European Summer Campus 2012, Strasbourg

iemn Institut d'Electronique, de Microélectronique et de Nanotechnologie

Coupling of electronic and mechanical degrees of freedom in quantum nanostructures

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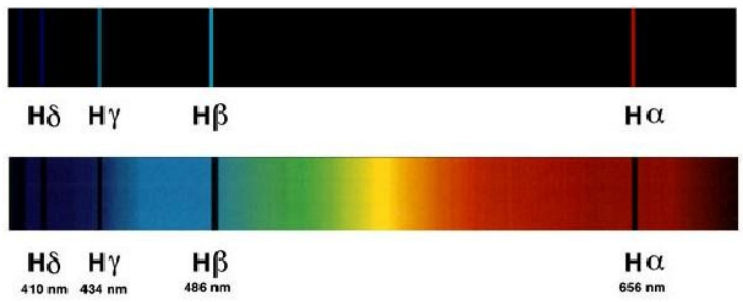
IEMN – CNRS, Villeneuve d'Ascq, France

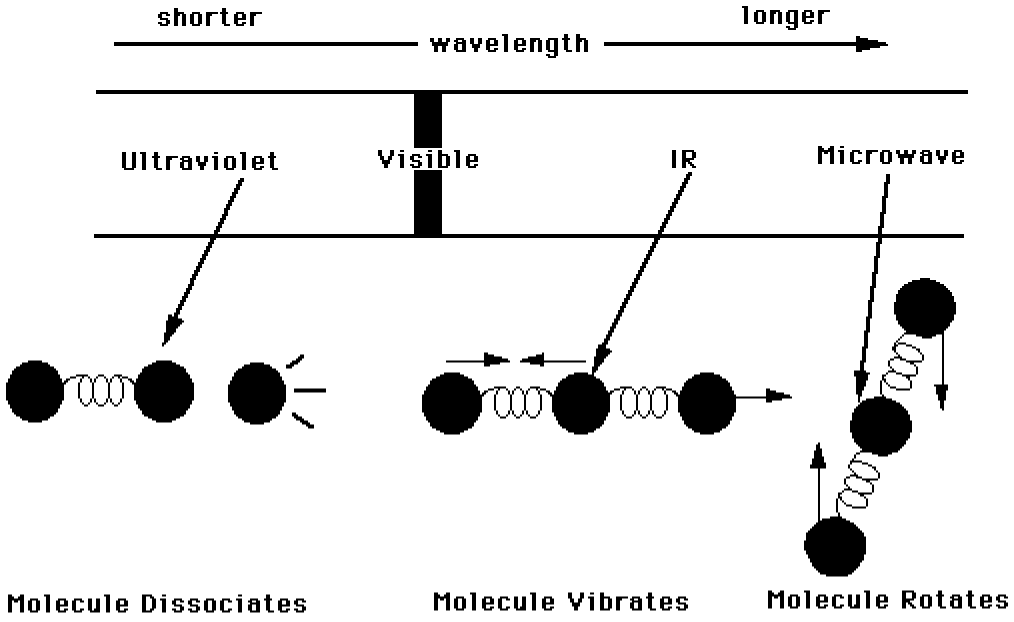
Introduction

- From the electronic structure of atoms to the vibrational spectrum of molecules
  - coupling of electronic and vibrational degree of freedom ⇒ Raman spectroscopy

Emission and Absorption Spectra for Hydrogen

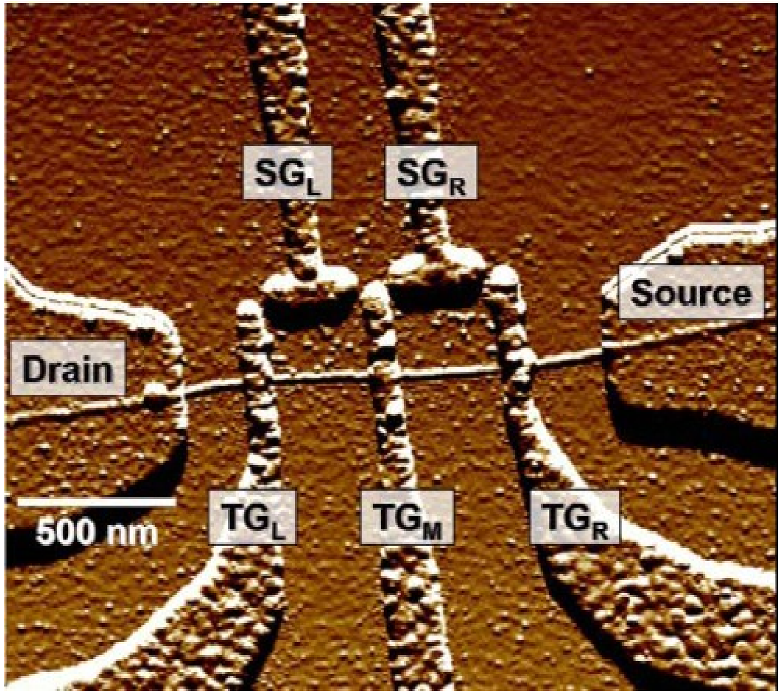


http://dosxx.colorado.edu/~bagenal/1010/SESSIONS/13.Light.html



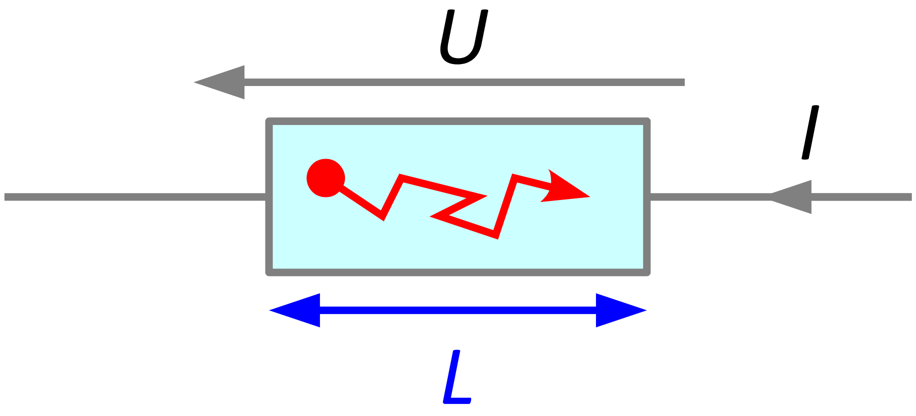
Introduction

- From the electronic structure of atoms to the vibrational spectrum of molecules
- Actual nanostructures closer to single molecules ⇒ do they show similar behavior?
  - e.g. carbon nanotubes



S. Sapmaz *et al.*, Nano Lett. **6**, 1350 (2006)

Introduction



$U = R\,I$ $\qquad$ $I = G\,U$

- Electronic transport
  - resistance (conductance) of a conductor
- Electrons are quantum particles
  - How quantum mechanics influences electronic transport?
  - What is a nanostructure in terms of quantum transport?
- Motion of the atoms of the conductor
  - microscopically: electron-phonon coupling
  - nanostructures: nanoelectromechanical systems (NEMS)
  - New behavior in quantum nanostructures?

Outline

- part 1: electronic transport in quantum nanostructures
  - length and energy scales of quantum electronic transport
  - Coulomb blockade and quantum dots
  - fabrication of nanostructures and measurement techniques
- part 2: coupling of electronic and mechanical degrees of freedom

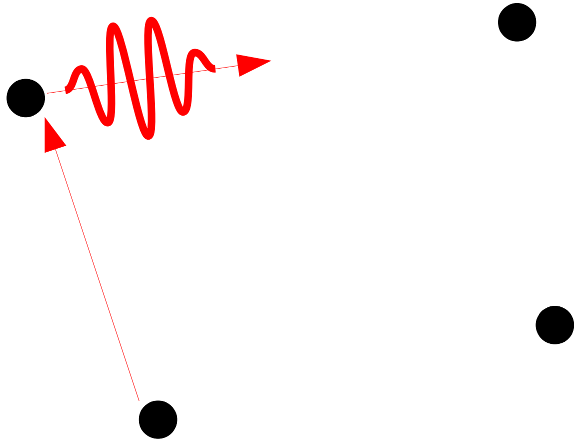
Length and energy scales of quantum electronic transport

Lengths scales for electronic transport

- Classical transport (Drude)
  - electron = particle (wave packet)
  - independent scattering (incoherent)
  - no interactions

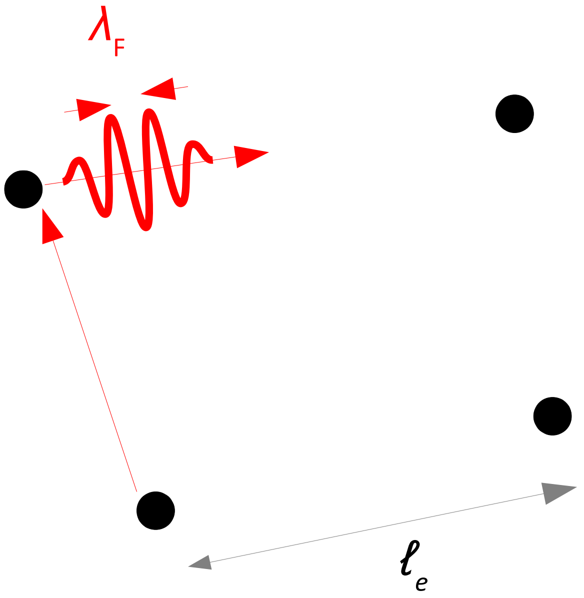
$$\boldsymbol{j} = \sigma \boldsymbol{E}$$

$$\sigma = \frac{n e^2 \tau_{tr}}{m}$$

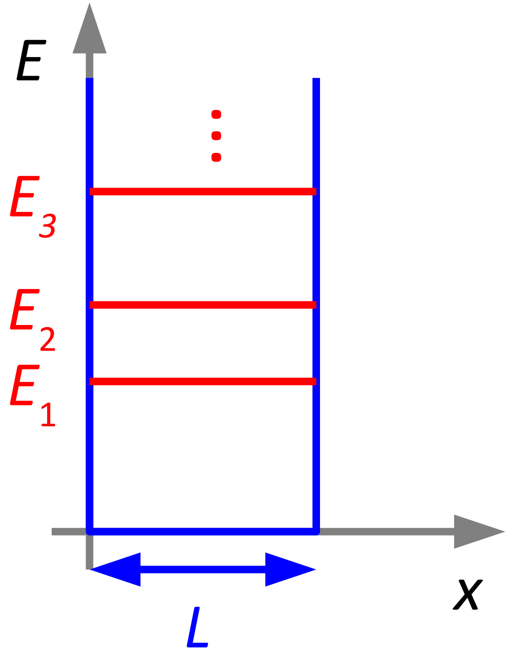


Lengths scales for electronic transport

- Fermi wave length λ_F
  - only electrons at E_F participate to the transport
- Mean free path ℓ_e
  - mean distance between two scattering events
- Phase coherent length ℓ_ϕ
  - memory of the phase
- Classical limit:
  - $\lambda_F < \ell_e$ and $\ell_\phi < \ell_e$

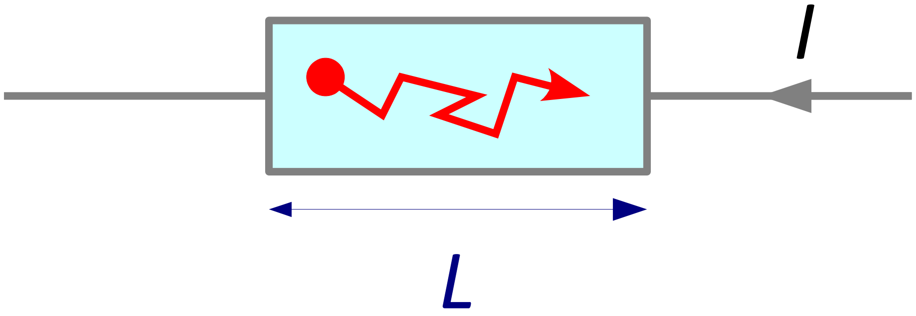


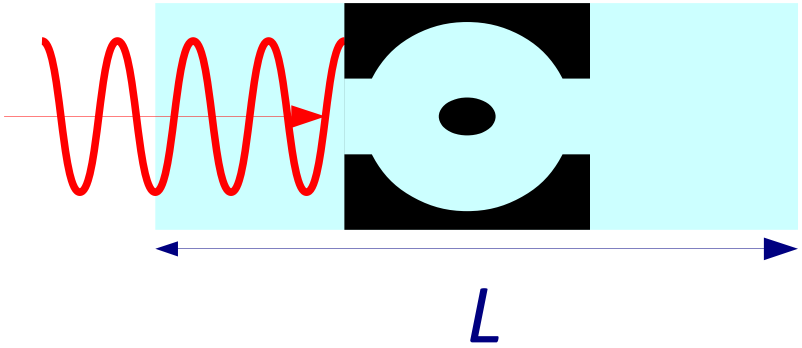
Energy scales



- Level spacing $\Delta = E_{i+1} - E_i$
  - energy quantization
- Charging energy e^2/C
  - effect of electron-electron interactions
- Thermal energy k_BT
  - energy averaging
  - decoherence (phonons, electron-electron interactions)

Length and energy scales in nanostructures

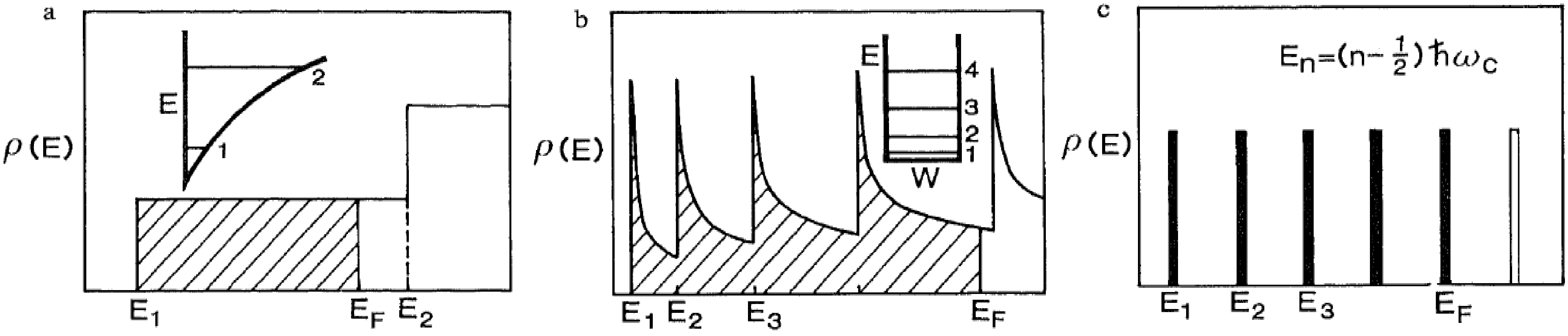




– $L \gg \ell_e$: diffusive	– $L < \ell_e$: ballistic
– $L \gg \ell_\phi$: incoherent	– $L < \ell_\phi$: coherent
– $L \gg \lambda_F$ and/or $\Delta < k_B T$: no quantum confinement	– $L \sim \lambda_F$ and $\Delta > k_B T$: quantum confinement
– $e^2/C < k_B T$: no charging effect	– $e^2/C > k_B T$: single charge effects

Quantum confinement

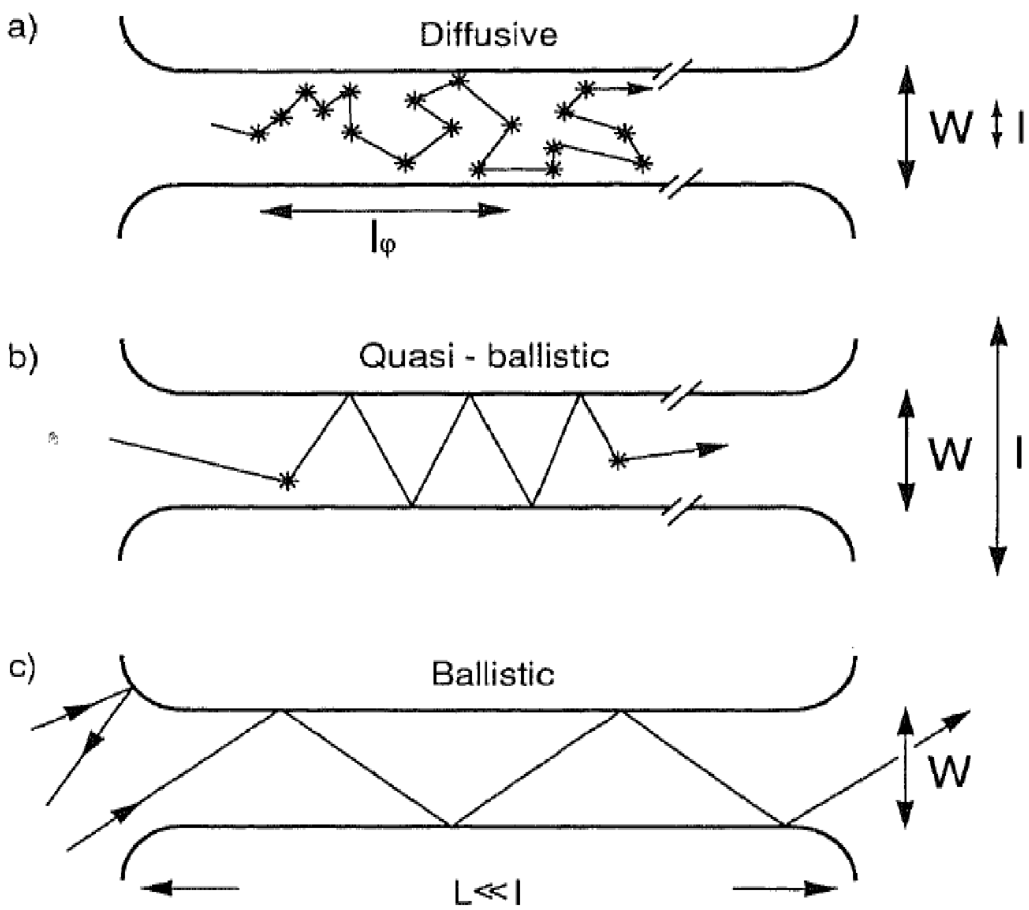
- Size of the system *L*
- $L \sim \lambda_F \Rightarrow$ quantum confinement (conductance quantization, nanophysics)
  - density of states in confined systems:



2D 1D 0D

Ballistic transport

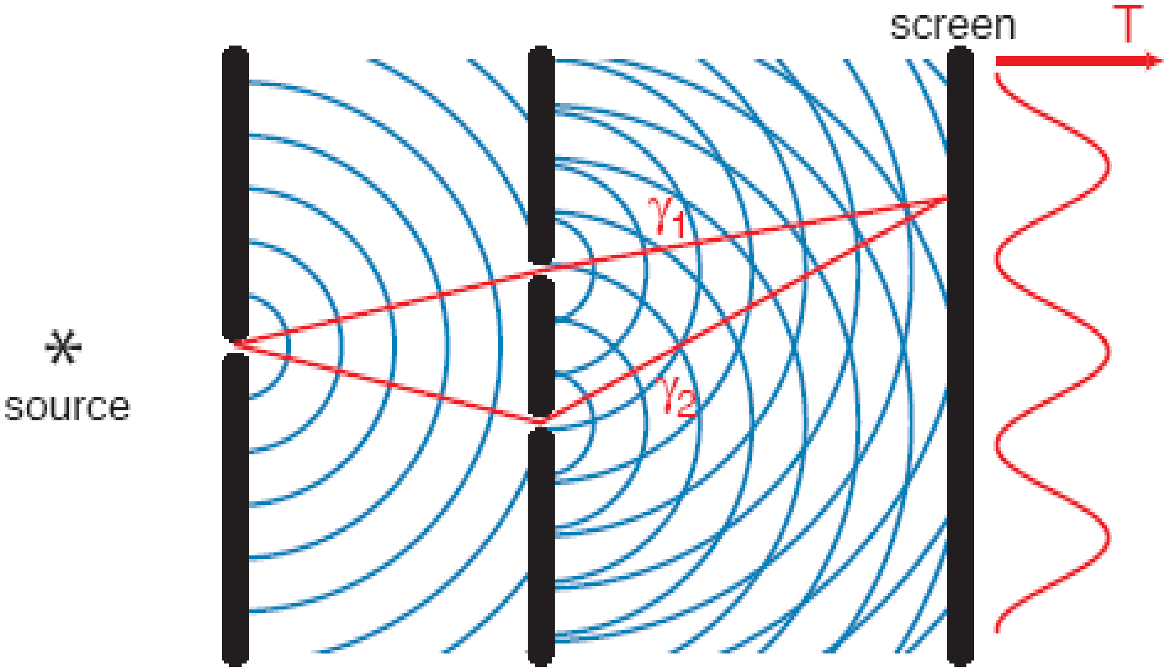
- Size of the system L
- $L < \ell_e \Rightarrow$ ballistic transport



H. van Houten *et al.*, in Physics and Technology of Submicron Structures (Springer, Berlin, 1988)

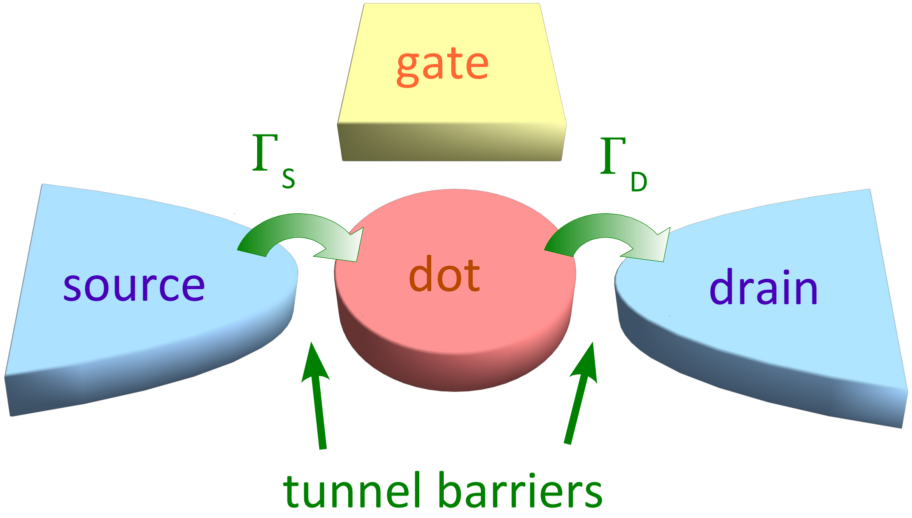
Coherent transport

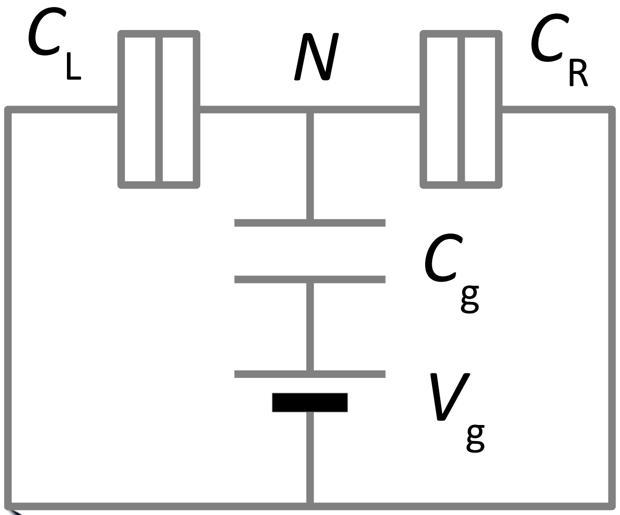
- Size of the system L
- $L < \ell_\varphi \Rightarrow$ interferences between electron wave functions (mesoscopic transport)



Coulomb blockade and quantum dots

Coulomb blockade: the single electron transistor





$$-Ne = Q_g + Q_L + Q_R$$

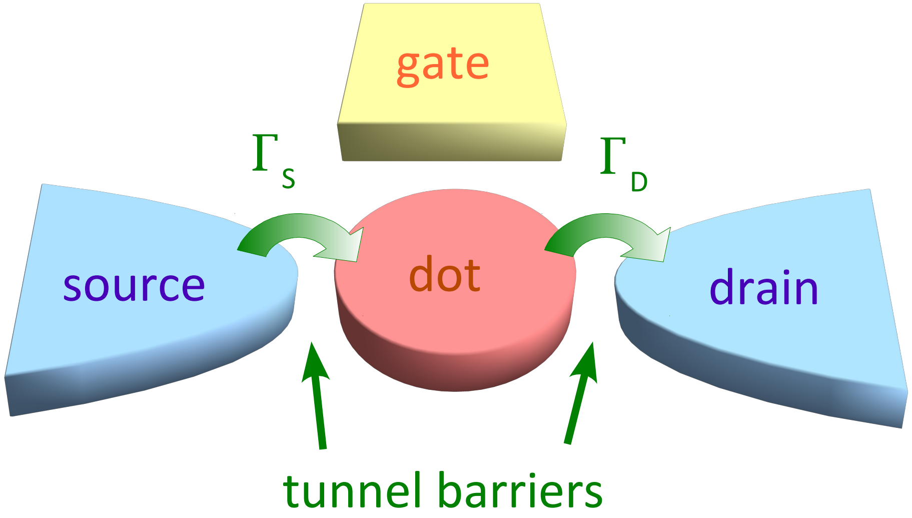
$$C = C_L + C_R + C_g$$

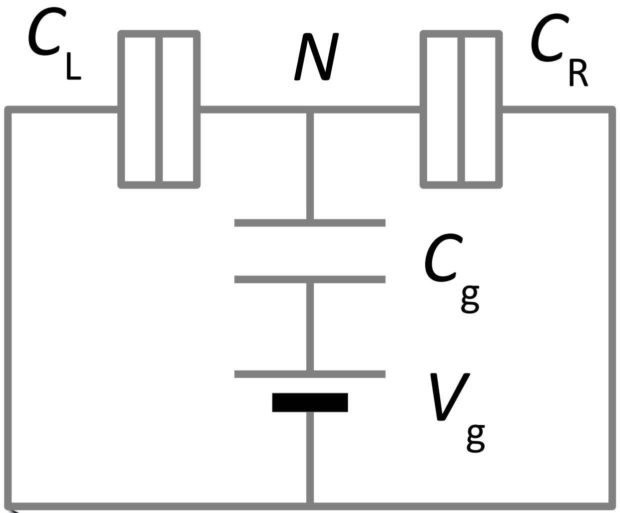
$$V_g = \frac{Q_L}{C_L} - \frac{Q_g}{C_g} = \frac{Q_R}{C_R} - \frac{Q_g}{C_g}$$

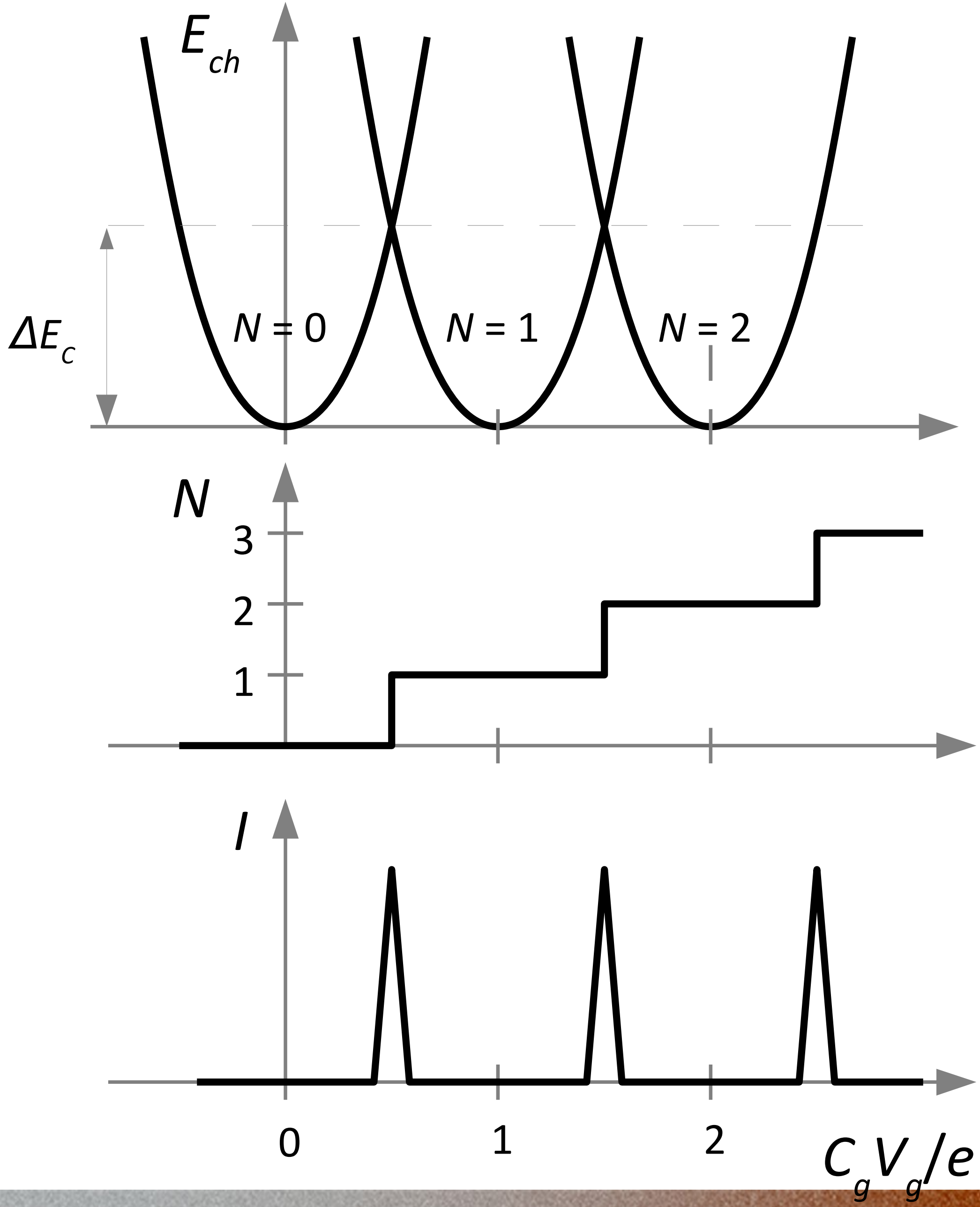
$$E_{ch}(N, V_g) = \frac{Q_L^2}{2C_L} + \frac{Q_R^2}{2C_R} + \frac{Q_g^2}{2C_g}$$

$$\approx \frac{(Ne - C_g V_g)^2}{2C}$$

Coulomb blockade: the single electron transistor

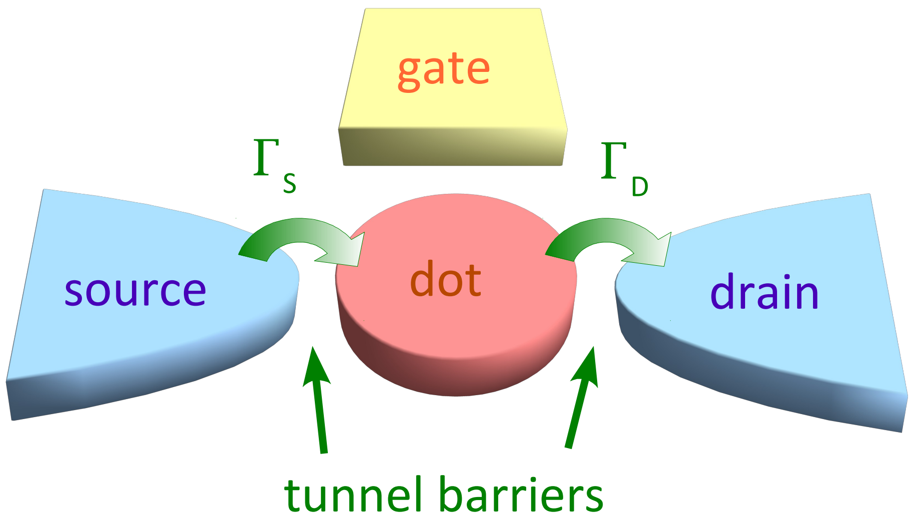


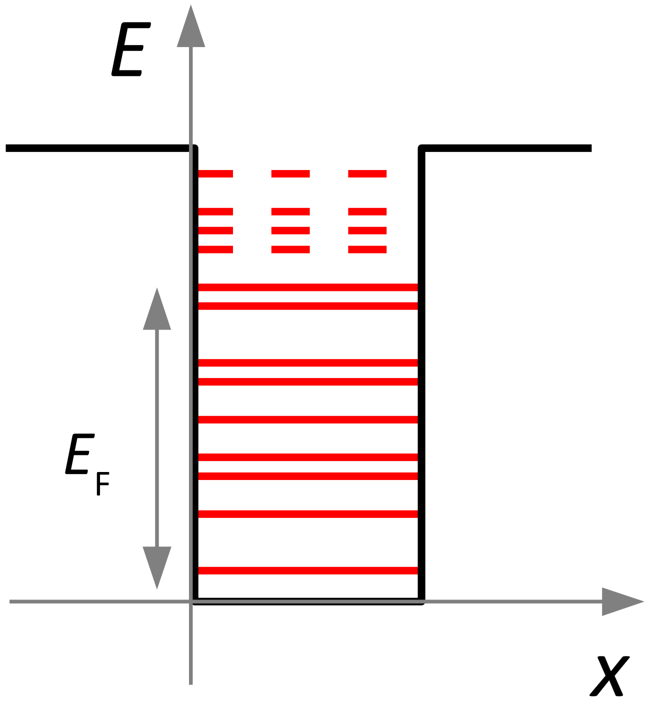




Confinement energy: the quantum dot

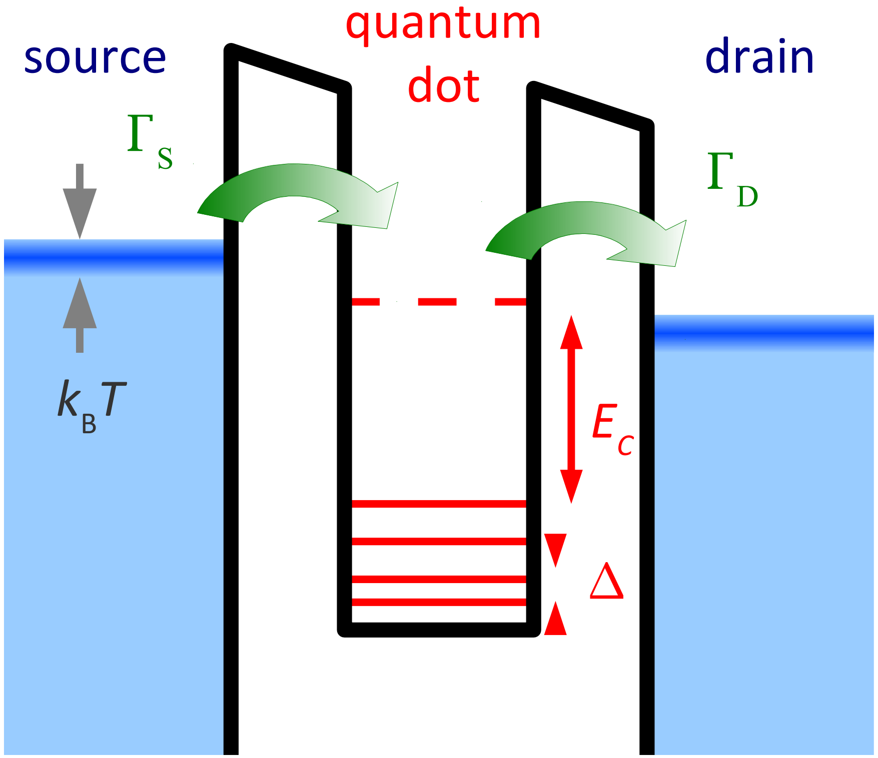
- Non-interacting particles: interference between reflected electron paths (Fabry-Perot) ⇒ discrete spectrum





Quantum dot = tunable artificial atom

- From the single electron transistor to the quantum dot



$$E_{ch}(N) \approx \left(N + \frac{1}{2}\right) E_C$$

$$E_C = \frac{e^2}{C} \approx \frac{e^2}{\varepsilon_0 \varepsilon_r L}$$

$\varepsilon_r = 1 \Rightarrow E_C \approx 200$ meV pour $L = 100$ nm

($\varepsilon_r < 1$ in usual semiconductors)

$$\Delta \approx \frac{\pi^2 \hbar^2}{m L^2}$$

$m = 9{,}1 \times 10^{-31}$ kg

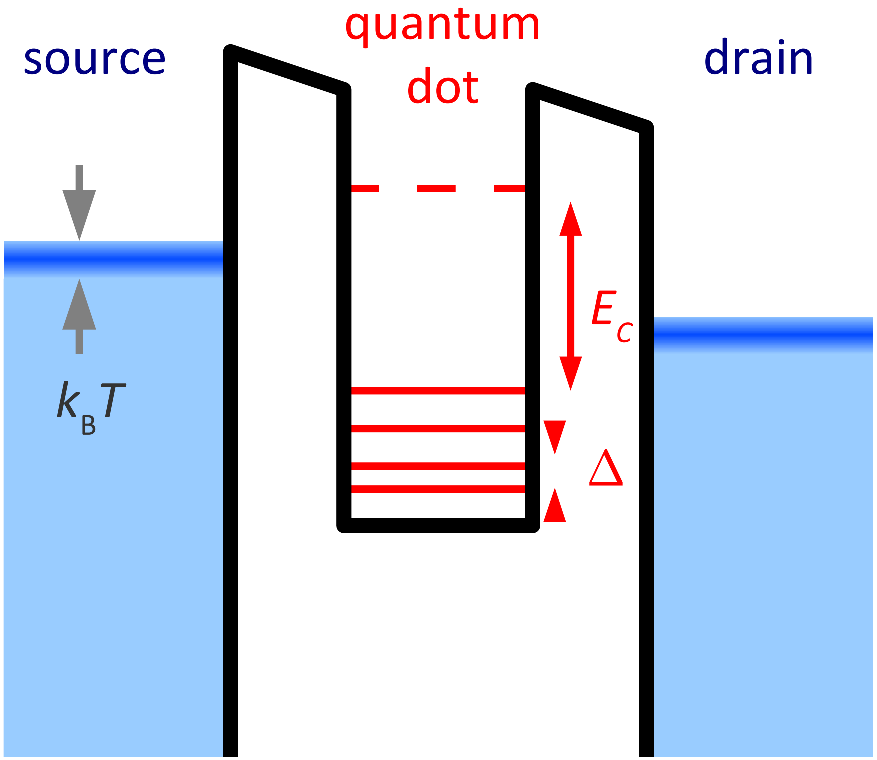
$\Rightarrow \Delta \approx 75$ µeV for $L = 100$ nm

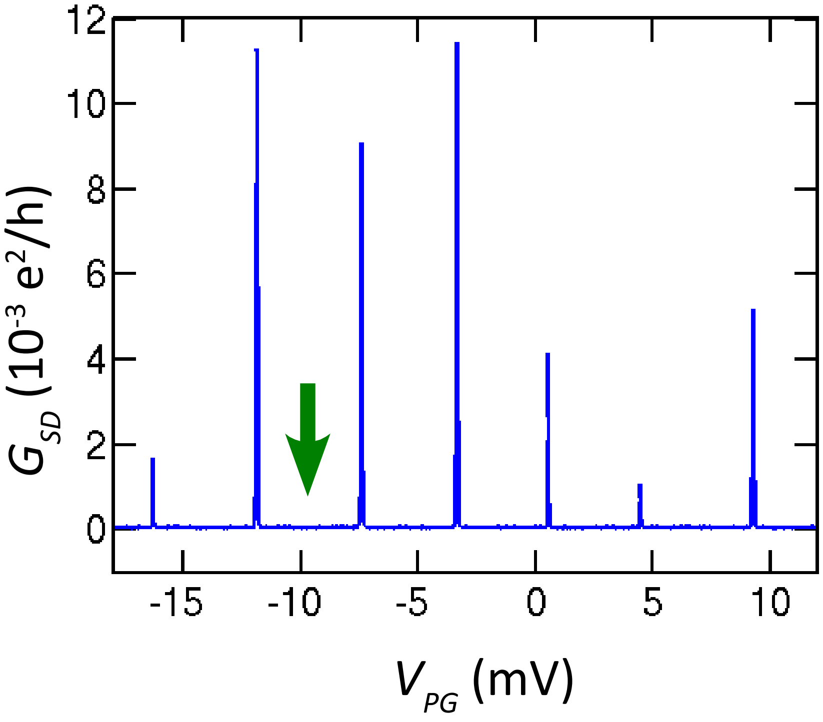
($m_e^* < m_e$ in usual semiconductors)

Electronic transport through a quantum dot

- Spectroscopy of electronic states

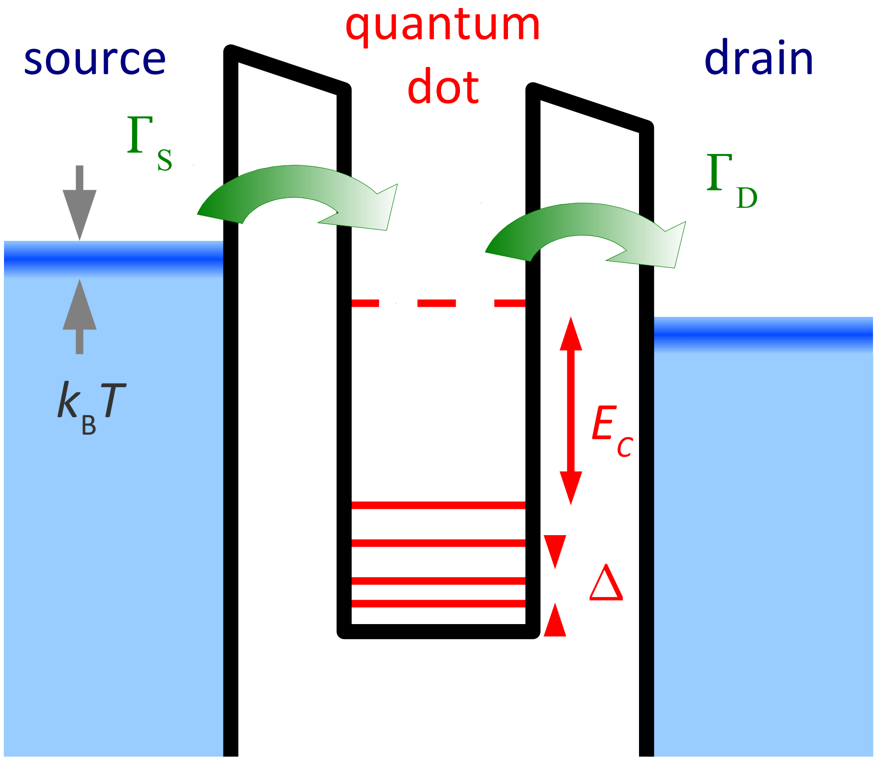
$$k_B T \ll \Delta < E_C$$





Electronic transport through a quantum dot

- Spectroscopy of electronic states



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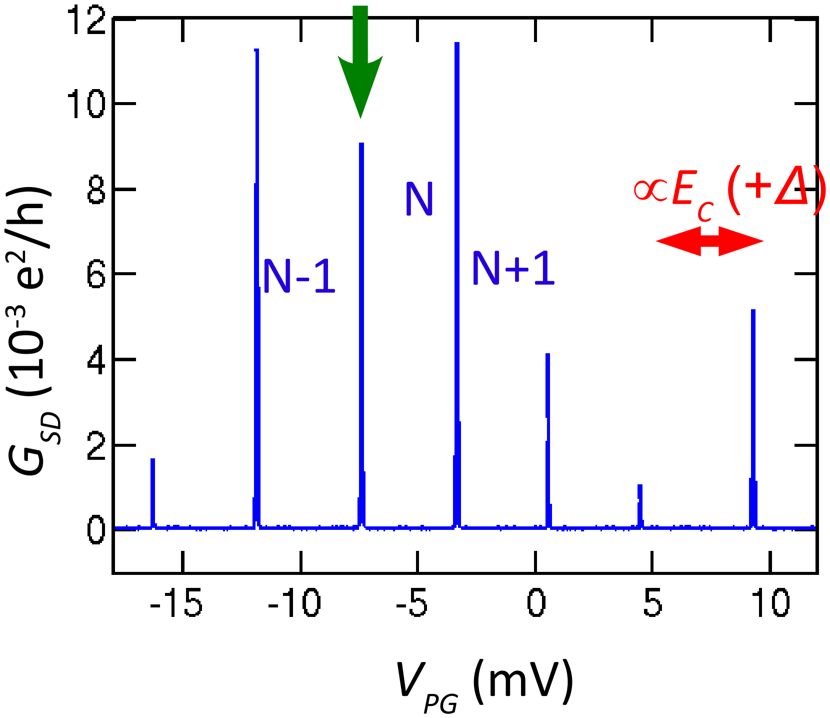

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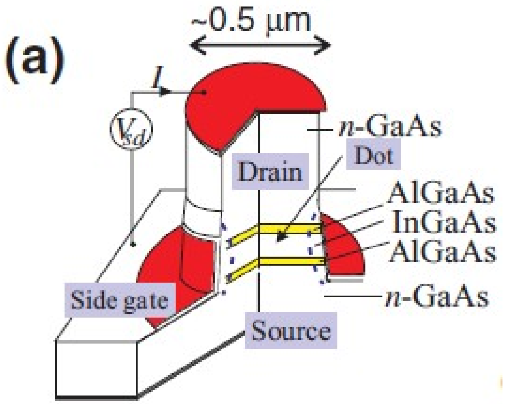
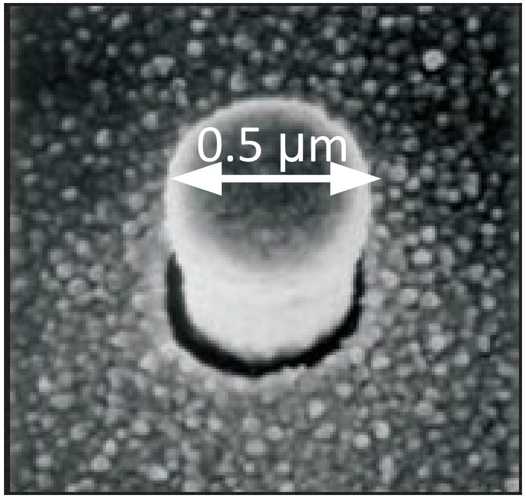
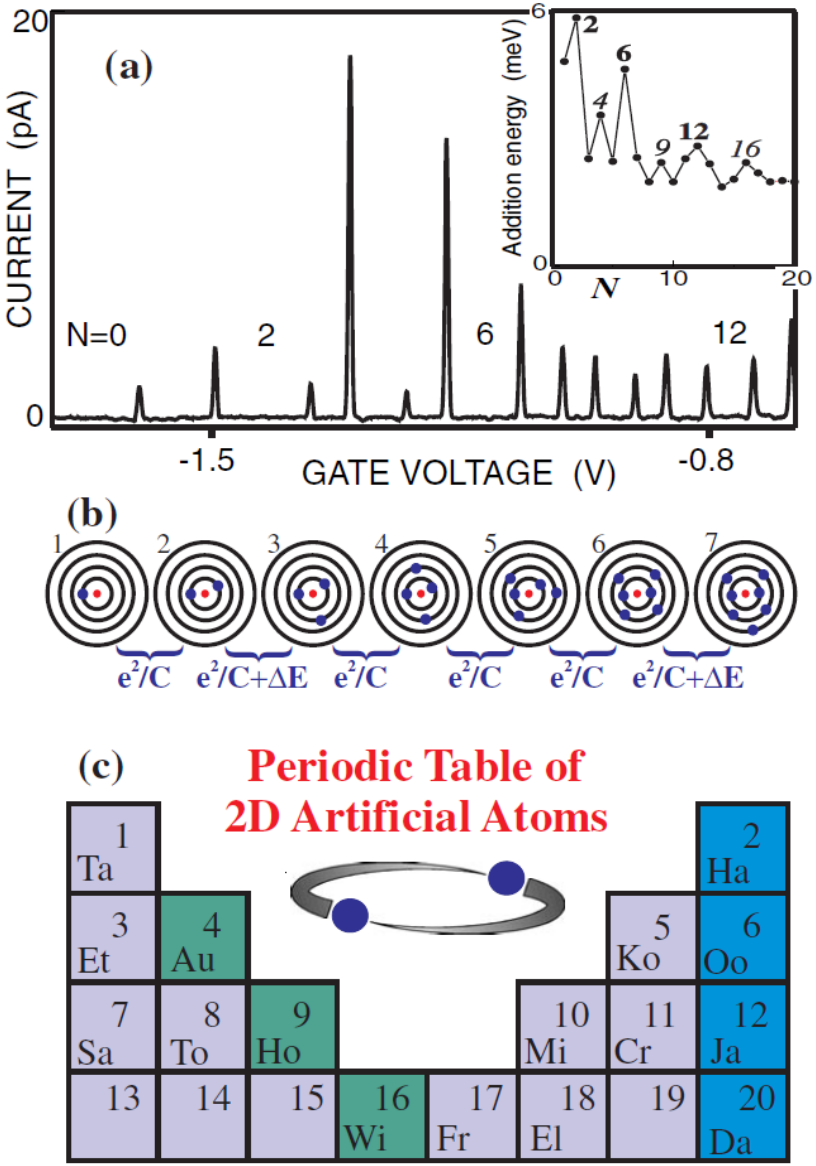
Quantum dot = tunable artificial atom





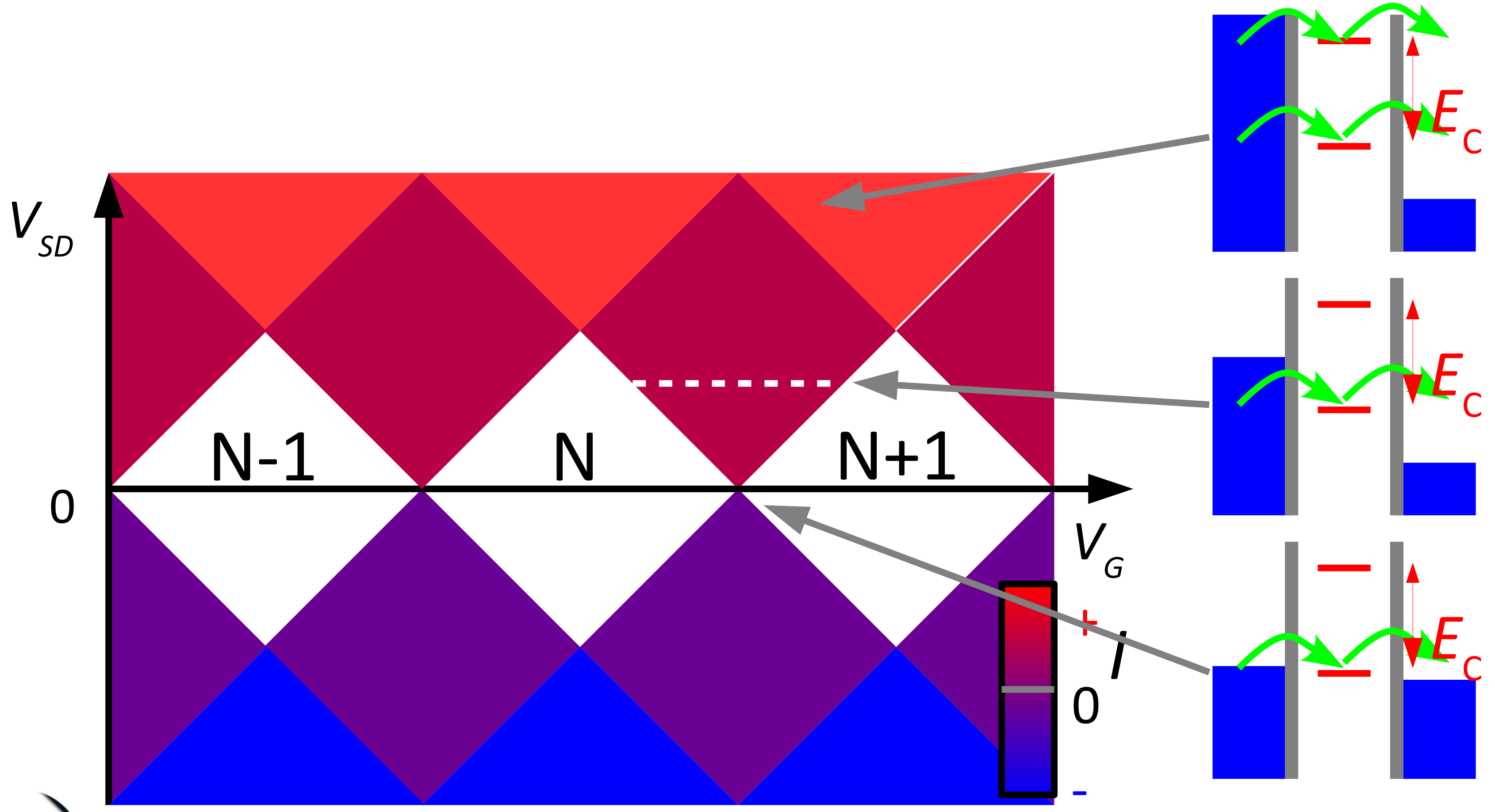
L.P. Kouwenhoven, D.G.Austin & S. Tarucha
Rep. Prog. Phys **64**, 701 (2001)



1 Ta							2 Ha
3 Et	4 Au					5 Ko	6 Oo
7 Sa	8 To	9 Ho			10 Mi	11 Cr	12 Ja
13	14	15	16 Wi	17 Fr	18 El	19	20 Da

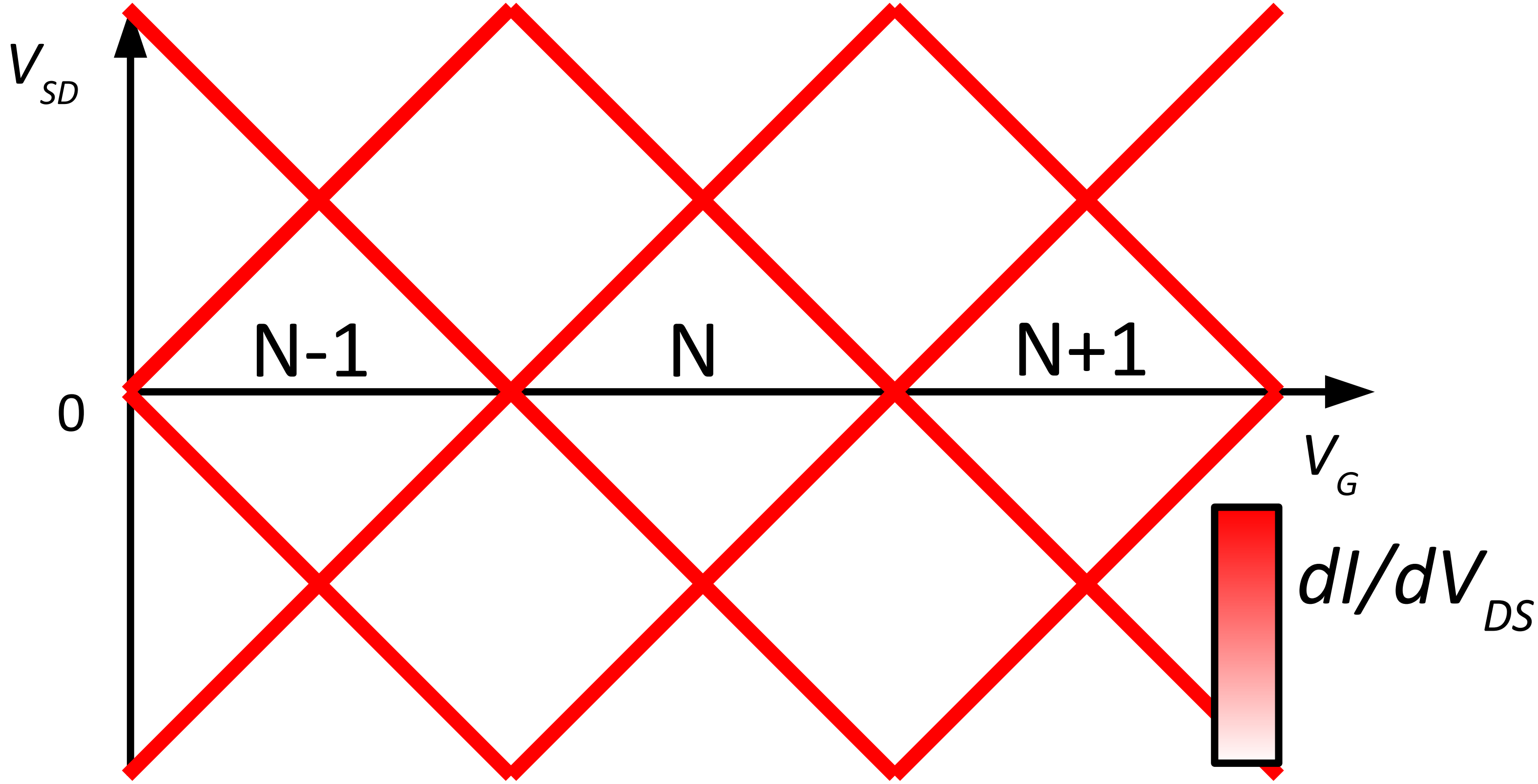
Quantum dots

- Charge stability diagram



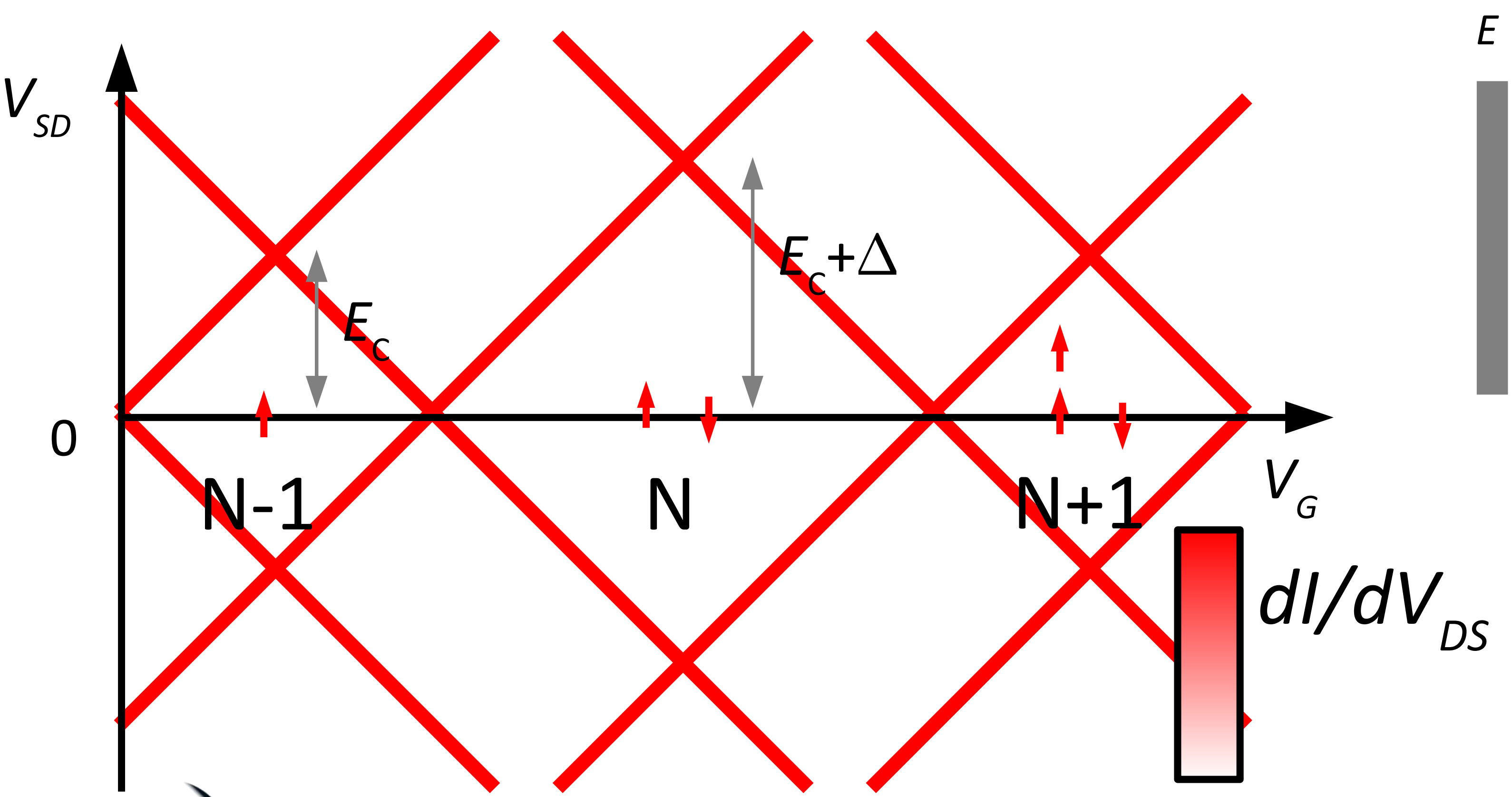
Quantum dots

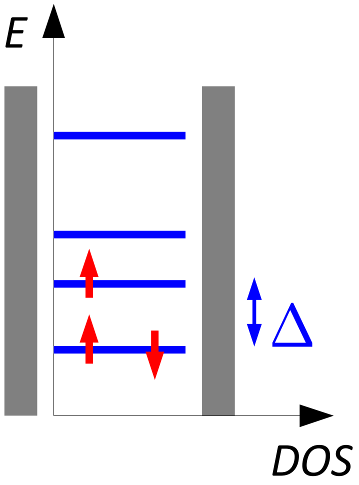
- Charge stability diagram (SET)



Quantum dots

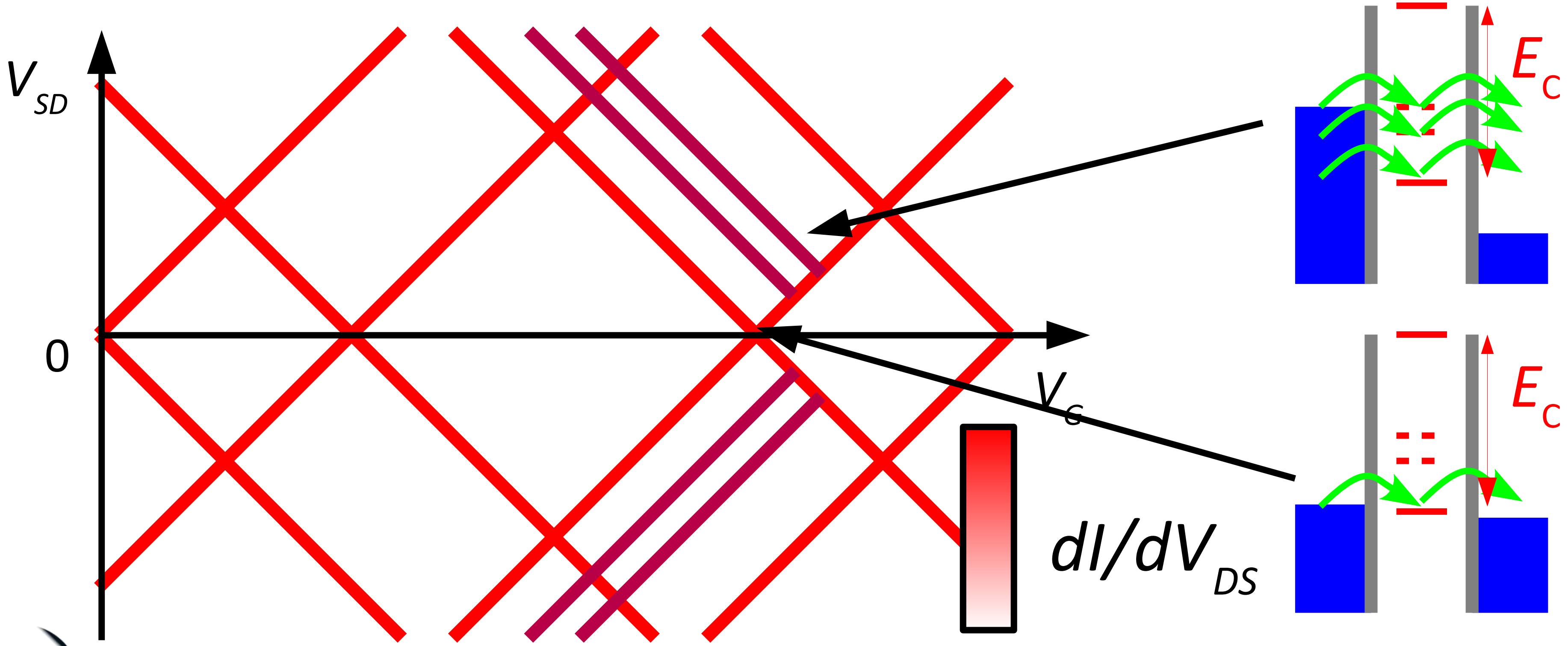
- Charge stability diagram (QD)





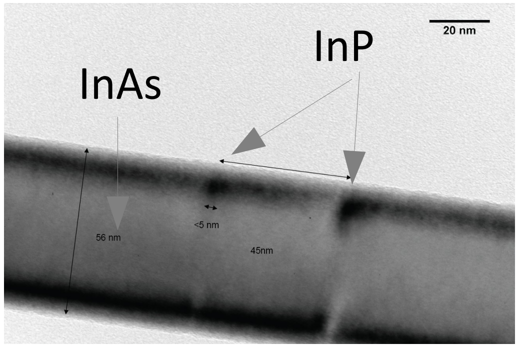
Quantum dots

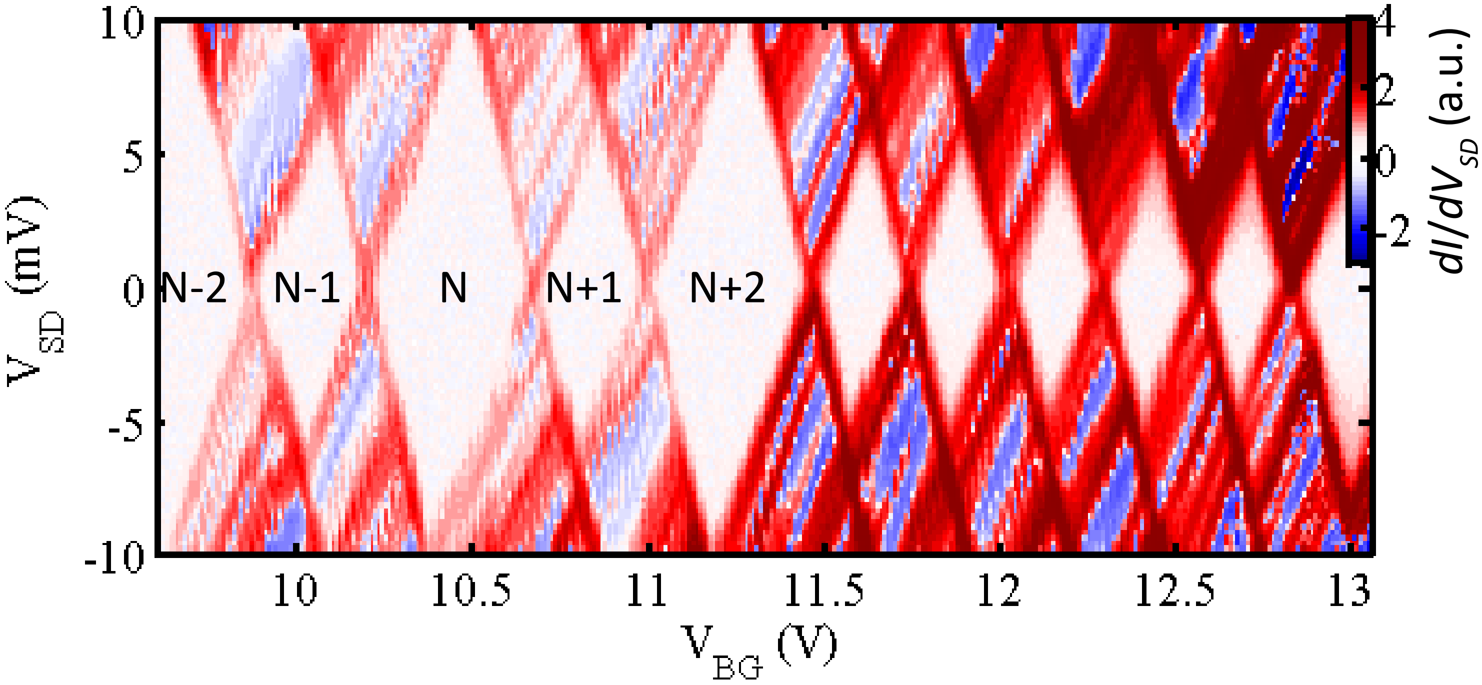
- Spectroscopy of excited states



Quantum dots

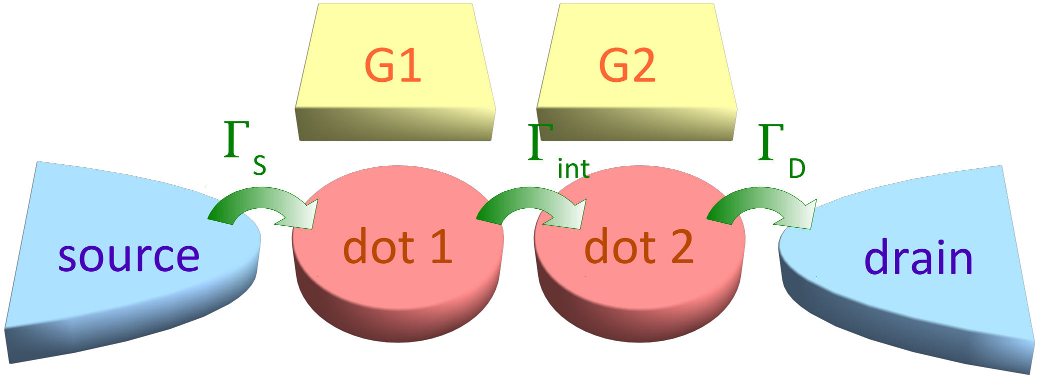
- experiment

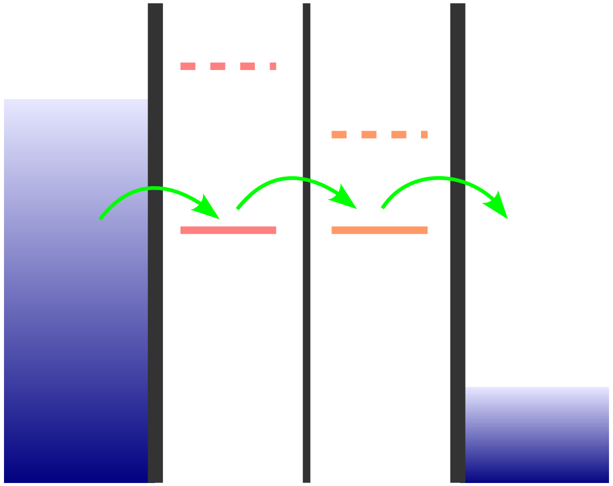




Multiple quantum dots = artificial molecules

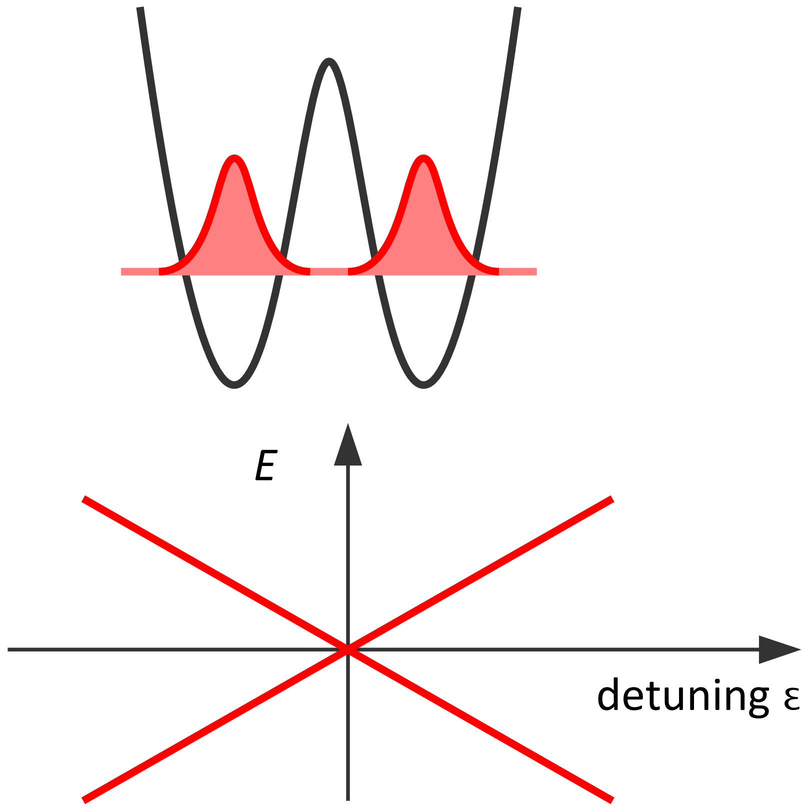
- Double quantum dot



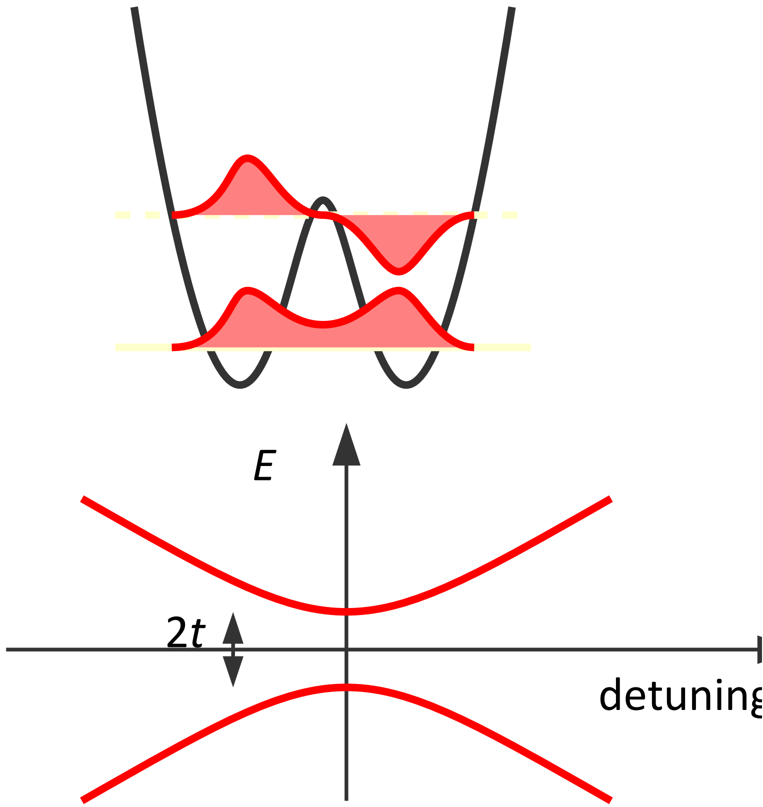


Molecular states in a double quantum dot

- Weak coupling



- Strong coupling: bonding and antibonding states



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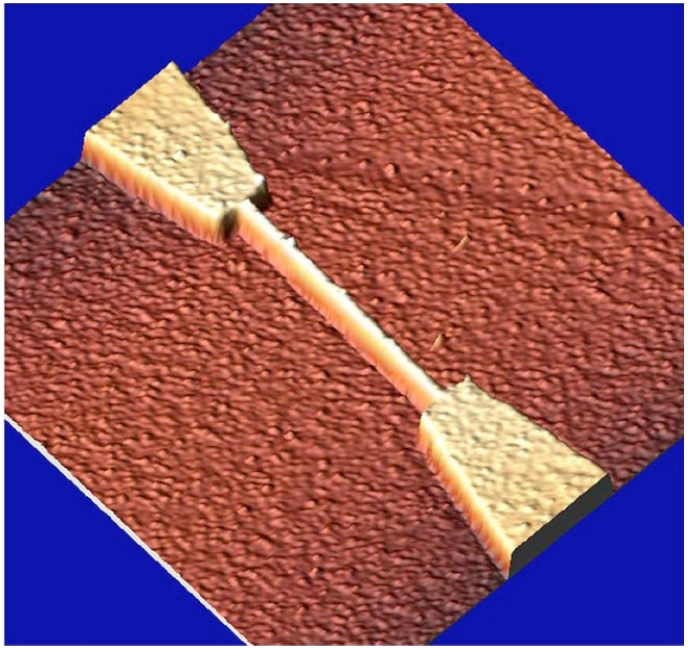
Fabrication of nanostructures and measurement techniques

Fabrication of nanostructures: top-down vs. bottom-up approaches

- Top-down

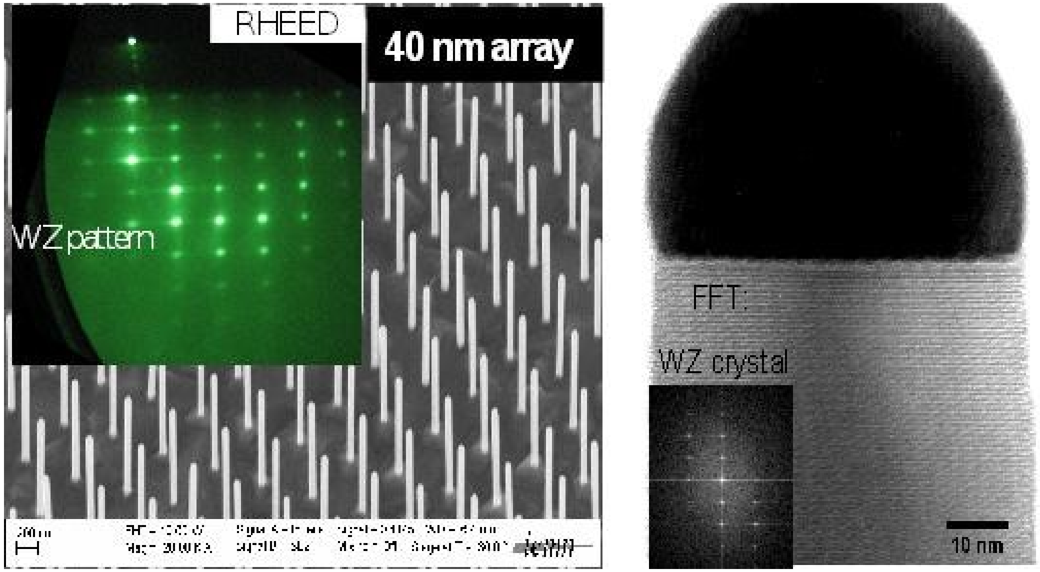
etched silicon nanowire
(35 nm width)



F. Vaurette (IEMN)

- Bottom-up

MBE-grown InAs nanowires
(40 nm diameter)



P. Caroff (IEMN)

Fabrication of nanostructures: top-down vs. bottom-up approaches

- Top-down
  - easy integration
  - large variety of shapes

  BUT
  - defects due to the lithography process
  - sequential process (electron beam lihography)

- Bottom-up
  - defect free
  - highly parallel
  - often low cost

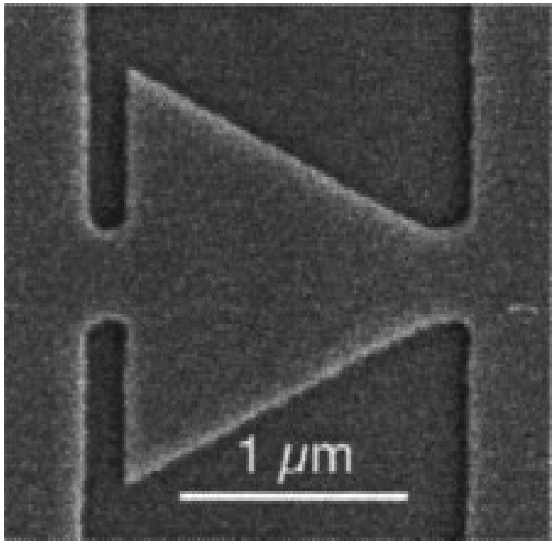
  BUT
  - difficult integration
  - shapes defined by the process

often combine both!

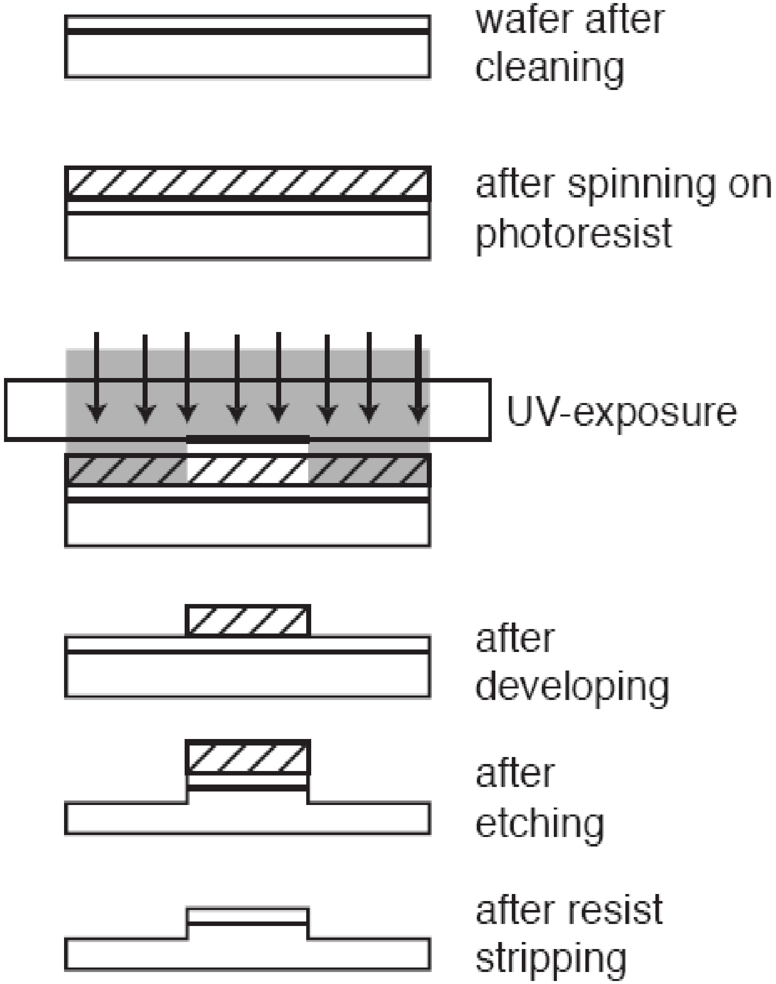
Top-down approaches

- Litography (opitcal or electron beam)

Structure defined by etching



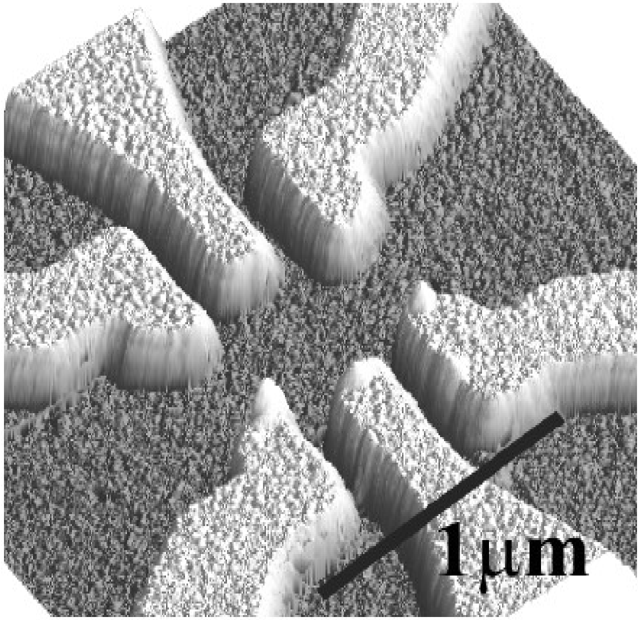
H. Linke *et al.*, Phys. Rev. B **51**, 15914 (2000)

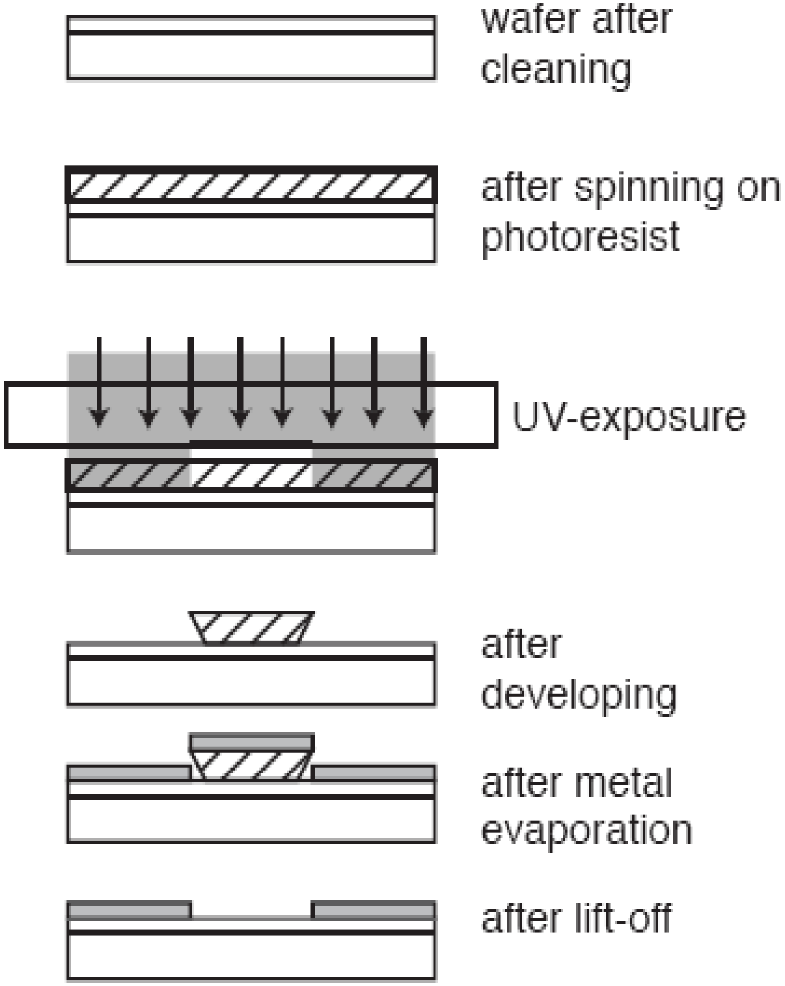


Top-down approaches

- Litography (opitcal or electron beam)

Structure defined by metal evaporation





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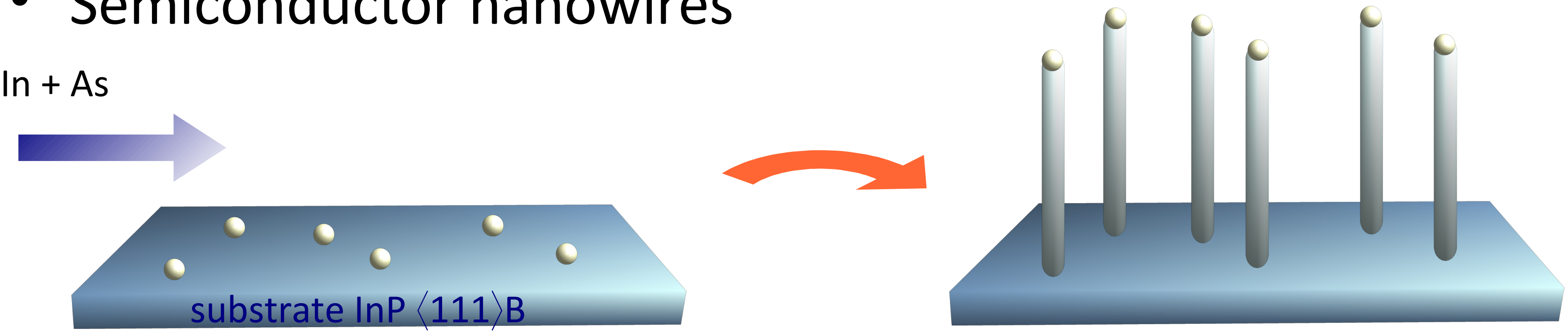
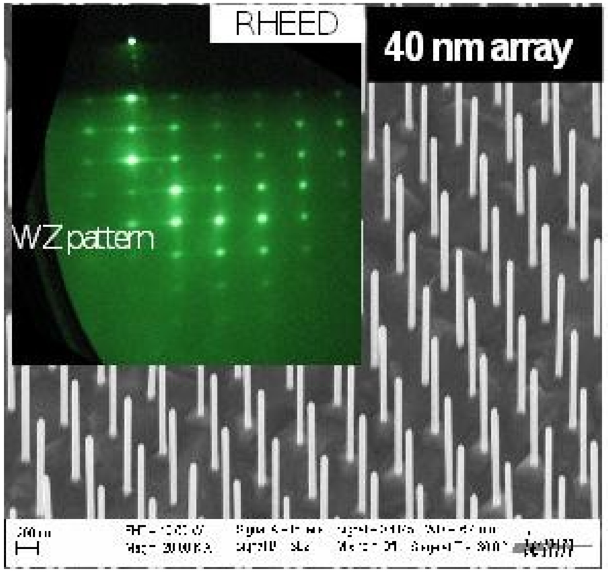
Bottom-up approaches

- Semiconductor nanowires


In + As

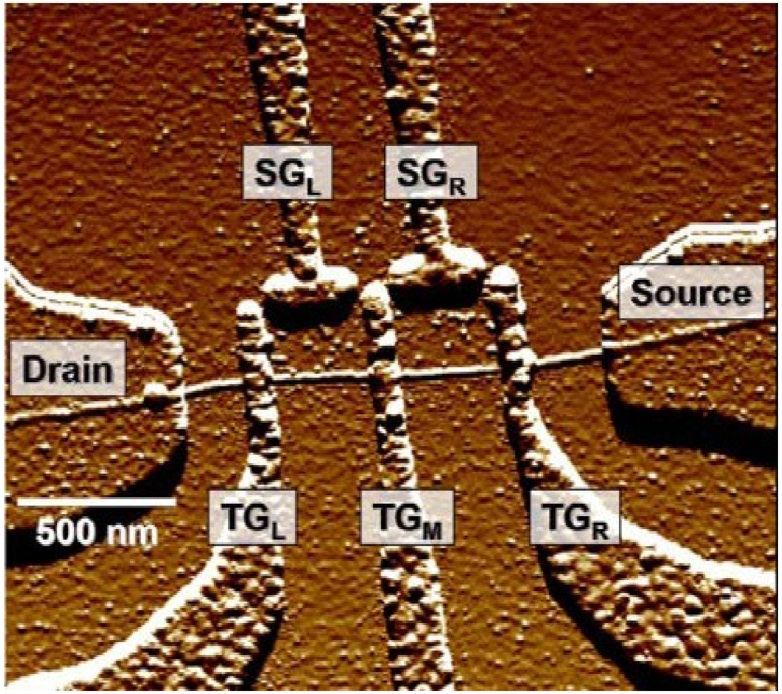
substrate InP ⟨111⟩B



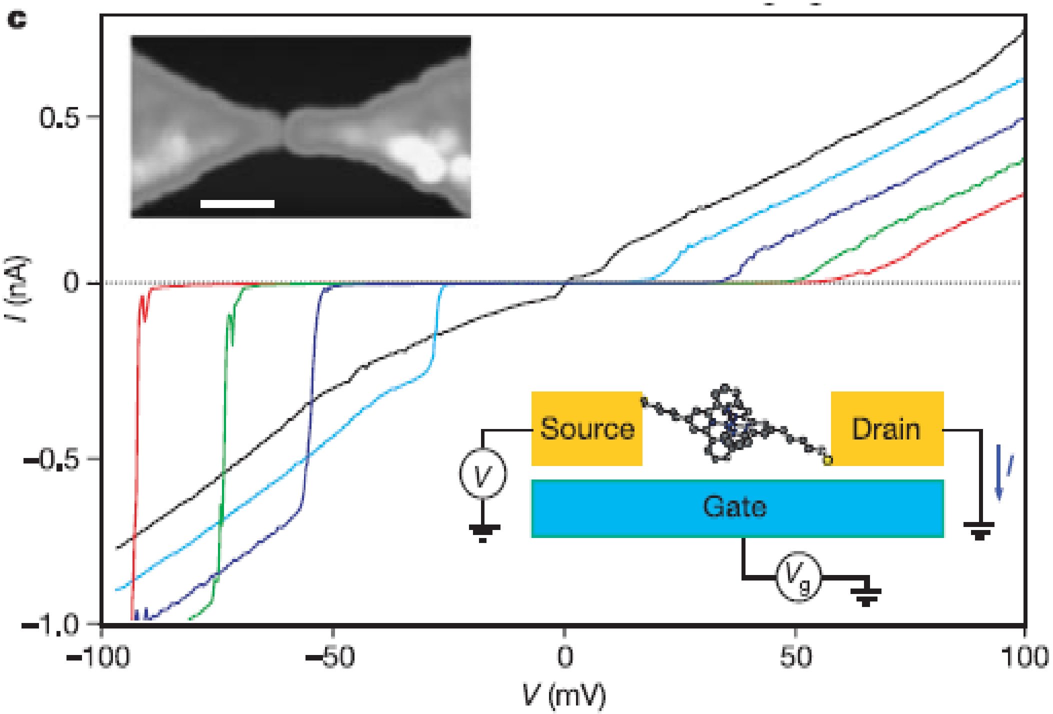
P. Caroff (IEMN)

Bottom-up approaches

- Molecular electronics
  - carbon nanotubes
  - single molecules

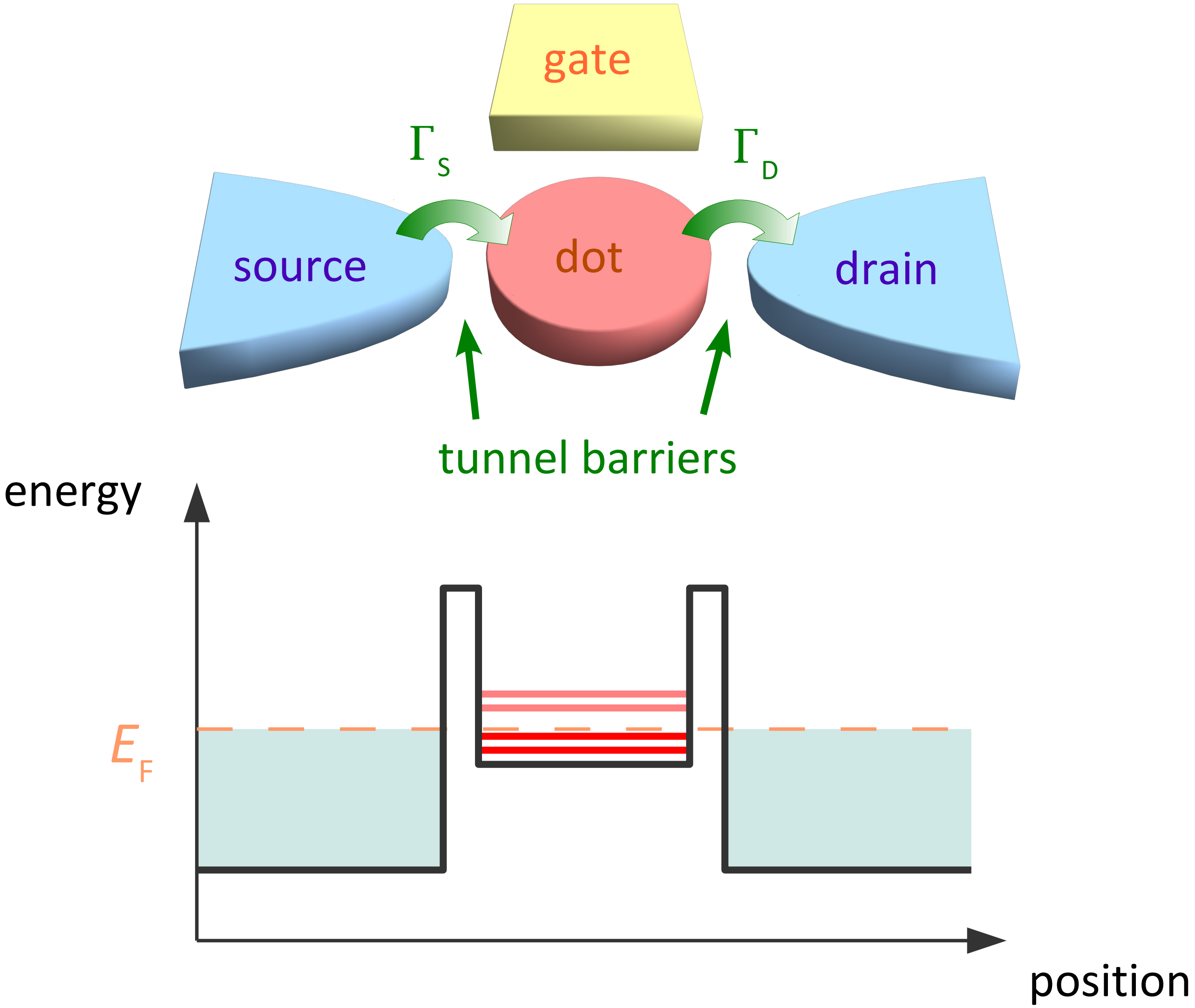


S. Sapmaz *et al.*, Nano Lett. **6**, 1350 (2006)



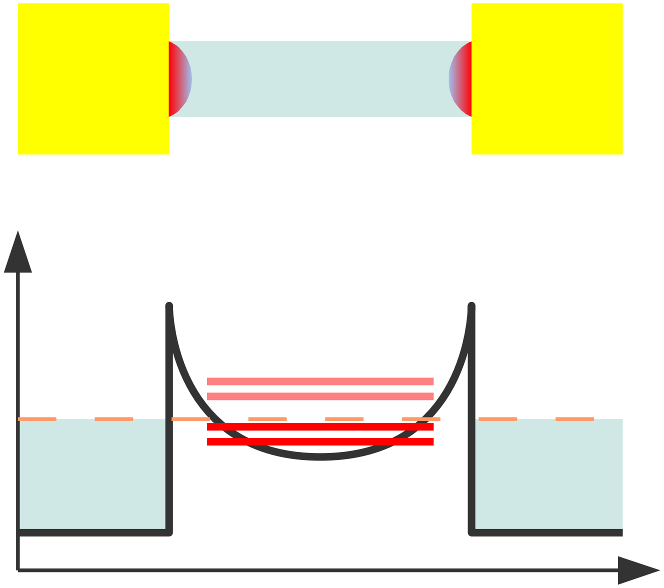
J. Park *et al.*, Nature **417**, 722 (2002)

Quantum dots for electrical transport

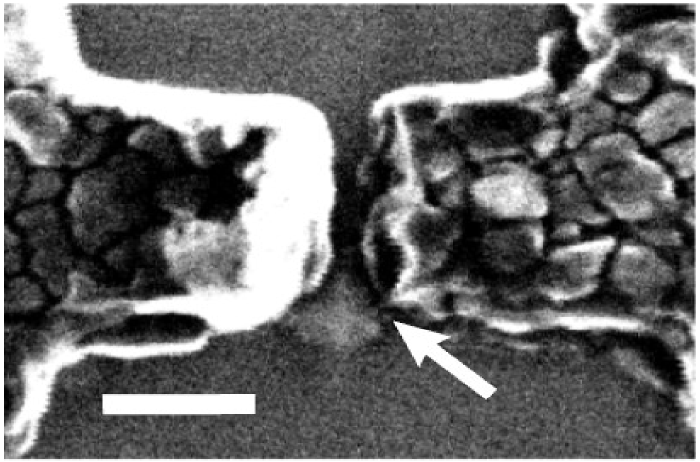


Quantum dots for electronic transport

- Schottky contacts on a nanomaterial
  - easy to make
  - average tunability



- self-assembled quantum dot

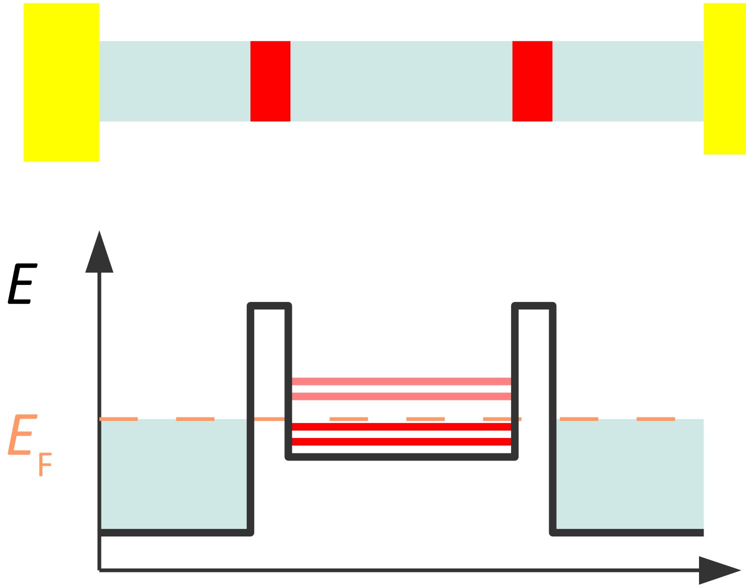


C. Buizert *et al.*, PRL **99**, 136806 (2007)

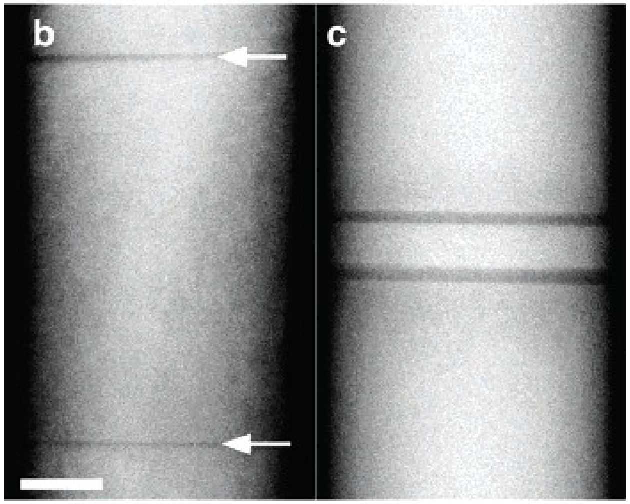
- semiconductor nanowires and carbon nanotubes

Quantum dots for electronic transport

- Heterostructure
  - high reproducibility
  - controlled size
  - low tunability



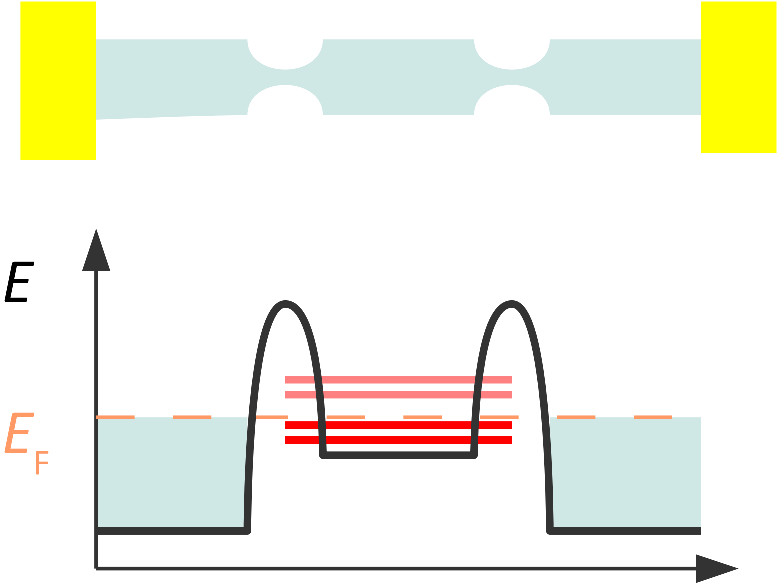
\- longitudinal heterostructures in nanowires



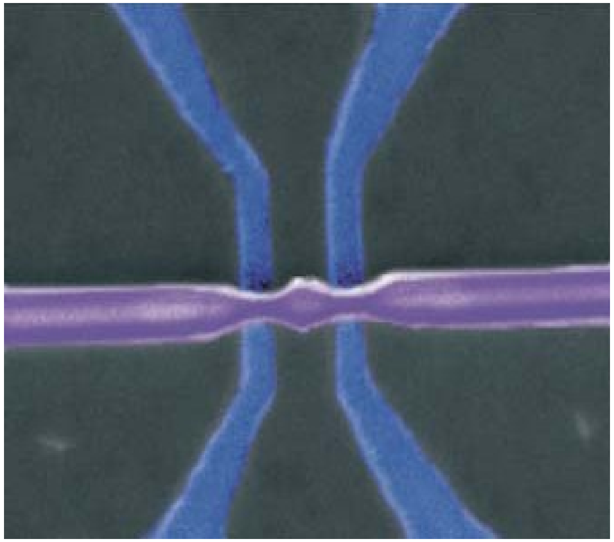
M. Björk *et al.*, Nano Lett. **4**, 1621 (2004)

Quantum dots for electronic transport

- Local etching
  - very versatile
  - average tunability



- local etching of a nanowire

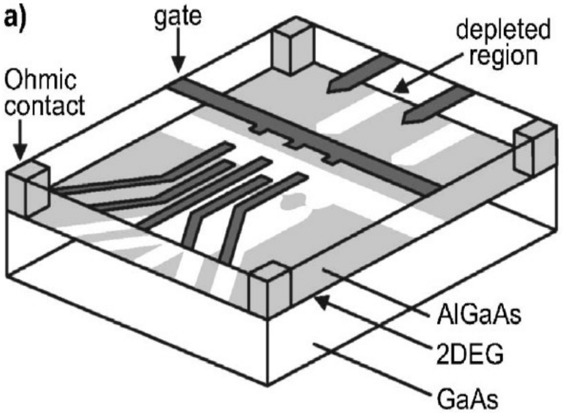


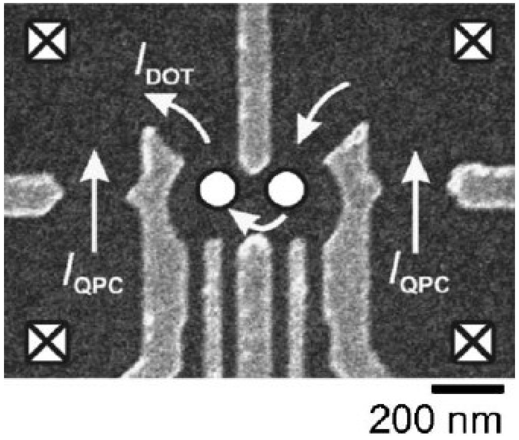
I. Shorubalko *et al.*, Nano Lett. **8**, 382 (2008)

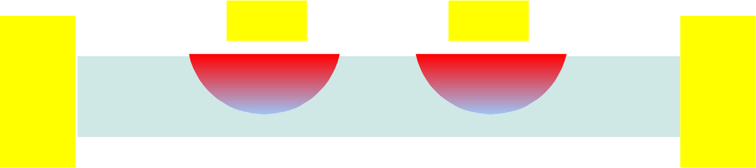
Quantum dots for electronic transport

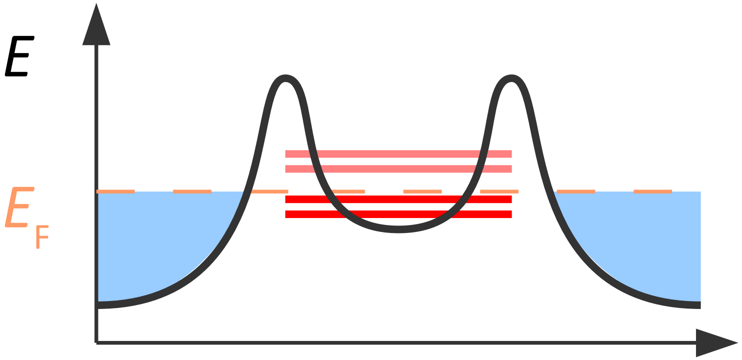
- from planar heterostructures

- Local depletion
  - high complexity
  - high tunability

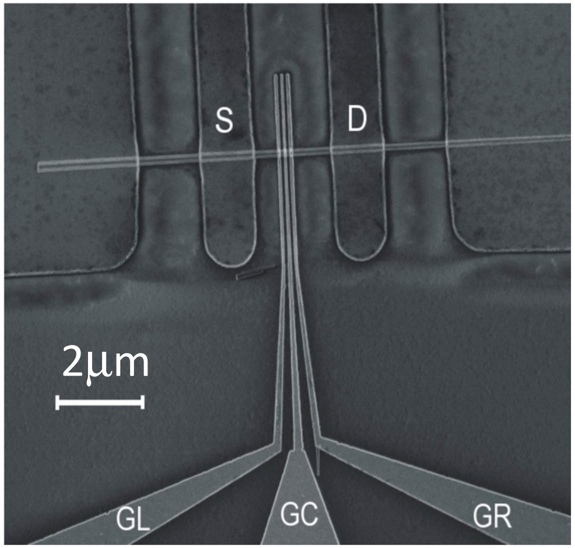




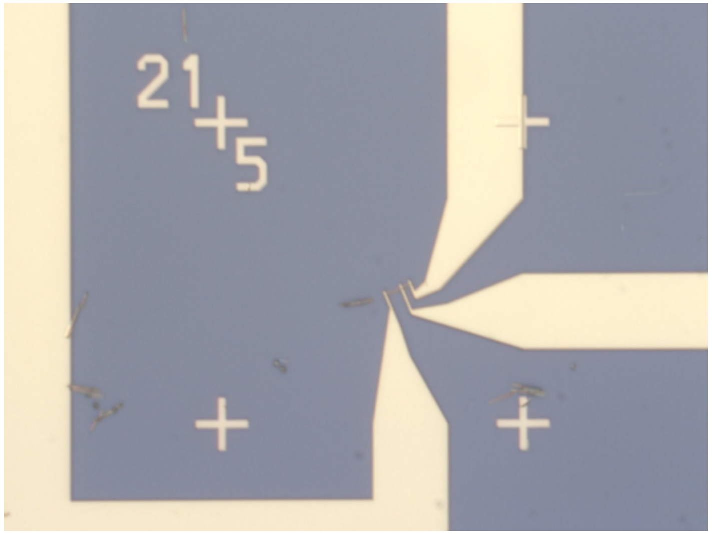


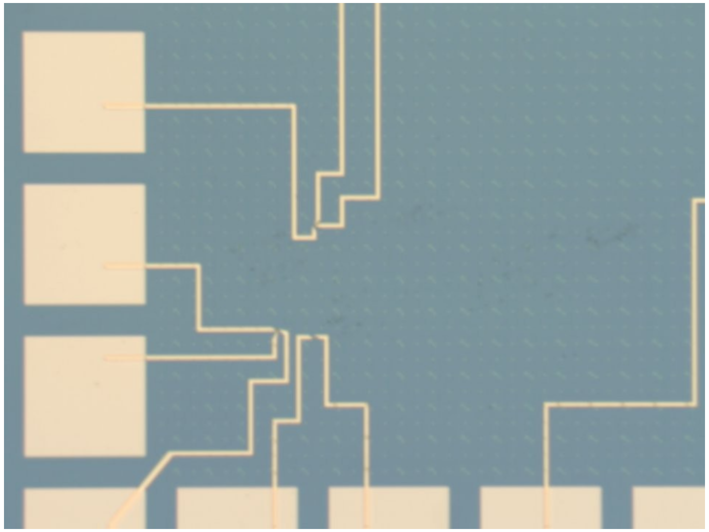


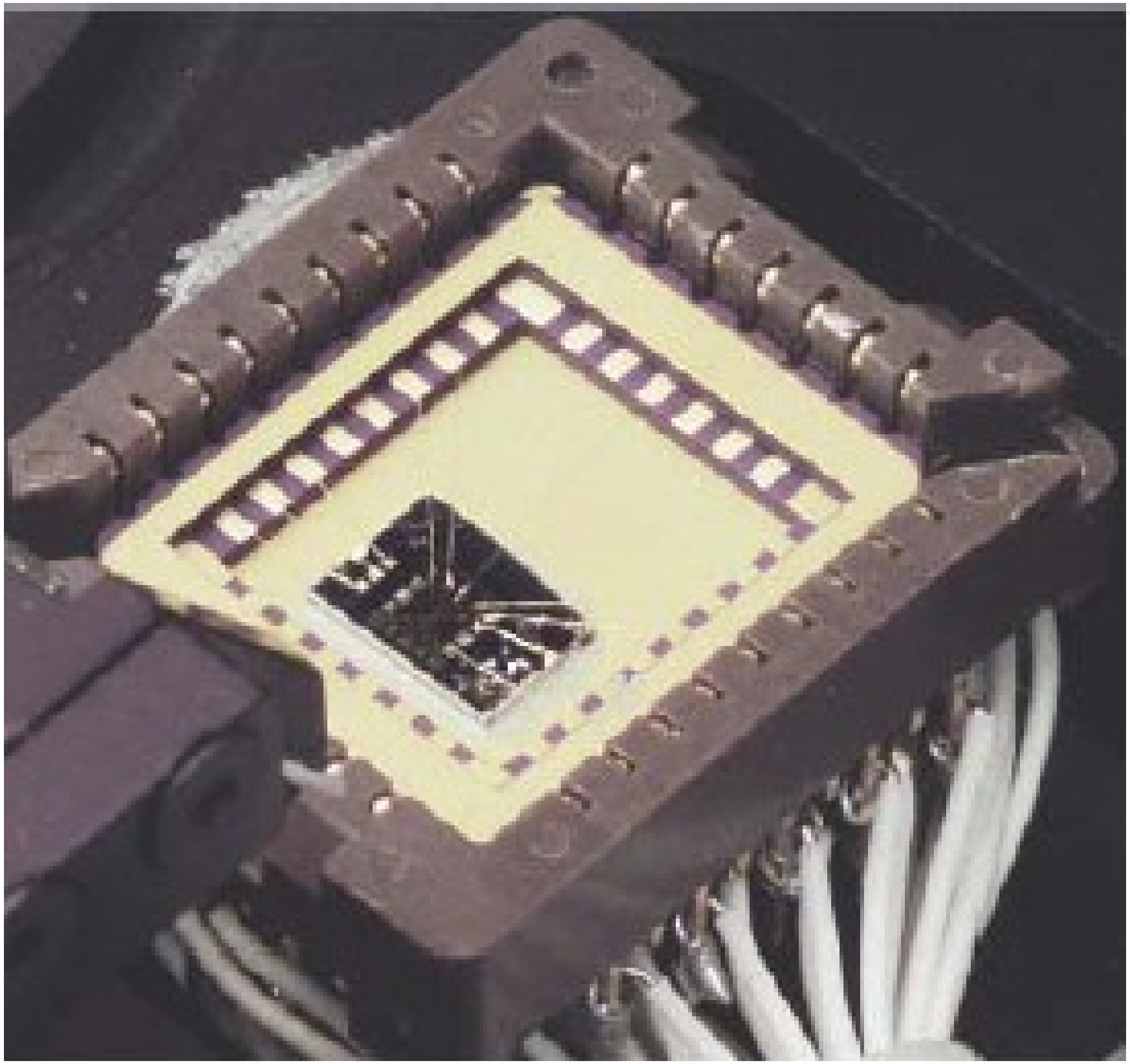
- or nanowires



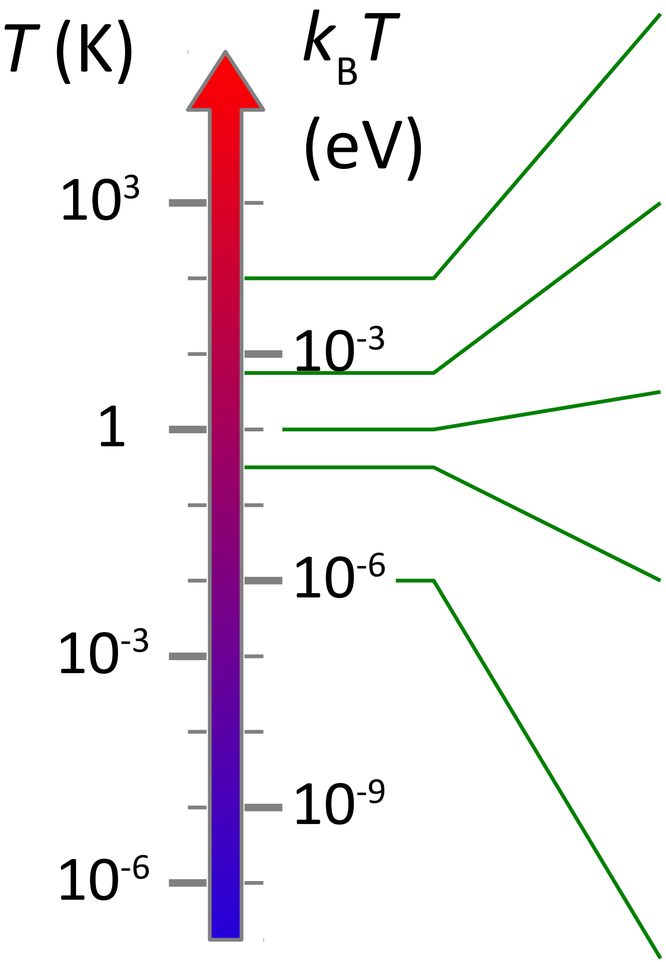
Contacts to the macroscopic world







Low temperature measurement



température ambiante (300 K, 25 meV)

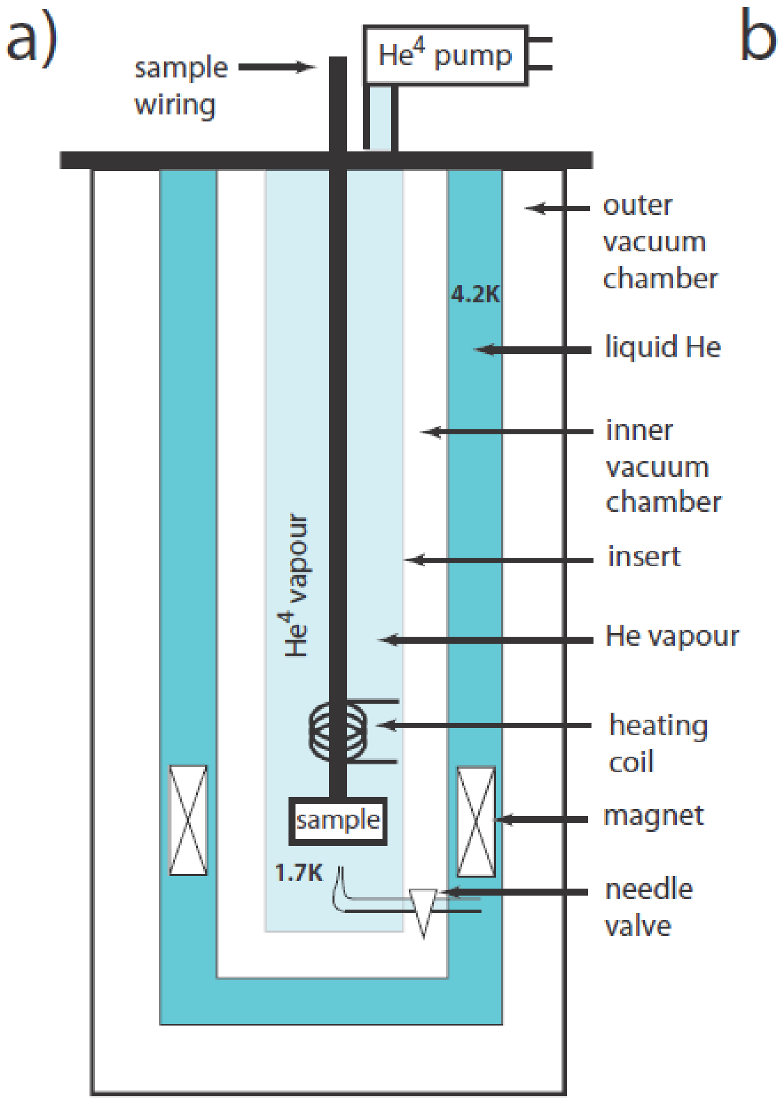
^{4}He liquide (4.2 K, 0.36 meV)

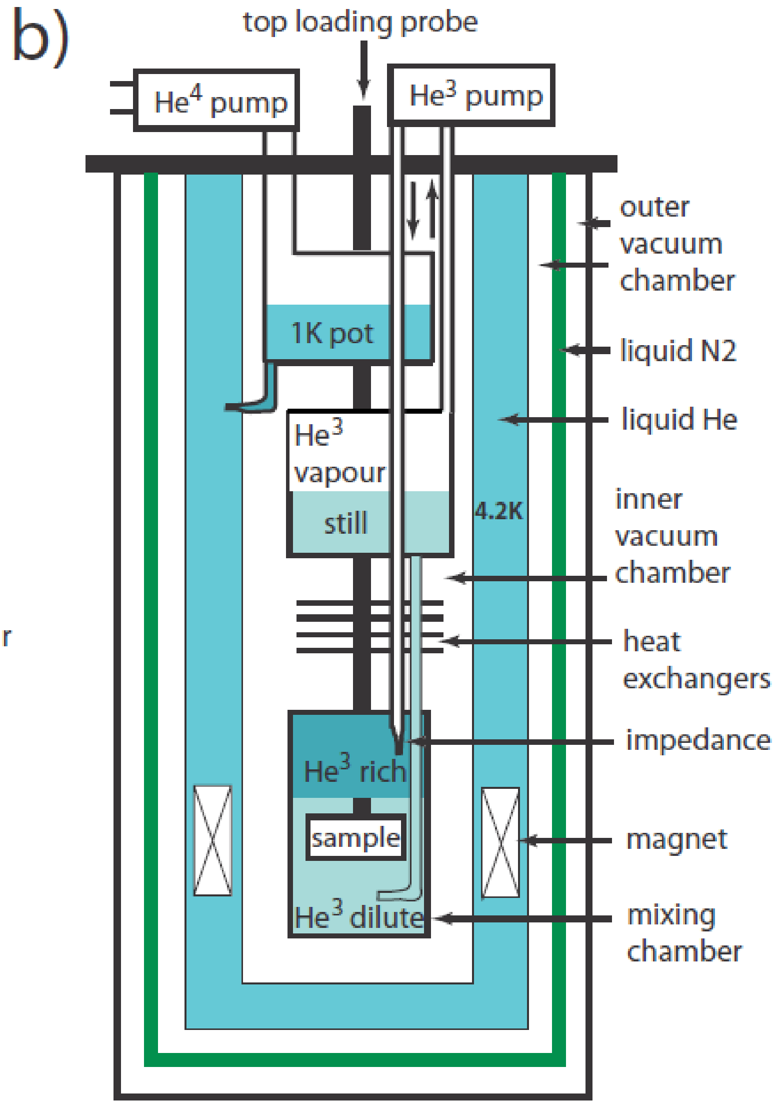
^{4}He pompé (1.2 K, 0.1 meV)

^{3}He liquide (300 mK, 25 µeV)

cryostat à dilution ^{3}He/^{4}He (10 mK, 0.9 µeV)

Low temperature measurement





Summary

- Part 1: Electronic transport in quantum nanostructures
  - Quantum effects can be observed on electronic transport for a sufficiently small size and at low temperature.
  - Electronic properties of small nanostructures (quantum dots) ressemble those of artificial atomes (or molecules)