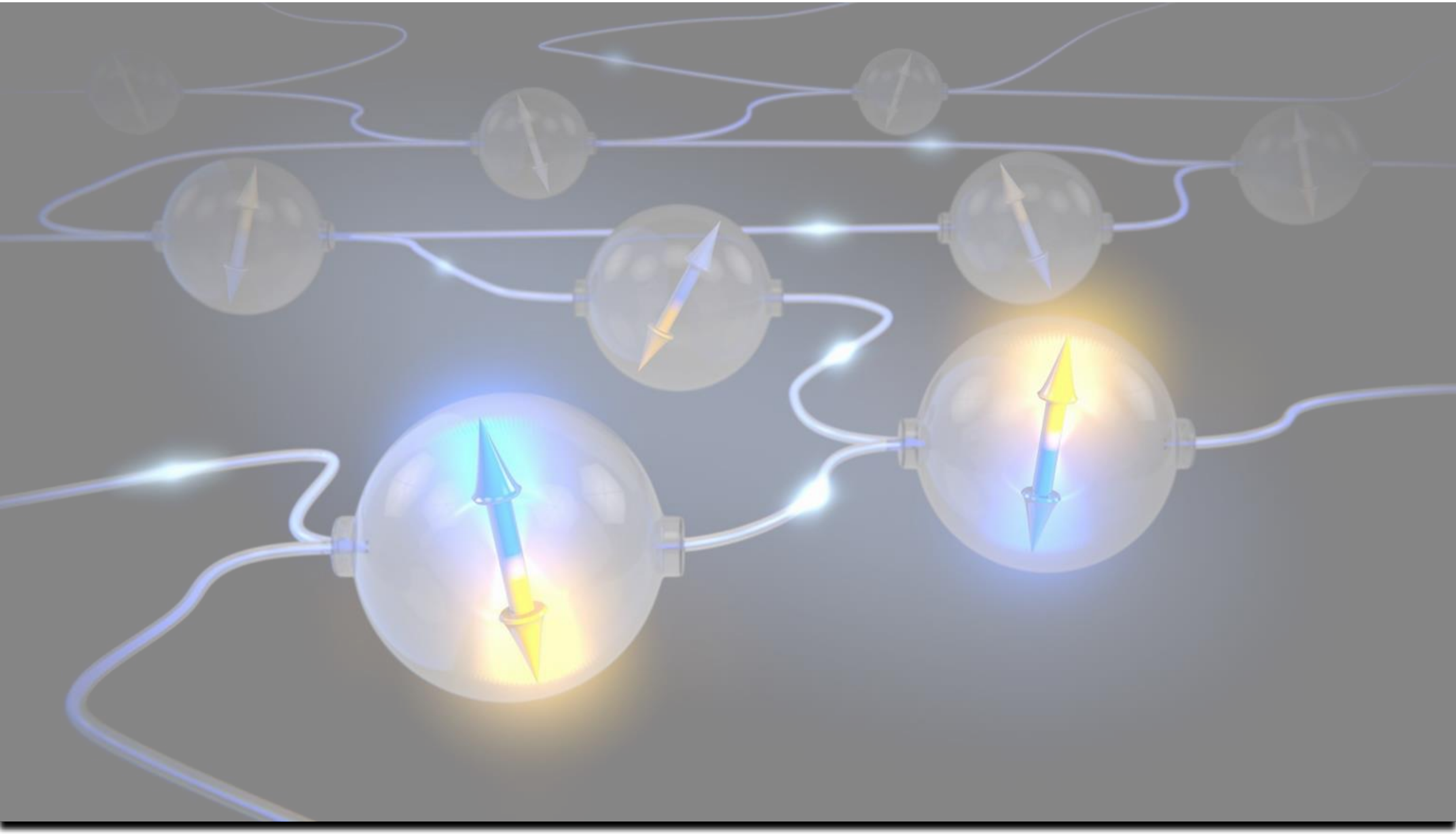
Introduction to SPIN QUBITs in SEMICONDUCTING QUANTUM DOTs

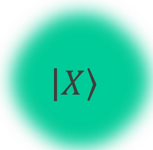


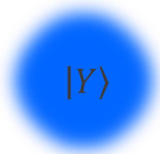
The electron SPIN as prototype of every 2-level system

Quantum State
Dirac Notation $|\boldsymbol{\Psi}\rangle$

Contains all the information about the systems

- A particle localized at the position x, $|X\rangle$
- A particle localized at the position y, $|Y\rangle$





SUPERPOSITION: Quantum Mechanics is a linear theory: all the possible sum of the possible states is also a state allowed.

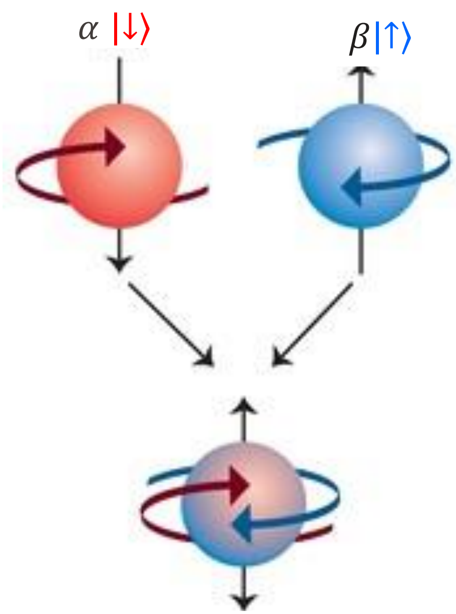
$\frac{1}{\sqrt{2}}(|X\rangle + |Y\rangle)$ is also an allowed state for our system

A particle in two places at once???
Convenient, but shocking!

The possibility of superposing states even in multiple-particle systems naturally results in the concept of ENTANGLEMENT.

A prototype for every artificial 2-level systems (qubits) is the **real spin of an electron**

- An electron can have a spin ↓, $|\downarrow\rangle$
- An electron can have a spin ↑, $|\uparrow\rangle$

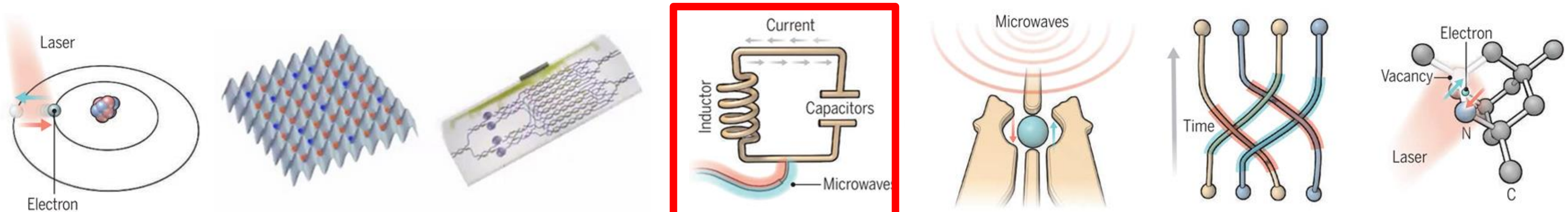


$$|\boldsymbol{\Psi}\rangle = \alpha\,|\downarrow\rangle + \beta|\uparrow\rangle$$
$$|\alpha|^2 + |\beta|^2 = 1$$

Multiple Quantum Platforms

In the race to build a quantum computer, researchers are pursuing many types of quantum bits, each with its own strengths and weaknesses

Natural Qubits | **Syntetic Qubits**



Trapped ions
Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

Neutral atoms
Neutral atoms, like ions, store qubits within electronic states. Interactions through excitation to Rydberg states

Photonics
Photonic qubits interact via linear elements

Superconducting loops
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.

Silicon quantum dots
These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.

Topological qubits
Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures.Their braided paths can encode quantum information.

Diamond vacancies
A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

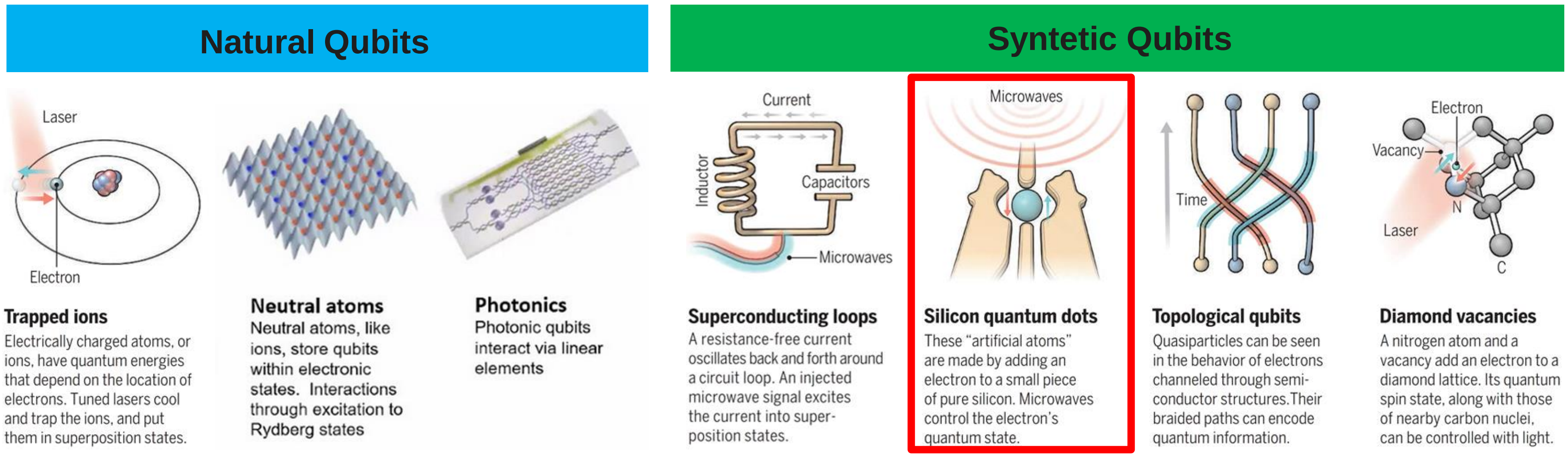
Define, control and readout the quantum states of single particles and photons gives insights into new quantum technology

Make use of the quantum properties to enance sensing, security in communication and bost computing and simulation.

Popkin, G.. "Quest for qubits." (2016): 1090-1093.

Multiple Quantum Platforms

In the race to build a quantum computer, researchers are pursuing many types of quantum bits, each with its own strengths and weaknesses



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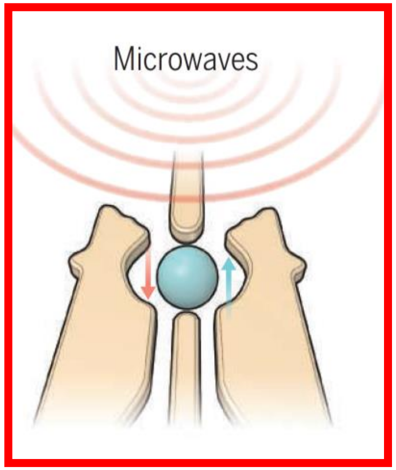
Semiconducting Spin Qubits

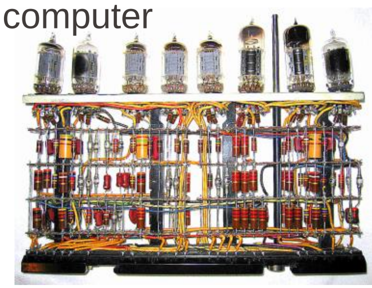


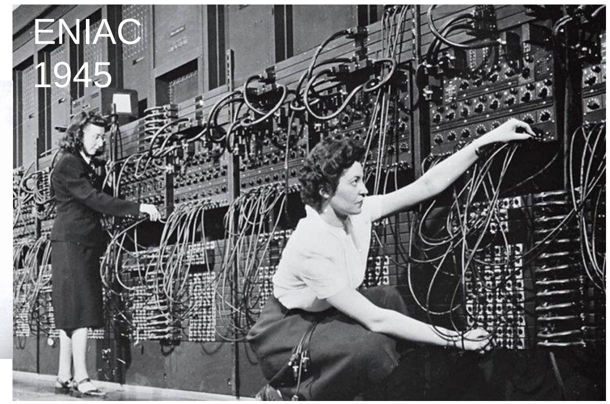
Semiconductor QDs platform

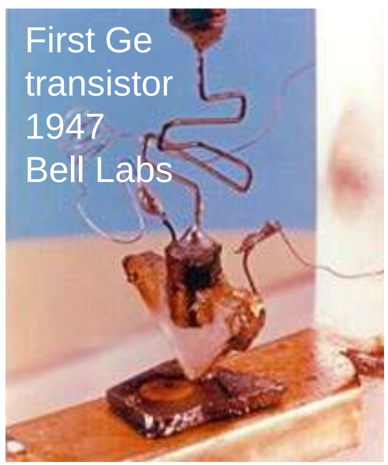
First Quantum Revolution in Information Technology was based on semiconductors

- Unprecedent series of success which provided us with novel extraordinary experimental tools.
- A revolutional societal and economic impact:
  - large part of GDP results from quantum technology;
  - no information society without lasers;
  - longer life expectation thanks to NMR;

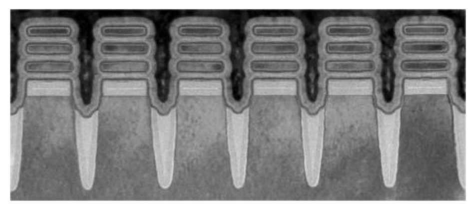
vacuum tube computer



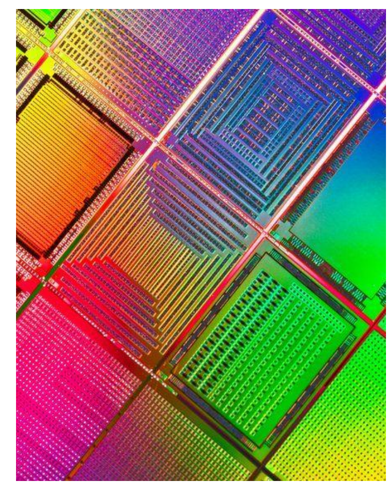




IBM 2-nanometer (nm) node 2021

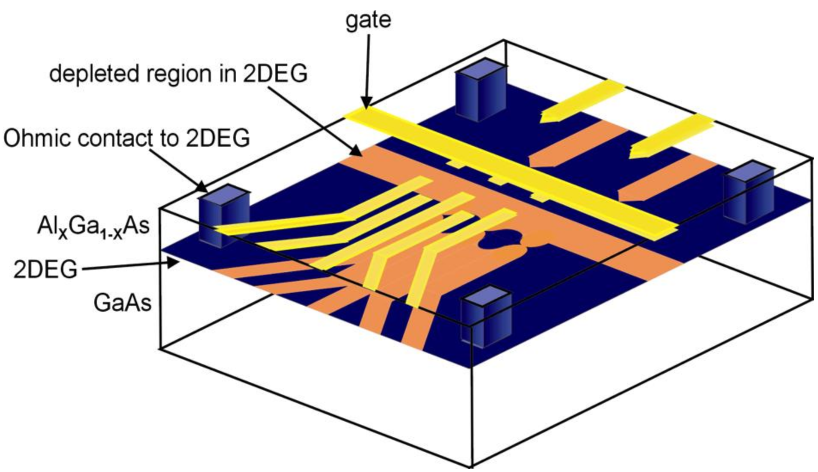


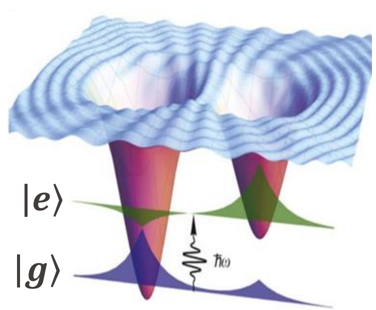
50 billion transistors in a space roughly the size of a fingernail

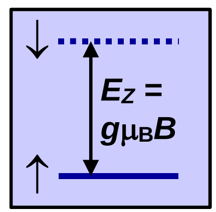


All-electrical semiconductor quantum dots

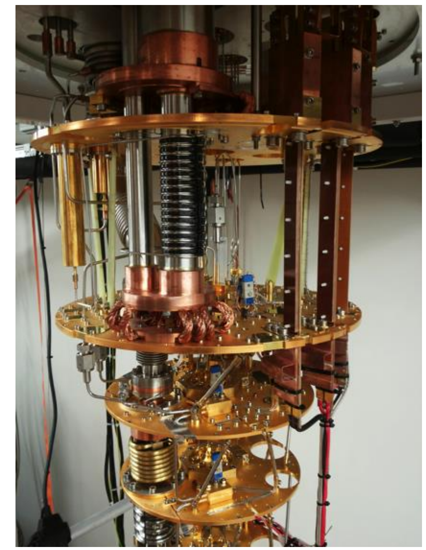
How to define Quantum Dots islands?

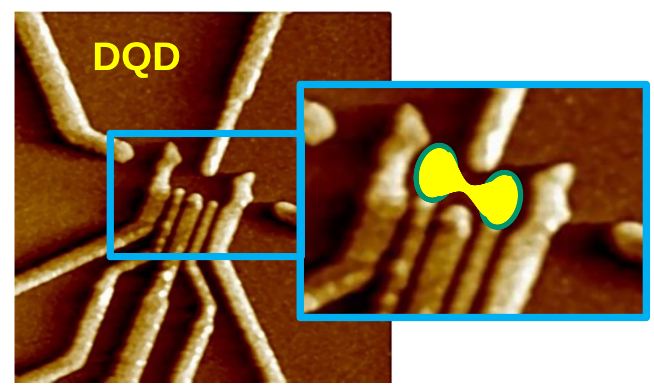






Dilution refrigerator





Confinement

- Discrete # charges
- Discrete orbitals

Electrical control and detection

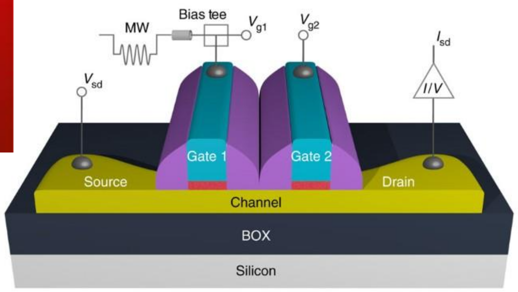
- Tunable # of electrons
- Tunable tunnel barriers

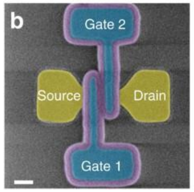
W. G. van der Wiel, et al., *Rev. Mod. Phys.* **75**, 1 (2002)

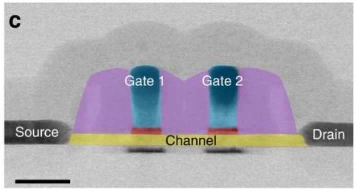
R. Hanson et al., *Rev. Mod. Phys*. **79**, 1217 (2007)

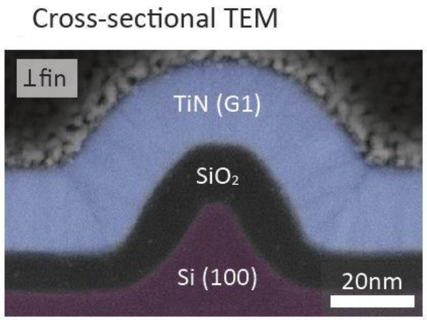
Leverage CMOS platform to design quantum bits

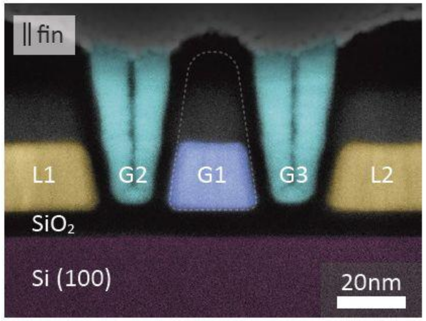
Silicon quantum bit (qubit) devices made with an industry-standard fabrication process

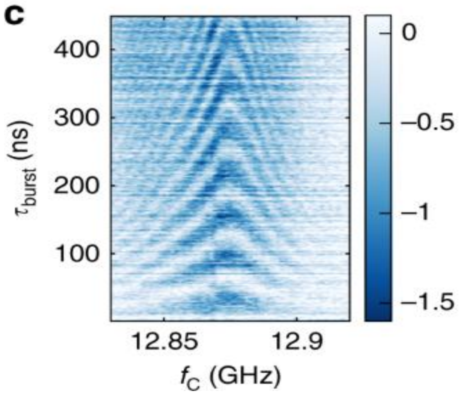




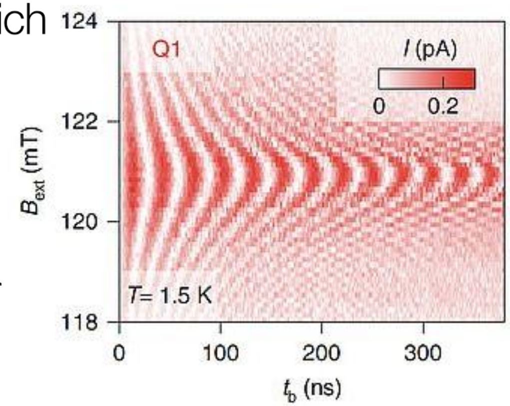




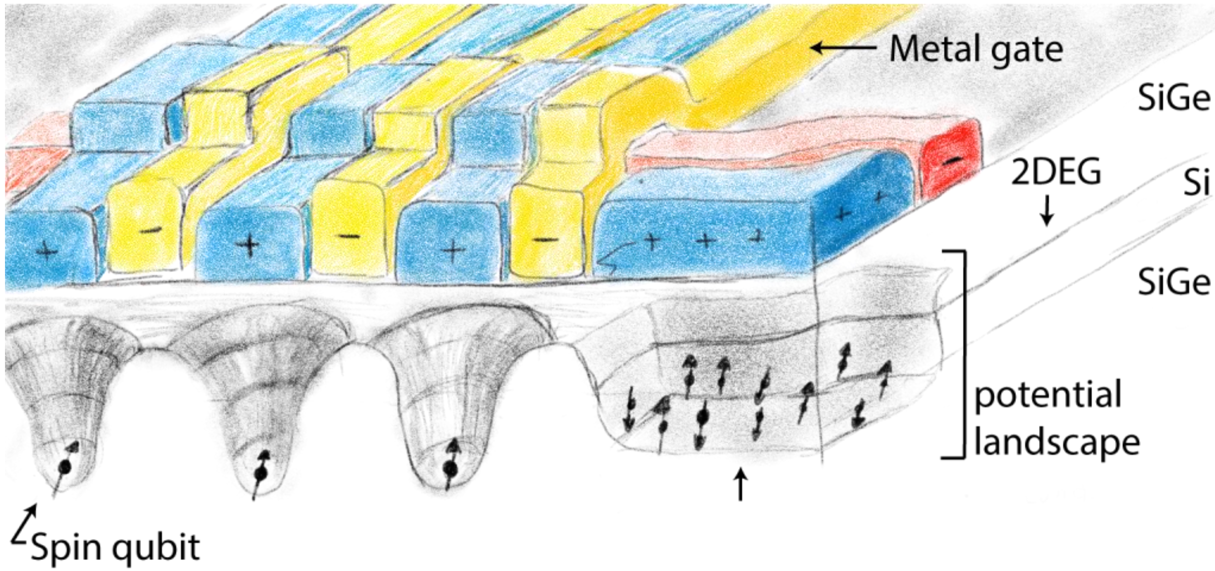


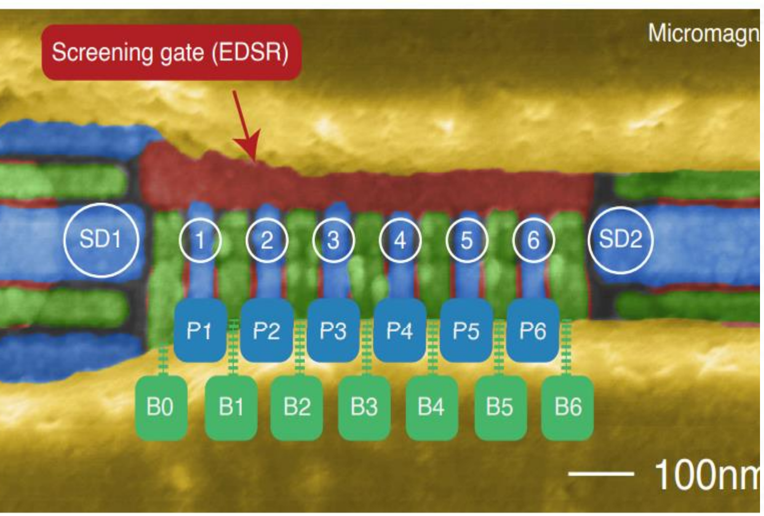


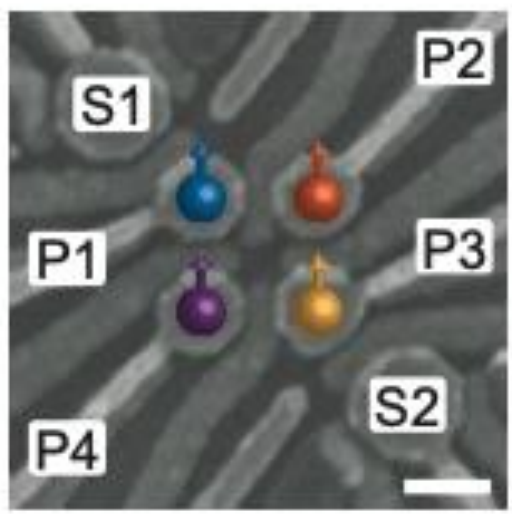
Leveraging the well-established complementary metal–oxide–semiconductor (CMOS) technology would be a clear asset to the development of scalable quantum computing architectures and to their co-integration with classical control hardware.



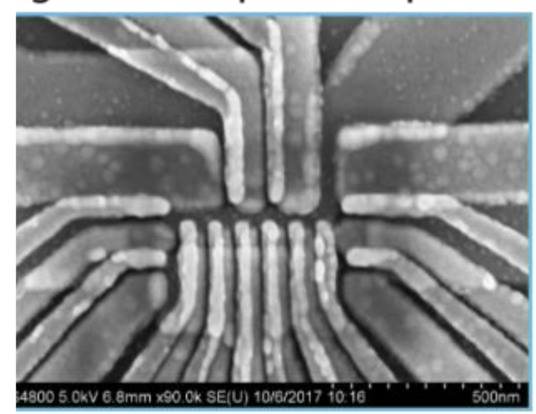
Rabi oscillations of a single spin qubit implemented in a transistor!!!



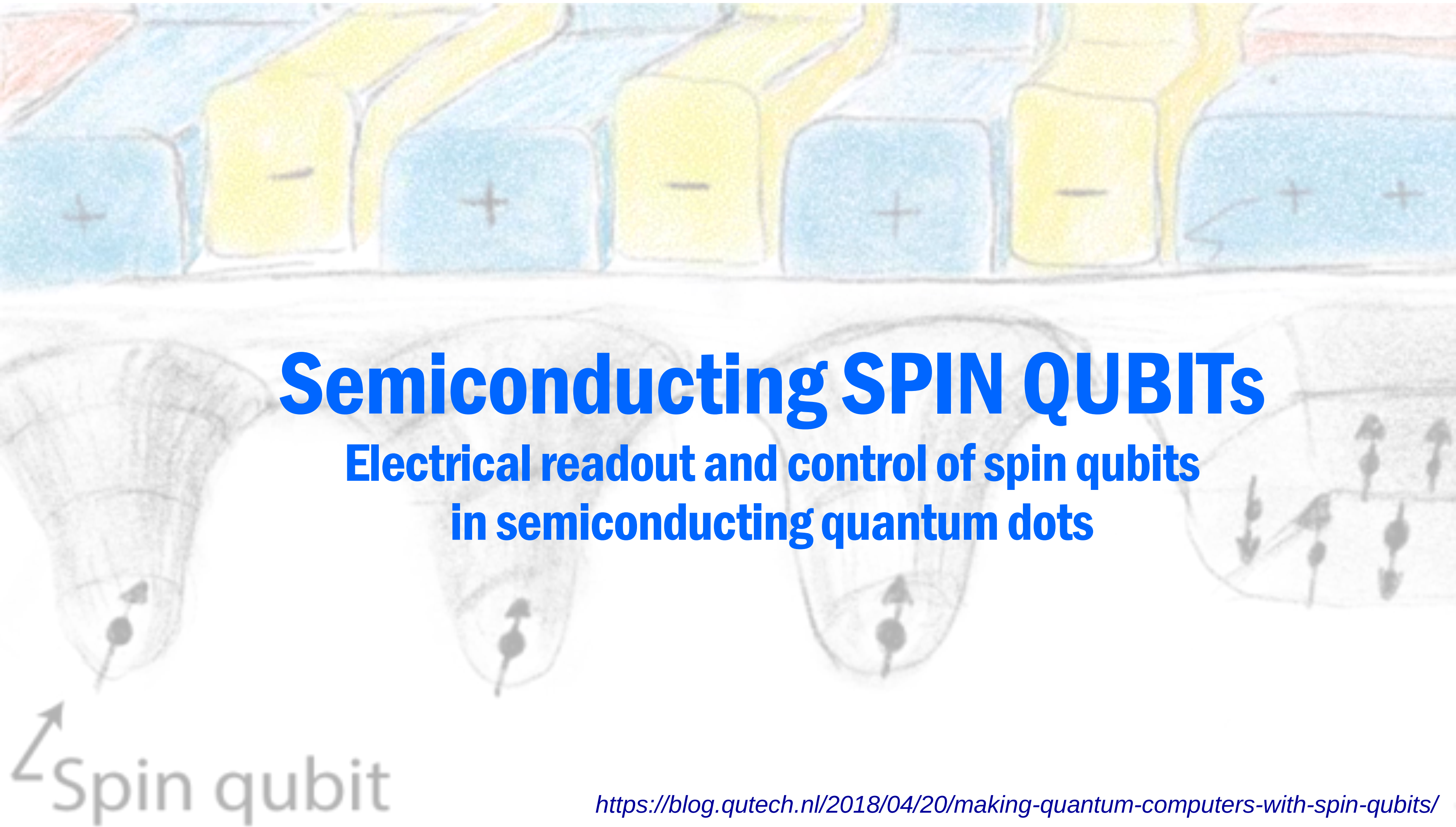




SEM picture of the metal gates on top of the qubits



https://blog.qutech.nl/2018/04/20/making-quantum-computers-with-spin-qubits/



Semiconducting SPIN QUBITs

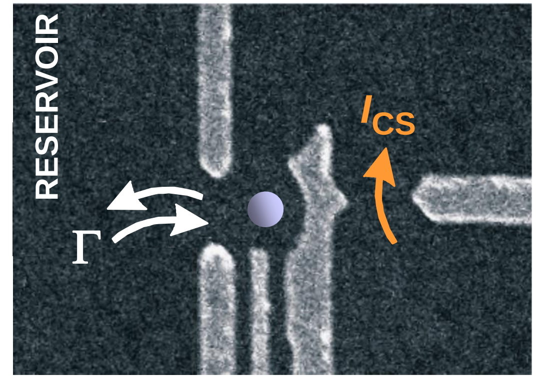
Electrical readout and control of spin qubits in semiconducting quantum dots

https://blog.qutech.nl/2018/04/20/making-quantum-computers-with-spin-qubits/

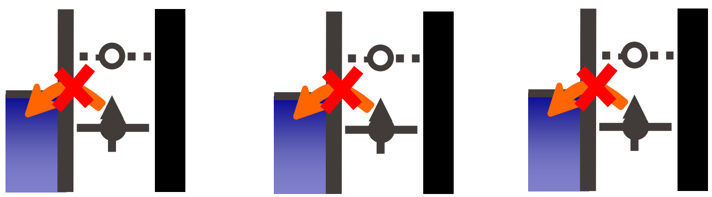
Spin Readout
spin-selective tunnelling
+ charge detection

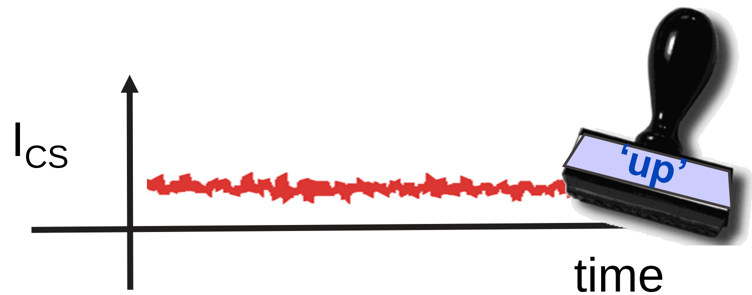
Spin to charge conversion mechanism

Charge Sensor (CS) responds to changes of charges stored in the QD

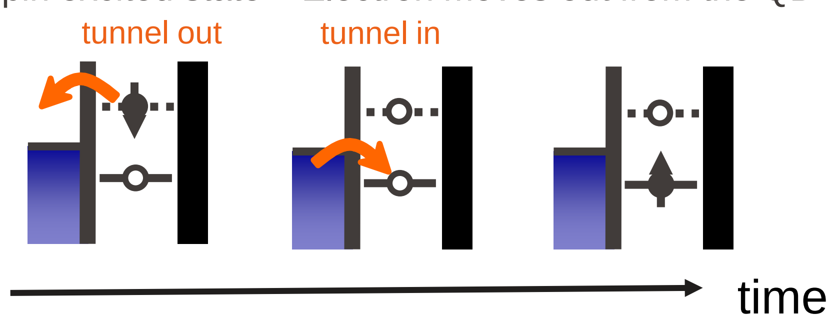


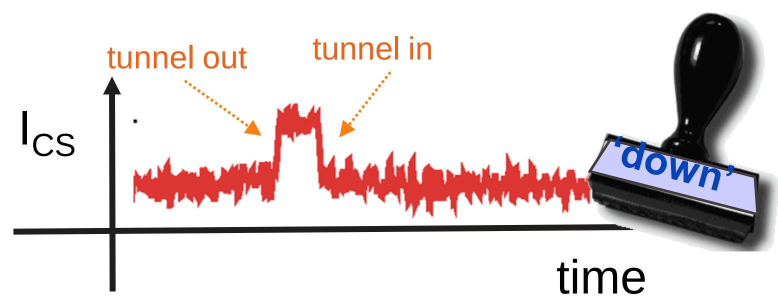
Spin ground state – Electron stays in the QD



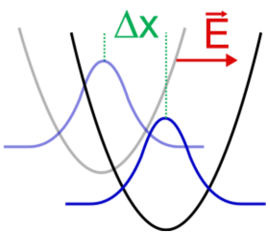


Spin excited state – Electron moves out from the QD

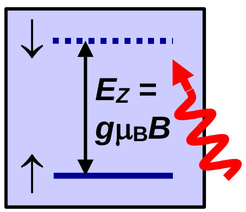


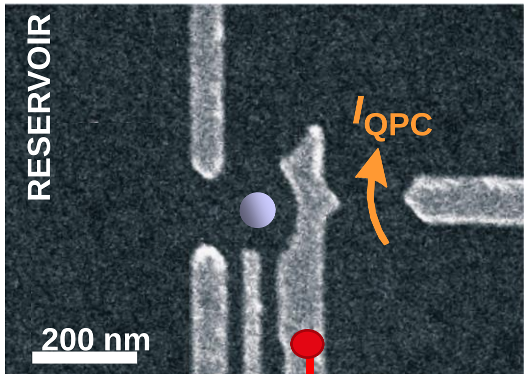


All-electrical semiconductor quantum dots

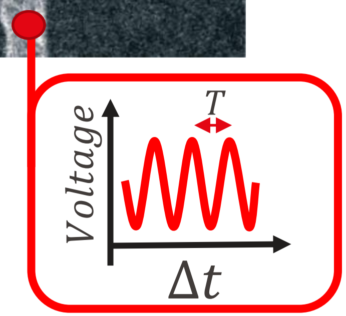


+ Spin-Orbit





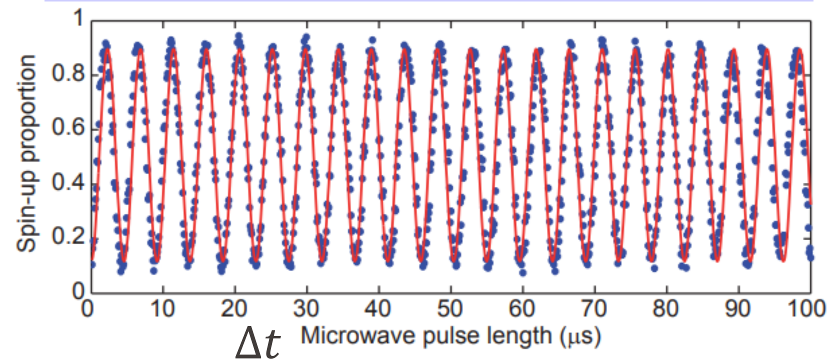
Control individual spins using microwave drives

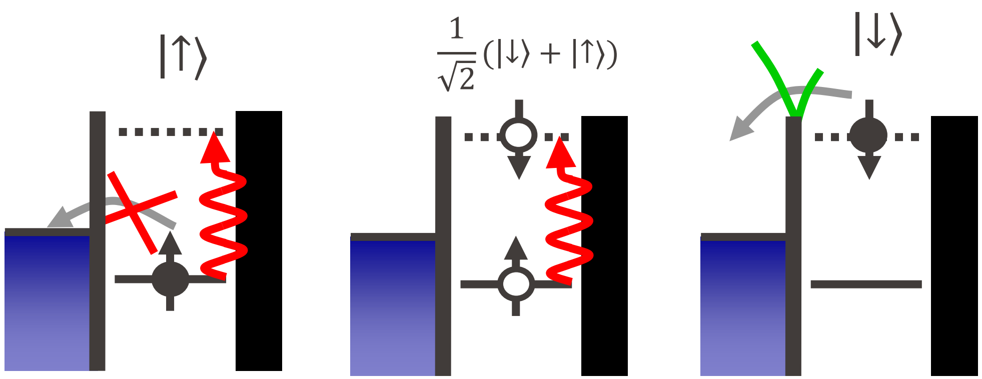


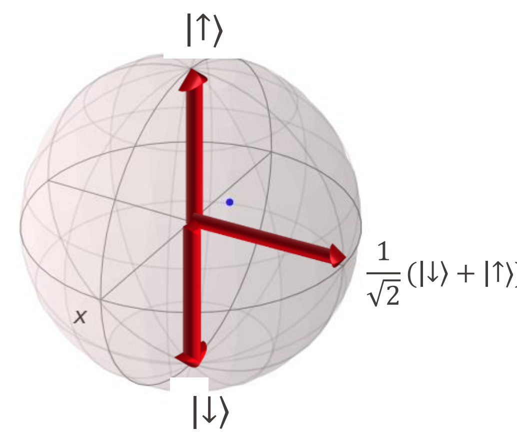
Single spin operations

EDSR pulsed microwave magnetic field

$$H_{RF} \sim \sum A_i(t)\cos(\omega_i t)\ \sigma_{xi}$$







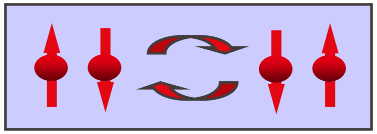
All-electrical semiconductor quantum dots

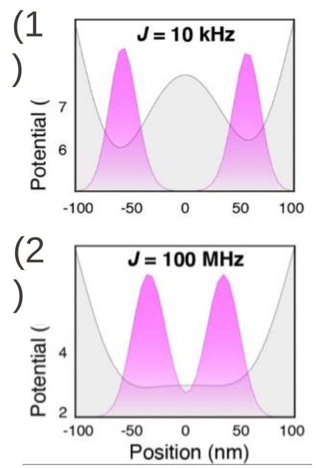
Two-spins operations

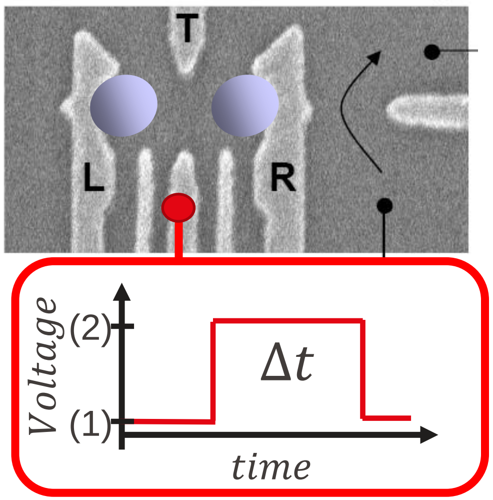
Electrical control of the coupling between neighbouring spins

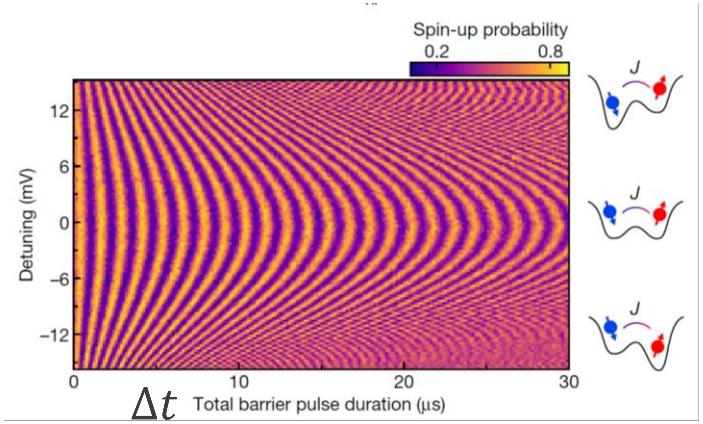
SWAP exchange interaction

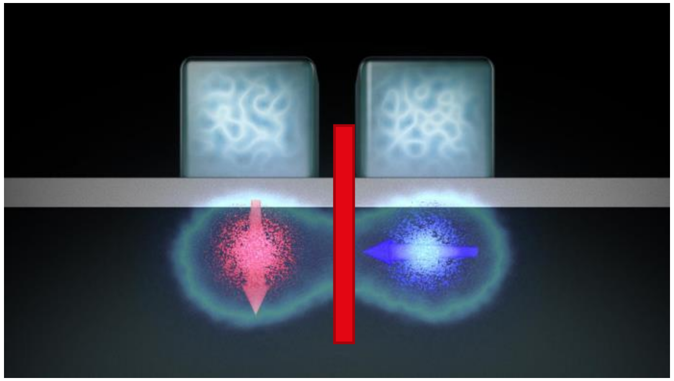
$$H_J \sim \Sigma\, J_{ij}(t)\;\; \sigma_i \cdot \sigma_j$$







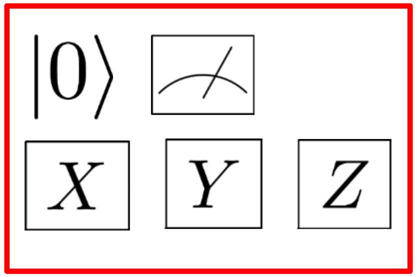


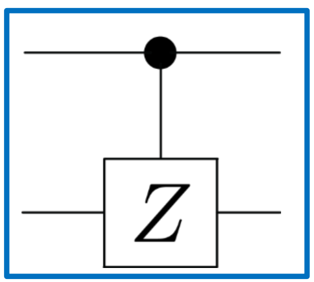


SPIN-SPIN interaction is SHORT RANGE !
(potential issues for scalability)

Long Coherence spins in silicon

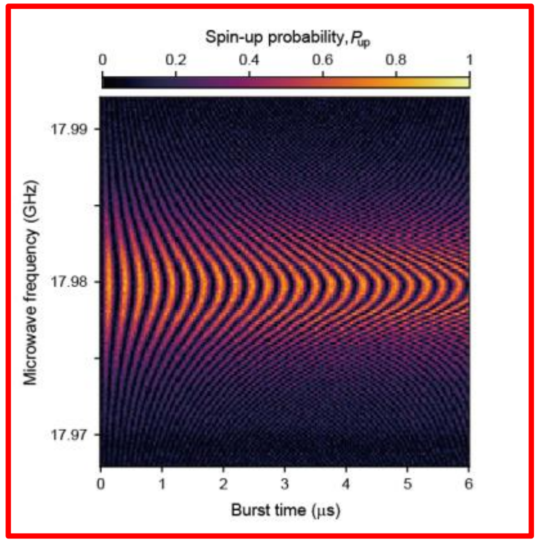
Single Qubit Gates





Two Qubits Gates

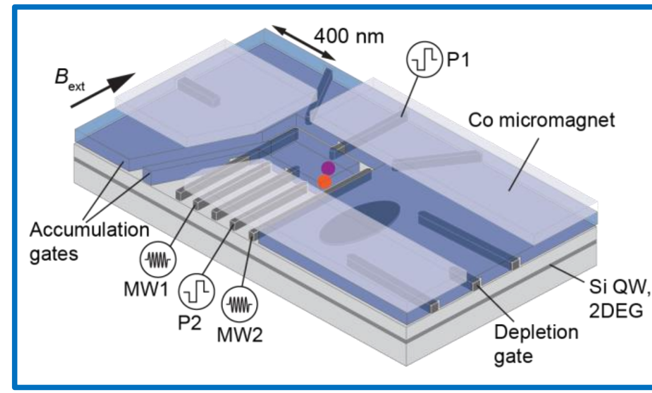
SiGe



Yoneda, et al. *Nat. Nanotech* **13**, 102 (2018)

For electron spin:
$T_2^* = 200$us
$T_2 = 28$ms
$T_1 = 100$ ms to s
$F_C = 99.9\%$

SiGe



Watson et al., *Nature* **555**, 633 (2018)

Xiao Xue, et al., *Nature* **601**, 343 (2022)

Computing with spin qubits at the surface code error threshold

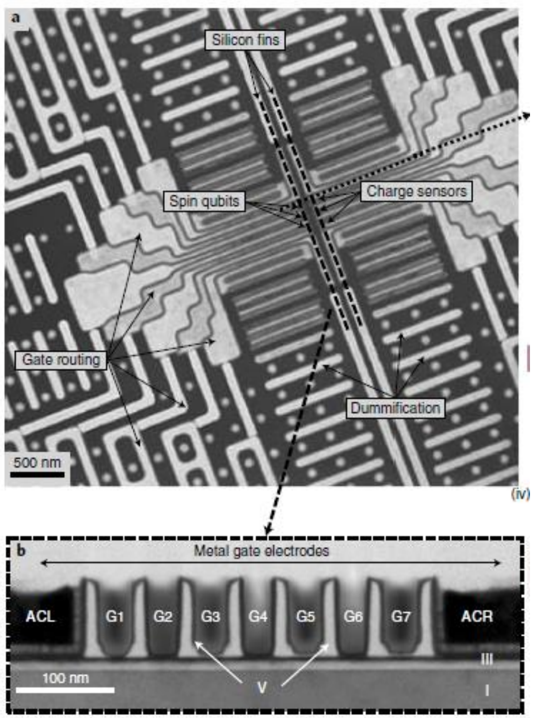
'Now that the 99% barrier for the two-qubit gate fidelity has been surpassed, semiconductor qubits have gained credibility as a leading platform, not only for scaling but also for high-fidelity control.'

State of the art of spin qubits

INTEL- TU Delft

Qubits made by advanced semiconductor manufacturing

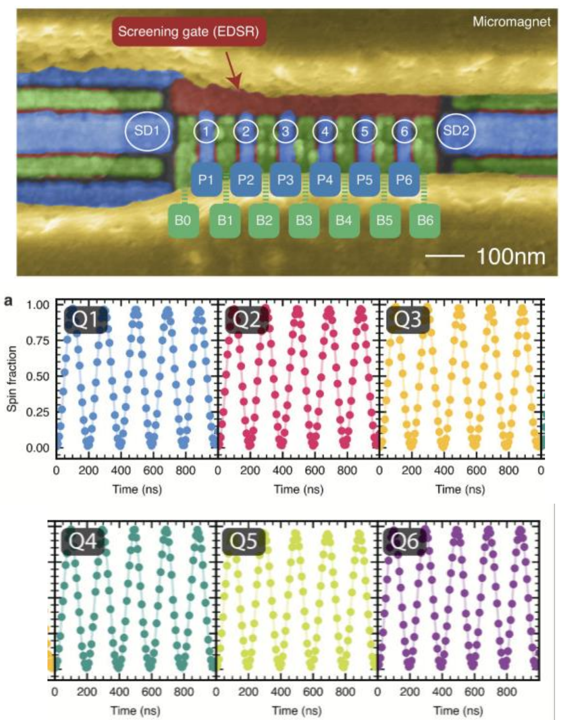
A. M. J. Zwerver, et al., *Nat. Electronics* **5**, 184 (2022)



TU Delft

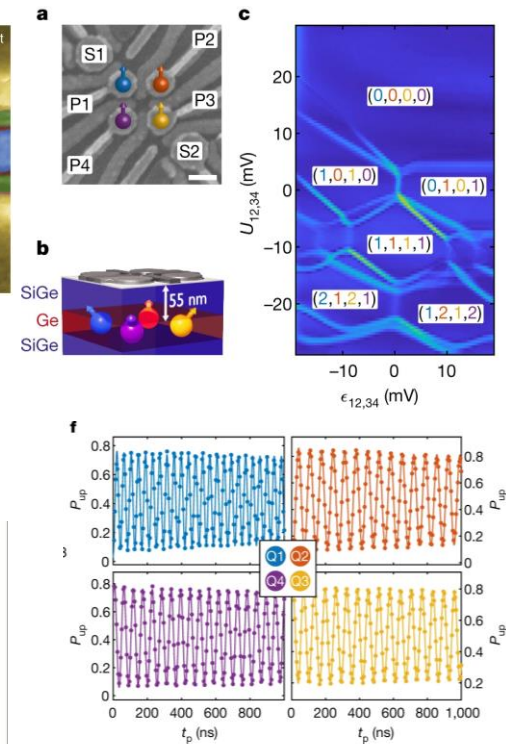
Universal control of a six-qubit quantum processor in silicon

S. G.J. Philips, et al., *Nature* **609**, 919–924 (2022)



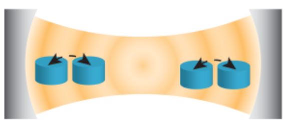
A four-qubit germanium quantum processor

N.W. Hendrickx et al., *Nature* **591**, 580–585 (2021)



Vision of a scalable spin qubit architecture

Circuit-QED approach

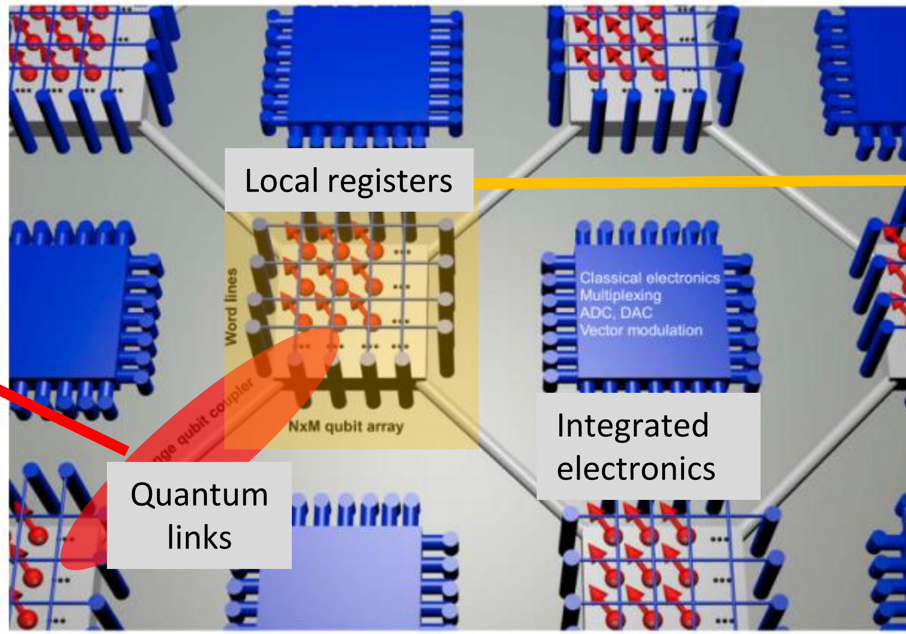


Coherent link ?

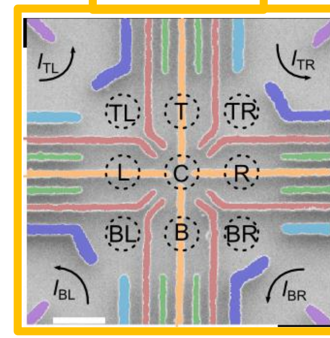
To couple distant spin qubits

Using the strengths of spin qubits:
"Hot, dense and coherent"

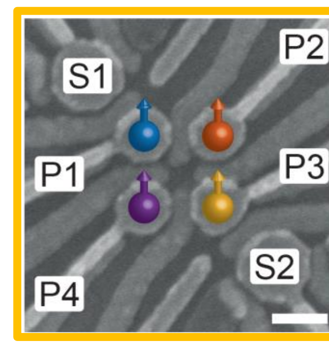
L. M. K. Vandersypen *et al.*, *npj Quantum Information* **3**, 34 (2017)



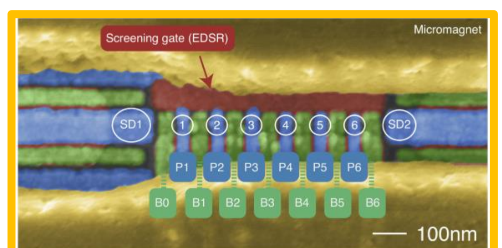
Quantum Register



P.-A. Mortemousque et al., *Nat. Nanotech.* ***16****, 296–301(2021)*



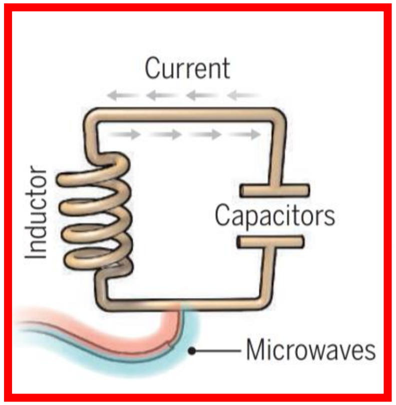
N.W. Hendrickx et al., *Nature* **591** (7851), 580-585

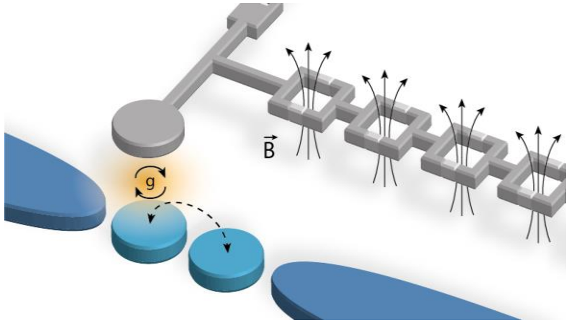


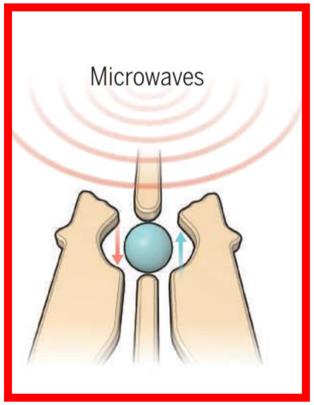
S. G.J. Philips, et al., *Nature* **609**, 919–924 (2022)

Quantum Dot - Cavity Hybrid Technology

Building a coherent interface for hybrid technology via high impedance resonators







Superconducting circuits platform

Hybrid QD-resonator devices

Semiconductor QDs platform

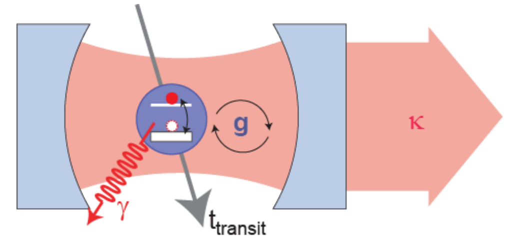
While both superconducting and semiconducting platforms have strong potential for **quantum technology** on their own, we will explore novel opportunities emerging at the interface between the two hardware.

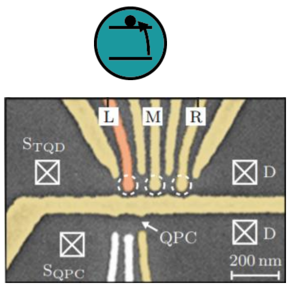
For investigating light-matter interaction **at the fundamental level** and implementing a rich set of novel applications **in quantum information technology**

Quantum Dot - Cavity Hybrid Technology

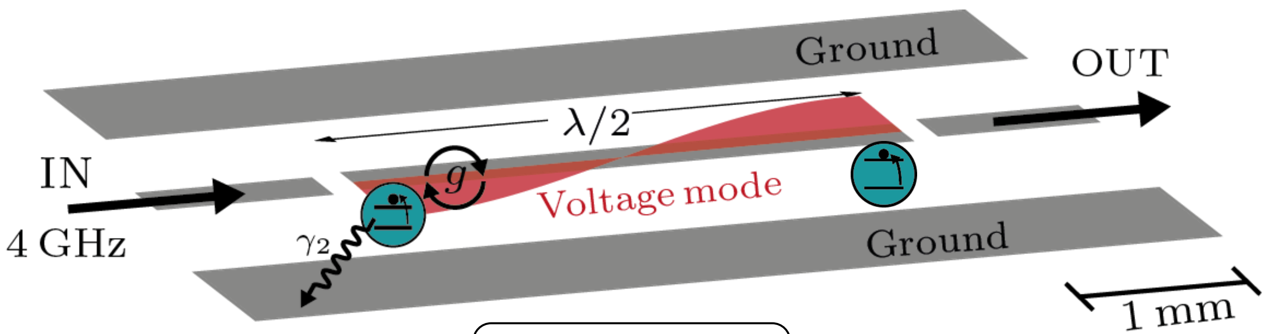
Circuit QED architecture: coherent link

Quantum Electrodynamics





electron spin



Interaction of distant qubits

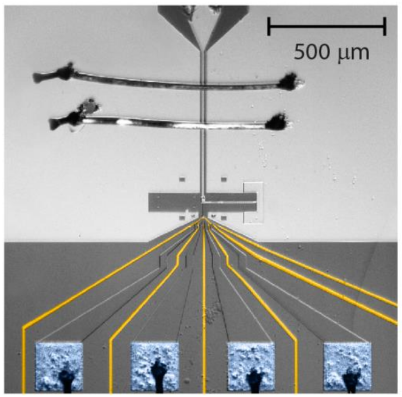
Blais *et al.*, *Phys Rev A* **69**, 062320 (2004)
Wallraff *et al.*, *Nature* **431**, 162 (2004)
Schoelkopf & Girvin, *Nature* **451**, 664 (2008)

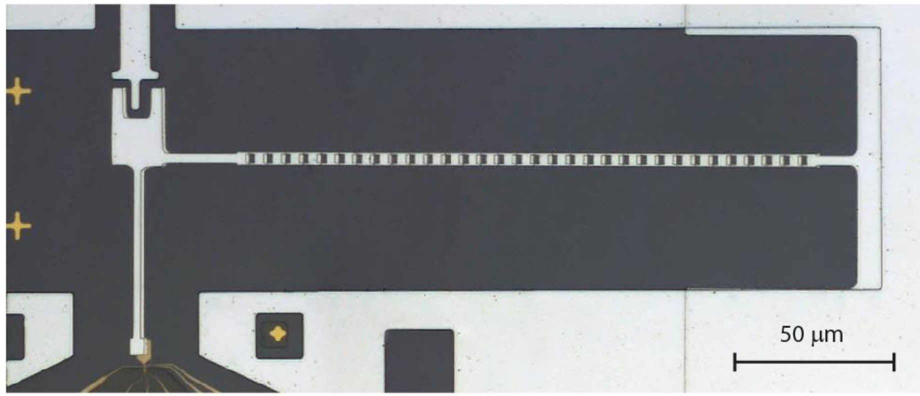
Raimond *et al.*, *Rev Mod Phys* **73**, 565 (2001)
Haroche & Raimond, OUP Oxford (2006)
Ye *et al.*, *Science* **320**, 1734 (2008)

Strong coupling of the qubit to a quantum information mediator (photon)

Quantum Dot - Cavity Hybrid Technology

Integrated GaAs DQD with SQUID Array Resonator in Hybrid Device

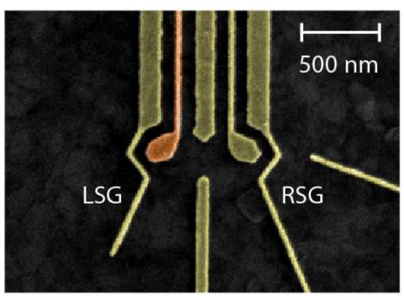




32 SQUID array resonator

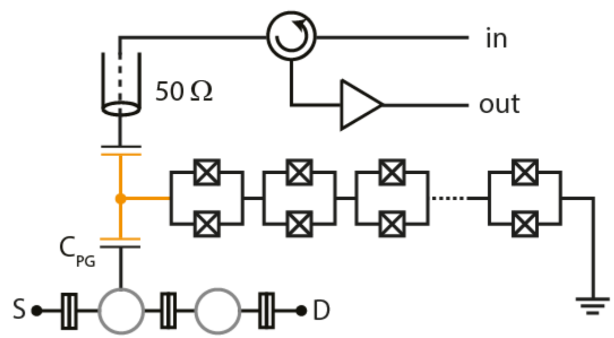
- 200 µm long
- Al based
- Dolan bridge technique

$$L_r \sim 40\, nH$$
$$C_r \sim 15\, fF$$
$$Z_r \sim 1.5\, k\Omega$$
$$f_r \sim 6\, GHz$$



Gate defined GaAs DQD

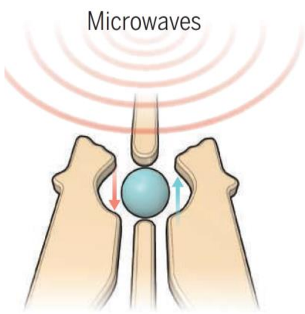
- On small mesa
- Resonator coupling gate not DC biased



Microwave reflectometry measurement

- Josephson parametric amplifier
- Custom FPGA electronics

Stockklauser*, Scarlino* *et al., PRX* **7**, 011030 (2017)



SPIN Qubits
in Quantum dots

Covering: basic concepts, measurement techniques,
implementations, qubit approaches, current trends

With figures and slides borrowed from
L. Vandersypen, J. Elzerman, R. Hanson, L. Kouwenhoven, M. Veldhorst (TU Delft)

Quantum dot

- A small semiconducting island where electrons are confined

→ discrete number of electrons

→ discrete energy level spacing

- Behavior in many ways similar to that of atoms

→ “artificial atoms”, with properties that can be engineered and controlled

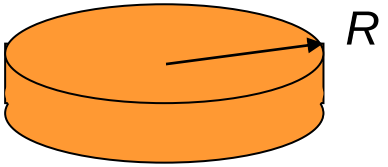
Energy scales

single electron charging energy: $E_C = e^2/C$

($C=8\varepsilon_r\varepsilon_o R$, *disk*)

R = 1 nm E_C = 0.3 eV => room temp.

R = 100 nm E_C = 3 meV => low temp.



confinement energy level spacing ΔE:

R = 1 nm E_l = 10 eV

R = 100 nm E_l = 1 meV

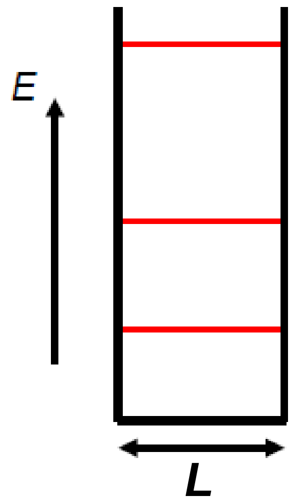
a particle trapped in
a cavity of radius R
$E_j = h^2/8mR^2$

thermal energy

T = 300 K kT ~ 26 meV
T = 4.2 K kT ~ 0.35 meV
T = 30 mK kT ~ 2.6 μeV

Atoms vs. Quantum Dots

Schrödinger:
electrons in confined systems occupy quantized energy levels



Particle in a box:

$$E_n = \frac{\hbar^2}{2m}\left(\frac{\pi n}{L}\right)^2, \quad n = 1, 2, 3\ldots$$

QDs: 0.1 meV
Atoms: 10 eV

Pauli:
each level can be occupied with one spin-up electron and one spin-down electron

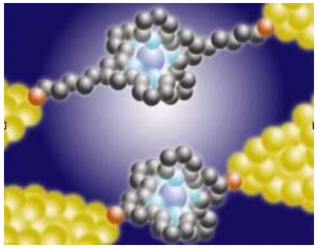
	Atom	Quantum dot
Confinement	r^{-1},strong, rigid, hard to tune	r^2, soft, parabolic, tunable
Symmetry	perfect, given by nature	never perfect, hard to achieve
Electrical addressing	hard to achieve	well suitable tunable coupling
Optical addressing	well suitable	well suitable
Coupling to	thermal photons, ...	photons, phonons, other electrons

Both systems give access to single electron/spin manipulation

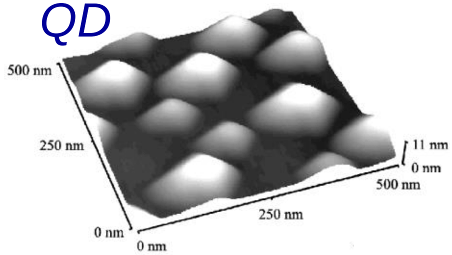
Examples of quantum dots

Electrostatically defined QD in semiconductors

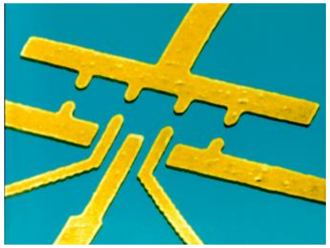
single molecule



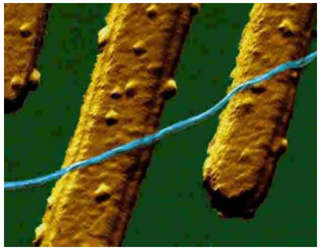
self-assembled QD



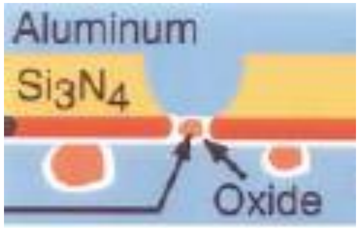
lateral QD



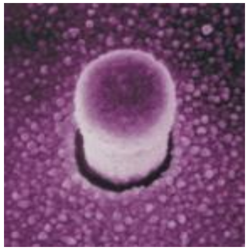
nanotube



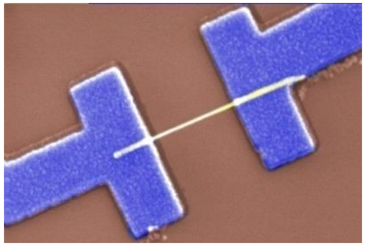
1 nm *10 nm* *100 nm* *1 μm*



metallic nanoparticle

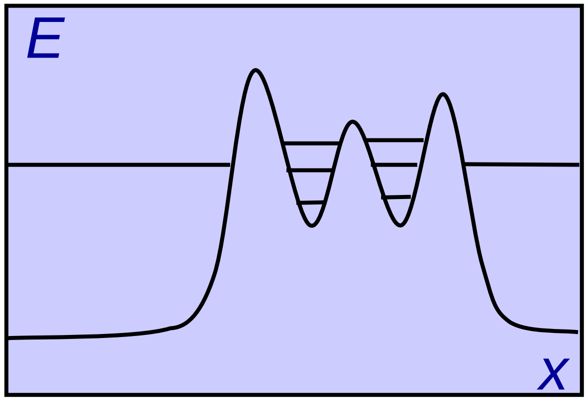


vertical QD

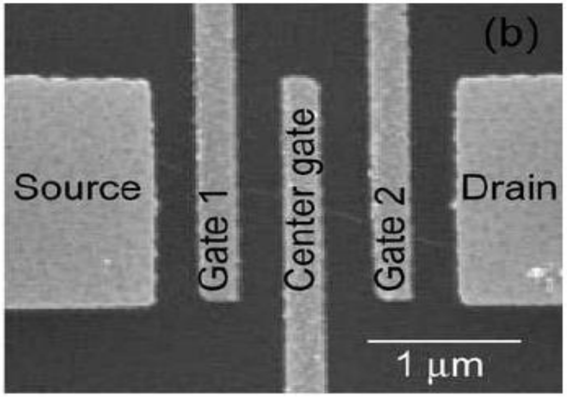


nanowire

Quantum dots – electrostatically defined

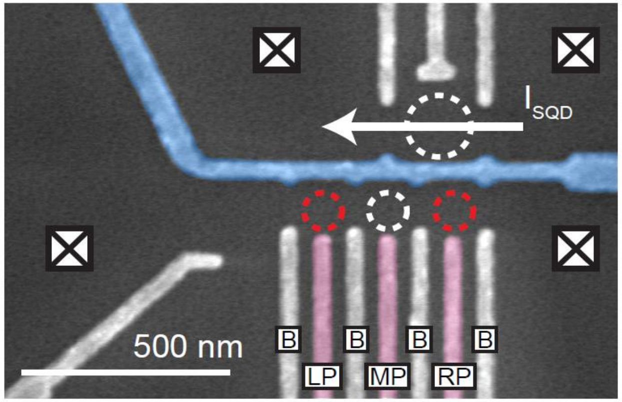


nanotube

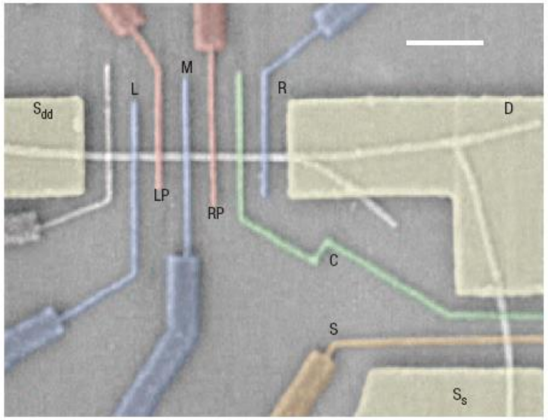


© Schoenenberger

2D electron gas



nanowire



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Quantum computation with quantum dots

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[1]Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106-4030
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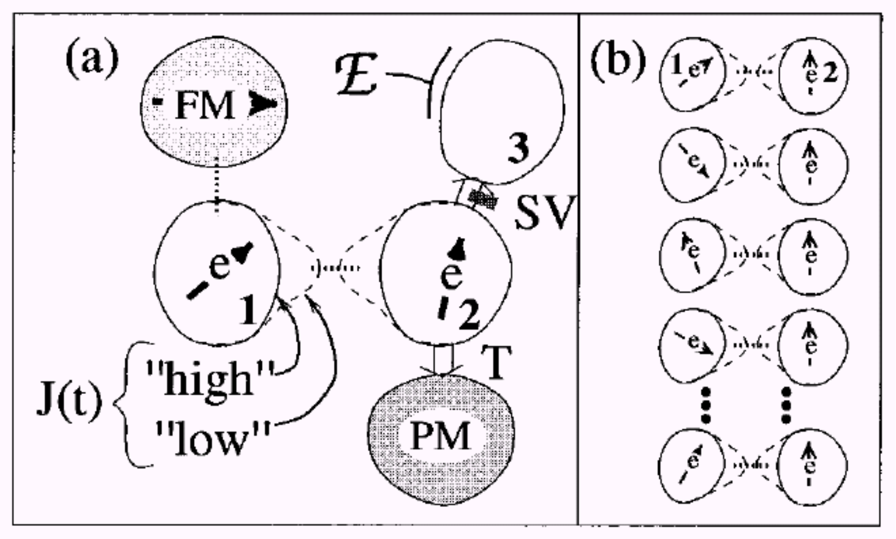
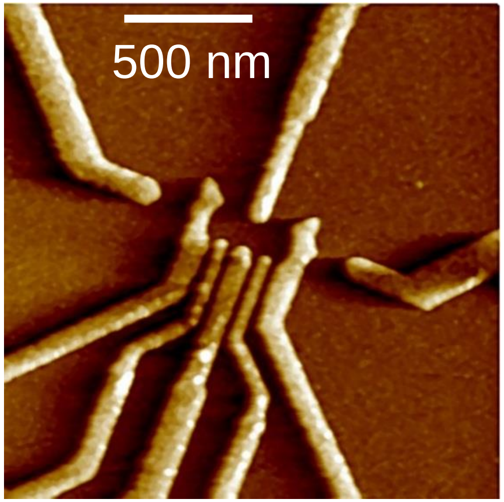
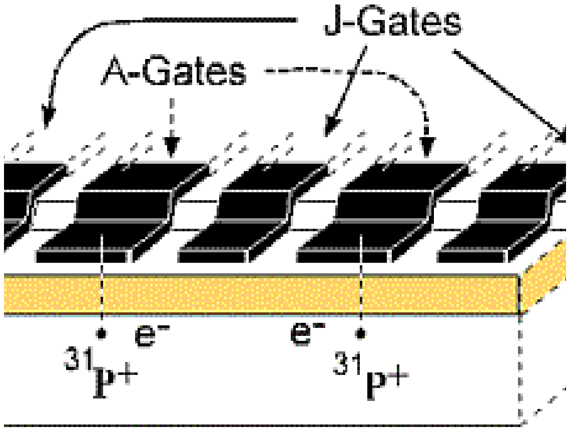
[3]IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598
(Received 9 January 1997; revised manuscript received 22 July 1997)

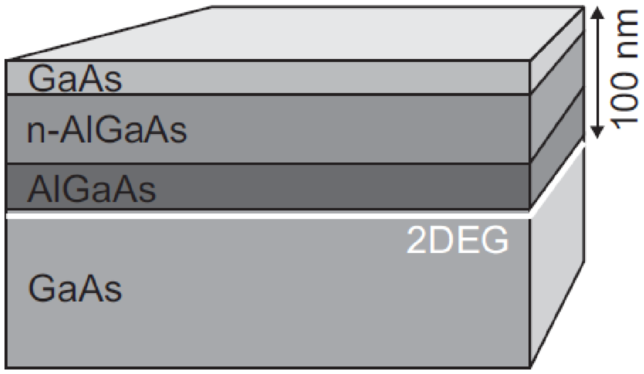


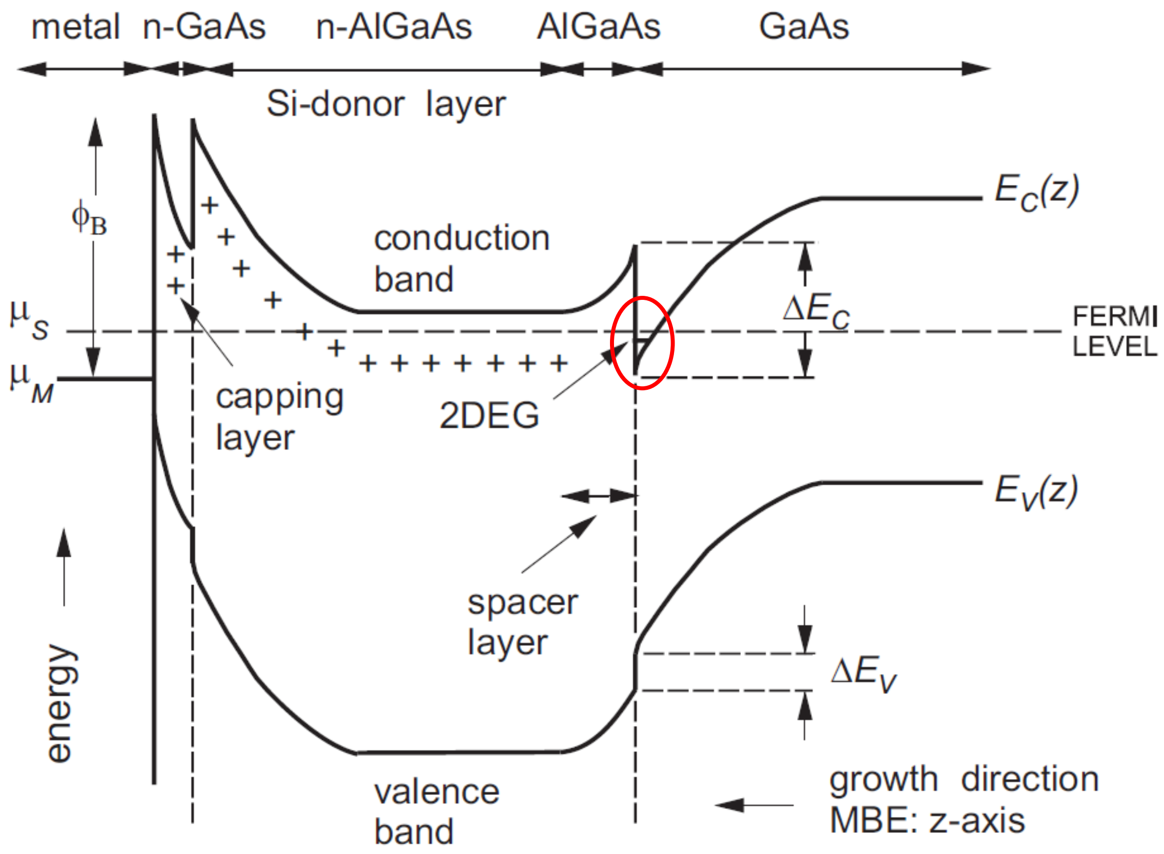


A Silicon-based Nuclear Spin Quantum Computer
B. E. Kane, Nature 393, 133 (1998).

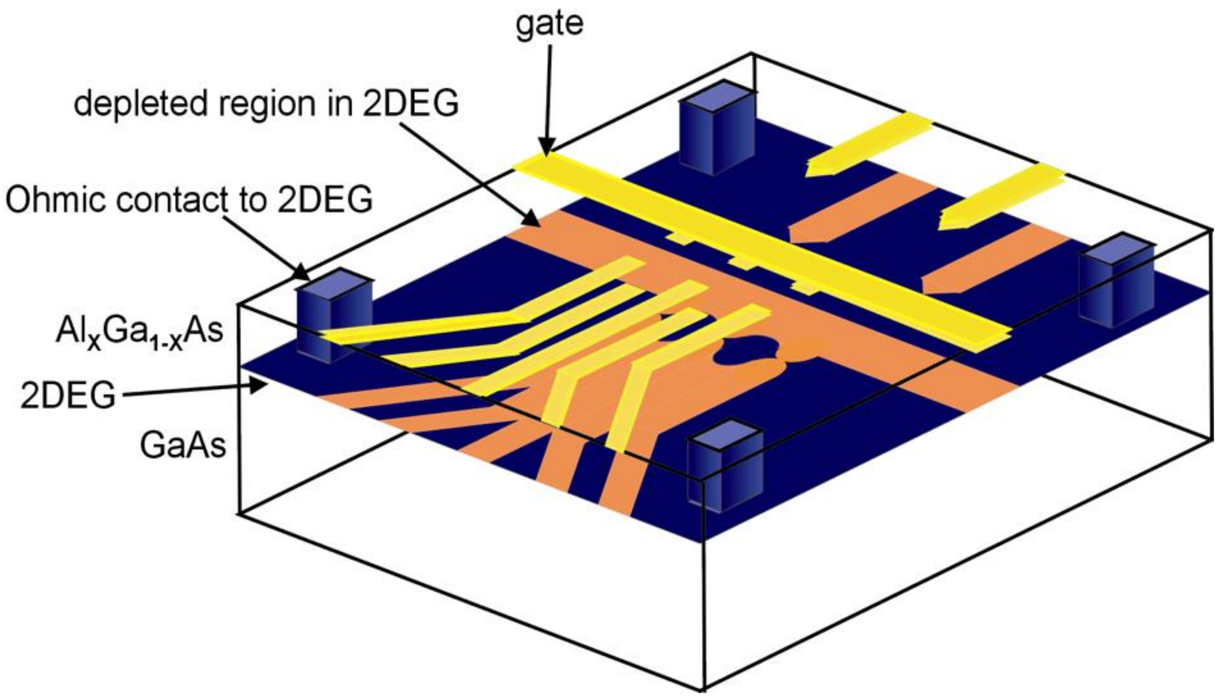


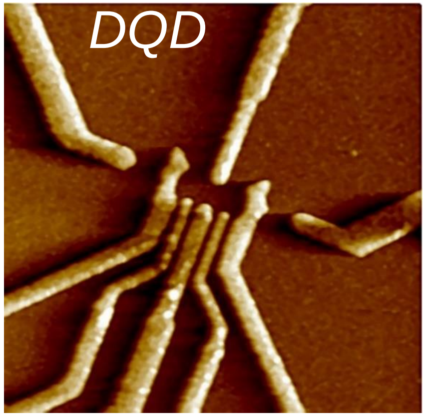
Main implementations so far:
Electrons in GaAs/AlGaAs or Si-based materials

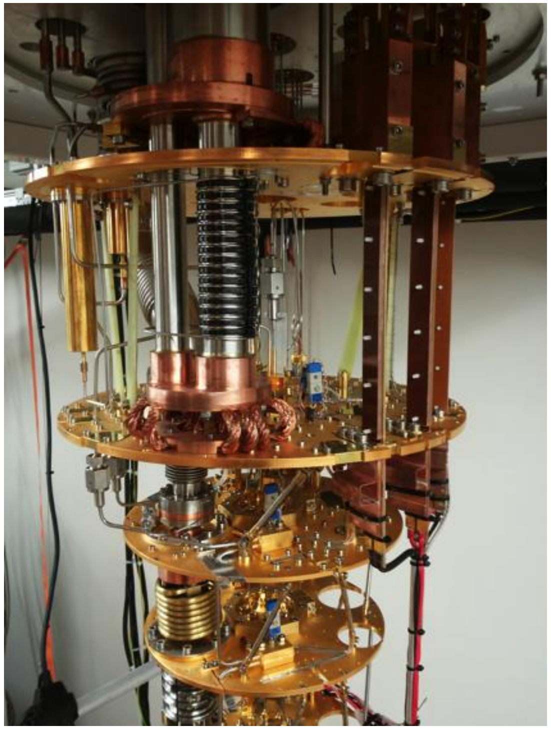




Quantum dots: hosts for electron spin qubits





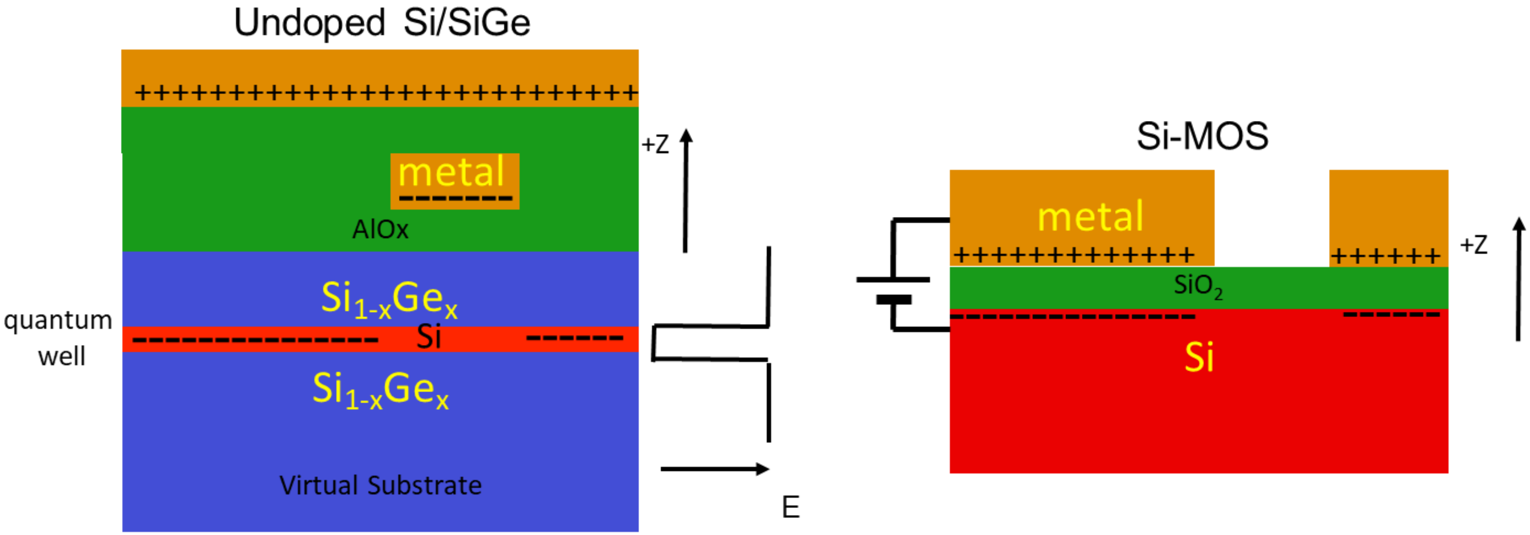


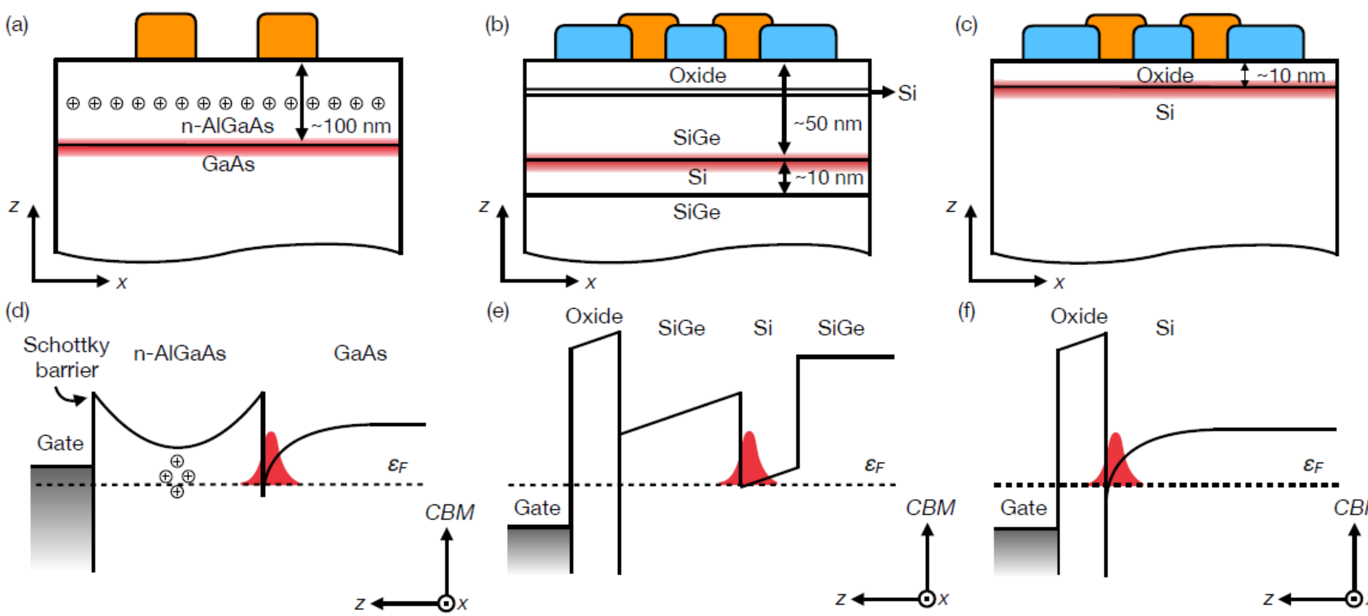
Discrete # charges, quantized orbitals

Electrical control and detection

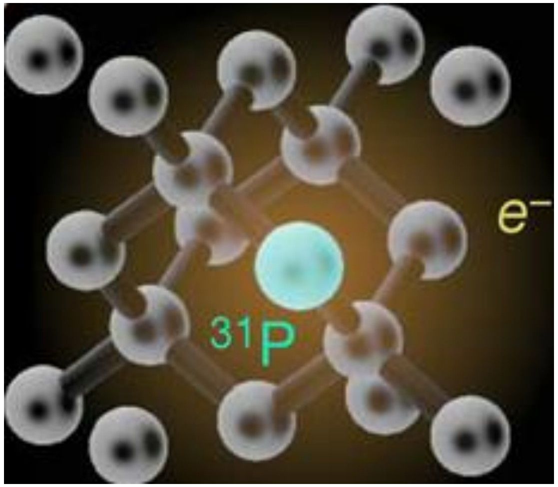
- Tunable # of electrons
- Tunable tunnel barriers
- Electrical contacts

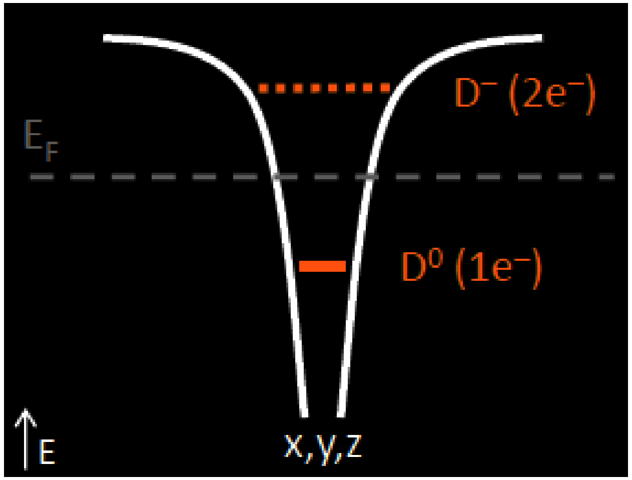
Accumulation versus depletion mode





Donors – ^{31}P in Si

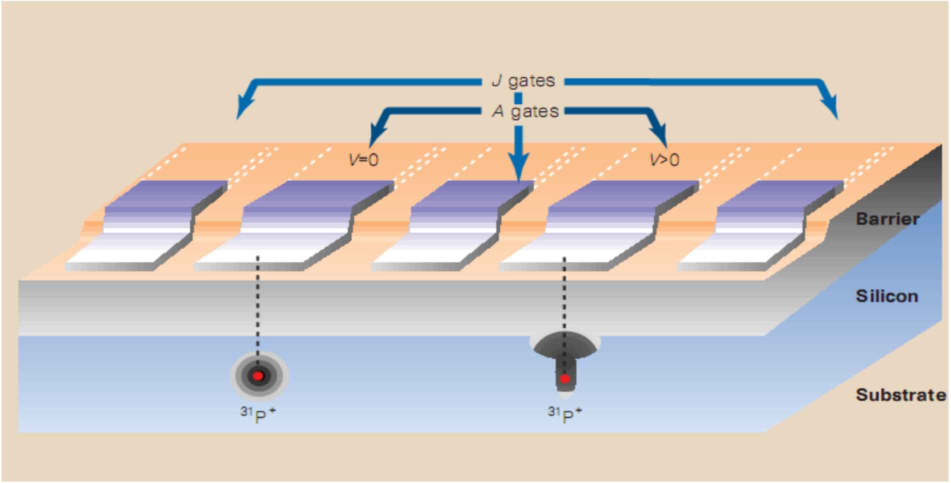




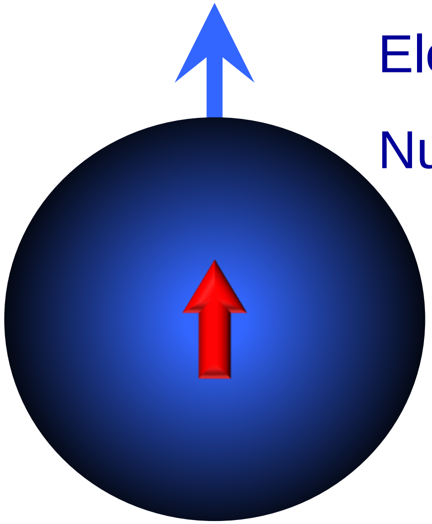
Loosely bound 15th electron of P

Bohr radius ~ 2.5 nm

Coulomb binding potential



B. Kane, Nature **393**, 133 (1998)

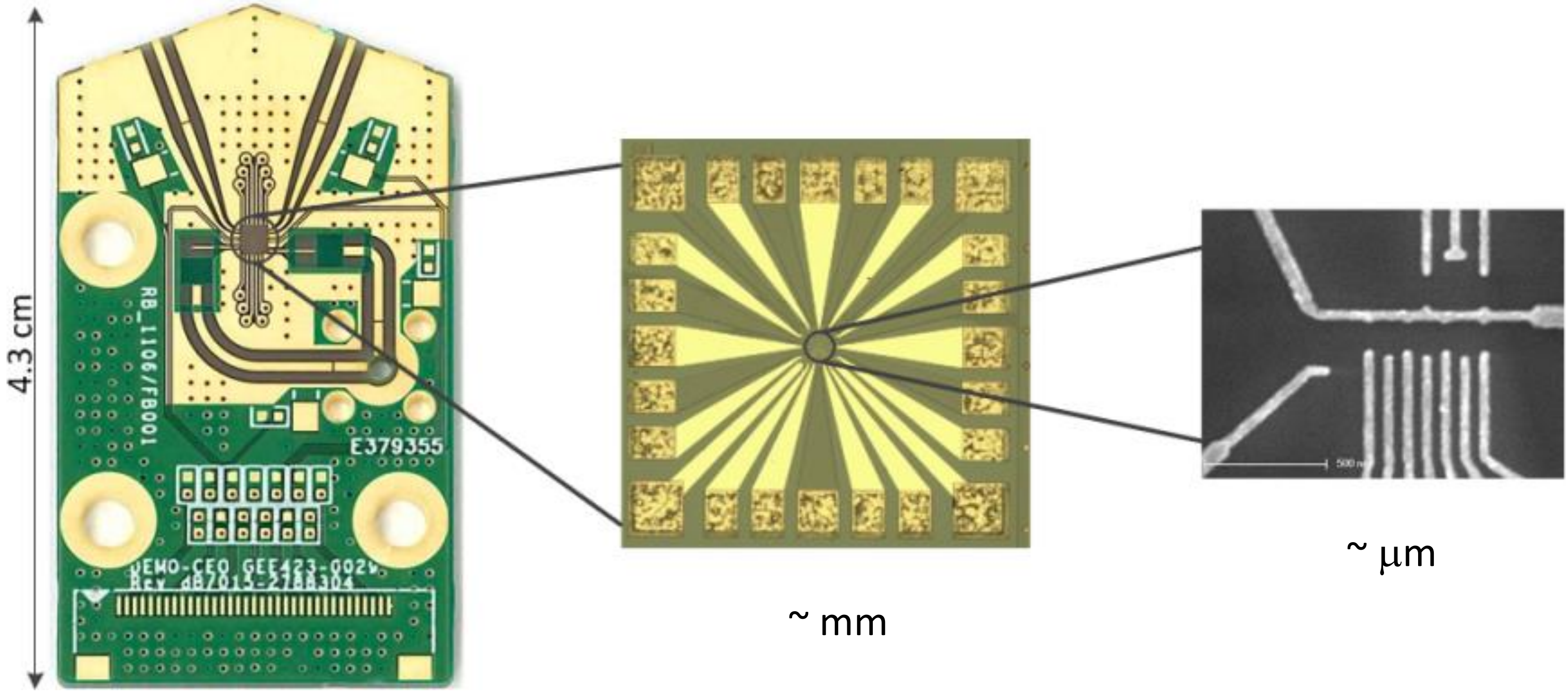


Electron spin ½

Nuclear spin 1/2

Images taken from A. Morello

Typical devices

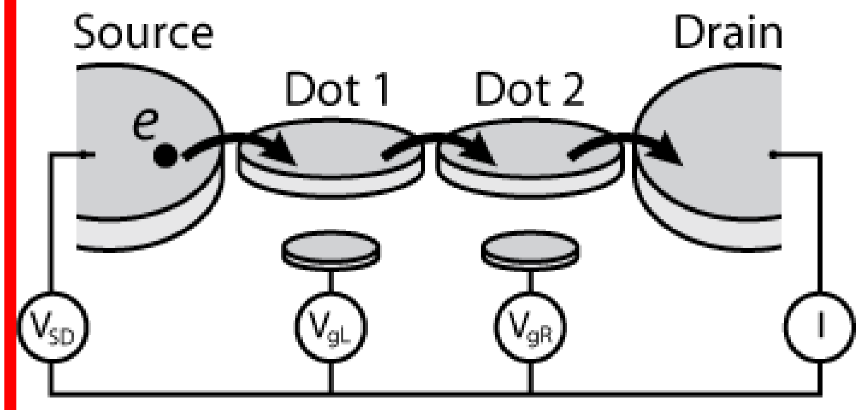


~ cm

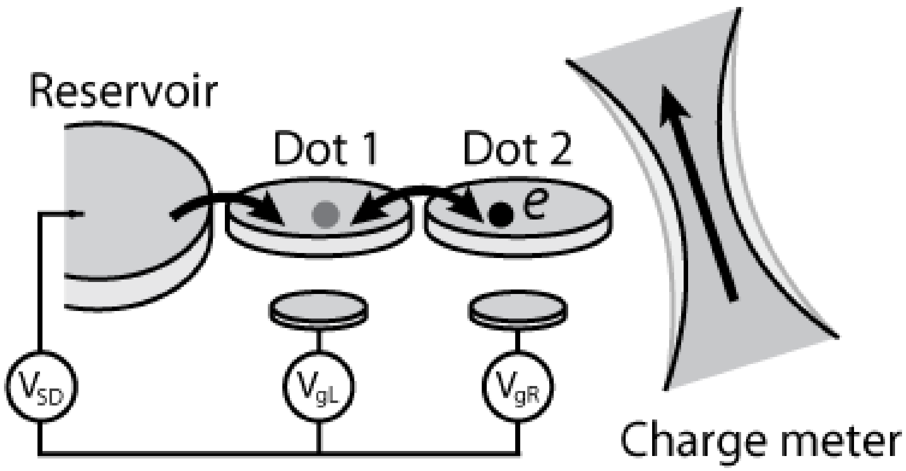
~ mm

~ μm

Electrical measurement of quantum dots

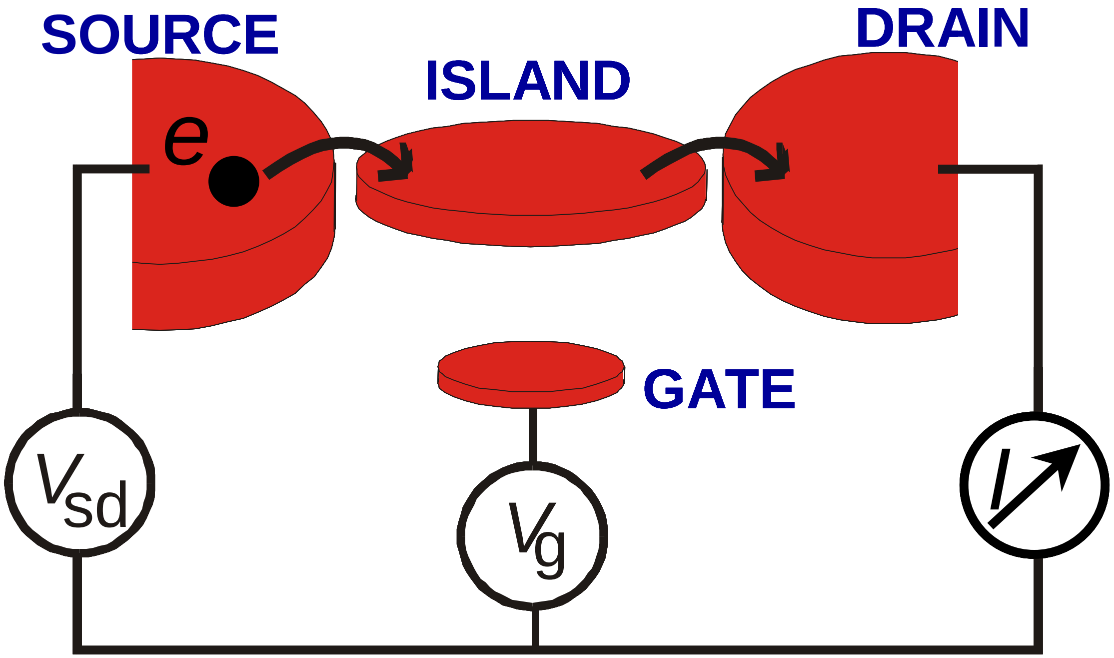


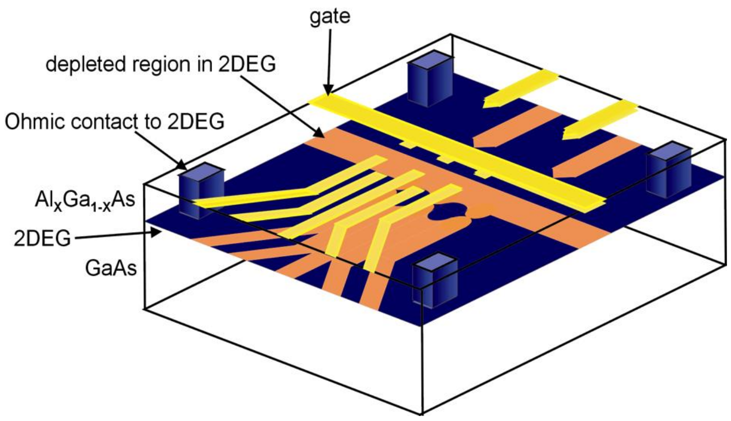
Electron transport through dots



Electron transport through QPC

Electrically controlled quantum dots

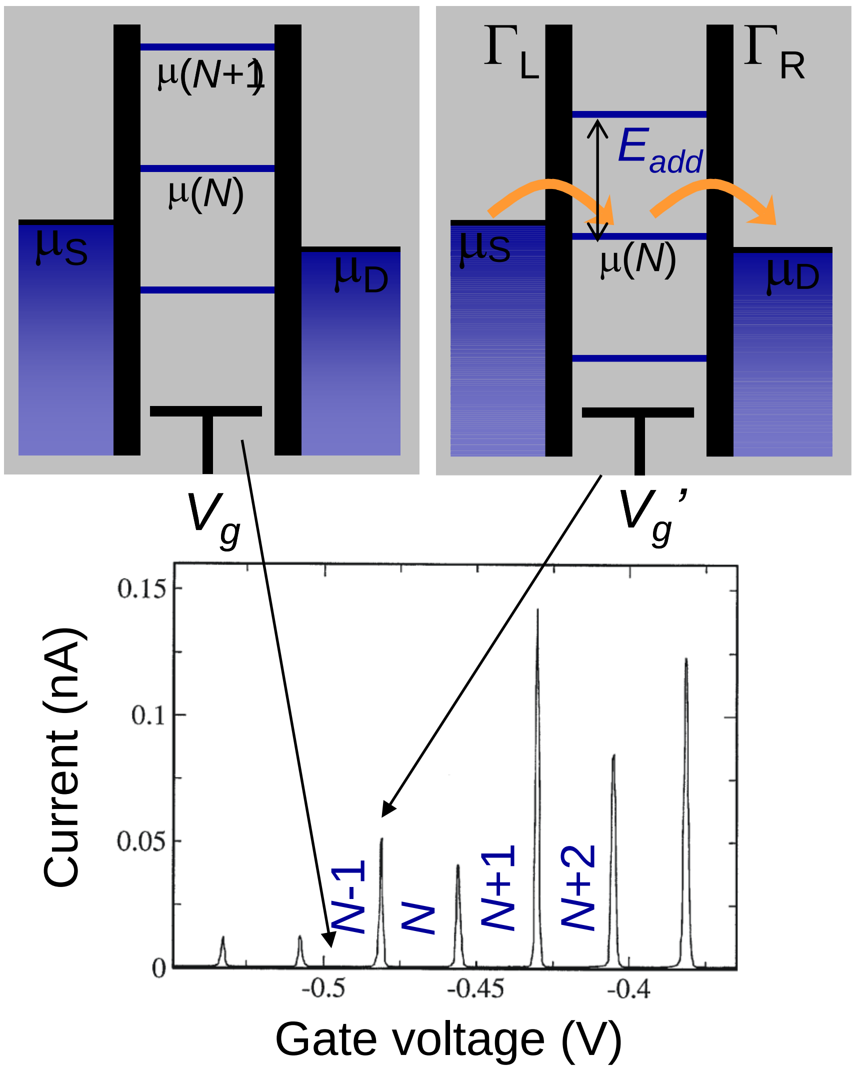




- Coupled via tunnel barriers to source and drain reservoirs
- Coupled capacitively to gate electrode(s)

Single electron tunneling

Linear response



$\mu(N)$ electrochemical potential,

Energy an electron needs to have in order to enter the dot

$\mu(N) = U(N) - U(N\text{-}1)$
with $U(N)$ total energy

E_{add} extra energy needed to add one electron

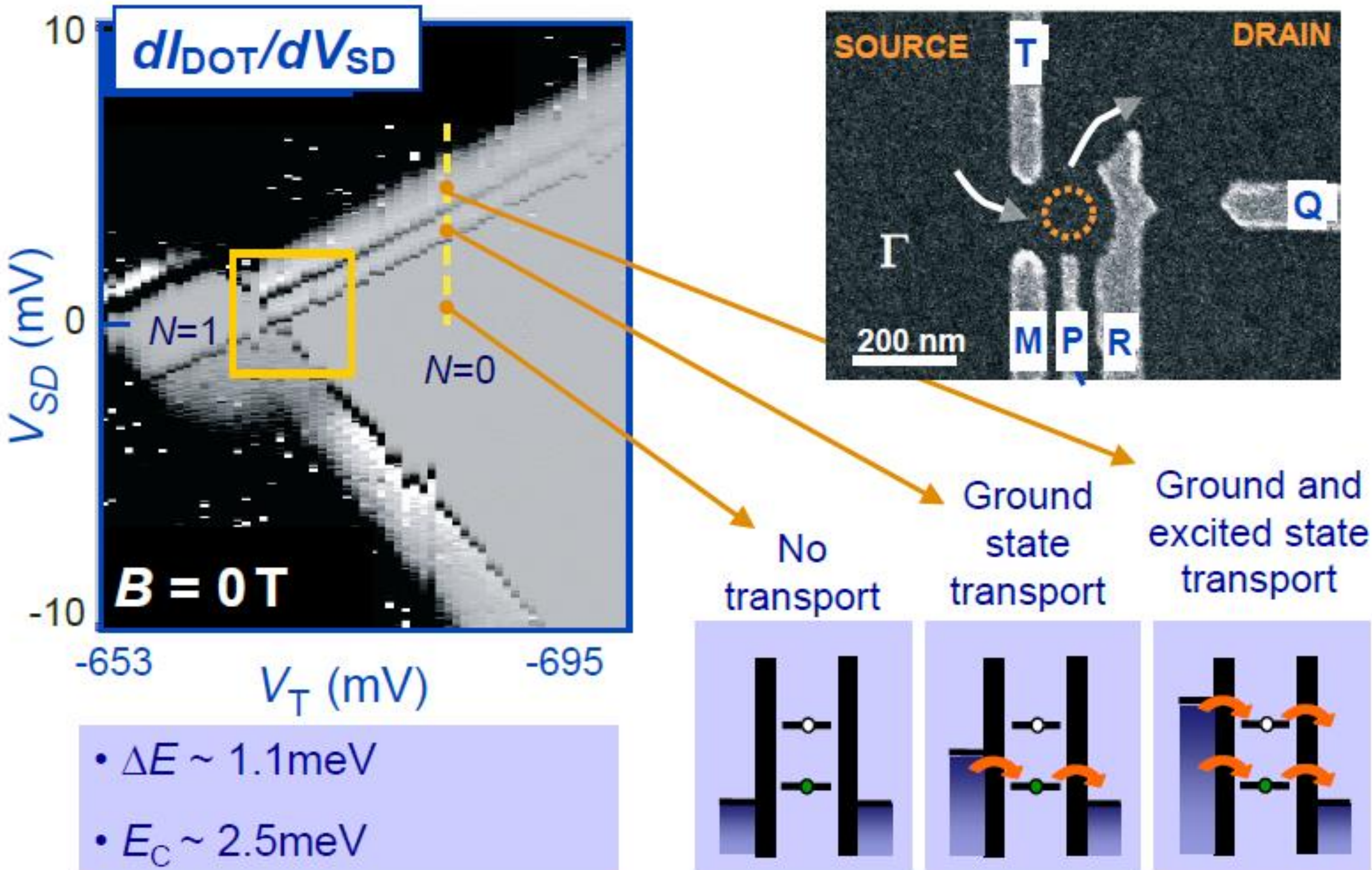
$E_{add} = \mu(N+1) - \mu(N)$

$E_{add} = E_c + \Delta E$

Charging energy

Confinement energy

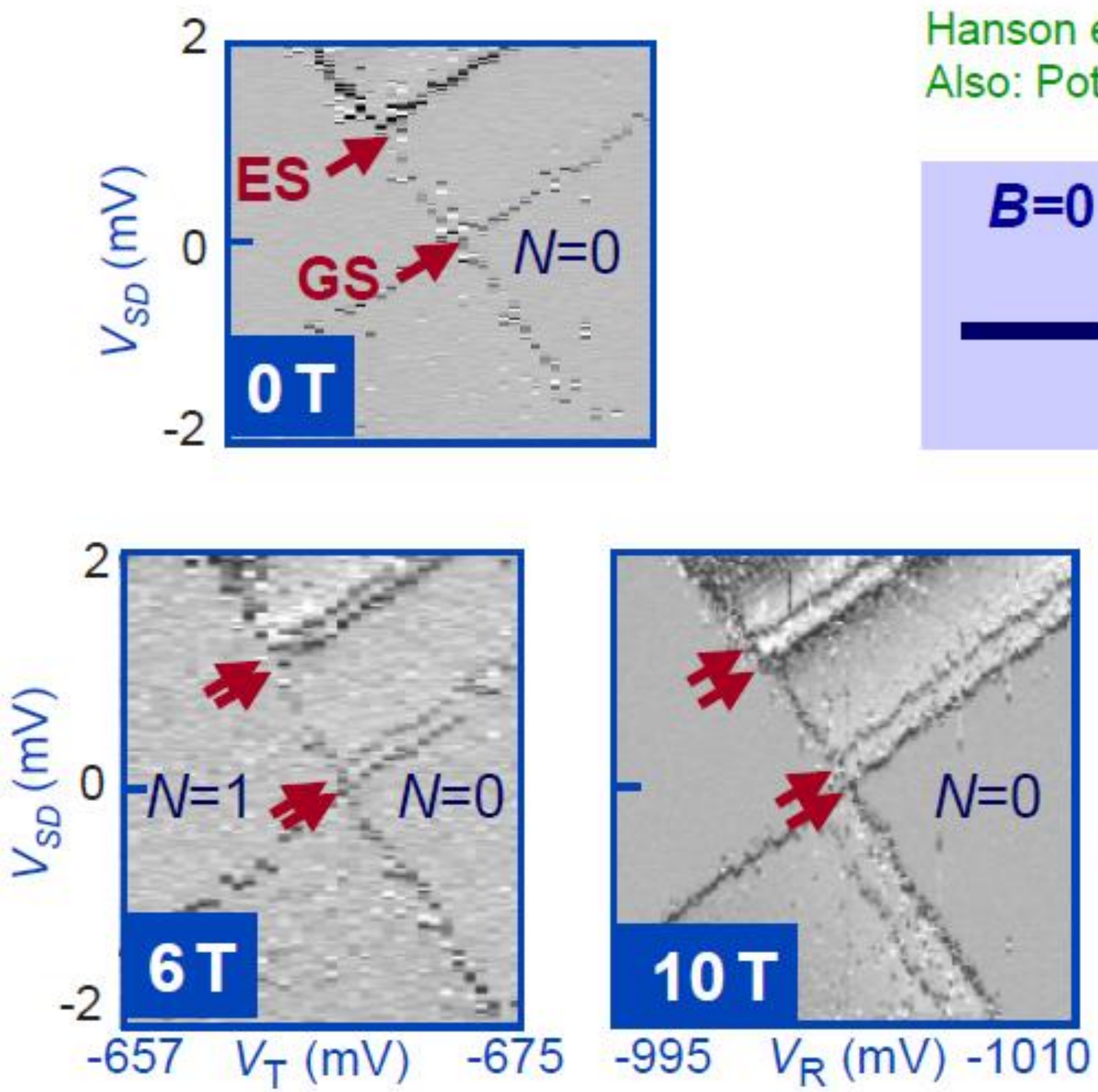
Energy level spectroscopy at B=0

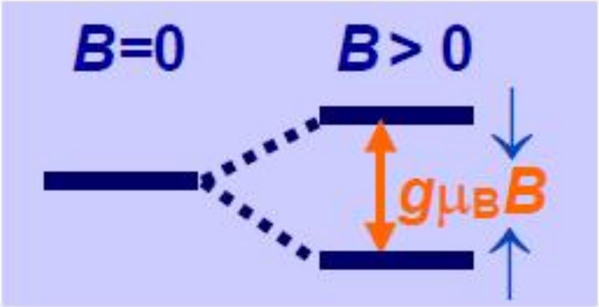


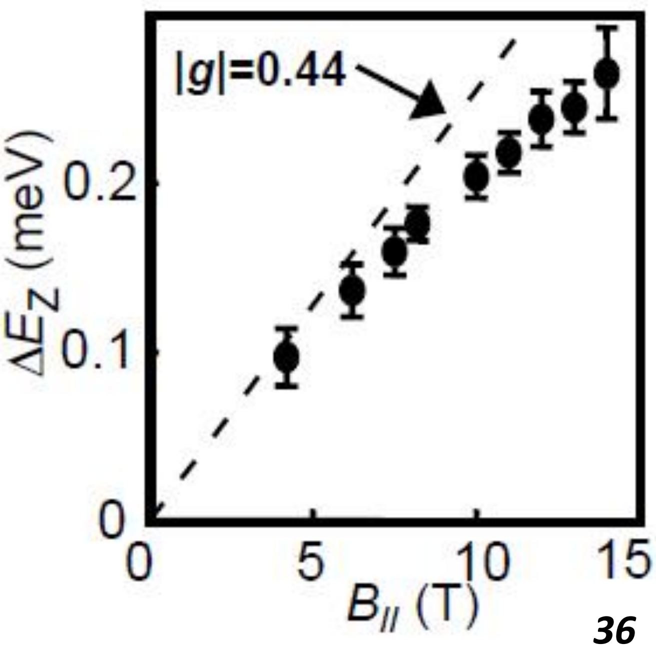
- ΔE ~ 1.1meV
- E_C ~ 2.5meV

Single electron Zeeman splitting in B//

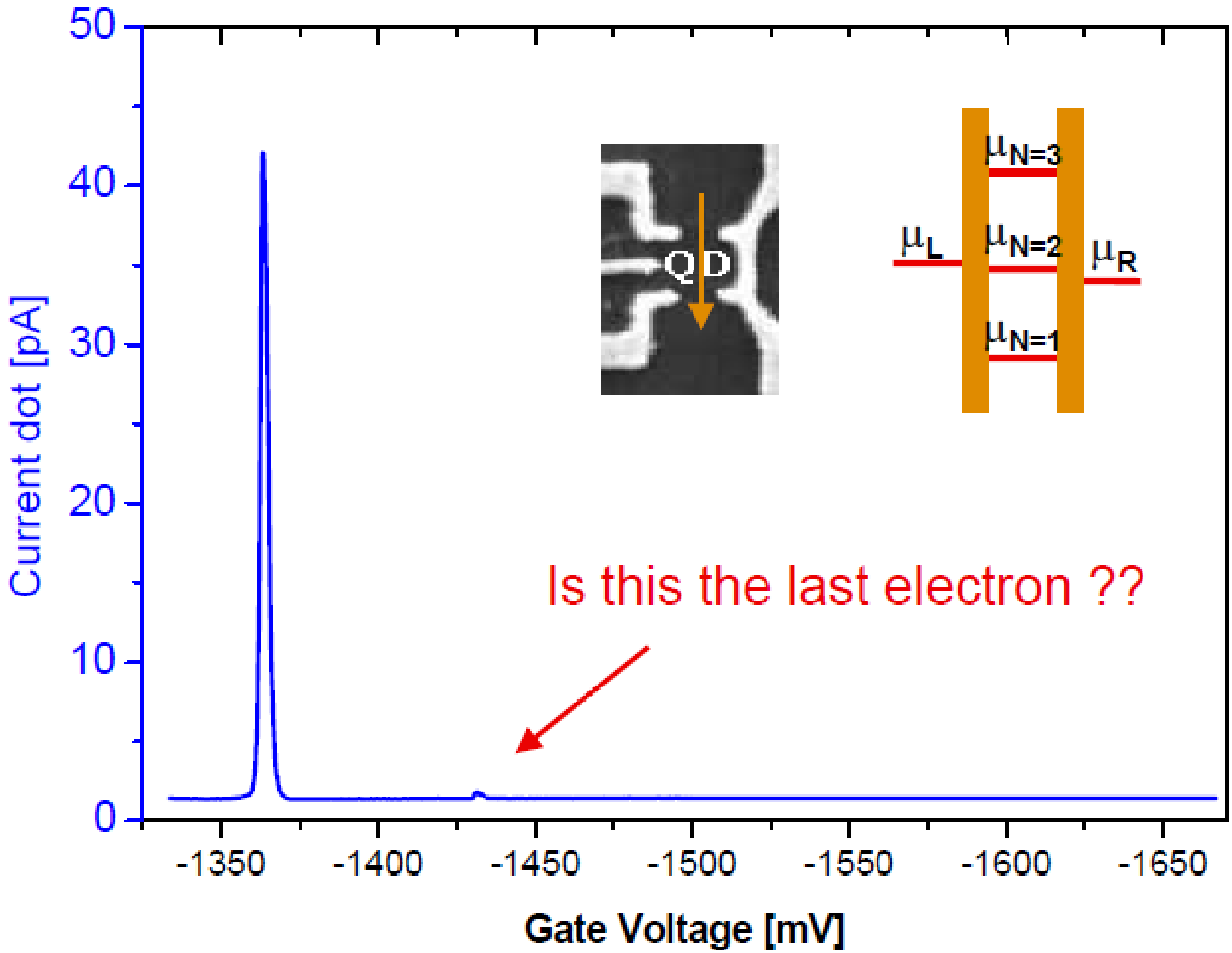
Hanson et al, PRL 91, 196802 (2003)
Also: Potok et al, PRL 91, 016802 (2003)



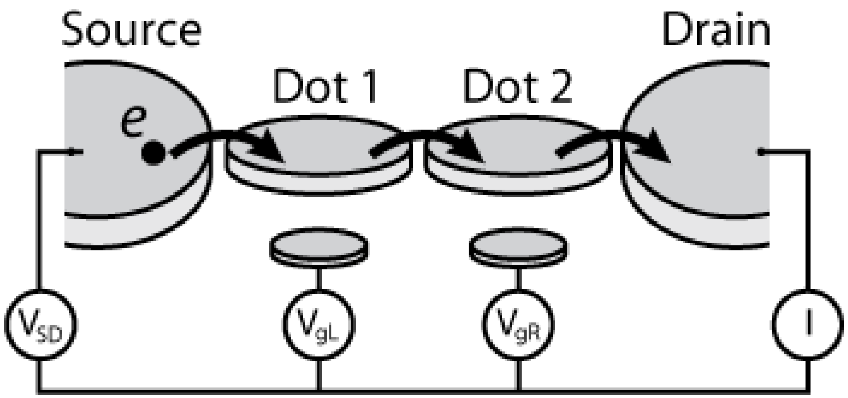




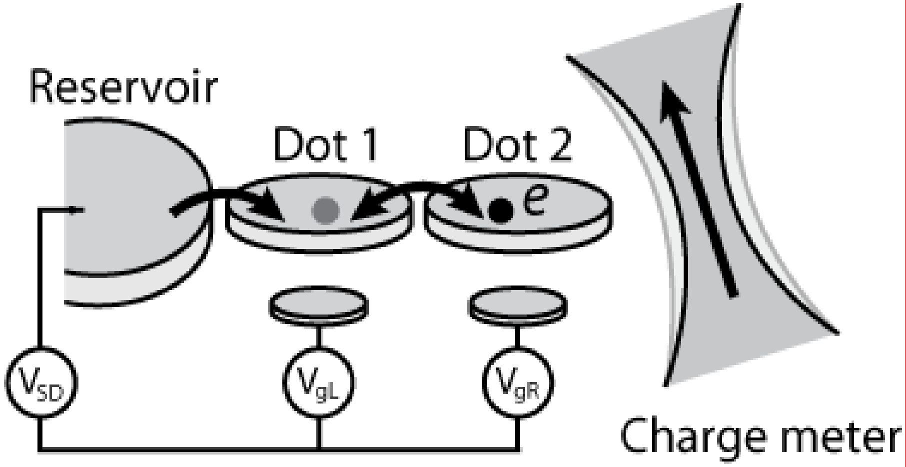
Toward the last electron



Electrical measurement of quantum dots



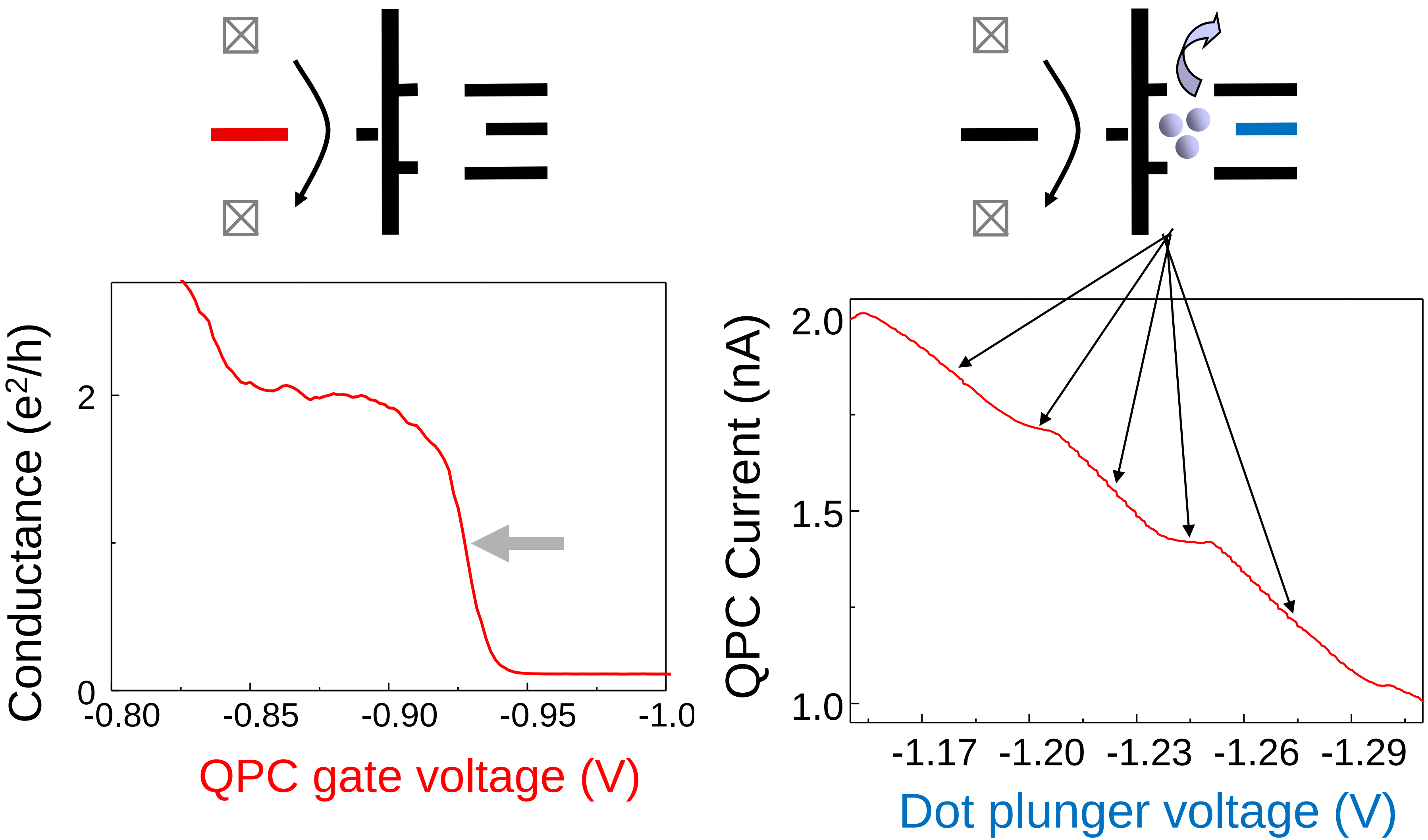
Electron transport
through dots



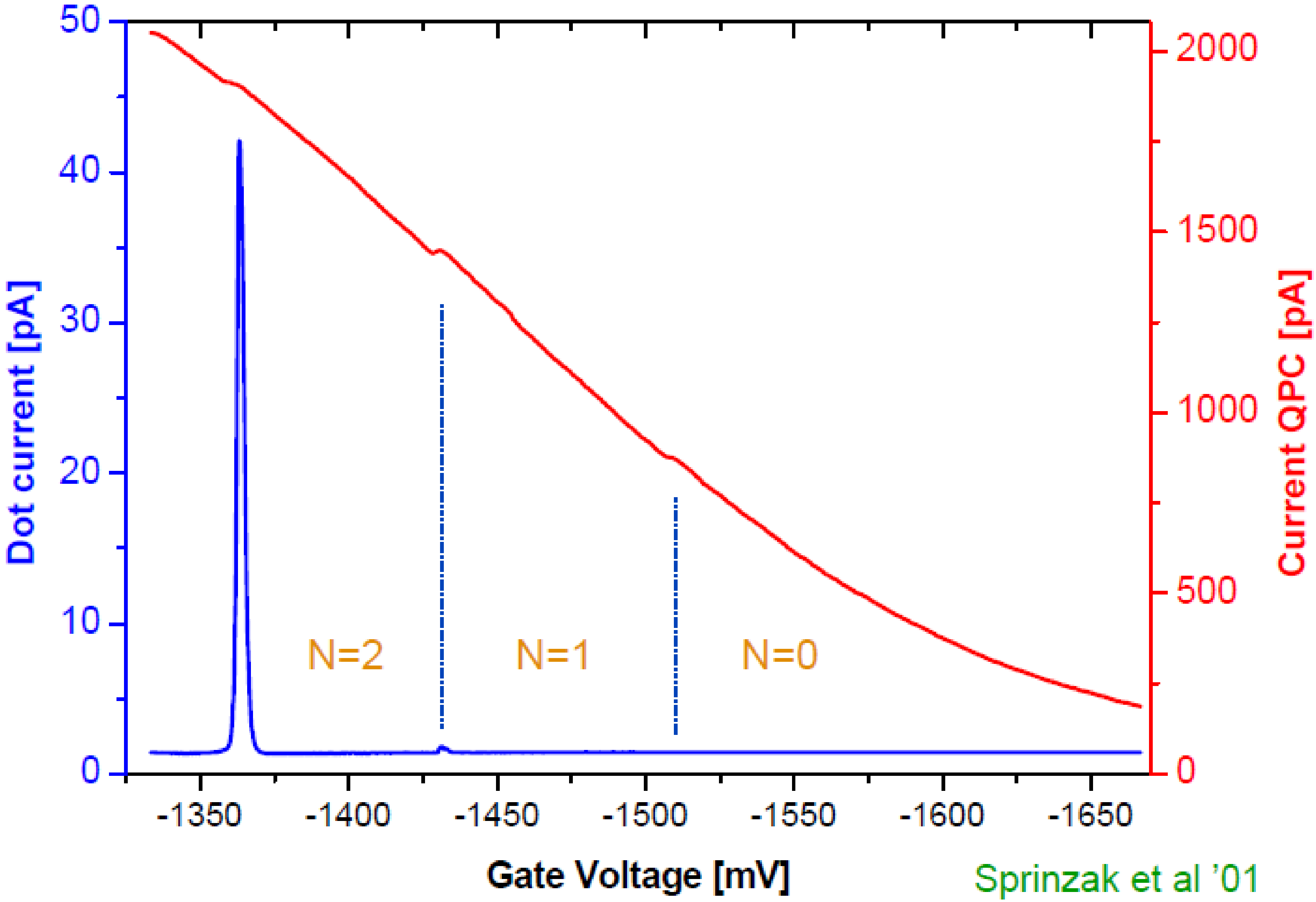
Electron transport
through QPC

A quantum point contact (QPC) as a charge detector

Field *et al*, PRL 1993

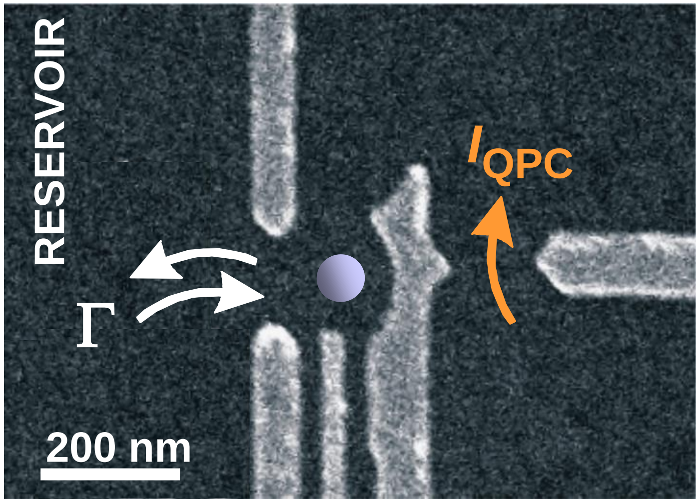


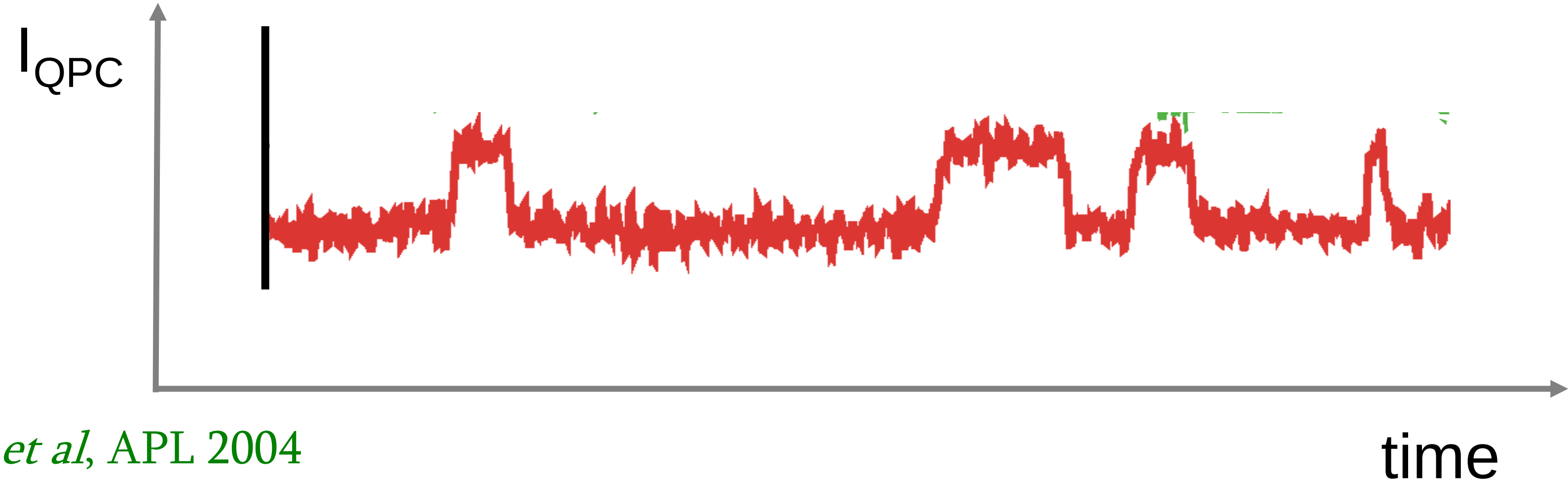
The last electron!



Sprinzak et al '01

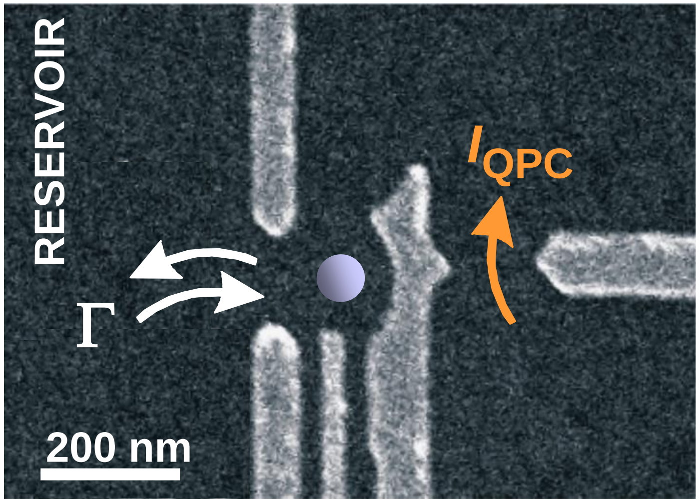
Real-time charge detection





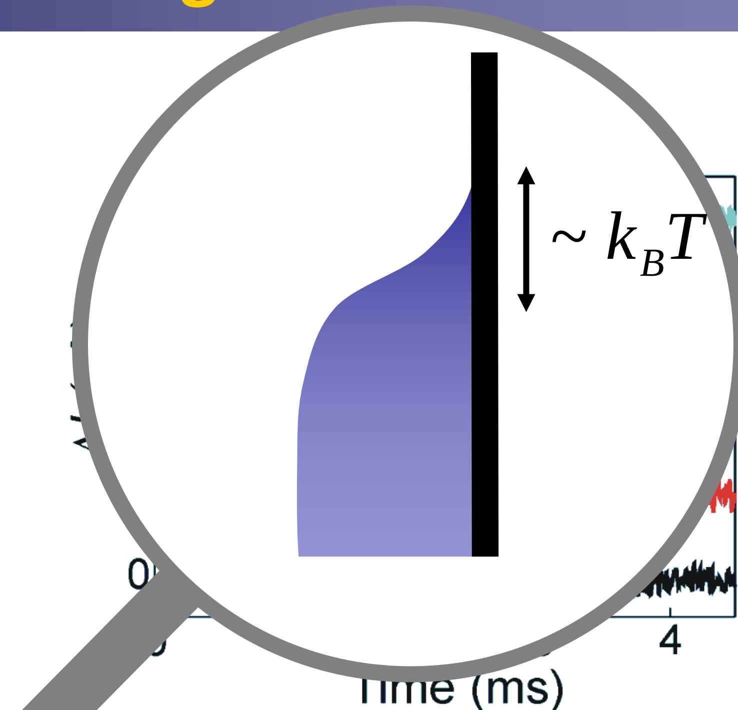
Vandersypen *et al*, APL 2004

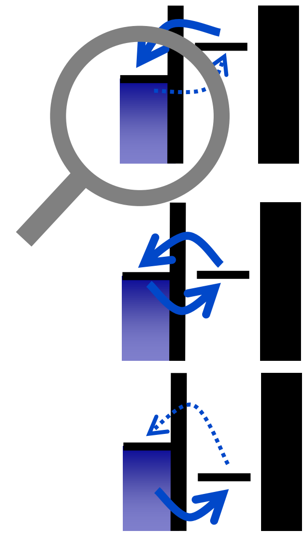
Real-time charge detection



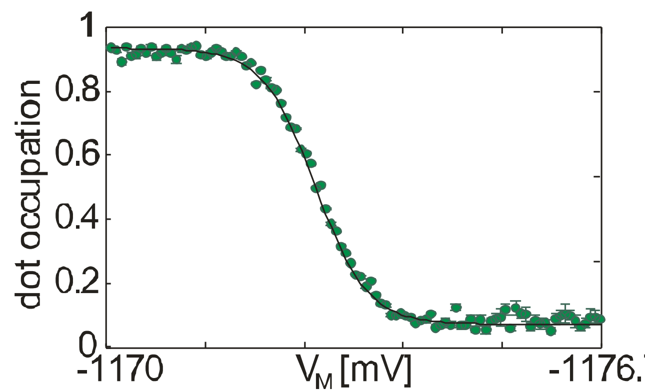
- V_{SD} ~ 1 mV
- I_{QPC} ~ 30 nA
- ΔI_{QPC} ~ 0.3 nA
- Shortest steps ~ 8 µs
- With cryogenic preamplifier (HEMT) shortest steps ~300ns

Vandersypen et al, *APL* ('04);
fast detection: Vink et al., *APL* ('07)

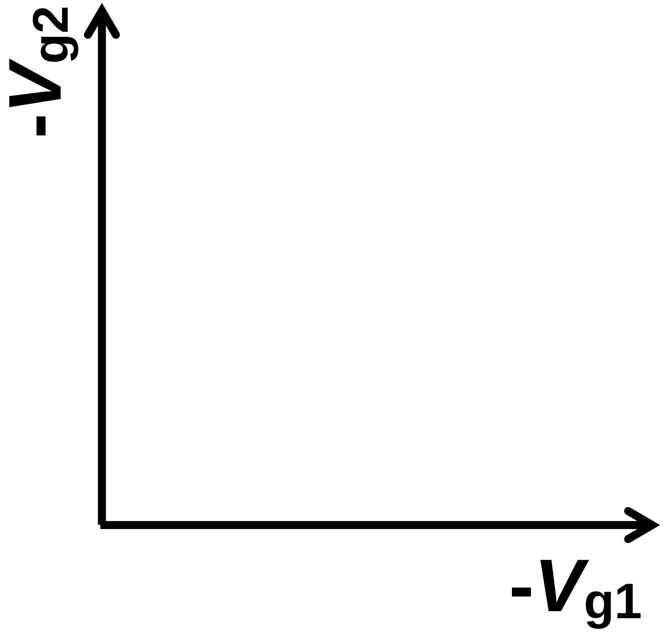


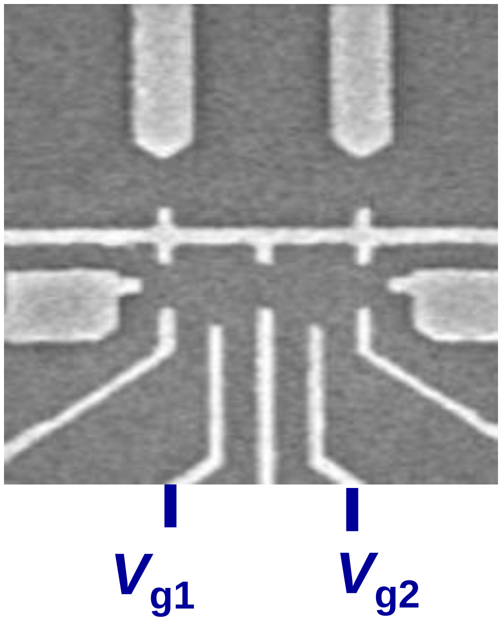


Change tunnel rate Γ by scanning through fermi distribution of the reservoir



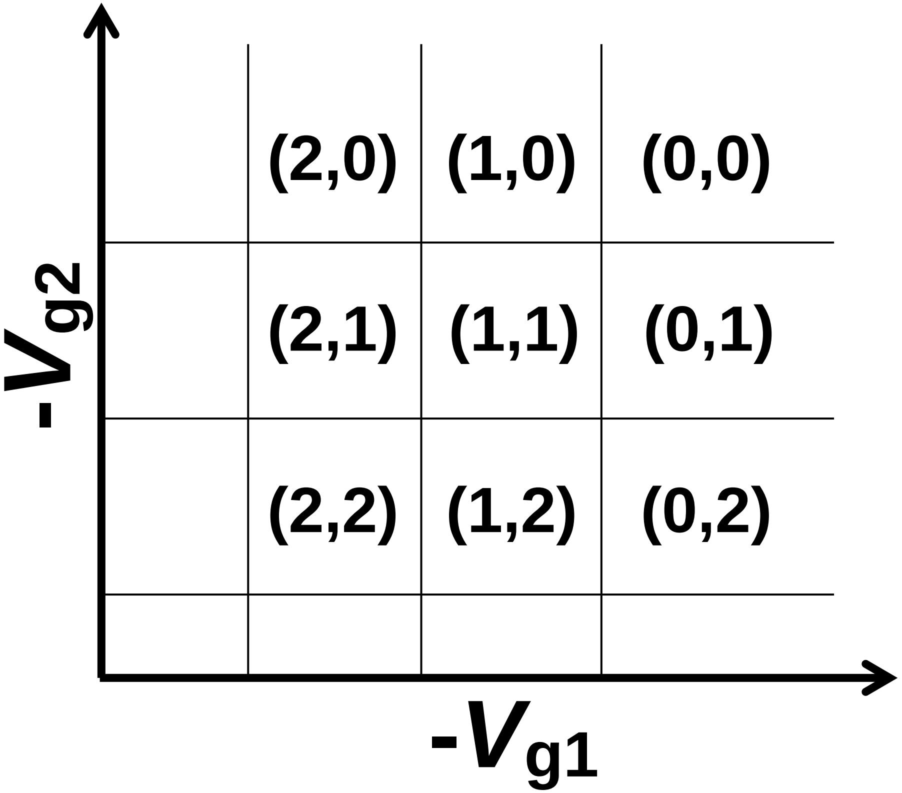
Two coupled quantum dots





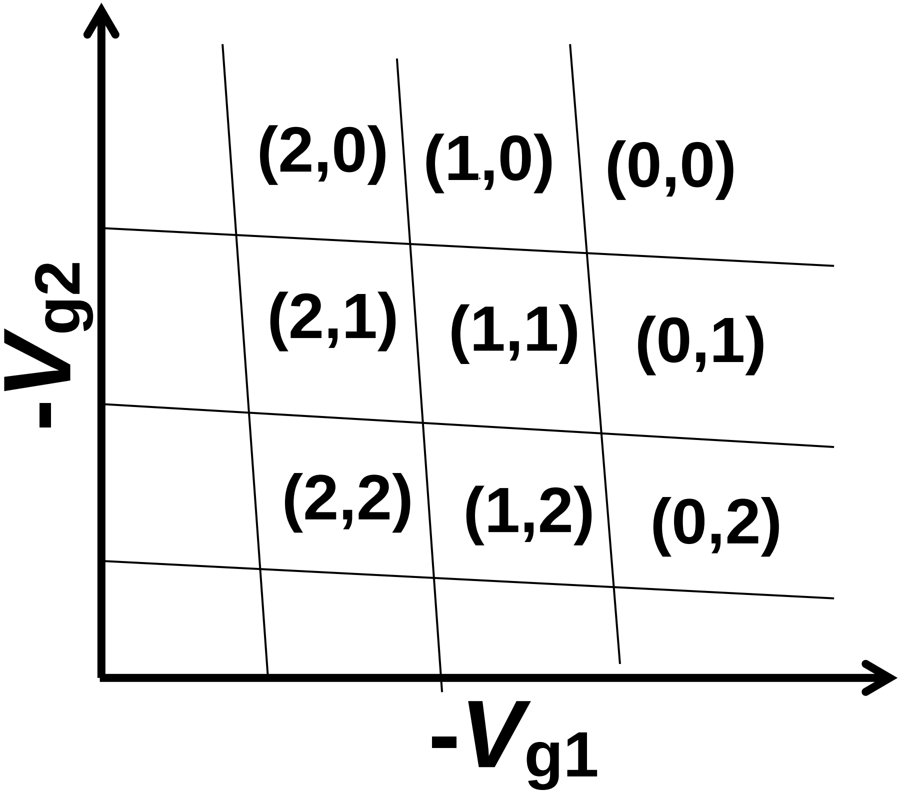
Two coupled quantum dots

Zero inter-dot capacitance, zero cross-talk

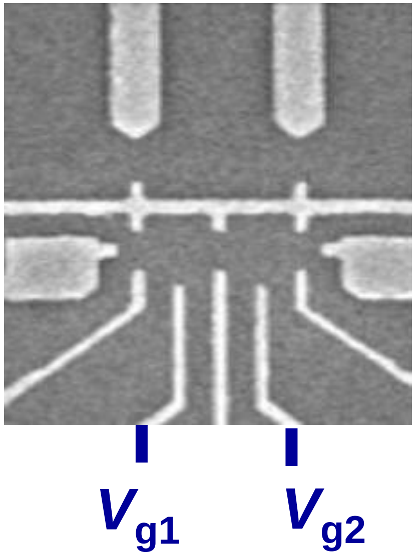


Two coupled quantum dots

Zero inter-dot capacitance, non-zero cross-talk

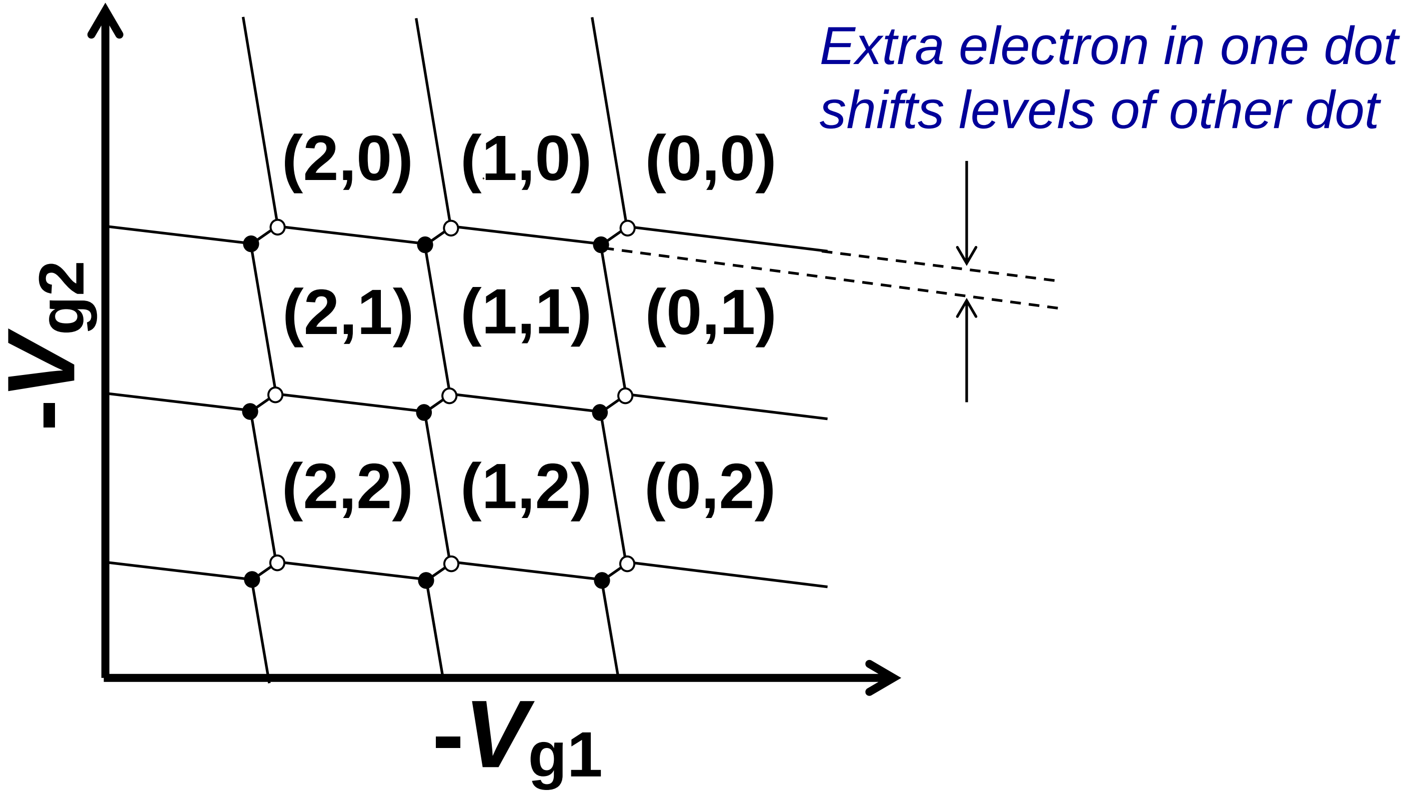


Left gate also affects right dot

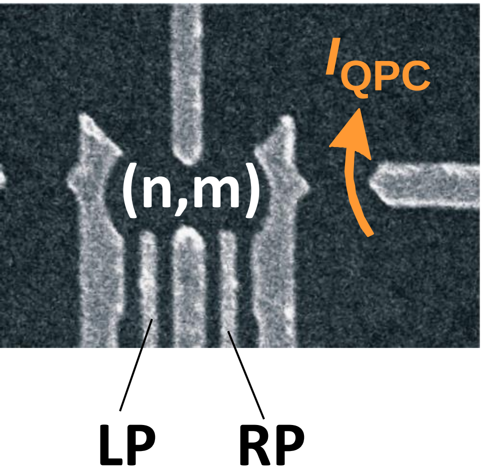


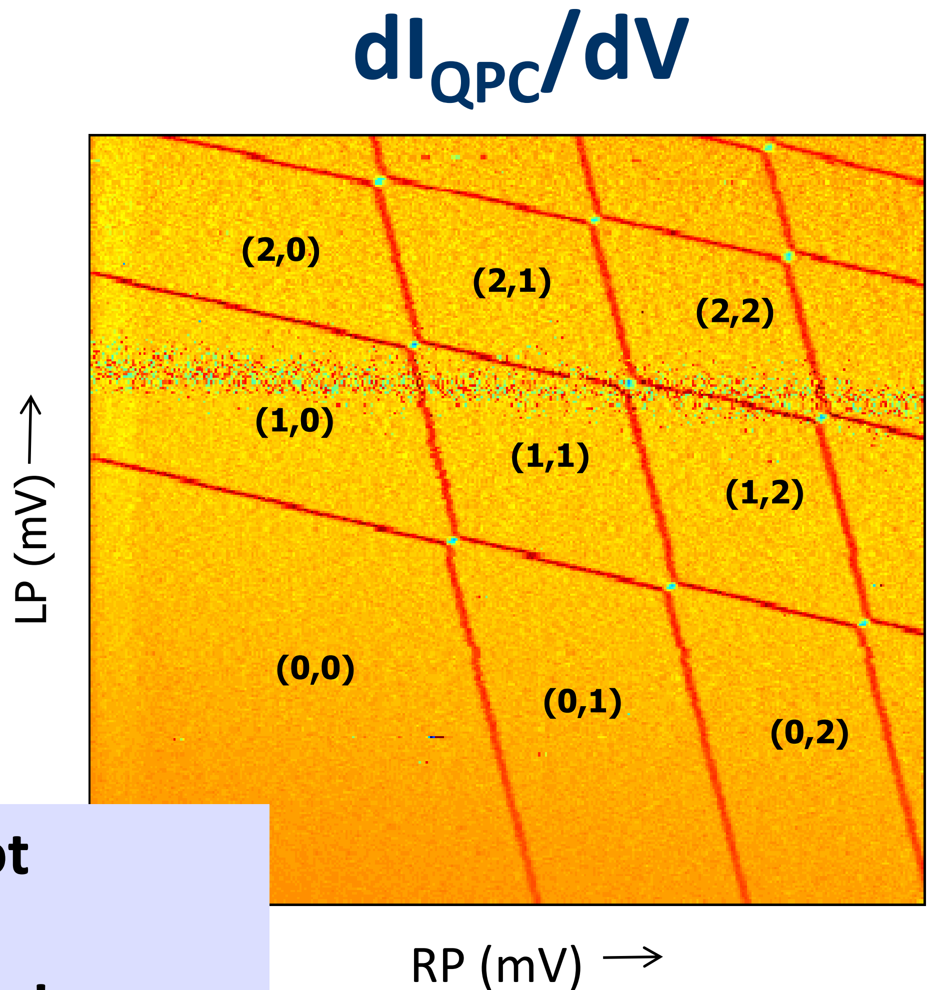
Two coupled quantum dots

Non-zero inter-dot capacitance and cross-talk



QPC – find the last electron

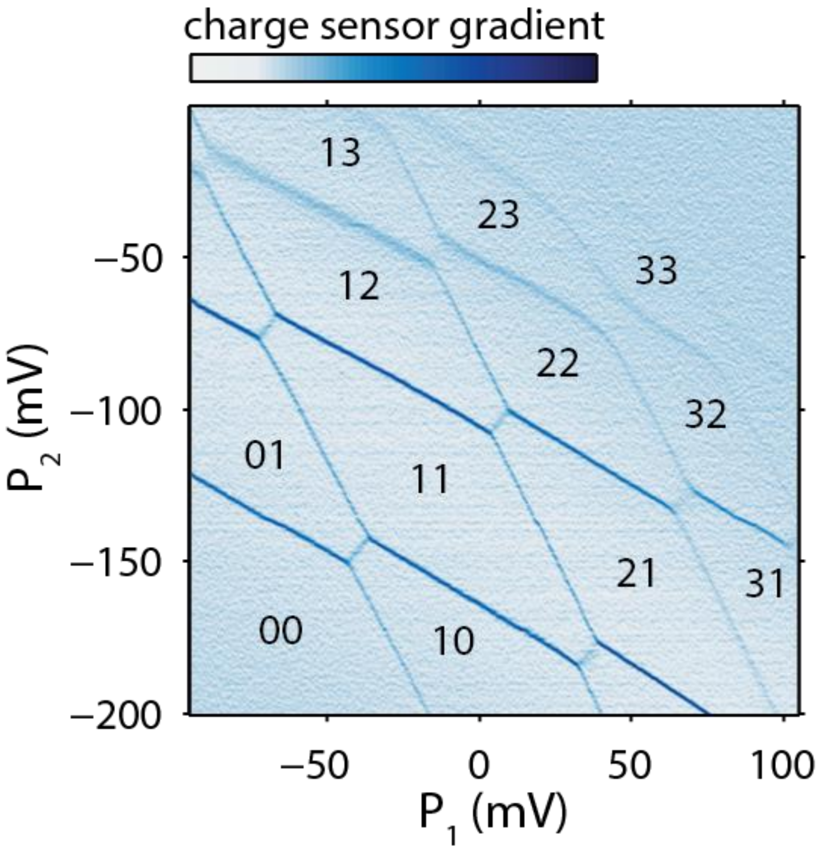


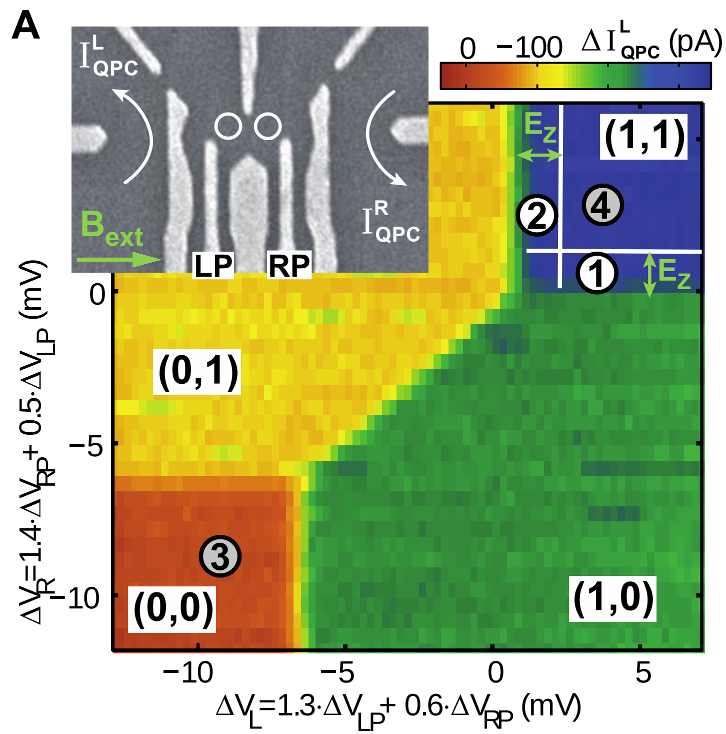


QPC detects all charge transitions, also between dots

Double dot emptied completely!

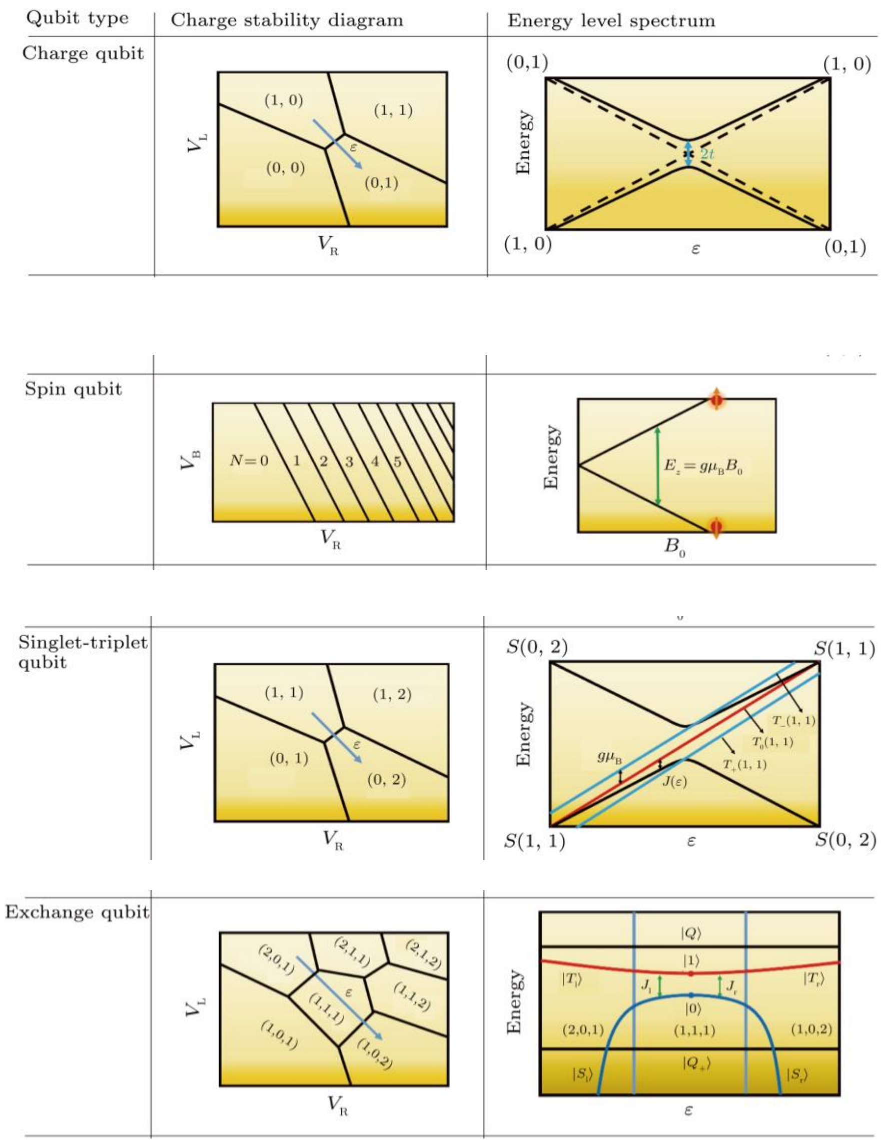
Charge detection in double dot

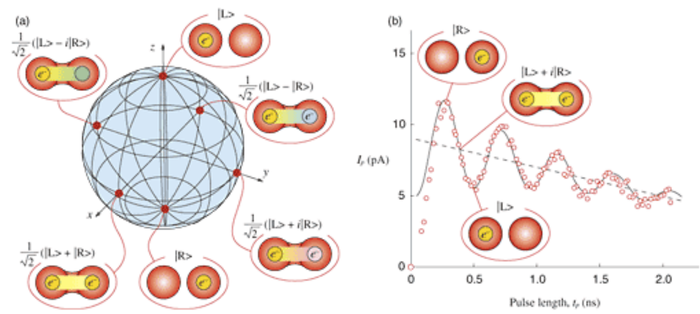


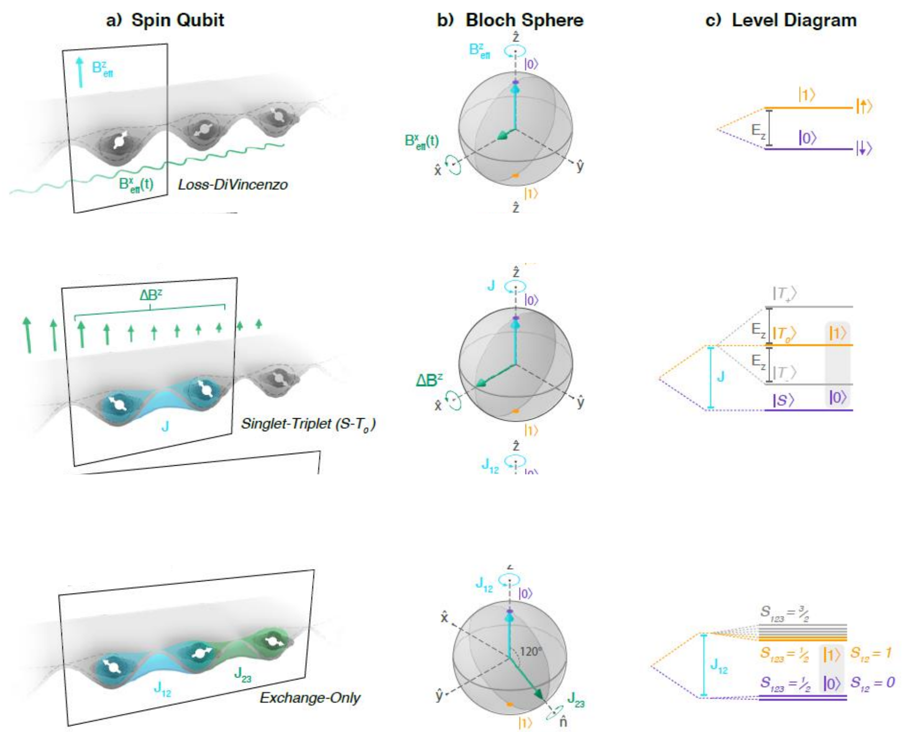


Number of charges on dot probed by external constriction/dot

Different types of QD-based qubits



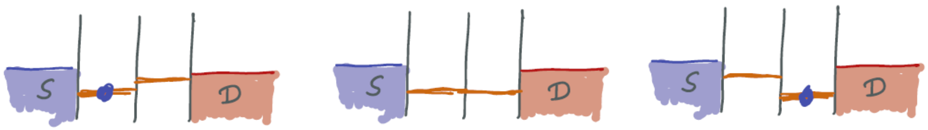




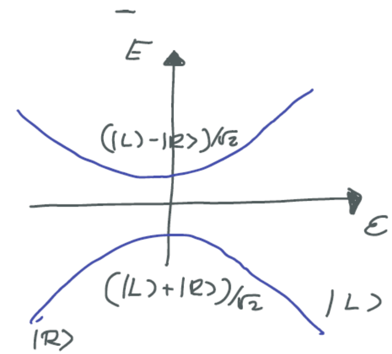
Charge qubit in a DQD

CHARGE QUBITS

$V_{G1} > V_{G2}$ | $V_{G1} = V_{G2}$ | $V_{G1} < V_{G2}$



$|L\rangle$ | WHERE IS THE ELECTRON? | $|R\rangle$



$$E_{1,2} = \pm\sqrt{(\varepsilon/2)^2 + t^2}$$

$$\Delta E_{L-R} = \varepsilon$$

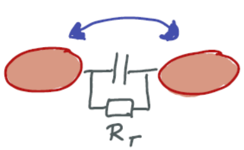
$$\rightarrow \quad H = \begin{bmatrix} -\varepsilon/2 & 0 \\ 0 & \varepsilon/2 \end{bmatrix} = \qquad \text{BASIS } \{ |L\rangle, |R\rangle \}$$

$$= -\frac{\varepsilon}{2} |L\rangle\langle L| + \frac{\varepsilon}{2} |R\rangle\langle R|$$

$$H|L\rangle = -\frac{\varepsilon}{2}$$
$$H|R\rangle = \frac{\varepsilon}{2}$$

$$H = -\frac{\varepsilon}{2}\sigma_z \, .$$

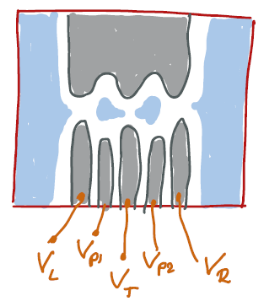
TUNNELING EVENTS



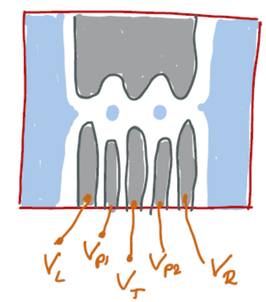
$$H_T = t\,\underbrace{\left[|L\rangle\langle R| + |R\rangle\langle L| \right]}_{\sigma_x}$$

$$H = -\frac{\varepsilon}{2}\sigma_z + \Delta\sigma_x$$

IF V_T NOT TOO NEGATIVE



IF V_T IS VERY NEGATIVE

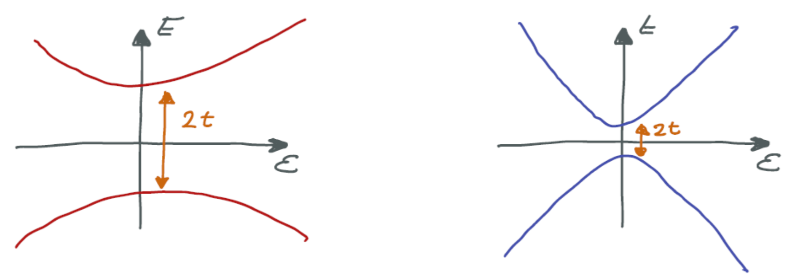


t IS LARGE

$|\psi_L(r)|^2 \, |\psi_R(r)|^2 >0$

t IS SMALL

$|\psi_L(r)|^2 \, |\psi_R(r)|^2 \approx 0$



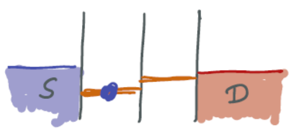
t TUNES THE CROSSOVER FROM LOCALIZED TO DELOCALIZED STATE

Charge qubit in a DQD

NON-ADIABATIC CONTROL

(1.) INITIALIZATION

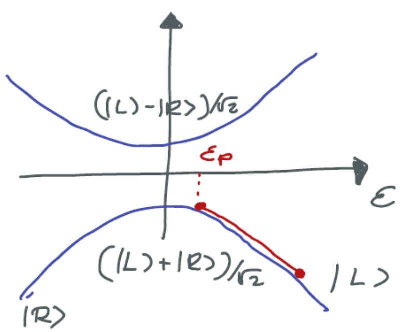
$\varepsilon \gg 0$



$|\Psi_0\rangle = |L\rangle$

$|L\rangle$

(2.) FAST GATE:



FOR EXAMPLE, $\varepsilon_p = 0.$ $\Rightarrow H = \Delta \sigma_x$

$\Rightarrow U = e^{-iHt_p}$

$R_x(\theta = 2 \cdot \Delta t) = e^{-i\Delta t \sigma_x}$

$\hookrightarrow$ X ROTATION

IF $\varepsilon_p \neq 0$ $H = \Delta \sigma_x - \varepsilon/2\, \sigma_z$

$U = e^{-i(\Delta\sigma_x - \varepsilon/2\,\sigma_z)t}$

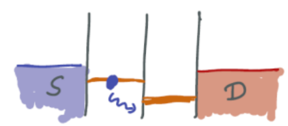
$\hookrightarrow$ ROTATION AROUND DIFFERENT AXIS

(3.) READ OUT

MEASURE THE POPULATION OF THE LEFT DOT

$M_L = |L\rangle\langle L|$

T_1 - MEASUREMENT



$|R\rangle$

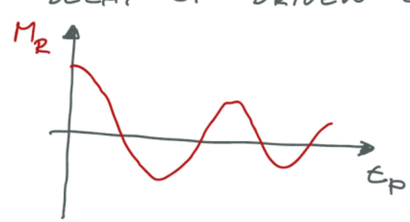
WHERE DOES THE ENERGY GO ?

$\rightarrow$ PHONONS

$T_1 \approx 30\,ns$

T_2 - MEASUREMENT

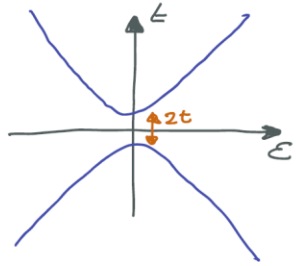
DECAY OF DRIVEN OSCILLATION



$T_2 \approx 7\,ns$

Charge qubit in a DQD

CHARGE NOISE: $H = -\frac{\varepsilon(t)}{2}\sigma_z + t(\varepsilon)$



$E(t) = \sqrt{[\varepsilon(t)]^2 + 4t(\varepsilon)^2}$

$\downarrow$

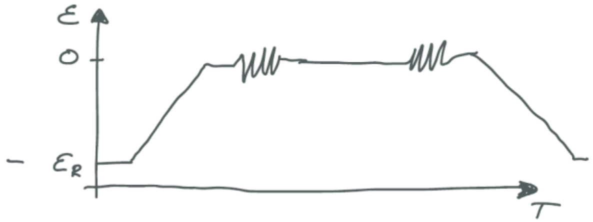
QUBIT FREQUENCY CHANGES

$\Downarrow$

PURE DEPHASING

BEST T_φ $\rightarrow$ @ $\varepsilon = 0$ FIRST-ORDER INSENSITIVE SWEET SPOT

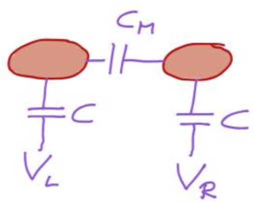
1. ADIABATIC TRANSFER OF $|R\rangle \rightarrow (|R\rangle + |L\rangle)/2$
2. $X_{\pi/2}$ ROTATION
3. WAIT TIME t
4. $X_{\pi/2}$ ROTATION
5. PROJECTING BACK TO $|R\rangle$

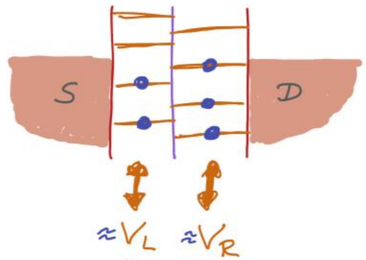


Charge qubit in a DQD

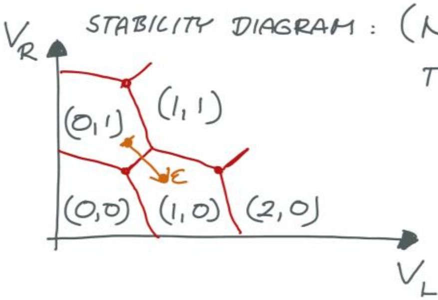
CHARGE QUBIT

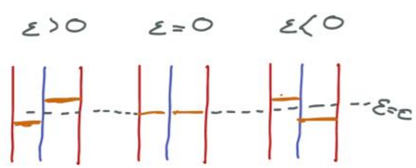
DOUBLE QUANTUM DOT:

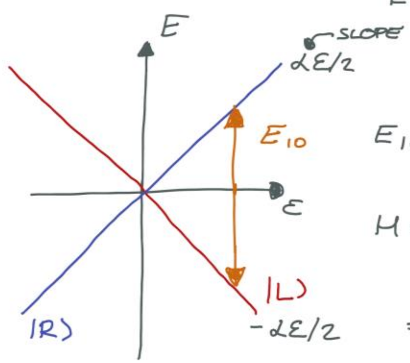




STABILITY DIAGRAM: (N_L, N_R) ELECTRONS ON THE DOT





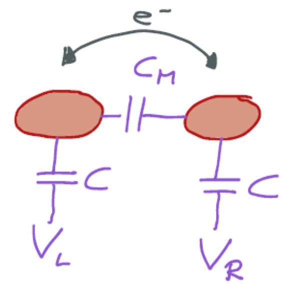


$$E_{10} = \frac{1}{2}\alpha\cdot\varepsilon - \left(-\alpha\frac{1}{2}\right)\varepsilon = \alpha\cdot\varepsilon$$

$$H = \frac{1}{2}\left[\alpha\cdot\varepsilon\,|R\rangle\langle R| + (-\alpha\varepsilon)|L\rangle\langle L|\right] =$$

$$= -\frac{1}{2}\alpha\cdot\varepsilon\,\sigma_z$$

IN $\begin{bmatrix} |L\rangle \\ |R\rangle \end{bmatrix}$ BASIS



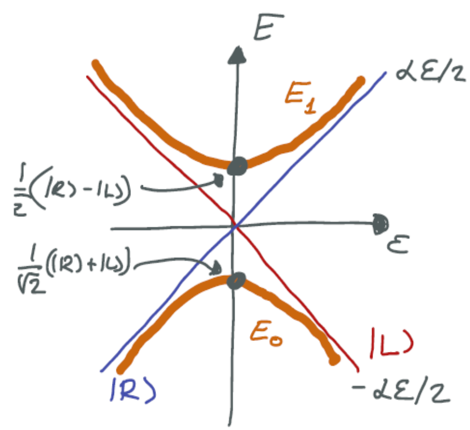
ELECTRONS JUMP:

$$H = -|t|\left[\,|L\rangle\langle R| + |R\rangle\langle L|\,\right] =$$

$$= -|t|\sigma_x$$

$$\boxed{H = -\frac{1}{2}\alpha\varepsilon\,\sigma_z - |t|\sigma_x}$$

$$E_{0,1} = \mp\sqrt{\left(\frac{1}{2}\alpha\varepsilon\right)^2 + |t|^2}$$



CHARGE HYBRIDIZATION

AT $\varepsilon = 0$

$E_{0,1} = \mp t \qquad \Delta E_\alpha = 2t$

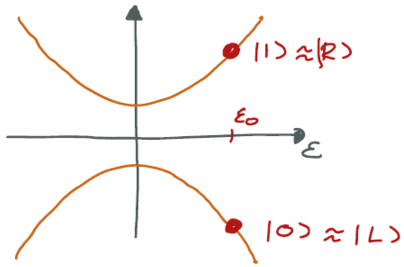
$$H = \begin{bmatrix} 0 & -t \\ -t & 0 \end{bmatrix}$$

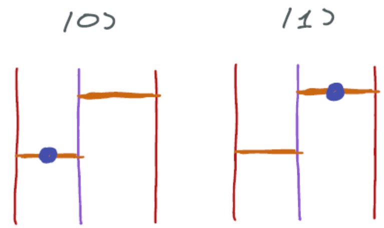
$\psi_0 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} \qquad E_0 = -t$

$\psi_1 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix} \qquad E_1 = t$

Charge qubit in a DQD

WE FIX $\varepsilon = \varepsilon_0 \gg 0$, AND DEFINE THE QUBIT THERE:





HOW TO DO A GATE?

FOR EXAMPLE $R_x(\pi)$ [X GATE]

1. $t=0$ $\quad \varepsilon = \varepsilon_0 \quad H \approx -\frac{1}{2}\alpha\varepsilon_0 \sigma_z \quad |0\rangle$

2. MOVE ε FAST (NON-ADIABATIC) TO $\varepsilon = 0$ ($\hbar/t <$)

$t = 0.1\,\text{ns} \quad |\psi\rangle = |0\rangle \quad H = -|t|\sigma_x$

$U = e^{i|t|\sigma_x/\hbar \cdot t} \quad |\psi(t)\rangle = U(t)|0\rangle$

$|t|\sigma_x/\hbar \cdot t_{GATE} = \pi/2$

$\Longrightarrow |\psi(t_{GATE})\rangle = |1\rangle$

3. MOVE ε FAST BACK TO ε_0

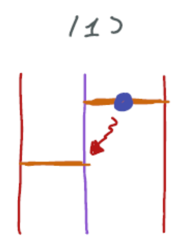
4. READ OUT: QPC – IS THE CHARGE IN THE LEFT OR RIGHT DOT?

NOTE IF WE MOVE TO A FINITE $\varepsilon \neq 0$,

$H = -|t|\sigma_x - \frac{1}{2}\varepsilon\alpha\sigma_z$

$\hookrightarrow$ UNIVERSAL CONTROL OF THE QUBIT

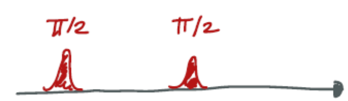
HOW GOOD IS THIS QUBIT?



DECAY OF THE EXCITED STATE

$T_1 \approx 10\,\text{ns}$

THE ENERGY GOES INTO PHONONS



$\frac{1}{2}(|0\rangle + |1\rangle) \rightarrow 50\%\,|0\rangle + 50\%\,|1\rangle$

$T_2 \approx 7\,\text{ns}$

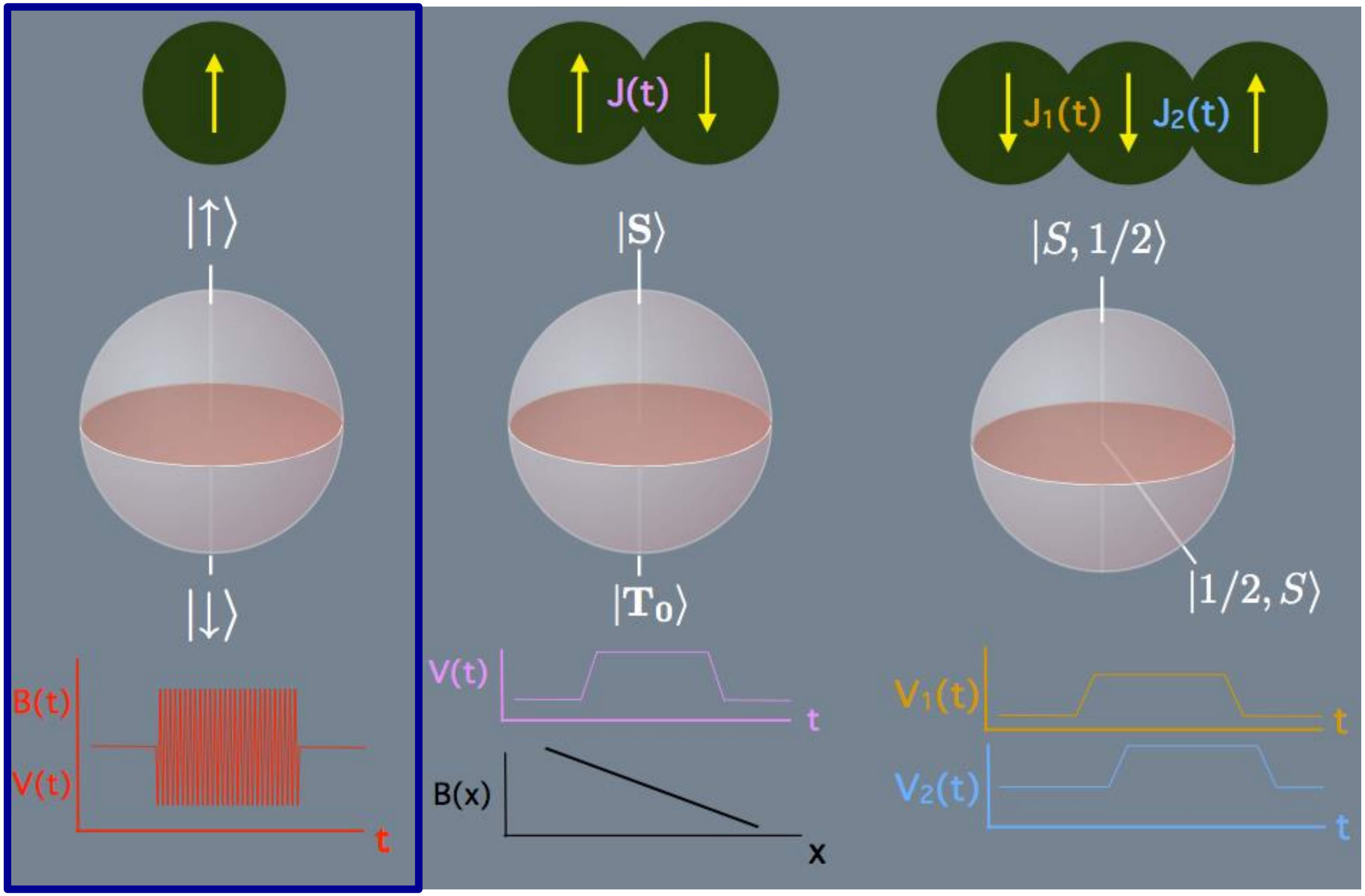
CHARGE NOISE CHANGES THE QUBIT FREQUENCY

$H_0 = -\frac{1}{2}\varepsilon_0\alpha\sigma_z$

$\hookrightarrow \varepsilon_0 + \delta\varepsilon$

GOOD STRATEGY FIND AN INSENSITIVE SPOT

Spin qubit flavors



Our focus
(for illustration)

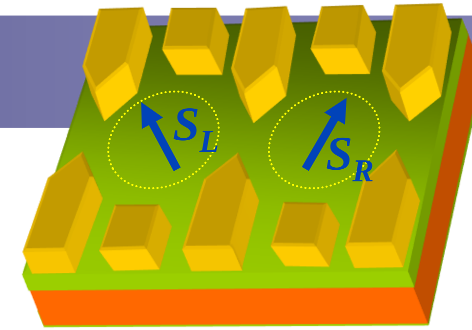
Other options:

Hybrid qubit

…

Image: C. Marcus

Spin qubits in quantum dots



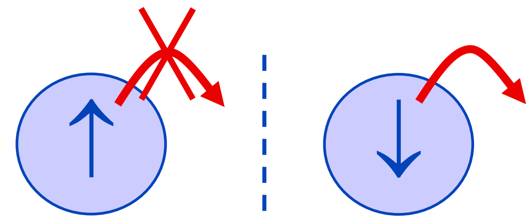
Loss & DiVincenzo, PRA 1998
Vandersypen et al., Proc. MQC02 (quant-ph/0207059)

Initialization 1-electron, low T, high B_0

$$H_0 \sim \sum \omega_i \, \sigma_{zi}$$

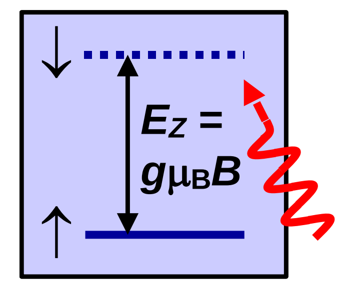
Read-out convert spin to charge

then measure charge



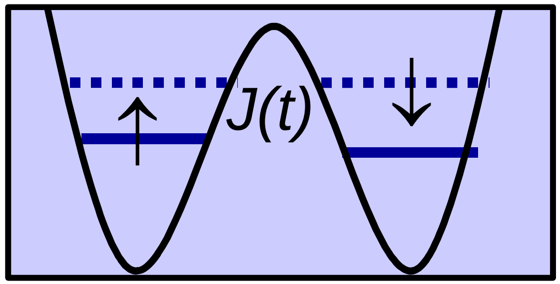
ESR pulsed microwave magnetic field

$$H_{RF} \sim \sum A_i(t) \cos(\omega_i t) \;\; \sigma_{xi}$$



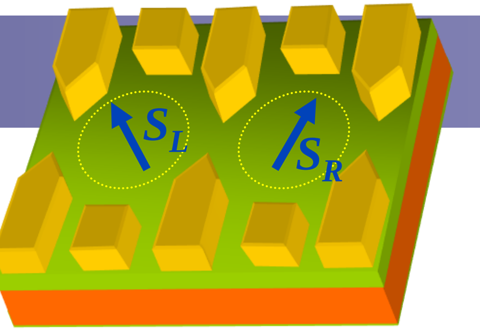
SWAP exchange interaction

$$H_J \sim \sum J_{ij}(t) \;\; \sigma_i \cdot \sigma_j$$



Coherence long relaxation time T_1
long coherence time T_2

Spin qubits in quantum dots



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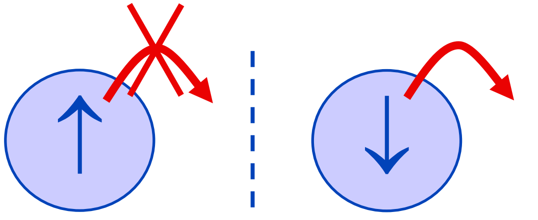
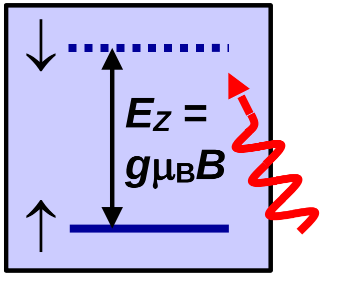


Read-out convert spin to charge

then measure charge



ESR pulsed microwave magnetic field

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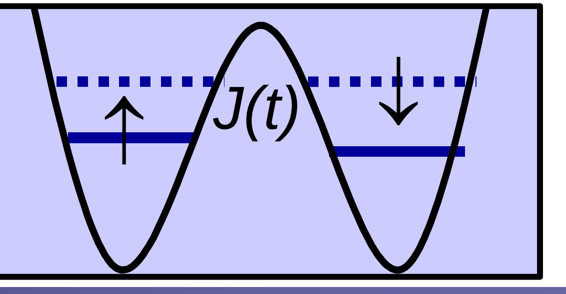
SWAP exchange interaction

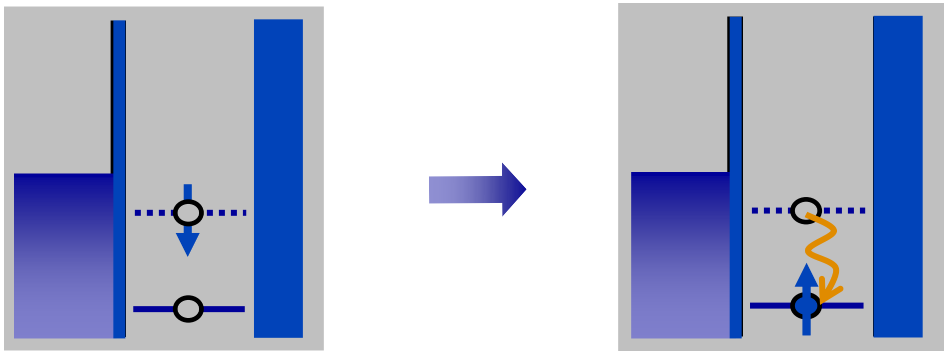
$$H_J \sim \sum J_{ij}(t) \;\; \sigma_i \cdot \sigma_j$$



Coherence long relaxation time T_1
long coherence time T_2

Initialization of a single electron spin

Method 1:
relaxation to
ground state



Method 2:
spin-selective
tunneling