Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE **Current Rectification by As-Grown Chemical Vapor Deposited Single-Walled Carbon Nanotubes**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Research Laboratory,ATTN: AMSRD-ARL-WM-BD,Aberdeen Proving Ground,MD,21005**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002137. Proceedings of the 2008 IEEE International Conference on Nanotechnology (8th) Held in Arlington, TX on August 18-21, 2008.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**2**	

Current Rectification by As-Grown Chemical Vapor Deposited Single-Walled Carbon Nanotubes

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Abstract—Observation of diode-like current (I) - voltage (V) characteristics of switches fabricated from chemical vapor deposited (CVD) as-grown single-walled carbon nanotube (SWNT) bundles are presented. Atomic force microscopic analysis of the device structure and surface topology of SWNT suggest the observed rectification of current to possibly result from (a) cross-tube junctions, (b) a mixture of metallic and semiconducting tubes in the SWNT bundles, and/or (c) chirality change along a single tube. The exact mechanism underlying the observed rectification could not be established. The diode-like behavior of SWNT devices discovered in this research opens up new applications of SWNTs as nanoscale AC-DC converter.

I. Introduction

Current rectification by single-walled carbon nanotube (SWNT) has been predicted from theoretical calculations [1,2] and has also been observed in a number of previous experiments [3-6]. Theoretical predictions suggest the cross or Y-type junctions, atomic defect, and/or changes in chirality along the tube axis to lead to current rectification due to Schottky – type junctions. Experimental observations have been made on Y-type junctions [4] with tubes having difference in diameter forming the junction, chemical doping of the tubes [5], as well as double-gate electrostatic doping of tubes [6], effectively creating p-n junction along a single tube. Here we present the experimental observation of current rectification by "as-grown" SWNT devices – that is with no external doping, varying in channel length from 3 μm to 10 μm. The fabricated devices are considered for application as AC-DC power converter.

II. Experimental

The SWNTs were grown on 100 nm thick SiO_2 layer on a heavily doped n-type Si substrate using polymer encapsulated metal nanoparticle catalyzed carbon vapor deposition (CVD) process [7]. The devices were then fabricated by photolithographically depositing metal (100 nm thick Au on 10 nm thick Ti) electrodes with varying source (S) - drain (D) separation. The sample was annealed at 200°C for 30 minutes to clean up any contamination. The topology of the SWNT was examined by Atomic Force Microscopy (AFM) (Veeco, CP-II) (Fig. 1). The fabricated devices were analyzed by scanning electron microscope (SEM: Hitachi S-4700) to investigate the structure of the devices and the gaps between the electrodes (Fig. 2). The electrical properties of the assembled devices were measured with the semiconductor (SC) analyzer system (Janis/Keithley-4200) (Fig. 3).

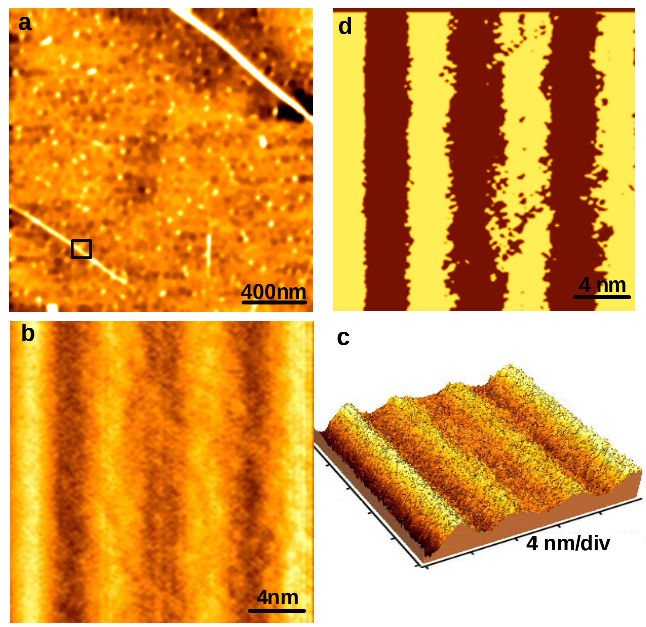

Fig. 1. (a) AFM topographical image of 2 μm x 2 μm scan area, (b) partial atomic resolution AFM topographical image of the area indicated in (a), (c) 3D image of (b) and (d) filtered image of (b) differentiating the topography in two color regime showing the defects in SWNTs.

A total of 135 devices were fabricated on the 15 mm x 15 mm chip, of which 35% were found to be active. The right lower inset is the AFM image of the device showing the connecting SWNT bundle. More than 70% of these active devices exhibited diode-like behavior as shown in Fig. 2, 15% showed Ohmic (metal-like) I-V, and the remaining showed no observable electrical activity. The diode-like characteristics were observed regardless of the difference in the channel length of the device.

III. RESULTS AND DISCUSSIONS

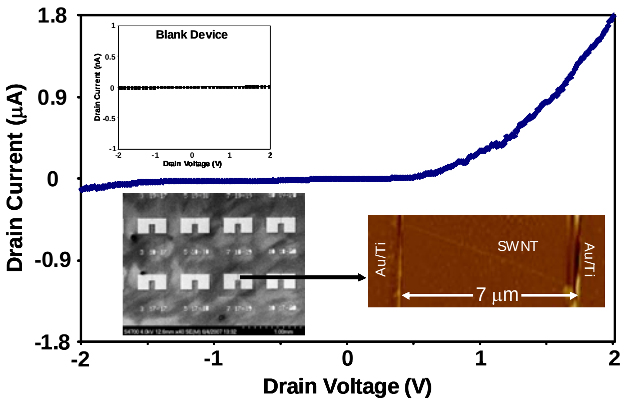

Fig. 2. Two-terminal I-V measurement of 7 μm-gap device. The lower inset shows the SEM image of different device patterns and an AFM image of 2.5 μm x 10μm scan area showing SWNTs connecting the two electrode pads. The upper left inset shows the I-V measurement of a blank 7μm-gap device.

Atomic resolution images of a select nanotube, shown in Fig. 1a, revealed that as-grown SWNTs are, in fact a bundle of several single strands of parallel aligned nanotubes (Fig. 1(b & c)). Further analyses of AFM images suggest possible defects (missing atoms) on tube-wall (Fig 1d). A typical I-V curve of a fabricated SWNT device obtained from a two-probe measurement is shown in Fig. 2. The I-V curve shown is for a 7 μm channel length device (lower inset). The upper inset is the I-V curve on a 7 μm length control device with no SWNT in the channel. The left lower inset shows the scanning electron micrograph (SEM) of the device layout. Furthermore, the SWNT diodes give high throughput of current in the forward bias (Fig. 2). A high-resolution AFM analysis of the nanotube bundles suggest some of the individual tubes to have mixed chirality, i.e. armchair as well as zig-zag along the tube direction, as shown in Fig. 3. It is conceivable that the mixed chirality morphology, which will lead to metallic and semiconducting characteristics in a single tube, could exhibit the observed diode-like I-V characteristics. Possibility of unimolecular SWNT diode has been discussed in previous studies [2-5]. However, since our devices also consist cross junctions with varying tube diameters (AFM image, not shown here) along different arms as well as bundles with possible mixed metallic-semiconducting tubes, we were unable to conclusively establish the physical mechanism of the observed current rectification. The important factor to note here is that the SWNT devices fabricated here intrinsically exhibit rectification without doping or externally modulating carrier concentrations along the tube. Thus we can rule out the possibility of a carrier-modulated p-n junction diode. This leaves us with the possibility of a Schottky diode with channels consisting of SWNTs with different work functions and possibly different electronic structure.

Regardless of the underlying physical mechanism, we believe that the process allows us to fabricate arrays of SWNT electronic switches in open channel configuration for different applications. Particularly, the devices realized here could be potentially used as nano and micro-scale AC-DC power converters.

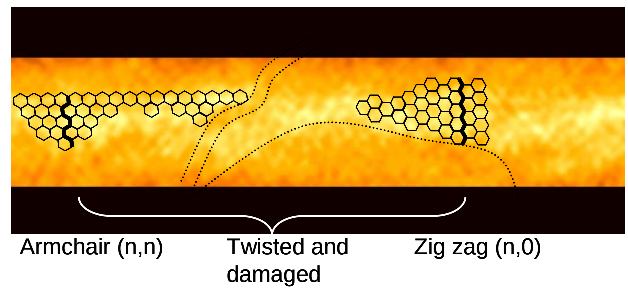

Fig. 3. Atomically resolved AFM image of a single strand of SWNT. The dotted lines show the twisting and possible fragments of bonds.

ACKNOWLEDGMENT

This project is supported through the Director's Research Initiative of the US Army Research Laboratory under ARL-DRI-07-WMR-10.

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