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Four-terminal measurements of SWNTs using MWNTs as voltage electrodes

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We report on electron transport measurements of single-wall carbon nanotubes in a four-terminal configuration with noninvasive voltage electrodes. The voltage drop is detected using multiwalled carbon nanotubes while the current is injected through nanofabricated Au electrodes. Measurements are carried at high temperature so that the four-terminal resistance directly gives the intrinsic resistance. The resistance is shown to result from weak disorder and from quantum interference effect corrections. In addition, we present Coulomb blockade measurements. The length of the quantum dot that is determined from the level spacing equals the separation between the Au electrodes.

1 Introduction

We have recently reported four-point resistance measurements on single-wall carbon nanotubes (SWNT) using multiwalled carbon nanotubes (MWNT) as noninvasive voltage electrodes [1]. We found that the nanotube resistance linearly increases with length at room temperature, in agreement with Ohm's law. In this regime, the four-point resistance is a direct measurement of the intrinsic resistance of the SWNT. At low temperature, however, the resistance can become negative. In this regime, four-point measurements can be described by the Landauer–Büttiker formalism taking into account quantum-interference effects. In this proceeding paper, we describe results in the high-temperature regime that probes the intrinsic resistance of the SWNT. In particular, the dependences of the four-point resistance on temperature and gate voltage are discussed. The resistance is shown to result from weak disorder along the SWNT and from quantum interference effects between different electron paths. In addition, we present two-point measurements at He temperature that show Coulomb blockade oscillations. Interestingly, we find an even-odd filling when sweeping the gate voltage. This allows the determination of the quantum dot length, which equals the separation between the gold current electrodes. This shows that MWNTs do not divide the SWNT in multiple quantum dots.

2 Four-terminal resistance measurements at high-temperature

The fabrication of SWNT devices for four-point measurements has been described in Ref. [1]. Briefly, ~1 nm diameter SWNTs grown by chemical vapour deposition [2] are selected with an atomic force mi-

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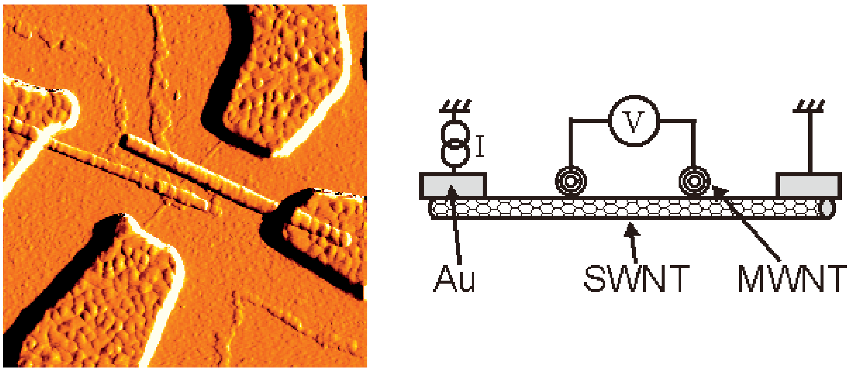

Fig. 1 (online colour at: www.pss-b.com) Atomic force microscopy image and schematic of the SWNT device for four-terminal measurements. The voltage drop is detected using multiwalled carbon nanotubes while the current is injected through nanofabricated Au electrodes.

croscopy (AFM). Noninvasive voltage electrodes are defined by positioning two MWNTs above the SWNT using AFM manipulation. Cr/Au electrodes are patterned for electric connection using electron-beam lithography (Fig. 1).

Insight into transport properties is obtained by decreasing the temperature T. Figure 2 shows that the four-terminal resistance R_{4pt} does not change for T above ~80 K, suggesting that the intrinsic resistance is related to some static disorder and not to phonons. At lower T, however, Fig. 2 shows that the four-terminal conductance $G_{4pt}=1/R_{4pt}$ fluctuates with sweeping of the backgate voltage V_g.

We now discuss the possible origin of these fluctuations. They may originate from low-transmission barriers created by the MWNTs or some static disorder that forms quantum dots along the tube. The transport may then be dominated by Coulomb blockade (CB). However, the conduction stays mostly constant with T above $T^* \approx 60$ K, the temperature at which fluctuations appear. This is in opposition to CB theory [3] that predicts $G = G_0(1 - E_c/3kT)$ for temperatures larger than the charging energy E_c, expected to be close to kT^*, where k is the Boltzmann constant. Moreover, the best fit between this model and measurements above T^* gives $E_c/k \approx 5$ K, which is much lower than T^*. Another mechanism is thus needed to account for the fluctuations.

The presence of disorder is expected to generate a complicated interference pattern along the tube that should vary with the Fermi level. This results in aperiodic conductance fluctuations around the classical conductance when sweeping V_g [4], which is consistent with our measurements. Such fluctuations appear when effects of thermal averaging and phase decoherence are weak enough so that the thermal length

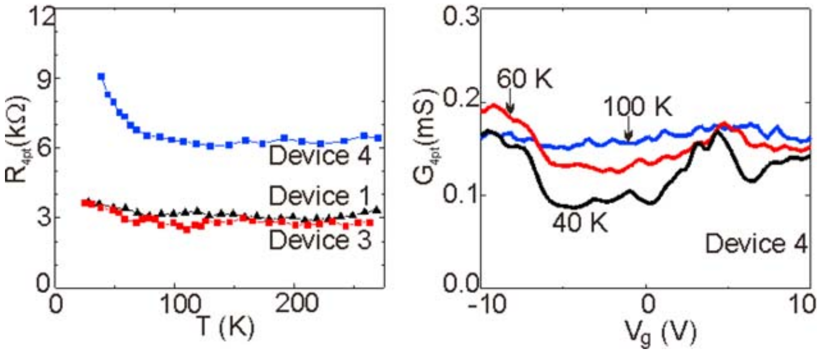

Fig. 2 (online colour at: www.pss-b.com) Four-terminal resistance as a function of temperature for $V_g = 0$. Four-terminal conductance as a function of gate voltage for different temperatures.

$L_T = hv_F/kT$ and the coherence length L_ϕ are larger than the elastic mean-free path l_e (h is Planck's constant, v_F is the Fermi velocity). Interestingly, L_T at $T^* = 60$ K is comparable to l_e determined using

$$R_{4pt} = \frac{h}{4e^2}\frac{L}{l_e} \tag{1}$$

with L the separation between the two MWNTs. The same is observed for devices 1 and 3. This suggests that thermal averaging is here at least as detrimental as decoherence. Note, moreover, that the amplitude of the fluctuations approaches e^2/h at ~40 K. This is expected [4] when the lower of L_T and L_ϕ is comparable to the separation between the voltage electrodes, which is again consistent with measurements since $L_T = 150$ nm and $L = 140$ nm. Overall, our measurements suggest that quantum-interference effects start to modify the classical resistance given by Eq. (1) around a few tens of Kelvin.

3 Two-terminal resistance measurements and Coulomb blockade at He temperature

Figure 3 shows Coulomb blockade measurements measured in a two-terminal configuration between the two Au current electrodes at 1.5 K. The Coulomb blockade peaks do not appear very regular, which probably results from the disorder along the SWNT. Interestingly, the Coulomb blockade peaks appear in pairs. This is better seen in the lower part of the figures. There, the peak separation between the Coulomb blockade (CB) peaks goes up and down as the gate voltage is swept. The peak separation reflects the addition energy E_{add}. Its even-odd alternation suggests two-electron shell filling [5]. The spin of the ground state alternates by 1/2 as consecutive electrons are added. For an electron number N in the dot that is odd, the $N + 1$ electron enters the same orbital as the N electron. The resulting separation of the CB peaks is E_c/α with α is the gate coupling efficiency. For even N, the $N + 1$ electron enters the next orbital. The resulting separation is then $(E_c + \Delta E)/\alpha.$ Using $\alpha = 1/6$ measured from Coulomb diamonds,

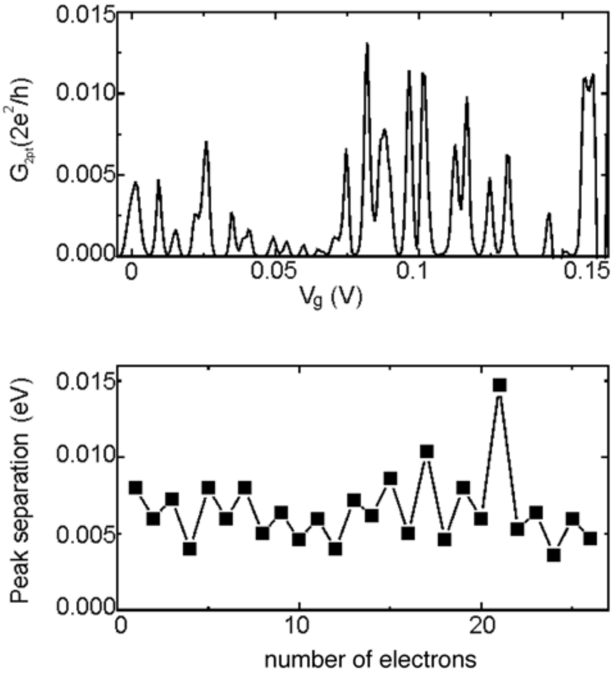

Fig. 3 Two-terminal conductance measured between the two Au current electrodes as a function of the gate voltage at 1.5 K. The corresponding peak separation is shown in the lower part of the figure.

we obtain an averaged $\Delta E \approx 0.5$ meV. The level spacing is related to the length L_{dot} of the quantum dot through

$$\Delta E = \frac{h v_{\mathrm{F}}}{2 L_{\mathrm{dot}}}, \qquad (2)$$

with v_{F} the Fermi velocity. We get 2.9 μm, which is very close to the 2.7 μm separation between the Au current electrodes. This is much longer than the 95 nm separation between the MWNTs. These measurements suggest that MWNTs are sufficiently noninvasive not to divide the SWNT in multiple quantum dots.

This result is in agreement with measurements of the length dependence of the four-terminal resistance at 300 K [1]. We have found that $R_{4\mathrm{pt}}$ linearly increases with the length, and $R_{4\mathrm{pt}}$ tends to zero as the length is reduced to zero. A significant resistance contribution from the MWNTs would give a finite $R_{4\mathrm{pt}}$ at zero length, in opposition to the measurements. This suggests that MWNTs are mainly noninvasive.

4 Conclusion

We have shown that quantum-interference effects start to modulate the four-point resistance of SWNTs below ~60 K. This happens when the thermal length is longer than the elastic mean-free path. The thermal length is 20 nm long at room temperature; hence it is likely that inclusion of these quantum-mechanical interference effects will ultimately be required in the design of practical multi-terminal intramolecular devices that are smaller than the thermal length.

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