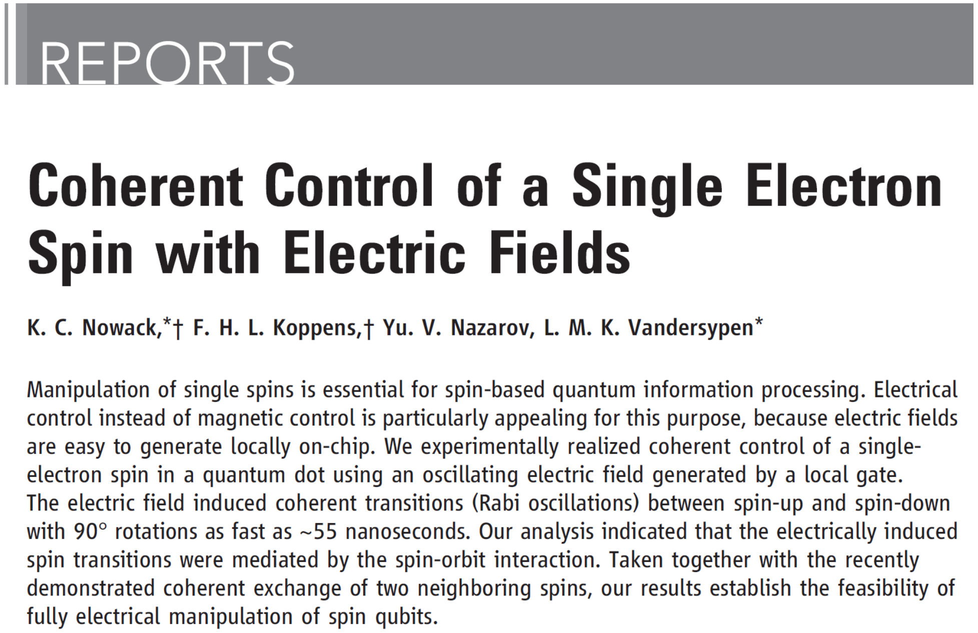
Control of single spin qubits in quantum dots

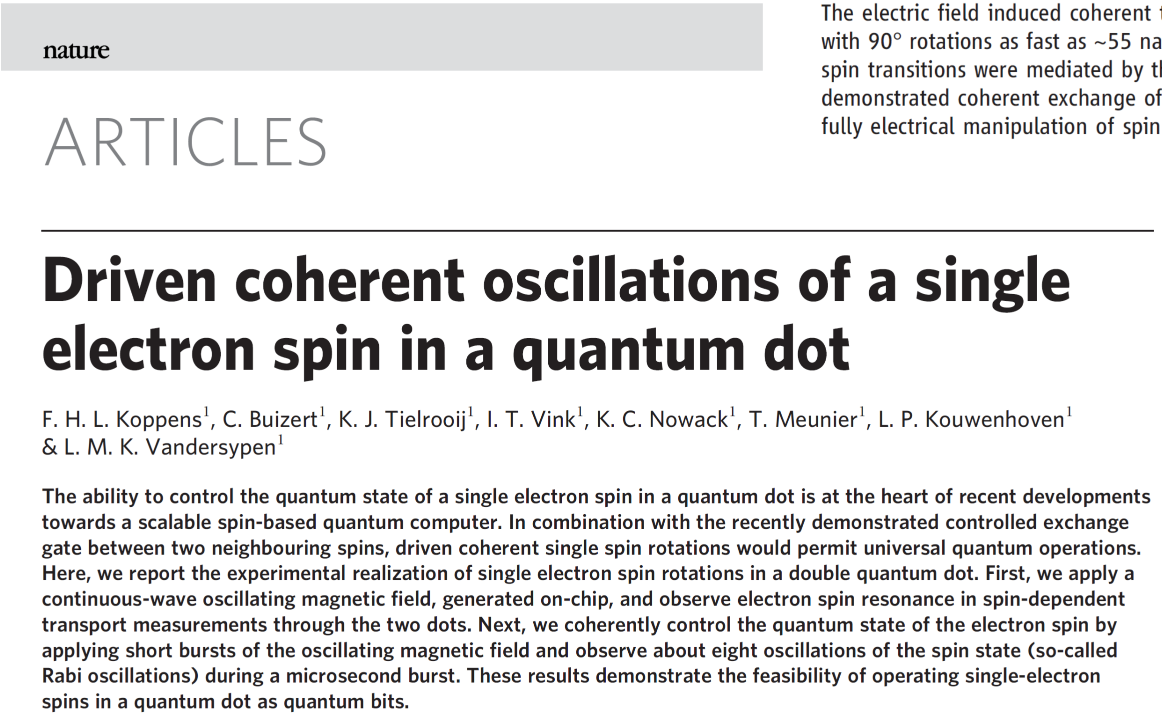


REPORTS

Coherent Control of a Single Electron Spin with Electric Fields

K. C. Nowack,*† F. H. L. Koppens,† Yu. V. Nazarov, L. M. K. Vandersypen*

Manipulation of single spins is essential for spin-based quantum information processing. Electrical control instead of magnetic control is particularly appealing for this purpose, because electric fields are easy to generate locally on-chip. We experimentally realized coherent control of a single-electron spin in a quantum dot using an oscillating electric field generated by a local gate. The electric field induced coherent transitions (Rabi oscillations) between spin-up and spin-down with 90° rotations as fast as ~55 nanoseconds. Our analysis indicated that the electrically induced spin transitions were mediated by the spin-orbit interaction. Taken together with the recently demonstrated coherent exchange of two neighboring spins, our results establish the feasibility of fully electrical manipulation of spin qubits.



nature

ARTICLES

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

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The ability to control the quantum state of a single electron spin in a quantum dot is at the heart of recent developments towards a scalable spin-based quantum computer. In combination with the recently demonstrated controlled exchange gate between two neighbouring spins, driven coherent single spin rotations would permit universal quantum operations. Here, we report the experimental realization of single electron spin rotations in a double quantum dot. First, we apply a continuous-wave oscillating magnetic field, generated on-chip, and observe electron spin resonance in spin-dependent transport measurements through the two dots. Next, we coherently control the quantum state of the electron spin by applying short bursts of the oscillating magnetic field and observe about eight oscillations of the spin state (so-called Rabi oscillations) during a microsecond burst. These results demonstrate the feasibility of operating single-electron spins in a quantum dot as quantum bits.

Martin Paesold

Arnhild Jacobsen

Outline

- Introduction
    - What is a quantum dot?
    - Split gate defined GaAs/AlGaAs quantum dots
    - Transport through single and double dots
    - Spin blockade

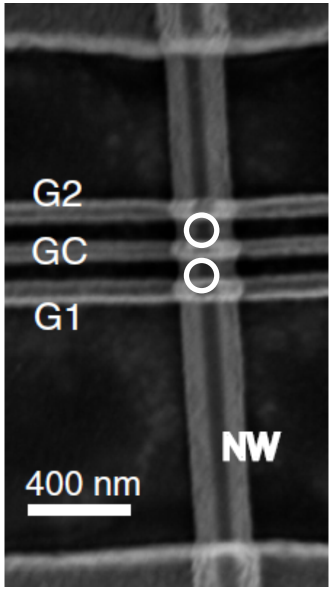
- Spin manipulation by a magnetic field (Koppens et al.)

- Spin manipulation by an electric field (Nowack et al.)

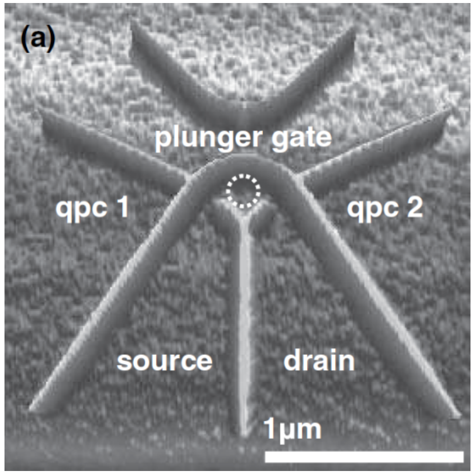
- Conclusion

What is a quantum dot?

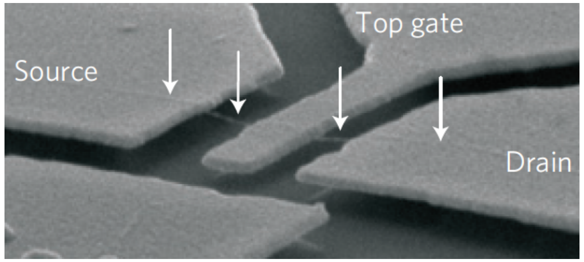
- A conductive island where the electrons are confined in all three spatial directions.
- Quantisized energy levels -> ”Artificial atom”.
- However, size and the shape and the strength of the confining potential are very different for atoms and quantum dots.
- Highly tunable system -> interesting research object.



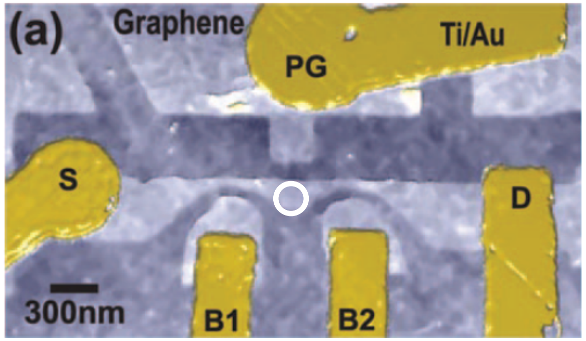
Nanowire DQD



P-type GaAs QD



Carbon nanotube QD

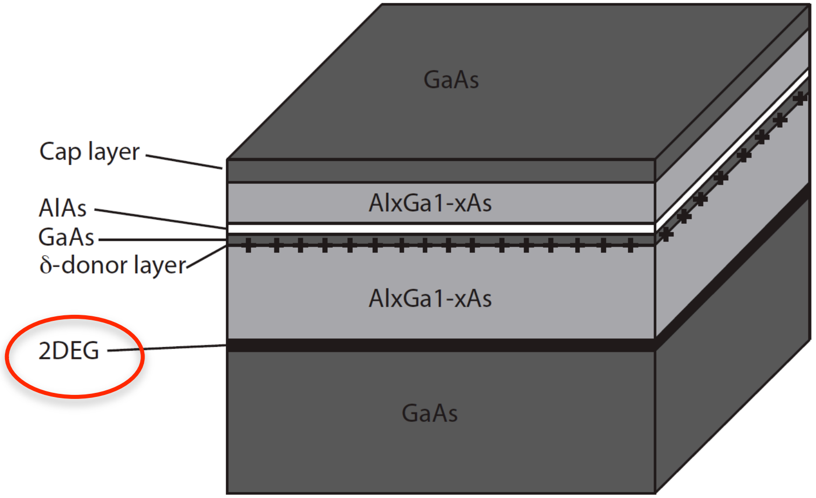


Graphene QD

Ensslin group, ETH

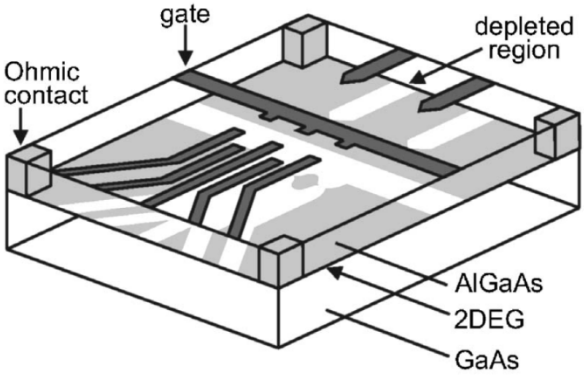
Gate defined GaAs/AlGaAs quantum dot

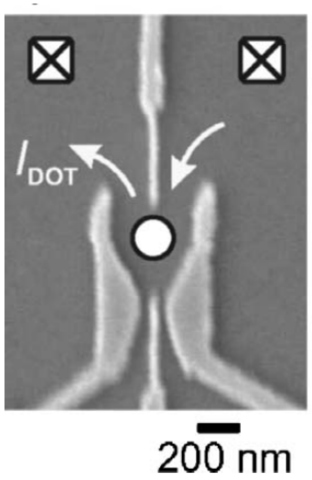
GaAs/AlGaAs heterostructure



- High quality wafers grown by molecular beam epitaxy (MBE).

- 2D electron gas (2DEG) formed at the interface between the GaAs and the AlGaAs layer.

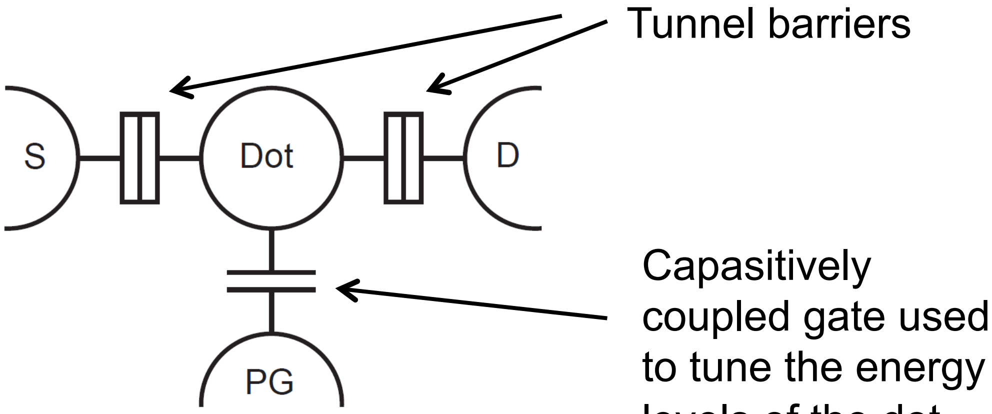




- By applying negative voltages to metal gates on top of the wafer the 2DEG below the gates will be depleated and nanostrucutres can be formed.

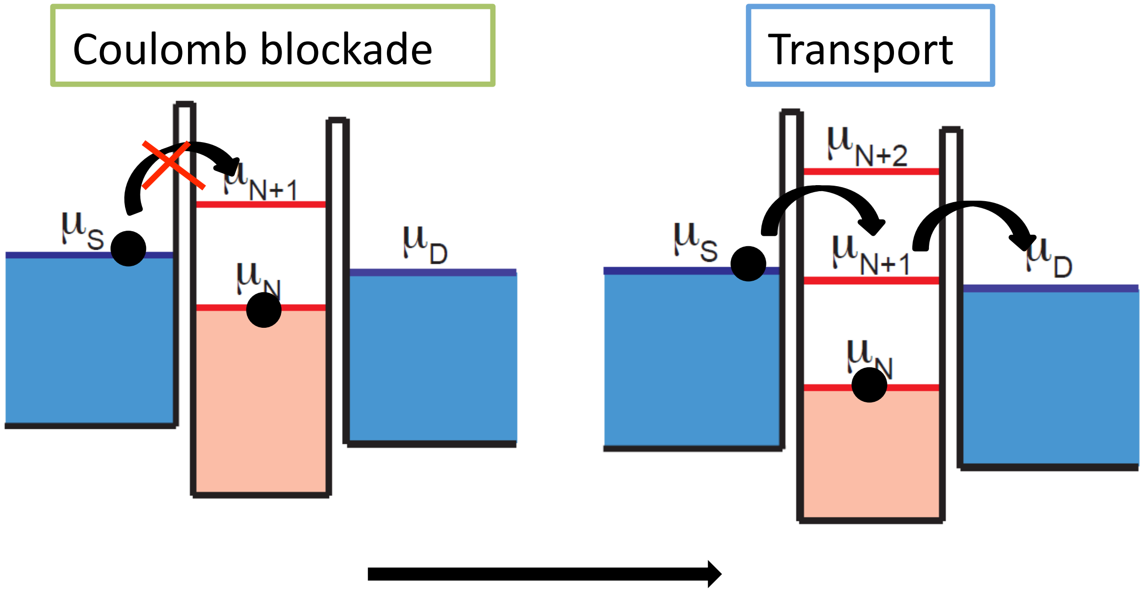
R. Hanson et.al, Rev. Mod. Phys 79,1217 (2007)

Transport through a quantum dot

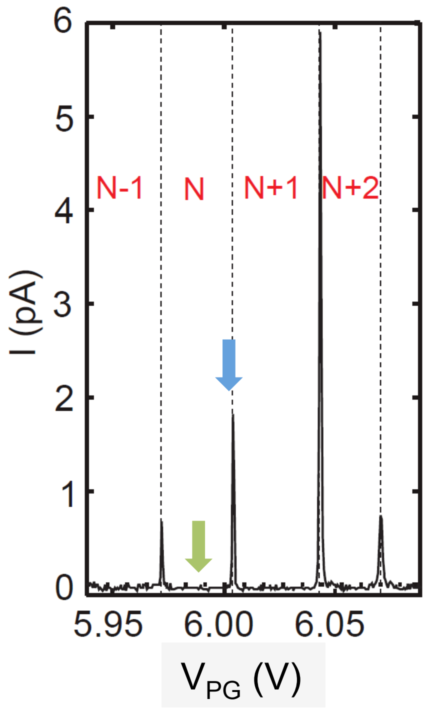


Tunnel barriers

Capasitively coupled gate used to tune the energy levels of the dot

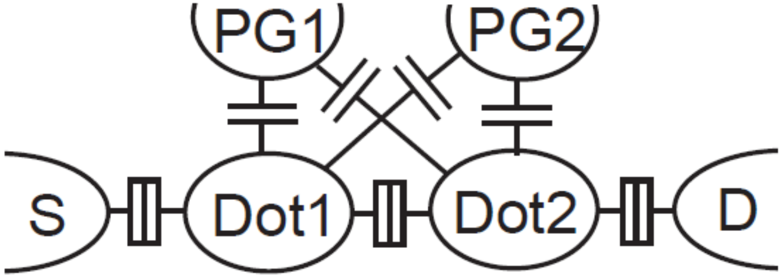


Energy levels of dot lowered

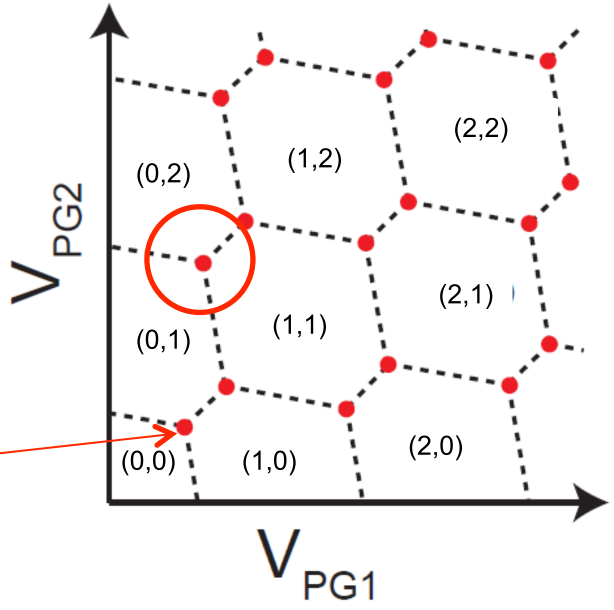


F.Molitor, Thesis ETH (2010)

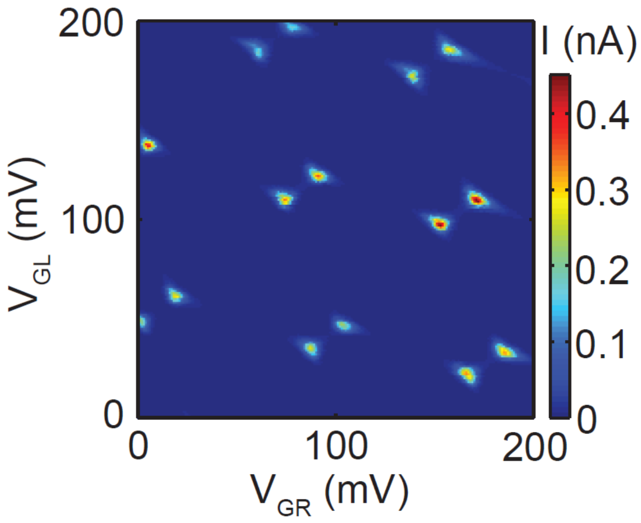
Transport through a double quantum dot



Charge stability diagram



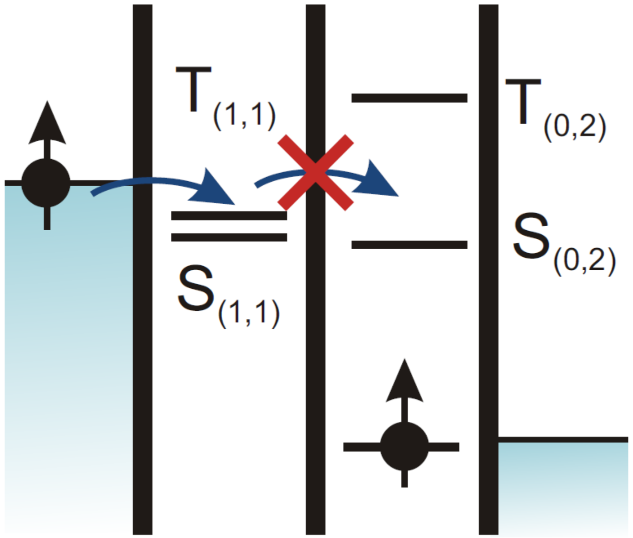
Current flowing

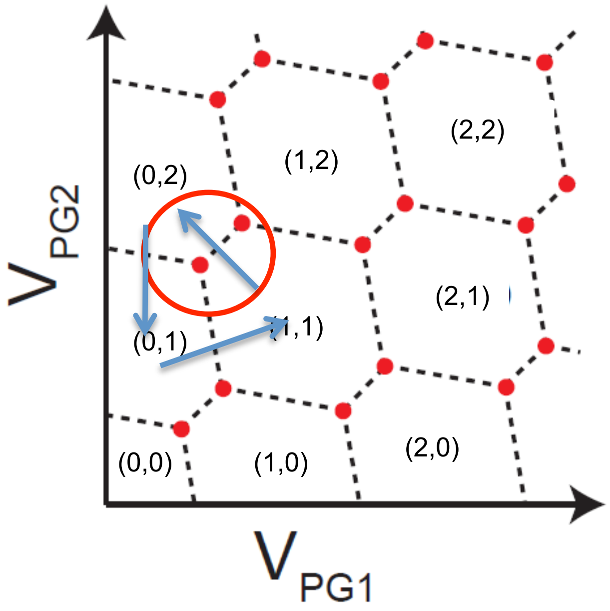


Spin blockade

F.Molitor, Thesis ETH (2010)

Spin blockade





Possible states

$$S = \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

$$T_0 = \left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

$$T_- = |\downarrow\downarrow\rangle$$

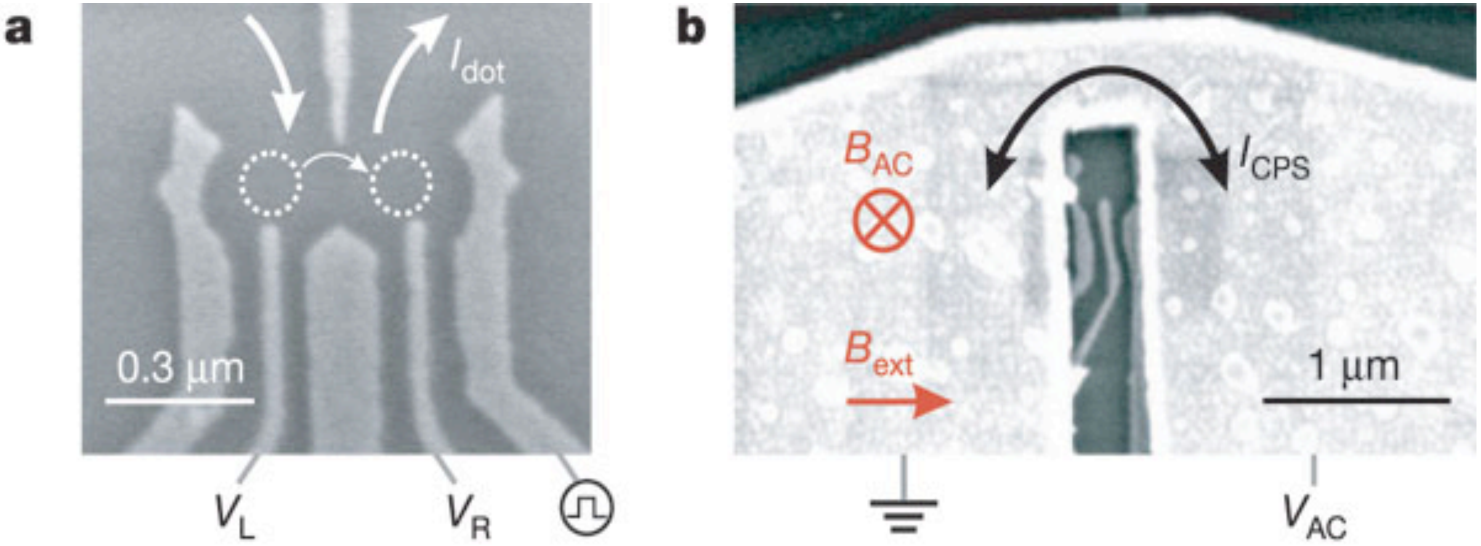
$$T_+ = |\uparrow\uparrow\rangle$$

- S(0,2)-T(0,2) splitting much larger than S(1,1)-T(1,1) splitting.

- T(1,1) -> S(0,2) is forbidden and T (0,2) is not available in energy.

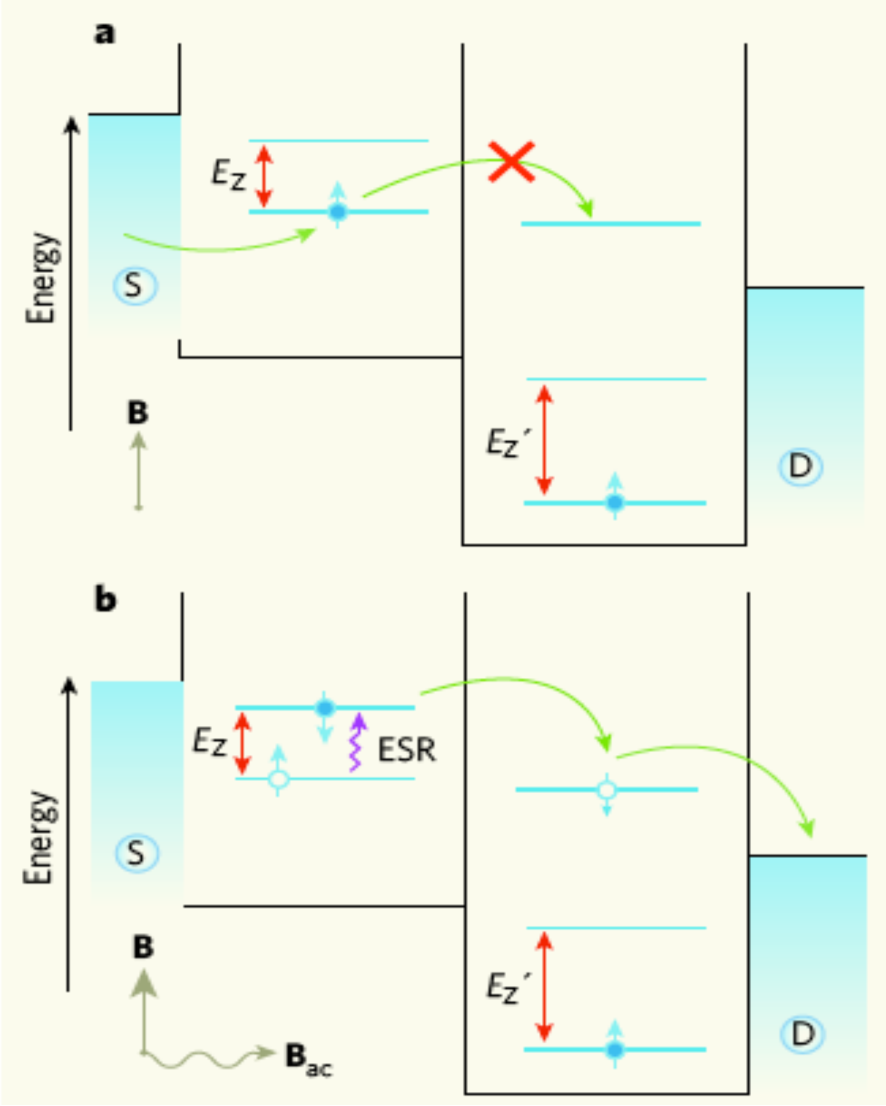
- In order to have transport the spin has to be flipped.

Sample



- Conduct transport measurements through double quantum dot
- 2D electron gas 90nm below surface
- Coplanar strip line to generate oscillating B-field

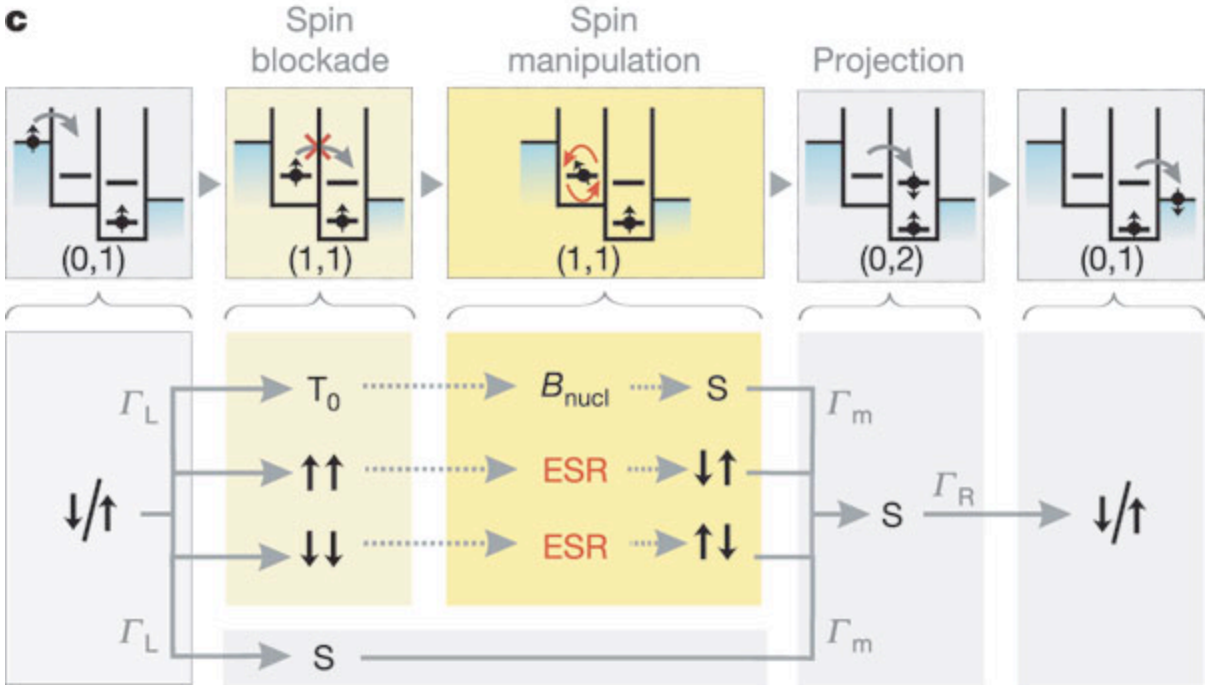
Electron spin resonance (ESR)



- Spin blockade
- Zeemann splitting due to static B-field
- Oscillating B-field rotates spin
- Current through quantum dot is proportional to rotation of spin
- Resonance condition

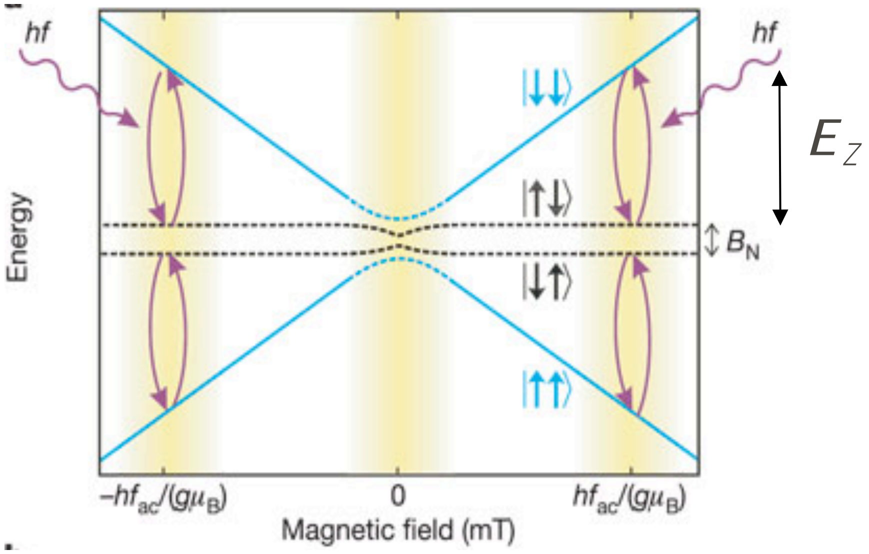
$$hf_{ac} = g\mu_B B_{ext}$$

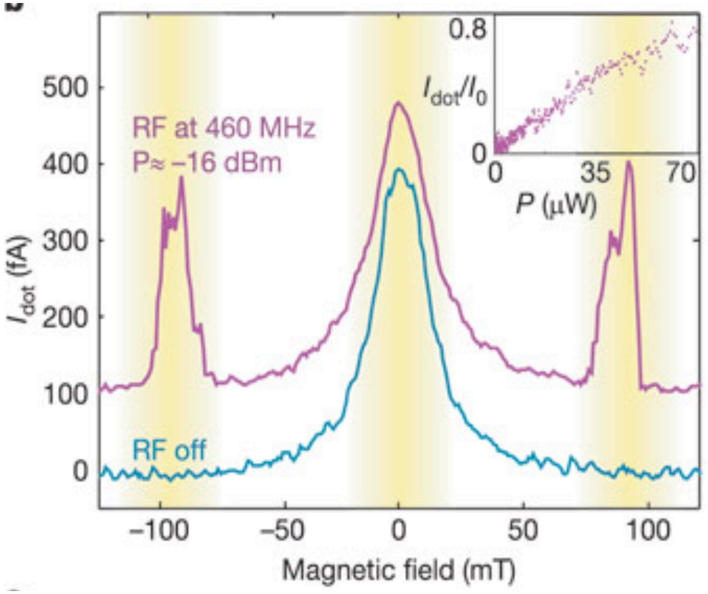
Experimental procedure



- Transport measurements, averaged over 1 sec
- Sweeping of frequency of B-field

Transport measurement

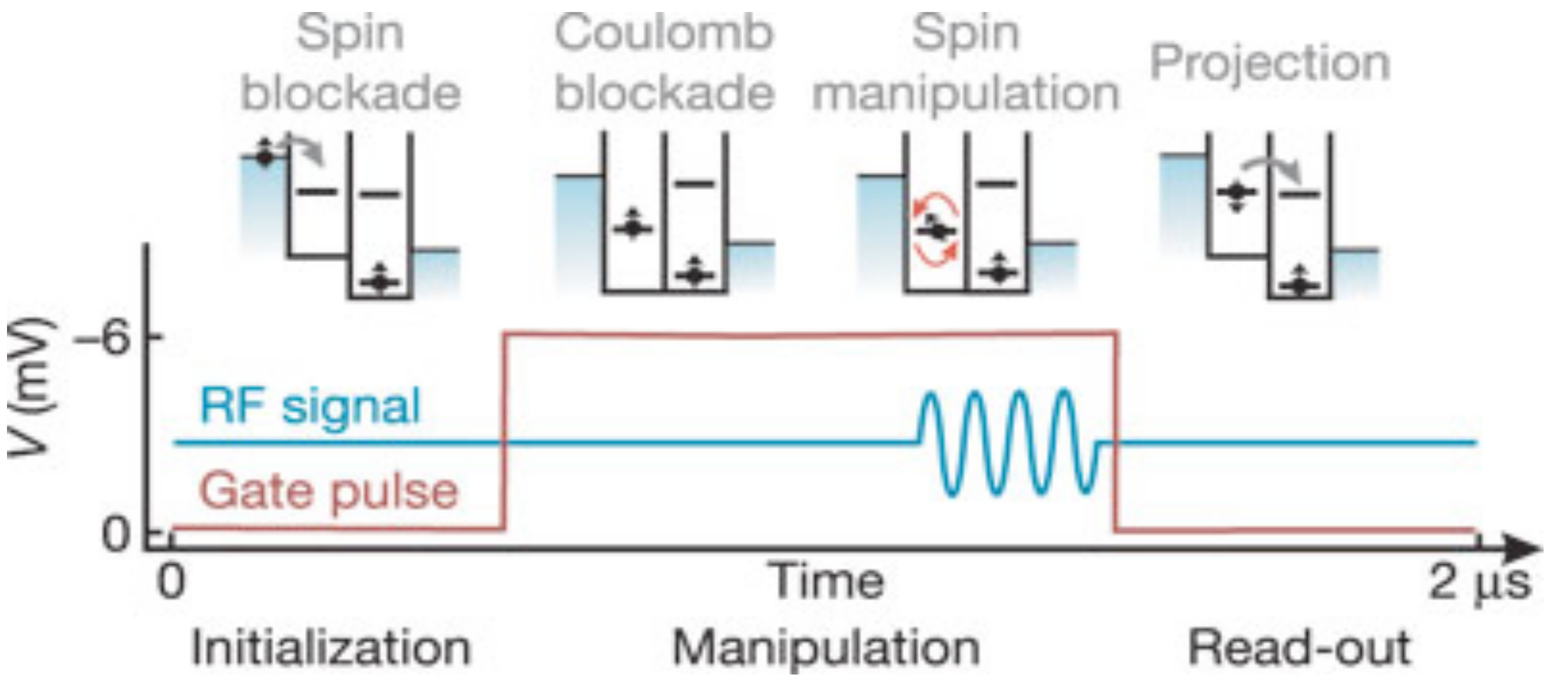




- (left) ESR, coupling of different states

- (right) current through quantum dot depending on static field
  → tuning of Zeemann splitting

Rabi oscillations (I)

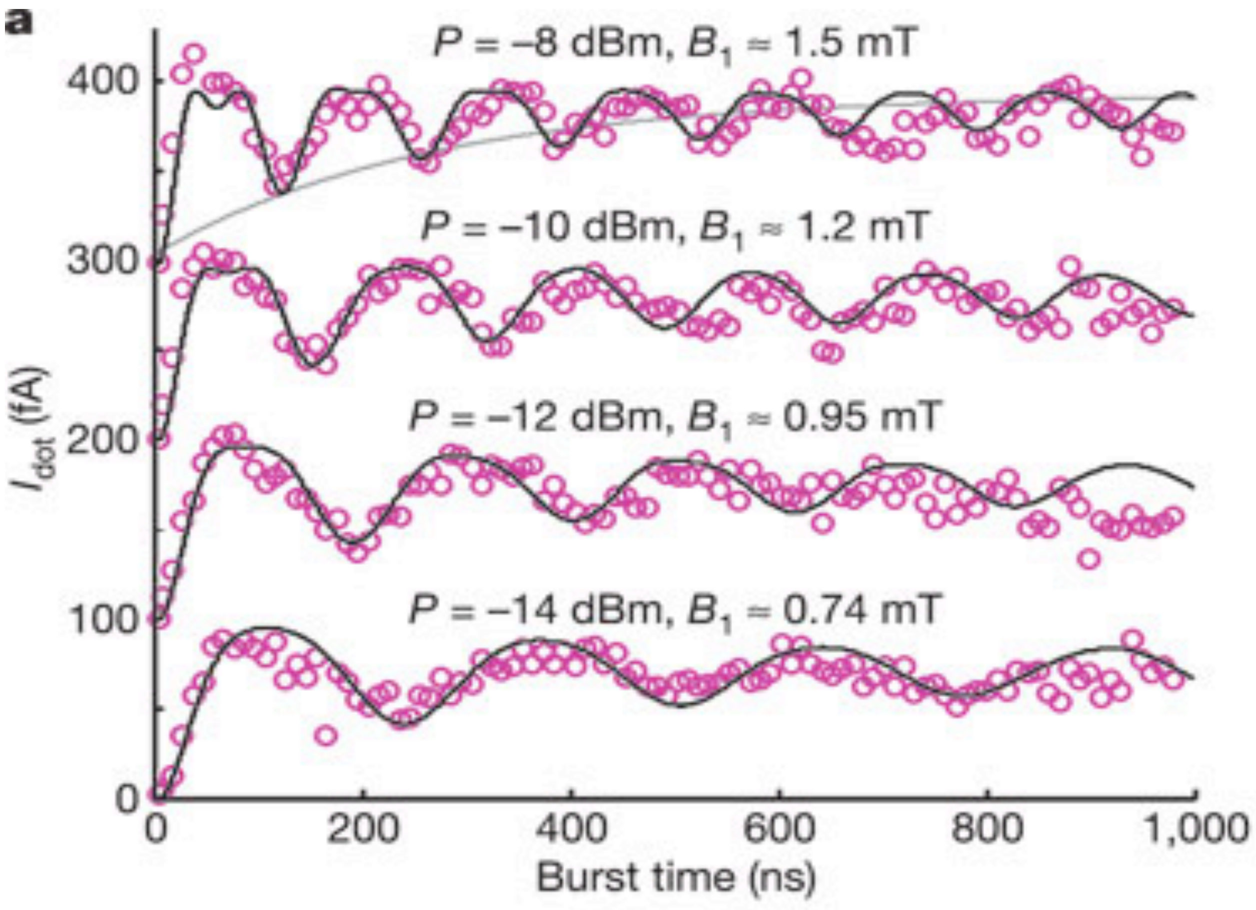


- Up to now we know that we can control a single spin. But can we do it coherently?

- Try to drive Rabi oscillation

- Isolate spin due to Coulomb blockade

Rabi oscillations (II)

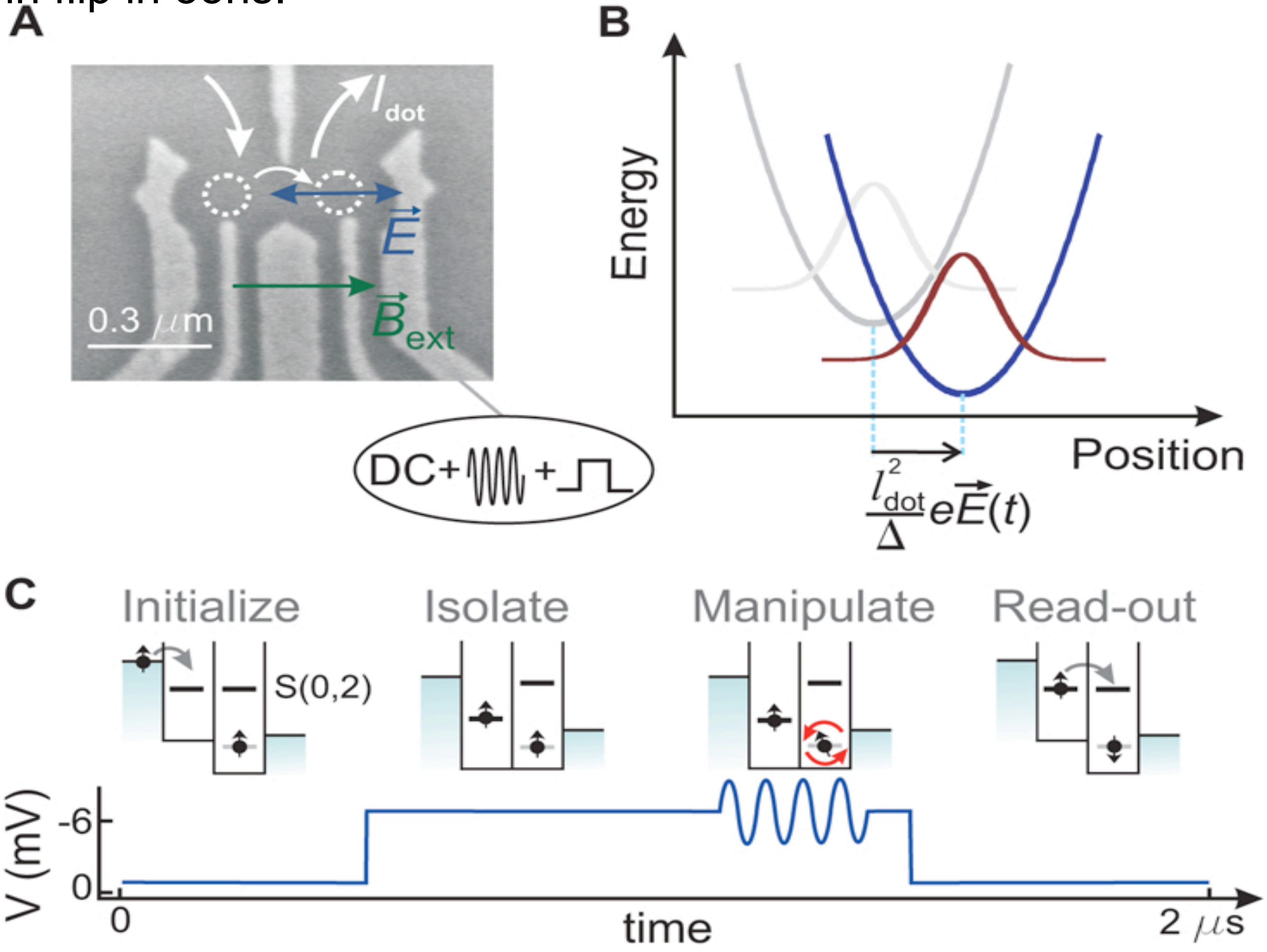


Spin rotations in 27ns

Alternative schemes

Apply oscillating electric fields.

Spin flip in 55ns.



Conclusion

- Coherent control of single electron spins is possible
- Switching times of 27ns with B-fields and 55ns with E-fields
- Last missing diVincenzo criterion. Quantum dots are therefore good candidates for a quantum computer

Thank you for your attention!