8-2015

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ABSTRACT

Due to their excellent electrical, optical, and mechanical properties, nanosized single wall carbon nanotubes (SWNTs) have attracted significant attention as a transducing element in nano-bio sensor research. Controlled assembly, device fabrication, and bio-functionalization of the SWNTs are crucial in creating the sensors. In this study, working biosensor platforms were created using dielectrophoretic assembly of single wall carbon nanotubes (SWNTs) as a bridge between two gold electrodes. SWNTs in a commercial SDS surfactant solution were dispensed in the gap between the two gold electrodes, followed by applying an ac voltage across the two electrodes. The dielectrophoresis aligns the CNTs and forms a bridge between the two electrodes. A copious washing and a subsequent annealing of the devices at 200 °C remove the surfactants and create an excellent semiconducting (p-type) bridge between the two electrodes. A liquid gated field effect transistor (LGFET) was built using DI water as the gate dielectric and the SWNT bridge as the channel. Negative gate voltages of the FET increased the drain current and applying a positive gate voltage of +0.5V depleted the channel of charges and turned the device off. The biosensor was verified using both the two terminal and three terminal devices. Genomic salmon DNA dissolved in DI water was applied on the SWNT bridge in both type of devices. In the two terminal device, the conductance of the bridge dropped by 65x after the binding of the DNA. In the LGFET, the transconductance of the device decreased 2X after the binding of the DNA. The binding of the DNA also suppressed hysteresis in the Drain Current vs Gate Voltage characteristics of the LGFET.

Keywords: Single Wall Carbon Nanotubes, Dielectrophoretic assembly, Biosensing, liquid gated FET

1. INTRODUCTION

Carbon nanotubes (CNTs) are tubular formations of carbon having a diameter on the nanometer scale [1]. They are classified as single wall carbon nanotubes (SWNTs) or multi-wall carbon nanotubes (MWNTs) depending upon single or multiple layers of graphene present. CNTs exhibit many unique properties including high tensile strength (almost 100x higher than steel), high elasticity (about 5x more resistance to bending than steel), high thermal conductivity (almost 10x higher than silver), and low weight with a density about a quarter that of steel [2]. Also, CNTs can form conductive chains (molecular wires) when aligned through dielectrophoresis [3]. SWNTs are attractive for nano-electronic transistors due to their low electron scattering and bandgap properties [2, 3]. Furthermore, the dimensional and chemical compatibility with DNA and proteins make the SWNTs attractive for biosensor applications such as diagnostics and drug delivery. SWNT biosensors exhibit large impedance changes due to interactions with local environment. Previous studies reported chemiresistive biosensors, developed by bridging two electrodes with protein functionalized CNTs, capable of detecting cortisol [5] and *Escherichia coli* [6]. Our study is limited to the SWNT based electronic devices for sensing biochemical changes in the local environment. The SWNTs exhibiting p-type semiconducting properties are chosen for the two and three terminal devices as a prototype for sensing the binding of biomolecules such as the genomic salmon deoxyribonucleic acid (DNA).

Nanobiosystems: Processing, Characterization, and Applications VIII, edited by Norihisa Kobayashi, Fahima Ouchen, Ileana Rau, Proc. of SPIE Vol. 9557, 95570K · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2193793

2. EXPERIMENTAL

Simple electrode structures of two rectangular pads with differing gaps between the electrodes were chosen for this research. The smallest electrodes (500 µm x 100 µm) were separated by 50 µm and the largest electrodes (3000 µm x 1500 µm) were separated by 500 µm. Our goal is to bridge the gap between the two electrodes by dispersing SWNTs in a solution and aligning the SWNTs using dielectrophoresis. While typical SWNT devices are built with a random network of tubes forming a continuous conduction path between the two electrodes, dielectrophoresis process enables one to obtain aligned CNT channel using an alternating current (AC) signal. CNTs suspended in a commercial sodium dodecyl sulphate (SDS) surfactant solution are used in this study. The sonication followed by centrifugation with SDS surfactant effectively solubilizes hydrophobic SWNTs to an individually suspended CNT-level dispersion. A droplet of CNT-SDS solution was placed in the gap between the two electrodes, followed by applying an ac voltage across the two electrodes for aligning the CNTs[3]. A 3V peak-peak and 1 kHz ac signal was applied for 60 seconds. This signal was sufficient to dielectrophoretically align the CNTs between the two electrodes. Once the ac signal is removed, a simple dc measurement across the two pads confirmed that there is an assembly of the CNTs with measured resistance ranging from a few tens of kΩ to hundreds of kΩ. The samples were then washed with copious DI water, and annealed at 200 °C for one hour to remove the surfactants and other organic impurities. Annealing of the samples resulted in improved conductivity of the electrical bridge between the two electrodes as the SWNTs are aligned and reduced the resistance to a few Ω level. The electrical current vs. voltage measurements were performed for the two terminal devices using a Keithley 2400 SourceMeter instrument by applying a dc voltage across the bridge and measuring the current through the bridge. The two terminal devices were tested before and after introducing genomic salmon DNA molecules in DI water. After the two terminal devices were characterized, three terminal liquid-gated field effect transistors were built with DI water as the liquid-gate dielectric. The two electrodes serve as the Source and Drain electrodes of the FET, and the SWNT bridge serves as the conducting channel for the FET. The FET's current-voltage characteristics were obtained before and after introducing genomic salmon DNA solution. Figures 1 and 2 show the two device structures used for this study.

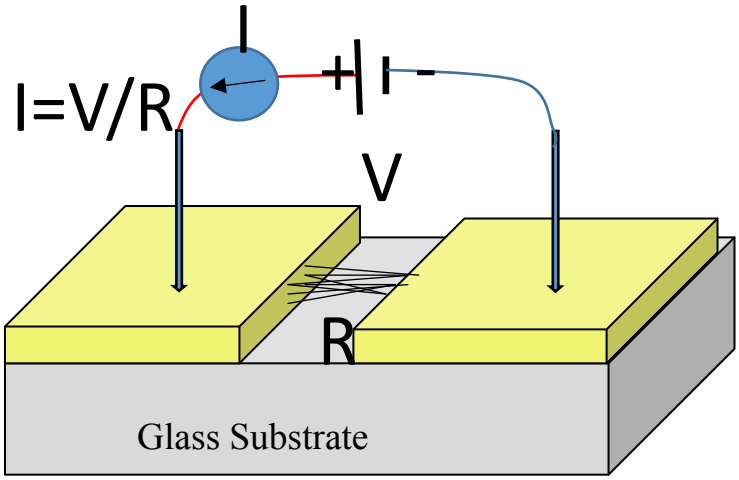

Figure 1. Two terminal device structure with the SWNT Bridge between the two electrodes.

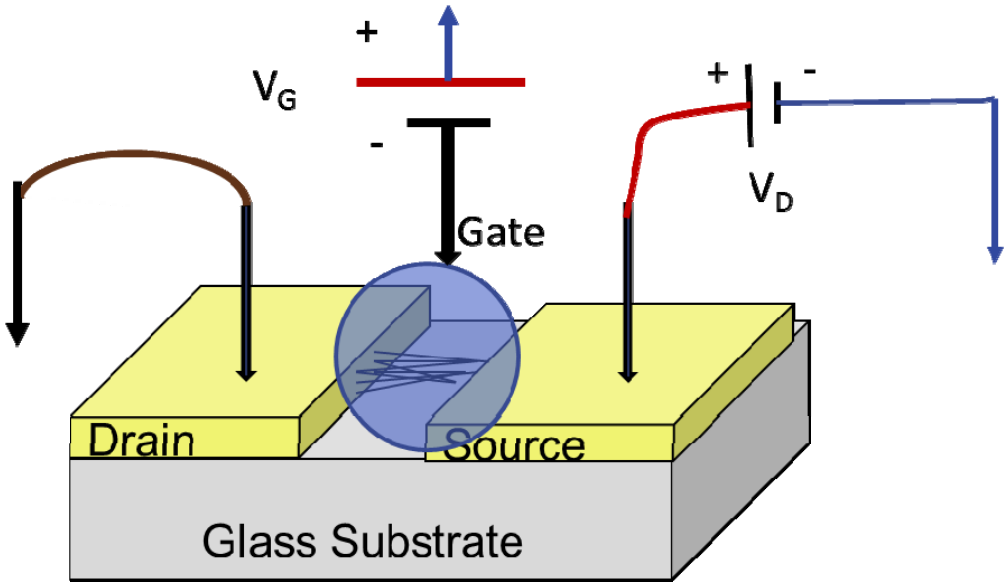

Figure 2. Three terminal device with a DI water used as a liquid gate dielectric.

3. RESULTS AND DISCUSSIONS

The I-V characteristics obtained on a two terminal device with SWNT Bridge is shown in figure 3. The two terminal device shows a linear conductance (resistance). The figure shows that the conductance improves more than 50 times after the annealing of the CNTs. Figure 4 shows the I-V characteristics of the two terminal device before and after binding the genomic salmon DNA. The conductance decreases by over 65 times. The large decrease in conductance or increase in resistance is most likely due to the p-type nature of SWNTs receptive to the binding to the phosphates of the DNA.

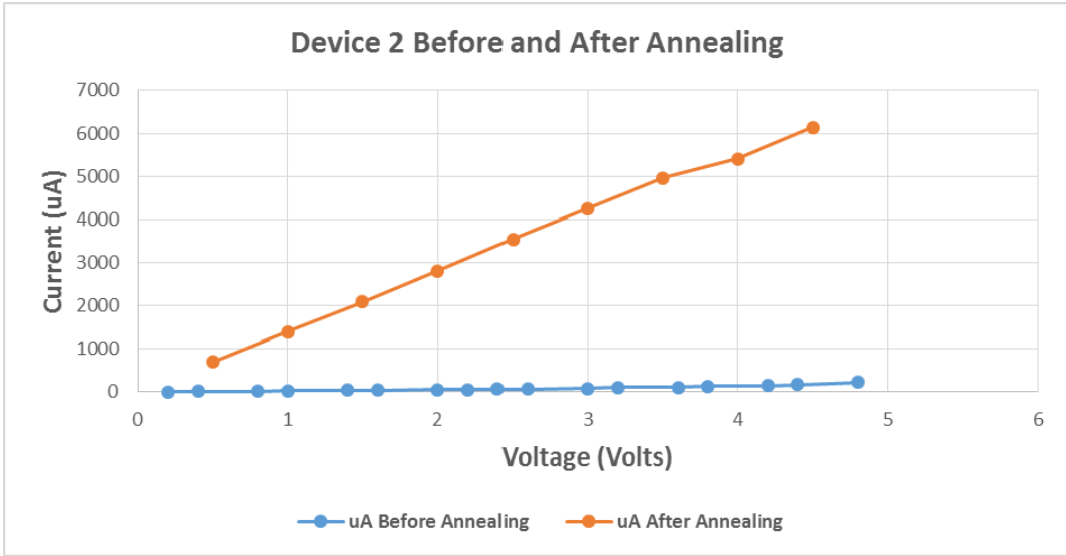

Figure 3. I-V characteristics of the two terminal device before and after annealing. The annealing improves the conductivity over 50 times. The device is a 3000 µm x 1500 µm pads with a separation of 500 µm.

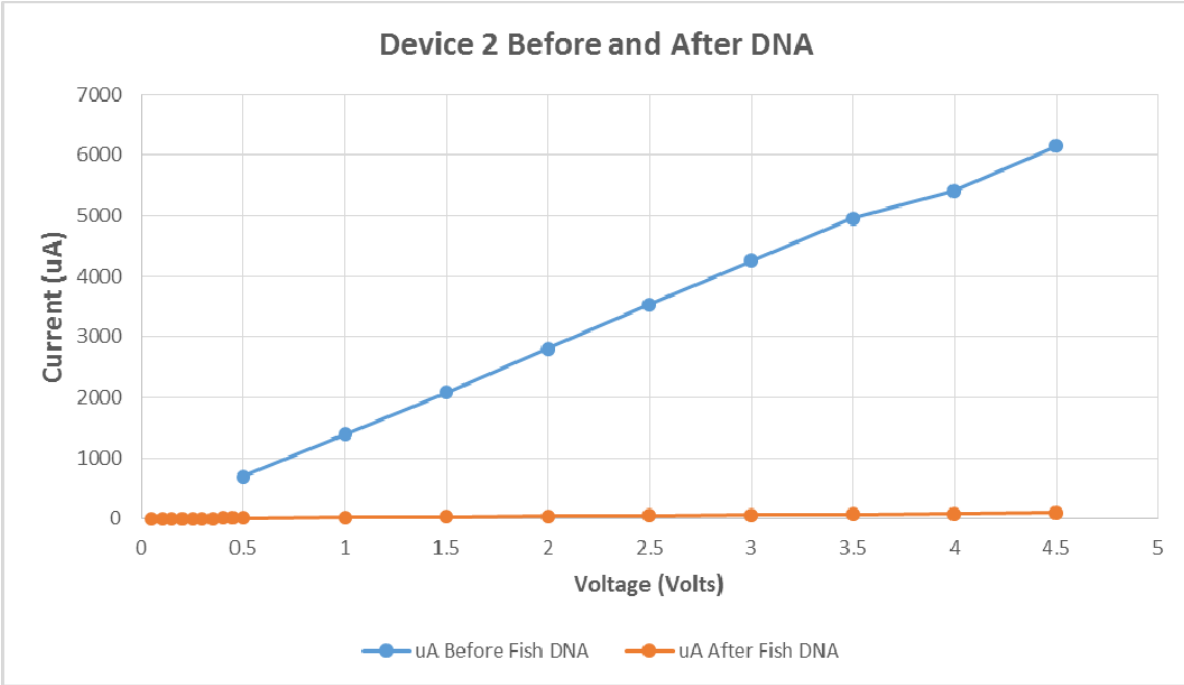

Figure 4. The change in conductance of the two terminal device before and after introducing genomic salmon DNA solution.

Figure 5 shows the current voltage characteristics of the three terminal device with the source electrode biased with a positive voltage and the drain grounded. The gate voltage is varied from positive to negative. The p-type nature of the SWNT Bridge requires a positive voltage to the gate to deplete the channel. Gate voltage controls the charges in the CNT channel. The current of a P-type semiconductor is measured by the movement of the holes towards the negative electrode (from Source to Drain). Positive gate voltage repels the positive charges within the CNTs (holes), while a negative gate voltage attracts the positive charges (holes), and creates a good conducting, low resistance channel. The figure 5 shows the drain current vs source-drain voltage for gate voltage of -0.5V to +0.5 V. The drain current decreases steadily as the gate voltage increases in the positive direction.

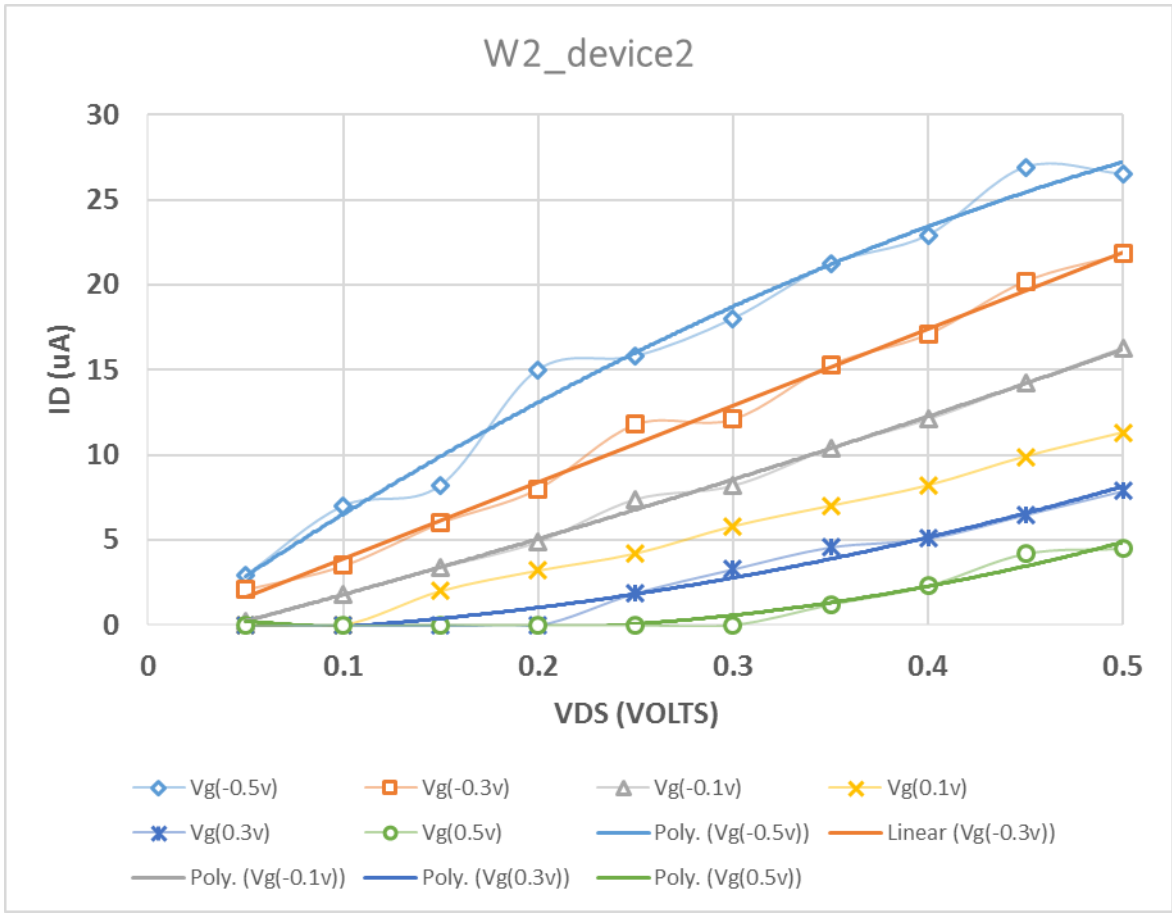

Figure 5. Drain current vs. source-drain voltage at different gate voltages. The linear curves are connecting the data points obtained in a linear fashion. The poly lines are polynomial fit for the data.

Figure 6 shows the Drain Current vs. Gate Voltage at a fixed Source-Drain voltage of 0.1V. The slope of the curve gives the transconductance (gm), which is a figure of merit for an FET device. The transconductance is roughly 3 μS before introducing the DNA and drops to roughly 1.5 μS after introducing the DNA. The drop in transconductance is most likely due to the negatively charged phosphate chains of DNA being attracted to the positive charges of the CNT channel. The surface charge state of the carbon nanotubes creates hysteresis in the liquid-gated FET measurements. It is worth noting that the hysteresis is significantly suppressed after the binding of the DNA molecules in the SWNT channel.

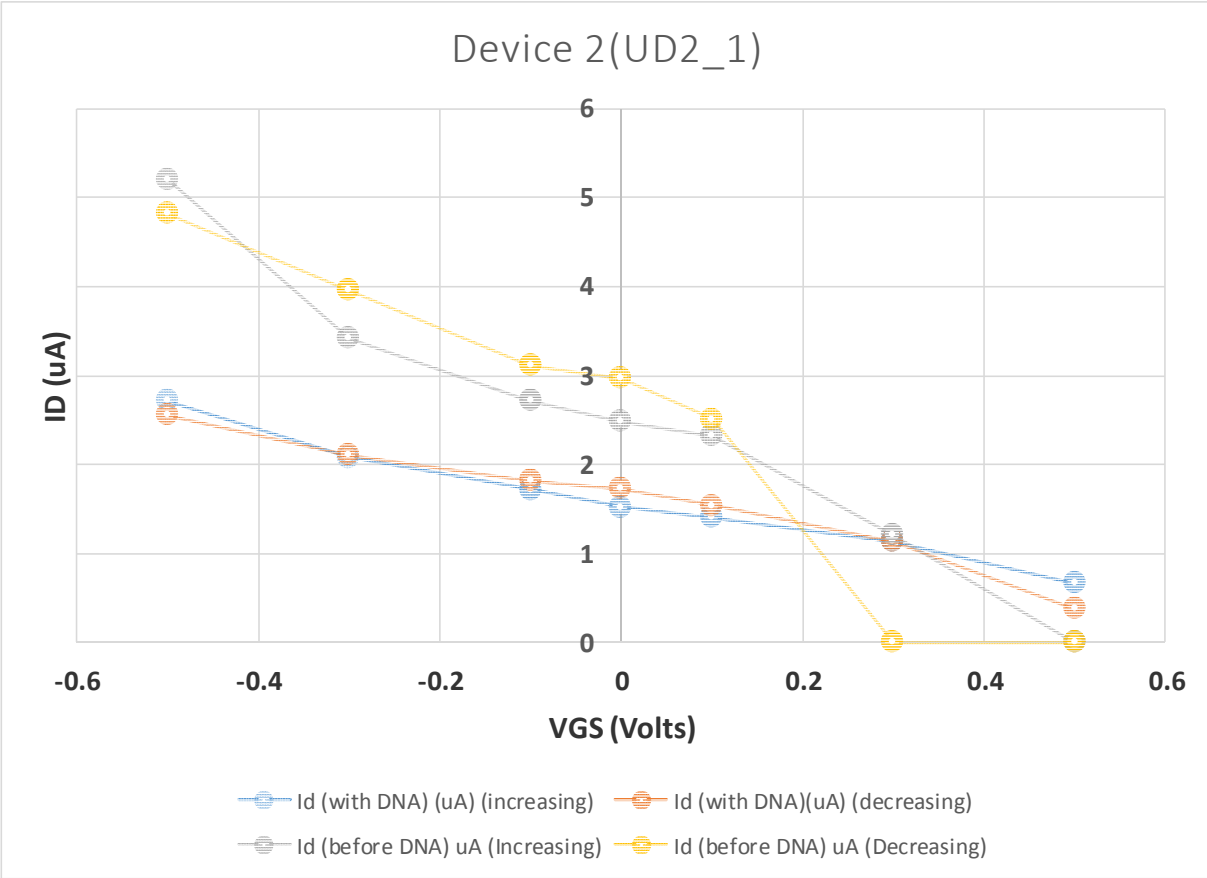

Figure 6. The Drain current vs the Gate voltage for the same device as shown in figure 5. Note that the devices show larger hysteresis before the binding of the DNA compared to after binding the DNA.

4. SUMMARY AND CONCLUSIONS

In conclusion, a working, functional biosensor platforms can be obtained by assembling single wall carbon nanotubes as a bridge between two electrodes through dielectrophoresis. The DEP assembled CNTFET characteristics were obtained in LGFET configuration. Further DNA-functionalization and FET characteristics change for the CNTFET indicates the developed device platform and fabrication process can be promising for future biosensor based on SWNT electronics. In the future, the SWNT biosensor can be implemented in an array for the detection of bacteria, viruses, airborne diseases, and single nucleotide polymorphisms in DNA for advanced, point-of-care diagnosis.

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