Liquid metal based flexible pressure sensor for tactile sensing of robots

Ruiyang Chen*
Department of physics, Wuhan University of Technology, Wuhan, China
jwwthu@163.com, 1901110384@pku.edu.cn

Abstract. In contrast to circuit made by rigid material, flexible electronic devices are fabricated by flexible conductive material and have potential future in field of wearable electronic devices, biomedicine and intelligent sensor. Liquid metal is a kind of metal or alloy material that can remain liquid at room temperature. In recent years, it has been widely used in the field of stretchable electronics. This research applied adhesion different of liquid metal on different materials' surface to print liquid metal circuit of certain pattern on thermal transfer paper and trans-printed the circuit to flexible base to fabricate stretchable and flexible pressure sensor. In the research we tested the electrical property of pressure sensor and applied the results to tactile feedback research of intelligent robot. Not only does this liquid metal pressure sensor have simple structure and low in cost, but is suitable for large area and mass production. We believe this pressure sensor can be widely used in field of human-computer interaction and robot intelligent sensing.

1. INTRODUCTION
As is known to all, printed circuit board (PCB) plays a very important role in our daily life and has been widely used in industrial production, national defense and medical and health fields. The traditional PCB manufacturing process is very complicated, which needs to go through more than ten steps. The whole process is time-consuming and power-consuming, accompanied by a lot of environmental pollution. Recent years, flexible electronics has been paid more and more attention. [1] In contrast to traditional rigid circuit boards, flexible circuit boards can be bent, folded or even stretched at will, which makes them of great application value in wearable devices, portable medical devices, skin electronics and other fields. [2] Different from the traditional circuits which are made by rigid material, flexible circuits have higher degrees of freedom, can fit closely on the surface of a variety of complex structure and human skin surface, and can be used for the detection of various physiological signals of human body and human body movement information, which have broad application prospects in the field of biomedical detection and human-computer interaction. The development and application of new materials is one of the bases for the development of human society. In the field of biomedical application, it is often necessary to use various electronic devices to collect physiological information of human body. However, traditional conductive materials, such as copper, tin, gold, silver, etc., have high mechanical strength, and the electronic circuit thus manufactured is not flexible and difficult to adapt to the soft matrix of human tissues. [3]

Comparing with traditional rigid electronic circuits, flexible electronic circuits require flexible conductive materials and packaging materials with low Young's modulus. Because of the particularity of conductive materials and packaging materials, the fabrication process of flexible electronic equipment requires some special techniques to obtain the specific mechanical and electrical properties.
With the development of material science, many flexible conductive materials with different conductive principles have been developed. Due to the particular application environments of flexible electronic equipment, the flexible conductive material needs to meet the requirements of high conductivity, while its Young's modulus needs to be low enough, and even needs to maintain good conductivity in the state of stretching, bending and torsion. At present, according to the conductive principle of flexible conductive materials, they can be divided into micro-nano metal conductive compound, [4] carbon-based conductive material, [5] ionic liquid, [6] organic polymer conductive material, [7] inorganic semiconductor material and so on. On the basis of developing a variety of flexible conductive materials, many researchers have also developed a series of matching flexible electronic fabrication processes according to the special physical and chemical properties of the materials. Among the numerous flexible electronic preparation technologies, the research ideas mainly focus on the advantages of the preparation technology such as convenience, low cost, high efficiency, large quantity and high precision, including screen printing, microchannel perfusion, 3D printing, transfer and magnetron sputtering.

Recent years, liquid metal material to receive the attention of researchers in field of flexible electronics, liquid metal with gallium substrate can keep the liquid state at room temperature, and has a strong biological safety, high electrical conductivity, as well as good liquidity, in the fields like thermal control and energy, printing electronics, biomedical and flexible machine has a broad application prospect. [8-9] Liquid metal materials can remain good liquidity at room temperature and have excellent compliance, which makes it possible to combine with flexible substrate to produce ultra-thin, soft and flexible electronic circuits that can be greatly stretched. At present, a variety of functional flexible conductive materials have been developed based on liquid metal materials, such as liquid metal composite prepared by doping metal nanoparticles in liquid metal, which shows good shaping ability and printing effect. [10] In addition, the flexible circuit manufacturing technology based on liquid metal materials has also obtained a series of research results. For example, manufacturing liquid metal circuits with high precision by method of injecting liquid metal directly into microflow channels. Using 3D printing equipment, [11] the circuit can be printed directly on the base surface. Transfer printing of liquid metal circuit can be realized by using the difference of adhesion of liquid metal material on different substrate surface. [12] At the same time, combining liquid metal with functional materials can produce electronic circuits with specific functions. [13] For example, mixing magnetic metal particles in liquid metal can produce magnetic liquid metal materials, encapsulating liquid metal in degradable polymer film can obtain degradable electronic circuit.

Here, we use the adhesion difference of liquid metal on different material surface to develop the technology of transferring liquid metal to silicone base and manufacturing flexible pressure sensor. This technology is easy to operate, low cost, suitable for large-scale manufacturing and customized circuits. We have developed a pressure sensor based on liquid metal, which can detect the external object's pressure on the robot's body surface, and convert it into resistance signal for collection and recording. Experimental results show that the surface pressure sensor has good electrical stability. We believe that this liquid metal pressure sensor has great application value in wearable devices, portable medical devices, skin electronics and other fields.

2. Another section of your paper

2.1. Materials

The component of the liquid metal (Gallium-indium eutectic alloys, EGaIn) is 75.5% gallium and 24.5% indium, which are purchased from Anhui Minor New Materials Co. Ltd. The pellet diameter of Copper powder is 12μm, and it is purchased from Beijing DK Nano Technology Co., Ltd. The encapsulated silicone Ecoflex 00-30 is purchased from Smooth-On, PA, USA. The laser printer LJ2205 is purchased Beijing Lenovo Co., Ltd.
2.2. Fabrication of Cu-EGaIn
The Gallium and indium are blended in a beaker according to the certain mass proportion, then the mixture is heated up to 200 centigrade for one hour. During the process, we use a glass rod to stir the sample constantly to mix the sample thoroughly. The copper powder is added to the surface of the EGaIn, the mass fraction of copper powder is 15%, and then we pour the NaOH solution (1mol/L) in the beaker and stir the sample constantly using a glass rod to make sure the copper can finally be mixed in the EGaIn.

2.3. Fabrication of flexible circuits
First, the circuit pattern is printed on the thermal transfer paper with printed toner by laser printer. Later, we spread the Cu-EGaIn evenly on the surface of roller and use the roller to trans-print the Cu-EGaIn on the surface of thermal transfer paper which have been experienced in the first step. Due to Cu-EGaIn has obvious difference in adhesion to the surface of thermal transfer paper and the surface of toner, the Cu-EGaIn can only adhere to the surface of the thermal transfer paper and form certain circuits.

Then, we pour the encapsulated silicone Ecoflex 00-30 on a flat surface and heat it for 3 minutes under the temperature of 60 °C to make the Ecoflex 00-30 form a thin film. The thermal transfer paper which have processed is put on the surface of the Ecoflex 00-30 thin film and the circuits on the thermal transfer paper is finally trans-printed on the thin film under extrusion. Then we connect the end points of the liquid metal circuits by copper lines, which can be used to connect with other circuits. Finally, we pour the Ecoflex 00-30 on the surface of the liquid metal circuits, and heat it under the temperature of 60 °C for 3 minutes to finish the encapsulation of the liquid metal circuits.

2.4. Electrical Tests
In this research, the Electrical performance tests are carried out by using digital source meter (Keithley, Model 2400). The photos are taken with a camera (Canon EOS 800D).

3. RESULTS AND DISCUSSION
In this research, instead of directly printing liquid metal circuits on the stretchable silicone surface, we used the adhesion difference of liquid metal materials on the substrate surface with different surface roughness to print the liquid metal pattern on the surface of the heat transfer paper, and then the liquid metal pattern is transferred to the stretchable silicone material surface. In this way, we can improve the printing accuracy of liquid metal circuits and reduce manufacturing costs. Figure 1A shows that the thermal transfer paper is a kind of extreme smooth material and liquid metal material has high adhesion on its surface. In contrast, after the toner printed on the surface of the thermal transfer paper, the toner forms a very tough interface which decreases the adhesion of liquid metal material on its surface, so the adhesion between liquid metal material and the toner surface is decreased. We use a roller to print the liquid metal material on the thermal transfer paper to accelerate the speed of printing and this method is suitable for large-area and large-volume circuit printing. In addition, liquid metal material has great adhesion on the surface of Ecoflex. Therefore, the liquid metal circuit on the thermal transfer paper can be trans-printed to the surface of the Ecoflex. We package liquid metal material circuit between the two layers of film of Ecoflex to fabricate flexible pressure sensor. This flexible pressure sensor can be transformed under pressure, which cause the change of its resistance. According this theory, this flexible pressure sensor can test the external pressure. The photos in Figure1B shows the process of fabricating the liquid metal material pressure sensor.
We print some liquid metal wires in different width (length of 10 cm, width of 0.1 mm, 0.3 mm, 0.5 mm, 1 mm, 3 mm, 5 mm) on the Ecoflex substrate and test their resistance. Figure 2A shows the resistance of these liquid metal wires. From the diagram we can find that the resistance of these wires dramatically decrease with the increase of their width. We find that the maximum resistance is 11.8Ω with the liquid metal wire width of 0.1mm and resistance of liquid metal wire decrease to 1Ω when the wire of 5mm in width. However, proportion between liquid metal wire’s width and their resistance is not same among wires in different width. This results may be caused by uneven Cu-EGaIn layer over the Ecoflex substrate which leads to local resistance to increase. Figure2B shows the electronic performance of liquid metal flexible wires under straining. According to the diagram, we find that a liquid metal flexible wire (original length is 10 cm) can be stretched to a maximum to 100% strain, which shows its great stretchability. What’s more, resistance of the wire increases remarkably with increasing of the level of strain. The resistance increases to 8.2Ω under situation of 100% strain from original resistance of 2.2Ω.
Figure 2 (A) The relationship between the liquid metal wire resistance and the wire width; (B) The tension-resistance curve of liquid metal wire; (C) Electrical stability test for liquid metal wire; (D) Physical drawing of wire before and after stretching liquid metal wire to 100% state.

Last, to test the stability of the liquid metal wire in constant stretch process, we stretch the wire from original state to 100% strain for 1000 times and record the resistance after every 100 stretching cycles. The result is shown in Figure 2C. Figure 2C reveals that the value of resistance does not occur obvious change during the constant stretching process. But the value still increases slightly. We attribute the change to the local oxidation on the Cu-EGaIn which has negative effects on the wire’s electronic performance with the increase in time of stretching. Even though, this slight change can be ignored comparing with the electronic components with high resistance. So Cu-EGaIn/fiber has great stability and is qualified for a long-time work. Figure 2D is picture of real products of the liquid metal wire before and after being stretched to 100% strain.

Stability is a vital figure to judge the performance of liquid metal wire. In our research, liquid metal wire which is made by the method of trans-printing shows excellent stability in form and electricity property. Liquid metal wire can keep in good outline from breaking even after process of large tensile deformation. What is more, with the increase of tensile amplitude, the value of resistance increase in a perfect linear relationship. The great stability can offer this liquid metal wire potential future in practical application. And this kind of liquid metal wire can not only be used as flexible wire which can be applied in fabrication of flexible circuit, but also can play a vital role in flexible sensor which can be used in field of human movement detection and human-computer interaction.

In this research, we employ the trans-printing technology to fabricate a liquid metal pressure sensor, which can be stocked to the surface of robot to offer the ability of tactile sensor. Furthermore, this pressure sensor can also be used as a device of human-computer interaction to translate the information of body movement to robot operation’s instructions. We test the resistance value of this sensor under different pressures and the results are showed in Figure 3A. According to Figure 3A, we
can find that the resistance value of the liquid metal wires increase constantly from original value around 11.7Ω under the increasing pressure. In our research, the maximum pressure applied to the sensor is 2.02N, in this situation the resistance of the sensor reaches the peak around 13.2N. Besides, Figure 3A also record other values of resistance when the sensor under different pressures and we also use curve to connect this individual points to reflect to tendency of the resistance change. After analysing the curvature of the curve, we can find that the speed of resistance change accelerates with the increasing of pressure. The resistance of the sensor depends on the form of the liquid metal circuit. Longer and narrower liquid metal wire has higher resistance value. So the higher pressure be pushed to sensor, the more deformed the liquid metal circuit and wire become, which can lead the resistance increases more remarkable.

**Figure 3 (A)** The relation curve between resistance and pressure of liquid metal pressure sensor; **(B)** Electrical stability test of liquid metal pressure sensor.

What’s more, the liquid metal sensor performs in great stability. To verify its stability, we apply same pressure to the liquid metal pressure sensor through multiple circles and record the value of resistance. The result is shown in Figure 3B. From Figure 3B, we can find that the resistance increase and decrease with the increase and decrease of the pressure. And in time of 16 seconds, we offer the sensor four same circles of pressure. After several times of pressing, the value of resistance is nearly change in a same pattern. It raises from original resistance of 11.4Ω and reaches the peak of 12.5Ω, finally it can back to the original resistance. It means that the resistance can reach a certain value when the sensor receives a certain pressure even after being used several times. Not only we prove the stability of the sensor, but also reveal that the resistance of liquid metal circuit has stable relationship with pressure. In this case, we can speculate surroundings’ pressure according to the value or resistance of liquid metal sensor.
4. CONCLUSIONS

In conclusion, this research developed a fast and low-cost method to fabricate liquid metal pressure sensor. In this research, we applied the adhesion difference of liquid metal material on toner and thermal transfer paper, printing circuit in certain pattern on thermal transfer paper, and then transprinted the circuit to surface of flexible Ecoflex film to fabricate pressure sensor. This liquid metal pressure sensor can suffer large wide of deformation, and it can translate pressure signal into resistance signal to complete the collection and analysis of pressure signal. Several related electrical tests have proved that this liquid metal pressure sensor has great stability in electricity which allow the sensor to test the pressure signal for a long time. Finally, we stucked this sensor to the surface of a robot to test pressure signal which is pressed by the surroundings and give the robot the sense of touch. But some flaws of this liquid metal sensor are still worth focusing and need to be improved in future study. For instance, the width of liquid metal circuit can be contracted to fabricate more accurate and tinier pressure sensor. Besides, the strength of Ecoflex film is poor, so it will be broken easily in some hard environments. This research has shown that the liquid metal pressure sensor has potential future in field of computer-human interaction and intelligent robot.

References

[1] Mallory L. Hammock, Alex Chortos, Benjamin C.-K. Tee, Jeffrey B.-H. Tok, and Zhenan Bao, “25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress[J]”, Advanced Materials, 2013(25): 5997–6038.

[2] Siegfried Bauer, Simona Bauer-Gogonea, Ingrid Graz, Martin Kaltenbrunner, Christoph Keplinger, and Reinhard Schwödauer, “25th Anniversary Article: A Soft Future: From Robots and Sensor Skin to Energy Harvesters [J]”, Advanced Materials, 2013(25):1-14.

[3] Aaron D. Mickle, Sang Min Won, Kyung Nim Noh, Jangyeol Yoon, Kathleen W. Meacham, Yeguang Xue, Lisa A. Mcllvried, Bryan A. Copits, Vijay K. Samineni, Kaitlyn E. Crawford, Do Hoon Kim, Paulome Srivastava, Bong Hoon Kim, Seunghwan Min, Young Shiuian, Yeojong Yun, Maria A. Payne, Jianpeng Zhang, Hokyung Jang, Yuhang Li, H. Henry Lai, Yonggang Huang, Sung-II Park, Robert W. Gereau IV, John A. Rogers, “A wireless closed-loop system for optogenetic peripheral neuromodulation [J]”, Nature, 2019(565):361–365.

[4] Klas Tybrandt, Janos Vörös, “Fast and Efficient Fabrication of Intrinsically Stretchable Multilayer Circuit Boards by Wax Pattern Assisted Filtration [J]”, Small, 2016 (12):180-184.

[5] Zheng Lou, Shuai Chen, Lili Wang, Kai Jiang, Guozhen Shen, “An ultra-sensitive and rapid response speed graphene pressure sensors for electronic skin and health monitoring[J]”, Nano Energy, 2016(23):7-14.

[6] Chong-Chan Kim, Hyun-Hee Lee, Kyu Hwan Oh, Jeong-Yun Sun, “Highly stretchable, transparent ionic touch panel[J]”, Science, 2016(353):682-687.

[7] Laura M. Ferrari, Sudha Sudha, Sergio Tarantino, Roberto Espositi, Francesco Bolzoni, Paolo Cavallari, Christian Cipriani, Virgilio Mattoli, and Francesco Greco, “Ultraconformable Temporary Tattoo Electrodes for Electrophysiology[J]”, Advanced Science, 2018(5):1700771.

[8] Biao Ma, Chengtao Xu, Junjie Chi, Jian Chen, Chao Zhao, and Hong Liu, “A Versatile Approach for Direct Patterning of Liquid Metal Using Magnetic Field[J]”, Advanced Functional Materials,2019, 1901370.

[9] Long Teng, Shichao Ye, Stephan Handschuh-Wang, Xiaohu Zhou, Tiansheng Gan, Xuechang Zhou, “Liquid Metal-Based Transient Circuits for Flexible and Recyclable Electronics [J]”, Advanced Functional Materials, 2018, 08739.

[10] Rui Guo, Xuyang Sun, Siyuan Yao, Minghui Duan, Hongzhang Wang, Jing Liu, and Zhongshuan Deng, “Semi-Liquid-Metal-(Ni-EGaIn)-Based Ultraconformable Electronic Tattoo[J]”, Advanced Materials Technologies, 2019, 190183.
[11] J. William Boley, Edward L. White, George T.-C. Chiu, and Rebecca K. Kramer, “Direct Writing of Gallium-Indium Alloy for Stretchable Electronics [J]”, Advanced Functional Materials, 2014(24):3501-3507.

[12] Tong Lu, Lauren Finkenauer, James Wissman, and Carmel Majidi, “Rapid Prototyping for Soft-Matter Electronics [J]”, Advanced Functional Materials, 2014(24):3351-3356.

[13] Guangyong Li, Xuan Wu and Dong-Weon Lee, “A galinstan-based inkjet printing system for highly stretchable electronics with self-healing capability [J]”, Royal Society of Chemistry, 2016(16):1366-1367.