A Method Study on Assembly of Single-Wall Carbon Nanotube Field Effect Transistor Using Dielectrophoresis

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Abstract. Single-wall carbon nanotubes are candidates for a number of building blocks in nanoscale electronics. With respect to the assembly of carbon nanotube field effect transistor, the dielectrophoresis technology is adopted, which assembles SWCNTs between the micro-electrodes, SWCNTs are affected by the electrophoretic force which is carried out by the related theoretical analysis in a nonuniform electric field. The driving electric field of dielectrophoresis is simulated by the comsol software. According to the simulation results, a number of the experiments are done. It turns out that the required experimental parameters of the efficient assembly of SWCNT were obtained. AFM scanning and electrical properties of SWCNTs show that the method can achieve the effective assembly of carbon nanotube field effect transistor. SWCNTs are driven in the microelectrode gap, having a good arrangement of uniform orientation and assembly results, and proportional to the arrangement density along the electrode width direction and the duration of DEP. Meanwhile, it also provides an effective method of assembly and manufacture for other one-dimensional nanomaterials assembly of nanoelectronic devices.

Introduction

A single-wall carbon nanotube (SWCNT) has been found as promising materials for nanoscale mechanical structures, because of their typical one-dimensional structure and unique properties [1]. After that, a number of applications for SWCNTs have been proposed, such as SWCNT field effect transistors (SWCNT-FETs), nanosensors, interconnects, and so forth. A SWCNT-FET has been demonstrated lately, which surpass a state of art Si MOSFET in terms of delay at the same ON-OFF ratio [2,3]. Compared with CMOSFET SWCNT-FET possess higher frequency response speed, smaller power consumption, higher conductivity and higher integration density, etc [4]. Of the FET based on SWCNT manufacturing technology and methods, have become one of the hot fronts about the field of nano science and technology research [5,6]. To date, assembly of the SWCNT-FET methods have mainly dielectrophoresis (DEP), atom force microscopy(AFM)-base nanowelding method, chemical growth method and so on [7]. However, chemical growth method shows low efficiency, poor reliability and reproducibility, which makes assembly location and electrical connection effect of SWCNT random. AFM can provide the operator with a versatile tool to perform high precision manipulation for SWCNTs, but AFM often have a low efficiency of imaging and manipulation, which limit its application in fabricating SWCNT-based nanodevices [8].

In this paper, with respect to the assembly and manufacture of SWCNT-FETs for the above-mentioned problems facing the development trends and technologies, DEP technology was taken
advantage of carrying out the effective assembly of SWCNTs between the microelectrodes. The driving electric field of dielectrophoresis was simulated by the comsol software. According to the simulation results, a number of the experiments were done. The applied alternating current voltage had a frequency of 2MHz and an amplitude of 10V. As a result, a number of successful and batch assembly of SWCNT-FETs could be achieved.

**Dielectrophoretic Manipulation**

Nano-devices for the realization of SWCNT assembly and manufacturing, electric field potential distribution and electric field strength to the effect of the SWCNT assembly were studied under the conditions of the DEP. When a polarizable particle was subjected to an alternating current electric field, the particle would be polarized to induce a dipole moment. Owing to the interaction of the dipole moment and the non-uniform electric field, the particle would be acted on by the DEP force. DEP manipulation induced movement of a SWCNT in non-uniform electric fields as shown in Fig.1. SWCNT would be exerted by a positive DEP force, and moved towards the regions of high electrical field strength[9].

![Fig. 1 Schematic diagram of SWCNT in the field driven by the DEP force](image1)

![Fig. 2 Electric field strength distribution of electric plane electrode](image2)

In the simplest possible approximation, the time-averaged DEP force for SWCNTs was given by the expression.

$$\langle F_{\text{DEP}}(t) \rangle = 2\pi ab^2 \varepsilon_m \text{Re}[K(\omega)] \nabla |E_{\text{rms}}|^2$$  \hspace{1cm} (1)$$

Where a was the length of SWCNT half, b was a SWCNT radius, $\varepsilon_m$ was the permittivity of the liquid medium, E was the rms magnitude of the local electric field, and Re[K(\omega)] was the real part of the Clausius Mossotti factor was expressed as:

$$K = \frac{\varepsilon_p^* - \varepsilon_m^*}{3(\varepsilon_p^* + (\varepsilon_p^* - \varepsilon_m^*)L//)}, \varepsilon^* = \varepsilon - i\sigma/\omega$$  \hspace{1cm} (2)$$

Where $\varepsilon_p^*$ and $\varepsilon_m^*$ were the complex permittivities of SWCNTs and the liquid medium, respectively. $L//$ was the depolarization factor, $\sigma$ was the conductivity, and $\omega=2\pi f$ was the angular frequency of the alternating current field. The DEP force for SWCNTs in the electric field, which was decided by $\nabla |E_{\text{rms}}|^2$ and Re[K(\omega)]. Under the condition of the applied electric field of 5 Vp-p and electrode gap of 1\mu m, through DEP force on the establishment of model, the electric field intensity distribution based on finite element method was shown in Fig. 2. Fig. 2 showed that the electric field strength of electrode gap region was stronger, while the electric field strength of
the end of electrode was strongest. SWCNTs would be inclined to align along the electric field lines in respect that they suspended in liquid medium, when an alternating current electric field was applied.

Assembly of Single-wall Carbon Nanotube Field Effect Transistors

SWCNT-FETs for good assembly result, the premise that good SWCNTs required pretreatment solution. Dielectrophoresis field was studied by theoretical analysis and simulation results, given the effective control of feasible assembly conditions.

SWCNT pretreatment. To prepare an individual suspension of SWCNTs, the accurately matched SWCNTs solution (The quality percentages of the matched SWCNTs solution and sodium dodecyl sulfate surfactant solution were respectively 0.1% and 1%).) was put in a test tube, sealed with plastic film, sonicated for 3h with frequency of 59kHz in the ultrasonication oscillator, rested for 1h, sonicated again for 2h, rested for over 3h and disposed by precipitating. The well dispersed uniform translucent SWCNTs solution was obtained. The impurities and bundles of SWCNTs could be removes due to the gradient-force generated during the process of ultracentrifugation. The upper 50% solution was removed after ultracentrifugation at 3000g for 2 hours. The remaining lower solution 50% of SWCNTs was hold on at 30000g for 2 hours. At last, the upper 50% solution was obtained, which should be more pure SWCNTs solution.

Dielectrophoresis assembly of single-wall carbon nanotube field effect transistors. During the process of dielectrophoretic assembly of SWCNT-FETs, the electric field required the frequency and the alternating voltage signal were applied through the probe. 0.5 µl of SWCNTs solution was transferred to the gap of microelectrodes defined as source and drain for a transistor functional structure. For SWCNTs assembly, the applied alternating current voltage had a frequency of 2MHz and a peak-to-peak voltage of 10V. The deposition time was 10s, which affected the number of SWCNTs assembled. The chip was treated with deionized water to move the remains of sodium dodecyl sulfate. Rinsing time was about 20s. The chips were put in the oven heated to 120 degrees, and 30 minutes, so that the water left in the chip was evaporated.

Experimental Results

The well pretreated SWCNTs solution was assembled by DEP according to the above method and set the parameters. Duration of different electrophoresis experiments were carried out. The results obtained were shown in Fig. 3. Fig. 3 shows SWCNTs driven by electric field were almost aligned and assembled between each pair of the electrodes. However, the departments of non-electrode gap were almost no SWCNTs deposition. DEP on the SWCNT had a strong effect of the drive and array assembly. Meanwhile, there were very few impurities, indicating the majority of impurities had been removed after rinsing. The SWCNTs arrangement density of the electrophoresis duration of 3s, 5s and 8s of Fig. 3 (a), (b) and (C) were contrasted, and proportional to the arrangement density along the electrode width direction and the duration of DEP.

![Fig. 3 Assembly results of SWCNTs with different duration](image)

To test the effectiveness of SWCNT-FET assembly and sensitivity, Agilent4155C semiconductor parameter analyzer used the assembly of the micro electrode structure of
SWCNT-FET electrical characteristics were tested. The results were shown in Fig. 4. The current between source and drain varied with gate voltage, respectively. The gate voltage varied from -16V to 16V, and the drain voltage varied from -1000mV to 1000mV. For different gate voltages, the output of the current curve of the corresponding changes, with significant field-effect characteristics was shown in Fig. 4, which achieved an effective physical assembly and electrical connections.

![Fig. 4  FET characteristics curves after assembly](image)

Summary

In this paper, with respect to the assembly of carbon nanotube field effect transistor, the dielectrophoresis technology was adopted, which assembled SWCNTs between micro-electrodes, SWCNTs were affected by the electrophoretic force which was carried out by the related theoretical analysis in a nonuniform electric field. The driving electric field of dielectrophoresis was simulated by the comsol software. According to the simulation results, a number of the experiments were done. It turned out that the required experimental parameters of the efficient assembly of SWCNT were obtained. SWCNTs in the micro-electrode arrangement of uniform orientation and assembly were achieved by DEP based on well pretreated SWCNTs. SWCNTs along the width direction of the arrangement of electrode density were proportional to duration of electrophoresis. A good SWCNT-FET field effect characteristics was obtained.

Acknowledgments

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