

Resistance of Telescoping Nanotubes

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Abstract. We present results on resistance measurements of multiwall nanotubes in the linear bearing geometry. We find that the resistance increases with telescoping distance, which may allow nanotubes to be used in applications as variable resistors. Our results also have implications for quantum mechanical charge transport, and indicate Thouless localization in nanotubes.

INTRODUCTION

Multiwall carbon nanotubes (MWNTs) comprise concentric carbon shells, with an interlayer spacing roughly equal to the van der Waals graphite interplane distance, 3.4\AA [1]. Charge transport in nanotubes is an interesting phenomenon to study, as some nanotubes could be metals and others semiconductors[2]. Furthermore, there is much interest in determining the length scales that are required for ballistic transport in nanotubes and the current distribution among the layers of a MWNT[3-7].

In the present study, we report on the electrical conductance of MWNTs measured using a nanoscale manipulation stage installed inside a high-resolution transmission electron microscope (TEM). The setup allows an individual nanotube to be selected and manipulated to contact a counter-electrode. Careful electrical measurements of the nanotube can then be made and correlated with observed mechanical properties of the nanotube.

EXPERIMENTAL

The starting point for the experiments reported here is the linear bearing geometry reported in previous studies of multiwall carbon nanotubes[8,9]. The findings of those studies will be summarized briefly as follows. Under the influence of large electrical currents ($\sim 200\text{ }\mu\text{A}$) multiwall nanotubes can be induced to peel, whereby the outer layers are removed, exposing the inner core nanotubes. The core nanotubes can then be bonded to the manipulation probe by applying a voltage (2-5 V) to the manipulation tip (in a current limited manner) and then bringing the manipulation tip gently into contact with the protruding core nanotube section. The small current which occurs during the contact can "spot weld" the core nanotube section to the manipulation probe. In this geometry it is then possible to withdraw the manipulation tip, extracting the core nanotube segment from its housing. In previous studies, the

frictional forces between nanotubes were carefully analyzed, and the nanotubes were found to be good linear bearings[9].

Figure 1 depicts the present experiment, where the resistance of the nanotube is measured throughout the extraction process. The current flowing through the nanotube is monitored using a sensitive electrometer, while the manipulation probe is held at a fixed voltage. The images of the telescoping nanotubes are recorded on a VHS video recorder, and the voltage and current values are overlaid onto the video signal so that direct correlations between nanotube resistance and telescoped distance(x) can be made.

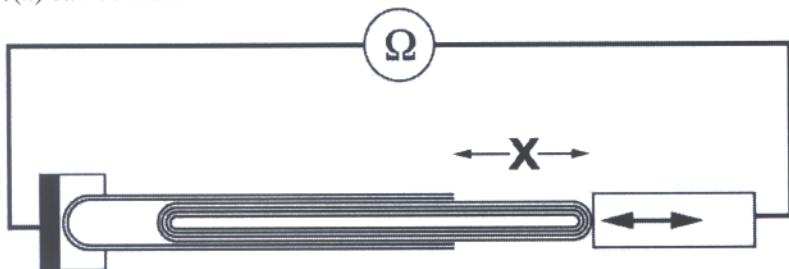


FIGURE 1. The nanotube telescoping geometry used for the present experiments. The nanotube is carefully extended while resistance measurements are continuously taken.

ANALYSIS AND CONCLUSIONS

In previous experiments, similar to those reported here, we found that the resistance of the nanotubes had no appreciable change in resistance during telescoping[10]. In the present communication we present further experiments that confirm these results and also uncover a new parameter range in which the resistance does change. The change is small, however, for nanotubes which have a high contact resistance, or which can only telescope a small distance. In such cases, the change in resistance cannot be observed, consistent with our previous findings. In nanotubes that can be telescoped long distances (greater than 1 micron), we find that the nanotubes always show an increase in resistance with increasing nanotube length. A typical plot of resistance vs. telescoping distance is shown in Figure 2. The contact resistance is not subtracted out from the data. The resistance data from a given nanotube are reproducible. That is, if the nanotube is extracted out a specific distance and then reinserted back in the same distance, the original resistance value is recovered. This suggests that multiwall nanotubes in the telescoped geometry could be used as high quality variable resistors. As such, they might find use in applications as a nanoscale linear position sensor or as a nanoscale rheostat in nanoelectromechanical systems (NEMS).

It is also evident from Figure 2 that the resistance increases in a nonlinear manner as a function of telescoping distance. This nonlinear increase cannot be explained by a simple classical Ohm's law interpretation, and could be an indication of the quantum mechanical nature of charge transport on carbon nanotubes. One possible simple scenario that could lead to a nonlinear resistance versus length would be if the transport were limited by electron tunneling from the telescoped nanotube core to the

nanotube housing. In such a case, it might be expected that the conductance of the junction would be directly proportional to the area of the overlap between the nanotube core and its housing. This would give a nonlinear increase in resistance versus telescope distance, but would give a linear decrease in conductance. The conductance is plotted in Figure 3 and demonstrates that this is, in fact, not the case. This implies that the conductance of the contact between the core nanotube and its housing is actually quite good, in agreement with previous studies[11], and that the resistance is dominated by the increasing length of nanotube segment through which the current must flow.

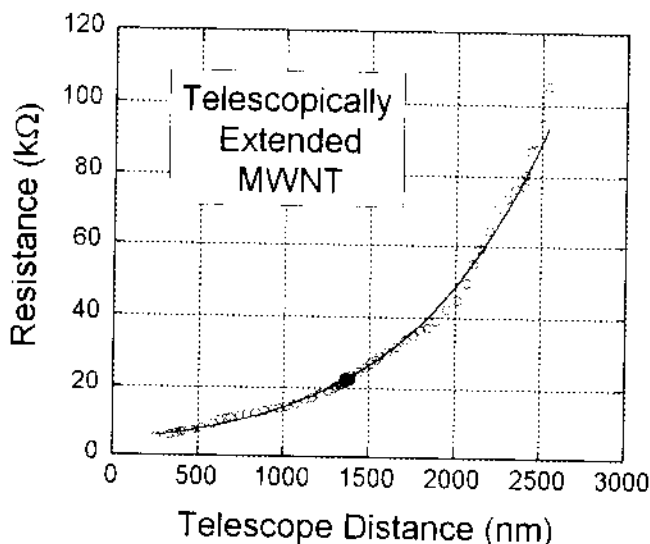


FIGURE 2. Resistance measured during telescoping of a multiwall carbon nanotube. The solid curve is an exponential fit to the data, as described in the text.

Now, we will address the issue of why the resistance increases in a nonlinear manner. It is evident that the increase in resistance is due to some sort of scattering of charge carriers in the nanotube. A simple incoherent scattering model, however, would give rise to a linear increase in resistance versus length. In a phase coherent system, however, scattering can instead cause localization of the electronic wavefunctions[12,13]. In such a system, the charge-carrying states can no longer be thought of as extended Bloch states, and have an overall "envelope function" with an exponentially decaying tail. As the size of the system is increased, the exponential decay of the wavefunctions leads to an exponentially increasing resistance. We have fit our resistance data to exponentials of the form $R = R_0 \exp(x/l_0)$, and we find striking agreement with theory. The l_0 value extracted from the fit in Figure 2 is 785 nm. Applying the same analysis to other nanotubes gives us l_0 values that only range from 500 nm to 800 nm, indicating that we are probing some intrinsic length scale of nanotube transport. From theory, l_0 has the interpretation of being the localization length, or the length of the exponential tail of the localized wavefunctions. This interpretation is in agreement with previous measurements of localization in nanotube systems[14].

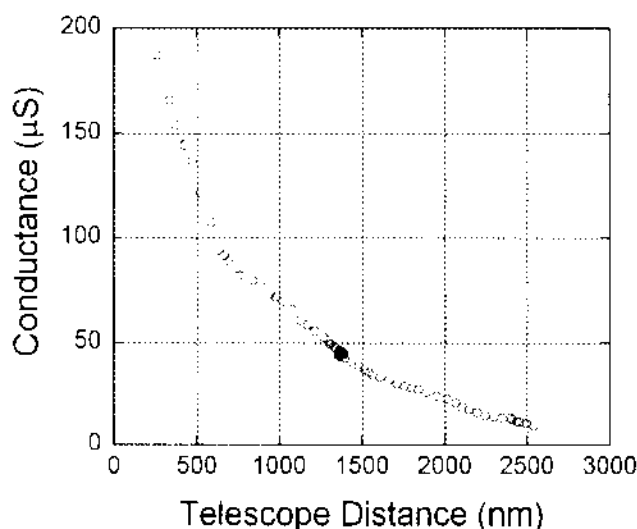


FIGURE 3. Conductance measured during telescoping of a multiwall carbon nanotube. The fact that the conductance does not drop linearly with length indicates that the contact between the core nanotube and its housing does not dominate the electrical resistance.

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