Carbon Nanotubes for Nanofluidic Devices

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We have discovered that hydrothermal synthesis[1,2] can produce multi-wall carbon nanotubes with a high aspect ratio, high degree of graphitization, and wide internal channels with superior smoothness at the nanometer scale. Many of these tubes are closed, while some remain opened. Typical hydrothermal nanotubes have large internal diameters (up to 90% of the outer diameter) and a very low specific weight. We frequently refer to them as "carbon nanopipes," due to their resemblance to pipes used in the macro world, but being orders of magnitude smaller. Thin-wall carbon pipes with internal diameters from 10 nm to 1000 nm have been produced. Hydrothermal nanopipes have nanoscale graphitic walls of 2-30 nm with minimal or no disorder and a high continuity of graphene planes. Those of the tubes that are capped, are gas-tight and can maintain hundreds of atmospheres of internal pressure in the vacuum (10^{-8} Torr) of a transmission electron microscope (TEM) even at temperatures above 500°C, thus, demonstrating very high containment strength. Some of the closed-end tubes contain a high-pressure encapsulated aqueous fluid (Fig. 1), which displays clearly segregated liquid and gas separated by well-defined curved interfaces.[3] None of the open-end nanotubes displayed any apparent fluid inclusions. Overall, the hydrothermal nanotubes appear to have a higher degree of graphitization than other carbon tubes of the same external diameter.

We have demonstrated [4,5] the use of hydrothermal capped carbon nanopipes as miniature pressure vessels, which form an experimental apparatus allowing direct observations of fluid dynamic phenomena occurring in the nanotube interior. This nanotube system has been used as a test platform for *in-situ* nanofluidic experiments in a transmission electron microscope (Fig. 1). Wetting, evaporation and condensation phenomena, as well as thermocapillary migration have been induced and monitored by means of electron irradiation, and the dynamics of the relevant processes has been analyzed.

This work may lead to the development of a new generation of carbon nanopipes (nanotubes with thin walls and a large internal diameter) for nanofluidic and other applications. *In-situ* experiments in these nanopipes facilitate understanding of the fluid processes in chemistry and biology. Understanding the behavior of fluids in nanochannels is also important for the efficient design and operation of future micro- and nano-fluidic devices. This creates a basis for the development of a variety of nanofluidic devices, such as nano-pumps, chemical factories on a chip, biochips, and nano-analytical devices that utilize channels of <100 nm in diameter. Availability of nanopipes and understanding of fluid dynamic phenomena at the nanoscale could result in the development of chemical and biological technologies.

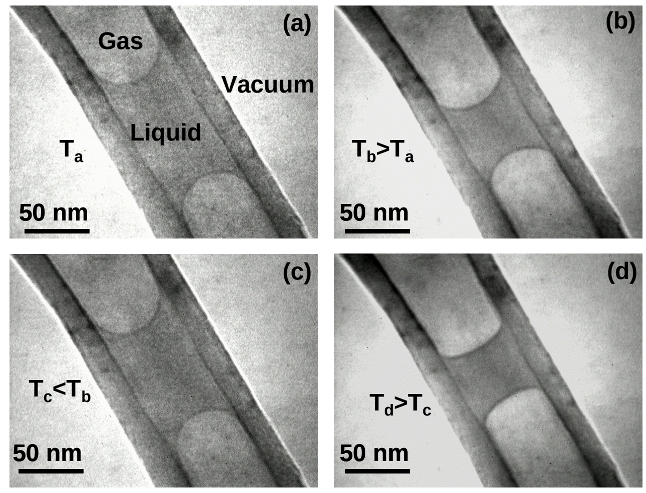

Fig. 1. TEM micrograph sequence of a typical carbon nanotube portion showing the reversible volume contraction/expansion of a liquid inclusion upon heating/cooling achieved by manipulating the electron beam. (a) initial shape of liquid at temperature T_a, (b) inclusion gets thinner after heating at $T_b>T_a$, (c) return to the initial size after cooling at $T_c<T_b$, (d) heating is repeated ($T_d>T_c$) resulting in a contraction of the liquid inclusion.

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