Yoon and Yun
Micro and Nano Systems Letters (2023) 11:6
https://doi.org/10.1186/s40486-023-00172-z

Micro and Nano Systems Letters

LETTER

Open Access

Fabrication and evaluation of a flexible temperature sensor array using multi-layer ceramic capacitors for spatial temperature mapping

Ji-Sung Yoon[1] and Kwang-Seok Yun[1*]

Abstract

This paper presents the development of a flexible temperature sensor array using multi-layer ceramic capacitors. By integrating the capacitors into a 5×5 array on a polydimethylsiloxane (PDMS) substrate, we exploit the principle of changing dielectric constant with temperature, which results in a change in capacitance. Our sensor array demonstrates a consistent decrease in capacitance with increasing temperature, with a sensitivity ranging from 1.42 to 1.62 pF/°C. This sensitivity range is maintained even when measurements are taken using a capacitance-to-voltage conversion circuit, with a sensitivity of 1.1 to 1.5 mV/°C. The repeatability and hysteresis of the sensors were also investigated, with the latter revealing a maximum error of 12.7%. Our findings provide valuable insights for the development of efficient, flexible, and reliable temperature sensor arrays using ceramic capacitors.

Keywords Flexible PDMS substrate, Ceramic capacitor array, Temperature sensor, MEMS sensor

Introduction

In recent years, the demand for flexible and wearable electronic devices has been growing rapidly, which necessitates advancements in sensor technology. One area of sensor technology that has received a considerable amount of attention is temperature sensors. These sensors have wide applications in industries such as healthcare, environmental monitoring, and consumer electronics [1–5]. While several techniques have been proposed for measuring temperature, there is still a need for a highly sensitive, flexible, and compact solution.

In this study, we utilize the electrical properties of ceramic capacitors in order to address this need [6–8]. A key feature of ceramic capacitors that makes them particularly attractive for such applications is that their capacitance is sensitive to temperature changes. This means that a change in temperature induces a corresponding change in capacitance, a phenomenon we harness for temperature sensing in this work.

This paper introduces a temperature sensor array fabricated on a flexible polydimethylsiloxane (PDMS) substrate using ceramic capacitors [9]. PDMS, a silicone-based organic polymer, is renowned for its flexibility, biocompatibility, and stability under various conditions, making it an ideal material for wearable applications. We have constructed a 2D array of ceramic capacitor elements on the PDMS substrate, enabling the acquisition of spatially resolved temperature data. This configuration leverages the principle that the capacitance of these elements changes as a function of temperature.

In the following sections, we will present our design approach for the sensor array, describe the fabrication processes, and discuss the experimental results

*Correspondence:
Kwang-Seok Yun
ksyun@sogang.ac.kr
[1] Department of Electronic Engineering, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul 04107, Korea

demonstrating the sensor's temperature sensitivity and spatial resolution capabilities.

Design and theory

As shown in Fig. 1, the proposed device is a temperature sensor array comprising a two-dimensional grid of ceramic capacitors embedded in a flexible polydimethylsiloxane (PDMS) substrate. This substrate serves as the backbone of the device, offering excellent flexibility that accommodates the varied use cases of this sensor array.

The ceramic capacitors are strategically arranged in a grid-like pattern across the PDMS substrate, with each capacitor functioning as an individual temperature sensing pixel. This configuration ensures spatially resolved temperature measurements across the entire surface of the device, which is particularly beneficial for applications such as human body temperature monitoring, surface temperature mapping of equipment, and environmental monitoring. To facilitate the electrical measurement of the capacitive changes in each pixel, the ceramic capacitors are externally wired using aluminum wires.

Our temperature sensor operates on the principle of temperature-induced capacitance changes in ceramic capacitors. The core mechanism relies on the property of the ceramic material used in capacitors, whose dielectric constant (or relative permittivity) is susceptible to temperature variations [10]. This behavior is rooted in the temperature-dependent movement of the atoms or molecules within the dielectric material. As the temperature increases, these atoms or molecules tend to vibrate more, leading to a shift in the dielectric constant. Consequently, this affects the capacitance, as the capacitance C of a capacitor is given by the formula $C = \varepsilon A/d$, where ε is the dielectric constant, A is the area of the plates, and d is the distance between the plates.

By harnessing this correlation between temperature and dielectric constant, our device can effectively convert temperature variations into measurable changes in capacitance. This provides us with a practical and sensitive method for detecting temperature changes, thereby offering new possibilities for temperature sensing in a wide range of applications. In this work, we used commercial multilayer ceramic chip capacitors (MLCCs) having a temperature dependency of -750 ± 120 ppm/°C (KMET U2J, Yageo Co.).

Fabrication and experimental setup

The fabrication process of the temperature sensor array is presented in Fig. 2a. The process begins with the preparation of a thin substrate layer using a blend of polydimethylsiloxane (PDMS) and EcoFlex in a 1:1 ratio. The combination of PDMS and EcoFlex exploits the advantageous properties of both materials, yielding a substrate with high flexibility and good thermal stability. This mixture was carefully cast to form a 1 mm thick layer. Following the substrate preparation, an array of holes was meticulously created at the locations where the capacitors were to be placed. Then the capacitors were carefully inserted into these preformed holes, enabling the embedding of the sensing elements within the flexible substrate. Next, aluminum wires were connected to each capacitor. This ensured a reliable pathway for the electrical signals to be extracted from each individual sensing element. The wires were fastened securely to avoid disconnection and to maintain a consistent signal transmission.

The final stage of the fabrication process entailed the application of a thin PDMS film layer on both sides of the substrate. This additional layer, which was approximately 0.1 mm thick, served multiple purposes. It not only offered added protection to the capacitors and the wiring but also provided a smoother surface finish to the sensor array. Figure 2b shows the photo of the fabricated sensor. As evident from the image, the device exhibits flexible and bendable characteristics. This makes it especially suitable for a range of flexible applications such as wearable devices worn by humans, objects in direct contact with the human body like chair cushions, or areas necessitating temperature measurements on intricate surfaces.

Our measurement setup, illustrated in Fig. 3a, employed an oven as a controlled environment and an LCR meter and a capacitance-to-voltage conversion circuit for data acquisition, as depicted in Fig. 3b. We

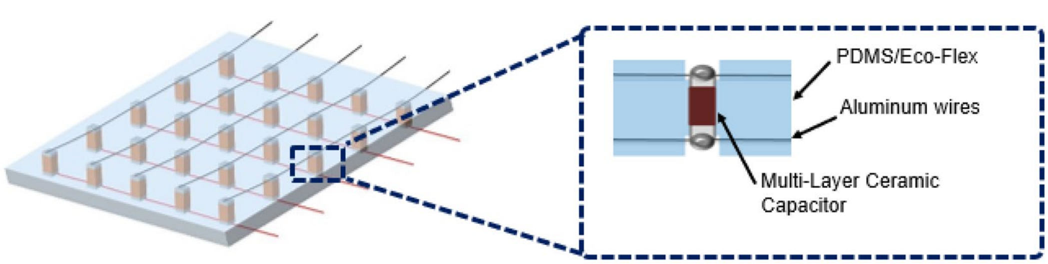
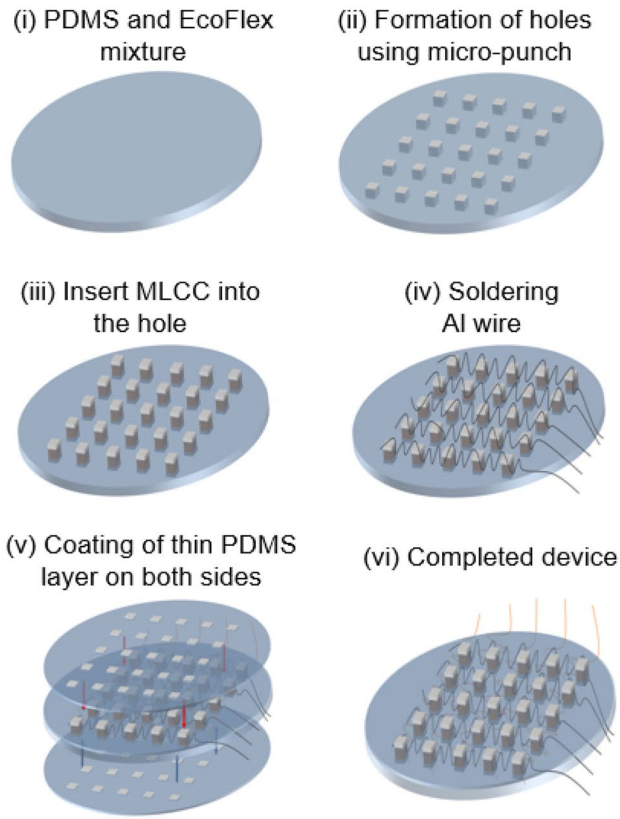
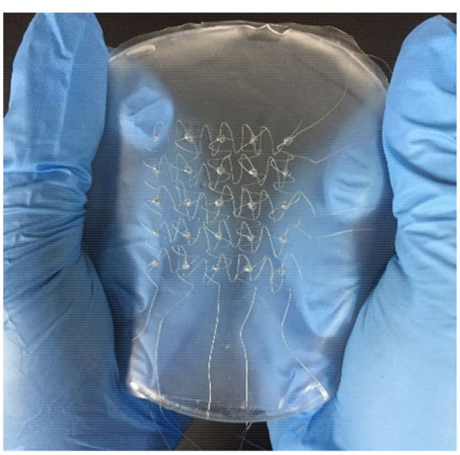


Fig. 1 Schematic view of the proposed temperature sensor array and magnified view of a single cell

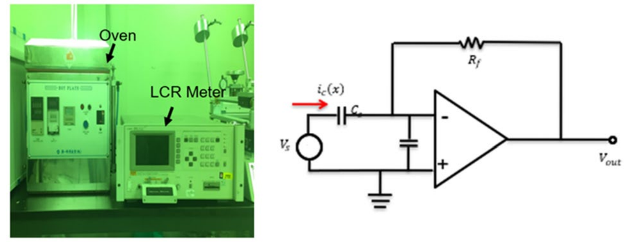


(a)



(b)

Fig. 2 **a** Fabrication processes. **b** Photo of the fabricated sensor



(a) (b)

Fig. 3 **a** Measurement setup. **b** Circuit for capacitance to voltage conversion

placed the fabricated sensor inside an oven, conducting measurements while adjusting the temperature. The LCR meter was used to precisely determine capacitance variations due to temperature changes. For potential real-time applications, a capacitance-to-voltage conversion circuit was also utilized. This circuit yielded an output signal with an amplitude corresponding to the sensor's capacitance, enabling straightforward real-time monitoring of temperature changes as voltage fluctuations.

Results and discussions

Figure 4a presents the results of a repeatability test, where a single capacitor, not encapsulated in PDMS, was measured four times under a range of temperatures (30–80 °C). The measurements consistently showed a decrease in capacitance value as the temperature increased, demonstrating the reliable performance of the capacitors. The sensitivity of the sensor was found to range between 1.54 and 1.62 pF/°C within this temperature range, illustrating a good response rate to temperature change. Figure 4b shows the sensor's hysteresis characteristics. Here, the temperature was increased from 25 °C to 80 °C and then reduced back to 25 °C while capacitance measurements were taken. The maximum hysteresis error was recorded at 60 °C, at approximately 12.7%.

Moving onto the fabricated sensor array, Fig. 5a provides the results from tests conducted on five arbitrarily chosen sensor cells in the array. While testing, the temperature was increased from 30 °C to 80 °C. The capacitors we used in our sensor cells exhibited tolerance errors, leading to slight variations in capacitance values between different cells. Nevertheless, the sensitivity was quite consistent across all cells, ranging between 1.42 and 1.58 pF/°C. Beyond the inherent error sources of the capacitor, variations arising from the fabrication process can also be another significant contributor to the observed discrepancies. Figure 5(b) shows the result from three measurements of a single sensor cell using the capacitance-to-voltage (C-V) conversion circuit. The sensitivity, in this case, was slightly varied, ranging from 1.1 to 1.5 mV/°C. These experimental results verify the sensor's robust performance and repeatability across multiple trials and setups. Further investigations could focus on minimizing the hysteresis error and reducing variability in the sensitivity of different sensor cells in the array.

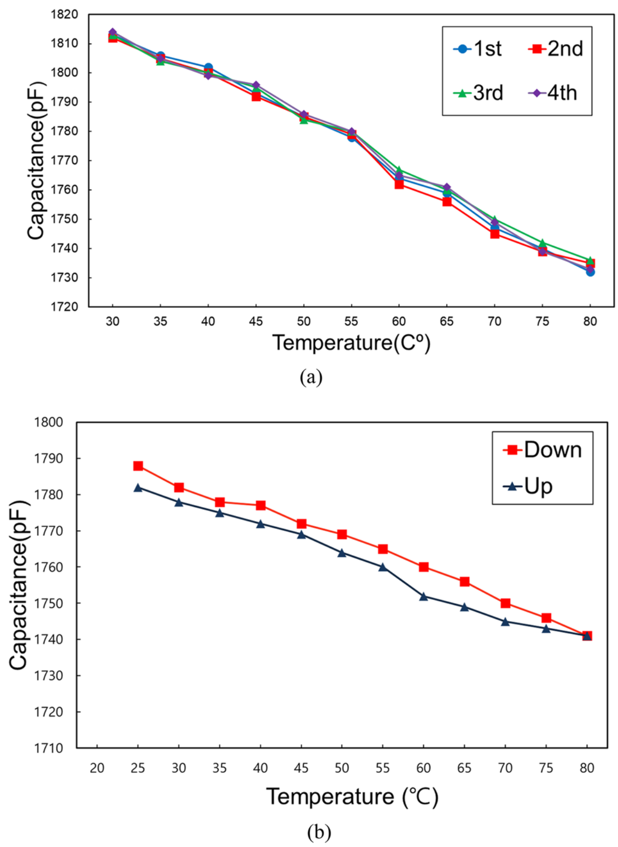


Fig. 4 **a** Four iterations of capacitance measurements for a standalone capacitor over a temperature range of 30 °C to 80 °C. **b** Hysteresis measurement results for the capacitor when the temperature is cycled from 25 °C to 80 °C and back

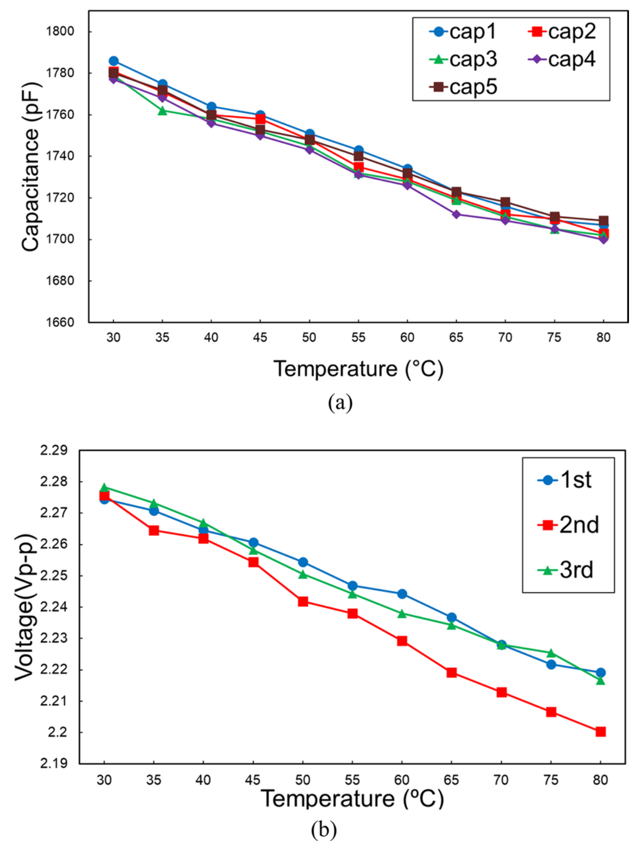


Fig. 5 **a** Capacitance variation of five sensors in the array as temperature is raised from 30 °C to 80 °C. **b** Sensitivity variation in a single sensor cell across three measurements using a capacitance-to-voltage circuit

Conclusions

In conclusion, we have successfully developed a flexible temperature sensor array using ceramic capacitors on a PDMS substrate. The sensor array exhibits excellent repeatability and consistent sensitivity to temperature changes, making it a promising platform for future temperature sensing applications. Our hysteresis analysis revealed an error of 12.7%, suggesting areas for potential optimization in future work. The exploration of a capacitance-to-voltage conversion circuit for real-time monitoring also yielded positive results, providing a promising direction for further research. Overall, this study has demonstrated the feasibility and potential of utilizing ceramic capacitors in the design of reliable and efficient temperature sensor arrays. Future work will focus on minimizing hysteresis error and refining the sensor array's performance.

Author contributions

J-SY participated in design, fabrication, and test the device and drafted the manuscript. K-SY conceived of the study, reviewed all test methods and results, and finalized the drafted manuscript.

Funding

This research was partially supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF-2016R1A2B4014629) and the National Research Foundation (NRF) funded by the Korea government (MSIT) (2022R1F1A10751652).

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Authors consent the Springer Open license agreement to publish the article.

Competing interests

The authors declare that they have no competing interests.

Received: 27 July 2023 Accepted: 30 August 2023
Published online: 13 September 2023

References

1. Mukhopadhyay SC (2015) Wearable sensors for human activity monitoring: a review. IEEE Sens J 15:1321–1330
2. Pantelopoulos A, Bourbakis NG (2010) A survey on wearable sensor-based systems for health monitoring and prognosis. IEEE Transactions on Systems, Man, and Cybernetics. Part C (Applications and Reviews) 40:1–12
3. Shewale PS, Yun K-S (2023) RGO decorated N-doped NiCo2O4 hollow microspheres onto activated carbon cloth for high-performance non-enzymatic electrochemical glucose detection. Heliyon 9:e17200
4. Kim K, Yun K-S (2019) Stretchable power-generating sensor array in textile structure using piezoelectric functional threads with hemispherical dome structures. Int J Precis Eng Manuf Green Tech. 6:699–710
5. Lee J-W, Yun K-S (2017) ECG monitoring garment using conductive carbon paste for reduced motion artifacts. Polymers (Basel) 9(9):439
6. Gan R, Lin H, Li J et al (2023) Thermal property of polyacrylate copolymers and their application in multilayer ceramic capacitor. J Polym Res 30:314
7. Freiman SW, Pohanka RC (1989) Review of mechanically related failures of ceramic capacitors and capacitor materials. J Am Ceram Soc 72:2258–2263
8. Coday S, Barth CB, Pilawa-Podgurski RCN (2018) Characterization and modeling of ceramic capacitor losses under large signal operating conditions. IEEE 19th Workshop on Control and Modeling for Power Electronics (COMPEL), Padua, Italy, pp 1–8.
9. Yoon J-S, Yun K-S (2017) Temperature sensor array using multi-layer ceramic capacitor. Korean MEMS Conference. Jeju, March 30–April 1, 2017. pp 122–123.
10. Jia W, Hou Y, Zheng M, Xu Y, Zhu M, Yang K, Cheng H, Sun S, Xing J (2018) Advances in lead-free high-temperature dielectric materials for ceramic capacitor application. IET Nanodielectrics 1:3–16

Publisher's Note