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High sensitive pressure sensors based on multiple coating technique*

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A multi-coating technique of reduced graphene oxide (RGO) was proposed to increase the sensitivity of paper-based pressure sensors. The maximum sensitivity of 17.6 kPa^{-1} under the 1.4 kPa was achieved. The electrical sensing mechanism is attributed to the percolation effect. Such paper pressure sensors were applied to monitor the motor vibration, which indicates the potential of mechanical flaw detection by analyzing the waveform difference.

Keywords: paper sensor, reduced graphene oxide, sensitivity

PACS: 81.05.ue, 07.07.Df, 75.75.–c **DOI:** 10.1088/1674-1056/ab6721

1. Introduction

Pressure sensors have a wide range of applications in the fields of health monitoring, joint motion sensing, human–machine interface control, and etc.[1] Most of the flexible stress sensors are composed of conduction sensitive composite materials on flexible substrates. Commonly used conduction sensitive materials include graphene,[2] carbon nanotubes,[3] nanowires,[4] and so on. These conduction materials can be organically combined with flexible substrate materials such as fibre fabric, sponge,[5] and PDMS[6] through a series of transfer or growth processes to form the desired flexible conductive strain composites. The sensing mechanisms of these flexible composite-based wearable stress sensors are mainly based on piezo resistive, capacitive, and piezoelectric effect.

The paper-based pressure sensor with microstructures and porous structures shows high sensitivity, fast response, and large measurement range.[7] It is also simply accessible and renewable at reasonably low prices.[8] Due to the advantages of better conductivity and flexibility, various types of graphene have become the first choice for conduction sensitive material. Among them, reduced graphene oxide (RGO) has been widely applied to the paper-based pressure sensors.[9]

In this paper, a multi-coating technique is developed for RGO paper-based pressure sensors with a sensitivity of 17.6 kPa^{-1}. The sensing mechanism of such sensors is attributed to the percolation effect. Application of such paper-based pressure sensors for health monitoring is demonstrated.

2. Methodology and fabrication process

Figure 1(a) shows the preparation process of the RGO paper-based sensors. The conduction sensitive material RGO was obtained by using the thermal reduction method.[10] After graphene oxide (GO) was put into deionized water with the concentration of 2 g/L, the solution was ultrasonically stirred for 3 h to acquire a fully dispersed GO fusion. After dipping into the GO fusion, the paper was thermally reduced at 200 °C for 4 h. After that, the RGO paper was cut into 1 cm×2 cm rectangle pieces with single layer or folded together for multi-layer structure. Finally, the RGO paper-based pressure sensor

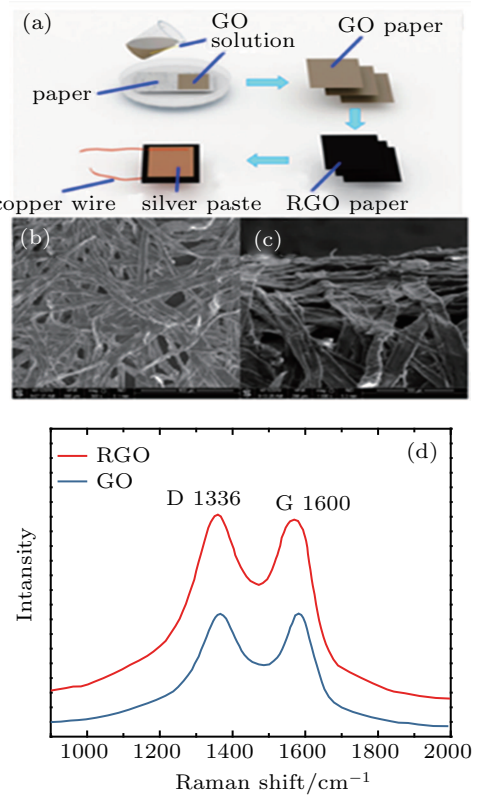


Fig. 1. (a) Preparation procedure of RGO paper-based sensors; SEM image of the (b) top view and (c) side view of the RGO coating paper, which presents the highly porous structure; (d) Raman spectra of GO-coating paper (blue) and RGO-coating paper (red).

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was set for electrical measurements by attaching a copper wire on the top and bottom of the paper edges. Then the prepared sensors were connected with the Keithley 4200 csc machine for current–voltage (I–V) measurements by putting different weights on the sensors to produce the pressure ranging from 200 Pa to 1400 Pa.

Figures 1(b) and 1(c) are the top and side views of the scanned electron microscopic (SEM) images of the RGO coated paper, respectively. It can be obviously seen that RGO particles stuck on the porous paper surface. Figure 1(d) shows the Raman spectra of GO (blue) and RGO (red), both of which are applied on the paper. The D to G peak intensity ratio of RGO obtained by thermal reduction is 1.16, while it is 1.06 for GO. The increase of the intensity ratio of the D to G peak after thermal reduction indicates that the graphene oxide is reduced, which is consistent with the theory.

3. Performance of single RGO coated paper sensors

Figure 2(a) shows the dependence of the resistance on the external pressure for the RGO paper-based sensors with 1 to 5 layers (1 L to 5 L for simplicity) of paper and once RGO coating. It can be seen that the relative resistance change $\Delta R/R_0$ increases sharply when the pressure is lower than 1.4 kPa, where R is the sheet resistance obtained from the I–V measurements, and ΔR is the change of resistance (with reference to the initial resistance) of the sheet. By increasing the number of paper layers, $\Delta R/R_0$ can be improved.

With increasing coating times of the GO fusion, the sensitivity of the paper sensors can be enhanced a lot. Figure 2(b) shows the influence of the coating times on $\Delta R/R_0$ under the same pressure. By increasing the paper layer number to 5, $\Delta R/R_0$ increases from 0 to 0.85 under the pressure of 1.4 kPa, which demonstrates high sensitivity in the small pressure range. The maximum relative sensitivity S achieved for the paper-based sensor is 17.6 kPa^{-1} when the pressure is 1.4 kPa, which indicates that it can sense an object as light as $\sim 10^{-8}$ g for a 1 mm^2 sensitive area if $\Delta R/R_0$ is 0.9.

Figure 2(c) presents the strain curve of a 5 L/5 C paper-based sensor under different pressure. It can be found that with the same pressure loading of 200 Pa, the coordinate gradient difference gradually decreases with the increase of pressure. The step difference of $\Delta R/R_0$ decreases with the increase of pressure. Figure 2(d) shows the hysteresis characteristic of our 5 L/5 C paper-based pressure sensors by gradually loading and releasing pressure. Good hysteresis characteristics represent good repeatability, and continuity with high stability under cyclic pressure.

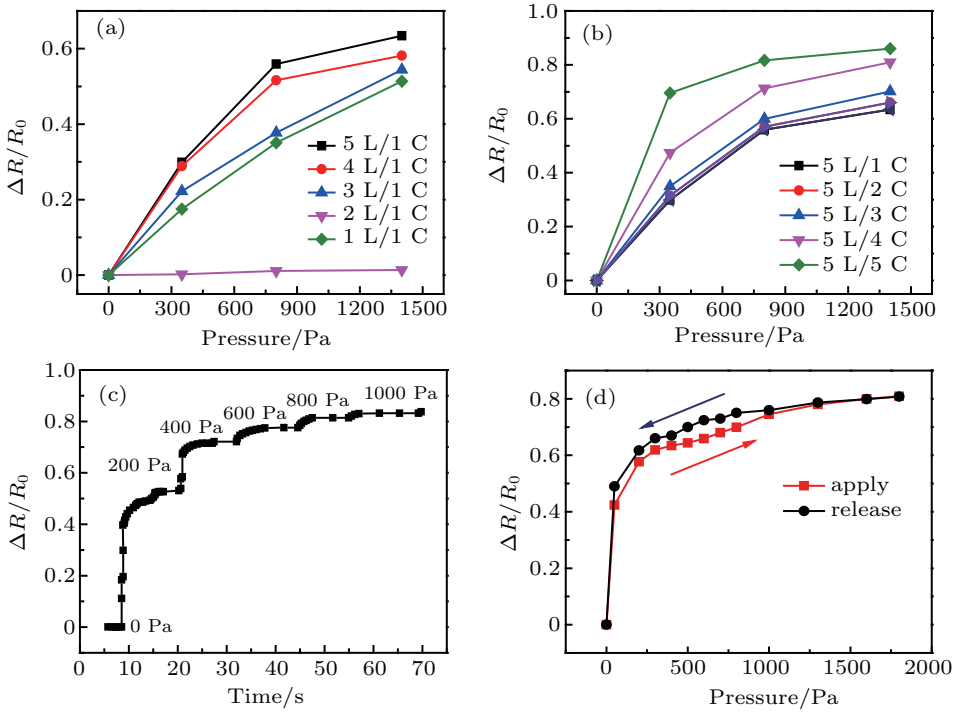


Fig. 2. Performance of RGO paper-based pressure sensors. (a) Relative resistance change $\Delta R/R_0$ dependence on pressure for 1 to 5 layer paper sensors, respectively, only with single coating of RGO; (b) $\Delta R/R_0$ dependence on pressure for 5-layer paper sensor with 1 to 5 coating times, respectively. (c) Stability of a 5 L/5 C paper sensor with increasing loading. The step is 200 Pa. (d) Hysteresis characteristic curve of a 5 L/5 C paper sensor.

The electrical sensing mechanism is attributed to the percolation effect, as illustrated in Fig. 3 The dots represent the RGO particles soaked on the papers. The electrical conduction is determined by the distance between the RGO particles attached on the porous layered paper sheet. Since the surface of the layered paper sheet of the sensors is uneven with many

micro wrinkles after dipping into RGO fusion, which results in the relatively large gap between the RGO particles, the initial contact between the layers of the multi-layer paper-based sensor is poor, hence the initial resistance is large, as illustrated in Fig. 3(a). If the sensor is fully squashed, the distance between the RGO particles nearby will vanish, and the connected RGO particles form several current paths. Then it will behavior as a conductor with a constant resistance, as illustrated in Fig. 3(c). At that time, the pressure sensors can not response to the external pressure. However, under the working state, the distance between two adjacent RGO particles can be tuned rapidly by applying or releasing even a small pressure due to the ultra-thin structure and flexibility of the paper sheet. If the distance of two adjacent RGO particles is near enough, a tunneling current generates under the electric field, which increases exponentially as a function of the distance. Hence, with the pressure applied, the electrical conduction state of the sensor will transit from isolated to conductive state. This is the typical percolation effect.

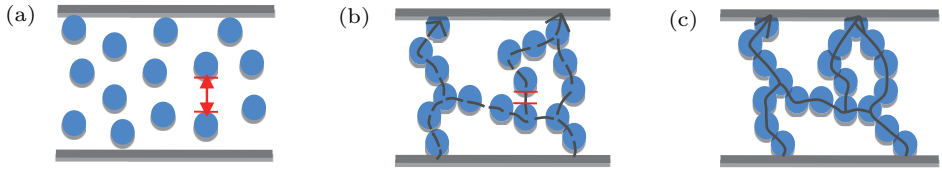


Fig. 3. Illustration of electrical sensing mechanism of a paper pressure sensor. (a) At the initial state, the distance between the adjacent RGO particles is relatively large, which results in the isolation state. (b) Under the pressure, the distance between the adjacent RGO particles is near enough, the tunneling current generates under the electric field. (c) Under a large pressure, the RGO particles connect with each other to form several current paths. The resistance will not response to the external pressure.

Various performance tests demonstrate that the RGO paper pressure sensor studied in this paper has high sensitivity, good hysteresis characteristics, and stability. These excellent properties lay the foundation for detecting weak pressure signals. Studies have shown that the sensor not only can be used to monitor the joint movement of the human body, such as clenching fists, wrist bending, and other signals, but also can be attached to the radial artery to monitor the pulse signals of the human body. We further explore its application in monitoring the mechanical pump operating conditions and mechanical probing based on our sensor's ability to sense weak pressure signals. The vibration of the pump periodically exerts a force on the sensor and the sensor converts the change of the external force into a change of the corresponding resistance and outputs it in the form of electrical signals. It has been observed that after attaching our paper sensor to the surface of the mechanical pump, the force applied on it by the mechanical pump will change due to the different vibrations generated by the mechanical pump under different working conditions. As shown in Fig. 4, there are two cycles of vibration detected. As shown in Fig. 4(a), when the mechanical pump is turned on instantly, the vibration is unstable, and the measured electrical signals are jagged. Most of the signals are small pulses, and the saw tooth pulses are few. After a certain period of time, the vibration frequency is stabilized, the measured amplitude of the electrical signal is presented in Fig. 4(b). After shutting down, the signals quickly decrease and stabilize, returning to the state before the pump is turned on. It can be seen that the sensor can effectively monitor the running condition of the mechanical pump. As a result, the paper sensors have the potential to be combined with the corresponding control system to realize the monitoring and alarm of the mechanical failure.

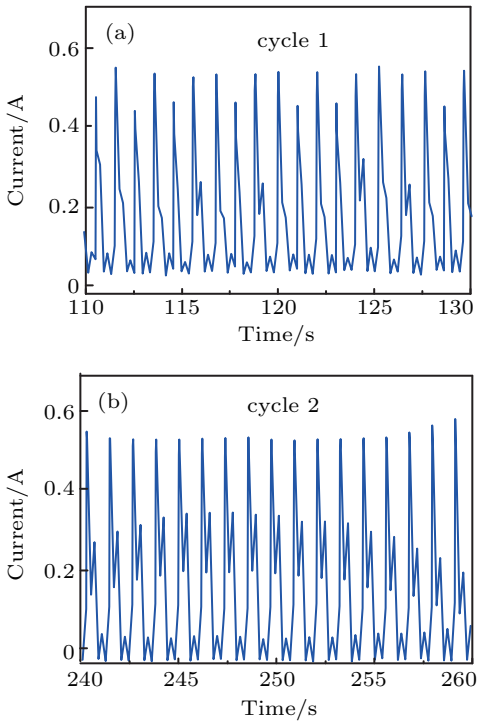


Fig. 4. Monitoring a vacuum pump operation: (a) vibrating signal detected at start-up of the pump, (b) stability of signal detected when the pump is in normal running condition.

4. Conclusion

A multi-coating technique of RGO on paper sheets was proposed to further improve the sensitivity of a pressure sensor. The highest relative sensitivity of 17.6 kPa^{-1} under the pressure of 1.4 kPa was achieved for a flexible RGO paper-based sensor, which also demonstrated a good repeatability and stability. The sensitivity of the paper-based sensors can be increased not only by cumulative the number of a layer, but also by the number of RGO coated layers in it.

A real-time monitoring of motor vibration status was demonstrated. The waveform presented a significant difference between the start-up and stable states, which indicates the potential applications of the RGO paper-based sensor in mechanical flaw detection.

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