From electron counting spectroscopy of CdSe quantum dots to carbon nanotube motors

Adrian Bachtold

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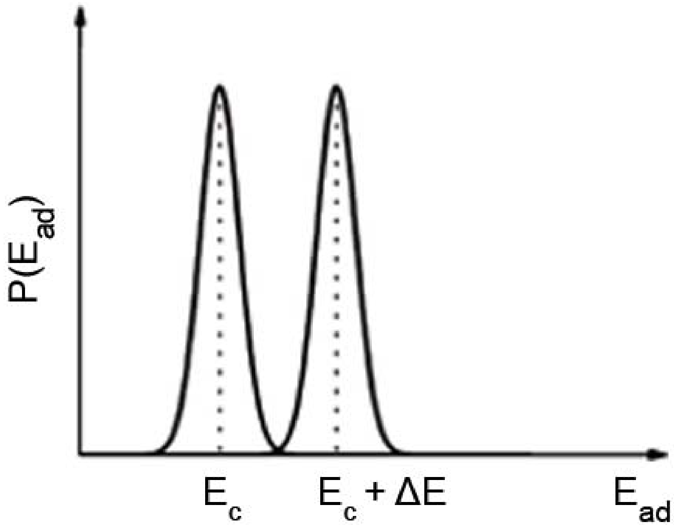
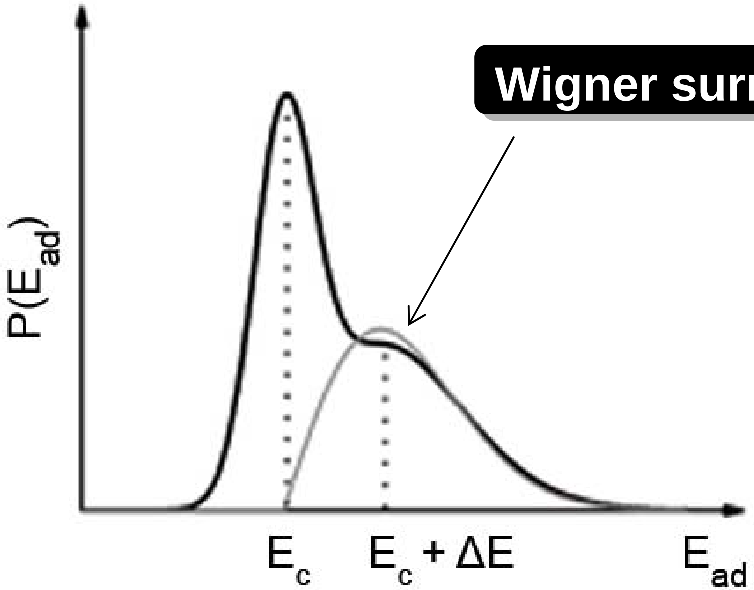
Bimodal Wigner distribution

Constant Interaction model

$$E_{ad}^{i} = \begin{cases} E_C & i = odd \\ E_C + \Delta E & i = even \end{cases}$$

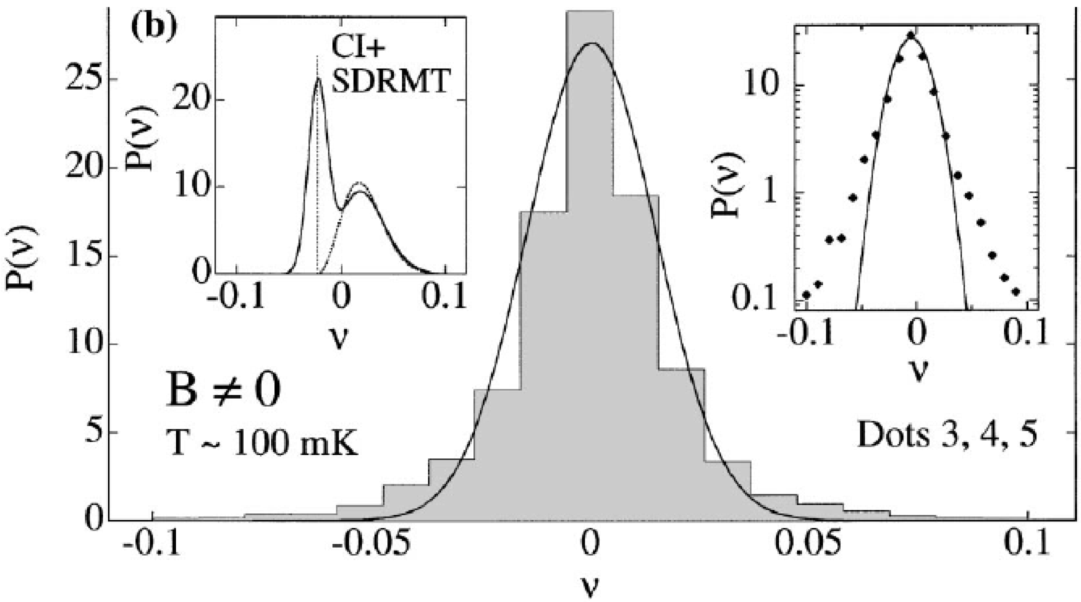


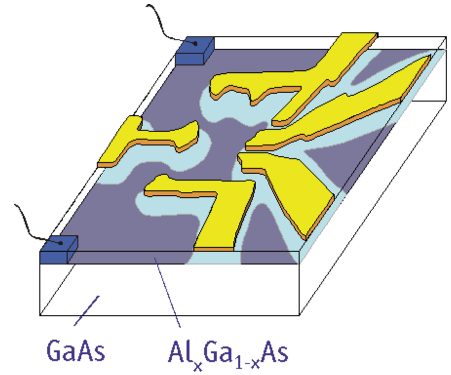
Disordered or chaotic quatum dot

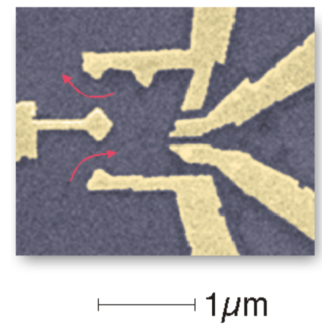


$$P(E_{ad}) = \frac{1}{2}[\delta(s) + \frac{\pi}{2}(s\exp(-\frac{\pi}{4}s^2))] \qquad s = \frac{E_{ad} - E_c}{<\Delta E>}$$

Previous experiments:
Gaussian distribution





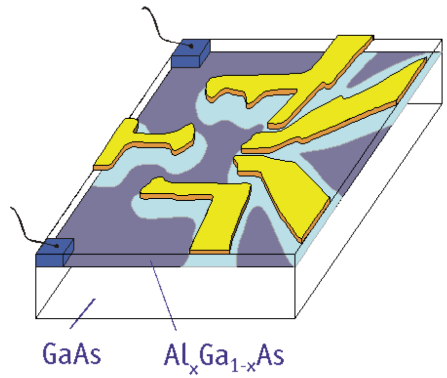


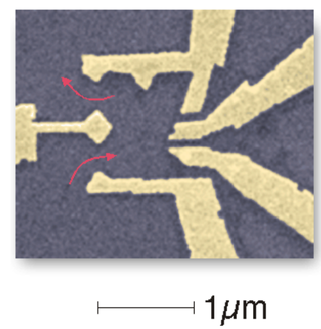
Marcus Lab

Sivan et al., PRL 1996
Patel et al., PRL 1998
Huibers et al., PRL 1998
Simmel et al.,. PRB 1999
Luscher et al., PRL 2001
Boehm et al., PRB 2005
Jdira et al., PRB 2006
Geim et al., Science 2008, and many more

Why Gaussian distribution ?

1- Shape deformation





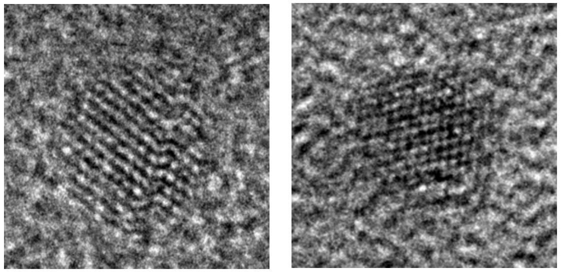
2- Coulomb interaction

Sivan et al., PRL 1996
Blanter et al., PRL 1997
Vallejos et al., PRL 1998
Berkovits, PRL 1998
and many more

CdSe colloidal quantum dots

1- Shape not deformed

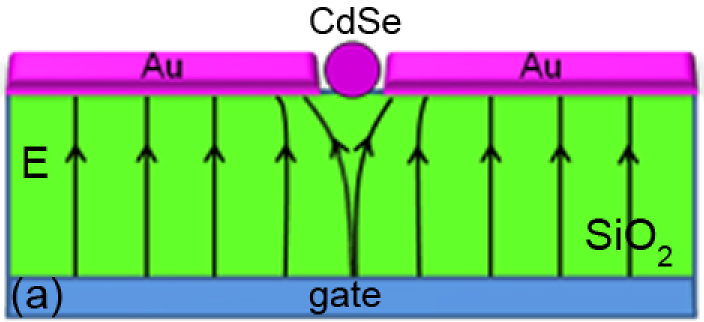
2- Coulomb interaction weak

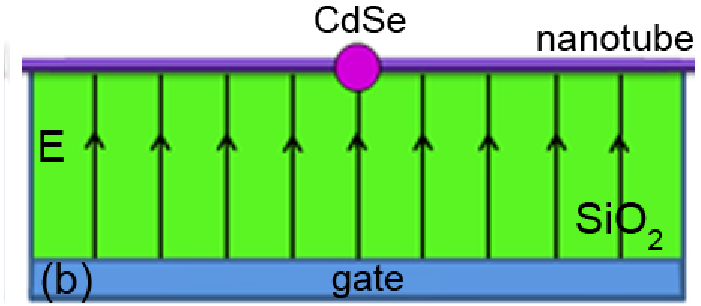


diameter 5 nm

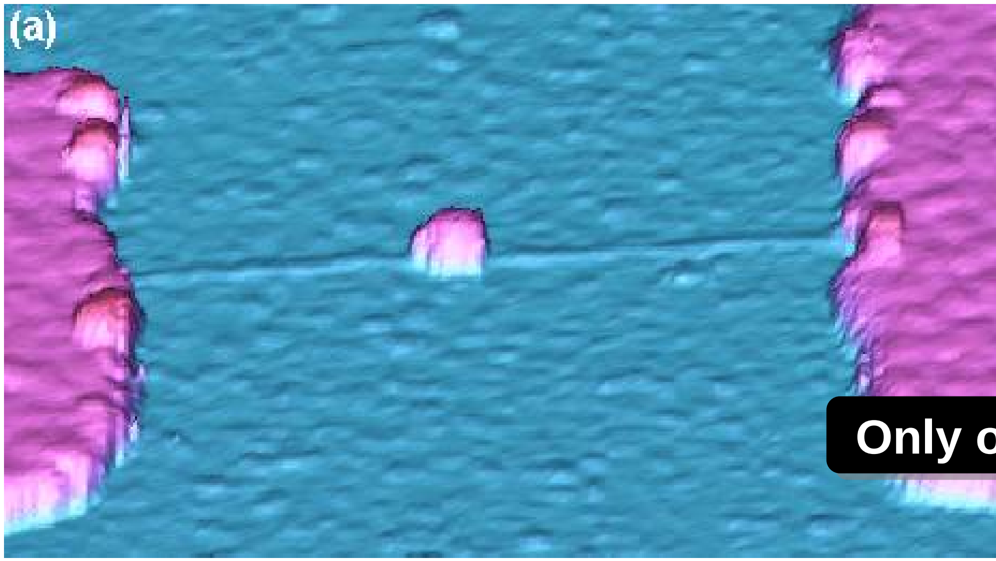
$$r_s = \frac{d}{2a_0 N^{1/3}}$$

$r_s < 0.27$ when N>10

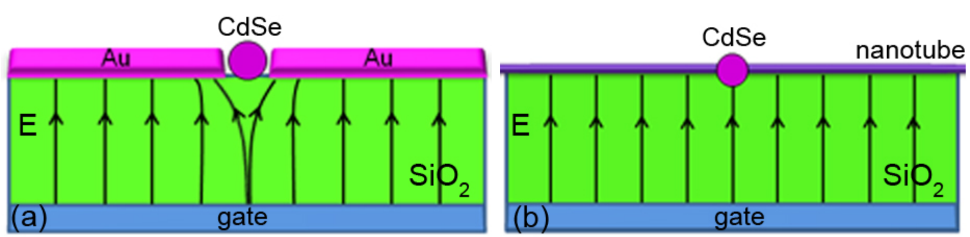




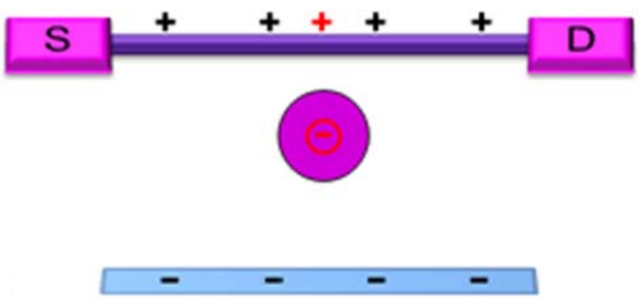
The device



Only one electrode - a carbon nanotube



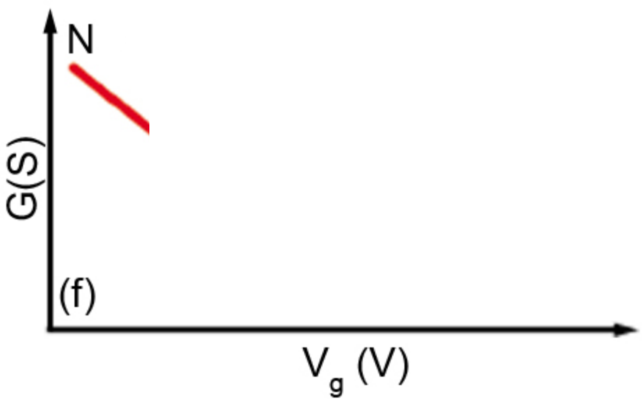
Electron Counting Spectroscopy



The nanotube has two roles:

- **electron reservoir**
- **it detects the transfer of single electrons onto the CdSe particle**

One electron transfer corresponds to one shift of the tube conductance

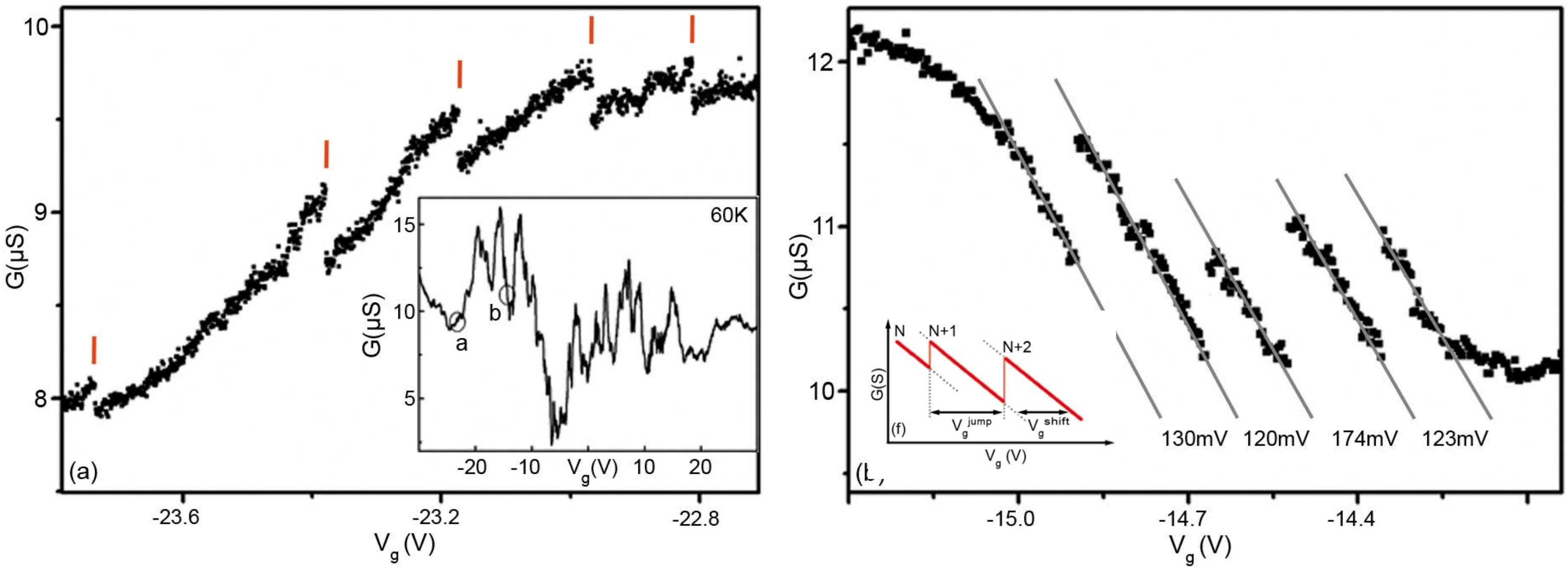


$$\Rightarrow \quad V_g^{shift} \sim E_{ad}$$

Energy to add one electron to the system

Gruneis, Esplandiu,Garcia-Sanchez, Bachtold, Nano Letters 2007

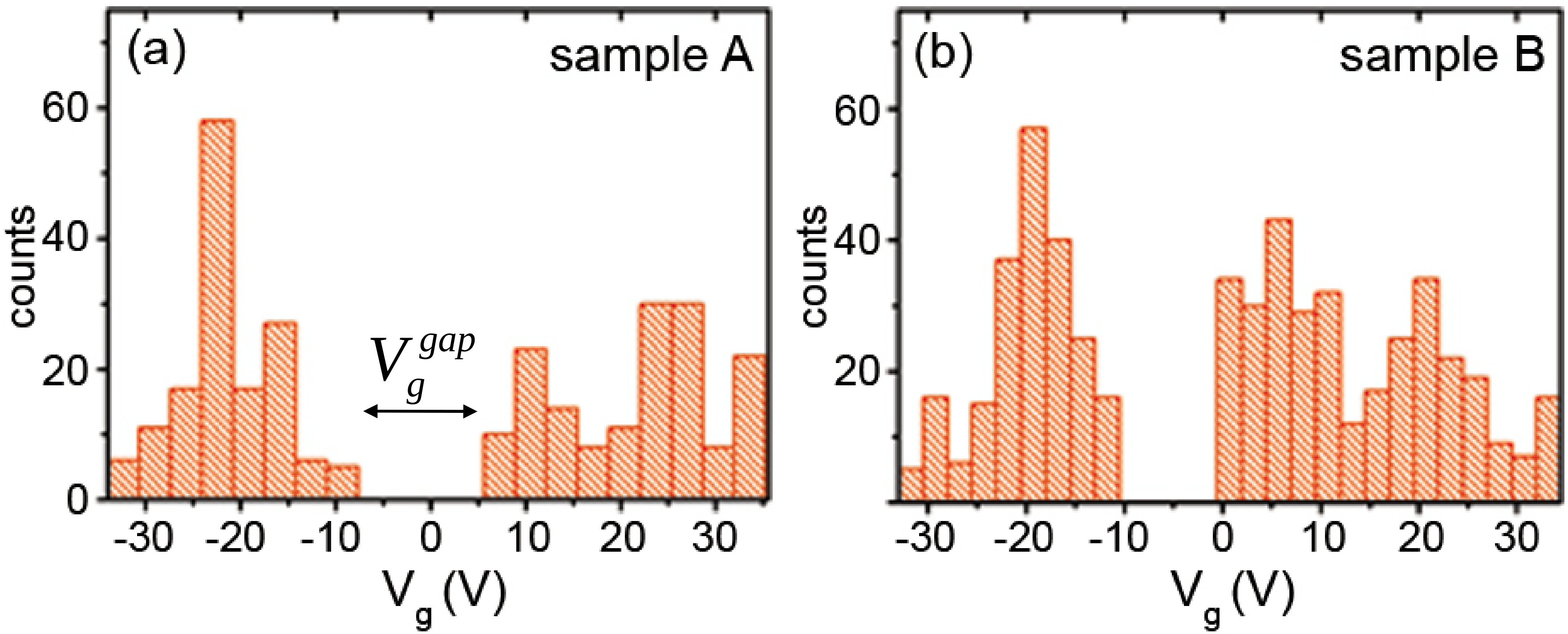
The experiment – electron transfers



We can put ~ 400 electrons (!) onto the 5nm CdSe dot

Zdrojek, Esplandiu, Barreiro, Bachtold, in preparation

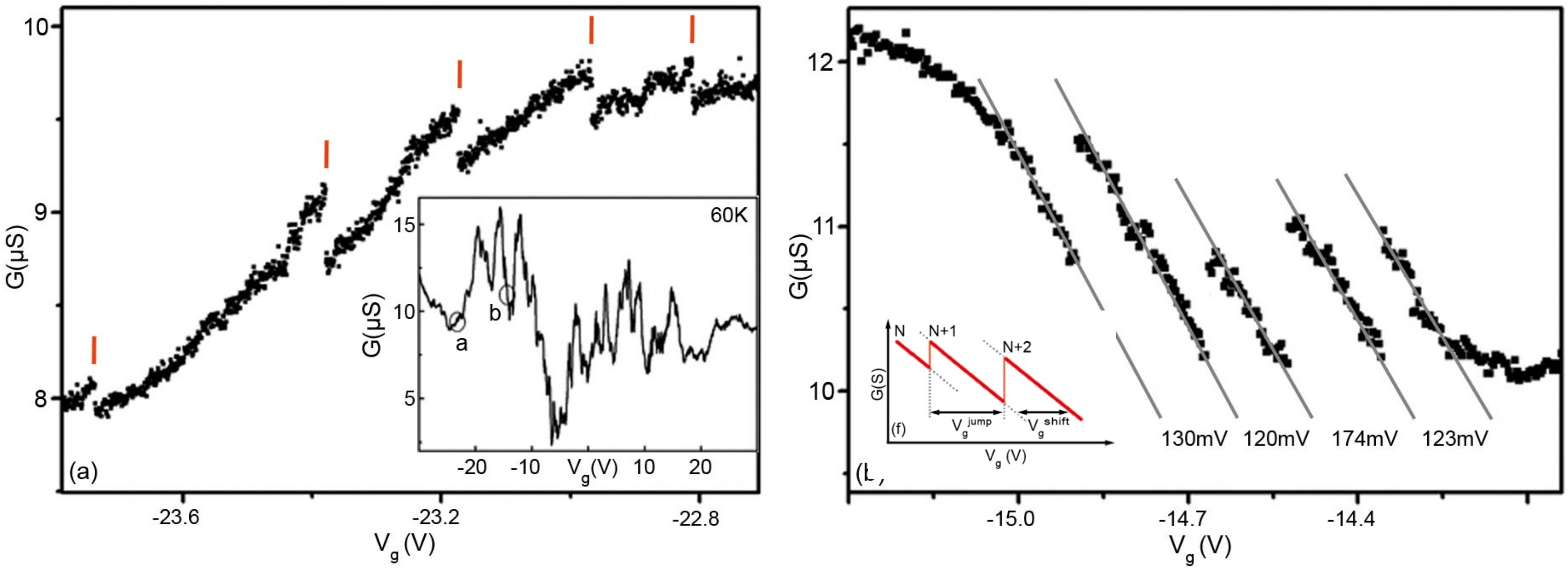
Electron counts vs. the gate voltage



The gate voltage gap ⇒ energy gap of the semiconducting CdSe dot

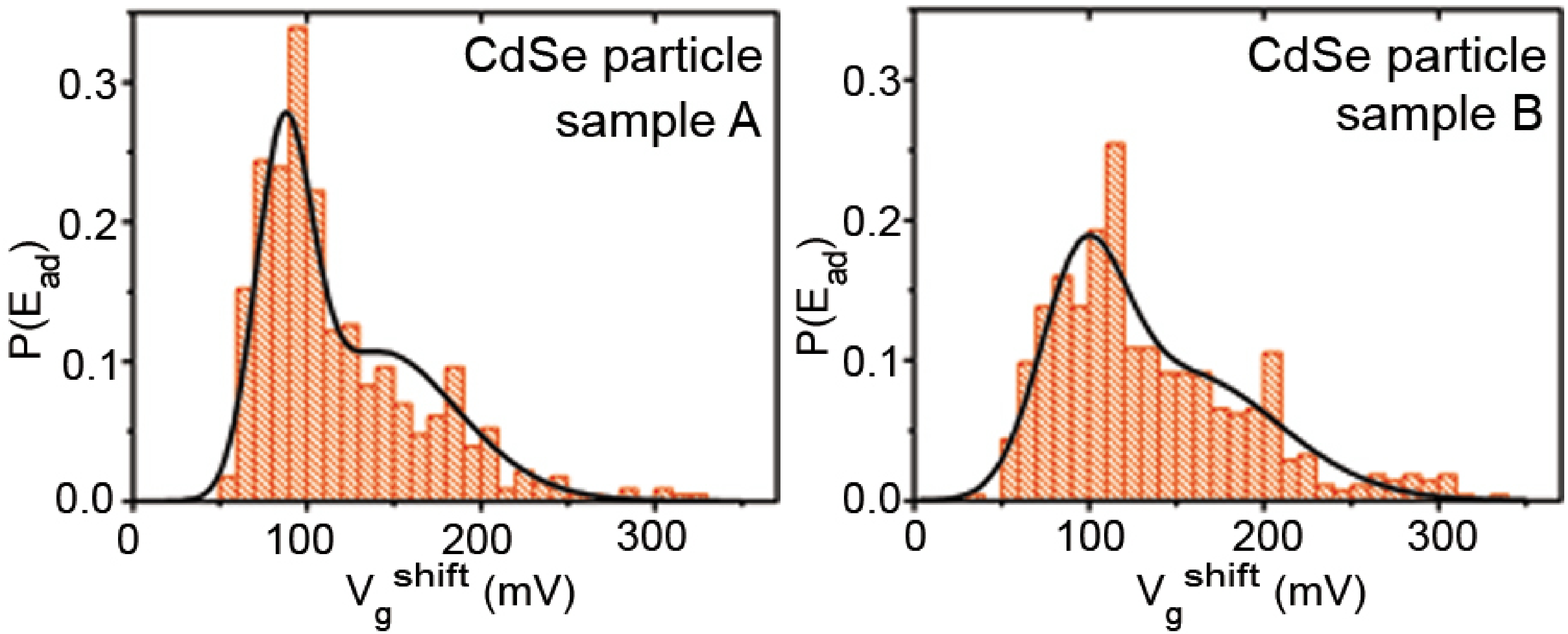
Zdrojek, Esplandiu, Barreiro, Bachtold, in preparation

The experiment – electron transfers



Shifts not equal ⇒ fluctuation of the addition energy

Distribution of the energy levels in the dot



Bimodal Wigner distribution of addition energy

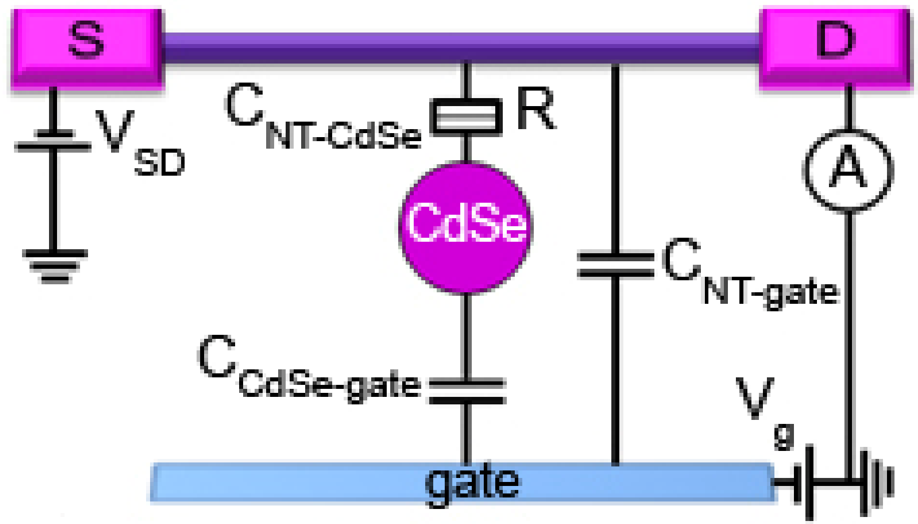
$$P(E_{ad}) = \frac{1}{2}[\delta(s) + \frac{\pi}{2}(s\exp(-\frac{\pi}{4}s^2))] \qquad s = \frac{E_{ad} - E_c}{<\Delta E>}$$

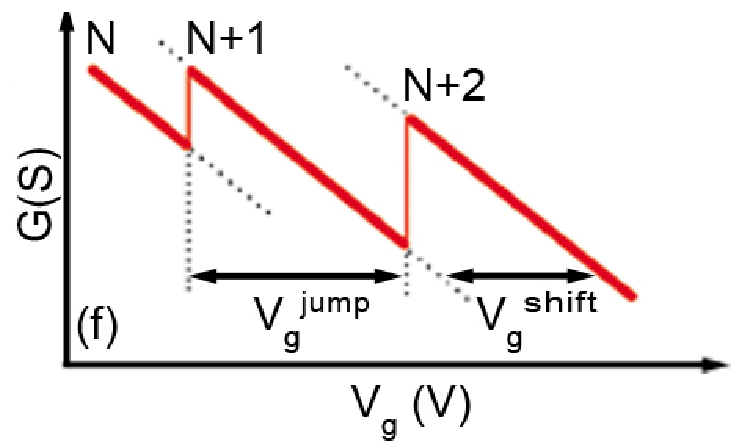
Energy levels of the dot vs. the gate voltage

$$eV_g^{shift} = \frac{C_{CdSe-NT}}{C_{NT-gate} + C_{CdSe-gate}} E_{ad}$$

$$e\Delta V_g^{jump} = \frac{C_{CdSe-NT}}{C_{CdSe-gate}} E_{ad}$$

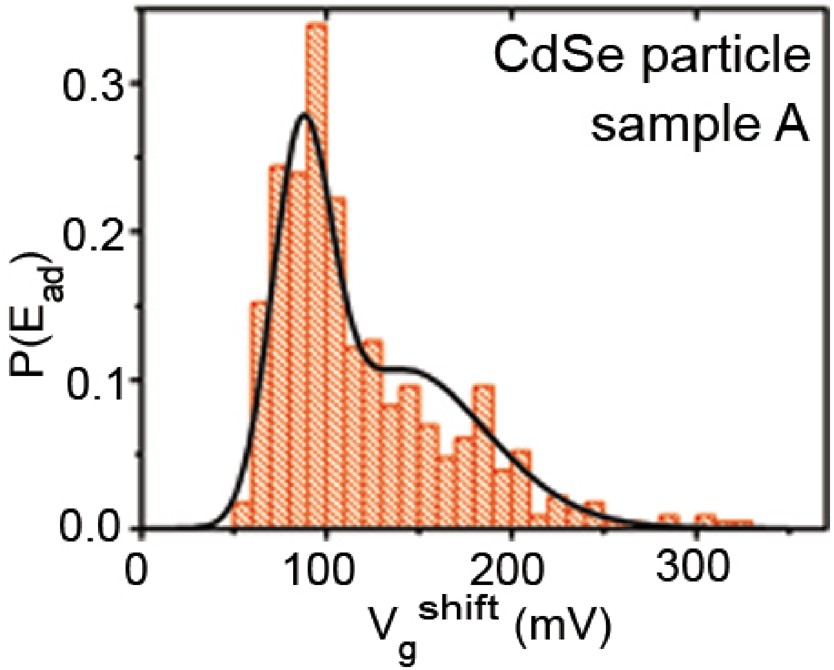
$$\Delta V_g^{gap} = \frac{C_{CdSe-NT}}{C_{CdSe-gate}} E_g$$

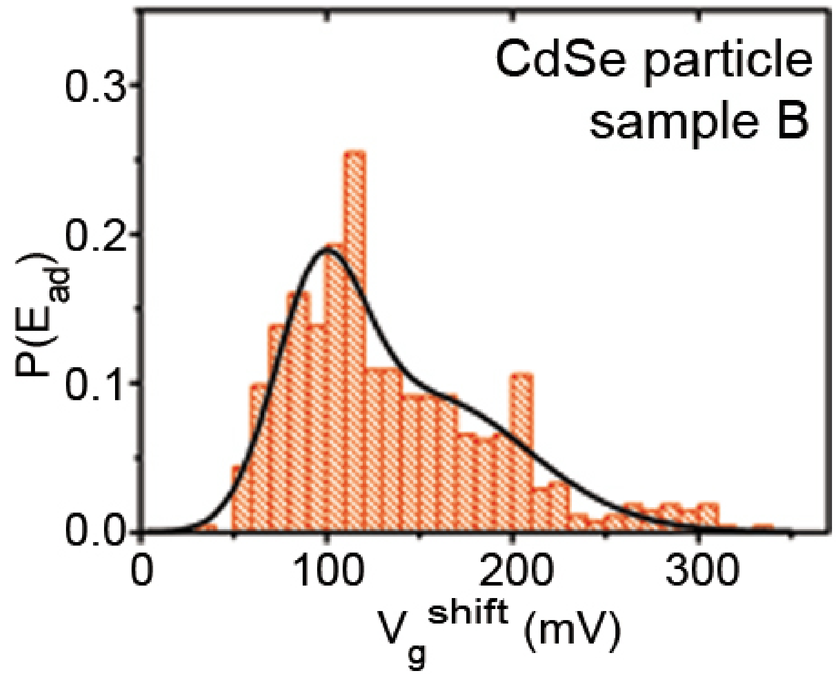




K. Yano, el al. *Proc. IEEE* **87** 633 (1999)
T. Dürkop, et al., Journal of Physics C 16, 553 (2004)
Gruneis, Esplandiu,Garcia-Sanchez, Bachtold, Nano Letters 2007

Distribution of the energy levels in the dot



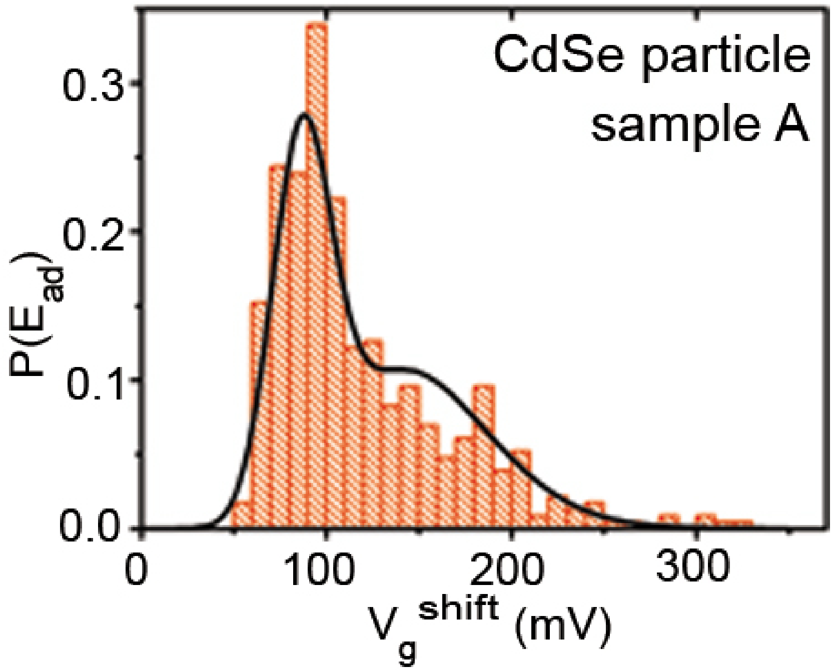


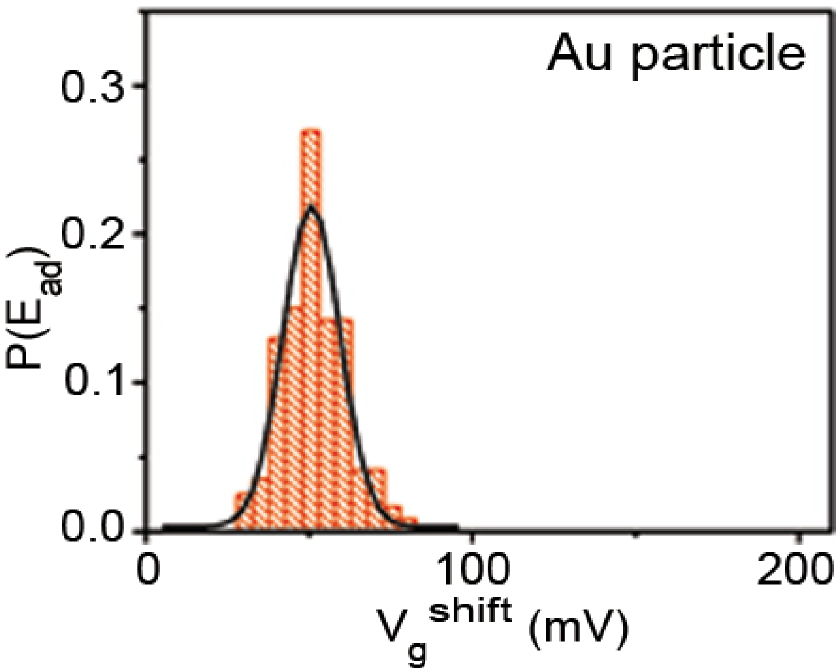
$$E_c \approx 23{,}2\ mV$$
$$<\Delta E> \approx 18{,}3\ mV$$

$$E_c \approx 19{,}2\ mV$$
$$<\Delta E> \approx 15\ mV$$

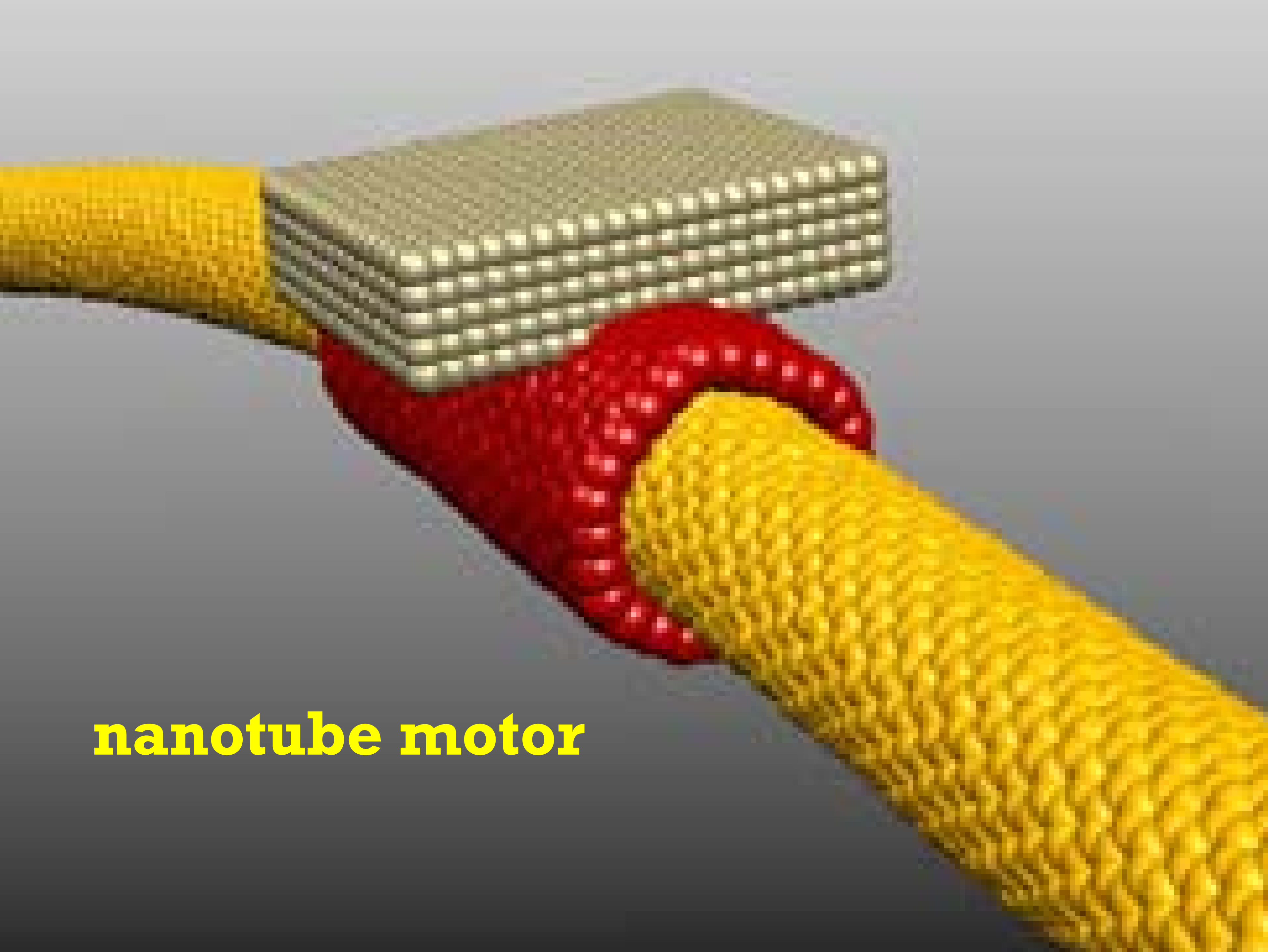
Klein, Roth, Lim, Alivisatos, McEuen, *Nature* **389**, 699 (1997).

Distribution of the energy levels in the dot

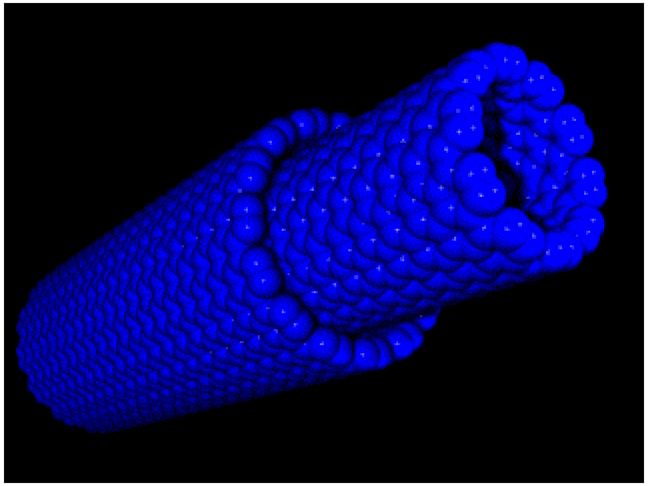


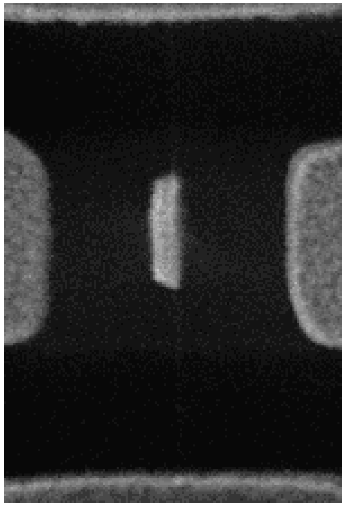


Au particle - only charging energy!


nanotube motor

molecular bearings

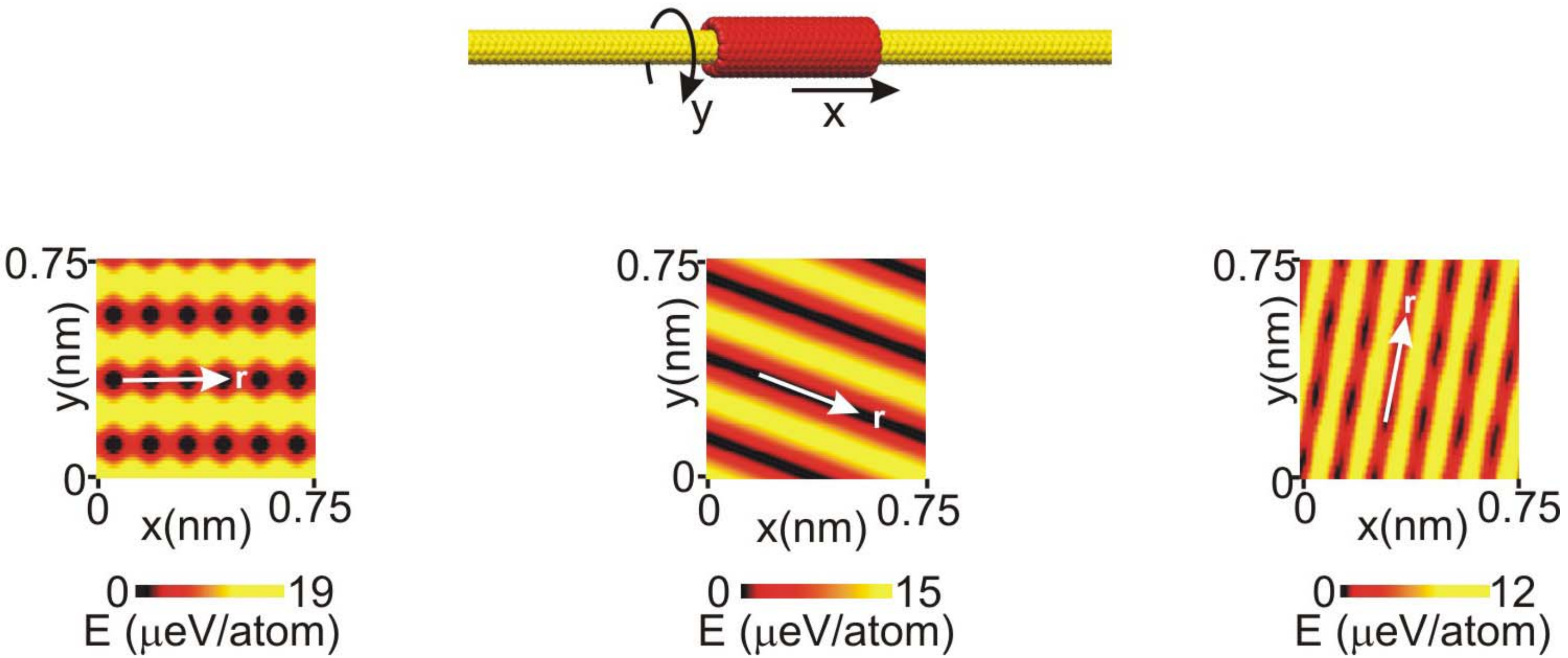




Zettl

Cumings, Zettl, Science 2000
Yu, Yakobson, Ruoff, J. Phys. Chem B 2000
Fennimore et al., Nature 2003
Bourlon et al., Nano Letters 2004
Kis et al., PRL 2006

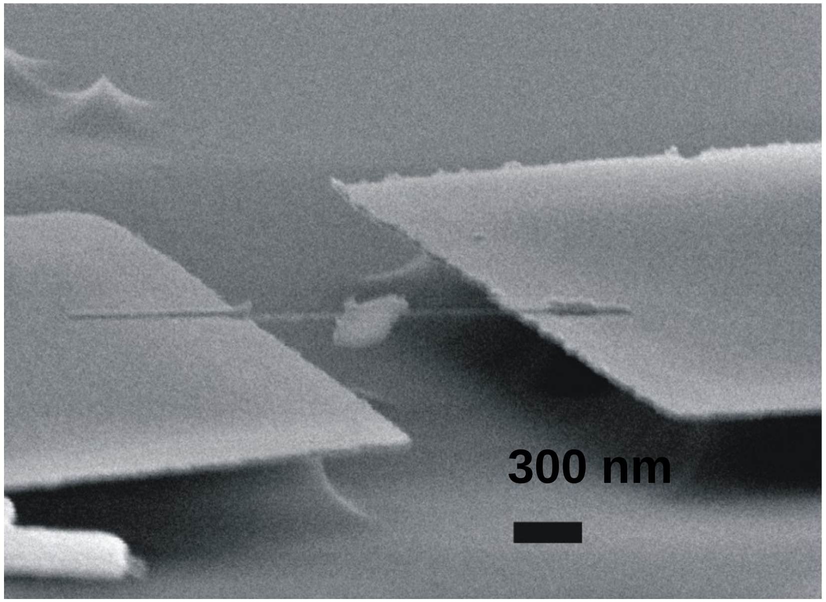
motion controlled by atomic arrangement

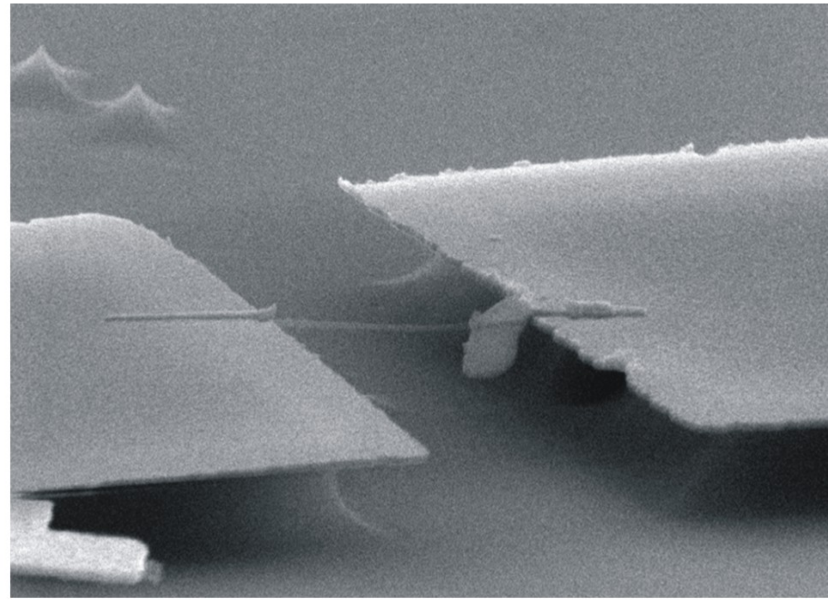


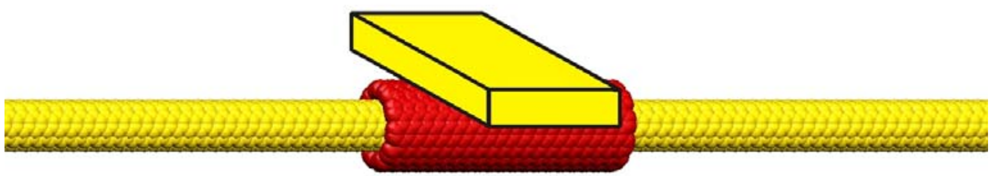
(5,5)-(10,10) **(29,9)-(38,8)** **(27,12)-(32,17)**

Saito, Matsuo, Kimura, Dresselhaus, Dresselhaus
Chemical Physics Letters 2001

device

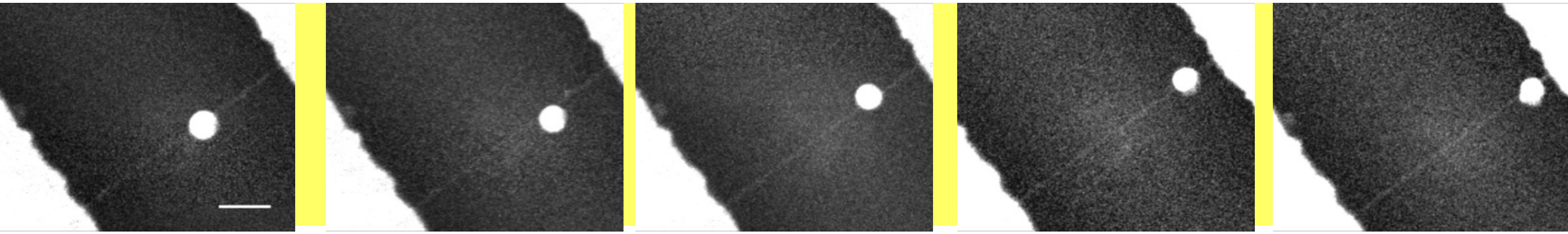


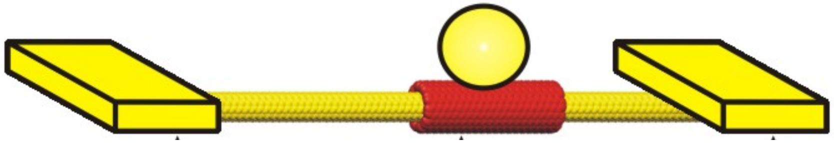




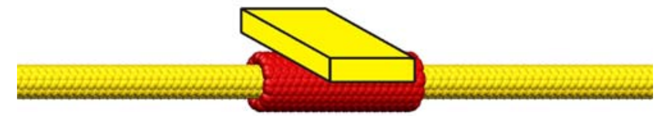
Barreiro, Rurali, Hernández, Moser, Pichler, Forro, Bachtold
Science (2008)

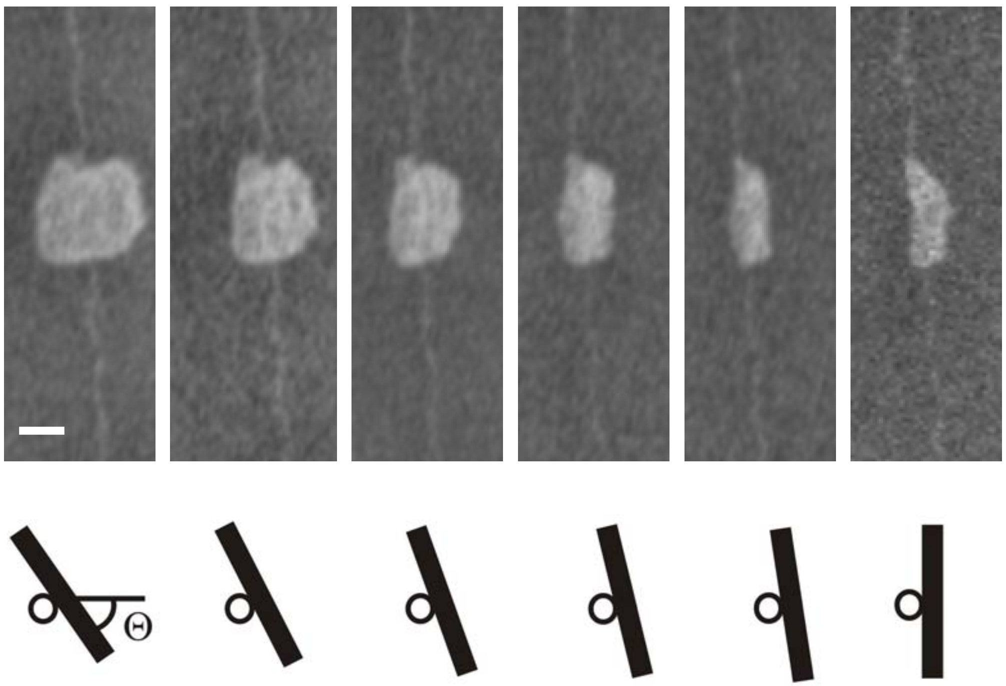
translation

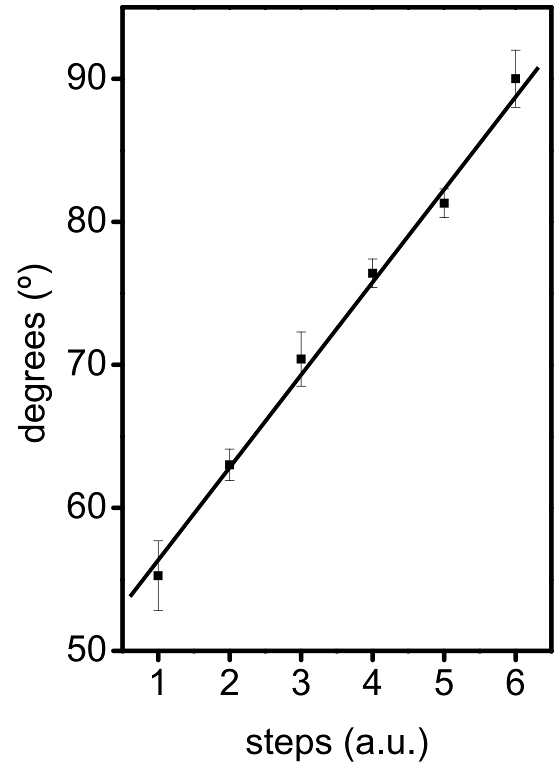




Stepwise rotation

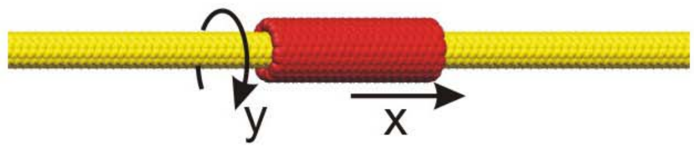


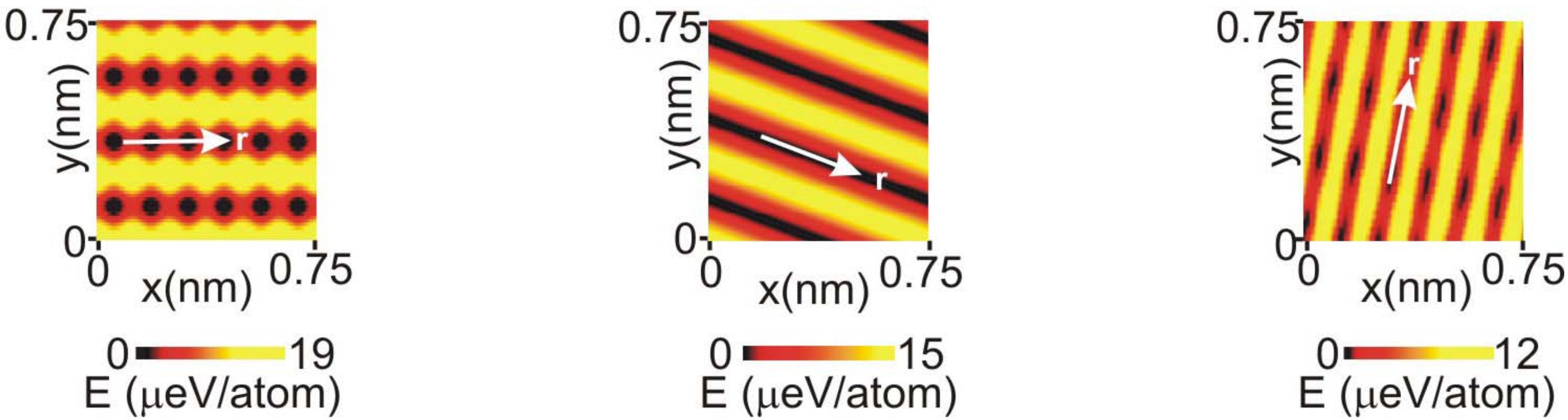




7° corresponds to about 0.4 nm displacement

motion controlled by atomic arrangement





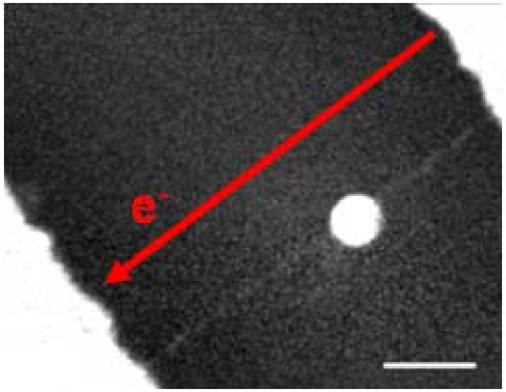
(5,5)-(10,10) **(29,9)-(38,8)** **(27,12)-(32,17)**

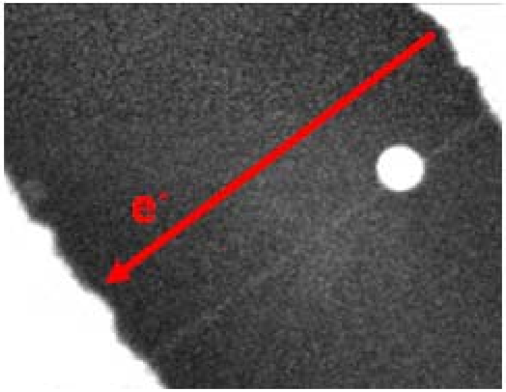
Saito, Matsuo, Kimura, Dresselhaus, Dresselhaus
Chemical Physics Letters 2001

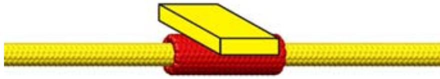
$$\Gamma = \frac{\omega}{2\pi} e^{-\frac{\Delta E}{k_B \cdot T}}$$

$\Delta E \sim 10\ \mu eV/atom$

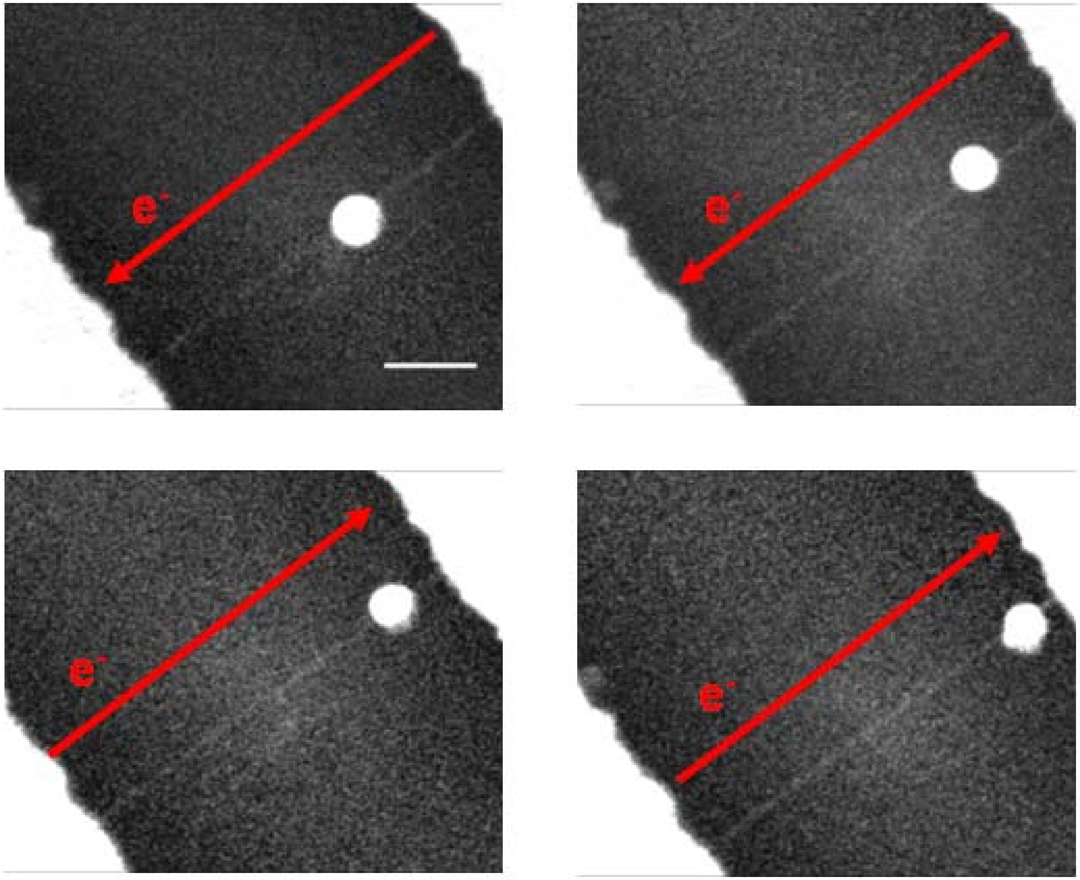
actuation

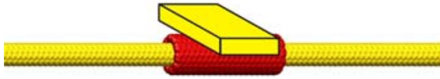




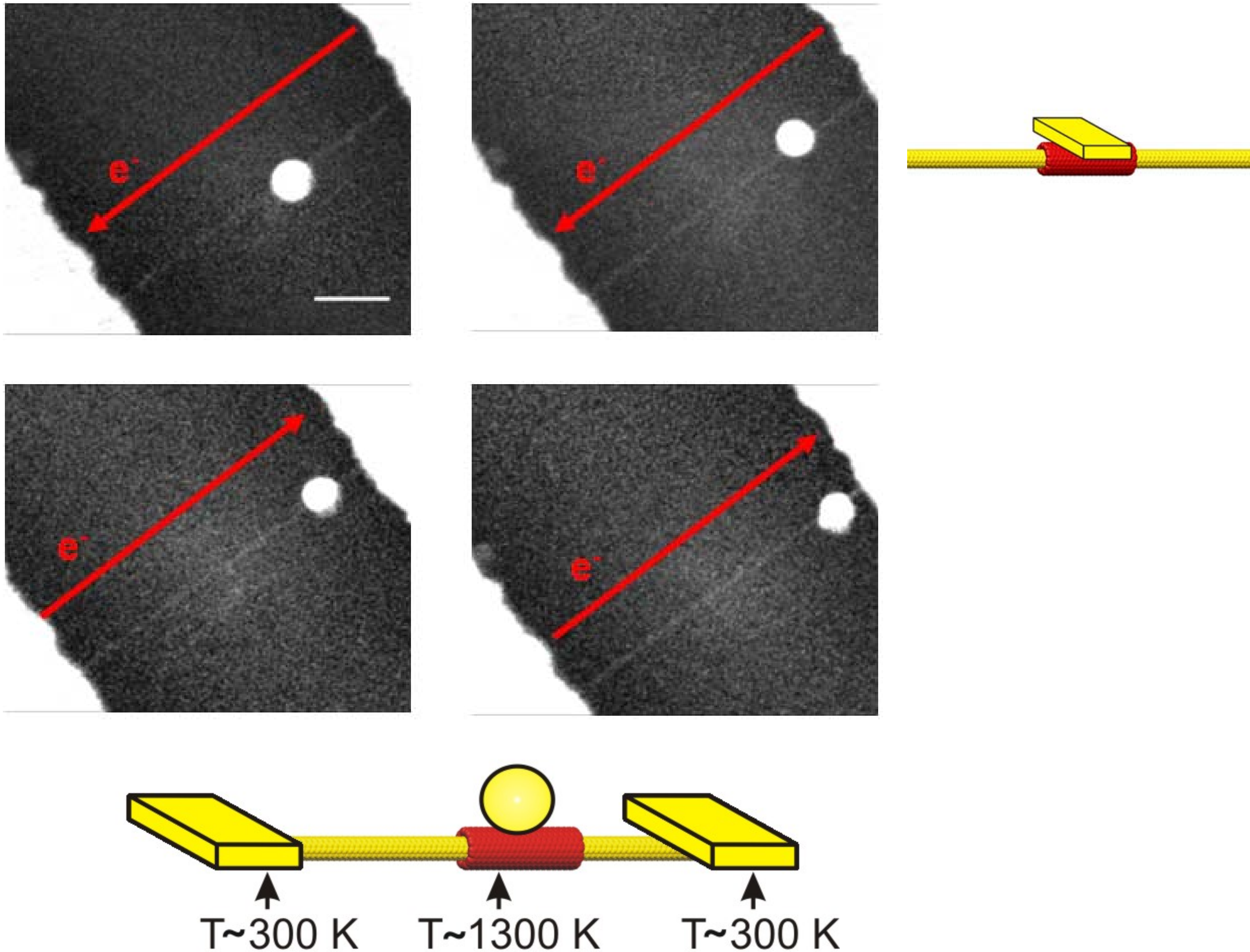


actuation

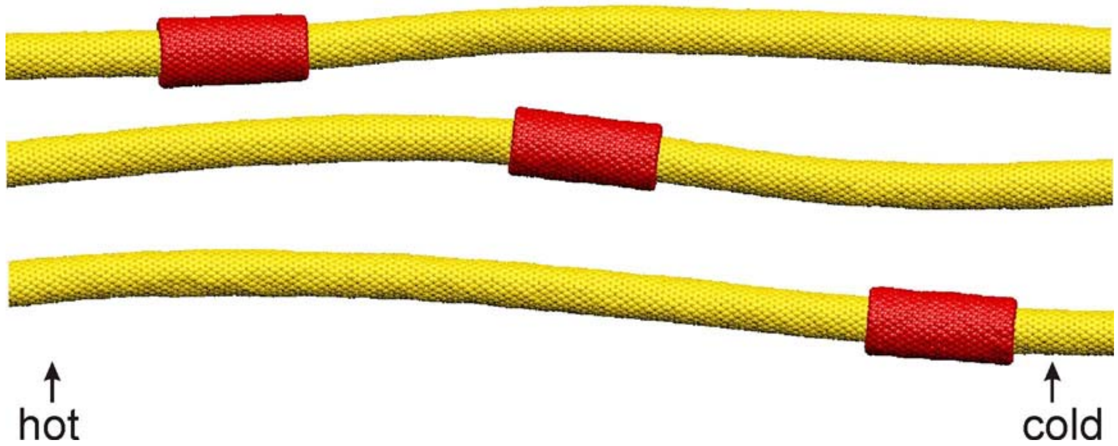




actuation

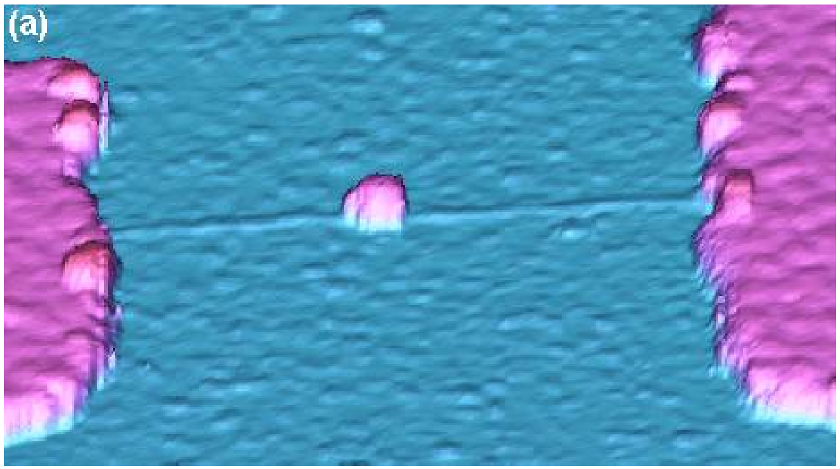


Molecular dynamics calculations



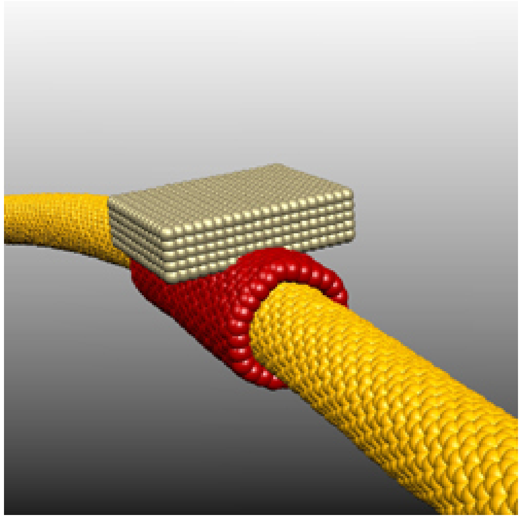
Rurali (UAB), Hernandez (ICMAB)

conclusion



electron counting spectroscopy

Nano Lett. 7, 3766 (2007)
in preparation



nanotube motor

Science 320, 775 (2008)

people & grants

Quantum NanoElectronics group

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Mariusz Zdrojek
Amelia Barreiro
Daniel Garcia
Marianna Sledzinska
Andreas Gruneis

grants

EURYI award
EU STREP CARDEQ
Intramurales Nanotubo resonador

Barcelona

Alvaro San Paulo
Francesc Perez
Albert Aguasca
Albert Verdaguer
David Jimenez
Ricardo Rurali
Eduardo Hernandez

Cornell

Arend van der Zande
Paul McEuen

Lausanne

Laszlo Forro

Dresden

Thomas Pichler