Sensors and Actuators A 199 (2013) 176–180

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Transparent film heaters using multi-walled carbon nanotube sheets

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ARTICLE INFO

Article history:
Received 29 January 2013
Received in revised form 22 May 2013
Accepted 28 May 2013
Available online 4 June 2013

Keywords:
Multi-walled carbon nanotube sheet
Heater
Transparent conductive film

ABSTRACT

This paper presents carbon nanotubes (CNTs) used as transparent heaters, which offer great advantages in miniaturization, high efficiency, low power consumption, and rapid response. Previously proposed transparent single-walled carbon nanotube (SWCNT) based heaters used to replace indium tin oxide (ITO) heaters were fabricated either by dielectrophoresis or the piece-wise alignment of read-out electronics around randomly dispersed CNTs. These methods require steps for purification, separation, and dispersion in a liquid or polymer in order to improve their electrical and optical properties. We studied a transparent film used for heating, fabricated by employing a multi-walled carbon nanotube (MWCNT) sheet. The sheet was made from a super-aligned MWCNT forest; the heater was fabricated by direct coating onto a glass substrate. The characteristics of the MWCNT sheet, i.e. a high transmittance of ~90% and a sheet resistance of ~756 Ω/sq, are comparable to previously reported SWCNT-based transparent films. These properties are directly applicable to applications such as window tinting and defrosters in production vehicles.

1. Introduction

Transparent conductive films (TCF) have garnered much attention, and they are widely used in many applications, such as solar voltaic cells, flat panel displays, and thermally-based sensors [1–3]. Generally, transparent conductive heaters have been made using an optically transparent substrate which is coated with electrically conductive as well as visually transparent elements. To date, the indium tin oxide (ITO) has had sufficiently suitable transparency ($T > 95\%$) and conductive properties ($R_s < 50\,\Omega$/sq) to fulfill market demand for transparent heaters, such as those used in avionic displays, liquid-crystal displays (LCD), and outdoor panel displays placed in severe environments. The reflection and transmission properties of ITO can be easily controlled [4–5] and the optimum coating and patterning methods offer excellent heating performance with good transparency. However, ITO film heaters have some disadvantages, such as a slow thermal response, brittleness, and cost [6–8]. These drawbacks in ITO films hinder their use in bendable electrical circuitry and flexible display applications. Recently, various efforts have been undertaken to develop transparent conducting films that overcome these ITO disadvantages.

Since the discovery of carbon nanotubes (CNT), there has been much research regarding their outstanding physical properties [9–10]. Films made of CNTs are one of the promising candidates for transparent conducting films (TCF) due to their high conductivity, mechanical flexibility, and the abundance of raw carbon materials. Therefore, CNT-TCFs have been investigated widely for use in transistors, electrodes, sensors, and actuators [7–8]. In particular, there are reports that single-walled CNT (SWCNT) films have low sheet resistance ($R_s < 150\,\Omega$/sq), high optical transparency ($T > 90\%$), and good thermal conductivity, which makes them ideal to replace ITO films [11–13]. A number of studies have been developed based on different working principles regarding the use of SWCNT films as TCFs [14–16]. However, SWCNTs still have some issues in their purification, separation, and dispersion in a liquid/polymer used to enhance their electrical and optical properties [17–18]. It is difficult to modify the density and thickness of the SWCNTs causing reduction in their production efficiency [19]. On the other hand, our group has previously [20–21] reported the spinning of MWCNT sheets from a MWCNT forest. The sheet has a transmittance of ~90% and a sheet resistance of ~753 Ω/sq. These figures are comparable to those found for SWCNTs and ITO and provide an excellent opportunity to use them in a wide range of applications for flexible conductive films. In this paper, we present a conductive transparent MWCNT sheet from a super-aligned MWCNT forest. The MWCNT sheet heater is formed using a simple fabrication process.

2. The experiment

The MWCNT forests were grown from iron films, which were deposited by electron-beam evaporation onto Si substrates with a 400-nm thick oxidized layer. The thickness of the Fe films was 6 nm and was monitored using a quartz-crystal sensor fixed inside the e-beam evaporation chamber. The CNT growth was performed in a quartz and stainless steel cylindrical CVD chamber having a

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http://dx.doi.org/10.1016/j.sna.2013.05.024

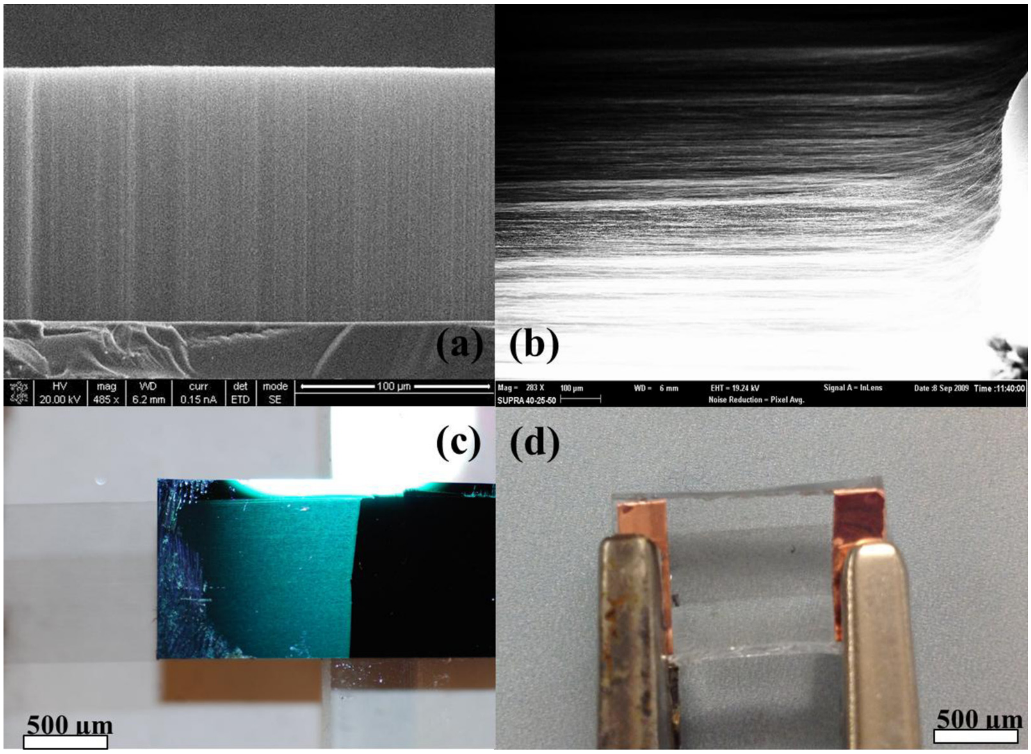

Fig. 1. High resolution SEM images of (a) MWCNT forest and (b) CNTs sheet pulling from the CNTs forest. Photographs of (c) ribbons pulling from Si substrate and (d) fabricated heater.

diameter of 60 mm at atmospheric pressure using a mixture of C_2H_2, He, and H_2 gases. The substrate was introduced into the CVD chamber and ramped to the set point temperature of 780 °C at a ramping rate of 50 °C/min while introducing He at 700 sccm and H_2 at 100 sccm. The growth of the CNTs was then carried out at the same temperature and pressure by adding C_2H_2 gas at 100 sccm to the flow for 5 min. After completing the growth of the CNTs, the sample was cooled to below 100 °C in the same H_2/He gas mixture. As shown in Fig. 1, the height of the MWCNT forests was about 150 μm having an average MWCNT diameter of 13.0 ± 2.4 nm. And the MWCNT sheets were directly pulled out from a super-aligned MWCNT forest. The MWCNT sheet was directly pulled onto glass. This provides a very simple and easy method to fabricate a TCF film. In order to increase the adhesion between the sheet and the substrate, ethanol was applied onto the entire surface of the MWCNT sheet on the substrate and dried at ambient temperatures for 2 h.

3. Results and discussions

The equations governing the total power consumption P of operating a MWCNT heater can be written as

$$P = \frac{V^2}{R} \quad (1)$$

where V is the voltage drop through the MWCNT heater, R is sheet resistance. The heat generated by the heater is equal to the sum of the heat lost by conduction in the substrates, convection to the air, and radiation [22]. The measured temperature is mainly due to the heat convection that the hot surface of MWCNTs to the surrounding air, thus heat loss occurs in the form of conduction and radiation. The convection to the air can be expressed as

$$\Delta P_{conv} = h_{conv} \cdot A_{conv} \cdot \Delta T \quad (2)$$

where h_{conv} is a geometrical factor depending on the shape and orientation of the heated surface, A_{conv} is the surface area and ΔT is the temperature difference between the heat source and surrounding environment. By (1) and (2), heat generation depends on the input power, resistance and the surface area of heater.

The three types of samples processed with different number of sheet layers were prepared on a glass substrate by overlaying the layers one, three, and five times. Fig. 2 shows the *I–V* measurement each sample using the four-point probe method; the resistances were ~756, ~342, and 172 Ω/sq for the 1, 3, and 5 layer samples, respectively. In order to investigate the use of the MWCNT sheet as an electrical heater, a series of voltage step functions were placed across the electrodes using a DC power supply. A thermocouple was, placed on the top surface of the sheet to detect the temperature variations. Fig. 3(a) shows the temperature variation of the MWCNT

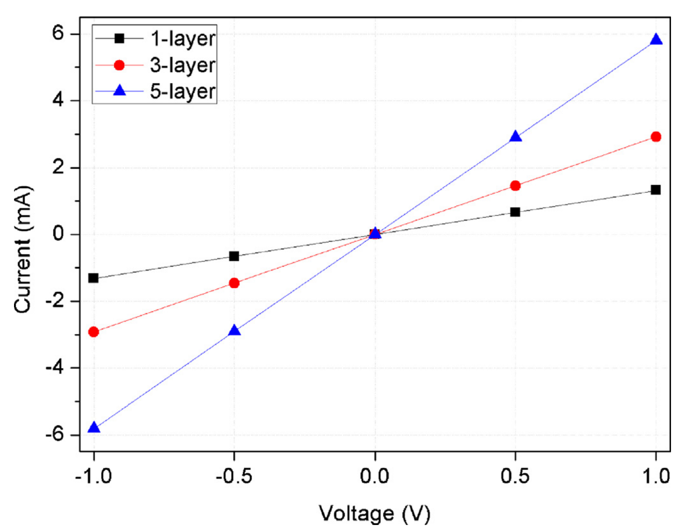

Fig. 2. The *I–V* measurement of the MWCNT forest sheet resistance.