Vol 15 No 11, November 2006
1009-1963/2006/15(11)/2731-04
Chinese Physics
© 2006 Chin. Phys. Soc.
and IOP Publishing Ltd

Properties of the incandescent light emitted from double-walled carbon nanotube filament*

Wei Jin-Quan(韦进全)[a], Sun Jia-Lin(孙家林)[b]†, Wu De-Hai(吴德海)[a],
Guo Ji-Hua(郭继华)[b], Luo Jian-Bin(骆建彬)[a], and Wang Kun-Lin(王昆林)[a]

[a] *Key Laboratory for Advanced Manufacturing by Materials Processing Technology of Education Ministry and Department of Mechanical Engineering, Tsinghua University, Beijing* 100084, *China*
[b] *Key Laboratory of Atomic and Molecular Nanosciences of Education Ministry and Department of Physics, Tsinghua University, Beijing* 100084, *China*

(Received 11 October 2005; revised manuscript received 10 July 2006)

We have studied the radiation of a double-walled carbon nanotube (DWNT) filament with a length of 4.5 mm and a diameter of 10 μm by applying an electric current through the filament. The DWNT filament starts emitting incandescent light at voltage $U = 6$ V. Emission spectra of the DWNT below temperature 1250 K can well be fitted to those of the blackbody radiation. The intensity of the incandescent light shows an exponential dependence on the voltage applied on the DWNT filaments. The resistance of the DWNT filaments is very stable at high temperatures between 900 and 1250 K during the emission of light in the experiments.

Keywords: double-walled carbon nanotube filament, emission spectra, exponential dependence

PACC: 7360, 7865

1. Introduction

Carbon nanotube (CNT) is an ideal one-dimensional material, which has attracted significant attention due to its unique structure and outstanding properties.[1,2] Electrically, CNTs usually exhibit semi-conductive and metallic properties according to their geometric structure.[3,4] The current carrying capacity of an individual carbon nanotube is about 10^9 A/cm^2, which is about 1000 times as large as that of the copper.[5–7] This offers CNT potential applications as an unique electric material.

Recently, it was reported that CNTs could emit fluorescent light when they were excited by a laser.[8,9] Electrically induced optical emission from a carbon nanotube field-effect transistor (FET) has also been demonstrated.[10] These experiments indicate that the CNT has also novel optical properties. Furthermore, a multi-walled carbon nanotube (MWNT) bundle with a length of about 100 μm could even emit partial-polarized incandescent light when an electric current is applied through the bundle.[11] For a longer MWNT filament with a length about 1 cm drawn from the aligned MWNT array, it starts emitting incandescent light at about 70 V,[11,12] the resistance of the MWNT filament declines after the emission of light at 70 V for 3 h. These novel optical properties have opened a new window to explore the photonic applications of CNTs on the nano-scale.

In this paper, we are particularly interested in the double-walled carbon nanotube (DWNT) filaments and their electrical and optical properties including the Joule heat emission. The DWNT is a typical case of one-dimensional materials between single-walled carbon nanotubes (SWNTs) and the MWNTs. DWNTs are expected to be physically unusual due to their large interlayer distance (from 0.34 to 0.41 nm).[13,14] Recently, long DWNTs filament with a length of 10–35 cm and high-quality films were prepared.[15] This makes it easy to test their macroscopic properties.

2. Experiment

The DWNT filaments used in our experiments were prepared by the improved chemical vapour deposition (CVD), which has been described in detail elsewhere.[15] In brief, xylene is used as carbon feedstock. Ferrocene containing 10 at % of brimstone was used as catalyst. Argon in a flowing rate of 3 L/min

*Project supported by the Key Grant Program of Chinese Ministry of Education (Grant No 306020) and National Center for Nanoscience and Technology, China.
†Corresponding author. E-mail: jlsun@tsinghua.edu.cn

and hydrogen in 500 mL/min were used as carrier gas. The reaction temperature is 1150 °C. Long DWNT filaments with a length of 10 cm were obtained after the reaction. The DWNT filament could be separated into smaller filaments in ethanol solution and they assembled into a dense filament after the ethanol solution evaporated. The DWNT filament with a length of 4.5 mm was connected with the tungsten electrodes by an annealed nickel foil. And then, the DWNT filament was sealed in a quartz tube pumped to a vacuum better than 10^{-3} Pa. The emission spectra of the DWNT filament were recorded by a prismatic spectrometer with an avalanche photodiode (APD).

3. Results and discussion

Before the experiment of the emission spectra, first we examine the structure of DWNT filaments by scanning electron microscopy (SEM) and high resolution transmission electron microscopy (HRTEM). The SEM image of the DWNT filament used in the DWNT bulb is shown in Fig.1(a). The DWNT filament in the bulb is about 10 μm in diameter and about 4.5 mm in length. Thousands of long DWNT bundles can be seen in the filament. The length of the DWNT bundles is longer than tens of micrometres. Very few impurities are observed in the sample, indicating the high purity of DWNT in the sample. The higher resolution SEM image of the DWNTs filaments in Fig.1(b) reveals that they are composed of DWNT bundles. Although some disordered and wrapped DWNT bundles are seen in the filament, most of the bundles are aligned along the axial direction.

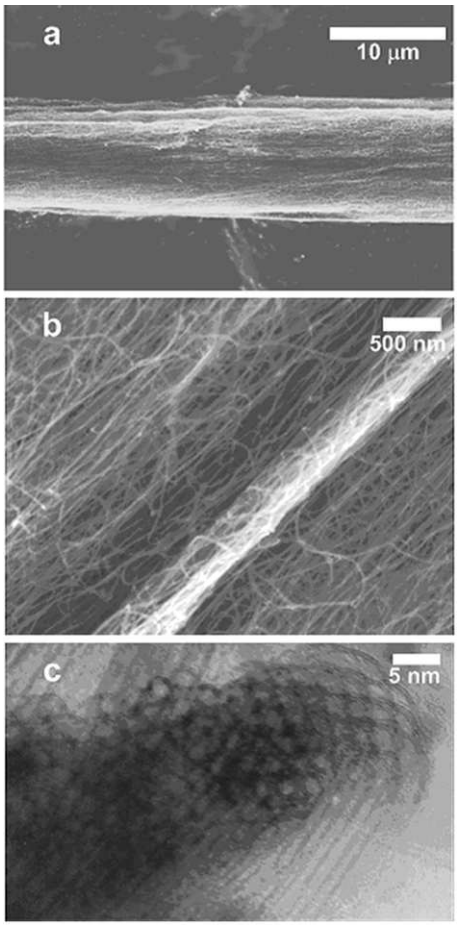


Fig.1. (a) Low-magnification SEM image, (b) high-resolution SEM image and (c) HRTEM image of the DWNT filament.

Furthermore, the details of a cross-section and a bending part of the DWNT bundles are imaged with the typical HRTEM technique. The concentric cylindrical structure of the DWNTs is clearly identified. The outer diameter of the DWNTs in the image is about 2.0 nm, and the interlayer distance of the DWNTs is about 0.4 nm according to the HRTEM image (Fig.1(c)).

The I–V curve of the DWNT filament (Fig.2) shows its metallic properties and can be well fitted by a linear relationship of I (mA) = 4.57 + U(V) when $U \geq 5$ V.

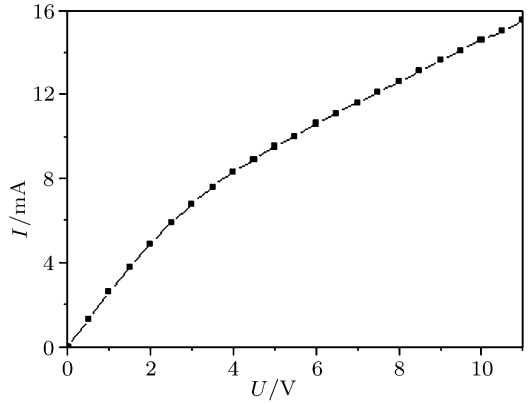


Fig.2. The $I-V$ curve of the DWNT filament.

The DWNT filament begins to emit incandescent light at about 6 V. The voltage at which DWNT filament starts emitting incandescent light is much lower than that of the MWNT filament reported in Ref.[11]. To avoid electroluminescence from CNTs, we only applied a voltage up to $U = 11$ V, at which the temperature of the DWNTs filaments is below 1300 K.

The emission spectra of the DWNT filament are shown in Fig.3(a). They are mainly located in the visible and infrared light region, which indicates that most of the electrical energy changes into Joule heat. The intensity of the incandescent light in each spectrum at the same wavelength increases quickly as the

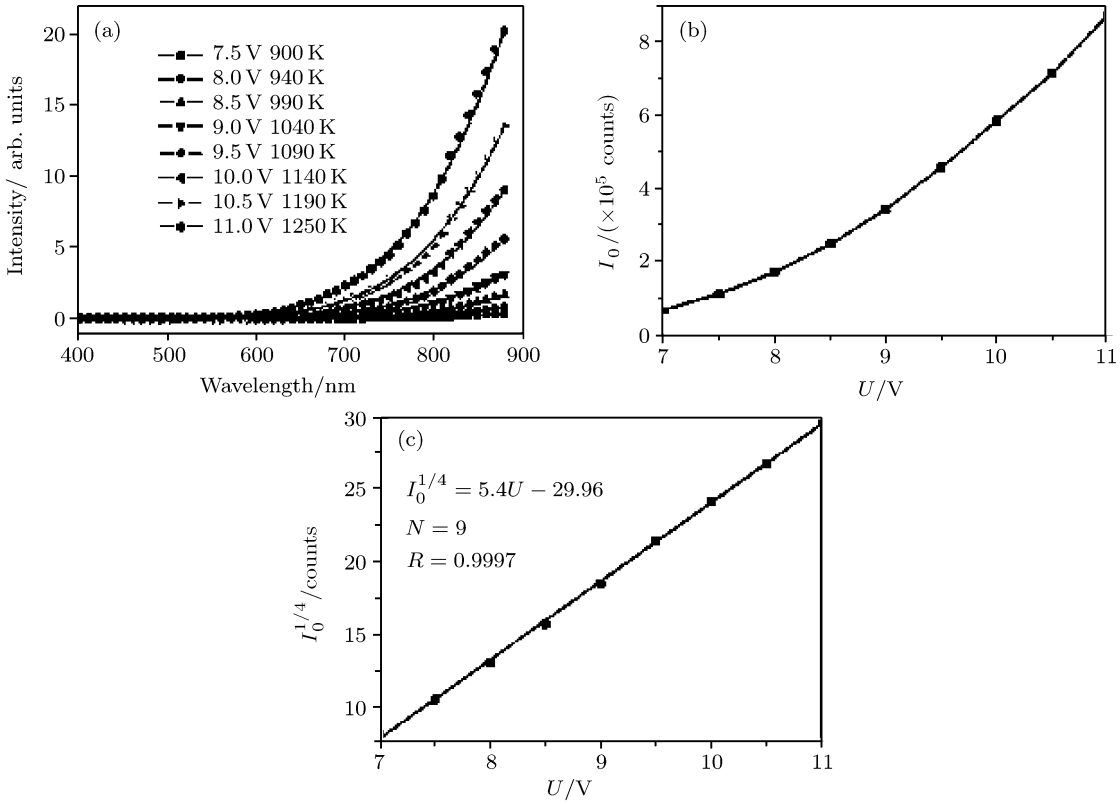


Fig.3. (a) The emission spectra of the DWNT filament at different voltages. (b) The dependence of the incandescent light intensity at 880 nm on the voltage. (c) The fourth root of the incandescent light intensity at 880 nm vs the voltage.

voltage increases, indicating the blue-shift of the incandescent light as the voltage is applied on the DWNT filament. The spectra of the DWNTs can be fitted by the blackbody emission very well. The lines in Fig.3(a) are the blackbody emission spectra at different temperatures. The resistance of the DWNT filament is very stable during the incandescent light emission for more than 100 h, which is also different from that of the MWNTs drawn from the MWNT array.[11]

The intensity of the DWNT filament emission increases quickly as the voltage increases, as shown in Fig.3(b). The intensity of the incandescent light from the DWNT filament can be fitted by using a formula of $I_0^{1/4} = A + BU$, where I_0 represents the intensity of the incandescent light, A and B are constants and U is the voltage. The fitted line of intensity versus voltage is shown in Fig.3(c). Similar results also can be obtained for other wavelengths and the total intensity of the incandescent light from the DWNT filament. It is needed to study further the mechanism behind the relation between the intensity of the incandescent light and the voltage applied on the DWNT filament.

4. Conclusion

In conclusion, the threshold voltage of the DWNT filament at which it begins to emit incandescent light has been found to be lower than that of the MWNTs. The emission spectra of the DWNT filament can be fitted by the blackbody emission. The fourth root of the intensity of incandescent light emitting from the DWNT filament varies linearly with the voltage applied on the filament. The resistance of the DWNT filament is very stable during the emission of incandescent light.

Acknowledgment

The authors wish to thank Prof. Zhu Jia-Lin and Prof. Zhang Wei-Ping at Department of Physics in Tsinghua University for valuable discussions.

References

[1] Dresselhaus M S, Dresselhaus G and Avouris P 2001 *Carbon Nanotubes: Synthesis, Structure, Properties, and Applications* (Berlin: Springer)

[2] Baughman R H, Zakhidov A A and de Heer W A 2002 *Science* **297** 787

[3] Wei B Q, Vajtai R and Ajayan P M 2001 *Appl. Phys. Lett.* **79** 1172

[4] Mintmire J W, Dunlap B I and White C T 1992 *Phys. Rev. Lett.* **68** 631

[5] Saito R, Fujita M, Dresselhaus G and Dresselhaus M S 1992 *Appl. Phys. Lett.* **60** 2204

[6] Wei B Q, Spolenak R, Kohler-Redlich P, Ruhle M and Arzt E 1999 *Appl. Phys. Lett.* **74** 3149

[7] O'Connell M J, Bachilo S M, Huffman C B, Moore V C, Strano M S, Haroz E H, Rialon K L, Boul P J, Noon W H, Kittrell C, Ma J P, Hauge R H, Weisman R B and Smalley R E 2002 *Science* **297** 593

[8] Bachilo S M, Strano M S, Kittrell C, Hauge R H, Smalley R E and Weisman R B 2002 *Science* **298** 2361

[9] Liang W J, Bockrath M, Bozovic D, Hafner J H, Tinkham M and Park H 2001 *Nature* **411** 665

[10] Misewich J A, Martel R, Avouris Ph, Tsang J C, Heinze S and Tersoff J 2003 *Science* **300** 783

[11] Li P, Jiang K L, Liu M, Li Q Q, Fan S S and Sun J L 2003 *Appl. Phys. Lett.* **82** 1763

[12] Jiang K L, Li Q Q and Fan S S 2002 *Nature* **419** 801

[13] Charlier A, McRae E, Heyd R, Charlier M F and Moretti D 1999 *Carbon* **37** 1779

[14] Hutchison J L, Kiselev N A, Krinichnaya E P, Krestinin A V, Loutfy R O, Morawsky A P, Muradyan V E, Obraztsova E D, Sloan J, Terekhov S V and Zakharov D N 2001 *Carbon* **39** 761

[15] Wei J Q, Jiang B, Wu D H and Wei B Q 2004 *J. Phys. Chem.* B **108** 8844