Sensors and Actuators B 192 (2014) 594–600

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Carbon nanotube based multifunctional flame sensor

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ARTICLE INFO

Article history:
Received 25 August 2013
Received in revised form 19 October 2013
Accepted 6 November 2013
Available online 15 November 2013

Keywords:
Carbon nanotubes
Flame
Sensor
Functionalization

ABSTRACT

Carbon nanotubes (CNT) due to its multifunctional characteristics has been presented as a flame sensor by combining both radiation and chemical sensitivity. Chemical functionalization enhances the sensitivity of CNT sensor toward any chemical modifications that are induced by the flame. Response of the sensor is revealed to be dependent on the measurement direction (longitudinal and transverse) as well as the radiation intensity. A nonlinear relation between the sensitivity and its distance from the source is used to calibrate the intensity of the flame. The present method allows a simpler approach for the flame detection by utilizing a calibration scheme to operate at any particular bias current and tune its sensitivity with respect to any working distance at a particular bias current.

1. Introduction

Carbon nanotubes (CNT) have been extensively used in the thrust areas of material research due to its extraordinary properties, because of which CNT has also replaced various conventional materials used in diverse applications. In addition, CNT has presented an ability to tune its conductance under different experimental conditions, for example, upon being irradiated with electromagnetic radiations of significant intensities, etc. [1,2]. It has been reported that CNT respond to electromagnetic radiations and hence, have successfully presented as infrared (IR) sensitive material [3,4]. Owing to its excellent electronic and optoelectronic properties, it is considered as an ideal material for IR photodetectors [4]. This implies that such a response of CNT can be exploited to detect various sources of radiations, for example from flame or fire. In general, flame-sensing materials in general should be very responsive to detect the presence of fires and at the same time should be capable of inhibiting false alarms. In such cases a novel property of an effective flame sensing material lies in its range of detection and response time. Moreover, ignition of the flame is accompanied by emission of gases like hydrocarbons and predominantly carbon dioxide upon complete combustion of air, which can block the conducting channels of the CNT through physisorption thereby making it more electrically resistive in nature [5]. While properties of CNT can be tuned by functionalizing it with various functional groups such as carboxyl, amine etc. it can also be used to enhance its sensitivity toward the proposed application [6]. In the present work, we have devised a method to develop such a flame sensor, which is shown to be sensitive to the above-mentioned parameters.

Conventional flame or fire sensors distinguish between the flame radiation and background radiation by mainly utilizing four primary optical flame-sensing technologies such as detection of ultraviolet (UV), combined detection of UV/IR, multi-spectrum IR, and visual flame imaging. Optical characteristics of the flame such as its shape and flickering provide a real time analysis through video processing [7]. These methods work on optical monitoring through camera, which is realized as extremely complicated in handling as well as real time data processing. In addition, an intelligent system requires a combination of smoke, fire and temperature detectors in an assembled manner to combat false alarms by incorporating extremely complex fault detection algorithms [8]. We have developed a simple flame sensor based on multiwalled carbon nanotubes (MWCNT), which not only detects a flame but this technique can also be used to estimate distance, hence the intensity along both the lateral and longitudinal directions of the flame. The sensor response showed a reversible nature after being exposed to a flame and the resulting response depends upon the intensity of emitted radiation. Through this work we explore a bilateral nature of sensor's response along two different orientations of the flame, which can be fruitfully utilized for various non-contact applications. For example, the short range of the response along one direction provides the scope for developing a proximity sensor as a highly sensitive device. On the other hand the long-range detection capability in the perpendicular direction can be materialized into fire safety alarms.

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0925-4005/$ – see front matter
http://dx.doi.org/10.1016/j.snb.2013.11.019

2. Materials and methods

2.1. Sensor fabrication

MWCNT was synthesized using chemical vapor deposition using a three-zone furnace. The end zones of the furnace were set at lower temperature while the middle zone of the furnace, which is the reaction zone, was set at 825 °C. Toluene and ferrocene were used as precursors acting as carbon source and catalyst, respectively. A chemical solution was obtained after mixing these chemicals in a mass ration of 0.02, which was heated at 200 °C. Chemical vapors were carried into a reaction zone by argon gas flowing at a constant flow rate of 800 sccm (standard cubic centimeter per minute). MWCNT were grown on a silicon dioxide substrate and scrapped off from the substrate for chemical functonalization. Acid treatment procedure was used to achieve —COOH functionalized MWCNT (COOH-MWCNT) as suggested by Khalili et al. by adding 100 mg of pristine MWCNT to 150 ml mixture of H_2SO_4/HNO_3 (3:1 by volume ratio) [9]. The carboxylated MWCNT thus prepared were dispersed in a 20 ml solution of de-ionized water and isopropyl alcohol using ultra-sonification [10]. Fig. 1a shows scanning electron micrograph (SEM) of the as-grown, entangled microstructure of CNT. CNT solution was then drop casted on to the silicon dioxide substrate between two pre-deposited aluminum electrodes as shown in Fig. 1b. The approximate size of the whole chip is $1 \times 3\,cm^2$. The distance between the electrodes was kept 100 μm. The amount of drop casted CNT on to the substrate determined the initial resistance of the MWCNT device that in turn depends upon the thickness of CNT layer (concentration of CNT between electrodes).

Fixing an initial resistance of the device could control the concentration of the CNT between electrodes in different devices. The responses from the CNT sensor devices are normalized with initial resistance to acquire a statistical variation in each experiment.

2.2. Sensor-setup

The experimental setup of the sensor comprised of MWCNT device (Fig. 1b) connected to a Keithley-2611 source meter as shown by schematic in Fig. 2a. A data acquisition module was used to observe and collect a typical response of the device in μV, when exposed to a source of flame such as a spirit lamp (which used ethyl alcohol as a burning fuel).

Sensor response was measured both along the lateral and longitudinal directions of the flame (Fig. 2b and c). A typical sensing response in the lateral direction of the CNT sensor is shown in Fig. 2d. A voltage response of the sensor upon applying a constant current of ~12 mA (a randomly chosen currant value within a detectable range of the sensor) was measured with the periodic exposures of flame and is plotted with the exposure time in seconds. A stable and reversible response can be seen for the five cycles of the flame exposure.

The effect of radiation only (without flame) was also evaluated using an IR source with variable power in the range of 18–23 dbm to irradiate the device with an optical fiber. The sensor was subjected to various bias currents ranging from 0 to 20 mA.

2.3. Signal conditioning and data acquisition module

The response of the MWCNT device (~μV) was amplified using a signal-conditioning module as shown in Figs. 2a and 3a to a range of mV using a Quantum X module. First phase of the signal conditioning circuit was a typical Wheatstone bridge, which yields a sensitive response of the device. The initial and stable resistance (without connecting to Wheatstone bridge) of a typical functionalized MWCNT device was measured around 180–200 Ω. Then, this device was connected to a Wheatstone bridge with equal or slightly higher resistance arms (considering the fact that slightly disparate arms would produce a very feeble deflection to counterpart the zero error which might be present), which provided an ideal sensitivity for a bridge with equal arms and can be expressed as $(\Delta V/V)/(\Delta R/R) = 1/4$ [11]. The arms of a Wheatstone bridge were employed depending upon the resistance value of the MWCNT sensor and in case of a device with a different resistance value, the values of arms of the Wheatstone bridge could be employed accordingly. The exposure to the flame caused the resistance of the device, (which acts as one of the arms of the Wheatstone bridge) to decrease, thereby inducing deflection in the bridge circuit.

An operational amplifier (op-amp) was employed to amplify the deflection of the Wheatstone bridge circuit and an IC-OP07CP was fabricated as an op-amp in differential configuration to add a gain to the circuit and hence the deflection in μV could be amplified (with the gain of R_f/R_i as shown in the circuit) to be approximately 20 times of the original from the chosen value of resistances. Now the amplified response of the device was provided to the microcontroller for data acquisition. Arduino Uno 4.0 board was used as a data acquisition module that took an analog voltage of the signal-conditioning module and showed the digital response by coupling it to a basic 16×2 inches Liquid Crystal Display (LCD) like Hitach HD 44780.

The algorithm of the Arduino Uno was developed on an Arduino toolkit and can be calibrated to measure the voltaic response and produce real time estimation of the distance. Fig. 3b shows a block diagram showing all the functional blocks of the sensor as described in this section.

2.4. Experimental procedure

Initially, the functionalized MWCNT device was tested at various values of applied bias currents and the response to the flame was monitored along both lateral as well as longitudinal directions of the flame exposure. In other words, upon traversing along both the directions, the device is exposed to the flame by sideways as well as to the top, respectively as was shown earlier in Fig. 2b and c. In general the laws of heat transfer state that the heat produced sideways from a flame, which is primarily due to radiation is much smaller than compared to that from the top of the flame due to convection. Hamins and Bundy reported that the total flux produced from a candle flame at a radial distance (along the lateral direction) of 5 mm was around $40\,kW/m^2$ whereas along the length of the flame at a height of 38 mm from its baseline was $90\,kW/m^2$ [12]. The distribution of total heat flux versus radial distance from the flame centerline at two longitudinal positions, which was recorded, clearly demarcates the convective heat transfer to be dominant over radiative heat flux as we move above the flame region [12]. Hence observations were made along these two axes (as shown in Fig. 2b) to distinguish the nature of electrical response in both the directions as well as the effect of change in distance between flame and CNT device.

The experiments were conducted by subjecting the MWCNT device to a range of bias currents (3–15 mA in case of lateral direction and 5–18 mA in vertical direction) refraining the amplified output of the microcontroller from going beyond its supply voltage. A fixed bias current supply of 5 mA (in the lateral direction) and 10 mA (in the longitudinal direction), which gave more amicable and consistent response for all distances of exposure, was used to observe any variation in the sensor response that occurred due to variation in the distance. The electrical response of the sensor increases the deflection in the Wheatstone bridge. Electrical responses were recorded at different distances from the flame as well as applied current for a time of 30 s of the flame exposure. Experiments were also conducted to reveal the response of the