

A Dual-Mode Stretchable Strain Sensor for Wearable Health Monitoring in Industrial Settings

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산업 환경에서의 웨어러블 헬스 모니터링을 위한 이중 모드 신축성 스트레인 센서

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Abstract

Wearable sensors for industrial health monitoring must simultaneously achieve high sensitivity to subtle physiological signals and mechanical robustness against large deformation during daily wear. Here, we report a dual-mode stretchable strain sensor (DSS) consisting of a metal layer and a functional polymer layer sequentially stacked on a stretchable elastomer substrate. Repeated pre-straining induced controlled microcracks in the metal layer and wrinkles in the polymer layer, enabling distinct dual-mode sensing behavior. The DSS showed a steep current decrease below 5% strain, with a sensitivity of approximately -1.28 mA/%, while maintaining a stable residual current of about 0.2 mA at higher strain levels, indicating preserved electrical conduction without complete pathway failure. The sensor also exhibited stable electrical performance under repeated tensile deformation up to 30% strain for 100 cycles. These results demonstrate that the proposed DSS provides both sensitive detection under small strain and stable operation under large deformation, highlighting its strong potential for garment-integrated health monitoring and early safety warning applications in industrial environments.

1. Introduction

The development of wearable devices has advanced the interface between humans and machine [1]. In addition, wearable sensors can be attached directly to the skin or integrated into clothing to detect physiological changes and enable healthcare monitoring [2]. These devices can track variations in body temperature [3], joint motion [4], respiration [5], and pulse during daily physical activities [6]. Furthermore, wearable devices enable long-term monitoring of physiological conditions and can provide warning signals when abnormal symptoms arise, allowing early intervention before serious incidents occur [7]. In particular, health monitoring in industrial environments has recently emerged as a critical issue, as it is directly linked to worker safety [8]. When abnormal behavior or physiological warning signs are detected, immediate

alerts can help prevent escalation into serious accidents and ensure the safety of workers.

Although attaching wearable sensors directly to workers or integrating them into workwear may help prevent industrial accidents in advance, several technical challenges remain for wearable devices. They must maintain mechanical robustness under repeated deformation [9], while preserving sensitivity and electrical signal stability regardless of the industrial environment. In addition, the sensors should not be deformed by sweat or body hair, nor should delamination occur at the interface with the attached surface [10]. In this regard, rather than attaching sensors directly to the skin, it is expected to be more advantageous to mount them on mesh-type textile materials, such as arm sleeves or tights, which can be worn in the same manner as regular clothing. Because garments made of such materials are stretched during

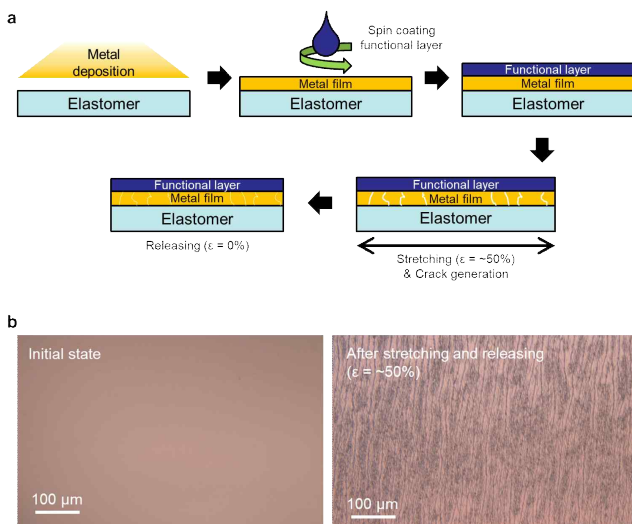
the dressing process, the sensors must also be stretchable and, after being worn, must retain their original sensitivity performance.

In this study, we propose a strain sensor with two distinct operating modes, achieved by sequentially stacking a metal layer and a functional polymer layer on a stretchable elastomer substrate. Under small strains of up to approximately 5%, the sensor exhibits sufficient sensitivity to detect subtle physiological changes such as heartbeat and respiration. At the same time, we present a design strategy that allows the sensor to withstand larger strains exceeding 5% during the processes of putting on and taking off garments, without device failure, and to recover its original sensing performance once the clothing returns to its initial state.

2. Fabrication and structure of dual-mode stretchable strain sensor (DSS)

2.1 Fabrication method

To fabricate the dual-mode strain sensor (DSS), two key components are required: a metal layer that responds sensitively to applied strain, and a functional layer that restores and preserves the original sensitivity once the strain is released.



[Fig 1.] Fabrication and optical microscopic (OM) images of the dual-mode strain sensor (DSS)

As shown in **Figure 1a**, a stretchable elastomer substrate is first prepared, followed by deposition

of a metal layer on its surface. A functional polymer layer is then spin-coated on top to enhance electrical stability. After completion of the entire stacking process and stabilization of the upper functional polymer layer, the sensor is intentionally subjected to repeated tensile strain of approximately 50% to induce crack formation in the metal layer. Once the strain is released, microscopic cracks remain in the metal layer, thereby completing the fabrication of the DSS.

2.2 Surface structure of the DSS

Figure 1b presents a top-view optical microscopic (OM) image of the fabricated DSS surface. In the initial state, the surface appears highly uniform and clear. However, after repeated application of 50% tensile strain, numerous micro-cracks and wrinkles are observed to form on the surface. The numerous cracks serve to rapidly disrupt the conductive current paths when strain is applied to the sensor, leading to a sharp increase in electrical resistance. Meanwhile, the wrinkles in the upper functional polymer layer not only prevent the conductive pathways from being completely lost even when the sensor is subjected to strains greater than 5%, but also help preserve the original sensitivity when the sensor returns to its initial length.

3 Electrical performance of the DSS

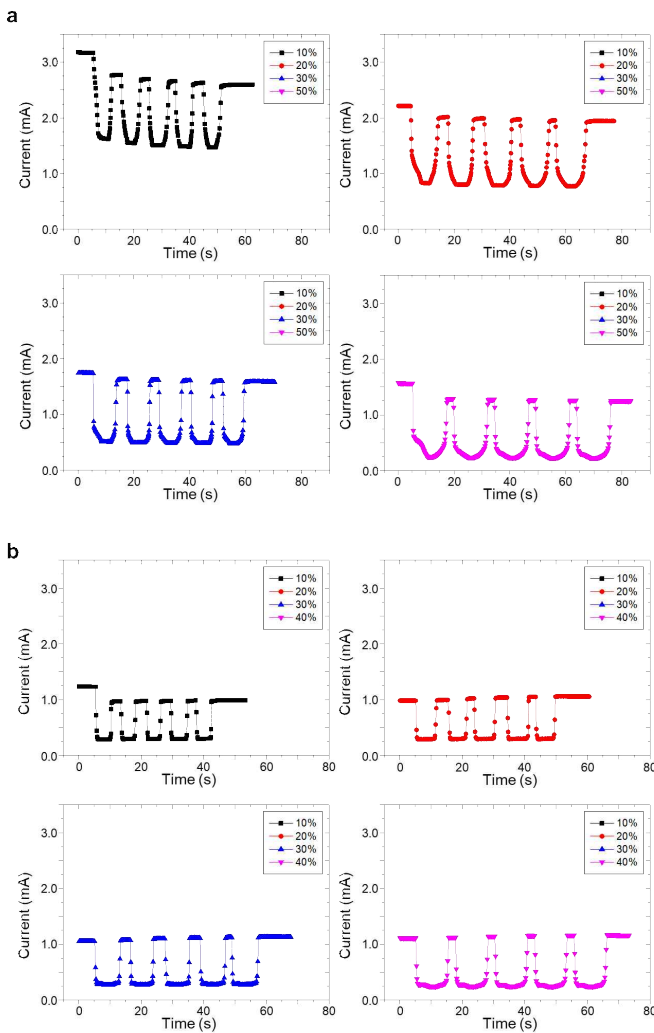
3.1 Sensor stabilization

Figure 2a shows the electrical characteristics of the DSS in its initial state under applied strain. In the unstrained state, the device exhibits a current of approximately 3 mA. However, as repeated cycles of 10% strain are applied, the electrical performance gradually deteriorates, leading to a progressive decrease in the current level. Upon subsequent repeated application of 20%, 30%, and 50% strain, the maximum current becomes stabilized at approximately 1.2 mA, while the current under applied strain decreases to around 0.2 mA.

Figure 2b presents the electrical performance after

repeated application of 50% strain. Once the device has been subjected to 50% strain, it exhibits nearly identical current behavior for all strain levels below 50%. This phenomenon can be interpreted as resulting from the formation of sufficient microcracks in the metal layer under repeated 50% strain. Consequently, the sensor shows a dual-mode response, operating in a low-current mode under applied strain and returning to a high-current mode once the strain is released. In addition, during the application of 10% strain, the current decreases abruptly, almost in a cliff-like manner. This sharp drop is attributed to the rapid increase in the separation distance between adjacent microcracks as strain is applied, which substantially reduces current flow.

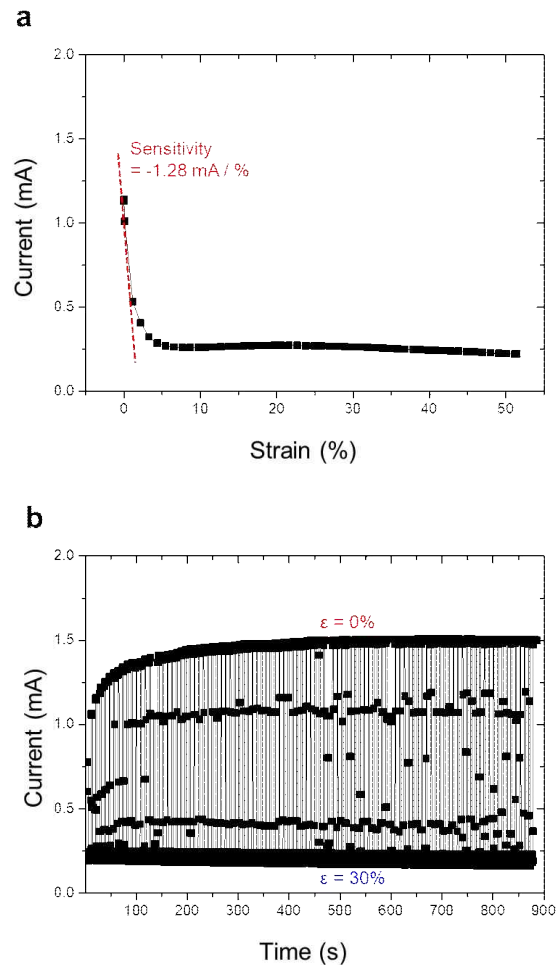
which the dual-mode transition of the DSS occurs. When the current change is measured as a function of strain, the current decreases steeply with a slope of approximately $-1.28 \text{ mA}/\%$ below 5% strain. After 5% strain, however, the current remains nearly constant at approximately 0.2 mA, indicating that the electrical current path is not completely destroyed but instead remains preserved. This suggests that, although most of the conductive pathways are disrupted by cracks in the metal layer, the overlying functional polymer layer maintains a residual current path at a low current level. Because the functional layer is integrated with the metal film, the current is interpreted not as flowing exclusively through the functional layer, but rather as passing intermittently through both the metal cracks and the functional layer.



[Fig. 2.] Electrical stabilization of the DSS applying strain (10~50%)

3.2 Sensitivity and reliability of the DSS

Figure 3a clearly illustrates the strain range in



[Fig 3.] Sensitivity of the DSS and 100 stretching cycle test

Figure 3b shows the electrical performance of the DSS

under repeated 30% tensile strain. A total of 100 strain cycles were applied, and during the initial several tens of cycles, the current measured upon returning to 0% strain gradually increased. This behavior suggests that repeated straining may promote the formation of a more stable interface between the upper functional layer and the cracks in the metal film. After several tens of cycles, the current at 0% strain was observed to saturate at approximately 1.5 mA, while a stable baseline current of approximately 0.25 mA was consistently maintained under 30% strain.

4. Conclusion

In this study, we developed a dual-mode stretchable strain sensor (DSS) that combines high sensitivity under small strain with stable operation under large deformation. The sensor exhibited distinct dual-mode behavior and maintained reliable electrical performance under repeated stretching. These characteristics suggest that the proposed DSS is well suited for integration into wearable workwear for continuous health monitoring in industrial environments. Because it can sensitively detect physiological signals while tolerating repeated deformation during daily wear, the DSS holds strong potential for practical adoption as a worker-safety monitoring platform.

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