ALL-PRINTED, PLANAR-TYPE MULTI-FUNCTIONAL WEARABLE FLEXIBLE PATCH INTEGRATED WITH ACCELERATION, TEMPERATURE, AND ECG SENSORS

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ABSTRACT

This study proposes a new structure and fabrication technique to realize a planar-type multi-functional flexible patch integrated with acceleration sensor for motion detection, skin temperature sensor, and electrocardiogram (ECG) sensor formed by all printing methods. Especially, by studying a strain engineering and proposing a new fabrication process and structure using kirigami concept, all sensors are successfully integrated and demonstrated in an in-plane polyethylene terephthalate (PET) film as the first proof-of-concept for human activity and health condition monitoring. This study may lead the Internet of Things concepts to realize not only multi-functional health monitoring patch, but also low-cost sensor sheets.

BACKGROUND

Wearable and flexible devices for health monitoring have been recently of great interests due to the demand of health and welfare life by monitoring and predicting health conditions[1-2]. If a comfortable and useful healthcare device like a bandage can be realized without increasing the device cost, it may be breakthrough for the wearable and healthcare societies. In fact, there have been many efforts to develop the flexible and stretchable sensors for several application such as healthcare/medical and robotic devices[3]. For the healthcare devices, main developments reported previously were for the health condition detections using the developed flexible/stretchable sensors. Although human motion and activity are an important parameter to diagnose the health condition based on the sensing results, flexible acceleration sensor has yet to be demonstrated. To address this concern, we have proposed a fully-printed acceleration sensor[4]. However, the device structure is complicated because many layers are required to assemble the acceleration sensor. To address this challenge, in this study, we propose and demonstrate all-printed planar-type multi-functional health monitoring patch. For acceleration sensor, a mass needs to move depending on an acceleration. To create a space for the mass movement, the structure needs to be three-dimensional. However, to reduce the complexity of fabrication process, it is better to integrate all sensors and electrodes in an in-plane PET film. To cover all requirements, stretchable structure was proposed to keep the movement space and comfortability when it is attached on a skin (Figure 1). We here discuss the electrical performance of the electrode over the kirigami structure and sensors.

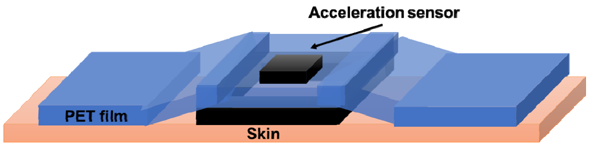

Figure 1: Cross-sectional image of proposed structure.

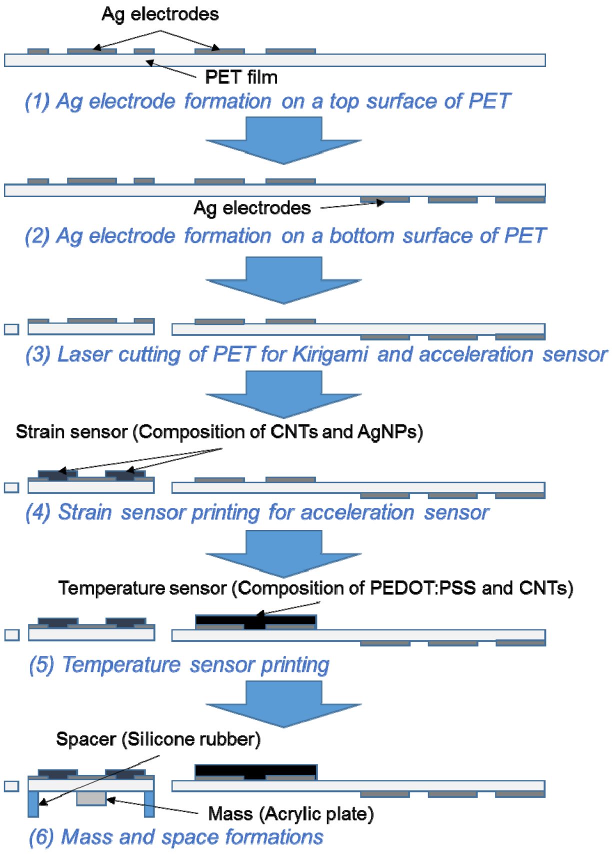

Figure 2: Fabrication process.

FABRICATION PROCESS

Fabrication process is shown in Figure 2. Briefly, the fabrication process of the printed, planar type multifunctional wearable flexible patch is explained. Ag electrodes were scree-printed on top and bottom surfaces of a PET film as electrodes (1) and ECG sensor (2), respectively. The PET film was then cut by using a laser cutter for kirigami structure and beams of the acceleration sensor (3). Strain sensors[5] formed by mixture of carbon nanotube (CNT) and Ag nanoparticles (AgNPs) were formed on the beam of the acceleration sensor (4). After forming the strain sensors, temperature sensor mixed with PEDOT:PSS and CNTs[6] were printed (5). Curing temperature of all printed ink including the electrodes and sensors was 70°C. Finally, an acrylic plate as a mass and silicone rubber as a spacer were attached on the PET film (6).

RESULTS AND DISCUSSION

Figure 3a shows a device integrated with acceleration sensor with kirigami structure, temperature sensor, and

ECG sensor. The acceleration sensor has four beams with strain sensors and Ag electrode as a ground line shown in Figure 3b.

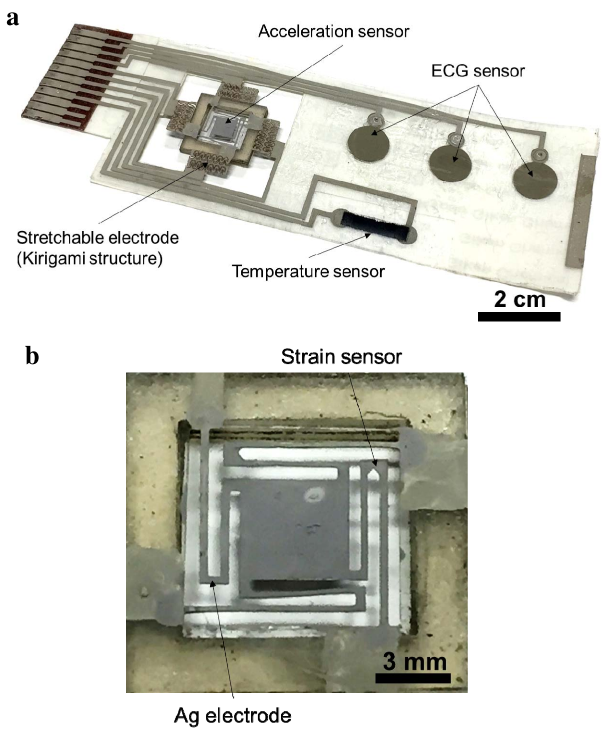

Figure 3: Photos of (a) multi-function in-plane flexible patch, and (b) zoom-up of a printed acceleration sensor.

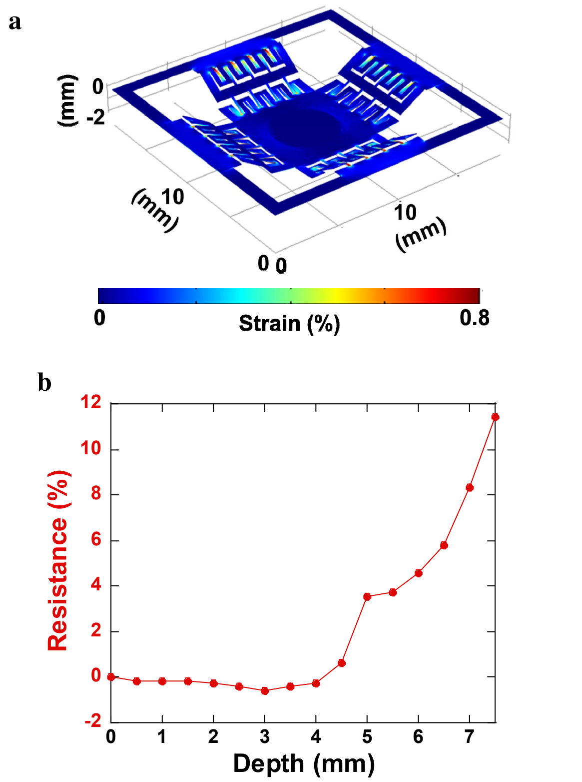

Figure 4: (a) FEM simulation of strain distribution at 2 mm depth deformation. (b) Experimental Ag electrode resistance as a function of deformation.

Stretchable electrode with kirigami structure

First, the strain distribution of Ag electrode with kirigami structure under stretch was analyzed by a finite element method (FEM). Figure 4a exhibits the strain distribution under 2 mm deformation. The maximum strain was applied at the edge of the kirigami structure to be ~0.8 %. To confirm the effect of this strain in Ag electrode, electrical resistance change was experimentally measured as a function of deformation. Figure 4b shows the electrical resistance change under applying the deformation, depicting that the electrode resistance does not change up to 4 mm deformation. However, over 4 mm deformation, resistance is drastically increased. This is most likely due to cracks in Ag electrode caused by high strain. Based on the results, this structure can withstand strain <1.6%, corresponding to the deformation of 4 mm, and the spacer was designed to be 2 mm.

Fundamental properties of printed acceleration sensor

Printed acceleration sensor (sensor size 7.5 mm×7.5 mm) for human motion detection was characterized by applying X-, Y-, and Z-direction acceleration. Figure 5 shows the resistance change for three axes acceleration when the acceleration around 30 m/s^2 is applied. The results clearly display that the resistance change depends on the acceleration direction. This trend is in good agreement with the theoretical strain distribution as a function of acceleration direction. Based on the strain engineering under acceleration direction, Z-axis acceleration has the highest strain in the beam in three axes. Figure 5 also shows some vibration of the resistance change caused by the beam vibration, suggesting that the strain sensor has enough response time to detect the acceleration. This strain distribution difference at the different acceleration direction allows it to distinguish the acceleration direction by measuring 2 or 3 strain sensors on the beam as shown in Figure 3b simultaneously.

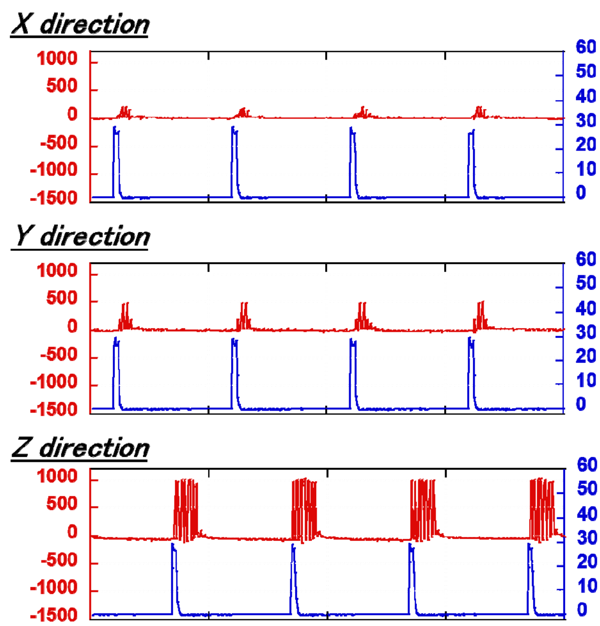

Figure 5: Resistance change of the strain sensor when X-, Y-, and Z-axes acceleration were applied.

Size dependence of acceleration sensor

Next, size (L) dependence of the total acceleration device between 10 mm and 7.5 mm was investigated to especially observe the detectable threshold acceleration using the printed strain sensor. Figure 6 indicates the resistance change of size difference as functions of three axis acceleration (Z-, Y-, and X-axes). The results show that larger size device has lower threshold of detectable acceleration (~5 m/s^2)(Figure 6a) than the smaller one (~15 m/s^2)(Figure 6b). This can be understood by the fundamental spring constant change (proportional to L^3) of the beam.

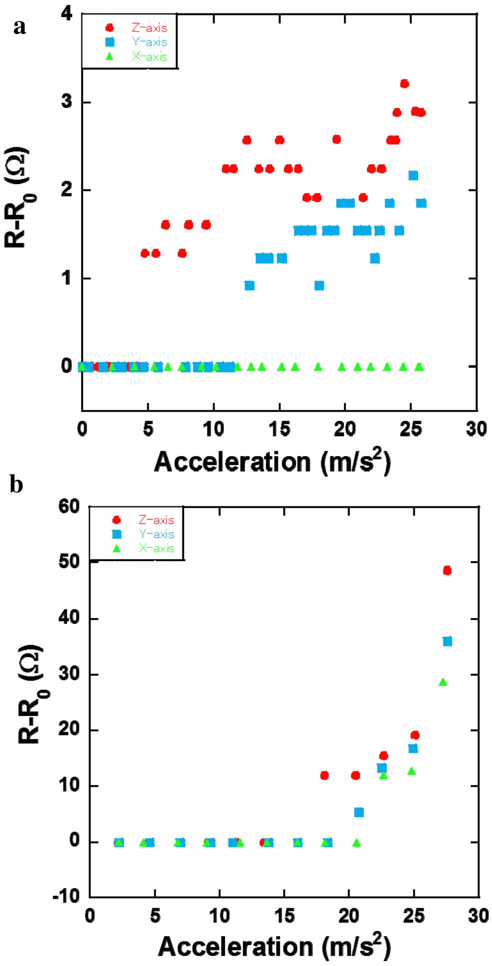

Figure 6: Resistance change of each acceleration direction of (a) 10mm×10mm and (b) 7.5mm×7.5mm sensor size.

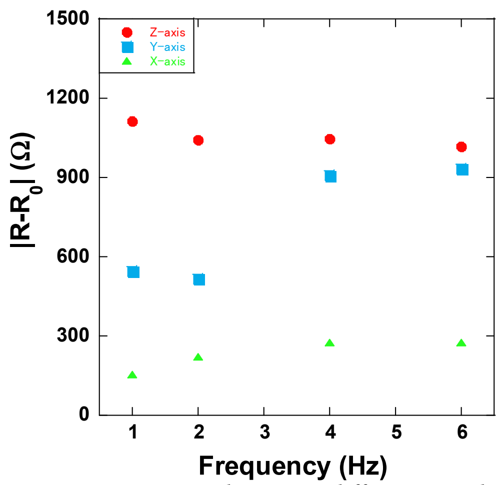

Figure 7: Resistance change at different acceleration frequency.

Frequency dependence of the acceleration sensor

As the motion detection using the acceleration sensor, frequency dependence of the sensor is also important parameter. Maximum frequency of human motion is around 4-5 Hz under exercise condition. The frequency dependence of output resistance change of the sensor was analyzed by applying the X-, Y-, and Z-axes acceleration up to 6 Hz as shown in Figure 7. Based on the results, this sensor can be measured at least 6 Hz operation speed without having significant degradation and output difference. This concludes that this sensor can monitor the human motion and activity.

Integrated temperature sensor

Printed temperature sensor output integrated with the acceleration sensor was characterized. Resistance change as a function of temperature change was analyzed as shown in Figure 8. Due to electron hopping mechanism to detect temperature change electrically, resistance is linearly decreased by increasing temperature. The temperature sensitivity extracted by the linear fitting in Figure 8 is ~1.3 %/°C, which is relatively high compared to other metal-based flexible temperature sensors.

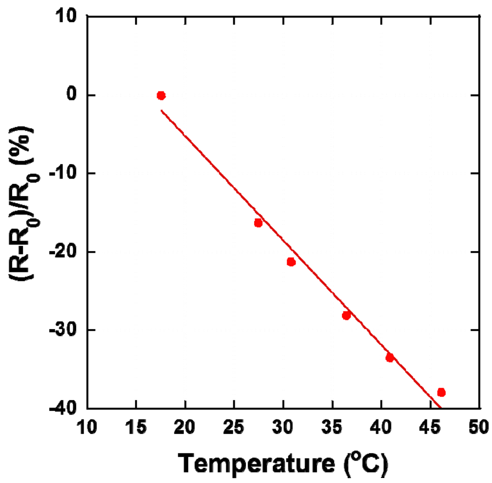

Figure 8: Normalized resistance change of the temperature sensor as a function of temperature.

ECG recording

Finally, ECG signal corresponding to the heartbeat rate was measured using three electrodes. To make low impedance between Ag electrodes and skin, commercially available ion gel was used. Figure 9 shows that ECG signal was successfully measured by using the printed multi-functional healthcare patch.

CONCLUSION

In this study, we proposed and demonstrated a planar-type printed multi-functional sensor sheet for a healthcare applications. Especially, printed acceleration sensor, temperature sensor, and ECG sensor were integrated on a PET film. Although there are still a lot of challenges to realize the practical device, this platform may be one of the promising approach to build the wearable and flexible healthcare devices in the future.

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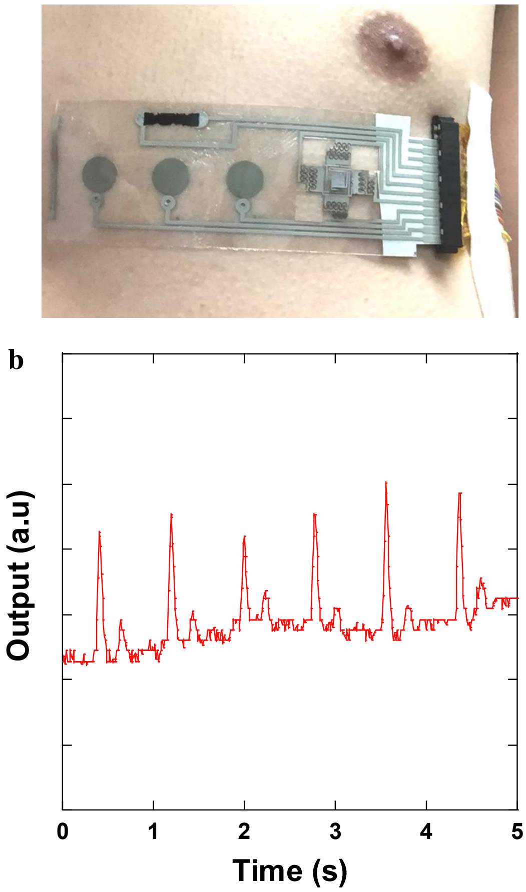

Figure 9: (a) Photo of the device attached on a skin. (b) Output results of ECG signal.

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