NANOELECTROMECHANICAL SYSTEMS BASED ON MULTI-WALLED NANOTUBES: NANOTHERMOMETER, NANORELAY AND NANOMOTOR

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Unique properties of carbon nanotubes, such as easy relative sliding and rotation of the walls and metallic conductivity, allow using the walls of nanotubes as a movable element and an element of electric circuit in nanoelectromechanical systems (NEMS). An example of such application is the nanotube-based nanomotor, which has been recently realized [1,2]. A new type of NEMS based on the nanotubes, for which the relative motion of the walls is controlled by the corrugation of the interwall interaction energy surface, has been proposed in [3] as a nanodrill and in [4,5]. Here we proposed three new NEMS of this type: an electromechanical nanothermometer, a nanorelay, which can also be used as a memory cell, and a nanomotor for transformation of forward force into relative rotation of the walls.

Both the conductivity, G, and the interwall interaction energy, U, of double-walled carbon nanotubes (DWNTs) depend periodically on relative displacement of the walls, z. Thus, the probability of relative displacement of the walls can be defined as $p(z)=A\exp(-U(z)/kT)$. The total conductivity of DWNT for a given temperature, $G(T)$, can be then found by integrating $\int G(z)p(z)dz$. We propose to use the dependence $G(T)$ for elaboration of electromechanical nanothermometer. Several principal schemes of such nanothermometer are shown on Figure 1. The density functional theory (DFT) calculations of the interwall interaction energy, $U(z)$, have been performed using the (6,6)@(11,11) DWNT as an example (the details of the method can be found in [5,6]). These calculations are used to estimate the minimal length of the nanothermometer for which relative diffusion of the walls does not hinder its operation. An analytical expression for the dependence $G(T)$ is also derived.

The schematics of a nanorelay based on relative motion of the walls of DWNT are shown on Figure 2. In this nanorelay, the inner wall is pushed out of the outer wall, connected to the electrode (3), by electrostatic force F_e and attracted to the electrode (4) by Van der Waals force F_a (position 'on'). The core can be retracted into the shell by capillary force F_c (position 'off'). The friction force F_f acting between the core and the shell is also taken into account. The force F_f arises due to the corrugation of the interwall interaction energy surface. The forces F_c and F_f are calculated using DFT, whereas F_a is calculated semi-empirically. Structure of the caps of the inner wall has been obtained using the Q-Chem 2.0 *ab initio* package. The force F_e and related voltages of switching have been calculated analytically for the capacity of the system. If the electrode (4) is copper, then $F_a>F_c$. Thus, the nanorelay shown on Figure 2A can be used as a memory cell for both the external and on-line storage. If the electrode (4) is a carbon nanotube, as shown on Figure 2B, and the size of a memory cell can be considerably reduced. For such nanorelay $F_a<F_c$, thus it can only be used as a memory cell of the on-line storage, for which $F_a+F_e>F_c$. However, we found that for DWNTs with the nonchiral commensurate walls it is possible to select the length of the outer wall so that friction force is great and therefore $F_a+F_f>F_c$. In this case the nanorelay shown on Figure 2B can also be used as a memory cell of the external storage. The schematics of nanorelays with the third control electrode are also considered. The possibility of producing a gas nanosensor based on the proposed nanorelays is discussed.

We also suggest the schematic of a nanomotor based on the four-walled nanotube and intended for transformation of forward force into the relative rotation of the walls. In such a nanomotor two inner walls are the rotational nanobearings and two outer walls have the thread-like potential relief of the interwall interaction energy, which operate as the nanobolt-nanonut pair. The theory which describes the operation of the nanomotor is presented.

References:

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Figures:

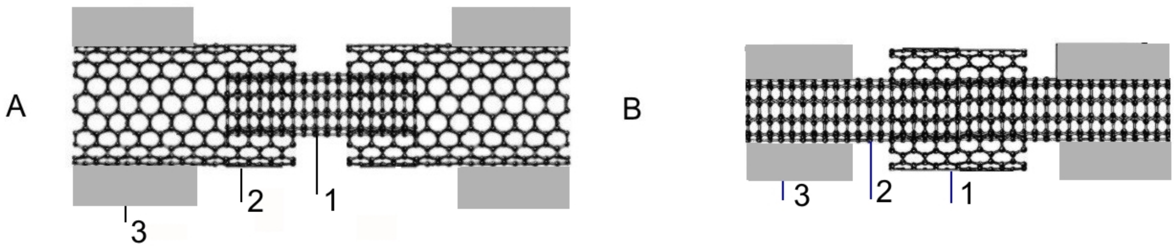

Figure 1. Schematic of electromechanical nanothermometer. A: telescopic nanothermometer with movable outer wall, B: shuttle nanothermometer with movable inner wall. The movable wall is marked off by (1), the fixed wall by (2) with the attached electrodes (3).

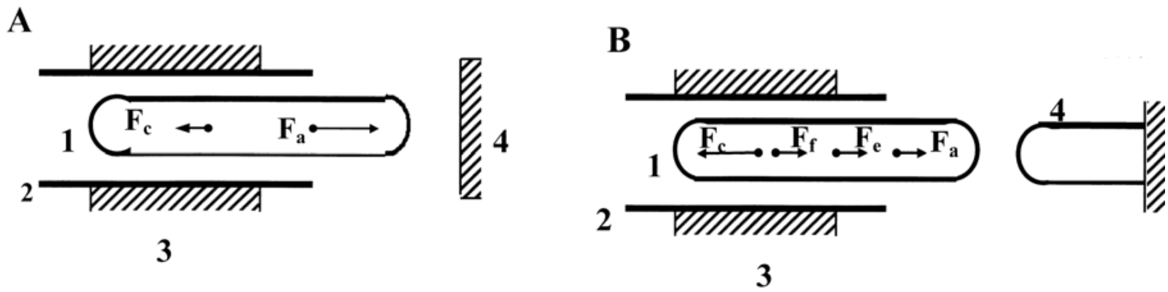

Figure 2. Schematic of double-wall nanotube-based memory cell in position 'on'. A: memory cell with flat second electrode, B: memory cell with carbon nanotube attached to second electrode. The movable inner wall is marked off by (1), the fixed outer wall by (2) with the attached electrodes (3) and (4).

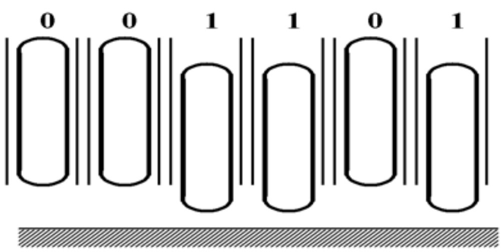

Figure 3. Example of the storage produced of nanotube-based memory cells.