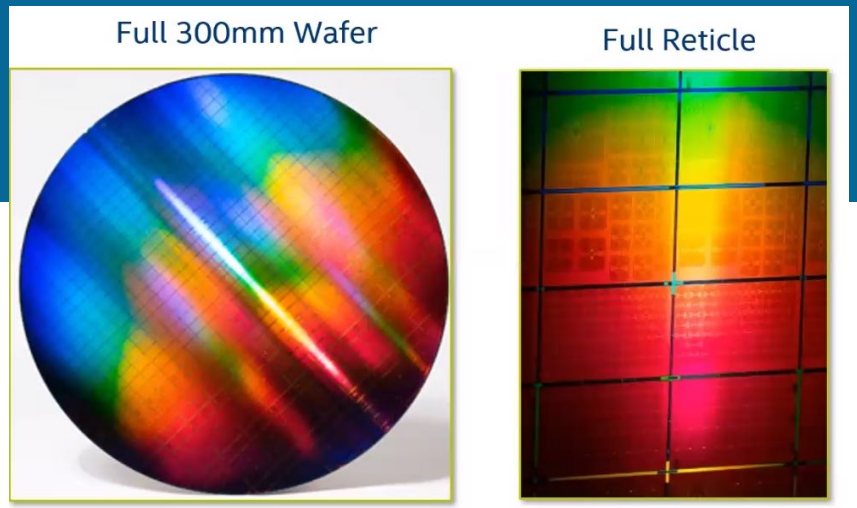
Dipartimento di Fisica
Università degli Studi di Milano

Istituto di Fotonica e Nanotecnologie
Consiglio Nazionale delle Ricerche

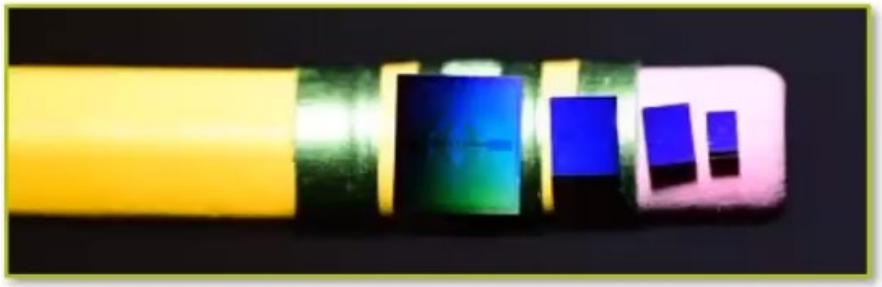
Spin qubits in silicon

Enrico Prati, PhD

INTEL



- Silicon chip - spin qubits
- 50M$ investment
- Available Free Simulator
- Development Spin Qubits -> array of 7



7 gate array

INTEL

Quantum co-processor: augmenting, not replacing, traditional HPC systems

~50+ Qubits: Proof of concept

- Computational power exceeds supercomputers
- Learning test bed for quantum "system"

~1000+ Qubits: Small problems

- Limited error correction
- Chemistry, materials design
- Optimization

~1M+ Qubits: Commercial scale

- Fault tolerant operation
- Cryptography
- Machine Learning

Spin qubits

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Perspective article

Is all-electrical silicon quantum computing feasible in the long term?

Elena Ferraro [a,*], Enrico Prati [b]

Table 3

Number of physical qubits per unit surface and area covered by 2 billions of physical qubits. The silicon hybrid qubit footprint refers to the 7 nm technology node.

	Semiconductor Single-Spin qubit	Semiconductor Hybrid qubit (Steane code)	Semiconductor Hybrid qubit (Surface code)	Superconductor Flux qubit (DWave like)	Superconductor Transmon qubit (IBM like)	Trapped Ion qubit
Mqb_{ph}/cm^2	8000	830	100×10^2	8×10^{-4}	10^{-5}	2×10^{-5}
$A_{chip}(mm^2)$	25	240	20	25×10^7	2×10^{10}	10^{10}
Reference	[75]	[5]	[5]	[79]	[80,81]	[82]

Home > Quantum Computing

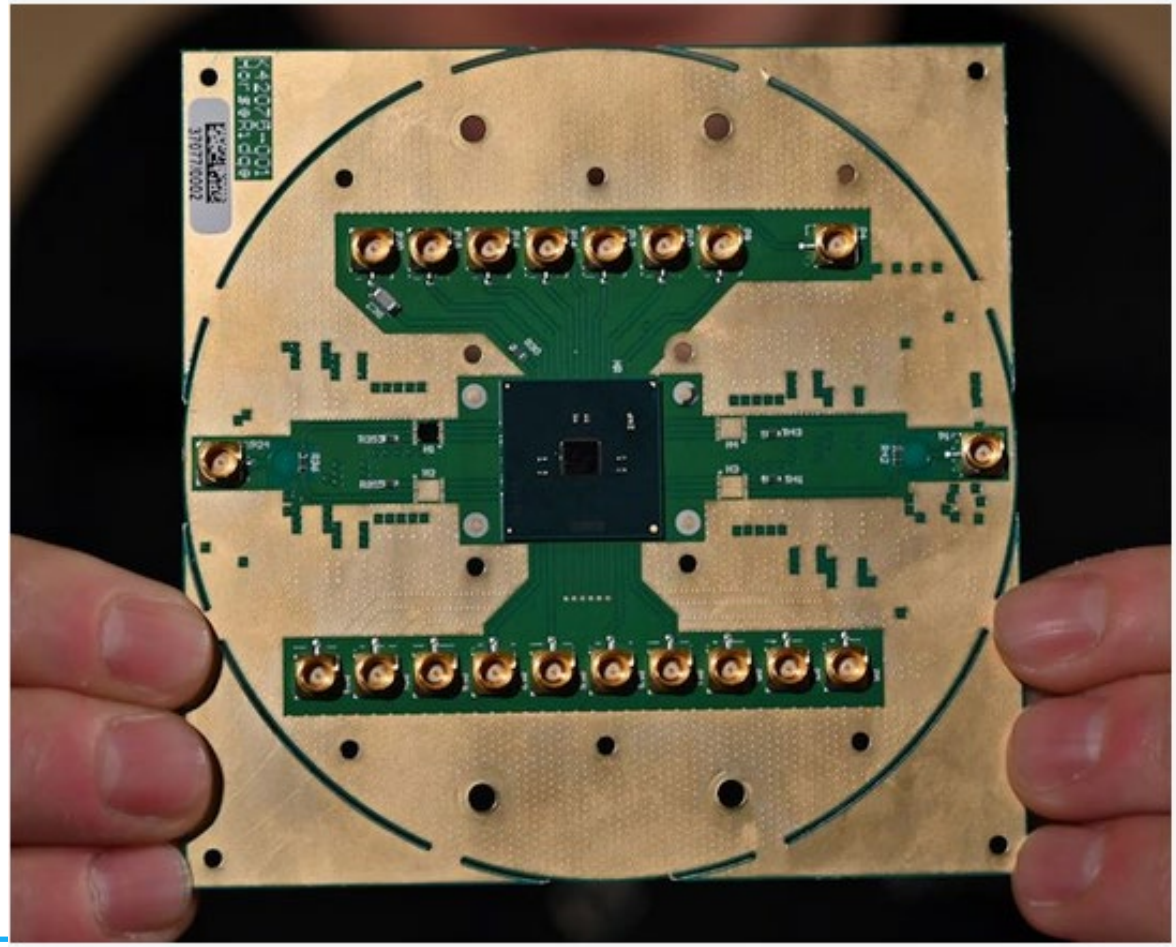
Intel Launches Horse Ridge Chip for Quantum Computing Systems

10 Comments

+ Add A Comment

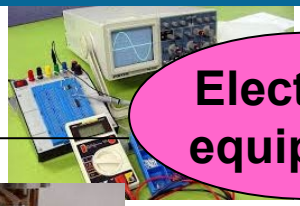
by Anton Shilov on December 10, 2019 2:15 PM EST

Posted in Quantum Computing | Intel | Servers | Horse Ridge

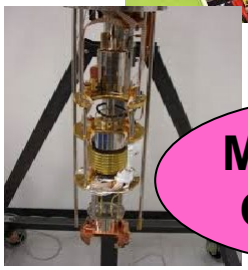


How to probe atomic scale nanoelectronics?

?



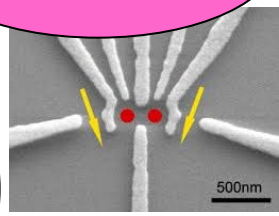
Electronic equipment



Millikelvin Cryostat

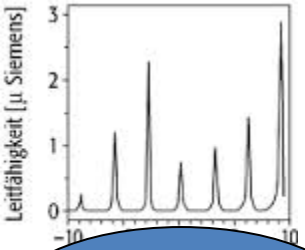
Experiments

Device



Microwave Irradiation

Magnet



Conductance

Coulomb blockade

Kirchoff method

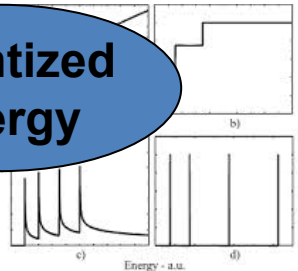
Concepts of Physics

Quantum tunneling

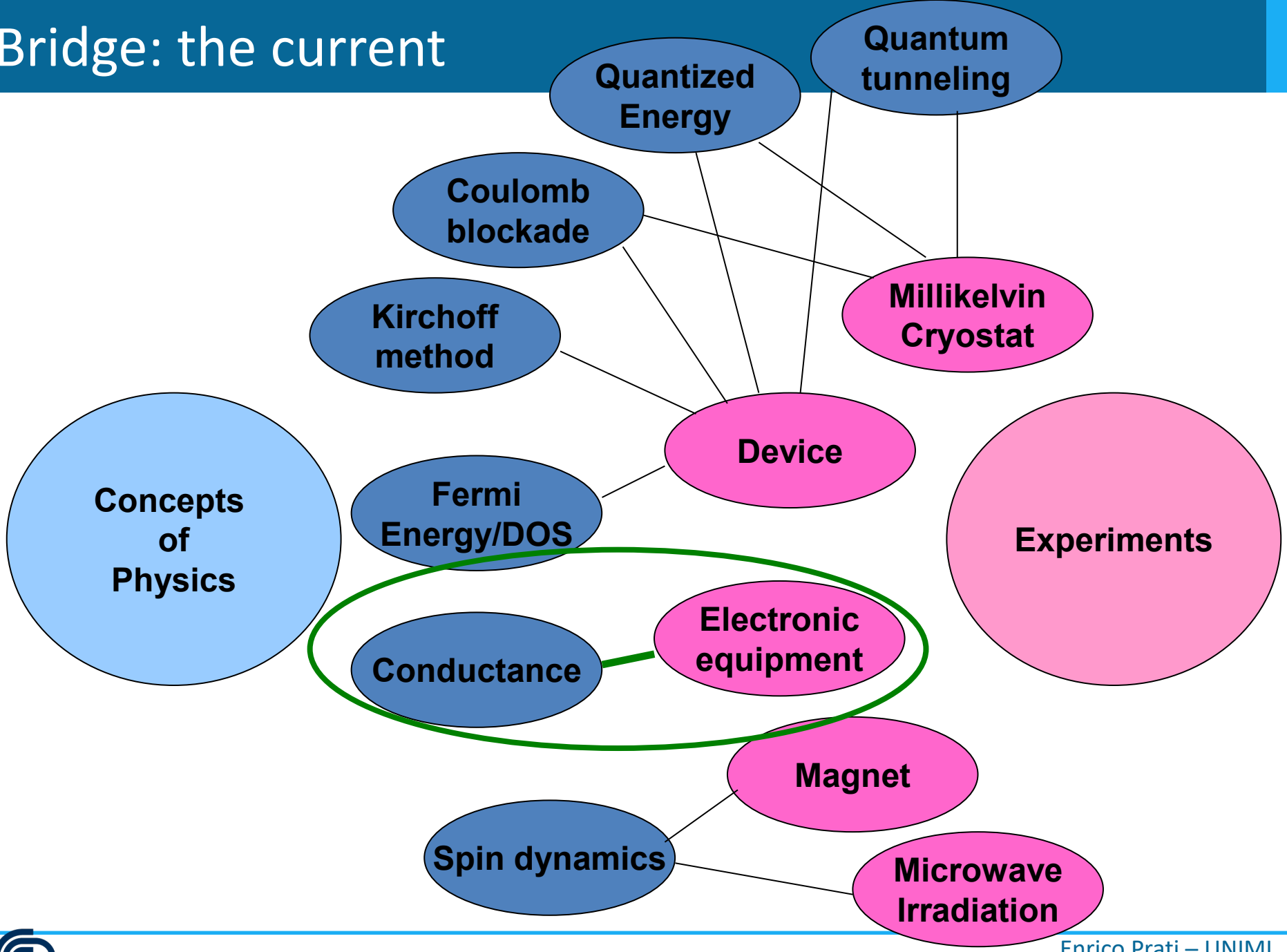
Spin dynamics

Fermi Energy/DOS

Quantized Energy



Bridge: the current

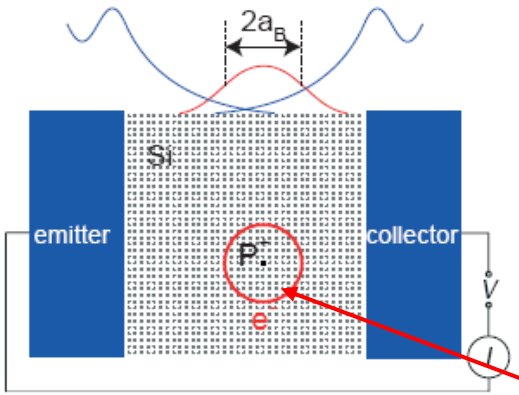


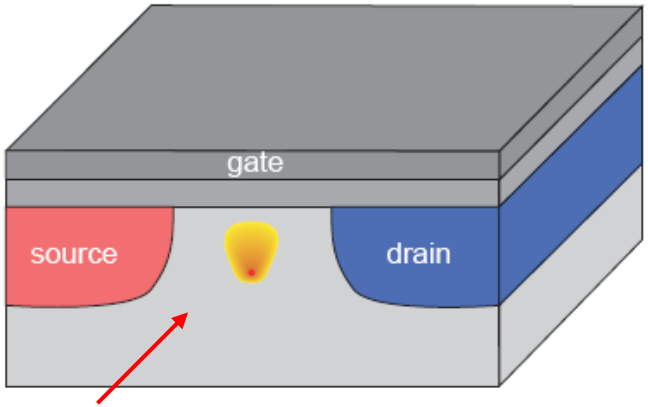
Basic device: a single electron transistor

Theory

- **Device**
- Fermi Energy
- Quantized Energy
- Quantum tunneling
- Coulomb blockade
- Conductance
- Kirchoff method

2 methods: electrostatic confinement of an e- or by a donor





P is a single phosphorus atom below the gate

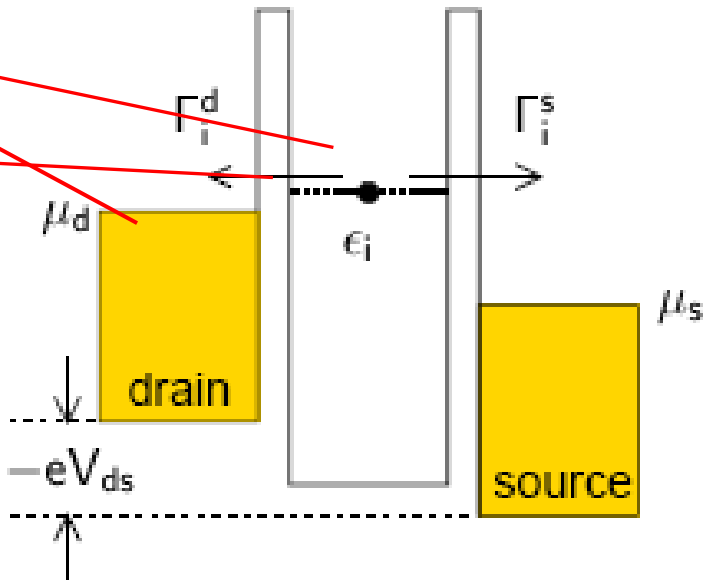
Scaling of the Bohr orbit:

$$r_{\text{dopant}} = \frac{\epsilon_r}{m^*} \cdot r_{\text{Hydrogen}}$$

$$r_{\text{Hydrogen}} = 0.05\,\text{nm}$$

$$r_{\text{P:Si}} = 2.5\,\text{nm}$$

$$r_{\text{P:Ge}} = 6.4\,\text{nm}$$



Kohn and Luttinger
Phys. Rev. 98, 915 (1955)

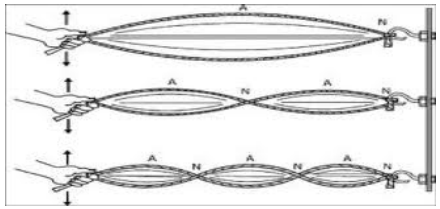
Density of States (DoS)

Theory

- Device
- **Fermi Energy/DOS**
- Quantized Energy
- Quantum tunneling
- Coulomb blockade
- Conductance
- Kirchoff method

$$\psi(\mathbf{r}) = C\exp(i\mathbf{k}\cdot\mathbf{r})$$

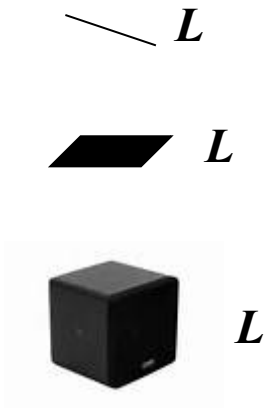
Electron wavefunction



$$p_i = \hbar k_i = \frac{n_i h}{2L}$$

Heuristic Quantization
Periodic Boundary Condition

- 1*d* $dn(E)\big|_{d=1} \propto \frac{dE}{\sqrt{E}}$
- 2*d* $dn(E)\big|_{d=2} \propto dE$
- 3*d* $dn(E)\big|_{d=3} \propto \sqrt{E}dE$



DoS =«how many states *g*(*E*) you have in *E* (energy) interval respectively»

Density of states and Fermi Energy

Theory

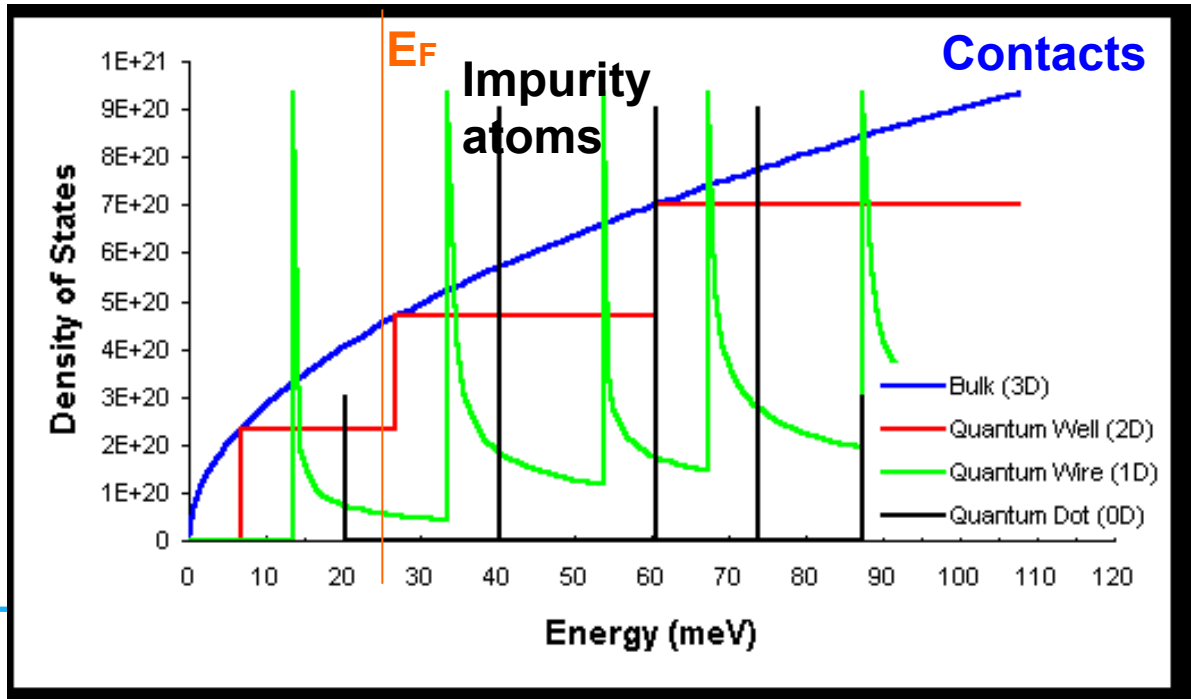
- Device
- **Fermi Energy/DOS**
- Quantized Energy
- Quantum tunneling
- Coulomb blockade
- Conductance
- Kirchoff method

- Condition to see discrete energy levels related effects:
  - $KT << \Delta E$ energy level spacing
  - $kT << \Gamma$ linewidth
- Temperature:

  4.2 K usual

  300 K for 2nm QD

Chemical potential: (of a thermodynamic system) is the amount by which the energy of the system would change if an additional particle were introduced, with the entropy and volume held fixed.
Fermi Energy: chemical potential at T=0



Confinement

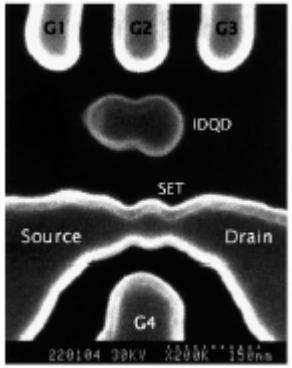
Theory

- Device
- Fermi Energy/DOS
- **Quantized Energy**
- Quantum tunneling
- Coulomb blockade
- Conductance
- Kirchoff method

Semiconductor nanostructures and quantum dots are fabricated by

1) Vertical confinement (d=3->2) via
   - Semiconductor/insulator interface (Si/SiO2)
   - Semiconductor/Semiconductor heterostructures (GaAs/AlGaAs or Si/SiGe)

2) Lateral confinement (d=2->1,0)
   - Split gate technique
   - Lithographically defined structures
   - Atomic inclusions
   - Point defects



Nature, 2007

Available online at www.sciencedirect.com
SCIENCE DIRECT®
Microelectronic Engineering 73–74 (2004) 701–706
MICROELECTRONIC ENGINEERING
www.elsevier.com/locate/mee

Single-electron polarization of an isolated double quantum dot in silicon

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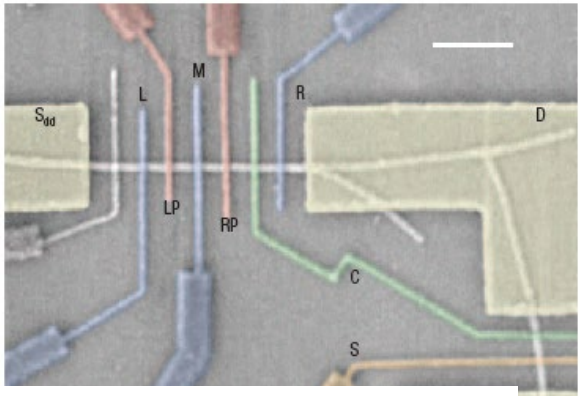
[b] Hitachi Cambridge Laboratory, Hitachi Europe Ltd., Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK

Available online 17 April 2004



Published online: 30 September 2007; doi:10.1038/nnano.2007.302

Tunneling through a single barrier

Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- **Quantum Tunneling**
- Coulomb blockade
- Conductance
- Kirchoff method

Schroedinger

$$-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}\Psi(x) + V(x)\Psi(x) = E\Psi(x)$$

Test function

$$\Psi(x) = e^{\Phi(x)}$$

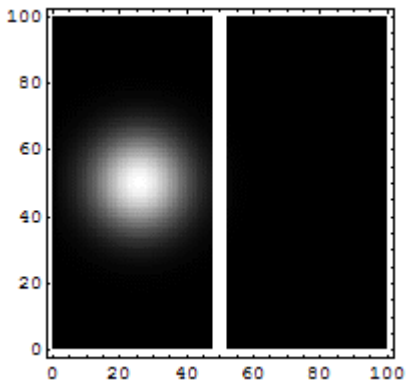
New equation

$$\Phi''(x) + \Phi'(x)^2 = \frac{2m}{\hbar^2}\left(V(x) - E\right).$$

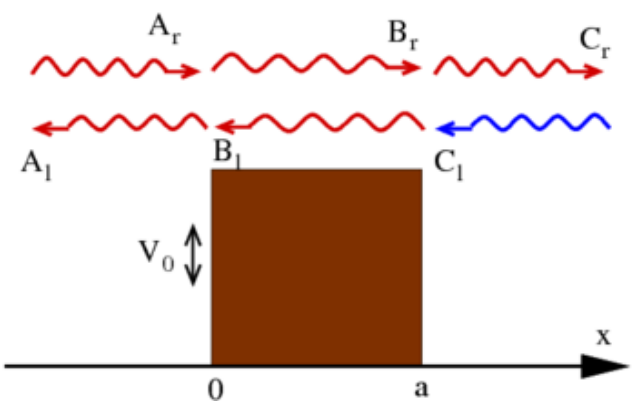
Solution: Airy f.

$$\Psi(x) = C_A Ai\left(\sqrt[3]{v_1}(x - x_1)\right) + C_B Bi\left(\sqrt[3]{v_1}(x - x_1)\right)$$

(v_1 coeff. X_1 turning point)



Square potential



$$r = \frac{(k_0^2 - k_1^2)\sin(ak_1)}{2ik_0k_1\cos(ak_1) + (k_0^2 + k_1^2)\sin(ak_1)}.$$

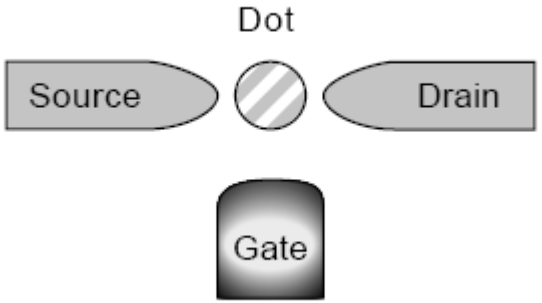
$$t = \frac{4k_0k_1e^{-ia(k_0-k_1)}}{(k_0+k_1)^2 - e^{2iak_1}(k_0-k_1)^2}$$

Tunneling in a quantum dot

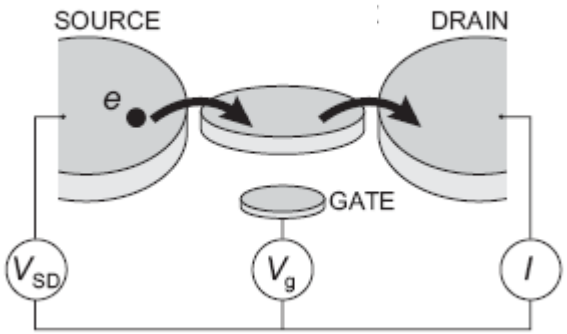
Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- **Quantum Tunneling**
- Coulomb blockade
- Conductance
- Kirchoff method

A **quantum dot** is a small box that can be filled with electrons.



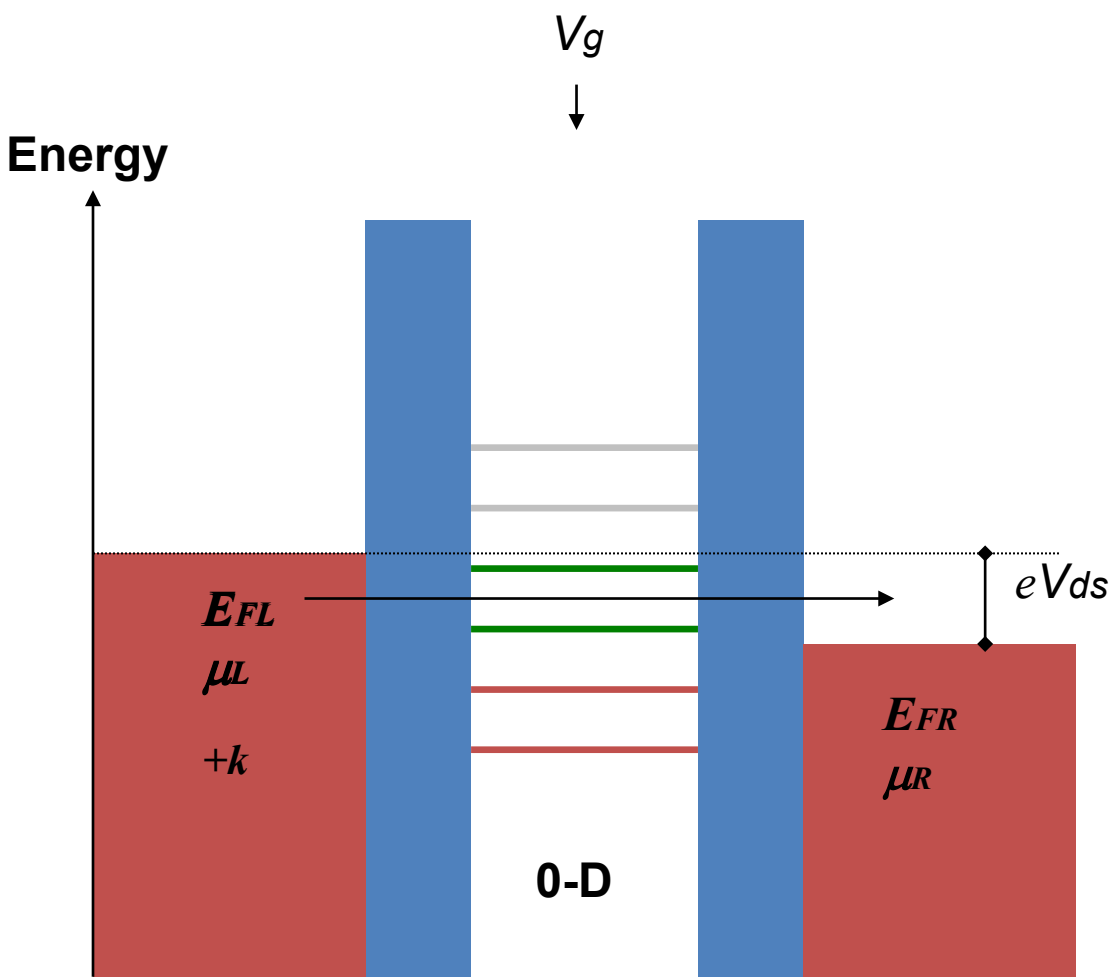
The box is coupled via tunnel barriers to a **source** and **drain** reservoirs (particles exchanges) capacitively coupled to a **gate** (which tunes the electrostatic dot/reservoir potential)



Quantum dots: sequential tunneling through 2 barriers

Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- **Quantum Tunneling**
- Coulomb blockade
- Conductance
- Kirchoff method



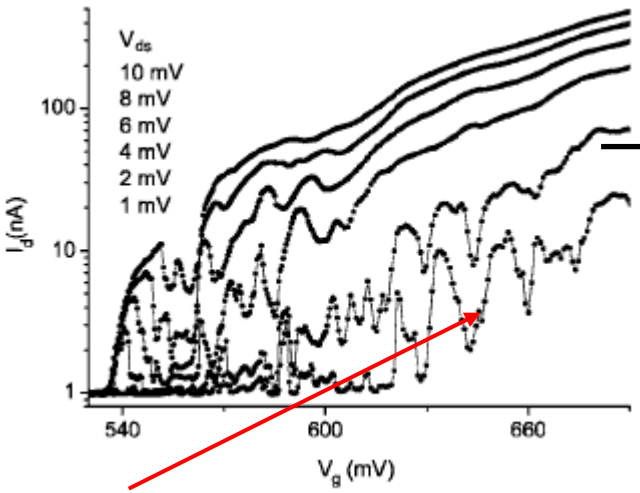
Si nanoFETs tunneling

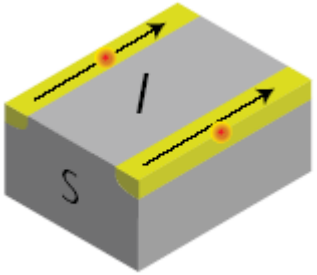
Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- **Quantum Tunneling**
- Coulomb blockade
- Conductance
- Kirchoff method

d = 2 (250 mK)

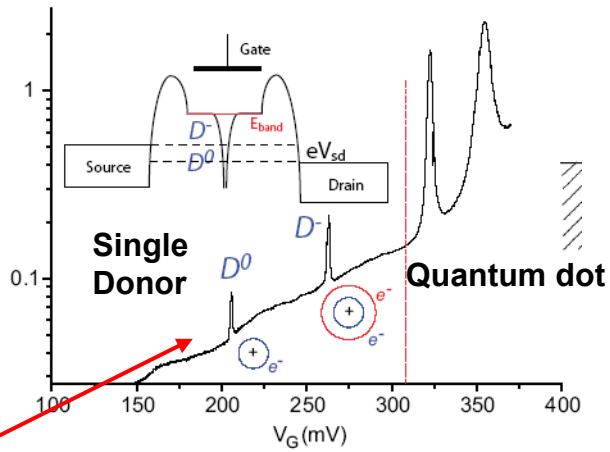
W 280 nm x L 180 nm





d = 1

Hopping between localized states (non Lorentzian)



Disorder!

Single localized states (Lorentzian)

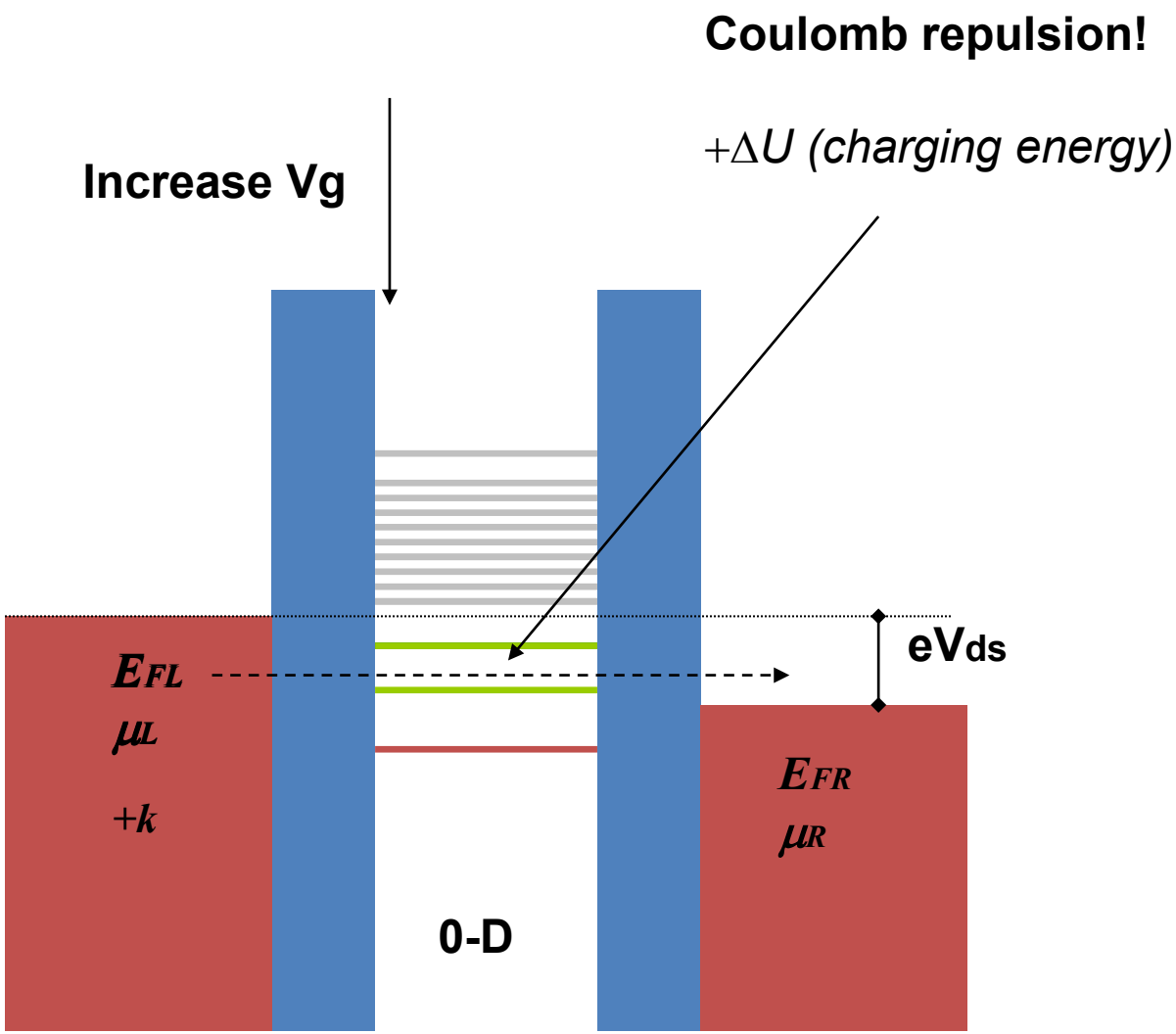
Rogge PRL 06

Clean coherent transport!

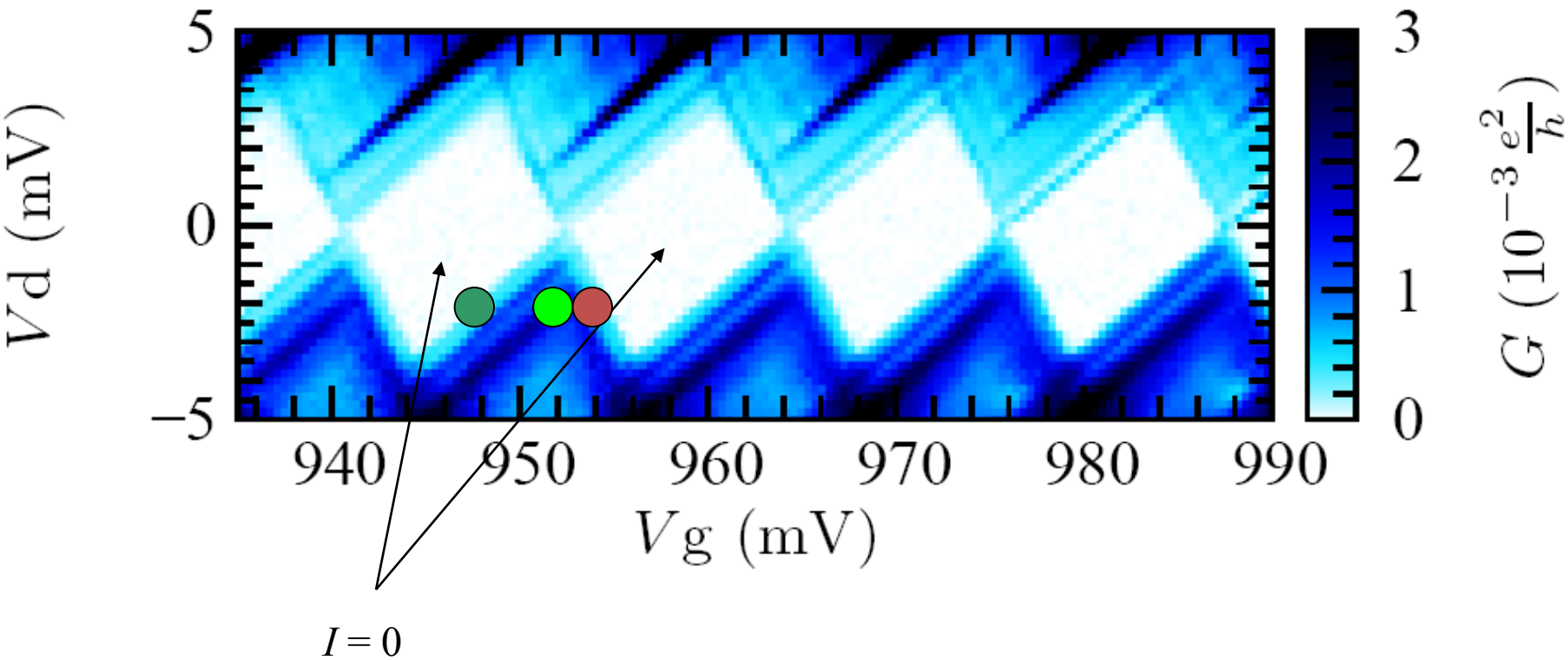
Charging energy

Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- Quantum Tunneling
- **Coulomb Blockade**
- Conductance
- Kirchoff method



Charge stability diagram of a quantum dot

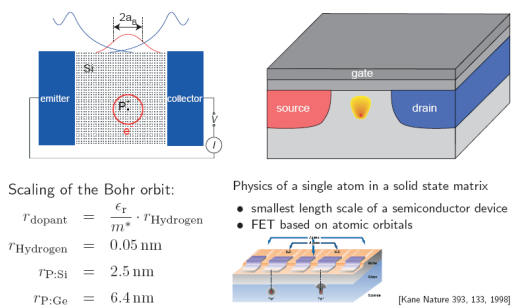


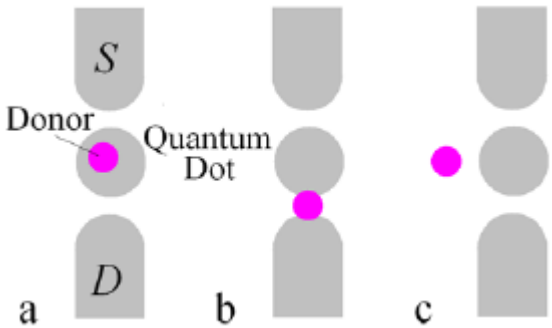
Typical units of conductance
Quantum of conductance: $2e^2/h$ and equals 77.48 microsiemens, (12.9*k*Ω)

Quantum dots with a single ion implanted

Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- Quantum Tunneling
- **Coulomb Blockade**
- Conductance
- Kirchoff method

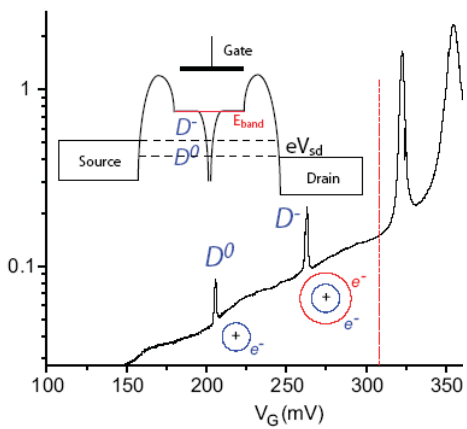


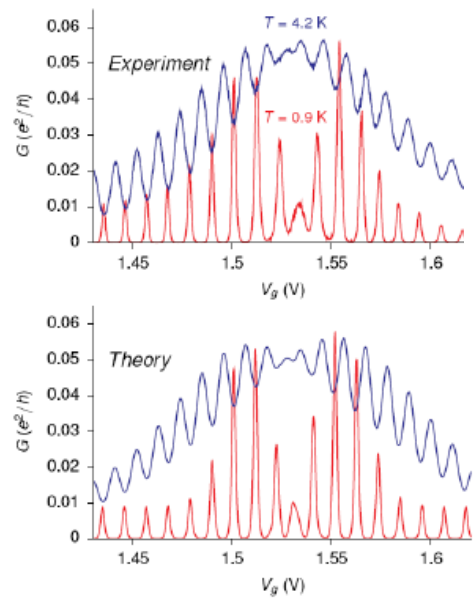


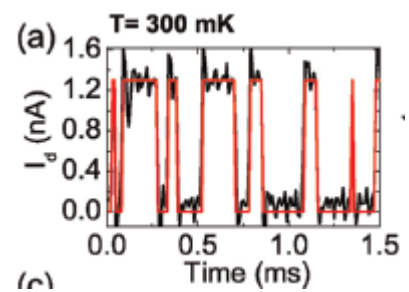
Sellier et al PRL 2006

Golovach et al PRB 2010

Mazzeo et al APL 2012







The quantum of conductance

Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- Quantum Tunneling
- Coulomb blockade
- **Conductance**
- Kirchoff method

$$G = \frac{1}{R} = \frac{I}{V}$$

Classical definition

$$G = \frac{\sigma A}{\ell}$$

Current of +*k* states given by linear density of electrons:

$I_+ = (e/L) \sum v f_+(E) =$

$= (e/L) \sum (dE/dk) f_+(E) / \hbar$

Quantum formalism

f_+ Fermi distribution for +k states

Which becomes in the continuum, with 2 spin states:

$= (2e/h) \int dE\, f_+(E)\, \theta(E - \mathcal{E}_{cutoff})$

$= (2e^2/h)\, M\, \Delta\mu / e$ (M is the number of modes)

$G = [(2e^2/h)\, M]^{-1} = 12.9\ k\Omega / M$

$(2e^2/h)$ is the quantum of conductance

Circuital view of the quantum dot and current

Theory

- Device
- Fermi Energy/DOS
- Quantized Energy
- Quantum Tunneling
- Coulomb blockade
- Conductance
- **Kirchoff method**

$$Q_A = \frac{C_A}{C_\Sigma}(ne - (C_B + C_G)V_{DS} + C_G V_G),$$

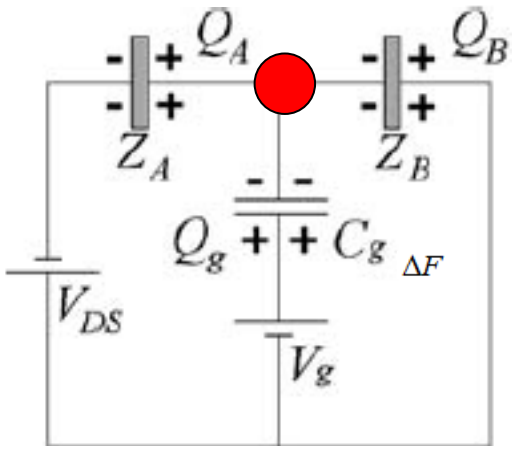
$$Q_B = -\frac{C_B}{C_\Sigma}(ne + C_A V_{DS} + C_G V_G),$$

$$Q_G = -\frac{C_G}{C_\Sigma}(ne + C_A V_{DS} - (C_A + C_B)V_G),$$

$$ne = Q_A - Q_B - Q_G$$

$$C_\Sigma = C_A + C_B + C_G$$

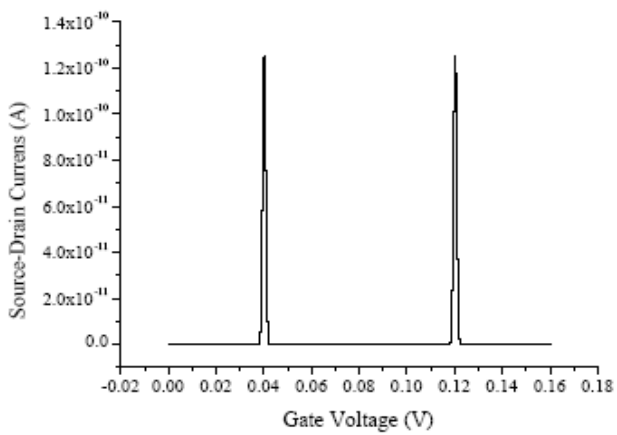
$$n_{dot} \rightarrow n_{dot} + 1$$

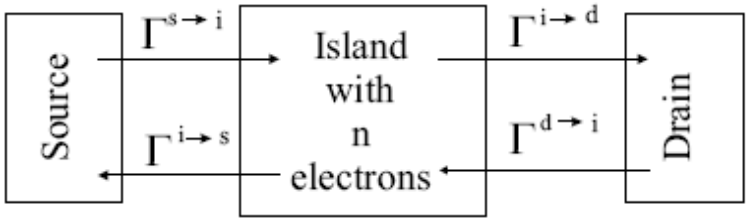


$$\Delta Q_A = -\frac{C_A}{C_\Sigma}e, \qquad \Delta Q_B = \frac{C_B}{C_\Sigma}e, \qquad \Delta Q_G = \frac{C_G}{C_\Sigma}e,$$

$$\Delta F = \frac{(ne)^2}{2C_\Sigma} - \frac{((n+1)e)^2}{2C_\Sigma} - V_{DS}\Delta Q_A + V_G \Delta Q_G,$$
$$= \frac{e}{C_\Sigma}((C_A - C_\Sigma)V_{DS} + C_G V_G - (n+1)e)$$

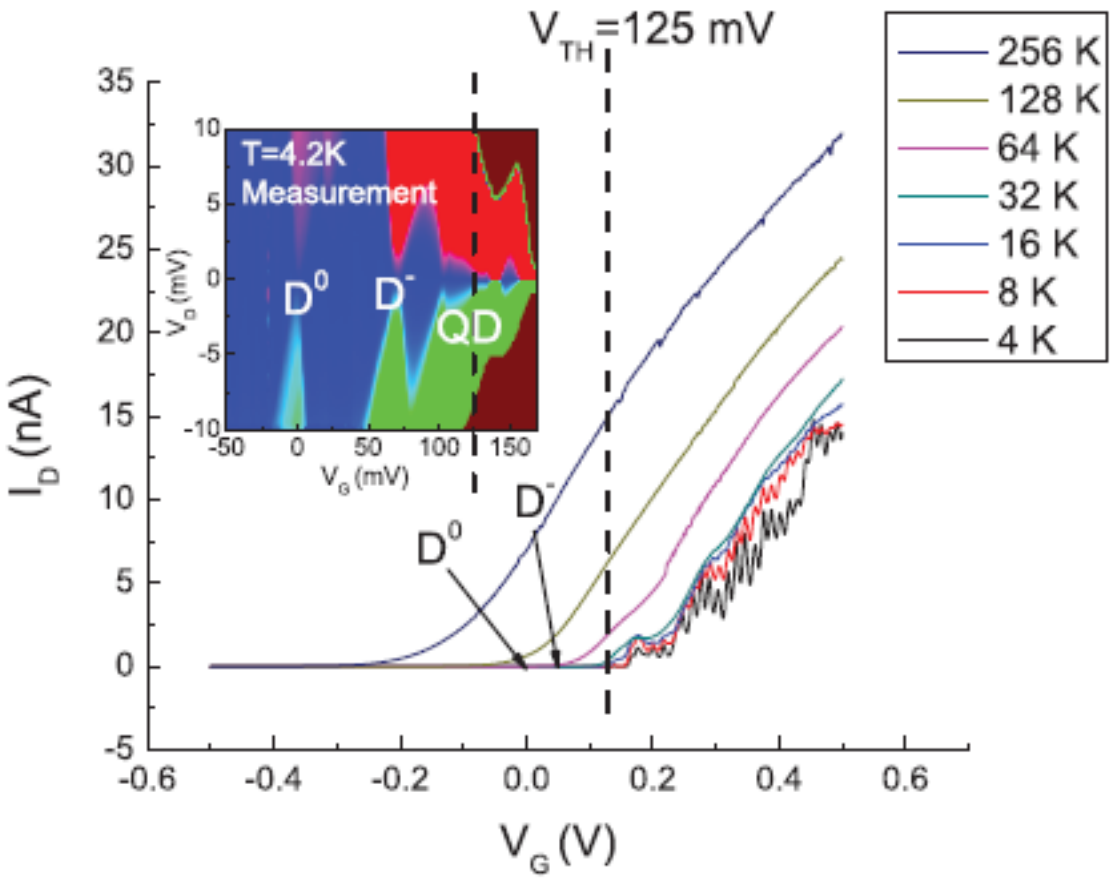
$$\Gamma(\Delta F) = \frac{1}{e^2 R_T}\frac{\Delta F}{(1 - \exp\frac{-\Delta W}{k_B T})}$$

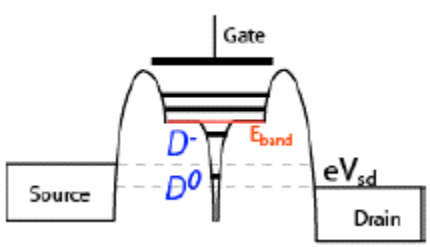


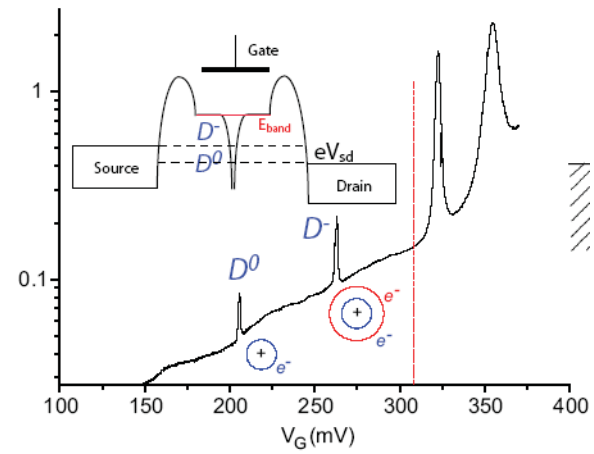


$$I = e\sum_{n=-\infty}^{n=+\infty} P(n)[\Gamma^s(n \rightarrow n+1) - \Gamma^s(n \rightarrow n-1)]$$

Spectroscopy: single As atom in FinFET



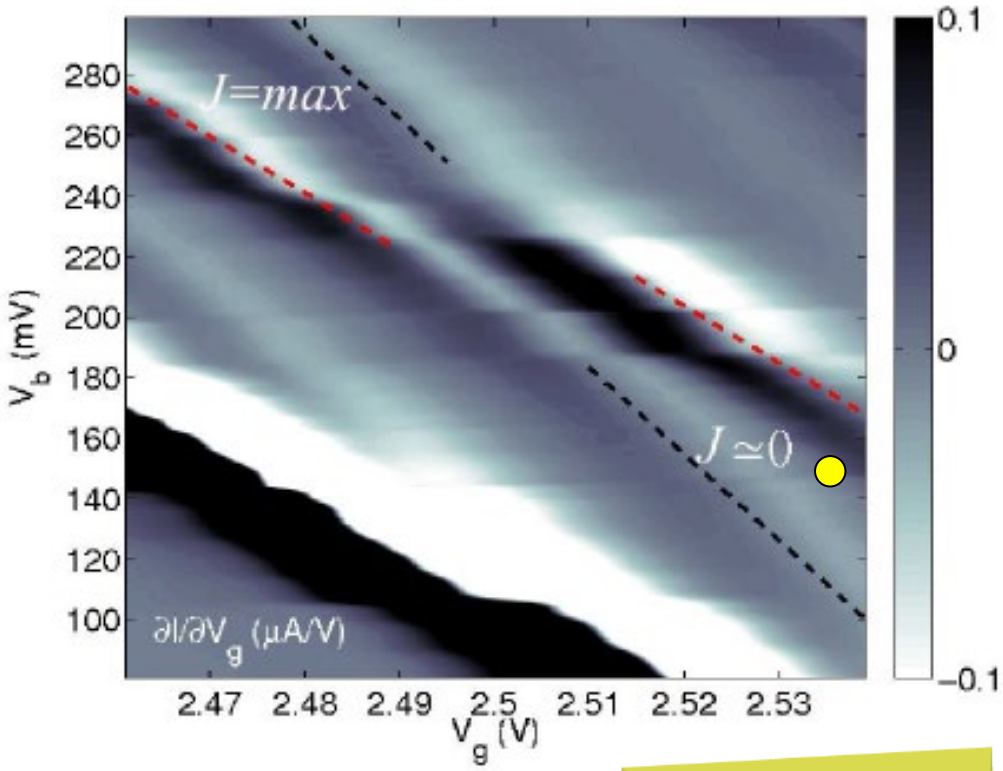


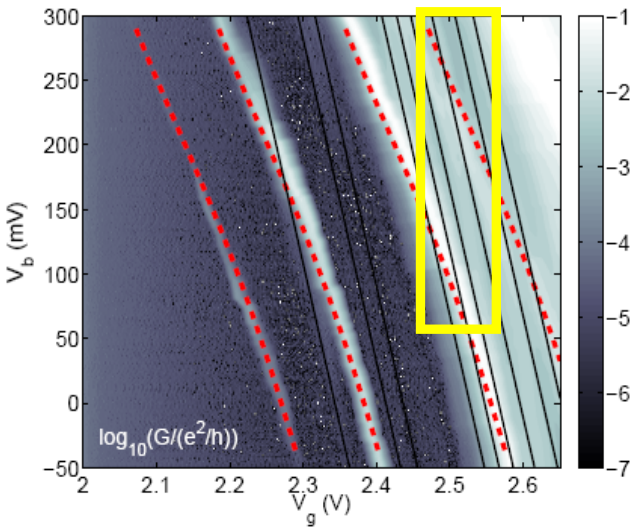


0 | 1 | 2

Sample: a commercial nanoFET
channel 70x50
contacts doped with As
1 good one every 10 samples

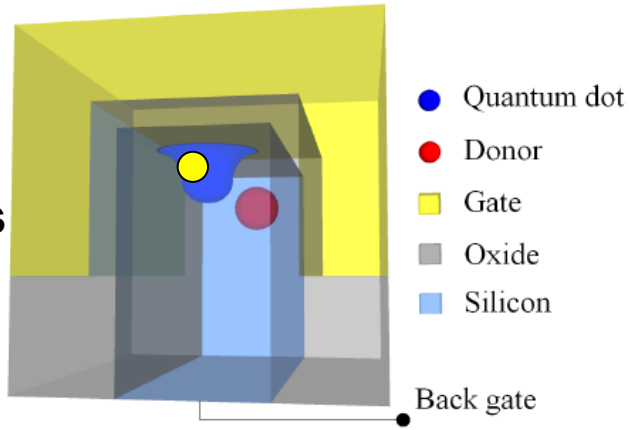
Moving an electron from a quantum dot to a donor





E. Prati et al Applied Physics Letters 2011

J exchange coupling of the Nth electron of the QD with the 3 electrons already bound to the DQD



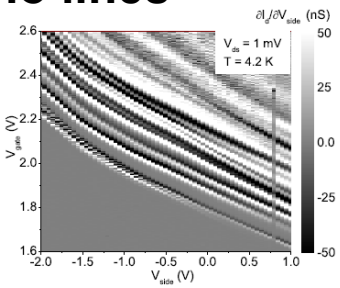
Single charge manipulation

Single charge state sensing

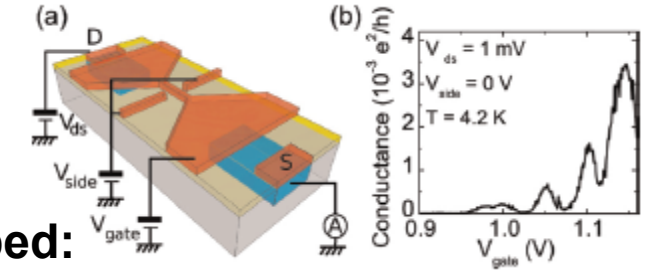
Experimental

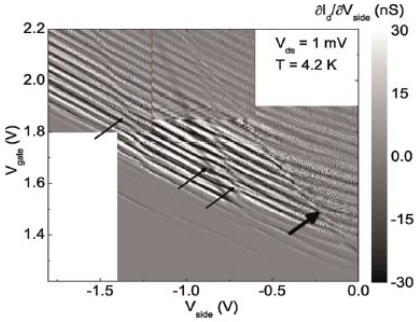
- **Single charge manipulation**
- **Single spin manipulation**
- **Solid state qubits**
- **Band formation**
- **CTAP**

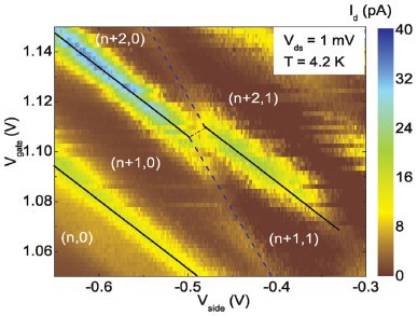
Undoped sample: no lines

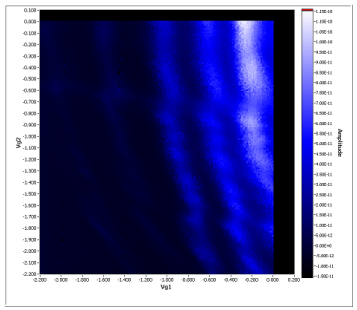


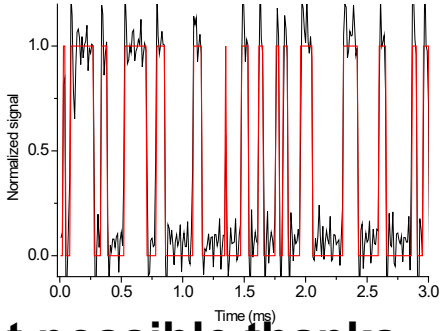
Doped: lines











Mazzeo et al., Applied Physics Letters 2012

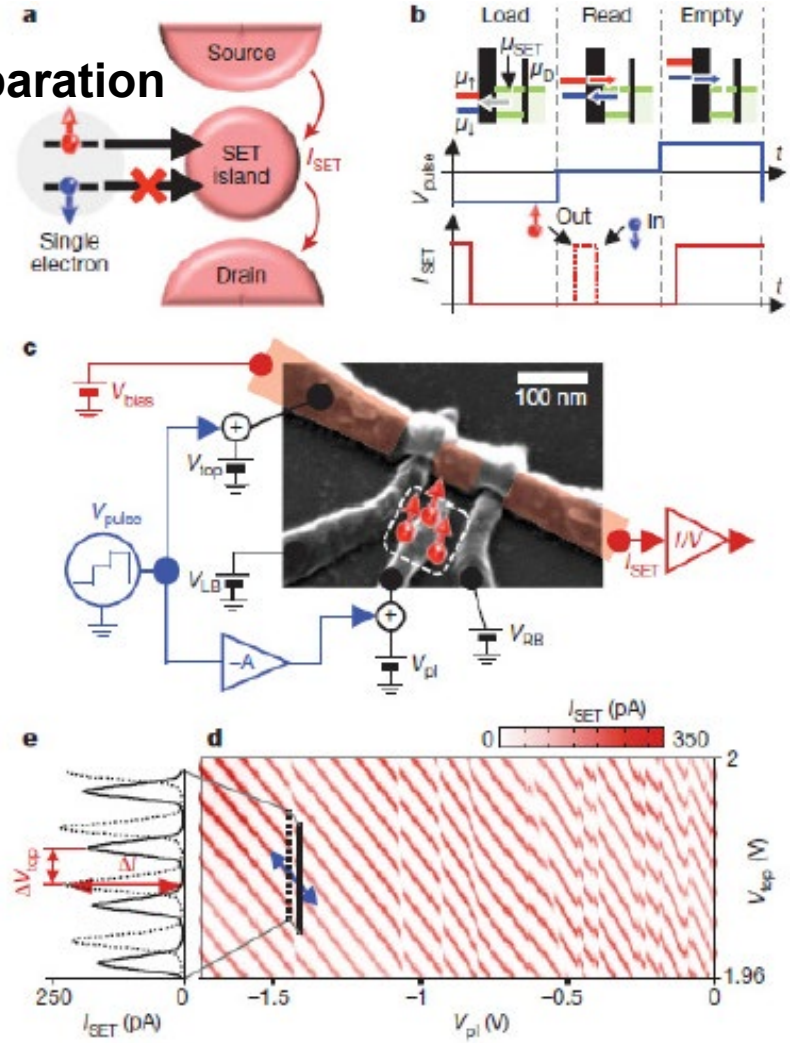
Measurement possible thanks to cryogenic amplifier (see G. Ferrari)

Spin state sensing: spin-to-charge conversion

Experimental

- Single charge manipulation
- Single spin manipulation
- Solid state qubits
- Band formation
- CTAP

Spin level separation by Zeeman Effect B= 1 T

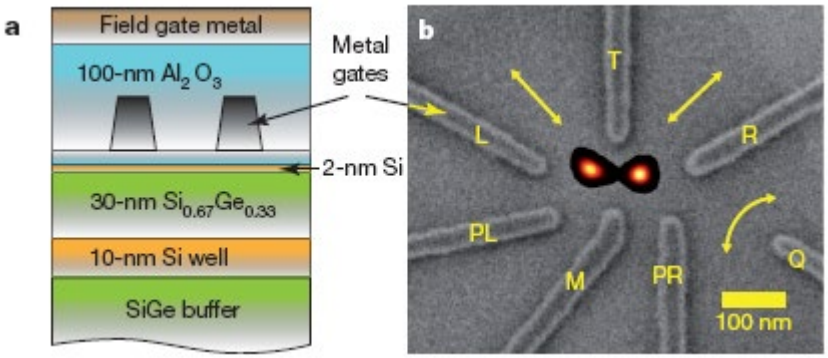


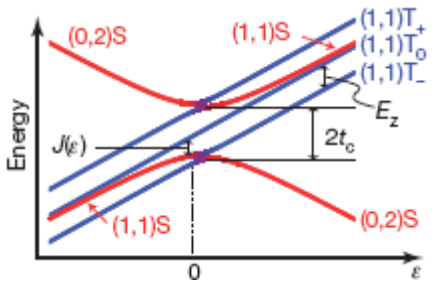
Single spin readout
A.Morello et al., Nature 2010

Singlet-triplet qubit

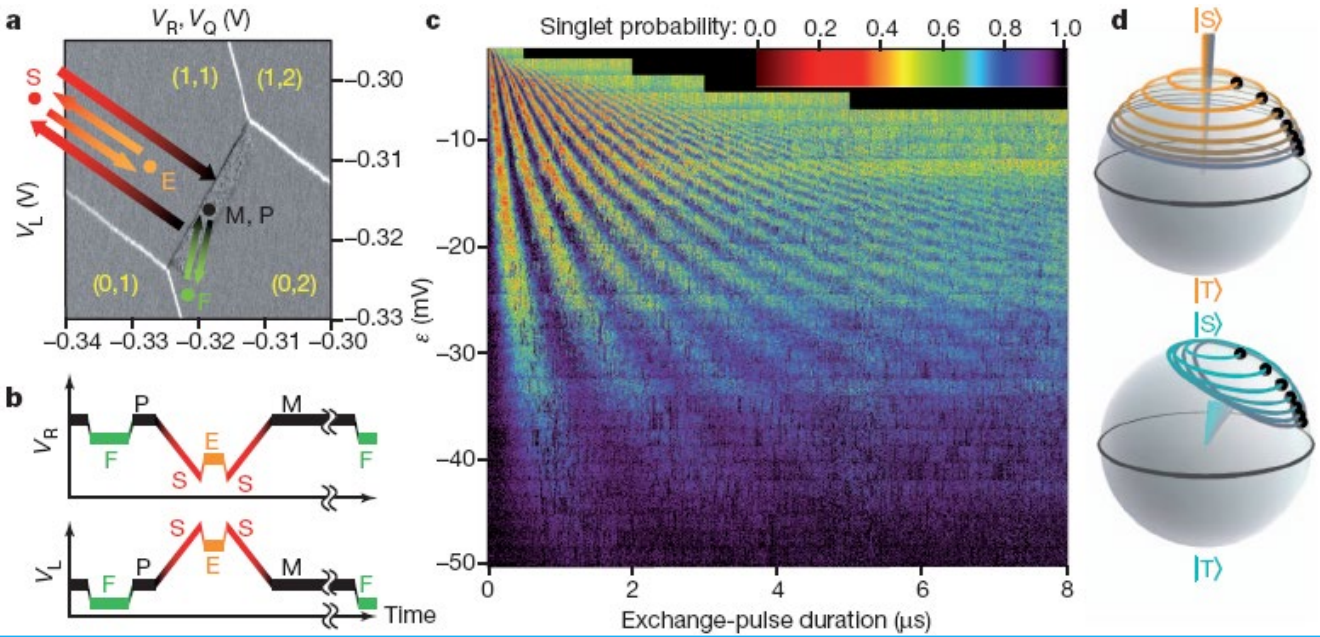
Experimental

- Single charge manipulation
- Single spin manipulation
- Solid state qubits
- Band formation
- CTAP





Energy splitting 140 ueV
T = 150 mK
Pulses: from 10 ns
Field 30 mT

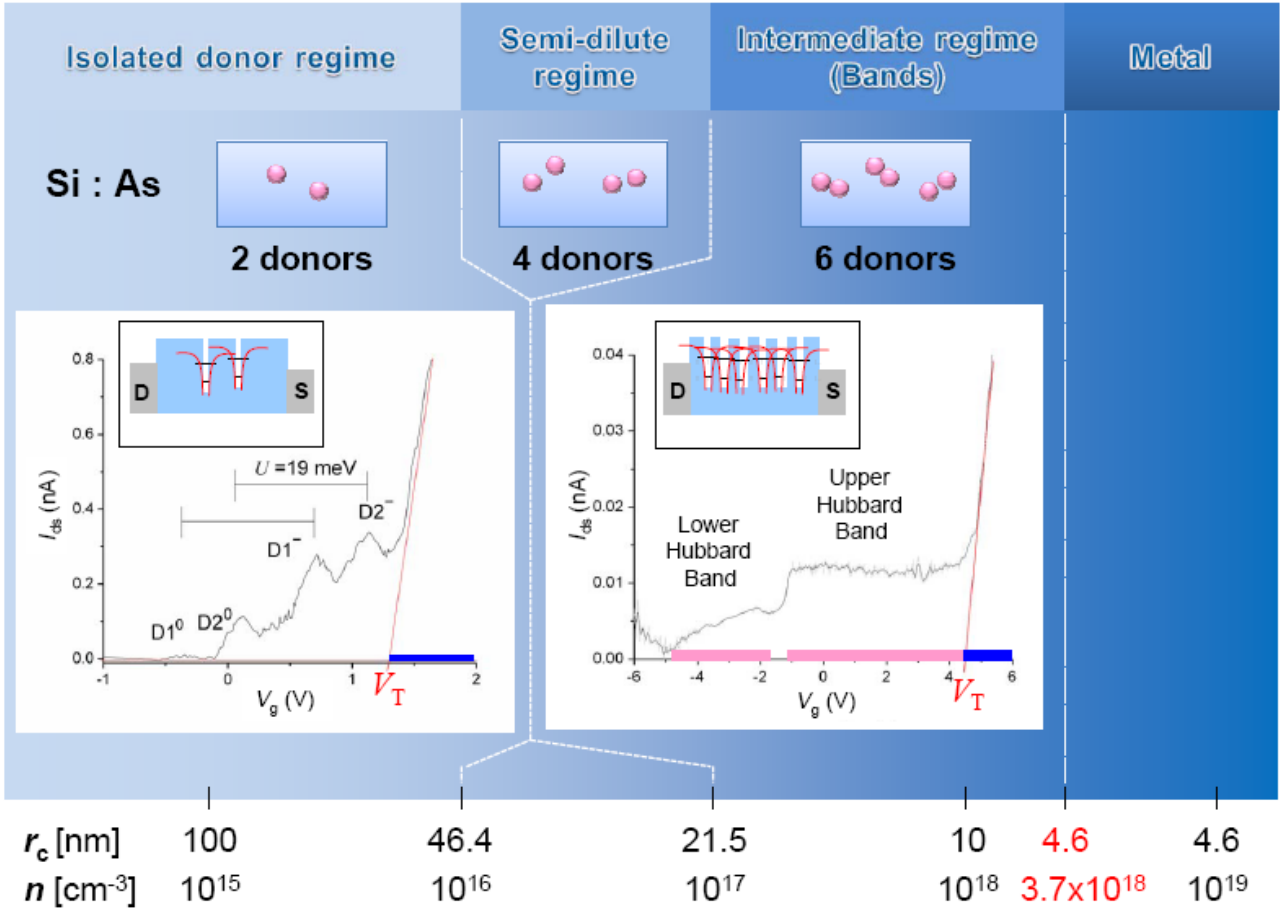


Maune et al.
Nature 2012
@HRL California

Hubbard (impurity) bands formation with 4 atoms

Experimental

- Single charge manipulation
- Single spin manipulation
- Solid state qubits
- Band formation
- CTAP

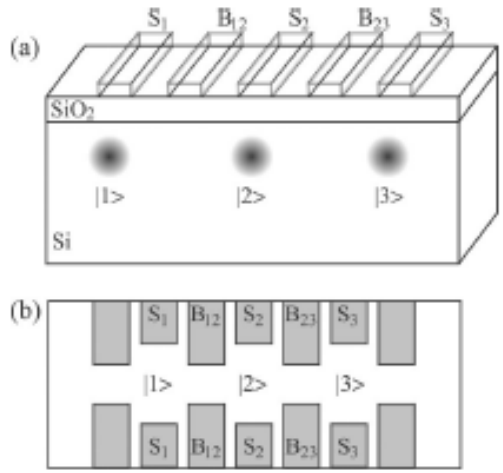


E. Prati, M. Hori, F. Guagliardo, G. Ferrari, T. Shinada, Nature Nanotech. (2012)

Coherent transport by adiabatic passage

Experimental

- Single charge manipulation
- Single spin manipulation
- Solid state qubits
- Band formation
- CTAP



$$\mathcal{H} = \hbar \begin{bmatrix} 0 & -\Omega_{12} & 0 \\ -\Omega_{12} & \Delta/\hbar & -\Omega_{23} \\ 0 & -\Omega_{23} & 0 \end{bmatrix}, \qquad (1)$$

where $\Omega_{\alpha\beta}=\Omega_{\alpha\beta}(t)$ is the coherent tunnelling rate between position eigenstates $|\alpha\rangle$ and $|\beta\rangle$ and $\Delta=E_2-E_1=E_2-E_3$. In

$$|\mathcal{D}_+\rangle = \sin\Theta_1 \sin\Theta_2 |1\rangle + \cos\Theta_2 |2\rangle + \cos\Theta_1 \sin\Theta_2 |3\rangle$$

$$|\mathcal{D}_-\rangle = \sin\Theta_1 \cos\Theta_2 |1\rangle - \sin\Theta_2 |2\rangle + \cos\Theta_1 \cos\Theta_2 |3\rangle$$

$$|\mathcal{D}_0\rangle = \cos\Theta_1 |1\rangle + 0|2\rangle - \sin\Theta_1 |3\rangle,$$

$$\Theta_1 = \arctan(\Omega_{12}/\Omega_{23}),$$

$$\Theta_2 = \frac{1}{2}\arctan[(\sqrt{(2\hbar\Omega_{12})^2 + (2\hbar\Omega_{23})^2})/\Delta].$$

The energies of these states are

$$\mathcal{E}_\pm = \frac{\Delta}{2} \pm \frac{1}{2}\sqrt{(2\hbar\Omega_{12})^2 + (2\hbar\Omega_{23})^2 + \Delta^2},$$

$$\mathcal{E}_0 = 0.$$

Pulses

$$\Omega_{\alpha\beta} = \Omega_{\alpha\beta}^{\max} \exp[-(t - t_{\alpha\beta})^2/(2\sigma_{\alpha\beta}^2)],$$

$$\Omega_{12}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max} + \sigma}{2}\right)^2 \Big/ (2\sigma^2)\right]$$

$\Delta=0$

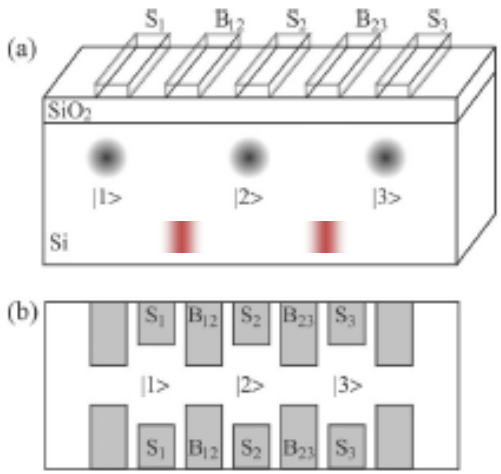
$$\Omega_{23}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max} - \sigma}{2}\right)^2 \Big/ (2\sigma^2)\right]$$

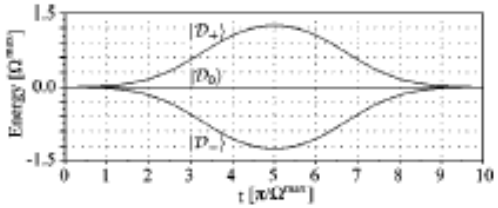
Coherent transport by adiabatic passage

$$|\mathcal{D}_+\rangle = \sin\Theta_1 \sin\Theta_2 |1\rangle + \cos\Theta_2 |2\rangle + \cos\Theta_1 \sin\Theta_2 |3\rangle$$

$$|\mathcal{D}_-\rangle = \sin\Theta_1 \cos\Theta_2 |1\rangle - \sin\Theta_2 |2\rangle + \cos\Theta_1 \cos\Theta_2 |3\rangle$$

$$|\mathcal{D}_0\rangle = \cos\Theta_1 |1\rangle + 0|2\rangle - \sin\Theta_1 |3\rangle,$$

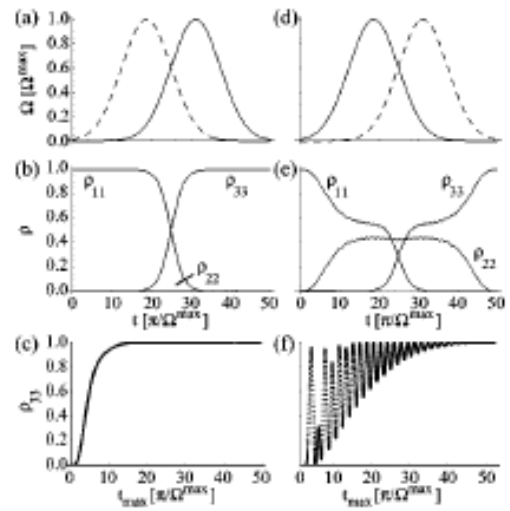




In order to proceed, we numerically solve the master equations for the density matrix, ρ,

$$\dot{\rho} = -\frac{i}{\hbar}[\mathcal{H},\rho] + \Gamma[\rho - \mathrm{diag}(\rho)], \qquad (8)$$

where Γ is the T_2 (pure dephasing) rate, assumed to act equally on all coherences. As we are primarily considering



$$\Omega_{\alpha\beta} = \Omega^{\max}_{\alpha\beta} \exp[-(t - t_{\alpha\beta})^2/(2\sigma^2_{\alpha\beta})],$$

$$\Omega_{12}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max} + \sigma}{2}\right)^2 \Big/ (2\sigma^2)\right]$$

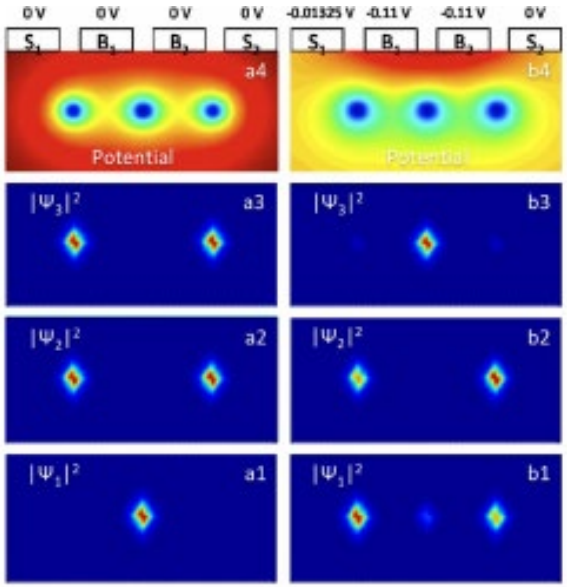
Δ=0

$$\Omega_{23}(t) = \Omega^{\max} \exp\left[-\left(t - \frac{t_{\max} - \sigma}{2}\right)^2 \Big/ (2\sigma^2)\right]$$

Coherent transport by adiabatic passage

Experimental

- Single charge manipulation
- Single spin manipulation
- Solid state qubits
- Band formation
- CTAP



Effect: the electron tunnels between distant sites without evolving through the intermediate sites.

PHYSICAL REVIEW B 80, 035302 (2009)

Atomistic simulations of adiabatic coherent electron transport in triple donor systems

Rajib Rahman,[1,*] Seung H. Park,[1] Jared H. Cole,[2,3] Andrew D. Greentree,[3] Richard P. Muller,[4] Gerhard Klimeck,[1,5] and Lloyd C. L. Hollenberg[3,†]

Suggested articles

Theoretical aspects of Coulomb blockade

PHYSICAL REVIEW B VOLUME 44, NUMBER 4 15 JULY 1991-II

Theory of Coulomb-blockade oscillations in the conductance of a quantum dot

C. W. J. Beenakker
Philips Research Laboratories, 5600 JA Eindhoven, The Netherlands
(Received 28 November 1990)

INSTITUTE OF PHYSICS PUBLISHING REPORTS ON PROGRESS IN PHYSICS
Rep. Prog. Phys. **64** (2001) 701–736 www.iop.org/Journals/rp PII: S0034-4885(01)60525-6

Experimental aspects of Coulomb blockade

Few-electron quantum dots

L P Kouwenhoven[1], D G Austing[2] and S Tarucha[2,3]

Experimental aspects of single atom transistors

LETTERS
PUBLISHED ONLINE: 19 FEBRUARY 2012 | DOI: 10.1038/NNANO.2012.21
nature nanotechnology

A single-atom transistor

Martin Fuechsle[1], Jill A. Miwa[1], Suddhasatta Mahapatra[1], Hoon Ryu[2], Sunhee Lee[3], Oliver Warschkow[4], Lloyd C. L. Hollenberg[5], Gerhard Klimeck[3] and Michelle Y. Simmons[1]*

Silicon qubits

De Michielis et al. J of Phys D 2023 (review in press)

Questions

- Enrico Prati enrico.prati_unimi.it

(EGEA, 2017)
Artificial intelligence
Quantum computers