Molecular Sensing with Single-Walled Carbon Nanotubes

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Single-walled carbon nanotubes (SWNT) are molecular wires composed of a layer of graphite rolled-up into a cylindrical tube. Recently, carbon nanotubes have attracted a growing interest to serve as active films in chemical sensors[1] due to their excellent electronic properties, such as high carrier mobilities[2] and ballistic transport.[3] Moreover, SWNTs are composed entirely of surface atoms, and therefore making them an ideal material for molecular sensors based on physical adsorption. Generally, three techniques are used to produce CNTs: 1) Carbon arch-discharge technique,[4] 2) Laser-ablation technique,[5] 3) Chemical vapor deposition (CVD) technique.[6] All three methods produce high quality CNTs, however CVD is the preferred technique because it affords the ability to grow well-ordered and perfectly aligned SWNT arrays over large areas.[1]

SWNT sensors are Field Effect Transistors (FETs) which are composed of either one SWNT or a network of SWNTs. Generally, SWNTFETs exhibit p-type transistor behavior under ambient conditions.[1] Adsorption of molecules on the surface of a SWNT induces a chemical gating effect to the SWNT which modulates the device conductance. This change in conductivity serves as the basis for chemical sensing and its magnitude is highly dependant on the electron donating/withdrawing properties of a particular analyte.[1]

Theoretical calculations and experimental results are in general disagreement with respect to the observed current changes and the SWNT-adsorbate interaction.[7] Theoretical calculations predict that gas molecules interact weakly with SWNTs and a minimal amount of charge transfer occurs.[7]. Moreover, Heinze et al. and Derycke et al. showed that oxygen gas exposure can alter the electrical characteristics of a SWNT device, and thus showing that the metal/SWNT contacts can affect the sensor response.[8] Also, Robinson et al. showed that structural defects introduced on the sidewall of a SWNT can act as adsorption sites for gas molecules.[9] SWNTFETs modified with defects showed higher electrical responses then the unmodified SWNTFETs, and therefore it is not clear if the electrical responses reported in the literature are entirely caused by charge transfer between the SWNT and the surface adsorbates.

SWNTFETs offer great promise for miniaturized, low power, and highly sensitive gas sensing technology. Kong et al. reported the first realization of a SWNT gas sensor and showed that the electrical response of a SWNTFET changes upon exposure to NO_2 and NH_3.[10] In addition, Qi et al. described that functionalizing a SWNT with polymers can impart both sensitivity and selectivity to a SWNT sensor.[11]

Incorporating SWNT networks as the sensing material of SWNTFETs can generate a SWNT device that exhibits sensitivity and selectivity as well as producing a new class of SWNT chemical sensors. Novak et al. described that networks of SWNT are capable of detecting 1 ppb of dimethyl methylphosphonate (DMMP). Moreover, they showed that these sensors are reversible and selective towards common interferents such as hydrocarbon vapors and humidity.[12] Snow et al. showed that the capacitance of SWNT network can be used to develop a new class of sensors which are fast, highly sensitive and completely reversible.[13] In a separate study, Snow et al. demonstrated that a device can be designed such that both capacitance and conductance measurements can be carried out simultaneously and discovered that the ratio of the conductance response to the capacitance response is intrinsic to a particular analyte, which can be used as a molecular fingerprint to assist in the identification of a vapor.[14]

Finally, in chemical sensing, achieving selectivity not sensitivity is the real problem.[15] SWNTs are sensitive to most surface adsorbates, and thus achieving sensor selectivity can be challenging. However, modifying the surface of a SWNT via thin-metal films, polymers films, and biomolecules can generate a selective SWNT sensor. For instance, Kong et al. developed a SWNT hydrogen gas sensor by evaporating a thin layer of Palladium metal on the surface of a SWNT.[16] In addition, Star et al. developed a SWNT sensor for carbon dioxide detection by utilizing a polymer/starch reconignition layer specific for CO_2 gas.[17] Recently, Staii et al. developed a new class of SWNT sensors by decorating the surface of a SWNT with single stranded DNA. This type of sensor is self-regenerating and enhances the electrical response of particular analytes.[18]

References

1. (a) Snow, E.S.; Perkins, F.K.; Robinson, J.A. "Chemical Vapor Detection Using Single-Walled Carbon Nanotubes" Chem. Soc. Rev. **2006**, 35, 1-10. (b) Sinha, N.; Ma, J.; Yeow, J.T.W. "Carbon Nanotube-Based Sensors" J. Nanocsi. Nanotechnol. **2006**, 6, 573-590.

2. Zhou, X.; Park, J.-Y.; Huang, S.; Liu, J.; McEuen, P.L. "Band Structure, Phonon Scattering and the Performance Limit of Single-Walled Carbon Nanotube Transistors" Phys. Rev. Lett. **2005**, 95, 146805-1-146805-4.

3. Javey, A.; Guo, J.; Wang, Q.; Lundstrom, M.; Dai, H. "Ballistic Carbon Nanotube Field-Effect Transistors" Nature **2003**, 424, 654-657.

4. Iijima, S. "Helical Microtubules of Graphitic Carbon" Nature **1991**, 354, 56-58

5. Thess, A.; Lee, R.; Nikolaev, P.; Dai, H.; Petit, P.; Robert, J.; Xu, C.; Lee, Y.-H.; Kim, S.-G.; Rinzler, A.G.; Colbert, D.T.; Scuseria, E.; Tomanek, D.; Fischer, J.E., Smalley, R.E. "Crystalline Ropes of Metallic Carbon Nanotubes" Science **1996**, 273, 483-487.

6. Cassell, A.M.; Raymakers, J.A.; Kong, J.; Dai, H. "Large Scale CVD Synthesis of Single-Walled Carbon Nanotubes" J. Phys. Chem. B **1999**, 103, 6484-6492.

7. Zhao, J.; Buldum, A.; Han, J.; Lu, J.-P. "Gas Molecule Adsorption in Carbon Nanotubes and Nanotube Bundles" Nanotechnology **2002**, 13, 195-200.

8. (a) Heinze, S.; Tersoff, J.; Martel, R.; Derycke, V.; Appenzeller, J.; Avouris, Ph. "Carbon Nanotubes as Schottky Barrier Transistors" Phys. Rev. Lett. **2002**, 89, 106801-1-106801-5. (b) Derycke, V.; Martel, R.; Appenzeller, J.; Avouris, Ph. "Controlling Doping and Carrier Injection in Carbon Nanotube Transistors" Appl. Phys. Lett. **2002**, 80, 2773-2775.

9. Robinson J.A.; Snow, E.S.; Badescu, S.C.; Reinecke, T.L.; Perkins, F.K. "Role of Defects in Single-Walled Carbon Nanotube Chemical Sensors" Nano Lett. **2006**, 6, 1747-1751.

10. Kong, J.; Franklin, N.R.; Zhou, C.; Chapline, M.G.; Peng, S.; Cho, K.; Dai, H. "Nanotube Molecular Wires as Chemical Sensors" Science **2000**, 287, 622-625.

11. Qi, P.; Vermesh, O.; Grecu, M.; Javey, A.; Dai, H. "Toward Large Arrays of Multiplex Functionalized Carbon Nanotube Sensors for Highly Sensitive and Selective Molecular Detection" Nano Lett. **2003**, 3, 347-351.

12. Novak, J.P.; Snow, E.S.; Houser, E.J.; Park, D.; Stepnowski, J.L.; Mcgill, R.A. "Nerve Agent Detection using Networks of Single-Walled Carbon Nanotubes" Appl. Phys. Lett. **2003**, 83, 4026-4028.

13. Snow, E.S.; Perkins, F.K.; Houser, E.J.; Badescu, S.C.; Reinecke, T.L. "Chemical Detection with a Singled-Walled Carbon Nanotube Capacitor" Science **2005**, 307, 1942-1945.

14. Snow, E.S.; Perkins, F.A. "Capacitance and Conductance of Single-Walled Carbon Nanotubes in the Presence of Chemical Vapors" Nano Lett. **2005**, 5, 2414-2417.

15. Ken S. Suslick, personal correspondence.

16. Kong, J.; Chapline, M.G.; Dai, H. "Functionalized Carbon Nanotubes for Molecular Hydrogen Sensors" Adv. Mater. **2001**, 13, 1384-1386.

17. Star, A.; Han, T.-R.; Joshi, V.; Gabriel, J.-C.P.; Grüner, G. "Nanoelectronic Carbon Dioxide Sensors" Adv. Mater. **2004**, 16, 2049-2052.

18. Staii, C.; Johnson, A.T.; Chen, M.; Gelperin, A. "DNA-Decorated Carbon Nanotubes for Chemical Sensing" Nano Lett. **2005**, 5, 1774-1778.