DEPENDENCE OF AC ELECTROPHORESIS CARBON NANOTUBE MANIPULATION ON MICROELECTRODE GEOMETRY

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Abstract

A rapid approach to form post-growth multi-walled carbon nanotube (MWNT) linkages between microelectrodes using AC electrophoresis is presented. Three types of microelectrodes with different geometrical shapes were fabricated to investigate the degree of MWNT linkages formation. The gap distance between the microelectrode pairs ranged from 10 μm to 30 μm. We experimentally observed that in 0.02 mg/ml MWNT-ethanol medium, MWNT with axial dimension ranging from 1 μm to 10 μm can bridge microelectrode pairs with gap distance smaller than 15 μm in applied sinusoidal AC frequency ranging from 100 Hz to 1 MHz and the electric field strength ranging from 0.3 $V/\mu m$ to 0.7 $V/\mu m$. This is a very fast and inexpensive approach to manipulate MWNT to any specific area of a patterned substrate using AC voltage source.

Keywords: Multi-walled carbon nanotubes, AC electrophoresis

I. INTRODUCTION

Carbon nanotubes were first discovered by Sumio Iijima in 1991 [1]. The discovery has aroused the interest of the scientific community to investigate the properties of carbon nanotubes. Based on their lattice geometry, carbon nanotubes can be classified as semi-conductive or conductive. A recent report showed that the electrical properties of MWNT can be tailor made by using current-induced electrical breakdown [2]. Moreover, carbon nanotube based electronics have been reported in the last few years [3, 4, 5]. Therefore, it seems that carbon nanotubes will become one of the most promising materials for future nanoelectronics. However, one fundamental barrier for carbon nanotube based nanoelectronics is the inability of batch manipulating carbon nanotubes within reasonable time [6]. Nowadays, atomic force microscopy (AFM) [7] or nanorobotic manipulator [8] is used to manipulate carbon nanotubes to specific locations on the substrate. However, traditional pick-and-place technique is unrealistic for nanoelectronics manufacturing where batch fabrication is highly desired. From the past works of K. Yamamoto et al. [9, 10], Y. Zhang et al. [11], and Y. Avigal and R. Kalish [12], carbon nanotubes can be successfully aligned and manipulated under electric field. Besides, electric-field assisted assembly has been employed successfully on inorganic [13] and metallic [14] nanowires, respectively. Therefore, in this project, we investigated the usage of electric field as an external source for large-scale manipulation of carbon nanotubes. This paper reports a method in fast manipulating post-growth MWNT to specific locations on glass substrates with microelectrodes of different geometrical designs by using AC electrophoresis.

II. CARBON NANOTUBE LINKAGES FORMATION BY AC ELECTROPHORESIS

A. Fabrication of Microelectrodes

Three types of microelectrodes (see Figure 1.) with different geometrical shapes were fabricated using image reversal process on glass substrate. A glass substrate was first coated with AZ5214 positive photoresist spun at 450 rpm for 6 seconds spreading followed by 3000 rpm for 30 seconds. The substrate was prebaked at 80 ^{o}C for 40 seconds. Then the substrate was exposed in ultra violet light inside Karl-Suss MA4 mask aligner system (λ =320 nm, mercury lamp power = 350 W) for 60 seconds. The substrate was then postbaked

at 100 ^{o}C for 60 seconds and followed by flood exposure in the same aligner system for 60 seconds. Next, the substrate was developed in non-diluted AZ300 developer for 2 minutes. The patterned substrate was then deposited with nickel and then by gold inside an electron-beam evaporator. After the metal deposition, the photoresist was lifted off using acetone. Due to poor adhesion between gold and glass substrate, nickel is used as adhesion layer between them. Although chrome is a more conventional adhesion layer, we have found that gold microelectrodes did not peel off easily using nickel as an interface as well.

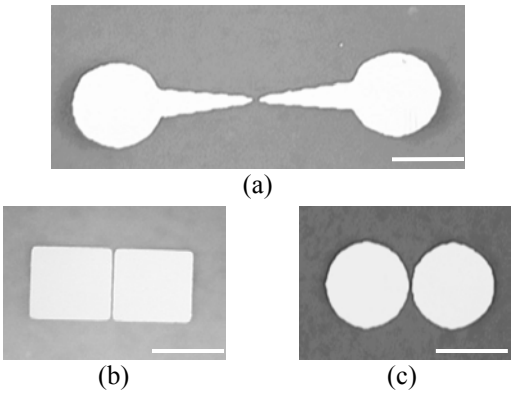


Figure 1. Microelectrodes with different geometrical shapes. The minimum gap distance in (a) and (b, c) are 30 μm and 10 μm, respectively, as confirmed by scanning electron microscope (SEM) measurement (Scale bar = 200 μm).

B. Sample Preparation

Multi-walled carbon nanotubes were ordered commercially from [15]. From the specifications of the manufacturer, these MWNT were prepared by chemical vapor deposition and their length and diameter are 1-10 μm and 10-30 nm, respectively. 10 mg of MWNT was dispersed ultrasonically in 500 ml ethanol (absolute) for 30 minutes. The purpose of sonication is to form stable colloidal suspension of MWNT within the ethanol to minimize the degree of aggregation. However, this stable state cannot be maintained more than a few hours [16]. Therefore, the dispersed MWNT should not be stayed too long for experiments.

C. Experimental Procedure

A micromanipulator system was used for probing the microelectrodes. Firstly, the probe tip of the micromanipulator was placed in position on a pair of microelectrodes. 10 μl of dispersed MWNT suspension was transferred to the patterned glass substrate by 6 ml gas syringe and AC electric field was then applied. Applied sinusoidal AC voltage with frequency of 1 MHz at 0.5 V/μm was used in Figure 2 and 3. The ethanol was evaporated within 20 seconds leaving the MWNT to reside between the gap of the microelectrodes (see figure 2a.) We have experimentally observed that no MWNT linkages were formed between the gaps of microelectrode pairs in locations other than the probed pair (see figure 2b). Most of the MWNT was directed to the probed microelectrode pair by AC electric field. The formation of MWNT linkages can be further confirmed by the SEM image (see figure 3). Resistance of 6.12 kΩ between the microelectrodes was found upon measurement which suggested that connection has been formed between the two microelectrodes.

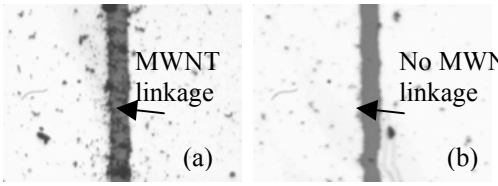


Figure 2. Comparison between two microelectrode pairs with 250 μm separation on glass substrate (Optical Magnification = 2000 X).

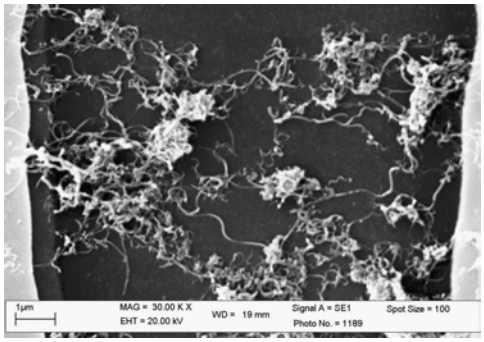


Figure 3. SEM picture showing the formation of MWNT linkages between the microelectrodes.

III. EFFECT OF GAP DISTANCE TO THE FORMATION OF CARBON NANOTUBE LINKAGES

We found that the formation of MWNT linkages is dependent on the gap distance between the microelectrodes. From observations, no MWNT linkages was formed with gap distance greater than 25 μm, with applied sinusoidal AC voltage at frequency ranging from 100 Hz to 1 MHz and electric field strength at 0.45 V/μm (see figure 4

a, b, c). The major reason is due to comparatively large ratio between the length of MWNT and the gap distance. In comparison, with gap distance between 10 μm and 15 μm , MWNT linkages could be formed with applied sinusoidal AC voltage at frequency ranging from 100 Hz to 1 MHz and electric field strength at 0.5 V / μm (see fig. 5 a, b, c). The resistivity measurements for the microelectrodes in Figure 5 a, b, c were 158 kΩ , 60 kΩ and 78 kΩ , respectively, which proved the connectivity between the microelectrodes. In Figure 5, aggregation was observed and this can further confirm the instability of carbon nanotubes in ethanol medium.

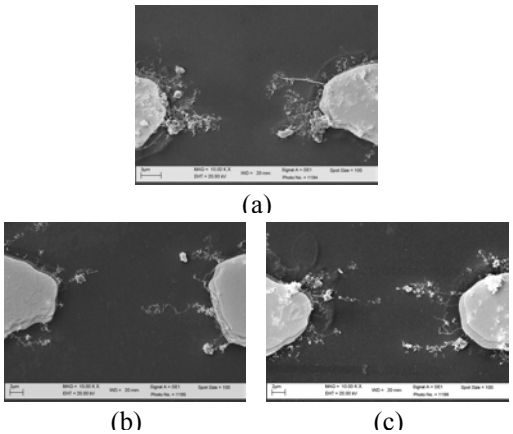


Figure 4. No MWNT linkages formation for gap distance between 25 μm and 30 μm . Applied frequency ranged from (a) 100 Hz (b) 10 kHz (c) 1 MHz.

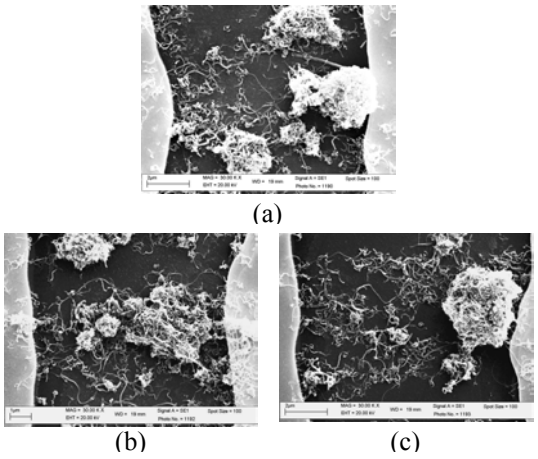


Figure 5. MWNT linkages formation for gap distance between 10 μm and 15 μm. Applied frequency ranged from (a) 100 Hz (b) 10 kHz (c) 1 MHz

IV. EFFECT OF GEOMETRICAL SHAPE TO THE FORMATION OF CARBON NANOTUBE LINKAGES

With the same minimum gap distance, more MWNT linkages could be formed between microelectrodes with square geometry than that of circular geometry (see fig. 6). In square geometry, the gap distance is constant between the microelectrodes and so the electric field is uniform along the gap. Therefore the chance for occurrence of MWNT linkages is the same along the gap, except at the edge of the microelectrodes where non-uniform electric field exists (see fig. 7). In circular geometry, most of the nanotube linkages was formed at the minimum gap distance and fewer linkages could be found in the part farther (see fig. 6 and fig. 7). This is due to the increase in ratio between the length of MWNT and the gap distance along the gap, which is less favourable for the linkage formation.

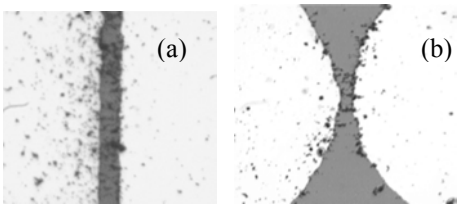


Figure 6. Nanotube linkages formation in microelectrodes with different geometry. (a) Square geometry and (b) Circular geometry. Applied frequency was 1 MHz at 0.7 V / μm . (Optical Magnification = 2000X)

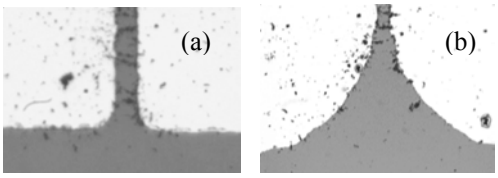
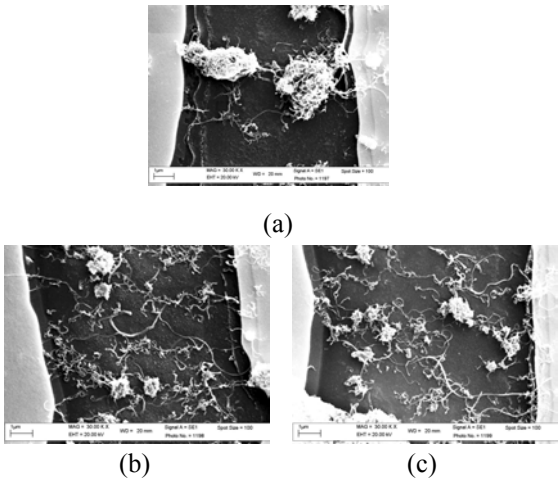


Figure 7. Formation of nanotube linkages at the lower part of the microelectrodes. (a) Square geometry and (b) Circular geometry. Applied frequency was 1 MHz at 0.7 V / μm . (Optical Magnification = 2000X)

V. FORMATION OF CARBON NANOTUBE LINKAGES IN DIFFERENT FREQENCY RANGE AND ELECTRIC FIELD STRENGTH

From experimental observations, MWNT linkages can be formed with gap distance from 10 μm to 15 μm in applied AC sinusoidal voltage with

frequency ranging from 100 Hz to 1 MHz and electric field strength ranging from 0.3 μm to 0.7 μm (see fig. 8). The resistivity measurements for the microelectrodes in Figure 8a, b, c are 36 kΩ, 10 kΩ and 19 kΩ, respectively. Currently, no apparent resistivity trends can be concluded in different frequency range and electric field strength. We speculate that, due to our inability to control the volume of nanotubes suspension precisely, the quantity of nanotubes transferred to the patterned substrate varied, which contributed to the inconsistency.



(a) (b) (c)

Figure 8. Formation of MWNT linkages with different electric field strength at 1M Hz. Electric field strength ranged from (a) 0.3 V/μm, (b) 0.5 V/μm, and (c) 0.7 V/μm.

VI. CONCLUSION

A technique in forming carbon nanotube linkages between microelectrodes by using AC electrophoresis has been demonstrated. Three geometrical designs to form nanotube linkages have been discussed. Besides, we have proven that AC electric field can direct MWNT to specific area of the patterned substrate. This method can be further extended to microelectrodes with smaller feature size. With microelectrodes in smaller feature size, we speculate that individual deposition of carbon nanotube will be possible. However, aggregation formation prohibits carbon nanotubes to deposit individually on the patterned substrate. In order to make carbon nanotube stabilize in ethanol or water medium without aggregation, addition of surfactants [16] can be implemented to the solution and this will be explored in the future. Future work involves batch manipulation of individual carbon nanotubes with microelectrodes in reduced feature size in developing novel nanoelectronic fabrication method.

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