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Research Article

Pencil-on-Paper Sensor for Water Detection

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This paper sets out a simple and affordable method for the manufacture of a water sensor involving drawing marks on paper using a flexible pencil. The sensor indicates flexible endurance variations upon exposure to water or a drying surface. It can be employed for the detection of water substances in ethanol. In addition, an experiment suggests the usefulness of the sensor for the sensing of breath. This shows the immense potential applications of the sensor for wearable and also health-inspecting electronic gadgetry.

1. Introduction

Extensive research is being carried out into the development of affordable and adaptable sensing gadgets [1–5]. Owing to their minimalism, affordability, and the rapidity with which they can be manufactured, paper sensors have been garnering more attention [6–9]. For instance, Gandhiraman et al. are working on scalable and inexpensive single-use paper sensors for use in the field of DNA detection on the basis of chemical vapor deposition [9]. In addition, microfluidic construction, jet printing, and photolithography have been studied with an eye to the manufacture of a cheap and straightforward paper sensor. However, an increase in the need to utilize special inks, instruments, and templates with these methods has also been noted.

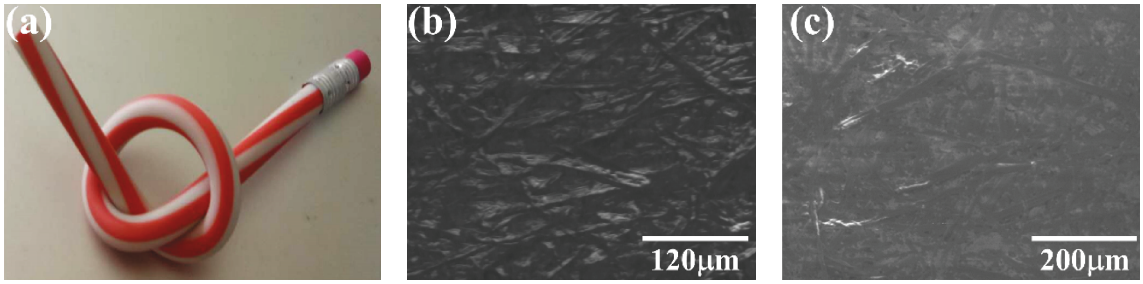
Fortunately, there is a technique whereby a pencil-on-paper sensor can be made through hand drawing on paper using a graphite pencil. The process makes the manufacture of sensors immensely simple and inexpensive. In addition, pencil-on-paper sensors have been used for a variety of types of analysis, for instance, bacterial [10], chemical compound [11], and gas [12] analysis. Nonetheless, pencil-on-paper sensors can potentially be used in other areas too.

Conversely, the water distribution system requires supplying essential amount of drinkable water at the demand points. Water leaks from the system are likely to give rise to issues and substantial water losses. It is substantially pivotal for water sensing that appears intensively demanding because of the polar character of water; moreover, what currently is being put to use is quite costly, together with being impractically implementable. Dichiara et al. performed a successful integration of nanomaterials in the paper, which are capable of electronic conductance, together with sensing water [13]. Nevertheless, there are necessaries for exploring extensively accessible low-cost commercial substances, together with a straightforward affordable manufacture, in particular, with the use of the pencil-on-paper methodology.

A flexible pencil can leave a graphite/polymer composite trace on paper [11] that can be used to sense the bases of variations in endurance. In this article, a straightforward and affordable approach a water-analytical sensor is hand-drawn onto paper using a flexible pencil. On its exposure to water, the sensor indicates the reversible endurance charges, making it utilizable for the detection of water in ethanol. Moreover, since it can detect water vapor in respiration, the sensor can be used to sense breathing. This suggests its large potential applicability in the area of wearable electronic gadgetry used for health inspection.

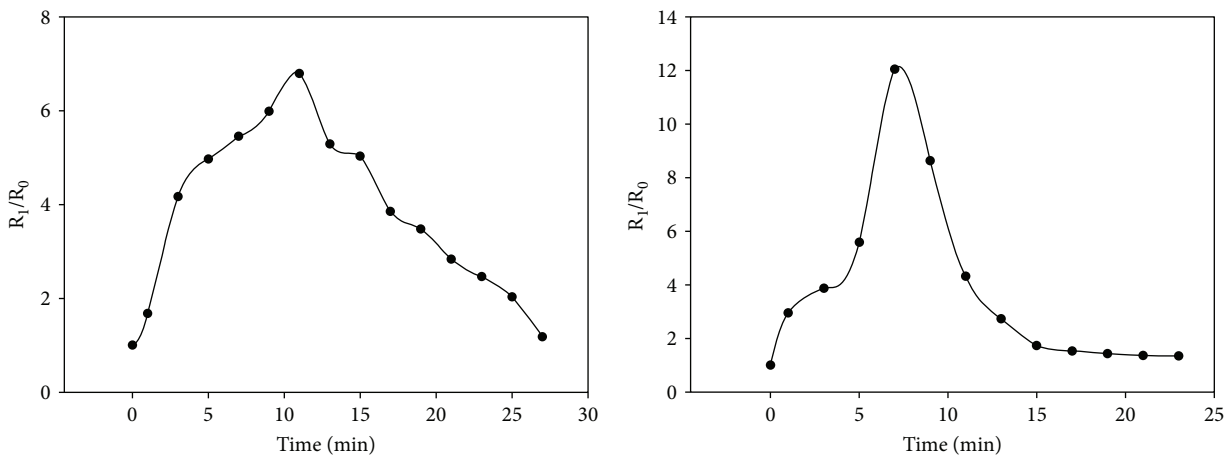
2. Experimental, Results, and Discussions

To manufacture our sensor, we drew on office paper with a graphite flexible pencil (see Figure 1(a)). The resultant drawing, ruler-guided in the orthogonal direction, formed a thin layer of graphite/polymer on the office paper. The pencil-trace was 2 cm wide and 4 cm long. Figure 1(b) is an image



(a) (b) (c)

Figure 1: (a) Photograph of graphite flexible pencil, (b) SEM image of the graphite/polymer traces, and (c) SEM image of the graphite/clay trace.



(a) (b)

Figure 2: R_1/R_0 versus time for (a) flexible pencil and (b) commercial 2B pencil.

of the graphite/polymer traces on the paper obtained using a scanning electron microscope (SEM).

By comparison, the pencil-on-paper sensor uses a commercial 2B pencil (with pencil leads comprising both graphite and clay) of the same parameters. Figure 1(c) is an image of the graphite/clay traces on the paper obtained using SEM.

The edges of the rectangular copper conductive tape were then used to fix the contact wires annexed to the pencil-trace. Measurement of the electronic characteristics of the strain sensors was performed using the FLUKE 8808A multimeter. Resistance was also measured. R_0 shows this measured resistance. Tap water was dropped onto the central area (2 cm × 2 cm) of the pencil-on-paper sensor. It was then left to dry. R_1 shows the respective resistances subsequent to the application of water. Figures 2(a) and 2(b) show the dependence of R_1/R_0 on the flexible pencil and the commercial 2B pencil, respectively. The sensor indicated the reversible endurance variations produced upon exposure to water or drying. Compared with the clay/graphite pencil sensor, the water sensor method showed larger endurance variations, in addition to a shorter recovery time.

The measured resistance R_1 subsequent to water trigger can be expressed as follows:

$$R_1 = 2 \times R_c + R_g, \tag{1}$$

where R_c is the contact resistance of the wire/copper tape with pencil graphite for one electrode; R_g is the resistance of the graphite resistor.

The total contact resistance comes from the constriction resistance and tunnel resistance. If the contact area is circular with a radius α, the calculation of contact resistance can be concluded from [14, 15].

$$R_c = \frac{\rho_1}{4\alpha} + \frac{\rho_2}{4\alpha} + \frac{\sigma}{\pi\alpha^2}, \tag{2}$$

where ρ_1 and ρ_2 are, respectively, the bulk resistivity of two contact members; σ is the tunnel resistivity.

It is believed that the resistance of the graphite resistor originates from graphite grain resistance and associated boundary resistance [16]. It is assumed that free carriers are trapped in the boundaries between graphite grains, creating a potential barrier which hinders the motion of carriers between graphite grains. Since the resistance of graphite grains is far smaller than that of the boundaries [17], the resistance of the graphite resistor can be approximated as boundary resistance, which is described as follows [18]:

$$R \sim \exp\left(\frac{\varphi}{kT}\right), \tag{3}$$

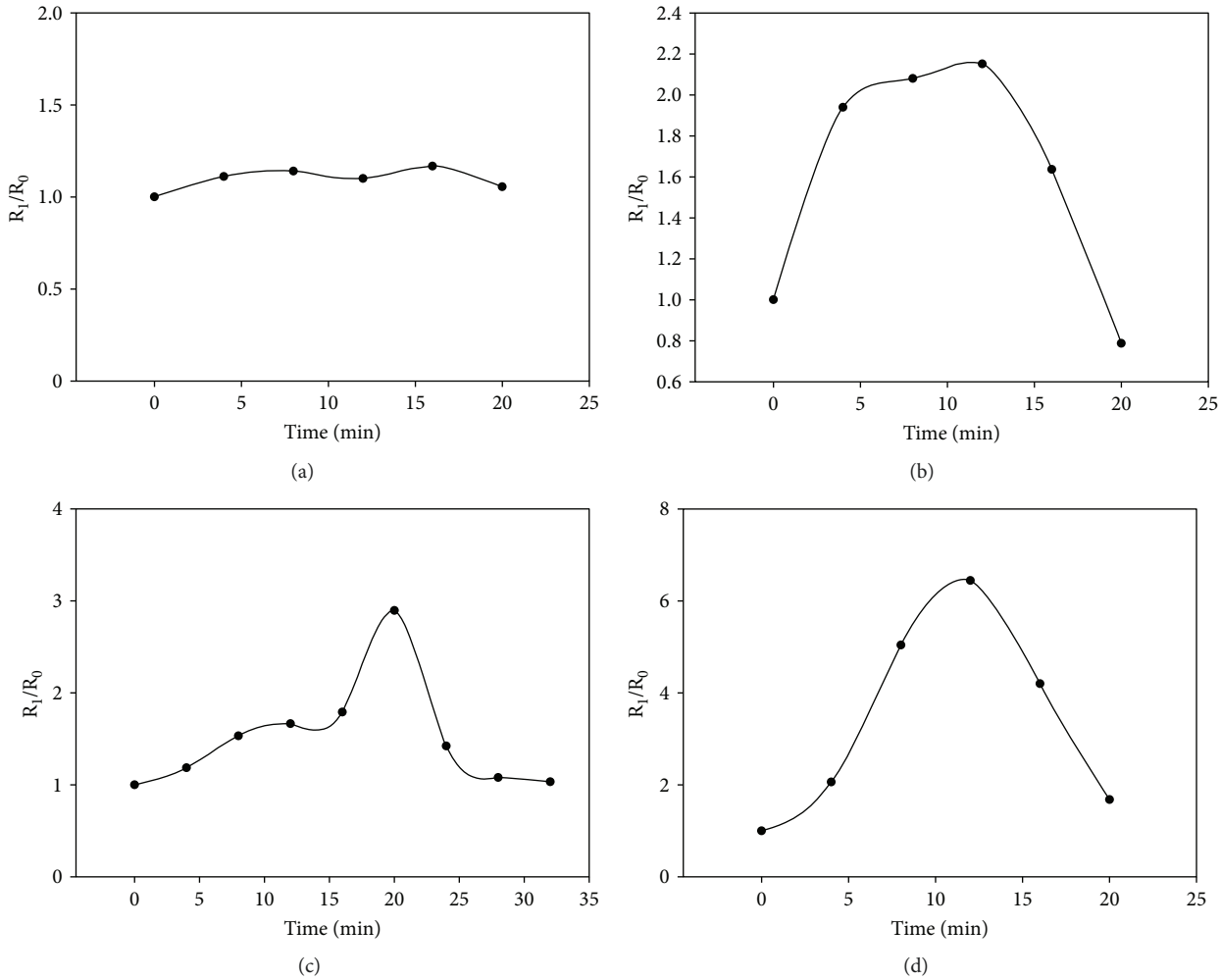


Figure 3: Resistance response with water volume fractions of (a) 0%, (b) 5%, (c) 30%, and (d) 60% of ethanol solution.

where k is the Boltzmann constant, φ is the potential barrier which impedes the motion of carriers between graphite grains, and T is the temperature. It is indicated that the application of the chemical substance increased the potential barrier.

It was observed that upon application of the pencil to the paper, graphite elements flaked off and remained attached to the paper fibers. Pencil traces may therefore explain the conductive thin layers produced out of the percolated graphite particle/blinder network on the paper. They may be resistant to both arbitrary formations and layouts. On the other hand, water uptake mainly takes place only in the amorphous areas of the paper cellulose microfibers [13]. The swelling of the paper substrate alters the conductive network of graphite particles, which decreases the potential barrier φ of neighboring graphite particles. In addition, the bulk resistivity of paper is decreased due to water absorption. When water molecules enter or exit the amorphous area of the paper, the cellulose chains either shift separately or move closer together, altering the electron shift through variation in the intertube space that exists between surrounding graphite particles over or under the tunneling space. This gives rise to the exclusive reversibility of the electrical endurance of the compounds.

Therefore, the measured resistance R_1 is decreased according to equation (1)–(3). It can be concluded that, in comparison with the graphite particle/clay networks, the graphite particle/polymer networks undergo larger graphite particle movement. This can be ascribed to the limited bonding between polymer blinder and paper fiber.

Figure 3 shows the endurance response demonstrated at water volume fractions of 0%, 5%, 30%, and 60% of the ethanol solution, respectively. As Figure 3 shows, no substantial resistance changes were observed in the application of the unadulterated ethanol. Nevertheless, on the increase of water content, the resistance exhibited a dramatic increase. The key findings show that the sensor can be utilized in one-time and affordable applications, for example, in the biomedical field.

The sensor sensitivity is defined as the maximum R_1/R_0 per unit change in the water content in ethanol. The data contained in Figures 2 and 3 show sensitivity of approximately 0.0581 per percent of water content in ethanol. The results also show that the sensor responses as expected when water percentage is 5%, indicating that water percentage resolution (the minimal water percentage which can be detected) of our sensor is less than 5%.

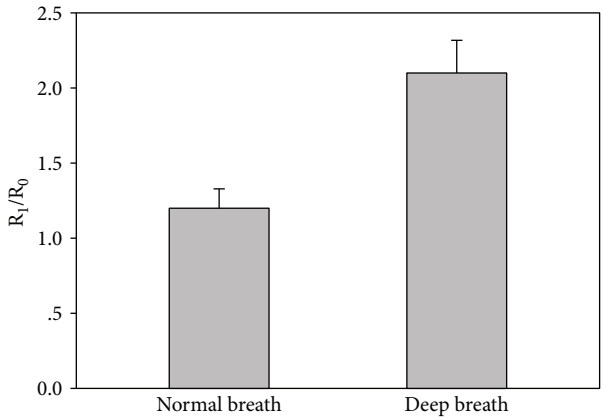


Figure 4: Resistance changes subject to normal breaths and deep breaths.

We positioned the paper-based water sensor in the textile mechanism masks for the purpose of demonstrating their application in the breathing sensing. The functional textile mask was joined with the multimeter, tracking the breathing function of the subjects after 2 minutes of breathing. On exhalation, full humidification of the breath was observed. This correspondingly augmented the quantity of water on the sensor. Figure 4 shows the resistance changes subjected to the standard and deep breaths. It can be concluded that there appear to be variations in R_1/R_0 between the standard breath and deep breath. The latter can be applied in human breathing inspection.

3. Conclusion

In this paper, a flexible pencil and paper were used to manufacture a graphite-based sensor for the purpose of water detection. The sensor manifested reversible resistance variations upon exposure to water or drying, making it utilizable in the detection of water in ethanol. Combining paper sensor and textile procedure masks made it possible to detect breathing. This provides a feasible solution to the recording and analysis of breathing patterns.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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