Materials Sciences and Applications, 2025, 16(4), 200-207
https://www.scirp.org/journal/msa
ISSN Online: 2153-1188
ISSN Print: 2153-117X

Liquid Metal Based Flexible Strain-Stress Sensor

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How to cite this paper: Yan, Y.C. (2025) Liquid Metal Based Flexible Strain-Stress Sensor. *Materials Sciences and Applications*, **16**, 200-207.
https://doi.org/10.4236/msa.2025.164011

Received: March 9, 2025
Accepted: April 20, 2025
Published: April 23, 2025

Abstract

Liquid metal based flexible strain-stress sensor is an electronic medical device that can accurately detect and respond to various strain and stress changes in the body, and it has become a highly sought-after research area in recent years. Many current-use rigid electrodes lack sufficient flexibility and durability, especially when applied to complex and dynamic environments, and may cause damage to the body. In contrast, the liquid metal based flexible strain-stress sensor simultaneously has the advantages of high electronic conductivity, stretchability, stability and biocompatibility. In this study, a high-performance flexible strain-stress sensor using gallium-indium alloy with excellent sensitivity and stability is developed by optimizing the liquid metal composition and sensor structure, which has a significant prospect and potential market in the fields of wearable electronics, human-machine interaction, and biomedical monitoring.

Keywords

Liquid Metal, Strain-Stress Sensor, Stability, Biocompatibility, Gallium-Indium Alloy

1. Introduction

The accurate detection of strain and stress changes is of utmost importance across diverse fields, including biomechanics, robotics, and health monitoring [1] [2]. Also, implantable and skin-attachable bioelectronics are essential in providing real-time and continuous monitoring of physiological signals for future point-of-care diagnostics, therapeutics, and rehabilitation. Over the years, numerous strain-stress sensors [3] have been developed. Traditional rigid sensors, like those made of metal foils, are widely utilized in industrial settings due to their high precision in static environments. However, they lack flexibility and conformability, rendering them unsuitable for applications that demand seamless integration with curved or dynamic surfaces, such as human skin or the moving parts of soft robots. Flexible sensors fabricated from polymers [4], while more adaptable, often suffer from low sensitivity, poor long-term stability, and limited conductivity. This restricts their ability to accurately detect minute changes in strain and stress, especially in real-time and continuous monitoring scenarios. The liquid-like nature of the metal allows it to adapt to various complex shapes and deformations without significant performance degradation. In contrast, some existing flexible sensors may have limitations in conforming to highly dynamic surfaces like human skin during complex movements. Besides, liquid-metal sensors usually have good electrical conductivity due to the nature of the metal. This allows for efficient signal transmission with low resistance, which is an advantage over some flexible sensors with relatively poor conductivity.

Ga-In liquid metal alloy [5] is characterized by good fluidity (surface tension = 0.5 N/m) and electric conductivity (conductivity = 3.1×10^6 S/m). The unique properties of liquid metal endow it with the potential to overcome the limitations of traditional sensor materials. It can be easily shaped and patterned into various forms, allowing for the creation of sensors with complex geometries. Moreover, its liquid-like nature enables it to maintain electrical connectivity even when subjected to large deformations, making it ideal for applications where high-strain tolerance is required. In the context of strain-stress sensors, liquid metal can be designed to detect both tensile and compressive forces, providing a more comprehensive understanding of the mechanical state of the monitored object. In this study, we present a novel liquid metal-based flexible strain-stress sensor. By carefully designing the composition of the gallium-indium alloy liquid metal (mass ratio of 9:1) and the structure of the sensor, we achieved a sensor with high sensitivity, capable of detecting minute strain and stress changes with high precision. To further optimize its performance and application potential, this gallium-indium alloy liquid metal electrode was encapsulated within a silicone rubber tube. This encapsulation not only protects the liquid metal but also provides mechanical support and a stable environment for the electrode during operation. In addition to the electrical and biocompatibility aspects, we also thoroughly tested the mechanical properties of the sensor. The results of these mechanical tests demonstrated the robustness and reliability of the sensor under different stress and strain conditions. The sensor also exhibits excellent long-term stability, maintaining its performance over extended periods of use. Furthermore, through a series of biocompatibility tests, we demonstrated its safety for use in *ex-vivo* environments, opening up new possibilities for applications in wearable health monitoring devices [6], human-machine interfaces, and biomedical research.

2. Experimental Section

2.1. Laboratory Equipment and Materials

Equipment and materials: beaker, glass rod, silicone gel, paper straws, steel needles, conductive silver paste, injector, brush, metal wires, hot-melt adhesive.

2.2. Process of Experiment

1) Making silicone rubber channels:

First, mix A and B liquid silicone gels together in the same proportion. Second, operate the vacuum oven to clear out the air bubbles. After that, the liquid gel was injected into paper straws by a larger needle pinhead after the failure of a thinner pinhead, which may be caused by the viscous quality of silicone gel. In order to keep the channels hollow to put in liquid metal afterwards, several steel needles were inserted into the straw molds filled with gels. Next, these molds were to be solidified by heat at 70˚C. When using the oven to heat silicone for curing, first, place the silicone sample in a suitable container and put it into the oven. Close the oven door tightly to ensure a sealed environment. Then, start the vacuum pump connected to the oven to evacuate the air inside, reducing the pressure to the required level. After that, set the desired temperature on the oven's control panel. Monitor the temperature and vacuum level during the heating process. Once the silicone has reached the curing time at the set temperature, turn off the heating function and slowly release the vacuum. After the oven has cooled down to a safe temperature, open the door and take out the cured silicone sample. Finally, peel off the paper skin outside the channels and draw out the needles. One of the four silicone rubber channels was successful enough to be used. The other three were not intact for bubbles remained inside during the injecting process.

2) Making liquid metal electrodes:

First, use the injector to inject liquid metal into the silicone rubber channels. During the process, the channel is posed in a U shape and the liquid metal overflowing out of the other end means that the channel is already full. Second, brush conductive silver paste on both ends of the channel and insert two wires into the

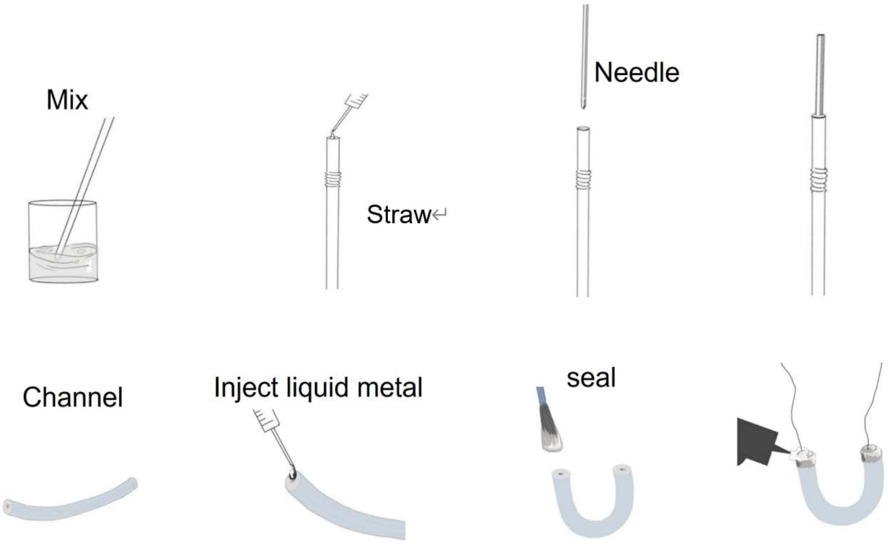

Figure 1. The fabrication process. Flexible channels were obtained by using metal needles as molds. After injecting liquid metal, the samples were encapsulated.

ends respectively. Third, squeeze hot-melt adhesive onto each end to keep the wire and the sliver paste in position, which proved to be the best way to fix them after several trials. Then, send the channels to the oven to be heated at 70˚C. Finally, take out the channels and the electrodes are finished. Figure 1 shows this process.

2.3. Gathering Data

1) Measurement of resistance change while fixing the electrode on human body: First, fix one end on the hand, the other on the upper arm, and the middle part on the hand wrist. Second, use metal clips to contact the wires at both ends. Third, watch the resistance change on the sensor when rotating the wrist and record the data.

2) Measurement of resistance change when stretching the electrodes: First, align one end of the ruler with the end of the electrode and fix them. Second, watch the resistance change on the sensor when stretching the electrodes to 110%, 120%, 130%, 140%, 150% and 160% respectively and record the data (Figure 2).

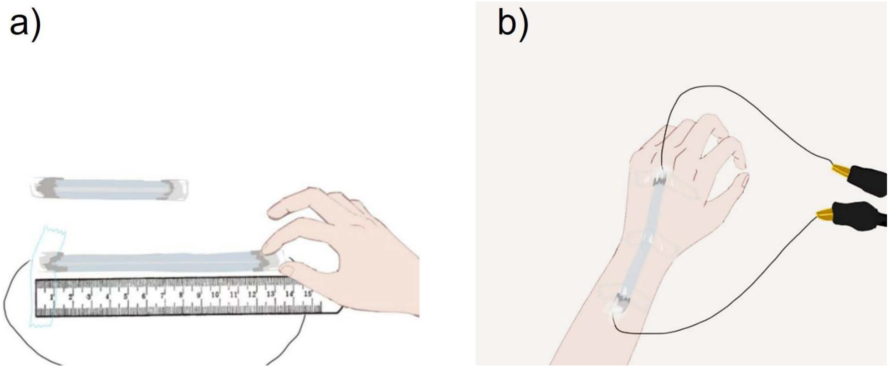

Figure 2. Schematic diagrams of tensile test and skin contact test of samples.

3) Measurement of the mechanical properties using tension tester: Put the sample on the test machine and stretch it until it breaks. Record the graph on the computer (Figure 3).

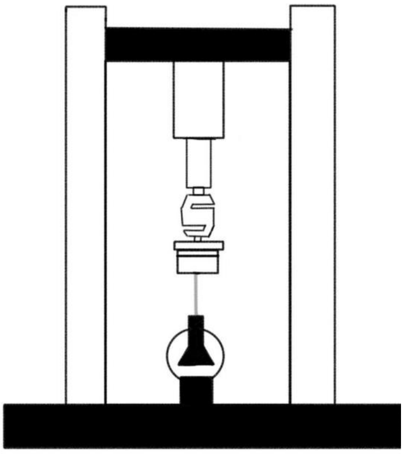

Figure 3. The stress test.

3. Results and Discussion

The strain sensitivity and electronic conductivity are significant parameters of the strain sensor. Here is the processed data of applying the sensor (**Figure 4**).

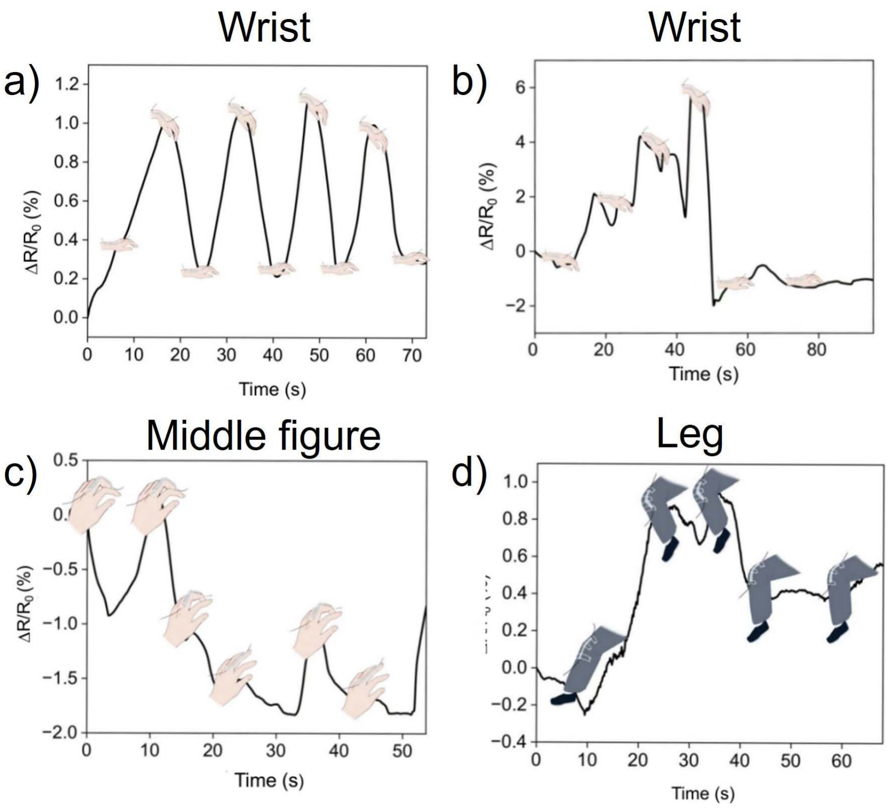

Figure 4. Human body motion detection. Tests of different wrist movements, finger bending, and leg bending.

From **Figures 1-3**, it is easy to see the change of resistance when applying the sensor to the wrist. When the wrist bends, the sensor is stretched. For a conductor like this, according to the resistance formula $R = \rho l/A$, where R is the resistance, ρ is the resistivity of the material, l is the length of the conductor, and A is the cross-sectional area. As the sensor is stretched, its length l increases, and at the same time, the cross-sectional area A decreases. Since resistance is directly proportional to length and inversely proportional to the cross-sectional area, both of these changes contribute to an increase in resistance. When putting the wrist flat, the sensor restores to the original length and the resistance decreases accordingly. **Figure 4** shows the change of resistance when applying the sensor on the middle finger, which proves to work perfectly as well. **Figure 5** shows the sensor on the leg. Though there is difficulty in fixing the sensor on the pants, it still proves to work well according to the data. These experiments tell the fact that this kind of sensor is capable of detecting small movements of human body [7] and can be applied to medical health data collection and monitoring. Besides, the flexibility quality of the sensor enables it to monitor movements without doing harm to the body or breaking its own structure. In future study, this sensor can be considered to be implanted in the body [8] in order to detect more subtle movements or nerve signals [9].

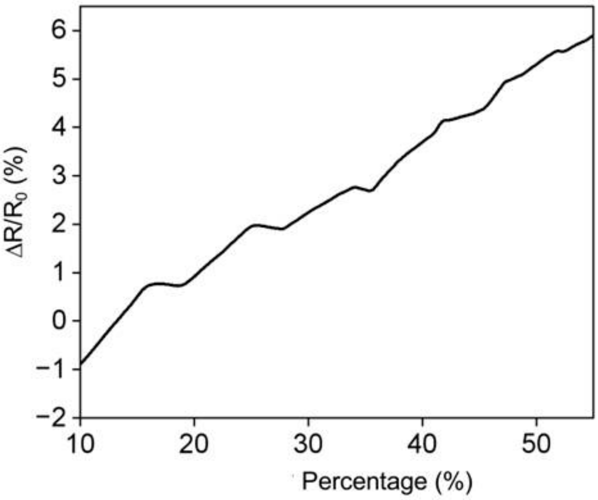

Figure 5. percentage change in resistance when stretching the sensor. As the stretching length increases, the corresponding resistance gradually increases.

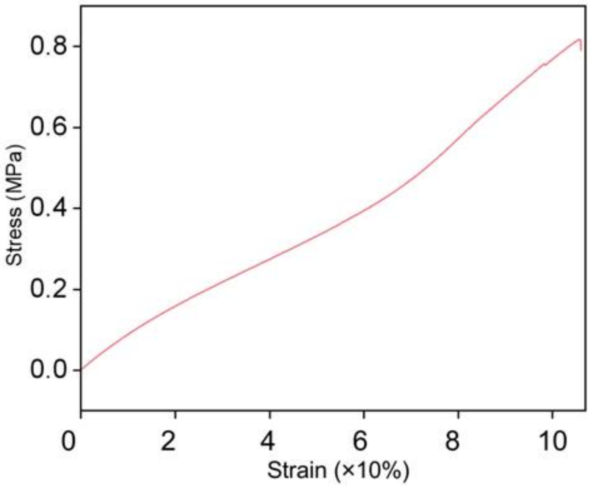

Figure 6. Mechanical properties tensile test.

Figure 5 shows the percentage of change in resistance when stretching the sensor to different lengths. **Figure 6** demonstrates the mechanical property of the sensor and the elastic modulus, which can be known from the slope of the graph. It is clear that the sensor reacts actively to stretching and has excellent mechanical properties. In practical application, the sensor can be stretched to a great length, so it can adapt to the constantly moving organisms and has high biocompatibility.

4. Conclusion

In this study, liquid metal as raw material is used to perform the stress-strain sensor function, addressing the limitations of traditional rigid electrodes. The liquid metal based flexible strain-stress sensor shows remarkable advantages. Its high electronic conductivity, stretchability, and stability make it an ideal candidate for a wide range of applications. The flexible sensor can adapt to complex and dynamic environments, such as the curved surface of the human body or the moving parts of soft robots. For example, when equipped on human joints, this sensor can achieve motion detection effectively. This adaptability enables seamless integration, providing real-time and continuous monitoring of physiological signals, which is crucial for wearable electronics, human-machine interaction, and biomedical monitoring. Also, it has potential applications in soft robotics for more flexible movement control, medical diagnostics for monitoring joint-related conditions, and in health care for continuous activity tracking and health assessment. The measurement of resistance change while the electrode is fixed on the human body has laid a foundation for further exploration of its practical applications. Overall, this flexible strain-stress sensor holds great promise and potential market in future technological development. However, further research is needed to optimize the performance, explore its implanting application, and expand its application scenarios. We believe this study will inspire more in-depth research in the field of flexible sensors and contribute to the development of related technologies.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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