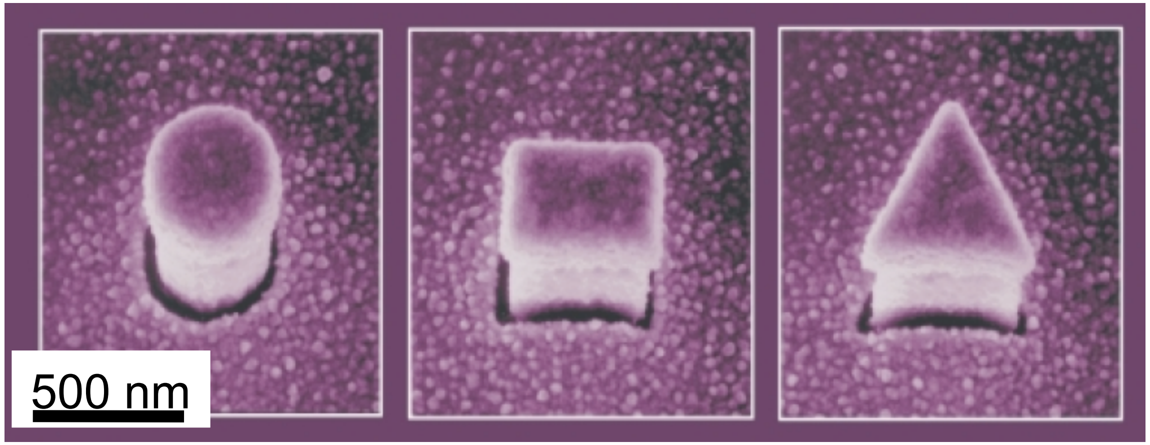
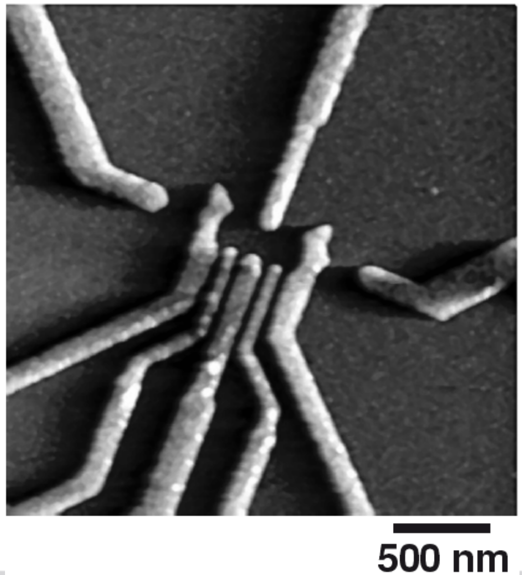
Solid-State Quantum Technologies

Lecture: Quantum Dots

Prof. Wernsdorfer (acknowledgement Jürgen Lisenfeld)





Lecture

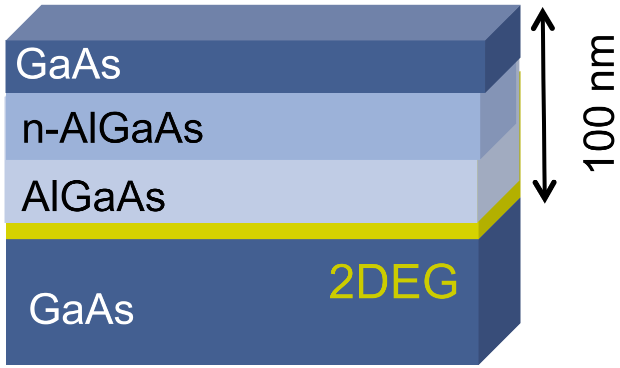
Karlsruhe Institute of Technology

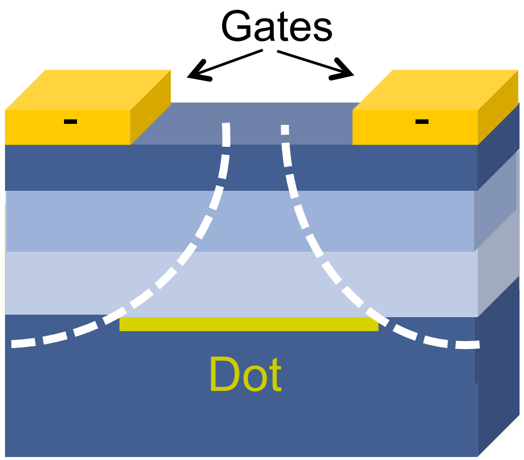
Quantum Dots

- The semiconductor Heterostructure and the **2-dimensional electron gas**
- The **Loss & DiVincenzo proposal**
- Lateral **(gated) Quantum Dots**
- Vertical Dots, Nanotubes, and self-formed Quantum Dots
- The **Quantum Point Contact**
- Experiments on **coherent Spin Manipulation**

2-dimensional electron gas (2DEG)

The **“Semiconductor Heterostructure”**





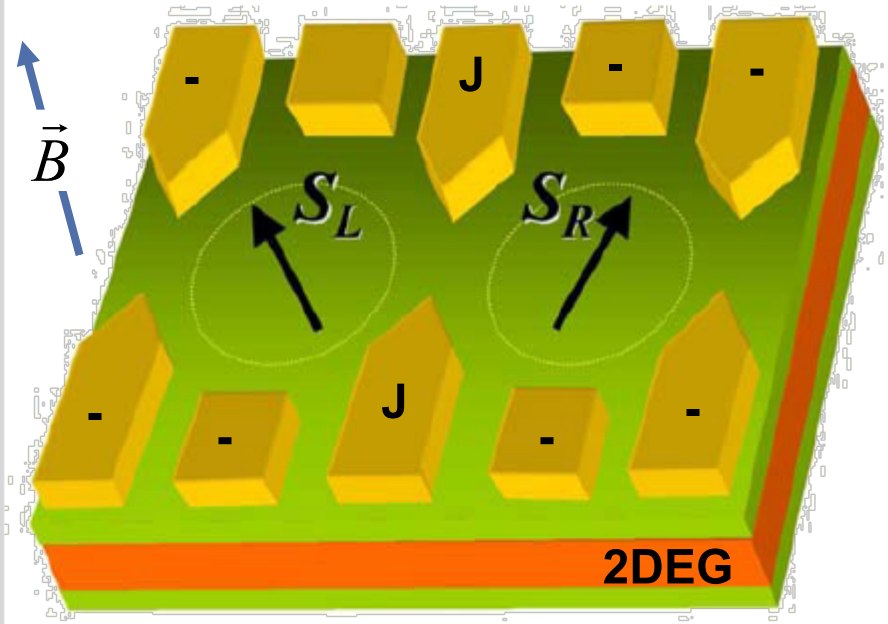
- **extra electrons** in doped n-AlGaAs are **trapped** at AlGaAs – GaAs interface
- a **10 nm** thick **2-dimensional electron gas** is formed
  - high electron mobility
  - low electron density (~3000/μm^2)

➔ electrons can be **confined to small areas** (“islands” or “**dots**”) **using gate electrodes**

➔ the solid – state version of an **electron trap.**

The Loss & DiVincenzo - Proposal

a two-dimensional spin quantum computer

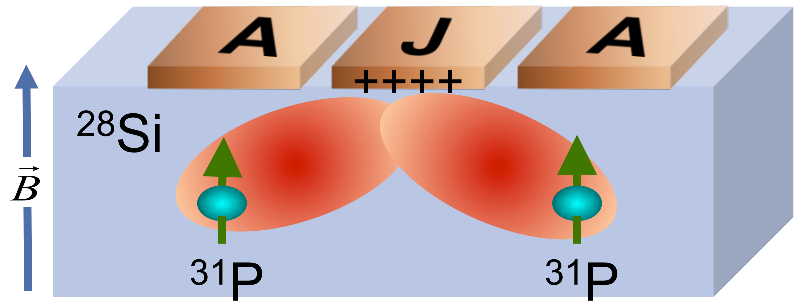


- **Spin** of electrons is used as **Qubit**
- applied **magnetic field** defines Qubit states $|\uparrow\rangle, |\downarrow\rangle$

$$E_\downarrow - E_\uparrow = g_{GaAs}\,\mu_B B \approx 25\,\mu eV/T$$

- **coupling** between **neighboring dots** is controlled by **J gates**
- only **nearest neighbor coupling** is possible.

- comparison with **Kane's proposal:**
  - coupling also controlled by **J gates**
  - **^{31}P** serves as an **"electron trap"**
  - e^- are only **mediators** between Qubits (the **nuclear spins** of ^{31}P)
  - high-precision **atom implantation** is required



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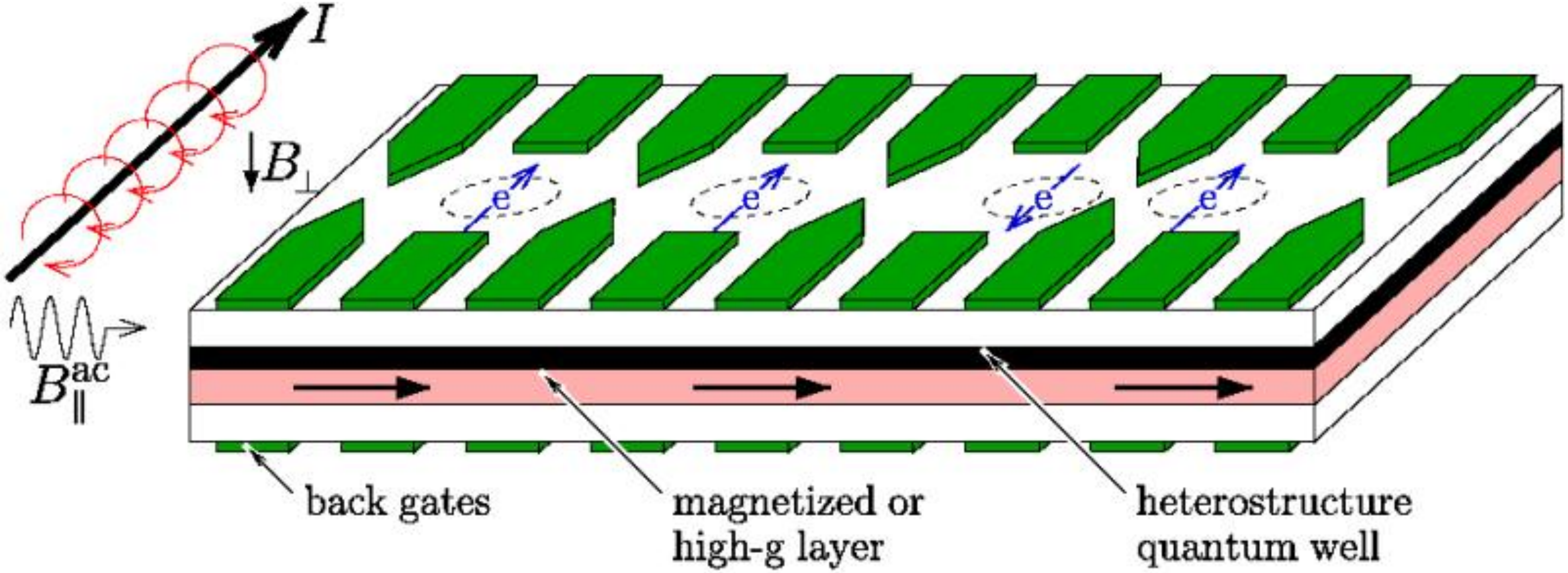


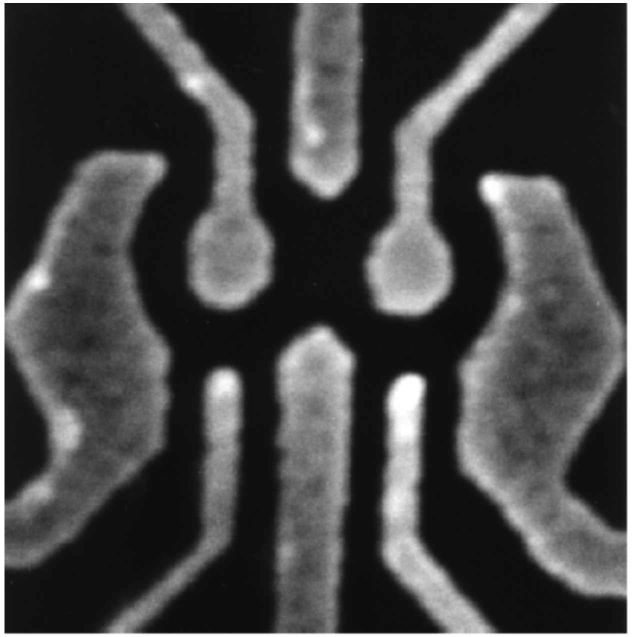
- a gradient magnetic field leads to different resonance frequencies of all qubits $\omega_{10} = g\,\mu_B B / \hbar$
- single Qubit operations by a resonant B_{ac} field

- back gates may **drag electrons** into **a magnetized layer**
  - ➔ **resonance frequency** can **be changed** by back **gate voltage**
  - ➔ application of AC voltage can provide resonantly oscillating magnetic field

The “Gundam” Double Quantum Dot

Karlsruhe Institute of Technology

Double Quantum Dot



200 nm

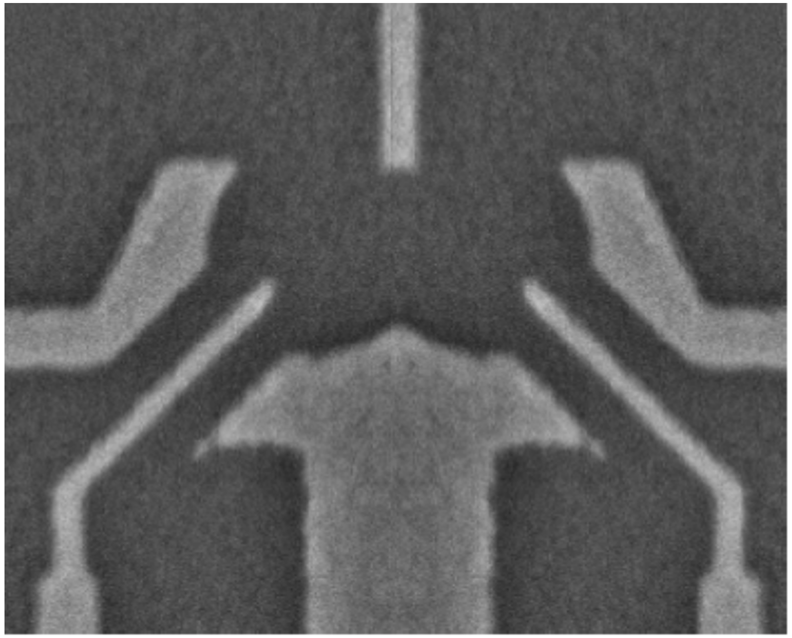
Elzerman et al. (2005)

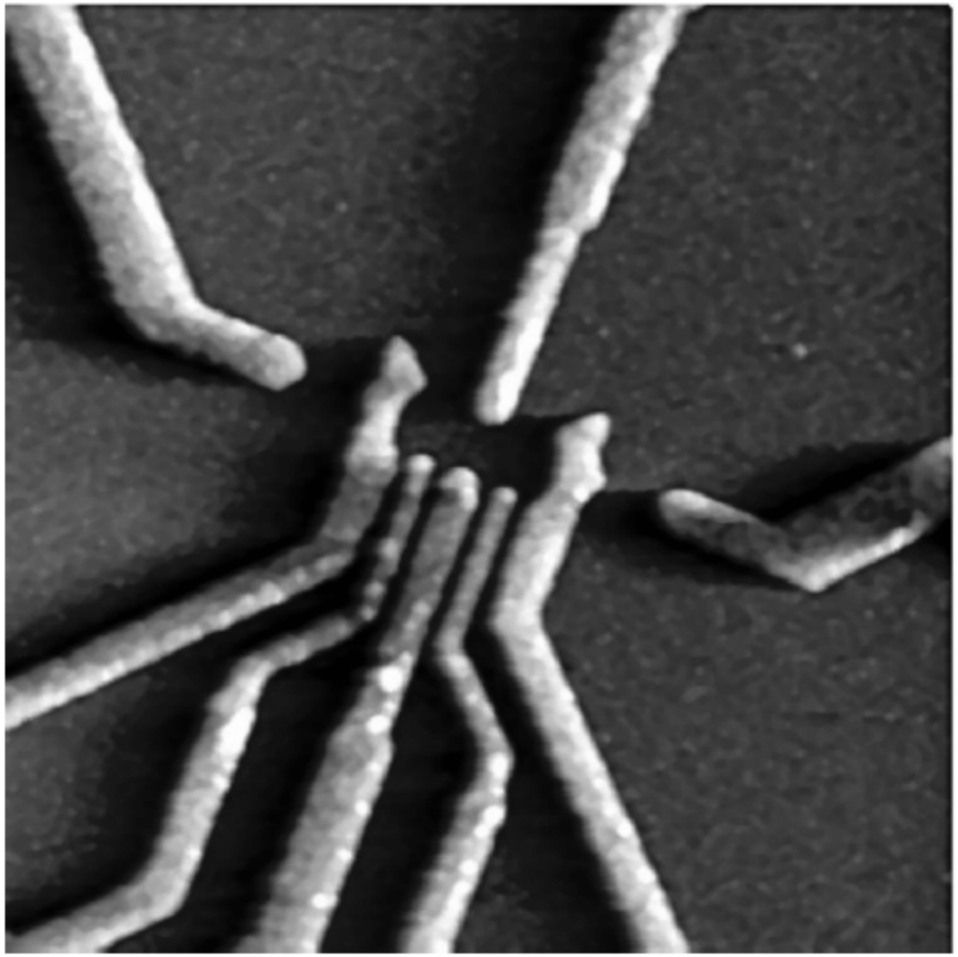
Gundam

1 m

Bandai et al. (1979)

Double Quantum Dot Designs



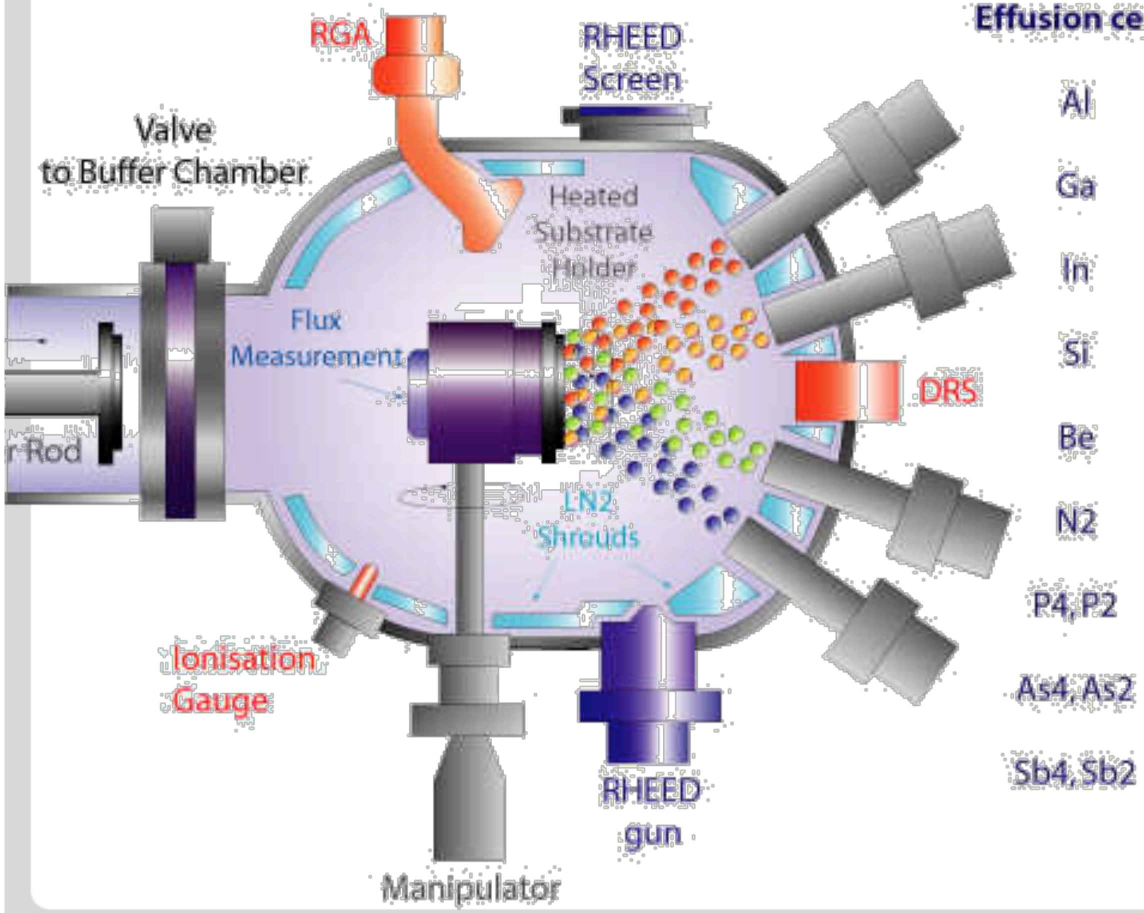


Elzerman et al. (2005)

Fabrication

Molecular Beam Epitaxy

- used to fabricate **crystalline layered** structures, such as the **semiconductor heterostructure**



- substrate in ultra **high vacuum**
- very **slow deposition rate** allows to grow **epitaxial** films, i.e. **monocrystalline** films
- heating the substrate assures flat growth by thermal **diffusion**
- film is analyzed *in situ* by **RHEED** (reflection high energy electron diffraction)

Fabrication
Molecular Beam Epitaxy

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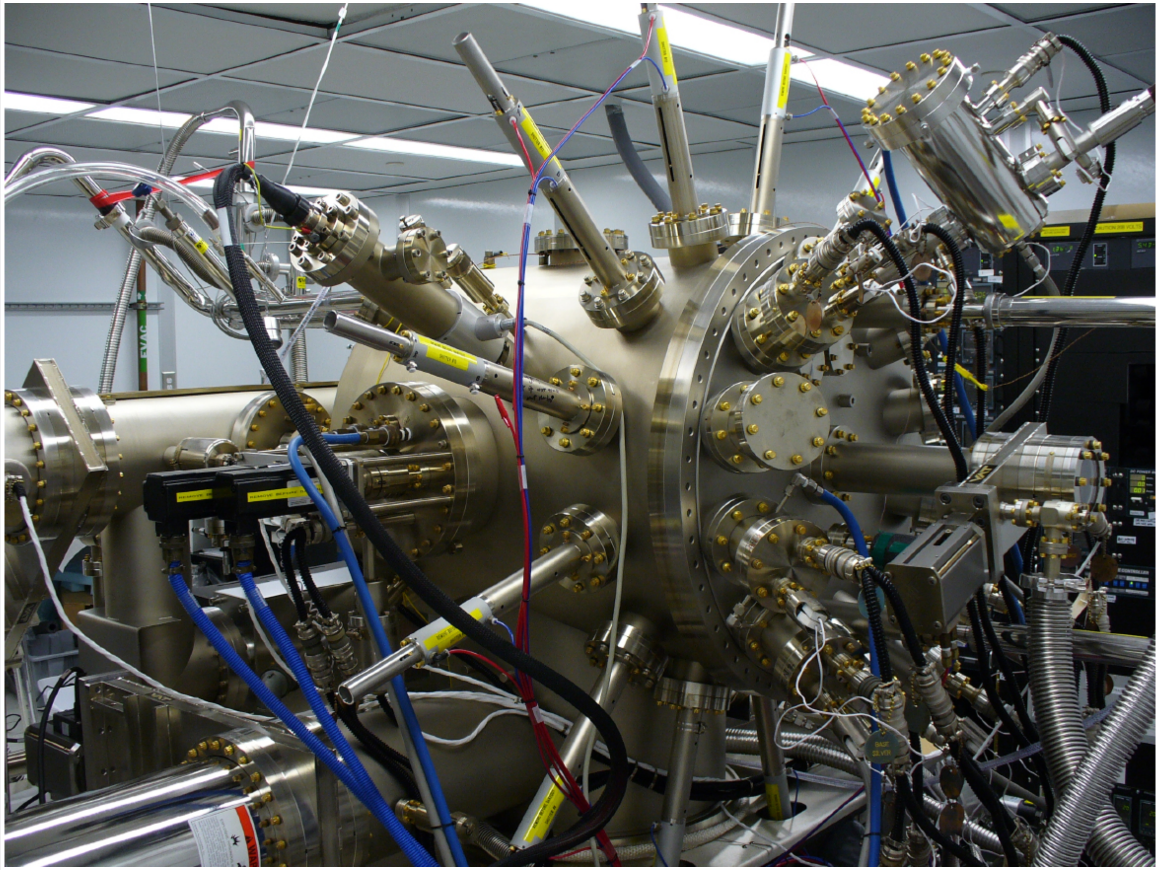

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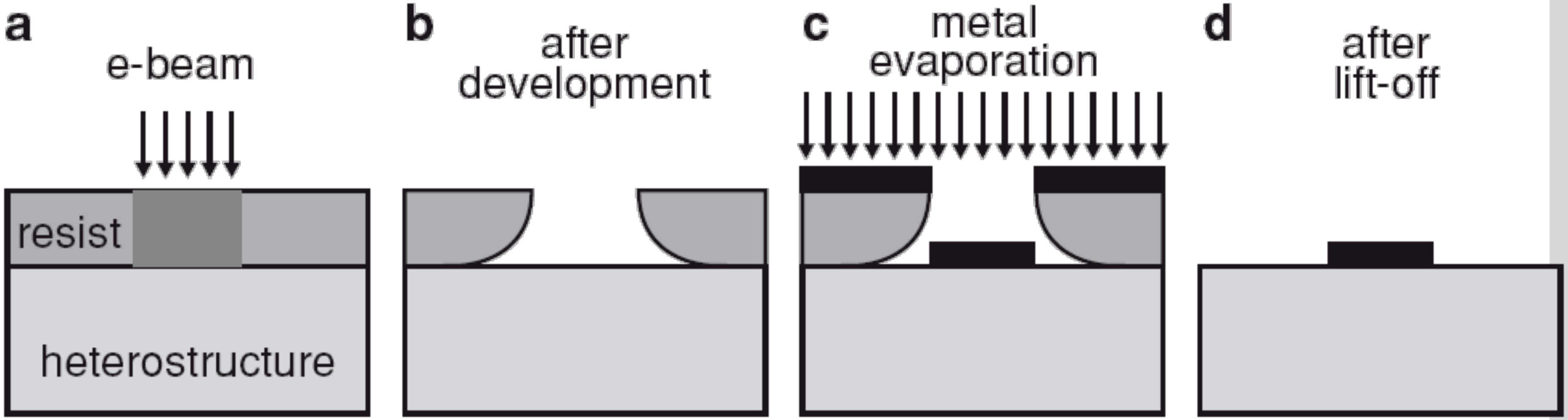
Lithography
to fabricate the gate electrodes



a • **Photoresist** (a polymer such as poly-methyl-methacrylate) is **spun** onto the substrate
• **Baking** hardens the resist (some resins evaporate)
• exposure using either a **photomask and UV light** (resolution ~ 1 µm) or **e-beam** (~ 10 nm): the radiation **breaks polymer chains** of the photoresist

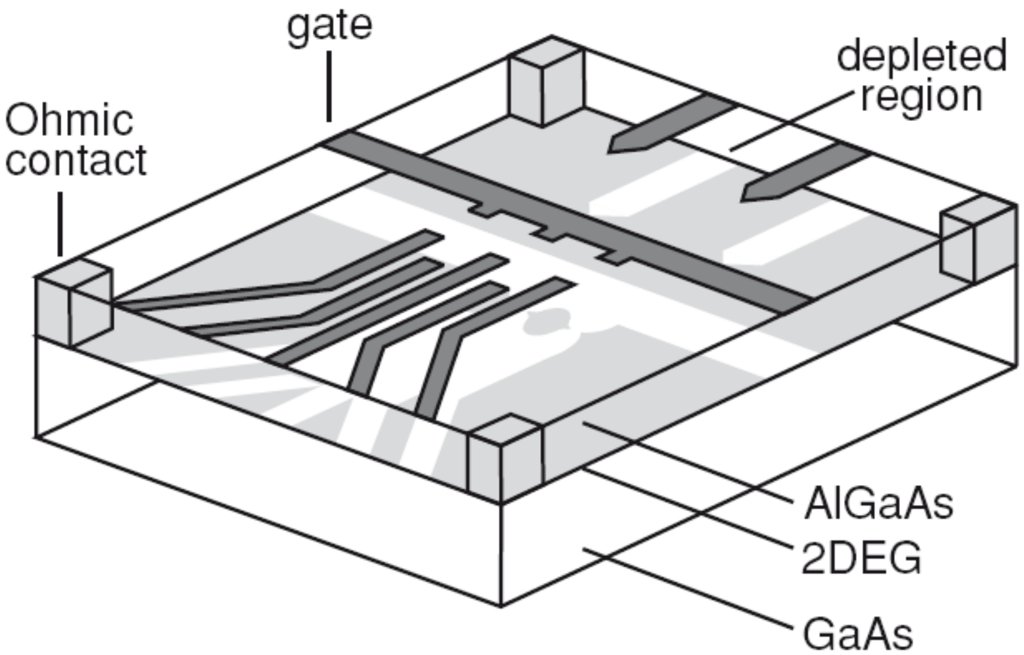
b • exposed resist is washed away (**broken polymer chains dissolve** in developer)

c • metal is **evaporated**, e.g. a ~ 100 nm thick layer of Au

d • the resist is washed away with e.g. Acetone ("**Lift-off**")

Contacting the electron gas

- an **electrical contact** to the electron gas is required to control its electrical potential.



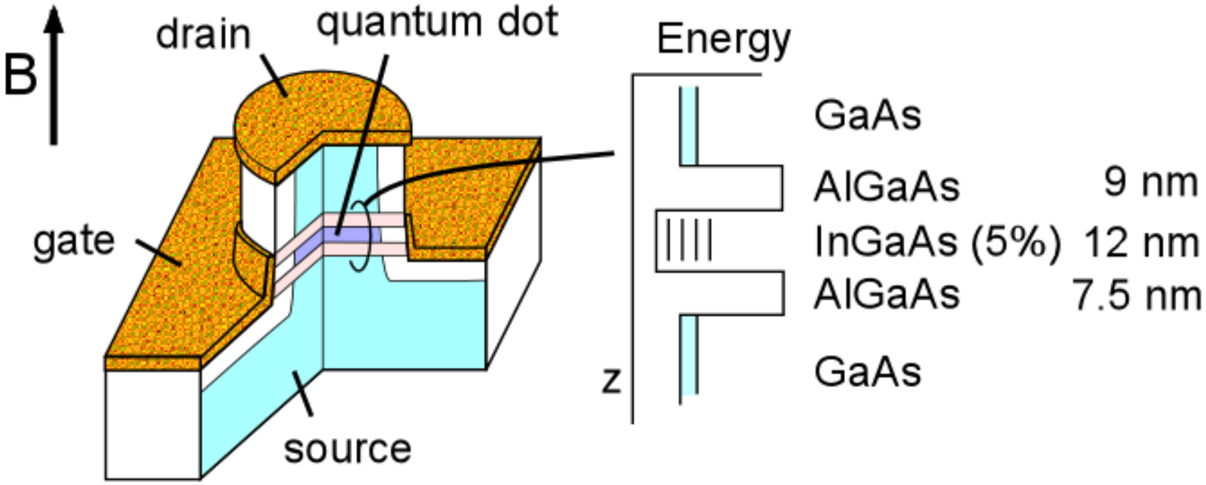
- Deposition of **metal pads** on the **surface**
- By **heating**, the **metal diffuses** into the material to the 2DEG

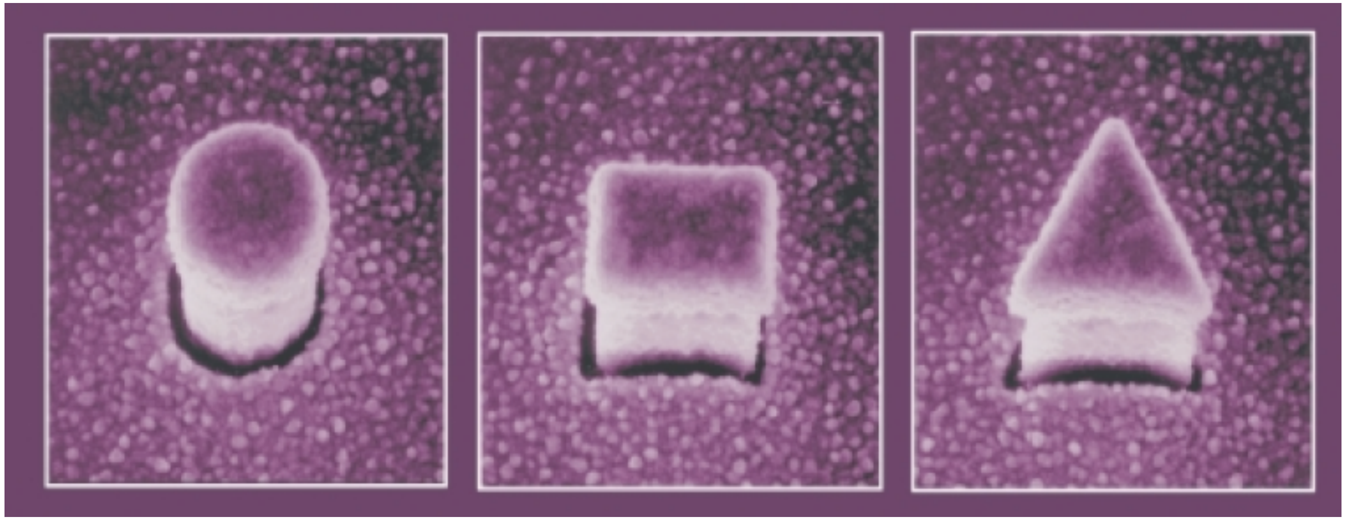
➜ **ohmic contacts** between the 2DEG and a surface bonding pad are made.

- **Rapid thermal annealing** is used to **heat** the sample in a few seconds to a few hundred °C.

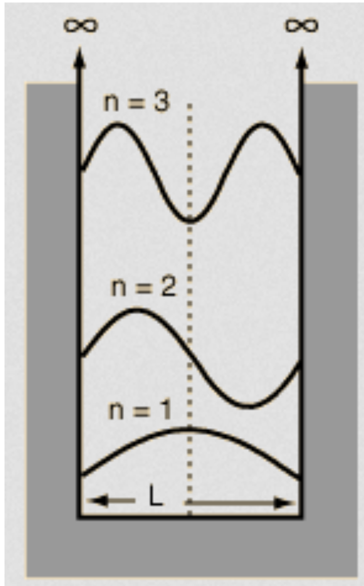
  The heat source is a bunch of lamps.

Vertical Quantum Dots





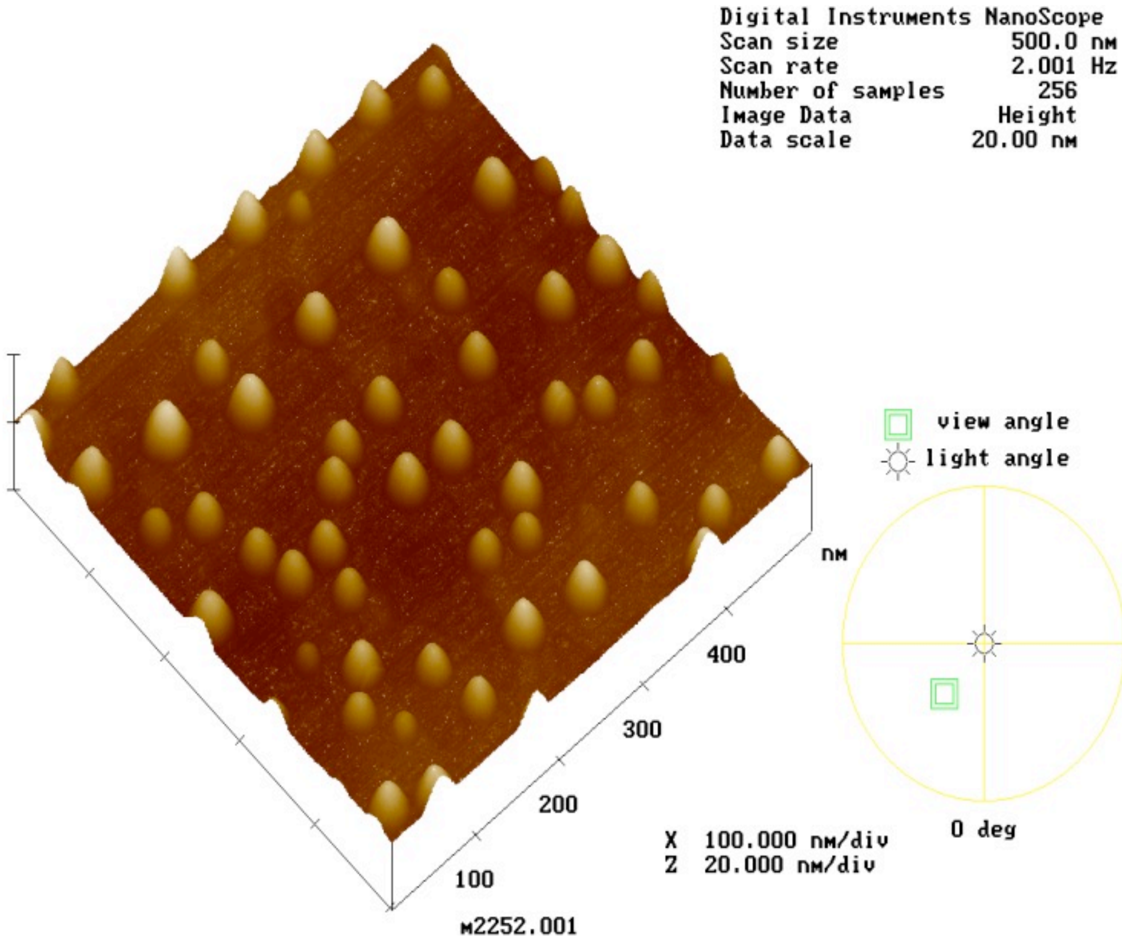
Realization of a "particle-in-a-box":



500 nm

Self-Assembled Quantum Dots

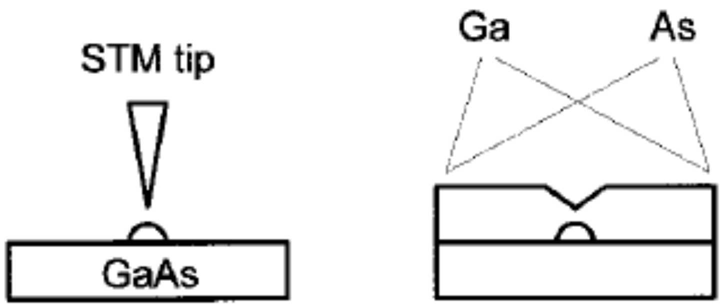
- Quantum Dots form **spontaneously** in suitable growth conditions

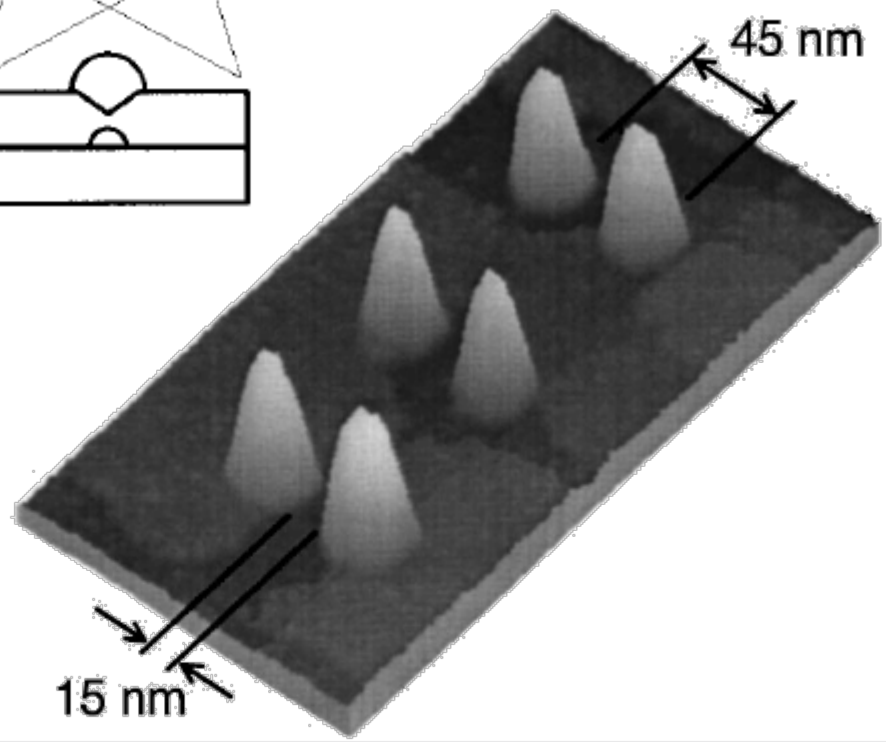


Self-organized growth of Quantum Dots

S. Kohmoto et al., Appl. Phys. Lett. 75, 3488 (1999)

- a voltage pulse on an STM tip **locally disturbs the GaAs**
- this creates a **nanohole** in subsequently deposited GaAs layer
- subsequent **self-organized growth** of QDs at **defined position**



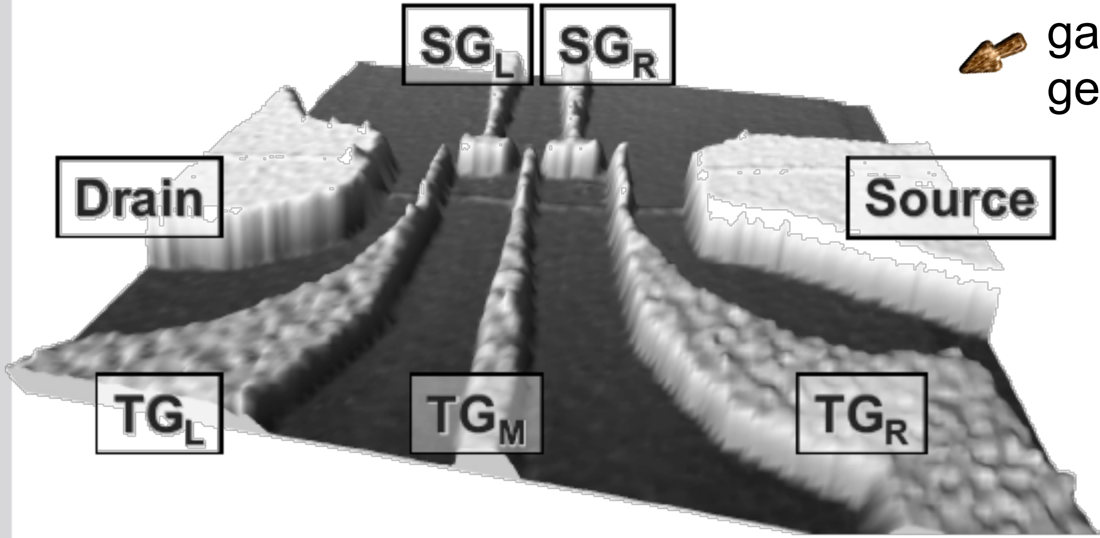


Solutions of Quantum Dots

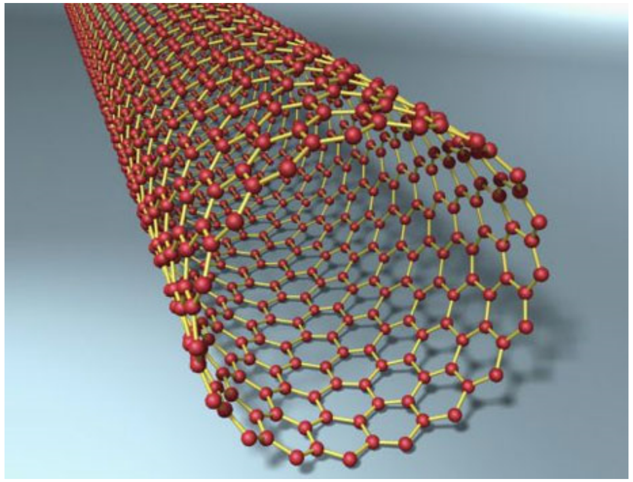
- nanocrystals of **2 to 10 nm** fabricated by colloidal synthesis
- size of the dot determines electronic energy levels: "**artificial atoms**"
- energy level spacing in **optical range** allows **optical pumping and readout**
- **Applications**:
  - Lasers (BluRay)
  - efficient solar cells
  - light conversion
  - LEDs
  - Displays
  - Medicine

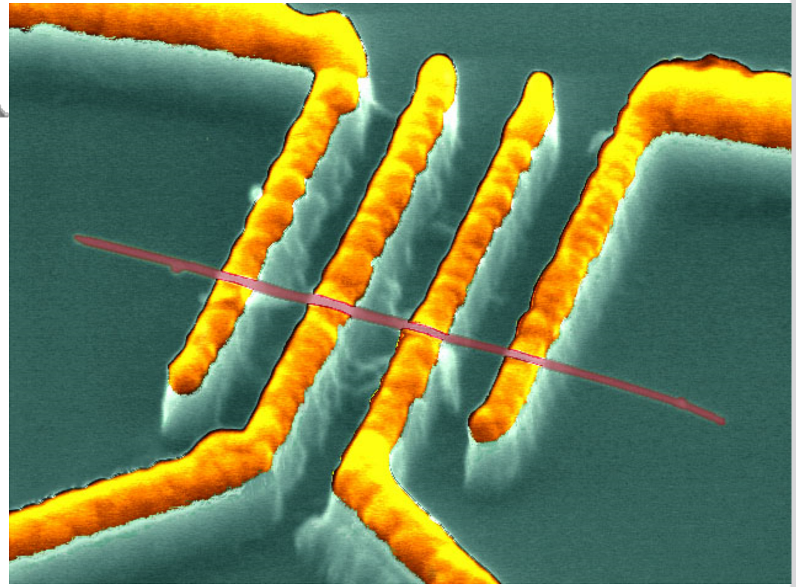
Solution of flourescent quantum dots. The emitted wave-length is proportional to the size of the dot.

Quantum Dots in Carbon Nanotubes



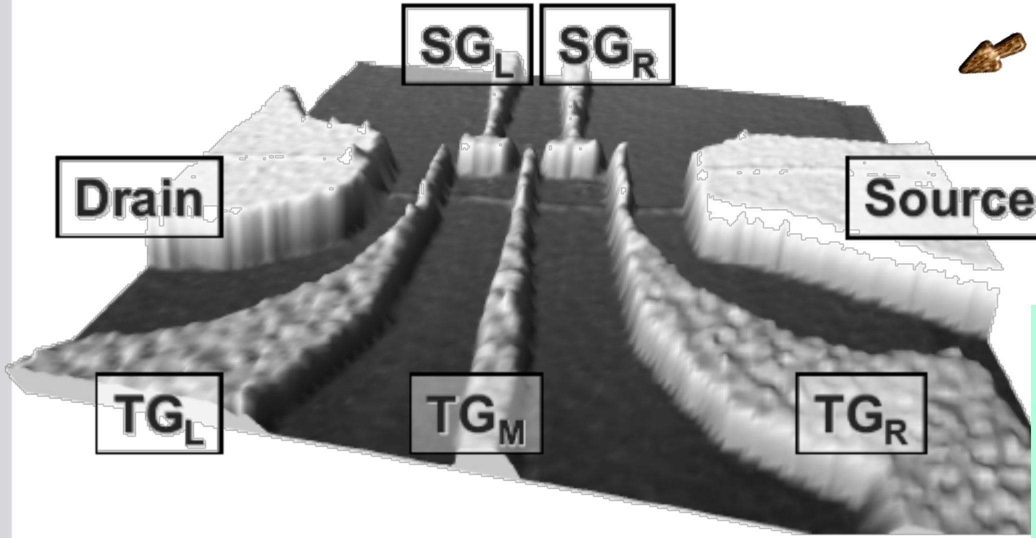
- gates fabricated on top of nanotube generate tunnel barriers defining dots





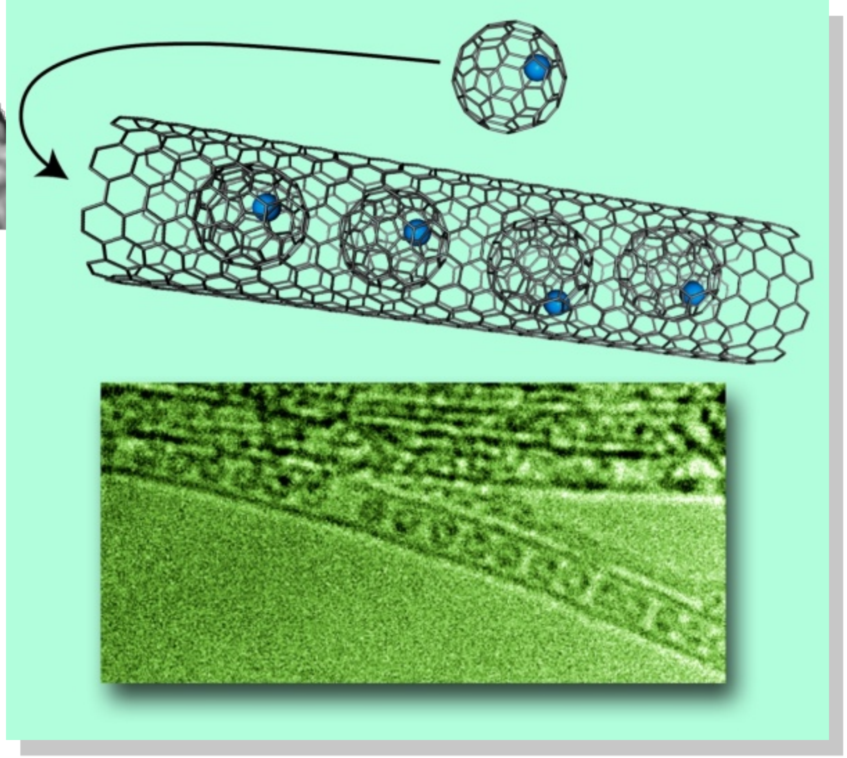
Nano-Electronics group at Univ. of Basel

Quantum Dots in Carbon Nanotubes



gates fabricated on top of nanotube generate tunnel barriers defining dots

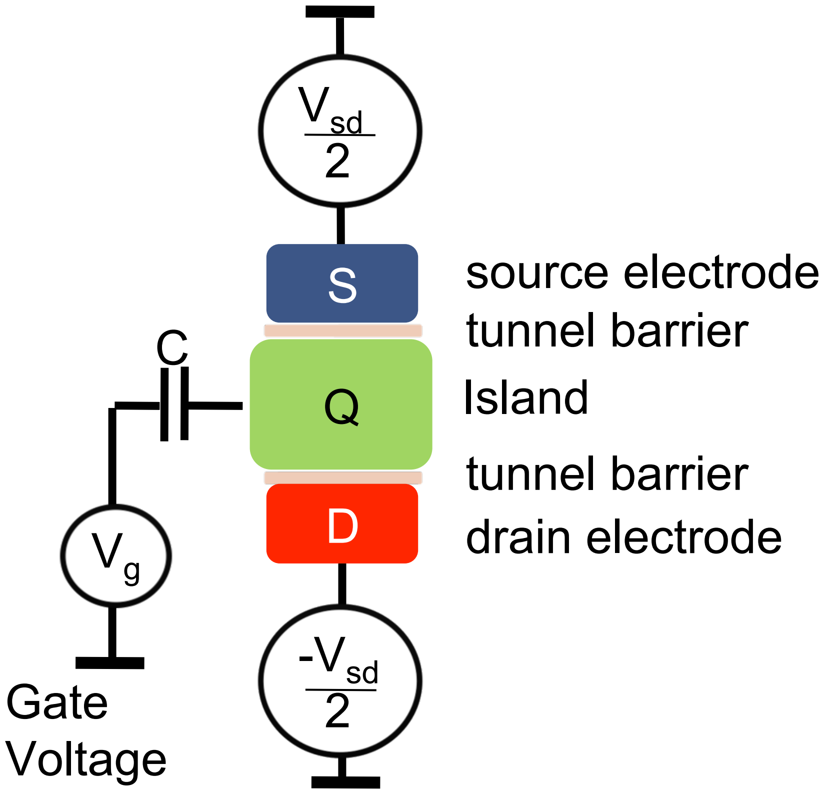
nanotubes can be filled with fullerenes, which contain spin ½ nuclei



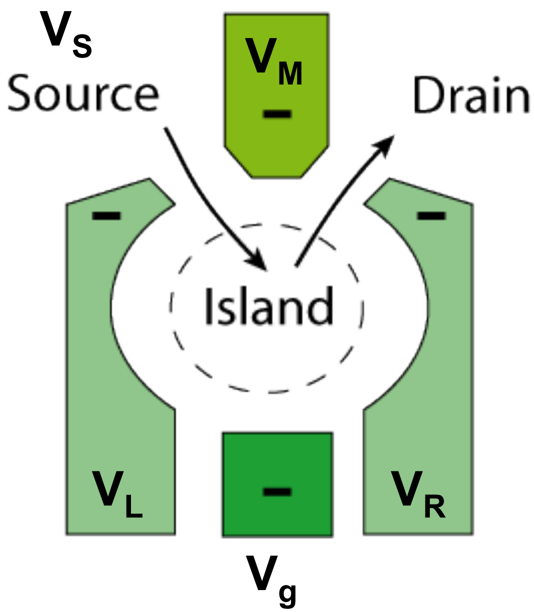
Transport through the Quantum Dot

The dot can be operated as a single electron transistor (SET)

- The **single electron transistor** (see also previous lecture)



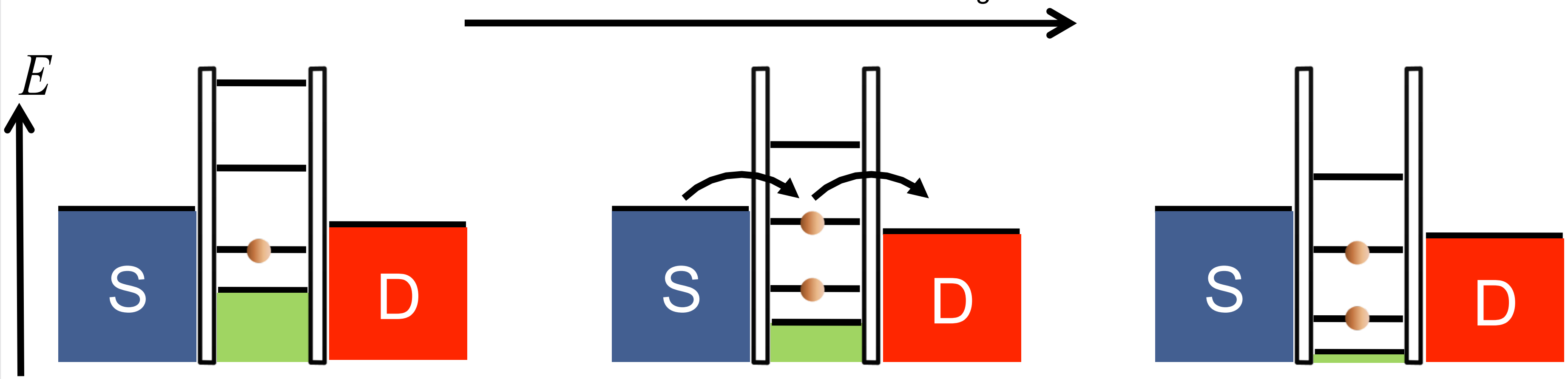
- A **quantum dot** formed by gates in a 2-dimensional electron gas



➔ The **tunnel barrier** between island and source or drain is controlled by voltages **V_M, V_L, V_R**.

Transport through Quantum Dots

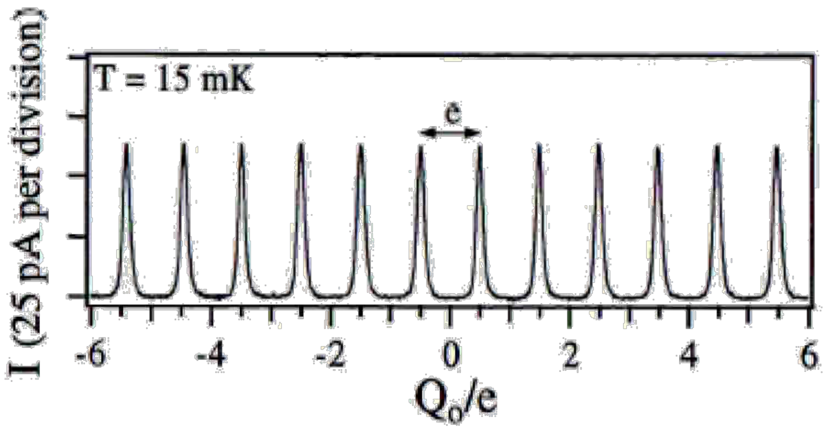
Increasing gate Voltage V_g



Coulomb blockade
conductance = 0

conductance $\neq 0$

Coulomb blockade
conductance = 0



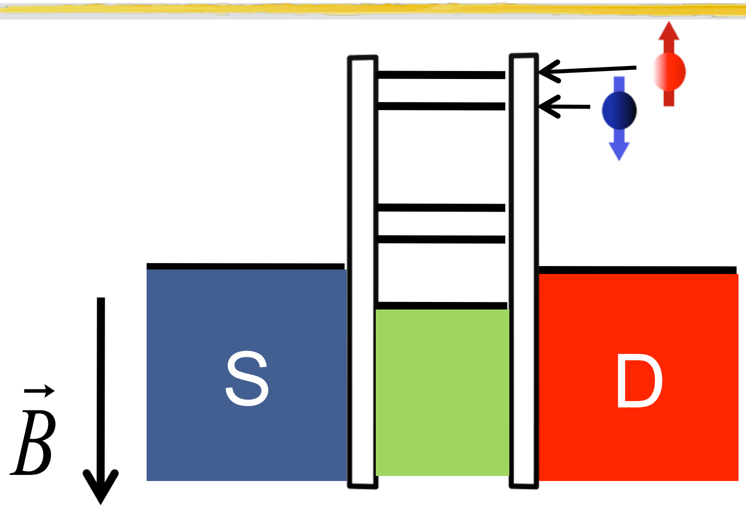
- **SET behaves like a transistor**:
  SD current can be switched on/off by gate voltage

- enormous **charge sensitivity**:

  a current of ~ 10^{10} electrons/s is switched by only **half an electron charge** on the gate !

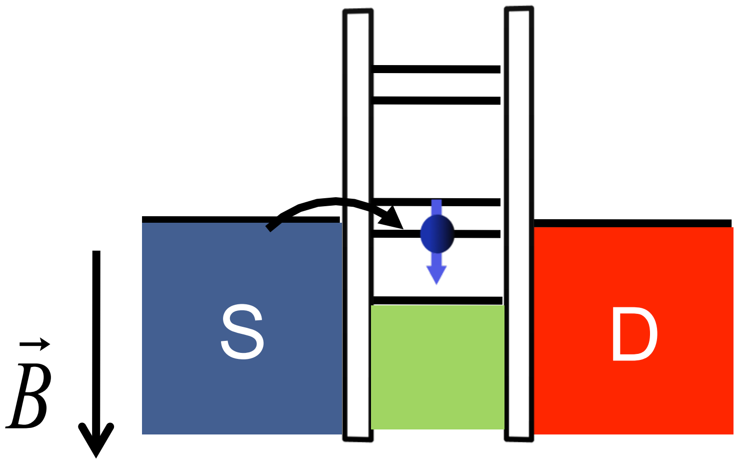
Hergenrother et al.

SET in magnetic field
Initializing the spin on the dot



- In magnetic field, energy levels split up according to electron spin.

$$E_{|\uparrow\rangle} - E_{|\downarrow\rangle} = g\,\mu_B B$$



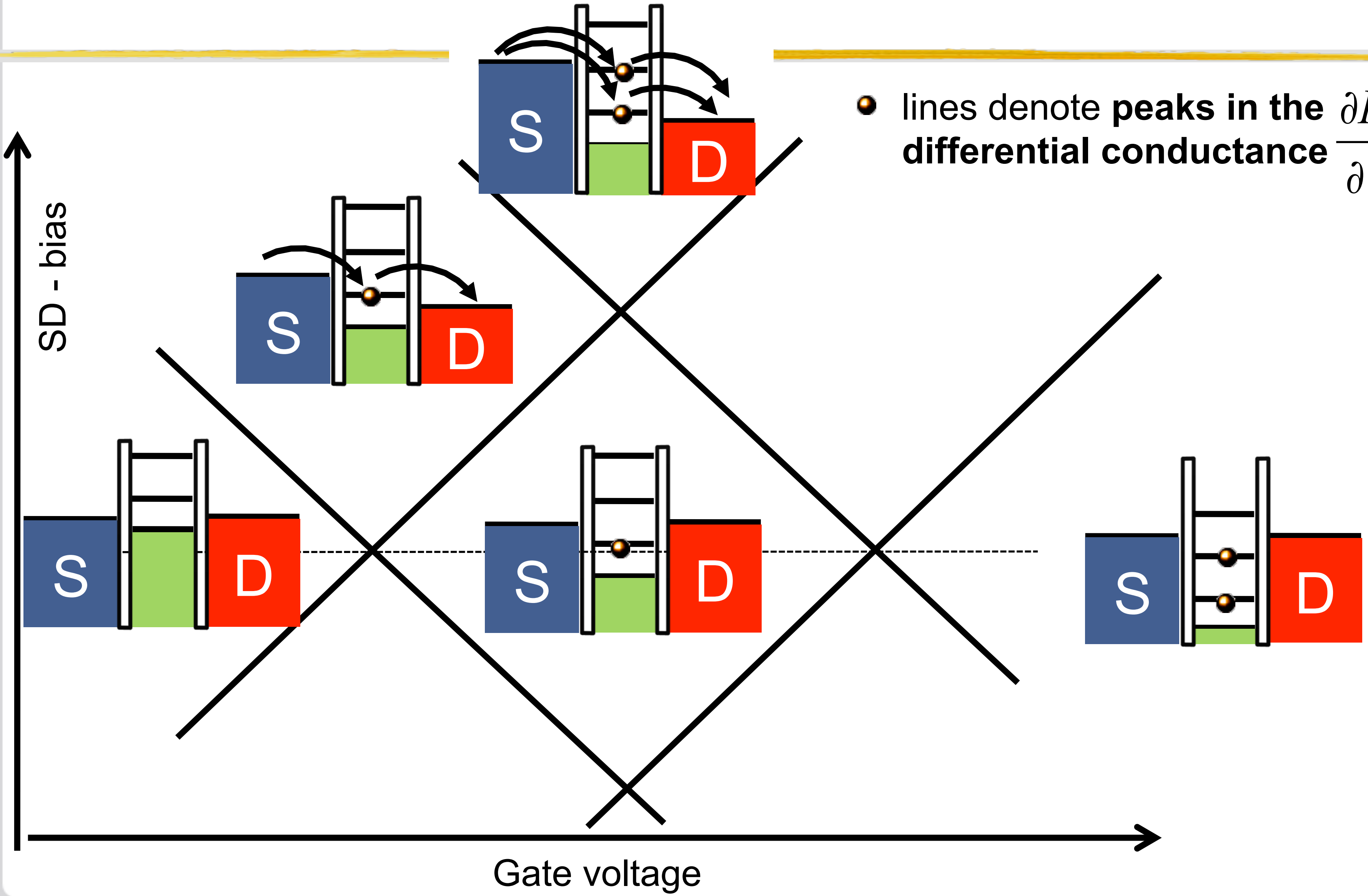
- Lowering the island potential such that **only the spin-down electron energy** lies **below** the S or D potential,

  the island is **initialized** with a **spin-down** electron.

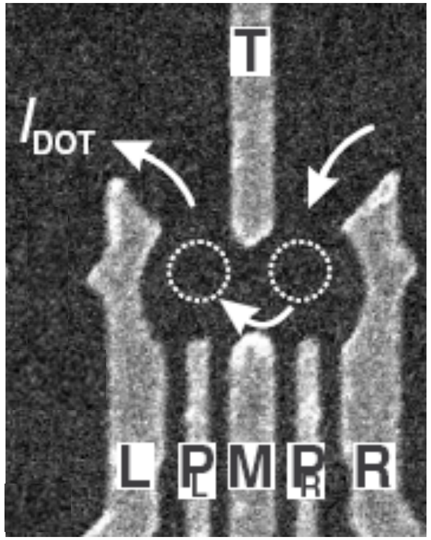
  (fulfills the 2nd **DiVincenzo criterion**)

Coulomb Diamonds

- lines denote **peaks in the differential conductance** $\frac{\partial I_{SD}}{\partial V}$

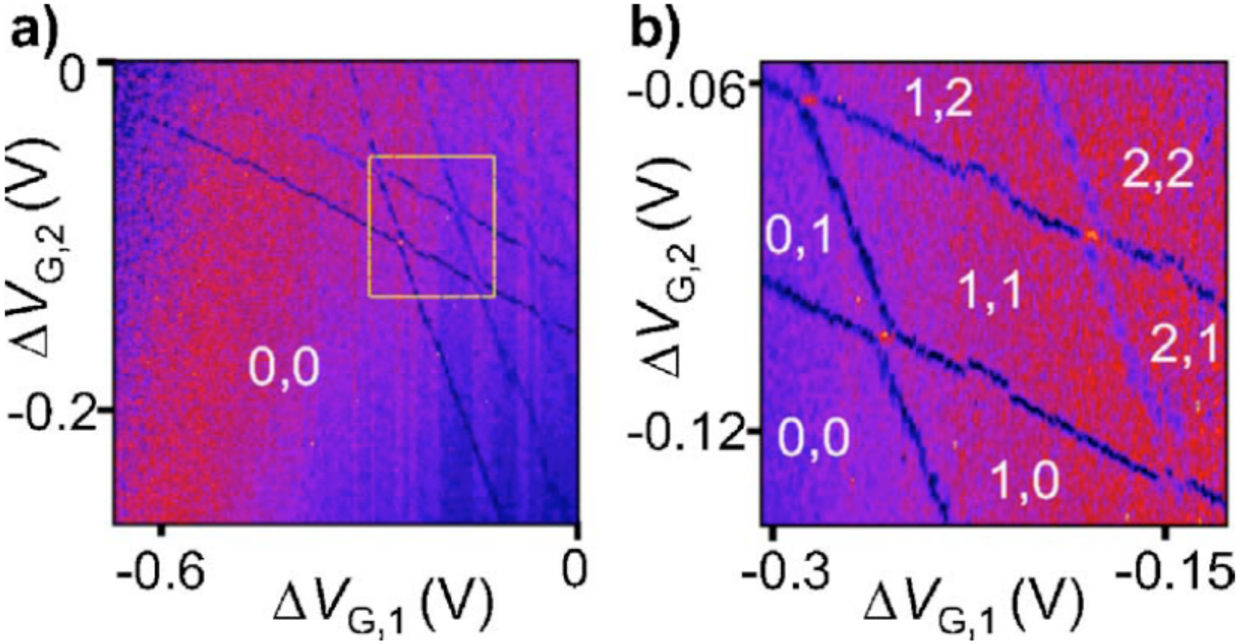


Coulomb Diamonds in a double Quantum Dot

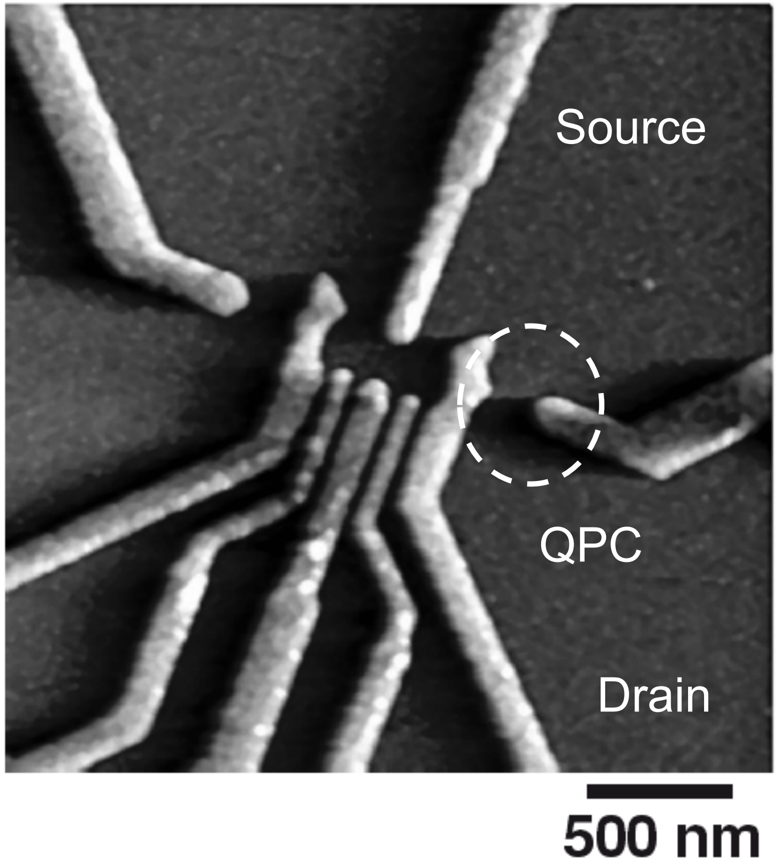


- **the number of electrons** on both dots can be controlled 1 by 1 via gate voltages.

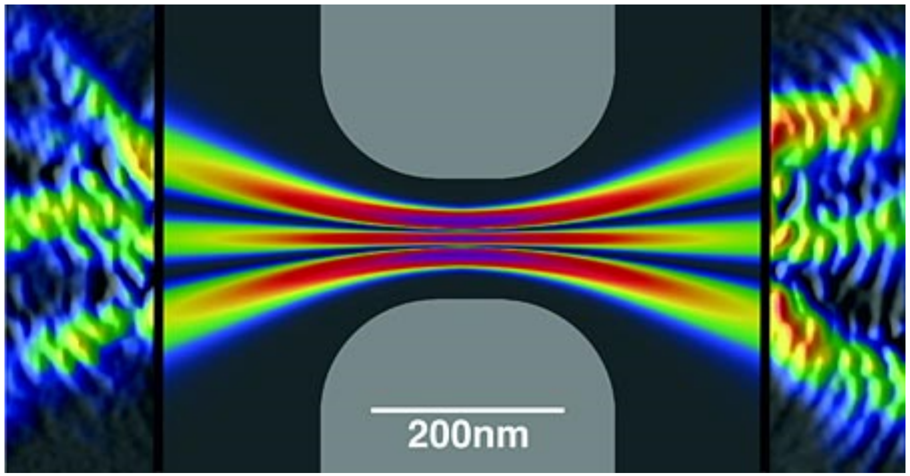
- **differential conductance** through quantum dot: (0,1 means 0 e^- on left, 1 e^- on right dot)



Readout of Quantum Dots by a Quantum Point Contact

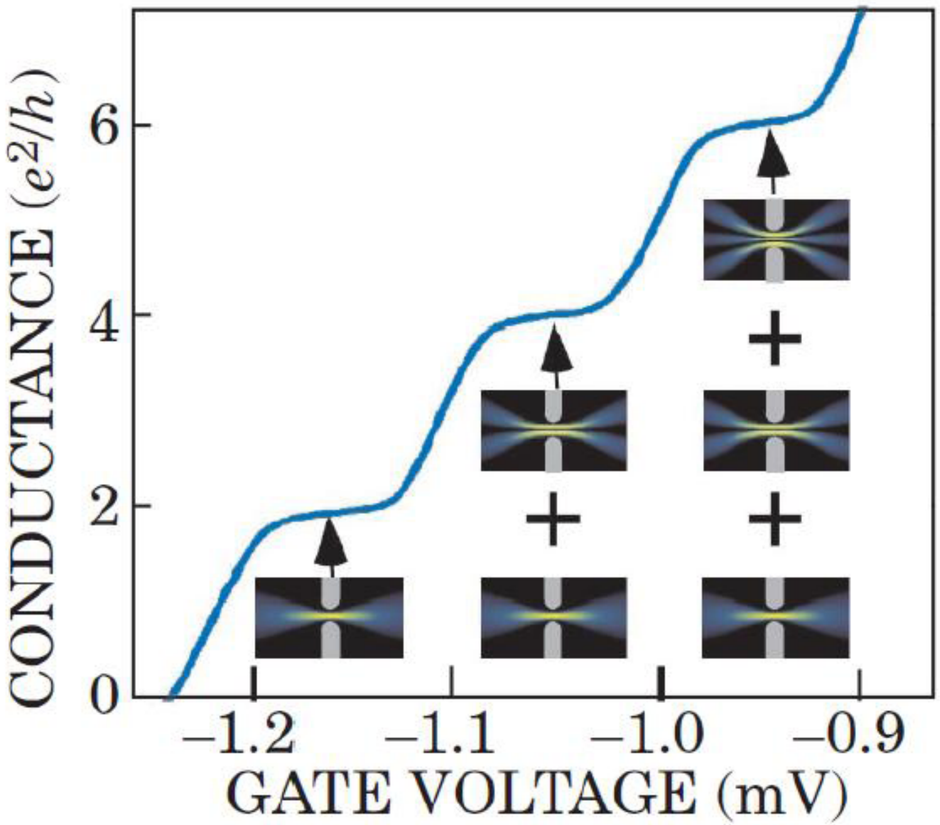


- a Quantum Point Contact (QPC) is a **narrow channel** of size **comparable** to the **electron wavelength** λ_{e-}
- the **width of the channel** is controlled by gate voltages
- the **transport** through the QPC is **quantized**



The Quantum Point Compact

conductance quantization



- the electron wavefunction has **discrete modes** because of the **confinement** in the transverse direction

• the current: $I = G\ V$

• the conductance: $G = N\ G_Q$

• the conductance quantum: $G_Q = \frac{2e^2}{h}$

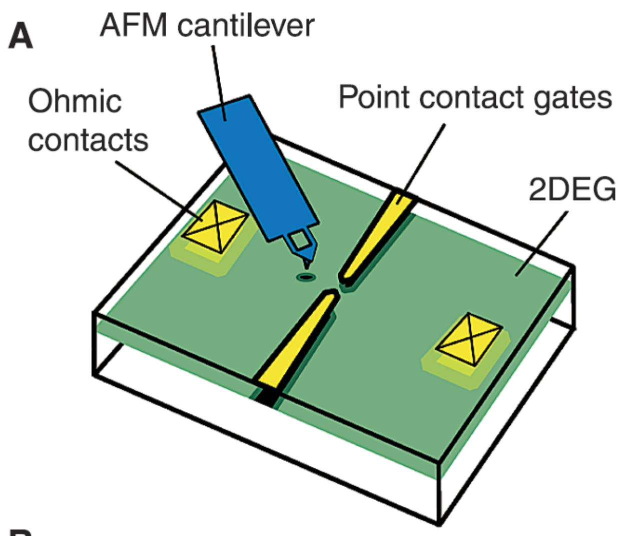
• number of modes N
N ~ width of QPC / electron wavelength

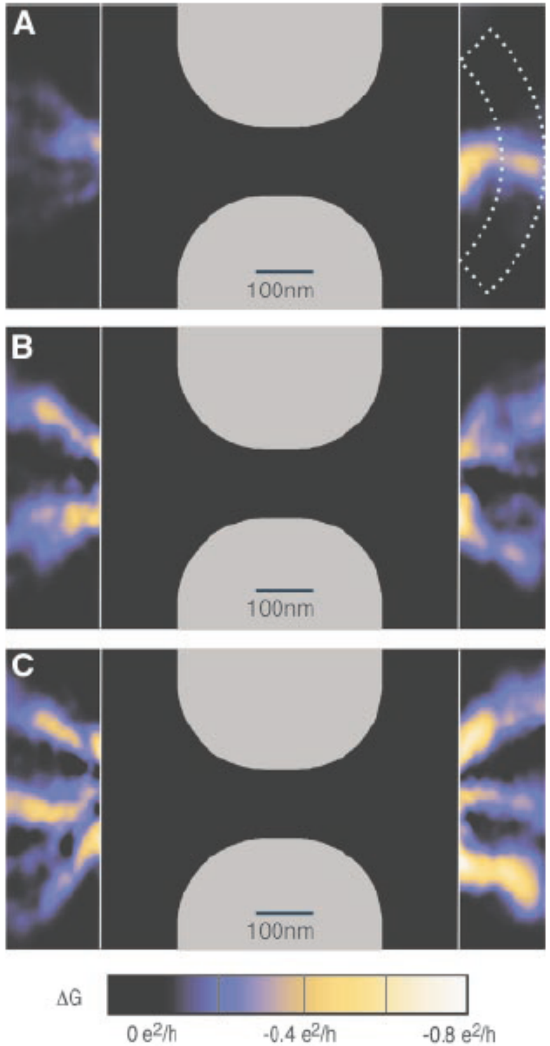
D. A. Wharam *et al., J. Phys. C: Solid State Phys.* **21** L209 (1988)
B.J. van Wees et al.*Phys. Rev.Lett.* **60**: 848–850 (1988)

Imaging Coherent Electron Flow from a Quantum Point Contact

The electron wavefunction's interference can be made visible by a measurement of the **QPC current** vs **tip position** of an atomic force microscope.

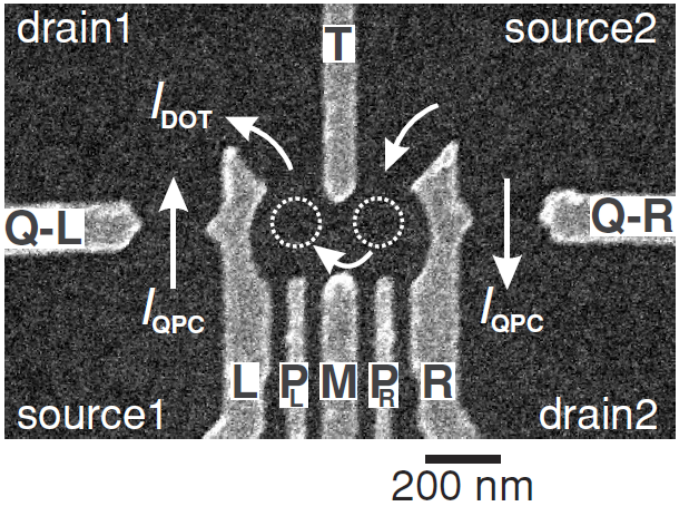
The **charged AFM tip** interrupts channels selectively, changing the conductance of the QPC.



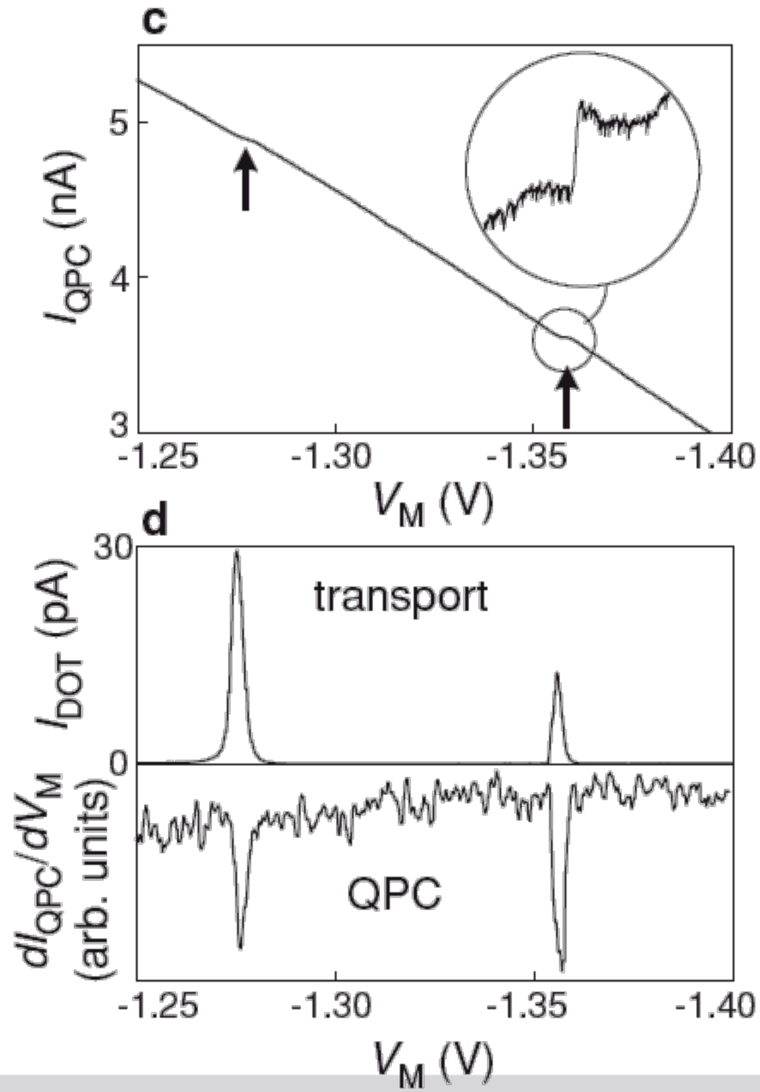


M.A. Topinka et al., Science 289, 2323 (2000)

Readout of Quantum Dots by a Quantum Point Contact

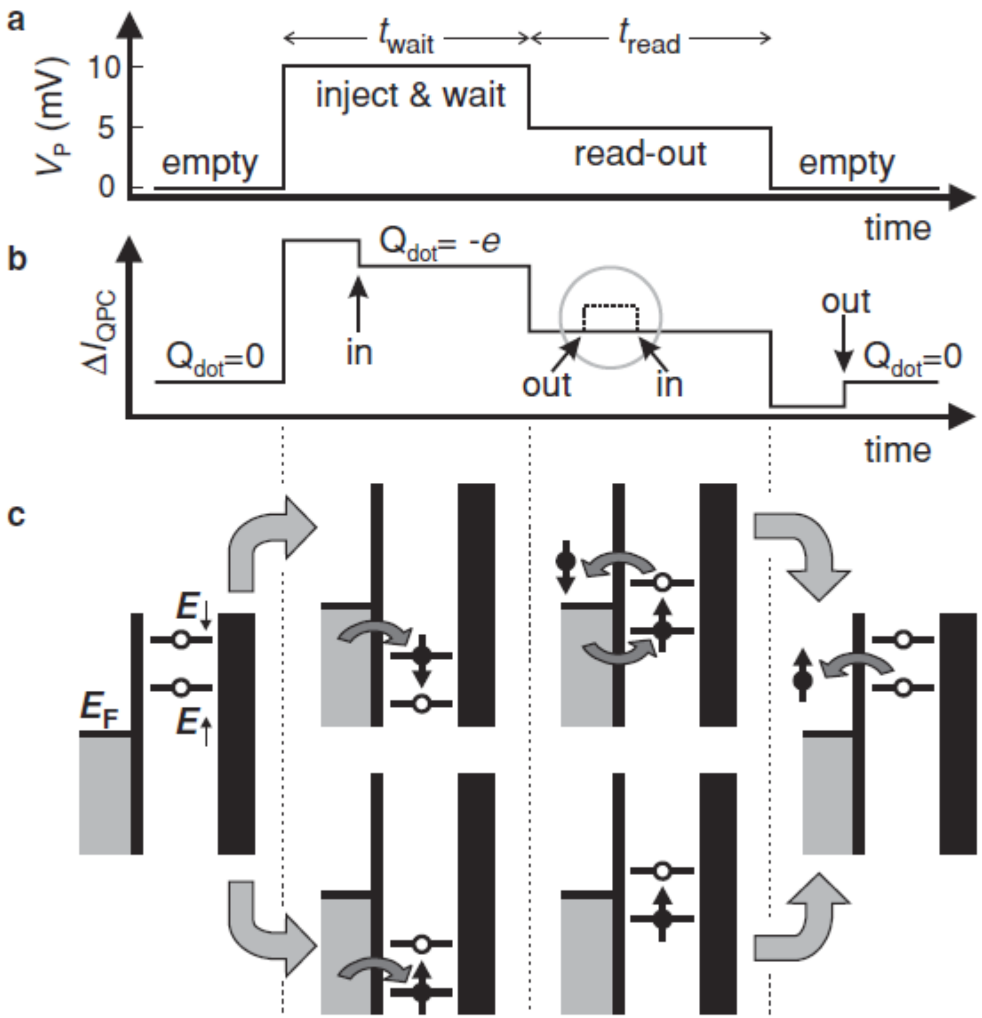


- changing voltage on gate M changes QPC potential and **pushes out electrons from the dot**
- **steps in I_{QPC}** indicate changing number of electrons on the dot
- the number of electrons on the dot can be measured without transport through the dot
- the charge sensitivity can be about $4 \cdot 10^{-5} e/\sqrt{Hz}$

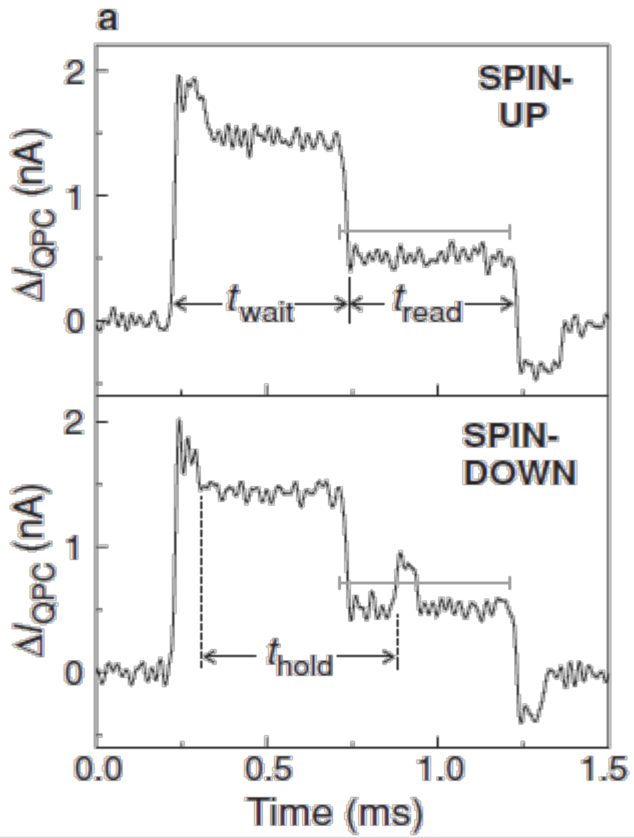


Single-Shot readout of the spin of an electron on a Quantum Dot

Elzerman et al., Nature **430**, 431-435 (2004)



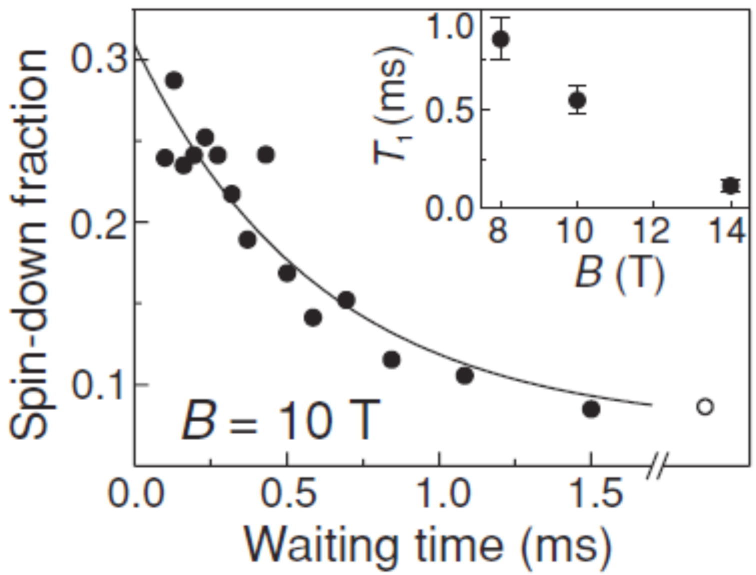
- the dot potential is adjusted to allow only spin-down electrons to leave the dot.
- the number of electrons on the dot is **continuously** measured by a **QPC**.

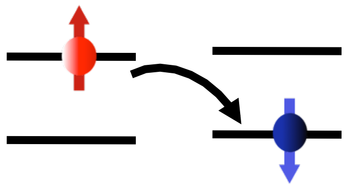


Single-Shot readout of the spin of an electron on a Quantum Dot

R. Hanson et al., Phys. Rev. Lett. **94**, 196802 (2005)

- **spin relaxation time**





- excited state decays at a half-lifetime of T1 ~ 0.8 ms

Single-Shot readout of the spin of an electron on a Quantum Dot

R. Hanson et al., Phys. Rev. Lett. **94**, 196802 (2005)

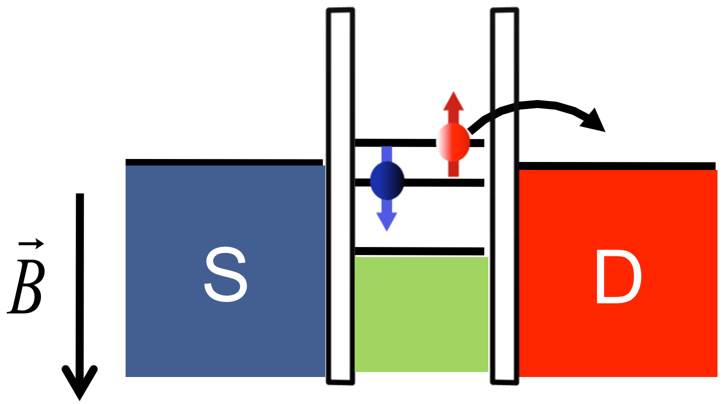
- Energy selective readout has disadvantages:
  - energy difference must **be larger than $k_B T$**
    → large fields are required, which limit the T_1 time
  - relies on **precise positioning** of the spin levels
    → very **sensitive to charge fluctuations**
  - very **sensitive to high frequency noise**

- different spin states may have a **different tunnel rate** out of the dot

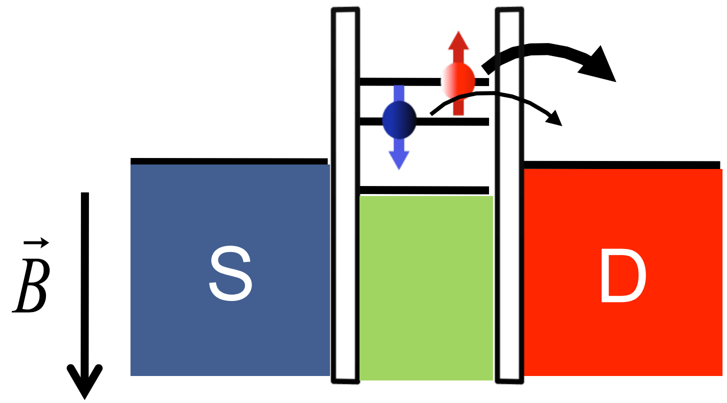
  e.g. because of dominance of one spin direction in the reservoir

  for two electrons:
  rate difference in tunelling from singlett and triplett states

- **Energy selective readout**



- **Tunnel-Rate selective readout**



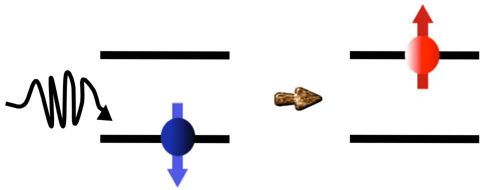
Resonant Spin Control

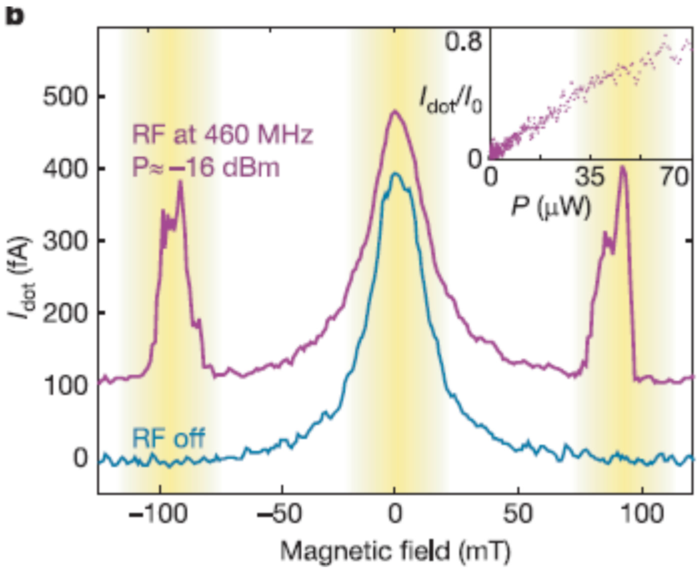
F.H.L. Koppens et al., Nature 442, 766 (2006)

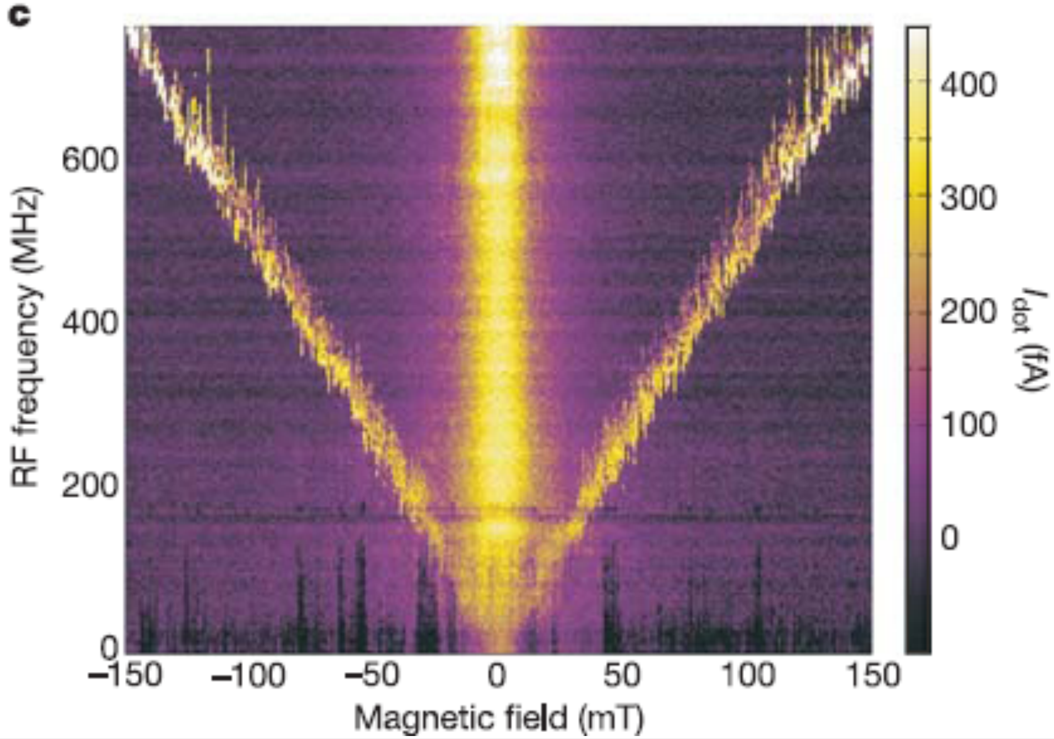
- **Spectroscopy**

  apply an rf **oscillating magnetic field**, vary **polarizing static field** strength

  Peaks in the current through the dot indicate **resonance**







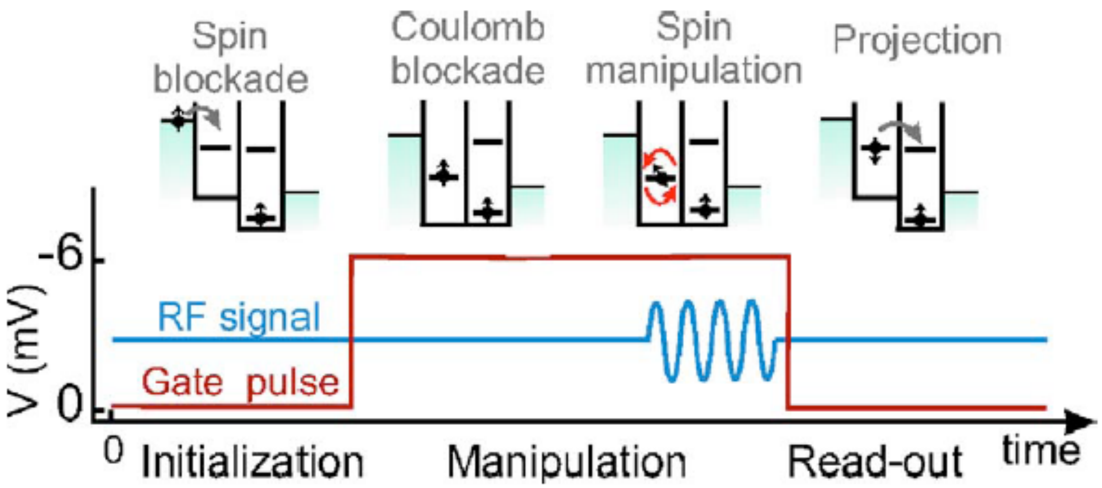
Resonant Spin Control

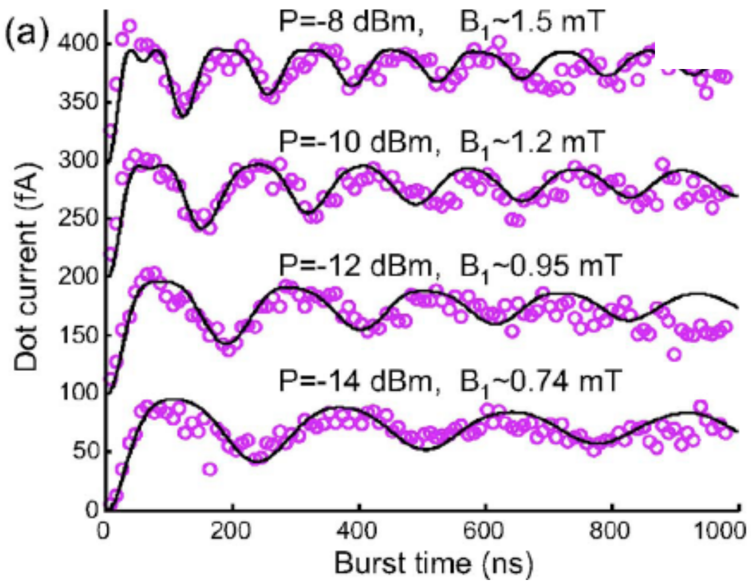
F.H.L. Koppens et al., Nature 442, 766 (2006)

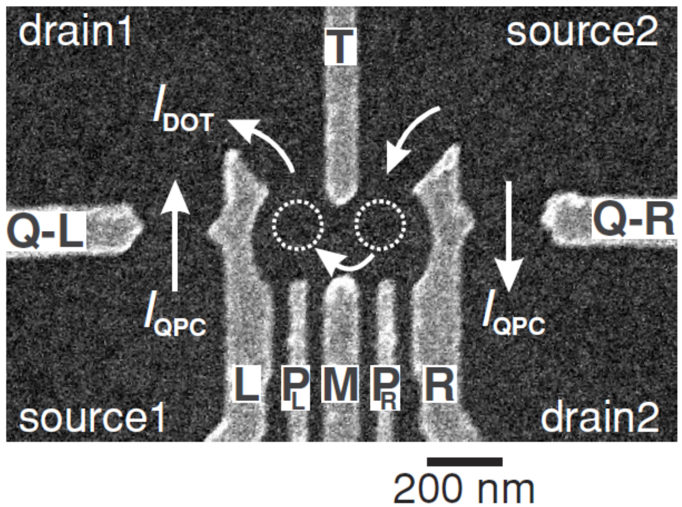
- **Rabi oscillation**

  a **spin-up** electron can‘t leave the dot due to **spin-blockade**

  flipping the spin via resonant drive starts current through dot







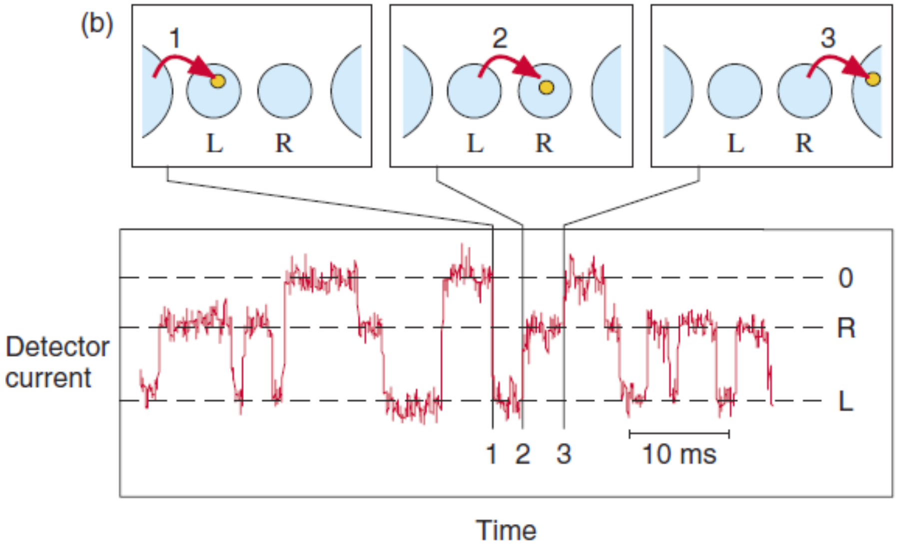
Using Quantum Dots as Charge Qubits

- a Qubit can also be defined from the **number of electrons on the island:**

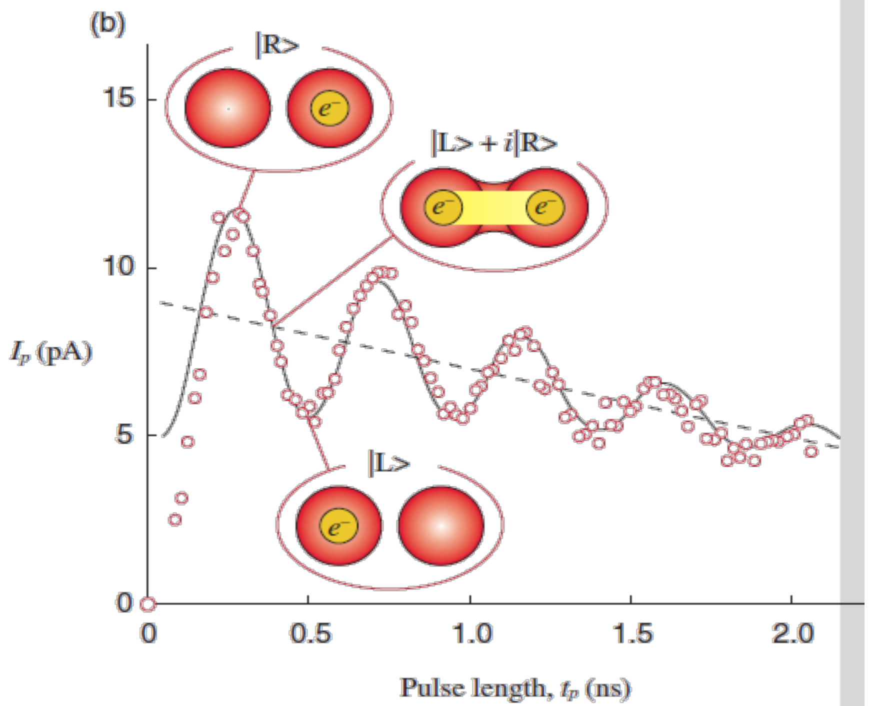
$$|0\rangle = \text{n} \quad \text{electrons on the dot}$$

$$|1\rangle = n+1 \text{ electrons on the dot}$$

- the QPC is sensitive enough to read out two neighboring quantum dots:

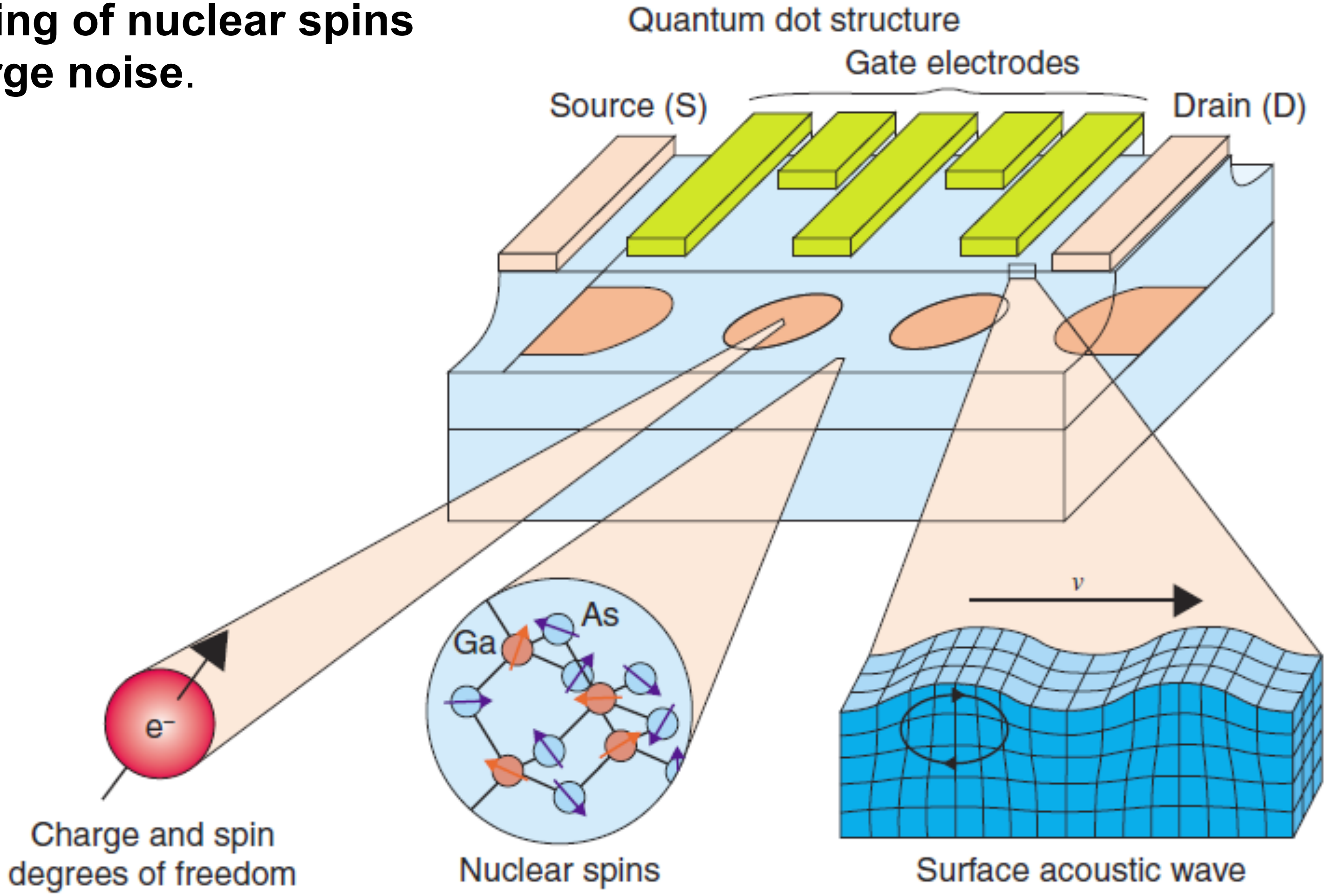


- Coherent oscillations of 1 electron **between two quantum dots**:
  - start with 1 electron on left dot
  - reduce tunnel barrier between dots during time t_p



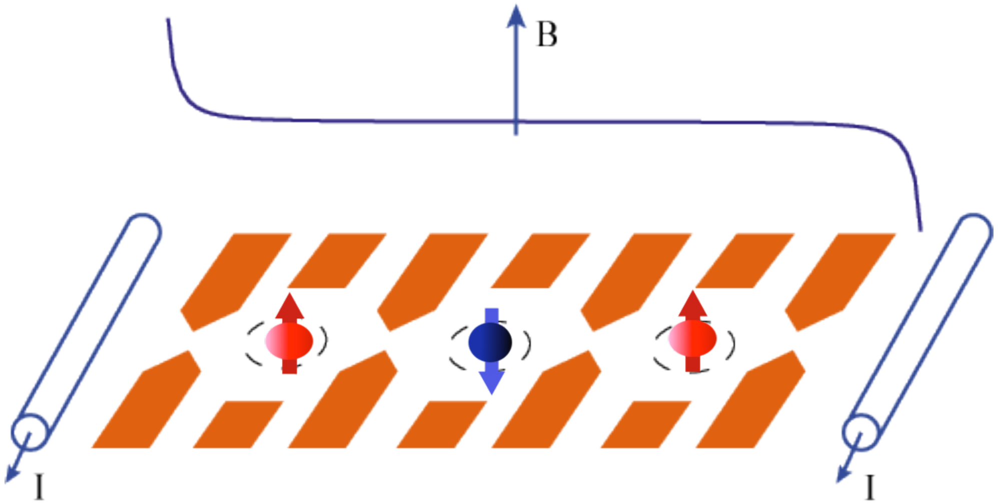
Decoherence in Quantum Dots

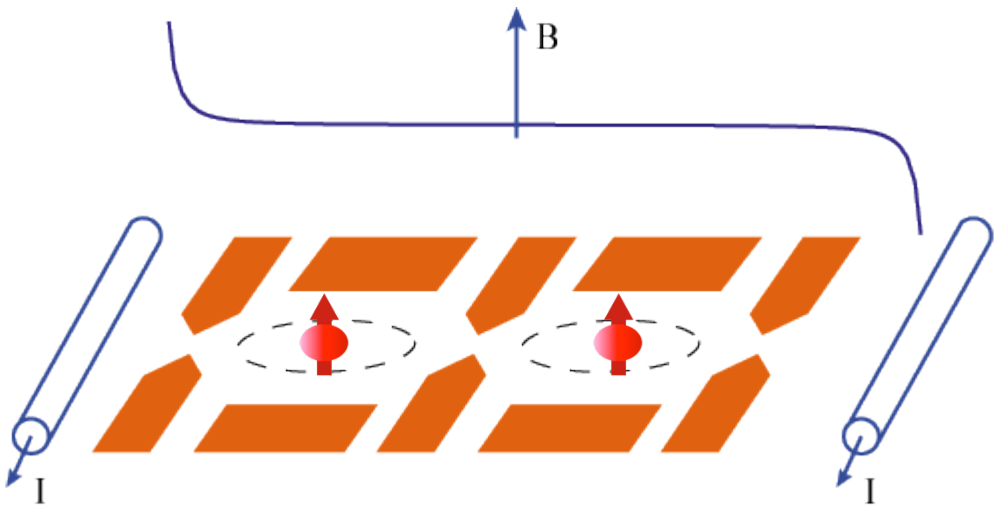
- most severe sources of decoherence are **flipping of nuclear spins** and **charge noise**.



Spin-Cluster Quantum Dots

F. Meier, J. Levy, and D. Loss, Phys. Rev. Lett. 90, 047901 (2003)





- **Problem**:

  strong field gradients are required to assure **separated resonance frequencies** in neighboring dots

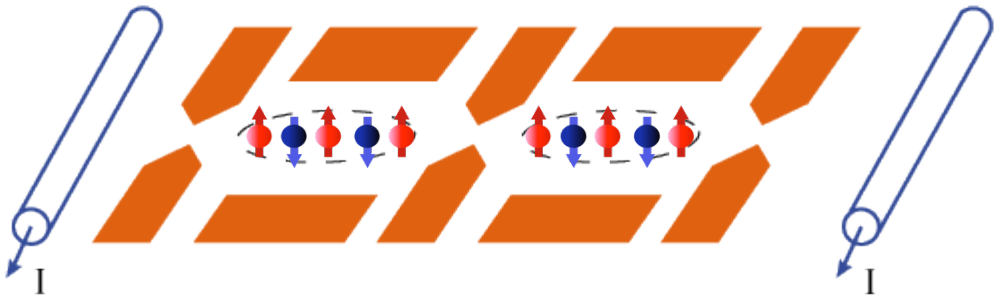
- **Solution:**

  make dots bigger

  ➭ **new problem:**
  interaction with neighboring spins becomes weaker

Spin-Cluster Quantum Dots

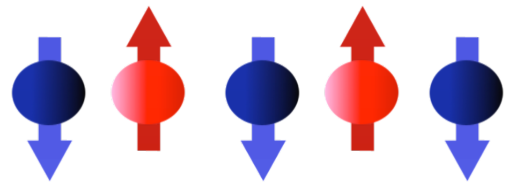
F. Meier, J. Levy, and D. Loss, Phys. Rev. Lett. 90, 047901 (2003)



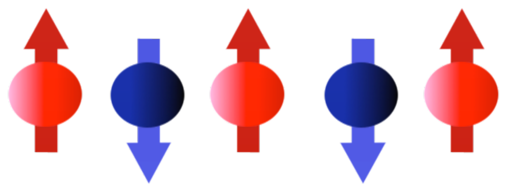
- **Problem:**
  interaction with neighboring spins becomes weaker

  - **Solution:**
    put more spins into each dot:
    Spin Cluster States

- **Odd** number of spins N
  Example: N = 5, qubit states:



$|0\rangle$



$|1\rangle$

- In general, states have no simple representation in single-spin product basis:

$$|0\rangle = \frac{2}{\sqrt{6}}|\uparrow_1\rangle|\downarrow_2\rangle|\uparrow_3\rangle - \frac{1}{\sqrt{6}}|\uparrow_1\rangle|\uparrow_2\rangle|\downarrow_3\rangle - \frac{1}{\sqrt{6}}|\downarrow_1\rangle|\uparrow_2\rangle|\uparrow_3\rangle$$

- Qubit basis **is protected** from higher lying states by gap $\sim J\pi^2 / 2N$

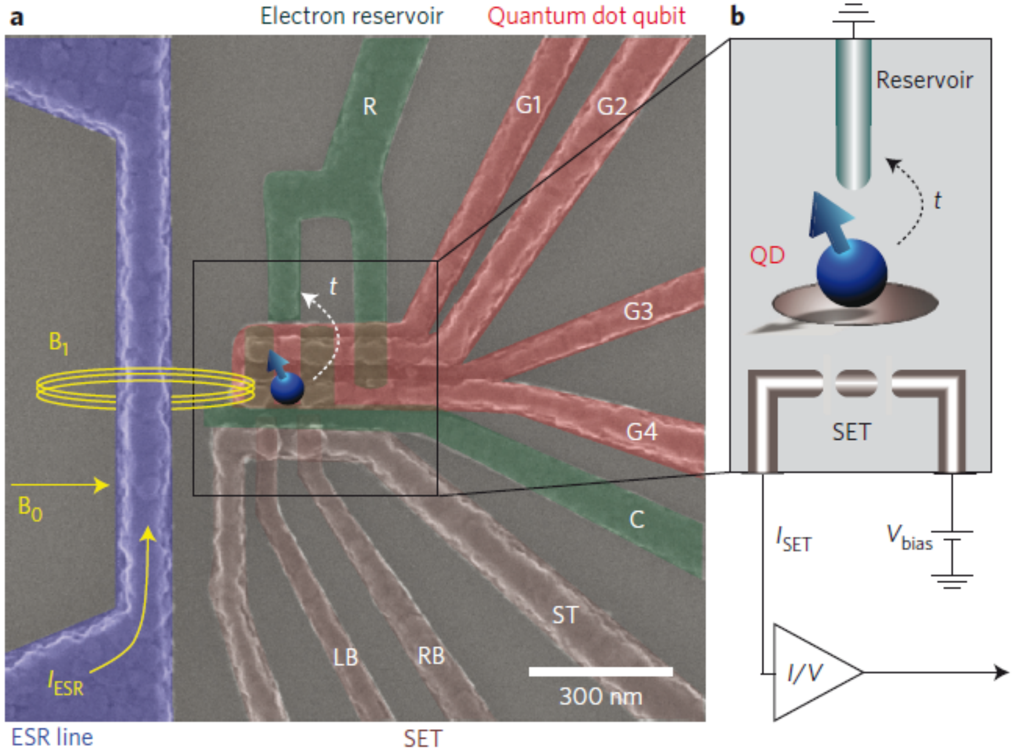
- Coupling to neighboring dots mostly mediated by spins **at the end of the chain**

State-of-the-art:

Long coherence times by using spin-free Silicon

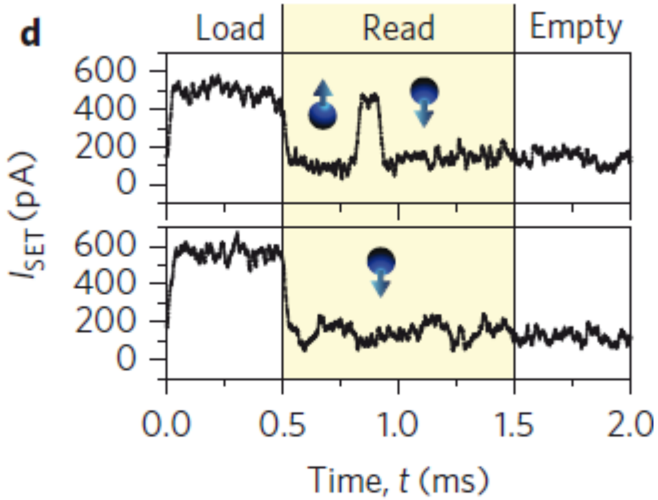
Karlsruhe Institute of Technology

- **Problem:** strong dephasing from nuclear spin bath: T_2<1 μs in GaAs/AlGaAs and Si/SiGe quantum dots
- Create Si/SiGe dots using isotopically pure ^{28}Si: T_2 = 120 μs, **T_2^* = 28 ms** (with refocussing)

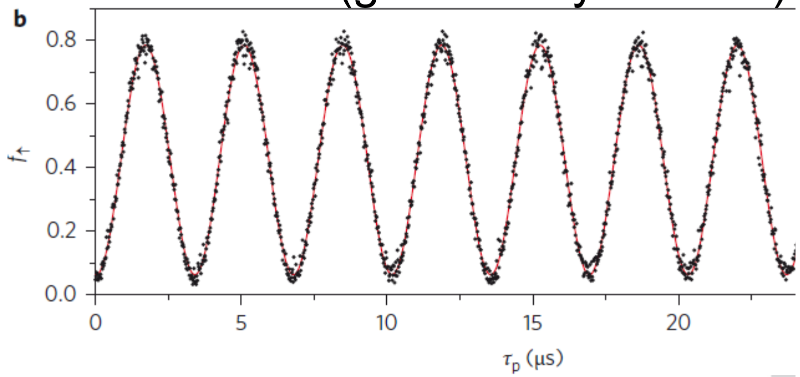


M. Veldhorst et al., Nature Nanotech. 216 (2014)

SET readout

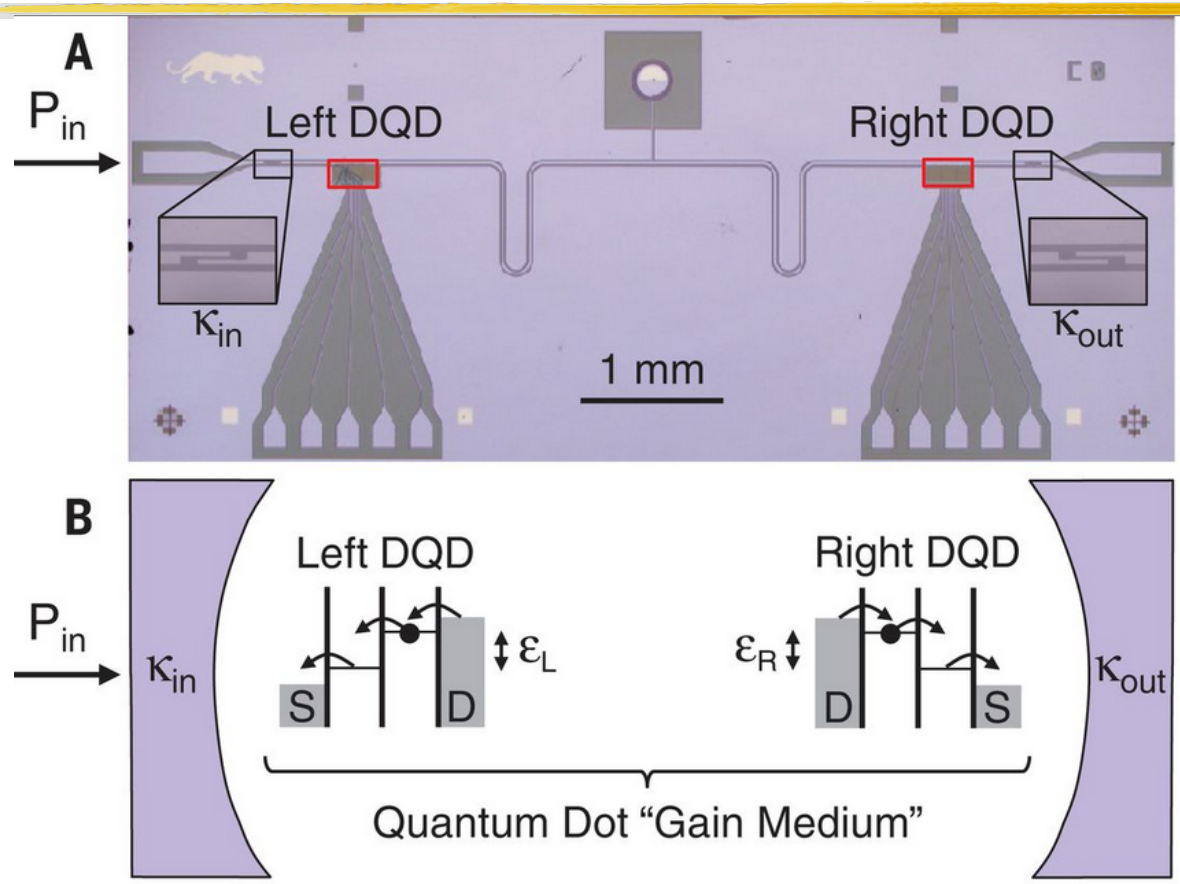


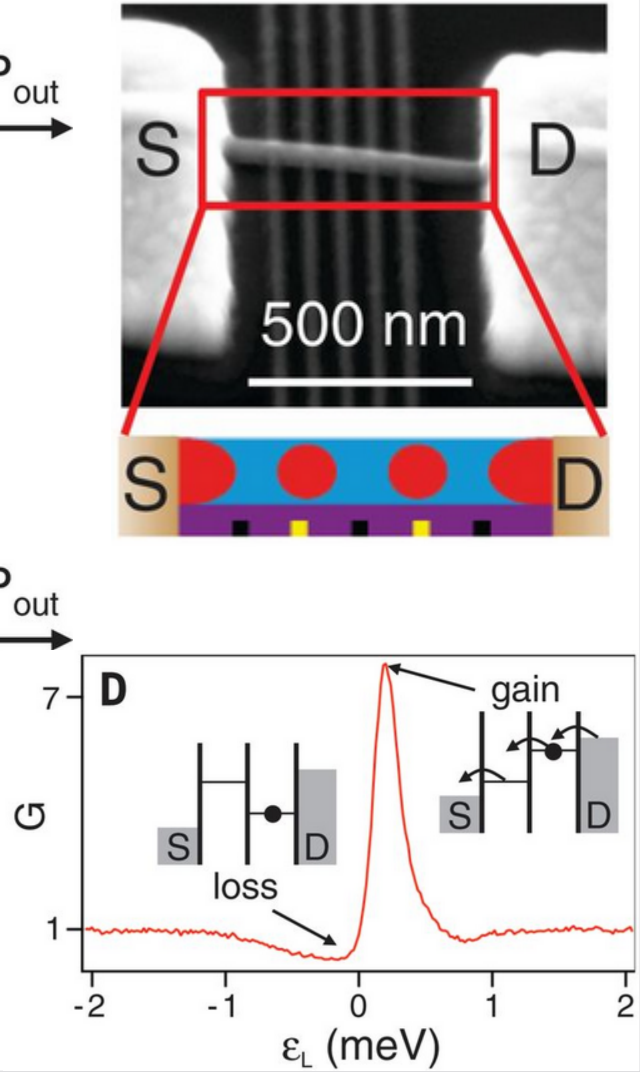
Rabi oscillation (gate fidelity 99.59%)



State-of-the-art:

Semiconductor double quantum dot micromaser

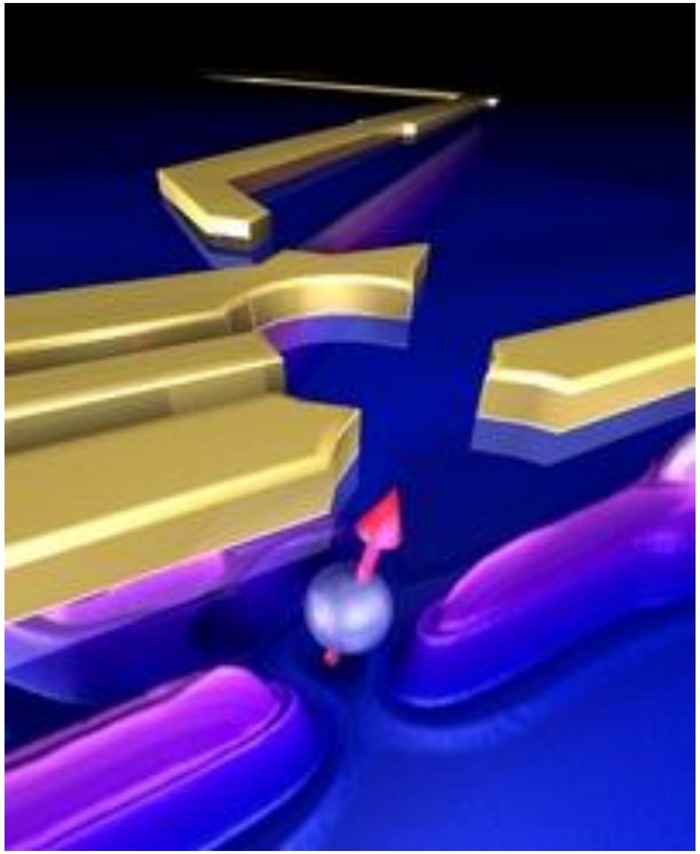




Y.-Y. Liu, J.R. Petta et al., Science 16, 347 (2015)

Quantum Dots : Summary

- **Pros**:
  - fabrication using **standard technologies** (but requiring isotopically clean materials)
  - **scalable** architecture
  - **electrical** control and readout
  - **long** energy relaxation time (~ ms)
  - **high-fidelity single-qubit gates**
- **Cons**:
  - short **dephasing** times (< 1 μs for conventional materials)
  - **charge noise** (switching)
- **One still needs to demonstrate:**
  - high-fidelity two-qubit gates
  - experiments with 3 or more qubits
  - execution of few-qubit algorithms
- **Outlook**: self-assembled dot structures (nanotubes, graphene..) may suffer less from dephasing



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- T. Fujisawa, Quantum Information Devices Using Semiconductor Quantum Dots, NTT Technical Review, Vol. 6, No. 1 (2008)

Quantum Point Contacts

- H. van Houten and C.W.J. Beenakker, *Quantum point contacts, Physics Today* **49** (7): 22–27 (1996)