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Transport through crossed nanotubes

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Abstract

In order to study the electronic properties of single-walled carbon nanotube junctions we have fabricated several devices consisting of two crossed nanotubes with electrical leads attached to each end of each nanotube. We correlate the properties of the junctions with the properties of the individual nanotubes: metal–metal, metal–semiconductor, and semiconductor–semiconductor junctions are all formed. We find that metal–metal SWNT junctions exhibit surprisingly high conductances of 0.1–0.2 e^2/h. Semiconductor–semiconductor junctions also show significant linear response conductance. Metal–semiconductor junctions behave as p-type Schottky diodes. All the junction types can reliably pass currents of hundreds of nanoamps.

Keywords: One-dimensional; Electron transport; Carbon nanotube

Electron transport experiments have shown that individual single-walled carbon nanotubes (SWNTs) are an ideal system for studying fundamental mesoscopic physics such as single-electron transport [1,2] and Luttinger liquid behavior [3]. Experiments have also demonstrated the utility of SWNTs as nanoscale electronic devices such as field-effect transistors (FETs) [4] and single-electron transistors (SETs) [1,2]. Electronic transport measurements on systems of more than one tube could greatly expand upon this base. Multiple-tube devices may prove ideal for constructing experiments to study basic physics such as coupled quantum dots and interacting Luttinger liquids. Moreover, the ability to integrate SWNTs into a device technology may rest upon finding ways to connect them into circuits; the properties of nanotube–nanotube junctions are then essential.

In order to study the properties of SWNT–SWNT junctions we have fabricated devices consisting of two crossed SWNTs with four electrical contacts, one on each end of each SWNT. The devices were fabricated on a backgated substrate consisting of degenerately doped silicon capped with 1μm SiO_2. Cr/Au alignment marks were defined on the SiO_2 surface by electron-beam lithography. The alignment marks consisted of 1μm^2 variously shaped features placed 8μm apart on the substrate, allowing for electrical contacts to be defined in a subsequent lithography with 100 nm accuracy over an area of 70 μm × 90 μm. SWNTs

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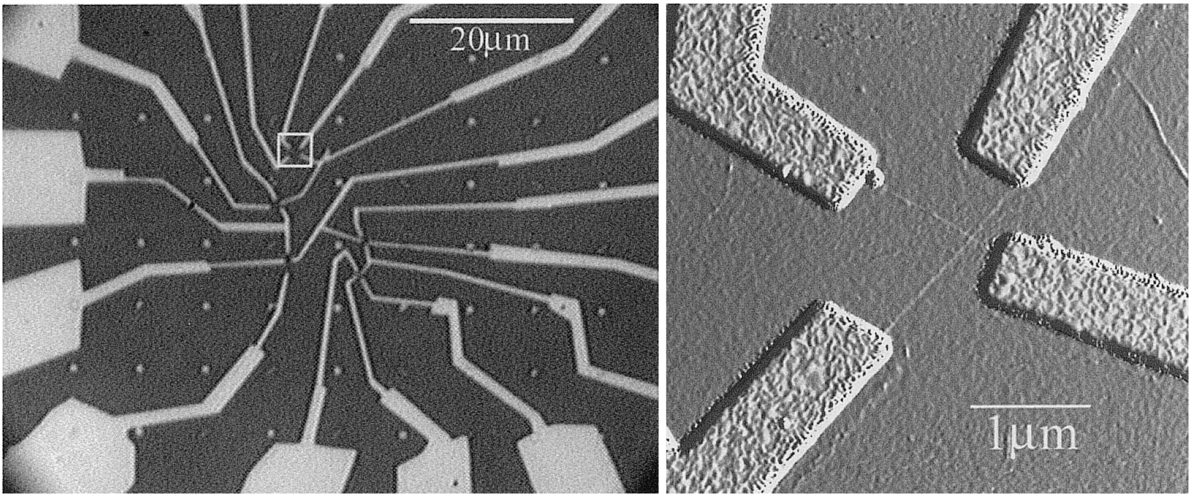

Fig. 1. (a) Optical micrograph showing Cr/Au electrical leads to five crossed SWNT devices. (b) Tapping mode AFM image (amplitude signal) of the area indicated by the white box in (a). Two SWNT are evident spanning between the Cr/Au electrodes.

synthesized via laser ablation were ultrasonically suspended in dichloroethane. The suspension was placed on the substrate for approximately 15 s, then washed off with isopropanol. An atomic force microscope (AFM) operating in tapping mode was used to locate favorably arranged crossed SWNTs relative to the alignment marks on the substrate. Objects whose height profile was consistent with single SWNTs ($\leqslant 1.4$ nm) were preferentially selected, but some devices consisting of small bundles of SWNTs were also fabricated. After locating the desired SWNTs, resist was applied over the substrate, and Cr/Au electrical contacts were fabricated on top of the SWNTs using a standard liftoff electron beam lithography technique. Large bonding pads to which wires could later be attached were defined in the same lithography step at a lower magnification.

Fig. 1 shows a completed device. The optical micrograph (Fig. 1a) shows the Cr/Au metal contacts and leads to five pairs of crossed SWNTs. The original alignment mark pattern can be seen as a regular array of small squares. One pair of crossed SWNTs can be seen in the AFM image (Fig. 1b) of the area denoted by the white box in Fig. 1a.

It is well known that SWNTs may be metallic or semiconducting depending on their chirality [5–7]. An individual SWNT defined by its circumferential vector (n, m) in terms of graphite lattice units is predicted to be metallic for $(n-m) = 3i$, where i is an integer, and semiconducting otherwise. Nominally metallic tubes with $n \neq m$ may actually be narrow-gap semiconductors [6], but we will group them here as metals. The two-terminal conductances at room temperature of individual nanotubes in the devices fall into two general classes of behavior, which have been identified as belonging to metallic and semiconducting SWNTs [4]. Metallic SWNTs have a room temperature linear response conductance which is nearly independent of gate voltage, while semiconducting SWNTs have a room temperature linear response conductance that is strongly gate voltage dependent, becoming conducting at negative gate bias and insulating at positive bias. Fig. 2 shows the two-terminal conductances at room temperature as a function of gate voltage of two individual nanotubes making up a crossed-nanotube device. The top trace indicates a conductance which is nearly independent of gate voltage – corresponding to a metallic nanotube, while the lower trace shows conduction only for negative gate biases – indicating a semiconducting nanotube. We find we can classify all the individual tubes in our crossed-nanotube devices as metallic or semiconducting according to this scheme. Thus we can divide crossed-SWNT devices into three flavors: metal–metal, metal–semiconductor, and semiconductor–semiconductor. We have observed all three types of crossed-SWNT devices.

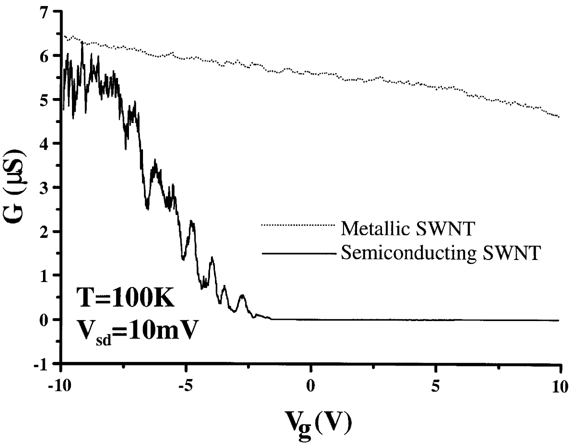

Fig. 2. Two-terminal conductances of individual metallic and semiconducting nanotubes as a function of gate voltage.

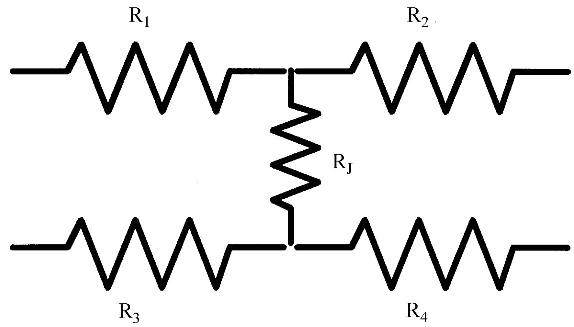

Fig. 3. Resistor network model for crossed SWNT devices.

With the above technique we have fabricated 10 crossed-tube devices (40 individual electrical contacts to nanotubes) with 38 contacts electrically conducting. The failure of a small percentage of the contacts may represent damage to the devices from electrostatic discharge, or poor alignment during the lithography step. We have also fabricated a number of devices using Ti/Au metal contacts with a lower success rate. Two terminal conductances at room temperature of the metallic SWNT were in the range 400 ns–25 μs; semiconducting SWNT, 1 ns–6 μs (at a gate voltage of −10 V).

Surprisingly, the two-terminal conductances measured across the junction are often comparable to the two-terminal conductances of the individual SWNT. We use a simple resistor network model (see Fig. 3) to estimate the junction resistance: the portion of each SWNT (including the contact resistance) on each side of the junction is treated as a single resistor R_{1-4}, and the junction was treated as a single resistor R_J connecting the two SWNT. The six measurable two-terminal conductances of the device can then be used to determine the values of the five resistors in the network. We find junction resistances of metal–metal junctions of 90–360 kΩ, corresponding to conductances of 0.07–0.28 e^2/h. This result is surprising, considering that the SWNT–SWNT junction is nearly atomic in size and presumably consists of only weakly (van der Waals) bonded graphite. These conductances are comparable to what is observed for the junctions between the large metal contact pads and the SWNTs, which are a few hundred nanometers in extent. Because of the much larger resistances of the semiconducting tubes, this method was less useful for determining the resistances of semiconductor–semiconductor junctions. However, the largest two-terminal conductance across a semiconductor–semiconductor junction indicates that such junctions may have conductances of greater than 0.02 e^2/h. All three types of SWNT junction are found to reliably pass currents of hundreds of nA.

Measured metal–semiconductor junctions show a much smaller linear response conductance of $(6-8)\times 10^{-4}$ e^2/h. Beyond linear response, however, the conductance increases, and the current–voltage ($I-V$) characteristics are asymmetric. Fig. 4 shows the I–V curves for two metal–semiconductor junctions measured at 50 K. The conductance of each junction is higher for positive bias applied to the semiconducting SWNT, and appears to saturate to a linear behavior with a non-zero x-intercept. This is what is qualitatively expected for a resistor in series with a Schottky diode consisting of a metal in contact with a p-type semiconductor (semiconducting SWNT are likely doped p-type by contact with the electrodes [4]). The x-intercept of the linear high-bias portion of the curve (dotted lines) gives a rough estimate of the Schottky barrier of 150–290 mV. The reverse-bias conductance of the diode shows a feature at approximately −500 to −600 mV. Semiconducting SWNT are observed to have band gaps of 400–900 meV [8,9], so the appearance of this feature ∼650–900 mV away from the forward-bias conduction onset may correspond to the alignment of the metal SWNT Fermi

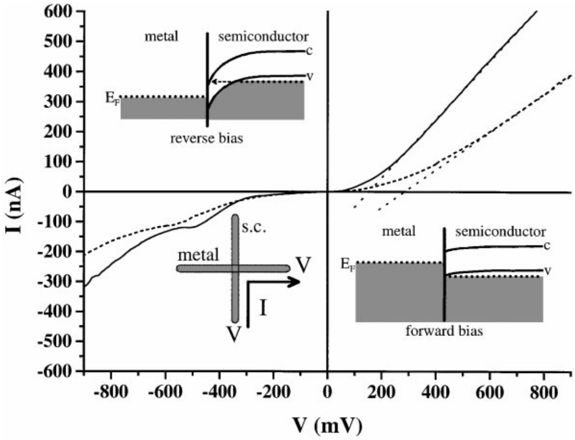

Fig. 4. Current as a function of bias voltage (applied to the semiconducting SWNT) for two metal–semiconductor SWNT junctions. The dotted lines are linear fits to the forward bias data (see text).

level with the conduction band of the semiconducting SWNT.

We have fabricated several devices consisting of a pair of crossed SWNT. We identify metal–metal, metal–semiconductor, and semiconductor–semiconductor junctions. Metal–metal junctions have linear response conductances as large as 0.28 e^2/h. Semiconductor–semiconductor junctions also have significant linear response conductances. Metal–semiconductor junctions act as nanoscale p-type Schottky diodes. The high conductance of SWNT junctions should have bearing on the interpretation of electronic transport in nanotube mats [10,11]. It also suggests that new multiple-SWNT devices may show interesting coherent electron transport effects. In light of the good junction conductances between SWNT, a device technology involving SWNT as devices as well as interconnects is potentially realizable.

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