Mater. Res. Soc. Symp. Proc. Vol. 1204 © 2010 Materials Research Society 1204-K17-03

On the Relation of Mechanical Deformation and Electrical Properties of BN Nanotubes

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ABSTRACT

Using a novel *in-situ* scanning tunneling microscope integrated into a 200kV transmission electron microscope (TEM), we have shown that boron nitride nanotubes (BNNTs) possess remarkable flexibility and convert from insulator to semi-conductor upon bending. To measure the electrical properties, the BNNT was bent between two gold contacts constructing a metal-semiconductor-metal circuit. The resistivity of the BNNT under bending condition was measured to be ~460 MΩ from the experimentally recorded current-voltage data. Our finding suggests that mechanical straining can improve the electrical transport in BN nanotubes via the reduction of the band gap.

INTRODUCTION

Boron nitride nanotubes (BNNTs) with structural and mechanical properties similar to carbon nanotubes (CNTs) [1], and wide band gap of 5.9eV [2] are the strongest insulators known to mankind [3]. Interestingly, theoretical calculations [4] predict that this insulating behavior can be changed into semiconducting via mechanical deformation. Only one experimental approach has been taken so far to demonstrate this behavior [3]. This work demonstrates the electrical behavior of BN nanotubes subjected to various degrees of mechanical straining. All the experimental measurements were conducted inside the chamber of a transmission electron microscope (TEM) using an *in-situ* scanning tunneling microcopy (STM) holder.

EXPERIMENTAL PROCEDURE

Our BNNTs were directly deposited on Si substrates by thermal chemical vapor deposition at 1100-1200 °C in a conventional tube furnace [5]. These BNNTs have a band gap ~5.9 eV [5], which is higher than those used in previous reports (~5.4 eV) [3]. These BNNTs are having high structural order as previously examined by high-resolution TEM, Raman, IR and electron energy loss spectroscopy [5]. Our experiments were conducted by STM under *in-situ* monitoring using JEOL JEM-4000FX 200kV TEM. Individual BNNTs were then attached on an Au wire by either light mechanical scratching on the as grown samples or using silver paste. This Au wire was then fixed on the tip of a piezo-driven holder that allows nanometer motion of the sample toward the AFM cantilever. Using the Nanofactory™ software (NFC3), sample position was adjustable with a precision of 1nm in X, Y and Z directions. Here, the sample is grounded and bias voltages were applied to the STM tip. Then the current-voltage (*I-V*) curves were measured using the Nanofactory™ instrument (up to ±100 V) power generator. To reduce the effect of electron beam irradiation on the *I-V* measurements, the electron beam was spread out.

RESULTS AND DISCUSSION

Figure 1a shows an individual BNNT under bending condition. STM tip is on right and gold wire is on left. Figure 1b represents the recorded I-*V* curve under the sweeping bias voltage of ± 100V applied. The black curve represents the electrical properties of the nanotube before applying the bending force. The current is almost zero even at very high bias voltages. It indicates that the nanotube is originally insulator. Upon bending, it can also be seen that the nanotube converts to semiconductor. Higher electrical current can be recorded and the highest values obtained at negative bias voltages, gray curve.

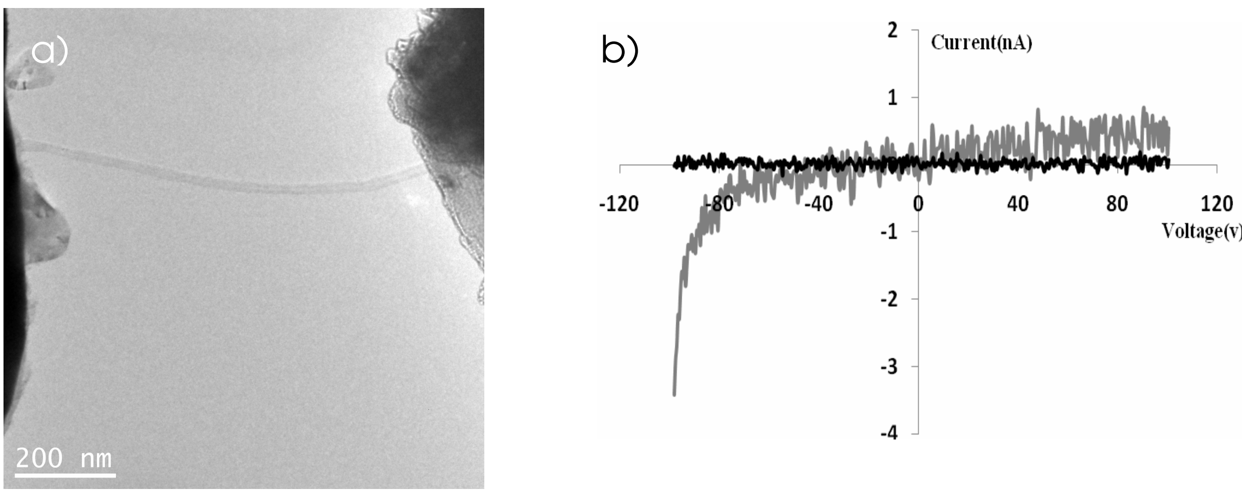

Figure 1. Right: TEM image of an individual BNNT under bending condition. Left: relative *I-V* curve shows the electrical behavior of the nanotube without bending (black curve), and under bending (gray curve).

Figure 2a shows an individual BNNT under more severe bending condition (higher bending angles). Upon releasing the applied force, the nanotube resumed its initial state and no sign of cracking or residual straining could be detected by close examination of the nanotube structure in the TEM. This unusual flexibility of BN nanotubes is in agreement with the previous reports [1]. Figure 2b represents associated *I-V* curve in almost the same range of bias voltage. One can see higher amount of electrical current could be detected in the nanotube under higher bending angle. This was more obvious in negative range of applied bias voltage.

The resistance, $R \sim dV/dI$, of the nanotube was measured from the slope of *I-V* curves in both deformed cases (Figure 1b and Figure 2b) as 0.7 GΩ and 0.46 GΩ, respectively. Before deformation, the resistance was measured to be above 2GΩ, higher than previously reported values [3]. One reason can be nanotube purity, by which the electrical response can be determined. The lower the defects density is, the higher the band gap would be. This means that as the deformation level increases, the resistance of the nanotube decreases significantly. Our calculated resistance of nanotubes under deformation (0.7 and 0.46 GΩ) is much higher than the value reported by Bai et al. [3], which was close to 0.2GΩ. One way to explain this can be expressed in terms of localization of deformation in our nanotubes shown by white arrows in Figure 2. In contrast the bending deformation conducted by Bai et al. appeared to be more uniform along the nanotube length.

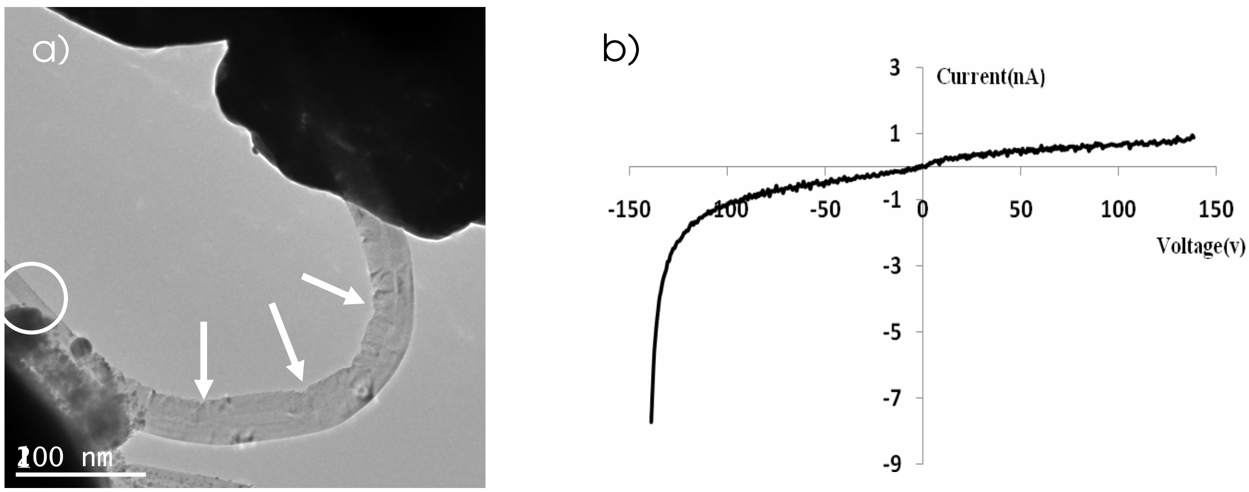

Figure 2. Right: TEM image of individual BNNT under severe bending condition. Left: relative *I-V* curve shows the electrical behavior of the nanotube under bending.

The higher electrical conductivity in negative bias ranges indicates that the BN nanotube acts as a *p*-type semiconductor under mechanical straining. As these BNNTs recovered to their original properties after unload the straining force and become insulating, the *p*-type behaviors detected here are not related to the original chemical/purity character if the BNNTs. However, these BNNTs are still having some intra-band defect levels [5] that may be activated under mechanical straining. The nature of these defects and their activation mechanism are not clear at this stage and should be subjected to future theoretical investigation.

ACKNOWLEDGEMENT

Yoke Khin Yap acknowledges supports from National Science Foundation CAREER Award (Award number 0447555, Division of Materials Research).

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