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Strain Sensors Based on Hybrid Electronics with Flexible Packaging

Daniel Zymelka[1] *and Yusuke Takei*[1]
[1]National Institute of Advanced Industrial Science and Technology
1-2-1 Namiki, Tsukuba 305-8564, Japan
daniel.zymelka@aist.go.jp

Summary: Flexible printed strain sensors have a broad range of applications, primarily in wearable technologies, but they are also being explored in less conventional areas, such as strain measurement on engineering structures - the main target application of the sensors investigated in this work. In response to the global challenge posed by the rapidly aging road and bridge infrastructure, this study focuses on the development of large-area, flexible strain sensors intended for civil infrastructure monitoring. The fabrication process and sensor design are based on a multilayered construction and hybrid electronics, combining printed electronics with conventional components. Sensor evaluation demonstrates good strain sensitivity and a linear output signal, indicating potential for practical applications in local strain distribution analysis.

Keywords: hybrid electronics, additive manufacturing, screen printing, strain sensors, strain mapping.

Introduction

Flexible strain sensors have a broad range of applications, primarily due to their ability to conform to diverse surfaces and their relatively low cost. The most common applications include wearable devices and robotics, but they are also increasingly being investigated for use in structural health monitoring (SHM) of civil engineering structures. In recent years, SHM has become a significant challenge for infrastructure administrators and an important concern.
The condition of infrastructure and the associated maintenance requirements, particularly for road bridges, are raising growing global concerns. For instance, Japan's road network includes over 700,000 bridges [1]. By the late 2020s, nearly 50% of these bridges will be over 50 years old, the typical lifespan after which deterioration accelerates and major renewal is generally required. Europe's bridge infrastructure is also extensive and rapidly aging.
In response to the global challenge posed by the aging bridge infrastructure, there has been growing interest in recent years in developing sensor systems for civil infrastructure monitoring using various technologies. Printed strain sensors, have shown great promise for monitoring local strain distribution around crack tips in concrete and steel structural elements [2], [3].
In this study, the fabrication process and design of a new strain sensor concept are presented. In contrast to the previously reported sensor design [2], this work introduces a multi-layered construction based on hybrid electronics, combining printed electronics with conventional components. The wiring system, contact pads, and sensors were screen printed onto thin polyimide substrates using silver and carbon conductive pastes. The sensors were then evaluated through bending tests to assess their strain sensitivity. The results demonstrate that the fabrication process enables the production of large-area, flexible sensor clusters with good strain sensitivity and a linear output signal within the strain range relevant to the target SHM application.

Materials and Methods

In the first step, the contact pads with wires were screen printed onto a 25 μm polyimide substrate using a silver paste (Toyobo DW-440L-29C). The printed patterns were then dried in a convection oven at 90 ℃ for 30 minutes. Next, three sensors were printed on top of the contact pads using a carbon paste (Toyobo DY-200L-2) and cured at 130 ℃ for 60 minutes. This polyimide sheet with the printed sensors served as the bottom layer of the complete sensor array structure. The contact pads were designed to transmit electrical signals

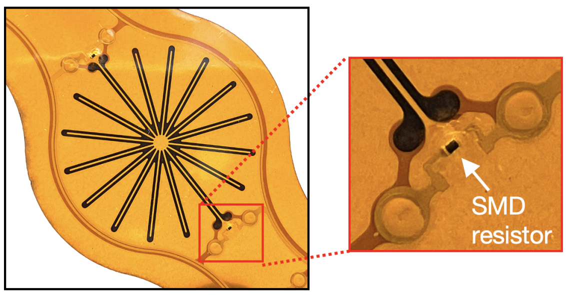

Fig. 1: Three polyimide layers incorporating printed layers of wires, contact pads, and sensing elements, integrated with SMD resistors, together comprise the structure of the sensors.

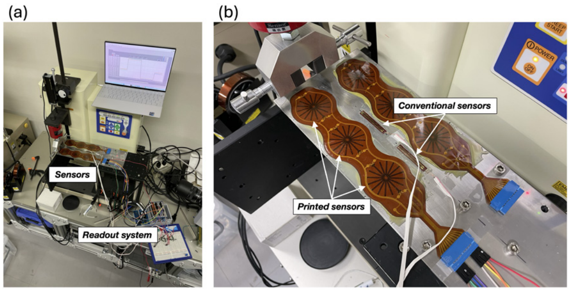

Fig. 2: a) Experimental setup used for the evaluation of the sensors. b) The array of three printed sensors was bonded to the metal plate, along with two conventional strain sensors used as references for the calibration process.

from the sensors, while the main wiring system was located on the top layer of the sensor construction.

The main wiring system was screen printed on a separate polyimide sheet using the same silver paste as used for the electrodes and cured at 130℃ for 60 minutes. The sensors were designed in a half-Wheatstone-bridge configuration, incorporating two active gauges made from the carbon paste. To complete the Wheatstone bridge, two SMD resistors were added for each individual sensor. These resistors were bonded at specific locations on the top layer, while the carbon-based sensing elements were located on the bottom layer (Fig. 1).

The top and bottom layers were bonded using a hot-melt adhesive. Prior to bonding, a laser was used to create vias at designated locations on the top layer. To establish electrical contact between the layers, the vias were filled with silver paste using a dispenser and subsequently cured in the oven. In the final step, a third polyimide layer (a cover layer) was bonded to the top layer to protect the printed wiring. The sensor array was then cut from the stacked layers into the desired shape. For evaluation, the sensors were bonded to a metal plate, as shown in Figure 2.

Results

During the analysis, the plate with the sensors was subjected to bending deformations, generating various levels of strain. As demonstrated in Figure 2, two conventional sensors were installed alongside the printed sensors, one in the middle and the other near the edge of the metal plate support, where larger strains were expected. The output signals from all printed sensors (Fig. 3a) and conventional sensors were measured simultaneously. Using specially developed software, the measured output voltage was converted into resistance changes, and the results were compared, as shown in Figure 3b.

The collected data demonstrate a uniform output signal from both printed sensors within the investigated strain range. This range corresponds to the typical strains encountered in practical structural health monitoring applications when no damage occurs. The output signal was linear and exhibited no hysteresis. The calculated gauge factor (GF), which specifies strain sensitivity, was approximately 6.1. For comparison, the GF of the conventional sensors was about 2. These results are promising for the practical implementation of the demonstrated printed sensors in monitoring engineering structures, particularly in applications requiring local strain distribution analysis, such as early crack detection or monitoring crack propagation.

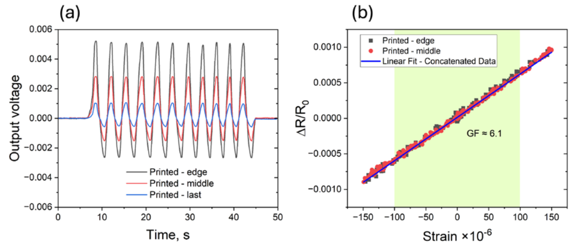

Fig. 3: a) Output signals from the printed sensors. b) Comparative analysis of resistance changes in the printed sensors and strain measured by conventional sensors.

Conclusion

This study demonstrates the fabrication and evaluation of flexible strain sensors with an original multilayered hybrid electronics design, specifically developed for structural health monitoring of engineering structures. The sensors exhibit good strain sensitivity and a linear output signal with no hysteresis, highlighting the potential of the printed sensors. The fabrication methods employed enable scaling up the construction to larger sensor arrays, thus increasing the sensing area. These promising results suggest that the developed sensor arrays are well suited for practical implementation in civil infrastructure monitoring.

References

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