Processing, Properties and Application of Double-Walled Carbon Nanotubes

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Abstract

Double-walled carbon nanotubes (DWCNTs) consist of two concentric cylinders of carbon and are a unique structural intermediate between single- (SWCNT) and multi- (MWCNT) walled carbon nanotubes. As such, they share many of the attributes of SWCNTs, such as their unique electronic properties; however as the simplest form of a MWCNT, they also offer insights into inter-wall coupling, which has a significant effect on the overall electronic properties of the nanotube.

Furthermore, the concentric structure of DWCNTs enables the outer wall to be selectively functionalized for further chemical processing or sensitization, whilst the inner wall remains in its pristine state and available for signal transduction. The strong coupling between the inner and outer wall, in conjunction with the sensitivity of nanotubes to their surrounding environment, enable the inner wall to indirectly sense chemical changes to the outer wall, without compromising its own structure.

In this thesis, a preliminary investigation into the electrochemical properties of as-prepared DWCNTs was conducted, where they appeared to be advantageous compared to their single-walled counter parts. This advantage arises from the secondary wall, which allows for covalent modification without compromising the sp^2 structure of the inner wall. Despite these observations, the inherent inhomogeneity of as-prepared DWCNT material remained a significant challenge for incorporation into sophisticated electronic and sensor devices. As such, the main focus of this thesis was to overcome the inherent inhomogeneity of DWCNT samples through the use of gel permeation, a well-established technique for separating SWCNTs by diameter, length, electronic character and chirality.

Upon successfully producing enriched DWCNT samples free of SWCNT and MWCNT contaminants, the technique was then further extended to sort DWCNTs according to the electronic character of the outer wall. Enriched metallic and semiconducting outer walled DWCNTs were then incorporated into single nanotube field effect transistors, where the electronic behavior of the four DWCNT types could be directly measured without the uncertainty associated with bulk nanotube films of unknown composition.

Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where due reference is made in the text.

Katherine Elizabeth Moore

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Publications

The following is a list of the original publications arising from the Author's Doctor of Philosophy studies, where this thesis incorporates material from publications 1 to 11.

[1] Moore, K.E., Tune, D.D., Flavel, B.S., *Sorting of Double-Walled Carbon Nanotubes.* In preparation, 2014.

[2] Moore, K.E., Pfohl, M., Hennrich, F., Tune, D.D., Chakradhanula, V.S.K., Kuebel, C., Shapter, J.G., Krupke, R. and Flavel, B.S., *Electronic Sorting of Double Walled Carbon Nanotubes via Gel Permeation***.** Submitted, 2014

[3] Moore, K.E., M. Pfohl, F. Hennrich, V.S. Chakradhanula, C. Kuebel, M.M. Kappes, J.G. Shapter, R. Krupke, and B.S. Flavel, *Separation of double-walled carbon nanotubes by size exclusion column chromatography.* ACS Nano, 2014. 8(7): p. 6756-64, DOI: 10.1021/nn500756a.

[4] Moore, K.E., Moritz, P., Hennrich, F., Kappas, M.M., Shapter, J.G., Krupke, R., Flavel, B.S., *Purification of Double Walled Carbon Nanotubes by Size Exclusion Chromatography* in *ICONN2014: International Conference on Nanoscience and Nanotechnology*. 2014. Adelaide, South Australia.

[5] Moore, K.E., Yu, J., Flavel, B.S., Shapter, J.G., *Vertically aligned double- and single- walled carbon nanotubes for electrochemical surfaces* in *5th Carbon Nanomaterial Biology, Medicine and Toxicology Satellite Symposium (CNBMT13)* 2013. Tallinn, Estonia.

[6] Moore, K.E., Yu, J., Flavel, B.S., Shapter, J.G., *Vertically aligned double- and single- walled carbon nanotubes for electrochemical surfaces* in *NT13: The Fourteenth International Conference on the Science and Application of Nanotubes.* 2013. Helsinki, Finland.

[7] Moore, K.E., Flavel, B.S., Yu, J., Abell, A., Shapter, J.G., *Ferrocene modified α-aminoisobutyric acid protein loading on single and double walled carbon nanotube electrochemical electrodes* in *Australian Nanotechnology Network (ANN) Early Career Researcher Symposium*. 2012. Melbourne, Victoria.

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[11] Moore, K.E., B.S. Flavel, C.J. Shearer, A.V. Ellis, and J.G. Shapter, *Electrochemistry of polystyrene intercalated vertically aligned single- and double-walled carbon nanotubes on gold electrodes.* Electrochemistry Communications, 2011. 13(11): p. 1190-1193, DOI: 10.1016/j.elecom.2011.08.047.

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[13] Horsley, J.R., J. Yu, K.E. Moore, J.G. Shapter, and A.D. Abell, *Unraveling the Interplay of Backbone Rigidity and Electron Rich Side-Chains on Electron Transfer in Peptides: The Realization of Tunable Molecular Wires.* Journal of the American Chemical Society, 2014. 136(35): p. 12479-12488, DOI: 10.1021/ja507175b.

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