In situ Cyclic Telescoping of Multi-Walled Carbon Nanotubes in a Transmission Electron Microscope

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1. Objective and Summary

The past decade has seen a strong increase in research efforts dedicated to flexible electronics. These devices are ultimately expected to scale down to nanometer-size in order to fit current trends regarding size and portability. Carbon nanotubes have been considered as potential candidates for nanoscale devices since their discovery, due to their low-dimensionality and unique physical properties. As a result, a large number of interesting results have been reported concerning the fabrication and performance of single-nanotube electronic and nanoelectromechanical system (NEMS) [1,2] devices.

In this work, we study the cyclic telescoping of multi-walled carbon nanotubes (MWCNTs) inside a high-resolution transmission electron microscope (HRTEM) equipped with a sharp tungsten micromanipulator [3]. The nanotubes are observed in real time, while simultaneously measuring their electrical properties. Experiments are conducted by first ‘sharpening’ a MWCNT by approaching it with a piezo-controlled tungsten tip and applying a single voltage pulse. This results in controlled and localized peeling of the outer walls, giving rise to a telescope structure. The exposed core is then contacted with the tungsten tip and reproducibly pulled out then re-inserted, while measuring conductance behaviour at each movement step. Results demonstrate that an electrical current can be maintained for multiple in-and-out cycles, and for telescoping distances of up to 650 nm. The systems display complex conductance behaviour, with of most MWCNT telescopes demonstrating diminishing conduction (and current) as a function of the number of cycles, while for some these properties improve. Control experiments have been carried out to investigate the effect of current annealing and beam damage on whole MWCNTs. One potential application for these structures is use as flexible electrical contacts, which allow for relative motion of the two electrodes, while maintaining electrical conduction.

2. Results and Discussion

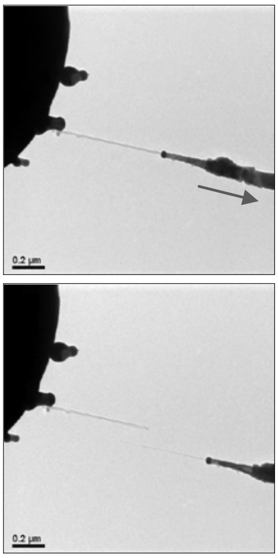

Fig. 1. An *in situ* telescoping run in HRTEM. The MWCNT inner core is entirely pulled out of the outer tubular shield.

Figure 1 shows representative telescoping of a MWCNT up to complete retraction of the inner core. An interesting observation is that the telescoped nanotubes can successfully recover from events that cause the complete de-coupling of the two segments. The core, which has been completely pulled out, can be repeatedly reinserted into the mother tube under delicate manipulations with a piezo-driven W tip. The conductance of the system returns to its previous value (for a similar telescoping distance), while the current through the system improves with respect to previous values. We conclude that the telescoped nanotubes are constantly in a state of equilibrium which is determined by the interplay of several environmental factors. In the absence of the electron beam of the microscope, the characteristics of the structures are influenced by mechanical deformations and structural reconfigurations due to Joule-heating induced temperature. Up to a certain dose rate, when present, the electron beam can lead to the improvement of the tube characteristics by creating links between adjacent walls, which comes in contrast to the degradation effects observed in standard experiments. Performance-wise, the structures display conductivity values which are better than the ones reported previously, which are maintained as the structure is de-coupled and re-attached, and which hold even for cases where the number of pulled walls is low (even for single-walled carbon nanotube retractions), making them attractive for future applications in flexible nanoelectronics.

3. References

[1] L.-M. Peng, Z. Zhang, S. Wang, Materials Today **17**, 433 (2014).
[2] A. Barreiro, R. Rurali, E.R. Hernandes, J. Mozer, T. Pichler, L. Forro, A. Bachtold, Science **320**, 775 (2008).
[3] D. Golberg *et al.* Advanced Materials **24**, 177 (2012).