Wearable strain sensors based on thin graphite films for human activity monitoring

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Abstract. Wearable health-monitoring devices have attracted increasing attention in disease diagnosis and health assessment. In many cases, such devices have been prepared by complicated multistep procedures which result in the waste of materials and require expensive facilities. In this study, we focused on pyrolytic graphite sheet (PGS), which is a low-cost, simple, and flexible material, used as wearable devices for monitoring human activity. We investigated wearable devices based on PGSs for the observation of elbow and finger motions. The thin graphite films were fabricated by cutting small films from PGSs. The wearable devices were then made from the thin graphite films assembled on a commercially available rubber glove. The human motions could be observed using the wearable devices. Therefore, these results suggested that the wearable devices based on thin graphite films may broaden their application in cost-effective wearable electronics for the observation of human activity.

1. Introduction
Recently, human activity monitoring using wearable devices have been widely applied in disease diagnosis and health assessment. In general, wearable health-monitoring devices for measuring human motions and human physiological signals, apply various flexible materials, including polymer nanofibers [1, 2], nanowires [3-5], carbon nanotubes [6-8], and graphene [9-11]. Despite the high flexibility and sensitivity, the wearable devices still present challenges because the fabrication of wearable devices is, in many cases, a complicated multistep procedure which results in the waste of materials and requires expensive facilities. The application and markets for wearable devices are limited by high costs and complex processes. Therefore, new low-cost materials and cost-effective fabrication processes for wearable health-monitoring devices are strongly required.

A commercially available pyrolytic graphite sheet (PGS) [12] is an inexpensive flexible sheet, and is easy to cut into any desired shapes and sizes using knives or scissors. Previously, it has been reported that the PGS, which possesses high thermal conductivity has been adopted as a heat spreader [13], and the diamagnetic levitation characteristics of the PGS has been studied for actuators and transport systems [14]. In addition, we have reported the use of thin graphite films as strain sensors, which were fabricated by cutting PGSs [15]. The unique properties of the thin graphite films make it suitable for the application in flexible devices. In this paper, we focused on PGS as a low-cost and simple flexible material, we have investigated wearable devices based on PGS for monitoring human activity.
2. Experimental methods

Figure 1(a) shows the schematic of the simple fabrication procedure of strain sensors using the thin graphite films. First, the thin graphite films were produced by cutting small films from 17-µm-thick PGSs. The thin graphite films were then attached to a flexible plastic substrate. Next, the thin graphite films were wired using silver conducting paste for electrical measurements. Finally, adhesives were used to cover the silver electrodes in order to prevent mechanical failure in the junctions connecting the thin graphite films and the silver electrodes. In case of need, the thin graphite film can be then thinned down using the mechanical exfoliation method. In addition, the thin graphite films attached to the adhesive tapes, which are usually the waste of the mechanical exfoliation method, may also be used in wearable strain sensors, as show in figure 1(b). Previously, the sensitivity of the sensors has been reported to increase when the thickness of the thin graphite films is reduced [15]. The relative change in the resistance of a 5-µm-thick sample was much larger than that of thicker samples; these relative changes in resistance were +3089% under +1.8% tensile bending strains, and −49% under −1.9% compressive bending strains [15]. To demonstrate the potential of the thin graphite films for monitoring human activity, we fabricated wearable devices using the thin graphite films for the observation of the elbow and finger motions, as shown in Figures 2(a), (b), and the performances of these wearable devices were investigated.

![Figure 1. Schematic of the fabrication of a thin graphite film. (a) The thin graphite films as strain sensors fabricated by cutting small films from a 17-µm-thick PGS. (b) A strain sensor based on a thin graphite film attached to an adhesive tape.](image)

![Figure 2. Photographs of the wearable devices based on thin graphite films for monitoring of the (a) elbow and (b) finger.](image)

3. Results and discussions

3.1. Application for elbow motion monitoring

To detect large-scale human motions, the thin graphite film was assembled on a commercially available rubber glove with some modifications over the elbow joint. Figure 3 shows that the resistance had changed during the flexion and extending motions of the elbow. In accordance with the movement of the human arm, the resistance of the thin graphite film changed. First, the resistance increased from 3.5 Ω to 13 Ω during the flexion of the elbow, in the time range from 3.1 to 3.8 s,
which was attributed to tensile bending strain. Then, during the extending elbow motion, the tensile bending strain decreased, and the resistance recovered to the initial state (R = 3.5 Ω) at a time of 5.8 s. The results indicate that the elbow motions, which are relatively larger joint motions, could be measured using the wearable devices using the thin graphite films.

![Figure 3](image)

**Figure 3.** Resistance as a function of time during the folding and extending of elbow motions.

### 3.2. Fabrication of data glove for finger motion monitoring

We have demonstrated the potential of the thin graphite films on wearable data gloves. The thin graphite films were assembled on an ultrathin glove over the middle finger joint. Figure 4 shows the middle finger’s motions of subject A, at 3 types of hand gestures, patterns α, β, and γ. The motions of the middle finger could be monitored using the data glove, and the output of the sensor was measured. In these results, the resistance change of the middle finger has peaks between pattern β and γ, as indicated with the dashed circles in Figure 4. We have concluded that the cause of the peaks is the motion specific to the person or the habit of the person. Insets of Figure 4 show the resistance change of the middle finger between pattern β and γ of two other people (subject B and C). In all cases, similar peaks could be measured, as indicated with the dashed circles in insets of Figure 4. Therefore, the cause of the peaks is possibly characteristics specific to human motions. These results indicated that our data glove could be applied as health care devices and even as controllers for virtual games.

![Figure 4](image)

**Figure 4.** Resistance versus time data for 3 types of hand gestures of subject A. The insets show the resistance change of subject B and C.
4. Summary and conclusions

We have investigated wearable devices simply and easily fabricated from PGSs for monitoring human activities. To demonstrate the potential of the wearable devices using the thin graphite films, human motions including elbow and finger motions were observed. The resistance of the thin graphite films were measured in accordance with the movement of the elbow and finger. In these results in of finger motion monitoring, typical resistance change in the middle finger were also measured, which are possibly characteristics specific to human motions. These results suggested that the wearable devices based on thin graphite films hold great potential for the detection of human motion, and for monitoring personal health and therapeutics.

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