

INVESTIGATION OF STRAIN GAUGE MEASUREMENT ON PAPER-BASED SENSOR WITH VARIOUS THICKNESS OF CARBON BASED CONDUCTIVE PAINT

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ABSTRACT

Strain sensor has been utilized in various applications, such as in healthcare monitoring, materials science experiment and environmental detection due to their durability, flexibility and affordable cost to consumers. Researchers have investigated that electrical conductive paints could alter the constantan alloy electrical resistance when subjected to mechanical strain. The conductive particles in the mixtures create the conductivity characteristic in its networks. When mechanical deformation occurs, it will change the material's electrical properties. In this research, we aim to study the effect of the carbon conductive paint paper-based strain sensor as a sensor coil in the fabricated device. Investigation of electrical resistance R as the length of the sensor altered and strain at specific angle was conducted. The specific conductive paint was painted on top of A4 printing paper, 80gsm. There were three sensor designs and two paint thicknesses which were 1 layer and 5 layers that have been premeditated. In the first experiment, the gauge factor design one was 0.67, followed by 0.33 and 0.50. All sensors were painted with 1 layer of conductive paint. For the 5 layers of the painted sensor, the gauge factor started with 0.47, then 0.16, and followed by 1.5. In conclusion, the suitable sensor design and thickness is the third design with 5 layers of painted conductive paint showed the highest sensitivity among the others.

Keyword: strain sensor, paper-based sensor, carbon conductive paint, resistance

INTRODUCTION

In principle, paper based substrate is associated to an eco-friendly material that have huge potential applications in electronic devices such as transistors [1] and energy storage devices [2], and sensors [3, 4] such as microfluidics-based biosensors [5, 6] at a low cost. Paper made from plant celluloses are principally plentiful and reproducible, while it holds features such as flexibility, recyclability, can be reformed mechanically, and can be degradable to safe the environment. These factors enhance the ability of paper-based substrate to become an adaptable and promising platform for wearable and flexible electronic devices (WEDs and FEDs) [7]. Several paper-based WEDs and FEDs have thus been proposed for the application in physical detection [8, 9], physiological sensing [10], electrical actuators [11], and washable electronics devices [12].

Strain sensors have been extensively investigated for biomechanics study and commonly utilized paper-based WEDs and FEDs. The variation in the piezoresistance of a conductive ingredients deposited on a paper substrate become the main principle of the paper-based (PB) sensors [13]. This alteration is related to the degree of applied strain on the fabricated substrate which will modify the network of the conductive material [14]. Various techniques have been developed to deposit the conductive material on the paper surface such as inkjet printing [15], hybrid nanopaper [16], crack-based strain sensor [17],

and wearable pressure sensors [18]. Either of these techniques will produce paper-based strain sensors, but they might require a specific technique to produce a good paper-based strain sensor depending on the uses of the sensors.

Furthermore, to develop a paper-based strain sensor, conductive materials must be deposited on the paper surface. These conductive materials can be developed by adding materials such as carbon black [19], polymer-graphene composite [20], carbon fibers [4] and also carbon nanotubes [21]. In addition, graphene, Ag, Au, ZnO nanowires were used to produce a conductive material [22, 23]. However, these materials are not cost-effective for large-scale production and wide applications.

Fabricated paper-based strain sensors based on graphene microfluidics and serpentine microchannels for detection of human motion [24]. This sensor is layered with polydimethylsiloxane (PDMS) in diluted heptane in order to give moisture-resistant and mechanical robust properties to the sensors. The fabrication of paper-based strain sensor utilized by dip-coating a filter paper in an aqueous suspension of carbon black (CB) and carboxymethyl cellulose (CMC) [24]. Meanwhile, double sided 3D printing on paper was investigated in microfluidic analytical devices [6]. Sensitive and stretchable strain sensor for human motion tracking utilizing a wrinkle-assisted crack structure with a unique formulated ink based on carbon black [25].

In this paper, a hand-painted paper-based strain sensor based on carbon conductive paint was successfully fabricated. The operating principle of this sensor is attributed to the change in resistance of the conductive paint structure under strain. This study used the different designs of the strain sensor and different thicknesses of the applied conductive paint on the paper substrate which are 1 layer and 5 layers. When the strain was applied to the fabricated device, resistance changed in order to obtain the gauge factors. All the measurement was measured by using Siglent SDM3055 bench-type digital multimeter which is connected to the power supply. The investigation work of conductive paint has potential contribution in biosensors field due to its ability to conduct the electricity and flexibility during sensors deformation.

MATERIALS AND METHODS

Materials

Carbon conductive paint from Bare Conductive® was purchased from a local supplier, water-based and has non-toxic ingredients. There are several basic elements needed to produce an electrically conductive paint which are functional materials, the carrier, and the binder [26]. The ability of conductive paint to conduct the electricity is well known by the functional materials such as carbon [27]. The functional materials should be at least 30% from the wet weight of the conductive paint and the recommended average size for the functional materials is from 40 μm to 150 μm . Next, the binder is also needed in order to produce a conductive paint as it holds the conductive materials together. Arabic gum, agar and carrageenan are usually used as a binder. The portion of the binder is approximately around 3-5% from the total weight of the composition. The binder needs to be dissolved first in water before the conductive materials can be added. The water function as a carrier in the composition.

Fabrication of paper-based sensor

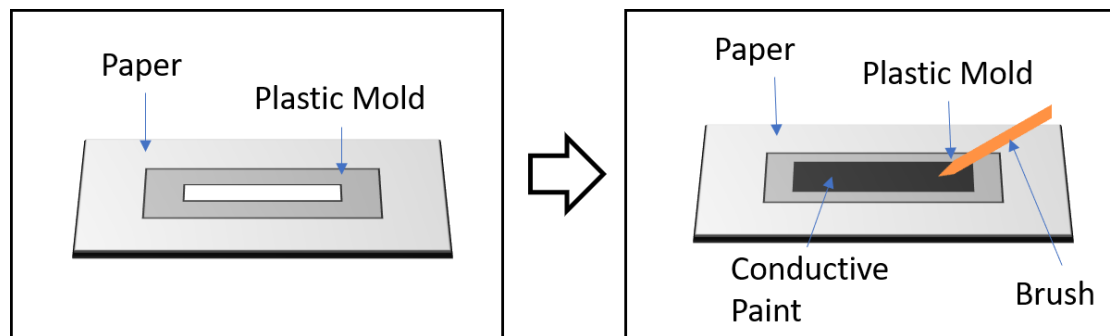


Figure 1. Schematic diagram for the fabrication method of the paper-based sensor.

Figure 1 shows the schematic diagram of the fabrication process. A mold was produced from a transparent polyvinyl chloride (PVC) binding cover according to the specific sensor's design. The plastic mold was placed on the surface of the A4 printing paper and was affixed using masking tape. Then, the carbon conductive paint was applied to the plastic mold to get a good sensor shape as the plastic mold prevent the paint from spreading out. To get a different thickness of the conductive paint coil on the paper surface, the conductive paint was applied multiple times such as 5 times. Since the exact thickness of the paint cannot be determined, so the best way to calculate the thickness is by calculating how many layers of conductive paint have been applied. The applied paint was left to dry overnight to make sure that the moisture on the paint was evaporated. These steps were repeated for all of the sensor designs as shown in Figure 2 and thicknesses.

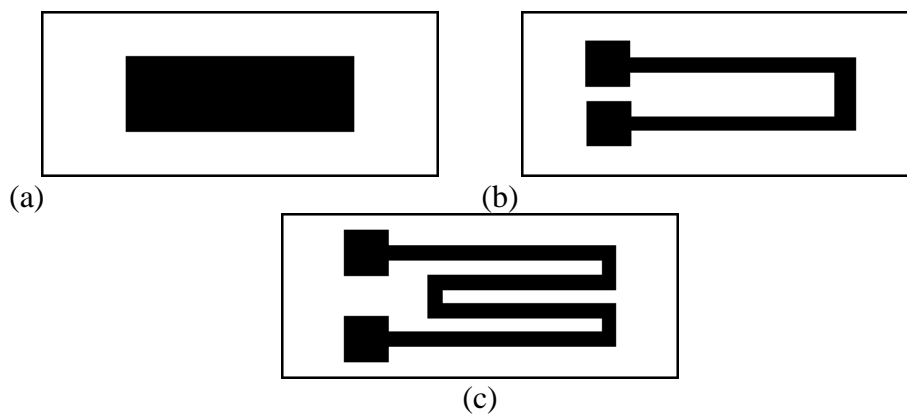


Figure 2. (a) Sensor Design 1, (b) Sensor Design 2, and (c) Sensor Design 3.

Measurements

The resistance analysis was conducted in the laboratory, by recording the voltage reading versus current values. Specific range of voltage varied and the current flow through the paper-based strain sensors were measured.

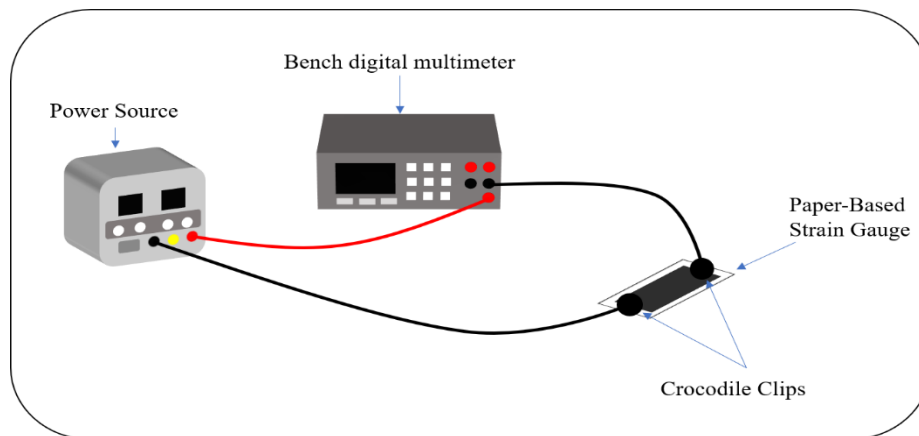


Figure 3. The schematic experimental setup for measuring current.

Figure 3 shows the schematic diagram of the experimental setup for current measurement. The resistance change according to the strain applied to the fabricated paper-based sensor was measured using a bench-type digital multimeter (Siglent SDM3055). The voltage was supplied by the power source connected to the digital multimeter and the multimeter was connected to the paper-based strain sensor that have been fabricated. The current flow will be recorded using the multimeter and then the voltage was varied with an increment of 0.1 Volt. until it reaches 5 Volts and at each increment, there will be 10 seconds delay to make sure that the reading of the multimeter is stable. There are 8 reading taken at each measurement and all of these reading was averaged to get a significant value.

For strain testing, one end of the paper-based strain sensor was connected to the digital multimeter and another end was connected to the power supply. This setup will make sure that this circuit is complete. The paper-based strain sensors were tested in several strain conditions which are when no strain was applied when the sensor was bent into 2 cm and lastly when the sensor was bent into 1 cm length. The testing conditions were shown in Figure 4 below.

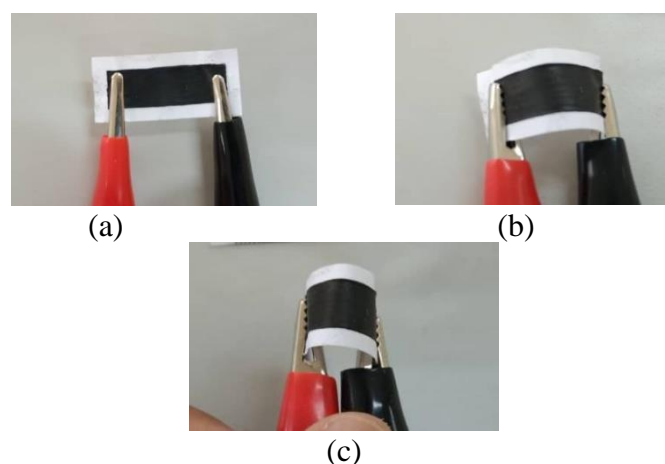


Figure 4. (a) No strain condition, (b) Bend 2 cm condition, and (c) Bend 1 cm condition

RESULTS AND DISCUSSION

By varying the thickness of the conductive paint on the paper surface from 1 layer to 5 layers, the current flow through the paint stripe was measured using the digital multimeter. Figure 5 until Figure 10 show the measured current against the applied voltage for all three sensor designs. The figures show that the current flow through the conductive paint stripe increased when the voltage applied increased despite the difference in conductive paint thickness. Noise patterns still can be seen within these graphs as the pinholes might also exist on the surface of the paint stripes.

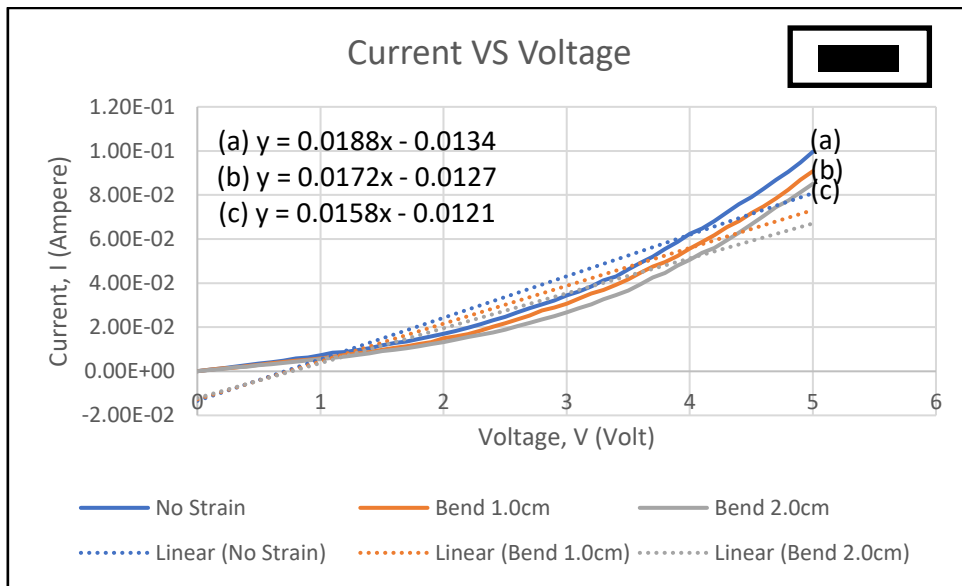


Figure 5. Current vs. voltage graph for 1 Layer Design 1 Sensor

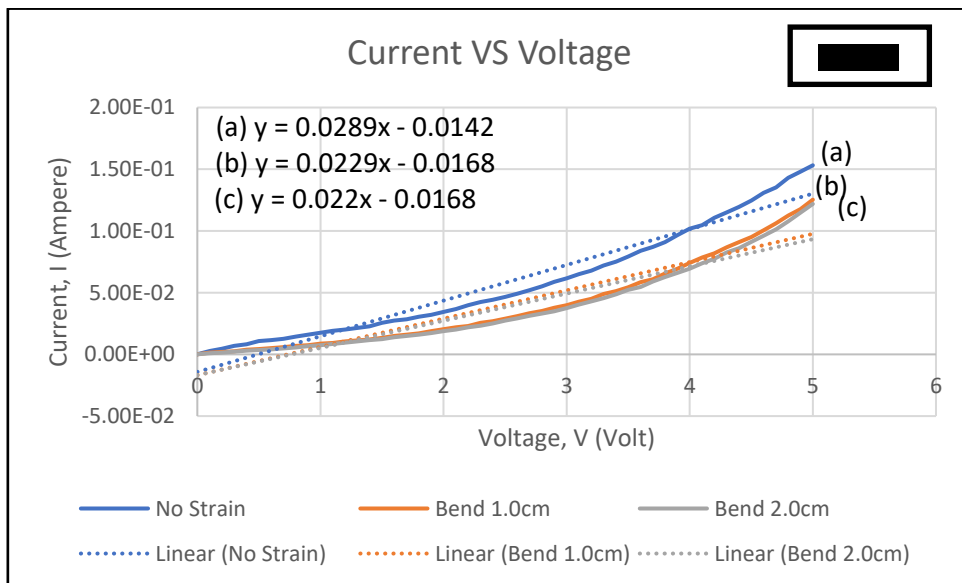


Figure 6. Current vs. voltage graph for 5 Layers Design 1 Sensor.

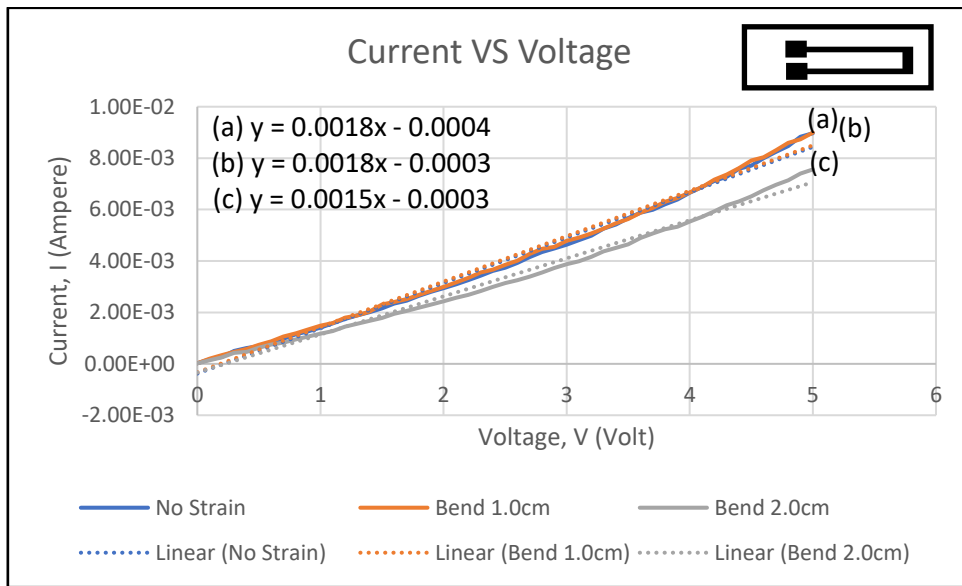


Figure 7. Current vs. voltage graph for 1 Layer Design 2 Sensor.

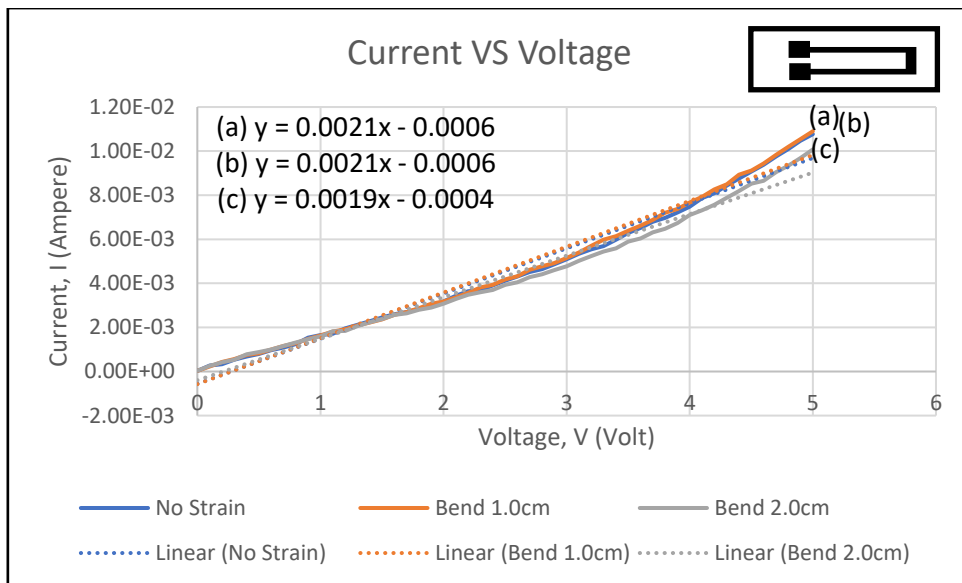


Figure 8. Current vs. voltage graph for 5 Layers Design 2 Sensor.

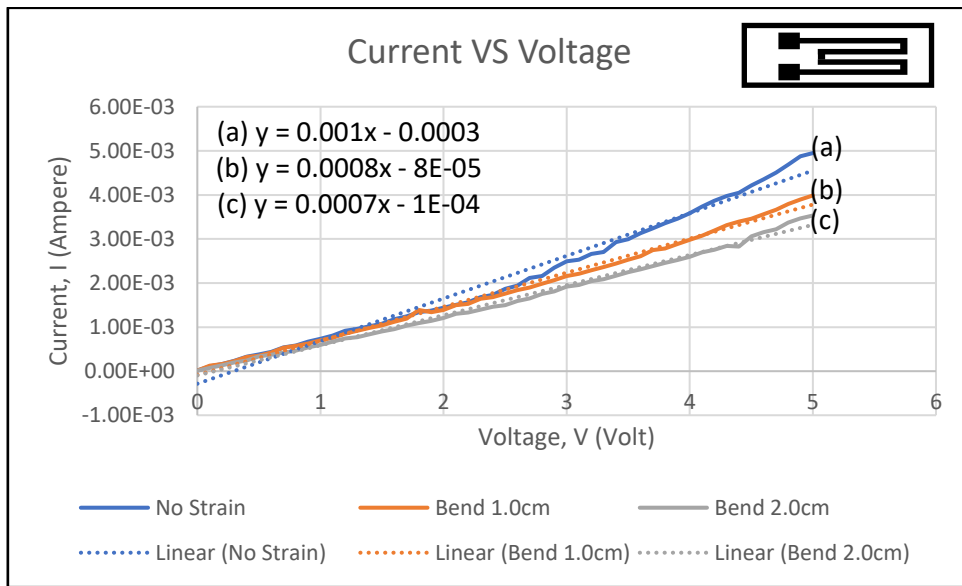


Figure 9. Current vs. voltage graph for 1 Layer Design 3 Sensor.

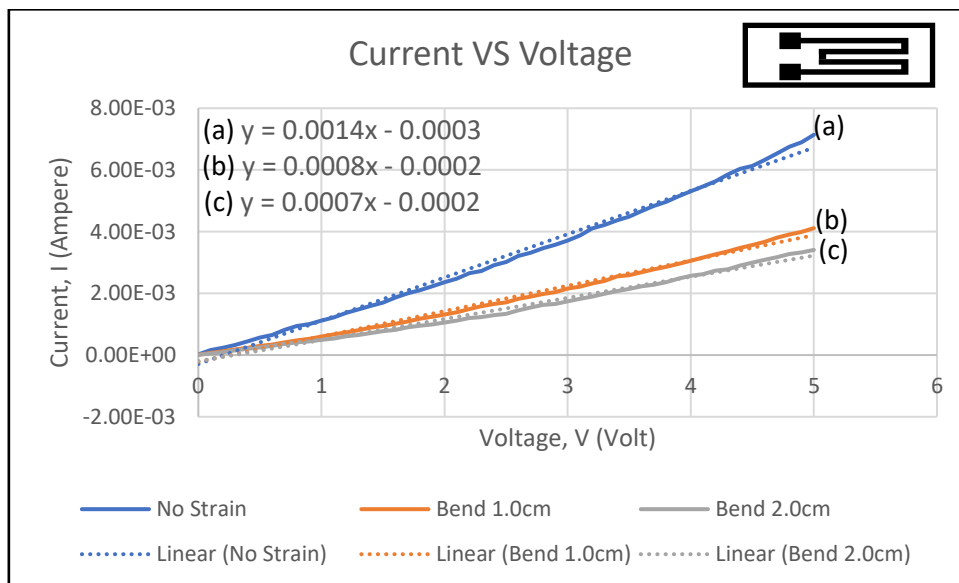


Figure 10. Current vs. voltage graph for 5 Layers Design 3 Sensor.

From all of these figures, it can be seen that even though the thickness of the paint stripes was increased, each sensor's behavior still obeys Ohm's law. It can be seen that the current (I) and voltage (V) have a linear relationship, when the voltage increased, current reading also in positive incremental value.

Table 1 shows that the summary of the result from Figure 5 until Figure 10. The table shows that the resistance of the 5 layers paint stripes for sensor design 1 and design 2 are lower than 1 layer paint stripes. However, for design 3, only the resistance for no strain

condition is lower on the 5 layers paint stripes compared to 1 layer. The other two conditions recorded that the resistance for 5 layers paint stripes is the same as the 1 layer paint stripes. This may be because of the nonuniformity of the paint stripes' thickness so that the current across the sensor is not uniform. Therefore, even though the resistance was the same when no strain was applied, it can give the same resistance across the sensor when a strain is applied to the sensor.

The geometrical differences in the sensor have given a different result in this analysis. If the paint stripes are thicker, the electrons flow through the stripes will be increased. This is because the channel for the electron to move is wider when the thickness of the paint stripes is thicker. However, the thicker the conductive paint stripes on the sensor's surface, the lower the probability of the thickness uniformity of the paint stripes. This is because there will be a part thicker than the other, for example, at the sensor's edge.

Table 1. Summary of Result for Different Paint Thickness

Paint's Layer	Design	Condition	Line Equation	Slope	Resistance (V/A or Ω)
1 Layer	1	No strain	$y = 0.0188x - 0.0134$	0.0188	53.19
		Bend 1.0cm	$y = 0.0172x - 0.0127$	0.0172	58.14
		Bend 2.0cm	$y = 0.0158x - 0.0121$	0.0158	63.29
	2	No strain	$y = 0.0018x - 0.0004$	0.0018	555.56
		Bend 1.0cm	$y = 0.0018x - 0.0003$	0.0018	555.56
		Bend 2.0cm	$y = 0.0015x - 0.0003$	0.0015	666.67
	3	No strain	$y = 0.001x - 0.0003$	0.0010	1000.00
		Bend 1.0cm	$y = 0.0008x - 8E-05$	0.0008	1250.00
		Bend 2.0cm	$y = 0.0007x - 1E-04$	0.0007	1428.57
5 Layers	1	No strain	$y = 0.0289x - 0.0142$	0.0289	34.60
		Bend 1.0cm	$y = 0.0229x - 0.0168$	0.0229	43.67
		Bend 2.0cm	$y = 0.022x - 0.0168$	0.0220	45.45
	2	No strain	$y = 0.0021x - 0.0006$	0.0021	476.19
		Bend 1.0cm	$y = 0.0021x - 0.0006$	0.0021	476.19
		Bend 2.0cm	$y = 0.0019x - 0.0004$	0.0019	526.32
	3	No strain	$y = 0.0014x - 0.0003$	0.0014	714.29
		Bend 1.0cm	$y = 0.0008x - 0.0002$	0.0008	1250.00
		Bend 2.0cm	$y = 0.0007x - 0.0002$	0.0007	1428.57

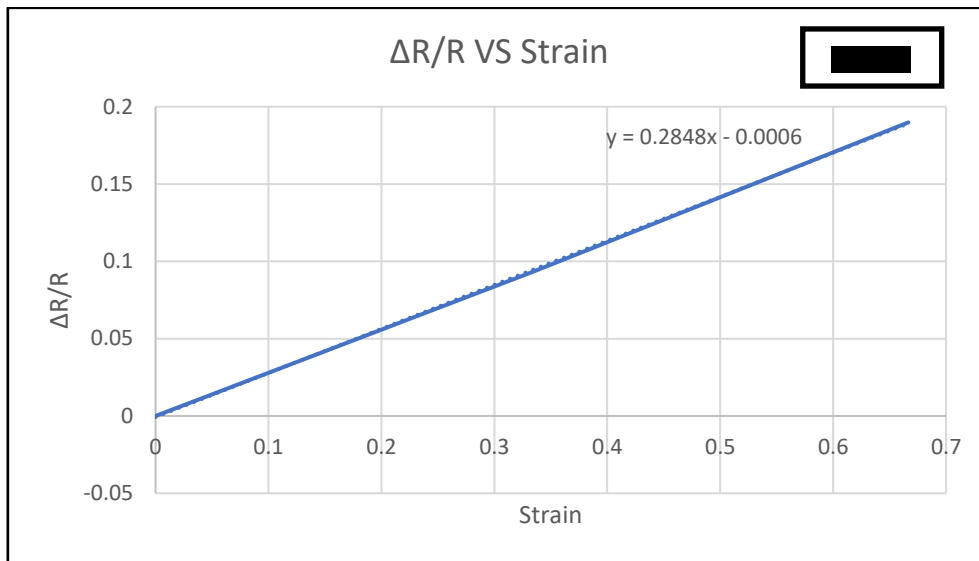


Figure 11. $\Delta R/R$ vs. strain graph for 1 Layer Design 1 Sensor.

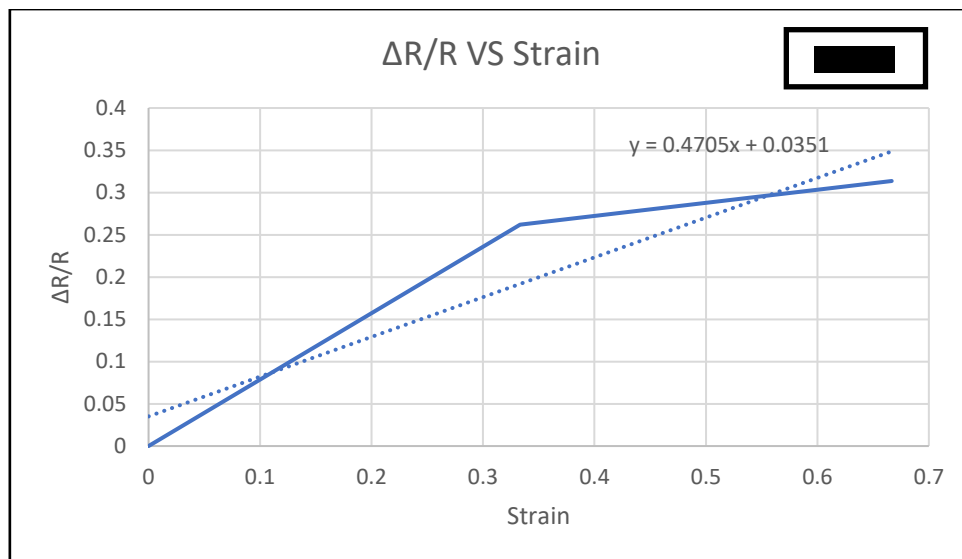


Figure 12. $\Delta R/R$ vs. strain graph for 5 Layers Design 1 Sensor.

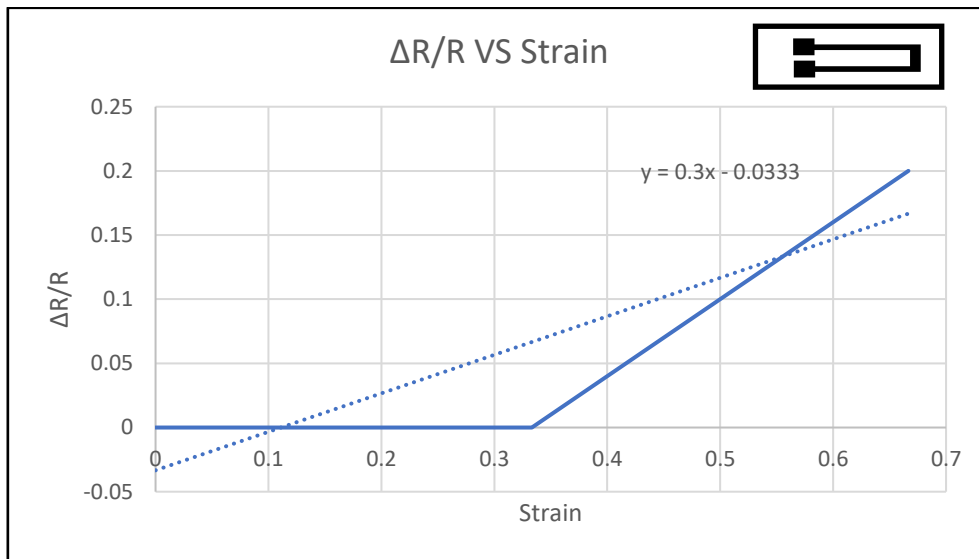


Figure 13. $\Delta R/R$ vs. strain graph for 1 Layer Design 2 Sensor.

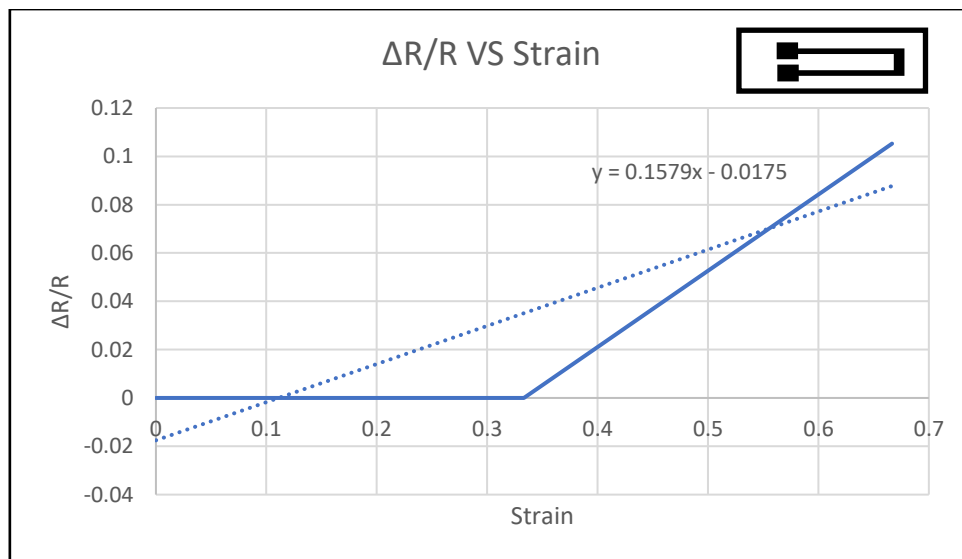


Figure 14. $\Delta R/R$ vs. strain graph for 5 Layers Design 2 Sensor.

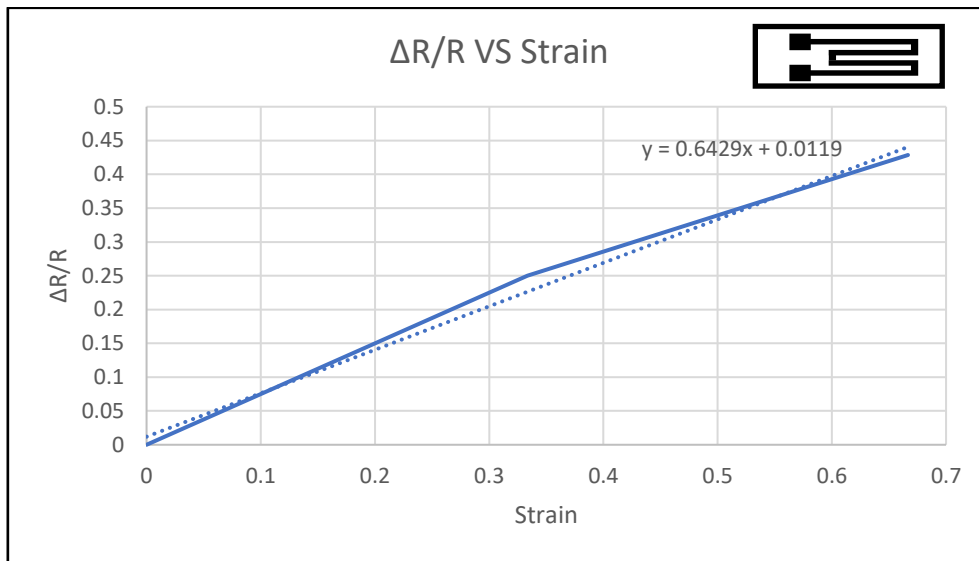


Figure 15. $\Delta R/R$ vs. strain graph for 1 Layer Design 3 Sensor.

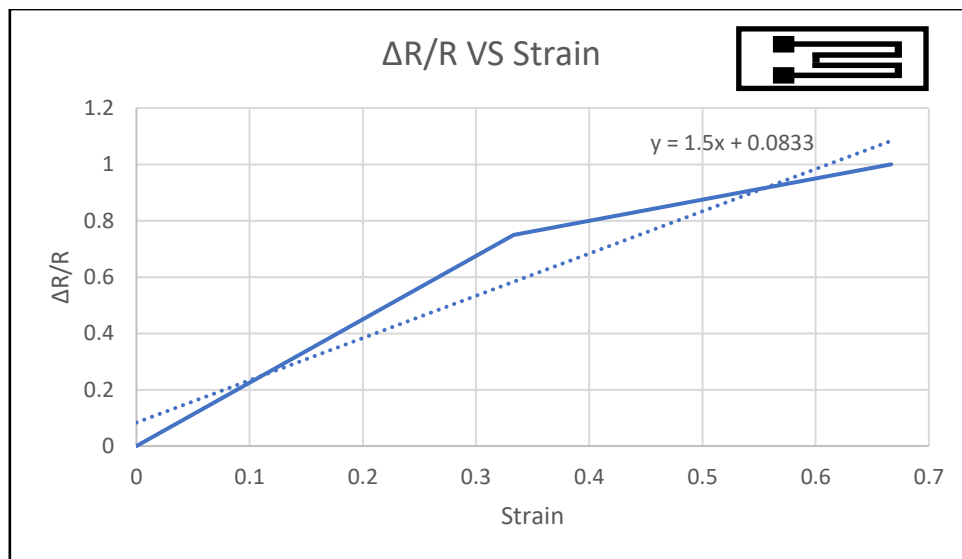


Figure 16. $\Delta R/R$ vs. strain graph for 5 Layers Design 3 Sensor.

Figure 11 until Figure 16 shows the resistance change against strain applied to the strain sensor with different conductive polymer thicknesses. For design 1, the gauge factor for 5 layers is higher than the 1 layer conductive polymer strain sensor. In addition, design 3 also follows this trend where the 5 layers conductive polymer strain sensor has a 1.5 gauge factor compared to the gauge factor of the 1 layer at 0.6429. In contrast, for design 2, the gauge factor for 1 conductive layer polymer is higher than the 5 layers. The gauge factor for the 1 layer conductive polymer is at 0.3, while the 5 layers conductive

polymer is at 0.1579. This might be due to the non-uniform thickness of the paint stripes as the thickness is too thick at a particular part, but it becomes too thin at other parts. To sum up, the thicker paint stripes will produce a higher sensitivity sensor, but it still depends on the design of the sensor.

CONCLUSION

The experimental results prove that the electrically conductive paint changes its electrical properties when it is subjected to mechanical strain. The electrical resistance was altered to respond to the deformation that occurs toward the sensors. The paper-based strain sensor based on carbon conductive paint was proposed and demonstrated in this work. The gauge factor or the sensitivity of the sensor is 0.67, 0.33 and 0.5 for design 1, design 2 and design 3 respectively for the 1 layer of conductive paint. On the other hand, the 5 layers conductive paint thickness recorded 0.47 of the gauge factor for design 1, 0.16 for design 2, and lastly, 1.5 for design 3. This can be concluded that the sensor's sensitivity also depends on the design, the geometrical shape of the sensor, and also the thickness of the conductive coil. Specific mold / mask or customized conductive ink printer could overcome the non-uniformity of the sample thickness. The carbon conductive paint characteristic can still be improved to increase the sensitivity of the sensor. This carbon conductive paint based strain sensor demonstrate the capability to be an alternative materials to the existing strain sensor in order to reduce electronic waste in the next future.

ACKNOWLEDGEMENT

The authors would like to thanks all contributors in Department of Physics, International Islamic University Malaysia (IIUM), and this research was fully funded by Ministry of Higher Education via Fundamental Research Grant Scheme (FRGS/1/2018/TK05/UIAM/02/7).

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