# **Electron Transport** in Single-Walled Carbon Nanotubes

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# Abstract

Single-walled carbon nanotubes (SWNTs) are emerging as an important new class of electronic materials. Both metallic and semiconducting SWNTs have electrical properties that rival or exceed the best metals or semiconductors known. In this article, we review recent transport and scanning probe experiments that investigate the electrical properties of SWNTs. We address the fundamental scattering mechanisms in SWNTs, both in linear response and at high bias. We also discuss the nature and properties of contacts to SWNTs. Finally, we discuss device performance issues and potential applications in electronics and sensing.

**Keywords:** electron transport, phonon scattering, single-walled carbon nanotubes, scanning probe.

## Introduction

Single-walled carbon nanotubes (SWNTs) are nanometer-diameter cylinders consisting of a single graphene sheet wrapped up to form a tube. They were discovered in the early 1990s,<sup>1,2</sup> and the first electrical measurements on individual tubes were performed in 1997-1998.3-5 Since then, a huge number of papers have been written on their electrical properties, including a number of excellent reviews.<sup>6–8</sup>Both experiments and theory have shown that SWNTs can be either metals or semiconductors, and their electrical properties can rival, or even exceed, the best metals or semiconductors known. In this article, we give a brief update on the status of the field of SWNT electronics. The data presented here are taken from work in which the authors were collaborators, but they are representative of the field.

The remarkable electrical properties of SWNTs stem from the unusual electronic structure of the two-dimensional (2D) material graphene. It has a bandgap in most directions in **k**-space, but has a vanishing bandgap along specific directions and is called a zero-bandgap semiconductor. When wrapped to form a SWNT, the momentum of the electrons moving around the circumference of the tube is quantized. The result is either a one-dimensional (1D) metal or semiconductor, depending on how the allowed momentum states compare with the preferred directions for conduction. Metallic SWNTs have a Fermi velocity  $v_{\rm F} = 8 \times 10^5$  m/s that is comparable to typical metals. Semiconducting SWNTs have a bandgap  $E_g = 0.9$  eV/*d*, where *d* is the diameter of the tube in nanometers.

A SWNT has four 1D channels in parallel due to spin degeneracy and the sublattice degeneracy of graphene. By the Landauer formula, the conductance is then

$$G = (4e^2/h)T,\tag{1}$$

where *e* is the electron charge, *h* is Planck's constant, and *T* is the transmission coefficient for electrons through the sample (see, for example, Reference 9). The conductance of a ballistic SWNT with perfect contacts (T = 1) is then

$$4e^2/h = 155 \,\mu\text{S},\tag{2}$$

corresponding to a resistance of 6.5 k $\Omega$ . Imperfect contacts will give rise to an additional contact resistance  $R_c$ . Finally, the presence of scatterers that give a mean free path  $\ell$  for backscattering contribute an ohmic resistance to the tube,

$$R_{\rm t} = (h/4e^2)L/\ell,\tag{3}$$

where L is the tube length. The total resistance is approximately the sum of these three contributions:

$$R = h/4e^2 + R_{\rm c} + R_{\rm t}.$$
 (4)

In the following, we will discuss the resistance of SWNT devices at room temperature in terms of these contributions. At low temperatures, SWNT devices exhibit a number of interesting quantum phenomena, but we refer the reader to existing reviews for a discussion of these topics.<sup>7,10,11</sup>

To make devices, nanotube growth and deposition techniques (described in the article by Liu et al. in this issue) are combined with semiconductor processing technologies. An example is shown in Figure 1. Source and drain electrodes allow the conducting properties of the nanotube to be measured, and a third gate electrode is used to control the carrier density on the tube. When the conductance of the tube is measured as the gate voltage is varied, two classes of behavior are seen. In





Figure 1. (a) Schematic illustration of a single-walled carbon nanotube (SWNT) device, showing the source, drain, and gate electrodes. (b) Atomic force microscopy (AFM) image of a SWNT device.

some cases, the conductance *G* is relatively independent of the gate voltage  $V_{g}$ , corresponding to a metallic tube. For other tubes, a dramatic dependence of *G* on  $V_{g}$  is seen, indicating semiconducting tubes. Metallic and semiconducting SWNT devices are discussed separately in the following sections.

# Metallic SWNTs

Devices made from metallic SWNTs were first measured in 1997.3,4 Two-terminal resistances at room temperature can vary significantly, ranging from as small as  $\sim$ 6 k $\Omega$  to many megaohms. Most of this variation is due to the variations in contact resistance between the electrodes and the tube. As techniques for making improved contacts have been developed, conductance values have steadily increased. The best contacts have been obtained by evaporating Au or Pd over the tube, often followed by an annealing step. A number of groups have seen conductances approaching the value ( $G = 4e^2/h$ ) predicted for a ballistic nanotube,<sup>12,13</sup> indicating long mean free paths. Other measurements corroborate this conclusion, such as scanning probe experiments that probe the local voltage drop along the length of the nanotube.14

The resistance versus channel length for a metallic SWNT is shown in Figure 2. The measurement was performed by using a gold-coated atomic force microscopy (AFM) tip as a movable metallic contact. The re-



Figure 2. Resistance versus length for a metallic single-walled carbon nanotube (SWNT). The device was measured using a gold-coated atomic force microscopy tip as a drain electrode, as illustrated in the upper-left inset. Lower-right inset shows the I–V characteristic of a metallic SWNT. The current increases linearly at low bias, but rolls over to a much lower slope at high bias before failing at V  $\approx$  4 V. At high bias, electrons emit high-energy phonons, dramatically decreasing the conductance. Main graph adapted from Reference 17.

sistance decreases linearly with length and is of the order of the quantized value  $h/4e^2$  at very short lengths. The measurements yield a resistance per unit length of  $R/L = 4 \text{ k}\Omega/\mu\text{m}$ , a mean free path of  $\ell \approx$  $2 \mu m$ , and a room-temperature resistivity of  $\rho \approx 10^{-6} \ \Omega$  cm. The conductivity of metallic nanotubes can thus be equal to, or even exceed, the conductivity of metals like copper at room temperature. The observed scattering length at low bias is believed to be caused by absorption and emission of low-energy acoustic phonons.15-17

Optic and zone-boundary phonons are too high in energy ( $\hbar\Omega \approx 0.15$ –2 eV) to be relevant at low source-drain voltages  $V_{\rm sd}$ . At high  $V_{\rm sd}$ , however, electrons can emit these phonons and efficiently backscatter. This leads to a dramatic reduction in the conductance at high bias, as was first reported by Yao et al.<sup>18</sup> This can be readily seen in the inset graph in Figure 2 by the change in slope around 1 V. The differential resistance dV/dI is ~800 k $\Omega/\mu$ m, yielding a mean free path of  $\sim 10 \text{ nm}$ , <sup>16–17</sup> more than 100 times shorter than at low bias. Still, the current carried at the point of failure is remarkably high, corresponding to a current density of  $j \approx 10^9$  A/cm<sup>2</sup>. This is orders of magnitude larger than current densities found in present-day interconnects. This large current density can be attributed to the strong covalent bonding of the atoms in the tube. Unlike in metals, there are no low-energy defects or dislocations that can easily lead to the motion of atoms in the conductor.

# Semiconducting SWNTs

Semiconducting SWNT devices were first reported by Tans et al. in 1998.<sup>5</sup> Figure 3 shows a measurement of the con-



Figure 3. (a) Conductance G versus gate voltage  $V_g$  for a semiconducting nanotube with Au contacts. The device conducts well in the p region, and weakly in the n region, due to the ohmic and Schottky contacts, respectively, as schematically illustrated in the insets. ductance of a semiconducting SWNT as the gate voltage applied to the conducting substrate is varied. The tube conducts at negative  $V_g$  and turns off with a positive  $V_g$ . The resistance change is many orders of magnitude between the on and off state. This device behavior is analogous to a *p*-type metal oxide semiconductor fieldeffect transistor (MOSFET), with the nanotube replacing Si as the semiconductor.

In the data of Figure 3, the conductance initially rises linearly with  $V_{\rm g}$  as additional holes are added to the nanotube. At more negative gate voltages, the conductance stops increasing and instead is constant. This limiting conductance is due both to the tube and to the contact resistance between the metallic electrodes and the tube. The value of this resistance can vary by orders of magnitude from device to device, but on-state resistances of ~10–50 k $\Omega$  can often be obtained with Au or Pd contacts.<sup>19,20</sup>

In the regime where *G* grows linearly with  $V_{g}$ , the properties of the device can be described by the ohmic relation

$$G = C_{g'}(V_{g} - V_{g0})\mu/L,$$
(5)

where  $C_{g'}$  is the capacitance per unit length of the tube,  $V_{go}$  is the threshold voltage, and  $\mu$  is the mobility. The capacitance per unit length of the tube can be estimated or obtained from other measurements such as Coulomb blockade at low temperatures.<sup>3,4,21</sup> Using this, we can infer the mobility of the tube. We find typical hole mobilities of 1000–10,000  $\text{cm}^2/\text{V}$  s for tubes grown by chemical vapor deposition (CVD), but mobilities as high as 20,000 cm<sup>2</sup>/V s have been reported.<sup>22</sup> This is significantly higher than the values reported to date in deposited nanotubes.<sup>23–26</sup> It is also higher than the mobilities in Si MOSFETs and is comparable to the in-plane mobility of graphene (30,000  $\text{cm}^2/\text{V}$ s), indicating that SWNTs are a remarkably high-quality semiconducting material.

At large positive gate voltages, weak *n*-type conductance is also observed, especially in larger-diameter tubes.27,28 The conductance in the *n*-type region is typically less than in the *p*-type region because of the work function of the Au electrodes. The Au Fermi level aligns with the valence band of the SWNT, making a p-type contact with a barrier for the injection of electrons, as shown schematically in Figure 3. Different metals, or even the same metal processed under different conditions, can have different band alignments. For many metals, the Fermi level resides in the bandgap, making a Schottky contact for both n and p regions.<sup>29,30</sup> The resulting device then acts as a Schottky barrier transistor, with very different scaling properties

with channel length than for a nanotube with ohmic contacts.

In air, a large hysteresis in *G* versus  $V_{g}$  is observed when sweeping up and back, with threshold voltage shifts of many volts being common. In addition, the threshold voltage and the resistance of the contacts are very sensitive to the processing history of the device-for example, heating or exposure to UV radiation drives off oxygen<sup>31</sup> and water vapor,<sup>32</sup> changing the device characteristics. Controlling adsorbate doping is an important challenge to be addressed. Recent work at IBM has taken important steps in this direction.<sup>24</sup> However, this sensitivity of the conductance to the local chemical environment has also spurred interest in nanotubes as chemical sensors.33,34

Controlled chemical doping of tubes, both *p*- and *n*-type, has been accomplished in a number of ways. Doping with alkali metals that donate electrons to the tube was first used to create *n*-type devices and later *n*-type transistors,  $^{35-37} p-n$  junctions,  $^{38}$  and p-n-p devices.  $^{39}$  Alkali metals are not stable in air, however, so other techniques are under development, such as using polymers for charge-transfer doping.  $^{40}$ 

In order to maximize device performance, the tube gate capacitance  $C_{g}'$  should be maximized. Recently, researchers have investigated a number of ways to increase the gate coupling, such as using a very thin Al oxide<sup>26</sup> or an electrolyte solution as a gate.<sup>41,42</sup> An example where a thin layer of a high-κ dielectric material, ZrO<sub>2</sub>, is used as the gate is shown in Figure 4.<sup>43</sup> I-Vcurves at different gate voltages are shown in Figure 4c. Standard FET behavior is seen; the current initially rises linearly with  $V_{\rm sd}$ and then becomes constant in the saturation region. The nanotube exhibits excellent electrical characteristics, with a maximum transconductance  $dI/dV_g = 12 \ \mu A/V$  at  $V_{\rm g} = 0.4$  V. Normalizing this to the device width of  $2d \approx 4$  nm gives a transconductance per unit width of  $\sim 3 \text{ mS}/\mu \text{m}$ . This is significantly better than current-generation MOSFETs.

The properties of the semiconducting SWNTs described here are quite remarkable. Perhaps most surprising is the high mobility obtained, given the small channel width and the simplicity of the fabrication methods employed. This is largely due to the lack of surface states in these devices. As is well known from bulk semiconductors, surface states generally degrade the operating properties of the device, and controlling them is one of the key technological challenges to device miniaturization. A SWNT solves the surface state problem in an elegant fashion. First, it begins with a 2D material with no chemically reactive dangling bonds. It then rids itself of the problem of edges by using the topological trick of rolling itself into a cylinder, which has no edges.

# **Challenges and Future Prospects**

The results given here show that singlewalled carbon nanotube devices possess excellent electronic properties. Metallic tubes have conductivities and current densities that meet or exceed the best metals, making them promising candidates for interconnects. Semiconducting SWNT field-effect transistors have mobilities and transconductances that meet or exceed the best semiconductors. These electronics applications are being vigorously pursued by a number of research labs and corporations, but many challenges remain, such as controlling the quality of the contacts to nanotubes.

Opportunities also exist for integrating nanotube electronics with other chemical, mechanical, or biological systems. For example, nanotube electronic devices function perfectly well in biological conditions (i.e., salty water)<sup>42</sup> and have dimensions comparable to typical biomolecules (e.g., DNA, whose width is approximately 2 nm). This makes nanotube electronic devices an excellent candidate for electrical sensing of individual biomolecules. Chemical specificity can be obtained by functionalizing the nanotube with an



Figure 4. (a) Schematic illustration and (b) transmission electron micrograph of a singlewalled carbon nanotube (SWNT) device with a thin  $ZrO_2$  layer as the gate dielectric (the "glue" layer is part of the sample preparation for imaging). (c) I–V characteristics at different gate voltages for a SWNT field-effect transistor using a  $ZrO_2$  gate. (Adapted from Reference 43.)

appropriate recognition site. Initial results using SWNTs for biological sensing have been reported.<sup>44–46</sup>

There are also a host of other device geometries under exploration beyond the simple wire and FET structures described here. Examples include the p-n and p-n-p devices mentioned previously,<sup>38,39</sup> nanotube/nanotube junctions,<sup>47-49</sup> and electromechanical devices.<sup>50–52</sup> For example, strain can be used to modify the bandgap of SWNTs.<sup>53</sup>

Much more challenging is the issue of device manufacturability. Although a great deal of work has been done, the progress to date has been modest. For example, in tube synthesis, the diameter of the tubes can be controlled reasonably well,54 but not their chirality. The synthesized tubes remain a mixture of metals and semiconductors. In CVD, the general location for tube growth can be set by patterning the catalyst material, but the number of tubes and their orientation relative to the substrate are still not well defined. Furthermore, the high growth temperature (900°C) for CVD tubes is incompatible with many other standard Si processes. The alternative approach, depositing tubes on a substrate after growth, avoids this high-temperature issue but still suffers from the chirality and positioning limitations discussed. Furthermore, the wet processing of the tubes may degrade their electrical properties. Efforts are under way to address these issues. For example, techand semiconducting SWNTs by dielectrophoresis<sup>57</sup> or their different chemical reactivity<sup>58</sup> are under development, as described in the article by Haddon et al. in this issue.

While much work remains to be done, there are apparently no fundamental barriers to the development of a highperformance electronic technology based on SWNTs. The science of nanotubes has come a long way in 10 years, and with the involvement of the engineering community to help improve reproducibility and manufacturability, the technology of nanotubes will likely see similar progress in the coming years.

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# Materials Data Sources

A listing of useful data sources for materials researchers, conveniently compiled in one location.

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