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Short communication

Synthesis of carbon nano-fibers on p-Si having improved temperature sensing capability

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ABSTRACT

Synthesis of an innovative material for temperature sensor based on carbon nano-fibers (CNFs) on p-Si substrates has been demonstrated. The CNF films were characterized by SEM, Raman and FTIR studies. First order Raman spectra indicated a G band at ~1597 cm^{-1} corresponding to the E_{2g} tangential stretching mode of an ordered graphitic structure with sp^2 hybridization and a D band located ~1350 cm^{-1} originated from disordered carbon. Gold fingers were deposited on the p-Si/CNF surface for resistance measurement. Temperature sensing properties were also investigated critically. Resistance changes with temperature ($\Delta R/R$) in p-Si/CNF films are found to be significantly large 30–60% Very stable, reproducible and improved temperature sensing properties would make this material superior to commonly available temperature sensors.

1. Introduction

Accurate temperature measurements are required in various measurement systems such as process control and instrumentation applications. In most cases, because of low level non-linear outputs, the sensor output must be properly conditioned and amplified before further processing can occur. Except for IC sensors, all temperature sensors have nonlinear transfer functions [1]. In the past, complex analog conditioning circuits were designed to correct for the sensor nonlinearity. Generally, manual calibration along with precision resistors to achieve the desired accuracy were needed [1,2].

Sensing of temperature through thermo-resistivity is of prime interest due to its inherent simplicity, reproducibility and the near linear variation of resistivity with temperature [3,4]. Generally, the relationship between temperature and resistance is not linear and is modeled with a standard polynomial equation. This is true for commonly used metals like platinum, nickel and certain alloyed forms of copper, which are used as temperature sensors [3]. But inherent low temperature coefficient of resistance (TCR) of these materials requires high performance signal conditioning circuitry to convert them into a signal suitable for a computer or a display or any other output device. This low level output signal renders attainable accuracy of commercial probes from about 0.1% to 1.0% [1,4,5]. Moreover, high cost of the material and the required packaging are not conducive to commercial exploitation of these resistance temperature detectors (RTD) [3]. Subsequently, silicon based temperature sensors were thought to be a viable alternative to the RTDs. In this regard, studies by Qui et al. [3], Gupta et al. [6] and Kewell et al. [7] may be worth mentioning. Gupta et al. [6] designed and fabricated temperature sensor based on bulk silicon which indicated a linear response over a temperature range of −50–150 °C. Qui et al. [3] reported the fabrication of a low-cost broad range silicon temperature sensor covering a range of temperature from 25 °C to 500 °C. An exponential functional dependence of resistance with temperature was indicated. Based on time decay of the luminescence emitted by Er-doped silicon, Kewell et al. [7] described a temperature sensor working in the temperature range of −40–150 K. However, the major drawback of this sensor was the requirement of bulky and high cost equipment. In recent years, Premchand [8] reported the fabrication of temperature sensor based on bulk silicon which can be easily packaged for harsh environment, operated at low temperatures and had high sensitivity. Only recently, Wong et al. [9] indicated the use of bulk multi-walled carbon nanotube (MWCNT) as temperature sensor material. They demonstrated that such sensors would consume much lower power than the sensors based on silicon and RTDs. The observed power consumption for these sensors was in μW range. But the reported response was not that large (−0.1 to −0.2%/°C). Crawford et al. [10] at Northeastern University, Boston discussed the design, fabrication, and testing aspects of a novel CNT-based temperature sensor in their technical report. The sensor utilized extremely small sized SWNTs having superior thermal and electrical properties. The sensor, thus fabricated, required microwatt range power. More recently, Yang et al. [11] showed that the long SWCNT array device had high sensitivity and low power

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consumption than ordinary platinum thermal resistor. It was indicated that this sensor could be utilized in high sensitivity temperatures or flow measurements in an ultra small scale.

Thus, search of materials with superior temperature coefficient of resistivity for temperature sensor has been the prime focus of researchers in the past decade [1–11]. In this study, a novel bi-layer p-Si(1 0 0)/carbon nanofibers (CNF) having significantly higher TCR is proposed. The above structure was obtained by depositing CNF directly onto p-Si substrates by simple electrodeposition technique. The films thus obtained were characterized by SEM, Raman and FTIR studies. Temperature sensing properties were also investigated critically.

2. Experimental details

CNFs were synthesized by electrolysis using acetonitrile (0.8% v/v) and deionized water as electrolyte. p-type single crystal silicon (1 0 0) wafers (0.5 mm thick) doped with different amount of boron were used as substrates to deposit the carbon nanofibers. The sheet resistances of the two types of silicon substrates used were ~0.01–0.02 Ω cm and 5–9 Ω cm. Electrolysis was carried out at atmospheric pressure and the bath temperature was kept at ~300 K. The size of the substrates used for electrodepositing CNF on them was ~10 mm × 8 mm × 0.3 mm and they were attached to a copper cathode. Graphite was used as the counter electrode (anode). Before mounting the substrates on the cathode, they were thoroughly cleaned and rinsed with deionized water and ethanol solution respectively. The electrodes were separated by a distance of ~8 mm. The applied d.c. voltage between the electrodes was kept ~16 V by using a d.c. power supply capable of generating stabilized voltage (30 V, 2 A). The deposition was carried for ~3 h. The typical thickness of the films as measured by an interferometer was ~300 nm. Details of deposition techniques are available from our earlier publication [12].

The surface morphology of the films was studied by Field Emission Scanning Electron Microscope (FESEM) (Carl Zeiss SUPRA® 55). AFM pictures were recorded by using a Nanosurf Easy Scan 2 in contact mode. FTIR spectra were recorded in the range of 400–4000 cm^{-1} by using a Nicolet™-380 FTIR spectrometer. Raman spectra were recorded using Renishaw inVia micro-Raman spectrometer using 514 nm Argon laser.

3. Results and discussion

3.1. Microstructural studies

Surface texture of bare silicon substrates and CNF films deposited on them has been studies by AFM. Fig. 1a and b shows the surface textures of bare silicon substrates having resistivities of 0.01–0.02 Ω cm and 5–9 Ω cm, respectively, while Fig. 1(c,d) shows the same for CNFs deposited on them. Corresponding 3-D AFM pictures are shown in the insets of Fig. 1. A very smooth surface could be observed (Fig. 1a,b) for both the p-Si substrates. Surface became very rough with the deposition of CNF on p-Si substrate (Fig. 1c,d). The surface roughness of the pure p-Si surface was ~2 nm while the surface of the p-Si/CNF increased manifold to ~10 nm.

Fig. 2(a–d) shows the scanning electron micrographs (SEM) of two representative CNF films deposited on two types of p-Si substrates. Both the CNF films deposited on p-Si (0.01–0.02 Ω cm)

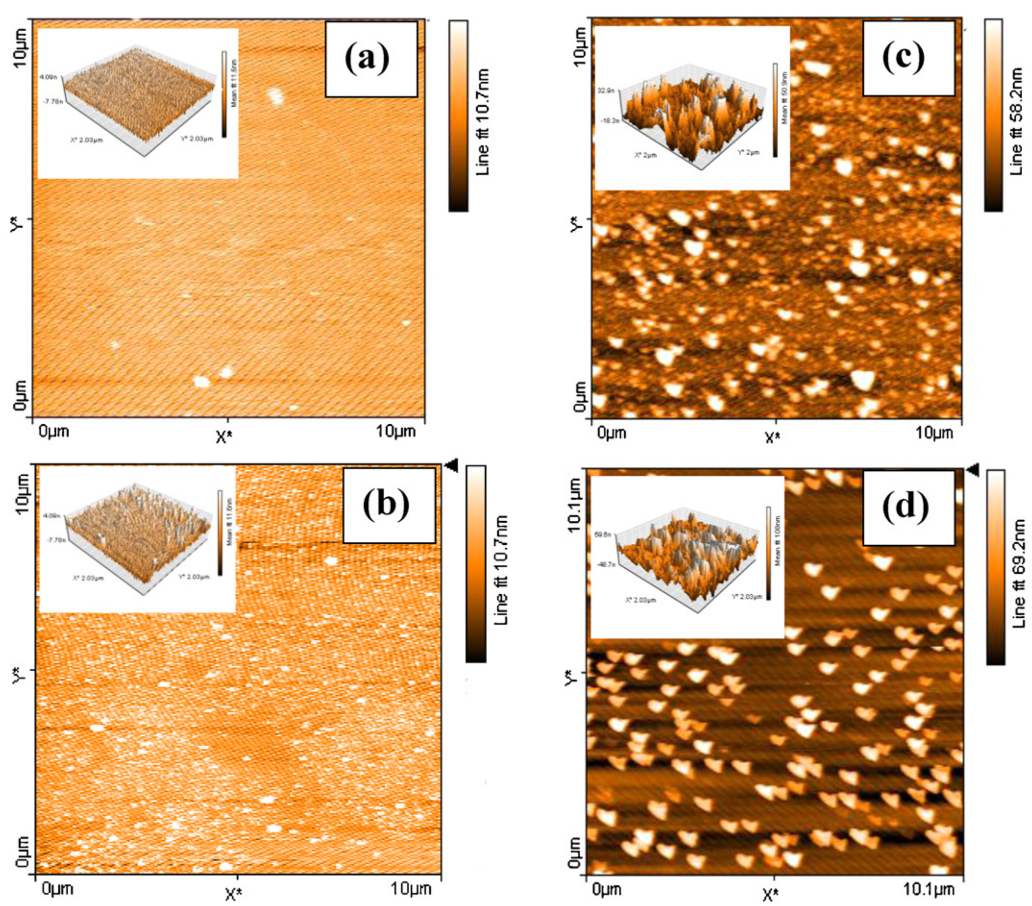

Fig. 1. AFM picture of: (a) pure p-Si substrates (0.01–0.02 Ω cm), (b) pure p-Si substrates (5–9 Ω cm) (c) CNF film deposited on (a) and (d) CNF film deposited on (b). Insets show the corresponding 3-D pictures.