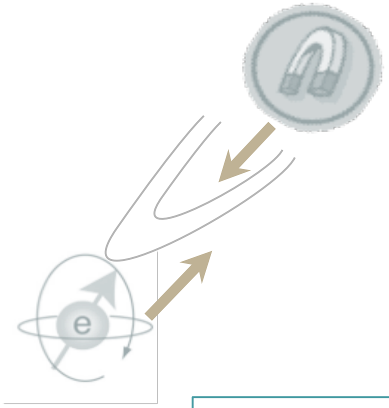
半導体中単一電子スピンの測定
Single spin detection in semiconductors

都倉 康弘

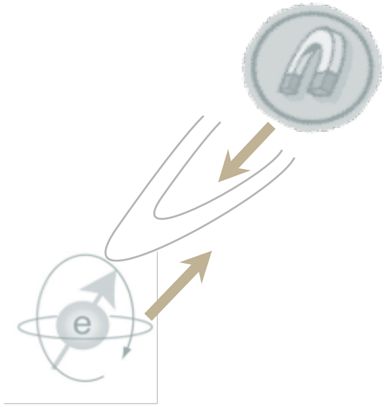
物理学セミナー 2012 10/24

このプレゼンテーション資料は、以下からアクセスできます:
http://www.u.tsukuba.ac.jp/~tokura.yasuhiro.ft/Lectures/PS7.pdf



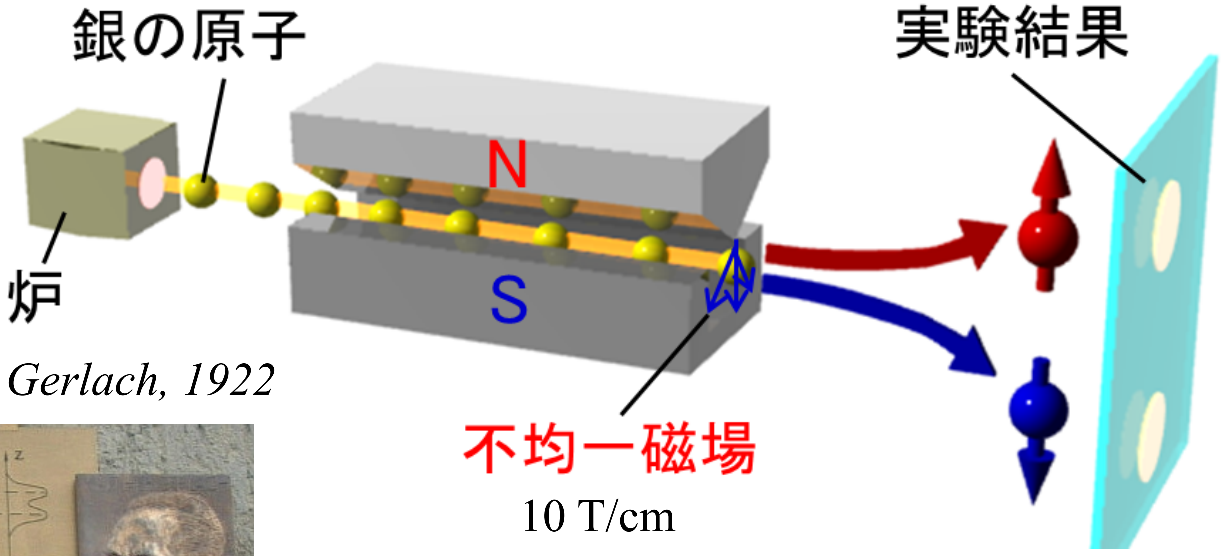
Plan of the seminar

1. Semiconductor quantum dots, quantum point contacts
2. Charge detection – which path detector
3. Spin detection - Spin to charge conversion
4. Current status of research of spin qubits
5. Prospects

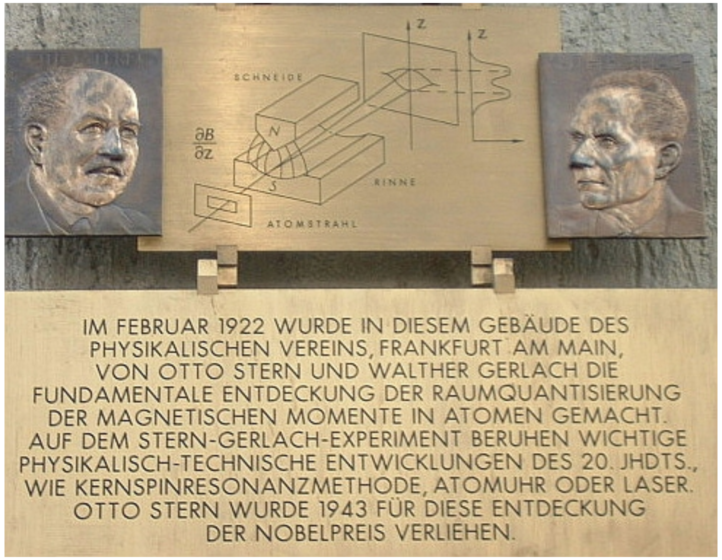


Electron spins

Spin: purely quantum mechanical object,
formulated by W. Pauli (1927) and P. Dirac (1928)



Otto Stern and Walther Gerlach, 1922



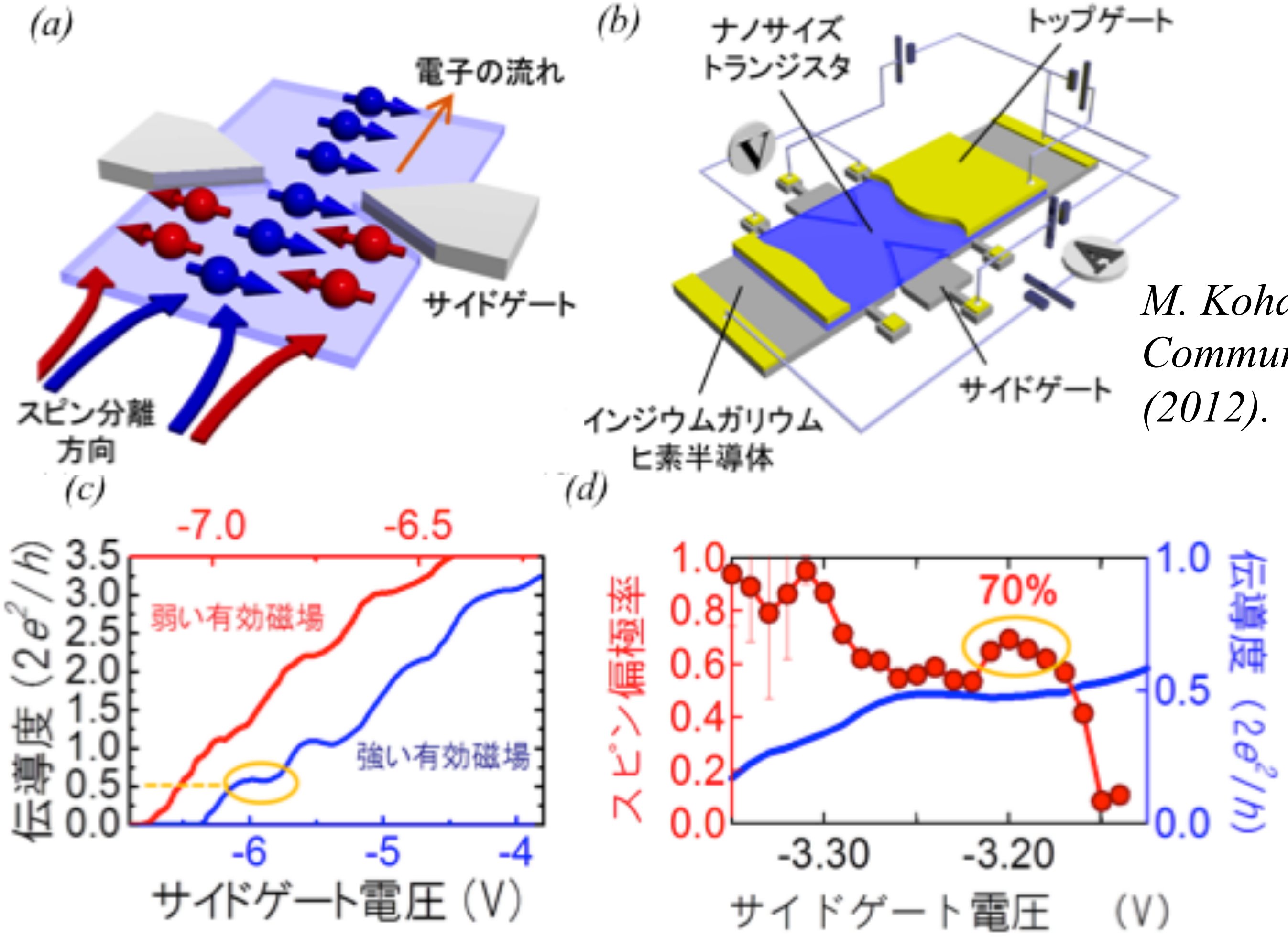
IM FEBRUAR 1922 WURDE IN DIESEM GEBÄUDE DES
PHYSIKALISCHEN VEREINS, FRANKFURT AM MAIN,
VON OTTO STERN UND WALTHER GERLACH DIE
FUNDAMENTALE ENTDECKUNG DER RAUMQUANTISIERUNG
DER MAGNETISCHEN MOMENTE IN ATOMEN GEMACHT.
AUF DEM STERN-GERLACH-EXPERIMENT BERUHEN WICHTIGE
PHYSIKALISCH-TECHNISCHE ENTWICKLUNGEN DES 20. JHDTS.,
WIE KERNSPINRESONANZMETHODE, ATOMUHR ODER LASER.
OTTO STERN WURDE 1943 FÜR DIESE ENTDECKUNG
DER NOBELPREIS VERLIEHEN.

「スピンはめぐる」 中央公論社　朝永振一郎

B. Friedrich and D. Herschbach, Phys. Today 56, 53 (2003).

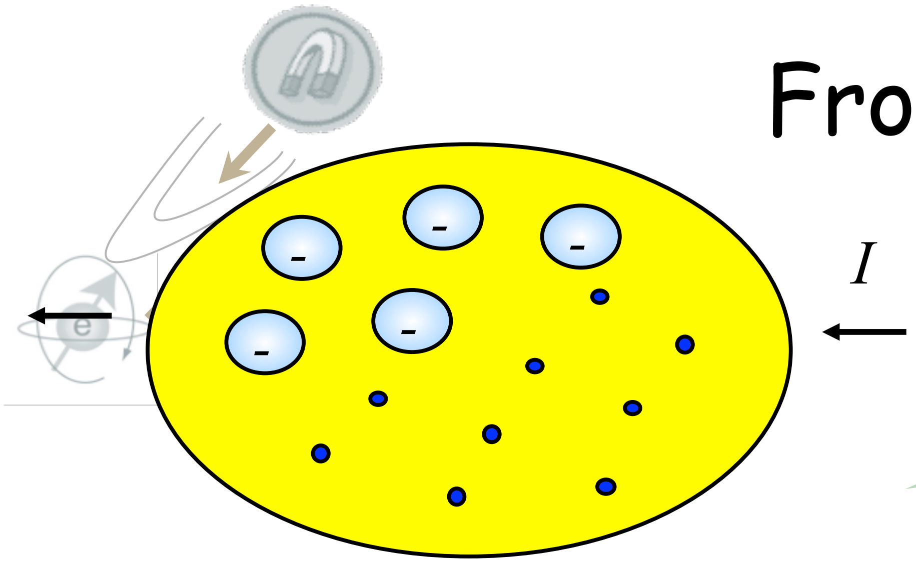
Stern-Gerlach exp. in semicond.

Spin-orbit effect provides an effective magnetic field to the spins.



M. Kohda, et al., Nature Communications 3, 1082 (2012).

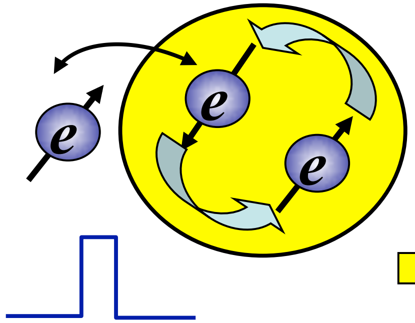
From macro to nano



Macroscopic system

\+

Ensemble measurement



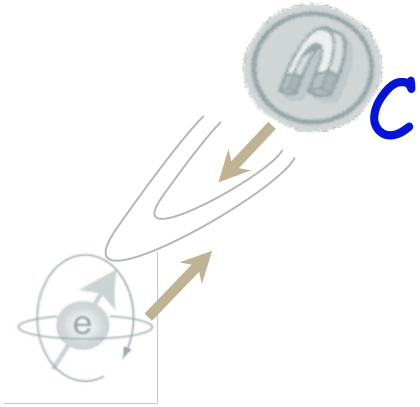
System of just one or two electrons

\+

Single shot measurement

Control over microscopic nature of energy quanta, correlation

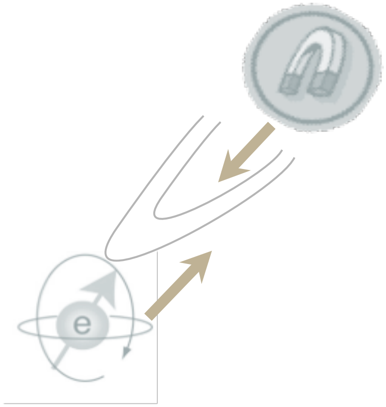
Also, a challenge to quantum information



Criteria of realizing quantum computers

D. P. DiVincenzo Fortschr. Phys. (2000).

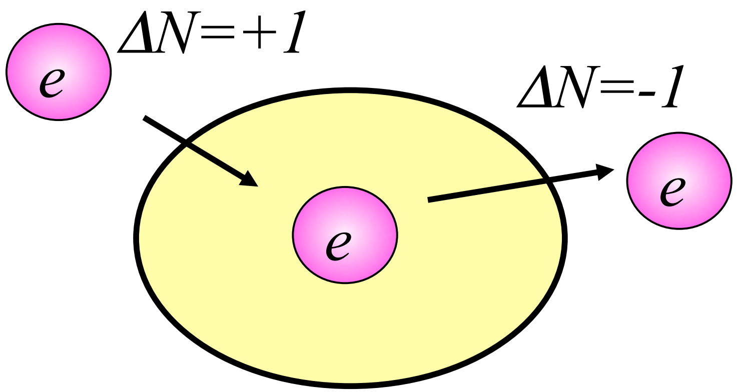
1. *A scalable physical system with well characterized qubits*
   (スケーラビリティ）
2. *The ability to initialize the state of the qubits to a simple fiducial state*
   （初期化）
3. *Long relevant decoherence times, much longer than the gate operation time*
   （良いコヒーレンス）
4. *A "universal" set of quantum gates* *（量子演算）*
5. *A qubit-specific measurement capability* *（読み出し）*



Objective

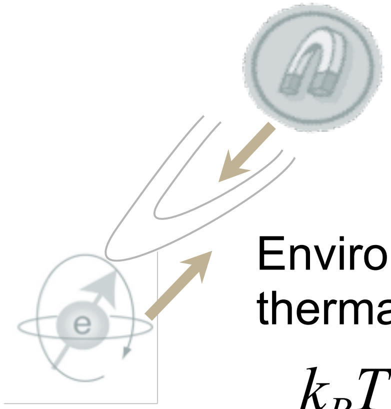
Current-sensitive measurement

$$\boldsymbol{I}=\boldsymbol{e}f_{tunnel\text{-}rate}$$



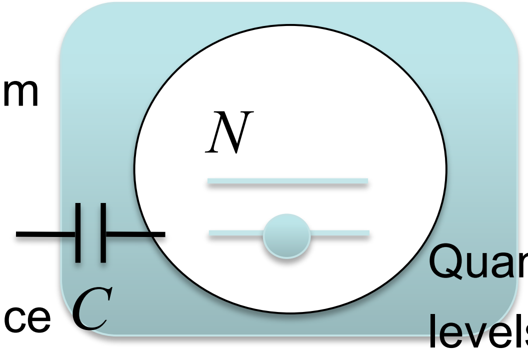
How to measure single “charge” and “spin” in real time ?

Quantum dots (QDs)



Environment in thermal equilibrium

$k_B T \quad \mu$



Total capacitance C

Quantized levels ε_i

Tunnel barrier

Total energy of *N* electrons

$$E(N) \sim \sum_{i=1}^{N} \varepsilon_i + {}_N C_2 U$$

Constant interaction model:

$$U \equiv \frac{e^2}{2C}$$

Stability condition of N electrons in the QD:

No addition $\quad \mu + \frac{1}{2} k_B T \ll E(N+1) - E(N) \quad \sim UN + \varepsilon_{N+1}$

No escape $\quad \mu - \frac{1}{2} k_B T \gg E(N) - E(N-1) \quad \sim U(N-1) + \varepsilon_N$

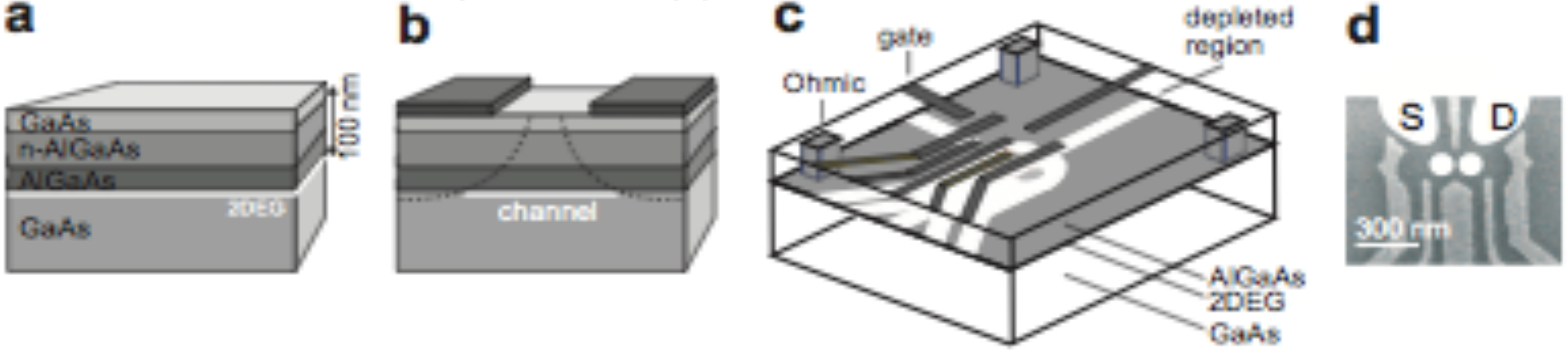
$$\boxed{U + \varepsilon_{N+1} - \varepsilon_N} \gg k_B T$$

Addition energy

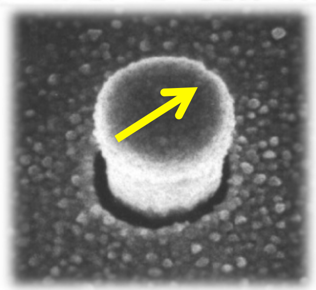
Coulomb blockade for
very low temperatures,
small capacitance,
large quantization energy

QD devices

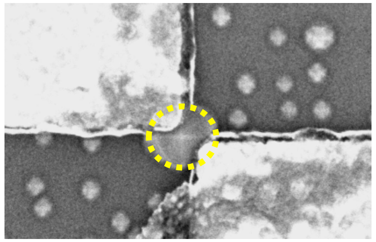
Top-down approach



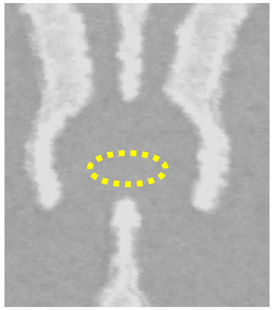
Advent of one-electron single QDs



Tarucha et al. PRL 96

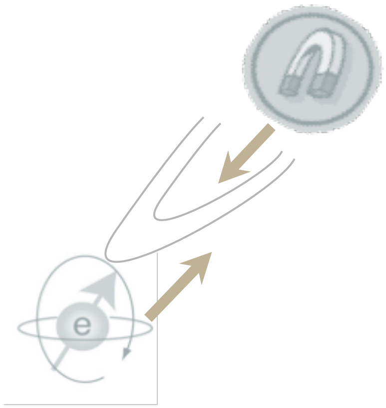


Jung et al. APL05

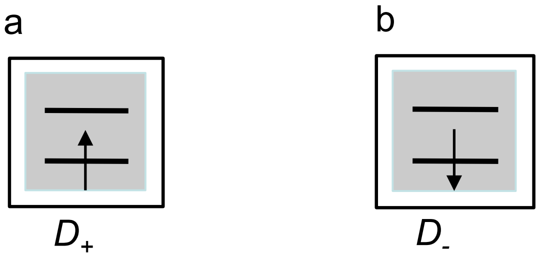


Ciorga et al. PRB 02

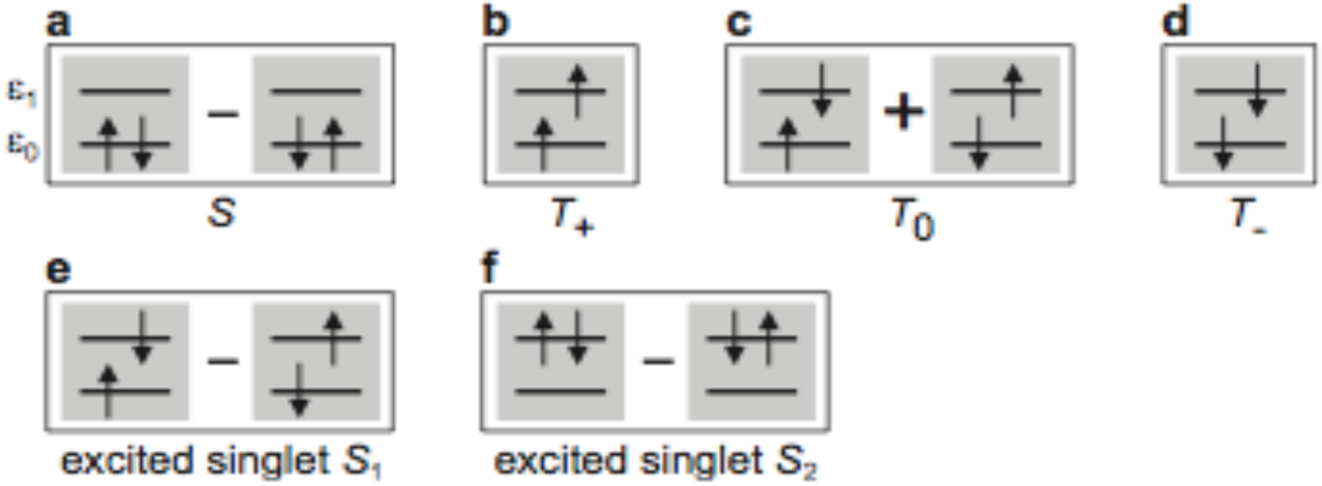
Spins in a QD



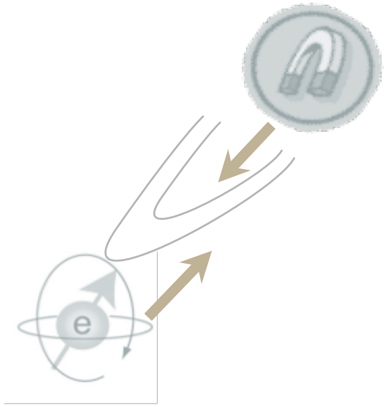
N=1



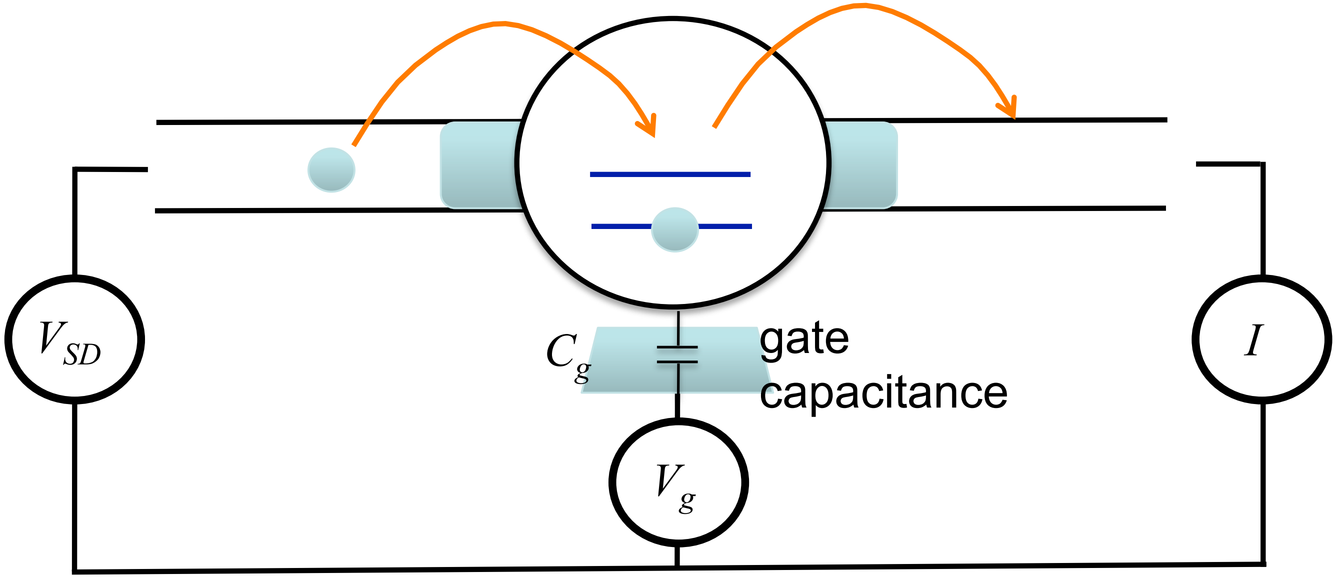
N=2



Simple… But, how can we probe these ?

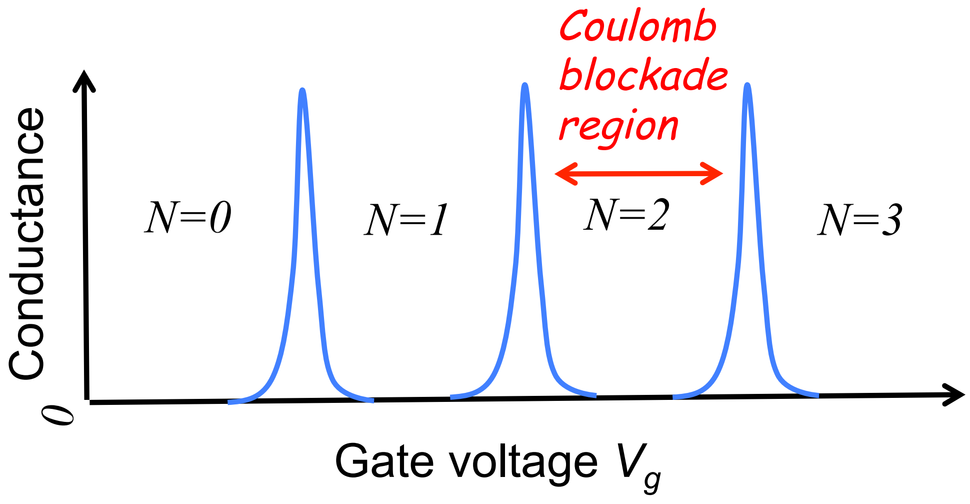


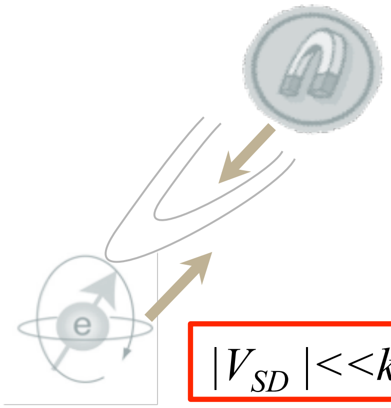
QDs coupled to the leads



Conductance $G=I/V_{SD}$ is peaked when ($|V_{SD}| << k_BT$)

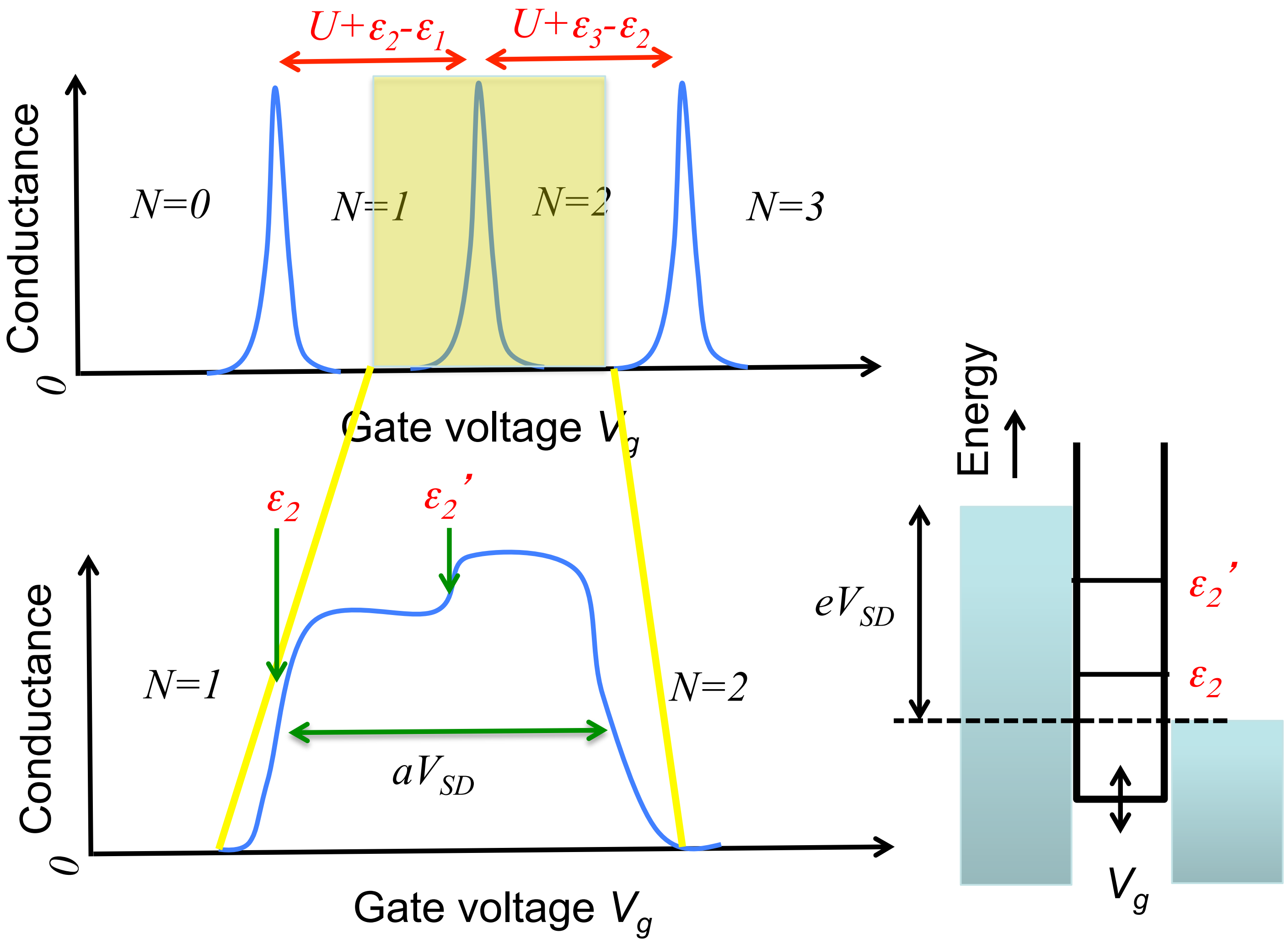
$$\begin{aligned} \mu &= E(N) - E(N-1) \\ &\approx U(N-1) + \varepsilon_N - \frac{C_g}{C} eV_g \end{aligned}$$





Tunneling spectroscopy

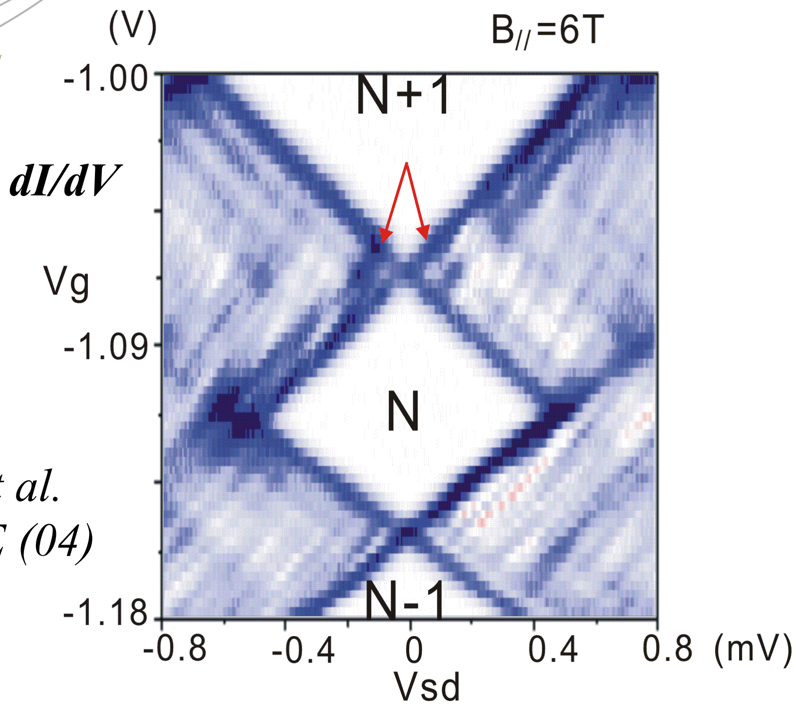
$|V_{SD}| << k_B T$



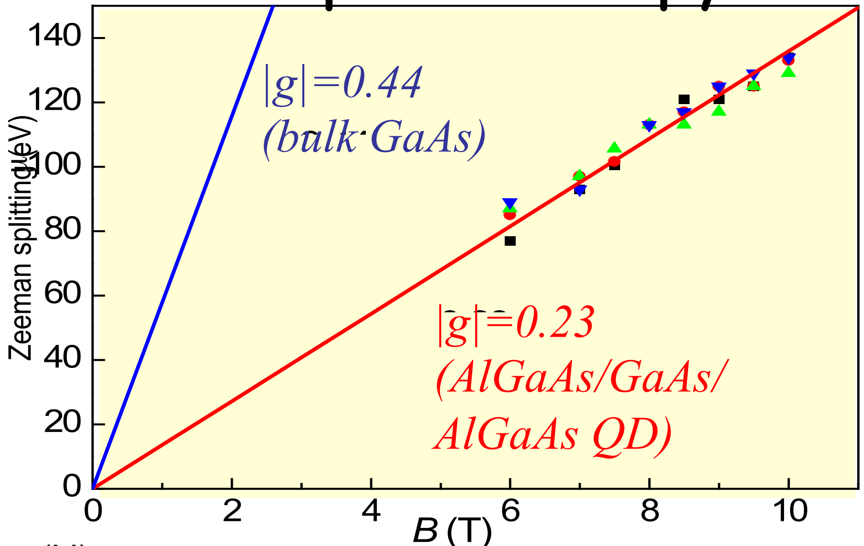
$|V_{SD}| >> k_B T$

*a: lever-arm factor

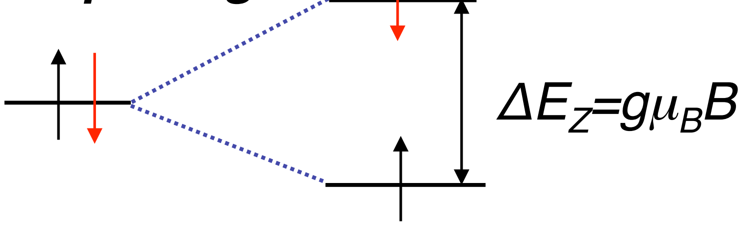
g-factor in QD: Excitation spectroscopy



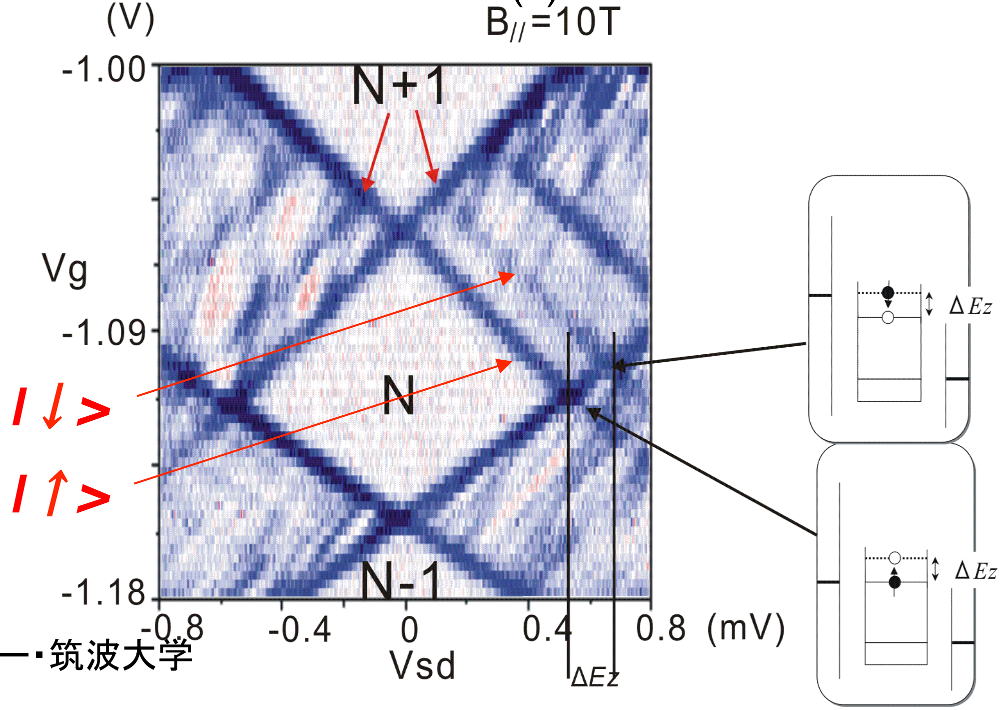
Kodera et al.
Physica E (04)

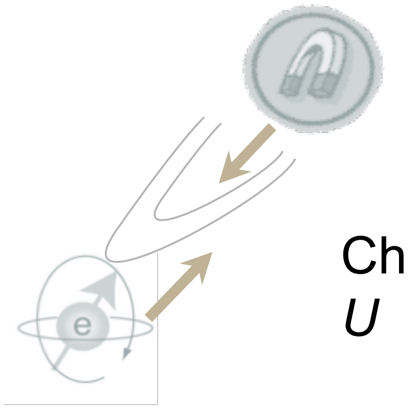


Zeeman splitting

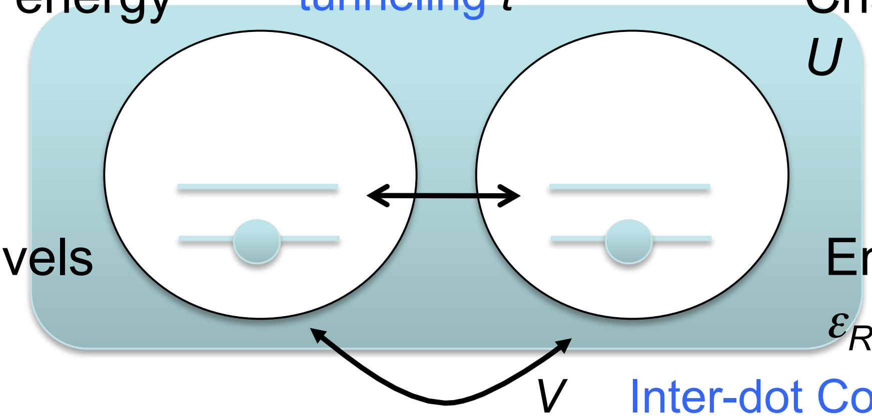


$\Delta E_Z = g\mu_B B$





Coupled quantum dots



Charging energy U

Quantum mechanical tunneling t

Charging energy U

Energy levels ε_{Li}

Energy levels ε_{Ri}

V Inter-dot Coulomb interaction

Minimum realization of Hubbard model:

$$\mathcal{H}_{DQD} = \sum_{\mu=L,R}\sum_{\sigma}\varepsilon_{\mu}\hat{a}^{\dagger}_{\mu,\sigma}\hat{a}_{\mu,\sigma} - t(\hat{a}^{\dagger}_{L,\sigma}\hat{a}_{R,\sigma} + \mathrm{H.c.})$$

$$+U\sum_{\mu=L,R}\hat{n}_{\mu,\uparrow}\hat{n}_{\mu,\downarrow} + V\hat{n}_{L}\hat{n}_{R}$$

$$\hat{n}_{\mu,\sigma} \equiv \hat{a}^{\dagger}_{\mu,\sigma}\hat{n}_{\mu,\sigma}$$

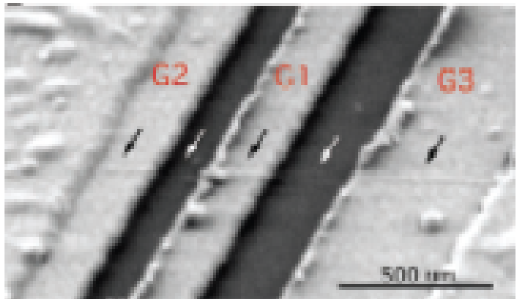
$$\hat{n}_{\mu} \equiv \sum_{\sigma}\hat{n}_{\mu,\sigma}$$

Double QDs holding few electrons

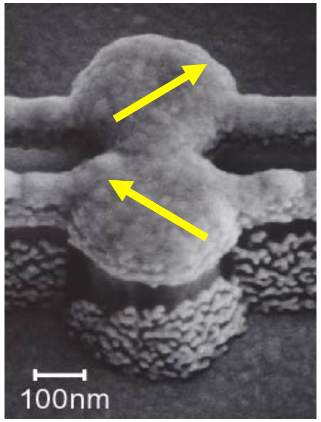
Fabrication of two QDs is straightforward extension in top-down approach, but realizing tunable coupling between the two QDs and going into few electron regime is not a simple task.

Advent of two-electron double QDs

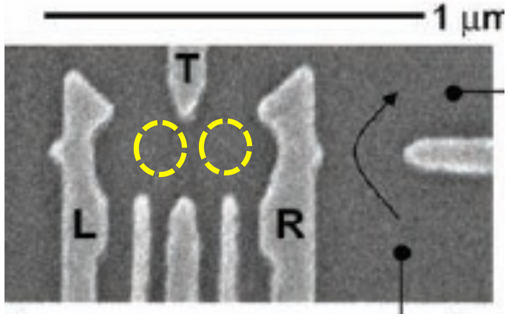
nanotube



Mason et al. Science 04



Hatano et al. Science 05



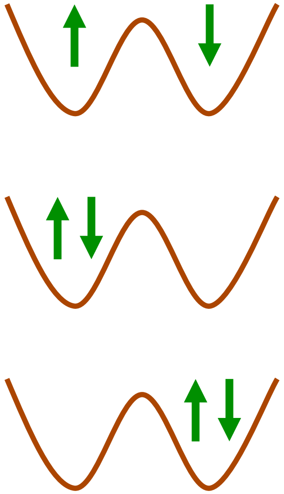
Petta et al. Science 04

Two electron basis functions

There are six two electron basis functions.

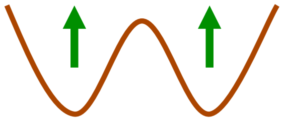
$$\begin{aligned}
|S(1,1)\rangle &= \frac{1}{\sqrt{2}}(a^\dagger_{L\uparrow}a^\dagger_{R\downarrow} - a^\dagger_{L\downarrow}a^\dagger_{R\uparrow}|0\rangle, \\
|S(2,0)\rangle &= a^\dagger_{L\uparrow}a^\dagger_{L\downarrow}|0\rangle, \\
|S(0,2)\rangle &= a^\dagger_{R\uparrow}a^\dagger_{R\downarrow}|0\rangle
\end{aligned}$$

Spin singlets



$$\begin{aligned}
|T^1\rangle &= a^\dagger_{L\uparrow}a^\dagger_{R\uparrow}|0\rangle, \\
|T^0\rangle &= \frac{1}{\sqrt{2}}(a^\dagger_{L\uparrow}a^\dagger_{R\downarrow} + a^\dagger_{L\downarrow}a^\dagger_{R\uparrow})|0\rangle, \\
|T^{-1}\rangle &= a^\dagger_{L\downarrow}a^\dagger_{R\downarrow}|0\rangle
\end{aligned}$$

Spin triplets



Eigen energies

Spin singlet Hamiltonian for basis *(|S(1,1)>, |S(2,0)>, |S(0,2)>).*

$$\mathcal{H}_S = \begin{pmatrix} 0 & \sqrt{2}t & \sqrt{2}t \\ \sqrt{2}t & U - V + \varepsilon & 0 \\ \sqrt{2}t & 0 & U - V - \varepsilon \end{pmatrix}$$

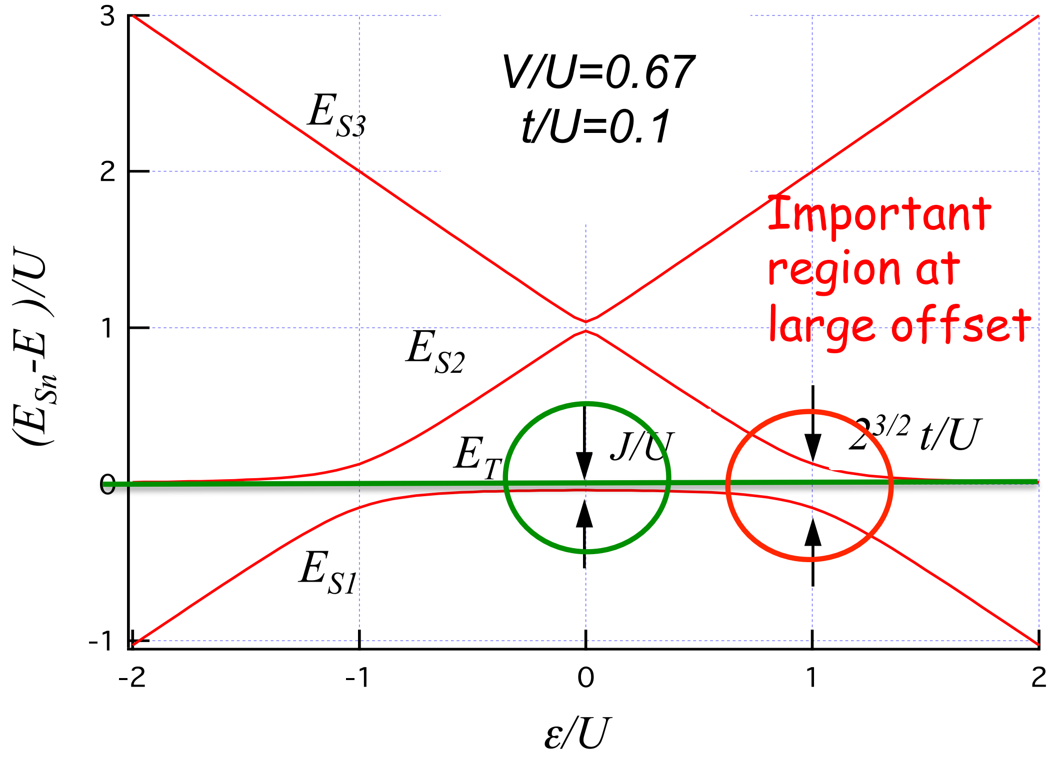
Triplet energy

$$E_T = V$$

Exchange energy J is defined by E_T-E_S

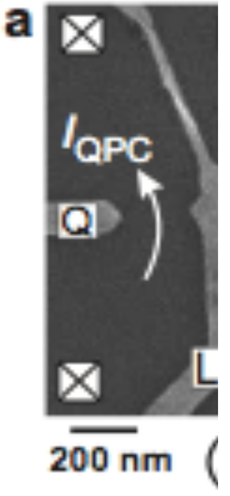
$$J \sim \frac{4t^2}{U}$$

for $|\varepsilon| << U\text{-}V$

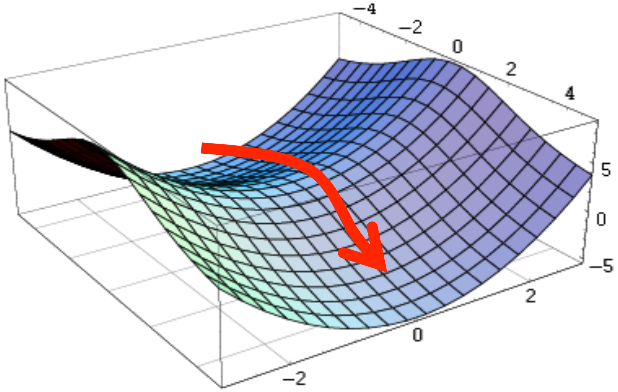


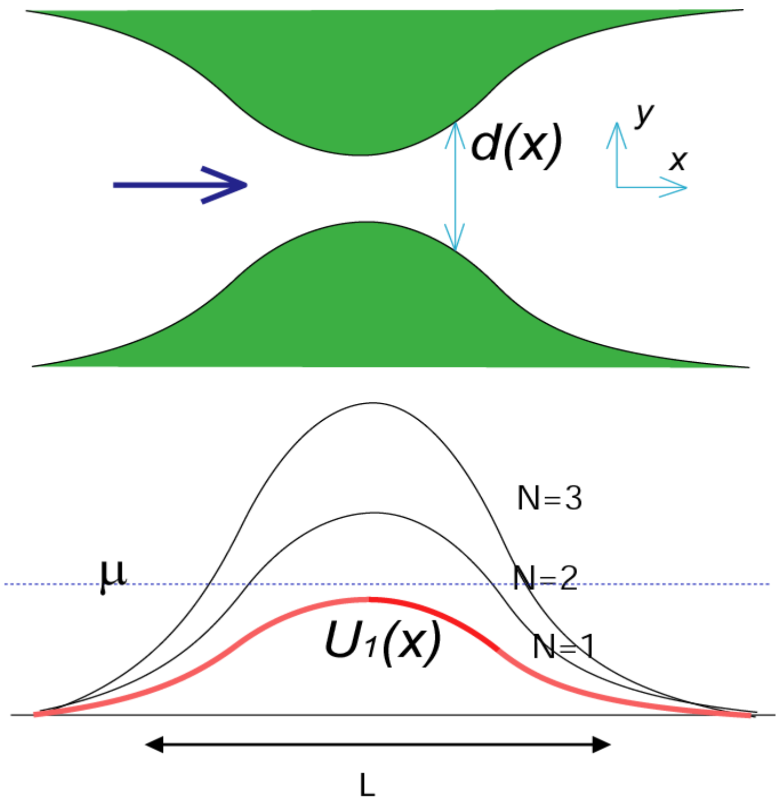
Quantum point contact (QPC)

Quantum point contact (QPC) is a vary short and narrow constriction.

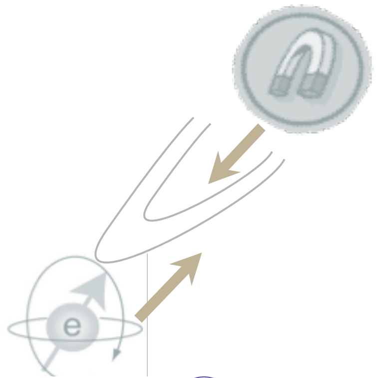


Landscape near QPC is the saddle point potential.

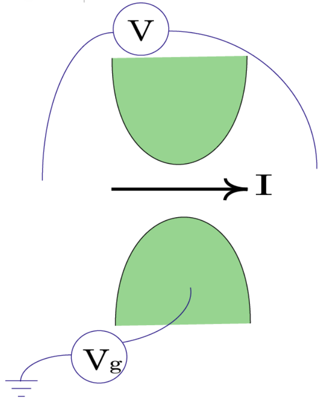


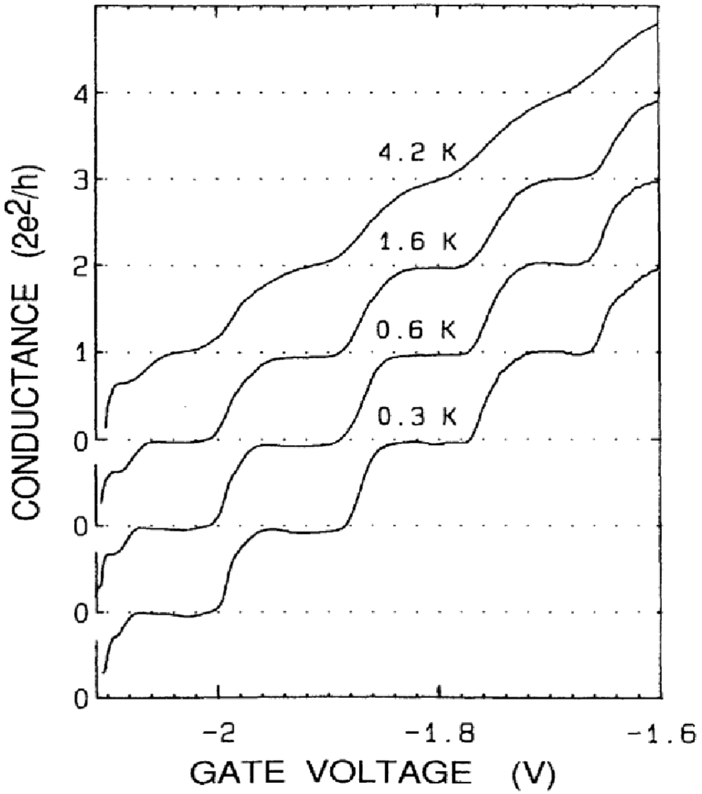


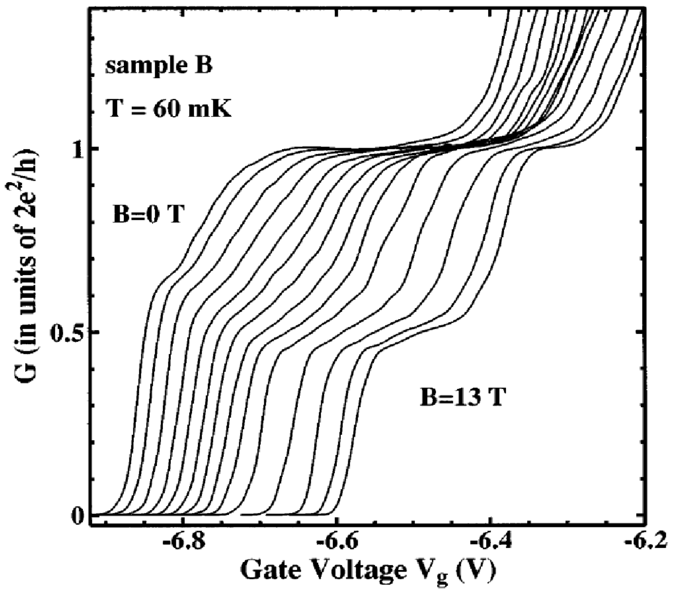
都倉康弘、固体物理 37 (2002) 363.



Conductance quantization



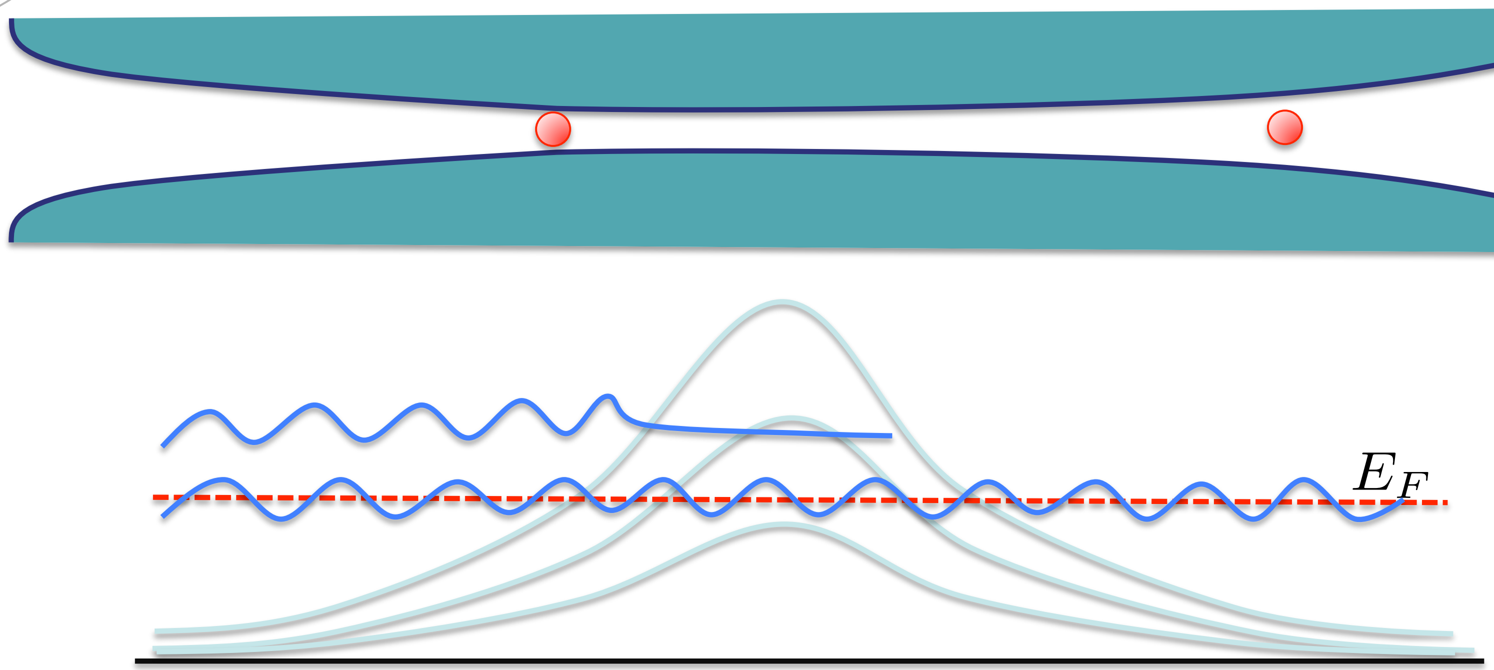




B.J.van Wees, et al, Phys. Rev. ***B 43****, 12431 (1991).*

K.J.Thomas, et al, Phys. Rev. Lett. 77, 135 (1996).

Adiabatic transport - no channel mixing



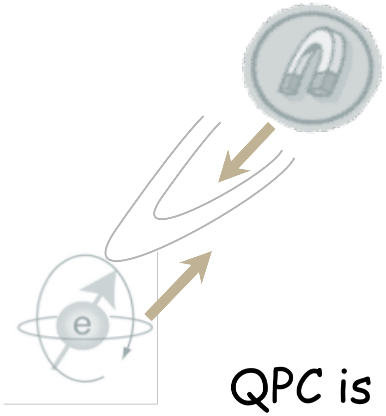
Conductance
Landauer's
formula

$$G = \frac{2e^2}{h}\sum_n T_n$$

Transmission probability
of mode *n* T_n

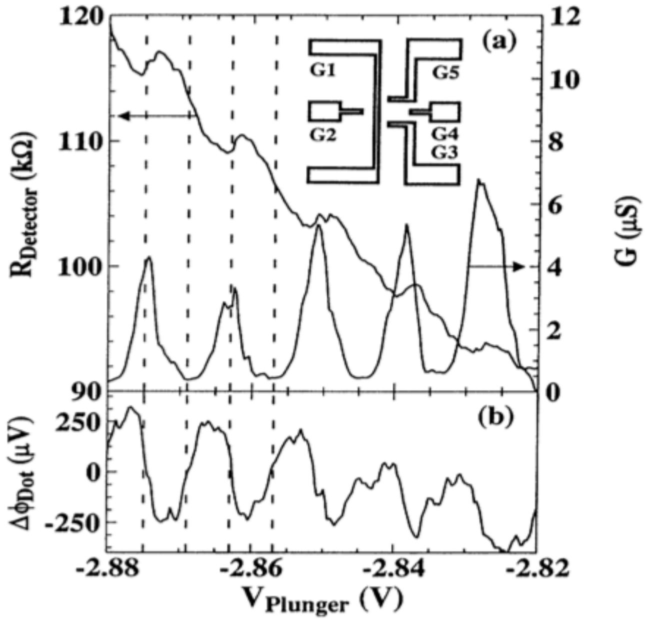
$T_n = 1$ Noiseless mode

QPC Charge detection



QPC is frequently used as a sensitive charge detector since the current changes with the potential barrier.

M. Field, et al., Phys. Rev. Lett. 70, 1311 (1993).



Necessary condition to the time required to distinguish the change of the QPC current by the change of transmission.

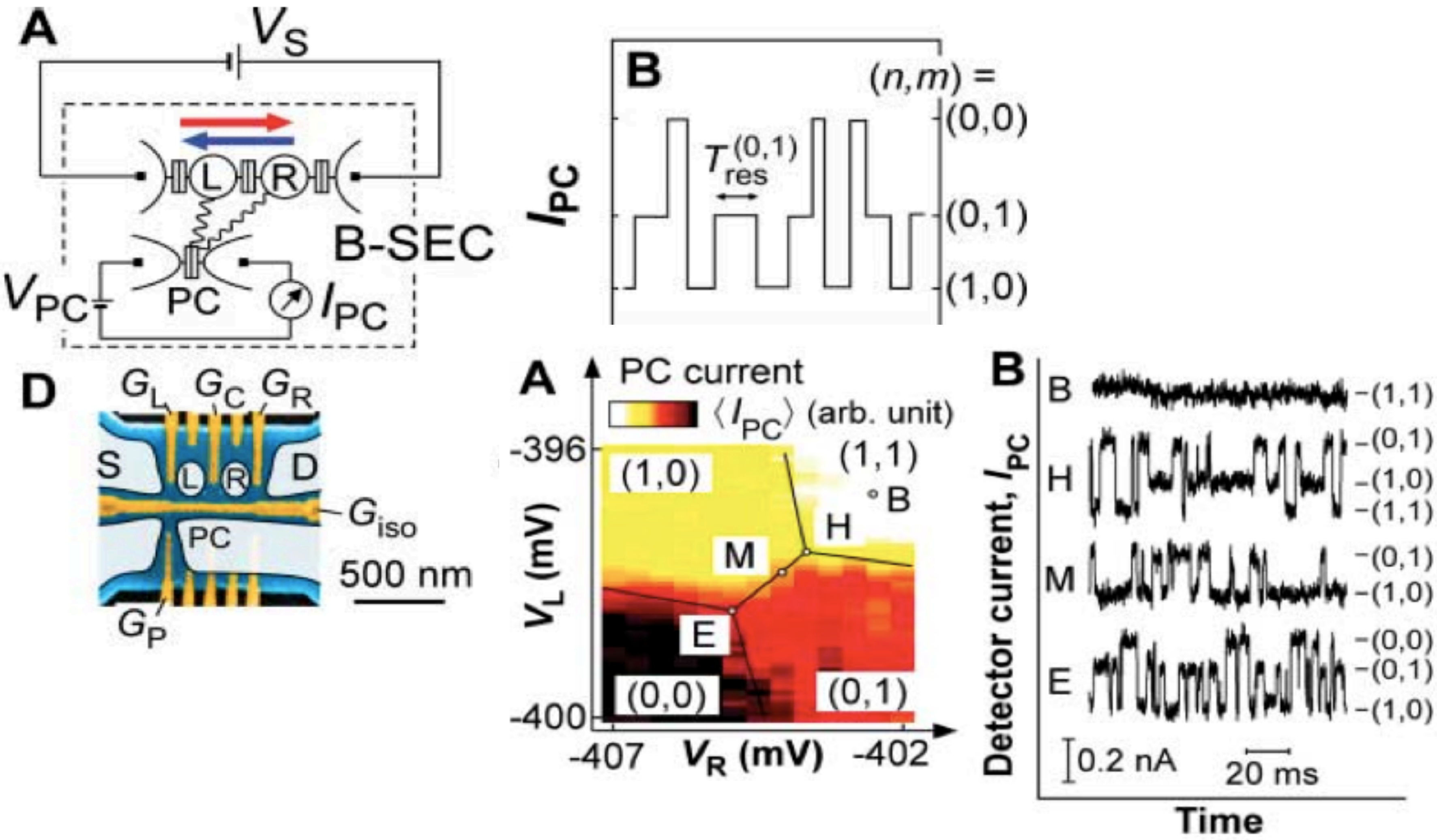
$$\boxed{t_d \frac{eV_{SD}}{\pi\hbar}\Delta\mathcal{T}} \geq \boxed{\sqrt{t_d \frac{eV_{SD}}{\pi\hbar}\mathcal{T}(1-\mathcal{T})}} \Rightarrow \frac{1}{t_d} \sim \frac{eV_{SD}}{h}\frac{(\Delta\mathcal{T})^2}{\mathcal{T}(1-\mathcal{T})}$$

Change of transferred charge

Fluctuation

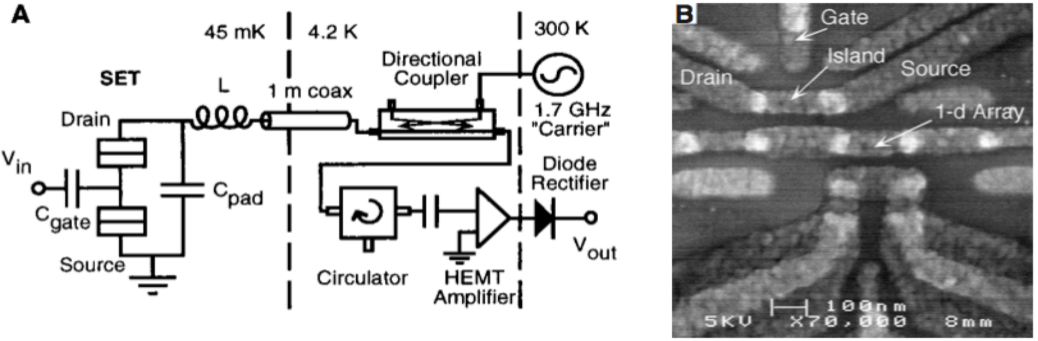
I. L. Aleiner, et al., Phys. Rev. Lett. 79, 3740 (1997).

Counting electrons

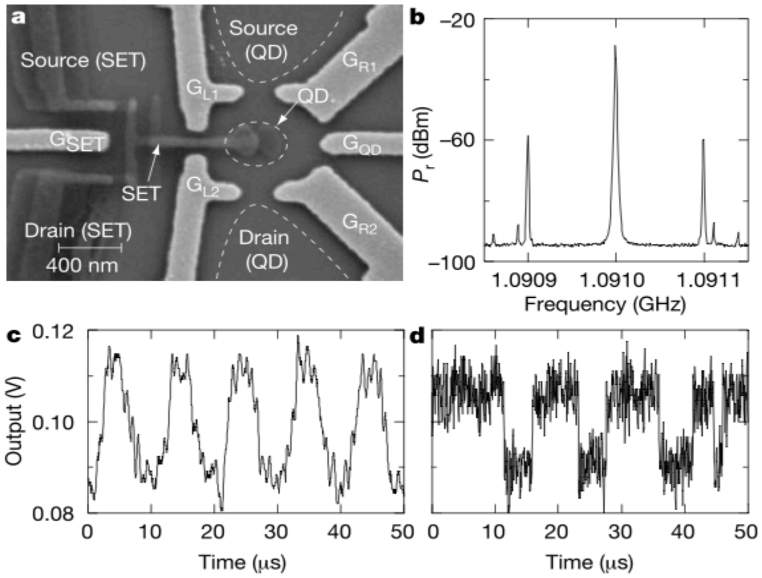


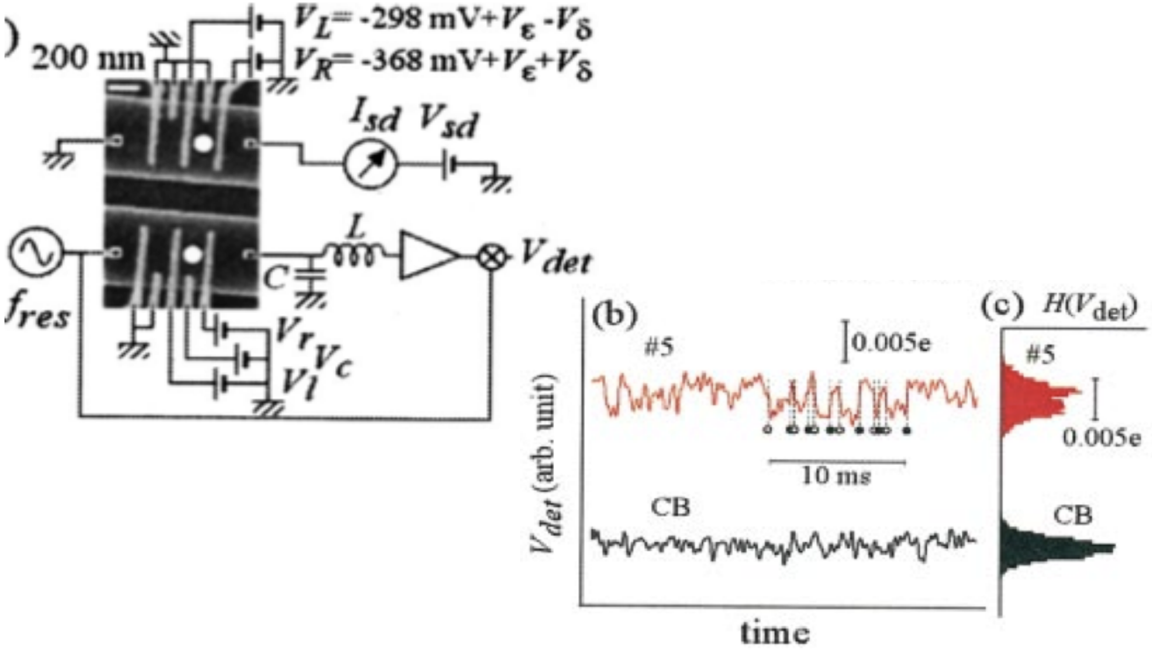
T. Fujisawa, et al., Science 312, 1634 (2006).

Radio-frequency(rf)-SET



R. J. Schoelkopf, et al., Science 280, 1238 (1998).





Wei Lu, et al., Nature 425, 422 (2003).

T. Fujisawa, et al., Appl. Phys. Lett. 84, 2343 (2003).

Single spin magnetic moment

Electron spin: tiny object

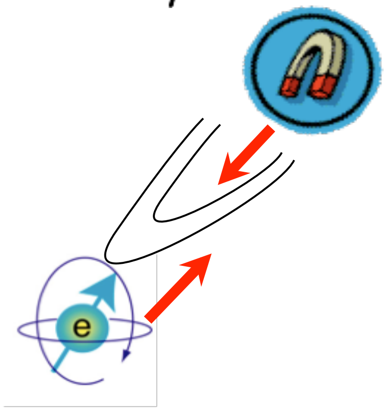
Force in a gradient field

Electron magnetic dipole moment

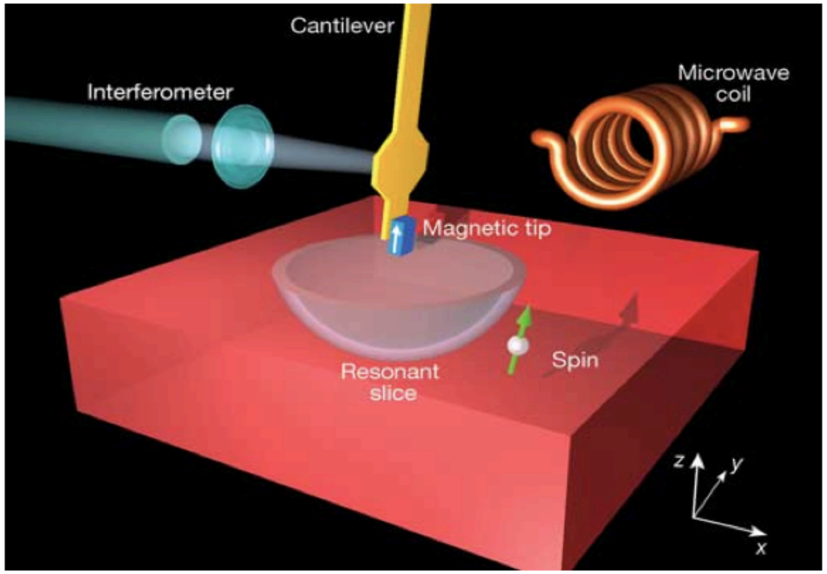
$$\begin{aligned} \mu_e &= -g\mu_B \frac{S}{\hbar} = -\frac{e\hbar}{4m_e} \\ U_z &= -\mu_e B \\ &= 2 \times 10^{-24} B(T) J \end{aligned}$$

$$\begin{aligned} F_z &= \frac{\partial U_z}{\partial r} \\ &= 2 \times 10^{-24} \frac{\partial B(T)}{\partial r} N \\ &= 2 b_{sl} (\frac{T}{\mu m}) a N \end{aligned}$$

Very weak interaction
with the environment.

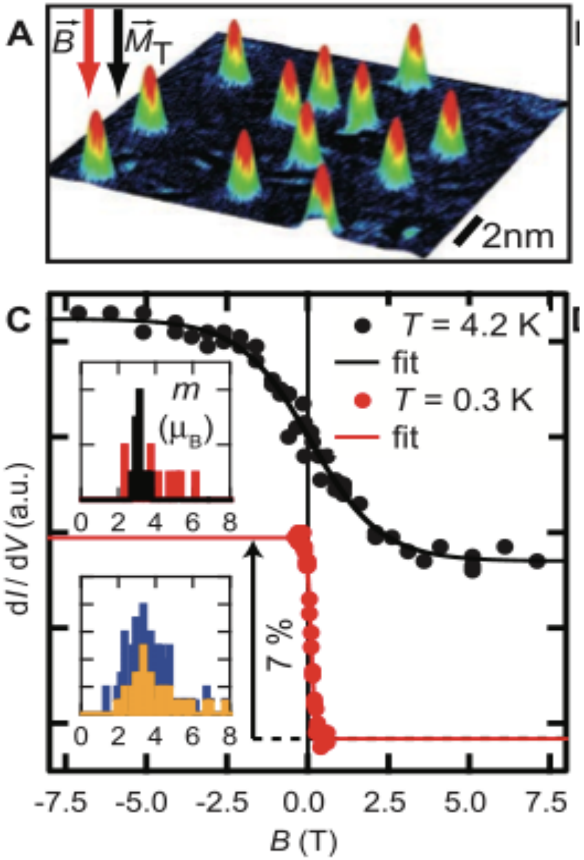


Single spin detection



Dangling bond (E' center) in silica,
Detected magnetically detected AFM

D. Rugar, et al., Nature 430, 329 (2004).

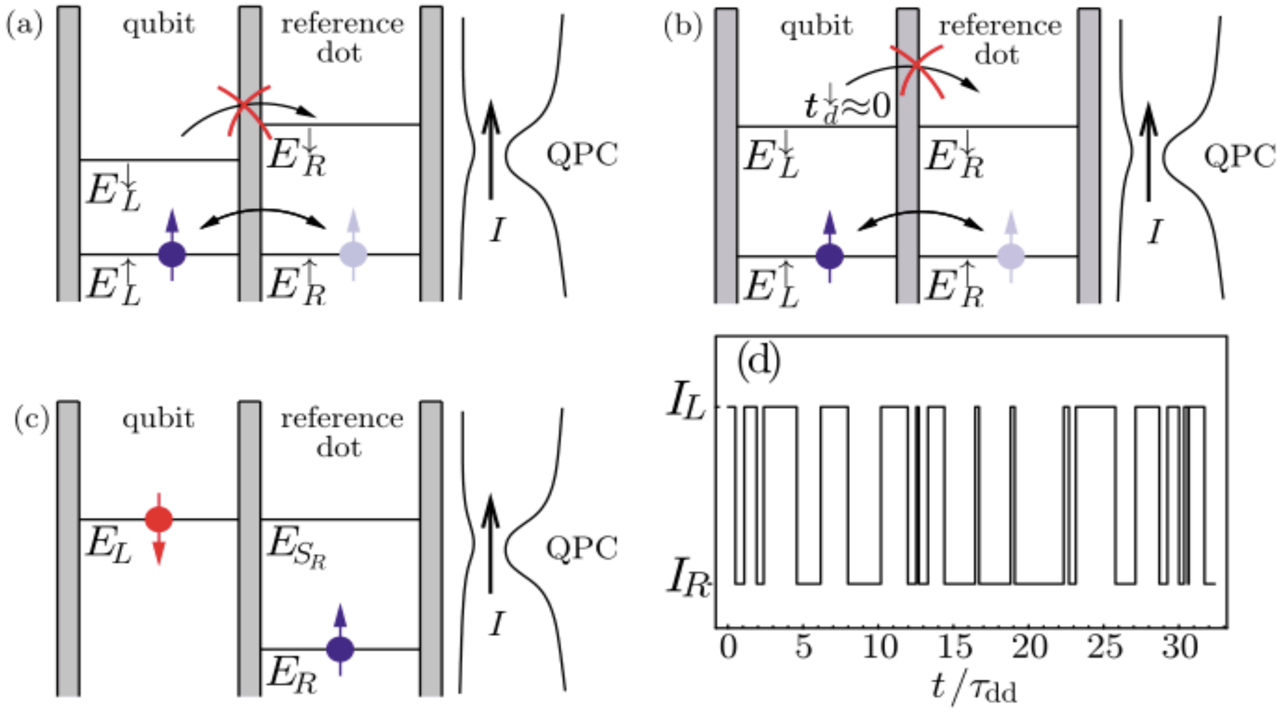


Co adatom on Pt
Spin polarized STM chip

F. Meier, et al., Science 320, 82 (2008).

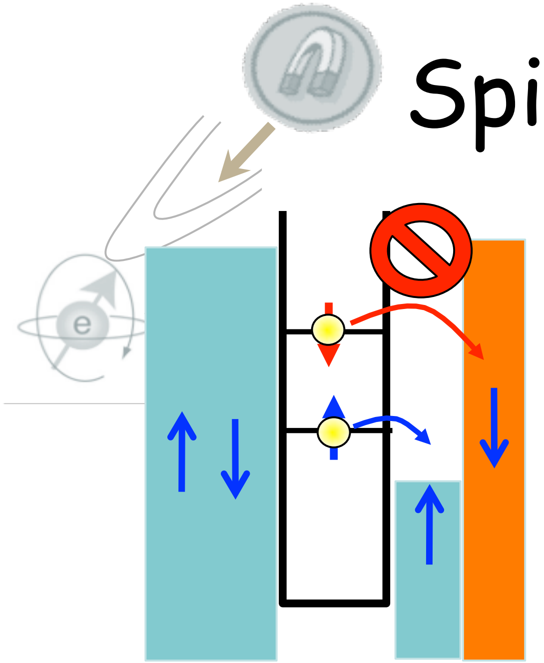
Basic idea: spin-charge conversion

Combining the spin with the orbital motion, we can detect spin states by the accompanying charge displacement or the current by charge detector or current meter.

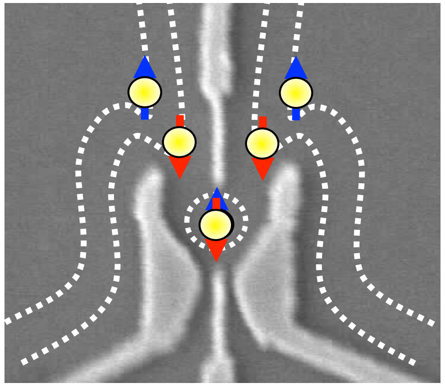


H-A. Engel, et al., Phys. Rev. Lett. 93, 106804 (2004).

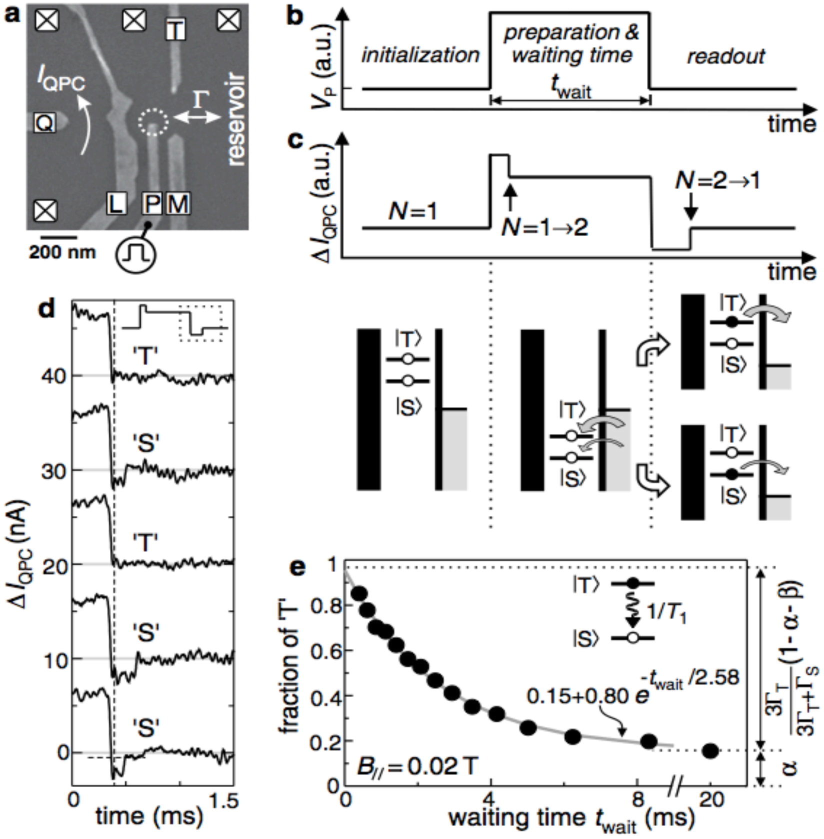
Spin selective tunnel probability



Ideally, spin selective reservoir can discriminate spin by checking charge.



M. Ciorga, et al., Phys. Rev. Lett. 88, 256804 (2002)

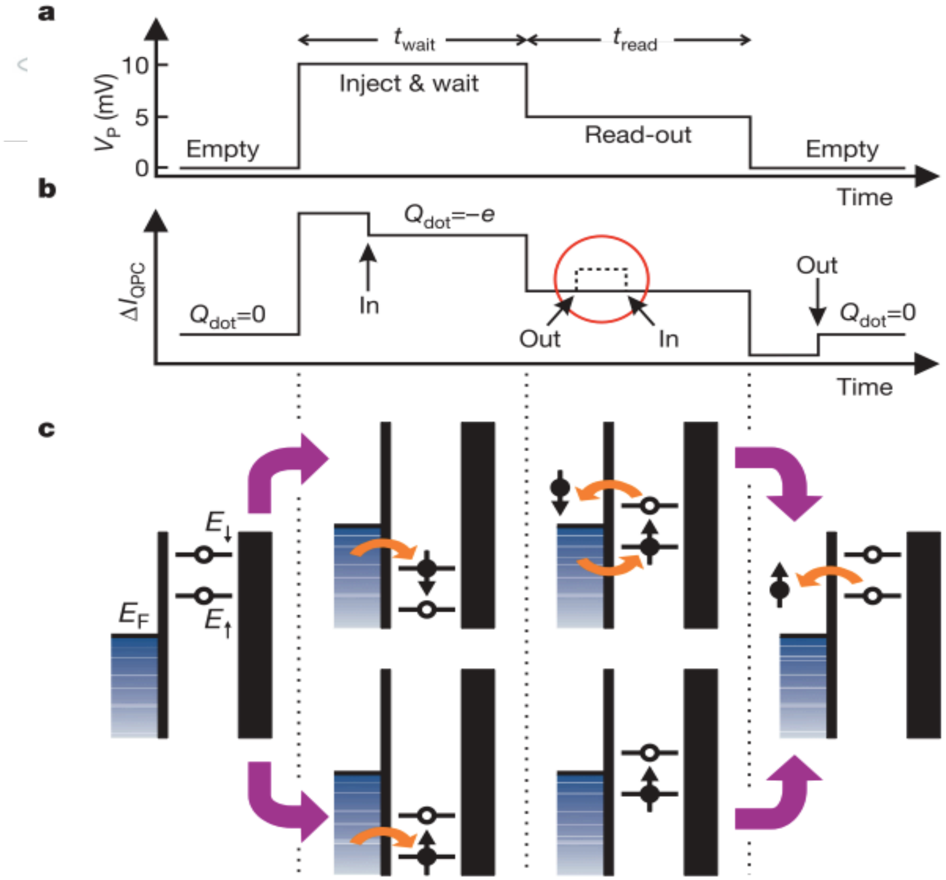


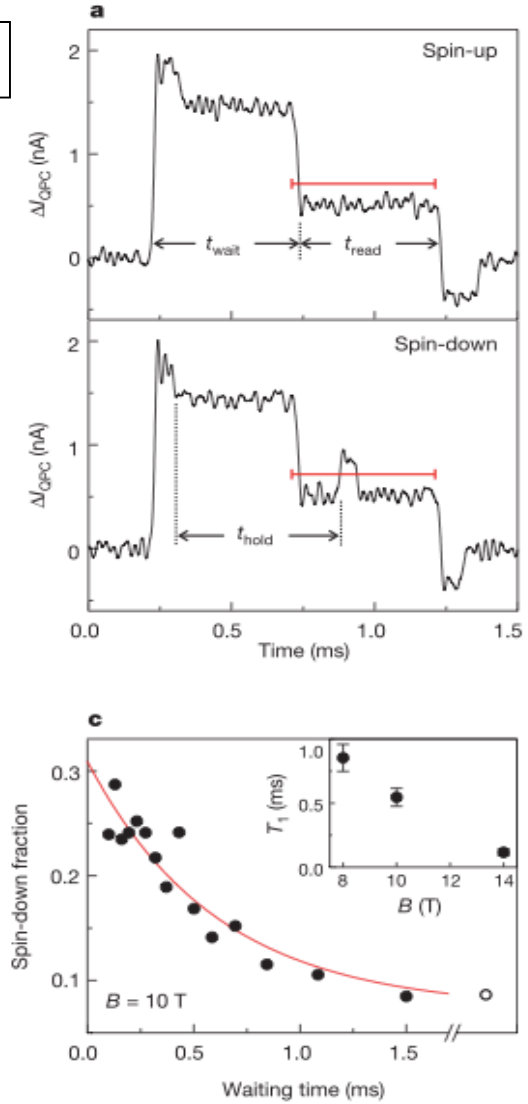
R. Hanson, et al., Phys. Rev. Lett. 94, 196802 (2005).

Single shot spin measurement

Energy selective

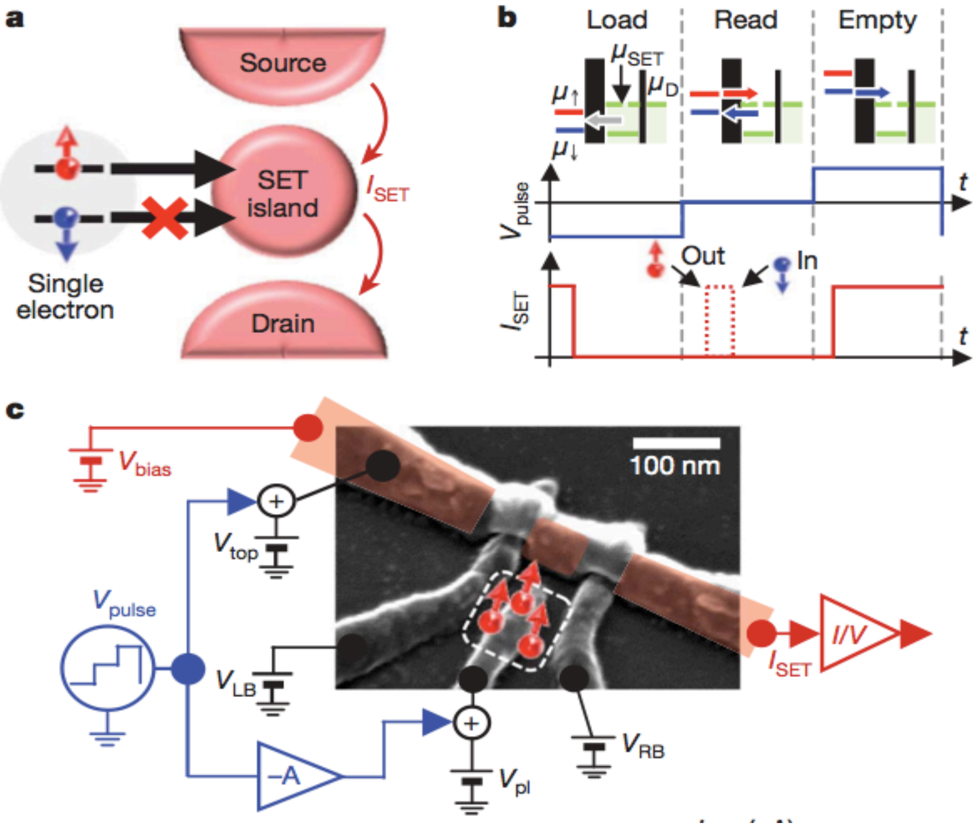
Zeeman energy $E_Z >> k_B T$

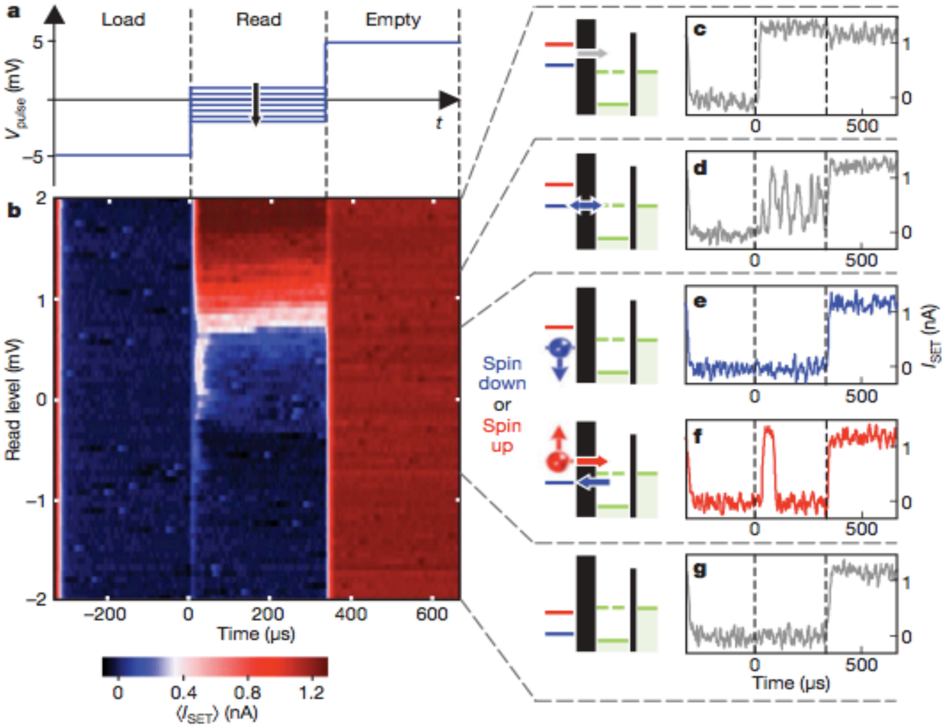




J. M. Elzerman, et al., Nature 430, 431 (2004).

Single shot of donor spin by SET

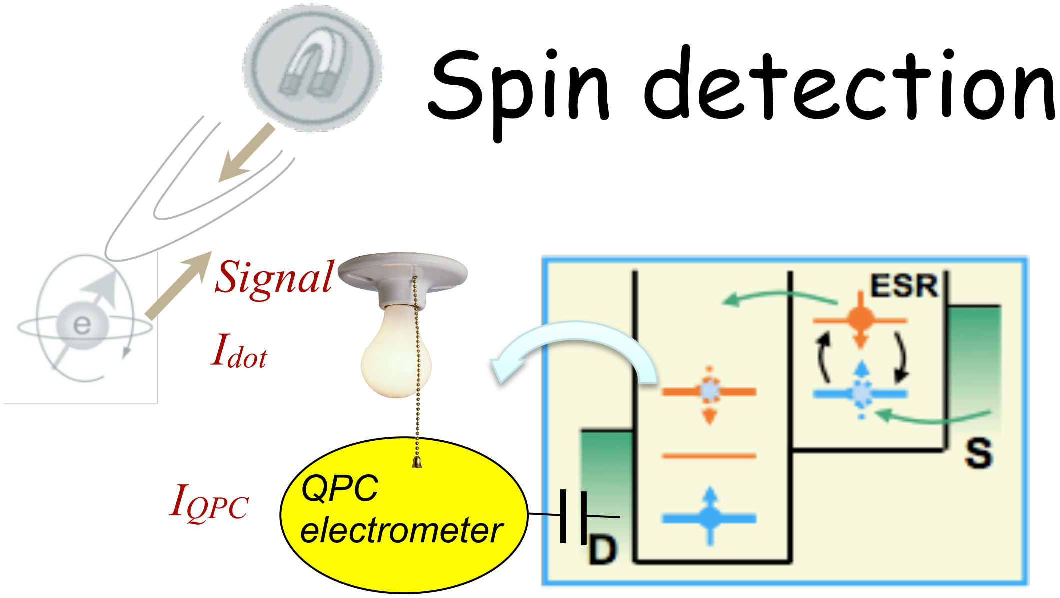




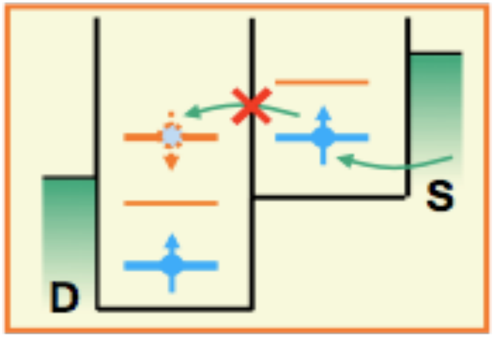
T_1~ 6s @ 1.5 T @ 200mK
Readout fidelity > 90%

A. Morello, et al., Nature 467, 687 (2010).

Spin detection using spin blockade



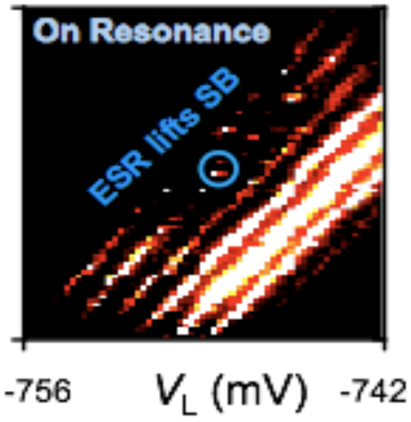
Spin triplet states

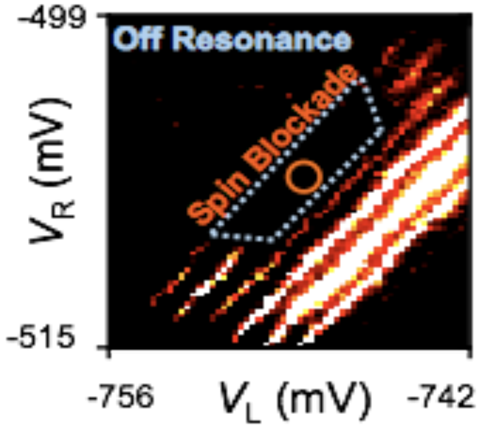


(1,0)←(2,0)←(1,1)←(1,0)

(1,0)←(2,0)✖(1,1)←(1,0)

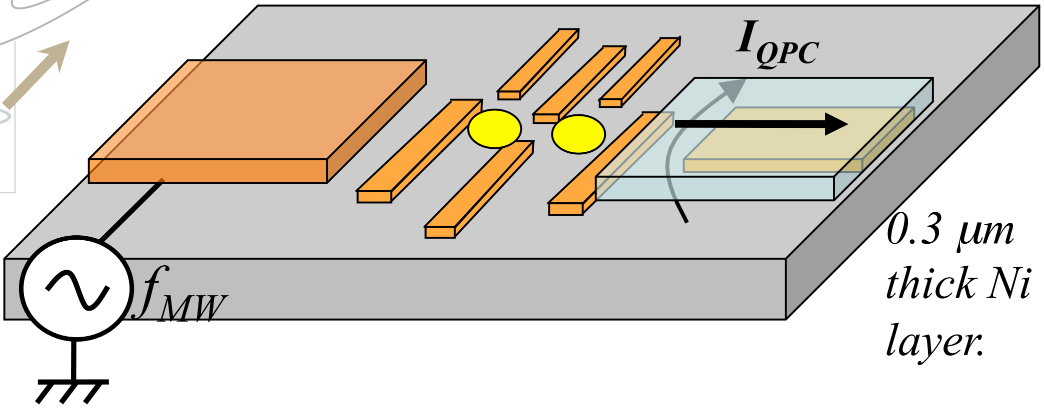
Signal only discriminates spin singlet/triplet or the event of spin flip.

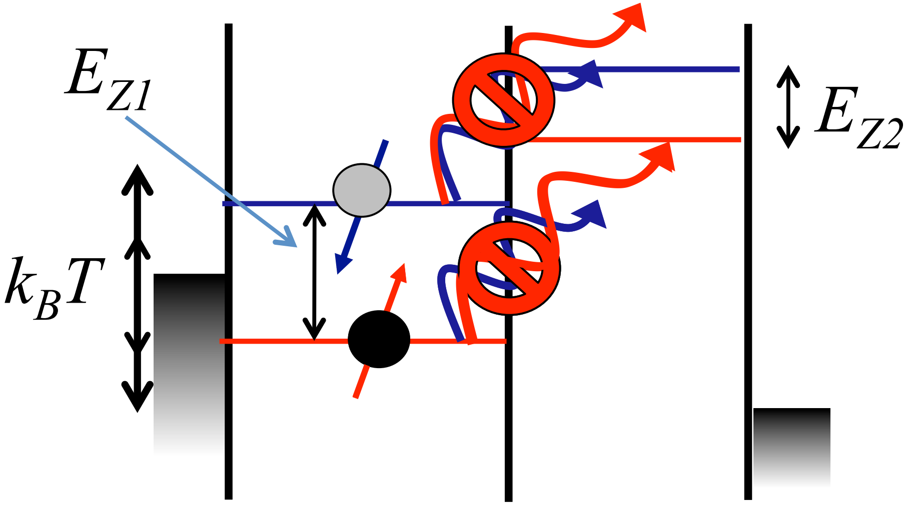


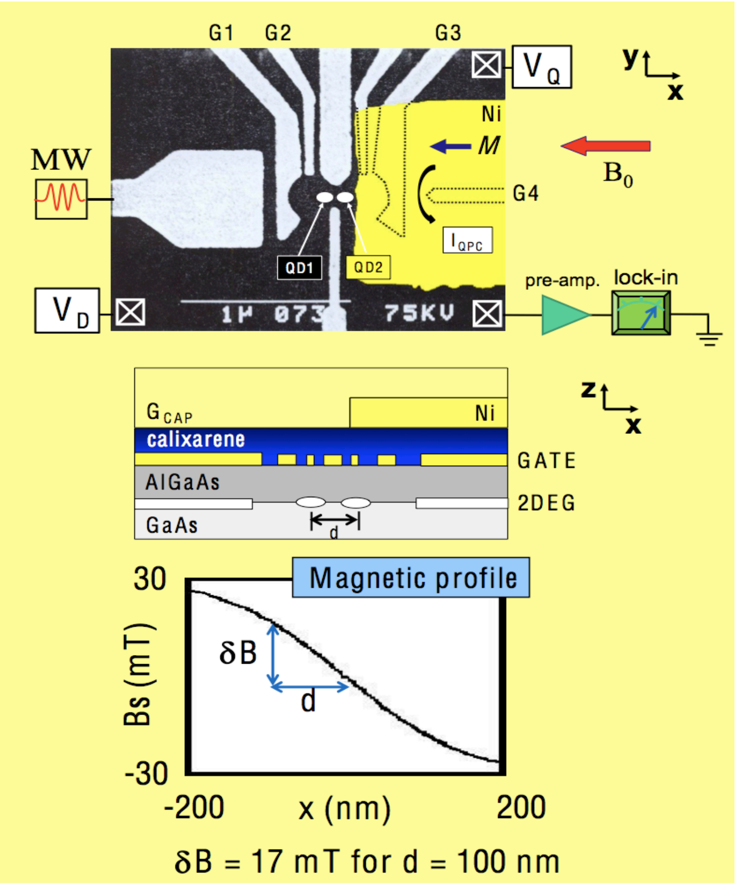


K Ono, et al., Science ***297****, 1313 (2002).*

Spin read-out using field gradient

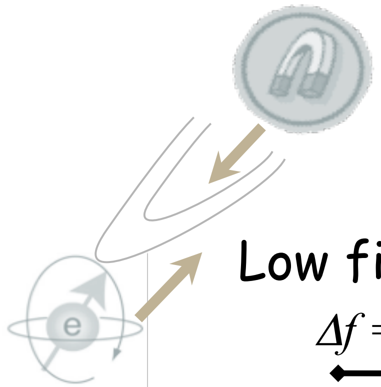






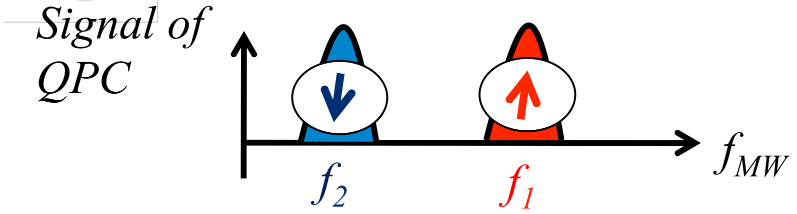
S. D. Barrett and T. M. Stace, PRL ***96****, 017405, (2006)*
J. -P. Zhang, et al., J. Phys. Condens. Matter ***20****, 395206 (2008)*

Experimental results

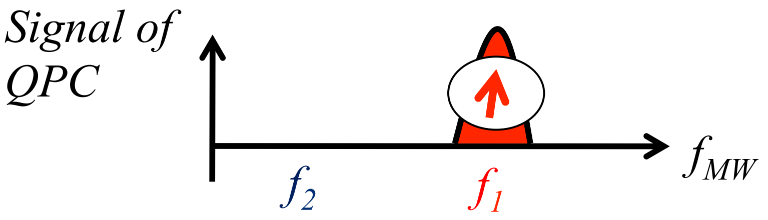


Low field: $E_{Z1} << k_BT$

$\Delta f = \Delta E_Z/h$

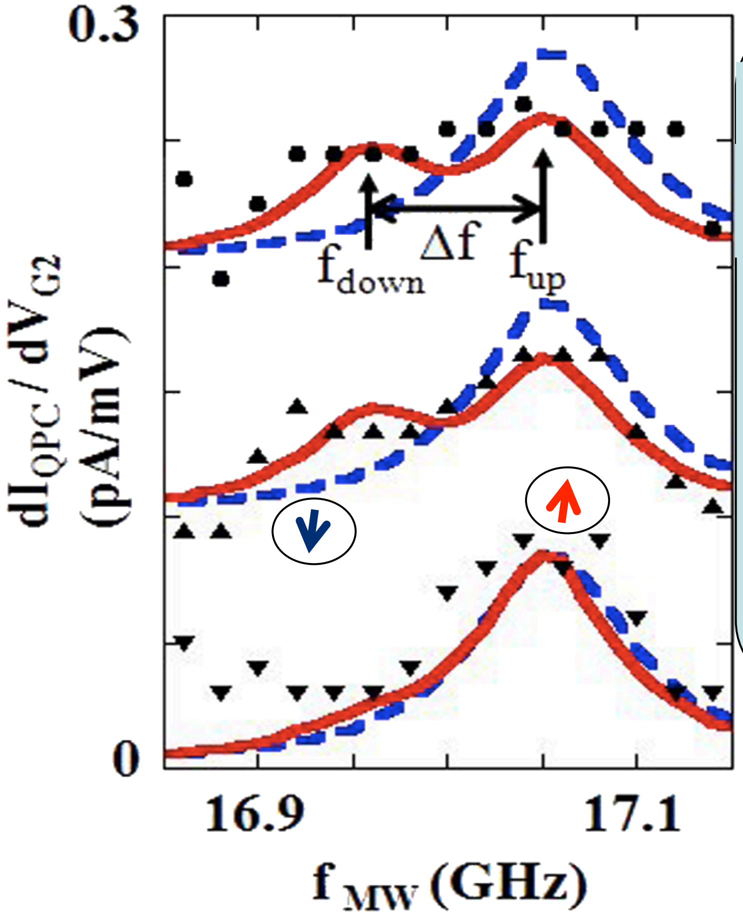


High field: $E_{Z1} >> k_BT$



Theoretical fit: $k_BT = 10mK$ (blue), 500mK(red)

$$L_\sigma = I_\sigma \gamma^2/((\mathrm{f}_{\mathrm{MW}} - \mathrm{f}_\sigma)^2 + \gamma^2)$$



Peak spacing:

$\Delta f = \Delta E_Z/h$

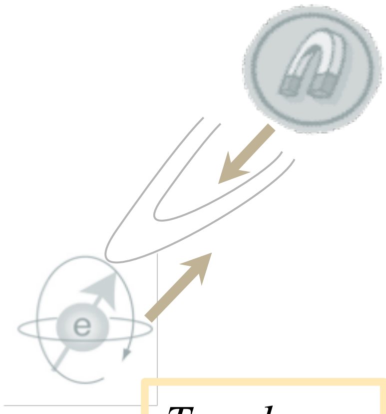
~ 100 +/- 10 MHz

~ 17 +/- 3.5 mT

Consistent with simulation results of ΔE_Z

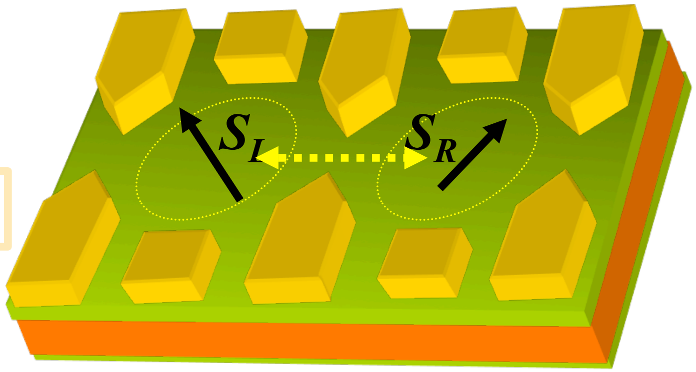
Y. -S. Shin et al., PRL ***104****, 046802 (2010).*

Static qubits and flying qubits



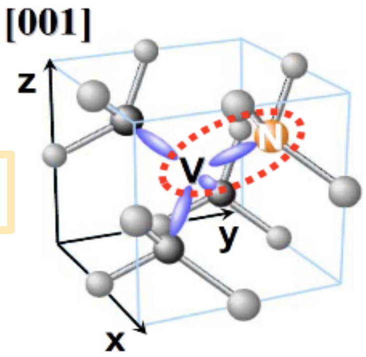
Top-down

Static



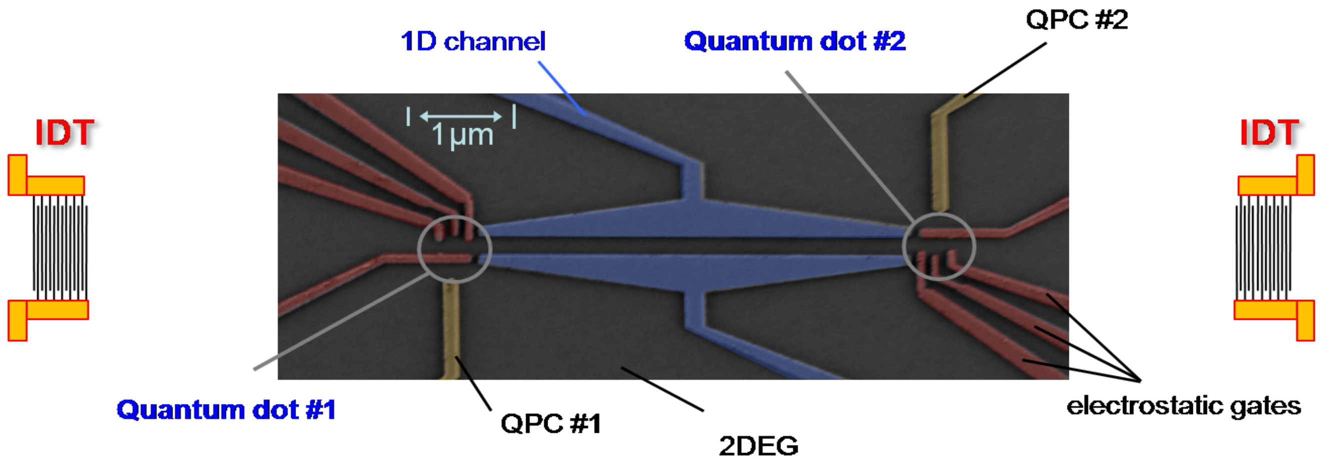
Loss and DiVincenzo PRA (98)

Bottom-up



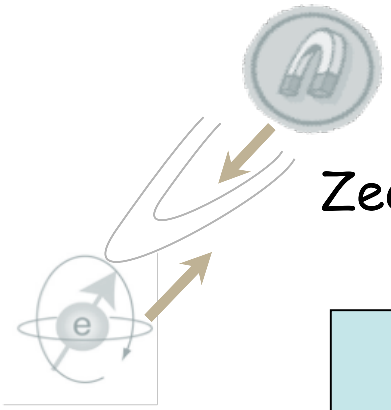
NV-center in diamond crystal

Flying

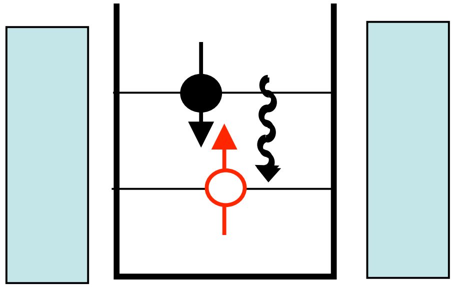


Surfing qubit on surface acoustic wave

Initialization



Zeeman splitting $E_{Zeeman} = g_{dot}\mu B$ ($|g_{dot}| < |g_{bulk}| = 0.44$ GaAs)



Polarization $= 1 - \exp[-E_{Zeeman}/k_BT]$

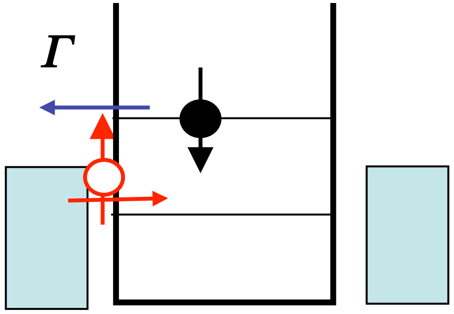
$>99\%$ pure state : $|\uparrow\rangle$ at 300mK

for E_{Zeeman} ($B = 8$ T) $> k_BT$

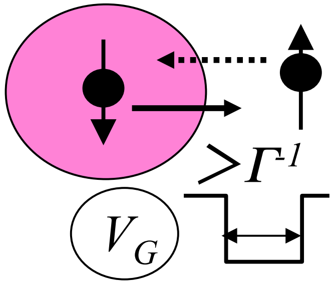
…Easy initialization by waiting for a time longer than T_1 (ms)

For fast Initialization

Spin exchange by tunneling between the QD and contact leads

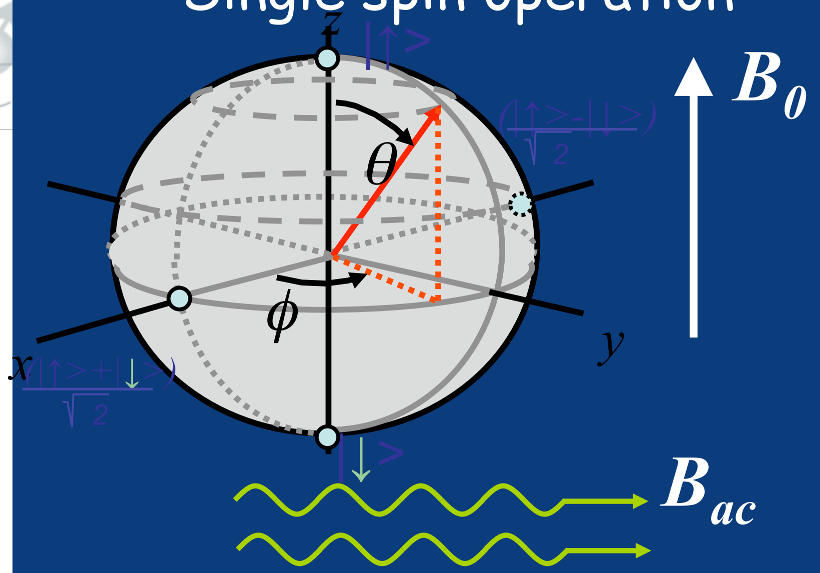


Initialization time $< \Gamma^{-1} \sim$ nsec



How to manipulate electron spins?

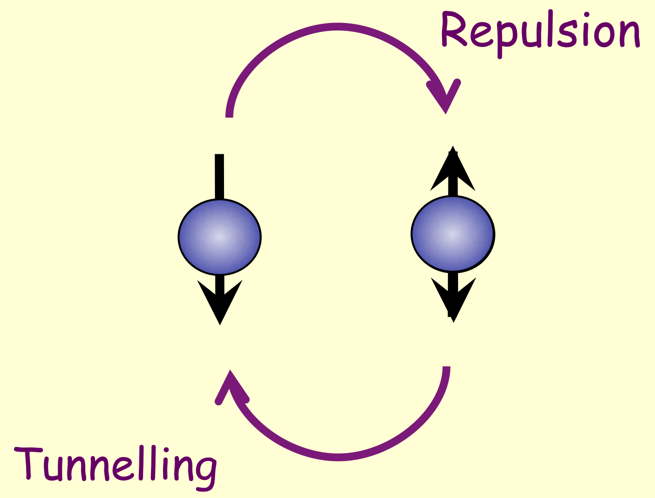
Single spin operation



Electron Spin Resonance

$$f_{B_{ac}} = E_Z / h = g\mu_B B_0 / h$$

Two-spin operation

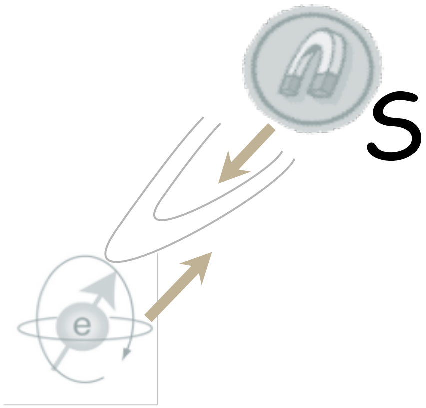


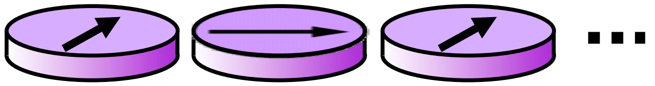
Exchange $J\mathbf{S}_1 \cdot \mathbf{S}_2$

J electrically controlled

R. Hanson et al. Review of Modern Physics ***79*** *(2007)*

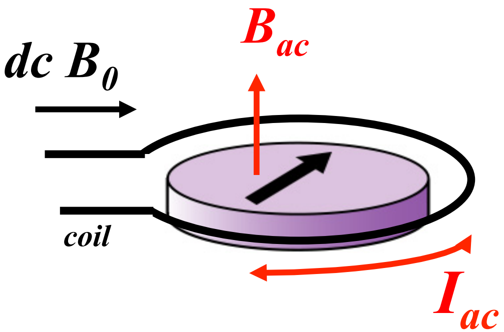
Single spin addressable ESR





"Global B_0 and local B_{ac} for single spin resonance"

Current driven ESR

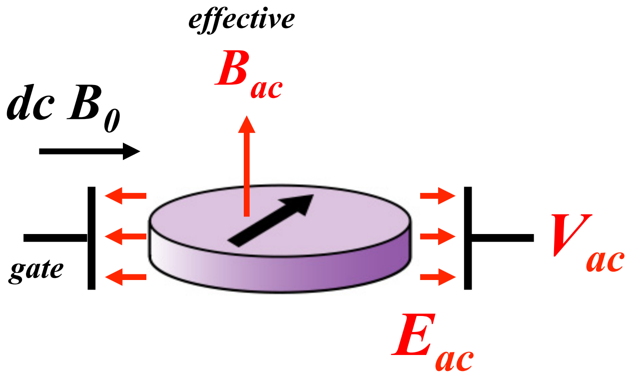


I_{ac} = 1 mA, B_{ac}~ 1 mT

π rotation: ~ 80 ns

Heating problem.
Difficult to localize.

Voltage driven ESR (EDSR)

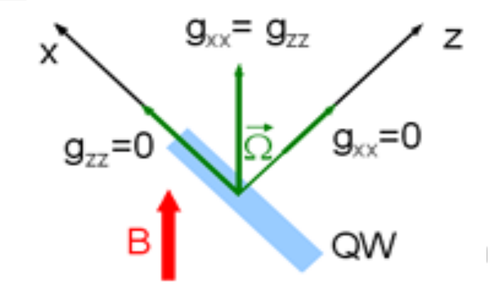


V_{ac} = 1 mV, E_{ac}~ kV/m

No heating problem/Easy to localize.
Need coupling mechanism.

Coupling mechanisms for EDSR

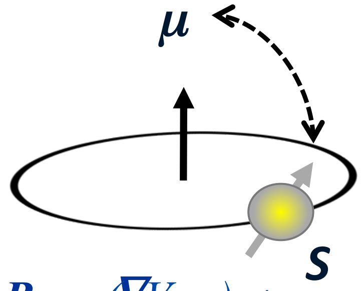
g-tensor modulation



Y. Kato
Science 2003,
R. Deacon
PRB 2011

g-tensor
engineering

Spin-orbit

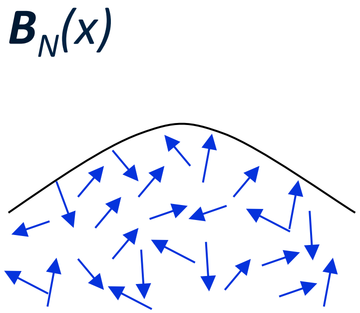


$B_{loc}=(\nabla V \times p)\sigma$

V. N. Golovach
PRB 2006,
K. C. Nowack
Science 2007

Material dep.
small in GaAs

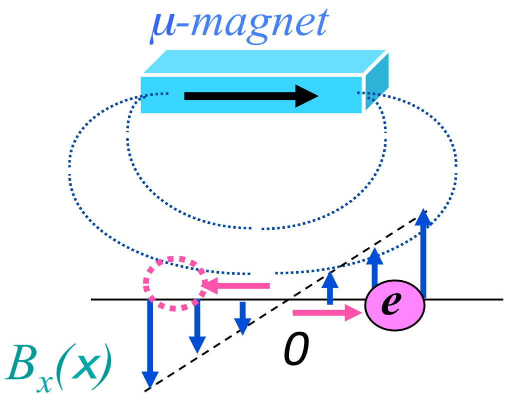
Hyperfine int.



E. A. Laird
PRL 2007,
E. Rashba
PRB 2008

not-coherent

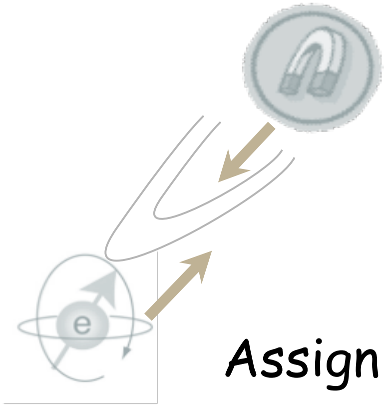
Slanting Zeeman field



Y. Tokura
PRL 2006,
M. Pioro-Ladriere
Nat. Phys. 2008

μ-magnet fabrication
addressable

Spin addressability

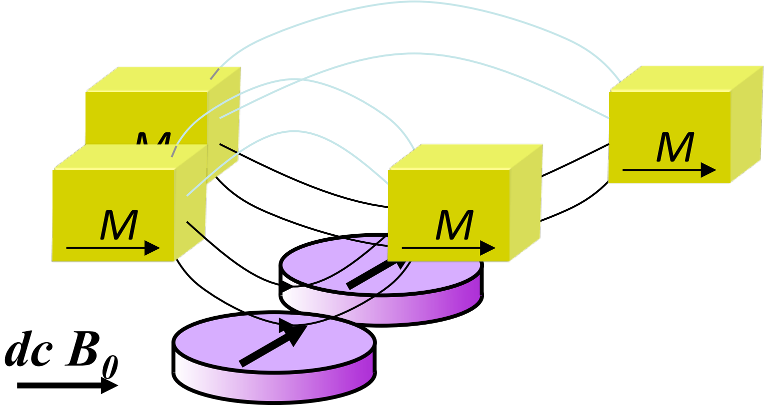


Addressability: $\Delta f_{ESR} > 1/T_2^*$

Assign different Zeeman energies to address them: $E_{zeeman} = g\mu_B B$

Control B

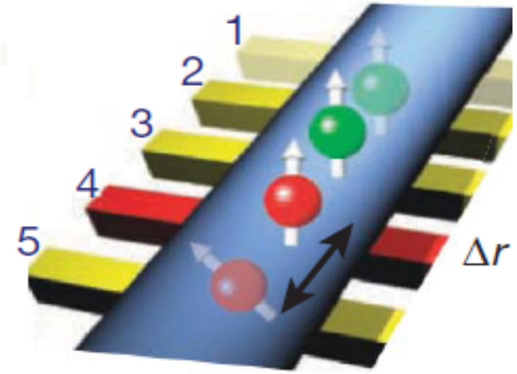
Micromagnets: GaAs coupled dots



T. Obata et al. PRB (2010)
R. Brunner et al. PRL (2011)

Control g

Spin-orbit interaction: InAs nanowire

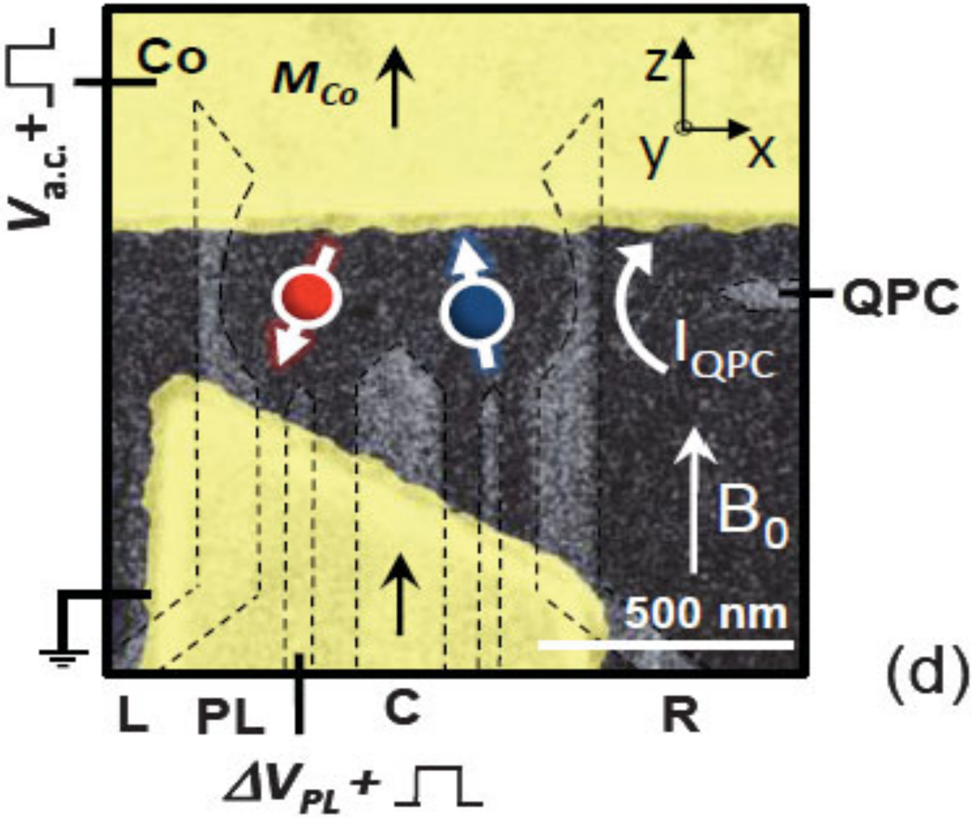


Size/shape of dots determines the value of g.

S. Nadj-Perge et al. Nature (2010)
Y. Kanai, et al., Nature Nano. (2011)
R. Deacon, et al., PRL (2011)

Prototype device

lateral DQD + charge sensor + split micro-magnets



❑ **Few- electron DQD**

Isolation of two single spins

Hanson et al. PRB (2002)

❑ **Pauli spin blockade**

ESR detection

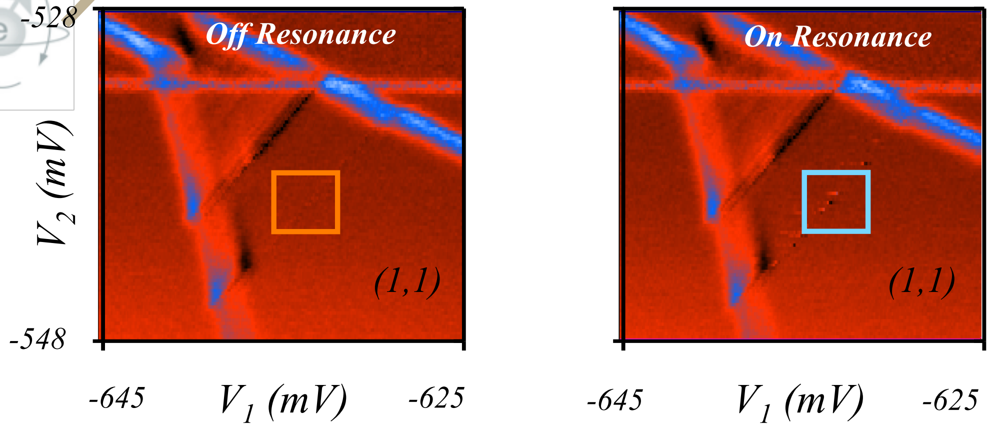
Koppens et al. Nature (2006)

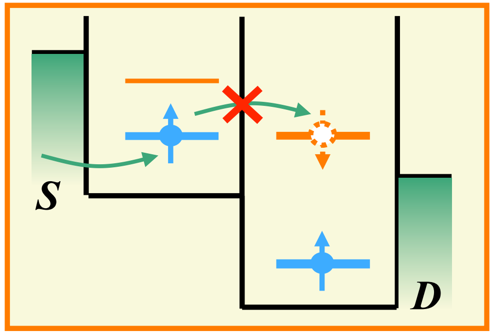
❑ **Split type micro-magnets**

Slanting magnetic field

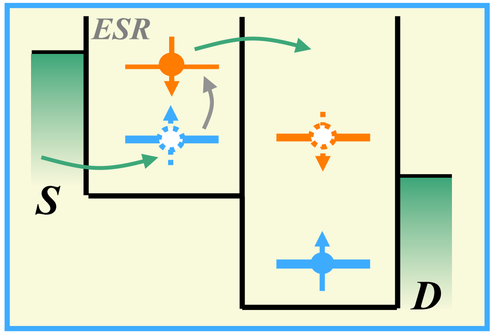
& Addressability

ESR lifts off the spin blockade





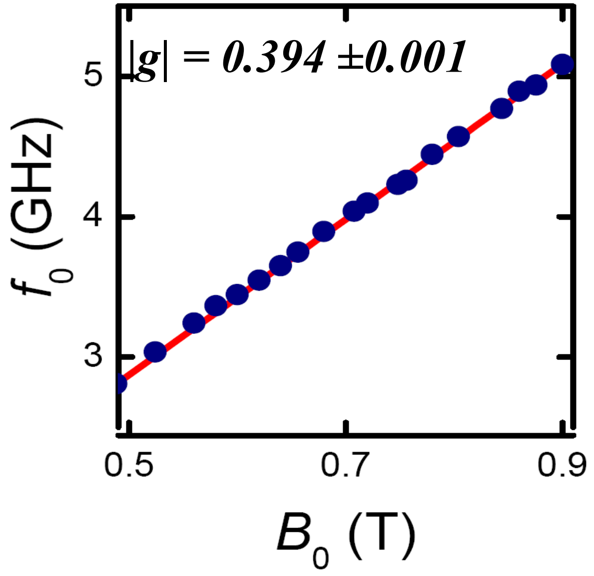
Blocked

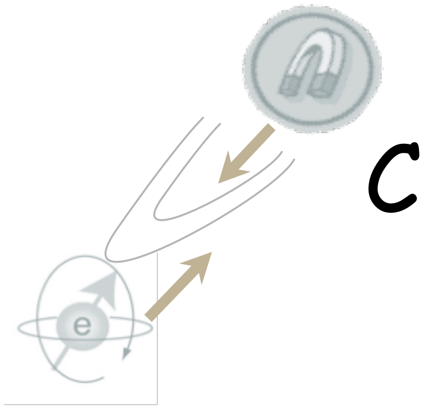


Unblocked

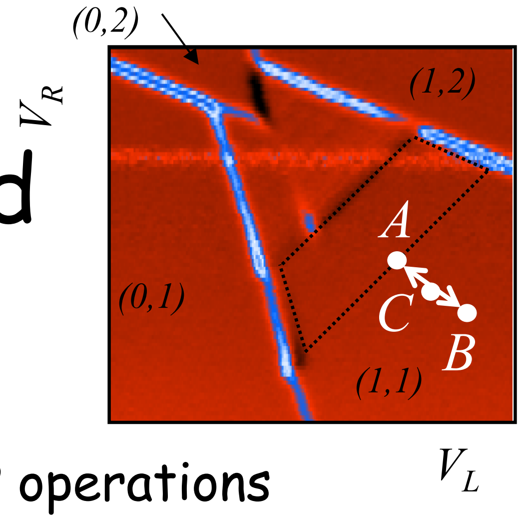
Continuous microwave excitation

f = 5.66 GHz, -34 dBm

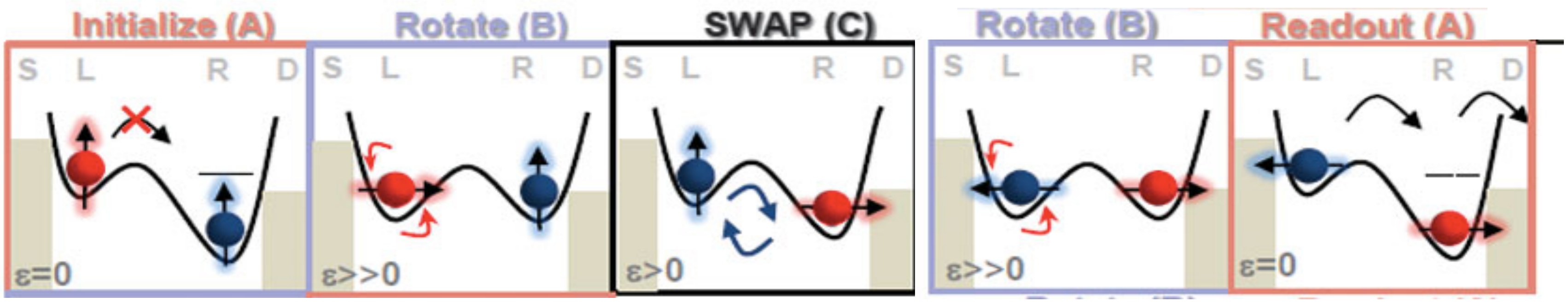


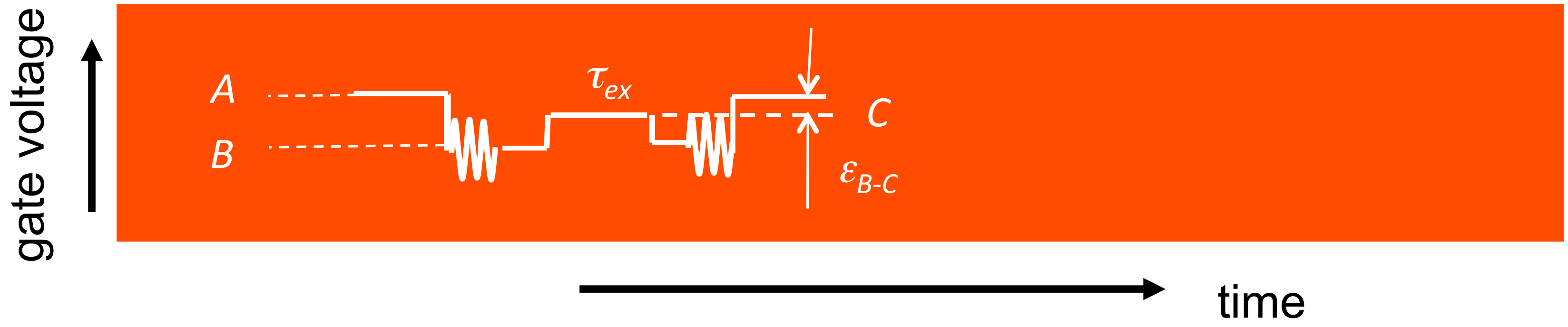


Combination of single and two qubit operations

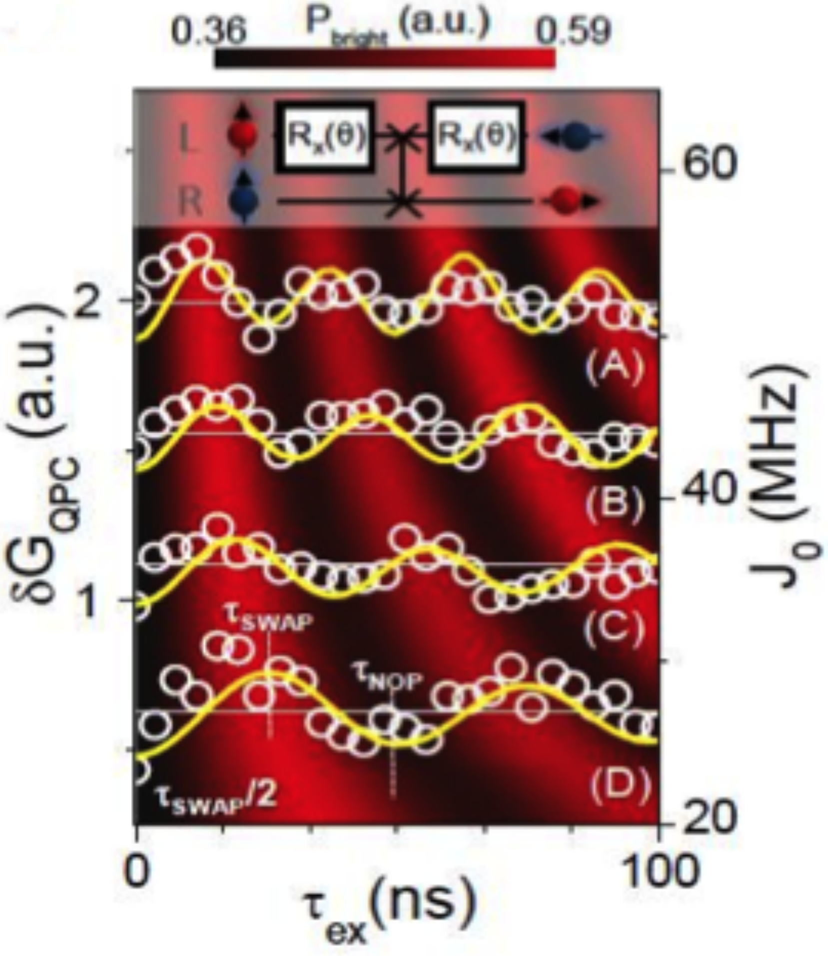


One spin manipulation (Hadamard) + two spin SWAP operations





Demonstration of “SWAP”s



Circles:
Experimental results of QPC detection

Solid lines:

Average over Gaussian distribution of nuclei

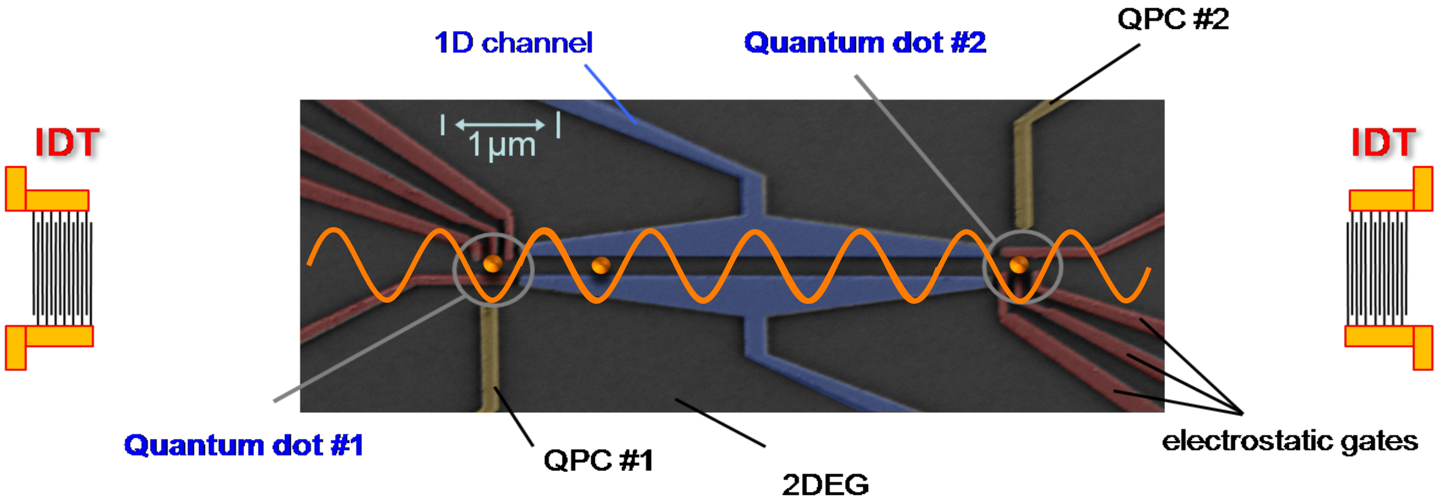
$$P_n(B_{Nn}) \equiv \frac{1}{\sqrt{2\pi}\Delta_n} e^{-\frac{B_{Nn}^2}{2\Delta_n^2}}$$

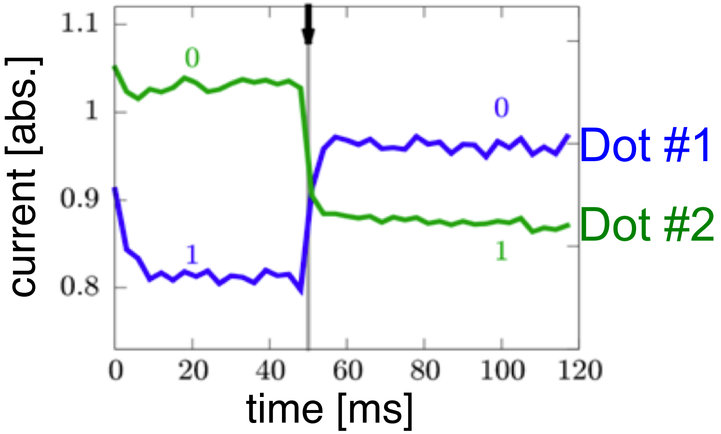
Δ_n Variance of nuclear spin fluctuation of *QDn ~ 0.27MHz*

R. Brunner, et al., PRL ***107,*** *146801 (2011)*

Surfing single electron

IDT generates a surface acoustic wave (wave length: 1 µm, velocity: ~2800 m/s)



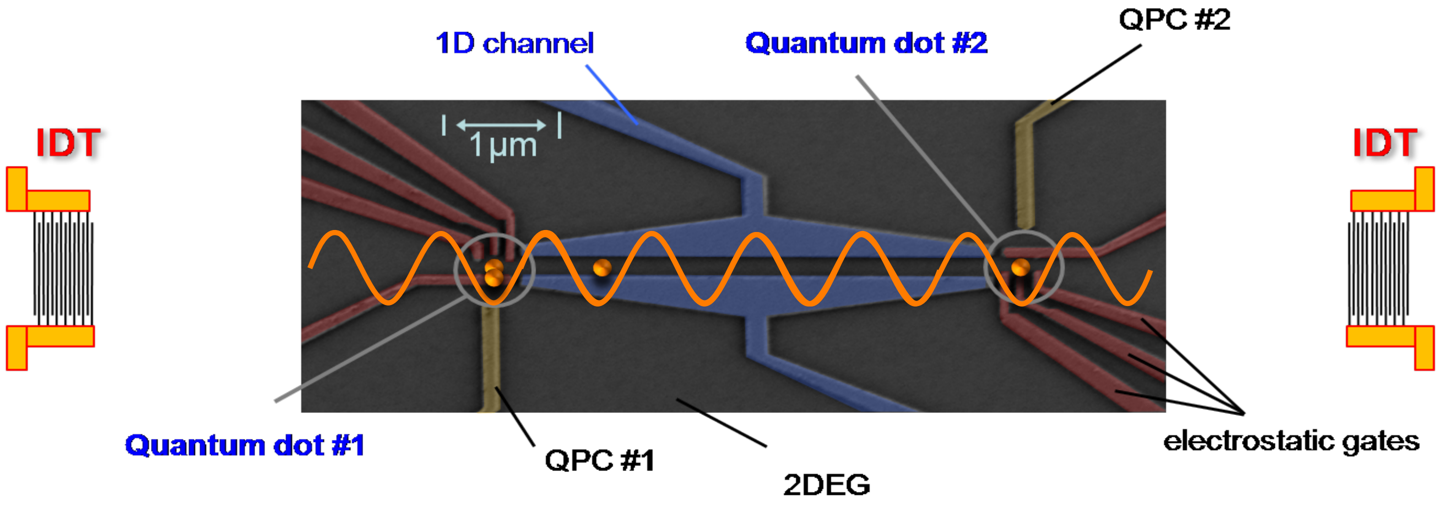


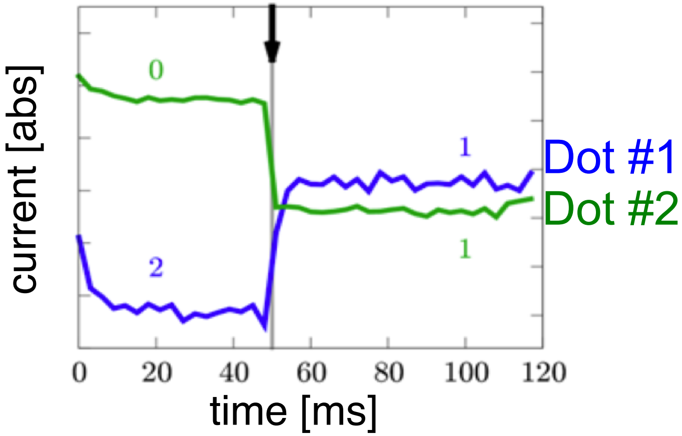
- Single electron source and detection (Fidelity > 90%)
- No electron-electron interaction while transfer
- Travelling time ~ 2 ns << T_2^*

⬇

Transfer of a *single electron spin* over a long distance

Transfer one of two electrons





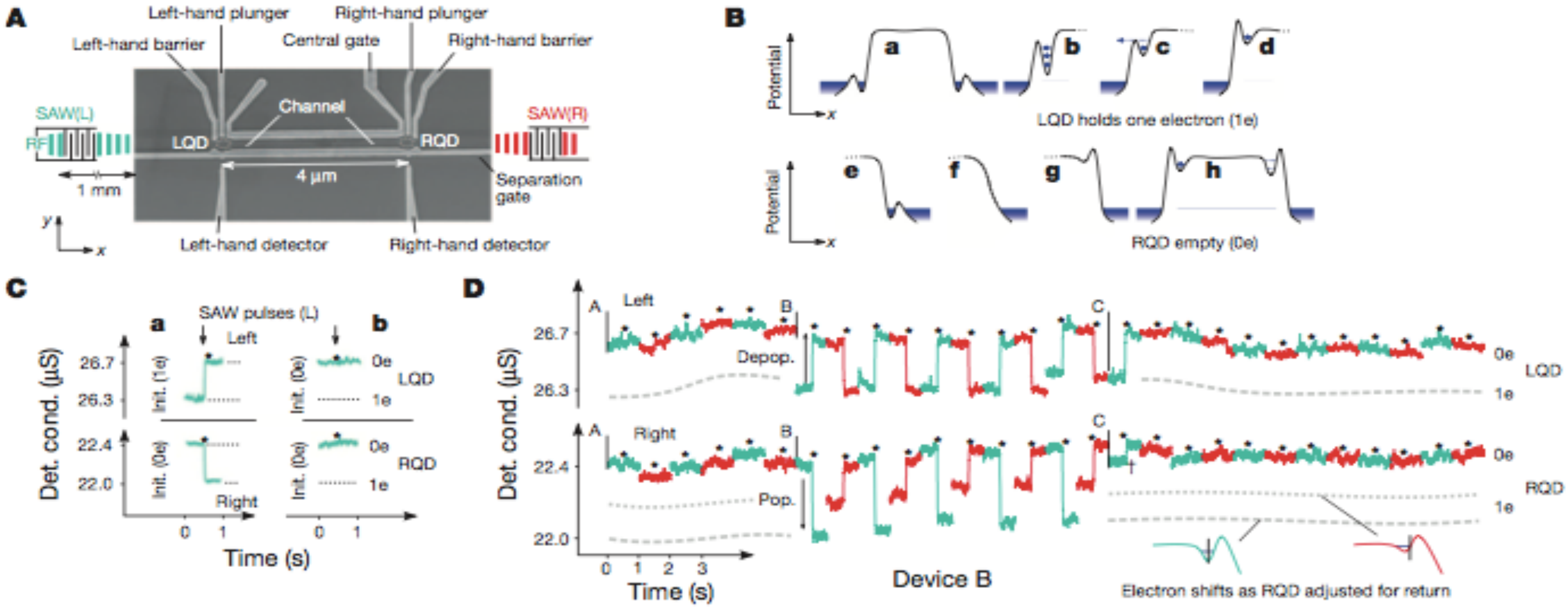
- Two electrons in a dot forms a spin singlet state
- Two electrons are separated into distant dots within a few ns (<<T_2^*) (Fidelity ~ 90%)

⬇

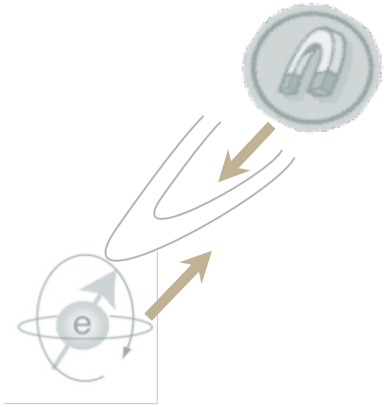
Non-local entanglement

S. Hermelin, et al., Nature 477, 435 (2011).

Catching ball of an electron



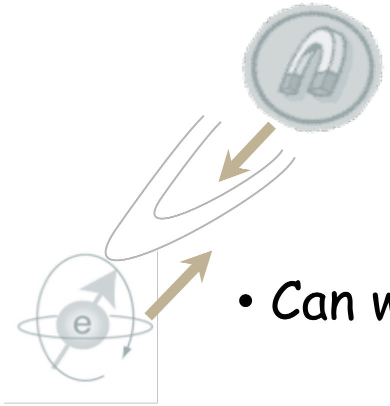
R. P. G. McNeil, et al., Nature 477, 439 (2011).



Criteria of realizing quantum computers

D. P. DiVincenzo Fortschr. Phys. (2000).

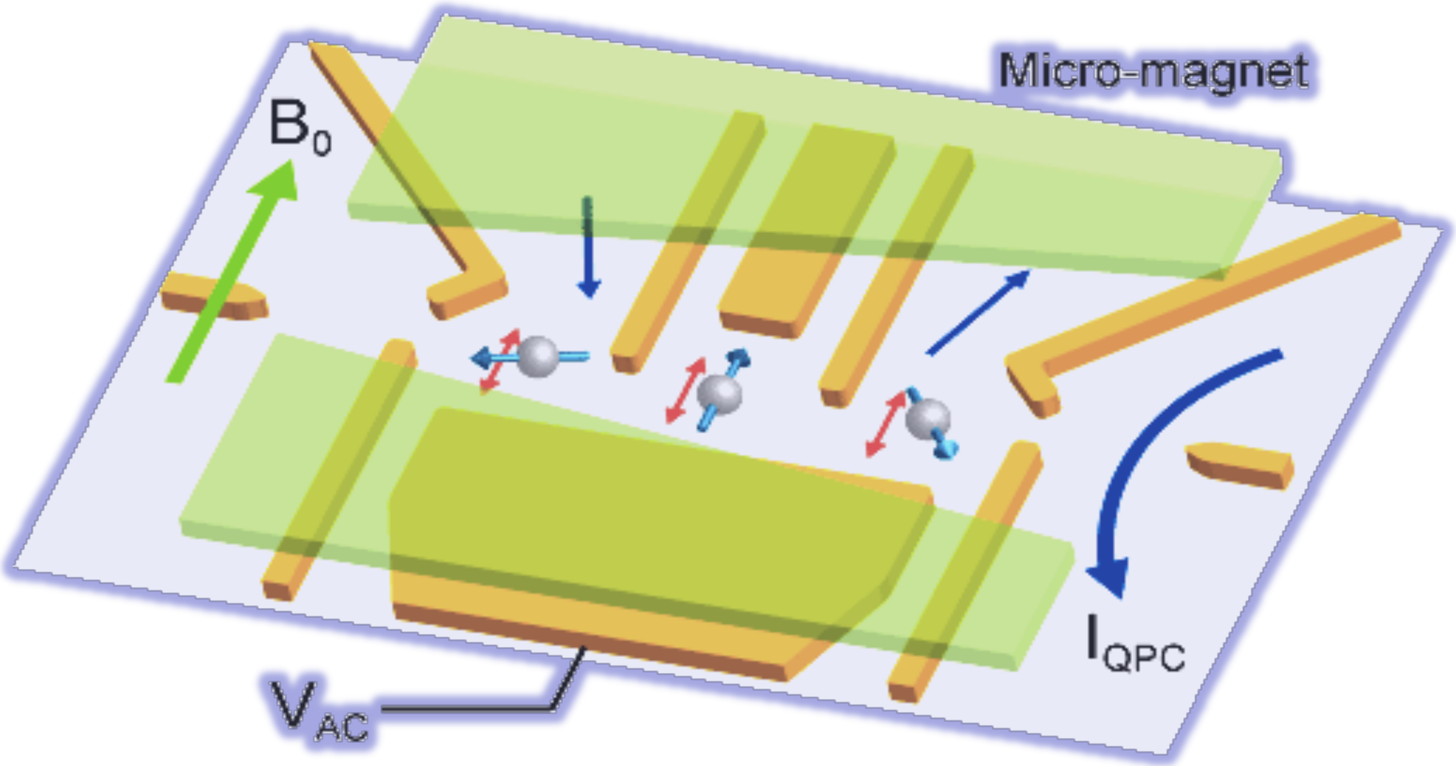
	Electrically controlled spin qubits
1. *A scalable physical system with well characterized qubits* (スケーラビリティ）	?
2. *The ability to initialize the state of the qubits to a simple fiducial state* （初期化）	✓
3. *Long relevant decoherence times, much longer than the gate operation time* （良いコヒーレンス）	△
4. *A "universal" set of quantum gates* （量子演算）	✓
5. *A qubit-specific measurement capability* （読み出し）	△



What are the next challenges?

- Can we solve the decoherence problem?
  - Feedback control of nuclear spins/dynamical decoupling
  - Nuclear-free material (Si/SiGe, Graphene…)
- Can we demonstrate one-shot two spin measurement required for Bell measurement ?
  - Parity spin measurement with QPC would be feasible.
- Is it possible to couple single spin to single photon/microwave?
  - Maybe, using InAs QD or dipole induced by slanting field.

Thank you for your attention!



Collaborators: S. Tarucha, T. Obata, Y-S. Shin (U. Tokyo), M. Pioro-Ladriere (U. Sherbrook), R. Brunner (Montanuniversitaet Leoben), W. van der Wiel (U. Twente), T. Kubo (U. Tsukuba)

Grants: Funding Program on World-Leading Innovative R and D on Science and Technology (FIRST) Quantum Information, MEXT Grant-in-Aid for Scientific Research on Innovative Areas, Quantum Cybernetics.