Experimental studies on SWNT bundling during FC-CVD synthesis

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We report recent studies on the synthesis of high quality SWCNTs with a ferrocene-based floating catalyst CVD reactor and show that SWCNT networks consisting of highly individualized SWCNTs exhibit substantially improved transparent conductive film (TCF) performance, when compared to previous work with bundled SWCNT TCFs [1]. For these experiments, SWCNT concentration was controllably reduced, leading to reduced bundling probability and formation networks consisting of dominantly individual SWCNTs with mean diameter of 1.1 nm and a narrow helicity distribution near armchair edge, as observed with HR-TEM and electron diffraction techniques. The individual SWCNT networks exhibit excellent performance as transparent conductors with micro-grid patterns [2] showing sheet resistances as low as 67 Ohm/sq. at 97 % transmittance after rapid nitric acid doping. In addition, we carried out the comprehensive statistical analysis on morphology, size and chemical compositions of large number of catalyst nanoparticles, including both catalytically active and inactive ones, by means of aberration-corrected high-resolution transmission electron microscopy. The average diameter of active catalyst particles (~3.3 nm) is over three times larger than that of SWNTs (~1.1 nm), and more than 50 % of the particles are active i.e. grow the tube.

In addition, we used our novel FC-CVD reactor based on spark discharge catalyst generation to experimentally study the effect of bundling on the performance of transparent conducting film (TCF) and thin film transistors (TFT). The synthesis of SWCNTs relies on generation of iron catalyst particles in the diameter range of 4±3 nm with precisely tunable concentration into nitrogen carrier gas with a spark generator, allowing to grow individual and high-quality SWCNTs from CO with well-defined diameter and length distributions. By controlling the gas phase residence time of the as formed SWCNTs prior depositing the network, we controlled the nanotube bundling. The TCFs fabricated of individual SWCNTs have intrinsically higher conductivity to transparency ratio compared to those fabricated of larger bundles. Similarly, network TFTs of individual SWCNTs exhibit higher uniformity in terms of both mobility and ON/OFF ratio compared to larger bundles, with ON/Off ratio up to 10^8 and mobilities above 100 $cm^2V^{-1}s^{-1}$, demonstrating the importance of individualization of SWNCTs.

[1] A. Kaskela, A. G. Nasibulin, M. Y. Timmermans, B. Aitchison, A. Papadimitratos, Y. Tian, Z. Zhu, H. Jiang, D. P. Brown, A. Zakhidov, and E. I. Kauppinen, “Aerosol-Synthesized SWCNT Networks with Tunable Conductivity and Transparency by a Dry Transfer Technique,” Nano Lett., vol. 10, no. 11, pp. 4349–4355, Nov. 2010.
[2] N. Fukaya, D. Y. Kim, S. Kishimoto, S. Noda, and Y. Ohno, "One-Step Sub-10 um Patterning of Carbon-Nanotube Thin Films for Transparent Conductor Applications", ACS Nano vol. 8, pp. 3285-3293, April 2014.