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CHAPTER 6

Single-Walled Carbon Nanotubes for Nanoelectronics

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I. Introduction

Around 1991, inspired by the discovery and mass production of cage-like fullerene molecules, several research groups began to consider the properties of a hypothetical carbon structure: a single layer of graphite wrapped into a seamless cylinder—the carbon nanotube (Hamada *et al.* 1992; Mintmire *et al.* 1992; Saito *et al.* 1992a). It was soon realized that carbon nanotubes may be metallic or semiconducting, and should be excellent one-dimensional (1D) conductors at room temperature. About the same time, carbon deposits resulting from the arcing of graphite rods to obtain fullerenes were investigated via transmission electron microscope (TEM) and revealed to contain concentrically nested carbon nanotubes (Iijima 1991) ("multi-walled carbon nanotubes" or MWNTs). Soon thereafter, single-walled carbon nanotubes (SWNTs) were synthesized (Bethune *et al.* 1993; Iijima and Ichihashi 1993). Measurments soon revealed a material with an extraordinary convergence of exceptional thermal, mechanical, and electrical properties: the thermal conductivity of individual MWNTs exceeds that of diamond at room temperature (Kim *et al.* 2001); the elastic modulus of carbon nanotubes may exceed 1 TPa, making them the strongest known fibers (Treacy *et al.* 1996; Wong *et al.* 1997; Poncharal *et al.* 1999); electrons are transported ballistically through SWNTs over distances greater than 1 μm at room temperature (Bachtold *et al.* 2000).

The first electrical experiments on individual metallic SWNTs were reported in 1997 (Bockrath *et al.* 1997; Tans *et al.* 1997), with experiments on individual semiconducting SWNTs in 1998 (Tans *et al.* 1998b). In the following 5 years, research into the electrical properties of nanotube devices has exploded. A picture has emerged of a material with superlative electrical properties: metallic SWNTs have conductivities comparable to the best metals, and can carry current densities exceeding 10^9 A/cm^2; semiconducting SWNTs have mobilities exceeding the best silicon MOSFETs. Still, enormous challenges remain to incorporating this material into a useful device technology: nanotubes are still expensive to manufacture, currently nanotubes cannot be sorted according to electronic property (metallic and semiconducting nanotubes are randomly mixed), and methods for placing nanotubes with precision onto substrates are in their infancy.

This chapter will serve to review the current status of research on carbon nanotubes for nanoelectronics applications. The focus will be on single-walled carbon nanotubes, whose properties are closest to ideal, though some of the conclusions will also apply to multi-walled nanotubes. It should be noted that there exist a number of excellent reviews of the electronic transport properties of individual single-walled (Dekker 1999; Nygard *et al.* 1999; McEuen 2000; Louie 2001; Yao *et al.* 2001) and multi-walled carbon nanotubes (Schonenberger *et al.* 1999; Schonenberger and Forró 2000; Forró and Schonenberger 2001).

This chapter is structured as follows. Sections II–IV will serve as a review of the fundamental theoretical and experimental work on the electronic properties of carbon nanotubes. Section II will introduce the theory of the electronic structure of carbon nanotubes, including the remarkable dependence of their electronic properties on structure. Section III will discuss the synthesis of carbon nanotubes, as well as the techniques used to place individual nanotubes into electronic circuits. Section IV will discuss the room temperature and cryogenic electronic transport properties of individual metallic and semiconducting SWNTs.

Section V will give an overview of the current state of research on nanoscale electronic devices incorporating carbon nanotubes. These devices range from field-effect and single-electron transistors to more exotic junction devices and electromechanical devices. Some significant advantages of carbon nanotubes for nanoelectronics become obvious: the exposed channel of the semiconducting nanotube transistor makes it an excellent candidate for chemical and biological sensing, the geometry of the carbon nanotube automatically guarantees small junction capacitance and high transconductance in nanotube single-electron transistors, the long electron mean free paths and high thermal conductivity in nanotubes suggests their use as interconnects to devices located at nanotube junctions, and the high stiffness and robustness of nanotubes makes them attractive for high-speed mechanical devices.

Sections VI–VII will attempt to look to the future of nanotube research. Section VI discusses the challenges that stand in the way of developing nanotube devices into useful technologies, such as the production of electronically uniform material, and the development of techniques for precise placement of nanotubes within circuits. Section VII will move beyond carbon nanotubes to pose the question: Are there other materials that have some of the advantageous properties of carbon nanotubes, but avoid some of the difficulties? Indeed a rapidly growing number of non-carbon nanotubes and nanowires have been synthesized, some with very attractive properties.