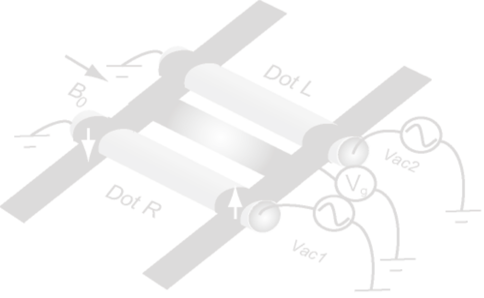
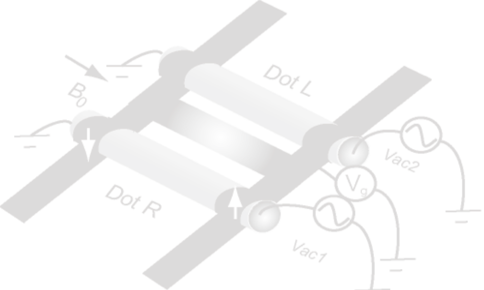


半導体を用いた量子情報処理
Quantum information processing in semiconductors

Yasuhiro Tokura (University of Tsukuba, NTT BRL)

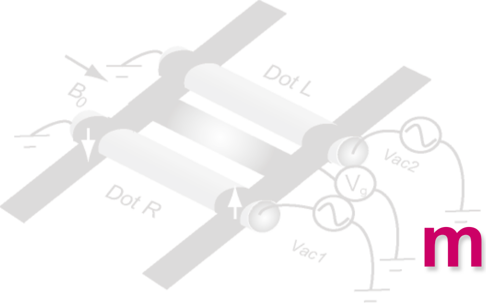
都倉康弘
ナノサイエンス・ナノテクノロジー専攻



The Nobel Prize in Physics 2012

“for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems”

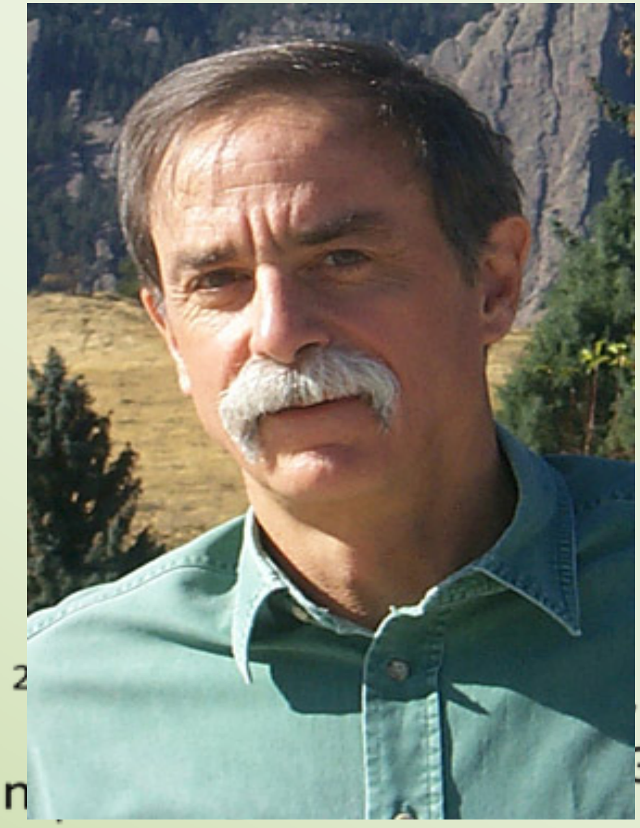
Serge Haroche, David J. Wineland



Measuring & manipulating of individual quantum systems matter (atom) ⇔ light (photon)

The Nobel Prize in Physics 2012

Ion in a trap



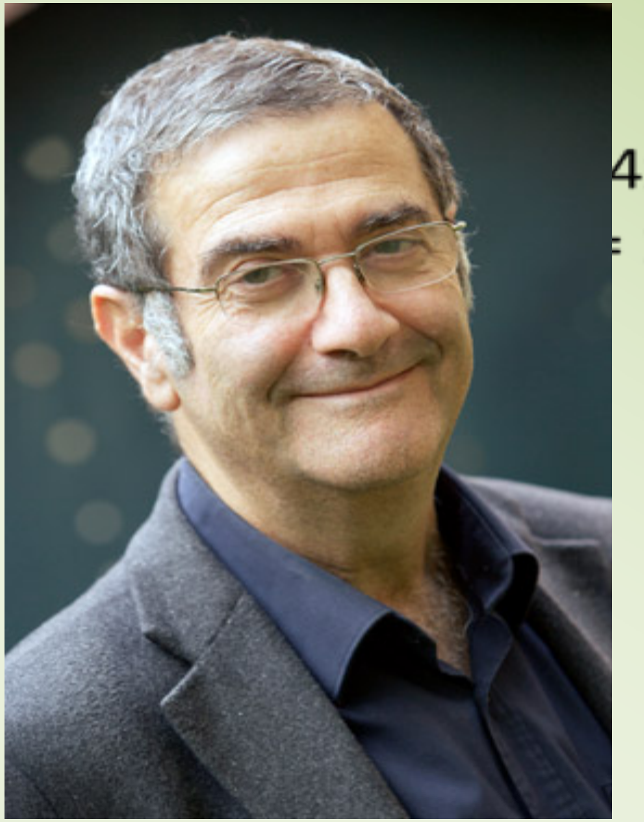
Be^+ 2 … $m_F=1$

GHz

F=2,n

David J. Wineland (NIST Boulder)

Photon in a cavity

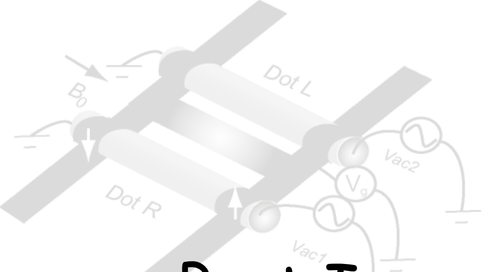


4x 10^{10}

130 ms

Serge Haroche (ENS Paris)

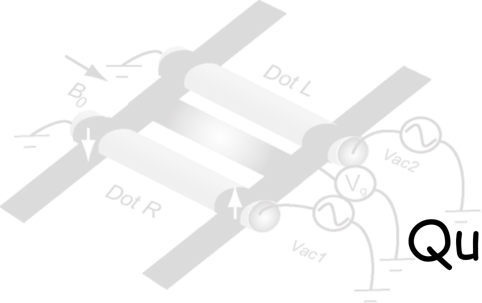
Scientific Background http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/press.html



Plan of this lecture

- Part I
    - Quantum dots (QDs), Double quantum dots
    - Charge qubits
    - Quantum point contacts: charge detection
    - Spin detection - Spin to charge conversion

- Part II
    - Single spin qubits
    - Exchange based (only) qubits
    - Flying qubits
    - Prospective



半導体を用いた量子情報処理
Quantum information processing in semiconductors

Part I

Semiconductor

Quantum Dots

Spin detection

Quantum Point Contacts

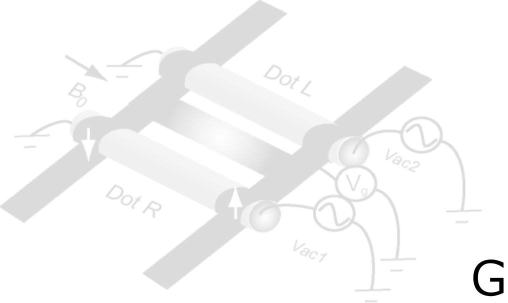
One sheet summary of semiconductor

We can enjoy the variety of material features and their combinations.

Band gap E_{gap}, - Important for optical interface
Effective mass m^* - scales `Quantum confinement', zero - metallic CNT/Graphene
Multi-valley (Silicon, CNT, Graphene) – additional quantum index ?

Lande g-factor g^* - magnetic coupling of spin, electrically tunable
Spin-orbit interaction (SOI) α,β
 − enabling electric control of spin / topological states, Majorana

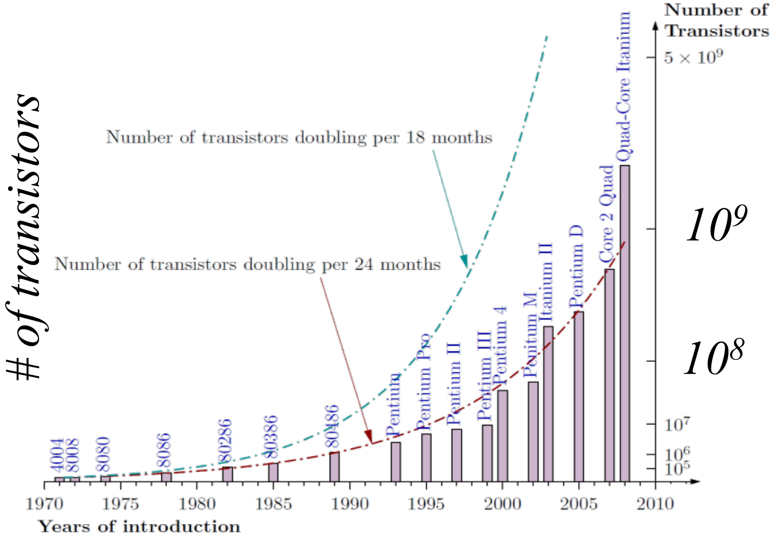
Hyperfine coupling A – enemy of spin coherence, isotope engineering
Deformation/Piezoelectric Phonon Ξ, h_{14} – another source of decoherence



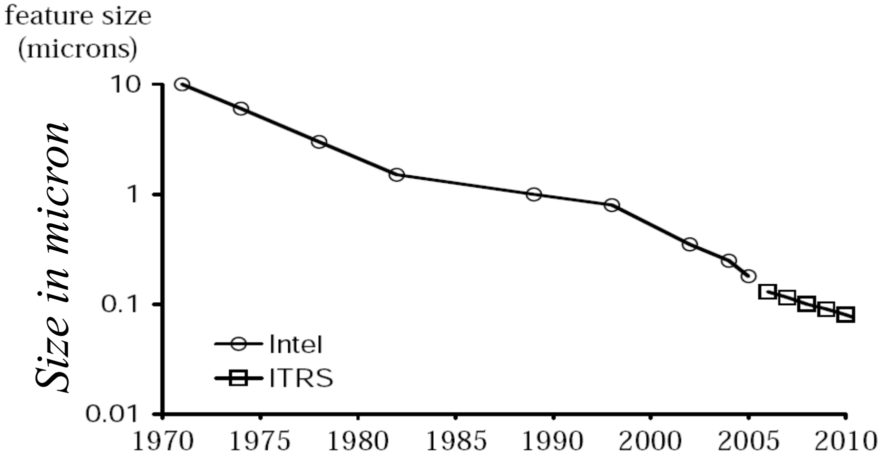
Nano-technology

Gordon E. Moore（Chairman Emeritus of Intel ）

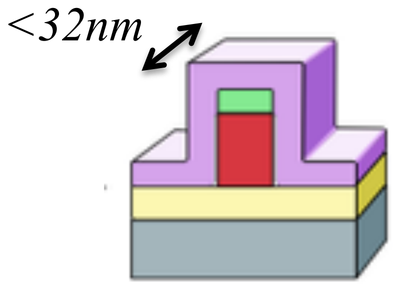
Moore’s law



Minimum Feature Size

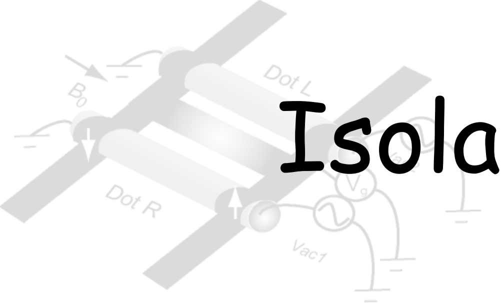


The decreasing minimum feature size of transistor components is shown for both Intel products and data reported by the International Technology Roadmap for Semiconductors (ITRS).



Fin-FET

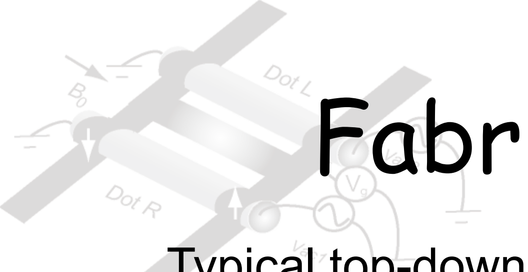
Potentially, the developed nano-technology for the semiconductor devices may help also to realize scalable quantum system.



Isolation of single charge and spin

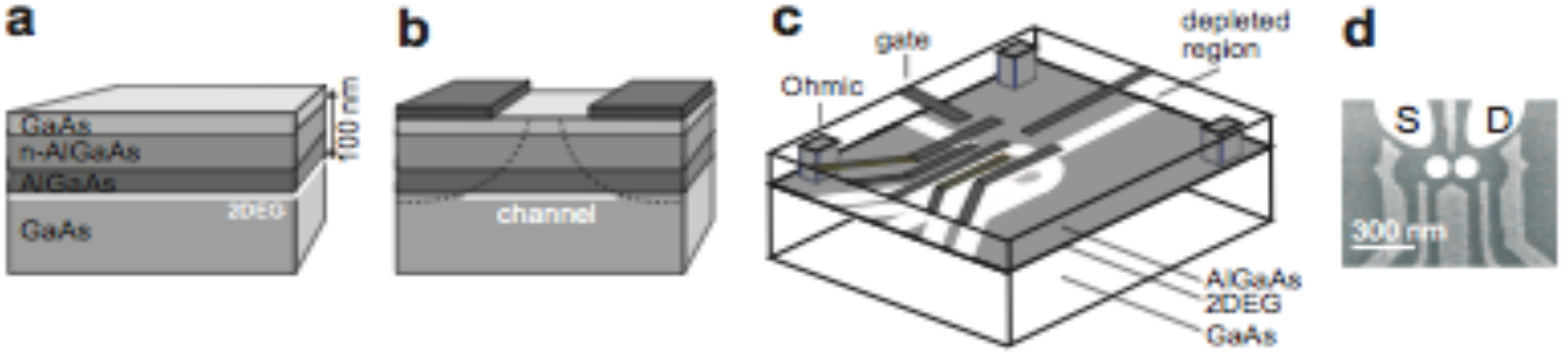
In contrast to naturally well-isolated systems like cold-atoms, ions, and photons, forming quantum two-level systems (qubits) in condensed matter is not an easy task.

Isolation of single electron (artificial atom) is an important milestone.

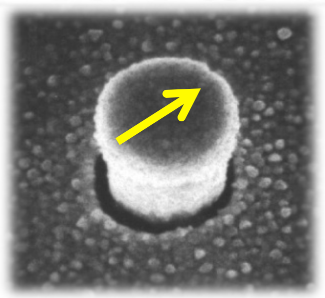


Fabrication of quantum dots (QDs)

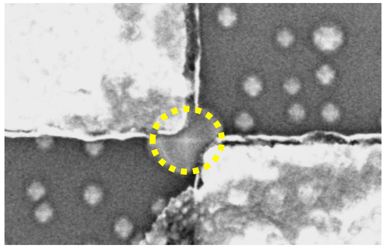
Typical top-down approach, starting from two-dimensional (2D) electron gas formed at the hetero-interface, and depleting selective areas by the surface metallic gates negatively biased.



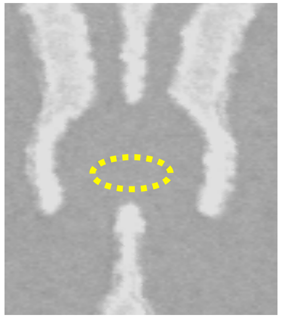
Advent of one-electron single QDs



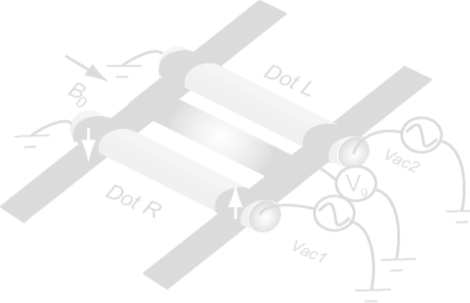
Tarucha et al. PRL 96



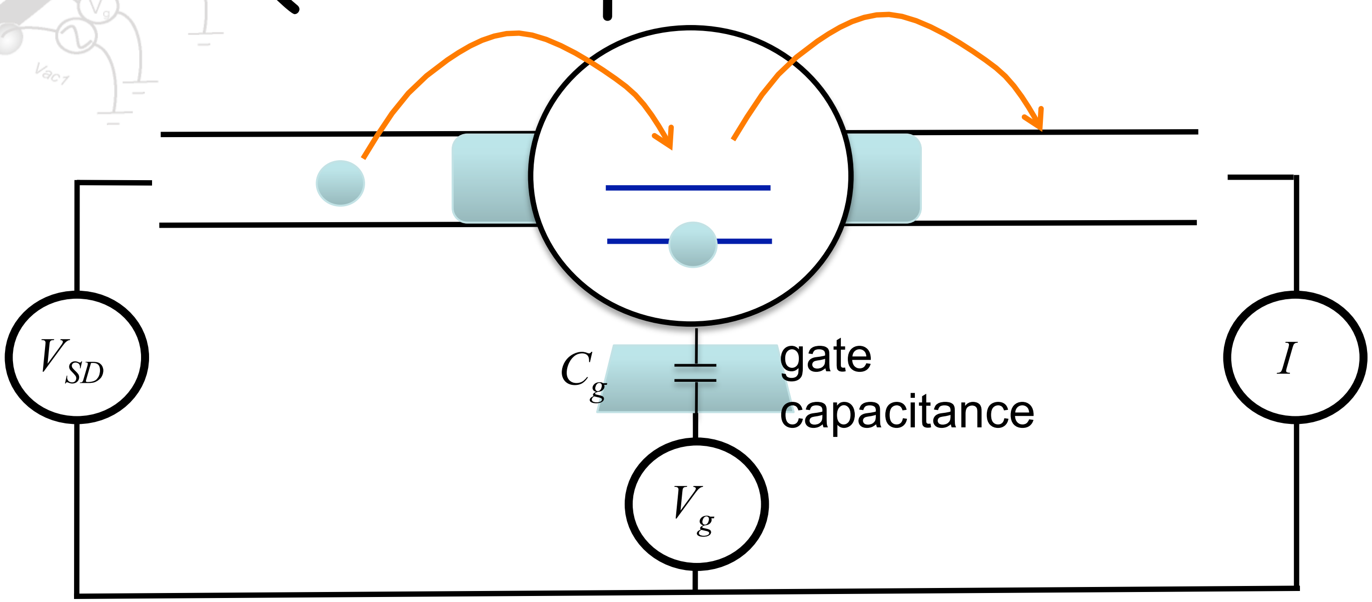
Jung et al. APL05

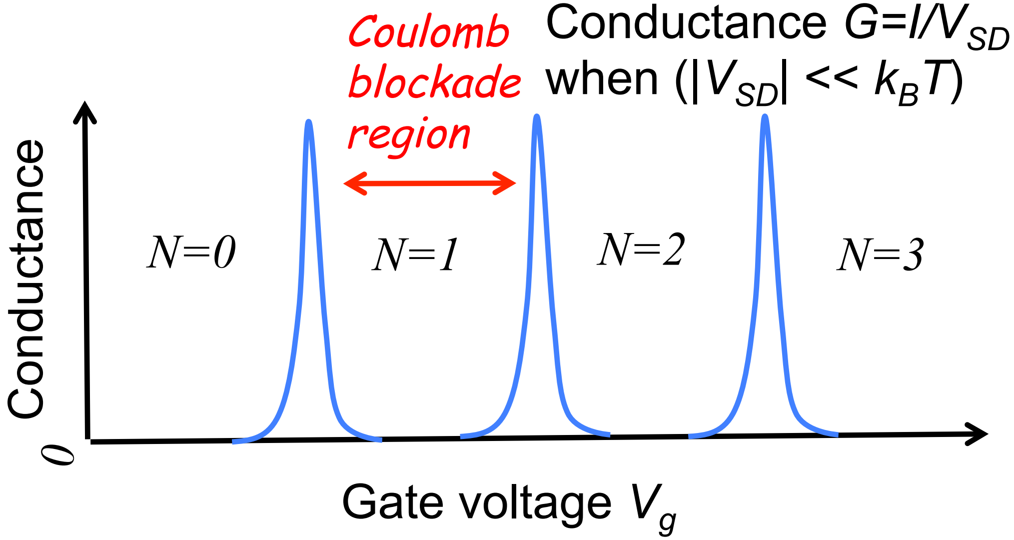


Ciorga et al. PRB 02



QDs coupled to the leads





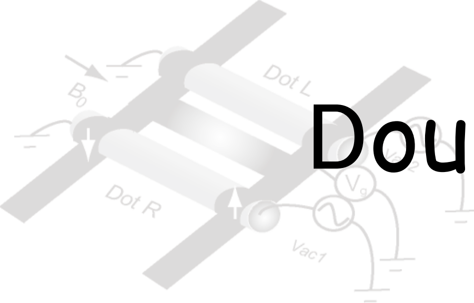
Conductance $G=I/V_{SD}$ is peaked when ($|V_{SD}| << k_BT$)

Total energy of N electrons

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

Constant interaction model: $U \equiv \dfrac{e^2}{2C}$

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

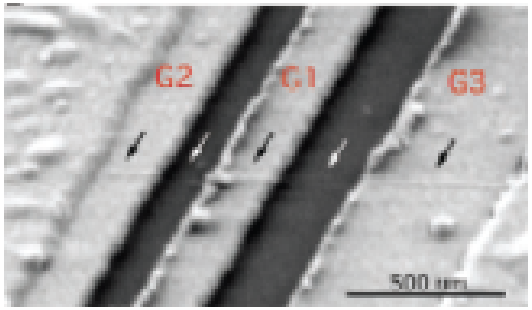


Double QDs holiding few electrons

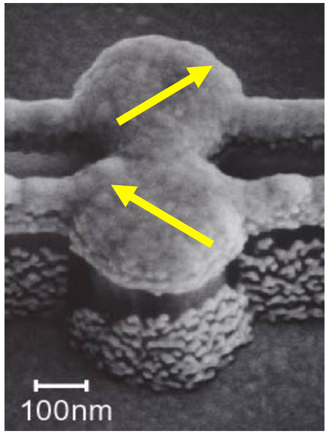
Fabrication of two QDs is straightforward extension in top-down approach, but realizing tunable coupling between the two QDs and going into few electron regime is not a simple task.

Advent of two-electron double QDs

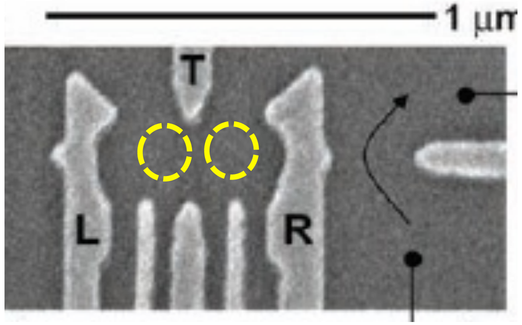
nanotube



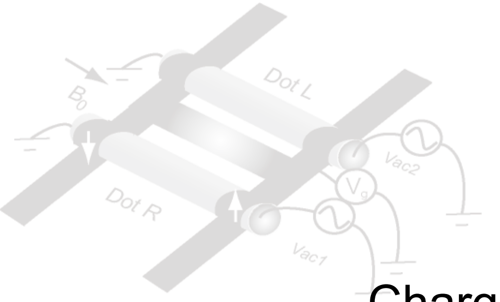
Mason et al. Science 04



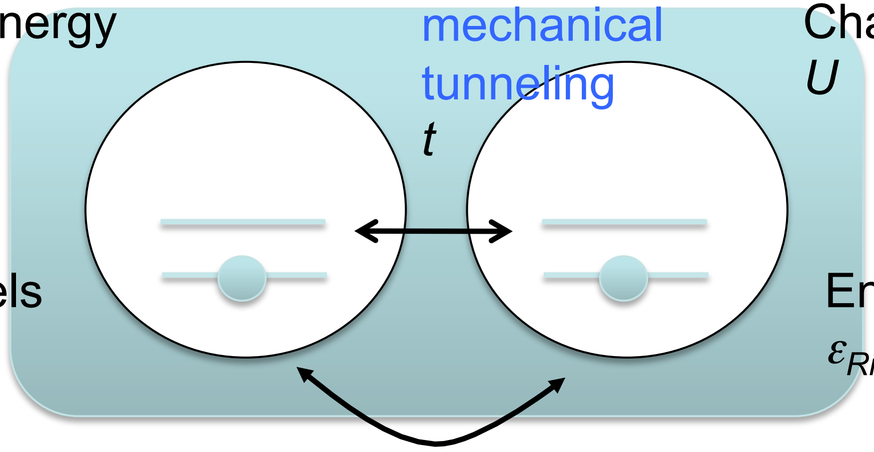
Hatano et al. Science 05



Petta et al. Science 04



Coupled quantum dots



Charging energy
U

Quantum mechanical tunneling
t

Charging energy
U

Energy levels
ε_{Li}

Energy levels
ε_{Ri}

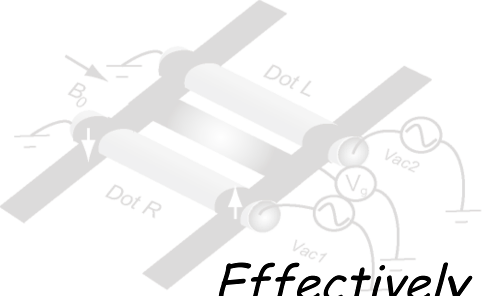
V Inter-dot Coulomb interaction

Minimum realization of Hubbard model:

$$\begin{aligned}\mathcal{H}_{DQD} \quad = \quad & \sum_{\mu=L,R} \sum_{\sigma} \varepsilon_\mu \hat{a}^\dagger_{\mu,\sigma} \hat{a}_{\mu,\sigma} - t(\hat{a}^\dagger_{L,\sigma} \hat{a}_{R,\sigma} + \mathrm{H.c.}) \\ & + U \sum_{\mu=L,R} \hat{n}_{\mu,\uparrow} \hat{n}_{\mu,\downarrow} + V \hat{n}_L \hat{n}_R\end{aligned}$$

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

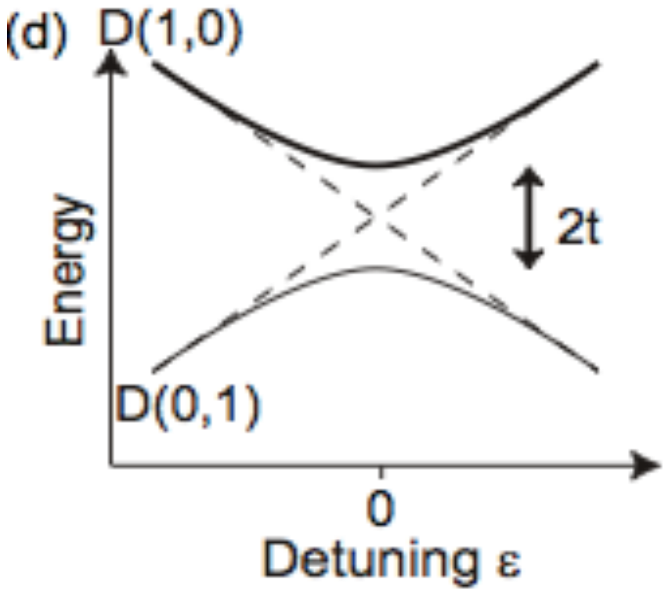
$$\hat{n}_\mu \equiv \sum_\sigma \hat{n}_{\mu,\sigma}$$

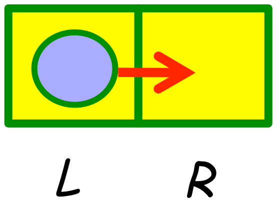


Charge qubit

Effectively one electron in coupled QDs is simple two level system: charge qubit.

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

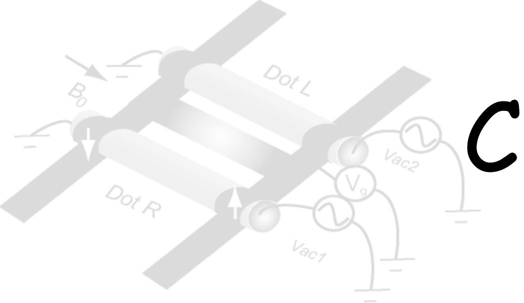




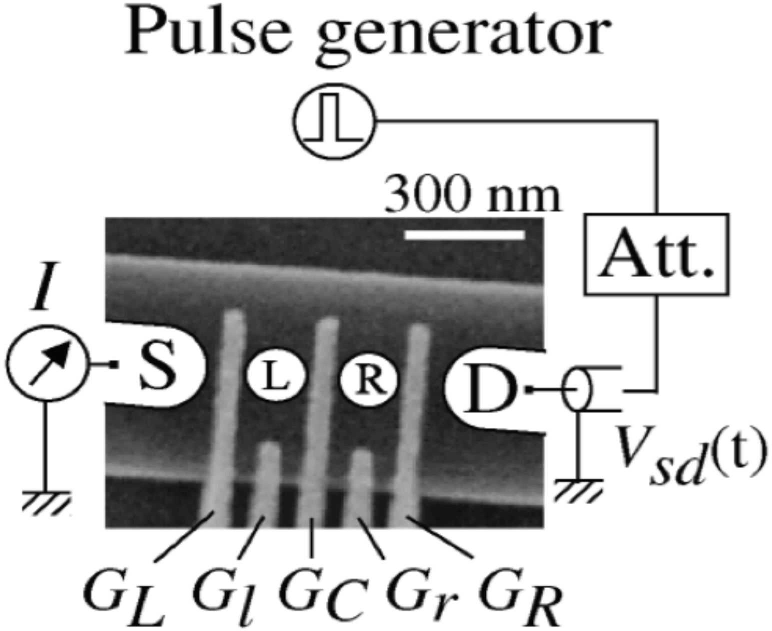
Detuning energy

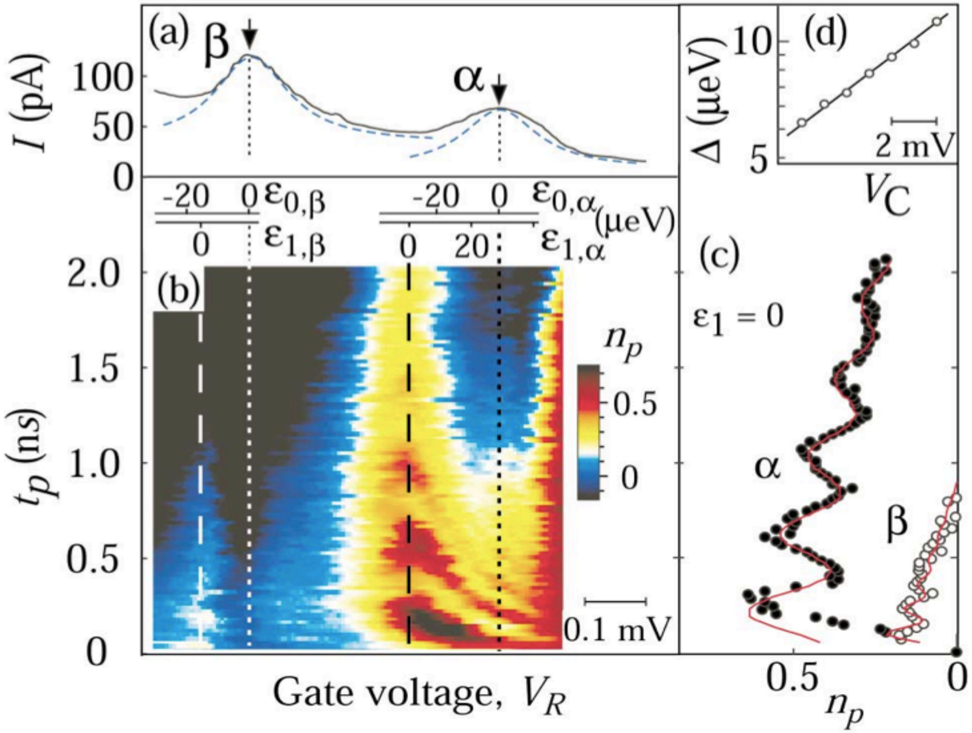
$$\varepsilon \equiv \varepsilon_L - \varepsilon_R$$

(n_L,n_R) represents n_L and n_R electrons in the left and right QDs, resp.



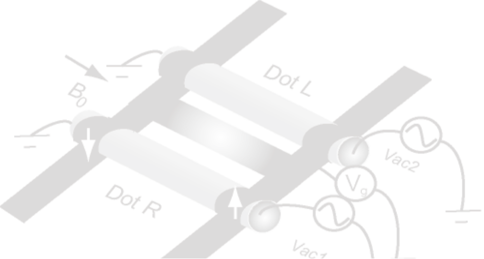
Charge qubit experiments



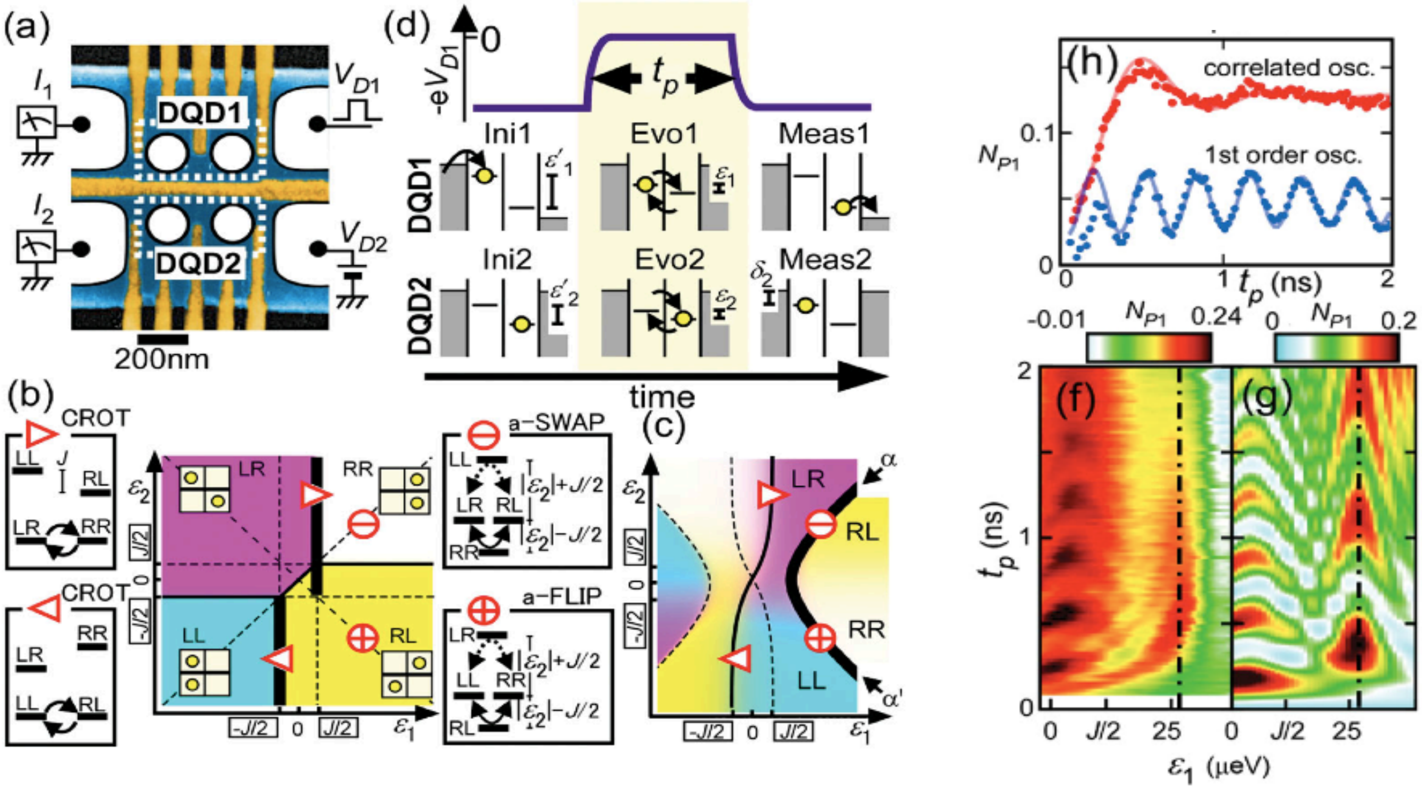


T^*_{Rabi}~1 ns
Origin:Cotunneling, Phonon

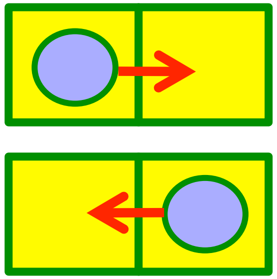
T. Hayashi, et al., Phys. Rev. Lett. 91, 226804 (2002).



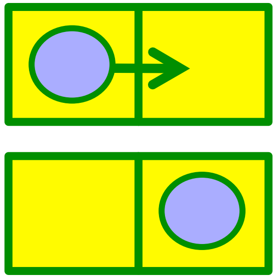
Coupled charge qubits



Mutual coherent osc.



Conditional coherent osc.

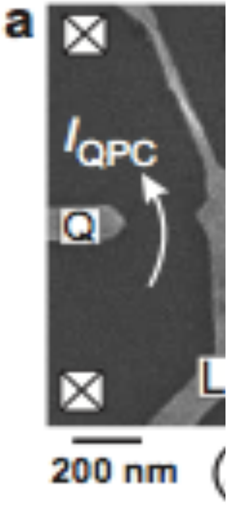


$$\mathcal{H}_{2DQD} = \frac{1}{2}\sum_i(\varepsilon_i\sigma_z^{(i)} - t_i\sigma_x^{(i)}) + \frac{J}{4}\sigma_z^{(1)}\otimes\sigma_z^{(2)}$$

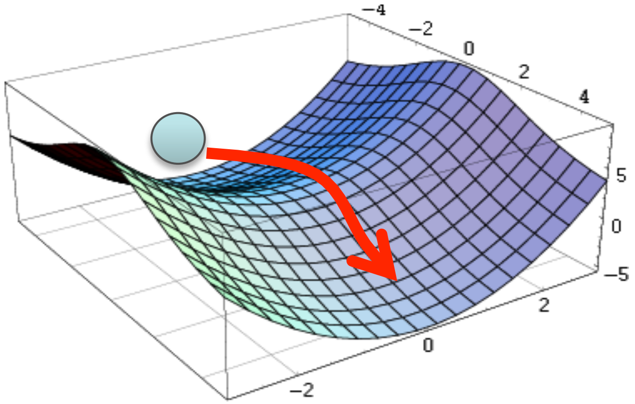
G. Shinkai, et al., Phys. Rev. Lett. 103, 056802 (2009).

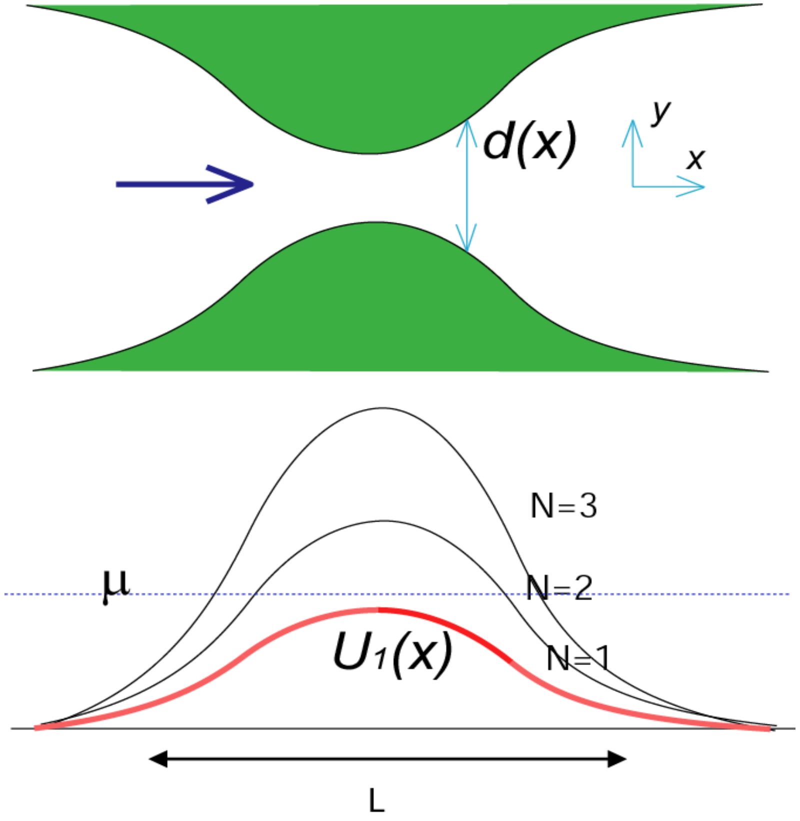
Quantum point contact (QPC)

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



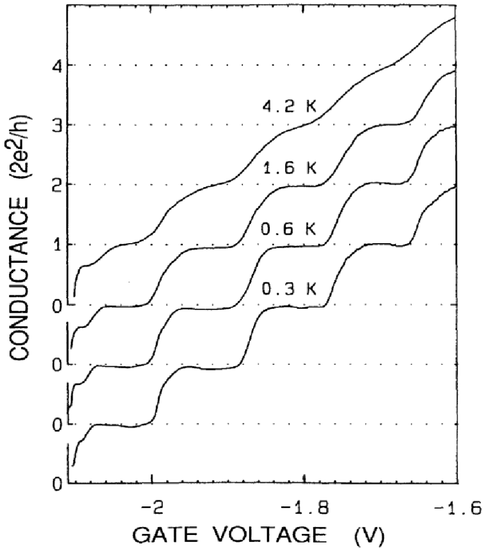
Landscape near QPC is the saddle point potential.



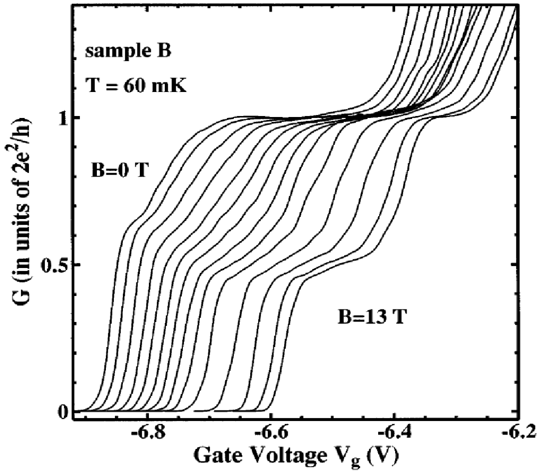


都倉康弘、固体物理 37 (2002) 363.

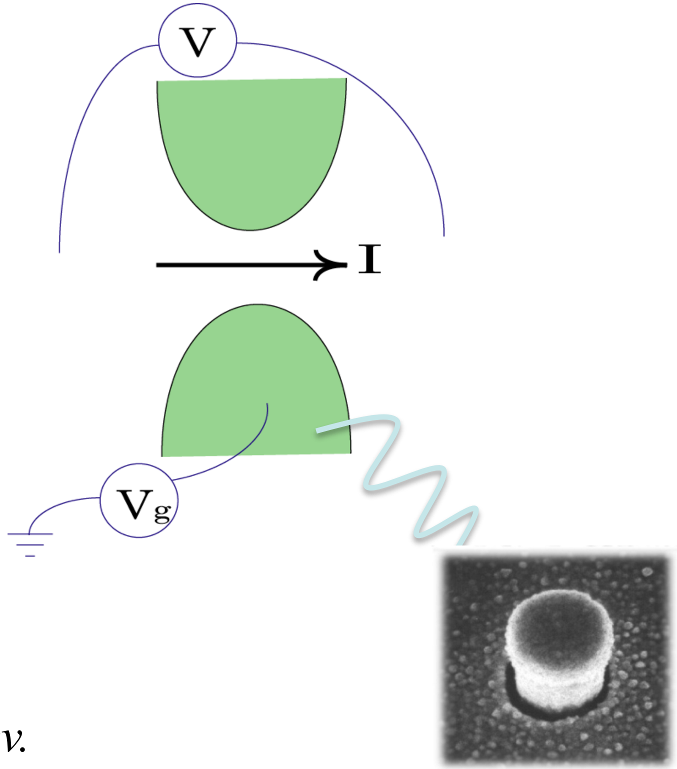
Quantized conductance- charge detection



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

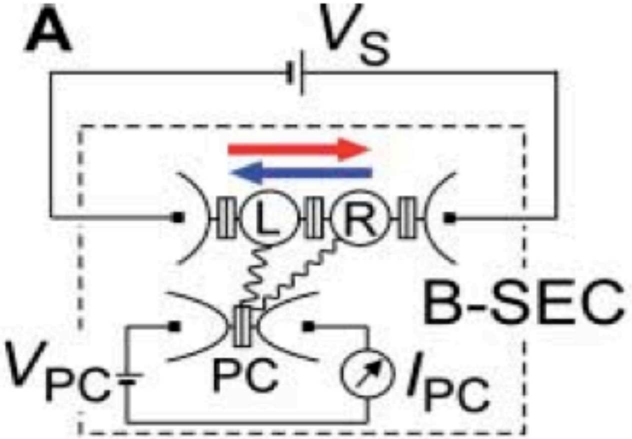


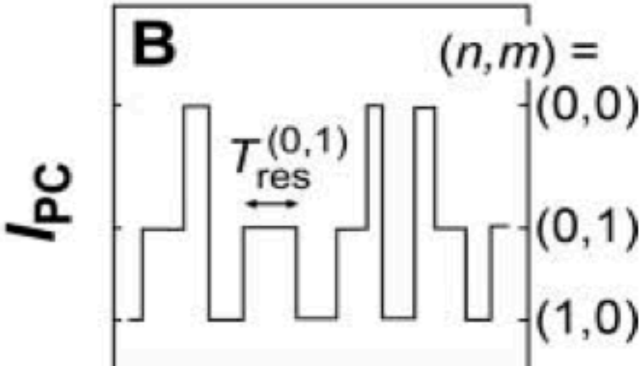
K.J.Thomas, et al, Phys. Rev. Lett. 77, 135 (1996).



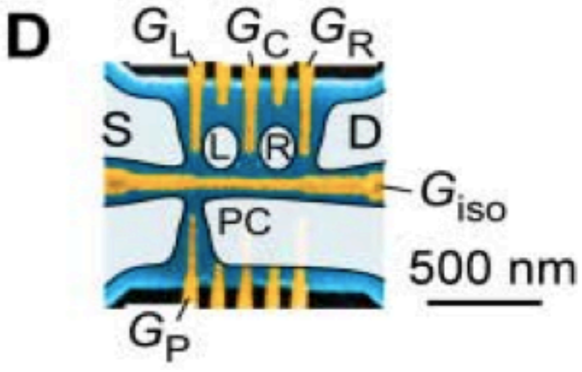
Accurate charge detector

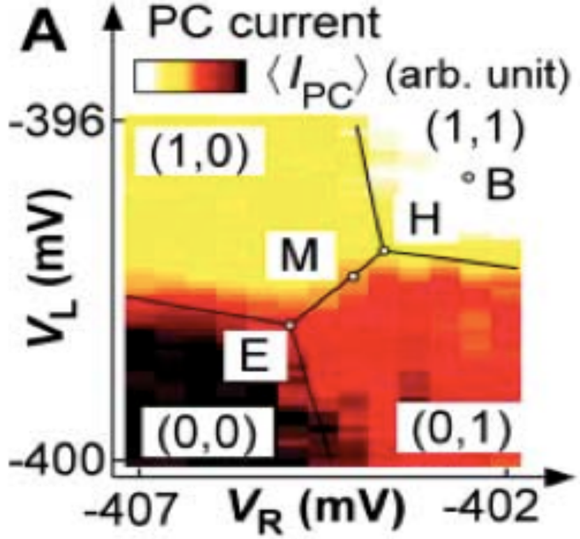
Counting electrons

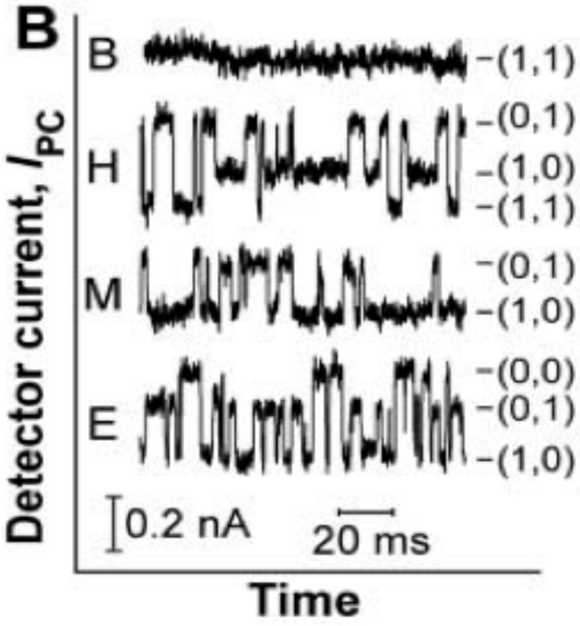




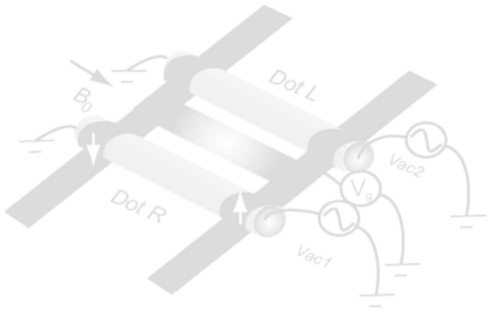
Real-time monitoring of the dynamics of the electron



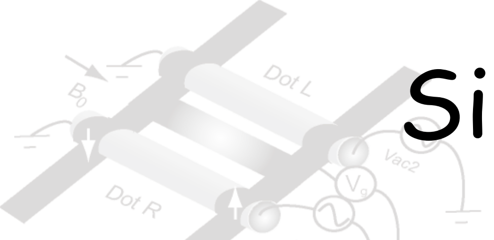




T. Fujisawa, et al., Science 312, 1634 (2006).



Spin detection



Single spin magnetic moment

Electron spin: tiny object

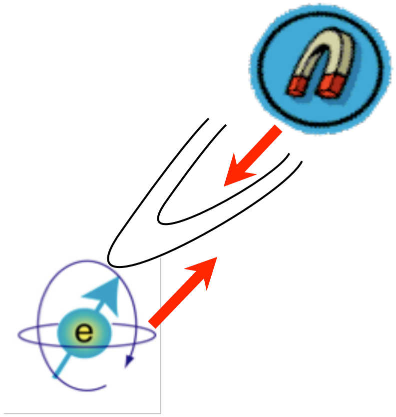
Electron magnetic dipole moment

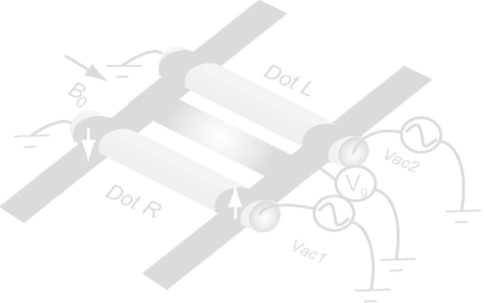
$$\begin{aligned}\mu_e &= -g\mu_B\frac{S}{\hbar} = -\frac{e\hbar}{4m_e}\\ U_z &= -\mu_e B\\ &= 2\times 10^{-24}B(T)J\end{aligned}$$

Force in a gradient field

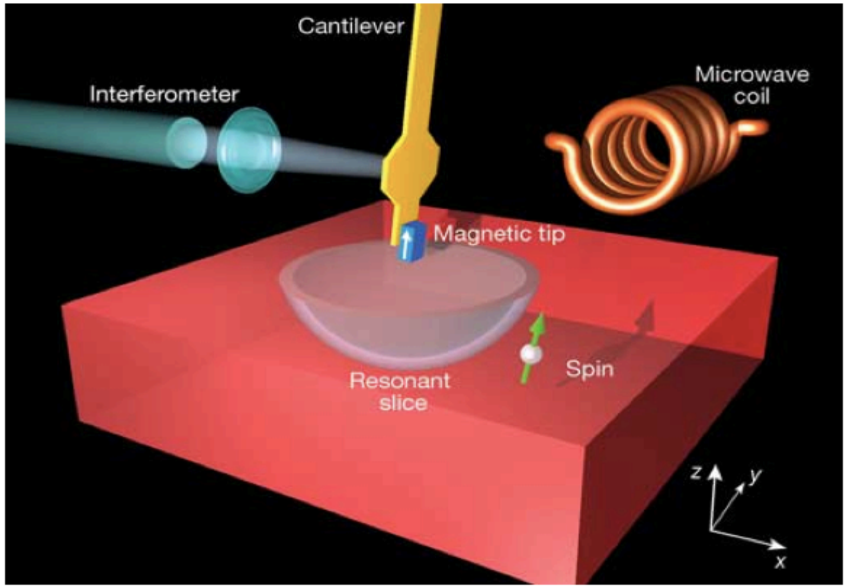
$$\begin{aligned}F_z &= \frac{\partial U_z}{\partial r}\\ &= 2\times 10^{-24}\frac{\partial B(T)}{\partial r}N\\ &= 2b_{sl}(\frac{T}{\mu m})aN\end{aligned}$$

Very weak interaction with the environment.



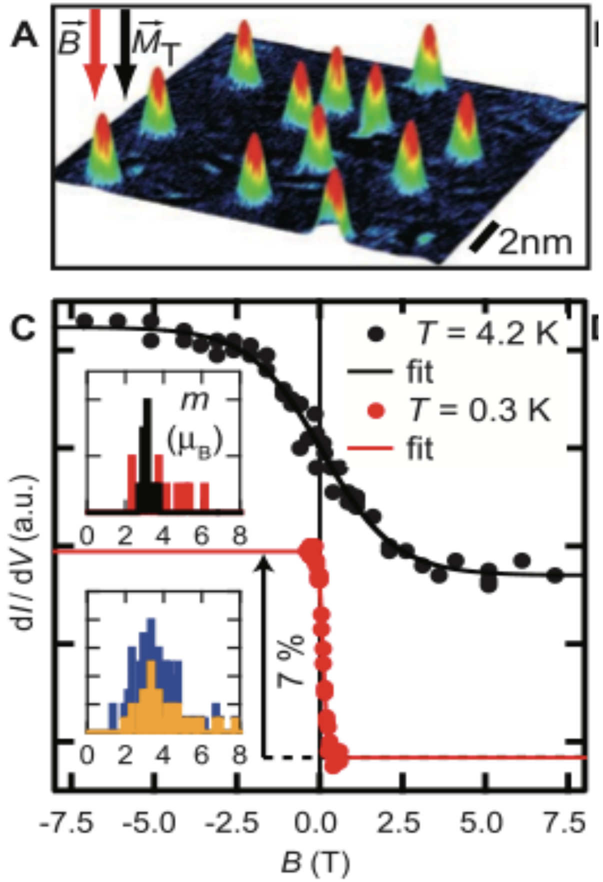


Single spin detection



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

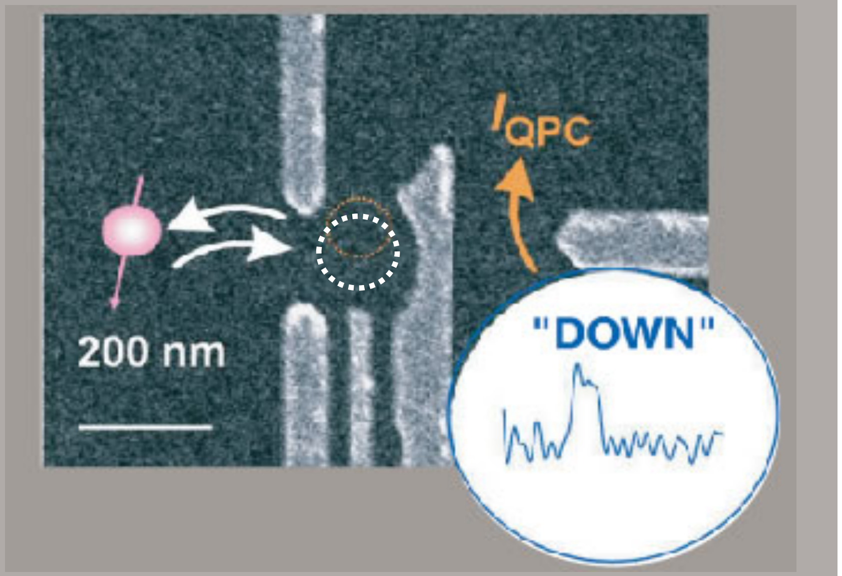
F. Meier, et al., Science 320, 82 (2008).

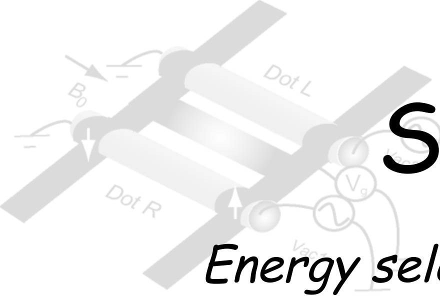
Basic idea: spin-charge conversion

Although, the detection of magnetic moment is hard, by combining the spin with the orbital motion, we can detect the accompanying charge displacement or the current by charge detector or current meter.

Single-shot

Elzerman et al. Nature (2004)

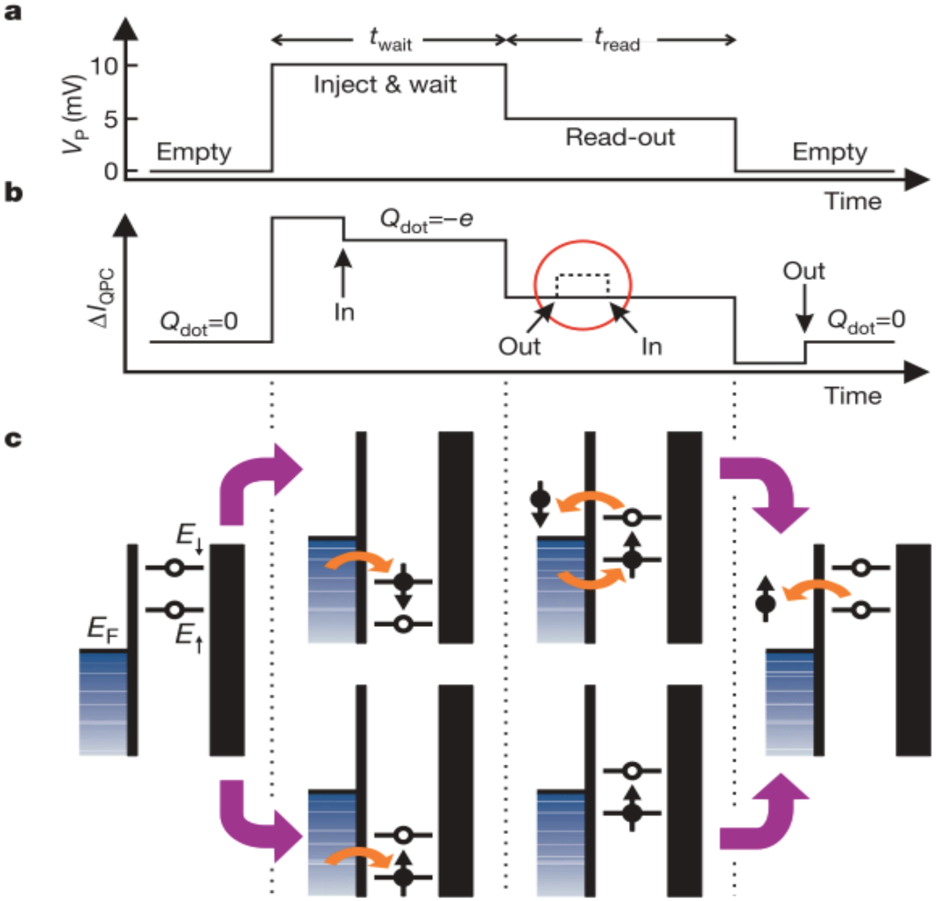


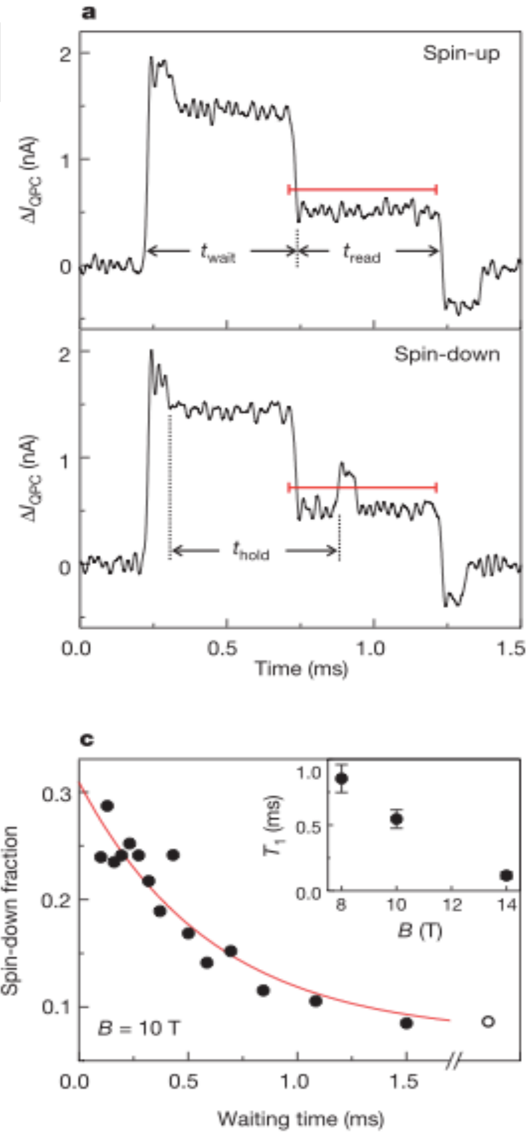


Single shot spin measurement

Energy selective

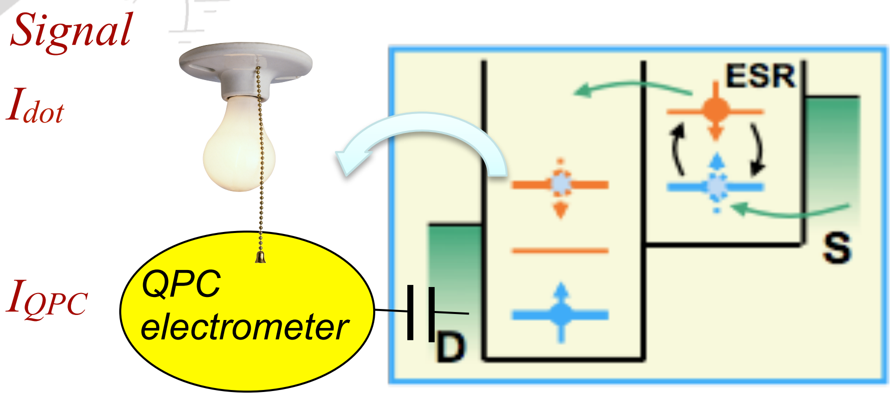
Zeeman energy $E_Z >> k_B T$



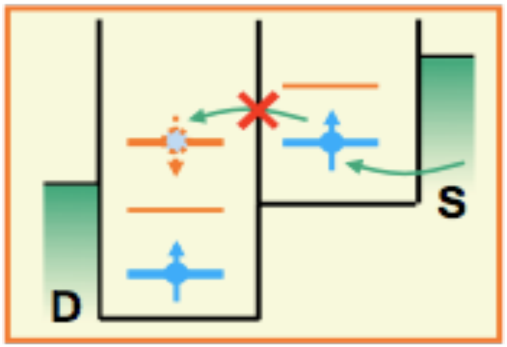


J. M. Elzerman, et al., Nature 430, 431 (2004).

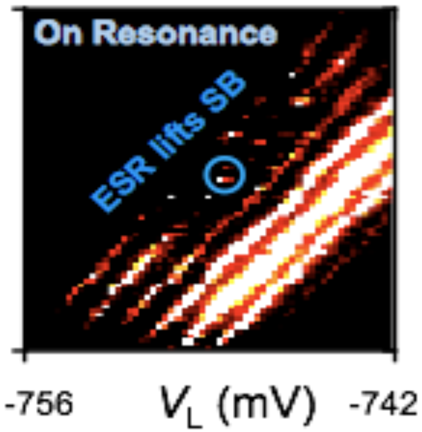
Spin detection using spin blockade



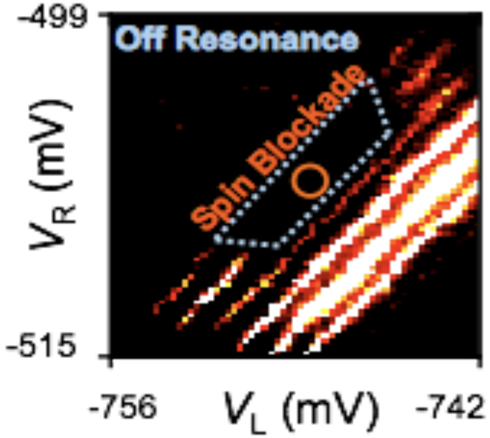
Spin triplet states



(1,0)←(2,0)←(1,1)←(1,0)

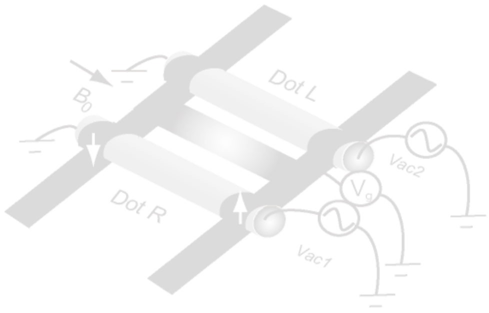


(1,0)←(2,0)✕(1,1)←(1,0)

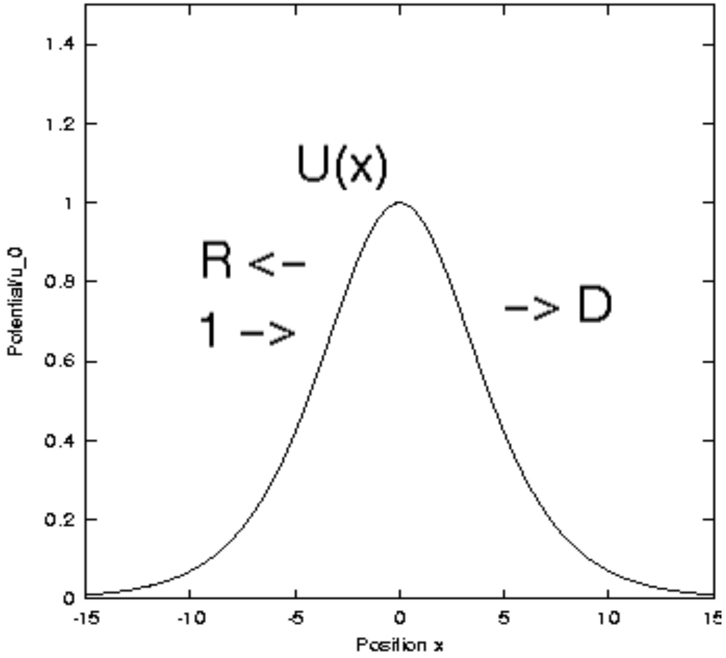


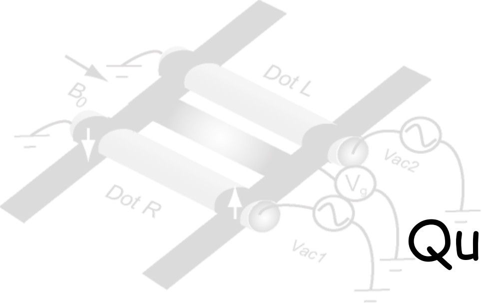
Signal only discriminates spin singlet/triplet or the event of spin flip.

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


B_0
Dot L
Dot R
Vac2
Vac1
V_g

End of Part I


U(x)
R <-
1 ->
-> D
Potential/u_0
Position x
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-15
-10
-5
0
5
10
15



半導体を用いた量子情報処理
Quantum information processing in semiconductors

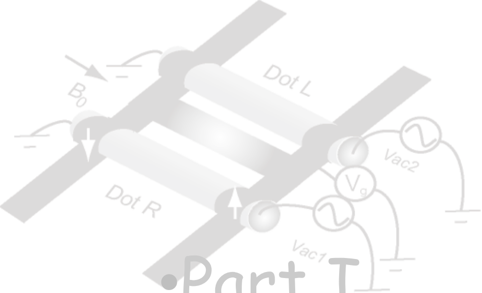
Part II

Exchange only qubits

Single spin qubits

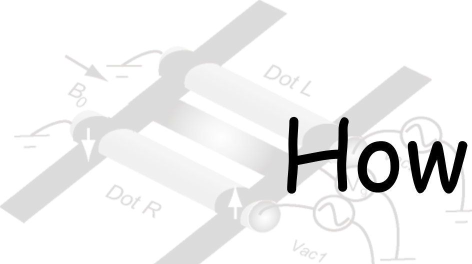
Flying qubits

Plan of this lecture



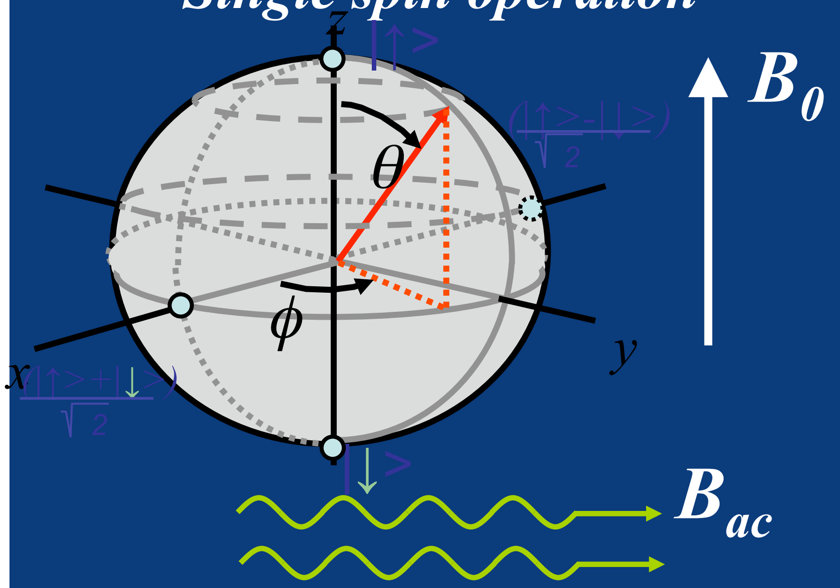
- Part I
  - Quantum dots (QDs), Double quantum dots
  - Charge qubits
  - Quantum point contacts: charge detection
  - Spin detection - Spin to charge conversion

- Part II
  - Single spin qubits
  - Exchange based (only) qubits
  - Flying qubits
  - Prospective



How to manipulate electron spins?

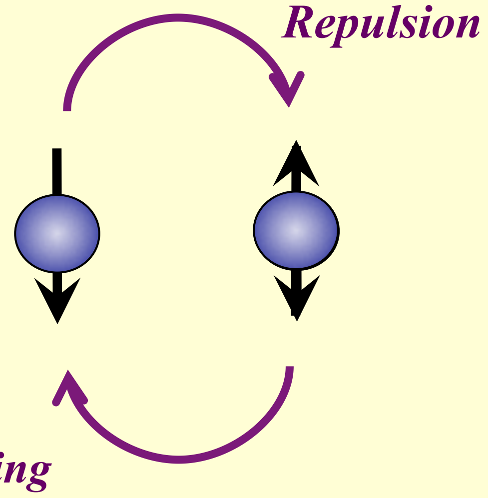
Single spin operation



Electron Spin Resonance

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

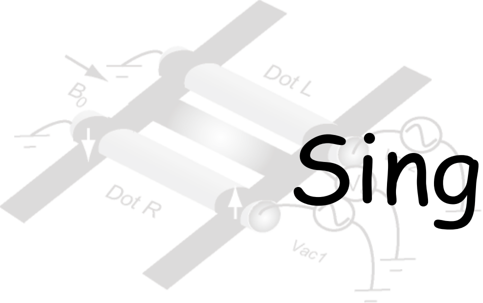
Two-spin operation



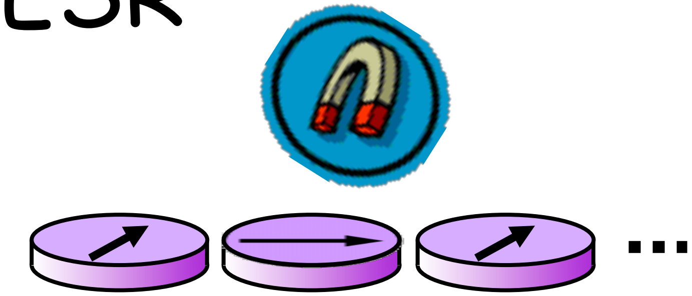
Exchange $J\mathbf{S}_1\cdot\mathbf{S}_2$

J electrically controlled

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

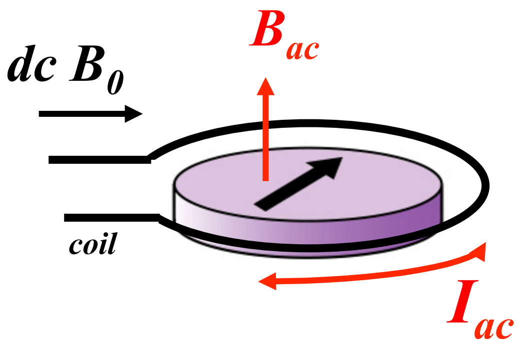


Single spin addressable ESR



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

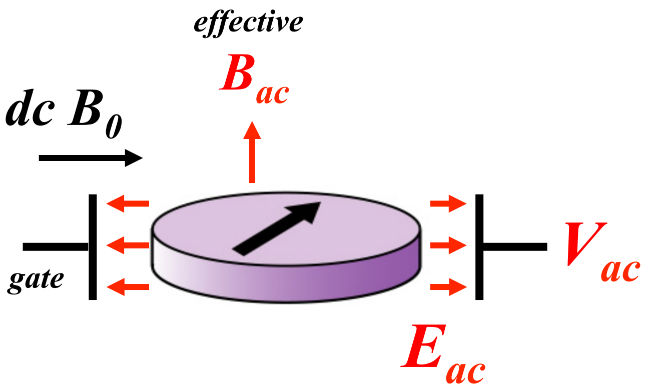
Current driven ESR



I_{ac} = 1 mA, B_{ac} ~ 1 mT
π rotation: ~ 80 ns

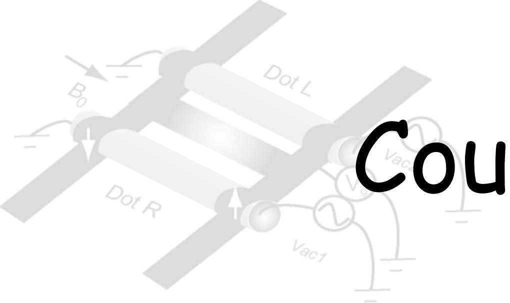
Heading problem.
Difficult to localize.

Voltage driven ESR (EDSR)



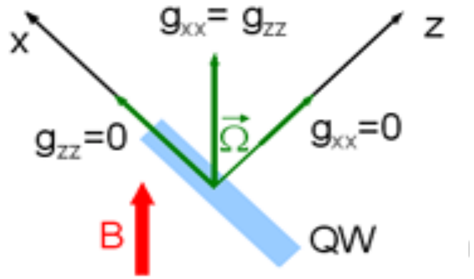
V_{ac} = 1 mV, E_{ac} ~ kV/m

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



Coupling mechanisms for EDSR

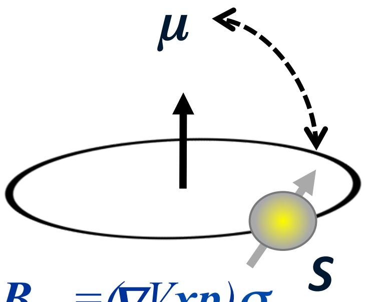
g-tensor modulation



Y. Kato
Science 2003,
R. Deacon
PRB 2011

g-tensor
engineering

Spin-orbit

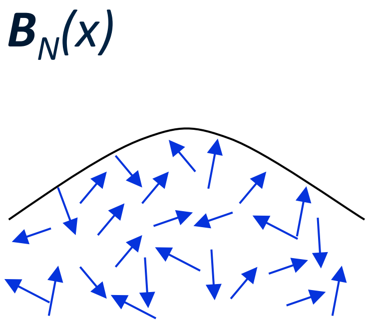


$B_{loc}=(\nabla V \times p)\sigma$

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

Material dep.
small in GaAs

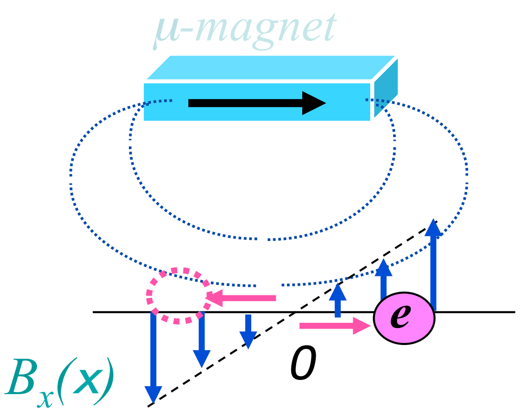
Hyperfine int.



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

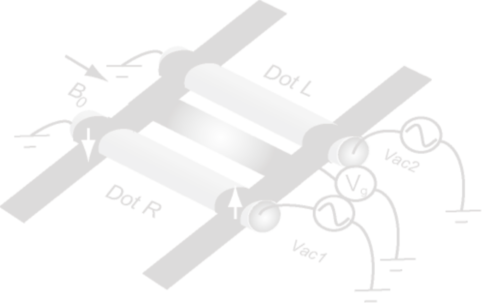
not-coherent

Slanting Zeeman field



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

μ-magnet fabrication
addressable



Spin addressability

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

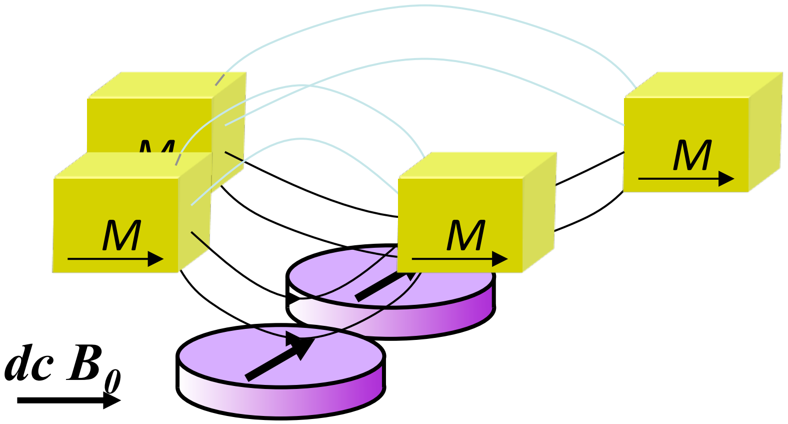
Assign different Zeeman energies to address them: $E_{zeeman}=g\mu_B B$

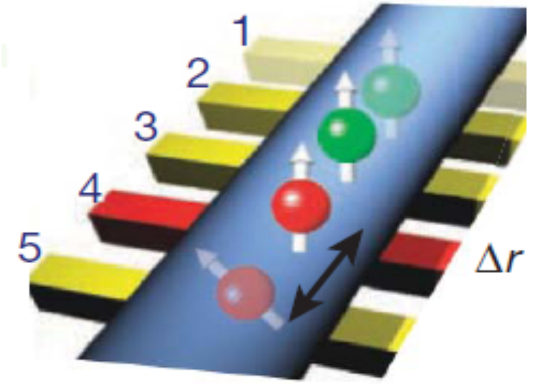
Control B

Control g

Micromagnets: GaAs coupled dots

Spin-orbit interaction: InAs nanowire

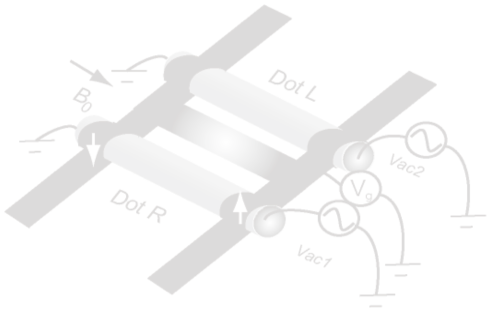




Size/shape of dots determines the value of g.

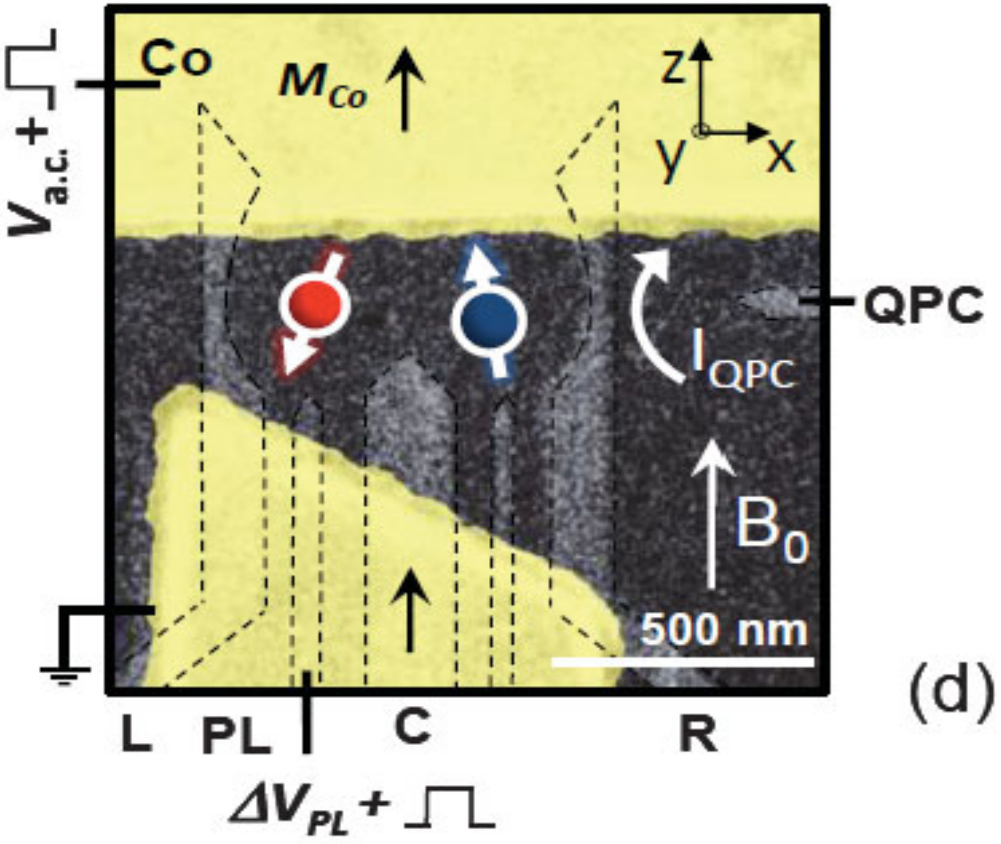
T. Obata et al. PRB (2010)
R. Brunner et al. PRL (2011)

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***

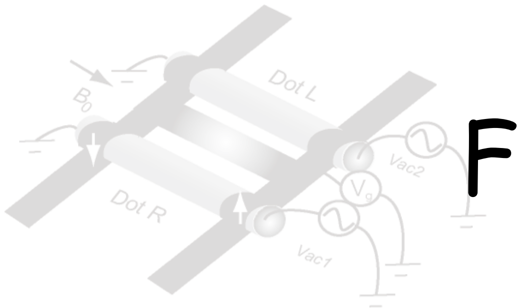
  ESR detection

  Koppens et al. Nature (2006)

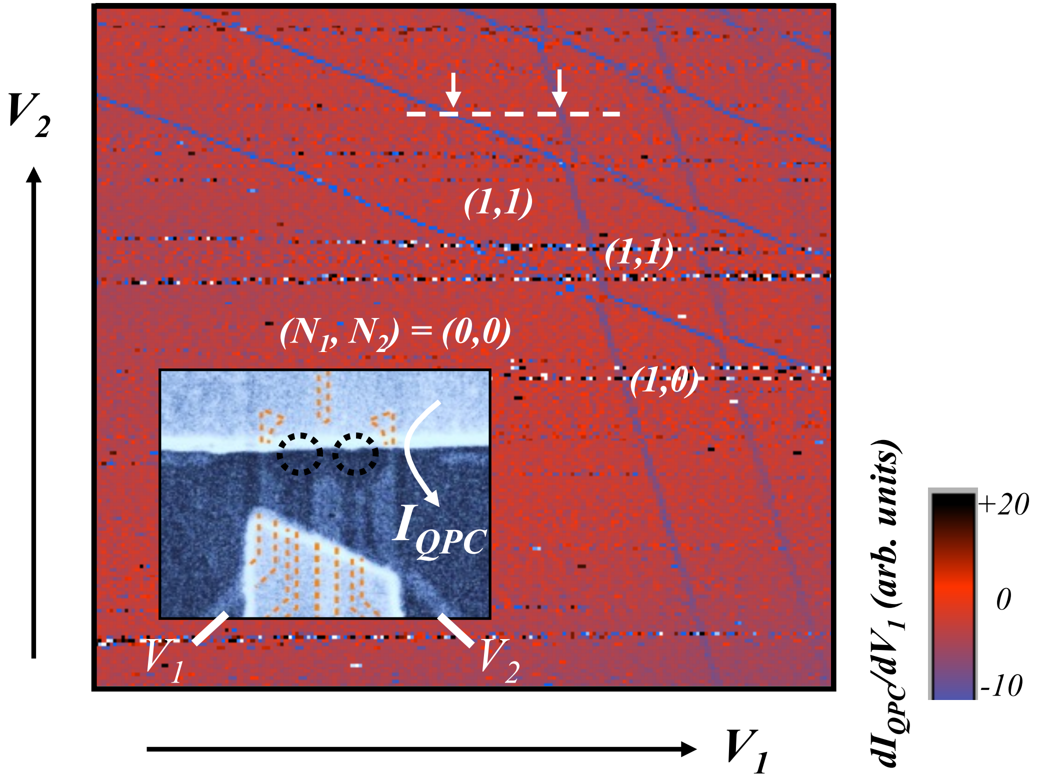
- ***Split type micro-magnets***

  Slanting magnetic field

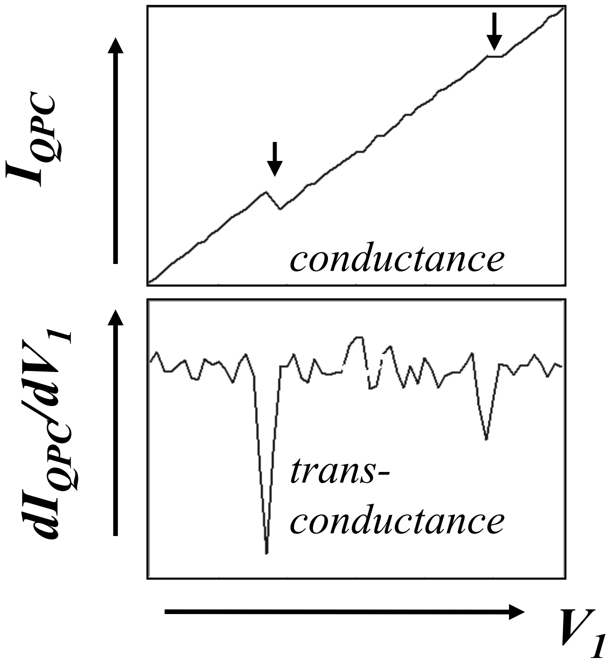
  & Addressability



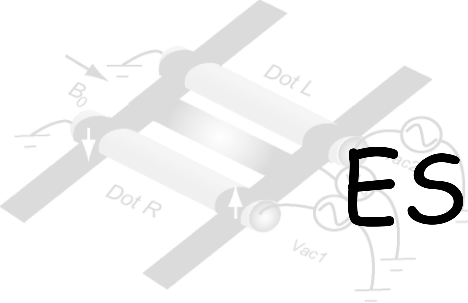
Formation of a double-dot



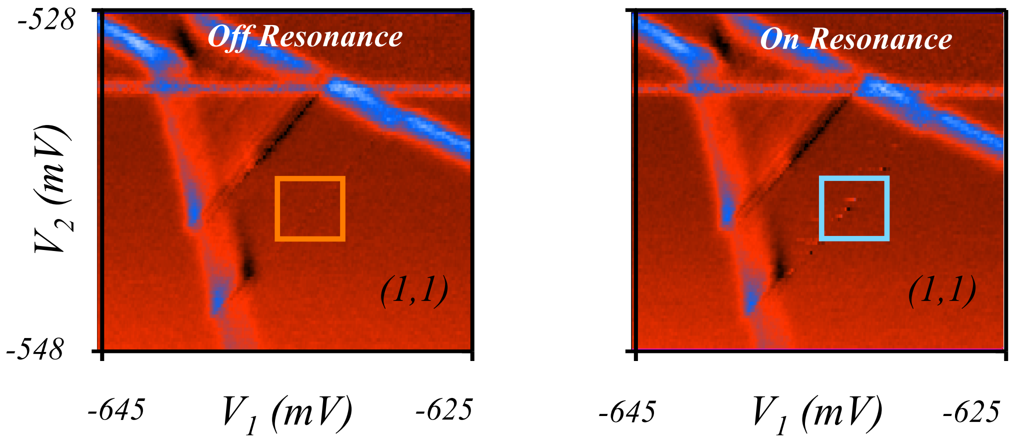
Stability diagram (transconductance)

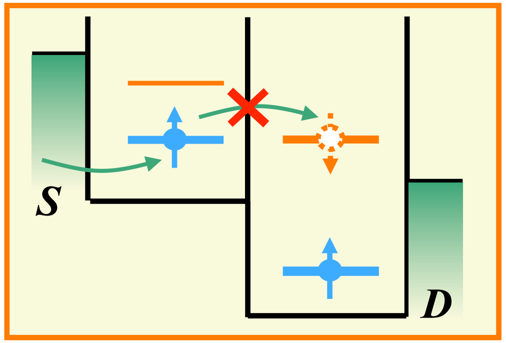


Charge sensing

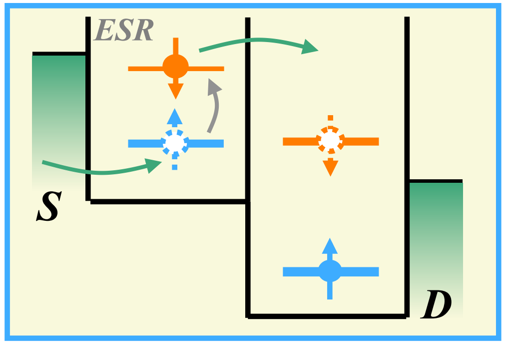


ESR lifts off the spin blockade



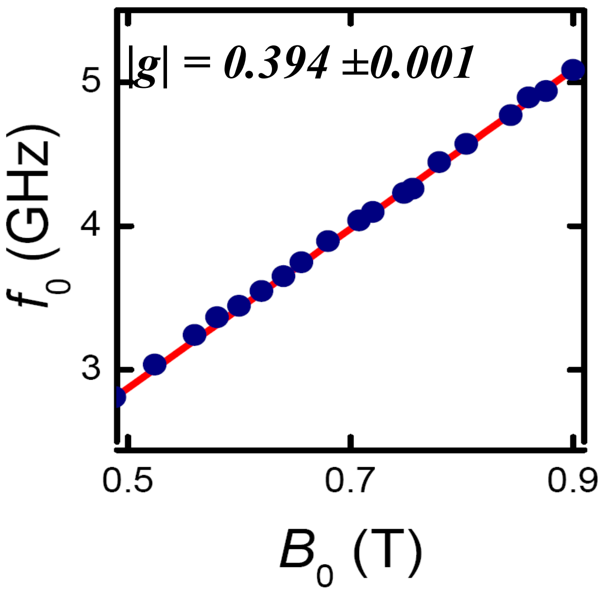


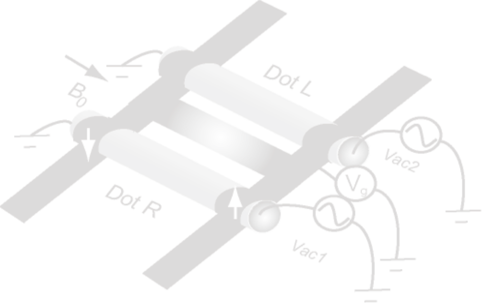
Blocked



Unblocked

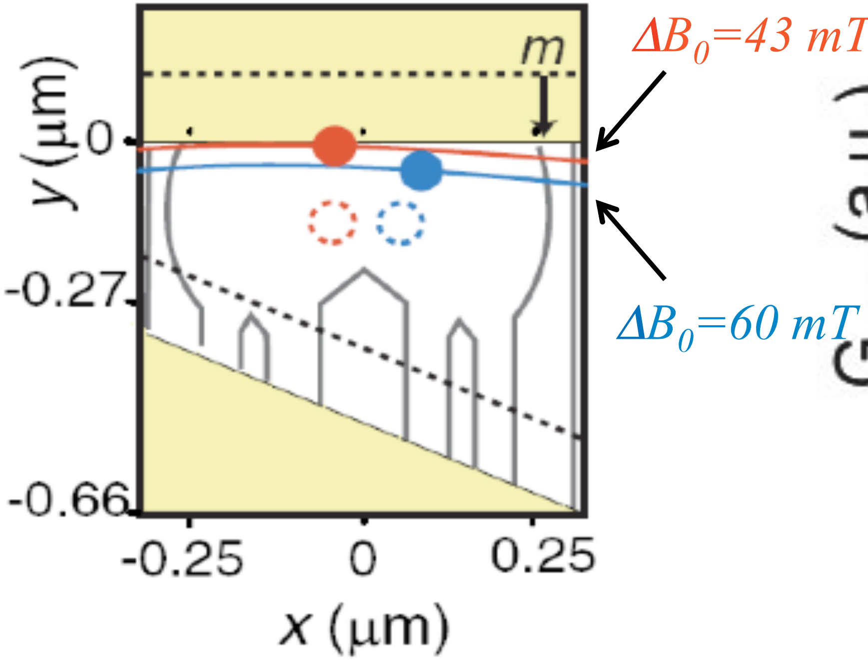
Continuous microwave excitation
f = 5.66 GHz, -34 dBm



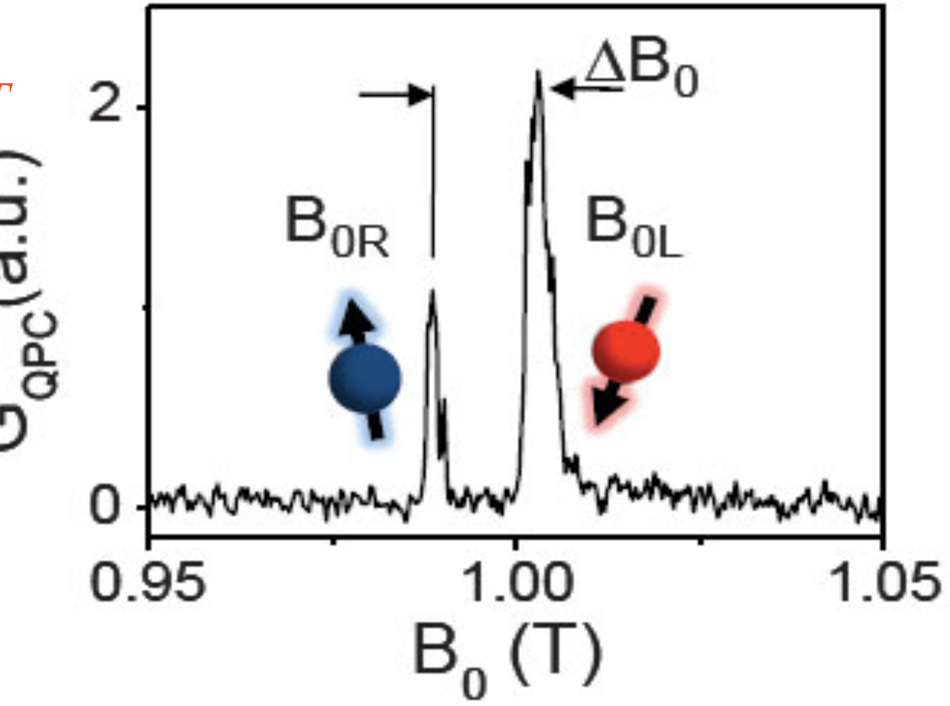


Two-spin addressing

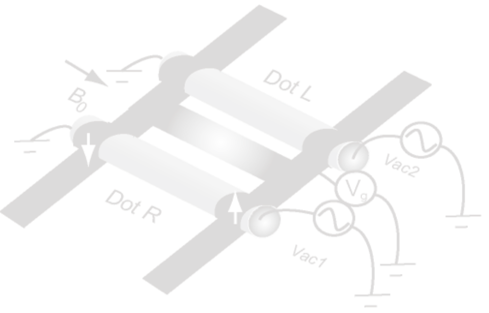
Simulation results



➔ $b_{SL1} = 0.15$ T/μm, $b_{SL2} = 0.26$ T/μm

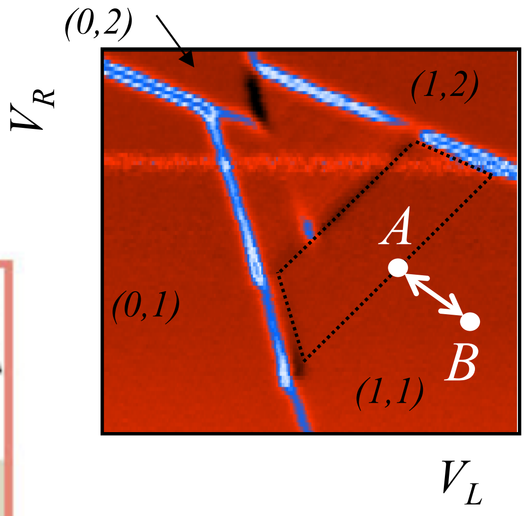


Misalignment m: 4x smaller b_{SL} than for optimal configuration.

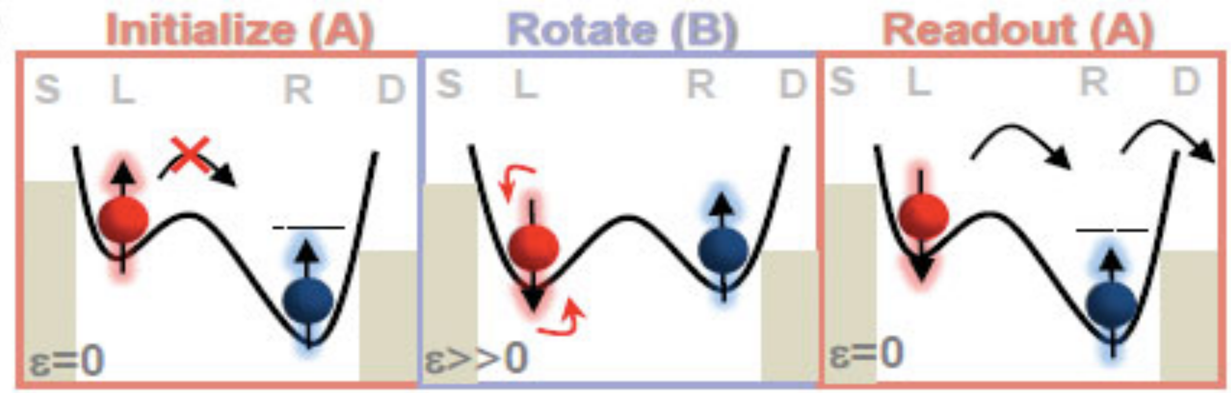


B_0
Dot L
Dot R
Vac2
Vac1
V_g

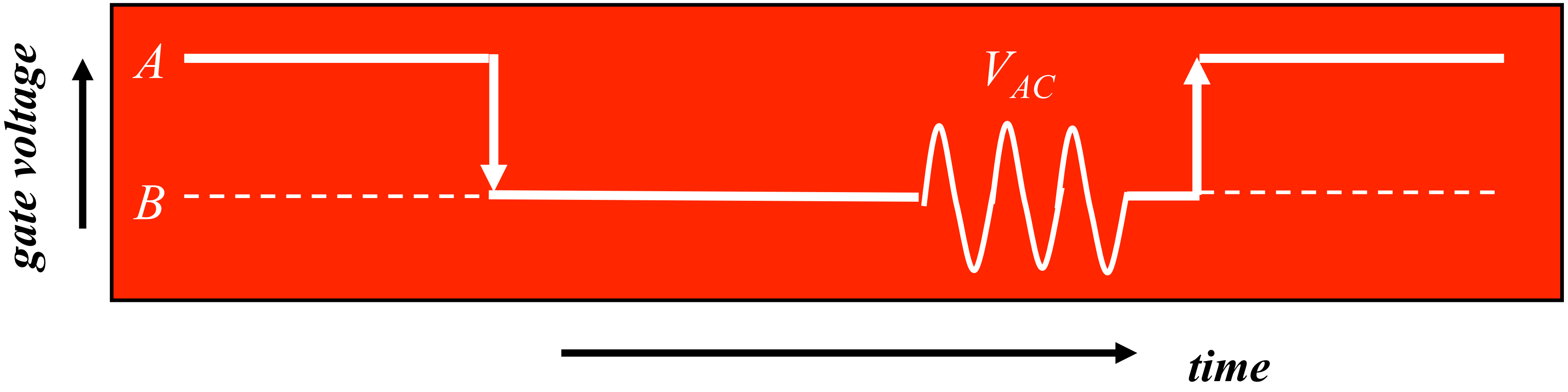
Pump & Probe



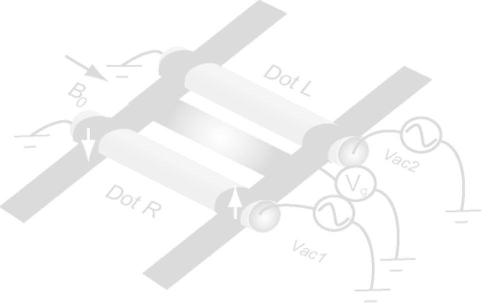
(0,2)
(1,2)
(0,1)
(1,1)
A
B
V_R
V_L



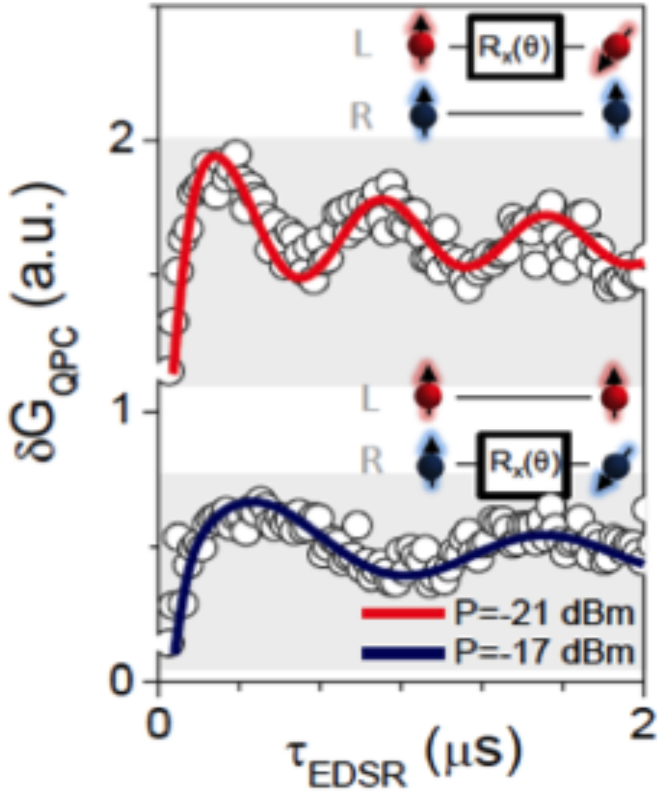
Initialize (A)
Rotate (B)
Readout (A)
S L R D
S L R D
S L R D
ε=0
ε>>0
ε=0



gate voltage
A
B
V_{AC}
time



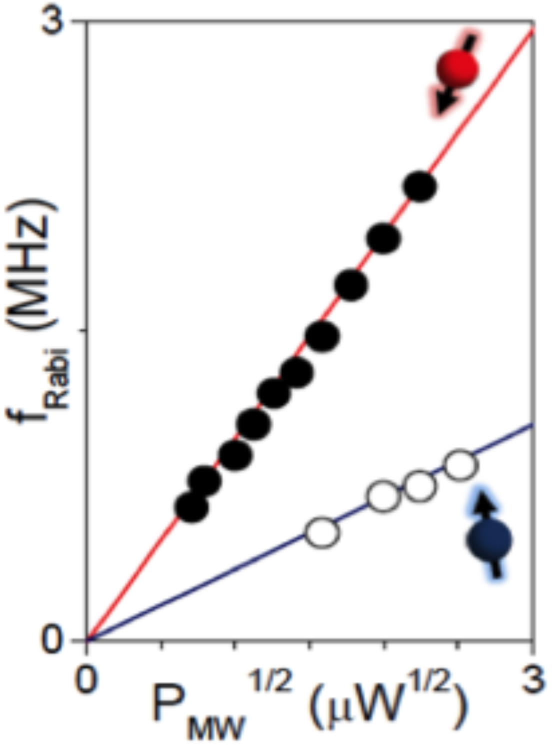
Rabi Oscillations



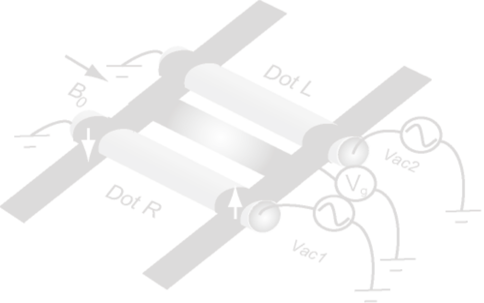
Fitting: Koppens et al. PRL 2007

$B \sim 2$ T

$f_{AB} \sim 11$GHz



Need improvement of Rabi frequency.



Two qubit operations

Control-Z gate:

$$U_{CZ}=\exp[i(\pi/2)\,S_1^z]\,\exp[-i(\pi/2)\,S_2^z]\,Usw^{1/2}\,\exp[i(\pi)\,S_1^z]\,Usw^{1/2}$$

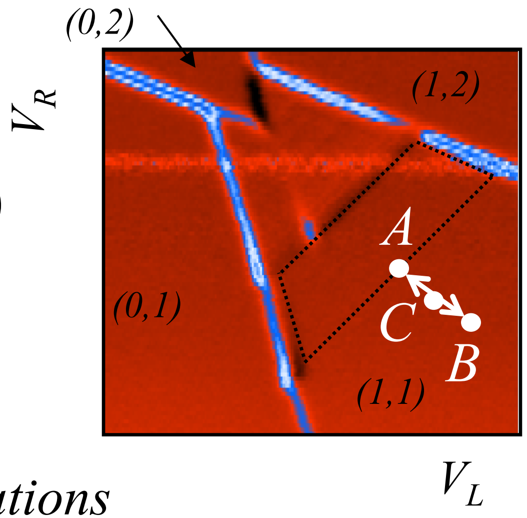
Square root SWAP of U_{SW}
between spin 1 and 2

Square root SWAP is realized with exchange interaction.

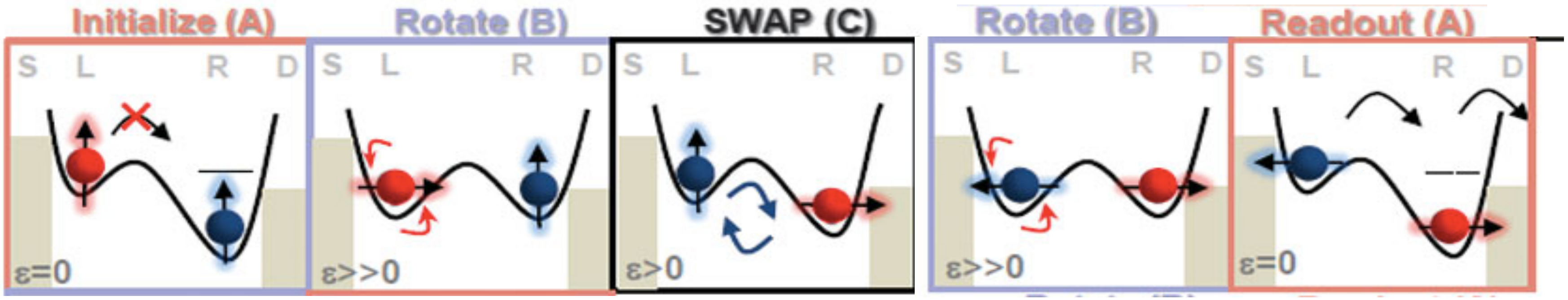
In addition, highly accurate SWAP gate is required to execute algorithm with qubits in chain.

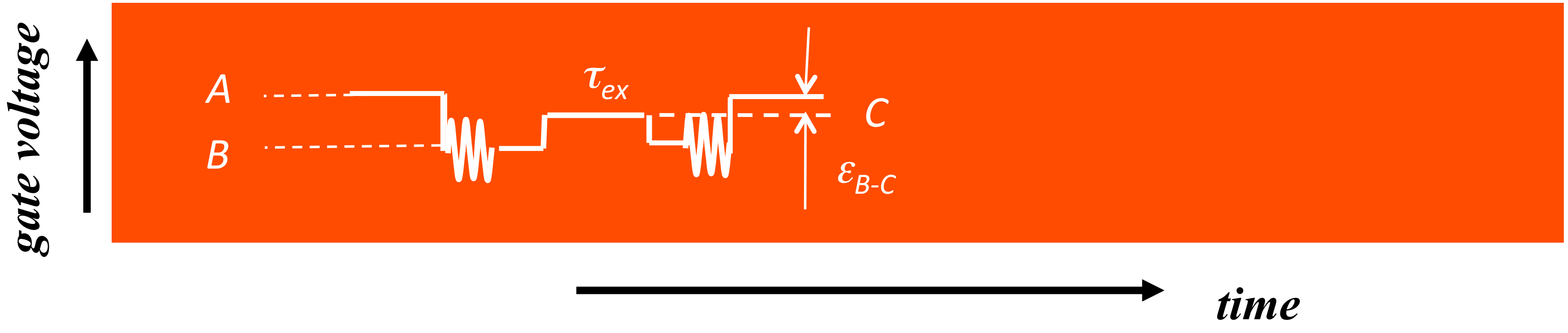
D. Loss and D. DiVincenzo, PRA(1998)

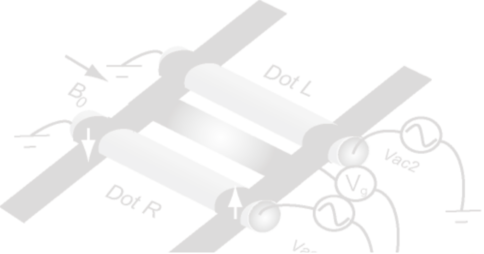
Combination of single and two qubit operations



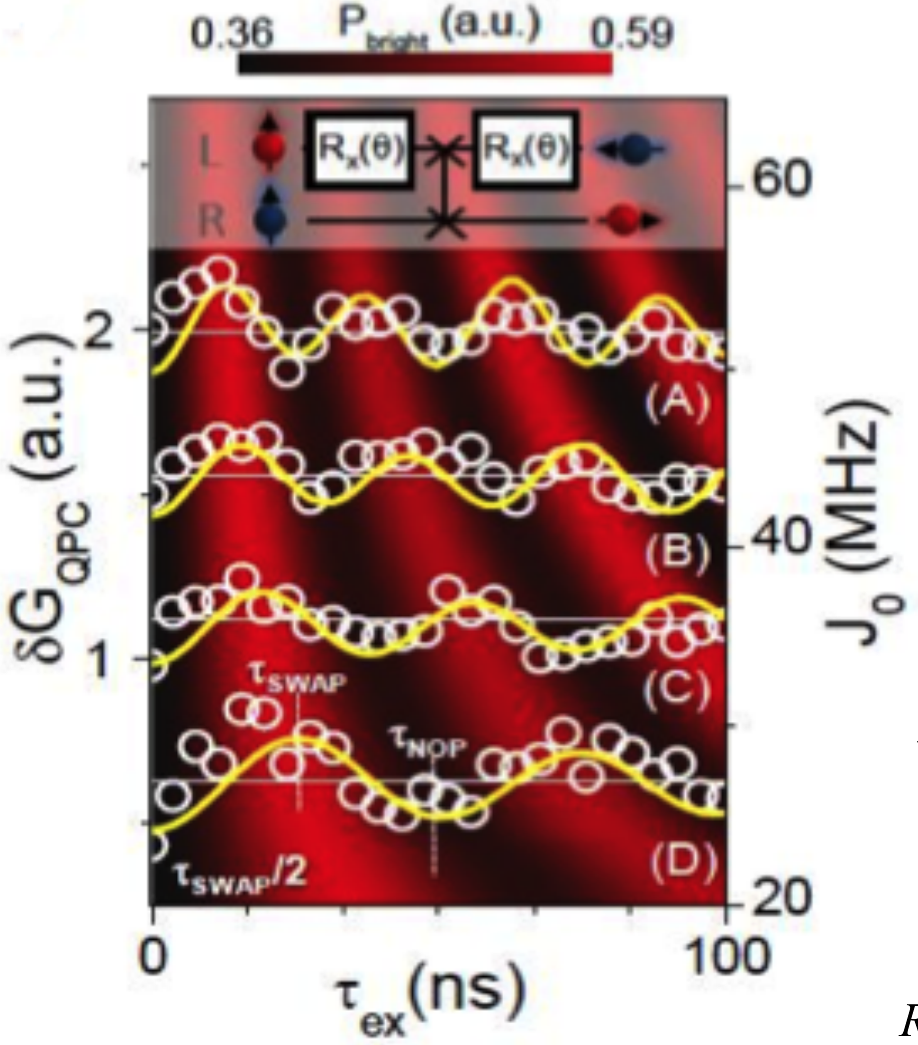
One spin manipulation (Hadamard) + two spin SWAP operations







Experimental

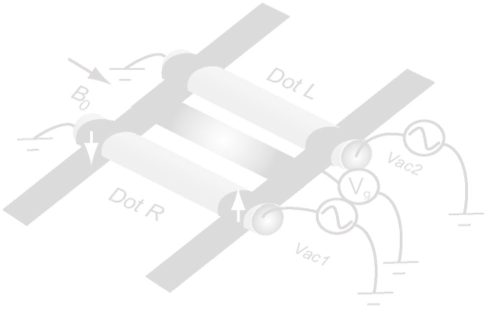


Solid lines:

Average over Gaussian distribution of nuclei

Two qubit operation is confirmed.

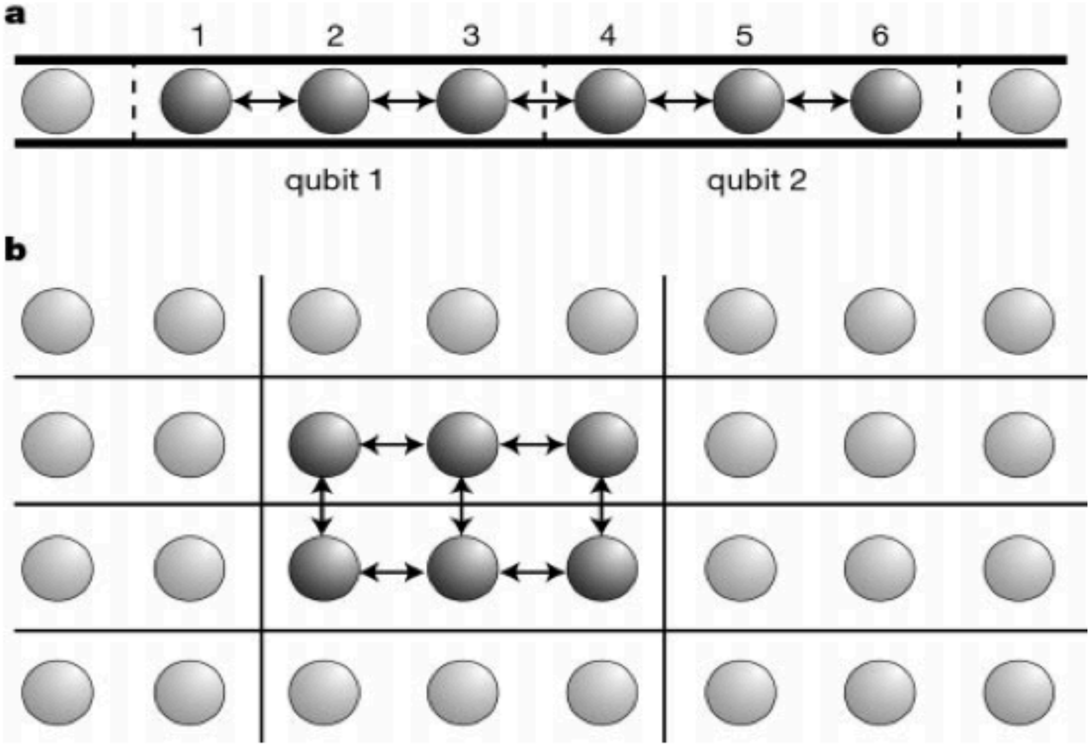
R. Brunner, et al., PRL ***107,*** *146801 (2011)*



Exchange only qubits

Exchange based Quantum computer

Logical qubits are made of three physical qubits, and all the operations are based on exchange couplings.

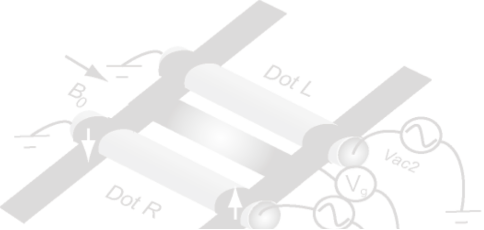


Logical *qubit*

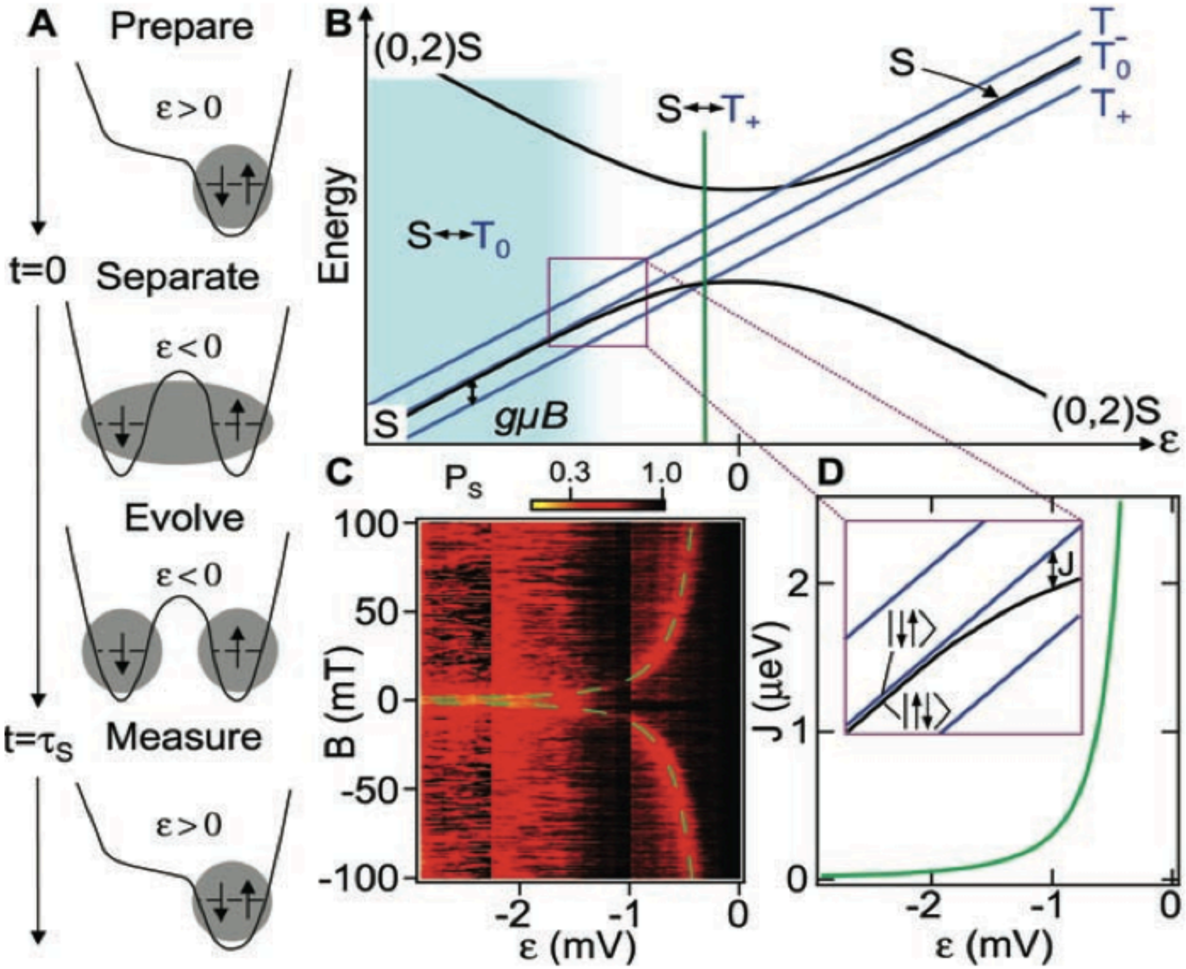
$$|0_L\rangle = |S\rangle|\uparrow\rangle$$

$$|1_L\rangle = \sqrt{\frac{2}{3}}|T_+\rangle|\downarrow\rangle - \sqrt{\frac{1}{3}}|T_0\rangle|\uparrow\rangle$$

D. P. DiVincenzo, et al., 408, 339 (2000).



Two-spin (S-T) qubit



J. R. Petta, et al., Science 309, 2180 (2005).

Logical *qubit*

$$|0_L\rangle = |S\rangle$$
$$|1_L\rangle = |T_0\rangle$$

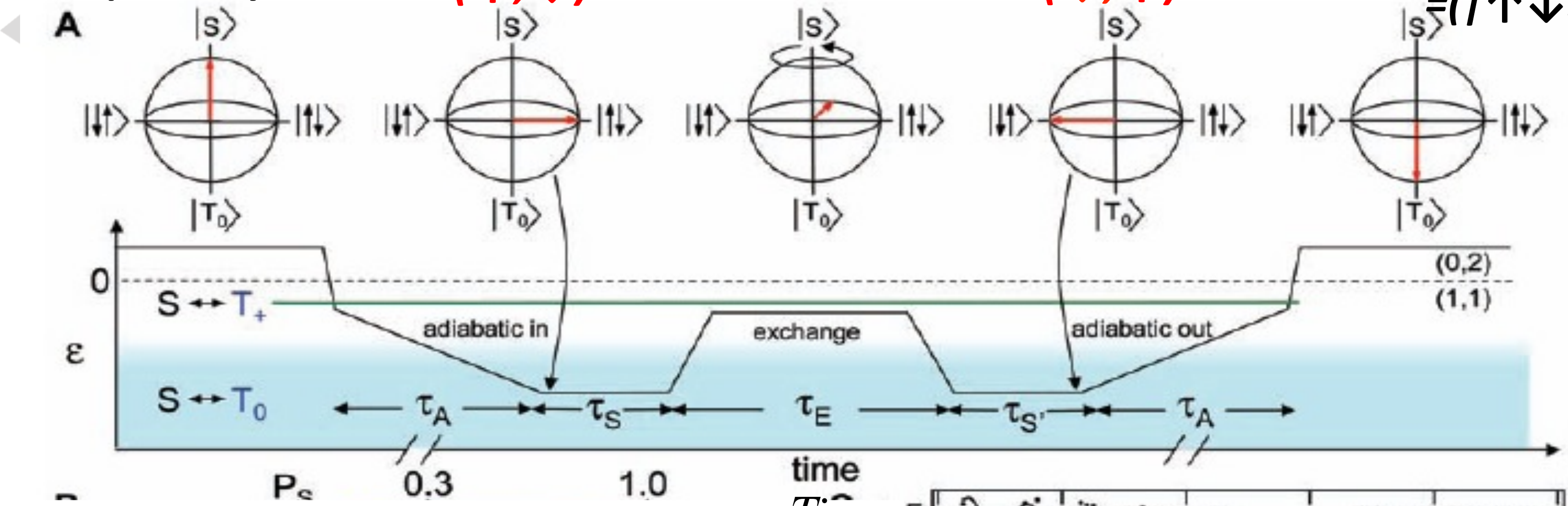
Effective Hamiltonian

$$\mathcal{H} = \frac{1}{2}J\sigma_z + \frac{1}{2}\Delta B_N^z\sigma_x$$

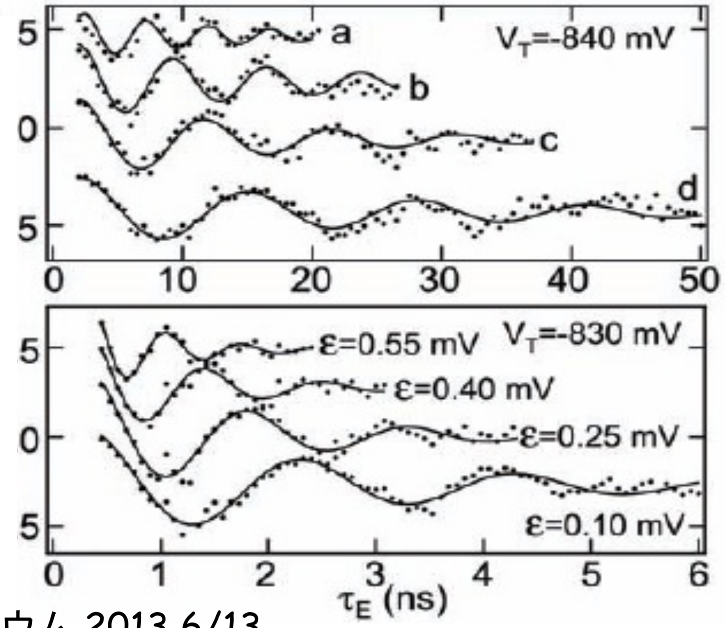
J	Tunable exchange energy
ΔB_N^z	Difference of the Overhauser fields

J manipulation: SWAP between |↑↓> and |↓↑>

$S(0,\uparrow\downarrow)$ → **$(\uparrow,\downarrow)$** $\xrightarrow{SWAP}$ **$(\downarrow,\uparrow)$** → **$T_0 = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$**



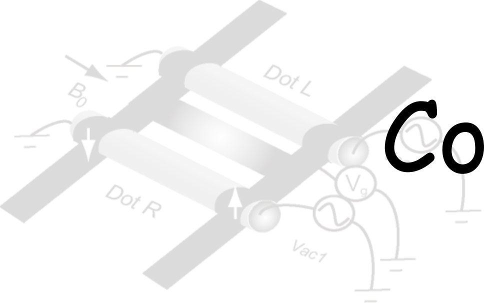
Time



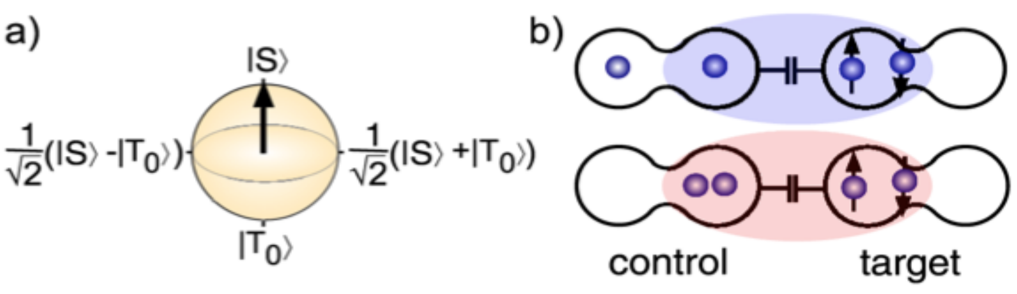
t_{SWAP}=360 psec *T_2^*~10ns*

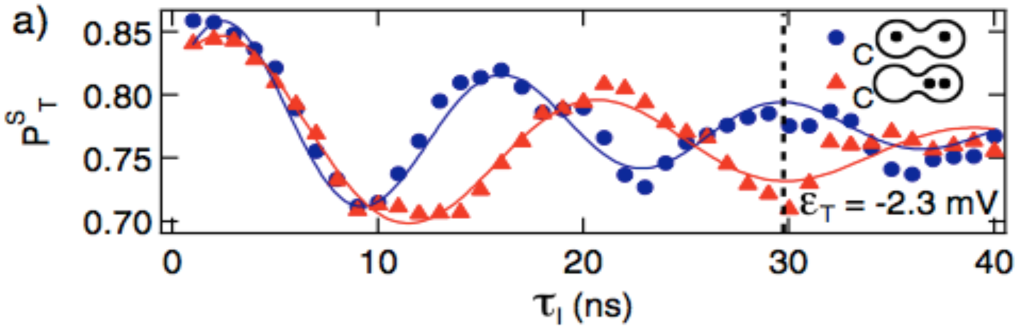
Rabi oscillations of a logical qubit

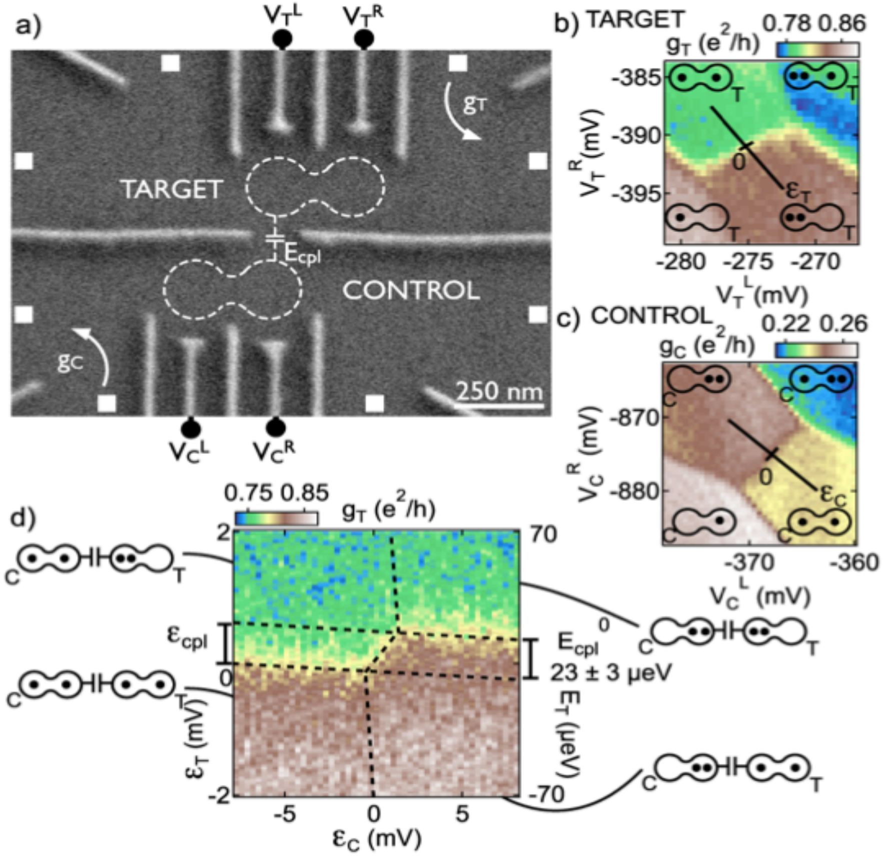
J itself is not enough to full control of the logical qubit. The Zeeman energy difference ΔE^z_N is important.



Coupling exchange only qubits

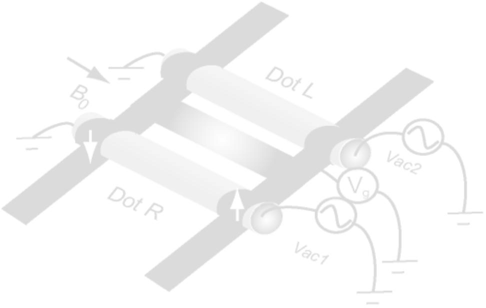




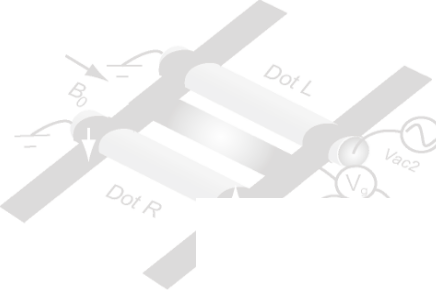


Rotation of target qubit conditioned
with control qubit.

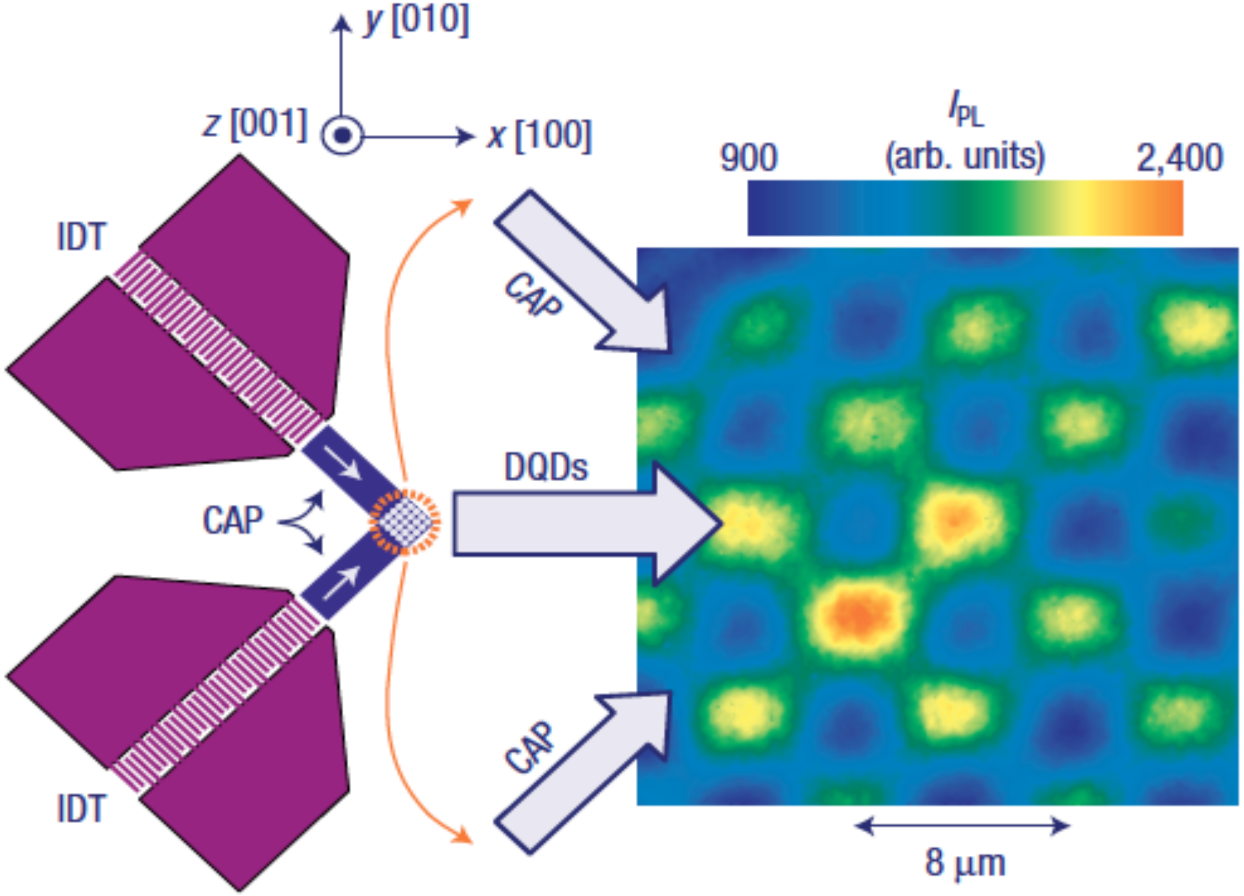
I. Van Weperen, et al., Phys. Rev. Lett. 107, 030506 (2011).



Flying qubits



Encapsulated flying qubits



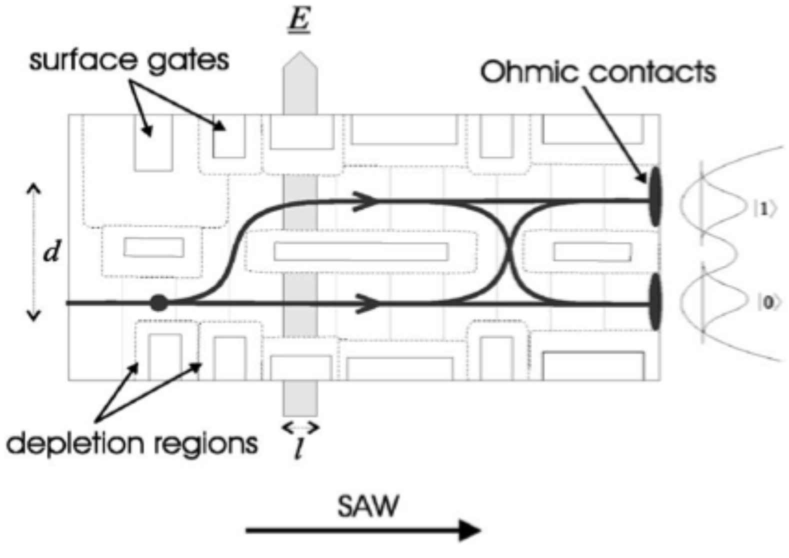
IDT: interdigitated transduser
CAP: coherent acoustic phonon

Stroboscopic photoluminescence image

Piezo-electric material, like GaAs, forms moving (dynamic) quantum dots (DQDs) by the surface acoustic waves (SAWs).

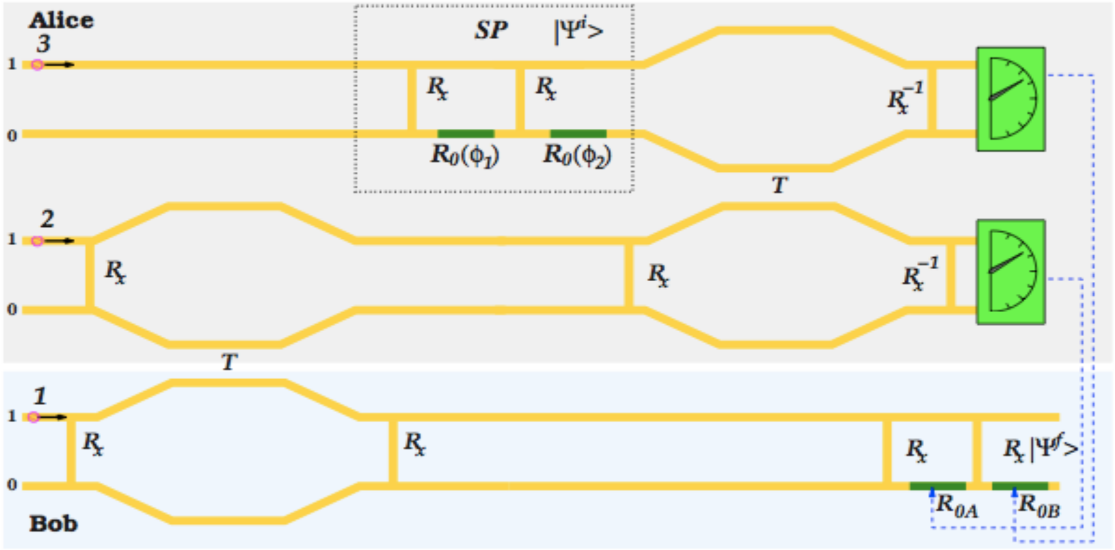
J. A. H. Stotz, R. Hey, P. V. Santos and K. H. Ploog, Nature Materials 41, 585 (2005).

Quantum logic by SAW



R. Rodriquez, et al., Phys. Rev. B 72, 085329 (2005).

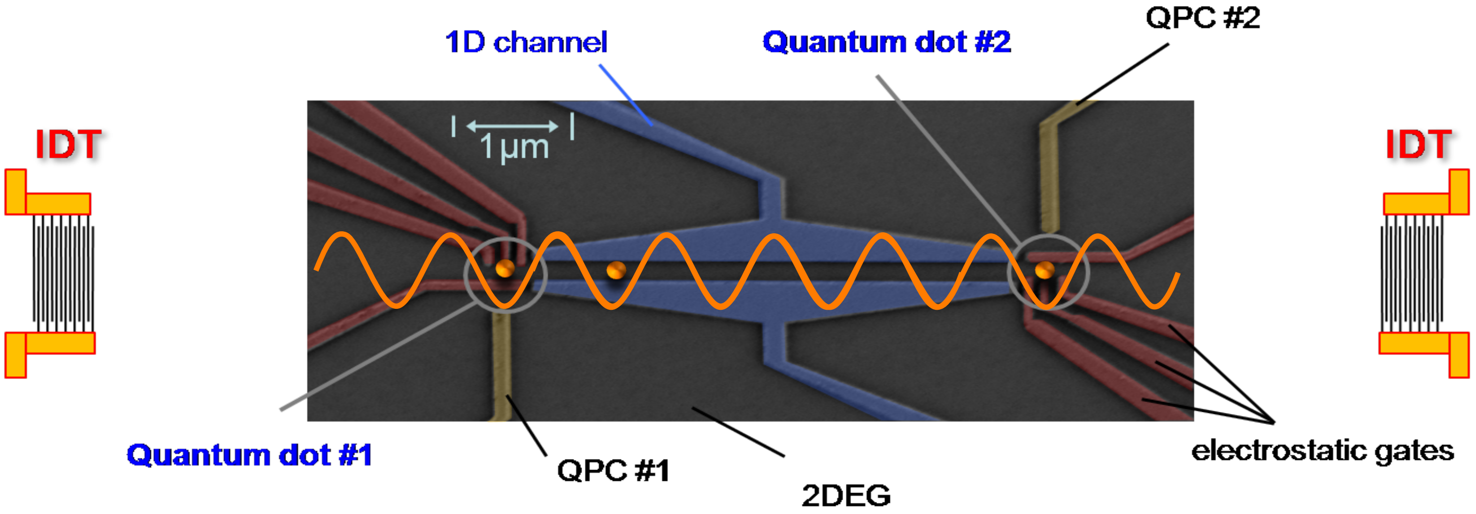
Theoretical proposals of logical circuit of flying qubits.

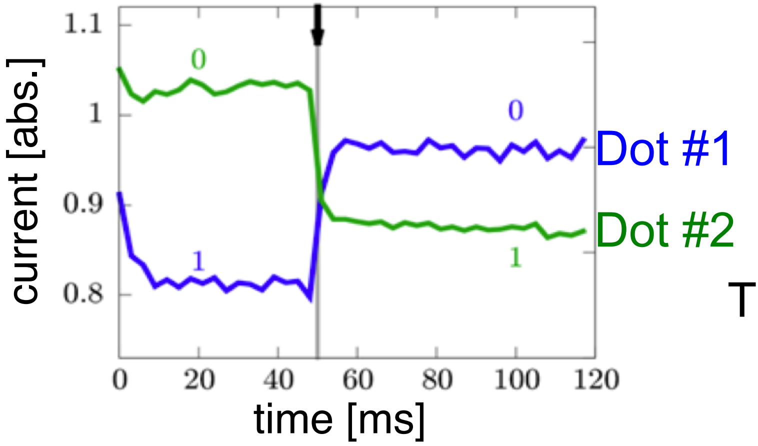


F. Buscemi, et al., Phys. Rev. B 81, 045312 (2010).

Surfing single electron

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



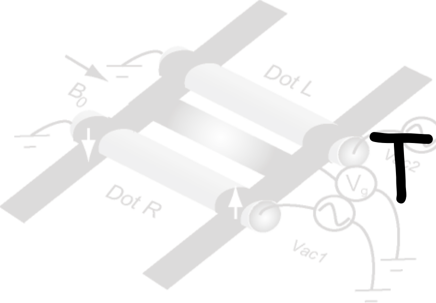


- Single electron source and detection (Fidelity > 90%)
- No electron-electron interaction while transfer
- Travelling time ~ 2 ns << T_2^*

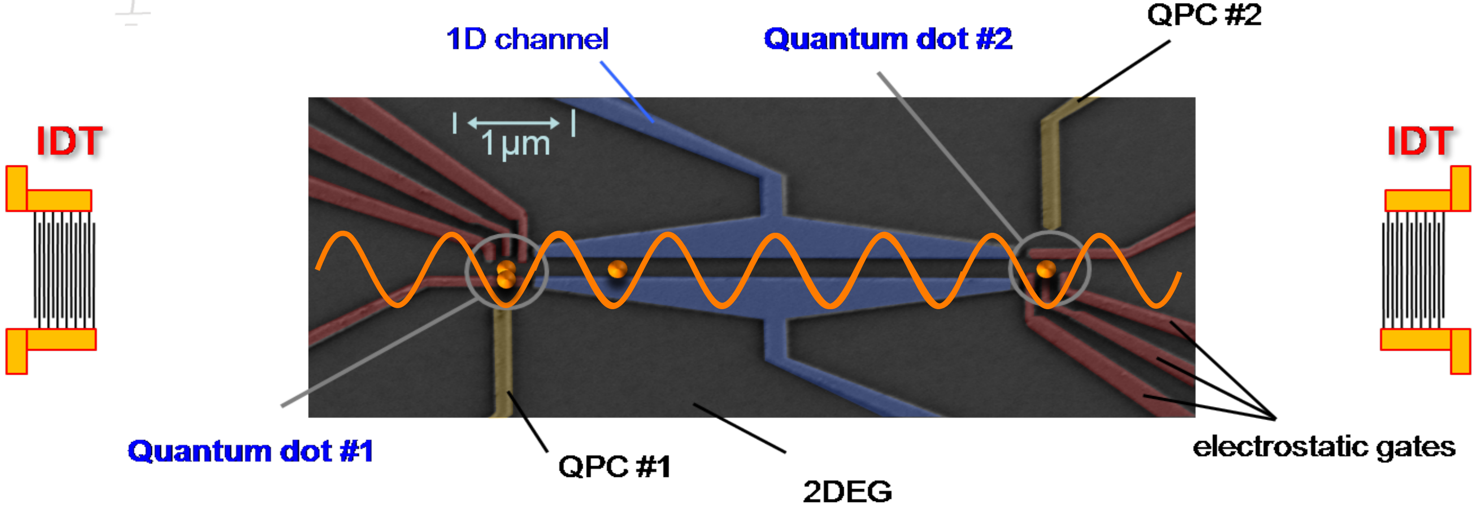
⬇

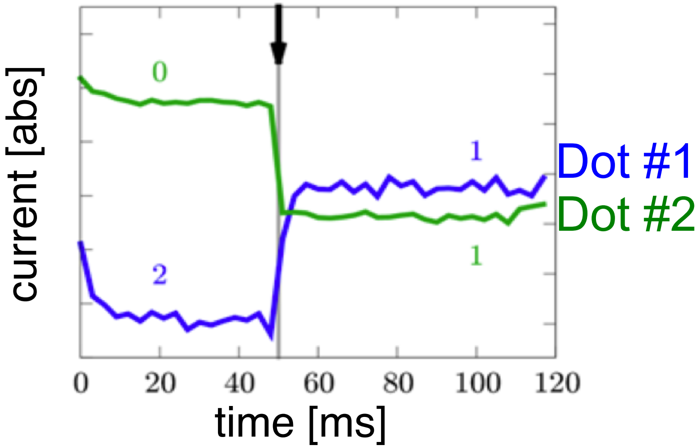
Transfer of a *single electron spin* over a long distance

Non-local entanglement
Quantum computation network



Transfer one of two electrons





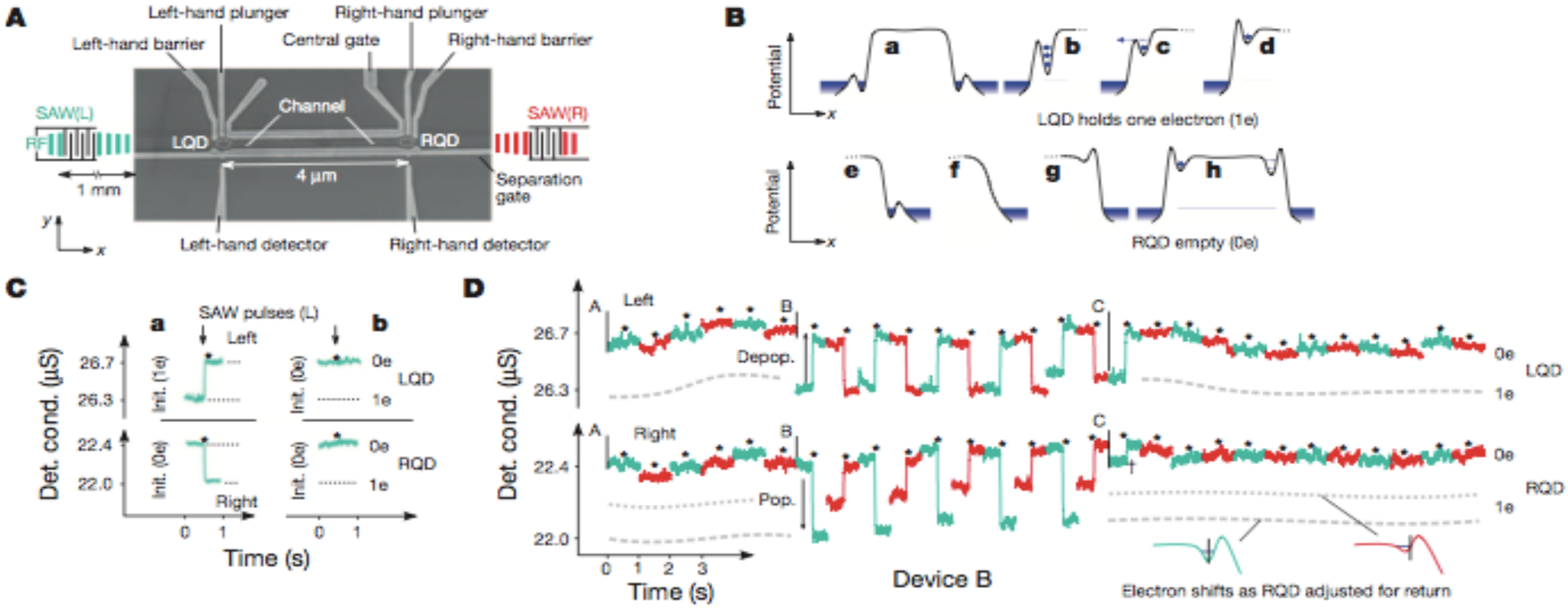
- Two electrons in a dot forms a spin singlet state
- Two electrons are separated into distant dots within a few ns (<<T_2^*) (Fidelity ~ 90%)

⬇

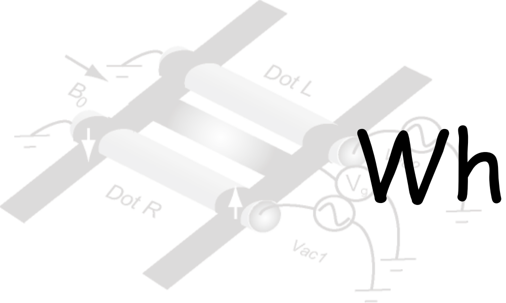
Non-local entanglement

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

Catching ball of an electron

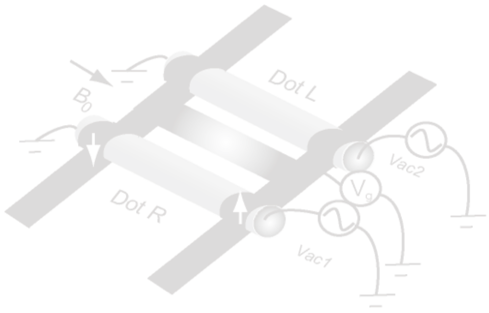


R. P. G. McNeil, et al., Nature 477, 439 (2011).



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 small-scale integration and error correction?*
  - *Triple, quadruple, or more, quantum dots.*
- *Is it possible to couple single spin to single photon/microwave?*
  - *Using InAs QD or dipole induced by slanting field.*



Thank you for your attention!