Electrically Driven Vaporization Of Multiwall Carbon Nanotubes For Rotary Bearing Creation

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Abstract. We have previously reported on the creation of nanoscale rotational actuators based on multiwall carbon nanotubes. During the fabrication of these devices, we torsionally sheared the outer walls of the MWCNT to form a rotational bearing. We have designed an alternate technique for forming a rotational bearing geometry using electrically driven vaporization (EDV) of multiwall nanotube shells. While applying this technique, we have discovered an interesting failure mode.

INTRODUCTION

Investigating the exact behavior of nanoscale systems is often quite difficult. Easily accessible imaging techniques such as optical or scanning electron microscopy may not offer high enough resolution, while techniques that do (scanning probe or transmission electron microscopy) are limited in what geometries and materials they can examine (such as planar, conductive or electron-transparent substrates). Components integrated in multi-planar devices on silicon wafers can be particularly hard to image. We recently reported on one such device, a rotational actuator mounted on a multiwall carbon nanotube bearing (see Figure 1) [1]. A gold plate attached to the outer walls of a suspended multiwall nanotube was torqued about the nanotube by electric fields until rotational freedom was achieved. From the lack of restoring force, we determined that one or more outer shells of the multiwall nanotube had failed and were rotating about an inner core. We here explore an alternate (and hopefully highly controlled) method for bearing creation: electrically driven vaporization to selectively remove the outer walls of the multiwall carbon nanotube. In principle, the controlled removal of these walls creates a desirable geometry in which the behavior of the bearing can be easily characterized. Furthermore, with no outer walls extending past the edges of the rotor, the rotor should be able to slide along the inner core, creating a combination of linear and rotational bearing. This opens the door for investigation into chiral mismatch between the inner and outer walls of a multiwall nanotube and its effect on linear translation between the two [2].

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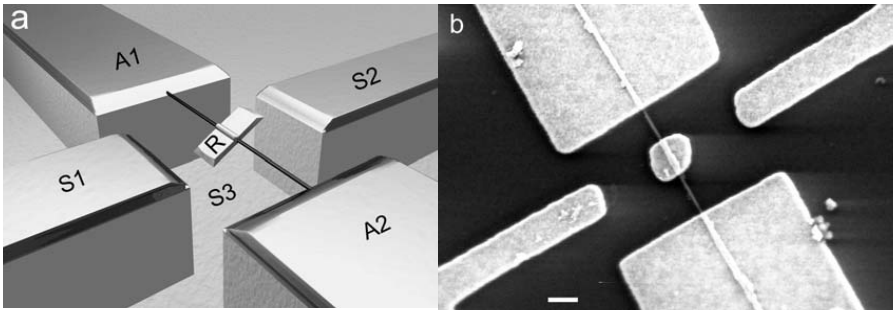

FIGURE 1. Rotational actuator mounted on a MWCNT. The gold rotor paddle can be rotated by applying voltages to the three stator electrodes (two surface stators and the conducting back gate). Artist's conception **(a)** and SEM image **(b)**. The scale bar is 300nm.

METHODS

Electrical driven vaporization (EDV) of the outer walls of a multiwall carbon nanotube (MWCNT) was first discovered by Cumings *et al* in 2000 [3]. By passing current through a MWCNT, they were able to instantaneously vaporize several walls, corresponding to a step up in the resistance of the MWCNT. Related work refining this technique to presumably step-by-step single wall vaporization has been reported by Collins *et al* [4], in which regularly spaced current steps corresponding to discrete steps in the thinning of the nanotube were presented. This technique has also been applied for use in sharpening STM/AFM tips [5] and in the fabrication of a torsional nanotube device with an architecture similar to ours [6].

We find that good electrical contact to the nanotubes is necessary for controlled vaporization to take place. Attempts made on devices with high resistance (>50 kΩ) result in breakage of the nanotube with no intermediate thinning observed. Devices with resistances lower than 10 kΩ reliably achieved stepwise current decays at constant bias voltages. These stepwise current decays sometimes exhibited current steps of equal magnitude (on the order of 10-20 μA, varying from device to device), but were often found to vary greatly (in the range of 5 to 25 μA) on a single device (see figure 2). The exact mechanism underlying these steps is still unknown.

Our first attempt to use EDV in our devices consisted of passing current from one anchor to the other, in the hope that sections of the outer walls would be removed on both sides of the rotor. We found, however, that once a shell failed on one side of the rotor (determined by scanning electron microscope (SEM) imaging of thinning of the MWCNT), all subsequent vaporization would happen on the same side, with no apparent failures occurring on the other side. This could not be remedied by reversing the bias, and would continue all the way to complete breakage of the nanotube.

We were able to vaporize sections of the MWCNT on both sides of the rotor, however, by making electrical contact to the center of the MWCNT and passing current through each side separately. The contact was made by adding an extra lithography step in the device fabrication, during which a thin strip of metal is evaporated to form a bridge between the stator electrodes and the rotor (see inset of figure 2). This contact, however, must later be removed for the device to be able to function. We therefore used Al or Ti, both of which, due to their very high etch rates in hydrofluoric acid, quickly disappear in the subsequent buffered hydrofluoric acid etch used to undercut and suspend the device. Due to the propensity of Al for oxidation we found Ti to be the ideal metal for this temporary contact.

Once a device was contacted with a Ti short we were able to pass current from the stators to either anchor in turn. It proved difficult, however, to induce equal amounts of damage on both sides; the resistance was rarely the same on both sides, often requiring different voltages and currents to begin the current cascades, and sometimes the nanotubes would completely fail without showing any steps at all. When they did occur, the cascades were sometimes difficult to controllably stop. Upon testing the devices *in situ* in an SEM, we found that many would have significantly reduced torsional spring constants. They would not, however, exhibit free bearing behavior – they would eventually break without showing the freedom of motion seen in the torsionally freed devices. We surmise that one side of the tube had been rotationally freed while the other remained as a torsional spring.

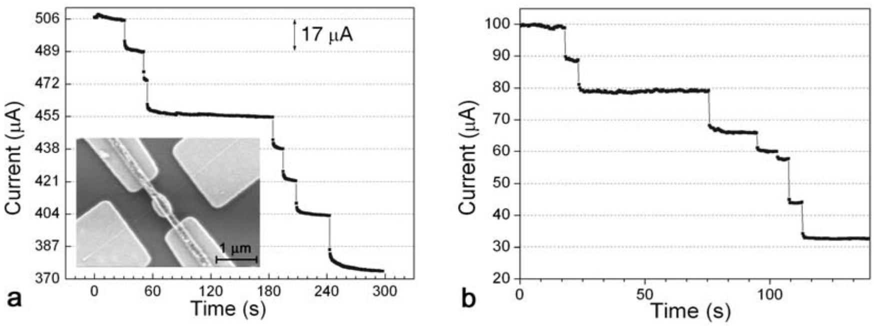

FIGURE 2. Cascades of current steps during EDV. **(a)** Some devices had remarkably equally-sized steps. **(b)** Many, however, showed a large variation in step size. The inset shows a scanning electron micrograph of a device with a Ti bridge connecting the stators to the rotor.

Despite these difficulties we were able to shed more light on the bearing nature of our devices. We repeatedly saw one particularly interesting failure mode. Instead of snapping at some point along its length (as was seen, for example, in devices freed by reactive ion etching [7]), the MWCNT would telescope out, dropping the rotor to the underlying surface (telescoping behavior in MWCNTs was first reported by Cumings & Zettl in 2000 [8]). The result of one such failure is shown in Figure 3. We were able to extend the MWCNT even further by attracting the rotor to the two side stators. Other devices failed similarly, some combining telescopic extension with rotation of the paddle. We submit two possible explanations for this failure mode. EDV may be able to remove internal, unexposed shells, in which case we are seeing the result of a break in the inner core near to the EDV-induced gap in the outer walls. This is contrary to the results of Collins *et al*, as they could correlate each current step with a thinning of the MWCNT (implying that each subsequent exposed wall is being removed). We find it more likely that the inner core is indeed decoupled from the outer shells and free to move, both linearly and rotationally, and we simply removed too many shells, making the exposed core too flexible to support the rotor.

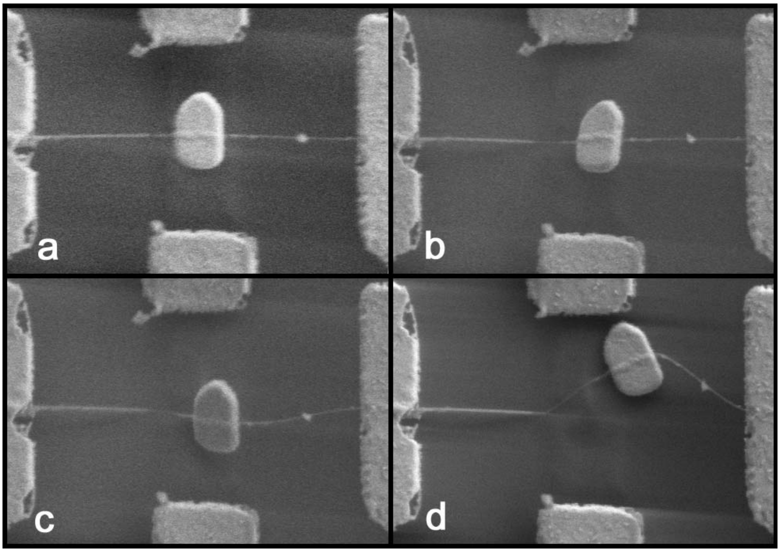

FIGURE 3. Telescopic failure of a MWCNT that has undergone EDV on both sides of the rotor paddle. The images are in sequential order, showing increasing extension: **(a)** No voltages applied. **(b)** Rotor pulled down towards substrate (voltage applied to back gate). **(c)** Rotor pulled towards lower stator. **(d)** Rotor pulled towards upper stator (though hard to see, the nanotube is still intact).

The difficulty of inducing equal damage and failure of the same shells on both sides of the rotor suggests this method requires additional refinement for creating reliable rotational bearings. Additional work on applying EDV to nanotube bearings and other geometries is in progress.

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