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

Amelia Barreiro

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Visionary concepts in nanoscience

microfabricated motors

LAAS, Toulouse
Molecular bearings

MWNTs → Low friction

Cumings, Zettl, Science 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

Saito, Matsuo, Kimura, Dresselhaus, Dresselhaus
Chemical Physics Letters 2001
Motion controlled by atomic arrangement
1. Nanofabrication and device characterisation
E-beam design preparation

Alignment marks

Nanotubes

SiO$_2$

Si substrate (gate)
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

$7^\circ$ corresponds to about 0.4 nm displacement
Motion controlled by atomic arrangement

Periodic barriers
\[ \Delta E \sim 10 \, \mu\text{eV/atom} \]
Thermally enhanced process

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

Approximation of linear harmonic oscillator:

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

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

Diffusion barrier $\Delta E \sim 0.017$ meV/atom

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

300 nm
Motion controlled by atomic arrangement

Periodic barriers

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

$\Delta E \sim 10 \, \mu\text{eV/atom}$
3. Driving mechanism
3. Driving mechanism

No electromigration!
Bulk Au melting point:
1064 °C

Joule heating

Melting temperature of Au versus cluster size
Thermal actuation

Phonons drive the motion

T~300 K  T~1300 K  T~300 K
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

![Graph showing displacement over time with different temperature gradients.](image-url)
5. Conclusion: new type of motion

our world

biological motors
ratchet effect

nanotube
thermal motors
Possible applications

Moving objects at the nanoscale

laser
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