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Carbon 42 (2004) 2263–2267
CARBON
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Fabrication of carbon nanotube field effect transistors by AC dielectrophoresis method

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Received 26 December 2003; accepted 4 May 2004
Available online 9 June 2004

Abstract

Single wall carbon nanotubes (SWNTs) suspended in isopropyl alcohol have been placed between two electrodes by AC dielectrophoresis method. The number of SWNTs bridging the two electrodes is controlled by SWNT concentration of the suspension and deposition time. Through selectively burning off the metallic SWNTs by current induced oxidation, the back-gate carbon nanotube field effect transistors (CNTFETs) with a channel current on–off ratio of up to 7×10^5 have been successfully fabricated. The success rate of the CNTFETs in 20 samples is 60%. These results suggest that AC dielectrophoresis placement method is an efficient technique to fabricate CNTFETs with some flexibilities of controlling CNT reconnection, length and orientation.

Keywords: A. Carbon nanotubes; C. Atomic force microscopy; D. Electrical (electronic) properties

1. Introduction

Single wall carbon nanotubes (SWNTs) are an ideal one-dimensional (1D) system because of their small diameter (of the order of 1 nm) and great length (of the order of micrometer). The 1D structure allows electrons to move in only two directions, leading to a reduced "phase space" for scattering processes [1]. In the absence of scattering, the transport is ballistic, which makes the carbon nanotube an ideal microelectronic device material, especially for field effect transistors (FETs). Since the first batch of CNT field effect transistors (CNTFETs) [2,3] were fabricated in 1998, their performance has been significantly improved in aspects of CNT channel current on–off ratio [4,5], hole mobility [6] and the CNT–metal electrode contacts [5]. However, how to selectively place semiconducting SWNTs in desirable locations is not solved. At present, two methods are generally used for CNTFET device fabrication. The first is to spin-coat SWNT suspension onto structured wafers [2,3,7,8]. However, the random distribution of SWNTs over the wafers is the major drawback of this method. The second method is to grow SWNTs along wafer surface to connect desirable electrodes [9,10]. The major disadvantages of this technique are the catalyst contamination and poor selectivity of SWNTs. Recently, DC and AC electrophoresis methods have attracted numerous interest. It has been demonstrated to be an efficient method to deposit large number of CNTs [11–13], SWNT matted sheet [14], and a single bundle with definite orientation [15]. Most recently, studies reported depositing single bundle simultaneously onto an array of electrodes [16]. However, except for Krupke et al. results obtained in vacuum [16], there has been no further report on the fabrication of CNTFETs using AC dielectrophoresis method.

This paper reports the CNTFETs fabricated by AC dielectrophoresis method at an ambient environment. SWNTs were connected between the source and drain electrodes along the direction of the electric field. The number of SWNTs is controlled by the SWNT concentration in the suspension and the deposition time.

2. Experimental

2.1. Carbon nanotube deposition

CNTFETs were fabricated on p-type silicon wafers which were thermally coated with a 500 nm thick silicon

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doi:10.1016/j.carbon.2004.05.002

dioxide layer. Source and drain electrodes were made of 20 nm thick Ti and 40 nm thick Au. The distance between the electrodes is in the range of 1–4 μm.

SWNTs with very high purity were deposited between two electrodes using AC dielectrophoresis method. The diameter of the SWNTs was around 1.4 nm. To prepare the CNT suspension, 1mg of SWCNTs were dispersed in 500 ml isopropyl alcohol (IPA) and ultrasonically treated for 10 min. The suspension was transparent after further dilution. A drop of the suspension was introduced onto the structured wafers on which an AC bias was applied, as shown in Fig. 1. The peak-to-peak AC voltage was between 4 and 8 V, depending on the electrode distance, and the frequency was fixed at 10 MHz. Monitoring the variation of the resistance between two electrodes is an easy way to confirm the connection of CNTs and the electrodes. The resistance was typically decreased to several hundred kΩ after CNTs bridged the electrodes. Once the resistance drop was detected, the AC bias was turned off immediately. After the CNTs had been deposited successfully, the wafer was rinsed using IPA and deionized water to clean the wafer surface. In this way, CNTs could be placed across any two of the four electrodes in Fig. 1. In addition, all the four electrodes could be connected pair by pair without influencing the CNT connection formed earlier. Fig. 2 shows CNT bundles between two electrodes. The diameters of the bundles are typically in the range of 40–80 nm. It is clear that the SWNTs bridge the electrodes along the direction of the electric field. If the two electrodes are parallel, the SWNT orientation is perpendicular to the parallel electrodes, as observed in Refs. [14–16]. Therefore, the SWNT length between them is controllably close to the distance between the parallel electrodes. The number of SWNTs between the electrodes is determined by the deposition time and SWNT

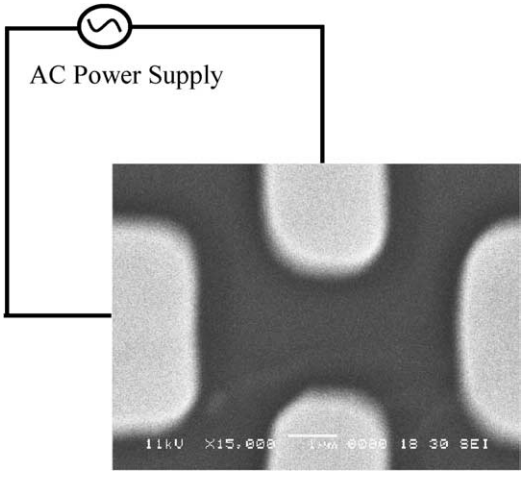

Fig. 1. SEM image of four Ti/Au electrodes (white parts) on p-type Si wafer with 500 nm thick SiO_2. AC bias voltage is applied between two adjacent electrodes, as indicated in the figure.

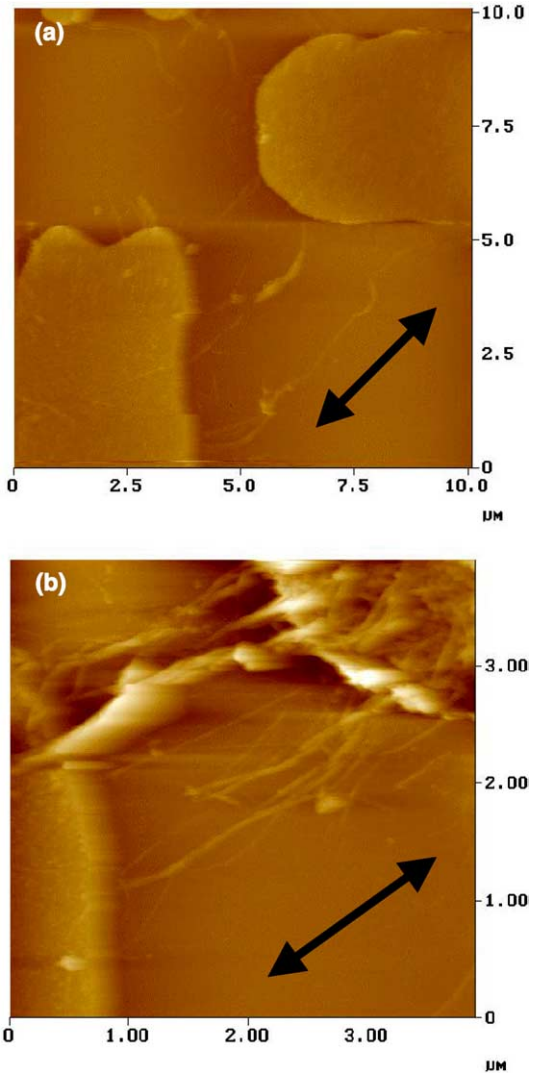

Fig. 2. AFM images of SWNTs bridging the adjacent electrodes. The deposition time is (a) 50 s and (b) 300 s, respectively. The black arrows indicate the direction of electric field.

concentration of the suspension. The longer the deposition time, the more the SWNTs are deposited.

Two forces can drive CNTs in the suspension to the electrodes [14,16]. The first is an electrophoretic force due to charge, the second is the dielectrophoretic force due to the dielectric constant difference between CNTs ε_p and the solvent medium ε_m. Since a high frequency AC bias was used here, the electrophoretic force did not affect the motion of the CNTs because of time averaging effect. The time-averaged dielectrophoretic force can be expressed approximately as follows:

$$\overrightarrow{F} \propto \varepsilon_m \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \nabla E_{rms}^2 \quad (1)$$

where E_{rms} is the average electric field strength [17]. Because the permittivity of the SWNTs is larger than the other contaminants (for example, amorphous carbon) in