

FABRICATION AND INVESTIGATION OF GRAPHENE BASED PRESSURE SENSOR

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ABSTRACT

In this work, we have reported the design, fabrication and characterization of the Graphene based piezoresistive pressure sensor. The size and thickness range of the graphene nano powder was $10\mu\text{m} \times 10\mu\text{m}$ and 5nm-20nm respectively. Graphene tablets of thickness 1.5mm were fabricated at a pressure of 353Mpa. The diameter of the sample was 15mm. Both sides of the pressed tablets were covered by silver paste to provide low resistance electric contacts. As the pressure was increased from 0 to 0.283kNm^{-2} , 5.4 times decrease in dc resistance was observed. The simulated results of the relative pressure-resistance relationship were in excellent agreement with experimental characteristics. Only 5% variations were found between experimental and simulated results. The device exhibits pressure sensitivity of $2.8\text{K}\Omega/\text{kNm}^{-2}$ with the applied pressure.

Keywords: Graphene; piezoresistivity; nanostructure; pressure sensor;

INTRODUCTION

Pressure sensors are mostly constructed on the basis of inductive, capacitive, piezoelectric and piezoresistive elements [1]. They are utilized to control and monitor the pressure in a variety of everyday applications. In scientific and industrial applications, there is a great demand for pressure sensors. For broad range of sensing applications, the existing technology based sensors become very expensive. Hence, there is a need to investigate new advanced materials for high performance and low cost fabrication of these sensors. Pressure sensors based on nano materials have higher sensitivity, lower weight and cost, exceptional stability and smaller size that are

expected to be the emerging technology for the next generation of sensors [2]. Piezoresistive- type pressure sensors exhibit outstanding promise for real time applications because of its easy fabrication process, low cost and simple device structure [3-6].

Currently, graphene is one of the most extensively studied nano material that has exceptional electrical and mechanical properties [7]. Graphene is only one atom thick two-dimensional (2D) sp^2 hybridized form of carbon, introduced in 2004 and vigorously boosted the potential improvement of NEMS and microelectronics devices. The exceptional electric and mechanical properties of graphene makes it convenient to design and fabricate graphene based pressure sensors which is a promising line of research. Graphene is the known strongest material; an effective thickness of 0.335nm graphene, can withstand more strain than steel with a Young's modulus of 1Tpa [8, 9]. A.M. Hurst et al presented a graphene pressure sensor based on an array of suspended circular graphene membranes over holes (diameter of $3\mu\text{m}$) in silicon dioxide on degenerately doped silicon and translated the applied pressure into the change in resistance by deflecting the graphene membrane [9]. They reported that graphene pressure sensors have potential advantages (such as high sensitivity and smaller dimension) over traditional pressure sensors. The charge carrier mobility of graphene, at room temperature, is ten times greater ($> 100,000\text{cm}^2/\text{Vs}$) than the conventional semiconductors lattices [10]. Numerous interesting results have been achieved in this area. For instance, Qijan Sun et al reported matrix of pressure sensors (sensitivity of 0.12kPa^{-1}) based on transparent and flexible GFETs for e-skin applications [11]. A pressure sensor based on vertical tunneling graphene field-effect transistors (VTGFETs) with six layers of hBN was demonstrated and analyzed theoretically by Nayereh Ghobadi et al. A sensitivity of $\sim 1300\text{pA/A/Pa}$ and a non-linearity error of 3.2% in the range of 30GPa were reported [12]. A. D. Smith et al, for the first time, experimentally investigated the effect of cavity shape on the piezoresistive pressure sensor based on the suspended graphene membrane and it was concluded that a smaller cavity size of $18\mu\text{m}$ provide a gauge factor of 89 [13]. H. Hossein zadegan et al reported a very high piezoresistive gauge factor of 1.8×10^4 by using graphene as a piezoresistive strain gauge on silicon nitride [14].

Owing to the properties discussed above, it will be interesting to deeper the knowledge about the physical and electrical properties of the graphene, hence it would be useful from the practical point of view to fabricate and investigate graphene based peizoresistive pressure sensors. In the present work, we have presented a novel sandwich type piezoresistive pressure sensor. The sensitivity of the piezoresistive pressure sensor is reported to $2.8\text{K}\Omega/\text{kNm}^{-2}$ that is much higher than the sensitivity values reported previously in the years 2014-2015 [3, 11]. It is believed that the present work could provide useful information for the fabrication and characterization of graphene-based pressure sensors, actuators and other electronics systems.

EXPERIMENTAL

Graphene nano powder was commercially purchased from Sun nanotech Co Ltd., China and was used as received to fabricate the graphene-based pressure sensor without any further modification. The thickness of the graphene layers varied between 5 and 20nm and its area size was 10x10 μ m. The powder was pressed by hydraulic press at a pressure of 353MPa to form a durable pellet. Low resistance electric contacts to the pellet were made by using silver paste. The simplified schematic diagram of Ag/graphene/Ag is shown in the Figure 1. The diameter and thickness of the pressed tablets was 15mm and 1.5mm respectively.

Figure 2 shows the detailed experimental setup used for the characterization of pressure sensor under load. It consists of metallic support (i), weight holder (ii), weight (iii), the sensor (aluminum support (vi), graphene (v), aluminum foil (vi) and terminals (vii) and (viii)). The major components of the experimental setup are weight and weight holder. These components were used from the traditional laboratory setup “Flexor: Cantilever Flexure Frame”. DC resistance of the sensor was measured by using an Escort ELC-132A meter at room temperature.

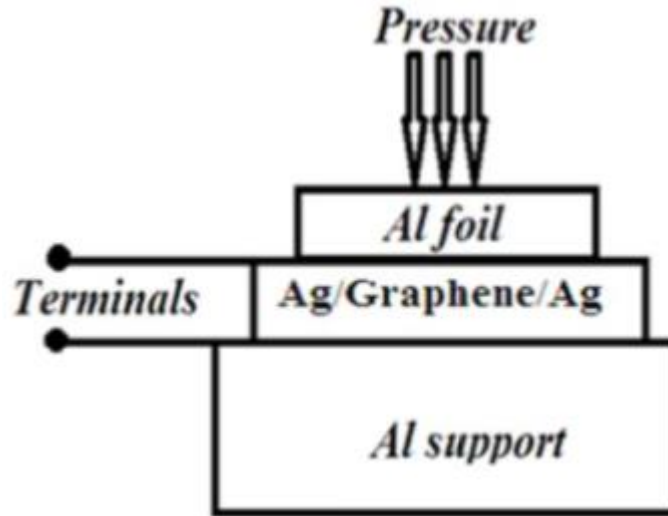


Figure.1: Schematic diagram of Ag/Graphene/Ag piezoresistive pressure sensor

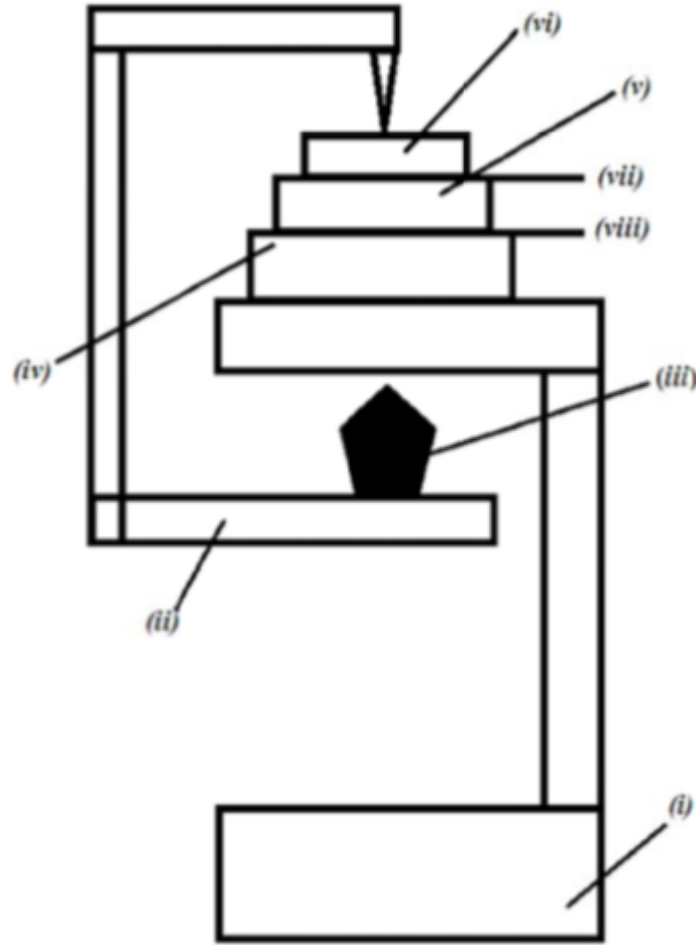


Figure 2: Detail experimental setup for characterization and investigation of piezoresistive pressure sensor with installed graphene-based piezoresistive pressure sensor: metallic support (i), weight holder (ii), weight (iii), the sensor (aluminum support (vi), graphene (v), aluminum foil (vi) and terminals ((vii) and (viii))

RESULTS AND DISCUSSION

Figure 3 depicts the resistance vs pressure relationship of Ag/Graphene/Ag piezoresistive pressure sensor. The variation in the resistance with the applied pressure was in the range of 65 K Ω to 12 K Ω and 0 kNm⁻² to 0.283 kNm⁻², respectively. It is seen that the resistance decreases almost 6 times with increase in the applied uniaxial pressure. The following expression can be used to determine the resistance of the pressure sensor [15].

$$R = d\rho/A = d/\sigma A \quad (1)$$

where d is the thickness or inter-electrode distance, A is the cross-sectional area of the aluminum foil electrode and ρ is resistivity ($\rho=1/\sigma$) where σ is conductivity).

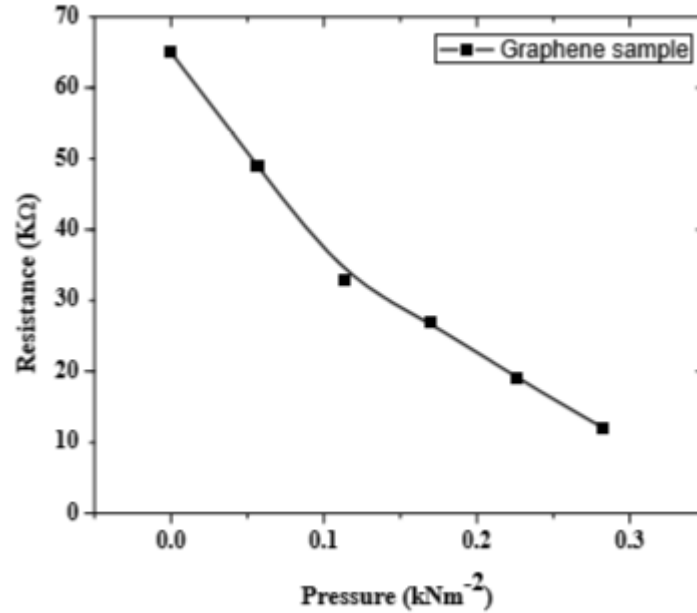


Figure 3: Pressure-resistance relationship for graphene-based piezoresistive pressure sensor fabricated at a pressure of 353MPa

There are two factors that cause to change the resistance of the sensor as shown in Eq. 1. The first reason is the change in geometrical parameters of the sensor whereas the second is the change in intrinsic properties (resistivity) of the material. In our case it may be assumed as that the second case is dominant due to the fact that densification of the particles occurs. Due to this the particles comes closer to each other, hence increases the conductivity and as a result resistance of the sample decreases.

The sensitivity (S) of pressure sensor can be calculated by the following expression [16, 17].

$$S = (\Delta R/R) / \Delta P \quad (2)$$

Where R is the sensor's initial resistance (at $P=0$ kNm⁻²), ΔR , ΔP is change in sensor's resistance and external uniaxial applied pressure, respectively. The sensor's sensitivity (S) was 2.8KΩ/kNm⁻². It can be noticed from the pressure-resistance characteristics (Figure 3) that the sensor is more sensitive to the lower values of the applied pressure as compared to its higher values.

The experimental result of the pressure-resistance relationship depicted in figure.3 can be simulated by using the following exponential function [18].

$$F(x) = e^{-x} \quad (3)$$

Equation (3) can be written in following form in this case

$$R/R_0 = e^{-PK} \quad (4)$$

Where P is the applied uniaxial pressure and K is the pressure-resistance factor. The simulated (Eq. 4) and experimental (Figure 3) relationships of pressure vs relative resistance of Ag/Graphene/Ag piezoresistive pressure sensor is shown in Figure 4.

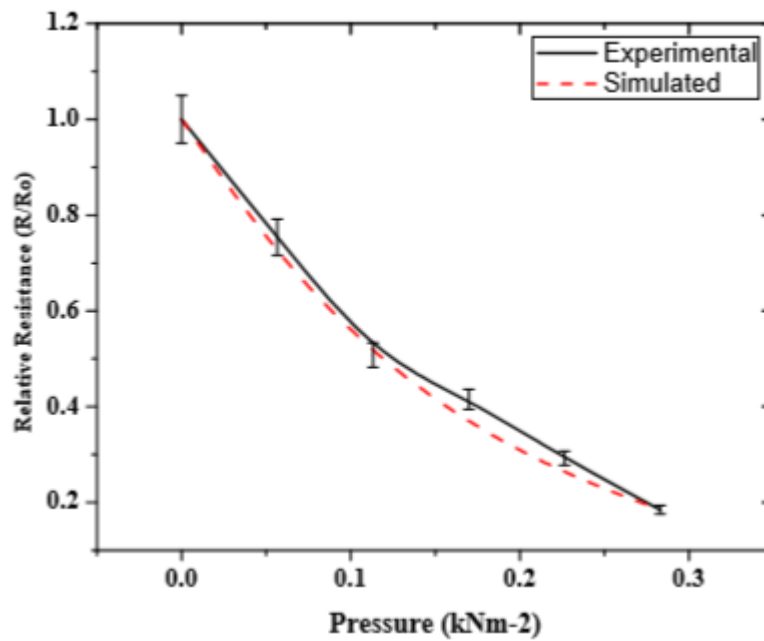


Figure.4: Simulated (dashed red line) and experimental (solid line) relative resistance-pressure relationship for Ag/Graphene/Ag piezoresistive pressure sensor

The pressure- resistance factor K in Eq. 4 was calculated ($K = 5.96 \text{ kN}^{-1}\text{m}^2$) at pressure 0.283 kNm^{-2} from the experimental characteristics shown in Figure 3. It can be observed from Figure 4 that the simulated result is in good agreement with the experimental result. The size of the error between simulated and experimental characteristics was only 5% computed by using Eq. 5.

$$\% \text{ error} = ((\text{Theoretical value} - \text{Experimental value}) / (\text{Theoretical value})) * 100 \quad (5)$$

The relative pressure-resistance experimental relationship for Ag/Graphene/Ag piezoresistive pressure sensor is quasi-linear that can be linearized by using a non-linear operational amplifier [19]. The conductivity in multicrystalline disordered semiconductor material is mostly based on hopping mechanism [20]. In hopping mechanism between specially separated sites, charge carriers hop out from one of these localized states to another to contribute in conductivity [21]. Percolation theory can be used to describe the conductivity in graphene that have such random and disordered geometrical structure. According to this theory, the effective conductivity of the multicrystalline disordered nano materials (graphene pallets in this case) can be calculated by the following equation.

$$\sigma = 1/LZ \quad (6)$$

where σ , Z and L is conductivity, resistance of the path with lowest average resistance and characteristics length, respectively. The characteristics length (L) depends on the concentration of particles or sites in multicrystalline disordered nano structures. The resistance of the Ag/Graphene/Ag sample may be influenced by variation in the temperature. Wheatstone bridge circuit shown in Figure 5 may be utilized to compensate the temperature effect that makes the sensor more suitable for practical applications.

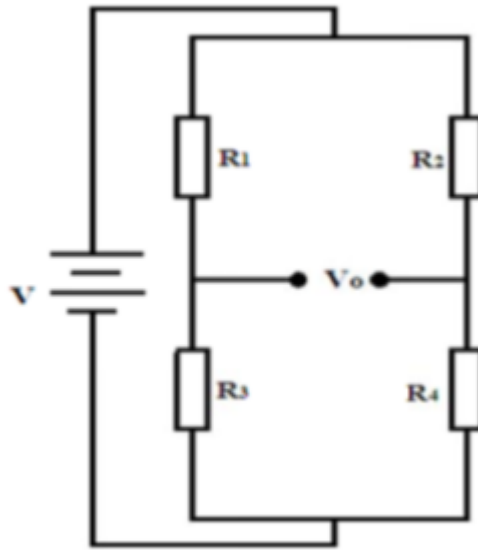


Figure.5: Schematic diagram of Wheatstone bridge with pressure sensor arrangement.

Different types of connections are possible to realize the Wheatstone bridge circuit shown in Figure 5, where V and V_0 are the input and output voltages respectively. Case.1: R_2 , R_3 and R_4 are the normal resistors while R_1 is the active resistance pressure sensor. Case.2: R_2 and R_4 are normal resistors; R_3 is the dummy resistance pressure sensor while R_1 is the active resistance pressure sensor. Case.3: R_3 and R_4 are normal

resistors; R_2 is the dummy resistance pressure sensor while R_1 is the active resistance pressure. The dummy sensor should be in pressure free region while the active resistance pressure sensor should be under pressure. The same thermal environment is needed for arrangement of dummy and active resistance pressure sensors. Case.1 can only be used when no temperature compensation is required [15].

CONCLUSION

The effect of pressure on the fabricated sensor was investigated. It was found that DC resistance of the device was decreased by 5.4 times as the external uniaxial pressure was increased from 0 to 0.283kNm^{-2} . The relative pressure-resistance relationship was simulated and compared with the experimental results that showed an excellent agreement with each other. The concept of percolation theory was used to understand the conduction mechanism between specially separated sites of particles in disordered nano materials.

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