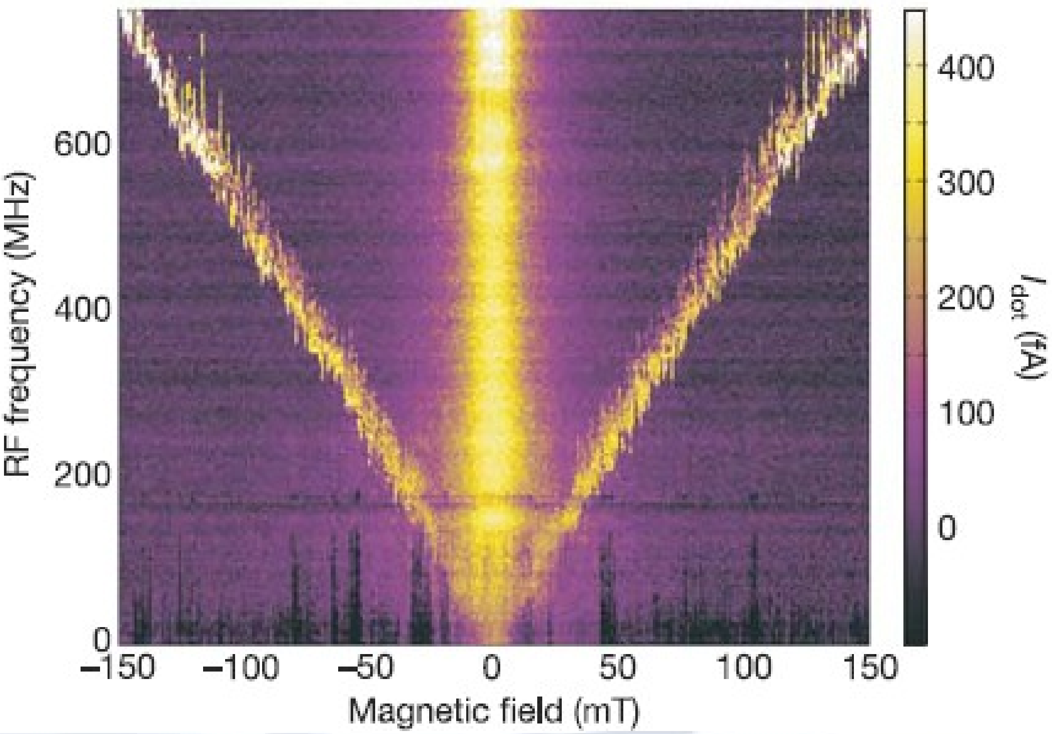


- ↑↓ = T_0 + S left electron moves to right dot

Results



- Observation of current depending on:
  - magnetic field
  - RF frequency



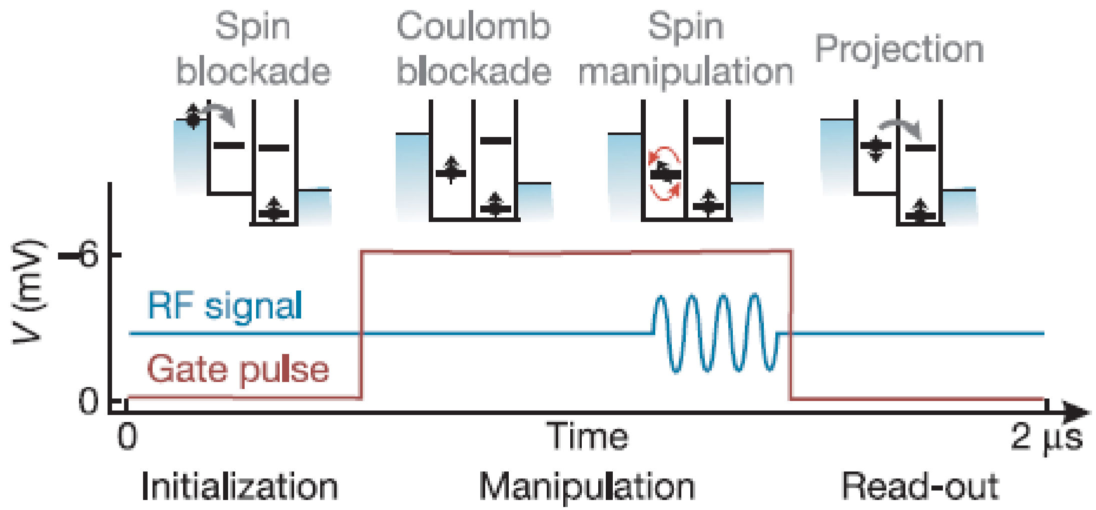
- From linear dependence of peak position on frequency:

  Estimation of electron spin g-factor ~ 0.35

Coherent Rabi Oscillations

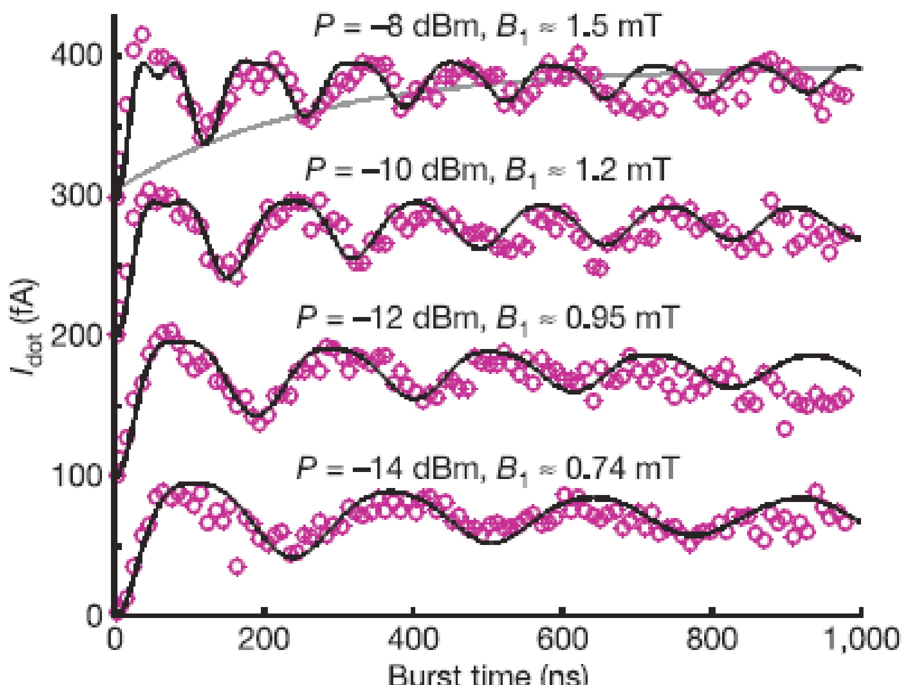
- Applying RF bursts with variable length
- Pulse the system into Coulomb blockade during spin manipulation

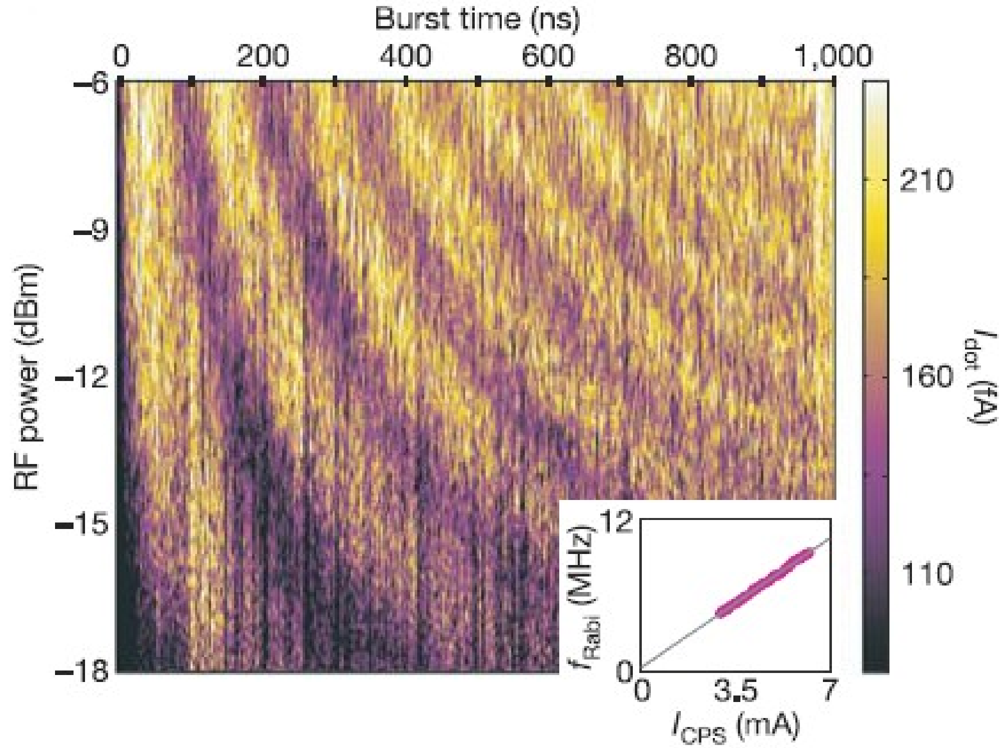
→ eliminates decoherence due to tunneling processes during spin rotation



Results

- Current oscillates with RF burst length
- Frequency depends linearly on burst amplitude
  → Rabi Oscillations
- Note: Oscillations visible up to 1 μs



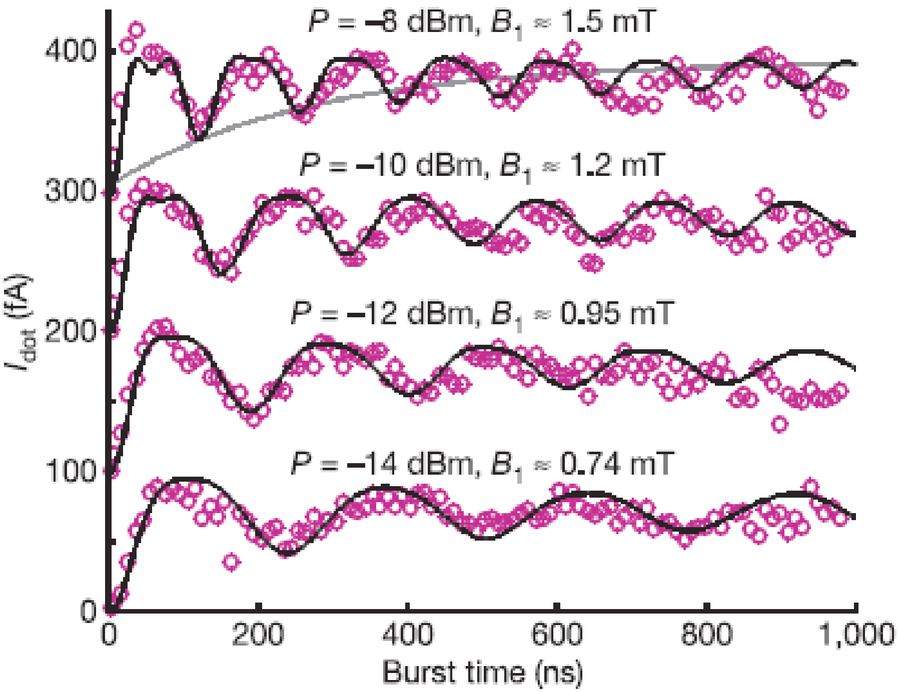


QM description of the process

$$H = g\mu_B(B_{ext} + B_{N,L})S_L + g\mu_B(B_{ext} + B_{N,R})S_R + g\mu_B cos(\omega t) B_{AC}(S_L + S_R)$$

- Used for finding an appropriate fit to the data
- Estimating the best flipping angle (131°)

  → Fidelity of 73%



Time evolution of spin states

RF on resonant with right spin only

$$|\uparrow\rangle|\uparrow\rangle \rightarrow |\uparrow\rangle\frac{|\uparrow\rangle+|\downarrow\rangle}{\sqrt{2}} \rightarrow |\uparrow\rangle|\downarrow\rangle \rightarrow$$

$$|\uparrow\rangle\frac{|\uparrow\rangle-|\downarrow\rangle}{\sqrt{2}} \rightarrow |\uparrow\rangle|\uparrow\rangle$$

RF on resonant with both spins

$$|\uparrow\rangle|\uparrow\rangle \rightarrow \frac{|\uparrow\rangle+|\downarrow\rangle}{\sqrt{2}}\frac{|\uparrow\rangle+|\downarrow\rangle}{\sqrt{2}} \rightarrow |\downarrow\rangle|\downarrow\rangle \rightarrow$$

$$\frac{|\uparrow\rangle-|\downarrow\rangle}{\sqrt{2}}\frac{|\uparrow\rangle-|\downarrow\rangle}{\sqrt{2}} \rightarrow |\uparrow\rangle|\uparrow\rangle$$

- Transitions between ↑ and ↓ for both
- Both resonant → current oscillations twice as fast
- Not observed in Exp. → only single spins excited

Motivation for E-Field induced manipulation

- E-Field generation can be done by exciting a local gate

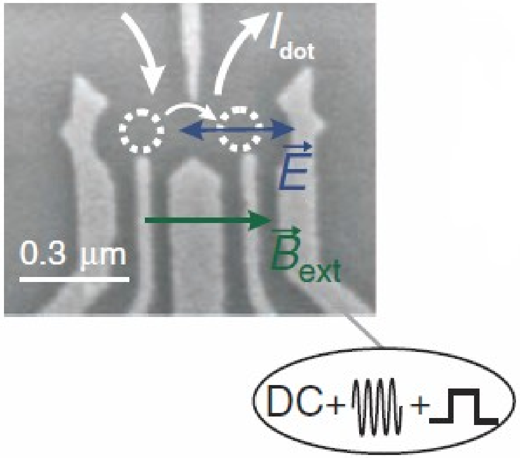
- Greater spatial selectivity than B-Fields

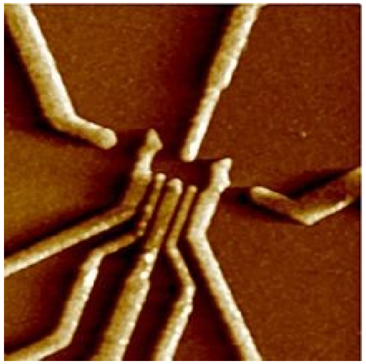
  $\rightarrow$ easier to address individual spins

Problem: No direct coupling between E-Field and Spin

Experimental Setup

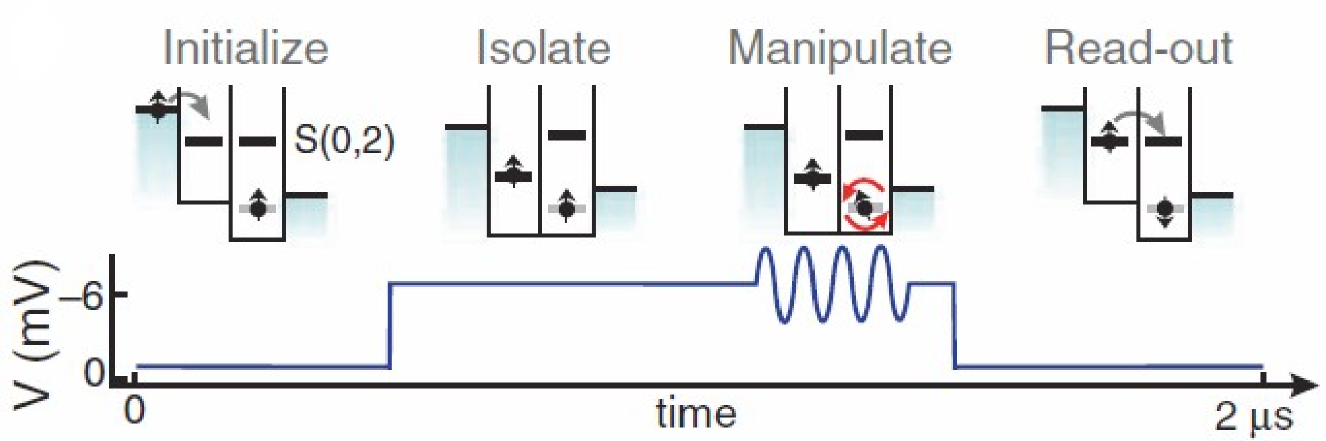
- Same device
- RF-signal on the rightmost gate induces E-field in right dot
- → E-field induced spin rotation





Measurement

- Pulse double dot into coulomb blockade
- Apply microwave burst to gate
- Measure average current flow

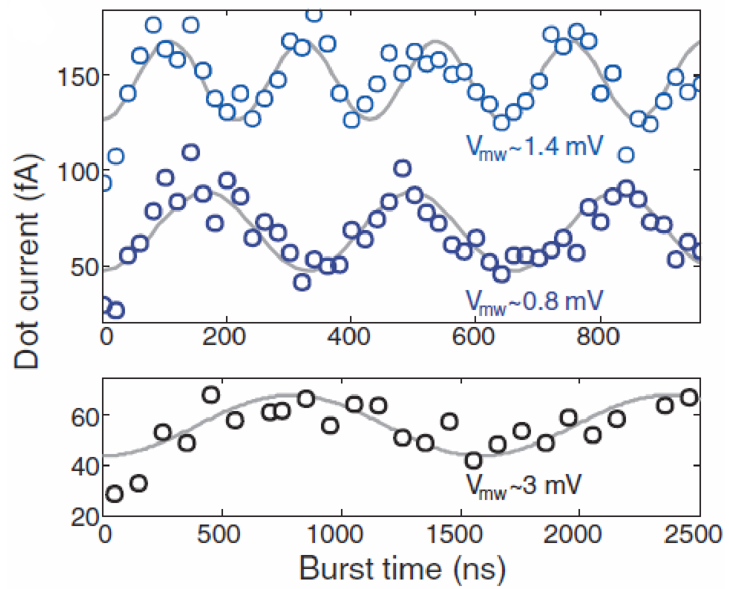


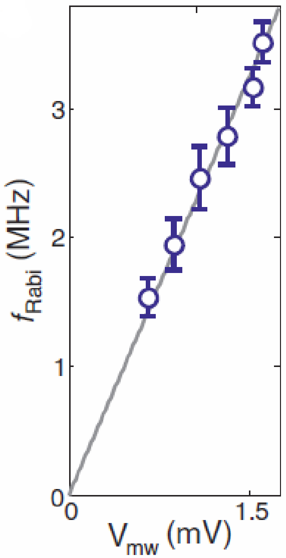
Coherent spin control

- Variable burst length reveals oscillations in measured current flow

- Linear scaling of oscillation frequency with driving amplitude

  → Rabi oscillations





What caused the oscillations?

- Possible answers:
  - Magnetic field $\vec{B}$ → Too small
  - B-field gradient $\nabla \vec{B}$ → Not applied
  - g-tensor modulation ∇g → g-tensor anisotropy very small in GaAs
  - Spatial variation of nuclear field $\nabla \vec{B}_N$ → Measurement time much longer than stable time of nuclear field gradient

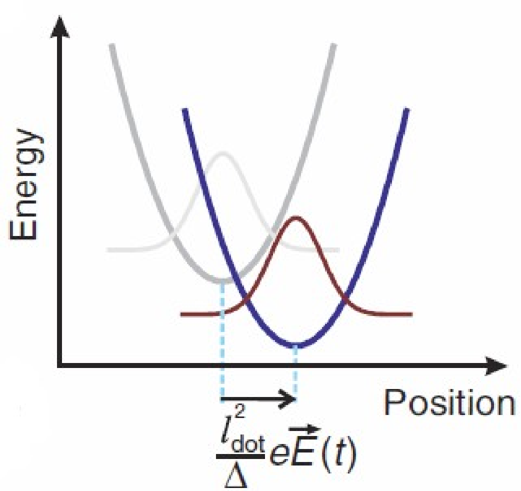
→ **Spin-orbit interaction**

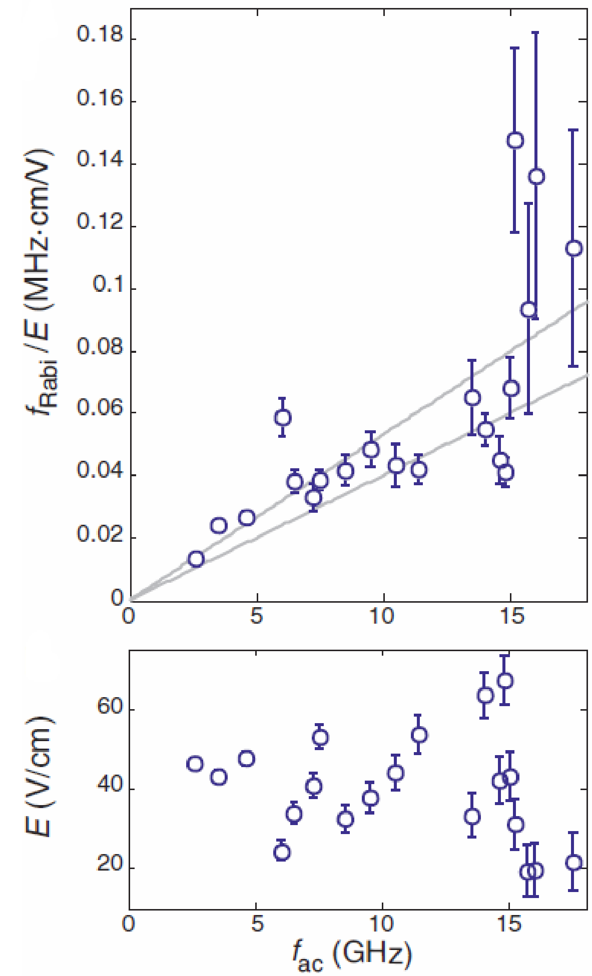
Spin-orbit interaction

- E-field periodically displaces electron wave function

  → oscillating effective B-field perpendicular to the external B-field

  → Rabi oscillations





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

Results Summary

Magnetic field:

- Driven coherent electron spin rotation
- $\pi/2$ rotations of 27 ns
  (Rabi period 108 ns)
- Fidelity of 73 % (due to flipping angle 131°)

Electric field:

- $\pi/2$ rotation in 55 ns

Limiting Factors

Magnetic driving

- Nuclear field fluctuations
- Cotunneling
- Inelastic transitions to the S(0,2) state

Electrical driving

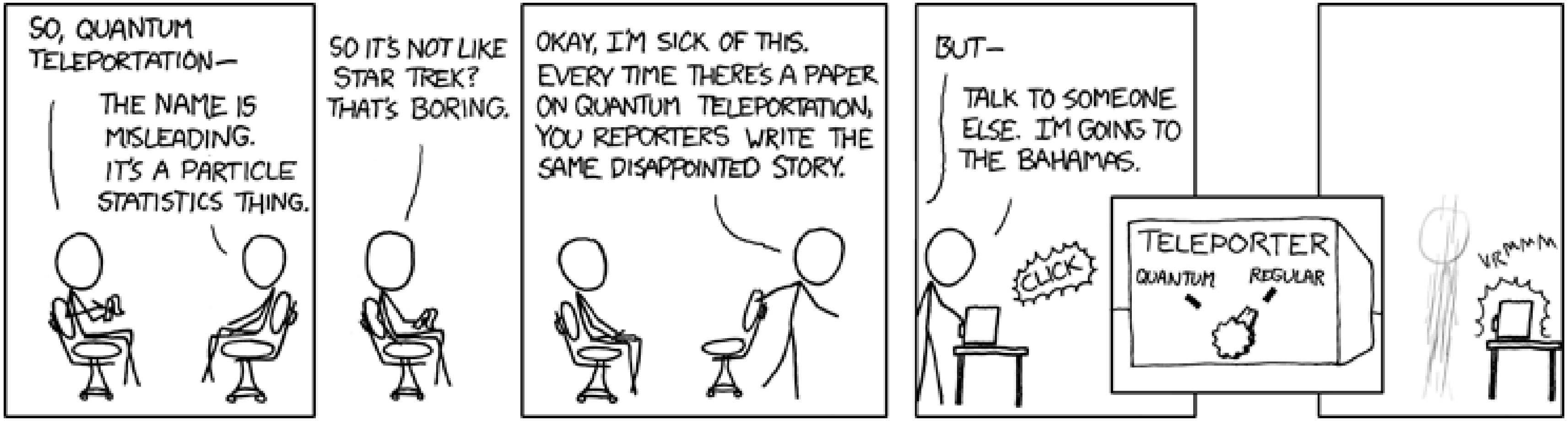
- Nuclear field fluctuations
- Photon-assisted tunneling

Improvement possibilities

- Suppressing photon-assisted tunneling by higher tunnel barriers
- Working at higher B_{ext} resp. B_{RF}
- Using materials with stronger spin-orbit interaction
- Optimise gate design
- Composite pulses to improve fidelity

Outlook

- Realisation of multiple spin systems with quantum dots
- Controllable addressing of spins in many dot systems using electric fields
- Implementation of simple quantum algorithms



http://imgs.xkcd.com/comics/quantum_teleportation.png

Thank you for your attention

Questions??