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Mini Review

Review of Liquid Metal-Based Strain and Tactile Sensors

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Abstract

With the popularity and multi-function of intelligent electronic equipment, the wearable electronic devices present a huge market prospect. Stretchable sensor, as an important wearable electronic device, is not only required to have high sensitivity, but also to have good stretchability, robustness, and other mechanical properties. Because the room temperature liquid metal has remarkable deformation ability and good electrical conductivity, it is applied to develop several new high-powered stretchable sensors. In this paper, the current researches of liquid metal-based strain and tactile sensors are reviewed, and future directions of those sensors are proposed according to the present challenges.

Keywords: Liquid metal; Strain sensor; Tactile sensor; Stretchable sensor

Introduction

As an important wearable electronic device, stretchable sensor has played a vital role in many fields, such as healthcare, motion detection, electronic skin, and etc [1-4]. Stretchable strain sensor and tactile sensor are two widely used stretchable sensors [3,5], which can transform external stretching or pressing stimulus signals into detectable electrical signals. The common signal transformations are force-resistance transformation and force-capacitance transformation [4,5]. Presently, the materials of reported stretchable strain and tactile sensors are mainly composite conductive polymer based on solid conductive fillers [3,5-7], including graphene, carbon nanotube, metal nanoparticle, and etc. Those strain and tactile sensors exhibit a remarkable electrical signal response to stretching and pressing, which means it, has an excellent sensitivity. However, the mechanical properties of those sensors are not ideal, such as stretchability and robustness [8,9], which makes it difficult to use for long time under a lager strain. The reason of this is the elastic modulus of conventional solid fillers are 5-6 orders of magnitude higher than that of elastic polymer matrix [8,10]. It severely limits the application and development of stretchable strain and tactile sensors. The room temperature liquid conductive materials have remarkable deformation ability. If they are applied to replace conventional solid conductive fillers, it is expected to prepare the high performance stretchable strain and tactile sensors by eliminating the elastic modulus mismatch. Gallium-based room temperature liquid metal (LM) is one of the ideal liquid conductive materials for their high conductivity, low melting point, and non-toxic. For examples, the conductivity and melting point of eutectic gallium-indium alloy (EGaIn) respectively are 3.4×106S/cm and 15.5 °C, and the conductivity and melting point of gallium-indium-tin alloy (Galinstan) respectively are 3.46×106S/cm and -19 °C [11]. In this review, we highlight several recent significant results related to liquid metal-based strain and tactile sensors, including preparation methods, sensor types, and application fields. Finally, some major challenges and perspectives are also discussed

Recent Development

Right now, a variety of technologies are available to prepare the LM-based strain and tactile sensors. The key point of preparation is how to pattern the LM on or into the elastic matrix [12]. Presently, there are five main methods to pattern the LM, including fluidic injection, stamp lithography, selective wetting, soft imprinting and direct-write printing.

1. Fluidic injection is injecting the LM into microchannel of elastic matrix or elastic fiber tube [13]

2. Stamp lithography is spreading the LM across a stiff stencil placed atop a elastic substrate, and then encapsulating the patterned LM by elastic material [14,15]

3. Selective wetting is utilizing the unique wettability of the LM with several metal (e.g. Sn, Au, and Cu) [16-18], spreading the LM on the substrate with pre-patterned wetting and non-wetting regions, and then encapsulating.

4. Soft imprinting is dipping a structured elastic stamp into LM and transferring it to another surface, embossing a LM film and producing separate structures by squeezing out metal, or by transferring from a single LM film into recesses on a structured surface [19,20]

5. Direct-write printing is utilizing the stickiness of thin oxide skin at the surface of LM to pattern by direct-write printing LM ink [21].

Depending on the different signal transformation mechanisms, the reported LM-based strain and tactile sensors can be divided into resistance type and capacitance type. For resistive-type LM-based strain and tactile sensors, the resistance of the sensors will change when external strain/pressure is applied to the LM-based active materials. Compared with traditional resistive-type sensors, the LM-based sensors not only exhibit excellent stretchability, but also have good robustness and small hysteresis coefficient. For examples, the resistive-type LM-based strain sensor reported by Wu et al. [22] can still be stable after 3500 cycles under 70% strain, and the hysteresis coefficient of sensor is only 0.11%; The resistive-type LM-based tactile sensor reported by Voget et al. [23] can measure the magnitude and direction of pressure; The resistive-type LM-based multi-functional sensor reported by Park et al. [24] can detect the strain from 0% to 250% and the pressure from 0kPa to 40kPa. For capacitance-type LM-based strain and tactile sensors, the mechanical deformation induced by the external strain/pressure leads to the change of overlap area or space between the two electrodes, and then results in variation of the capacitance. The function of capacitance-type LM-based sensors is determined by the structure of two LM conductors. In addition to the traditional parallel plate structure, the common structure of two LM conductors is cross array structure, flat comb structure, and double helix fibers structure. The capacitance-type sensor with cross array structure can be used to detect the tactile pressure distribution. For example, Li et al. [25] adopted fluidic injection method to successfully prepare a capacitance-type LM-based sensor with cross array structure, which realized the millimeter-level detection of pressure distribution. The capacitance-type sensor with flat comb structure usually is used to detect strain. For example, Tabatabai et al. [14] adopted stamp lithography method to prepare a capacitance-type LM-based sensor with flat comb structure, which has a good linear response during stretched from 0% to 250%. The capacitance-type sensor with double helix fibers structure, such as prepared by Cooper et al. [26] using fluidic injection method, can be used for strain sensor, tactile sensor, and torsion sensor. Furthermore, the LM microdroplets can be embedded into the elastic matrix to prepare a stretchable composite material with high dielectric constant [27], which can be used for dielectric layer of capacitance-type sensor.

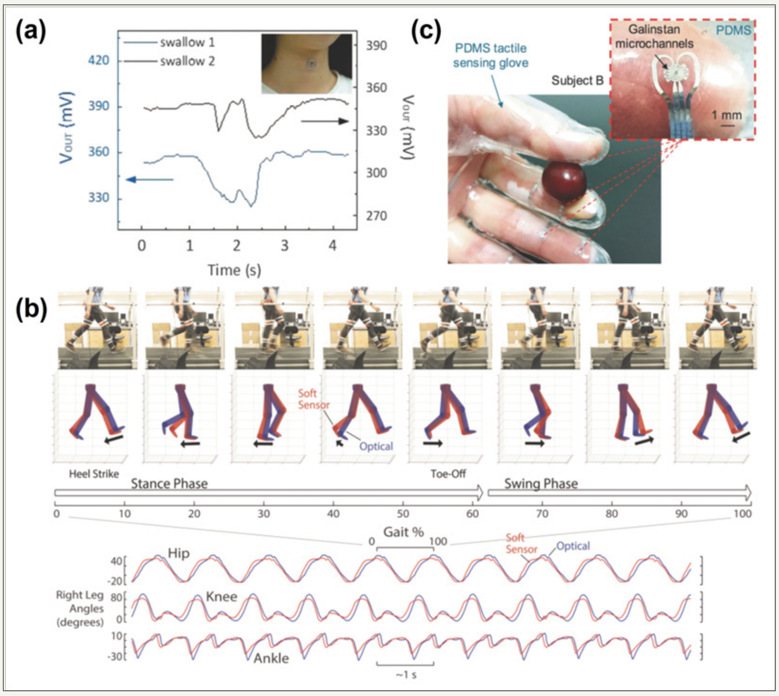

Figure 1: The application of LM-based strain and tactile sensors.

1a: The real-time wireless monitoring of muscle motion upon swallowing [29]

1b: The real-time monitoring of human gait during walking and running [30]

1c: Photograph of the PDMS glove electronic skin embedding multiple LM-based tactile sensors worn while grasping a grape [33].

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Now, LM-based strain and tactile sensors have been widely used in medical healthcare, motion detection, electronic skin, and etc. In medical healthcare, Xi et al. [28] utilized a microtubular LM-based tactile sensor (Φ=250μm) to achieve continuous real-time monitoring of arterial pulse waves; Jeong et al. [29] used a multifunctional LM-based integrated system of sensors to achieve real-time wireless monitoring of muscle motion upon swallowing or during speech, as shown in Figure 1a. In motion detection, Mengüc et al. [30] developed a detection system using several LM-based strain sensors for human gait measurement during walking and running, and the root mean square errors are less than 5° and 15°, respectively, for walking speed of 0.89m/s and running speed of 2.7m/s, as shown in Figure 1b; Matsuzaki et al. [31] identified slight differences of the folding states of finger by a data glove, which is composed of LM-based strain sensors. In electronic skin, Kim et al. [32] prepared a fingertip electronic skin based on LM by soft imprinting method, which can perceive the bending, touching, and pressing motion of finger; Gao et al. [33] prepared a PDMS glove electronic skin embedding multiple LM-based tactile sensors (Figure 1c) to provide comprehensive tactile feedback of a human hand when touching or holding objects.

Conclusion

In the field of flexible electronics, the LM-base strain and tactile sensors have gradually displayed their unique advantages. However, the existing room temperature liquid metal will solidify and turn into solid at low temperature, which leads to existing LM-based sensors cannot work properly. Therefore, the low temperature LM is needed. Moreover, the performances of sensor are closely related to the structure and pattern of sensor. For the LM-based strain and tactile sensors, the research of structure and pattern has just begun and needs to be further developed. In general, the development of LM-based strain and tactile sensors is in its infancy, which means it not only has more important research value and broad application prospect, but also faces many challenges.

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