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Flexible tactile sensor based on reduced graphene oxide and polydimethylsiloxane

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Abstract: Fabrication of flexible tactile sensor has been extensively investigated for various applications in robotic, biomedical and automotive fields. Although many research works have been proposing various kinds of tactile sensor design, there is still room for improvement, especially on the simplicity of the structure and understanding of the device operation. In this work, simple tactile sensor was fabricated using reduced graphene oxide (rGO) and polydimethylsiloxane (PDMS). The proposed sensor is made from two PDMS layers which were attached with rGO film and copper electrodes. The rGO film on PDMS layer was fabricated via drop-casting of graphene oxide dispersion and reduction using ascorbic acid. The copper electrode on PDMS was fabricated through photolithography and wet etching. Tactile sensors with reduced graphene oxide film deposited using dispersion concentration varied from 0.4 to 1 mg/ml were fabricated and analyzed. The fabricated sensors were characterized under application of force between 0.5 to 1.4 N. The fabricated device successfully worked as tactile sensor, whereas the resistance decreased as the applied force increased. This is due to the increase of contact area between reduced graphene oxide and electrode. Real time response test confirmed the device functionality. It was found that the sensor made from 0.8 mg/ml gave the highest sensitivity at 10.3 MΩ/N. Compared to other reported works, the proposed flexible sensor structure is relatively simple and can be fabricated using less complicated process. Thus, it is favorable for mass production of the low-cost tactile sensor.

Keywords: Force sensor, tactile sensor, reduced graphene oxide, polydimethylsiloxane.

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1. INTRODUCTION

Tactile sensor is a transducer that measures the change of physical environment in contact and output the changes into electrical signal [1]. The type of tactile sensor depends on the transducer type, which can be resistive, capacitive, piezoelectric, barometric and optical [2-5]. Tactile sensor can be said as skin for robot, as tactile sensing detects the small change of the physical environment in contact. Tactile sensor is also studied for various applications such as in biomedical and automotive fields.

In recent years, graphene-based material has gained a lot of attention among researchers. Graphene is a two-dimensional (2D) carbon allotrope with a honey-comb lattice shape in which each carbon atom forms one vertex [6]. It has strong mechanical strength and flexible [2]. Intensive and extensive studies have been done to apply the graphene-based material in various types of sensor. Graphene has also been used in tactile sensing technology. One of the derivatives of graphene is reduced graphene oxide (rGO), which can be synthesized through oxidation of graphite to graphene oxide (GO) followed by reduction of GO [6]. The rGO has good electric conductivity and suitable to be used in flexible tactile sensor. The related examples of usage of rGO in tactile sensor were presented in references [2] and [7]. An inkjet-printed piezoresistive back-to-back graphene tactile sensor used for endo-surgery palpation applications [7].

In this project, the functionality of a resistive tactile sensor made from rGO and polydimethylsiloxane (PDMS) was investigated. The resistive type of tactile sensor is chosen because it is simpler and made from less layer compared to capacitive type. The resistive based required only one layer of electrode while capacitive based required two electrodes layer. There are two objectives for this project. Firstly, is to fabricate the flexible tactile sensor using PDMS and rGO. PDMS as a force transmission or force concentration medium [3] and sensor protection layer [4]. Secondly, to investigate the relationship between the thickness of rGO and the performance of sensor, that is sensitivity, linearity and repeatability.

2. OVERVIEW OF TACTILE SENSOR USING PDMS

PDMS is a flexible, non-toxic and inert material [5]. The elasticity of PDMS depends on the ratio of PDMS to curing agent. As the ratio increased, the hardness of PDMS will be decreased [5]. PDMS layer is used to concentrate the external force [3], this force will then change the shape of PDMS which cause the change of electrical characteristic of conductor attached to it. The electrical characteristic change depends on the device design structure. The electrical characteristic stated here can be resistance, capacitance, and voltage. Therefore, the mechanical force is translated into electrical signal which is ready to be measured and converted into digital signal. Besides, the

PDMS also protects the electrode from mechanical damage [4], because PDMS is a flexible material which can absorb external impact. Table 1 summarizes several works on tactile sensor using PDMS.

Table 1. Related works on tactile sensor using PDMS

Reference no.	Summary
[2]	• Resistive based sensor • Using rGO on Polyethylene naphthalene (PEN) layer • rGO coated using spray coating
[3]	• Capacitive based sensor • Small enough to integrate into prosthetic hand • Can have real-time images visualization-based object hold in prosthetic hand
[4]	• Resistive based sensor • Able to detect 3D force, XYZ • Good linearity between force and resistance
[5]	• Barometric based sensor • Demonstrated that PDMS is a good surface protector • Demonstrated the method to calibrate and test sensor • The relationship between air pressure and load stress is linear
[8]	• Piezoelectric based sensor • Have PDMS bump of 2 mm • Able to encode the roughness of materials.

3. METHODOLOGY

3.1 Design and Working Principle

Figure 1 illustrates the cross section of the proposed design of the sensor structure. The tactile sensor has four layers. The first layer is PDMS with thickness of 1 mm. Second layer is a thin layer below the PDMS which is rGO. Third layer is electrode layer and sticker paper. The electrode layer is made up of copper. The sticker layer covers the copper track which prevents contact between rGO and copper. The last layer is a PDMS layer with thickness of 1 mm. The electrode area size is 5 x 5 mm. When no force acts on the PDMS layer, the rGO layer will not touch the electrode. Therefore, the resistance between the electrodes will be infinity. As the force applied on the PDMS increases, the contact area between rGO and electrodes increase, therefore the resistance will be decreased.

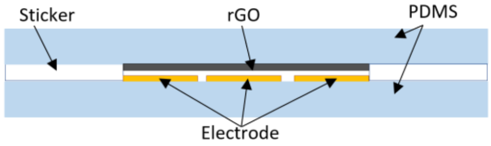


Figure 1. Cross section of the proposed design.

3.2 Fabrication Procedure

GO films with different thickness were formed by drop casting GO aqueous dispersion with different concentration (i.e. 1 mg/ml, 0.8 mg/ml, 0.6 mg/ml and 0.4 mg/ml). The dispersions with various concentration were prepared by adding water to 1 mg/ml GO. 20 µl GO dispersion was drop casted on slide glass heated at 100 °C. A thin layer of GO was formed on glass slide. The GO film was reduced to rGO by putting the glass slide into 50 mg/ml ascorbic acid at 60 °C for 30 minutes. This will increase the electrical conductivity of GO.

PDMS fabrication could be divided into two parts, upper PDMS layer with rGO and lower PDMS layer with copper electrode. PDMS was mixed to curing agent with ratio of 10:1 and degassing in vacuum chamber to remove air bubbles. For upper PDMS layer, the PDMS mixture was poured onto slide glass with rGO and for lower PDMS layer, PDMS mixture was poured into a mold with thickness of 1 mm. Both layers will have a thickness of 1 mm. The PDMS mixture was set in room temperature for one day. The next day, PDMS was peeled off. The upper PDMS substrate will have rGO on it and lower PDMS substrate was cut into the size of 2.5 cm × 7.5 cm.

Next stage is copper electrode fabrication. Copper tape was applied onto lower PDMS. Design A of Figure 2 shows the copper electrode design which consists of array of four sensors. The electrode was formed by photolithography and etching of copper layer. The mask design used in the photolithography is shown in design B of Figure 2. Photolithography process was carried out in a yellow room until being developed to prevent exposure to ultraviolet (UV) light. Negative photoresist (Sigma Aldrich) was mixed to thinner with volume ratio of 1:1. Spin coater was used to spin coat the photoresist onto lower PDMS substrate. Two layers of photoresist were coated and prebaked on a hotplate at 80 °C for 20 minutes. After that, the printed mask was placed onto the lower PDMS substrate and exposed to UV light for 6 seconds, developed with developer for 60 seconds and rinsed with isopropyl alcohol (IPA). After the development, electrode pattern could be observed on the substrate. The substrate underwent post bake for 10 minutes at 120 °C before copper etching process. The copper surface covered by photoresist remained after the etching process. The photoresist was removed using remover solution. Figure 3 shows the fabricated lower PDMS substrate with patterned copper electrode.

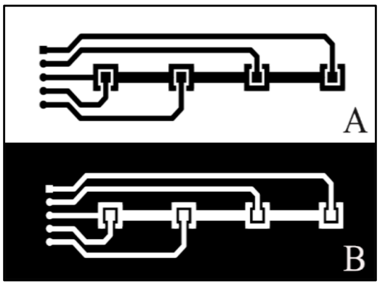


Figure 2. Photolithography mask for electrode

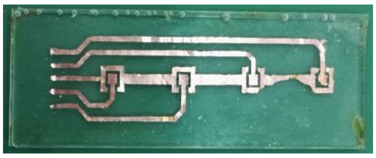


Figure 3. Lower PDMS layer after etching.

Then, sticker layer which functions as spacer was pasted onto the lower PDMS substrate. Wire was soldered to the terminals of copper electrode track. Finally, the upper PDMS layer was aligned onto the lower PDMS layer which consisted of four tactile sensors. Figure 4 shows the fabricated arrays of four tactile sensors.

Figure 4. Four tactile sensors in one sample.

3.3 Sensor Characterization

Figure 5 shows the measurement set-up. Three types of test were conducted to the fabricated rGO tactile sensor. The tests were current-voltage (I-V) measurement, real time resistance measurement and resistance versus force. For all the tests, force was applied by moving the sensor towards probe of HF-50 force gauge using XYZ linear stage.

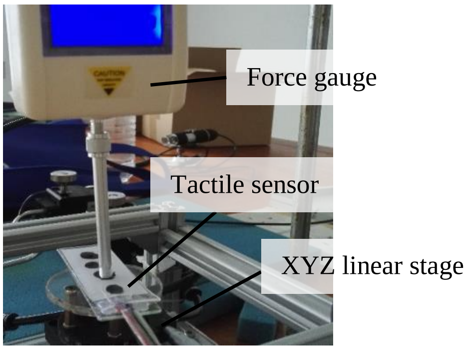


Figure 5. Measurement setup

Firstly, for the I-V measurement, Keysight parameter analyzer (model B1500) was used. Voltage was applied across the two terminals of sensor and the value of current was recorded. The voltage was sweep from -0.5 V to 0.5 V. Graph of current versus voltage was plotted. Secondly, real time resistance measurement, a fixed 0.5 V was applied to the sensor. The real-time sensor response towards the change of applied force was monitored for 35 seconds. During the measurement, the force was varied from zero to approximately 1 N. Simultaneously force value was also logged to computer. Thirdly, in resistance versus force measurement, different force was applied to the sensor and the corresponding resistance across the terminal of sensor was recorded using Pro'skit Mt-1710 multimeter.

4. RESULT AND ANALYSIS

4.1 Current-Voltage Characteristics

Figure 6 shows the I-V characteristic of the sensor made from 0.8 mg/ml rGO film under different applied force. It is observed that, when force was applied, current flows along the rGO channel. The electrical conduction indicated that rGO is an electrical conductive material. From Figure 6, the line of the graph is almost linear for voltage from -0.5 V to 0.5 V, therefore it can be said that the resistance is constant for constant force applied. The resistance, R is determined from the slope according to equation (1).

$$R = \frac{\Delta V}{\Delta I} \quad (1)$$

Besides, the slope of line increases as the force applied increases, which means that the resistance decreases at higher force.

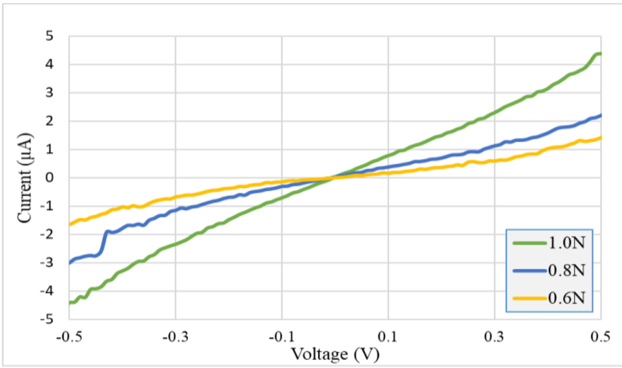
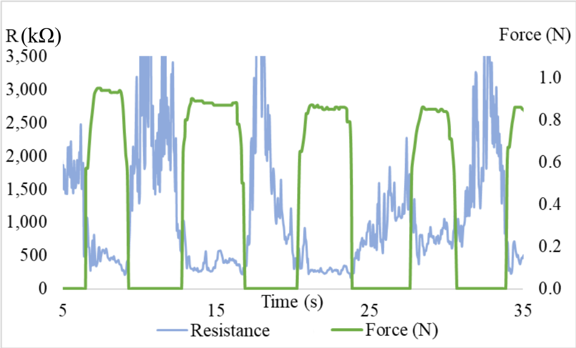


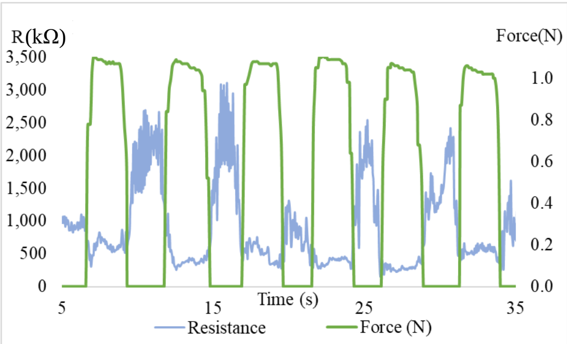
Figure 6. I-V characteristics of sample made from 0.8 mg/ml GO

4.2 Real Time Resistance Measurement

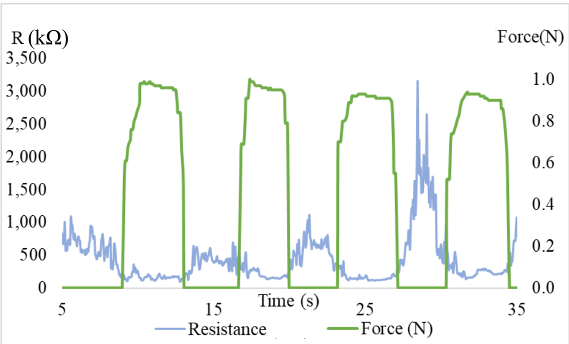
The resistance of the tactile sensor decreases as there is force applied on it. The force gauge can sense a minimum of 0.5 N force. Hence, the minimum applied force was limited to 0.5 N. Figure shows that the fabricated sensor can repeatedly detect the change in force. Although, the resistance signal will have some noise, it is able to distinguish between no force and with force applied.



(a)



(b)



(c)

Figure 7. Resistance and force against time for (a)1 mg/ml, (b) 0.8 mg/ml and (c) 0.6 mg/ml

4.3 Resistance against Force Characteristics

Figure 8 shows resistance change when different force was applied for four types of sensors (i.e. sensor with rGO formed from different dispersion concentration). For comparison, y-axis value is resistance difference. Generally, for all of the sensor types, the resistance decreases as the force applied increase. This phenomenon can be explained as the force applied increases, the area of contact between rGO and electrode will increase as well. Therefore, the resistance decreased. According to figure 8, at a fixed force, higher concentration of GO will have greater change in resistance. It can be said that higher concentration will have lower resistance per mm^2.

In case of 1 mg/ml GO sample, the change of resistance decreases with increase in force and become constant from 1.1 N and beyond. The changes become constant due to almost all the area of rGO is in contact with electrode. For 0.6 mg/ml, when force applied increase, the resistance decreases until 0.9 N, and the resistance increases again. To explain this phenomenon, after all the rGO is in contact with electrode, more force applied will cause the expansion of PDMS and rGO, therefore causing decrease in number of rGO per area and the resistance will increase. Reference [4] demonstrated that resistance decreases with force increases due to expansion of conductive rubber. For 0.8 mg/ml, the change of resistance is almost linear for 0.5 N until 1.4 N.

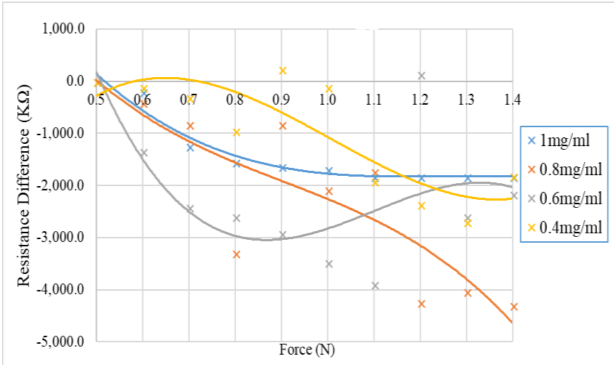


Figure 8. Resistance difference against force

Table 2 shows the sensitivity of different rGO concentration. The sensitivity was defined as how much the resistance change when force is changed. The value was calculated from 0.5 N to 0.8 N, because in this force range the sensor resistance decreases with force increased. 0.8 mg/ml GO's tactile sensor has the highest sensitivity, that is 10. 3 MΩ/N.

Table 2. Sensitivity of the tactile sensors

Sensitivity (MΩ/N)			
1.0mg/ml	0.8mg/ml	0.6mg/ml	0.4mg/ml
-5.7	-10.3	-8.9	-3.0

5. CONCLUSION

In conclusion, four arrays of tactile sensor are successfully fabricated based on different concentration of rGO and PDMS. It is demonstrated that the resistance decreases as force applied increased before the force limit. From the experimental result, 0.8 mg/ml of GO 's tactile sensor has the widest detection range compared to others.

ACKNOWLEDGMENT

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REFERENCES

[1] S. Jain and D. Bhatia, "A novel design of tactile sensor using piezoresistive cantilever for robotic application,"*IEEE 7th Power India International Conference (PIICON)*, Rajasthan, 2016, pp 1-5.

[2] S. Chun, H. Jung, Y. Choi, G. Bae, J. P. Kil and W. Park, "A tactile sensor using a graphene film formed by the reduced graphene oxide flakes and its detection of surface morphology," *Carbon*, 94, 982-pp 987, 2015

[3] Y. Wang, K. Xi, G. Liang, M. Mei and Z. Chen, “A flexible capacitive tactile sensor array for prosthetic hand real-time contact force measurement,” *2014 IEEE International Conference on Information and Automation (ICIA)*, Hailar, 2014, pp 937-942.

[4] K. Xi, Y. Wang, D. Mei, G. Liang and Z. Chen, “A flexible tactile sensor array based on pressure conductive rubber for three-axis force and slip detection,” *2015 IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, Busan, 2015, pp 476-481.

[5] C. Yang, C. Zhang, W. Xie, H. Jiang and Z. Wang, “Tactile array sensor for manipulator based on the barometric chips,” *2017 IEEE 60th International Midwest Symposium on Circuits and Systems (MWSCAS)*, Boston, 2017, pp 1268-1271.

[6] M. P. Lavin-Lopez, A. Paton-Carrero, L. Sanchez-Silva, J. L. Valverde and A. Romero,”Influence of the reduction strategy in the synthesis of reduced graphene oxide,” *Advanced Powder Technology*, 28, pp 3195-3203, 2017.

[7] Y. M. Fu, M. C. Chou, Y. T. Cheng, E. B. Secor and M. C. Hersam, “An inkjet printed piezoresistive back-to-back graphene tactile sensor for endosurgical palpation applications,” *2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS)*, Las Vegas, 2017, pp 612-615.

[8] W. Liu, P. Yu, C. Gu, X. Cheng and X. Fu, “Fingertip piezoelectric tactile sensor array for roughness encoding under varying scanning velocity,” *IEEE Sensors*, 17, pp 6867-6879, 2017.