A low-voltage magnetic nanorelay design


Calculated operating parameters for a novel design of a reed switch (based on cantilevered nanotubes filled with magnetic endofullerenes) show the feasibility of room-temperature operation at 100mV applied voltage.

The remarkable elastic properties and metallic conductivity of carbon nanotubes (CNTs) allow them to be used as parts of nanoelectromechanical systems1–5 and many different electromechanical nanorelays have already been constructed in a wide range of designs. These are based on the crossbar relative position of two carbon nanotubes,6 cantilevered7,8 and suspended9 nanotubes, telescopic extension of nanotubes,10,11 and a magnetic shuttle inside a carbon nanotube.12 These nanorelays are controlled by an electric field and require voltages between one and tens of volts for operation. These relatively high voltages have several disadvantages, including parasitic charging.

In the last few years, researchers have discovered how to obtain a variety of endofullerenes (a fullerene acting as a cage for an atom or cluster of atoms) and ‘nanotube peapods’ (nanotubes filled with fullerenes), including nanotube peapods filled with magnetic endofullerenes,13–16 even in macroscopic amounts.17 The magnetic moments $M_{ef}$ of many fullerenes with encapsulated magnetic atoms are known,13,16 and the largest belongs to the fullerene C$_{80}$ filled with tri-holmium nitride, known as (Ho$_3$N)@C$_{80}$. For this endofullerene, $M_{ef}$ is equal to 21 Bohr magnetons ($\mu_B$). This large magnetic moment and the metallic conductivity of CNTs make it possible to construct a magnetic-field-sensitive element by placing endofullerenes inside a CNT.

We propose a new type of nanorelay based on peapod CNTs with encapsulated magnetic endofullerenes. This allows us to disconnect control and controlled circuits, analogously to known19 macroscopic reed switches. We have calculated the operating parameters of such a novel nanorelay operated with a magnetic field, based on two (Ho$_3$N)@C$_{80}@$CNT(21,21) nanotube peapods (see Figure 1). The chirality indices (21,21) describe the way in which the nanotube is rolled up and correspond to an armchair metallic CNT. We found that it would operate at much lower voltage (c. 100mV) than existing nanorelays.

The proposed nanorelay has the following operational principles. When a magnetic field is applied, the majority of the magnetic moments of the endofullerenes line up in the direction of the magnetic field (see Figure 1a). As a result, the attraction between the CNTs rises. The condition for the nanorelay switching is determined by the balance of the magnetic and elastostatic forces.20 The amplitude of thermal vibrations of the tips of the CNTs rises. The condition for the nanorelay switching is determined by the balance of the magnetic and elastostatic forces.20 The amplitude of thermal vibrations of the tips of the CNTs rises. The condition for the nanorelay switching is determined by the balance of the magnetic and elastostatic forces.20 The amplitude of thermal vibrations of the tips of the CNTs rises. The condition for the nanorelay switching is determined by the balance of the magnetic and elastostatic forces.20

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is the distance between the CNTs that corresponds to their contact, \( R \) is the nanotube radius, and \( \Delta R = 0.34\text{nm} \) is the thickness of nanotube wall, which is taken to be equal to the interlayer distance of graphite. For this condition, one can use an estimate \( k(x^{th}_0 - x^{min}_0)^2 / 2 > k_B T / 2 \), where \( 2x^{th}_0 \) is the minimal distance between the CNTs limited by thermal vibrations, \( k \) is the nanotube bending stiffness, \( k_B \) is the Boltzmann constant, and \( T \) is temperature.

We calculated the operational characteristics of the nanorelay (see Figure 2). We assumed that the magnetic endofullerenes inside the nanotubes form a superparamagnetic phase. Thus, the magnetic moment corresponding to the magnetic saturation is \( N_{ef} M_{ef} \), where \( N_{ef} = 3L / \delta_{ef} \) is the number of the endofullerenes in the fully filled (21,21) nanotube. Here \( \delta_{ef} \approx (0.8 + 0.34)\text{nm} \), where 0.8nm is the diameter of endofullerene \((\text{Ho}_3\text{N})@C_{80}\), 0.34nm is the distance between the surfaces of adjacent endofullerenes, and \( M_{ef} = 21\mu_B \).

The switching time \( \tau \) of the nanorelay cannot be considerably less than the period of free bending vibrations of the nanotube. We and others have estimated this for the (21,21) CNT of length \( L = 0.75\mu\text{m} \) as \(^{20,21}\)

\[
\tau \approx 2\pi \frac{2L^2}{\beta_0 R_{ex}} \sqrt{\frac{\rho}{Y}} \approx 50\text{ns},
\]

where \( \beta_0 \approx 1.8751 \) for the fundamental vibration mode, \( R_{ex} = R + \Delta R / 2 = 1.594\text{nm} \) is the external radius of the nanotube, \( Y \) is Young’s modulus, approximately equal to 1.2TPa,\(^{22,23}\) and \( \rho \approx 1.93\text{g/cm}^3 \) is the density of the nanotube fully filled with \((\text{Ho}_3\text{N})@C_{80}\). To turn on the nanorelay by applying the magnetic field with induction \( B_{min} \approx 300\text{mT} \) for the nanotube of 0.75um length, and \( x^{th}_0 \approx 9.1\text{nm}, \) see Figure 2) it is necessary to use current \( I = 150\text{mA} \) passing through wire 3 (see Figure 1), which is positioned at distance \( d = 1\mu\text{m} \) from the CNTs, for a time interval somewhat larger than \( \tau \approx 50\text{ns} \).

Our nanorelay is controlled by a magnetic field and not an electric field, as previous nanorelays were. This has the advantage that we exclude parasitic charging in the nanodevice. Another advantage is that the voltages necessary for the calculated current (150mA) are lower than in previously proposed nanorelays controlled by an electric field (about 100mV rather than between 1 and tens of volts.) Decoupling (isolation) of control and controlled circuits is another well known\(^{19} \) and obvious advantage.

In summary, we propose a reed switch based on cantilevered CNTs filled with magnetic endofullerenes. The nanorelay turns on as a result of bending of the CNTs by a magnetic force. Operational characteristics of the nanorelay based on the (21,21) CNTs fully filled with \((\text{Ho}_3\text{N})@C_{80}\) endofullerenes are calculated. It is shown that this nanorelay can operate at room temperature.

![Figure 2](image_url)

**Figure 2.** (a) Plot of the minimal magnetic field induction \( B_{min} \) necessary for turning on the nanorelay versus the nanotube length \( L \) (left axis) at \( T = 300\text{K} \). The dependences of half of the minimal \((2x^{th}_0)\) and maximal \((2x^{max}_o)\) distances between the nanotubes for which the nanorelay operation is possible on the nanotube length \( L \) (right axis); \( x^{min}_0 = 1.594\text{nm} \). (b) Plot of the induction \( B \) necessary for the nanorelay to turn on versus the distance \( 2x_0 \) between the nanotubes for nanotube length \( L = 0.75\mu\text{m} \). Arrows indicate the values of \( x^{th}_0, x^{max}_0 \) and \( B_{min} \) shown in (a). (c) A cross-section of the (21,21) nanotube \((2R_{in} \approx 2.5\text{nm}, 2R_{ex} \approx 3.19\text{nm}) \) filled with \((\text{Ho}_3\text{N})@C_{80}\); \( \delta_{ef} \approx 1.14\text{nm} \).

Realizing the proposed nanorelay requires two separate techniques to be combined: a nanorelay based on cantilevered nanotubes must be fabricated,\(^{7,8} \) and the nanotubes must be filled with magnetic endofullerenes.\(^{13–16} \) We hope that this will be possible within the next few years.

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