Available online at www.sciencedirect.com
ScienceDirect
Materials Letters 62 (2008) 843–845
materials letters
www.elsevier.com/locate/matlet

AOT dispersed single-walled carbon nanotubes for transistor device application

Shiunchin C. Wang [a], Hui Yang [a,b,*], Sarbajit Banerjee [c], Irving P. Herman [c], Daniel L. Akins [a,*]

[a] CASI and Department of Chemistry, The City College of The City University of New York, New York, New York 10031, USA
[b] Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, PR China
[c] Nanoscale Science and Engineering Center, Columbia University, New York, NY 10027, USA, and Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10027, USA

Received 5 March 2007; accepted 2 July 2007
Available online 6 July 2007

Abstract

The precise placement of single-walled carbon nanotubes (SWNTs) in device configurations has been accomplished by AC dielectrophoresis using a biomimetic surfactant, dioctyl sodium sulfosuccinate (i.e. AOT) dispersed SWNTs. To better serve the utilization of SWNTs/AOT for device fabrication, the dispersion of SWNTs in AOT aqueous solutions was investigated at different micellar concentrations and compared with other surfactants. UV–Vis–NIR spectroscopy and AFM microscopy have been employed to characterize solubilized individual SWNTs. Additionally, dispersed solution has been utilized to align SWNTs in field-effect transistor geometrics. We have ascertained that the AOT isolated individual tubes, well-protected from breakdown during sonication, are good candidates for device applications.

Keywords: Carbon nanotube; Characterization method; Dielectrics; Nanomaterials; Surfactant

1. Introduction

A phenomenal era of expanded research and development opportunities emerged because of single-walled carbon nanotubes' (SWNTs) unusual structural and electrical properties. In 1998, Trans et al. [1] reported the fabrication of field-effect transistors (FET) using carbon nanotubes as bridge to connect the gap between source and drain terminals. To date, various methods have been employed to search for better performance by growing tubes on FET substrate [2] or placing surfactant dispersed SWNT directly on the electrode [3]. Surfactant dispersed individual SWNTs have been made for better control of aligning tubes over AC dielectrophoretic deposition process [4]. However, the insolubility of SWNTs has been a hindrance to exploit their unique properties. To surmount this problem, nanotubes can be dispersed into solutions through either covalent [5] or non-covalent [6] interactions to improve solubility and to unbundled the aggregate ropes that are formed from intertube van der Waals interactions. For FET applications, maintaining electronic properties of the tubes is necessary. An anionic surfactant AOT is used to solubilize and debundle SWNTs in aqueous solution without altering the tubes' electronic property. The short tail structure of AOT might allow efficient intercalation between bundled SWNT constituents. To better serve the usage of SWNTs/AOT for transistor devices, the dispersion of SWNTs/AOT was investigated at different micellar concentrations and with other surfactants. To demonstrate the potential device applications of these individualized tubes, the fabricated field-effect transistors were exhibited by aligning SWNTs/AOT in device geometries by AC dielectrophoresis.

2. Experimental

SWNTs were purchased from Carbon Nanotechnologies, Inc. Concentration of AOT aqueous solutions were prepared in 0.05, 0.1, 0.2, 0.5 and 1.0 wt.%. HiPco SWNTs were added to the AOT solutions to a final SWNT concentration of 1 mg/mL

* Corresponding authors. Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, PR China. Tel./fax: +86 21 32200534.
E-mail addresses: hyang@mail.sim.ac.cn (H. Yang), akins@sci.ccny.cuny.edu (D.L. Akins).

0167-577X/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.matlet.2007.07.001

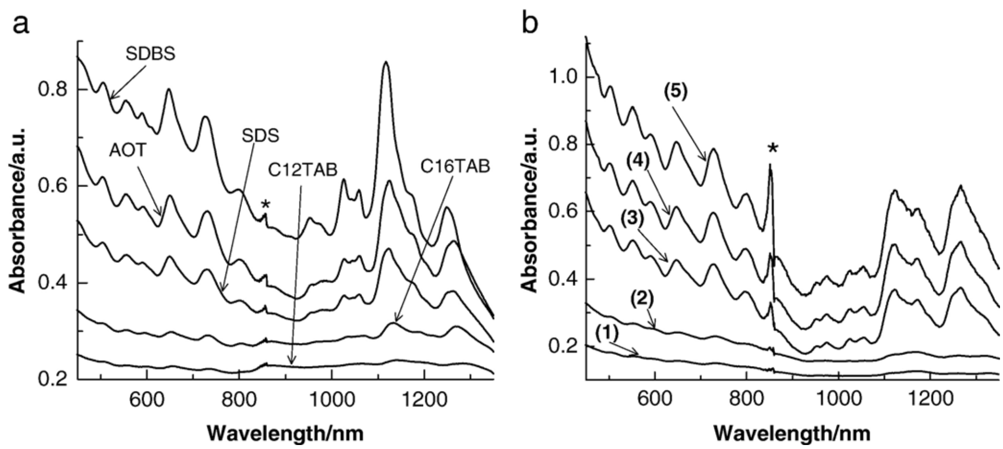

Fig. 1. UV–Vis–NIR spectra depicted dispersion of AOT with other surfactants (A) and AOT concentration in (1) 0.05, (2) 0.1, (3) 0.2, (4) 0.5 and (5) 1.0 wt.% (B).

with 2 h sonication then 2 h centrifugation (17,000 rpm). Four 0.5 wt.% surfactants, anionic (SDBS and SDS) and cationic (C_{12}TAB and C_{16}TAB), were also separately used to disperse SWNTs.

For AC dielectrophoretic alignment of SWNTs, microelectrode structures with a 3 μm gap were fabricated on Si/SiO_2 (500 nm) substrates by electron-beam lithography followed by the evaporation of 5 nm Cr and then 50 nm Au. A peak-to-peak voltage (5 MHz, 8 V) was applied across the electrodes. The AOT dispersed SWNTs (8 μL) was dropped in the gap from 1 to 5 min, and was then washed with ~800 μL deionized water. Scanning electron microscopy (SEM) images were obtained on a Hitachi S4700 at an accelerating voltage of 0.8 kV. The device characteristics of the obtained SWNT/FETs were studied using a HP4145 semiconductor parameter analyzer using the silicon substrate as a back gate.

3. Results and discussion

Fig. 1A shows absorption spectra of SWNTs dispersed in five different surfactant solutions. The solubilities of SWNTs dispersed in anionic surfactants (SDBS, SDS and AOT) are higher than the cationic surfactants (C_{12}TAB and C_{16}TAB). The double-tailed AOT is shown to solubilize the SWNT sample better than SDS. Moreover, AOT displays similarity as SDBS (a commonly used surfactant for SWNTs dispersion). Thus, AOT appears to be a good noncovalent wrapping species for debundling SWNTs. The critical micelle concentration (CMC) is an important parameter when surface tension of a surfactant can influence the formation of micellar structures within host solutions [7]. Concentrations of AOT that exceed the CMC would be expected to have some visible effects on dispersion of the nanotubes [8]. Fig. 1B shows that AOT concentration exceeding the CMC results in sharp peaks of singularity that denotes well-dispersed SWNTs [9].

Fig. 2 provides AFM images of SWNTs originally in 0.5 wt.% AOT aqueous solution. The AFM phase and height images reveal separated, individual SWNTs coated with AOT. The height of the tubes is visualized as approximately 2 nm. This dimension can be rationalized as resulting from SWNTs surrounded by one layer of surfactant. Moreover, it can be seen from the figure that the mean length of SWNTs/AOT dispersion is longer than dispersed by other surfactants, suggesting that the AOT isolated individual tubes were well-protected from breakdown during sonication. Longer SWNTs are beneficial for FET fabrication.

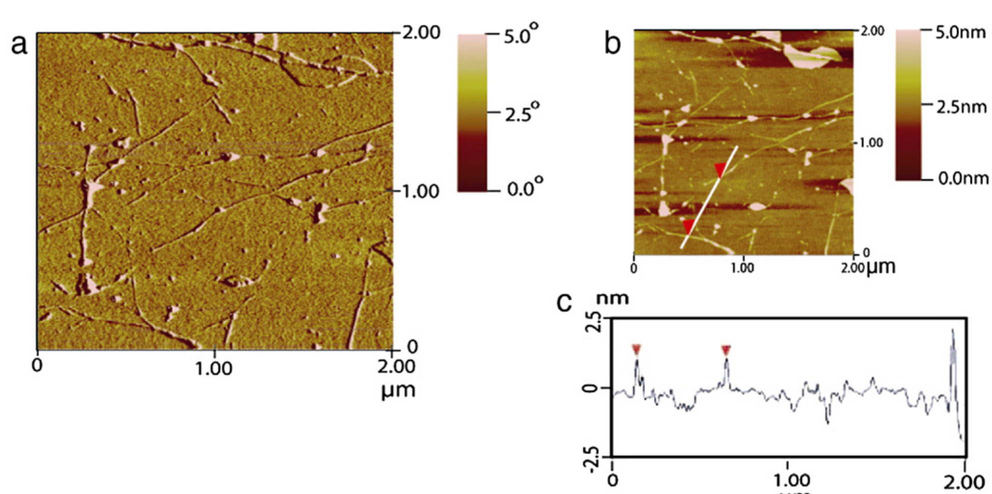

Fig. 2. Tapping mode AFM image of dispersion of SWNTs/AOT in phase image (A), height image (B), and height analysis (C).

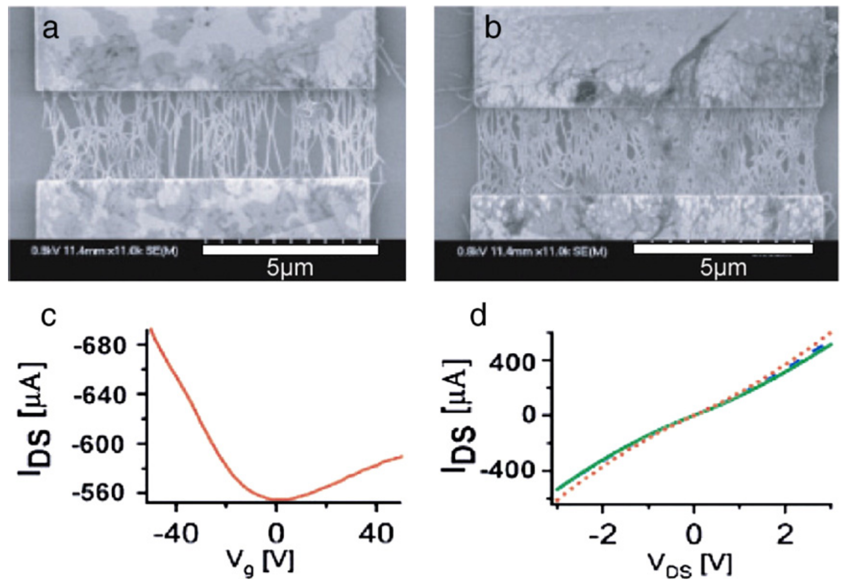

Fig. 3. SEM images of SWNTs aligned by AC dielectrophoresis of deposition times in (a) 4 and (b) 5 min. (c) The drain–source current versus the gate voltage for the device in (b). (d) Plot of the drain–source current versus V_{DS} at three different gate voltages at −50 V (red), 50 V (blue) and 0 V (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 shows SEM images of SWNTs aligned across the gaps by AC dielectrophoresis [10]. The dielectrophoretic force is proportional to the difference between the complex dielectric constants of the nanotube and the water medium. Metallic nanotubes have a much higher dielectric constant than water (ε=79) due to the presence of mobile carriers (effectively infinite). Semiconducting SWNTs have a bandgap dependent dielectric constant (~2–5); however, due to the large surface conductance induced by the electric double layer at the surfactant interface, both metallic and semiconducting species are pulled into the gap [5]. Zeta potential measurements (−65.6 mV), indicate that the AOT–SWNT micelles carry a significant negative charge, which is not surprising given the anionic nature of the surfactant. The number of nanotubes in the gap can be controlled by the duration of the dielectrophoresis process from 1 to 5 min. The dielectrophoretically aligned nanotubes initially have high contact resistances (ranging up to 10 MΩ) due to the presence of the surfactant at the contacts. However, upon annealing under nitrogen at 300 °C, the contacts are significantly improved and ambipolar devices are obtained as shown in part c and d of Fig. 3.

4. Conclusions

The data suggest the simplicity and efficiency of using AOT for dispersion of SWNTs. The isolated tubes are good candidates for nanotube transistor applications. Moreover, AOT surfactant encapsulated tubes are well-protected from break down during sonication. This is a factor for choosing AOT to use in device alignment. We have demonstrated the precise placement of these long individual nanotubes in device geometries. Ambipolar transport has been demonstrated for a SWNTs network device.

Acknowledgments

H.Y. thanks the National Natural Science Foundation of China (20673136), the GF Fundamental Foundation of China (A1320070025), the National "863" High-Technology Research Program of China (2006AA05Z136), the 100 People Plan Program of the Chinese Academy of Sciences and Pujiang Program of Shanghai City (No. 06PJ14110). D.L.A. thanks NSF-IGERT grant DGE-9972892; NSF-MRSEC grant DMR-0213574; NSF-NSEC grant CHE-0117752; and DoD-ARO Cooperative Agreement DAAD19-01-1-0759 and grant W911NF-04-1-0029.

References

[1] S.J. Tans, A.R.M. Verschueren, C. Dekker, Nature 393 (1998) 49–52.
[2] R.V. Seidel, A.P. Graham, J. Kretz, B. Rajasekharan, G.S. Duesberg, M. Liebau, E. Unger, F. Kreupl, W. Hoenlein, Nano Lett. 5 (2005) 147–150.
[3] Y. Kim, S. Hong, S. Jung, M.S. Strano, J. Choi, S. Baik, J. Phys. Chem., B 110 (2006) 1541–1545.
[4] R. Krupke, F. Hennrich, H.B. Weber, M.M. Kappes, H.v. Löhneysen, Nano Lett. 3 (2003) 1019–1023.
[5] S. Banerjee, T. Hemraj-Benny, S.S. Wong, Adv. Mater. 17 (2005) 17–29.
[6] A. Star, Y. Liu, K. Grant, L. Ridvan, J.F. Stoddart, D.W. Steuerman, M.R. Diehl, A. Boukai, J.R. Heath, Macromolecules 36 (2003) 553–560.
[7] B.P. Binks, W.-G. Cho, P.D.I. Fletcher, D.N. Petsev, Langmuir 16 (2000) 1025–1034.
[8] O. Matarredona, H. Rhoads, Z. Li, J.H. Harwell, L. Balzano, D.E. Resasco, J. Phys. Chem., B 107 (2003) 13357–13367.
[9] M.S. Strano, C.A. Dyke, M.L. Usrey, P.W. Barone, M.J. Allen, H. Shan, C. Kittrell, R.H. Huge, J.M. Tour, R.E. Smalley, Science 301 (2003) 1519–1522.
[10] S. Banerjee, B. White, L. Huang, B.J. Rego, S. O'Brien, I.P. Herman, J. Vac. Sci. Technol., B 24 (2006) 3173–3178.