Engineering Nanomotor Components from Multi-Walled Carbon Nanotubes via Reactive Ion Etching

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Abstract. It has been shown that a multi-walled carbon nanotube (MWCNT) can be used as the rotation enabling element for nanoelectromechanical systems. Modification of the MWCNT to create a rotational bearing in previous devices has concentrated on smaller diameter tubes and mechanical methods to create the bearing. We here investigate reactive ion etching of a MWCNT as a means to engineer nanomotor components, including the rotational bearing.

INTRODUCTION

We recently reported on the fabrication of a rotational actuator mounted on a multiwall carbon nanotube (MWCNT) bearing [1]. In our attempts to better understand the nature of this bearing, we have tried several approaches (see, for example, the report on electrically driven vaporization, also in these proceedings). Here we present one approach, the use of reactive ion etching to partially remove the outer walls of a MWCNT.

A model of our previously produced devices is shown in Figure 1. A MWCNT is suspended between two anchor electrodes. A rotor plate is attached to the middle of the MWCNT, and voltages applied to three stators (two side electrodes and the conductive back gate) are used to control the position and velocity of the rotor. The chief obstacle in the fabrication of these devices is the modification of the MWCNT to create the bearing and axle assembly on which the rotor plate rotates. In our original report, we used very large electrostatic fields to torque the rotor and twist the outer walls of the MWCNT beyond the elastic limit, ultimately breaking those walls and freeing the rotor to rotate.

Although torsional stress did prove to be effective in freeing the nanotube for rotational movement, it also presented several limitations. We found it to be effective only on thinner MWCNTs, of diameter less than approximately 20 nm. For thicker tubes, the electrostatic fields required to rotate the device exceeded the breakdown strength of the surface dielectric. Furthermore, the electrostatic fields required to free each of the thinner MWCNTs varied, depending on tube's diameter and the rotor's exact dimensions, necessitating that each device be freed individually. Finally, the

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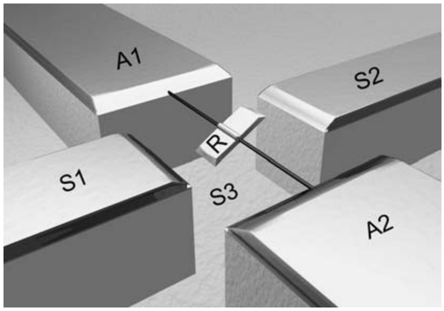

FIGURE 1. A model of the rotational actuator. A rotor paddle (R) is attached to a suspended MWCNT. Two anchors (A1, A2) provide mechanical and electrical contact. Two stator electrodes (S1, S2) and the conductive back gate (S3) provide control over the position and velocity of the rotor.

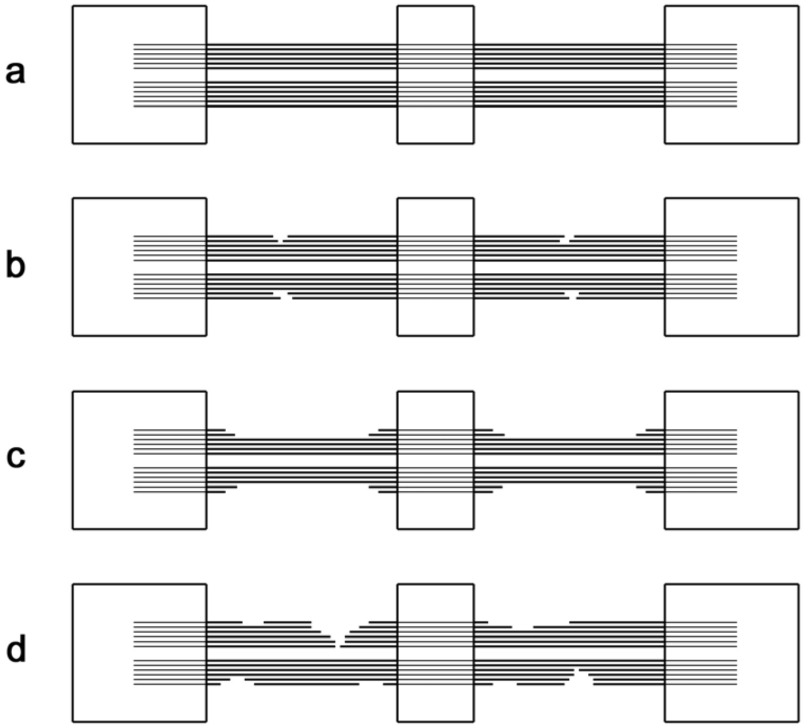

FIGURE 2. A model of bearing creation by various methods: **(a)** An actuator in its pristine state, with all walls intact. Anchors hold the MWCNT on each end, with a rotor paddle suspended in the middle. **(b)** The presumed result of torsional shearing. Though free to rotate, the rotor cannot slide along the nanotube. **(c)** An alternate geometry, in which the rotor can both spin and shuttle along the inner core. **(d)** The apparent outcome of RIE, with localized etch pits causing extensive damage to the inner core before rotational freedom can be achieved.

presumed mechanism of rotational liberation does not allow us to fully investigate the rotational bearing nature of the MWCNT. Torsional stress should damage the outer shell of the MWCNT locally, at one point on either side of the rotor, without affecting the rest of the shell: as the torsional stress is increased, and the shell begins to weaken at some point along its length, it will twist more at that point, and further damage will occur there. Therefore the position of the rotor along the axis of the nanotube is fixed, since the remaining sections of outer shell prevent it from sliding (see Figure 2b). This, in turn, prevents us from testing the full bearing nature of the devices, which we could do by shuttling the rotor along the MWCNT, testing both its linear and rotational freedom. This would also allow us to investigate chiral mismatch and the possibility of the axle bearing assembly undergoing a screw-like effect as it is translated rotationally [2,3].

In hopes of finding a method more suitable for use with all diameters of tubes, and that would at the same time allow the rotor axial freedom, we have investigated the effects of reactive ion etching (RIE).

METHODS

Reactive Ion Etching (RIE) is a technique that is commonly used in semiconductor fabrication to selectively remove material in a controlled and uniform manner. This motivated us to try to reactively etch a MWCNT, hoping to controllably remove the entire outer wall irrespective of its diameter. Given the common use of oxidation to purify raw MWCNT soot we chose to use O_2 as our etching gas. Samples containing suspended MWCNT devices (with rotors and stators already in place) with varying nanotube diameters were placed in a Plasma-Therm PK-12 Parallel Plate Plasma Etcher. The samples were etched in O_2 plasmas at a pressure of 100 mTorr and a power of 15 W for up to 40 seconds.

After etching, the devices were placed in a scanning electron microscope (SEM) for *in situ* analysis of their torsional behavior. We found that devices subjected to identical plasma treatment had their torsional strength weakened to varying degrees. Some devices even appeared to be free, requiring only low applied voltages for large angular displacements, and several times the rotors were already in the vertical position (rotated 90°) when first loaded into the SEM. Meanwhile, other devices, while weakened, still had appreciable torsional strength, and could only be slightly deflected with large applied voltages. We also found several devices that appeared to be stuck to the underlying silicon oxide surface. The MWCNTs were slightly extended, to the point where the rotor could not rotate without touching the substrate. We have seen both from this and from other experiments that once a rotor has touched the surface it is very hard to overcome the van der Waals attraction and pull it out of contact.

Unfortunately, the devices that appeared to be free were prone to failure, unlike the torsionally sheared devices reported earlier. After several rotations the MWCNT would snap somewhere along its length (see Figure 3). Previous work on O_2 etching of graphite surfaces provides insight as to the mechanism of these failures [4]. It was found that instead of etching the surface uniformly, layer by layer, deep etch pits develop at defect locations (see Figure 2d). The presence of etch pits would explain the sudden failure of the MWCNTs. This also provides an explanation for why the effect of the same plasma dose could vary greatly from tube to tube.

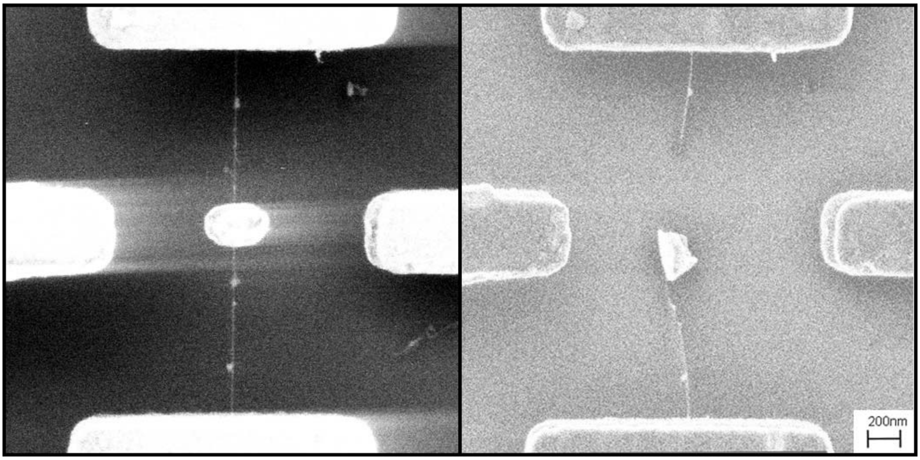

FIGURE 3. SEM micrographs of a MWCNT actuator. The image on the left shows it in its pristine state. The device was then subjected to RIE, after which the torsional spring constant was greatly reduced. Shortly after testing began, however, the device failed, shown in the image at right. The scale bar is 200 nm.

While RIE with O_2 plasma was successful in rotationally freeing the tubes, the lack of uniformity in rotational freedom from tube to tube, their abrupt snapping failure, and the common problem of adhesion to the surface demonstrate that more work on refining this technique is in order.

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