

# A THREE DIMENSIONAL THERMAL SENSOR BASED ON SINGLE-WALLED CARBON NANOTUBES

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**Abstract:** We present a novel three-dimensional thermal sensor based on Single-Walled Carbon Nanotubes (SWNTs) utilizing dielectrophoretic (DEP) assembly. The sensor is fabricated using a hybrid assembly technique combining top down (fabrication of the microplatform) and bottom up (DEP assembly) approaches. Encapsulating the structure with a thin (1 $\mu$ m) parylene layer protects it from the environment and also improves the contact resistance. Both single and multi finger assembly electrode structures have been utilized to manufacture the 3D thermal sensor and its thermal sensitivity is measured with a heated chuck. The resistances of the structures decrease more than 10% across a temperature range from 25°C to 65°C. The temperature coefficient of resistance for the SWNT-based thermal sensor is measured and ranged from -0.154 to -0.24% for the single electrode device and varied from -0.3 to -0.57% for the multielectrode device.

**Keyword:** Single-Walled Carbon Nanotubes, Dielectrophoretic Assembly, Thermal sensor, Nanoscale integration

## 1. INTRODUCTION

Carbon nanotubes (CNTs) may serve as the potential building blocks for the next generation of electronic devices due to their attractive properties. For instance, they are compact, lightweight and have excellent electrical, mechanical and thermal properties. First discovered by S. Iijima in 1991 [1], CNTs have been used in sensing applications including gas sensors [2], pressure sensors [3], and thermal sensors [4-5]. Most efforts up to now utilized Multi Walled Carbon Nanotubes (MWNTs). Single Walled Carbon Nanotubes (SWNTs) are smaller, yet have very similar attractive properties as the MWNTs. SWNTs with high surface to volume ratio will be more sensitive to the environment than their MWNT counterparts. Finally, all of the thermal sensors fabricated up to now are fabricated on planar two-dimensional (2D) surfaces.

Controlling the placement of CNTs in a precise manner had been difficult due to their small size and natural tendency to cling together [1]. Atomic force microscopy (AFM) is typically used to

manipulate individual CNTs [6]. However, this is a time-consuming process and not compatible with high rate nanomanufacturing. In our approach, we have used Dielectrophoretic (DEP) assembly to manipulate SWNTs on to the proper areas for nanoscale integration. DEP assembly is low-cost, versatile, low temperature (23°C) and compatible with batch fabrication.

In this paper, a novel SWNT-based three-dimensional (3D) thermal sensor fabricated using Dielectrophoretic assembly technique is reported.

## 2. DIELECTROPHORETIC ASSEMBLY

### 2.1 Background information and theory

The approaches for controlled manipulation of nanoparticles include template-directed synthesis, atomic and scanning force microscopy and nanorobotic manipulations. But, these methods have low throughput and are not suitable for the production environment. DEP, coined by H. A. Pohl [7], refers to the force exerted on the induced dipole moment of small nanomaterials suspended

in insulating dielectric liquids by a nonuniform AC or DC electric field.

The direction of the DEP force depends on the electrical properties of both the nanomaterials and the suspending medium, which is given in Eqns. (1) and (2) for the case of AC signals [8]:

$$\langle F_{DEP}(t) \rangle = 2\pi ab^2 \epsilon_m \operatorname{Re}(K) \nabla |E_{rms}|^2 \quad (1)$$

$$K = \frac{\epsilon_p^* - \epsilon_m^*}{3[\epsilon_m^* + (\epsilon_p^* - \epsilon_m^*)L_{||}]} \quad (2)$$

where  $E_{rms}$  is the electrical field,  $a$  and  $b$  are the length and radius of the nanomaterials, and  $\epsilon_m$  and  $\epsilon_p$  represent permittivity of the nanomaterials and the medium, respectively.  $K$ , Clausius-Mosotti factor, shows the interrelationship between the frequency-dependent properties of the nanomaterials and the medium. When  $\operatorname{Re}(K)$  is greater than 0, the assembly process is achieved through a positive dielectrophoretic force (PDEP) otherwise it is achieved through a negative dielectrophoretic force (NDEP). For PDEP assembly, nanomaterials are attracted to regions where the electric field strength is highest. Alternately, for NDEP assembly, the nanomaterials are attracted to the regions of lowest field strength. In this paper, we used a frequency of 10MHz [9], and utilized PDEP force to incorporate SWNTs onto the 3D electrodes.

## 2.2 Electrode design

We have designed and fabricated our 3D electrodes so that the two metal electrodes are separated by a thin parylene layer in a vertical architecture allowing high density integration. Parylene, deposited at room temperature, is a pin-hole free, conformal and an insulating film. While fabricating the 3D assembly platform, a thin Parylene layer is used as a dielectric layer due to its excellent insulating properties such as high resistivity ( $6 \times 10^{16} \Omega\text{-cm}$ ) and high breakdown voltage ( $300\text{V}/\mu\text{m}$ ).

## 2.3 Electric field distribution analysis

Numerical analysis (FEMLAB) of the electric potential and the electric field distribution of the 3D DEP assembly process of SWNTs is shown in Fig.1. In the presence of SWNTs, both the electric

potential and the electric field will rearrange, accordingly. Furthermore, as seen in Fig.1, we notice that the SWNTs will experience a force

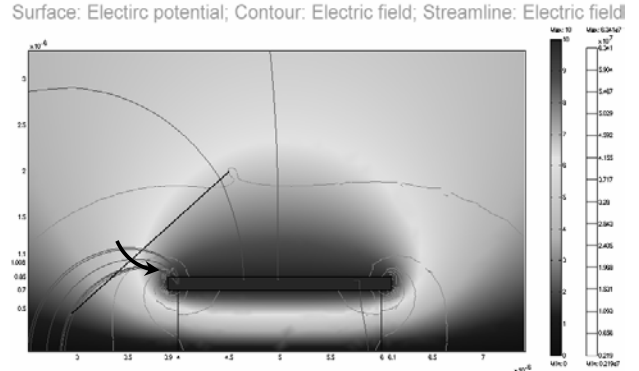


Fig.1: Finite Element analysis of the DEP assembly of SWNTs

from the edge of the top electrode for PDEP, as shown with an arrow. Additionally, the simulations suggest that after the DEP assembly, the SWNTs will align between the top and the bottom electrodes along the field lines.

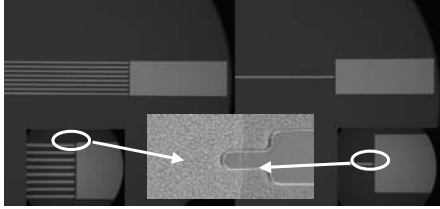
## 3. FABRICATION

The fabrication process starts by growing a  $1\mu\text{m}$  thick isolation oxide layer on a  $3''$  silicon wafer. A Cr/Au layer ( $200\text{\AA}/1500\text{\AA}$ ) is then deposited and patterned to serve as the first metal electrode by a liftoff process. A thin parylene-C dielectric layer is then deposited at room temperature. Next, the second metal layer (Cr/Au  $200\text{\AA}/1500\text{\AA}$ ) is deposited and patterned using lift-off technique. These two metal layers form the 3-dimensional electrodes for assembling the SWNTs. Utilizing the second metal layer as a mask, we then etch the parylene-C layer with an inductively coupled plasma (ICP) reactor using  $\text{O}_2$  gas. Finally, a thin layer of parylene-C ( $1.0\mu\text{m}$ ) is deposited as the encapsulation layer and the contacts are opened using the ICP tool for measurement purposes. Two set of assembly structures, including single and multi finger electrodes are designed and fabricated as shown in Fig.2.

## 4. RESULTS AND DISCUSSION

### 4.1 Assembly and I-V measurement

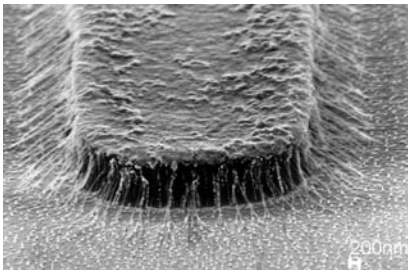
Commercially available SWNTs suspended in



*Fig.2:* Optical pictures of the assembly electrodes. Inset shows the SEM micrograph

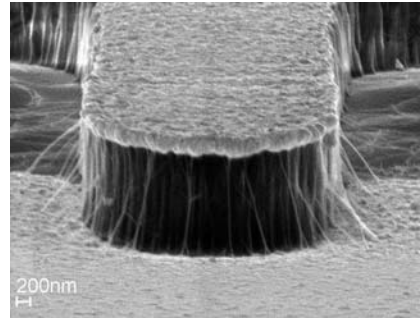
an aqueous solution are used as the active layer for the thermal sensor. The average diameter of the SWNTs is between 2-5nm and the average length varied from 3-5 $\mu$ m. The DEP assembly is achieved by applying 10V and 5V peak-to-peak AC voltage at a constant frequency of 10MHz. A 5  $\mu$ l solution of ammonium hydroxide is added into the CNT solution to improve the conductivity of the SWNTs. Prior to the assembly process, SWNTs solution is ultrasonicated for 5 minutes to ensure that the suspended CNTs are well dispersed. After the AC voltage is applied to the assembly electrodes, a droplet (2-3 $\mu$ l) of the SWNT solution is dispensed on top of the assembly area. Following 30 seconds of assembly, the sample is blow-dried and the power is turned off resulting in an assembled vertical nanotube bridge between the electrodes.

Fig.3 and Fig.4 show the SEM micrographs of the 3D assembled SWNT bundles connecting top

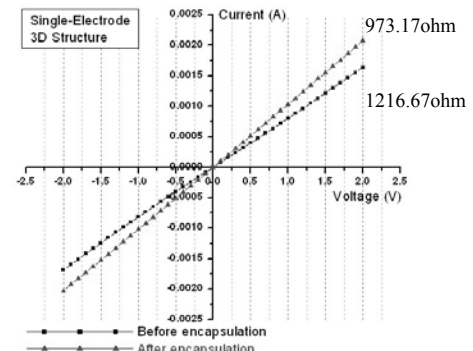


*Fig.3:* SEM micrograph of the thermal sensor assembled with 10V pp before encapsulation

and bottom electrodes. The density of the assembled bundles can be controlled by varying the electric field. By reducing the assembly voltage, we were able to assemble less dense SWNT bundles as seen in Fig.4. Following the assembly, I-V measurements are conducted to ensure the connectivity between the electrodes. Fig.5 illustrates the I-V measurement taken from a sample single electrode device before and after encapsulation. Encapsulation of the SWNT sensor



*Fig.4:* SEM micrograph of the thermal sensor assembled with 5V pp before encapsulation

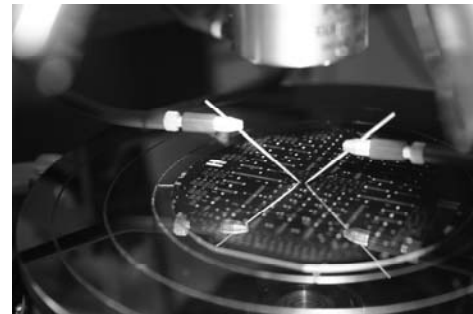


*Fig.5* Measured I-V curve of SWNT bridge from single-finger electrode

improves the two-terminal resistance and also protects it from the environment.

#### 4.2 Thermal sensitivity of SWNTs

To investigate the effect of temperature on SWNTs, we have placed the 3D thermal sensor on a SUSS PM5 analytical probe system (with a heatable chuck) as seen in Fig.6 and the change in resistance is measured. The temperature is varied from 25 $^{\circ}$ C to 65 $^{\circ}$ C with 10 $^{\circ}$ C increments. Fig.7 and Fig.8 display the measured temperature response from the single and multifinger thermal sensors. As reported by H.-L. Nguyen [10], SWNTs are sensitive to temperature and their



*Fig.6:* Device under test

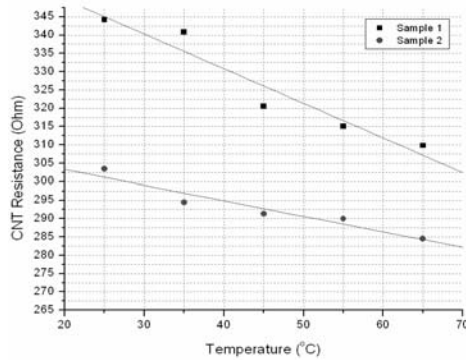


Fig. 7: Measured resistance vs temperature from a single finger electrode sensor

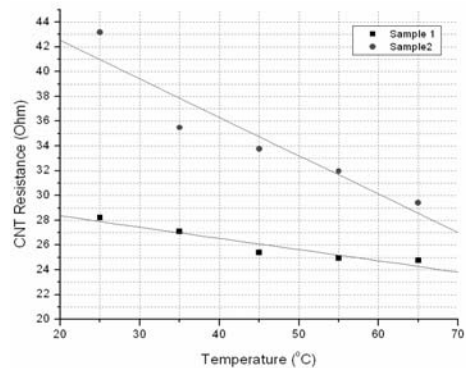


Fig. 8: Measured resistance vs temperature from a multi finger electrode sensor

resistance drops with increasing temperature. As the temperature is increased from 25°C to 65°C, the resistance values in both cases drop more than 10%. The calculated TCR value from the single electrode device varied from -0.154 to -0.24%, whereas the TCR of the multielectrode sensor varied from -0.3 to -0.57%. Comparing our data with the previously reported 2D thermal sensors made of MWNTs [4-5], we were able to achieve higher (2x) sensitivity.

## 5. CONCLUSIONS

Single-Walled Carbon Nanotubes are utilized as the active layer of a thermal sensor. Utilizing dielectrophoretic assembly, the SWNT sensor was created in a 3D architecture. The calculated TCR value from the single electrode device varied from -0.154 to -0.24%, whereas the TCR of the multielectrode sensor varied from -0.3 to -0.57%. The obtained sensitivity values are twice that of those measured from MWNT sensors.

## ACKNOWLEDGMENT

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