

Transport in disordered carbon nanotubes

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Abstract

Carbon nanotubes of high intrinsic resistivity have been studied. The conductance of the nanotubes has been measured as a function of voltage and temperature. The results on a sample, whose contact resistances nearly equal the resistance of the tube itself, are interpreted in terms of strong tunneling SET model.

Key words: carbon nanotubes; strong tunneling; disorder

Carbon nanotubes have raised interest as possible realisations of ballistic quantum wires. We have studied the opposite limit, i. e. disordered multiwalled carbon nanotubes. In most of our samples the resistance is actually dominated by the intrinsic resistance of the tube, R_{NT} , while we estimate the contact resistances R_C to be rather low, well below 5 k Ω . In this paper we describe results on one of our samples, where the two contributions are nearly equal, $R_{NT} \sim R_C$, in the framework of strong tunneling SET (Single Electron Transistor) model [1,2].

The nanotubes used in this study have been synthesised by chemical vapour deposition method [3]. AFM studies have shown that these tubes have intrinsic curvature, which clearly indicates that their structure is not perfect. The tubes were dispersed in dichloroethane and deposited on a silicon substrate. In order to obtain good electrical contacts, it was found useful to oxidise the samples in air (300-400 C, 10 min) prior to evaporation of the contacts (Ti/Au) on top of them. With such treatment we typically get samples with a 2-lead resistance $R_{2t} < 100$ k Ω .

An example of the difference between 2- and 4-lead measurements is shown in Fig. 1. If we define $R_C = (R_{2t} - R_{4t})/2$, our samples give $R_C \approx 0.8-2$ k Ω , and correspondingly $\rho = (R_{tot} - 2R_C)/L \approx 40-110$ k $\Omega/\mu\text{m}$. However, when the tube resistivity is so high, the path

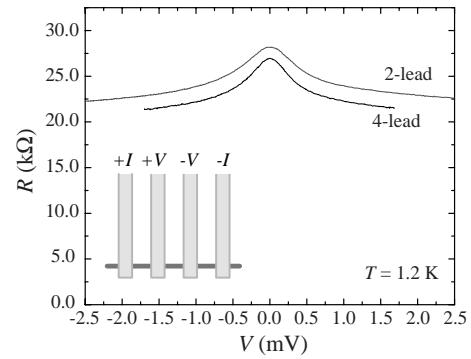


Fig. 1. Differential resistance measured using 4-lead and 2-lead geometries. The only difference appears to be a temperature independent shift by 2 k Ω .

of least resistance may no longer run along the tube. For example, if the resistivity is 100 k $\Omega/\mu\text{m}$ and the contact resistance is around 10 k Ω or less, significant part of the current flows through the voltage probes (typical width of our contacts $\sim 0.2 \mu\text{m}$). Therefore, the 4-lead measurement no longer separates the contribution of contacts correctly, and for low ohmic contacts the results of 2- and 4-terminal measurements become identical.

Most of our samples show weak or negligible change of conductance in response to gate voltage, $\Delta G/G \leq 10\%$ at 0.2 K. This is an additional indication of low contact resistances: the charging effects are reduced in

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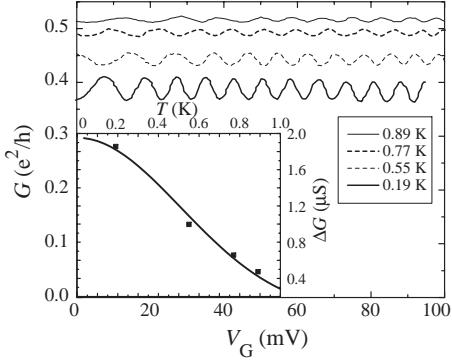


Fig. 2. Gate oscillations measured at $T = 0.2\text{--}0.9\text{ K}$. The inset shows the oscillation amplitude vs. temperature, and a fitting curve from strong tunneling theory $\Delta G = A \exp(-(T/T_0)^2)$. The fit gives $T_0 = 0.72\text{ K}$. The room temperature resistance of the sample was $24\text{ k}\Omega$ and the length of the tube section between electrodes $0.29\text{ }\mu\text{m}$.

comparison with a similar nanotube-SET made of an arc-discharge grown nanotube [4]. Here we concentrate on a sample, which had the most prominent periodic gate oscillations. Assuming that it can be characterised as a strong tunneling SET, we are able to estimate the contact resistances rather accurately. In Fig. 2 the conductance *vs.* gate voltage is plotted at a few different temperatures. One may note that the oscillations are relatively regular and nearly sinusoidal. In the inset, the oscillation amplitude has been plotted as a function of temperature. The solid line is a fitting curve obtained from the strong tunneling SET theory [1,2]: $\Delta G = A \exp(-(T/T_0)^2)$, where $T_0^2 = 6hE_C^2/(e^2\pi^4 R_T)$. Here R_T is the resistance of one tunnel junction and E_C is the charging energy. Because the tunneling resistances cannot be larger than half of the asymptotic resistance $29\text{ k}\Omega$, we find an upper limit $E_C < 2.2\text{ K}$.

The charging energy E_C can be estimated from the measured differential conductance, which is shown in Fig. 3 together with two curves calculated from the strong tunneling theory with $E_C = 1.5\text{ K}$ and $T_0 = 0.72\text{ K}$. These values give $R_T \approx 7\text{ k}\Omega$, and $\rho_{\text{NT}} \approx 60\text{ k}\Omega/\mu\text{m}$. Total capacitance is 0.6 fF , which is reasonable for a nanotube with total length of $2.6\text{ }\mu\text{m}$. In fact, the charging energy is very close to the one obtained previously for standard weak tunneling SET with a nanotube of similar size as an island [4]. Because the intrinsic resistance of the nanotube is of the same order as R_T , it has been included in the fit. A resistor representing the nanotube is added in series with the SET so that the sum $R_{\text{NT}} + 2R_T$ gives the correct asymptotic value. The nanotube resistance is assumed to be independent of temperature and bias voltage.

The parameter $E_C = 1.5\text{ K}$ was obtained by fitting the data set at $T = 0.14\text{ K}$ (see Fig. 3). Clearly the simple-minded model above is not sufficient to account fully for the data: it cannot describe the temperature

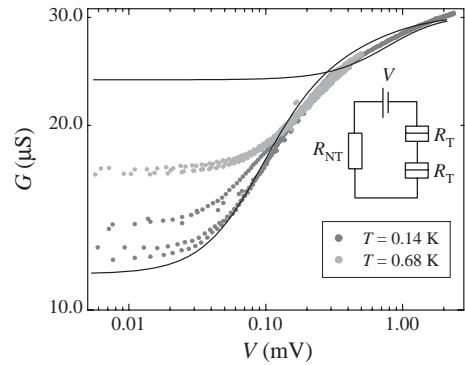


Fig. 3. Differential conductance *vs.* voltage. The spreading of experimental points visible at the lowest temperatures results from low frequency background charge fluctuations which cause the SET to jump to a different charge state from time to time. The solid lines are calculated from the strong tunneling theory with $E_C = 1.5\text{ K}$ at temperatures of the experimental points.

dependence correctly. There are two ways to improve from here. First of all, the conductance of the nanotube does depend on temperature and voltage. Secondly, the tunneling is affected by the diffusive environment of the junctions, formed by the nanotube. We find that the high voltage tails of the zero-bias anomaly are, up to first order, well described by $\Delta G \propto 1/\sqrt{V}$. This behaviour, to be described in detail elsewhere [5], could in fact result from either of the two cases. Therefore, in an intermediate case when $R_{\text{NT}} \sim R_T$, the complete separation of the different contributions is difficult.

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