Liquid Metal Interdigitated Capacitive Strain Sensor with Normal Stress Insensitivity

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Soft and stretchable sensors of strain are important for human–machine interfaces, soft robotics, and electronic skins. However, soft strain sensors generally cannot distinguish in-plane strain from normal stress. For example, stretching a sensor often gives a similar signal to pressing the sensor. To solve this problem, a liquid metal (LM)-interdigitated capacitive strain sensor that is insensitive to normal stress is introduced. The sensor contains LM-interdigitated electrodes prepared by vacuum filling of LM into lithographically defined microchannels. The capacitance between the LM electrodes decreases with increasing strain due to geometric changes. Because of the liquid nature of the electrodes, the sensor exhibits high stretchability (100% strain) and repeatability with gauge factor of −0.3. Due to the elasticity of the device, the sensor has low hysteresis (<1%) and no crosstalk between strain and normal stress sensing. These types of soft sensors may find use in wearable devices.

1. Introduction

Strain sensors built from soft and stretchable materials have attracted tremendous interest in the fields of human–machine interfaces, soft robotics, and electronic skins.[1,2] These strain sensors can help monitor the motion of soft robots or convert

human motions into electrical signals. Currently, various strain-sensing mechanisms such as capacitive,[3] piezoresistive,[4–6] and piezoelectric[7] have been employed to fabricate strain sensors. Among these sensing mechanisms, capacitive sensing has advantages over others owing to its temperature independence, low power consumption, and low hysteresis behavior.[8]

A typical capacitor consists of two electrodes that sandwich a dielectric layer. The capacitance is defined as \( C = \varepsilon_0 \varepsilon_r A/d \), in which \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon_r \) is the relative permittivity of the dielectric layer, \( A \) is the area of electrodes, and \( d \) is the distance between electrodes. Strain alters the geometry of the capacitor. If strain is applied perpendicular to dimension \( d \) (we call this “stretching”), the Poisson effect causes \( d \) to decrease and \( A \) to increase, resulting in an increase in capacitance. This type of deformation is useful for detecting things like joint position or skin extension. It is also possible to deform the capacitor by applying normal stress, which can be done by pressing the sensor.[5–9] Normal stress applied to a typical parallel plate capacitive sensor decreases \( d \), resulting in an increase in capacitance. Therefore, typical parallel plate type capacitive strain sensors cannot distinguish strain from normal stress.[10] This is problematic for wearable devices since it is difficult to avoid inadvertently pressing the sensor if it is mounted on the skin.

For improving the specific selectivity of sensors to particular physical stimulation, some methods have been adopted.[11–13] Interdigitated capacitive strain sensors (ICSSs)—with coplanar electrodes—can decouple strain from normal stress. ICSSs also have the appeal of linear strain sensing and low hysteresis.[14] The capacitance of the ICSS arises between the interdigitated electrodes. Stretching the capacitor in-plane in the direction perpendicular to the electrodes increases the distance between any two electrodes and decreases the thickness and length of electrodes. Combined, these changes decrease the capacitance of the ICSS.[15] Here, the capacitance directly between the electrodes is negligible compared with the capacitance from the fringing fields since the electrodes are only several micrometers thick. Applying normal stress to an ICSS results in a negligible change in distance between electrodes because of the low aspect ratio, resulting in an insignificant change of total capacitance.

A key design consideration of ICSSs is that electrodes should possess electrical conductivity even under strain. Numerous
stretched thin films of materials, such as networks of Ag nanowires or carbon nanotubes, have been chosen as electrodes of ICSSs and can maintain electrical conductivity under modest strains.\cite{12,16,17} However, these strain sensors are not able to remain functional at strains over 100%, and thus cannot be used in large strain situations. To solve this problem, liquid metals (LMs) have attracted substantial attention.\cite{18} Due to the fluidity and high durability, LMs can maintain excellent electrical conductivity even under larger strain,\cite{19} which makes them an outstanding conductor for stretchable electronic components such as soft circuits\cite{20} and electrodes.\cite{21}

Here, we introduce a LM-interdigitated capacitive strain sensor (LMICSS) consisting of a polydimethylsiloxane (PDMS) microfluidic network filled with LM, as shown in Figure 1a. As expected, the capacitance decreases with increasing strain. The sensor is highly stretchable (100%) with a gauge factor of $-0.3$ and good durability. In addition, the sensor has low hysteresis ($<1\%$) and is crosstalk-free between strain and normal stress sensing due to its coplanar electrode microchannel. Finally, we present practical applications of the sensor, such as human motion detection and gesture recognition.

2. Results and Discussion

2.1. Fabrication and Characterization

The fabrication process is shown in Figure 1b (see Supporting Information for details). Briefly, the mold for the PDMS microchannel was prepared lithographically. After casting and curing, the PDMS microchannel was bonded with another PDMS slab after oxygen plasma treatment. Finally, LM was filled into the encapsulated microchannel using vacuum filling.\cite{22} Using this
method, we fabricated micrometer-size LM-interdigitated microfluidic channels, as presented in Figure 1c. This interdigitated strain sensor consists of many electrodes with an initial length ($l_0$), a width ($w_0$), a thickness ($t_0$), and a spacing ($d_0$) of 1 cm, 100 $\mu$m, 50 $\mu$m, and 200 $\mu$m, respectively. Because of the single-layer structure, the strain sensor conforms well to the human hand, as shown in Figure 2a. Meanwhile, PDMS and LM endow the sensor with excellent stretchability, limited only by the inherent properties of the PDMS (Figure 2b). Meanwhile, the microfluidic strain sensor exhibits excellent flexibility under twisting, bending, and even folding into a roll, as presented in Figure 2c.

2.2. Mechanism of the LMICSS

The capacitance of a unit cell of the interdigitated capacitor, $C_u$, consists of three capacitances in parallel: two fringing electrical field capacitances $C_{su1}$ and $C_{su2}$ generated between two coplanar opposite electrodes and a parallel-plate capacitance $C_m$ in between the electrodes, as shown in Figure 3a. The total capacitance $C$ is the sum of the capacitance of unit cell $C_u$, and can be expressed as

$$C = (N - 1)C_u = (N - 1)(C_{su1} + C_{su2} + C_m)$$

$$C_{su1} = C_{su2} = \frac{2\varepsilon \varepsilon_0 l_0}{\pi} \ln \left( \frac{2w_0 + d_0}{d_0} \right) + \sqrt{\left( \frac{2w_0 + d_0}{d_0} \right)^2 - 1}$$

$$C_m = \frac{\varepsilon \varepsilon_0 l_0}{d_0}$$ (3)

where $N$ is the number of fingers forming the interdigitated capacitor, $\varepsilon_r$ is the relative permittivity of PDMS, $\varepsilon_0$ is the vacuum permittivity.

Figure 3b shows a schematic of the sensor stretched in the direction perpendicular to its electrodes. When the strain sensor is stretched along that direction, $d_0$ increases to $(1 + \varepsilon) d_0$, and $l_0$ and $t_0$ decrease to $(1 - \nu\varepsilon) l_0$ and $(1 - \nu\varepsilon) t_0$, respectively, where $\varepsilon$ is the strain applied to the sensor, and $\nu$ is the Poisson’s ratio of PDMS. Because of the effect of the Poisson’s ratio, during strain $C$ decreases to a new value $C'$, and can be expressed as

$$C' = (N - 1)C_u' = (N - 1)(C_{su1}' + C_{su2}' + C_m')$$

$$C_{su1}' = C_{su2}' = \frac{2\varepsilon \varepsilon_0 (1 - \nu\varepsilon) l_0}{\pi} \ln \left( \frac{2w_0 + d_0}{d_0} \right) + \sqrt{\left( \frac{2w_0 + d_0}{d_0} \right)^2 - 1}$$

$$C_m' = \frac{\varepsilon \varepsilon_0 (1 - \nu\varepsilon) l_0}{(1 + \varepsilon) d_0}$$ (6)

The fringing capacitance of the LMICSS is greater than the parallel capacitance according to the Equation (2) and (3), so the strain sensor detects the strain based mainly on the change of the fringing-field capacitance. When the normal stress is applied on the sensor, the change of the distance between the electrodes is negligible. Thus, the strain sensor exhibits insensitivity to normal stress and thereby decouples the in-plane strain sensing from normal stress.

Figure 2. Images of LMICSS. a) Photos of the LMICSS show that the soft and stretchable sensor can conform to surfaces. b) Photos of the microchannel of the strain sensor before and after stretching. c) Photos of the LMICSS show flexibility and bendability.
2.3. Sensor Characterization

Figure 4a shows the strain sensor under different strains. The strain sensor can be easily stretched to a strain of 100% without failure. This strain is only limited by the mechanical properties of the silicone that encases the liquid metal. The comparison of the max stretch limit between the strain sensor and PDMS slab is shown in Figure S1, Supporting Information. The sensors exhibit metallic electrical conductivity and excellent mechanical properties because of the fluidity and electrical conductivity of LM. The variation in the relative capacitance $C$ with the applied strain of the LMICSS is shown in Figure 4b. The LMICSS shows an almost linear behavior in terms of the variation in the relative capacitance $C$ with the applied strain. The $C$ of the LMICSS decreases with the increase of the applied strain along the direction perpendicular to its electrodes. Consequently, the GF of the strain sensor is $0.3$. Meanwhile, the strain sensor was stretched to 5% at a stretching rate of 300 mm min$^{-1}$ to test the response time and recovery time of the LMICSS. As shown in Figure S2, Supporting Information, the normalized capacitance rapidly descended within 500 ms. After releasing the strain sensor, the strain sensor recovered within a time of 1 s. In addition, the performance of the LMICSS stretched along the direction parallel to its electrodes also were investigated. Figure S3, Supporting Information, shows that the $C$ of the LMICSS increases with the increase of the applied strain along the direction parallel to its electrodes, and its GF is 0.69.

Figure 4c shows the hysteresis of the strain sensor at a tensile rate of 5 and 20 mm min$^{-1}$, respectively. The LMICSS exhibits low hysteresis below strains of 50% when stretched at different rates. Although the capacitive hysteresis increases when the stretching rate is 20 mm min$^{-1}$, the change in $\Delta C/C_0$ relative to 5 mm min$^{-1}$ is within 0.01. The hysteresis of the strain sensor below strains of 80% at a tensile rate of 5 mm min$^{-1}$ is shown in Figure S4, Supporting Information. The result shows that the LMICSS still exhibits low hysteresis.

To assess the cycling hysteresis of the strain sensor, we applied tensile strain at a stretching rate of 5 mm min$^{-1}$ to the sensor repeatedly. The $\Delta C/C_0$ of the sensor is shown in Figure 4d. The phase shift between the applied strain and the $\Delta C/C_0$ is negligible, indicating a good dynamic response of the strain sensor. The durability of the strain sensor was also investigated. As shown in Figure 4e,f, the sensor provides reproducible results during repeated strain cycling at 30% strain.
Figure 4. Characterization of the LMICSS. a) Photographs of the LMICSS under different strains. b) Plot of normalized change in capacitance versus applied strain. c) Hysteresis of the LMICSS at different strain rates. d) Dynamic performances of the LMICSS. e) Durability test of the sensor over 300 strain cycles with 30% strain. f) The $\Delta C/C_0$ of the LMICSS at the outset and the end of the durability test.

Figure 5. The response of the LMICSS to the normal stress. a) Photographs of the sensor without stretching under different normal stress. b) Plot of $\Delta C/C_0$ versus normal stress. c) Photographs of the sensor with 20% strain under normal stress. d) Plot of $\Delta C/C_0$ versus normal stress under 20% strain.
Figure 6. a) The theoretical $\Delta C/C_0$ of the LMICSS versus the experimental $\Delta C/C_0$. b) Plot of the simulation versus the experimental $\Delta C/C_0$ of the LMICSS. c) The simulation mold and the electric-field distribution before and after stretching.

Figure 7. a) Photos of the LMICSS with $d_0$ of 200 μm and the microchannel (inset). b) Photos of the LMICSS with $d_0$ of 1000 μm and the microchannel (inset). c) Plot of $\Delta C/C_0$ versus applied strain. d) Hysteresis of the LMICSSs.
Furthermore, the reliability of the strain sensor against temperature variations is tested. As shown in Figure S5, Supporting Information, the capacitance of the strain sensor decreases slightly when the temperature of ambient temperature arises from 25 to 105 °C, resulting in a decrease of $\Delta C/C_0$. This is due to the spacing between electrodes increasing when the substrate was heated because of the thermal expansion, leading to a decrease in $\Delta C/C_0$.

The strain sensor is insensitive to normal stress, as shown conceptually in Figure 3c. For experimental verification of the insensitivity of the strain sensor to normal stress, we applied normal stresses to the sensor using various weights varied from 10 to 17.5 N, as shown in Figure 5a. The $\Delta C/C_0$ of the strain sensor does not change during addition and subtraction of the weights, as shown in Figure 5b. The $\Delta C/C_0$ response of the strain sensor to normal stress under 20% tensile strain was also conducted, as shown in Figure 5c. The $\Delta C/C_0$ of the strain sensor at a strain of 20% only changes 0.004 after adding the weights ranging from 10 to 17.5 N, indicating the insensitivity to the normal stress even under stretching, as shown in Figure 5c. The performance of the strain sensor under the larger normal stress is shown in Figure S5, Supporting Information.

For an in-depth verification of the performance of the strain sensor, we calculated the theoretical value of $\Delta C/C_0$ of the strain sensor and compared it with the experimental value. We verified the geometrical changes that occur during elongation (Figure S6, Supporting Information). The measured $\Delta C/C_0$ is in accordance with the theoretical curve deduced from the Equation (6), as shown in Figure 6a. Besides that, the performance of the strain sensor is also certified through a finite element simulation, as shown in Figure 6b. The simulation model consists of a PDMS substrate with LM-interdigitated electrodes. When it is

Figure 8. a) The $\Delta C/C_0$ of the sensor at the elbow. b) Plot of the $\Delta C/C_0$ for the movement of the wrist; c) The $\Delta C/C_0$ of the sensor to the movement of the fingers.
stretched along the direction perpendicular to its electrodes, the increase of electrodes spacing and the decrease of the electrode thickness decreases the total capacitance \( C \). In addition, the measured \( \Delta C/C_0 \) is also in line with the finite element simulation curve up to strains of 20%. The deviation between the simulation and measured curves arises from the difference between the Poisson ratio of the simulated substrate and the real Poisson ratio of the PDMS substrate. The addition of LM would influence the Poisson ratio of the PDMS substrate. However, it is not the main point of this paper so the real Poisson ratio of the PDMS substrate is not considered. The models before and after stretching are shown in Figure 6c.

To investigate the influence of the electrode size on the performance of the strain sensor, another capacitive strain sensor composed of multiple electrode fingers was fabricated. The initial length \( (l_0) \), width \( (w_0) \), thickness \( (t_0) \), and spacing \( (d_0) \) of the comparison sensor were 1 cm, 100 \( \mu \)m, 50 \( \mu \)m, and 1 cm, respectively. Figure 7a, b show the photos of the two strain sensors. As shown in Figure 7c, the capacitance of the strain sensor decreases as the strain increases. This response is consistent with the response of the strain sensor with \( d_0 \) of 200 \( \mu \)m. However, the GF of the strain sensor with \( d_0 \) of 1 cm is smaller than that of the strain sensor with \( d_0 \) of 200 \( \mu \)m. Both strain sensors exhibit low hysteresis within strain of 50\%, as shown in Figure 7d, indicating that spacing does not affect the hysteresis of the LMICSS.

2.4. Applications

The LMICSS has potential applications in wearables to detect dynamic human motion due to its good stretchability and durability. We adhered the strain sensors to the wrist, elbow, and fingers to detect body motions, as shown in Figure 8a–c. Since the total thickness is less than 1 mm, the strain sensor can be easily mounted on the elbow and wrist without impeding the movement of these joints. The sensor can clearly distinguish the releasing and stretching states of the elbow and wrist, as shown in Figure 8a, b. Furthermore, a smart glove was fabricated for recognizing human gestures by mounting the strain sensors on the fingers. Bending or unfolding fingers increases or decreases the capacitance rapidly, which proves that the glove can detect finger motions in real-time, as shown in Figure 8c.

3. Conclusion

This article introduces an LMICSS. The conductivity and fluidity of LM and stretchability of PDMS allow the LMICSS to detect strain up to 100\%. The vacuum filling method successfully fills LM into the microchannels for facile fabrication. The LMICSS showed a GF of \(-0.3\). The hysteresis is negligible for strain \(<50\%\). The LMICSS shows stable cyclic sensing and mechanical performance at strains of 30\%. The crosstalk between in-plane strain and normal stress of typical capacitive strain sensors was solved by placing the electrodes of the capacitor in the same plane. The sensor can be used to measure the motions of human joints. In addition, we prepared a smart glove based on the sensor, which can clearly distinguish the gesture numbers from 1 to 4.

4. Experimental Section

Materials: PDMS (Sylgard 184) was purchased from Dow Corning. The SU-8305 and SU-8 developer were purchased from MicroChem. LM (Gallium indium tin, Galinstan) was supplied by Rare Metal Products Co., Ltd. Suzhou Haichuan.

Fabrication Processes of the LMICSS: The entire lithography process is shown in Figure S3, Supporting Information. At first, the SU-8305 negative photoresist was spin-coated on the silicon wafer by 500 rpm (ramp rate of 100 rpm s\(^{-1}\)) for 11 s, followed by 2000 rpm (ramp rate of 300 rpm s\(^{-1}\)) for 30 s. This was ensued by pre-exposure baking at 95 °C for 15 min. Then the SU-8 layer was patterned using ultraviolet (UV) lithography for 4 s (250 m cm\(^{-2}\) exposure energy). Specimens were post-exposure baked at 65 °C for 1 min and 95 °C for 5 min. After cooling to room temperature, specimens were immersed in SU-8 developer to remove uncrosslinked photoresist from the SU-8 layer. Next, mixed PDMS (10:1 mass ratio of elastomer base to curing agent) was spin-coated on the silicon wafer with microfluidic channel and heated by a heating plate at 80 °C for 4 h. After the PDMS has solidified, the PDMS was peeled from the silicon wafer, then used biopsy punch to drill a hole with a diameter of 1 mm as inlet hole at each end of the two electrodes. Used same method fabricated PDMS flexible substrate without microfluidic channel. Then two PDMS flexible substrates were bonded together using plasma. At last, two drops of LM were placed over the two inlet holes, and set the device in a vacuum chamber for 20 min. After releasing the vacuum, the atmospheric pressure propelled LM to flow into the microchannels. To maintain the good connection between the wires and the LM microchannel, extra LM was dropped on the inlet hole as a “reservoir”, as shown in Figure S9, Supporting Information. When the LM at the connecting position is insufficient, the LM stored in the “reservoir” can flow into the connecting position to fill the vacancy because of the excellent fluidity of the LM. Finally, wires were inserted in the two ends of the microchannel through the two inlet holes, then sealed and fasted by glue.

Experimental Equipment: The elastomer solution was mixed by a vacuum mixer (HMV600, Shenzhen Hasai Technology Co., Ltd., 2500 rpm \( \text{min}^{-1} \)). The oxygen plasma treatment was conducted by a plasma cleaner (PTL-VM500, 225W for 17 s). The capacitance was measured by a HIOKI IM3536 LCR. The mechanical properties were measured using SENS CMT 6502 Universal Testing Machine. The optical images were captured using a Canon camera. The PDMS and photoresist were spin-coated by a spin coater (KW-4A, Institute of Microelectronics of The Chinese Academy of Sciences). PDMS and photoresist were heated by a heating plate (DB-XAB, Shanghai Lichen-Bx Instrument Technology Co., Ltd.).

All experiments complied with guidelines by the Taiyuan University of Technology. All subjects were volunteers (co-authors of the work) and provided informed consent.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.
Data Availability Statement

Research data are not shared.

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