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Short communication

Carbon nanotube ink for writing on cellulose paper

Jin-Woo Han *, Beomseok Kim, Jing Li, M. Meyyappan

Center for Nanotechnology, NASA Ames Research Center, Moffett Field, CA 94035, USA

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ABSTRACT

A water-based conductive carbon nanotube (CNT) ink was synthesized with single-walled CNT and sodium dodecylbenezenesulfonate as surfactant. Direct writing on paper using this ink was demonstrated with off-the-shelf nib and cartridges in a fountain pen handwriting tool. It is lightweight and portable which allows writing on curved substrates. The through paper via was easily achieved by wetting method. Dual-side and multi-layer paper circuit boards were demonstrated by direct writing. The drawn pattern displays uniformity and reproducibility. The exceptional adhesion of CNT on cellulose paper shows good robustness against bending, folding, crumpling and other mechanical stress. A chemical sensor fabricated by direct writing showed good response down to 10 ppm of ammonia vapor in air.

1. Introduction

Carbon nanotube (CNT) as a nanomaterial has received much attention in the last two decades due to its extraordinary electrical, optical, chemical, and mechanical properties. A variety of deposition and alignment methods have been used for device applications. The active material in most device demonstrations is in a network form because forming cross-linked bundle of CNTs is simpler than aligning a single nanotube. Direct deposition of bulk-produced CNTs has been widely tried using various techniques such as drop-casting, spin coating, vacuum filtration, Langmuir–Blodgett deposition and dip coating. These methods commonly result in a two dimensional sheet; however, patterning of the thin film is needed for applications such as electronic devices, sensors and actuators in order to tailor the thin film to the desired shape. Patterning involves a series of processes such as masking the CNTs with a chemical resist, chemically eliminating the exposed portion and removing the mask material. Although the patterning technique is matured, it sometimes contaminates and alters the properties of CNTs. Therefore, direct writing or direct printing methods can be an attractive alternative to patterning.

The direct writing processes are not only simpler and cheaper but they also open new opportunities for flexible, foldable, stretchable, and disposable substrates. A notable example is the emerging interest in paper electronics [1,2]. The cellulose paper is an extraordinary material due to its diversity. The paper can be hydrophilic or hydrophobic, porous or nonporous, opaque or transparent, strong or delicate, coarse or smooth depending on the manufacturing process and additives used [3]. The cost per length is the lowest among any human-made materials. Printing methods such as handwriting, screen printing, plotting, inkjet printing and roll-to-roll printing have long been matured throughout human history. Recently, fundamental electronic building blocks have been demonstrated on paper substrates including thin-film transistor [4], non-volatile memory [5], RF antenna [6], displays [7], solar cell [8], battery [9], supercapacitor [10], biological assays [11], chemical sensors [12] and circuit board [13]. The critical step for building a paper electronic system is to connect individual components with one another. Inkjet and roll-to-roll techniques are available to print interconnects. However, the features of the interconnection process of the present fountain pen writing compared to the inkjet/roll-to roll approaches allow a distinctive application domain. The inkjet/roll-to-roll printings are computer-aided, fast and accurate. The fountain pen process is cheap, simple and compact to carry in shirt pocket, and allows hand drawing even on curved/folded structures. Therefore, the features of fountain pen process are suitable for rapid prototyping, concept proofing, circuit revision on the field, and demonstration for education.

The present work demonstrates hand-drawing of circuit board using a fountain pen with CNT ink. Single walled CNT (SWCNT) was used to synthesize the conductive ink and an off-the shelf fountain pen tip was used to write on conventional paper. The resistance under different mechanical stress conditions was assessed and resistance to crumpling and moisture was also tested. The vertical through paper interconnection, alignment method for multilayer board, a simple LED circuit and a chemical sensor were demonstrated.

* Corresponding author. Tel.: +1 4087020216; fax: +1 6506045244.
E-mail address: jin-woo.han@nasa.gov (J.-W. Han).

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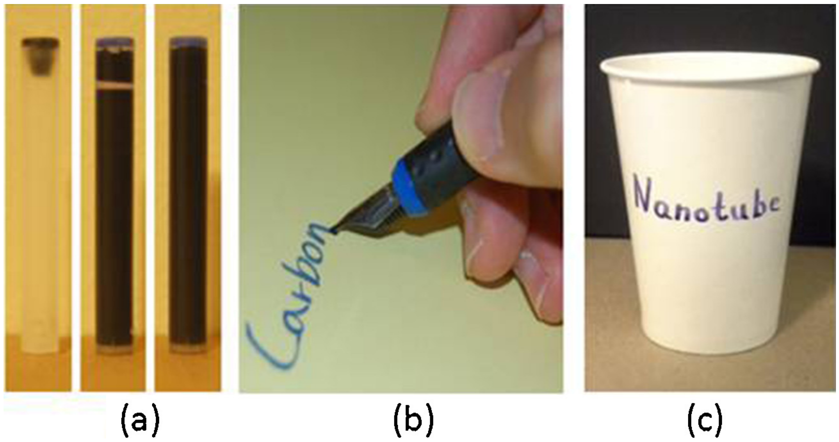

Fig. 1. Fountain pen ink cartridges: empty, as-synthesized ink, and the ink after 1 week. The CNTs are still well dispersed after 1 week. (b) Direct handwriting of the word 'Carbon' using an off-the-shelf fountain pen with CNT ink on a copying paper. (c) The letter 'Nanotube' written on a paper cup.

2. Experimental work

The water-based ink was prepared by mixing SWCNTs and sodium dodecylbenezenesulfonate (SDBS) as a surfactant. 50 mg of SWCNTs and 100 mg of SDBS were dispersed in 10 mL of deionized water. After bath sonication for 10 min, the SWCNT dispersion was probe-sonicated for 90 min at 25 W. A fountain pen nib and cartridge found in office supply stores were used. The CNT fountain pen becomes ready to write by filling the CNT ink into the empty cartridge. As shown in Fig. 1(a), the CNT is in well-dispersed condition for 30 days. The CNT patterns can be written on ordinary copy paper as well as on curved surface of paper cup, as shown in Fig. 1(b) and (c). Dispersed SWCNT was deposited on a filter paper (3.5 cm radius) using a paint brush. Approximately 0.12 mL of the solution was used to cover one filter paper. Based on this result, 50 cm $\times$ 50 cm can be covered with 50 mg of SWCNTs. The initial resistance of the SWCNT-deposited filter paper was below 20 kΩ/cm after drying in air.

3. Results and discussion

In order to investigate the continuity of the CNT pattern, 400 cm long rectilinear test patterns were drawn as shown in Fig. 2(a) and the current–voltage (*I–V*) characteristic were measured. Fig. 2(b)

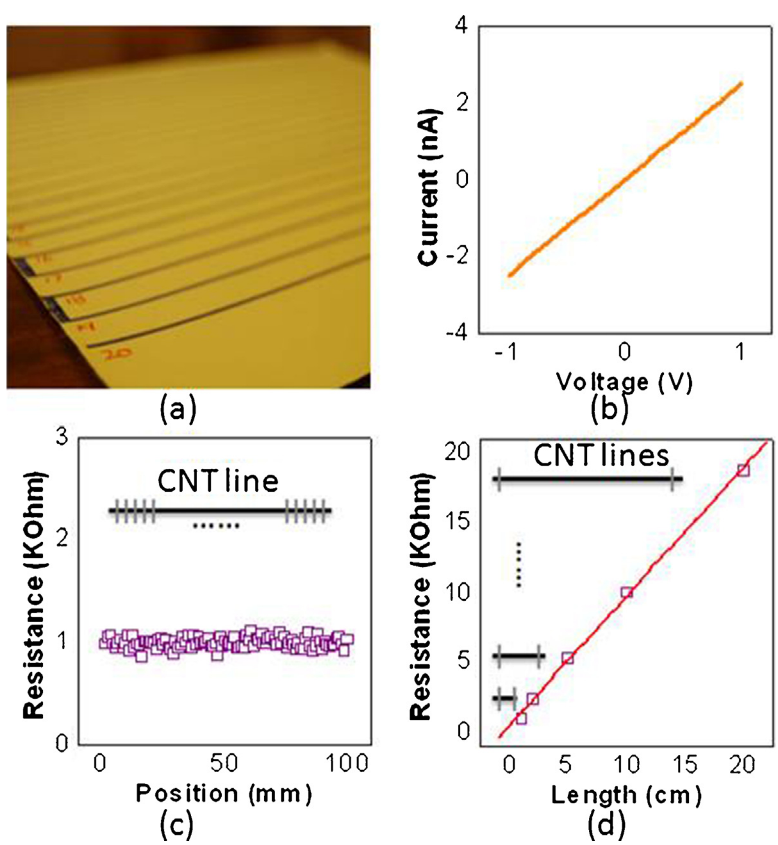

Fig. 2. Rectilinear test pattern for verifying the continuity of CNT network: the total length of the lines is 4 m. (b) *I–V* characteristics of line pattern in (a). The current increases linearly with voltage at a resistance of 4.1 MΩ, which signifies that CNT lines are electrically continuous. (c) The characteristics of inter-line resistance segmented by 1 mm within 10 cm line: the resistances measured by shifting from left to right show that the mean and standard deviation are 0.99 kΩ and 0.05 kΩ, respectively. (d) The intra-line resistance uniformity for various lines with different lengths: the resistance linearly increases with increasing length, implying that the electrical characteristics are reproducible.