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Flexible heartbeat sensor for wearable device

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ABSTRACT

We demonstrate a flexible strain-gauge sensor and its use in a wearable application for heart rate detection. This polymer-based strain-gauge sensor was fabricated using a double-sided fabrication method with polymer and metal, i.e., polyimide and nickel-chrome. The fabrication process for this strain-gauge sensor is compatible with the conventional flexible printed circuit board (FPCB) processes facilitating its commercialization. The fabricated sensor showed a linear relation for an applied normal force of more than 930 kPa, with a minimum detectable force of 6.25 Pa. This sensor can also linearly detect a bending radius from 5 mm to 100 mm. It is a thin, flexible, compact, and inexpensive (for mass production) heart rate detection sensor that is highly sensitive compared to the established optical photoplethysmography (PPG) sensors. It can detect not only the timing of heart pulsation, but also the amplitude or shape of the pulse signal. The proposed strain-gauge sensor can be applicable to various applications for smart devices requiring heartbeat detection.

1. Introduction

Heartbeat monitoring sensors have been developed in various wearable applications such as wearable bands and watches (Apple support, 2016; Fitbit, 2016; Jawbone, 2016; Samsung electronics, 2016). Such devices are rapidly evolving with heartbeat monitoring function because heartbeat monitoring is highly important healthcare factor, not only for patients but also for healthy people who are interested in maintaining their health (Mukhopadhyay, 2015; Pang et al., 2013; Takei et al., 2015; Trung and Lee, 2016). Many of the heartbeat monitoring sensors of wearable devices are typically based on optical detection method such as photoplethysmography (PPG) (Tamura et al., 2014; Zhang, 2015). PPG is an optical sensor detecting blood volume change in a blood vessel according to heartbeat. In other words, it senses the rate of blood flow as controlled by the heart's pumping action. Usually, it consists of LEDs as light sources and photodetectors as sensors that are hard optical components to be employed in wearable applications that should be placed on curved parts of human body.

Resistive strain-gauge sensor that can detect resistance change has been widely studied for many years and it was firstly applied to electronic weight scale (Boyle, 1992; Hoffmann, 1989). The strain-gauge sensor detects mechanical strain, that is, basically length change of the metal induced by substrate deformation due to weight or pressure. The metal strain is manifested to accompany change in electrical resistance. Conventional strain-gauge sensor for a weight scale is mostly fabricated using metal foil that is relatively thick (~1 µm) and low resistance material (typically 120–350 Ω), which causes relatively high power dissipation for a wearable device. Recently, various resistive strain-gauge sensors made with various nanomaterials have been developed for electronic skin and human motion monitoring applications (Amjadi et al., 2014; Muth et al., 2014; Trung and Lee, 2016; Roh et al., 2015; Wang et al., 2014a, b; Yamada et al., 2011), e.g., strain and pressure sensors based on SWCNTs (Wang et al., 2014a, b; Yamada et al., 2011), Au nanowires (Gong et al., 2014), and Pt-coated nanohairs (Pang et al., 2012), graphene (Fu et al., 2011). However, the fabrication of these devices requires complicated processes due to the use of nanomaterials comparing to that of the conventional metal strain gauges limiting their mass production, and the devices have relatively low dynamic ranges, such as 1.2 kPa (Wang et al., 2014a, b), 1.5 kPa (Pang et al., 2012), 5 kPa (Gong et al., 2014), and 15 kPa (Shu et al., 2015).

In this study, we demonstrate a flexible and wearable resistive strain-gauge sensor enabling heartbeat detection, which can be fabricated by roll-to-roll method suitable for mass production. The metal thickness of this sensor is approximately 40 nm, which is less than that of the conventional design; therefore, it can be fabricated using a roll-to-roll process instead of the manual unit process for conventional sensors. Our sensor has a relatively high resistance value (~6 kΩ), and therefore its power consumption is theoretically lower than that of the

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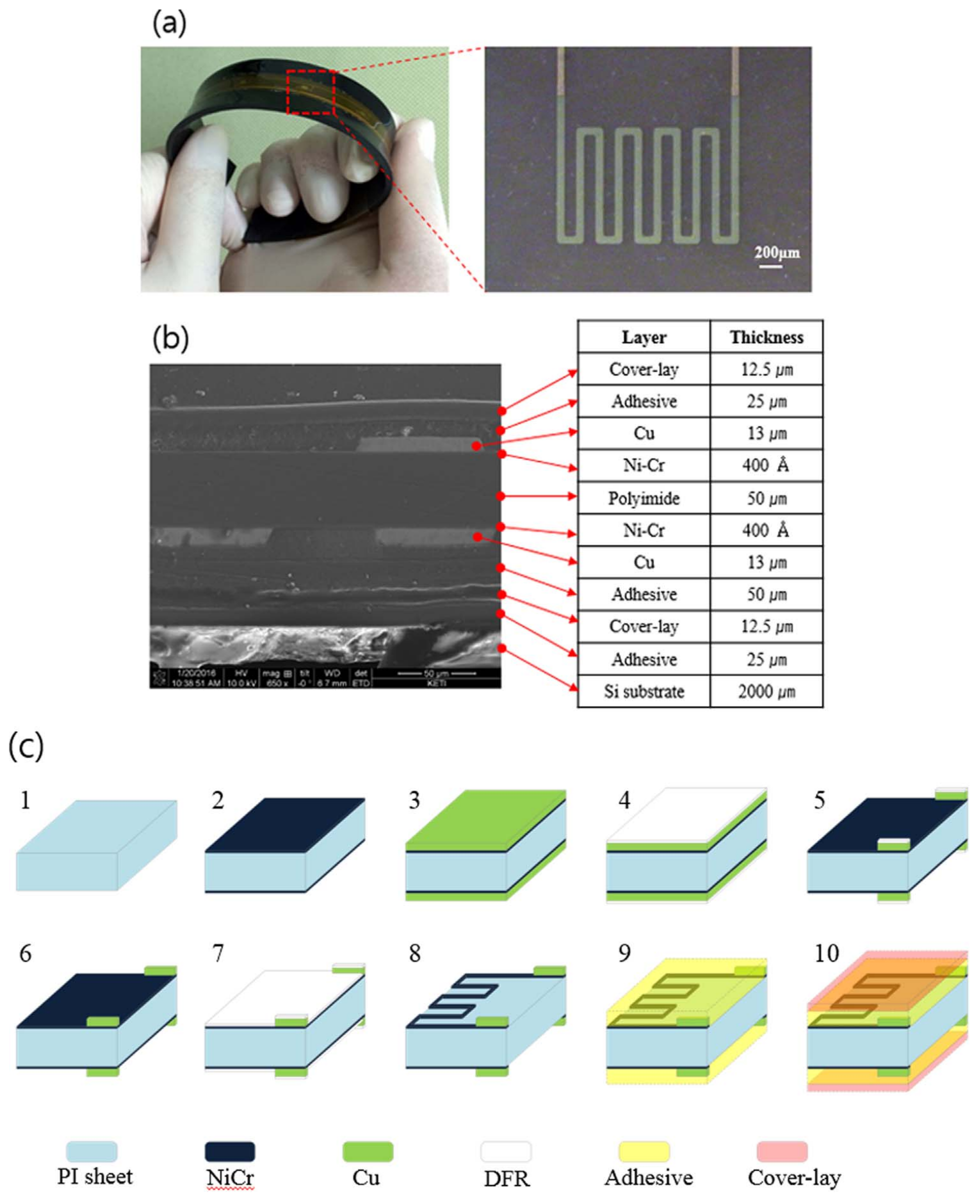

Fig. 1. Images of the proposed strain-gauge sensor: (a) Photograph of the fabricated sensor array with silicone elastomer. Region of interest (dotted red line) was magnified by an optical microscope. (b) Cross-section of the fabricated strain-gauge sensor by SEM. The name and thickness of each layer is indicated in the table. (c) Fabrication procedures of the strain-gauge sensor. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

conventional sensor by a factor of approximately 17, indicating its usefulness in smart-device applications. Also, the proposed sensor has a wider dynamic range than previously reported resistance-type pressure sensors in literatures (Gong et al., 2014; Pang et al., 2012; Shu et al., 2015) and performance summary in Table S1 (Dagdeviren et al., 2014; Jiang et al., 2010; Schwartz et al., 2013). The proposed strain-gauge sensor can be applicable to various applications for smart devices requiring heartbeat detection.

2. Material and methods

2.1. Design of strain-gauge sensor

The proposed flexible strain-gauge sensor consists of metallic micro patterns on an insulating flexible substrate. When a certain amount of force is introduced, the substrate as well as the metallic strain-sensitive patterns are deformed, causing the electrical resistance to change. The sensing part of the sensor was designed to have a square-wave shape, with a line width of 70 μm and line gap of 130 μm (Fig. 1(a)). To compensate for the resistance variation of the metal according to the ambient temperature (Hoffmann, 2001), the same sensor was also duplicated in the back side; therefore, this sensor is a double-sided sensor with a thickness of approximately 150 μm (Fig. 1(b)). To apply this strain gauge device as a heartbeat sensor, the active area of the strain sensitive grid pattern was designed with a size of 1.2 mm×1.2 mm, and six sensors were arrayed to wind around the wrist. The resistance of each strain sensitive pattern was approximately 6 kΩ and the resistance variation was less than 10%.

2.2. Fabrication processes of strain-gauge sensor

As described in Fig. 1(c), the base material for the sensor substrate consists of polyimide (PI) for flexibility guarantee, sputtered nickel-chrome with a thickness of 0.04 μm for strain sensing, and electro-plated copper with a thickness of 13 μm for electrical contact. With this substrate, the sensor fabrication was performed in order of flexible substrate cutting, patterning using dry film resist (DFR), and cover-lay manufacturing and attaching. Finally, the sensor was attached to a