INVITED PAPER

Electronic Skins Based on Liquid Metals

This article discusses liquid metal alloys of gallium which provide unique physical and chemical properties for e-skin, originating from their high thermal and electrical conductivities.

By Jiong Yang, Wenlong Cheng, and Kourosh Kalantar-Zadeh

ABSTRACT | The implementation and exploration of liquid metals for soft electronics, especially electronic skins (e-skins), are fast increasing. The growing field has received special attention since research regarding gallium-based alloys has intensified as these alloys are much safer in comparison to their more hazardous counterpart, mercury. Liquid metal alloys of gallium provide unique physical and chemical properties for e-skin. These properties originate from their high thermal and electrical conductivities and the fact that the liquid metal is an electronic melt in contrast to the ionic liquid. The formation of 2-D oxides on the surface of liquid gallium alloys, with large van der Waals forces, also adds to their uniqueness. Liquid metals, whether in bulk form or particulated morphologies, provide stretchabilities that surpass any other systems, allowing for the formation of super malleable e-skins. As such, they present certain opportunities for developing elements with extraordinary softness, malleability, and skin compatibility: stretchable wires and electrodes, memories, electronic components such as resistors, coils, diodes, and transistors, soft sensors, energy harvesting/storage elements, and self-healing systems. Presence of the 2-D metal compound skin also helps in accessing the non-Newtonian characteristics of gallium-based alloys that permit the formation of microparticles/nanoparticles and specific fluidics and grant printability in three dimensions. Liquid alloys of gallium, their properties, and applications for e-skins are discussed in this review, and the wealth of opportunities for future applications within soft and stretchable electronics is explored.

KEYWORDS | Electronic skin (e-skin); energy harvesting; energy storage; gallium; liquid metal; metal oxide; self-healing; soft sensor.

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I. INTRODUCTION

Skin is the largest and also one of the most important organs of the human body. It protects us, interacts with the external environment, senses changes in the surrounding area, and sends signals to human brains for corresponding reactions. It endures harsh environmental conditions and functions accordingly, which is ensured by its deformability, stretchability, and self-healing features. With the prosperity of robots and Internet of Things (IoT), electronic skin (e-skin) that is deformable, stretchable, reconfigurable, self-healable, and biosensible/chemosensible is highly desired as the signal interchange medium to mimic the human skin when attached to curved or irregular surfaces, operating in complicated environments. Tremendous efforts have been devoted to the study of e-skin [1]–[19], and a point of view in this field has just been published [20]. To date, various materials, including carbon [1], [21], silver nanowires [22], gold nanowires [23], [24], and conducting polymers [25], [26], have been used to design various e-skin materials and devices. Examples of e-skin applications based on different materials are presented in Fig. 1. While noting that each type of materials has intrinsic pros and cons, gallium-based liquid metals have recently emerged as new materials of choice for e-skin applications because of their unique combination of high electrical and thermal conductivities, nonhazardous and liquid-state nature at physiological temperature [27]–[36]. Based on data from Web of Science with the relevant keyword (liquid metal skin), the annual publication in this field increased by seven times over the

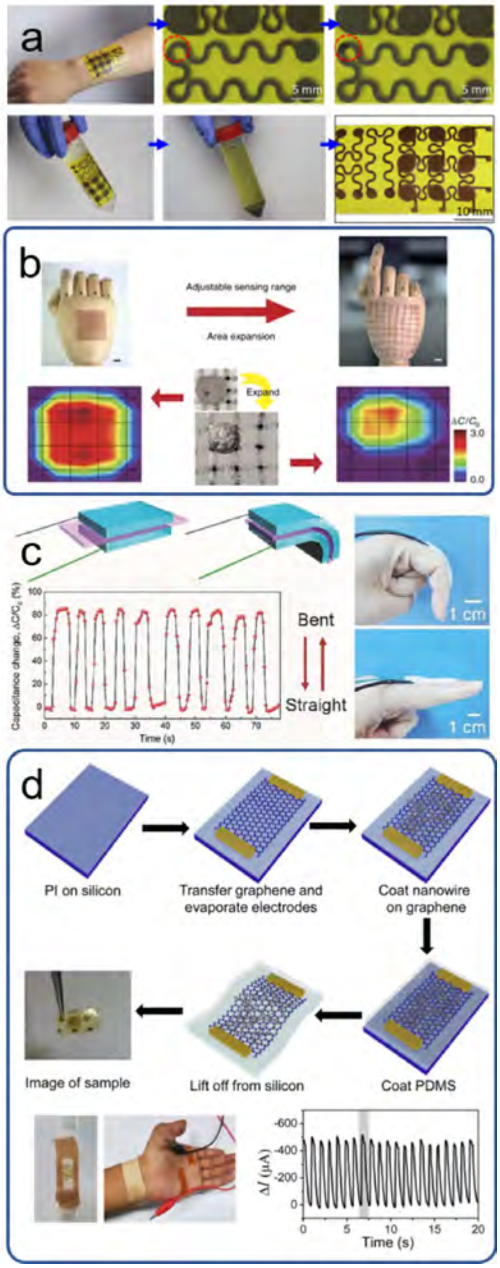

Fig. 1. ***E-skin applications based on different materials. (a) Rehealable (top) and recyclable (bottom) e-skin based on oligomers/monomers and silver nanoparticles. Adjusted with permission from [13]. Copyright CC BY-NC 4.0. (b) Adjustable and expandable pressure sensors based on polymide networked rigid metals. Adjusted with permission from [15]. Copyright CC BY 4.0. (c) Flexible motion sensors based on hydrogel. Adjusted with permission from [16]. Copyright 2017 Wiley. (d) Flexible piezoelectric-induced pressure sensors based on the graphene/nanowires heterostructure. Adjusted with permission from [17]. Copyright 2017 American Chemical Society.***

past decade, and the annual citation kept increasing by roughly 30% in average during that time.

Gallium-based liquid metals have attracted significant attention for incorporation in e-skin because: 1) they remain in liquid state with low viscosity at room and body temperatures [37]–[41], which ensures their deformability, stretchability, and reconfigurability, which are limited only by the encapsulating materials; 2) they own metallic thermal and electrical conductivity [42]–[46], which are essential for efficient signal transfer; 3) they can be designed to show self-healing features because of the moderate viscosity and high stability in ambient conditions [47]–[49]; and 4) they can be developed into different types of sensors to detect various biological and chemical substances [50]–[54]. Extensive investigations have been conducted to reveal the unique properties of liquid metals in different applications, but further efforts are still necessary to realize functional e-skin devices.

Due to their superior electrical conductivity and mechanical deformability, gallium-based liquid metals can act as electrodes and interconnects for compliant electrical circuits and e-skin connections. In addition, liquid gallium alloys can be further fabricated into all kinds of electronic components, including resistors [55], inductors [34], [55], [56], capacitors [56]–[58], diodes [59], [60], memristors (i.e., memory resistors) [61], and transistors [36], [62], [63], as well as essential communications components such as antennas [64]–[67], which can facilitate the signal transfer in e-skin. They can also be used for forming the components of microfluidics [67]–[69]. Liquid metals can be stretched at extraordinary lengths [32], [33], [70], [71]. Metal oxides formed on the surface of gallium-based liquid metals can be separated as high-quality crystalline and atomically thin semiconductors, which can be used for printing atomically thin transistors, photodetectors, and transparent conductors with high malleability for e-skin elements [72]–[75]. Furthermore, gallium alloys can be fabricated into different kinds of soft sensors, such as capacitive sensors [76], resistive sensors [77], acceleration sensors [78], and electrochemical sensors [79], which are all essential parts of e-skin. Gallium-based liquid metals exhibit impressive self-healing [80], [81], which can be used for fabricating self-healable e-skin. Last, gallium-based liquid metals are biocompatible and have also been used in many bioapplications that have been hailed to be the future of e-skin [82]–[85].

Gallium-based liquid metals are generally encapsulated into rubbery polymers for e-skin applications [33], [55], [58], [67], [86]–[89]. The encapsulation of liquid metals can be channel shaped [55], [67], forming small islands [87], [89], [90] or larger bulks [58], [88]. They can be squeezed into relatively flat layers of liquid metals sandwiched between polymeric layers [33], [53], [57]. Liquid metals can be used in the shape of much smaller balls, in accumulation while touching each other [35], [79], [81]. In this case, a large number of these balls are packed together to form the bulk of the functional materials. These balls can be made using various sonication methods [79], [81], [91], [92], resulting in a high dispersity of dimensions or using fluidic methods

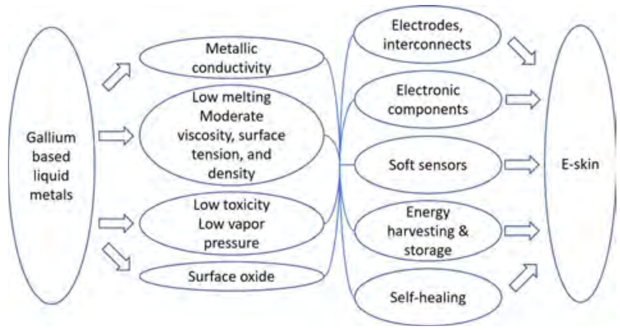

Fig. 2. ***Schematic of the structure of this review on e-skin based on liquid metals.***

that use shear and laminar forces to form more controlled spheres in dimensions [35], [89].

In this review, we will first summarize the unique properties of gallium-based liquid metals and their surface metal oxide layers in Section II. We will then review the recent progress of different e-skin applications using gallium-based liquid metals, including electrodes and interconnects in Section III, electronic components (i.e., resistors, inductors, capacitors, diodes, memristors, and transistors) in Section IV, soft sensors in Section V, energy harvesting and storage in Section VI, and self-healing systems in Section VII. Afterward, we will discuss the drawbacks and limitations of gallium-based liquid metals, and a perspective and outlook in this field will be given in the final section. A structure of this review is illustrated in Fig. 2.

II. GALLIUM-BASED LIQUID METALS AND OXIDES

Gallium in pure form has a melting point of 29.8 °C [38], which means that it remains in a liquid form while in contact with the human skin. Gallium and gallium-based liquid metals, such as EGaIn [93] (eutectic gallium–indium, 75 wt% and 25 wt% for gallium and indium, respectively) and Galinstan [94] (eutectic gallium–indium–tin, 68.5 wt%, 21.5 wt%, and 10 wt% for gallium, indium, and tin, respectively), are the most common alloys with melting points below room temperature. Self-limiting surface oxides of these alloys, which are predominantly made of gallium oxide [72], can improve their wettability [32], [95]. This skin oxide with a wide yet tunable bandgap provides desirable optical and electronic characteristics, which may enable novel e-skin applications. Some unique properties of gallium-based liquid metals are discussed here.

A. Thermal and Electrical Conductivities

Gallium and liquid gallium alloys are materials that contain a pool of electrons. In liquid form, they still retain metallic thermal and electrical conductivities, making them promising candidates as building blocks of e-skin. We have summarized the thermal and electrical conductivities of gallium, EGaIn, and Galinstan in Table 1. We have also included the values of copper and typical ionic liquid in the table for comparison. The thermal and electrical conductivities of gallium and its liquid alloys are approximately one order lower in magnitude than those of copper but at the same time orders of magnitudes higher than their ionic liquid counterparts.

B. Melting Point, Viscosity, Surface Tension, and Density

Gallium-based liquid metals are mainly composed of post-transition metals and adjacent elements in the periodic table. The melting point of gallium is 29.8 °C, which, as we previously highlighted, remains in a liquid state when contacting with human skin. Certain gallium alloys have even lower melting points. For example, the melting points of EGaIn and Galinstan are 15.7 °C and −19 °C, respectively. Other metals can also be coalloyed into liquid gallium alloys and the alloy remains liquid at room temperature [72]. Elemental hafnium, aluminum, gadolinium, copper, and silver have been successfully alloyed in Galinstan at ∼1 wt% [72], and previous experiments

Table 1 Bulk Physical Properties of Gallium, Gallium Alloys, Copper, and Typical Ionic Liquid

	Gallium	EGaIn	Galinstan	Copper	Typical ionic liquid
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	28.7[96] (@350 K)	26.4[97] (@310 K)	25.4[97] (@310 K)	401[98]	<0.2[99] ($[C_2mim]$-$[EtSO_4]$)
Electrical conductivity ($S \cdot m^{-1}$)	3.4×10^6 [100]	3.3×10^6[97]	3.1×10^6[97]	59.6×10^6[98]	1.5[101] ([bmim][DCA]@308.15 K)
Melting point (°C)	29.8[38]	15.7[102]	-19[102]	1083[103]	-
Viscosity ($kg \cdot m^{-1} \cdot s^{-1}$)	2.04×10^{-3}[48]	1.99×10^{-3}[48]	2.40×10^{-3}[104]	-	~100[105]
Surface tension ($mN \cdot m^{-1}$)	708[106] (@ 303 K)	~435[107]	535±11[108]	1258[109] (@1373 K)	~36[110] ($[C_1C_1Im][Tf_2N]$ @300 K)
Density ($g \cdot cm^{-3}$)	6.09[111] (@303 K)	6.25[112] (@323 K)	6.44[113] (@293 K)	7.90[114] (@1385 K)	1.56[110] ($[C_1C_1Im][Tf_2N]$ @300 K)
Vapor pressure (Pa)	1[113] (@1400 K)	$<1.33\times10^{-10}$[113] (@573 K)	$<1.33\times10^{-6}$[113] (@773 K)	-	-

showed that up to 10 wt% of copper [115] and ~13.5 wt% of nickel [116] can be coalloyed into EGaIn. Furthermore, gallium-based liquid metals show supercooling effect, and they remain in liquid form even when cooled down to a temperature well below their melting points [117]–[119]. The dynamic viscosities of gallium and gallium-based liquid metals are low, approximately twice to that of water. For example, liquid gallium has a viscosity of 2.04×10^{-3} kg $\cdot$ m^{-1} $\cdot$ s^{-1}, and EGaIn has a viscosity of 1.99×10^{-3} kg $\cdot$ m^{-1} $\cdot$ s^{-1}, the reduction probably due to the effect of liquid indium having a lower viscosity of 1.69×10^{-3} kg $\cdot$ m^{-1} $\cdot$ s^{-1} [48]. It should be noted that the existence of oxygen significantly enhances the wettability of gallium and its alloys, making them adhere strongly to other surfaces by creating large areas of van der Waals attraction [90], [120]. We have also summarized the surface tension and density of gallium and its alloys in Table 1. Comparatively high surface tension of gallium-based liquid metals can be related to their high densities. The existence of surface oxide and high surface tension of liquid gallium alloys contributes to their printability. Overall, some of the physical properties are common for all gallium-based liquid metals.

C. Toxicity

Compared to the widely known toxic liquid metal of mercury, gallium-based liquid metals are considered nontoxic based on current understandings due to their extremely low vapor pressure at room temperature and negligible solubility in water [102]. A recent review [113] has summarized that the vapor pressure of gallium and EGaIn is 1 Pa at 1037 °C and $<1.33 \times 10^{-10}$ Pa at 300 °C, as given in Table 1. In comparison, the vapor pressure of mercury reaches 1 Pa at 42 °C. In fact, gallium-based liquid metals are relatively safe to be used for therapeutics such as melanoma therapy by electrical stimulation via liquid metal electrodes directly printed on the skin [121]. However, it should be noted that some recent studies have revealed that gallium-based liquid metals may to some degree be toxic to cells [122], [123]. Additional care should be practiced when dealing with liquid metal compounds. Two case studies have been reported on the acute poisoning when working with gallium fluoride [124] and carrying out reactions of gallium halides with chalcogenide complexes in 4-methylpyridine [125]. In addition, gallium arsenide is potentially carcinogenic [126]. Furthermore, ultrafine gallium-rich particles, with yet unknown health impacts, can be released by semiconductor processes [127], and gallium-based liquid metals can circulate into plants from the soil, which should also be explored for their effects [128]–[130]. Several previous reviews have also briefly discussed the toxicity of gallium compounds [131]–[133]. Considering that gallium-based liquid metals and their salts can be harmful to the environment, they need to be carefully handled. Potential hazards of gallium, its salts, and alloys need to be further explored.

D. Surface Oxide

Thermodynamically, a self-limiting gallium oxide layer forms on gallium-based liquid metals even at oxygen concentrations as low as ppm level or when immersed in liquid with dissolved oxygen [134]. Fig. 3(a) shows that the surface oxide layer can sustain as the microchannel of liquid metals. This thin layer of oxide increases the wettability of liquid metals and, therefore, is desired for certain applications, including liquid metal patterning [53], [135], supporting 3-D structures of liquid metal flows [134], and some self-healing systems where gallium-based liquid metals need to be encapsulated by surface oxide layer before external impact [35], [81]. On the other hand, this oxide layer needs to be removed to realize the full control of liquidity and to make use of their conductive nature, such as the actuation of oxide-free liquid metals [90], laser [136], and mechanical [137] sintering of the surface oxide layer on liquid metals to gain conductivity [Fig. 3(b) and (c)], and some micropatterning techniques using dewetting [120]. Different methods have been proposed to effectively eliminate the surface oxide layer. For example, one can simply put gallium-based liquid metals in acidic or basic environments to remove the gallium oxide layer as it reacts with both acids and bases. In addition, applying a negative electric field can also reduce this surface oxide.

The oxide layer on the surface of gallium-based liquid metals dominates their rheological behaviors because of its elastic nature, which allows the formation of stable structures in microchannels [107] and facilitates various patterning techniques of liquid gallium alloys [87], [120], [139]–[142]. This non-Newtonian behavior of gallium-based liquid metals has also been demonstrated in a Galinstan marble coated with nanoparticles, where the Galinstan marble rebounded after free falling and impacting on substrates [138], as shown in Fig. 3(d).

In addition to being used in the metal forms, gallium-based liquid metals can also act as a reactive environment to print high-quality atomically thin metal oxide layers on various substrates for e-skin application [72] [Fig. 3(e)]. So far, by taking advantage of this technique and further processing, different 2-D layers have been successfully separated with wafer-scale lateral dimension, including gallium sulfide (GaS) for photodetector applications [75], tin oxide (SnO) with a broad bandgap of ~4.2 eV for potential ultraviolet applications [74], and gallium phosphate ($GaPO_4$) for piezoelectricity applications [73]. In fact, many metal oxides can be prepared and separated uniquely from the reaction environment of liquid gallium alloys by coalloying them with other metals and relying on the fact that their oxides can appear on the surface of liquid metals when the process is thermodynamically favorable. Metal oxides can also be separated in liquid by gas injection or sonication, as presented in [72] and [143], and the prepared metal oxide nanoflakes can be used for photocatalytic applications due to their rich trap states [143].

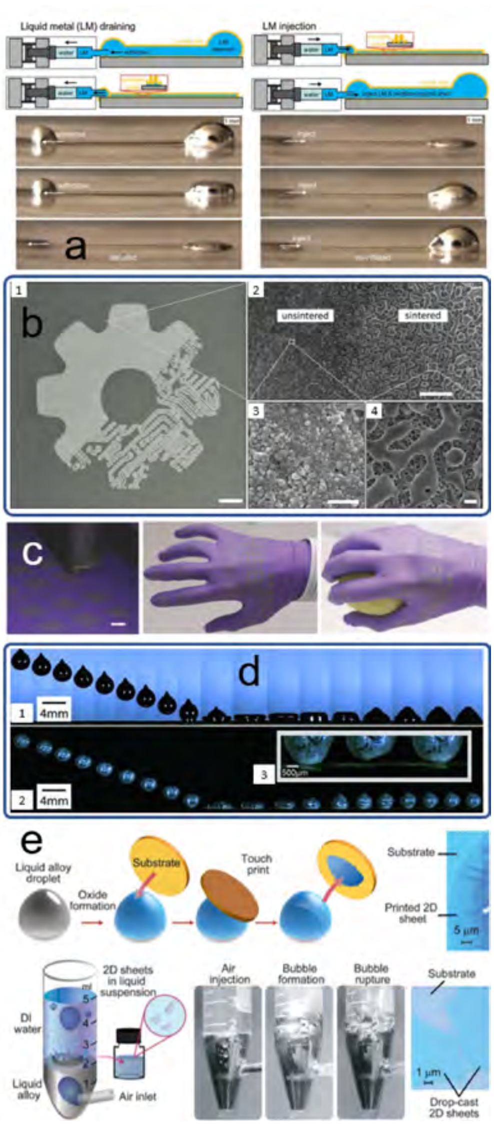

Fig. 3. ***Metal oxides on the surface of gallium-based liquid metals. (a) Draining (left) and injection (right) of Galinstan from/into gallium oxide skin microchannels. Adjusted with permission from Ref [134]. Copyright 2015 Springer. (b) Laser sintering of gallium oxide on EGaIn to form a conductive pathway. Sections 2–4 are zoomed-in images of corresponding areas. Scale bar: 2 mm, 10 μm, 1 μm, and 1 μm for 1, 2, 3, and 4, respectively. Adjusted with permission from Ref [136]. Copyright 2018 American Chemical Society. (c) Inkjet printing of EGaIn nanoparticles and mechanical sintering of surface oxides for wearable sensing applications. Scale bar: 5 mm. Adjusted with permission from Ref [137]. Copyright 2015 Wiley. (d) Free falling of Galinstan pendent drop (top, 1) and Galinstan marble coated with tungsten oxide (bottom, 2). Section 3 is the zoomed-in image of the last three frames in 2. Adjusted with permission from [138]. Copyright 2013 Wiley. (e) Mechanical transfer (top) and gas injection (bottom) to prepare atomically thin metal oxide layers from Galinstan. Adjusted with permission from [72]. Copyright 2018 American Association for the Advancement of Science.***

III. ELECTRODES AND INTERCONNECTS

Gallium-based liquid metals can be used as electrodes and interconnects in e-skins, which offer the following attributes: 1) compared to mercury, gallium-based liquid metals are almost nontoxic due to their low vapor pressure at room temperature [144] and biocompatibility [145]–[147]; 2) gallium-based liquid metals are highly deformable and conformable while maintaining a superior conductivity when used in wearable electronics, and their deformability and conformability are essentially limited only by the encapsulating medium; 3) gallium-based liquid metals can maintain a soft touch with contact materials, thus avoiding potential damage or penetration; and 4) the wettability of gallium-based liquid metals can be tuned by applying an electric field, making them promising candidates for reconfigurable electrodes and interconnects. With the aforementioned advantages, electrodes and interconnects based on liquid metals can be used in all electronic devices of e-skin components.

Electrodes and interconnects based on liquid gallium alloys have been demonstrated for energy harvesting [32], [57], [148], [149], sensors [53], [54], [76], [150], compliant electrical contacts [29], [33], [55], [70], [95], [135], [146], [151]–[156], and electrical characterizations [47], [157], [158]. Because of their liquid form at room temperature, gallium alloys can tolerate high deformation and maintain total contact with the dielectric material when being used as electrodes for energy harvesting applications, including triboelectricity, piezoelectricity, and thermoelectricity, resulting in the high energy conversion efficiencies under various deformations in wearable electronics. Energy harvesting devices based on liquid gallium alloys will be discussed in detail in the later section. Moreover, gallium-based liquid metals can be used as electrodes for sensors on e-skin because of their high conductivity and large deformability. Considering that sensors are major parts of e-skin, it will be discussed separately in the later section.

In addition to energy harvesting and sensor applications, gallium-based liquid metals can also be utilized as compliant electrodes and interconnects for other applications. For example, Ren *et al.* [156] recently reported dispersing magnetic iron particles into the Galinstan matrix to form Galinstan-based adaptive and magnetoactive electrodes, as shown in Fig. 4(a), and their modulus and viscosity are dependent on the iron molar percentage. By using EGaIn-grid electrodes encapsulated in organic polymers, a stretchable electroluminescence device that can maintain light emission with tensile strain up to 50% was successfully fabricated [33]. Stretchable thermoelectric generators have also been demonstrated by combining rigid solid thermoelectric materials with gallium-based alloys [70]. Furthermore, Ozutemiz *et al.* [95] demonstrated EGaIn–copper interfaces as electrical interconnects for the microelectronics integration, and Hirsh *et al.* [151] showed that Ga–$AuGa_2$ biphasic thin metal films can function as stretchable interconnects for light-emitting diodes, as shown in Fig. 4(b) and (c), respectively. Theoretically, gallium-based liquid metals can be used as electrodes and intercon-

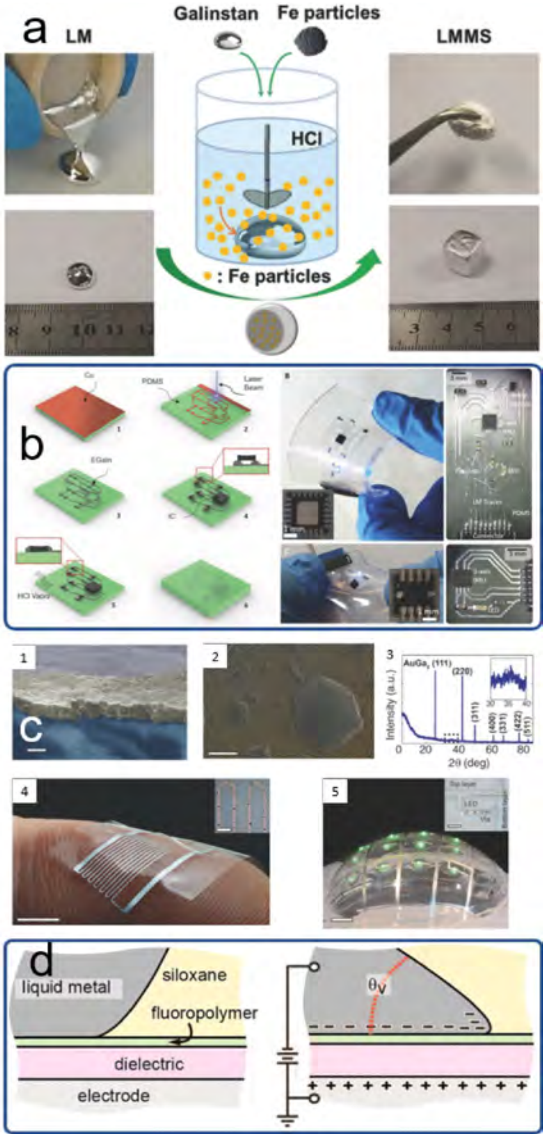

Fig. 4. ***Electrodes and interconnects based on liquid gallium alloys. (a) Adaptive magnetoactive electrodes made from Galinstan and iron particles. Adjusted with permission from [156]. Copyright 2018 Wiley. (b) Microelectronics integration of electronic components interconnected by EGaIn-copper interfacing. Adjusted with permission from [95]. Copyright 2018 Wiley. (c) Light-emitting diodes interconnected by intrinsically stretchable gold-gallium thin films. Sections 1 and 2 are the false-color SEM images of the biphasic gold-gallium film on PDMS. Scale bar: 500 nm for 1 and 5 μm for 2, respectively. Section 3 is the XRD pattern of gold-gallium film. Sections 4 and 5 are the photograph of biphasic gold-gallium interconnects. Scale bar: 5 mm and 500 μm for Section 4 and the inset in Section 4, respectively; 15 and 2 mm for Section 5 and the inset in Section 5, respectively. Adjusted with permission from [151]. Copyright 2016 Wiley. (d) Electrowetting and actuation of oxide-free Galinstan. Adjusted with permission from [90]. Copyright 2016 American Chemical Society.***

nects for almost all e-skin applications because of their superb combination of deformability and conductivity. Recent research advances mainly focus on patterning and encapsulation methods of liquid metals, their integration with other commercial devices, and their adaptability with conventional semiconductor fabrication techniques.

Another advantage of gallium-based liquid metals is their electrochemically adjustable wettability. Holcomb *et al.* [90] and Diebold *et al.* [87] demonstrated electrowetting and actuation of gallium-based liquid metals. By using acidified siloxane to continuously eliminate the surface oxide formed on liquid gallium alloys, they reached a scenario [90] that a conducting fluid (liquid metal) is surrounded by an insulating fluid (acidified siloxane) on an electrode but separated by a dielectric layer, resulting in a decrease in the contact angle by around 50° with reference to gallium-based liquid metals, as shown in Fig. 4(d). Based on the above-mentioned electrowetting and actuation, gallium-based liquid metals can be used as reconfigurable electrodes and interconnects that can turn on/off electric circuits in e-skin with an electric field.

IV. ELECTRONIC COMPONENTS

Gallium-based liquid metals have been utilized to fabricate different kinds of flexible electronic components for e-skin, including resistors [55], [61], inductors [34], [55], capacitors [55], [76], [95], antennas [64]–[67], [159], memristors [61], diodes [59], [60], and transistors [36], [62], [63]. These applications can be roughly divided into two categories based on whether they make use of the surface oxide of gallium alloys or not. Generally, resistors, inductors, and capacitors can form one group as they all rely on the conductivity of liquid metals, where the surface oxide layer serves to improve their wettability. On the other hand, memristors and diodes take advantage of the electric control of the surface oxide layer on liquid gallium alloys to fulfill their functions. In addition, atomically thin metal oxide layer separated from liquid metals can be used to fabricate transistors by conventional semiconductor techniques. Integrating these fundamental electronic components into e-skin will enable essential functions, such as sensing, signal processing, telecommunication, and energy transfer.

A. Resistors

Although conductivity of liquid gallium alloys is high compared to other flexible conducting materials such as ionic liquids and hydrogels [160], they are still less conductive than highly conductive rigid metals such as copper. Thanks to the eutectic nature of gallium alloys, gallium-based liquid metals can be fabricated into resistors via the deliberate yet simple control of channel lengths and cross sections. In an example [55], it was shown that with a channel width of 5 μm and thickness of 1 μm, EGaIn-based resistors [Fig. 5(a)] possess a linearly scaled resistance of 1 kΩ per 17 mm in channel length, which corresponds well with calculated values. Taking into account the relatively large resistivity of liquid gallium alloys, their resistance needs to be carefully considered in electrical circuits,

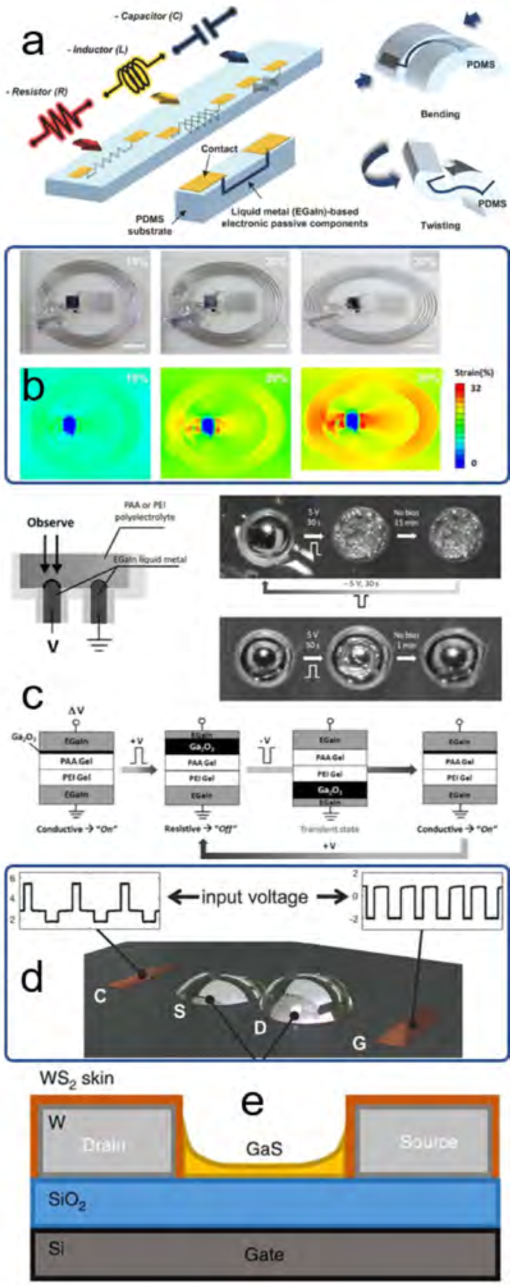

Fig. 5. ***Electronic components made from gallium-based liquid metals and metal oxides for e-skin applications. (a) Schematic of deformable resistors, inductors, and capacitors. Adjusted with permission from [55]. Copyright 2017 Wiley. (b) Stretchable antennas based on Galinstan. Adjusted with permission from [54]. Copyright CC BY 4.0. (c) Proposed working mechanism of memristors with EGaIn/polyacrylic acid gel/polyethyleneimine gel/EGaIn structure. Adjusted with permission from [61]. Copyright 2011 Wiley. (d) Field-controlled electrical switch with two EGaIn droplets acting as source and drain and two copper electrodes acting as counter and gate. Adjusted with permission from [62]. Copyright CC BY 4.0. (e) Schematic of the GaS transistor. Adjusted with permission from [75]. Copyright CC BY 4.0.***

especially those with complicated structures. It should be noted that the dimensions of liquid metal channels change when resistors are deformed, rendering a corresponding modulation in their resistance, which can be utilized for e-skin sensing applications after precise calibrations.

B. Inductors and Capacitors

Inductors and capacitors are passive energy storage components in electrical circuits, and they can be highly deformable when fabricated by using liquid gallium alloys embedded in soft elastomers. Highly deformable planar spiral inductors have been fabricated with EGaIn [55], [56]. They act as a short circuit under direct current, and the current lags when an alternating voltage is applied. As can be expected, the inductors respond monotonically to deformation, which can be used for sensing applications. Another example [34] of inductors based on liquid gallium alloys is the fabrication of miniaturized electromagnetic actuators based on EGaIn. Silicone foils filled with EGaIn show high thermal conductivity, and an array of those soft coils can act as vibrotactile actuators and soft 3-D grippers for wearable devices and e-skin. According to a recent review [161], liquid metals can be used to fabricate soft actuators and sensors for robotics. With liquid-state flexibility, gallium-based liquid metals can be used for fabricating inductors compliant with complicated surfaces. In addition, sophisticated design needs to be explored to maintain their performance under excessive deformation in e-skin. Capacitors are another kind of application of gallium-based liquid metals for flexible e-skin due to their high conductivities under large deformation, and we will discuss them in the soft sensor section.

C. Antennas

Antennas are essential parts of communications, and smart e-skins require them for transmitting and receiving signals to personal computers and mobile phones. It has been shown that adjustable antennas can be formed using gallium-based liquid metals [65], [66], [159], [162]–[164]. Specifically, it has been demonstrated that the electrowetting of liquid metals can be applied to radio frequency applications such as fabricating reconfigurable polarizers [87] and frequency-adjustable antennas [165]. Antennas made from gallium-based liquid metals have been demonstrated to realize wireless energy and signal transfer between e-skin and bulk devices under deformation [54], as shown in Fig. 5(b).

D. Diodes, Memristors, and Transistors

By making use of the surface oxide of gallium-based liquid metals and electrically controlling it, So *et al.* [60] and Koo *et al.* [61] have successfully fabricated prototypal soft diodes and memristors using EGaIn, as shown in Fig. 5(c), which can be essential parts of e-skin applications. The current rectification effect of diodes is realized by the oxidization and reduction of the nonconductive oxide layer on EGaIn, which corresponds to the backward and forward modes of diodes, respectively. By choosing different contacting materials with certain pH values to EGaIn, the electrically induced oxide layer can either stay or be removed post the electrical bias, thus forming an asymmetry, which leads to the memristor behavior. Apart from that, a thermal diode [59] based on liquid metal mercury was also fabricated by taking advantage of the thermal expansion of mercury, and gallium-based liquid metals can also be used for similar applications with superior performance considering their higher thermal conductivities, but still several challenging fabrication problems need to be surmounted, such as their strong wettability after oxidation.

Transistors are the cornerstone of modern semiconductor industries, and gallium-based liquid metals are fundamentally limited in transistor applications because of their metallic nature. The progress so far includes examples such as a transistorlike liquid metal switch [as shown in Fig. 5(d)] where two EGaIn droplets act as source and drain and two copper electrodes act as counter and gate with an effective conductance ON/OFF ratio of over 10^3 [62] and a carbon nanotube (CNT) transistors interconnected by EGaIn with an ON/OFF ratio over 10^4 [63]. In addition, surface metal oxides, reduced oxides, and other p-type and n-type semiconductors can be utilized to form liquid metal–semiconductor or more complicated and interesting junctions, which can be further explored for establishing diodes and transistors [138]. Furthermore, gallium-based liquid metals, such as EGaIn and Galinstan, can be the reaction environment for room temperature synthesis of atomically thin metal oxide layers that cannot achieve 2-D stratified structures by any other approaches [72]. Due to the weak interaction between liquid metals and the surface oxide, wafer-scale atomically thin oxide layers can be transferred to other substrates, and then, they can be further processed to prepare atomically thin sulfides, phosphates, or other metallic compounds. For example, a two-step chemical vapor treatment of hydrogen chloride vapor and sulfur vapor exposure can transform the separated atomically thin gallium oxides into semiconducting gallium sulfide at a relatively low processing temperature of $\sim$300 °C [75]. Afterward, these crystalline semiconducting metal compound layers can be fabricated into transistors [Fig. 5(e)] to be incorporated into e-skin [74], [75].

V. SOFT SENSORS

Compared to the human skin, e-skin can be advantageous in several aspects, including its reconfigurability and biosensibility/chemosensibility. In addition, e-skin made from gallium-based liquid metals can be highly deformable while functioning and monitoring various signals on the human skin or complex artificial surfaces. So far, significant attention has been put on the sensing applications using gallium-based liquid metals, and different kinds of sensors have been fabricated to be the essential part of e-skin, such as strain sensors, pressure sensors, tactile sensors, acceleration sensors, and gas sensors. To date, sensors made from liquid gallium alloys mainly fall into three categories, capacitive sensing [57], [58], [76], [150], [166]–[169], resistive sensing [53], [54], [77], [79], [170]–[173], and electrochemical sensing [74], [79], [138], [174]–[176]. With the alteration of the surrounding environment, capacitive sensing measures the capacitance change between two or more groups of liquid metal electrodes, and resistive sensing measures the resistance change of the electrical conductors. Electrochemical sensors operate based on the fact that liquid metals can selectively accommodate other metals and release them at specific voltages with reference to that of gallium alloys.

Gallium-based liquid metals have been used for fabricating 1-D, 2-D, and 3-D soft capacitive sensors. 1-D torsion, strain, and touch sensors have been developed by intertwining two fibers filled with EGaIn, and they can measure torsion up to 800 rad $\cdot$ m^{-1}, as shown in Fig. 6(a) [76]. By having an orthogonally arranged double-layer of EGaIn electrodes embedded in a thin, compliant polymer membrane, Li *et al.* [150] fabricated a deformable tactile sensor [Fig. 6(b)] that was able to detect strain or pressure distributions with a high spatial resolution of $\sim$1 mm. To further improve the sensitivity and dynamic range of 2-D capacitive sensors, liquid metal droplets arrays utilized in [169] and more complex device structures can be considered. In addition, due to the self-healing property of gallium-based liquid metals, one can even reconfigure a frequency sensor from two to three dimensions, as presented in [57]. Furthermore, Nakadegawa *et al.* [167] and Nagatomo and Miki [168] have proposed millimeter-scale three-axis capacitive force sensors based on Galinstan that could detect both shear and reactive forces in the range of 0–5 N, which could be potentially attached to endoscopes to detect early-stage tumors in human bodies. Logically, such multidimensional capacitive sensors based on liquid gallium alloys can be incorporated as e-skin for other health applications.

Flexible resistive sensors can also be made from gallium-based liquid metals. For example, Matsuzaki and Tabayashi [53], Jeong *et al.* [54], Gao *et al.* [170], and Yeo *et al.* [173] have fabricated wearable pressure/strain sensors as e-skin to detect body gestures by monitoring the real-time output voltage changes of the liquid gallium alloy electrical circuit. In addition to the demonstration of different voltage outputs under various hand gestures in the other three works, Gao *et al.* [170] also demonstrated precise heartbeat monitoring with an increased sensibility. A recent review [177] also summarized advanced healthcare applications in e-skin devices. Xi *et al.* [77] demonstrated a microtubular pressure sensor [Fig. 6(c)] based on EGaIn with a force sensitivity of 68 N^{-1} and a low detection limit of 5 mN with a human-hair comparable footprint of $\sim$120 μm. Galinstan has also been fabricated as viscometers to measure the viscosity of Newtonian and non-Newtonian fluids by measuring the resistivity change when different fluids flow through and cause cross-sectional area changes in the Galinstan channel [172]. To increase

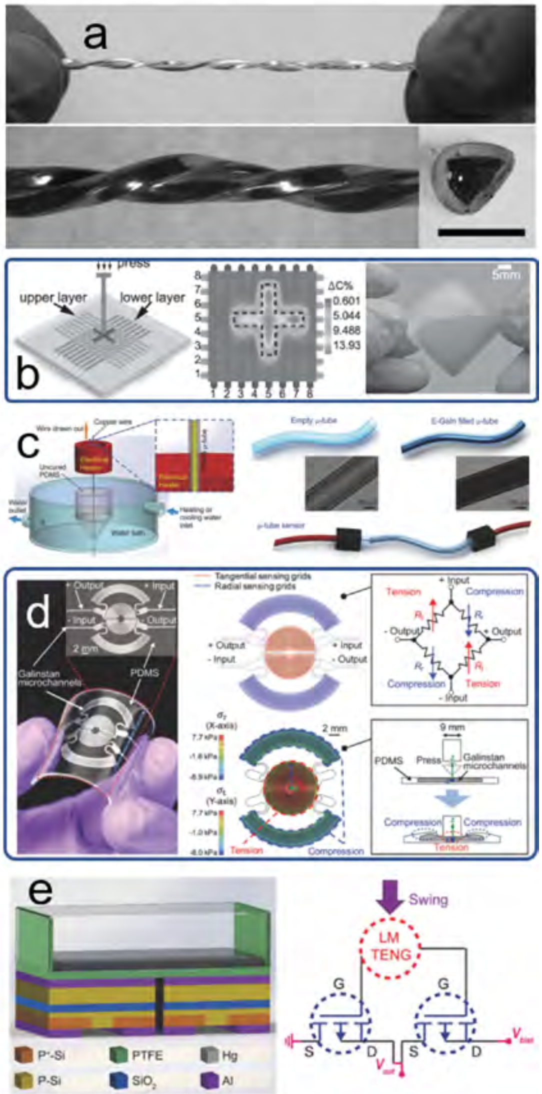

Fig. 6. ***Soft sensors based on liquid metals. (a) Two intertwined fibers filled with EGaIn as torsion, strain, and touch sensors. Scale bar: 1 mm. Adjusted with permission from [76]. Copyright 2017 Wiley. (b) Soft tactile sensor composed of two groups of orthogonally arranged microchannels filled with EGaIn. Adjusted with permission from [150]. Copyright 2016 AIP Publishing LLC. (c) Highly sensitive microtubular tactile sensor based on EGaIn. Adjusted with permission from [77]. Copyright 2017 Wiley. (d) Microfluidic diaphragm pressure sensor based on Galinstan. Adjusted with permission from [170]. Copyright 2017 Wiley. (e) Electronic gradienter based on two liquid metal tribotronic transistors. Adjusted with permission from [36]. Copyright 2018 Wiley.***

the sensibility, Gao *et al.* [170] proposed a Galinstan-based pressure sensor [Fig. 6(d)] in the form of a Wheatstone bridge circuit for health and touch monitoring, which can resolve less than 50-Pa pressure changes with a detection limit lower than 100 Pa. One unique advantage of e-skin is its biosensibility/chemosensibility, and gas sensors with detection limits as low as 1 ppm for NO_2 and 20 ppm for NH_3 have been achieved with oxidized Galinstan [79]. By fabricating heterojunctions of Galinstan and ionic liquid in a stretchable polydimethylsiloxane (PDMS) substrate, Ota *et al.* [52] successfully demonstrated compliant temperature, humidity, and gas sensors that can be incorporated into e-skin.

Electrochemically sensing heavy metal ions at extremely low concentrations is a unique advantage of gallium-based liquid metals. By applying stripping voltammetry and using Galinstan or Galinstan/metal oxide junctions as working electrodes, concentrations down to 100 ppb of Pb^{2+} in electrolytes have been detected, and the presence of surface-embedded particles or liquid metal particulates with high surface-to-volume ratios can greatly enhance the sensitivity [138], [176]. Other types of sensors have also been fabricated using liquid metals. For example, Zhang *et al.* [78] demonstrated a self-powered acceleration sensor that can detect acceleration in the range of 0–60 $\mathrm{m \cdot s^{-2}}$ with a sensitivity of 0.26 $\mathrm{V \cdot s \cdot m^{-2}}$. It is based on a triboelectric nanogenerator (TENG) with mercury and nanofiber-networked polyvinylidene fluoride (nn-PVDF) as two triboelectric materials. Although this acceleration sensor was made from nonstick mercury, one can also use gallium-based liquid metals by continuous elimination of the surface oxide, as presented in [87] and [90], or by implementing approaches to effectively isolate the sensor from oxygen. Moreover, Bu *et al.* [36] first demonstrated the incorporation of liquid metals into tribotronic devices and successfully fabricated an electronic gradienter [Fig. 6(e)] based on two liquid metal tribotronic transistors, which could measure angle oscillations with a large sensing range of $\sim 60^\circ$ and high sensibility up to 170 mV per degree. Although the authors used mercury as the electrode, this work can naturally be expanded to gallium-based liquid metals. Table 2 summarizes different types of sensors based on liquid gallium alloys, including their functions, dynamic ranges, and sensitivities.

VI. ENERGY HARVESTING AND STORAGE

Gallium and its alloy have traditionally been used as working electrodes for lithium-ion batteries and can be charged as large as two lithium atoms for any one gallium [178]. Electrical circuits in e-skin rely on compliant power supplies to realize fully flexible functioning, and several approaches have been proposed for energy harvesting, including near-field communication for wireless power transfer [54], triboelectricity [32], [148], [149], piezoelectricity [73], [179], and thermoelectricity [70], [86]. Furthermore, gallium and its liquid alloys have long been investigated for lithium-ion batteries for energy storage [180]–[183], and they can potentially be used within e-skin. Two reviews [184], [185] have been recently published on the energy solution of e-skin.

Triboelectric generators based on liquid gallium alloys have been extensively studied for e-skin applications. By sealing liquid metals in highly deformable silicone or other dielectric materials and making essential electrical contacts, one can fabricate a TENG working in

Table 2 Different Types of Sensors Based on Liquid Metals

Ref	Type	Function	Range	Sensitivity	Remarks
58	Capacitive sensing	Inertial sensing	3.5-6 pF	-	Gesture recognition
76		Strain sensing	800 rad/m	-	-
167		Force sensing	5 N	0.49%/N	-
169		Touch sensing	0.7 N	147 pF/N	-
53	Resistive sensing	Strain sensing	up to 50%	-	Limited by encapsulating material
77		Tactile sensing	-	2.8/N and >68/N for forces <5 and >500 mN	Pulse sensing
170		Pressure sensing	60 kPa	~10%/kPa	Heartrate monitoring
171		Strain sensing	700%	-	-
172		Pressure sensing	230 kPa	-	-
173		Tactile sensing	100 kPa	0.05/kPa	Gesture monitoring
79	Electrochemical sensing	Gas sensing	-	1 ppm for NO_2, 20 ppm for NH_3,	Response and recovery time, >30 and >45 min
138		Heavy metal ion sensing	-	10 mmol/L for Pb^{2+} and Cd^{2+}	-
174		Organic compounds sensing	-	3.37×10^{-5}%/ppm	Response and recovery time, ~1.45/1.87 min
176		Heavy metal ion sensing	-	100 ppb of Pb^{2+}	-

different modes, such as vertical contact-separation mode, lateral sliding mode, single-electrode mode, and freestanding triboelectric-layer mode [186]. Previous publications reported that gallium-based TENG can provide a charge density of 68.4 and 84.5 $\mu C \cdot m^{-2}$ [32], and the charge density of mercury-based TENG can be over 400 $\mu C \cdot m^{-2}$ [149]. This huge difference is directly related to the instant formation of an oxide layer on the surface of gallium alloys, which leads to the screening of generated tribocharges [149]. Specifically, a TENG [Fig. 7(a)] based on Galinstan even remained functional under a strain up to 300% [32]. It should be noted that oxygen also influences the performance of mercury-based TENG. For example, Chen *et al.* [148] pointed it out that the charge density of a mercury-based TENG can vary from +100 to −160 $\mu C \cdot m^{-2}$ when the oxygen concentration increases from 0 to over 2000 ppm. Therefore, one should consider the application environment of TENG based on liquid metals to achieve the optimal performance.

Piezoelectric and thermoelectric generators have also been proposed by making use of gallium-based liquid metals. Yu *et al.* [179] successfully improved the piezoelectric performance of electrospun PVDF fibers by using Galinstan as the flexible electrode, as shown in Fig. 7(b), compared to the solid-state aluminum electrode. In this work, the expanded contact area led to improved piezoelectric performance. A thermoelectric generator was fabricated by using liquid Galinstan interconnecting solid Bi_2Te_3 pellets, as shown in Fig. 7(c), which exhibited a power density of 40.6 $\mu W \cdot cm^{-2}$ under a 20 °C temperature difference at an average temperature of 25 °C, and it can be tolerated up to 60% stretch during 1000 cycles without distinct performance deterioration [70]. These thermoelectric power generators can take advantage of the temperature difference between the body and the environment. However, such power density values are still relatively low for many practical applications. In fact, gallium and its liquid alloys have traditionally been used as electrodes for lithium-ion batteries for energy storages. Self-healed anodes based on liquid gallium–indium alloys [182] [Fig. 7(d)] have been demonstrated with a super long cycling life of over 4000 cycles with a capacity of ∼400 $mA \cdot h \cdot g^{-1}$ at a current density of 4000 $mA \cdot g^{-1}$, which surpasses many other metal anodes reported so far. In addition, by using a Galinstan/silicon nanocomposite with spontaneous repairing capability as the anode for lithium-ion batteries, a reversible capacity of 1500 $mA \cdot h \cdot g^{-1}$ at a current density of 4000 $mA \cdot g^{-1}$ has been demonstrated [187]. Pairing e-skin with energy harvesting and storage devices based on liquid gallium alloys opens the way for developing future self-sustainable e-skin systems.

VII. SELF-HEALING

Akin to biological skins, e-skin needs to maintain functionality and deformability under different impact loadings, such as severe bending, twisting, rupturing, and cutting. For these applications, self-healing is a core characteristic for e-skin. In order to achieve self-healing in e-skin, many approaches have been explored, including the autonomic release of microencapsulated healing agent to heal polymer composites [188], the dynamic reconstruction of nanostructured conducting CNT networks [189], the ion–dipole interaction in highly stretchable ionic conductors [190], and the dynamic bonding in conjugated polymers with a solvent and thermal healing treatment [191]. Due to their fluidity and metallic conductivity, gallium-based liquid metals have been proposed as potential self-healing agents for e-skin applications. So *et al.* [192] demonstrated self-healing for antennas made from EGaIn embedded in PDMS elastomeric channels that could heal spontaneously after cutting, which was facilitated by the reconnecting nature of PDMS and the soft oxide surface of EGaIn. Later on, Blaiszik *et al.* [91] reported autonomic restoration of electrical conductivity after cutting of the rigid metal in a highly integrated circuit by the release and transportation of EGaIn microcapsules with an average size of ∼200 μm, and the self-healing occurred vary fast in the time scale of ∼160 μs. The limitation of this

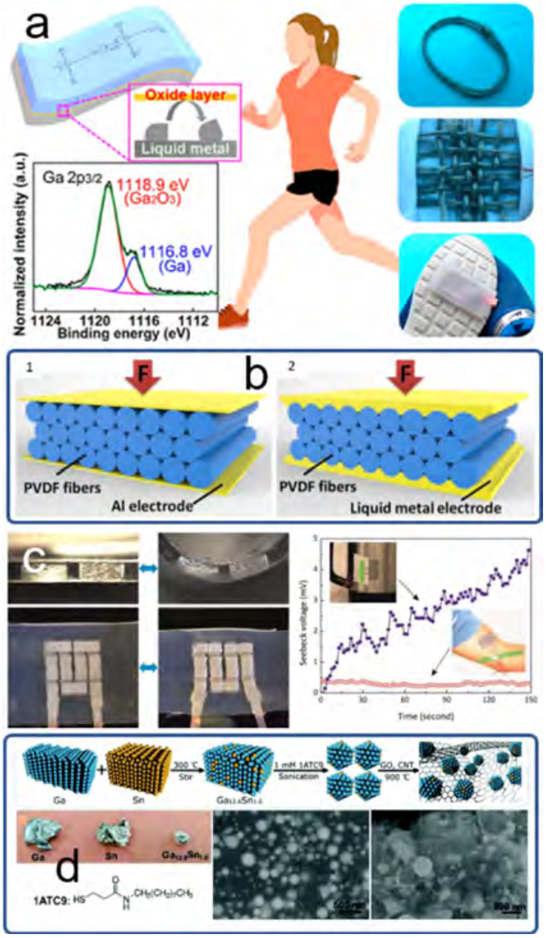

Fig. 7. ***Energy harvesting and storage with liquid gallium alloys. (a) Demonstration of stretchable TENG based on Galinstan for mechanical energy harvesting from arm shaking (top right), hand patting (top middle), and walking (top bottom). Adjusted with permission from [32]. Copyright 2018 American Chemical Society. (b) Schematic of contact between PVDF fibers and solid aluminum (1, left) and liquid Galinstan (2, right) electrodes for piezoelectricity generation. Adjusted with permission from [179]. Copyright 2018 The Electrochemical Society. (c) Arm-attachable and stretchable thermoelectric generators using Galinstan as interconnects. Adjusted with permission from [70]. Copyright 2017 American Chemical Society. (d) Lithium-ion battery anodes composed of gallium-indium alloys on the reduced graphene oxide (GO)/CNT skeleton. Adjusted with permission from [182]. Copyright 2017 Royal Society of Chemistry.***

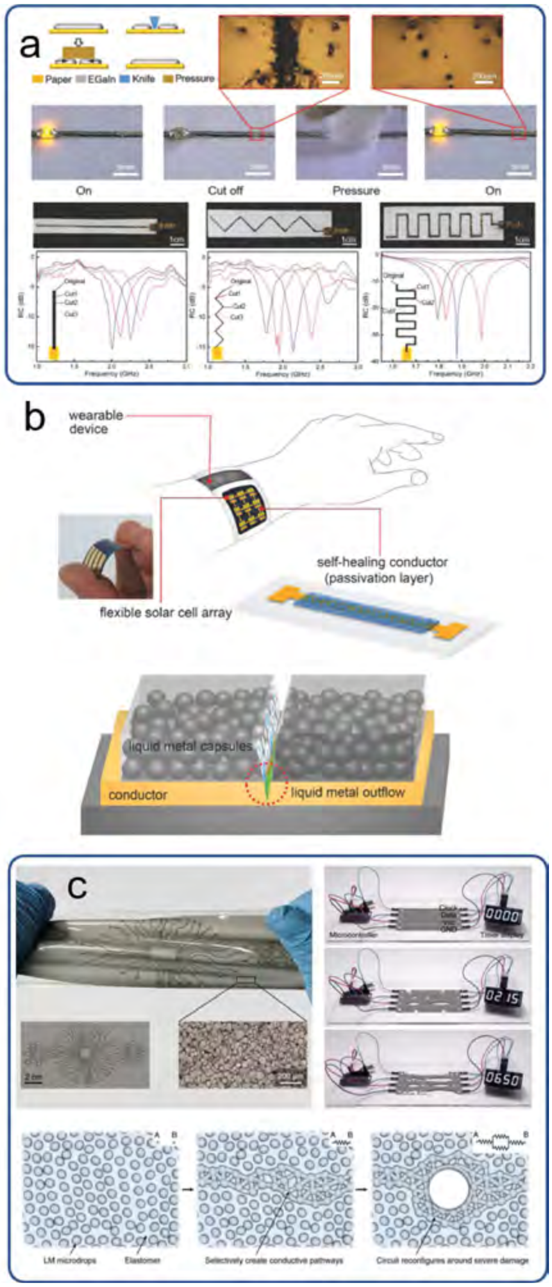

Fig. 8. ***Self-healing e-skin systems based on liquid gallium alloys. (a) Self-healable EGaIn lines used for reconfigurable antennas. Adjusted with permission from [80]. Copyright 2018 Wiley. (b) Schematic of a flexible solar powered watch embedded with self-healing EGaIn microcapsules. Adjusted with permission from [81]. Copyright 2018 Wiley. (c) Stretchable EGaIn-elastomer composite for self-healing soft-matter electronic quadruped. Adjusted with permission from [35]. Copyright 2018 Nature Publishing Group.***

approach is that EGaIn capsules are limited to single self-healing usage due to the large EGaIn capsule sizes and their sparse distributions. Liu *et al.* [193] proposed self-healing Galinstan electrodes with in-plane self-healing capability that could heal under the impact of an electric actuation. Self-healing of electronic circuits made from gallium-based liquid metals has also been proved by other research groups, and in most circumstances, self-healing happened when disconnected parts of circuits were put together [80], [194], [195], with one example shown in Fig. 8(a). The above-mentioned self-healing based on liquid gallium alloys has certain limitations [35], including temporary functional loss during healing, need for manual intervention, dependence on external sources for damage detection, and need for external energy such as heat or mechanical forces.

Recently, more efforts have been put into the self-healing of e-skin based on liquid gallium alloys to realize spontaneous and autonomic self-healing. By using the same method presented in [91], Chu *et al.* [81] prepared gallium-based liquid metal microcapsules with an average size of $\sim$5.5 μm by polymerizing liquid $Ga_{0.61}In_{0.25}Sn_{0.13}Zn_{0.01}$ (Sn and Zn increase the wettability of the liquid metal) and dispersing the microcapsules in a prepolymeric network, and the flocculated microcapsules can realize fast healing of an electrical circuit within 2 min. A schematic of wearable devices with self-healing conductors is illustrated in Fig. 8(b). The efficient self-healing comes from the small capsule size and the large capsule concentration in the prepolymer. More recently, Markvicka *et al.* [35] presented an electrical material composed of EGaIn microdroplets in a soft silicone elastomer that could undergo autonomously self-healing without any external involvement under bending, twisting, cutting, and partial material removal, as shown in Fig. 8(c). They showed that upon severe external mechanical impacts, liquid metal microdroplets could rupture and release EGaIn to interconnect with each other to form new conductive channels in the elastomer, thus realizing autonomous self-healing. By following the approaches mentioned above, future research can offer the precise size control of liquid metal droplets (micro or nano), other possible morphologies, and their well-controlled distribution to realize reliable, fast, and repeatable self-healing.

VIII. CONCLUSIONS AND PERSPECTIVES

To date, gallium-based liquid metals have been proposed and demonstrated for a variety of e-skin applications, and many future opportunities still exist, whereas certain limitations remaining to be addressed. We present some of such opportunities and potential future investigations in this section.

A. Patterning

Different patterning techniques of gallium-based liquid metals have been proposed, and a previous review [102] suggests that these techniques could be briefly divided into lithography enabled, injection, additive, and subtractive. However, challenges still exist because they are liquid and not compatible with conventional semiconductor fabrication techniques. Lithography-enabled patterning usually involves pattern transfer [57] or selective wetting [142], and injection patterning normally requires prefabrication of microfluidic channel in soft elastomers [51], [69], [170], [196]. Multilayer patterning and alignment of gallium-based liquid metals remain a significant challenge despite the current progress of liquid metal-filled soft through-PDMS via [55]. In order to realize mass production and patterning of liquid gallium alloys, liquid metal deposition in an oxygen-controlled environment on patterns generated by lithography can be considered. Printing has been used and seems to become more conventionally accepted for forming various patterns of liquid metals, and it is expected to be more widely implemented for e-skin designs.

B. Coalloying and Substrate Effects

Gallium-based liquid metals coalloy with other metals, and this has been used for their selective wetting and plating on gold or other metal traces [115], [141], [142], [151], [197]–[199]. However, this coalloying also raises the problem that gallium naturally and gradually takes up other metals. The interaction properties of gallium with other metals are peculiar and somehow selective, which vary from galvanic replacement [200] to form eutectic alloys [151] or even establishing slushes [115]. The resulting metal mixes can be promising catalysts used as junctions or selective electrochemical sensors. Gallium also has a different wetting effect on various polymeric substrates. Therefore, the interfacial impacts need to be carefully considered when using liquid metals in contact with other metals and materials for e-skin applications.

C. Manipulation of Surface Oxide

As we discussed, the surface metal oxide on gallium-based liquid metals can facilitate their wetting on different substrates, and the exfoliated metal oxides are also potential candidates for the semiconductor industry. However, the surface oxide is not desired in some cases, especially considering their spontaneous formation with the presence of oxygen. Oxygen-free or acidic/basic environment can prevent the formation of the oxide layer or constantly remove it. It has also been demonstrated that surfactants such as thiols can control the growth of the metal oxide layer outside the EGaIn nanoparticles [201]. It has been theoretically predicted and experimentally demonstrated that certain metal oxides can come out from liquid gallium alloys and that they can be separated and transferred onto other substrates for semiconductor fabrication [72]–[75]. This metal oxide skin is also a barrier for thermal and electronic conductivities and its thickness can be controlled via chemical or thermal means to modulate the conductivity. Microparticles and nanoparticles can be embedded into this surface oxide and change the wetting effect between the encapsulating polymer and liquid metals. More work can be carried out in order to make the full use of the surface oxides and their functionalities. For example, by improving the crystalline quality of metal oxides isolated from liquid gallium alloys, they can be used to investigate the fundamental physics, and they can also be applied to optoelectronic applications such as diodes, photodetectors, and light-emitting diodes within the structure of the e-skin.

D. Integration

The integration of billions of transistors into a central processing unit makes it super powerful, and the integration of components/devices made from liquid gallium alloys is also desired. However, because of the liquid nature of gallium-based liquid metals, the miniaturization of devices made from them is challenging, rendering the integration of different components with various functions hardly realizable. A feature size down to micrometer of gallium-based liquid metal patterns has been reached in several demonstrations [54], [77], [202], and the technology to fabricate smaller feature sizes is needed in the future. So far, gallium-based liquid metal nanoparticles have been prepared via specific sonication techniques [201], [203], but they are not compatible with electrical circuits. It should be considered that the semiconducting skin together with the metallic core can establish the semiconducting–metallic junctions that are the base of electronics and optics. On the other hand, the technological challenges are still far-fetched, and the liquid metal-based nanoparticles can be placed on the top of each other or surfaces to form electronic circuits. Other future work regarding gallium-based liquid metals includes multilayer integration of miniaturized devices based on liquid gallium alloys for multiplex purposes.

E. Microfluidics

Microfluidics has been hailed as the future basis for point-of-care diagnostics. With the advancement of microfluidics, soft components based on liquid gallium alloys have shown their capabilities for pumping/mixing liquid flows in the microfluidic channels embedded into e-skin. Prototypal pumps and active micromixtures based on liquid gallium alloys have been demonstrated, which function based on electrical field-induced wetting and dewetting [88], [204], [205]. With relatively simple designs, pumps and mixers based on liquid metals can be used to generate biofluids to different locations of e-skin circuits or push ionic liquids to form ionic circuits with desired functionalities, such as sensing or actuation, and makeshift electronics, to mimic the smarter components of human skin and underskin such as blood vessels. With further development, it may lead to smart elastic microfluidic systems with multiple functionalities similar to human blood vessels.

F. Protection

Potentially, e-skin based on liquid gallium alloys can be established to protect us from external impacts, such as heat, mechanical loading, or chemical substances, being like the second skinlike smart tattoo vest. Current designs and prototypes of gallium-based liquid metal devices mainly focus on sensing environmental conditions, and the investigation on reaction to external stimuli is underexplored. E-skin based on liquid gallium alloys can protect us from cutting or punching if it hardens under extreme external force, a property that some alloys offer. Similarly, e-skin made from liquid gallium alloys can be fabricated to automatically assist human skin to accelerate or slow down body heat dissipation in hot or cold environments, thus keeping us in a comfortable environment. Electrochemical sensors based on liquid metals can be incorporated into e-skin to detect harmful heavy metal ions. In addition to sensing chemical and biology substances, e-skin based on liquid gallium alloys should be fabricated to react with harmful substances and prevent them from entering the human body. Moreover, gallium-based liquid metals are impermeable to UV light and many other hazardous beams. Both passive and active e-skin can be developed using liquid metals to protect human from such exposures to harmful radiations.

All in all, the field of liquid metals, and especially their implementation for e-skin applications, is still in infancy. There are great future opportunities to develop intelligent, either passive or active, e-skin of remarkable functionalities that can conduct various tasks, and the forthcoming research will reveal the exciting opportunities they will offer. ■

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