Multichannel Ballistic Transport in Multiwall Carbon Nanotubes

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The electric transport properties of an individual vertical multiwall carbon nanotube (MWCNT) were studied *in situ* at room temperature in a scanning electron microscope chamber. It was found that the single MWCNT has a large current-carrying capacity, and the maximum current can reach 7.27 mA. At the same time, a very low resistance of about 34.4 Ω and a high conductance of about (460–490)G_0 were obtained. The experimental observations imply a multichannel quasiballistic conducting behavior occurring in the MWCNTs with large diameter, which can be attributed to the participation of multiple walls in electrical transport and the large diameter of the MWCNTs.

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The electron transport behaviors of carbon nanotubes serving as nanoelectrical materials have received extensive attention due to their potential applications [1,2]. Specifically, nanotubes may provide future interconnects [3] in nanoelectronic devices and circuits, since their current-carrying capacities are several orders of magnitude larger than present-day metal interconnects due to their ballistic transport property [4]. Generally, the current in a metallic single-walled carbon nanotube (SWCNT) saturates at 20–25 μA [5], while the current in multiwalled carbon nanotubes (MWCNTs) saturates at a similar value with only the outer shell contributing [6]. These transport experiments suggest that carbon nanotubes are remarkably good conductors with long electron mean free paths [1,7]. Here, we explore an approach that ensures that each shell of the MWCNTs contributes to the saturation current to obtain a very high current-carrying capacity—that is to say, we realize multichannel electron transport in MWCNTs.

It is known that when the length of a conductor is smaller than the electron mean free path, the electron transport is ballistic, in which case each conducting channel contributes to the total conductance a unit G_0 ($G_0 = 2e^2/h$). A metallic SWCNT has two bands crossing the Fermi level, so $2G_0$ is expected for a perfect metallic SWCNT. However, the theoretical $2G_0$ conductance for SWCNTs may not be applicable to each shell of a MWCNT: some measurements of MWCNTs have reported a conductance $<2G_0$. The reason that MWCNTs have conductance similar to SWCNTs is that the present measurement methods, such as two-terminal or four-terminal techniques, form contacts only to the outmost wall of the MWCNT [8–17], and thereby they can detect only surface current passing through the outer wall of the MWCNT. Moreover, the interaction of the tube walls reduces the conductance as described by Sanvito *et al.* in Ref. [18]. The present techniques for making contact electrodes, such as photolithography and electron beam lithography, can also introduce contact resistance, negative impurities, and contaminations, which may further distort the measurement results. In this Letter, we report a new technique, which combines the contact electrode formation with the carbon nanotube growth. A perfect electrical contact with MWCNTs can thus be formed. The transport properties of large diameter MWCNTs are studied *in situ* in a scanning electron microscope (SEM) system. Quasiballistic conductance is observed in an individual MWCNT, and the mechanism of electron transport in MWCNTs is explained in theory. The measured transport conductance in our experiment is much greater than $2G_0$.

Individual high-aspect-ratio carbon nanotubes are grown by plasma enhanced hot filament chemical vapor deposition. A tungsten filament is used as the substrate, and the trace of Fe (about 0.002 at. %) in the tungsten filament acts as the catalyst. The reaction occurs with a mixture of methane and hydrogen gases at flow rates of 10 and 50 sccm. The total pressure during the carbon nanotubes' growth was 25 Torr; the dc plasma was operated at 50 mA and -500 V. The substrate temperature during growth was about 750 °C, measured by a thermocouple. As-grown nanotubes were very straight with lengths ranging from 6 to 30 μm and a density less than $10^6/\mathrm{cm}^2$ as shown in Fig. 1. Transmission electron microscopy showed that the as-grown nanotubes had a multiwall structure with outer and inner diameters of 100 and 50 nm. The selected area electron diffraction pattern of our carbon nanotubes presented a crystalloid graphite structure. The energy dispersion x-ray shows that, except for carbon, there are no nonnegligible impurities inside the MWCNT. As the carbon nanotube is grown directly on a tungsten filament substrate, its perfect Ohmic contact with the tungsten filament is guaranteed. The contact at the other end is also a tungsten filament which has been electrochemically etched to form a probe with tip radius of 100 nm. The probe is fitted inside the SEM chamber and is movable so that it can be brought into contact with the single carbon nanotube. Prior to the *I-V* measurement, a low voltage is applied between the probe and the nanotube to generate a dis-

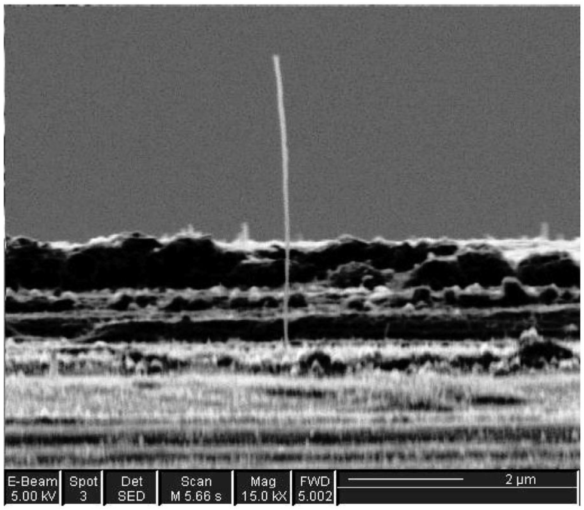

FIG. 1. SEM image of an individual multiwall carbon nanotube.

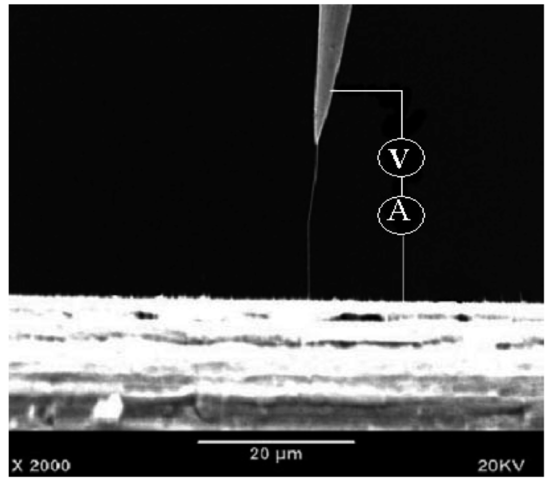

FIG. 2. An illustration of measuring the *I*-*V* characteristics of a single multiwall nanotube in the SEM setup equipped with a moveable probe.

charge, resulting in a local high temperature. The local high temperature causes the tungsten probe to be welded to the nanotube, forming a perfect Ohmic contact between the probe and the nanotube. In contrast to the previous two-terminal or four-terminal methods in which only the outer wall of the MWCNT is in contact with the electrical leads and only the outer wall of the MWCNT participates in the transport measurement, our new electrode-MWCNT system can provide a much better contact between the electrical leads and the nanotube such that both the outer and the inner walls of the tube contact leads very well.

Another advantage of this new system is that clean carbon nanotubes are grown directly on electrically conductive substrates, which can be directly measured in the SEM chamber without postprocessing steps. This is in contrast to conventional fabrication methods where carbon nanotubes undergo purification, separation, and other processes, which potentially can introduce damage and impurities into the nanotubes. Figure 2 shows a SEM image of the MWCNT connected with the tungsten probe and substrate. It forms a closed circuit system for *I*-*V* measurement.

Figure 3(a) shows the current-voltage characteristics of a single MWCNT. It can be seen that when the voltage is within ± 0.2 V the *I*-*V* plot is linear, which indicates that the MWCNT is metallic with a resistance of 34.4 Ω. The metallic carbon nanotubes (CNTs) are highly stable as long as the electron (hole) energy is not high enough to excite optical phonons. If the applied voltage is outside the range ± 0.2 V, optical phonons become excited. At high energy, the optical phonon scattering becomes dominant compared with the scattering from acoustic phonon, which results in the current saturation [19]. The resulting energy consumption eventually leads to the destruction of the ballistic transport process in the CNT, as seen in Fig. 3(a), where current saturation is observed at higher voltages ($V >$ 0.25 V). Previous reports indicated that a MWCNT would break down at dissipated power of 300 μW [14]. In our experiment, the total current can reach 7.27 mA when a bias voltage of 0.25 V is applied, which corresponds to a current density of about 10^8 A/cm^2 and a dissipated power of 1.82 mW. Such enormous power handling capability cannot be explained by a simple heat transfer theory. By

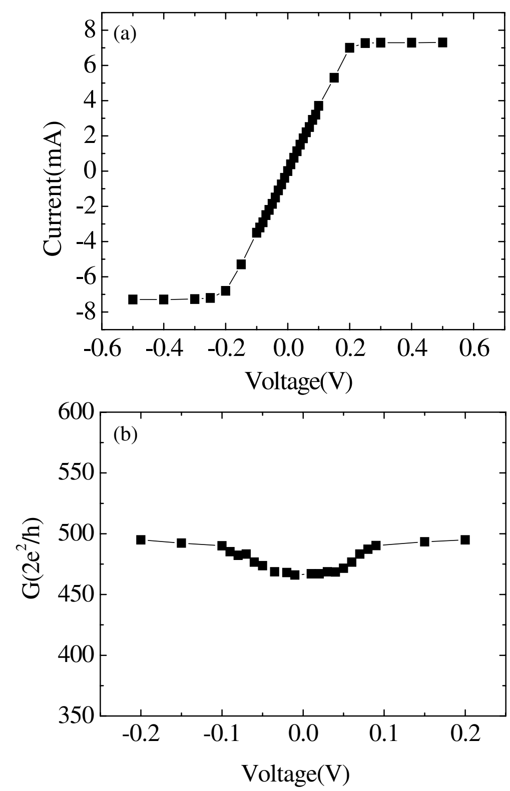

FIG. 3. (a) *I*-*V* characteristic curves of an as-grown single multiwall carbon nanotube at room temperature. (b) Conduction trace of a single multiwalled carbon nanotube.

simple heat transfer analysis, the temperature in the middle of the MWCNT would be at least several ten thousands K at such high current density if the thermal conductivity is assumed as 25 $\mathrm{W m^{-1} K^{-1}}$ [20]. This is not possible because the nanotubes will melt at 4450 K. Therefore, the only explanation for the phenomena is the quasiballistic conductive behavior occurring in the measured single MWCNT. To ballistic transport, Joule heat is generally dissipated in the leads to the tube (the ballistic element) and not in the tube itself [17]. To further confirm this picture, we have carried out measurements after the MWCNT has been burned shorter: the measured *I-V* curve and conductance were found to remain almost unchanged. This provides clear evidence that the MWCNT is a ballistic conductor and suggests that the mean free path l can reach the length of the MWCNT, 25 μm, in comparison to existing experiments which measured several micrometers [17,21]. Jiang *et al.*. [22] have obtained a universal expression of l for all metallic nanotubes:

$$l = \frac{2\sqrt{3}\pi V_0^2 r}{2\sigma_\epsilon^2 + 9\sigma_V^2}, \tag{1}$$

where σ_ϵ and σ_V are variances of the on-site energy ϵ and the nearest-neighbor tight-binding parameter V_0. V_0 is taken as -2.7 eV from experiments [23], and r is the radius of the SWCNT. From this equation, l is proportional to r. This linear dependent relationship between l and r holds for each metallic component shell of a MWCNT. The diameters of the MWCNTs in former experiments were only several nanometers, while in ours they are about 100 nm—1 order of magnitude greater. From Eq. (1), the mean free path of our MWCNT should also be one order greater than several micrometers. Besides the above theoretical analysis, Ando and Nakanishi reported that the absence of backscattering is responsible for the long mean free path in carbon nanotubes [24]. In the experiment of Ref. [21], Berger *et al.* also obtained a mean free path greater than 30 μm at room temperature. It is therefore acceptable that the mean free path of our MWCNT can reach 25 μm, the length of our MWCNT.

As shown in Fig. 3(b), the conductance at zero bias is measured to be about $460G_0$. This value is much larger than former measurements for MWCNTs. Earlier results were usually less than $2G_0$ for a single MWCNT. The biggest difference between our device and existing ones is that each wall in our MWCNT has excellent contact with electrodes at both ends and current flows through all the walls of the MWCNT, while in previous measurements only the outmost walls have good contacts with the electrodes and currents flow mostly from the outmost walls. Considering a MWCNT with outer and inner diameters of 100 and 50 nm, respectively, and the intervals between the walls to be 3.4 Å, such a tube includes at most 74 walls. Even if we assume each composing wall is conductive and offers $2G_0$ to the conductance, the maximum conductance of this MWCNT is expected to be $148G_0$, which is distinctly smaller than the measured conductance, $460G_0$. We now try to understand how can this be.

The factors that may affect the conductance of a MWCNT are mainly the structure and diameter of each composing SWCNT, temperature and impurity, etc. Because of the high purity of our MWCNT, the effect of impurity on conductance is not considered here. We will discuss that the room temperature environment and the large diameter of the MWCNT are the main origins of the large measured conductance. First, we explain that all CNTs with large diameters will be conductive at room temperature, so that the structure details (or chirality) are not as crucial as they are in CNTs with small diameters. At room temperature ($T = 300$ K), $k_B T \approx 0.0258$ eV. Thus energy differences smaller than 0.0258 eV are smeared by temperature. For a semiconducting SWCNT, the energy gap E_g depends upon the reciprocal nanotube diameter d_t,

$$E_g = \frac{V_0 a_{\text{C-C}}}{d_t}, \tag{2}$$

where $a_{\text{C-C}} = 0.142$ nm is the nearest-neighbor C-C bond length, and $V_0 = -2.7$ eV is the nearest-neighboring tight-binding parameter. From Eq. (2), when the nanotube diameter is larger than 15 nm the energy gap becomes smaller than 0.0258 eV. So all the shells of our MWCNT with inner diameter of 50 nm, including the semiconducting ones, are conducting. Next, many subbands of a SWCNT with large diameter can extend to Fermi level E_F at room temperature to contribute to conductance. For a subband below E_F, which is labeled with i, the probability of its electrons appearing at E_F obeys the following relation:

$$f_i = \frac{1}{e^{|E_{\text{occ}}^i - E_F|/k_B T} + 1}, \tag{3}$$

where f_i is the distribution function, and E_{occ}^i is the highest occupied energy of the subband i. We can use f_i as a weight to value the contribution of this subband to the total conductance. Thus, the total conduction channels N of a MWCNT at E_F is

$$N = \sum_j^{N_{\text{wall}}} \sum_i^{N_{\text{subb}}^j} f_{ij} = \sum_j^{N_{\text{wall}}} \sum_i^{N_{\text{subb}}^j} \frac{1}{e^{|E_{occ}^{ij} - E_F|/k_B T} + 1}, \tag{4}$$

where N_{wall} is the number of walls in a MWCNT and N_{subb}^j is the number of subbands of the jth wall. Besides the occupied subbands below E_F, the empty subbands above E_F also contribute to conductivity. For these empty subbands, it is more convenient to introduce holes to describe their contributions to conductance at finite temperature. In Eq. (4) the contributions of the empty subbands have been included in N_{subb}^j. For example, $N_{\text{subb}}^j = 4n$ for (n, n) or $(n, 0)$ carbon nanotubes. Actually, only a few subbands close to E_F are important. We consider 15 subbands for each wall in our estimate and take the outer and inner diameters of a MWCNT to be 100 and 50 nm, respectively;

we set T to be 300 K. Then from Eq. (4), N is found to be about 416 if we treat all the walls of the MWCNT to be armchair SWCNTs, and about 455 if all the walls are zigzag SWCNTs. Thus, by considering room temperature, the theoretical estimate and the measured conductance, $460G_0$, agree well. According to the above analysis, the conductance will increase with the increase of temperature. This temperature dependent behavior has been verified by some reported works [25–27].

Figure 3(b) shows the measured conductance as a function of the bias. With the increase of bias, more and more subbands enter the energy window between the chemical potentials of the two electrodes. However, the increase of conductance is not comparable to the large number of subbands entering the energy window. At zero bias, electrons are transmitted only when they are injected into the bands extending through the Fermi level. While at nonzero bias, electrons between the two chemical potentials in the two electrodes have to travel through a special region where the local Fermi energies are equal to injected electron energies. In the absence of significant intersubband tunneling, only electrons injected in the bands whose tails cross the Fermi level at zero bias are transmitted through the mentioned special region and electrons injected in the other bands are reflected in this region. This kind of reflection is called Bragg reflection [28]. Hence, the conductance does not follow the increase of the number of the bands within the energy window when we increase the bias. The slight increase of conductance with bias occurs because the bias decreases the barrier height and thus increases the Zenner tunneling.

In conclusion, the capability of carrying large current at low bias voltage has been found on MWCNTs with perfect Ohmic contacts. The behavior can be explained by quasi-ballistic transport of electrons in MWCNTs with large diameter and the participation of the inner walls of the CNT. The conductance in our experiment is found to be $490G_0$, much larger than the $2G_0$ theoretically predicted for SWCNTs and measured in previous experimental work for MWCNTs. The large current handling capability, or high conduction, is due to the participation of multiple walls in electrical transport and the large diameter of the MWCNT used in our experiment. Such a high conductance MWCNT could prove to be viable as conductive wires in place of the copper, aluminum, or metal silicide wires used in today's integrated circuits.

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