# Carbon nanotube–cuprous oxide composite based pressure sensors

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In this paper, we present the design, the fabrication, and the experimental results of carbon nanotube (CNT) and $Cu_2O$ composite based pressure sensors. The pressed tablets of the CNT–$Cu_2O$ composite are fabricated at a pressure of 353 MPa. The diameters of the multiwalled nanotubes (MWNTs) are between 10 nm and 30 nm. The sizes of the $Cu_2O$ micro particles are in the range of 3–4 μm. The average diameter and the average thickness of the pressed tablets are 10 mm and 4.0 mm, respectively. In order to make low resistance electric contacts, the two sides of the pressed tablet are covered by silver pastes. The direct current resistance of the pressure sensor decreases by 3.3 times as the pressure increases up to 37 kN/m$^2$. The simulation result of the resistance–pressure relationship is in good agreement with the experimental result within a variation of ±2%.

**Keywords:** carbon nanotubes, $Cu_2O$ micro-powder, pressure sensor, simulation

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## 1. Introduction

Pressure transducers are mostly used with resistance, capacitance, inductance, and piezoelectric sensors and with devices such as diaphragms and bellows.[1,2] Due to their excellent electronic, mechanical, and thermal properties, carbon nanotubes and their composites have aroused great interest in their applications to sensors and actuators.[3,4] These sensing and actuating devices have been used in electronic switches, nano-tweezers, organic, optoelectronic, photovoltaics elements for mechanical damage detection, and electromechanical transducers.[3,5,6]

Electronically, carbon nanotubes (CNTs) can be metallic, semiconducting, or small-gap semiconducting (SGS) materials depending on the orientation of the graphene lattice with respect to the axis of the tube.[7] Various types of sensors based on single-walled carbon nanotubes (SWCNTs), double-walled carbon nanotubes (DWCNTs), and multi-walled carbon nanotubes (MWCNTs) have been fabricated and investigated.[8−10] The interesting electromechanical properties make the CNT a suitable material for fabricating piezoresistors in mechanical sensors, such as strain gauges, accelerometers, and pressure sensors.[7,11−15] The use of SWCNTs as mechanical actuators and a comparison of their performance with those of natural muscles were reported by Baughman *et al.* for the first time.[16] A piezoresistive pressure sensor based on multi-walled carbon nanotubes and polydimethylsiloxane (PDMS) was fabricated by Hwang *et al.*[4] The poly (3 hexylthiophene) (P3HT) was also used for the homogenous dispersion of MWCNTs in the composite. The reported results showed that in response to the change in pressure from 0 MPa to 0.12 MPa, the relative resistance changed from 1 to 1.21. Due to the extremely low operating pressure, that sensor could be used for finger sensing. Bautista-Quijano *et al.*[3] reported the piezoresistive and the electrical responses of polymeric films of polysulfone (PSF) modified with 0.05–1.0 w/w MWCNTs. It was found that with the CNT content increasing from 0.05 w/w to 0.5 w/w, the gauge factor increased from 0.48 to 0.74. The piezoresistances of CNTs on deformable thin-film silicon nitride membranes were investigated,[7] and it was found that the values of the gauge factor ($\Delta R/R\varepsilon$) were 400 and 850 for the semiconducting and the SGS tubes, respectively, whereas the maximum value of the gauge factor in silicon was 200.

Despite the fact that the ongoing research focuses

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mainly on SWCNTs, MWCNTs are more suited for macrosize applications due to their rapidly growing large scale production technology.[3] In view of the technological and the economic advantages of MWCNTs, we design, fabricate, and investigate resistive pressure sensors based on the composites of commercially produced CNTs and $Cu_2O$. The cuprous oxide ($Cu_2O$) is a photosensitive p-type semiconductor ($E_g$ = 2.17 eV) with particular magnetic properties suited for applications in electronics, magnetic storage, energy conversion sensors, and field emission devices.[17−19] The non-toxicity and simple fabrication process of $Cu_2O$ along with the abundance of copper in nature makes it highly attractive for technical applications and fundamental research.[17,18] The fabrications of nanodots and nanostructure thin films of $Cu_2O$ were reported in Refs. [20] and [21], the modifications of MWCNTs by Cu, CuO, and $Cu_2O$ were reported in Ref. [17], and the preparation of $Cu_2O$/MWCNT (multi-walled carbon nanotubes) nano-composites by low temperature fixture method was reported in Ref. [22].

As is known, the fabrication of materials based on composites allows us to modify their properties, which include specific and sample resistances. The modification is controlled by changing the ratio of elements in the composite. The fabrication of CNT–$Cu_2O$ composite based pressure sensors and the investigation of their properties is useful from a practical point of view and for deepening the knowledge about the physical properties of the constituents. Therefore, it is interesting to investigate the resistance–pressure relationship. In this paper, we describe the design, the fabrication, and the investigation of resistive pressure sensors based on a CNT–$Cu_2O$ composite.

## 2. Experimental procedure

For making the CNT–$Cu_2O$ composite, the commercially produced CNT nanopowder and $Cu_2O$ micro-powder were purchased from Sun Nanotech Co Ltd., China and WINLAB, UK, respectively. The diameters of the multiwalled nanotubes varied from 10 nm to 30 nm, while the sizes of the $Cu_2O$ micro particles were in the range of 3–4 μm. The blend of CNTs (25 wt.%) and $Cu_2O$ (75 wt.%) was prepared by using the mortar and pestle. Tablets of 10 mm in diameter and 4 mm in thickness were fabricated by pressing the CNT–$Cu_2O$ composites at a pressure of 353 MPa. In order to make low resistance electric contacts, the two sides of the pressed tablets were covered by silver pastes. Figure 1 shows photographs of one of the samples.

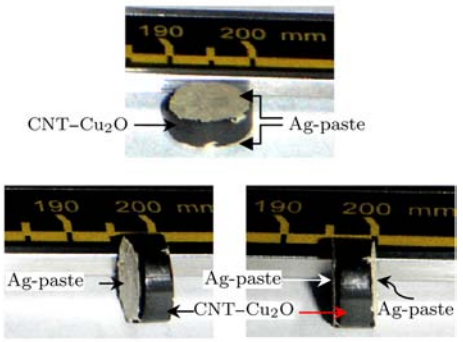



**Fig. 1.** (colour online) Photographs of a sample from various angles.

For measuring the DC resistance of the pressure sensors, an ESCORT ELC-132A meter was used. A detailed description about the setup for the measurement of the influence of the pressure on the resistance of the sensors was given in Ref. [23]. Figure 2 shows the experimental setup for the investigation of the pressure sensors. The setup comprises of (i) a support, (ii) a weight holder, (iii) weights, and (iv) a CNT–$Cu_2O$ pressure sensor. The pressure could be changed by changing the weights in the conventional laboratory setup. The sensor resistance and the applied pressure were measured at 25 °C.

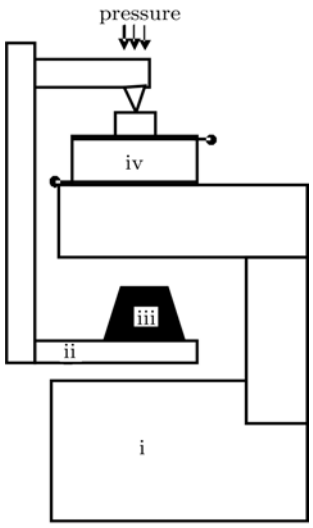



**Fig. 2.** Experimental setup for investigation of the CNT–$Cu_2O$ sensor under pressure, composed of support (i), weight holder (ii) with weights (iii), and CNT–$Cu_2O$ pressure sensor (iv).

## 3. Results and discussion

Figure 3 shows the resistance–pressure relationships for one of the CNT–$Cu_2O$ pressure sensors. It can be seen that the sensor has a low hysteresis (2.7 % on average) for the resistance–pressure relationship and a good repeatability. The direct-current (DC) resistance of the pressure sensor is decreased by 3.3 times as the pressure is increased to 37 kN/m$^2$. The sensor resistance ($R$) is calculated by the following equation:

$$R = \frac{d\rho}{A} = \frac{d}{\sigma A}, \tag{1}$$

where $d$ is the inter-electrode distance (thickness of the pressed tablets), $A$ is the cross-section of the CNT–$Cu_2O$ pressed tablet, and $\rho$ is the resistivity ($\rho = 1/\sigma, \sigma$ is the conductivity) of the pressed tablet. For the observed resistance–pressure relationship, the increase in the conductivity of sensor is probably due to the densification of the CNT–$Cu_2O$ powder under the effect of pressure and the squeezing of the particles.

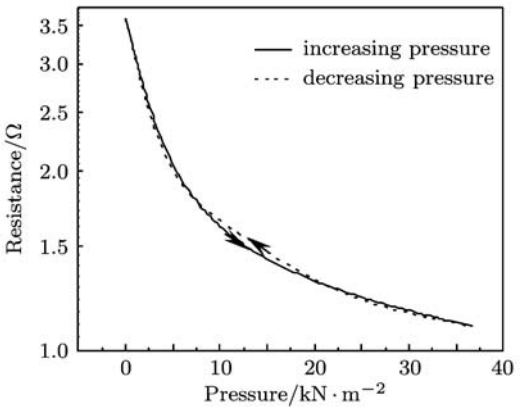



**Fig. 3.** Resistance–pressure relationship for CNT–$Cu_2O$ pressure sensor.

For simulating the resistance–pressure relationship, the following exponential function ($f(x) = \mathrm{e}^{-x}$) can be used:[24]

$$\frac{R}{R_0} = \mathrm{e}^{-pK}, \tag{2}$$

where $p$ is the pressure, $K$ is the resistance–pressure factor, $R_0$ and $R$ are the resistances of the sensor at atmospheric pressure and under the uniaxial pressure, respectively. We modify the above relation to

$$R/R_0 = \mathrm{e}^{-6pK_\mathrm{m}p_\mathrm{m}/(p_\mathrm{m}+5p)}, \tag{3}$$

where $p_\mathrm{m}$ is the maximum pressure, and $K_\mathrm{m}$ is the resistance–pressure factor under the maximum pressure. From the experimental data shown in Fig. 3, the value of $K_\mathrm{m}$ is 0.0323 m$^2$/kN. The experimental and the simulated (using Eq. (3)) results are plotted in Fig. 4, which are in good agreement with each other. The simulation results coincide with the experimental results within a variation of ±2 %.

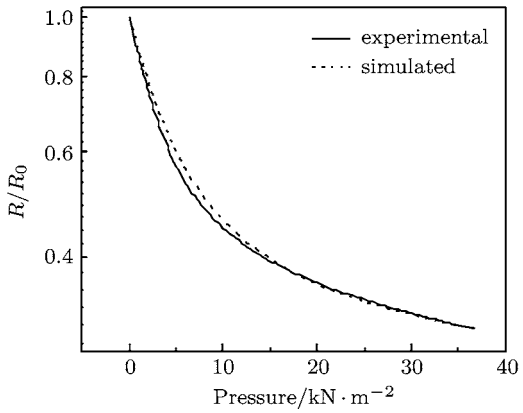



**Fig. 4.** Experimental (solid line from the sensor shown in Fig. 3) and simulated (dashed line) relative resistance–pressure relationships for CNT–$Cu_2O$ pressure sensor.

The mechanism of conductivity in the CNT–$Cu_2O$ sensor can be considered as the transition through the spatially separated sites or particles, which can be described by the percolation theory.[25,26] According to the percolation theory, the effective conductivity ($\sigma$) of the CNT sample can be calculated from

$$\sigma = \frac{1}{LZ}, \tag{4}$$

where $L$ is the characteristic length depending on the concentration of the sites or the particles, and $Z$ is the resistance of the path with the lowest average resistance. With the increase in pressure, the CNT–$Cu_2O$ pressed tablet between the silver electrodes is squeezed, resulting in the decrease of the characteristic length and the reduction of the path resistance. Consequently, the conductivity increases, and the resistance of the sensor decreases accordingly, which is observed in the experimental results (Fig. 3). On the other hand, the resistance of the sample also decreases due to the increase in the cross-sectional area of the CNT–$Cu_2O$ pressed tablet (Eq. (1)) under the effect of pressure (Fig. 2). The experimental results reveal that the conductivity, which is an intrinsic property, varies under the effect of pressure, and the variation in the geometrical parameter of the sample also causes the resistance to change. It can be assumed that the conductivity increases not only due to the densification of the sample but also due to the increase in the conductivity of the nanoparticles.

Depending on the orientation of the graphene lattice with respect to the axis of the tube, the CNT may be semiconducting, small-gap semiconducting, or metallic.[7] Our preliminary investigations[27] show that the conductivity of the CNT used in this work increases with the increase of the temperature, exhibiting the semiconductive property. At the same time, $Cu_2O$ is semiconductor as well. The charge carrier density ($n_i$) is described by the following equation:[28]

$$n_i = N_0 \exp(-E_g/2kT), \tag{5}$$

where $N_0$ is the effective density of states, $E_g$ is the energy gap, $k$ is the Boltzmann coefficient, and $T$ is the absolute temperature. In our case, we can assume that the charge carrier density increases due to the decrease in the energy gap ($E_g$) of the particles under the effect of pressure and then the conductivity increases accordingly. In principle, the mobility of the charge carriers might be increased as well due to the decrease of the activation energy of mobility[28] and/or the scattering of the charge carriers caused by the atomic vibrations during the transport process. The contribution of the mobility to the conductivity can be investigated in future by the Hall effect measurement.[29]

The investigation of the CNT (25 wt.%)–$Cu_2O$ (75 wt.%) composite based pressure sensors shows that these sensors have adequate sensitivity for practical applications. Moreover, the initial resistance of the sensor may be increased by increasing the amount of $Cu_2O$ in the composite, which will be further investigated. The improvement on the initial resistance will be helpful to reduce the effect of the metallic wire resistance on the sensitivity of the sensor.[13]

As the experimental resistance–pressure relationship for the CNT–$Cu_2O$ sensor (Fig. 3) is non-linear, it can be linearized by nonlinear op-amps.[30] The fluctuation of the temperature may also affect the resistance of the CNT–$Cu_2O$ based pressure sensor. To compensate the effect of temperature in the practical utilization of the sensor, a Wheatstone bridge may be used.[13] Figure 5 shows the Wheatstone bridge circuit, which can be realized by four kinds of connections. In case 1, $R_1$ is the active resistance sensor, $R_2$, $R_3$, and $R_4$ are the ordinary resistors. This circuit is used if the temperature compensation is not required. In cases 2 and 3, $R_1$ is the active resistance sensor, $R_2$ or $R_3$ is a dummy resistor, $R_3$ or $R_2$ and $R_4$ are the ordinary resistors. The active and the dummy sensors should be placed in the same thermal environment, the active sensor is under the pressure, while the dummy sensor is in a pressure-free region. Detailed analysis of these four cases is given in Ref. [13].

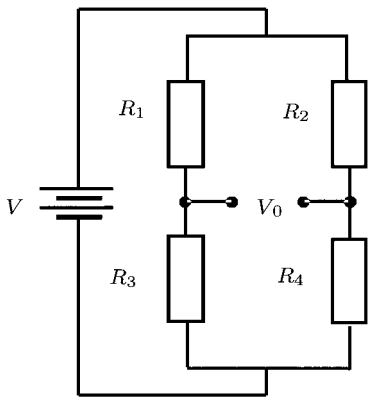



**Fig. 5.** Schematic diagram of pressure sensor arrangement in the Wheatstone bridge, where $V_0$ is the output voltage.

## 4. Conclusion

CNT (25 wt.%) and $Cu_2O$ (75 wt.%) composite based pressure sensors are investigated. It is found that the DC resistance of the pressure sensor is decreased by 3.3 times as the pressure is increased to 37 kN/m$^2$. The resistance–pressure relationships is simulated. The mechanism of the conductivity in the CNT–$Cu_2O$ sensor is discussed. It can be considered as the transition through spatially separated sites or particles, which can be understood by the percolation theory. As the resistance–pressure relationship is nonlinear, it is proposed to linearize the relationship by nonlinear op-amps. To compensate the effect of temperature on the resistance of the CNT–$Cu_2O$ based pressure sensor, the use of the Wheatstone bridge based circuit is proposed, which will make the sensors ready for practical applications.

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