

Mesoscopic thermal transport and energy dissipation in carbon nanotubes

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Abstract

We have measured the thermal conductivity of an individual multiwalled carbon nanotube (MWNT) using a microfabricated suspended device. The observed thermal conductivity is more than 3000 W/K-m at room temperature, which is two orders of magnitude higher than the estimation from previous experiments that used macroscopic mat samples. In addition, the temperature distributions in electrically heated MWNTs have been measured with a scanning thermal microscope. The temperature profiles along the tube axis in MWNTs indicate the bulk dissipation of electronic energy to phonons, which suggests diffusive electronic transport. © 2002 Elsevier Science B.V. All rights reserved.

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Carbon nanotubes are expected to have high thermal conductivity [1] and can conduct heat efficiently, thus preventing structure damage while used as current-carrying wires in micro/nano devices. Previous electronic transport measurements at high electric field regime [2,3] suggested that carbon nanotubes can carry substantial amounts of current before their structural failure. To investigate these intriguing electrical and thermal properties, mesoscopic experimental methods at a single nanotube level are desirable.

The thermal conductivity of carbon nanotubes have been measured by several groups using a millimeter sized mat sample [4–6]. Although these studies demonstrated qualitative understanding of the low-dimensional nature of these materials, it is difficult to extract absolute values of the thermal

conductivity in a mat sample due to the presence of numerous uncertain tube–tube junctions that might be the dominant barriers to the thermal transport through the sample.

To perform mesoscopic thermal transport measurements, we have developed a microfabricated suspended device, hybridized with multiwalled nanotubes (MWNTs), to probe thermal transport free from a substrate contact. Suspended structures were fabricated on a silicon nitride/silicon oxide/silicon multiplayer by pattern transfer and electron beam lithography, followed by metalizations and etching processes. Fig. 1(a) shows a representative device including two $10\ \mu\text{m} \times 10\ \mu\text{m}$ adjacent silicon nitride membrane ($0.5\ \mu\text{m}$ thick) islands suspended with $200\ \mu\text{m}$ long silicon nitride beams. On each island, a Pt thin film resistor, fabricated by electron beam lithography, serves as a heater to increase the temperature of the suspended island. These resistors are electrically connected to contact pads by the metal lines on the suspending legs. Since the resistance of the resistor

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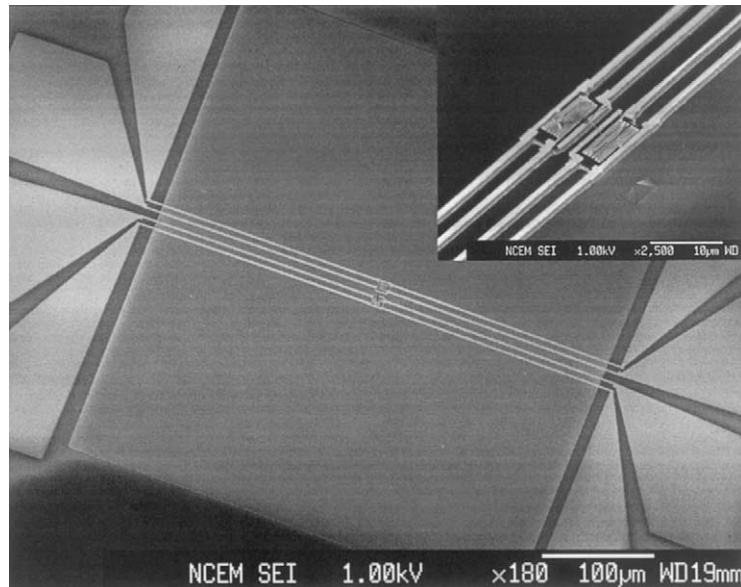


Fig. 1. SEM image of a suspended device to measure the thermal conductivity of an individual carbon nanotube. Inset represents an angled detail view of the central part of the device. A MWNT with the diameter of 14 nm bridges two suspended islands.

changes with temperature, they also serve as a thermometer to measure the temperature of each island.

A mechanical manipulation similar to that used for the fabrication of a nanotube scanning probe microscopy tip was used to place MWNTs on the desired part of the device. This approach routinely produces a nanotube device that can be used to measure the thermal conductivity of the bridging nanotube segment. Shown in the inset of Fig. 1 is an example of such a device. An individual MWNT with a diameter of 14 nm forms a thermal path between two suspended islands otherwise thermally isolated from each other. A bias voltage applied to one of the resistors, R_h , creates Joule heat, P , and increases the temperature, T_h , of the heater island from the thermal bath temperature T_0 . In a steady state, there is a heat transfer to the other island through the nanotubes, and thus also the temperature, T_s , of the resistor R_s rises. From the relation between T_h and T_s to P , we can estimate the thermal conductance of the MWNT [7].

Shown in Fig. 2 is the resulting thermal conductivity of the individual MWNT in Fig. 1, after geometrical consideration of its diameter (14 nm)

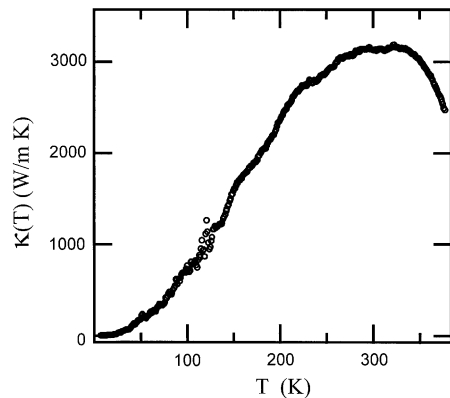


Fig. 2. The temperature dependent thermal conductivity of the MWNT in Fig. 1 (adapted from Ref. [7]).

and length (2.5 μm). This result shows remarkable differences from the previous ‘bulk’ measurements. Most significantly, the room temperature value of the thermal conductivity is over 3000 W/K-m, whereas the previous ‘bulk’ measurement on a MWNT mat using the 3ω method estimates only 20 W/K-m [4]. Note that our observed value is also an order of magnitude higher than that of an aligned SWNT sample (250 W/K-m) [6], but

comparable to the recent theoretical expectation, 6000 W/K-m [1]. This large difference between mesoscopic and ‘bulk’ measurements suggests that numerous highly resistive thermal junctions between the tubes largely dominate the thermal transport in mat samples used in the previous study.

In addition to the mesoscopic thermal conductivity measurement, we have measured the temperature distributions in electrically heated MWNTs with a scanning thermal microscope. The nature of the electron transport in carbon nanotubes is closely related to the energy dissipation mechanism, and is often correlated with the temperature distribution along the tubes. Therefore, by measuring the local temperature along the carbon nanotubes under electron transport, we should be able to correlate the nature of the electronic transport to the energy dissipation mechanism.

To probe the local temperature of MWNTs, thermal probe atomic force microscope (AFM) tips have been fabricated and used in our experiments [8]. The micro-patterned Pt and Cr lines form a junction at the apex of the AFM tip that has a lateral topographic spatial resolution ~ 30 nm and thermal spatial resolution ~ 80 nm.

Shown in Fig. 3 is the simultaneously taken topographic and corresponding thermal signal, ΔT_m , on a 10 nm diameter MWNT device fabricated on 1 mm silicon oxide/silicon surface. Clearly, ΔT_m is higher near the MWNT with the estimated tube temperature increase ~ 30 K at its highest position. The total electronic power dissipated in this device $22 \mu\text{W}$ along the length of the tube. This dissipated energy is transferred to the substrate eventually. Since the heat flow through the silicon oxide substrate is proportional to the temperature gradient, the power dissipation through the substrate, Q , can be estimated from this image. The estimated Q is $8.5 \mu\text{W}$, where the tube length $L \sim 4 \mu\text{m}$. From this value, the junction thermal conductance per unit length of tube could be computed: $K_j = Q/L(T_t - T_s) \sim 0.08 \text{ W/K-m}$ where T_t and T_s is the tube and substrate temperature underneath of the tube, respectively.

Fig. 3(c) shows the temperature map along the tube. This temperature profile exhibits a roughly

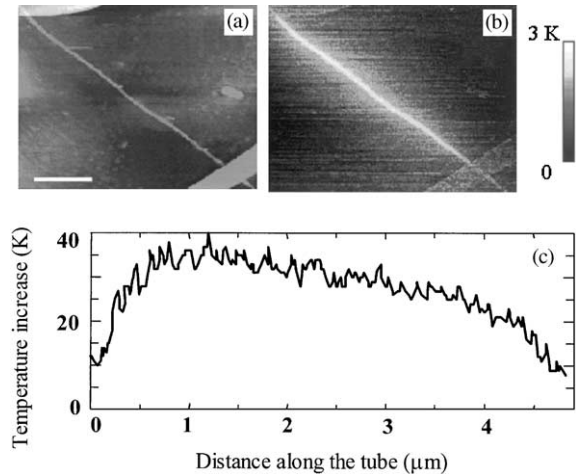


Fig. 3. (a) Topographic image of a MWNT device. Scale bar represent 1 μm . (b) the corresponding thermal signal simultaneously taken with (a). The applied bias voltage on the MWNT was 1 V and the current was $22 \mu\text{A}$. (c) Temperature profile along the tube axis.

parabolic temperature distribution along the tube length with a negative curvature. This temperature variation is indeed expected for a classical Ohmic conductor that has a finite bulk dissipation P inside the conductor. We also found that the tube temperature at the middle of the MWNT increases quadratically as a function of the bias voltage V [9]. Since $P = V^2/R$ for a dissipative Ohmic conductor where R is the resistance of the tube, these observations suggest that MWNTs are energy dissipative in the electron transport and thus are a diffusive conductor.

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