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An exceptional bimorph effect and a low quality factor from carbon nanotube–polymer composites

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Abstract
Microcantilever actuators made from carbon nanotube polymer are driven at very low pull-in voltages and the thermal bimorph effect reaches 325 μm at 26–110 °C, much greater than the values for existing devices.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

Carbon nanotube (CNT) composites exhibit great potential for engineering and electronic applications and recent studies show that nanotube composites can be operated as field driven cantilever actuators at very low pull-in voltage [1]. In this work, we find that nanotube composites display an exceptional electrothermal actuation (bimorph effect) and that the quality factor measured from AC field driven devices is only 12, much lower than those for existing microelectromechanical system (MEMS).

2. Experimental details

Multi-walled CNTs are grown on Fe defined poly-silicon substrate via acetylene pyrolysis and CNT–parylene composite is produced as follows. First, solid parylene dimers are vaporized at 150 °C in a stainless steel chamber and the vapor is introduced into a neighboring furnace (680 °C) to mix with methylenemethylene. Second, the mixture is readily converted into stable monomeric diradical para-xylylene which is then re-directed into a room temperature deposition chamber where it simultaneously polymerizes and adsorbs onto grown CNTs. Third, CNT–polymer actuators are suspended by removing underlying poly-silicon via vapor-phase XeF_2 [1].

3. Results and discussion

Figure 1(a) shows microcantilever actuators made of CNT–polymer composite and their bimorph effect is characterized as follows. The cantilever beam remains still between 0 and 100 μA and continuous deflection occurs at 100–200 μA, by 25 μm (figure 1(b)). A large deflection (235 μm) appears between 200 and 400 and the cantilever actuator finally touches the substrate at 450 μA. Figure 1(c) plots the thermal deflection versus input current, which indicates that the total displacement driven by the bimorph effect is 325 μm and the analog manipulation reaches 250 μm between 200 and 400 μA (analog manipulation means a linear relationship between the working displacement and input current). This outcome is significant because bimorph actuation in conventional devices is severely constrained by beam rigidity, and working deflection barely exceeds 200 μm [2–4]. We believe that the large bimorph deflection seen here is attributable to polymer softening by Joule heating (resistive current) and this is

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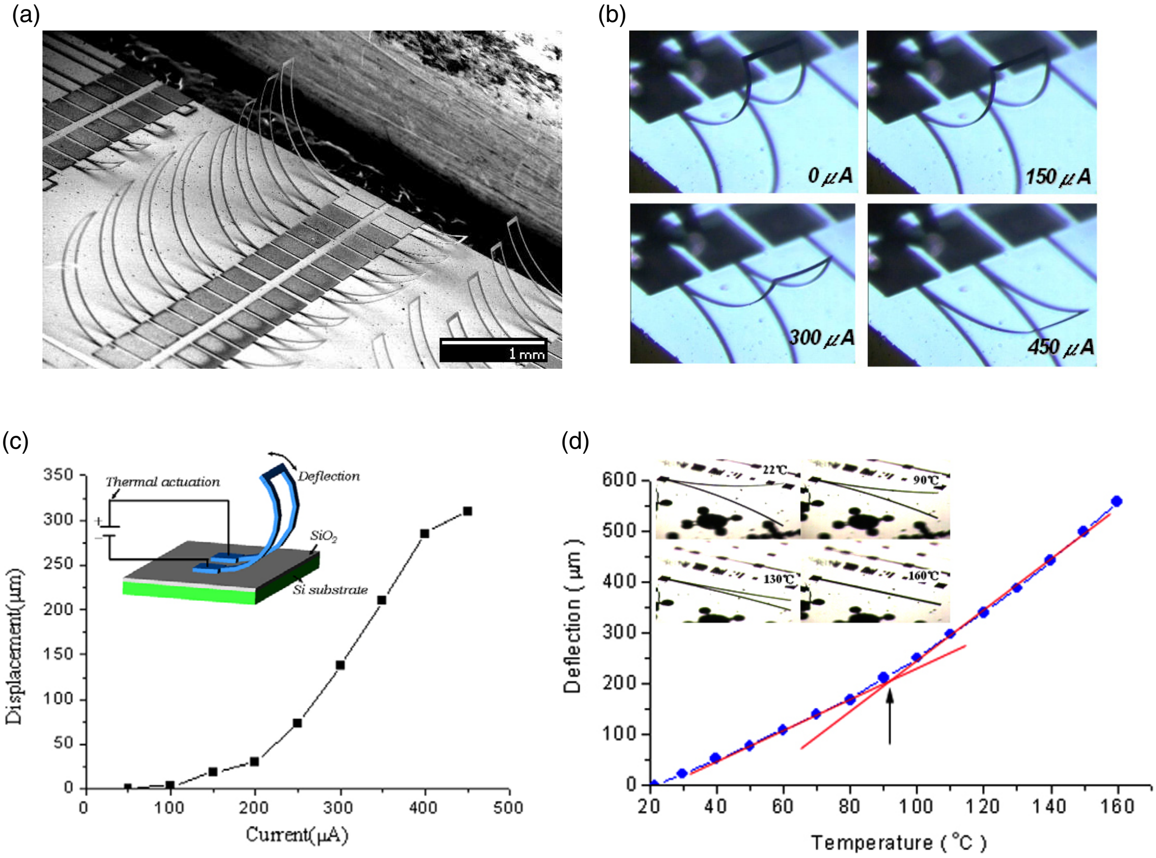

Figure 1. (a) Bimorph actuators made from CNT–polymer composites. (b) *In situ* optical recording of bimorph actuation. (c) Profile of thermal displacement versus input current; the inset shows electrical connections. (d) A CNT cantilever actuator driven by an underlying hot plate at different temperatures.

verified below. First, the output displacement normalized to the beam length (100 μm) as a function of temperature for current devices is 0.15 $\mu\text{m}/(100\ \mu\text{m} \times {}^\circ\text{C})$ which is much greater than values for existing bimorph thermal actuators, e.g. 0.01 $\mu\text{m}/(100\,\mu\text{m}\times {}^\circ\text{C})$ [5], 0.06 $\mu\text{m}/(100\,\mu\text{m}\times {}^\circ\text{C})$ [6], and 0.1 $\mu\text{m}/(100\ \mu\text{m} \times {}^\circ\text{C})$ [7]. Second, a single composite actuator driven by an underlying hot plate shows that the thermal deflection at 90–160 °C (parylene softening point) is greater than those at 20–90 °C, and the increment is a factor of 1.5, measured from the profile slopes (figure 1(d)).

Figure 2(a) shows a composite cantilever driven by an AC electrostatic field, and the pull-in voltage for full deflection (560 μm) is 50 V (a supporting video is available at stacks.iop.org/Nano/19/135304). This value is very low compared with those for existing microcantilevers which demand at least 500 V for a similar displacement [3, 4]. We believe that the field enhancement from nanotubes is responsible for the low pull-in voltage [8, 9]. First, the output deflection versus pull-in voltage simulated by ANSYS commercial finite element software reveals that if CNT–polymer composites are treated as homogeneous conductors (i.e. no field enhancement) the driving potential is 1300 V (green rectangle, figure 2(b)), exceeding the observed data (blue star) 26-fold. Second, if cantilever deflection is considered as an electrical work done, then the electrostatic force (F) acting on the homogeneous cantilever beam is $F = q\boldsymbol{E}$ (q: charge quantity, $\boldsymbol{E}$: electric field). According to reported data [9], the capacitance and q for CNT composites are taken to be 1×10^{-11} F and 5×10^{-10} C respectively, and substitution of the above numbers into the equation gives $F = 100\ \mu$N. This value is two orders of magnitude greater than the actual force acting on the cantilever beam (2.2 μN) estimated on the basis of $\delta_{\text{Max}} = PL^3/3EI$ (L: cantilever length, E: elastic modulus, I: area moment of inertia) [10]. Third, a similar beam structure made from Si has been tested (red triangle, figure 2(b)) and simulated (greenish dot) in comparison with the CNT device. Experimental and simulated profiles appear to be similar and the maximum deflection is 200 μm at 250 V for the former and at 300 V for the latter. Profiles seen here again verify that the Si device requires a larger driving potential and beam deflection is truly limited by structural rigidity. It is noteworthy that when the cantilever beam is driven by underlying electrostatics the displacement firstly occurs at the fixed end where the field intensity is much greater than that at the free end (inset, figure 2(b)). This non-uniform field distribution along the beam length is usually reflected as a curve in the deflection versus voltage profile. Compared with the field distribution in Si devices, that in CNT composite is relatively uniform and this is supported by a nearly vertical profile (blue star), corresponding to simultaneous beam movement upon field attraction. In addition to the profile slope, the field enhancements within

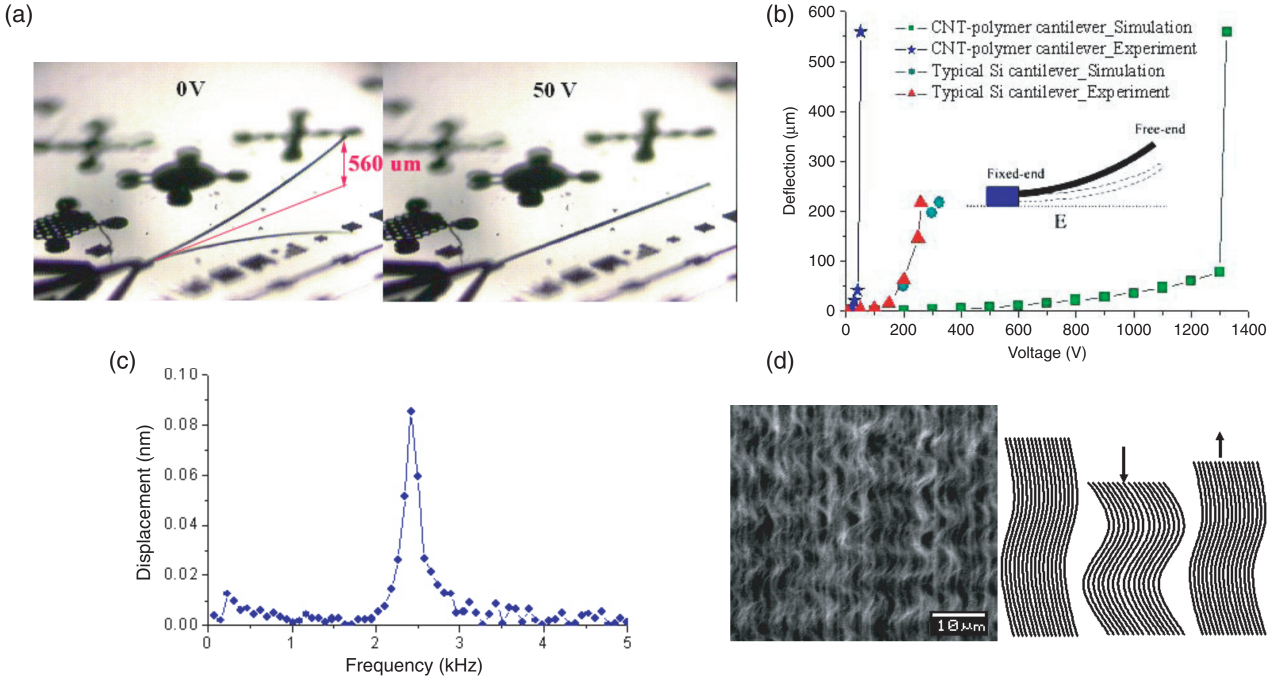

Figure 2. (a) Cantilever actuator excited at 0 V (left) and 50 V (right) respectively. (b) Profiles of displacement versus voltage obtained from simulation (green rectangle) and experiment (blue star) for the CNT composite beam, and from simulation (greenish dot) and experiment (red triangle) for the Si beam. Inset: delineation of beam movement from underlying electrostatic attraction. (c) Profile of displacement versus vibration frequency. (d) SEM image of as grown nanotube morphology (left) and elastic deformations of aligned nanotubes (right).

CNT and Si beam structures can also be compared by looking at the area (A) enclosed between the driving voltages at the minimum and maximum deflection ($D_{\max}$); the ratio $D_{\max}/A$ represents the displacement rate upon constant static attraction: the greater $D_{\max}/A$, the faster the movement. Here we obtained $D_{\max}/A = 8.2$ and 0.6 μm V^{-1} for CNT and Si beams respectively.

The above data clearly indicate that a large pull-in voltage is required if nanotubes do not exert a field amplification within the cantilever beam. Another important factor in governing field driven deflection is that cantilever actuators demand a low quality factor ($Q \leqslant 50$) because fast deflection leads to severe beam vibration and structural disintegration. The vibration resonance f_n of a composite actuator driven in an AC field has been measured in ambient conditions using a laser Doppler vibrometer and a resonance is detected at 2.5 kHz (figure 2(c)). Insertion of the resonance frequency and bandwidth into the equation $Q = (f_1 - f_2)/f_n$ (f_1 and f_2: half-power frequencies) yields $Q = 12$, a value which is much lower than existing MEMS values (Q = 30–50) [2]. The low quality factor means a large damping, and we believe that weaving nanotubes within polymer behave as nanosprings [11] and are responsible for the low Q. Previous workers have discovered that when composites are subjected to compression a shear stress emerges at the tube–polymer interface and the load transfer from polymer to nanotubes is significantly lagged. This yields stress concentration at the interface, and tubules tend to curl in order to release the surrounding stress (damping via the Euler-type buckling) [12]. In our study, aligned nanotubes are already curled into spring-like structures as produced (figure 2(d)), so the damping is only through coupling of nanotube springs with beam oscillation; the former act as energy absorbers and the main mass provides the latter. The natural oscillation frequency ω_o of bare nanotubes is 10^4 Hz [13] and substitution of the damped frequency (ω_D = 2.5 kHz) observed in figure 2(c) into the equation $\omega_D = \omega_o(1 - \zeta^2)^{1/2}$ yields a damping ratio (ζ) of 0.96, indicative of strong damping by incorporated nanotubes ($\zeta \to 0$ for the undamped system). For CNT composites, the damping ratio (ζ) is determined by the binding strength at the polymer–nanotube interface, and weak interfacial binding leads to individual oscillators. The $\zeta \sim 1$ observed here verifies that (i) the nanotube–polymer blending using thermal deposition of monomers (experimental section) yields a sufficient interfacial binding, and (ii) strong coupling of the main mass with nanosprings gives a low Q.

Acknowledgments

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