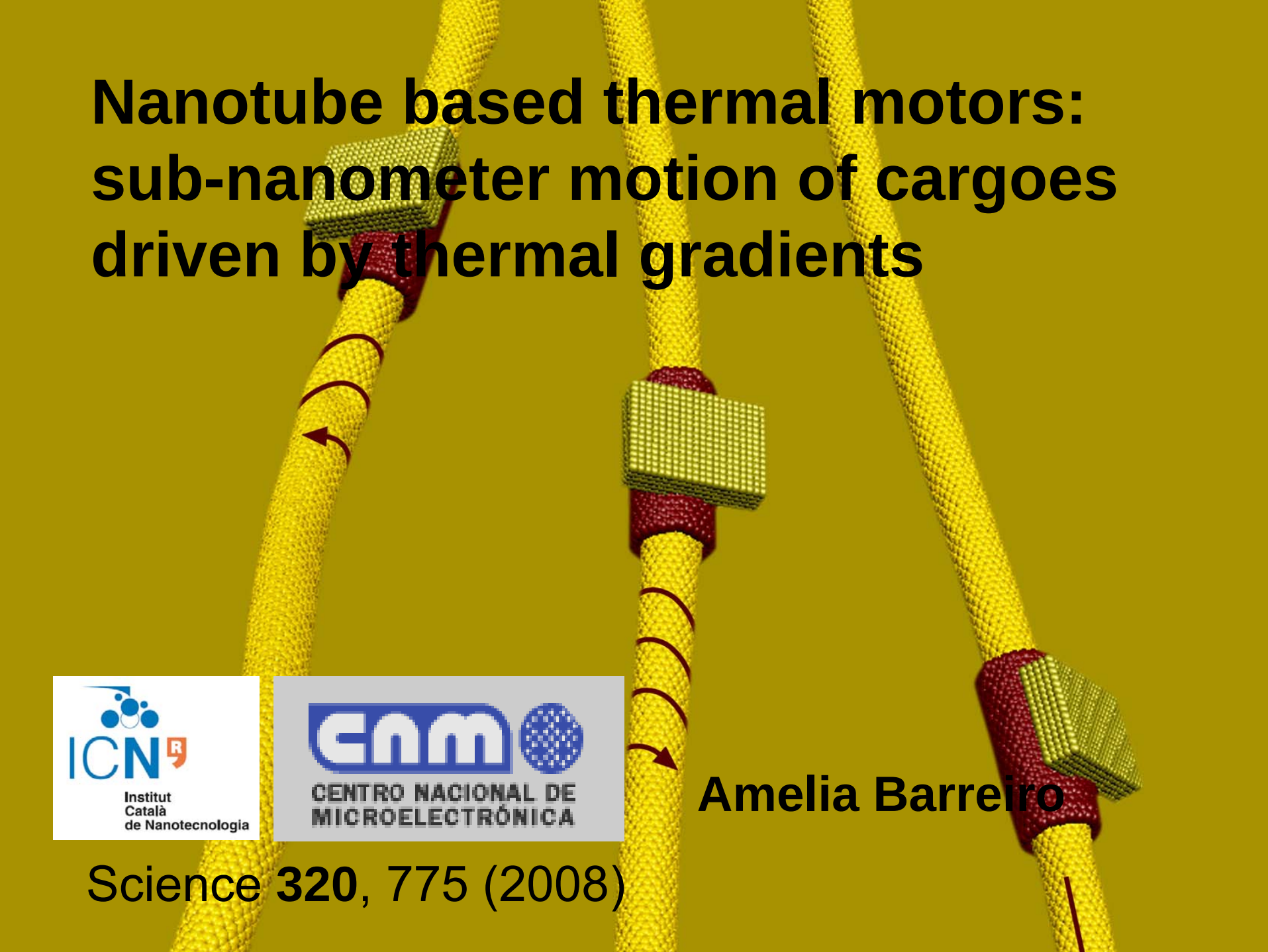
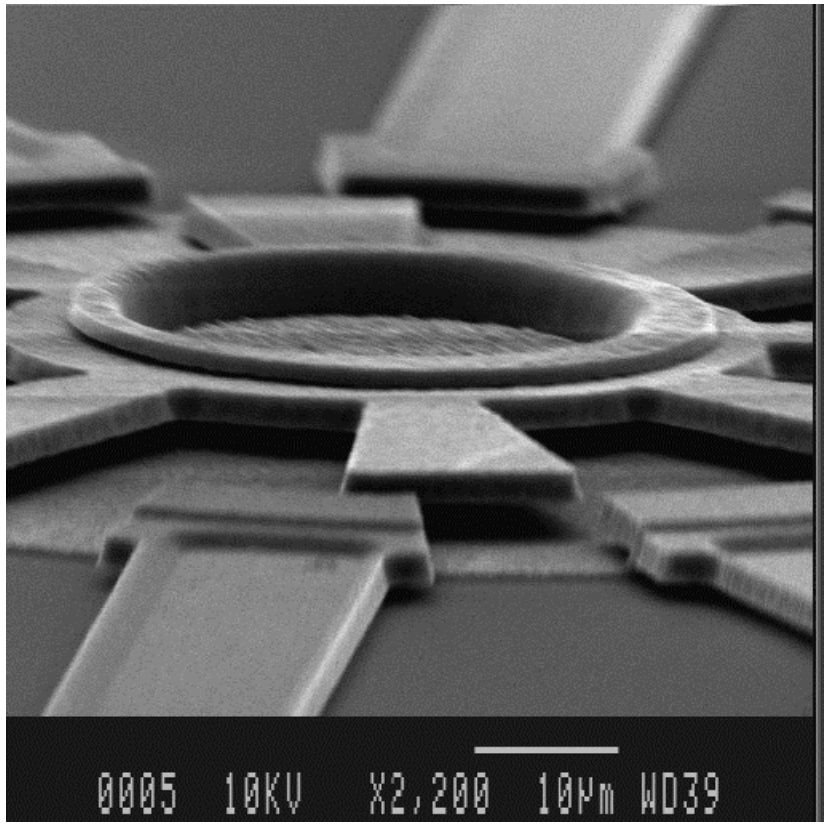
Nanotube based thermal motors: sub-nanometer motion of cargoes driven by thermal gradients



Amelia Barreiro

Science **320**, 775 (2008)

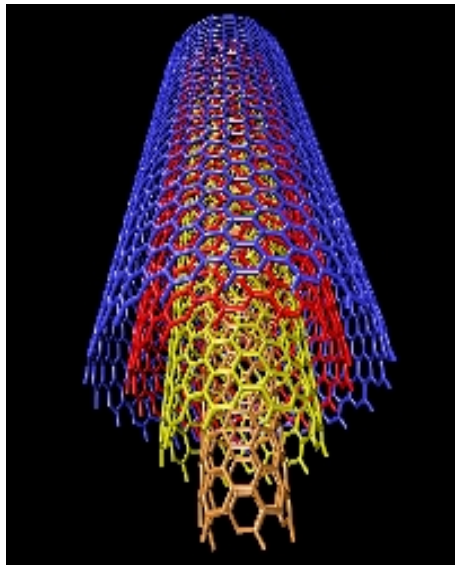
Visionary concepts in nanoscience

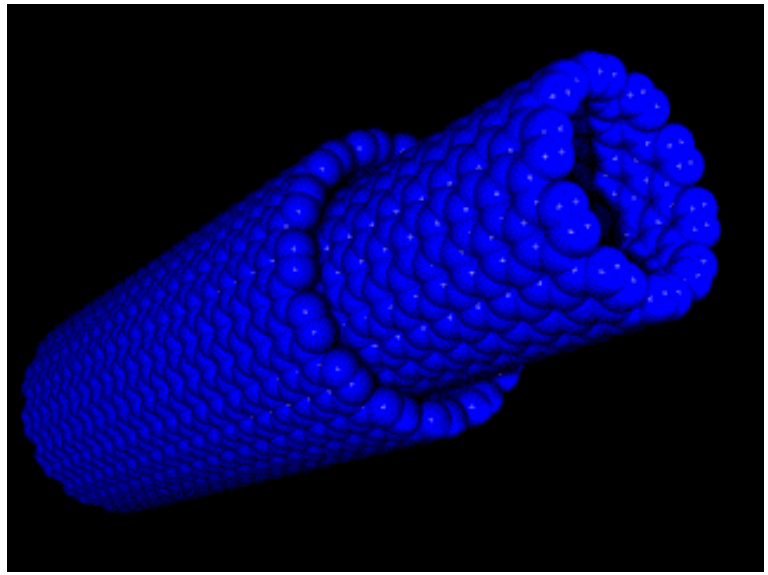


microfabricated motors

LAAS, Toulouse

Molecular bearings

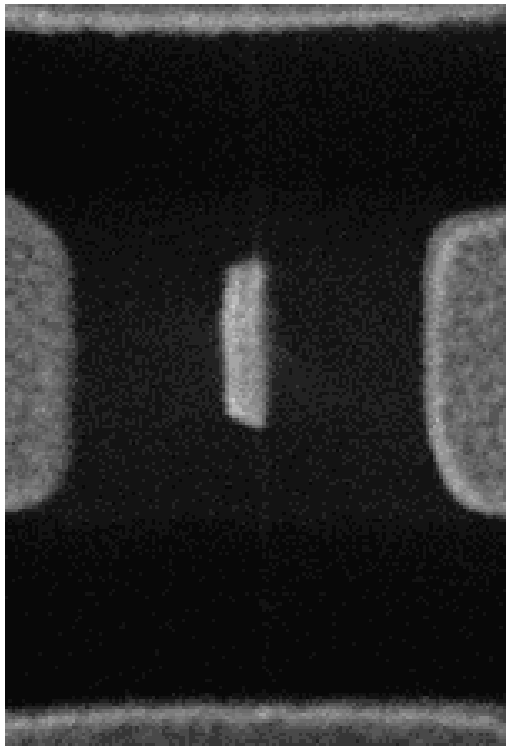


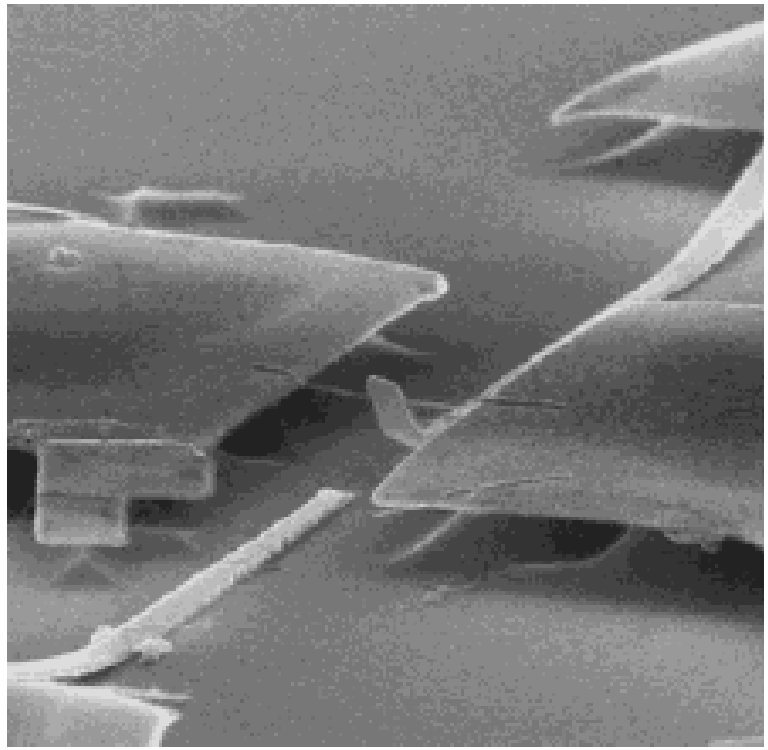


MWNTs → **Low friction**

Cumings, Zettl, Science 2000
Yu, Yakobson, Ruoff, J. Phys. Chem B 2000
Kis et al., PRL 2006

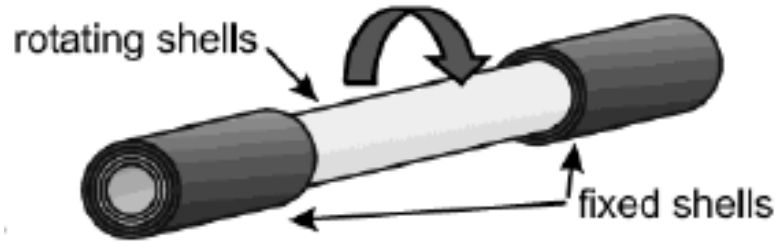
Molecular bearings



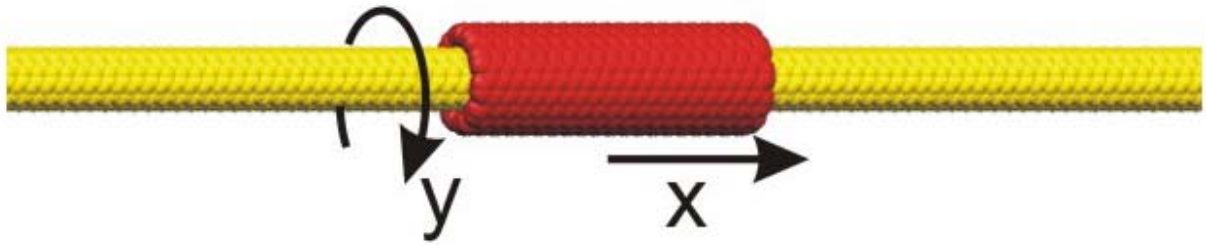


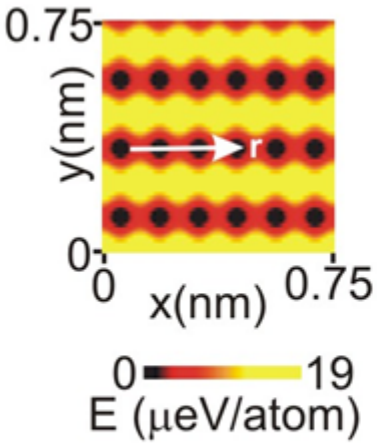
MWNTs ⇒ **Low friction**

Fennimore et al., Nature 2003
Bourlon et al., Nano Letters 2004

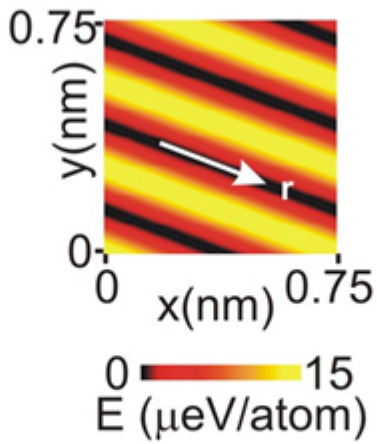


Motion controlled by atomic arrangement

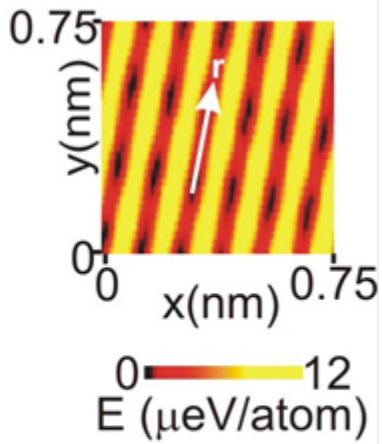




(5,5) - (10,10)



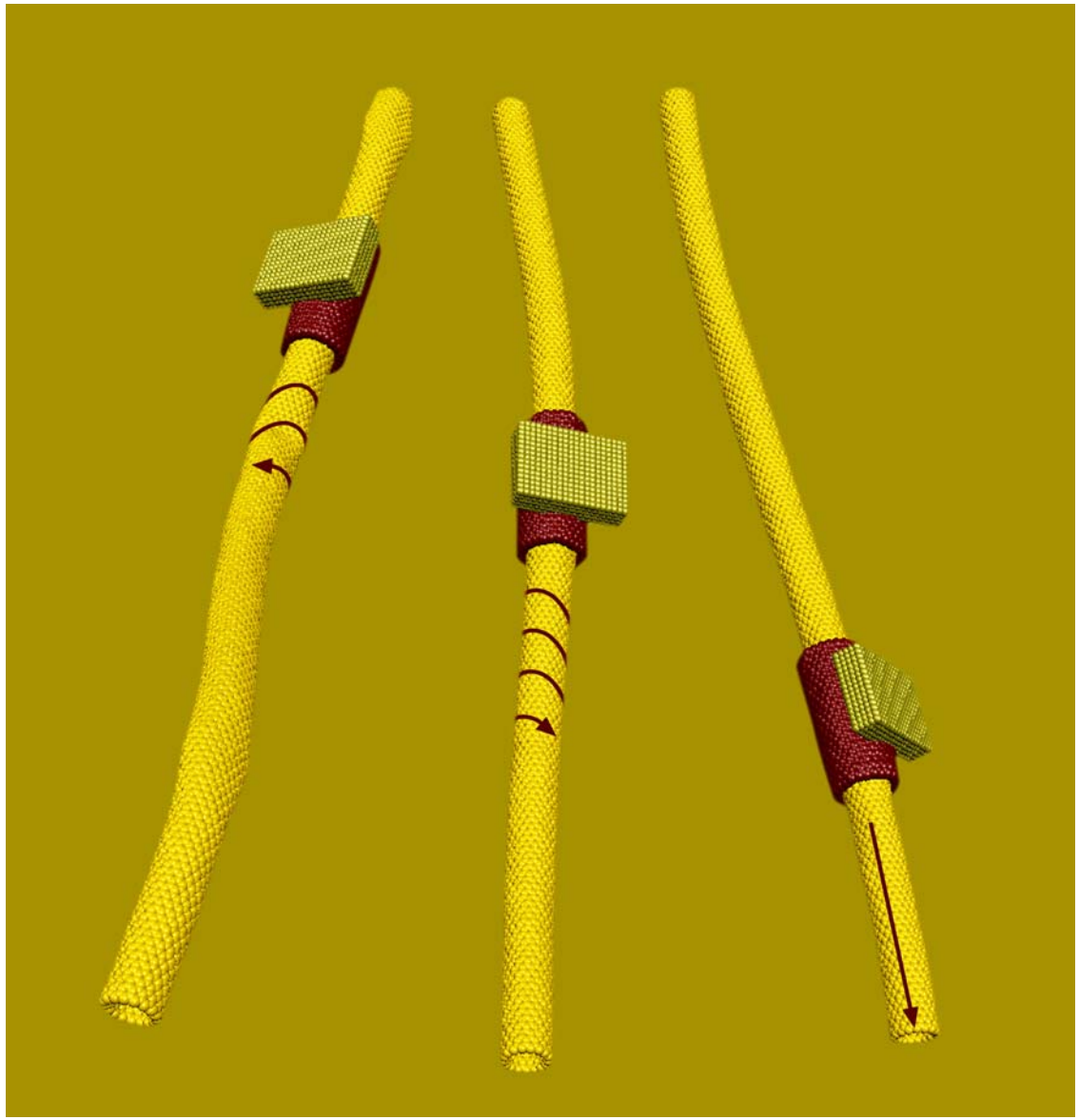
(29,9) - (38,8)



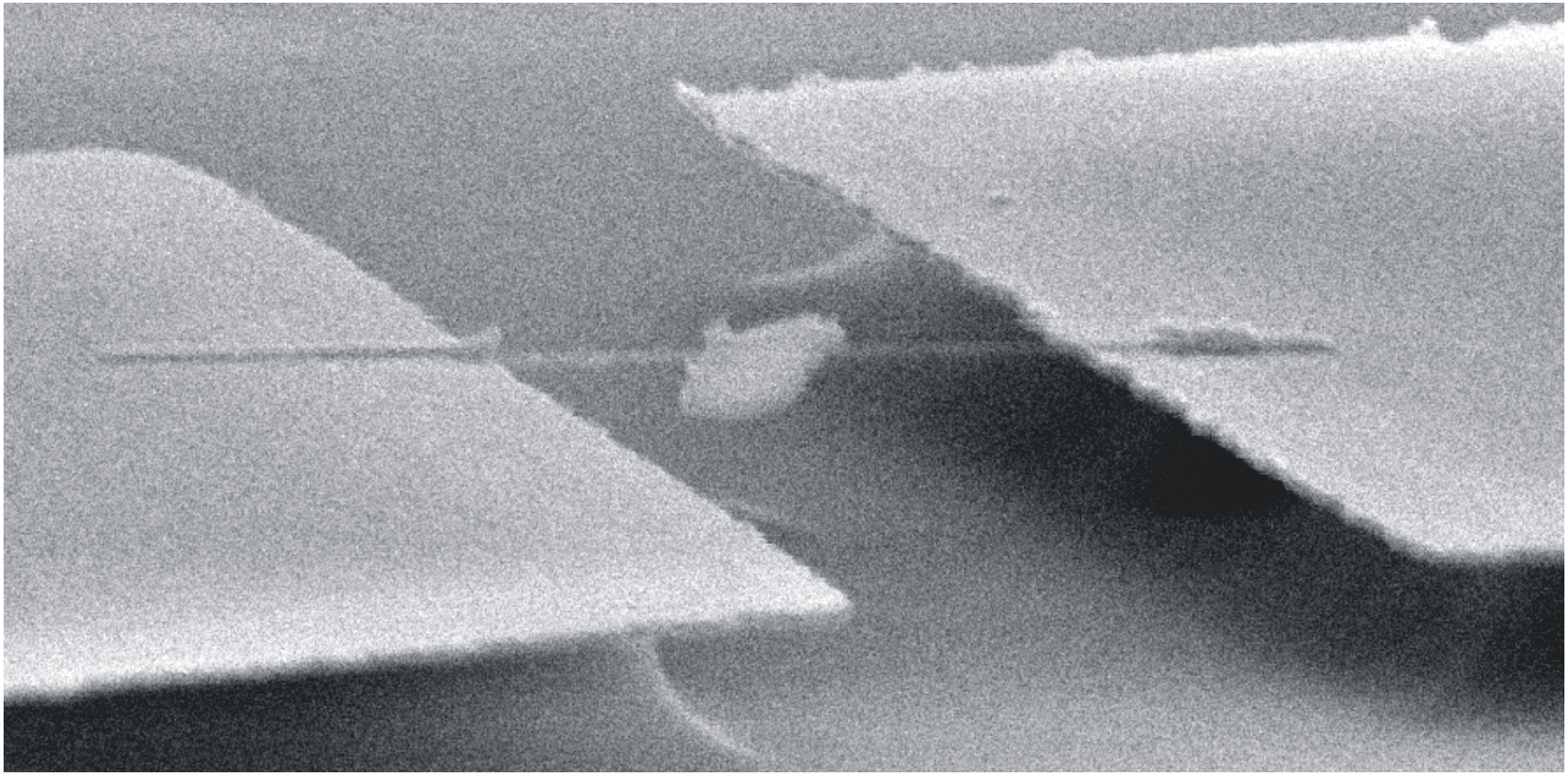
(27,12) - (32,17)

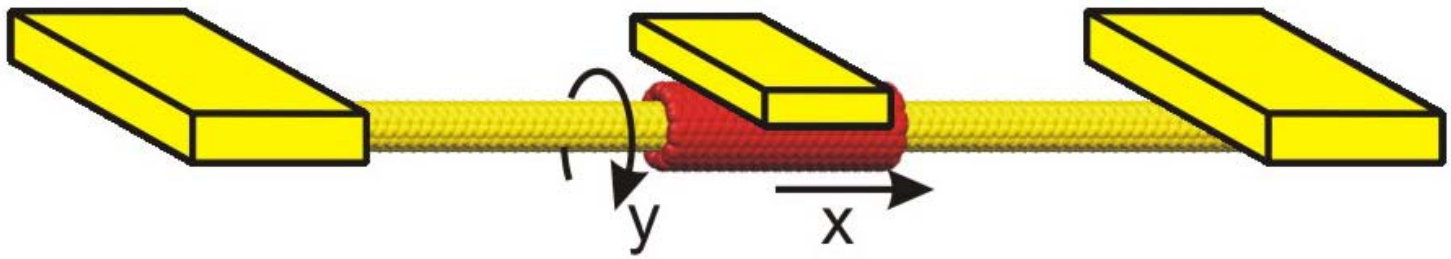
Saito, Matsuo, Kimura, Dresselhaus, Dresselhaus
Chemical Physics Letters 2001

Motion controlled by atomic arrangement

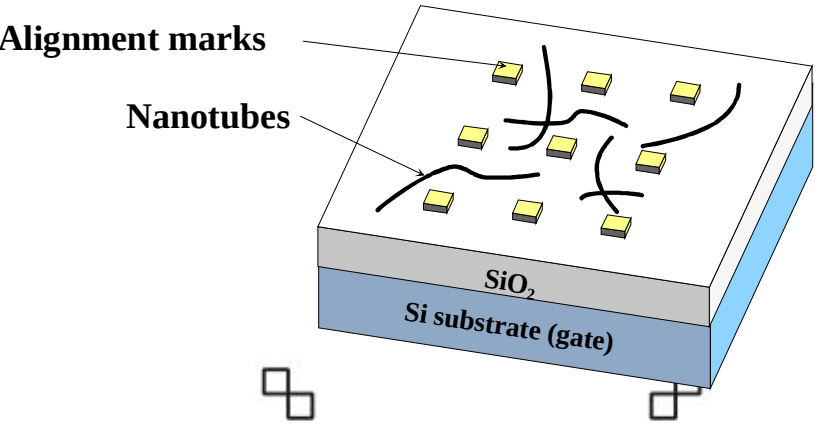


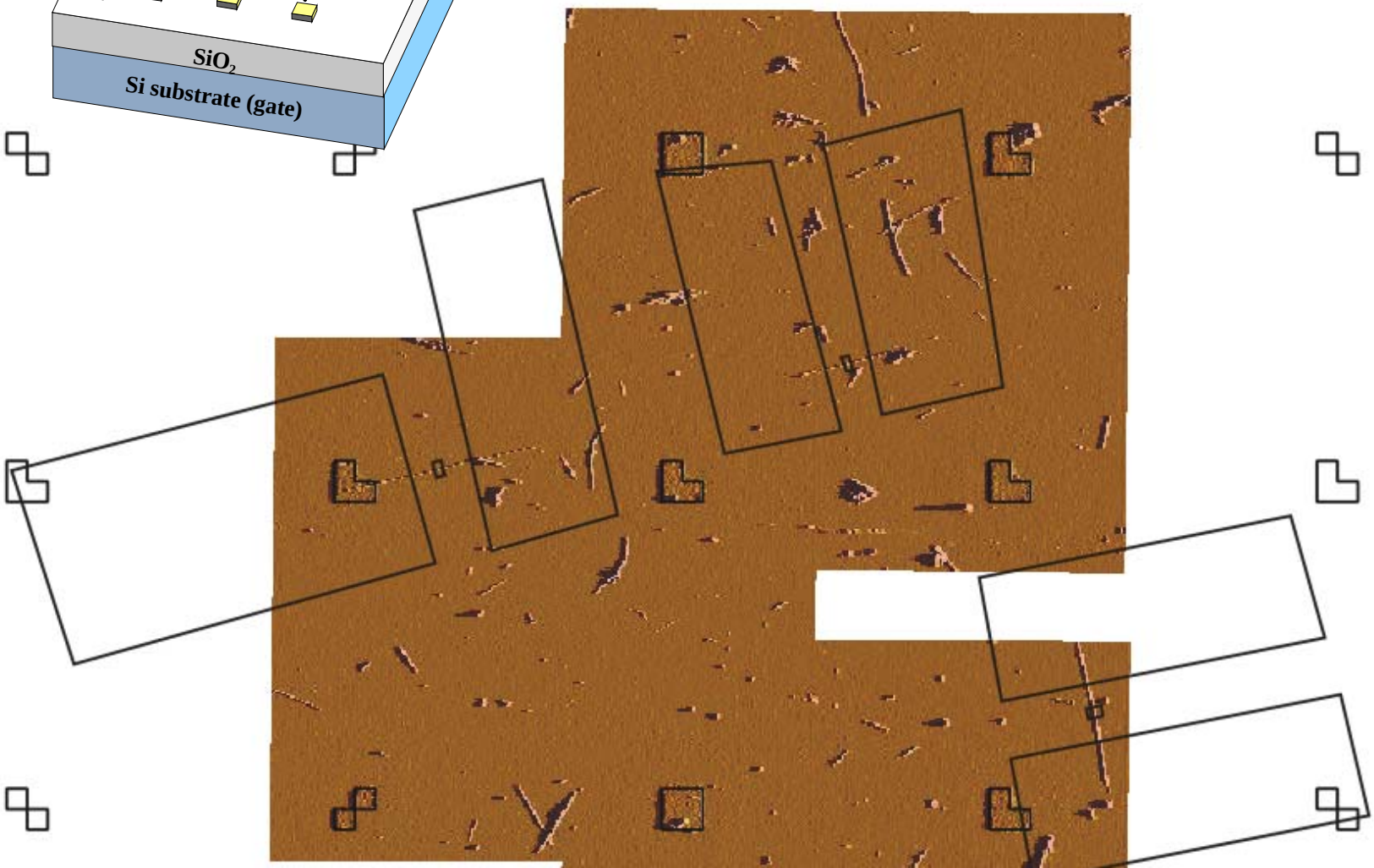
1. Nanofabrication and device characterisation



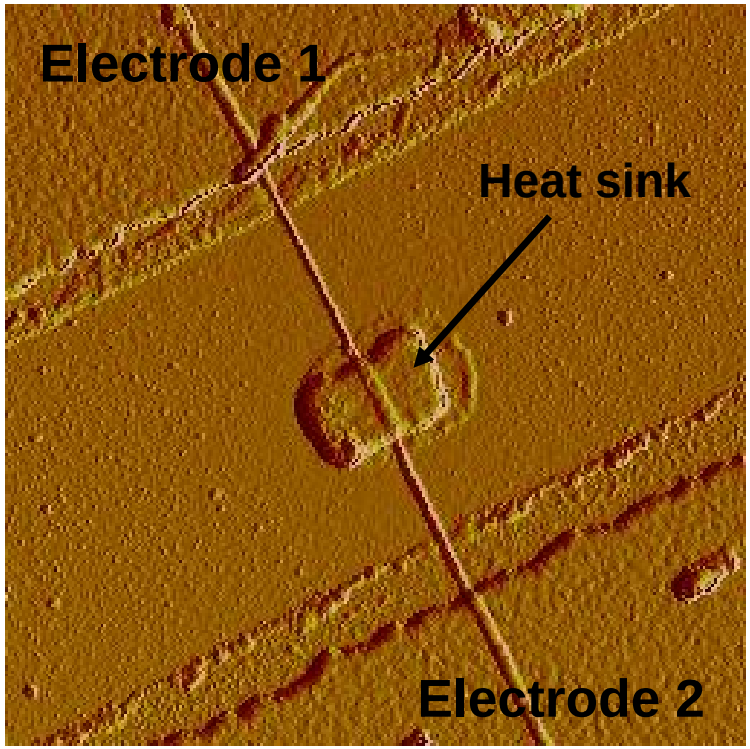


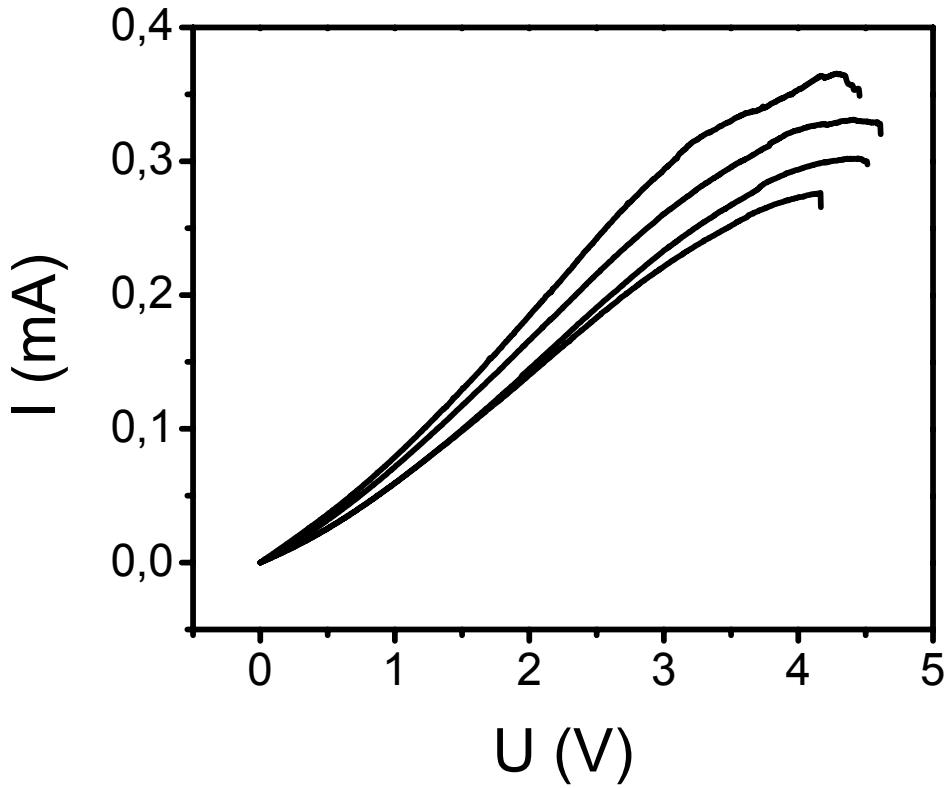
E-beam design preparation





Nano-Engineering

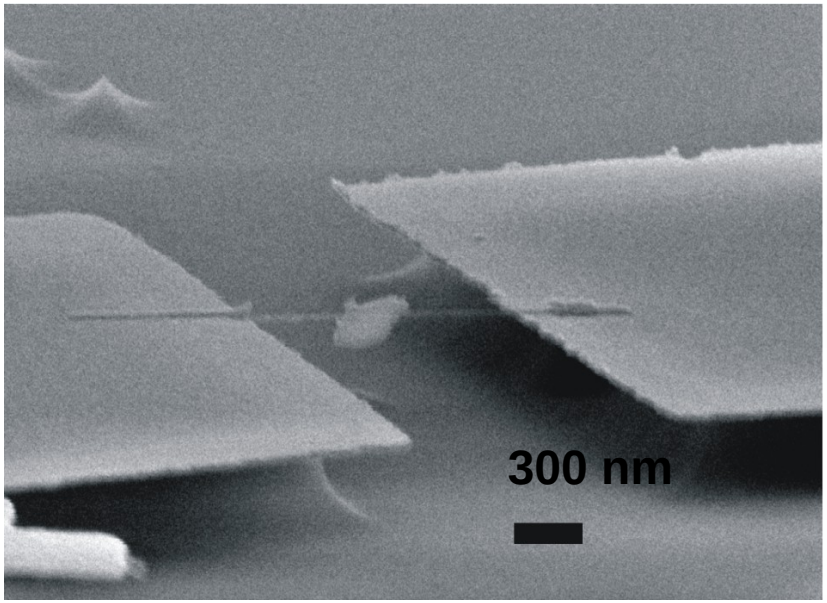


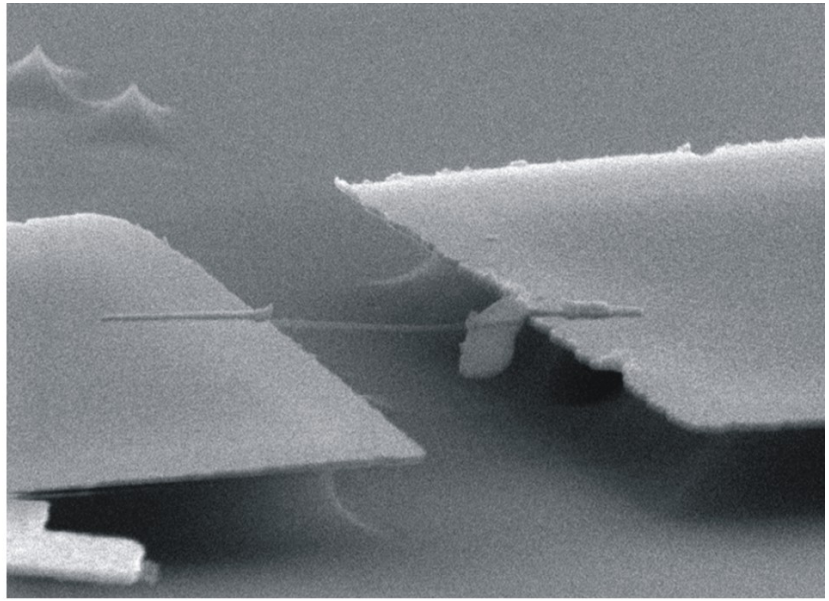


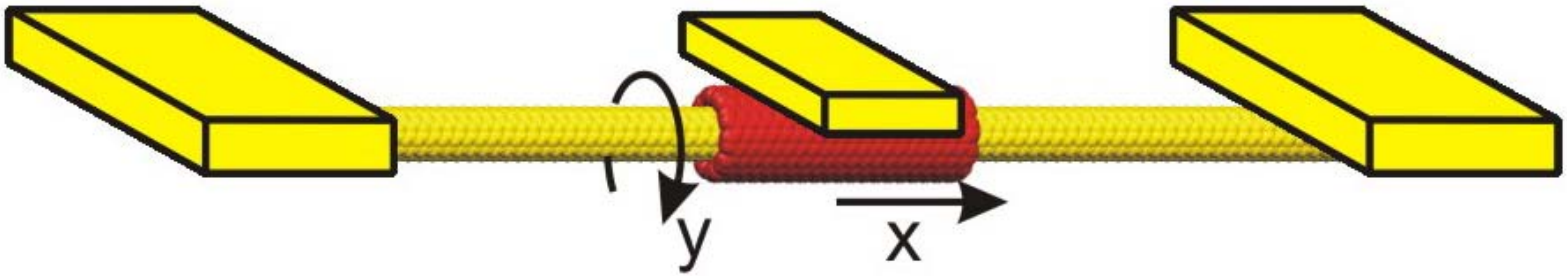
Collins et al, Science 2001

Bourlon et al, PRL 2004

Etching



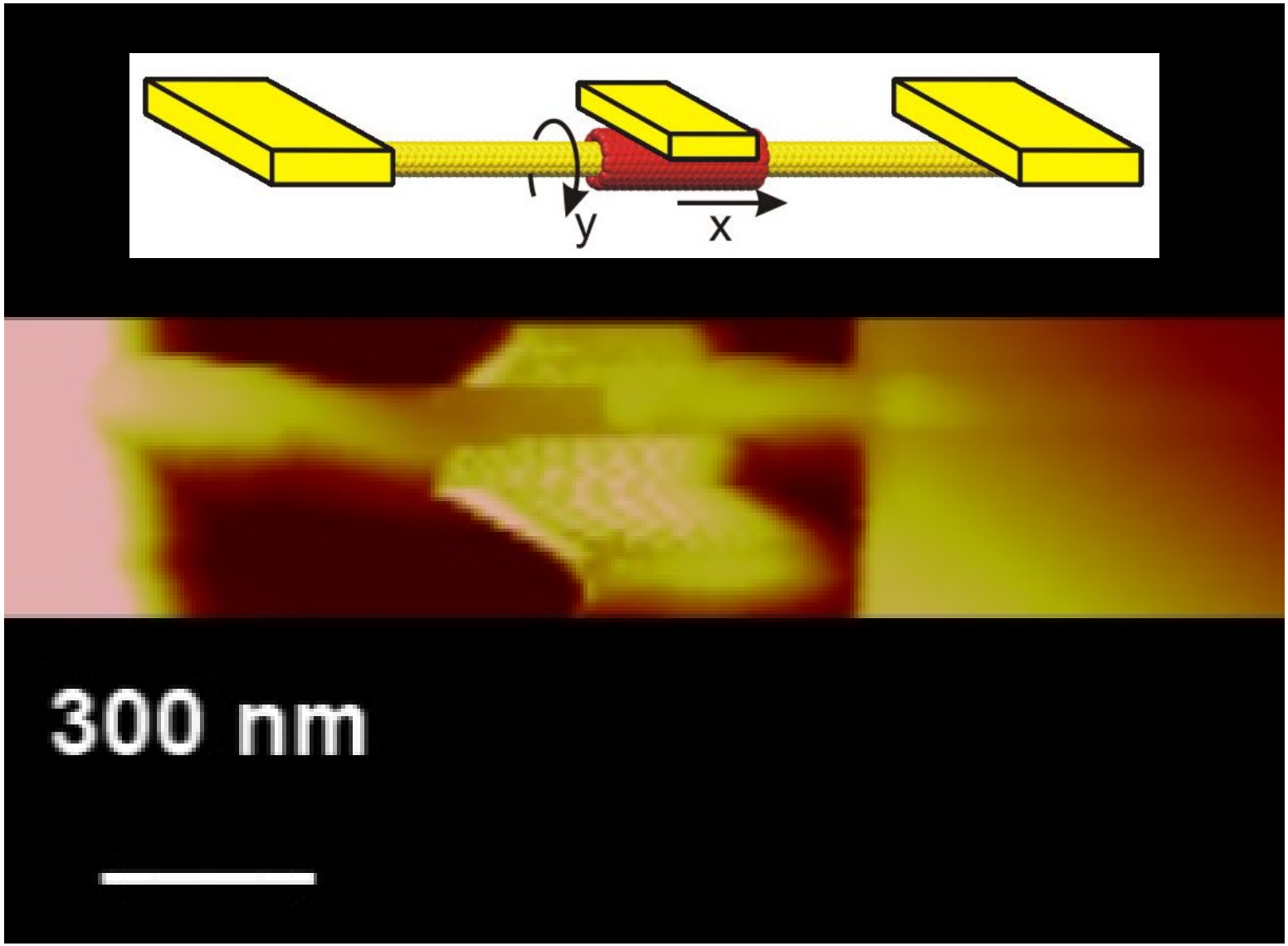




Verification of the device layout

move the plate with an AFM tip

AFM actuation



Engineered vs non-engineered devices

Statistics of engineered samples:

10 out of 11 devices moved (35 – 680 kΩ)

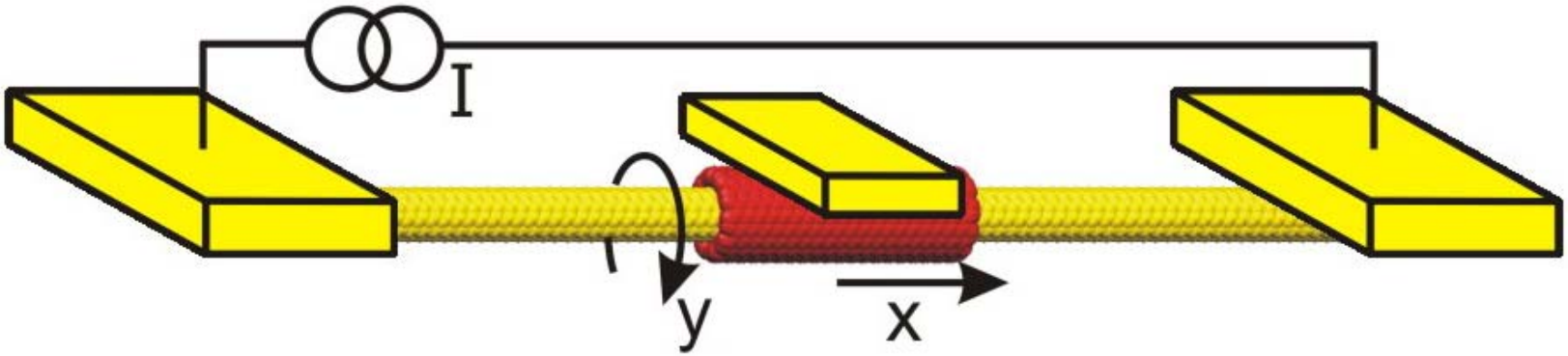
- 6 purely rotated
- 4 showed translation combined with rotation

2 of 2 did NOT move (1.2 M Ω and 1.5 M Ω)

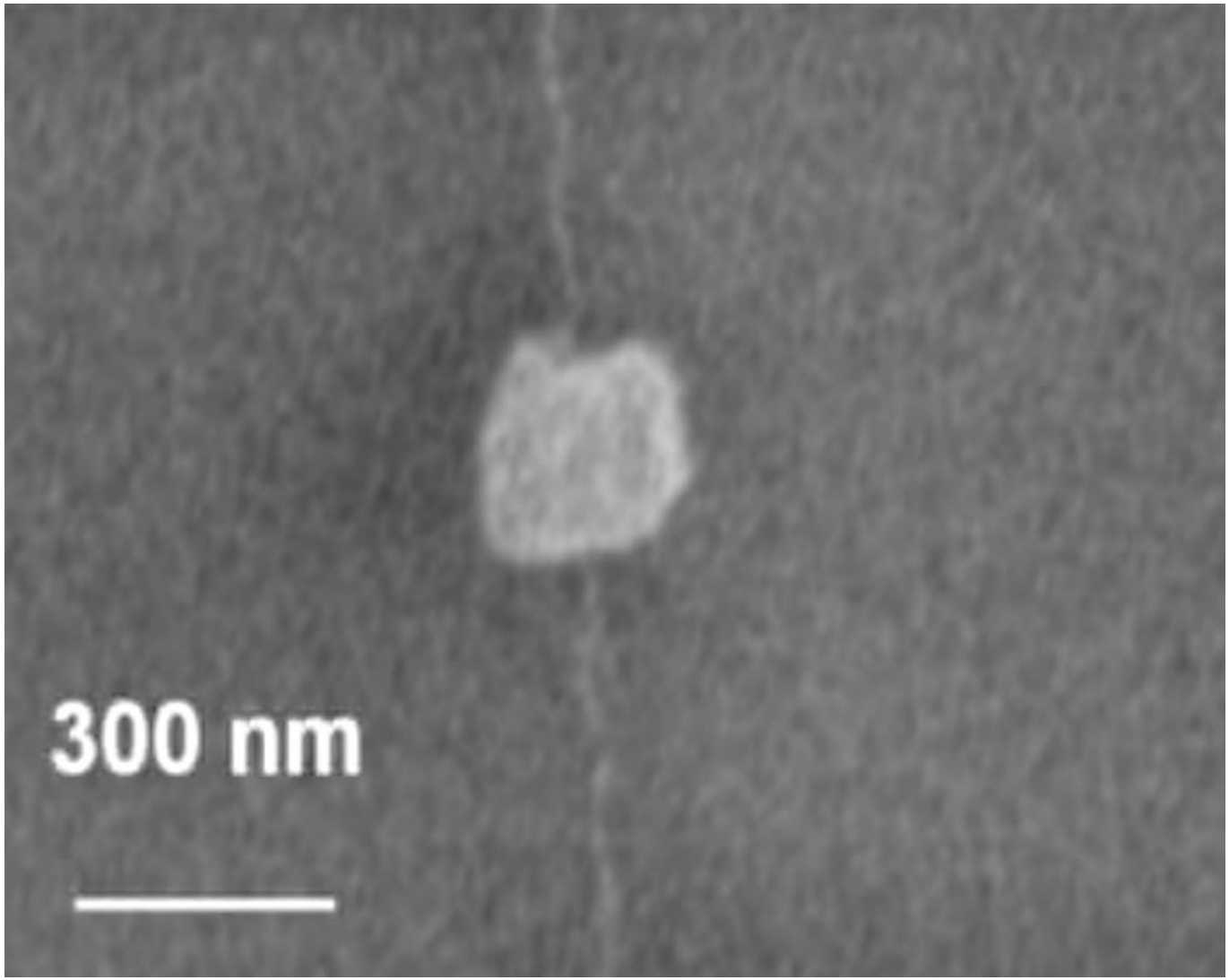
Statistics of non-engineered samples:

5 of 5 devices did NOT move (13 kΩ – 78 kΩ)

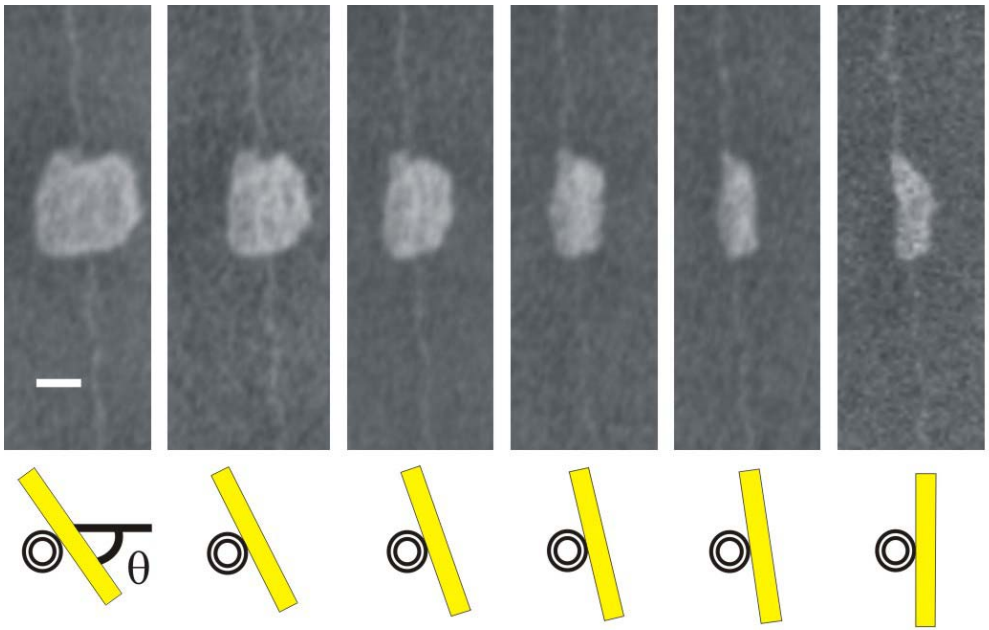
2. Motion upon passing a large current

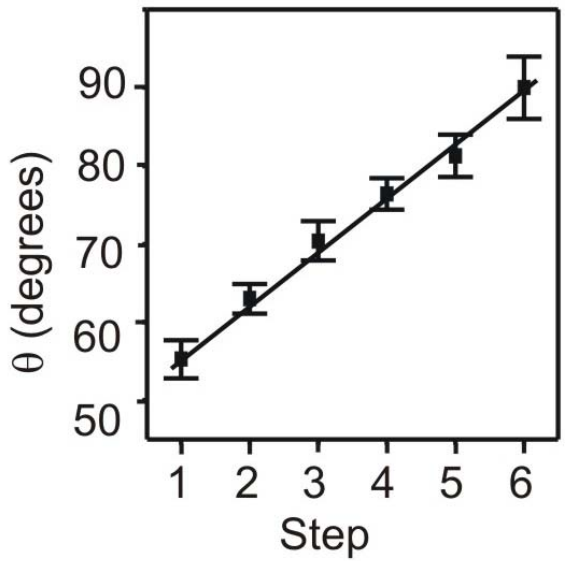


Stepwise rotation



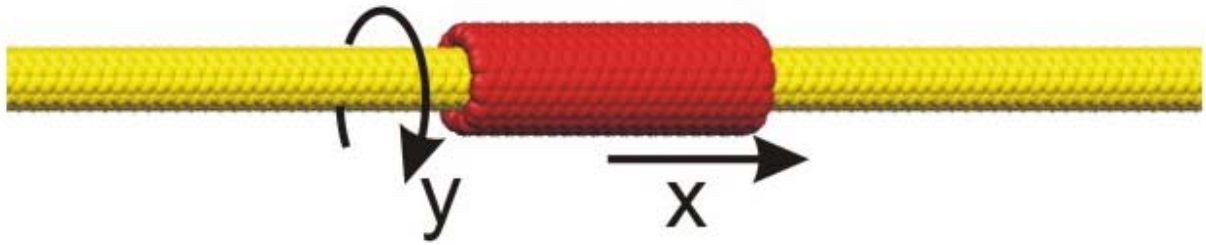
Stepwise rotation

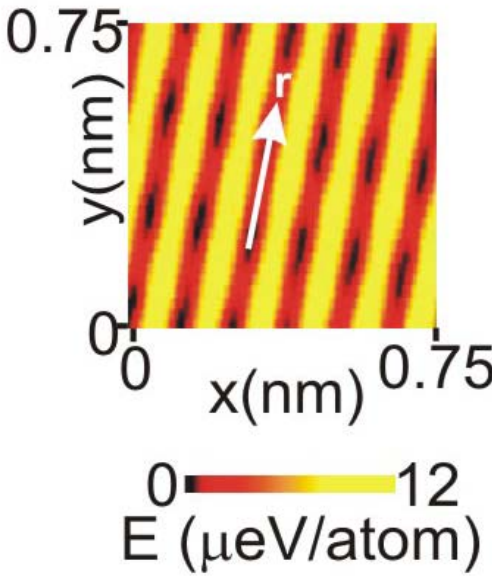




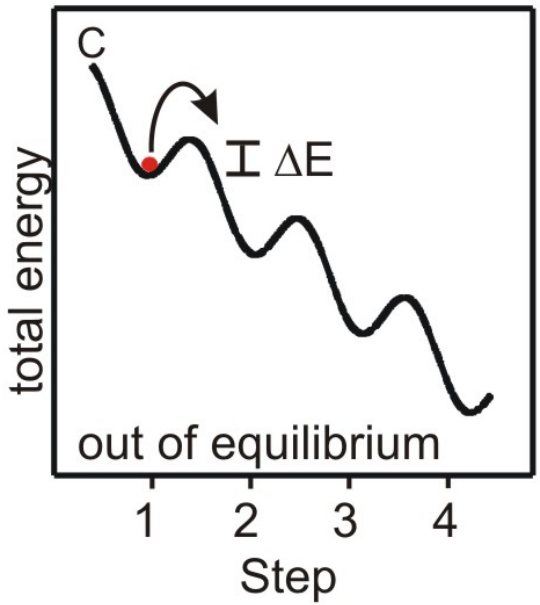
7º corresponds to about 0.4 nm displacement

Motion controlled by atomic arrangement





(27,12)-(32,17)



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

Periodic barriers

ΔE ~ 10 μeV/atom

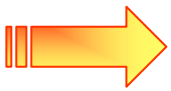
Thermally enhanced process

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

Approximation of linear harmonic oscillator:

$$\omega = \sqrt{\frac{k}{m}}, \qquad k = \frac{\partial^2 E}{\partial r^2} \approx \frac{\Delta E}{a_0^2}$$

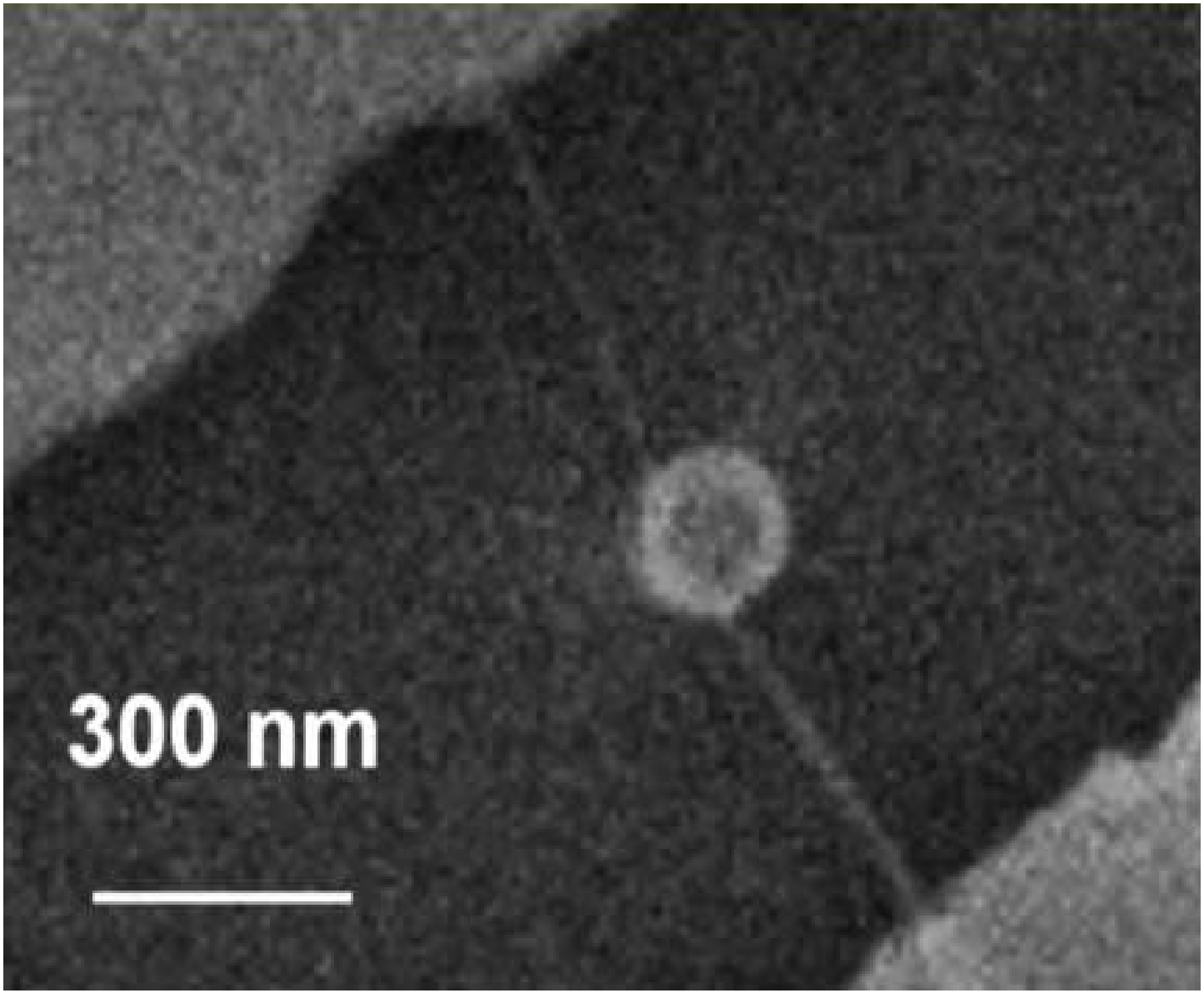
diffusion rate $\Gamma \sim$ 1 Hz, a_0=1 nm,
m mass of gold plate



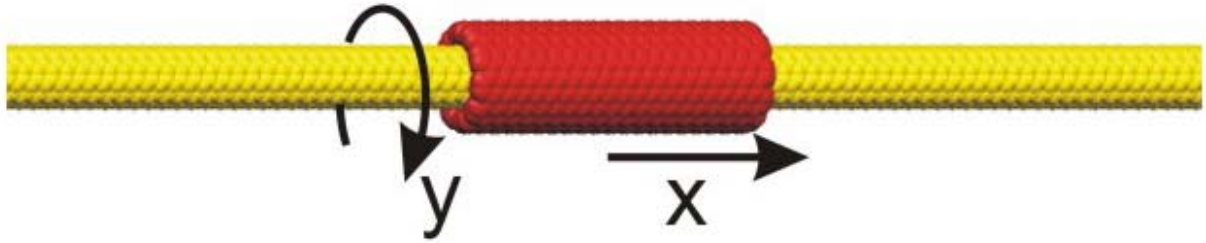
Diffusion barrier ΔE ~ 0.017 meV/atom

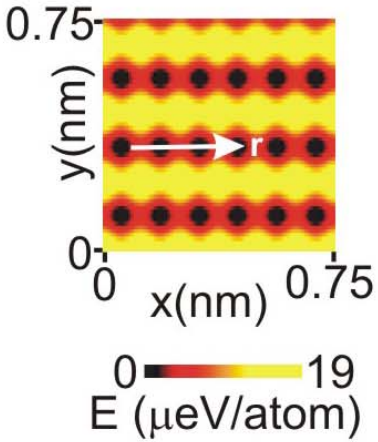
Saito et al. predict a potential barrier of 0.010 meV/atom

Rotation

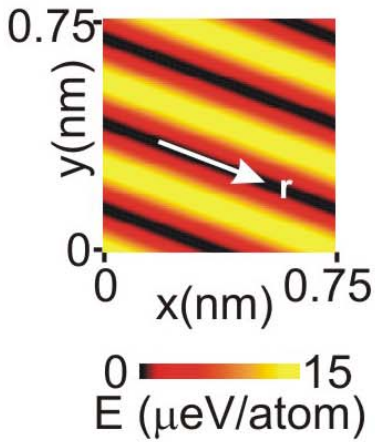


Motion controlled by atomic arrangement

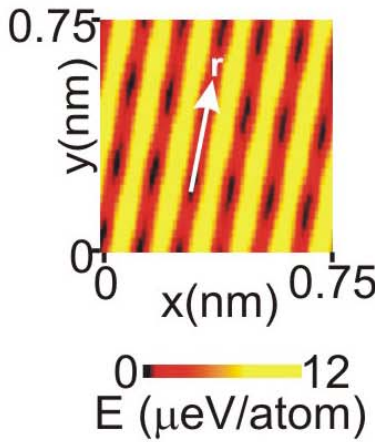




(5,5)-(10,10)



(29,9)-(38,8)



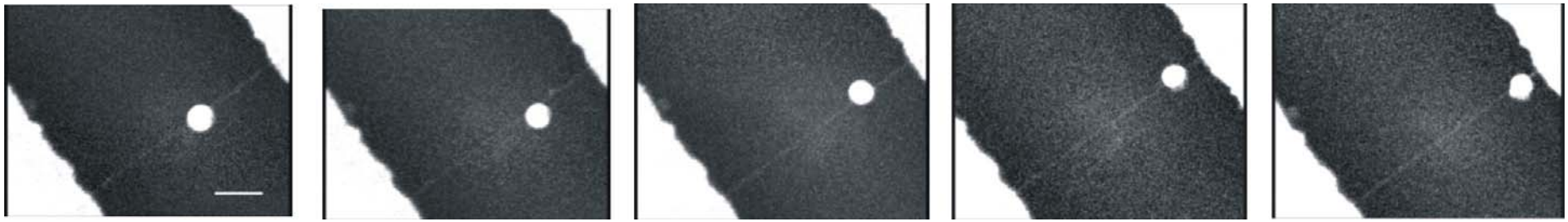
(27,12)-(32,17)

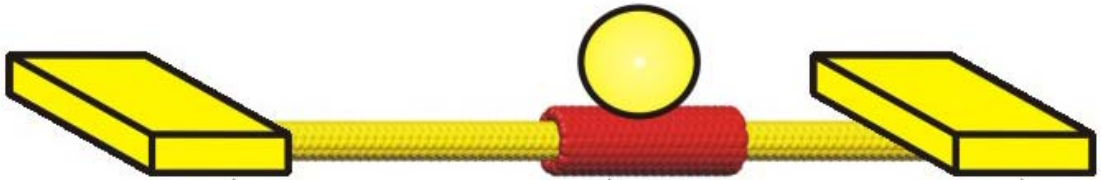
Saito, Matsuo, Kimura, Dresselhaus, Dresselhaus
Chemical Physics Letters 2001

Periodic barriers

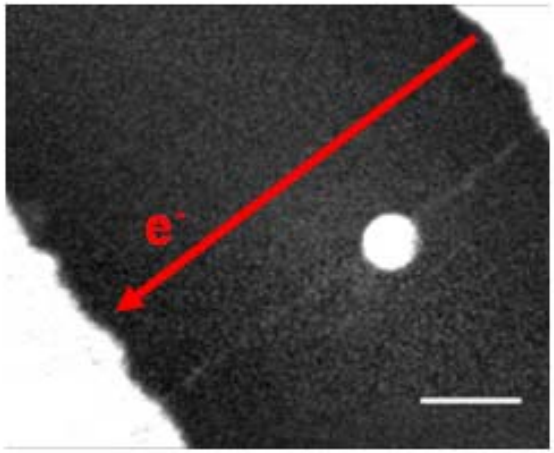
ΔE ~ 10 μeV/atom

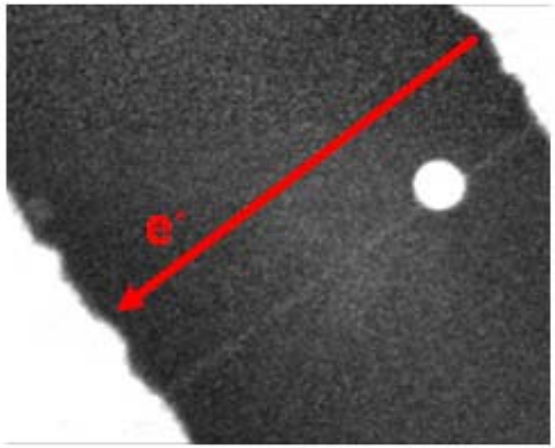
Translation



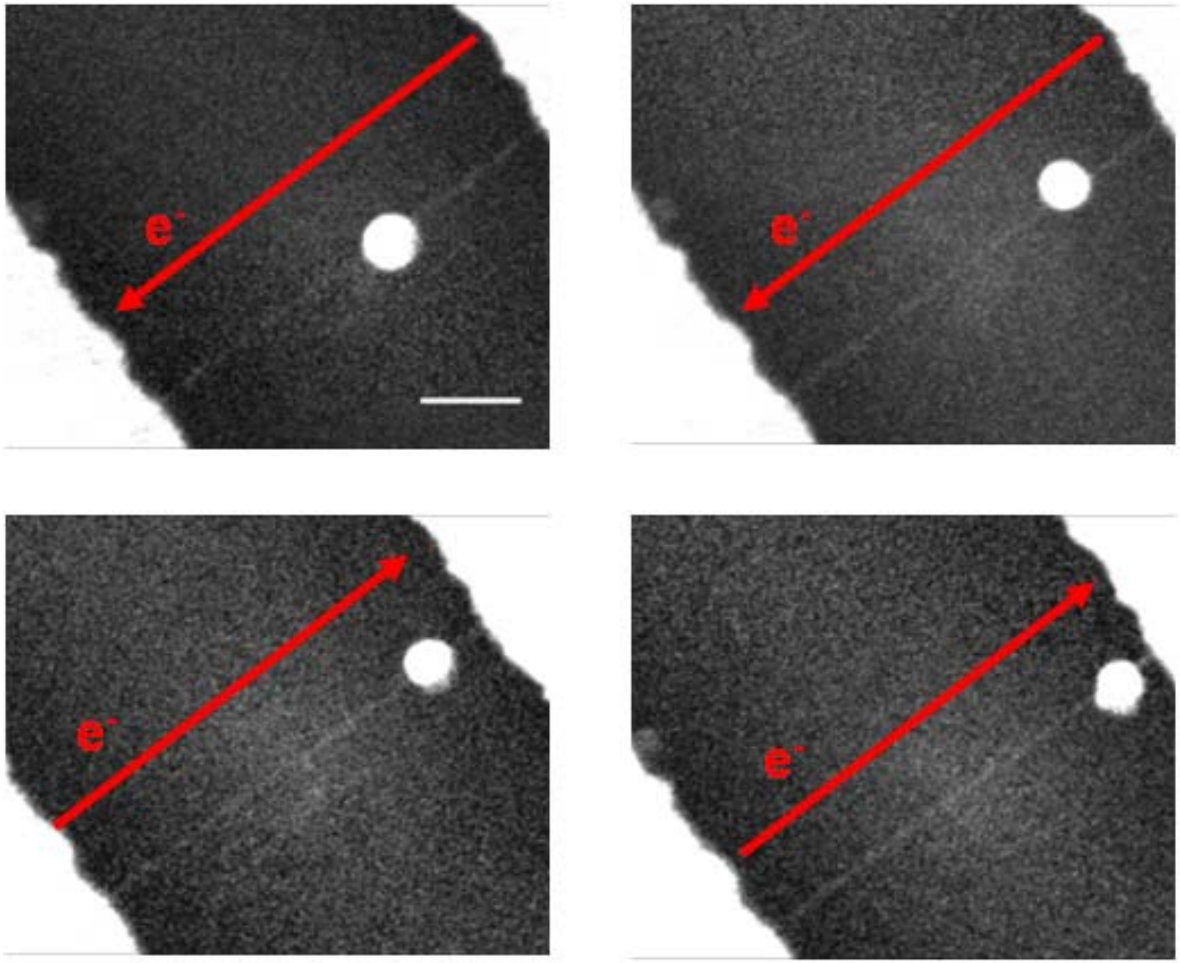


3. Driving mechanism



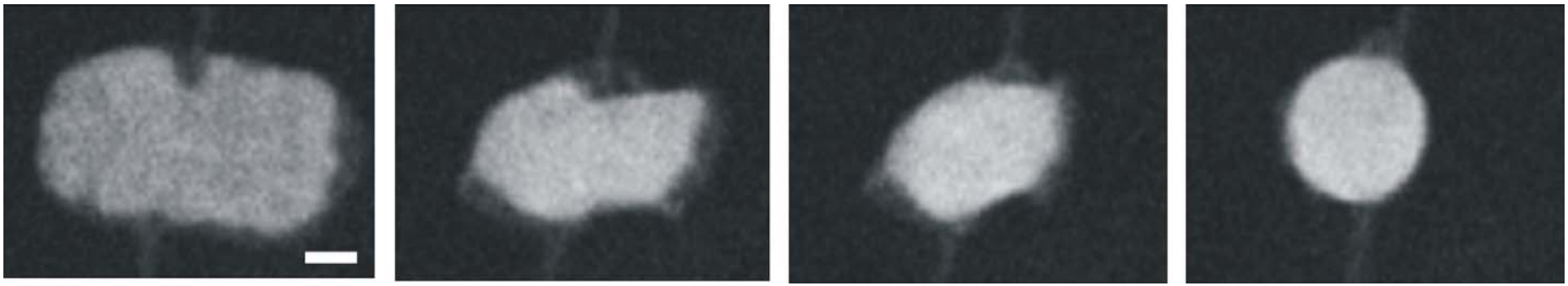


3. Driving mechanism

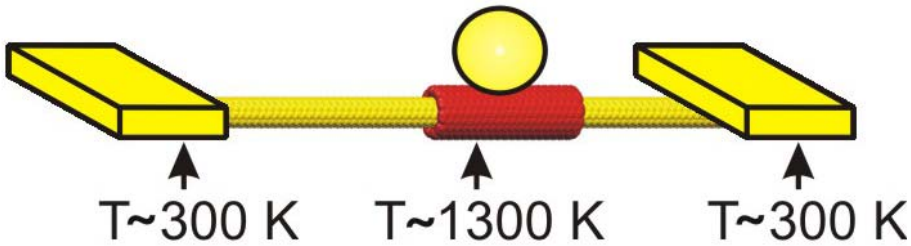


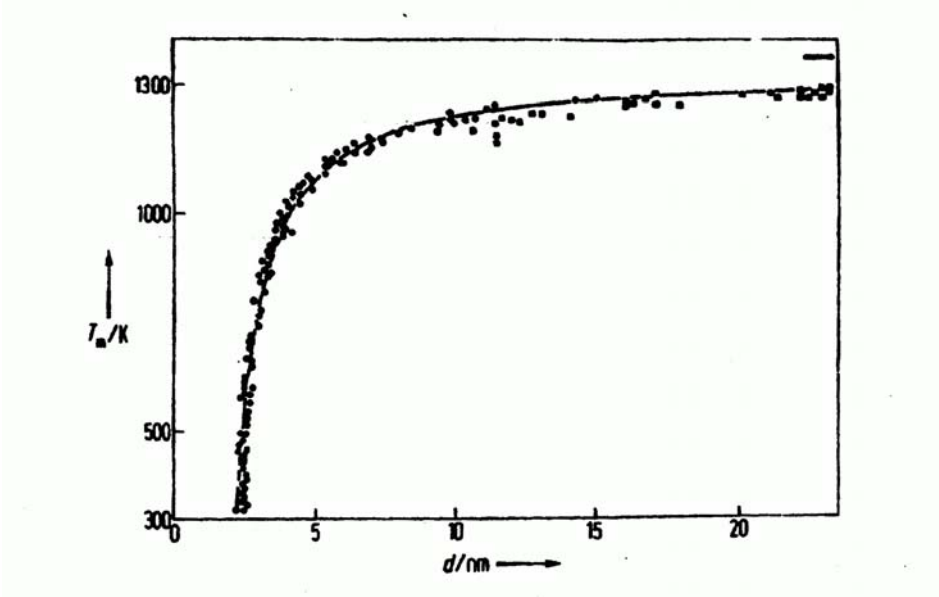
No electromigration!

Thermal Energy



Bulk Au melting point:
1064 ºC

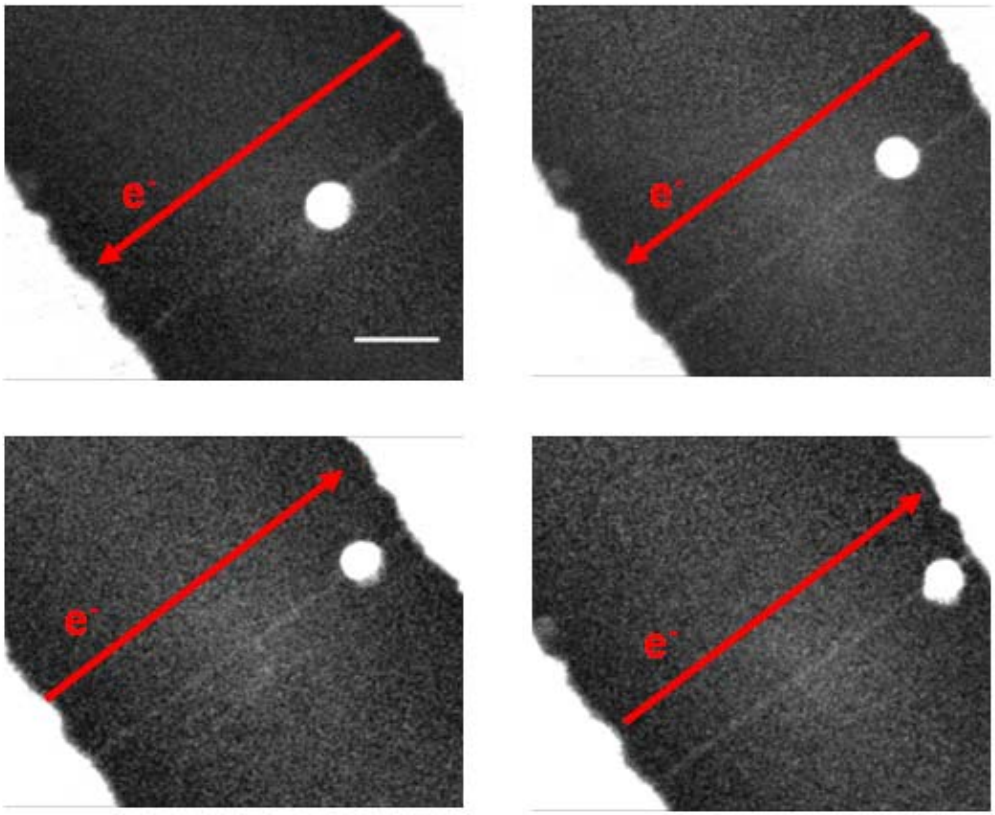




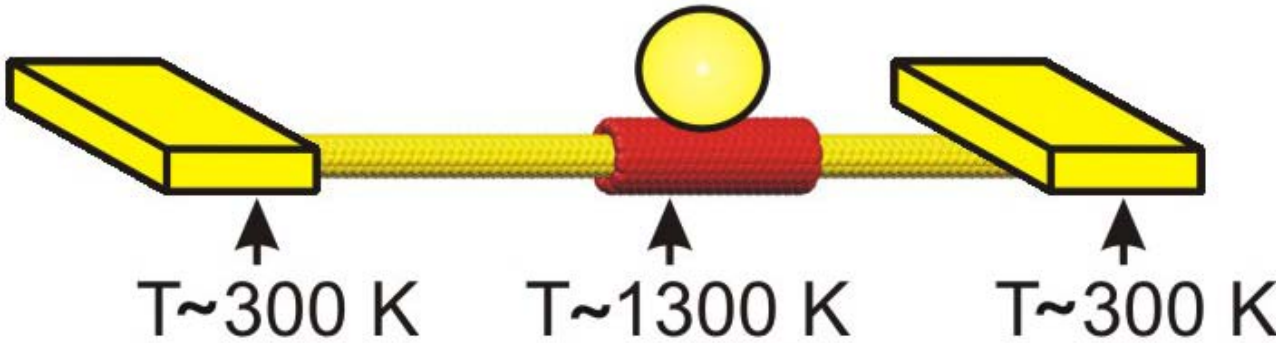
Melting temperature of Au versus cluster size

Joule heating

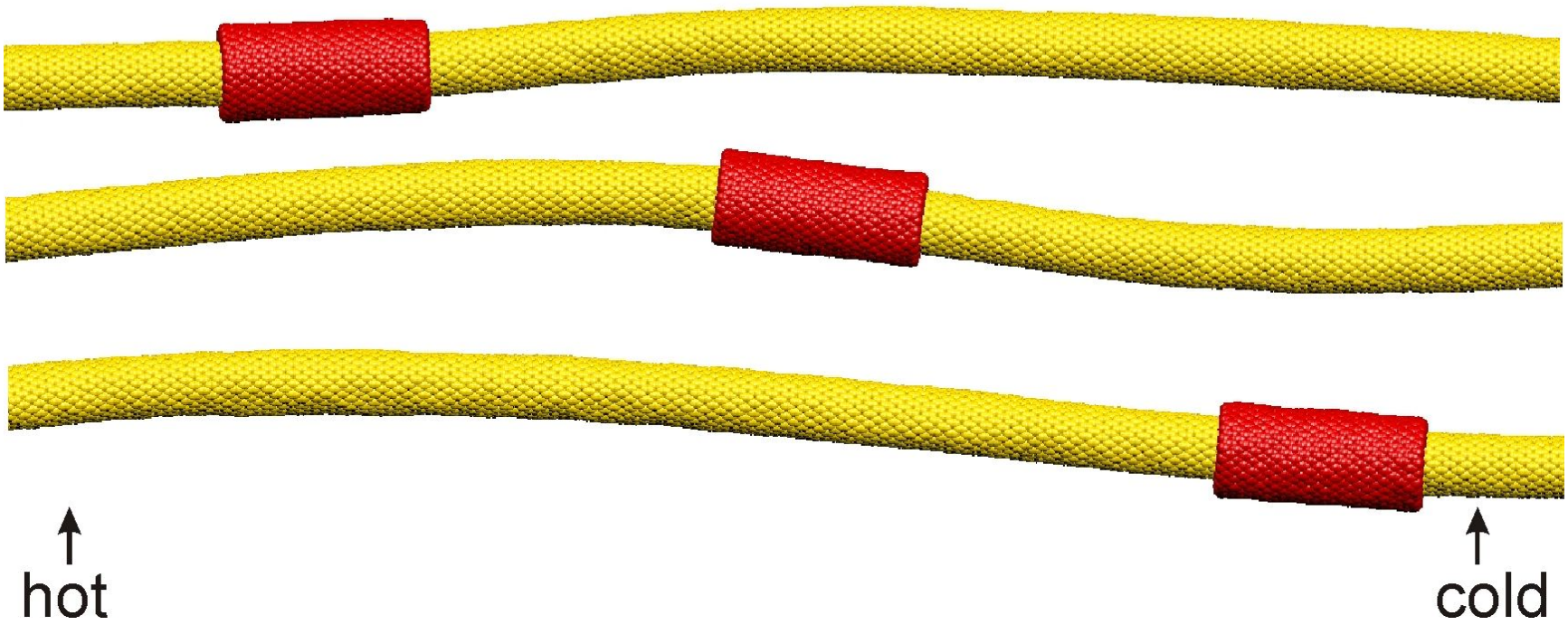
Thermal actuation



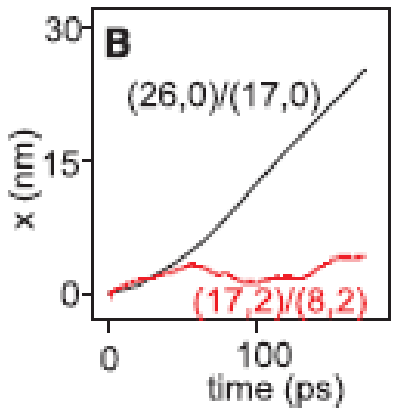
Phonons drive the motion

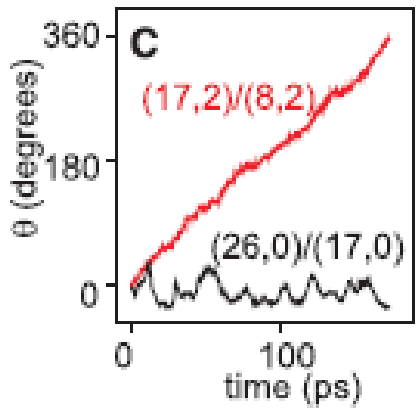


4. Molecular dynamics calculations



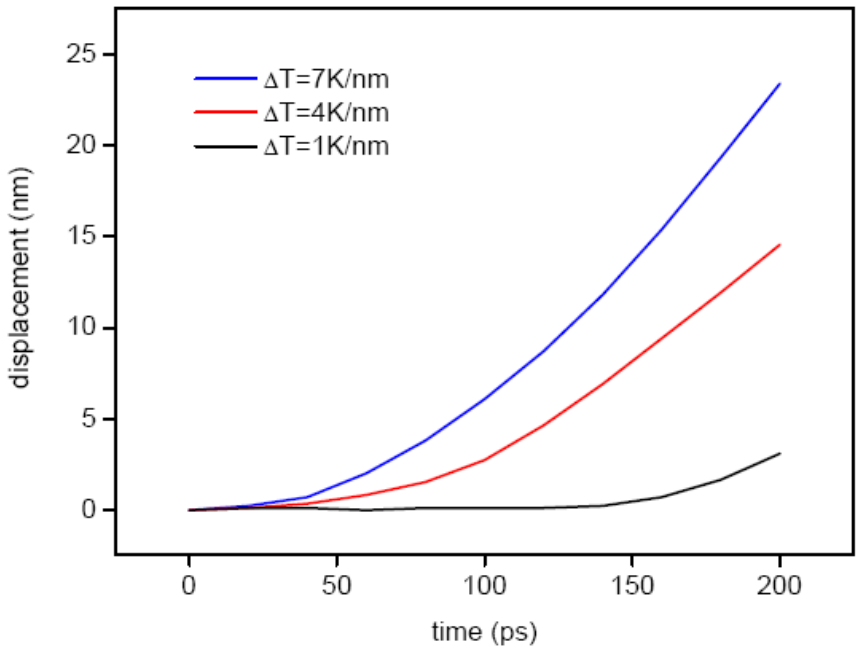
R. Rurali (UAB), E. Hernández (ICMAB)

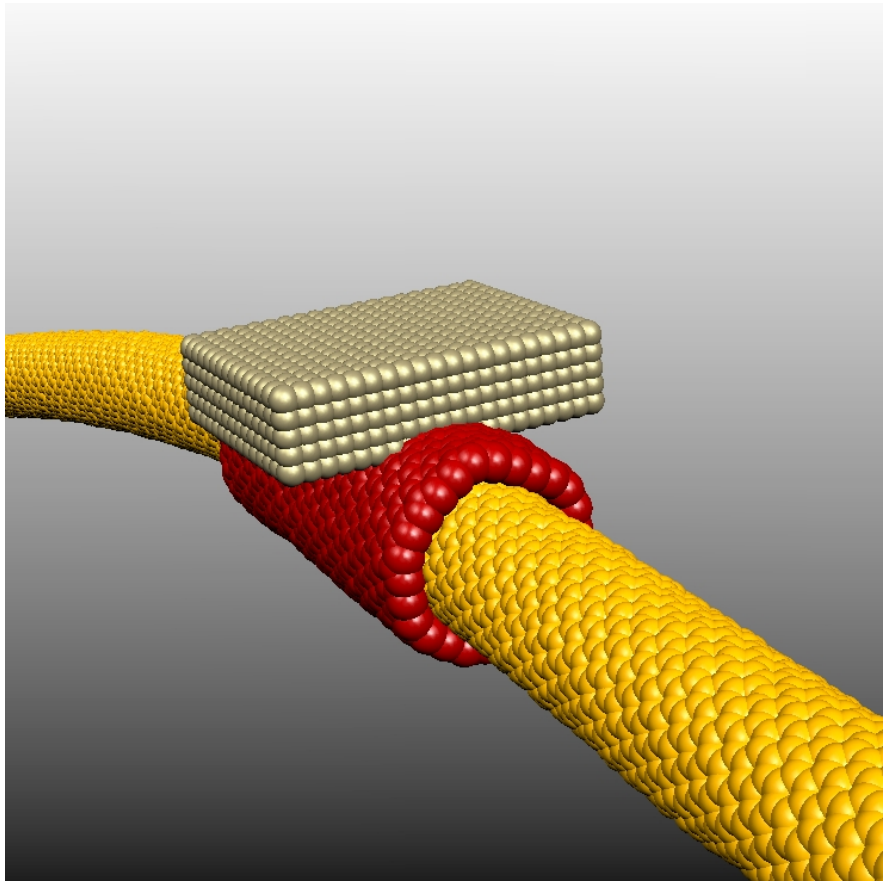




Speed of translation

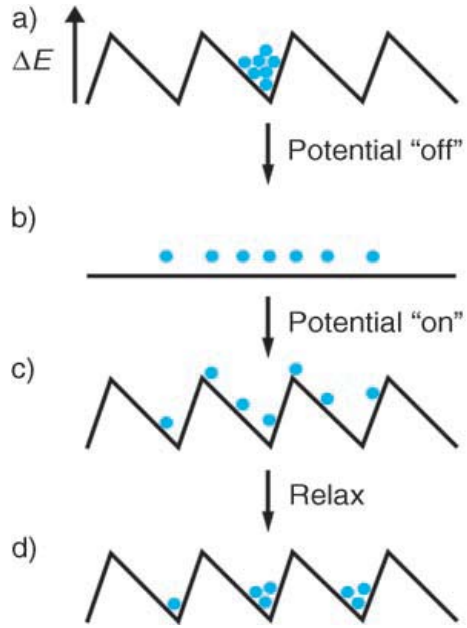
- Mass of the moveable shell
- Number of atoms of the moveable shell
- Temperature gradient



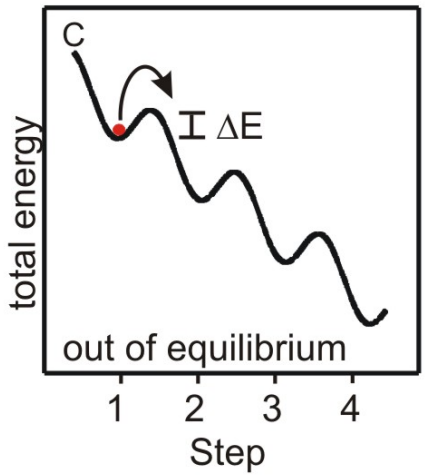


5. Conclusion: new type of motion

our world



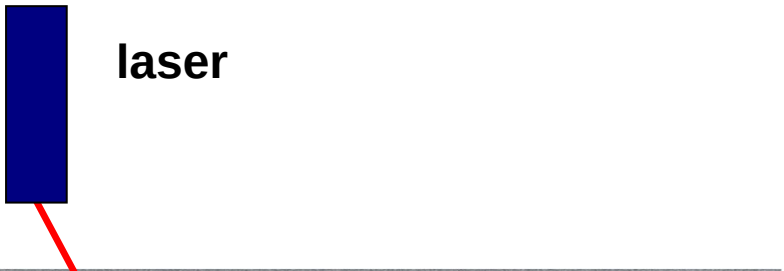
biological motors
ratchet effect

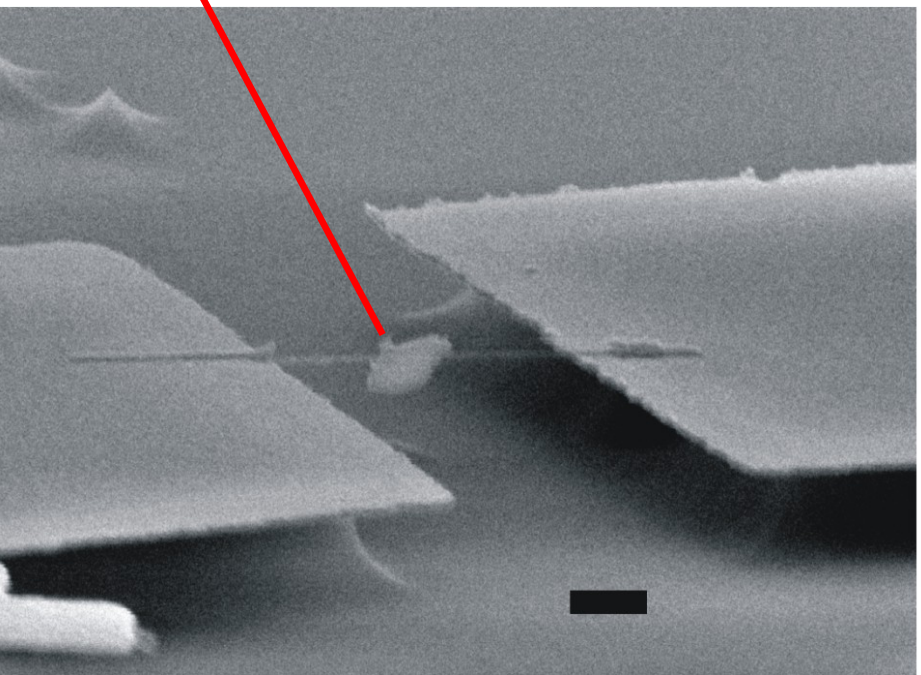


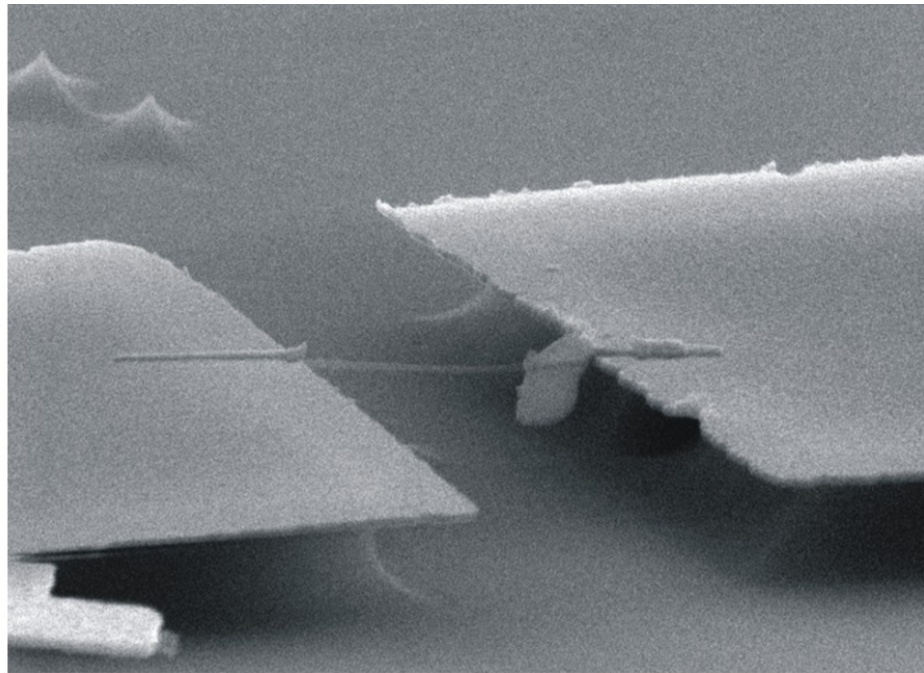
nanotube
thermal motors

Possible applications

Moving objects at the nanoscale







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Laszlo Forró