Electromechanical Properties of Multiwall Carbon Nanotubes

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Abstract. We examine electrical and coupled electromechanical properties of multiwall carbon nanotubes using transport measurements performed *in-situ* inside a high resolution transmission electron microscope (TEM). In one experiment, large electrical currents are passed through the nanotubes and the failure modes for nanotube "burnout" examined . In a second set of experiments, the electrical resistance between the ends of nanotubes is measured as the tubes are either "telescoped" or partially telescoped and then severely but reversibly mechanically kinked. Our experimental results have implications for nanotube quantum charge transport mechanisms.

Multiwall carbon nanotubes (MWNTs) are comprised of concentric nanotube shells, each shell apparently "just fitting" inside the next, with an intertube spacing roughly equal to the van der Waals graphite interplane distance, 3.4Å[1]. This geometrical constraint suggests that some of the nanotube shells are individually either metals or semiconductors[2]. The composite shell structure may have a complex electrical behavior, especially if charge is transported from one concentric tube shell to the next. In addition, defect structures can affect nanotube transport. Some previous experiments have suggested that singlewalled carbon nanotubes (SWNTs) are more likely to behave as ballistic transport channels than are MWNTs[3]. On the other hand, careful "mercury dipping" experiments on MWNTs have indicated electrical conductance quantization plateaus suggestive of ballistic transport, perhaps confined to only the outer nanotube shell[4-6]. Magnetic flux quantization experiments have received similar interpretations[7].

We here report on electrical conductance measurements performed on MWNTs placed inside a high resolution transmission electron microscope (TEM) fitted with a custom-made electro-mechanical manipulation stage (with x,y,z coarse and fine mechanical motion control). The stage allows an individual MWNT to be selected, bonded to electrodes in a two-probe configuration, and mechanically manipulated while the resistance is monitored and the nanotube is viewed under high microscope magnification. The same apparatus has been previously used to "sharpen and peel" individual MWNTs[8] and to "telescope" the inner core tubes from the outer shell housing, thus forming low-friction linear bearings[9].

In the first set of experiments to be described here, a MWNT is contacted and the electrical current through it is steadily increased until the nanotube electrically and

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mechanically fails, i.e. "burns out". One of several different nanotube failure modes might be expected, depending on the details of the transport mechanism of the MWNT. For example, if the nanotube is indeed a ballistic conductor, then the electrical resistance is confined to the contacts. The contacts therefore are the hot spots for energy dissipation (Power = IV), and these might be expected to fail first (i.e. the contacts should "blow off"). If, on the other hand, the MWNT is a dissipative conductor, with the dissipation more or less uniformly distributed along the length of the tube (but the thermal heat sinking largely confined to the end contacts with a minimal cooling contribution from black body radiation), then the nanotube should assume a well-known temperature profile[10] with a maximum temperature realized at the half-way point along the tube. In this case tube failure would initiate exactly half-way between contacts, in a perhaps catastrophic fuse-like vaporization mode.

Experimentally, neither of these failure modes is observed! Inevitably, as the current is increased past a critical value (typically of order 200 μA) the nanotube "burns out" in a seemingly random location, at a position where even high-resolution TEM imaging (prior to failure) shows no evidence for any obvious nanotube defect structure. MWNTs are never observed to "blow off" the contacts, nor to fail exactly in the middle of the tube. Upon failure, the nanotube appears to mechanically separate over a small region (more like a cut of the tube rather than a fuse-like meltdown), and the two independent leftover pieces of the tube (still attached to the independent electrodes) appear to remain largely intact. If one assumes that the nanotube fails at the most severe defect, then one might expect that the remaining tube portions are more "defect free" than the original tube. Hence, successive burnouts of the remaining tube segments might be used to "purify" a given MWNT, in the sense that the largest remaining defects are successively cut out. We have tested this hypothesis, and indeed the remaining tube segments always have significantly higher threshold currents than the parent tube.

We now describe a second set of experiments, for which a MWNT is first sharpened and peeled[8], thus exposing core tubes. The manipulator electrode is then spot-welded to the core tubes and these are telescoped out of the housing tubes[9]. During the telescoping, the electrical resistance between the "ends" of the tube is monitored. It should be stated at the outset that the "spot welding" method of electrical contact leaves some ambiguity as to which of the concentric core tubes are actually physically contacted (similar ambiguities exist for electrical contact to the housing tubes as well). Nevertheless, at the very least we may assume that the largest diameter core tube is well contacted, and similarly is the largest diameter housing tube. A schematic for the experimental contact and mechanical manipulation configuration is shown in Fig. 1A.

One possible outcome of such an experiment is that the matrix element for charge transfer between the largest diameter core tube and the smallest diameter housing tube depends linearly on the physical "overlap area" between the tubes. In this case the resistance between the ends of the telescoping MWNT might then behave as a sliding variable resistor (a nanotrimpot!). On the other hand, one could imagine other possibilities, such as oscillations in the resistance with telescoping (as transfer matrix element resonances are encountered, depending on the chirality differences beween

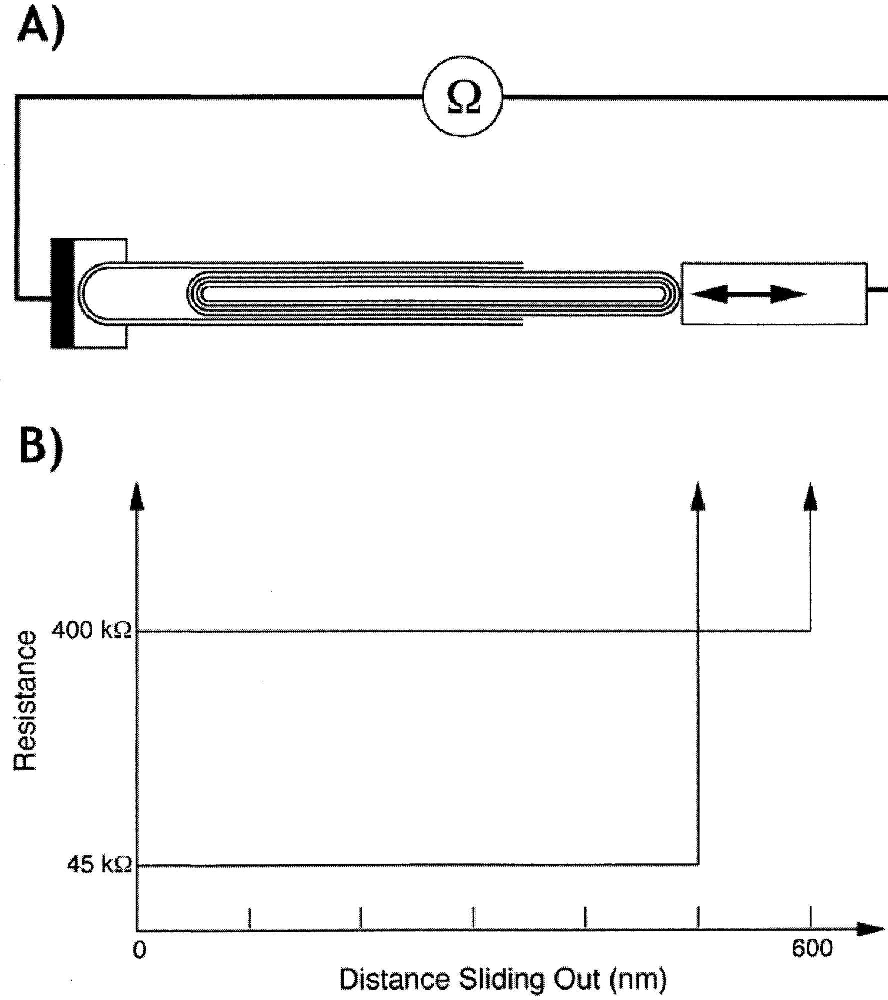

FIGURE 1. A) Schematic for in-situ resistance measurement for a "telescoping" MWNT. B) Resistance vs. core tube displacement for two independent MWNTs.

the particular tubes in sliding contact), or even a steadily *increasing* conductance with *decreasing* overlap area (due to reduced destructive interference of the electronic wavefunctions).

Fig. 1B shows the experimentally determined electrical resistance versus core sliding distance for two independent telescoping nanotubes. One nanotube had an original (fully retracted) resistance of 400kΩ while the other had an original resistance of 45kΩ. As Fig. 1B shows, the resistance of both telescoped tubes is fully *independent* of the distance the core tubes are withdrawn. Only when the core tubes are completely removed from the housing does the resistance change (it jumps to infinity, as expected). The independence of the resistance for core sliding was observed for both core withdrawal and core insertion directions for these tubes, i.e. for telescoping in and out (we were unsuccessful in attempts to reinsert the core into the original housing once the parts were completely separated; this was prevented by the inevitable thermal vibrations of the cantilevered tubes coupled with "zero clearances" for the core and housing parts). The distance-independence of the resistance data of Fib. 1B is somewhat surprising. We do not know to what extent contact resistance dominates the resistance data.

In another experiment similar to that just described in Fig. 1, we did observe a change in resistance with core sliding distance (thus realizing the nanotrimpot). For this particular MWNT the resistance before telescoping was unusually small, of order 6k□ (almost precisely corresponding to a quantum conductance of $G=2e^2/h$), perhaps suggestive of "perfect" contacts.

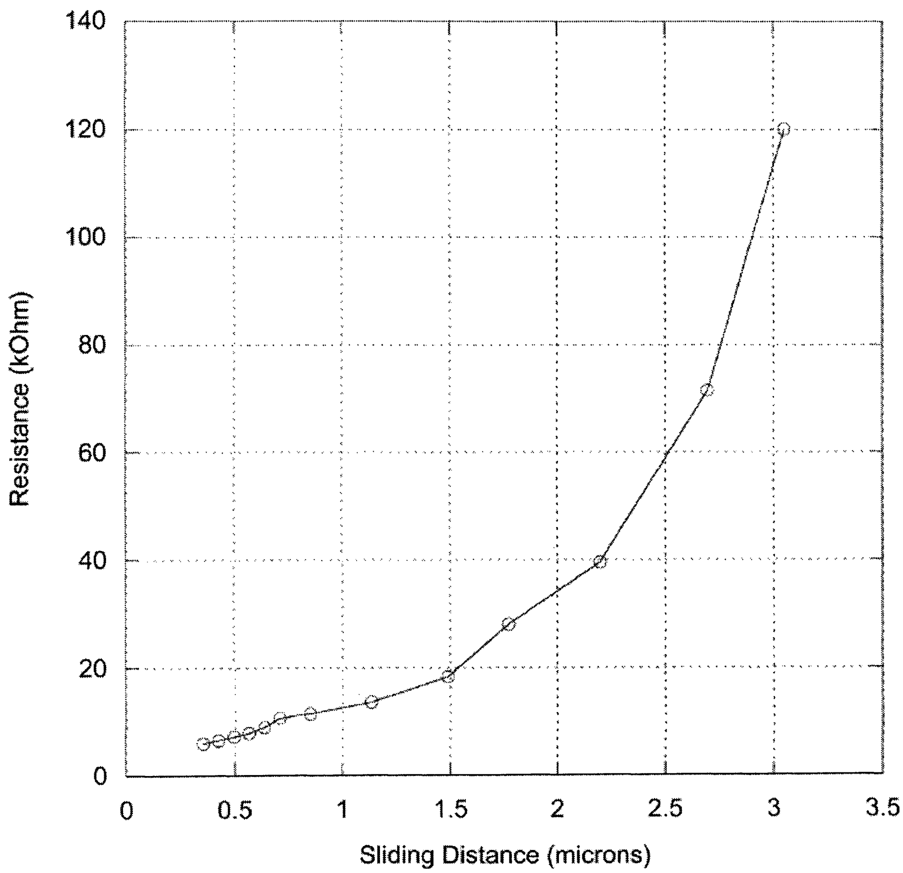

FIGURE 2. Resistance vs. core tube displacement for a MWNT that had an unusually high conductance prior to telescoping.

Fig. 2 shows the resistance between nanotube ends for this MWNT as it is telescoped out. After 3 μm of sliding distance (close to full extension), the resistance has increased by a factor of 20, to 120kΩ. The resistance increase with sliding distance for this MWNT is not linear, but exponential, reminiscent of transport in localized electronic systems.

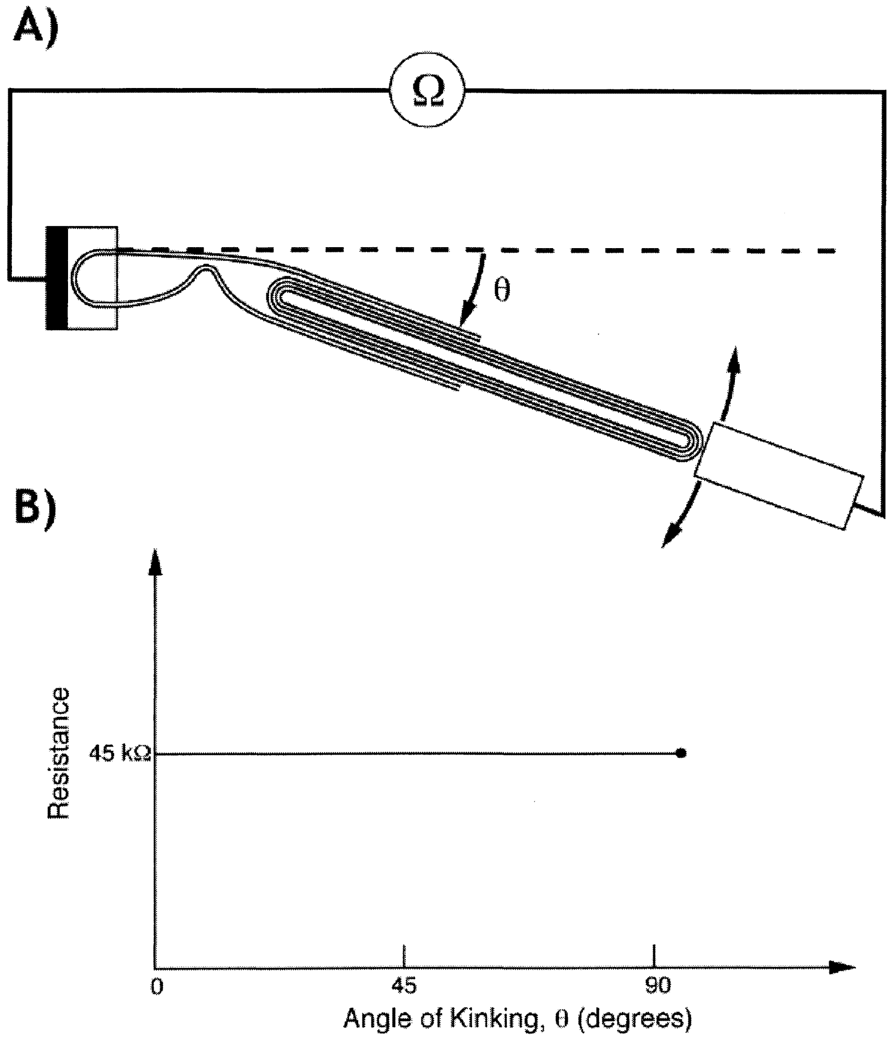

FIGURE 3. A) Schematic for in-situ resistance measurement for a telescoped and kinked MWNT. B) Resistance vs. kink angle.

Fig. 3 shows another experimental configuration we have used to investigate electromechanical response in MWNTs. As shown schematically in Fig. 3A, a MWNT is first partially telescoped out, then lateral forces are applied to the ends of the core structure to induce controlled "kinking" in nanotube fabric. The kinking occurs in the large diameter "hollowed out" region of the tube, where the housing tubes are no longer supported by the inner core tubes. The kinking position can be controlled by varying the extension of the core tubes. All the while, the resistance between the ends of the tube is monitored. Fig. 3B shows the measured electrical resistance as the tube is kinked from its unperturbed straight configuration ($\theta=0^{o}$) to a severe right-angle kink ($\theta=90^{o}$). Surprisingly, no resistance changes are observed even for such extreme kinking. All kinking here performed was fully reversible, with no permanent tears in the nanotube fabric. Our findings suggest that even severely mechanically deformed nanotubes are good electrical conductors (somewhat akin to flexible electromagnetic waveguides).

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