Nanotubes:
Stiff, Elastic, and Electronically Diverse

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A nanotube is an arrangement of atoms in a single tube or set of concentric tubes enclosed upon each other. These tubes typically have a radial diameter of nanometers and lengths ranging from nanometers to greater than micrometers. One of the first reports of C nanotubes was published in 1991 by Iijima,[1] and in 1992 Tenne described the discovery of WS_2 nanotubes.[2] Since then, the synthesis and properties of these materials have been extensively studied.

The main advances in the synthesis of C nanotubes have centered on the development of methods to make long, single-walled nanotubes in large quantities. These methods include arc discharge,[3] laser ablation,[4] and metal-catalyzed chemical vapour deposition.[5] One of the current models for the mechanism of nanotube growth is the base growth mechanism.[6]

Other long nanotubes, including BN,[7] WS_2, and MoS_2, have also been grown recently. Multi-walled MoS_2 nanotubes have been synthesized by heat treatment of MoS_2 powder,[8] template growth,[9] and the reductive sulfidization of MoO_3 particles.[10] Multi-walled WS_2 nanotubes have been produced by the reductive sulfidization of WO_3 particles using H_2S and H_2.[11] The sulfidization process is proposed to proceed from the outside of the particle in, as H_2S diffuses radially inward and H_2O diffuses outward. This process results in the formation of a multi-walled nanotube structure.

The electronic properties of single walled C nanotubes were theorized to be highly dependent on their wrapping topology.[12] This wrapping is depicted below in figure 1. Tubes are indexed by a wrapping vector, (n,m), with n and m representing integer multiples of the unit cell vectors. There are three types of tubes: armchair (n=m), zig-zag (n,0), and 'chiral' (any other index). Scanning tunneling microscopy studies showed that the topology of the nanotubes was related to their electronic properties: all armchair single wall nanotubes are zero band gap materials, whereas zigzag or chiral

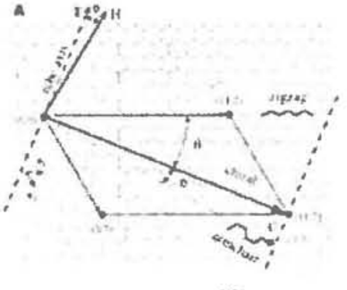

Figure 1[16]

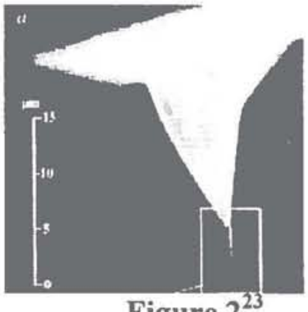

Figure 2[23]

tubes with integer values of (n-m)/3 are either small or zero band gap materials.[13-15] Nanotubes with other topologies behave as semiconductors, with a typical band gap greater than 0.6eV.[13-15]

Nanotubes have been theoretically predicted to have impressive mechanical properties, with a Young's modulus of 1.1–5.5 TPa.[16,17] Recently, the Young's modulus was directly measured using amplitude modulation,[18] beam deflection,[19] and anchored measurements.[20] The values of the Young's modulus of multi-walled nanotubes measured using these techniques ranged from 0.8-1.9 TPa, is similar to the experimental in-plane graphite value of 1.06 TPa, one of the stiffest materials known. The mechanical properties of both C and WS_2 nanotubes make them useful in SFM experiments.[20,21] For example, figure 2 shows a nanotube bundle mounted on a SFM tip, which was used to image a trench that the original pyramidal tip could not image.

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