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Review

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Advanced liquid metal interfaces: engineering embodied cognition in closed-loop human-machine ecosystems

Wenqi Wang[a], Jun Yang[a, *], Boya Song[a,b], Zhouyang Hu[a], Fangqing Wang[b], Sanwei Hao[b,*], Changyou Shao[c,*], Peng Fu[e], Hailin Cong[b], and Caofeng Pan[d,*]

[a] Beijing Key Laboratory of Lignocellulosic Chemistry, College of Materials Science and Technology, Beijing Forestry University, Beijing 100083, China.

[b] School of Materials Science and Engineering, Shandong University of Technology, Zibo 255000, China.

[c] Liaoning Key Laboratory of Lignocellulose Chemistry and BioMaterials, College of Light Industry and Chemical Engineering, Dalian Polytechnic University, Dalian 116034, China.

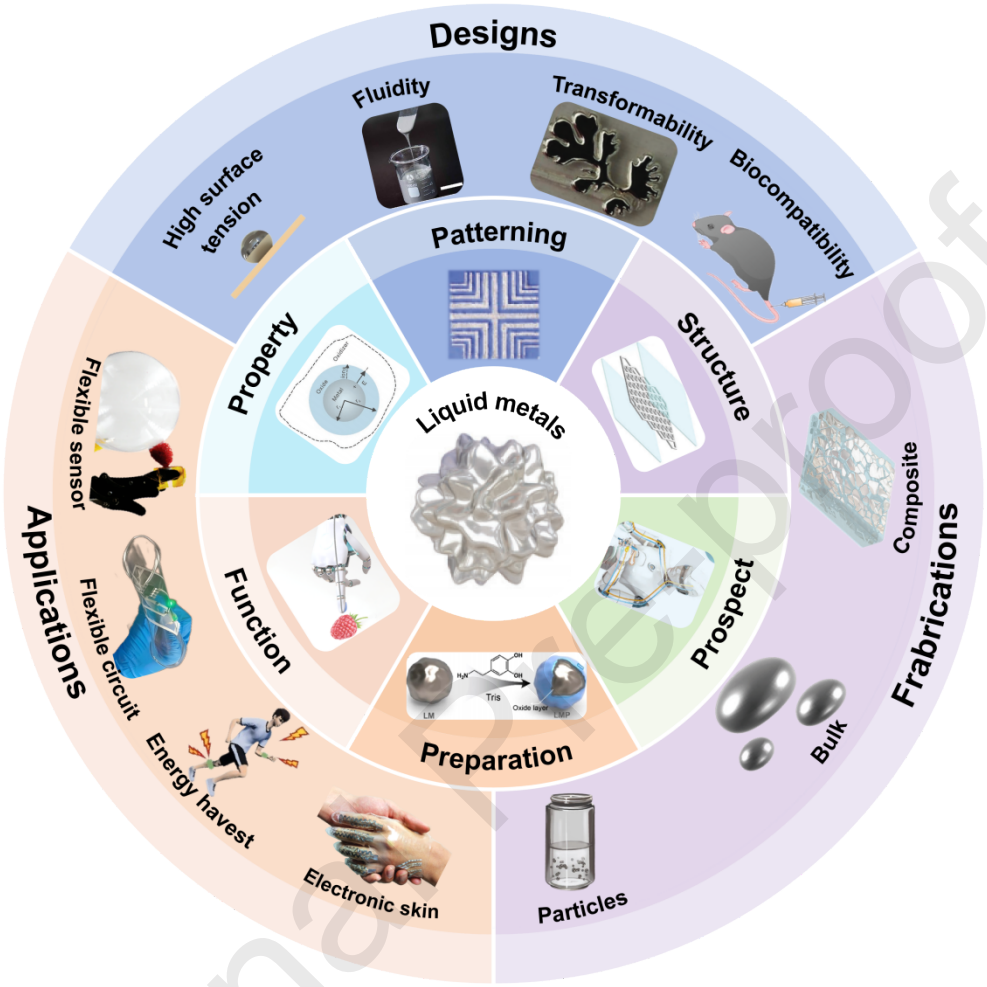
[d] Institute of Atomic Manufacturing, Beihang University, Beijing 100191, China

[e] School of Agricultural Engineering and Food Science, Shandong University of Technology, Zibo 255000, China.

*Corresponding Authors

*E-mail: yangjun11@bjfu.edu.cn; haosanwei@sdut.edu.cn; shaocy@dlpu.edu.cn; pancaofeng@buaa.edu.cn

Graphical abstract



以镓基合金为代表的液态金属，因其兼具固态与液态的双重特性与优异的自适应能力，为人与机器走向无缝融合的智能生态提供了关键支撑。与固体金属不同，镓基液态金属既能如水流般流动、变形，紧密贴合复杂的生物组织，又拥有优异的导电性，这使其具备构建多功能集成的高度仿生智能界面的潜力。镓基液态金属界面有望赋予机器“身体智能”，推动人机协同迈向具备感知、自适应与学习能力的新阶段。

Abstract

The persistent discord between rigid electronics and dynamic biological systems necessitates paradigm-shifting materials to realize seamless human-machine symbiosis. As inherently adaptive mediators, gallium-based liquid metals (Ga-LMs), have evolved beyond traditional flexible circuitry to pioneer disruptive closed-loop interfaces in neuroprosthetics, responsive robotics, and embodied artificial intelligence. Dynamic interfacial engineering provides a foundational strategy for orchestrating Ga-LMs' solid-liquid duality through field-guided topological adaptation, reversible morphological reconfiguration, and stimuli-responsive self-organization. In this review, we present the hierarchical design of Ga-LMs-enabled cybernetic systems from molecular-scale mediation to functional macroscopic assemblies. We provide a mechanistic perspective on how the electronic compliance, energy transduction efficiency, and adaptive response fidelity of these interfaces can be regulated via interfacial dynamics. Meanwhile, by emphasizing significant capabilities of Ga-LMs in smart healthcare, soft robotics, and intelligent assistive devices, this review identifies persistent challenges in long-term operational stability, biosafety protocols, and heterogeneous system interoperability as pivotal frontiers requiring concerted research efforts. Finally, we examine how such approaches advance closed-loop electronics through self-passivating architectures and bioresorbable designs, while highlighting critical challenges in chronic biocompatibility and cross-system interoperability. We call for intensified focus on interfacial decoding strategies to fully unlock liquid metals' potential as human-machine interfaces for cognitive-physical harmonization in closed-loop human-machine ecosystems.

Keywords: Gallium-based liquid metal, Human-machine interfaces, Flexible sensor, Energy system, Alloy,

1. Introduction

Propelled by the iterative evolution of artificial intelligence technologies, human-machine interaction has emerged as a core enabling technology for achieving seamless communication between humans and robotic systems [1]. Human-machine interfaces (HMI) have demonstrated significant technological potential across diversified application scenarios, including intelligent robotic clusters, precision medical assistance systems, smart home and intelligent vehicle platforms, as well as immersive virtual reality environments [2,3]. Functioning as the core mediation layer in human-machine interactive systems, HMI establishes a closed-loop architecture for bidirectional information pathways by converting users' physiological signals and physical stimuli into machine-interpretable command topologies. Through conformal human-machine interface technologies, wearable devices (e.g., exoskeleton systems) achieve precise control of complex operational tasks, demonstrating dynamic response accuracy at the submillimeter level. Furthermore, bio-integrated devices have revealed

revolutionary possibilities for replacing or enhancing human organ functions, opening new dimensions for physiological capacity augmentation. Although conventional rigid components retain application value in HMI domains, their mechanical-electrical mismatch with soft devices and biological tissues under large strain conditions has become a critical bottleneck restricting real-life scenario applications. To solve this issue, gallium-based liquid metals (Ga-LMs), including eutectic/biphasic Ga-In alloys, biphasic Ga-In alloy, Galinstan, and Ga-based composites, have emerged as promising candidates for flexible interconnects and wiring technologies, particularly due to their unique combination of metallic conductivity (exemplified by eutectic Ga-In alloy with $\sigma \approx 3.4\times10^{6}$ S m^{-1}) and inherent fluidic properties [4,5].**Error! Reference source not found.**

Recent groundbreaking advancements in Ga-LMs have provided pivotal technological support for leapfrog development in intelligent human-machine interaction systems [6]. Firstly, Ga-LMs-based adaptive electronic devices demonstrate unique advantages in conformal integration with complex curved surfaces of biological tissues, achieving topological adaptability with micron-level surface conforming accuracy. The room-temperature fluids with low melting point exhibit superior surface tension (>400 mN m^{-1}, composition-dependent) and excellent fluidity. Their enhanced fluidity arises from low bulk viscosity (2×10^{-3} Pa s, double that of water) and reduced kinematic viscosity (3×10^{-7} m^2 s^{-1}) [7]. These rheological characteristics enable Ga-LMs to exhibit water-like flow behavior at ambient temperature, with dynamic wetting angles below 10° [8]. Secondly, Ga-LMs have emerged as transformative components in advanced compliant electronics, where their intrinsic metallic conductivity synergizes with programmable viscoelastic behavior to enable stress-adaptive conductive networks [9]. Additionally, driven by advances in bionics, Ga-LMs act as essential components in constructing advanced HMI systems through their multifaceted functionalities, encompassing flexible actuation modules, intelligent sensing units, self-powered systems, logical computing devices, reconfigurable circuits, and transformable skeletal structures. Thirdly, the growing demand for intelligent assistance in daily life has spurred the need for highly sophisticated HMI for daily-life scenarios, requiring composite functionalities including multi-task collaborative processing, adaptive environmental interaction, and autonomous decision-making. Ga-LMs play a key role in material and fabrication advancement for developing multifunctional, energy-efficient, compatible and autonomous robots. The universal compatibility with HMI systems originates from five intrinsic characteristics: programmable surface tension, extraordinary conductivity, intelligent rheological behavior, environmental barrier effects, and dynamic morphological adaptability. These characteristics fundamentally expand the design dimensions of functional devices, enabling closed-loop system integration of dynamic energy and intelligent response, thereby propelling human-machine interaction into a new paradigm of human-machine symbiosis.

Emerging as a transformative class of functional materials, Ga-LMs exhibit

distinctive physicochemical properties that have proven to be critical components in next-generation HMI systems for closed-loop electronic application. This review aims to offer an exhaustive analysis of these unique material characteristics, systematically establishing their fundamental structure-property relationships and indispensable contributions to HMI technological advancements. Next, focusing on material construction and advanced fabrication techniques, this work provides in-depth analysis of how micro-nano patterning technologies achieve submicron-level functional unit integration of liquid metals on flexible substrates, overcoming mechanical constraints inherent to rigid substrates through precision manufacturing approaches. Finally, we thoroughly analyze the multifaceted applications of Ga-LMs in next-generation HMI, ranging from stretchable self-healing circuits, multimodal intelligent sensing systems, and bio-inspired epidermal electronics to flexible energy devices and human function augmentation. This review comprehensively demonstrates the potential of Ga-LMs in HMI systems, emphasizing their critical roles in closed-loop human-machine interaction, adaptive bioelectronics, and AI-enhanced systems. Prospective insights address challenges in long-term stability, biosafety, and heterogeneous system compatibility, and chart pathways for technological convergence in future closed-loop electronic applications, including intelligent healthcare, soft robotics, and human capability enhancement (Fig. 1).

Fig. 1. Morphology, fabrication and multifunctional applications of Ga-LMs.

2. The inherent properties of Ga-LMs propelling innovations in HMI

2.1 Surface tension

Gallium-based liquid metals (Ga-LMs) leverage multicomponent alloy engineering (In/Sn/Zn integration) to access tailored metallurgical phase spaces (EGaIn, Galinstan, GaInSnZn), enabling strategic modulation of interfacial energetics [10]. This interfacial behavior arises from their ultrahigh surface tension (approximately 400 mN m^{-1}, intrinsically governed by alloy stoichiometry) [11], which drives autonomous spherical nanodroplet self-organization while imposing constrained spreading dynamics on surfaces wetting behavior, a dualistic characteristic that necessitates advanced interfacial engineering for effective integration into functional composites [12]. Ga-LMs demonstrate exceptional chemical reactivity under ambient conditions, undergoing spontaneous surface oxidation analogous to their main-group counterpart, aluminum [13]. Notably, when exposed to trace oxygen concentrations (≥1 ppm), the high reactivity of Ga-LMs facilitate instantaneous interfacial reactions, leading to the formation of an ultrathin interfacial oxide layer (0.5−5 nm) at the metal-air boundary [14].

Importantly, the formation process of this oxides is inherently self-limiting and can be characterized by the Cabrera-Mott model [10]. Upon atmospheric oxygen exposure, Ga-LMs spontaneously generate a surface oxide layer through electron tunneling from the metal core to the adsorbed oxygen, inducing a built-in electric field gradient (termed the Mott field) within the oxide matrix. The Mott field significantly reduces the activation energy for metal ion diffusion, thereby accelerating the surface oxides growth until field attenuation by increasing layer thickness terminates the process [15]. Remarkably, incorporation of lower-melting-point metals (e.g., In, Sn) into Ga-LMs effectively depress the melting temperature while maintaining gallium oxide (Ga_2O_3) as the predominant surface species. The preferential oxidation phenomenon originates from the relatively low standard reduction potential (E^0 = -0.56 V vs. SHE) and Gibbs free energy compared to other liquid metal constituents (e.g., indium and tin) in alloy. The thermodynamic driving force ensures selective gallium oxidation, yielding Ga^{3+} enrichment in the passivation layer. The corresponding reaction can be described by the following Eq. (1): [16]

$$4Ga + 3O_2 = 2Ga_2O_3, (1)$$

The native natural gallium oxide layer plays an important role in Ga-LMs processing to meet application-specific manufacturing requirements [17]. This functionality arises from two distinctive characteristics of the oxide layer. The first feature is that the oxide layer enhances wettability on non-metallic surfaces, enabling precision printing and patterning. The other comprises that the hydrophilic substrates (e.g., polyvinyl alcohol

(PVA), polymethacrylate (PMA), poly2-Hydroxyethyl acrylate, etc.) readily form interfacial bonds with hydroxyl-terminated oxide surfaces, creating robust intermetallic adhesive interfaces. Guo et al. [18] developed a one-step transfer-printing process utilizing the strong interaction between PMA and gallium oxide, wherein PMA acts as a universal polymeric adhesive, enabling the direct fabrication of intricate Ga-LM-based conductive architectures on substrates with low wettability. Conversely, the weak interfacial adhesion strength between Ga-LMs and the oxide layer contributes to the spontaneous exfoliation of Cabrera-Mott grown oxide skin, providing unique opportunities for creating ultra-thin 2D materials. Multiple separation strategies have been developed, including mechanical exfoliation, printing and chemical vapor deposition (CVD). Zavabeti et al. [19] demonstrated a representative process of transferring the surface oxides using an adhesive substrate, thereby establishing Ga-LMs as versatile platforms for the scalable and high-throughput fabrication of two-dimensional materials. When Ga-LMs interact with aqueous environment, the changes in composition and state of the surface oxides hold significant importance for determining the interfacial properties of liquid metal in solutions. Both oxygen molecules and water molecules act as thermodynamic drivers for promoting the oxidation of Ga-LMs. Consequently, aqueous environments facilitate the formation of gallium-based oxide layers [20]**Error! Reference source not found.**, as described by the reaction equations:

$$2\mathrm{Ga(l)} + 3\mathrm{H_2O(l)} = \mathrm{Ga_2O_3(s)} + 3\mathrm{H_2(g)}, (2)$$

$$4\mathrm{Ga(l)} + \mathrm{Ga_2O_3(s)} = 3\mathrm{Ga_2O(s)}, (3)$$

$$\mathrm{Ga_2O(s)} + 2\mathrm{H_2O(l)} = \mathrm{Ga_2O_3(s)} + 2\mathrm{H_2(g)}. (4)$$

At the same time, it has been demonstrated that water can react with gallium as shown in Eq. (5) to form gallium oxide hydroxide. Furthermore, under appropriate conditions for aqueous solutions, gallium oxide may undergo hydrolysis to yield gallium oxide hydroxide, as indicated by reaction Eq. (6).

$$4\mathrm{Ga(l)} + 2\mathrm{H_2O(g)} + 3\mathrm{O_2} = 4\mathrm{GaOOH}, (5)$$

$$2\mathrm{Ga_2O_3(s)} + 2\mathrm{H_2O(l)} = 4\mathrm{GaOOH}. (6)$$

The amphoteric characteristics of gallium oxide make it unstable under acidic or alkaline conditions, and can react with HCl or NaOH solutions to form water-soluble products, as described in Eqs. (7) and (8) [21].

$$\mathrm{Ga_2O_3(s)} + 6\mathrm{HCl(l)} = 2\mathrm{GaCl_3(l)} + 2\mathrm{H_2O(l)}, (7)$$

$$\mathrm{Ga_2O_3(s)} + 2\mathrm{NaOH(l)} + 3\mathrm{H_2O(l)} = 2\mathrm{NaGa(OH)_4(l)}. (8)$$

Following this interaction, the oxidation layer is effectively removed. The low concentration of acid fails to compromise the integrity of this thin oxide layer even under equilibrium conditions between hydrochloric acid (HCl) and alkaline solutions [22]. In contrast to acidic treatments, alkaline solutions with appropriate concentrations demonstrate enhanced efficacy in oxide removal and restoration of high-tension states in oxidized liquid metals. Meticulous regulation of the interfacial tension of Ga-LMs through appropriate methods is anticipated to uncover new characteristics and functionalities of compositional regulation systems for liquid metals, thereby revealing their potential applications. The interfacial tension of Ga-LMs varies with applied electric potentials due to charge density modulation at the interface [23,24], as quantified by Lippmann's Eq. (9):

$$\gamma = \gamma_0 - \frac{1}{2} C(V - V_0)^2. \quad (9)$$

This electrocapillary relationship depends on four parameters: the intrinsic surface tension at zero charge potential (γ_0), capacitance (C), zero charge potential (V_0), and the surface charging voltage (V) across the electric double layer (EDL). These EDL-governed interfacial properties ultimately dictate the conductivity of Ga-LMs, which plays a fundamental role in closed-loop electronic systems by directly determining response speed, signal fidelity, energy efficiency, and operational reliability of the systems.

2.2 Conductivity

Ga-LMs exhibit exceptional electron transport properties. For instance, Galinstan achieves an electrical conductivity of 3.46×10^6 S m^{-1}, surpassing non-metallic liquid dielectrics by 6−10 orders of magnitude [25]. This establishes Ga-LMs as a promising material class for HMI in advanced closed-loop systems. Particularly, Ga-LMs maintain theoretically infinite deformability while preserving continuous conductive pathways, a unique combination that positions these materials as ideal candidates for next-generation reconfigurable electronics and shape-adaptive conductive architectures. This section critically reviews recent advances in the electrical conductivity applications of Ga-LMs, particularly emphasizing their transformative potential in deformable electronics. Recent reviews highlight significant advancements in Ga based antennas. Owing to their exceptional electrical conductivity, Ga-LMs have emerged as highly efficient antenna materials [26]. The spectral characteristics of antennas are inherently governed by their geometric configurations, thus giving them the capability to physically deform and reconfigure. Ga-LMs architectures present unprecedented opportunities for developing tunable and reconfigurable antenna systems. For example, Ga-LMs have been successfully employed in fabricating diverse antenna architectures, including dipoles, loops, coils and inductors, spherical caps, patch antennas, monopoles, radio-frequency antennas, phase-shifting coaxial transmission lines, as well as

reconfigurable antennas and filters. In certain scenarios, Ga-LMs based circuits demonstrate exceptional stability against frequency variation during mechanical deformation through strategic architectural design. Ai et al. [27] employed advanced thermocompression techniques to integrate gallium-based liquid metal conductor with supramolecular confinement (LMSC) into textile fibers seamlessly (Fig. 2a), achieving robust wireless data transmission via NFC protocols. This system functions as a wireless HMI controller, translating tactile inputs into digital commands and maintaining stable frequency response during mechanical deformation by optimized spiral design geometry. In a parallel development, Teng et al. [28] fabricated a recyclable transient LM-based circuit (Fig. 2b). This approach has been extended to fabricate intricate circuit architectures, including strain gauges, spiral configurations, and Peano curves.

Recent advances focus on multifunctional elastomers derived from Ga-LMs, featuring tunable structural design, superior mechanical performance, and exceptional environmental resilience. Ga-LMs serve as deformable conductive fillers, offering advantages over rigid particulates by enabling percolation-based volumetric conductivity without compromising elastomer flexibility [29]. Two fabrication paradigms dominate: (1) contiguous Ga-LM droplet arrays formed via capillary assembly, and (2) direct lithography in microfluidic channels, both enabling isotropic conductivity ($\sigma > 10^6$ S m^{-1}) with large strain tolerance. However, challenges persist due to Ga-LMs inherently high surface tension and difficulties in micromachining of microchannels. Polydispersity and batch-to-batch inconsistencies in Ga-LMs droplets further lead to non-uniform spatial distribution, limiting application-specific performance. Consequently, developing Ga-LMs elastomers with monodisperse droplets and scalable fabrication processes remains a priority. For instance, a conductive elastomer incorporating LM droplets in PDMS employed a needle array with rotational motion to generate controlled shear forces, enabling precise droplet formation with diameters tunable (10–100 μm) (Fig.2c). These LM droplet-embedded elastomers function effectively as flexible conductive components in energy conversion systems and can transduce mechanical stimuli into electrical signals under compressive and tensile stresses. Therefore, the synergistic convergence of intrinsic metallic conductivity, structural adaptability, and autonomous self-healing in Ga-LMs makes them promising candidates for advanced flexible electronics, particularly in human-machine interfaces demanding cyber-physical coupling for next-generation closed-loop electronics systems.

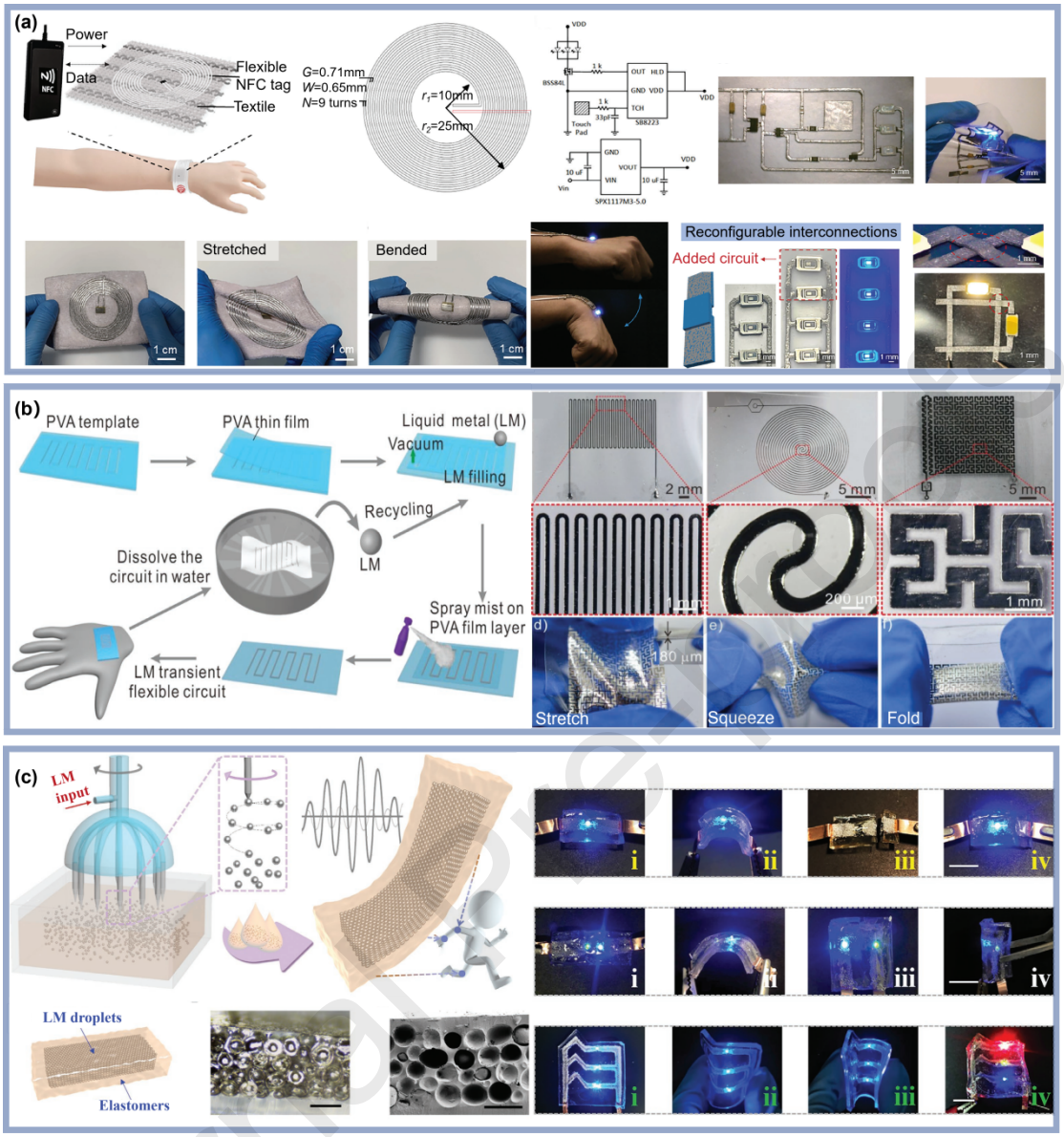


Fig. 2. The illustration of the conductivity of Ga-LMs. (a) Application of the Ga-LMs conductor in a textile-based stretchable NFC system and schematic diagram of reconfigurable interconnects by Ga-LMs conductor with supramolecular confinement. Reproduced with permission from Ref. [27]. Copyright 2025, Wiley-VCH. (b) Schematic illustration of the synthesis and regeneration procedures for PVA-embedded recyclable transient circuits using Ga-LMs. Top panels display macroscopic and microscopic characterization of patterned Ga-LMs within PVA matrices. Mechanical compliance testing of a 180 μm Ga-LMs circuit demonstrates exceptional tolerance to stretching, compression, and folding. Reproduced with permission from Ref. [28]. Copyright 2019, Wiley-VCH. (c) Design framework for programmable elastomeric circuits incorporating microfluidic-engineered Ga-LMs droplets. These spherical conductive fillers, prepared via rotating microfluidic platform, enable fabrication of strain-responsive composites. Mechanically robust Ga-LMs-incorporated elastomers exhibit promising performance in real-time monitoring of human motion patterns. Reproduced with permission from Ref. [30]. Copyright 2025, Wiley-VCH.

2.3 Fluidity

Ga-LMs maintain liquid-state behavior at room temperature (25 °C), exhibiting characteristically low dynamic viscosities of 0.882 mPa·s (Ga), 2.379 mPa s (EGaIn), and 2.602 mPa s (EGaInSn) [25]. The combination of low melting temperatures (e.g., ~19 °C for Galinstan) and ultralow Young's modulus endows Ga-LMs with exceptional stress-responsive fluidity, enabling dynamic shape adaptation to environmental contours [31]. Such fluidity further permits Ga-LMs to be cast into molds or coated onto substrates with ease, rendering them highly compatible with various manufacturing processes. For example, microfluidics, a technology integrating functional fluids into chip-scale systems with portability, miniaturization, and energy efficiency, has demonstrated significant potential in drug screening, biosensing, wearable health monitoring, and microfabrication [32]. Furthermore, the flow behavior ensures the filling of microfluidic channels, while its self-healing arises from rapid oxide skin formation, and combined with the low cohesion of the oxide skin these properties prevent outflow of the Ga-LMs. It should be emphasized that the native oxide layer increases the viscosity of Ga-LMs. To restore high fluidity, chemical treatments (e.g., acid, base, or HCl vapor) [33] or electrochemical methods (e.g., direct current application in electrolytes) can be employed to remove surface oxides, yielding droplets with restored surface tension. Zhang et al. [34] developed a femtosecond-laser direct-writing strategy to fabricate high-resolution microchannels (minimum width: 1.5 μm) and multilayer microvias on planar surfaces, enabling 10-layer interconnects through sequential Ga-LMs injection (Fig. 3a). This method enables customizable flexible electronics with multiscale sensing and soft circuit integration. Self-healing electronics exhibit remarkable damage tolerance through autonomous functional restoration, offering enhanced operational durability.

Current research on Ga-LMs platforms primarily emphasizes conductivity recovery rather than comprehensive performance restoration. Designing Ga-LMs elastomer composites capable of simultaneously recovering both electrical conductivity and mechanical stretchability elasticity presents significance [35]. Leveraging the inherent self-healing capability of polymers and the synergistic fluidic-solid healing mechanisms of Ga-LMs, self-healing devices can be fabricated via the encapsulation in elastomeric matrices for crack-triggered healing, and the direct embedding for stress-induced interfacial reconnection [36]. When Ga-LMs with high fluidity are integrated with the stretchable substrates, the resulting composites exhibit exceptional stretchability and self-healing behavior. Metallic bonding in Ga-LMs enables dynamic bond breaking and reformation under mechanical stress, a characteristic that facilitates conformation to complex geometries and enables applications in flexible electronics and soft robotics. As illustrated in Fig. 3b, an areal density-optimized Ga-LMs electrode printed on hydrogel withstood 1500% strain, retained over 95% conductivity after self-healing, and endured repeated stretching, cutting, and healing cycles [37]. Magnetic fields further enable healing in magnetic LM composites. Kim et al. [38] developed an

MXene-encapsulated magnetic LM that reconnects within seconds under a 200 mT magnetic field, maintaining stable resistance over 30 damage-healing cycles (Fig. 3c). This minor resistance shift is attributed to interfacial contact effects between reconnected fragments, while the bulk conductivity of Ga-LMs dominated the comprehensive performance of composite. Ga-LMs inks strike a balance between printability and functionality through composition design, field control and microstructure optimization, enabling customized requirements for scenarios ranging from microelectronics to soft robotics [39,40]. Fig. 3d demonstrates the direct epidermal coating of intrinsically conductive Ga-LMs particles through multi-scale dense packing, ensuring mechanical durability and conformal skin integration [41]. To enhance substrate versatility (Fig. 3e), Tang et al [42] developed screen-printable Ga-LMs inks by employing tailored polymer formulations, achieving precise patterning of intricate geometries on PDMS surfaces while maintaining exceptional stretchability.

As a quick summary, the fluidity of Ga-LMs presents transformative opportunities for HMI development. Their intrinsic fluidic nature enables dynamic conformability to biological surfaces and spontaneous reconfiguration of conductive pathways, essential for creating adaptive interfaces that transcend conventional rigid electronics. The synergy between flow-induced morphological adaptability and self-healing capabilities facilitates robust, fatigue-resistant HMIs capable of maintaining electrical continuity under extreme mechanical deformations. Particularly, the reversible liquid-solid transitions mediated by surface oxide modulation allow Ga-LMs to function as reconfigurable circuit elements in responsive haptic interfaces and strain-mapping epidermal sensors. Such fluidic intelligence, when integrated with advanced manufacturing techniques like microfluidic patterning and magnetic field-assisted alignment, opens avenues for developing HMIs with multimodal sensing functionalities.

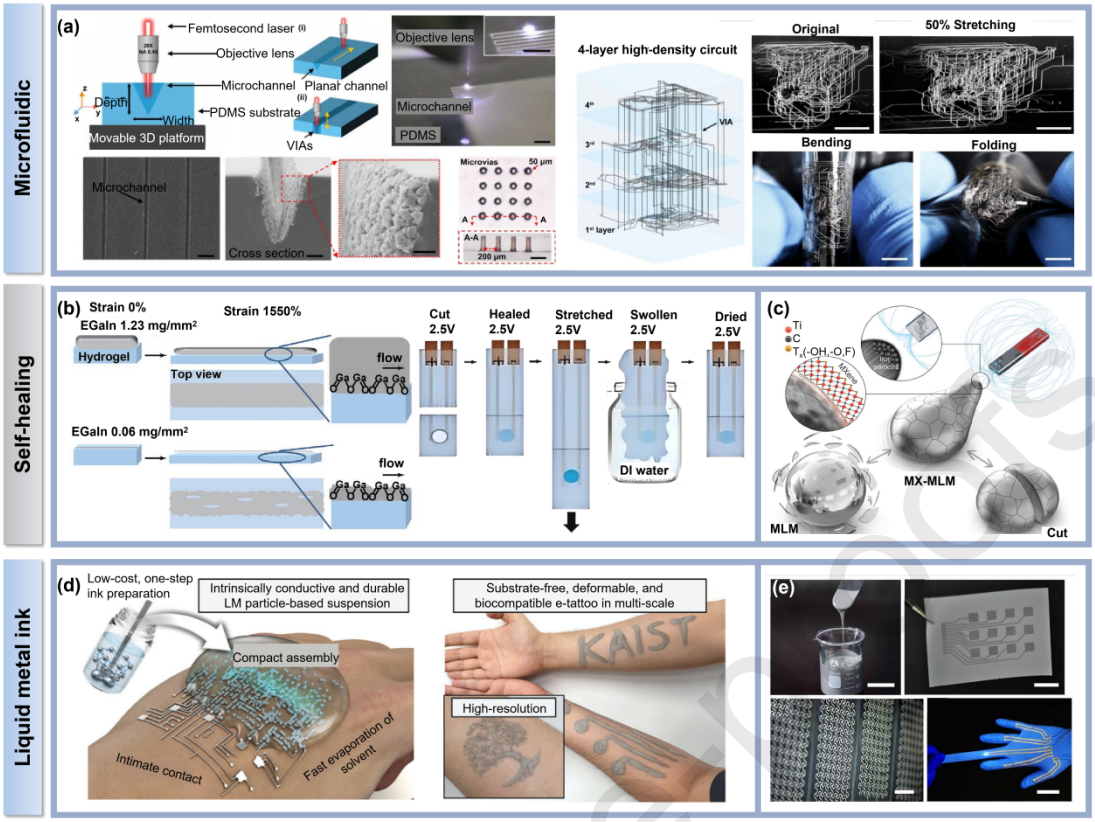


Fig. 3. Fluidity of Ga-LMs. (a) Femtosecond laser direct writing enables precise microchannel fabrication on PDMS substrates for constructing multilayer liquid metal-based high-density interconnects (HDI) in flexible electronics. Reproduced with permission from Ref. [34].**Error! Reference source not found.** Copyright 2025, IOP. (b) Schematic illustrations demonstrating encapsulated EGaIn electrodes maintaining electrical integrity under sequential mechanical stresses (stretching, aqueous swelling), physical damage, and autonomous recovery. Reproduced with permission from Ref. [37]. Copyright 2020, Wiley-VCH. (c) Operational schematics of MX-MLM: magnetically responsive reconfiguration and material recyclability (left); intrinsic self-healing mechanisms (right). Reproduced with permission from Ref. [38]. Copyright 2022, Wiley-VCH. (d) High-definition optical image showcasing conformally adhered gallium-based liquid metal electronic tattoos on epidermal substrates. Reproduced with permission from Ref. [41]. Copyright 2022, Wiley-VCH. (e) The ink of the Ga-LMs polymer conductors and patterning using it. Reproduced with permission from Ref. [42].**Error! Reference source not found.** Copyright 2019, American Chemical Society.

2.4 Biocompatibility

Prior to the emergence of Ga-LMs as fluid conductive materials, mercury, despite its high toxicity and volatility, was historically explored in broader electronic contexts for its liquid-phase properties. However, these inherent risks underscore the necessity for safer alternatives like Ga-LMs, which retain favorable fluidity while eliminating toxicity concerns. Ga-LMs demonstrate low toxicity, fulfilling the bio-safety prerequisites required for practical applications in bioelectronics [43-45]. The multifunctionality of Ga-LMs opens new avenues for interdisciplinary research,

particularly in bio-responsive interfaces, smart therapeutics, and human-machine symbiosis [46,47]. Recent advances highlighting the therapeutic efficacy and biocompatibility of Ga-LMs underscore their potential for biomedical implementations spanning oncological interventions to neural engineering. For example, Lu et al. [48] EGaIn nanospheres with thiol-functionalized polymer matrices (Fig. 4a). *In vivo* toxicological evaluation in mice revealed no significant hepatotoxicity or nephrotoxicity at 45 mg/kg over 90 days, with transient hematological changes recovering fully by day 20 and no histopathological organ damage, confirming high biocompatibility and supporting their use as a safe nanomedicine platform. Additionally, Liu et al. [49] proposed an amplification-targeting strategy utilizing orally administered Ga-LMs nano-agents to effectively scavenge reactive oxygen and nitrogen species (RONS) and modulate the dysregulated microbiome, thereby alleviating inflammatory bowel diseases (IBDs) (Fig. 4b).

Notably, materials designed for epidermal interfaces targeting next-generation wearable electronics must simultaneously combine two essential characteristics: breathability to maintain cutaneous homeostasis and inherent biocompatibility to ensure long-term user safety [50]. Zhou et al. [51] reported a spatial wettability adjustment strategy that resolved the interfacial compatibility limitations of liquid metals (LM) within porous substrates, enabling the fabrication of LM-based physiological electrodes with enhanced durability and long-term biocompatibility (Fig. 4c). Following one-week forearm application in human trials, porous samples caused no adverse dermatological reactions, while all nonporous controls developed significant erythema. In a parallel advancement, Wu et al. [52] presented novel adaptive magnetic liquid metal microrobots (LMMRs) designed to overcome the structural instability and constrained maneuverability of conventional magnetic microrobots in biological environments (Fig. 4d). The system employed Ga-L as a matrix, wherein iron nanoparticles (Fe NPs) are encapsulated to form monodisperse microdroplets with diameters below 10 μm. Cytotoxicity assessment revealed >90% viability of neuroblastoma cells at LMMRs concentrations ≤100 μg mL^{-1}, indicating negligible cytotoxicity. Blood biochemistry analyses and histopathological examinations showed no detectable systemic toxicity, substantiating favorable biosafety profiles.

To conclude, Ga-LMs redefine the paradigm of bio-interfacial devices, offering a safe platform for next-generation neural prosthetics, adaptive biosensors, and minimally invasive medical robotics [53]. Their unique combination of malleability, magneto-responsive behavior, and surface-engineering versatility enables seamless integration with biological systems, as evidenced by successful blood-brain barrier penetration [52], neuron-specific calcium flux modulation, and inflammation-targeted drug delivery. This biocompatibility-driven advancement bridges critical gaps in HMI development, where material-tissue symbiosis is paramount for chronic usability and precision therapeutics. Future advances in surface chemistry and hybrid nanofabrication will further amplify their role in creating intelligent, life-integrated

bioelectronic systems.

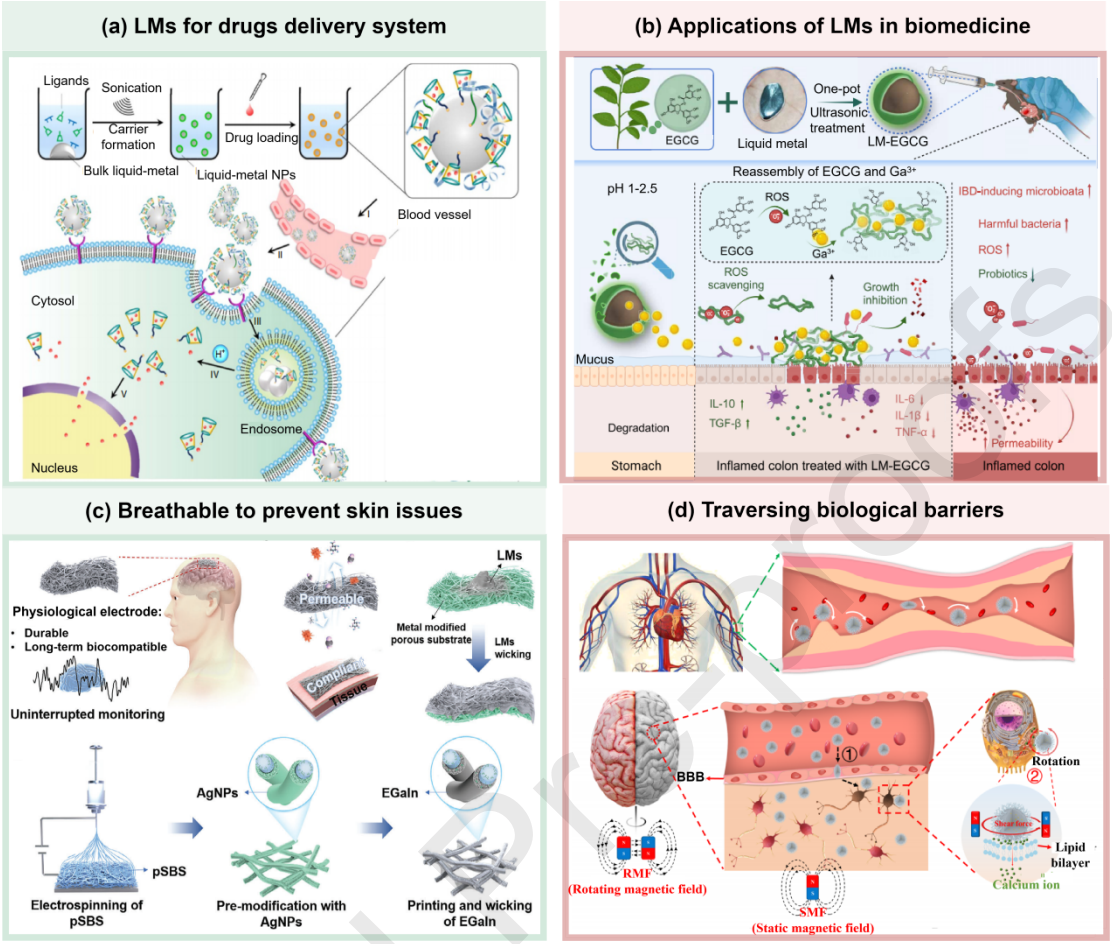


Fig. 4. Biocompatibility of Ga-LMs. (a) Schematic design of the reconfigurable liquid-metal transport platform. Reproduced with permission from Ref. [48]. Copyright 2025, Wiley-VCH. (b) The construction of gallium liquid metal agents and the mechanism for colitis treatment. Reproduced with permission from Ref. [49]. Copyright 2015, Springer Nature (c) Fabrication and application of the durable and long-term biocompatible physiological LM electrode. Reproduced with permission from Ref. [51]. Copyright 2024, American Association for the Advancement of Science (d) Conceptual schematic diagram of magnetic liquid metal microrobots moving through a capillary and climbing over vascular endothelium through deformation. Reproduced with permission from Ref. [52]. Copyright 2024, American Chemical Society.

2.5 Wettability

The wettability of Ga-LMs, governed by their hydrophilic or hydrophobic interactions with surrounding media, is adversely affected by oxygen incorporation, primarily by enhancing interfacial adhesion. Typically, Ga-LMs exhibit poor wetting on inert surfaces owing to their inherently high surface tension. Under aerobic conditions, these metals spontaneously form a substrate-adherent oxide passivation layer that mechanically restricts flow [54]. In the absence of an oxide layer, bare metals

exhibit high interfacial energy, resulting in insufficient wetting of most surfaces. Tailoring the interfacial properties of Ga-LMs is critical for enabling high-precision patterning in HMI device performance by achieving controlled wettability and adhesion while addressing inherent material limitations [55]. This can be accomplished through substrate surface engineering or strategic incorporation of functional interlayers. The unique adaptive wetting behavior exhibited by room-temperature Ga-LMs enables versatile applications via precision modulation of their interfacial characteristics, demonstrating significant potential for advanced functional systems. Guo et al. [18] developed a patterned PMA adhesive system that selectively confines EGaIn to defined regions on paper substrates. Fig. 5a illustrates the lift-up test procedure, revealing a marked divergence between conditions. The EGaIn droplet adhered strongly to PMA-coated areas, resisting detachment even at 90° tilt angles, whereas it readily rolled off unmodified paper at 26°, demonstrating the potential for creating stable conductive traces in flexible interfaces.

Another way to enhance wettability and adhesion properties of Ga-LMs is the regulation of oxidation to rheologically modify Ga-LMs or just mixing Ga-LMs with other sticky substances. Rheological modification enables shape control through structural reorganization. For example, an effective strategy to modulate LM rheological behavior involves dispersing LM into microscale droplets within another fluid, which significantly enhances processability for precision dispensing and patterning applications. Chen et al. [56] fabricated EGaIn particles (1.1 μm average size) in cyclohexanone through sonicating, subsequently mixing them with polyester polyol-rich thermoplastic polyurethane (pp-TPU) to create liquid metal composite (LMC) ink. As depicted in Fig. 5b, the ink demonstrates superior wettability across multiple polymer substrates (TPU: 67.4°, PET: 56.8°, VHB: 65.6°, PI: 39.5°), exhibiting contact angles approximately 50% lower than pure eGaIn, enabling enhanced adhesion and facilitating direct writing for soft electronic applications. Recent bioinspired strategies, exemplified by Rahim et al. [57], have achieved stable gallium-based liquid metal inks via tannic acid-mediated assembly of catechol/gallol functional groups. This natural adhesion chemistry enables direct writing on diverse substrates (flexible/rigid, metallic/polymeric, flat/curved) using standard ballpoint pens (Fig. 5c). The universal adhesion mechanism originates from interfacial coordination between polyphenolic moieties and substrate surfaces. This adhesion paradigm demonstrates robust substrate compatibility through ligand-to-metal charge transfer interactions, where polyphenolic moieties undergo molecular level conjugation with variable surface coordination sites while maintaining mesoscale structural reorganization capacity for efficient energy distribution across different material interfaces. In summary, interfacial engineering of Ga-LMs wettability enables precise patterning and robust adhesion in HMI devices. Future development should focus on surface modification techniques and composite design to realize scalable, high-resolution Ga-LMs circuits for wearable bioelectronics and soft robotic interfaces.

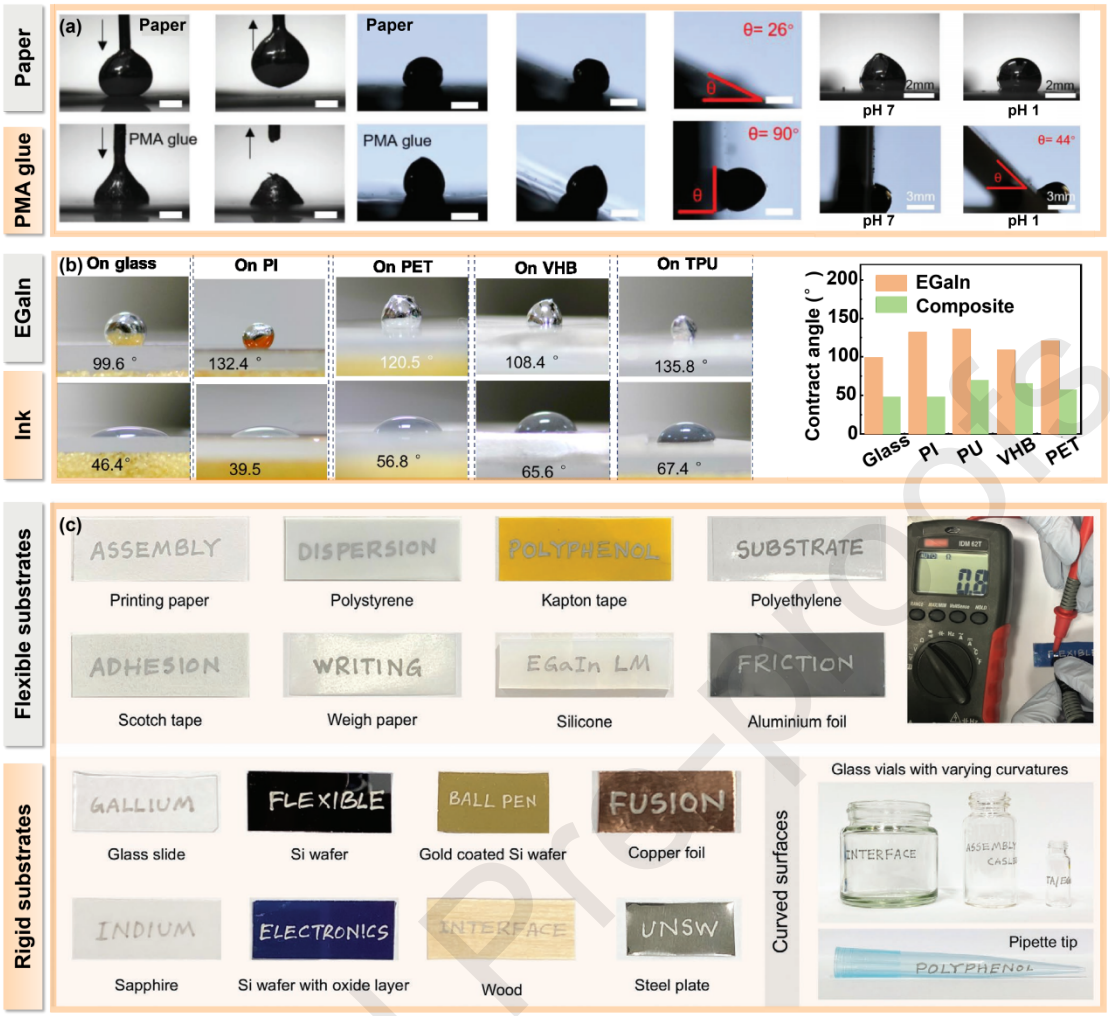


Fig. 5. Wettability and adhesion of Ga-LMs. **(a)** The adhesion tests of the EGaIn on paper and PMA glue. Reproduced with permission from Ref. [18]. Copyright 2018, Wiley-VCH. **(b)** The contact angle of eGaIn and LMC ink on various substrates. The contact angle of eGaIn and LMC ink on glass, PI, PET, VHB and TPU substrates, respectively. Reproduced with permission from Ref. [56]. Copyright 2023, Wiley-VCH. **(c)** Hand-written traces by a ballpoint pen filled with the EGaIn inks. Reproduced with permission from Ref. [57]. Copyright 2021, Wiley-VCH.

2.6 Transformability

2.6.1 Electrical manipulation

A pivotal study by Sheng et al. [58] on electrically induced diverse transformations of the liquid metals (LMs) has inspired the development of transformable functional machines. Under applied electric fields, liquid metals undergo substantial morphological transformations, transitioning from planar films to spherical architectures within seconds. These electrically actuated transitions yield unprecedented surface area amplifications exceeding three orders of magnitude, a phenomenon unobserved in prior studies. The field-induced oxidation dynamics and

electrochemical parameter modulations fundamentally govern the interfacial tension alterations driving these macroscopic morphological reconfigurations, establishing a robust mechanistic framework for understanding electrocapillary phenomena in liquid metal systems [59]. In the 1870s, Lippmann first observed electrocapillarity, a phenomenon enabling interfacial tension modulation in LMs [23]. The interfacial tension of LMs in an electrolyte can be reversibly modulated by applied electrical potentials. As a prototypical amphoteric metal, gallium reacts with alkaline solutions to generate anionic species such as $[Ga(OH)_4]^-$, thereby including electrical double layer (EDL) formation at the interface [60].

Under application of voltage, EDL potential difference undergoes disruption, enabling surface tension determination through Lippmann's equation. When confined within an alkaline electrolyte under square-wave stimulation (200 Hz, 5 V_{p-p}, 2.5 V DC offset, Fig. 6a, liquid metal droplets maintain static equilibrium while inducing directional electrolyte flow at 5 mL min^{-1} with ultralow power consumption (15 mW), demonstrating efficient electrowetting-mediated fluid transport. A Marangoni-driven liquid metal actuator was engineered by fixing LM units between substrate electrodes under AC stimulation (4 V, 100 Hz sinusoidal waveform), achieving programmable liquid manipulation through spontaneous surface tension gradient navigation. This asymmetric electrocapillary effect triggers chaotic fluid motion via continuous morphological reconfiguration of LMs along interfacial tension differentials. The interplay of electric field frequency, AC amplitude, and solution conductivity produces diverse LM droplet behaviors, including flow reversal, horizontal oscillation, and vertical oscillation. Although the terms electrocapillarity and electrowetting are often conflated, they describe distinct phenomena. Following the classification by Jackel et al., electrocapillarity involves electric potential-mediated adjustments to interfacial tension in fluid-fluid systems, while electrowetting pertains to electrocapillarity-driven changes in fluid-solid wetting behavior. These phenomena, though both governed by EDL charge redistribution [61], exhibit fundamentally distinct mechanisms. According to Faraday's law, the gallium oxide formation rate can be written as:

$$F_{\mathrm{rate}} = \frac{d_{\mathrm{m}}}{d_{\mathrm{t}}} = \frac{M_{\mathrm{q}}}{F_{\mathrm{n}}} \frac{U}{R} \quad , \tag{10}$$

where F is Faraday's constant, M is the molar mass of the oxide, n is the valency of the oxide, U is the voltage applied, and R is the electric resistance of the system. This equation reveals that increasing the voltage enhances both the surface area change and transformation rate. Fig. 6b demonstrates electrocapillary behavior of EGaIn droplets on Cu anodes during DC polarization (10 s) [62]. Upon voltage activation, droplets exhibited progressive spreading with temporal enhancement in both spreading kinetics and terminal coverage area. Notably, hydrophobic characteristics (contact angles >90°)

persisted throughout the spreading process, showing negligible angular variation during electrical stimulation. After power cutoff, droplets initially retracted into spherical caps, followed by pinning of the triple line that stabilized the contact diameter while reducing the apparent contact angle. These observations suggest a competition between electrowetting-driven spreading forces and surface interaction-induced hysteresis. To achieve ultralow interfacial tension, an electrochemical oxidation method is developed, known as electrochemical controlled capillarity/oxidation (Fig. 6c). This approach, first pioneered through redox-active surfactants, enables active manipulation of surface tension gradients to direct organic liquid droplets in microfluidic networks. In essence, electrochemically driven deposition of surfactant-analogous moieties effectively mitigates interfacial tension. The initial researchers to report the systematic demonstration of elevated oxidative potentials under acidic conditions work by Tsai et al. [63], demonstrated that applying high oxidative potentials in acidic media drastically reduces the surface tension of liquid Ga, causing the droplet to spread due to gravity and increase its surface area on the substrate. The evolving oxide layer progressively inhibits subsequent morphological dynamics by forming a physical confinement. Thus, an acid or base solution is essential to simultaneously dissolve the surface oxides.

2.6.2 Chemical manipulation

As shown in Fig. 6d, the LMs in solution will spontaneously form an EDL at its interface. Importantly, the interfacial tension gradient enabling autonomous propulsion of liquid metal droplets can be dynamically controlled through electrochemical modulation of the EDL in ambient solutions. Current liquid metal systems predominantly demonstrate continuous structural adaptations but rarely achieve substantial discrete transformations. Elucidating the chemically mediated mechanisms governing such transitions holds both fundamental and applied significance in advanced functional materials. Ma et al. [64] conceived a chemotaxic LMs system capable of mimicking leukocyte behaviors, such as controllable self-propulsion, obstacle surmounting, climbing opposing gravity, and complex terrain traversal. Systematic screening of metal salt ion-acid systems revealed distinct behavioral patterns in Ga-LMs: the Ag^{+} system predominantly induces self-driven deformation, the Fe^{3+} system favors self-propulsion with minimal deformation, and the Cu^{2+} system supports concurrent self-propulsion and deformation. Notably, the Cu^{2+} system demonstrates high fidelity leukocyte-mimetic behavior through dynamic pseudopodia formation and chemotaxis-responsive navigation, establishing a bioinspired framework for soft robotic actuator design.

2.6.3 Magnetic manipulation

The actuation strategies for LMs typically rely on aqueous environments, which may limit applications in transformable machines. Alternatively, magnetic field enables precise, remote, and programmable control over designed objects [65]. Remote

magnetic actuation mitigates interference from external fuel sources, undesired chemical reactions, and electrode-induced electrolyte decomposition, thereby preserving material integrity [66,67]. However, conventional liquid metal elements exhibit minimal magnetic susceptibility. To circumvent this inherent limitation, integration of magnetic additives enables programmable deformation in response to external magnetic fields. This modification endows liquid metals with magnetic responsiveness, enabling their programmable manipulation. A representative approach involves magneto-responsive liquid metal droplets. As illustrated in Fig. 6e**,** Cr_2Te_3-coated liquid metal (CT-LM) droplets were fabricated via a simple self-assembly process, forming a core-shell structure with Cr_2Te_3 nanosheets as the outer coating and liquid metal as the core [68]. This architecture retains the inherent deformability of liquid metal while enabling magnetically driven shape transformation and locomotion on diverse substrates (Cu, Ag, Ni, glass, and polyimide) without residual contamination. Additionally, recyclable CT-LM droplets enhanced their potential for use in sustainable electronic devices. Alternatively, the diverse manipulation of slurry-like uniform dispersions of magnetic particles within LMs. Wang et al. [69] developed a magnetically sensitized soft architecture comprising magnetized liquid metal droplets embedded in a stretchable elastomer matrix (methyl vinyl polysiloxane/Pt-catalyzed polymethylhydrosiloxane). Under magnetic actuation via permanent magnets, Fe-doped liquid metal droplets demonstrated rapid solidification accompanied by exothermic phase transitions. Pre-engineered configurations of metallic inclusions enabled spatially-defined thermal patterning (Fig. 6f), with optical contrast persisting >120 s through controlled energy dissipation.

2.6.4 Other forms of elicitation

Ga-LMs demonstrate stimuli-responsive behavior to diverse environmental inputs including light, sound, thermal variations, and moisture gradients [70,71]. For instance, Zhao et al. [72] reported for the first time the spin phenomenon of liquid metal droplets on ice through two-fluid solid-liquid phase transformation and liquid film lubrication, which was likened to ice dance. When a droplet of Ga-LMs at room temperature is placed on an ice cube, the adjacent ice rapidly melts as the gallium metal droplet. Concurrently, the metal droplet spins swiftly and gradually submerge into the ice hollow (Fig. 6g). The droplet exhibits multiple distinct motion modes, including unidirectional rotation in either clockwise or counterclockwise directions, dynamic direction reversal during motion, and vertical descent under gravitational forces. The mechanism driving the spin of the droplet involves instant solidification and heat release occurring upon contact with ice. This reaction causes rapid melting of the surrounding ice and establishes a lubricating water film via a two-fluid solid-liquid phase change. Additionally, bubbles released from beneath the ice exert an unbalanced force around the droplet, further promoting its spinning motion. As shown in Fig. 6h,

the principle works in both solution environments and sealed microfluidic channels due to the ability of acoustic waves to travel through diverse materials. Polymers or ligands can be deposited on the particles by sonicating the LMs in the presence of these substances. Light, a form of high-frequency electromagnetic radiation, has the potential to remotely activate materials. Optical modulation enables precise control over stimuli-responsive systems by adjusting parameters such as wavelength, intensity, and exposure duration. As demonstrated in Fig. 6i, near-infrared irradiation induces localized heat and reactive oxygen species generation within LM nanocapsules, triggering their disintegration. These stimuli-responsive properties have enabled the development of multifunctional LM-based platforms for advanced biomedical applications, including on-demand drug delivery, light-guided microfluidic manipulation, and *in vivo* biomedical labeling in live animal models.

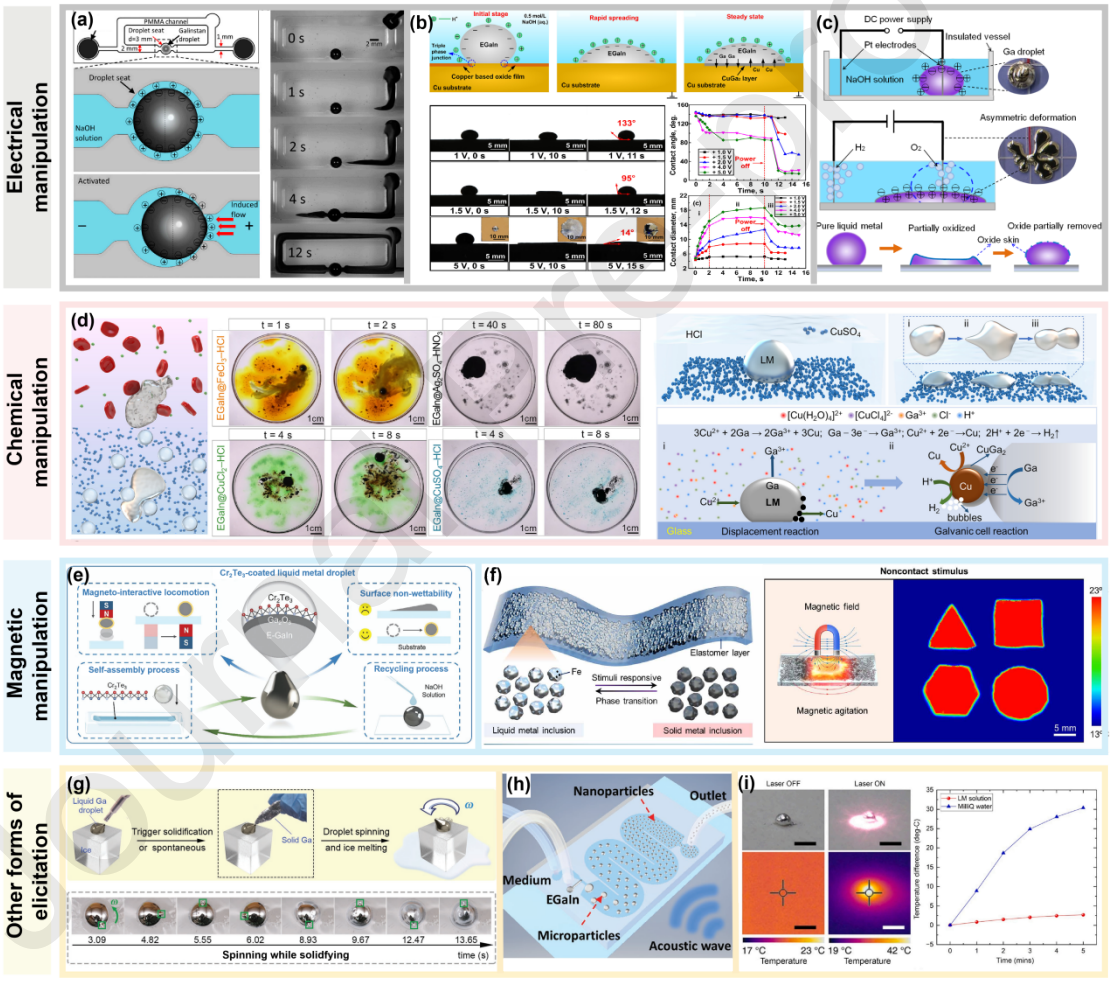


Fig. 6. Transformability of Ga-LMs. Electrical manipulation. **(a)** Electrocapillarity utilizes charges in the EDL to realize modest changes in surface tension. Reproduced with permission from Ref. [73]. Copyright 2014, National Academy of Sciences. **(b)** Continuous electrowetting induces surface tension gradients for liquid metal actuation in microchannels. Reproduced with permission from Ref. [62]. Copyright 2019, Elsevier. **(c)** Electrochemical capillarity leverages interfacial redox reactions to modulate surface tension dynamically. Reproduced with permission from Ref. [74].

Copyright 2014, Springer Nature. Chemical manipulation. **(d)** Biomimetic liquid metal leukocytes with magnetic responsiveness are engineered to replicate biological locomotion through advanced structural design and fabrication. Reproduced with permission from Ref. [64]. Copyright 2025, Cell Press. Magnetic manipulation. **(e)** Cr_2Te_3-functionalized EGaIn droplets enable magneto-driven navigation, superhydrophobic behavior, and programmable self-assembly/recycling cycles, as depicted schematically. Reproduced with permission from Ref. [75]. Copyright 2024, Wiley-VCH. **(f)** Schematics of liquid metal-elastomer architecture with Fe-incorporated liquid metal droplets as the phase transition inclusion. The solidification of supercooled Fe-containing Ga droplets in the elastomer when mechanically stretched (elongated) by 120% strain and applying a magnetic field. Reproduced with permission from Ref. [68]. Copyright 2024, American Association for the Advancement of Science. Other forms of elicitation. **(g)** Demonstration of rotational dynamics in liquid metal droplets on ice substrates. Reproduced with permission from Ref. [72]. Copyright 2023, Wiley-VCH. **(h)** Schematic illustrating the acoustic wave-driven generation of liquid metal microdroplets at T-junctions, followed by their progressive fragmentation into nanoparticles during microchannel transport. Reproduced with permission from Ref. [76]. Copyright 2018, Wiley-VCH. **(i)** Multimodal imaging (visible/thermographic) reveals structural transformations of liquid metal droplets following 785 nm laser irradiation. Reproduced with permission from Ref. [77]. Copyright 2017, Springer Nature.

3. The morphology and fabrication of Ga-LMs

3.1 Bulk Ga-LMs

The intrinsic nature of Ga-LMs, combining metallic conductivity, thermal response with fluidic deformability and biocompatibility on the surface of organisms, enables unprecedented integration into soft, reconfigurable systems that mimic biological compliance. This section delineates transformative strategies in Ga-LMs design, from particle-scale functionalization to macro-scale hybrid systems, and demonstrates their role in overcoming limitations of conventional flexible electronics. Fig. 7 schematically illustrates three prototypical architectures of Ga-LMs. Bulk Ga-LMs are defined as monolithic systems exhibiting concurrent metallic characteristics, including electrical, thermal, optical, and chemical properties, with fluidic attributes [78]. This unique material combination arises from their fundamentally dual nature as metallic liquids. The distinctive physical properties of bulk Ga-LMs enable unconventional fluidic applications, particularly derived from their uniquely contrasting physical properties compared to conventional Newtonian fluids like water or oil. Bulk Ga-LMs can be encapsulated into prefabricated elastomers with lattice structures composed of individual cells. The lattice structure can be arranged periodically to form different 3D structures and thus acquire various functions [79]. The Ga-LMs lattice architectures act as structural frameworks that enable dynamic fluidic behavior and programmable shape morphing. Upon heating above the phase transition temperature, these metallic frameworks transition to an adaptive fluid state, allowing structural reconfiguration, while subsequent solidification retains structural integrity

and load-bearing capacity. Significantly, such architected lattices can be fabricated via additive manufacturing techniques, thereby enabling precise geometric control through either direct 3D printing or the assembly of modular lattice units. The benefit of 3D printing lies in its structural controllability, which aligns well with other complex structures. Ga-LMs can be directly printed onto existing substrates, while their inherent high cohesion and distinct density disparity relative to surrounding gaseous or liquid media promote the formation of discrete, phase-separated droplets that effectively mitigate cavitation phenomena [80]. The resulting expancel microspheres-liquid metal (EMLM) foam exhibits smart functionalities including adjustable rigidity and shape memory capabilities as demonstrated in Fig. 7a.

Furthermore, leveraging the inherent conductivity of liquid metals, this material allows the fabrication of flexible circuits conforming to three-dimensional soft substrates. Bulk Ga-LMs achieve high intrinsic conductivity through geometric continuity of the liquid phase. The surface oxide layer plays a critical role in maintaining electrical stability under strain by facilitating quantum tunneling. While preserving essential material properties, this approach successfully integrates both the conductive characteristics and tunability stiffness of liquid metals through optimized physical and chemical processing techniques.**Error! Reference source not found.** The inherent fluidity of Ga enables unconventional processing methods unattainable with solid metals, as illustrated by diverse patterning strategies for Ga-LMs in Fig. 7b. Strategic incorporation of metallic particles modulates Ga-LMs' melting behavior, flow dynamics, and oxidation resistance, enhancing reliability and operational stability in electronic systems. Metal-doped Ga-LMs alloys exhibit improved printability and electrical performance while broadening functional applications [81]. Advanced fabrication approaches have been developed through interfacial engineering, including substrate-direct patterning via controlled oxide layer formation during mechanical agitation. Notably, silicone elastomer-supported Ga-LMs composites have been engineered for stretchable electrodes through stencil-guided deposition, leveraging tunable surface oxidation and optimized substrate wettability to achieve precise architectures.

3.2 Particles

Ga-LMs nanoparticles, having garnered significant research attention in nanotechnology applications [82,83], demonstrate remarkable structural stability with coalescence resistance that persists unless subjected to deliberate native oxide removal processes. Electrical conductivity can be activated through mechanical sintering, freezing-induced expansion, or electrochemical wetting, which disrupt the insulating oxide barrier to form conductive pathways. These particles exhibit exceptional properties including high surface area for enhanced catalytic reactivity, microscale plasmonic optical behavior, and unique phase characteristics that promote supercooling in confined geometries. Significantly, they provide a metallic alternative to

conventional polymer/oxide colloids while maintaining desirable soft-matter attributes required for flexible applications. Recent advances in Ga-LMs particle fabrication have demonstrated multiple synthesis strategies, primarily involving mechanical or acoustic energy-driven fragmentation of bulk LM precursors within carrier fluids. As illustrated in Fig. 7c, three principal methodologies have been established: probe sonication, high-speed shear mixing, and piezoelectric transducer-assisted nebulization, all yielding nanoparticles (LMNPs) with diameters spanning 10–1000 nm. The final particle size distribution depends critically on applied energy parameters, though these top-down approaches inherently produce polydisperse systems due to stochastic bulk metal fragmentation. An alternative approach employs high-pressure microfluidic orifice systems to achieve controlled shear-induced particle generation. Notably, a breakthrough surfactant-free synthesis technique enables precision engineering of Ga-LM nanoparticles through physical vapor deposition on diverse substrates (Fig. 7d). This process features surface functionalization via atom transfer radical polymerization (ATRP), where polymeric monomer brushes are covalently anchored to LM droplet interfaces. Subsequent crosslinking creates robust interfacial bonds between the elastomeric matrix and metallic phase, enabling homogeneous LM dispersion. The resultant composite exhibits exceptional elasticity coupled with enhanced thermal conductivity, demonstrating synergistic multifunctional performance unattainable through conventional methods.

3.3 Ga-LMs composite

Recent advancements in Ga-LMs polymer composites have shifted research focus toward systems comprising elastomeric matrices reinforced with Ga-LMs fillers [84]. This emerging paradigm leverages the synergistic integration of microscale Ga-LMs suspensions and deformable droplets within flexible substrates, enabling unprecedented multi-modulus enhancement of elastomeric materials. Mechanical blending stands as a fundamental fabrication strategy for Ga-LMs polymer composites, offering direct processability through homogeneous dispersion of liquid metal phases in elastomer precursors (Fig. 7e). Subsequent curing protocols employ diverse post-processing methodologies, with thermal quenching of electronic inks emerging as a particularly effective phase-stabilization approach. Nevertheless, liquid metal droplets within the polymer network are separated by an oxide film that forms immediately upon air exposure, which results in LM-polymer composites usually exhibit insulating properties. To activate and tailor electrical conductivity, external stimuli can be employed to dynamically reconfigure the internal conductive network. Specifically, compressive strain forces the deformation and contact of adjacent LM droplets, causing a dramatic resistance reduction. Under tensile strain, the network undergoes structural anisotropy, generating direction-dependent electrical resistance characterized by axial enhancement coupled with transverse attenuation. Undoubtedly, achieving stimuli-responsive electrical conductivity in LM-polymer composites is critical to many future practical applications. Unlike ceramic-based counterparts, Ga-LMs retain fluidity,

allowing dynamically reconfigurable conductive networks that respond to multiple stimuli (mechanical stress, thermal gradients, laser irradiation, acoustic waves, and magnetic fields). The solidification-induced volumetric expansion of Ga enables effective electrical interconnection through particle displacement within polymer matrices. Pioneering work by White et al. demonstrated laser-induced sintering of Ga-LMs for programmable circuit formation, while subsequent investigations by Liu et al. [85] elucidated the fundamental mechanisms of focused ion beam and UV laser sintering processes, expanding their technological applications (Fig. 7f). Ga-LMs achieve versatile multifunctional integration in soft systems through cross-scale engineering strategies, from functional nanoparticles to hybrid architectures, overcoming limitations of traditional flexible electronics. However, precision patterning of Ga-LMs into defined architectures remains a critical challenge addressed through advanced fabrication techniques, such as sintering, which will be systematically discussed in the following sections.

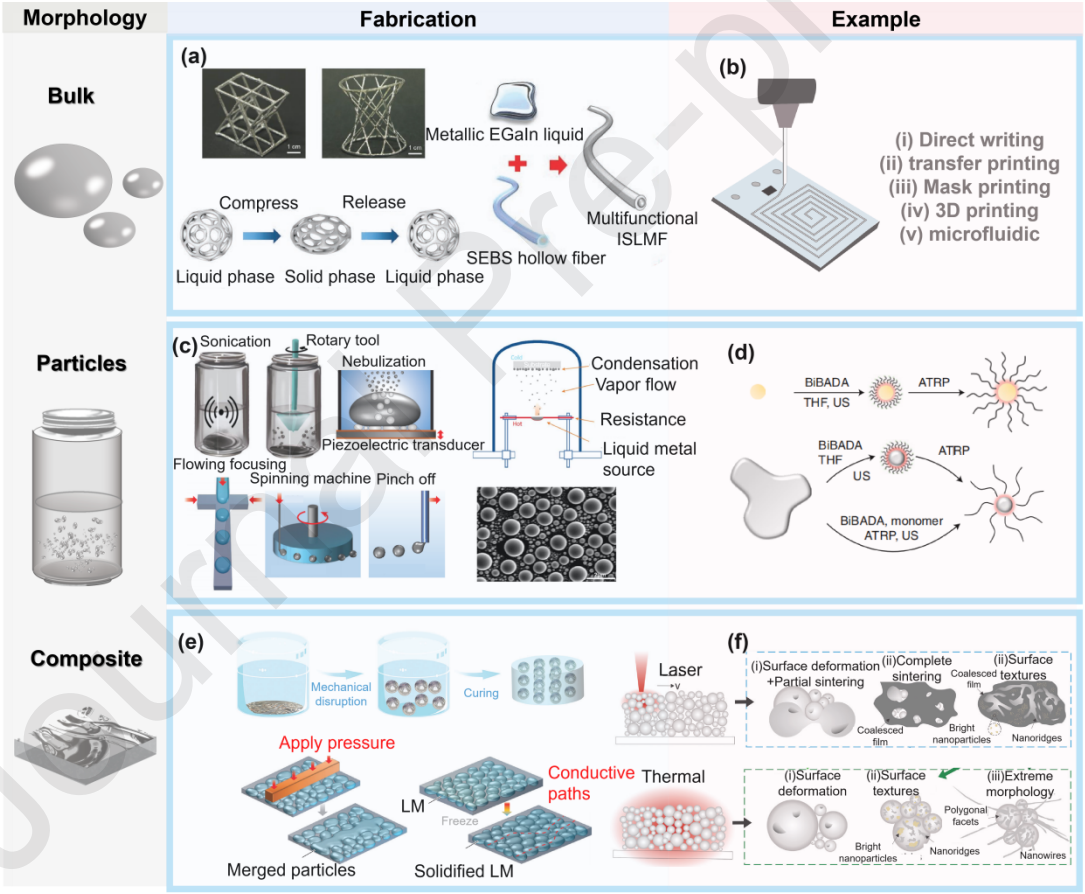


Fig. 7. The embodiments of Ga-LMs and fabrication methodologies. Bulk. **(a)** Fabrication of Bulk Ga-LMs: Thermal-induced phase transition mechanism in Ga-polymer foam composites through temperature modulation, accompanied by liquid metal surface deposition on engineered substrates. Reproduced with permission from Ref. [80,86,87]. Copyright 2021, Elsevier. Copyright 2021, Wiley-VCH. Copyright 2022, Wiley-VCH. **(b)** Liquid metals demonstrate distinctive patterning capabilities compared to conventional solid-phase metallic systems. Ga-LMs particles. **(c)** Strategy

for dispersing liquid metals into droplets. Reproduced with permission from Ref. [82,88]. Copyright 2021, Annual Reviews. Copyright 2018, Elsevier. **(d)** Sequential nanoparticle functionalization via BiBADA chemistry followed by surface-initiated ATRP, illustrating stepwise LM droplet modification and site-specific polymerization initiation. Ga-LMs composite. Reproduced with permission from Ref. [89]. Copyright 2019, Springer Nature. **(e)** Methods for constructing Ga-LMs composites: Fabrication of homogeneous LM-elastomer composites through mechanical dispersion, achieving percolation-driven conductive networks via particle coalescence during matrix deformation. Reproduced with permission from Ref. [90]. Copyright 2023, Wiley-VCH. Copyright 2021, Annual Reviews. **(f)** Laser-induced sintering mechanism of LM particles, characterized by localized surface restructuring and interparticle bridging through deformation-activated metallurgical bonding. Reproduced with permission from Ref. [85]. Copyright 2019, Royal Society of Chemistry.

4 Patterning methods for Ga-LMs

The burgeoning interest in Ga-LMs patterning stems from their ability to achieve resolution down to the submicron scale, heralding a new era for the development of groundbreaking devices. Ga-LMs patterning can be categorized based on the inherent properties of these materials as a starting point. The fluidity, conductivity, and wettability inherent to Ga-LMs, combined with their unique characteristics and high surface tension, create both challenges and opportunities in the development of Ga-LMs patterning.

4.1 Direct writing

The liquid metal is extruded from the nozzle, as illustrated in Fig. 8a. Initially, it forms a sphere due to the influence of surface tension and coalesces upon contact. Ultimately, it accumulates onto the substrate to create a specific pattern. Writing with a ballpoint pen on a substrate follows principles analogous to the extrusion process. The shear force produced by the adhesive layer formed between the Ga-LMs surface and the wetted substrate induces the flow of Ga-LMs from both the nozzle and the ballpoint pen (Fig. 8b and c). This method presents both merits and drawbacks. A notable advantage is that it can rapidly form specific patterns and establish electrical connections. Furthermore, it can be directly utilized for liquid metal applications without requiring additional treatment. However, there exist certain challenges that need to be solved: (i) The successful adhesion of the metal oxide layer to the substrate is crucial, therefore adheres superficially on the substrate are necessary (such as a smooth or hydrophilic surface). (ii) The bond between the metal droplets and the substrate tends to be weak; consequently, most of the Ga-LMs adhere superficially of the substrate. In some instances, further encapsulation may be required to prevent displacement caused by vibrations. (iii) The diameter of the printed Ga-LMs structure is determined by both the nozzle and ballpoint pen diameter. Furthermore, both printing

height (the distance between the nozzle and substrate) and dispersing pressure play significant roles in achieving optimal patterning results.

4.2 Transfer printing

Transfer printing represents a direct methodology for patterning that leverages the wetting behavior of liquid metals (Fig. 8d). This technique entails the exchange of liquid metal between two distinct substrates: the donor substrate, which dispenses the liquid metal, and the recipient substrate. The disparity in adhesive characteristics between these two surfaces poses significant challenges to achieving seamless transfer of liquid metal from donor to recipient substrates. Numerous cutting-edge techniques have emerged to enhance liquid metal transfer capabilities. These methods include modifying the wettability of the recipient substrate through mechanisms such as pressure application, laser irradiation, or temperature manipulation. Alternatively, strategies may involve reducing adhesion between oxide layers on liquid metals and their donor surfaces. As illustrated in Fig. 8e, Guo et al. [18] demonstrated how intricate conductive patterns can be fabricated on substrates lacking optimal wettability for liquid metals via transfer printing processes. Central to this advancement is the incorporation of poly(methyl acrylate) (PMA) as a polymer-based adhesive bridging the liquid metal and substrate. After successful transfer onto paper, the transferred liquid metal confined solely within paths etched by PMA glue. However, transfer printing encounters inherent limitations determined by parameters associated with both substrate materials. The achievable resolution may only reach hundreds of microns with low material universality across different applications.

4.3 Mask printing

The mask serves as a crucial tool designed to facilitate the formation of intricate and delicate patterns using liquid metal ink as shown in Fig. 8f. Chen et al. [56] multi-layered integrated stretchable electronics by mask printing methods (Fig. 8g). Generally, this mask is a meticulously prepared stencil that permits the passage of liquid metal ink through its apertures. Subsequently, liquid metal ink is uniformly applied across the surface of the mask using tools such as a squeegee or spray apparatus. Throughout this procedure, it is essential to note that the adhesion of the oxide layer to the substrate should not be underestimated. Fig. 8h illustrates the integrated of soft electronic components fabricated on a biopolymeric hydrogel substrate [91]. The merits of this approach lie in its remarkable potential for swift, extensive, and automated production and effective reusability of the mask. However, several areas of concern that warrant attention: (i) In this method, the mask assumes a pivotal role in dictating the resolution of the printing process. However, the intricacy of the print influenced by the mask often is compromised by its limited durability. (ii) The application of liquid metal can obscure the mask, leading to a reduced reusability as well as challenges in recycling and processing. (iii) Unlike the directed inkjet writing (DIW) technique, mask printing

allows direct use without requiring pre-treatment of the liquid metal. The high surface area of liquid metal makes it difficult to create intricate patterns at high resolutions with masks, frequently resulting in incomplete coverage. Even when employing a spraying technique rather than a squeegee for uniform distribution during this process, it is necessary to convert the liquid metal into pellets to facilitate effective spraying. Fig. 8i illustrated the TPU substrate prepared by electrospinning and the LM circuit patterned on the TPU membrane by the stencil printing [92].

4.4 3D printing

Fig. 8j illustrates the remarkable application of advanced 3D printing technology in the intricate patterning of liquid metals [86]. To enhance clarity and facilitate comprehension, this process can be succinctly categorized into two distinct methodologies: direct and indirect approaches. The indirect method involves creating a high-resolution model through advanced 3D printing techniques, followed by transfer-printing to achieve precise patterning. For instance, Park et al. [33] employed intricately designed 3D-printed molds for transfer printing, and successfully transferred EGaIn micropattern electrodes onto hydrogels (Fig. 8k). Under optical microscopy, these EGaIn periodic patterns showed widths as narrow as 100 μm. Conversely, another approach focuses on augmenting liquid metals to make them compatible with 3D printing. Lin et al. introduced a technique that enhances the patterning capabilities of liquid metal through high internal phase emulsion gel ink (Fig. 8l). With a remarkable liquid metal content of 82.5%, this ink exhibits exceptional shape stability and enables the fabrication of complex three-dimensional constructs such as hollow tetrahedrons and suspended grids. Moreover, it is compatible with non-planar substrates (such as PET and PTFE), which allow for in-situ 3D printing while also supporting alternating deposition with materials like PDMS and epoxy resin, thereby paving the way for multi-layer circuits and multifunctional devices. This advancement addresses the inherent challenges associated with directly printing of liquid metal owing to its low viscosity and superior surface tension.

4.5 Other methods

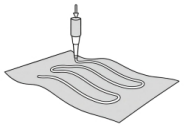
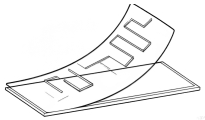
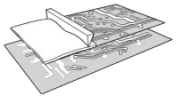
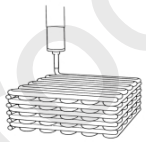
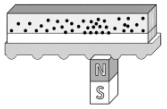
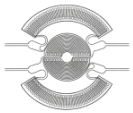
Ga-LMs can serve as versatile core components in microfluidic systems, existing either as discrete droplets/marbles or within polymer-embedded composites exhibiting isotropic/anisotropic configurations. The rational design of microchannel geometries allows for precise manipulation of the shape of Ga-LMs (Fig. 8m). Metal patterning is accomplished through the precise manipulation of liquid metal via magnetic fields as shown in Fig. 8n. However, GA-LMs necessitate the incorporation of additional metallic particulates to augment their magnetic properties. These liquid metals exhibit a remarkable self-healing capability, which is facilitated by interactions between magnetic particles and external magnets [93,94]. Despite the aforementioned advantages, the efficacy of magnetically controlled liquid metal remains critically

dependent on the adhesion of its oxidized surface layer to the substrate. In contrast to patterns formed through nozzle extrusion techniques, those shaped under magnetic guidance typically demonstrate reduced resolution and pattern fidelity.

As a flexible and stretchable conductor, the development of patterning techniques for Ga-LMs is a crucial step towards its industrialization. However, the practical application of Ga-LMs patterning technologies involves an inherent trade-off between scalability and cost-effectiveness. Mask printing exhibits substantial scalability for high-volume production, mirroring critical features of mature manufacturing platforms through continuous-operation capability, high-speed processing, and automated system compatibility. However, its deployment in cutting-edge applications encounters persistent resolution barriers compromising precision-sensitive patterning requirements. In contrast, additive manufacturing exhibits a lower output per unit time due to its longer production time for individual parts. However, it excels in minimizing material waste, which presents a significant cost advantage for expensive materials or complex designs. Furthermore, it eliminates the need for costly hardware such as molds and masks, making it particularly suited for prototyping, customized products, and small-batch production.

In summary, the diverse patterning techniques for Ga-LMs, ranging from direct writing and printing to molding and magnetic manipulation, each present a unique set of capabilities and limitations. As discussed, their suitability for industrial adoption is fundamentally governed by a trade-off between scalability, cost-effectiveness, and resolution. The systematic comparison in Table 1 consolidates these key parameters, including mechanisms, material requirements, advantages, and disadvantages, to provide a clear decision-making framework. This analysis underscores the absence of a universal solution and highlights that the optimal choice is governed by the particular requirements of each application.

Table 1. Comparison of key characteristics across Ga-LMs based patterning techniques.

Pattern method	Direct writing	Transfer printing	Mask printing	3D printing	Magnetic printing	Microchannel injection
Representative diagram						
Mechanisms	Shear force-induced liquid metal flow from nozzle/pen tip	Interfacial adhesion differentials between donor and receptor substrates	Squeegeeing/spraying deposition prefabricated templates	Advanced 3D printing technology	Controlling magnetic Ga-LMs through magnets	Fill predefined microchannels for patterning
Material requirements	Low viscosity and stable oxide layer	Tunable adhesion of oxide layer	Pretreatment High-precision mask	Printability	Magnetic particle-doped liquid metal	Oxygen permeability and Geometric constraints
Precision	100-500 μm	20-100 μm	≤200 μm	50-200 μm	>500μm	≈10 μm
Cost	Very Low	Low	Medium-High	Low	Very Low	Medium
Electrical Stability	Moderate	High	Moderate	Moderate	Low	Excellent

Substrate Adaptability	Versatile (skin, curved surfaces, paper)	Requires adhesion layer	Flat surfaces only (curvature radius > 50 mm)	Porous/curved surfaces	3D non-planar surfaces	Pre-fabricated channel substrates
Advantages	■ Quickly patterns ■ High flexible ■ Mold-free	■ Multi-material compatibility ■ Cost-effective	■ Suitable for rapid, large-scale and automated production ■ Production with reusable masks	■ Construct complex structures ■ Additive manufacturing reduces material waste	■ Super-hydrophobic surface compatibility ■ Self-healing capability ■ Non-contact magnetic guidance	■ High resolution ■ Simple micro-tunnel filling ■ Excellent fluidity enable easy injection into microchannels or sealing layers
Disadvantages	■ Relies on oxide-substrate adhesion ■ Post-process packaging necessity ■ Nozzle/pen diameter restricts design ■ Low scalability	■ Low transfer efficiency ■ low resolution	■ Resolution-durability trade-off ■ Low material utilization ■ Requirement for material pre-processing ■ Risk of incomplete coverage	■ Low production efficiency ■ Requires post-processing	■ Low-resolution patterning feature ■ Magnetic particle doping dependent	■ Wettability-related filling issues ■ Risk of leakage or delamination ■ Difficulty in filling dead-end channels ■ Limitation to simple structural designs
References	[123]	[31]	[128]	[56]	[132]	[48]

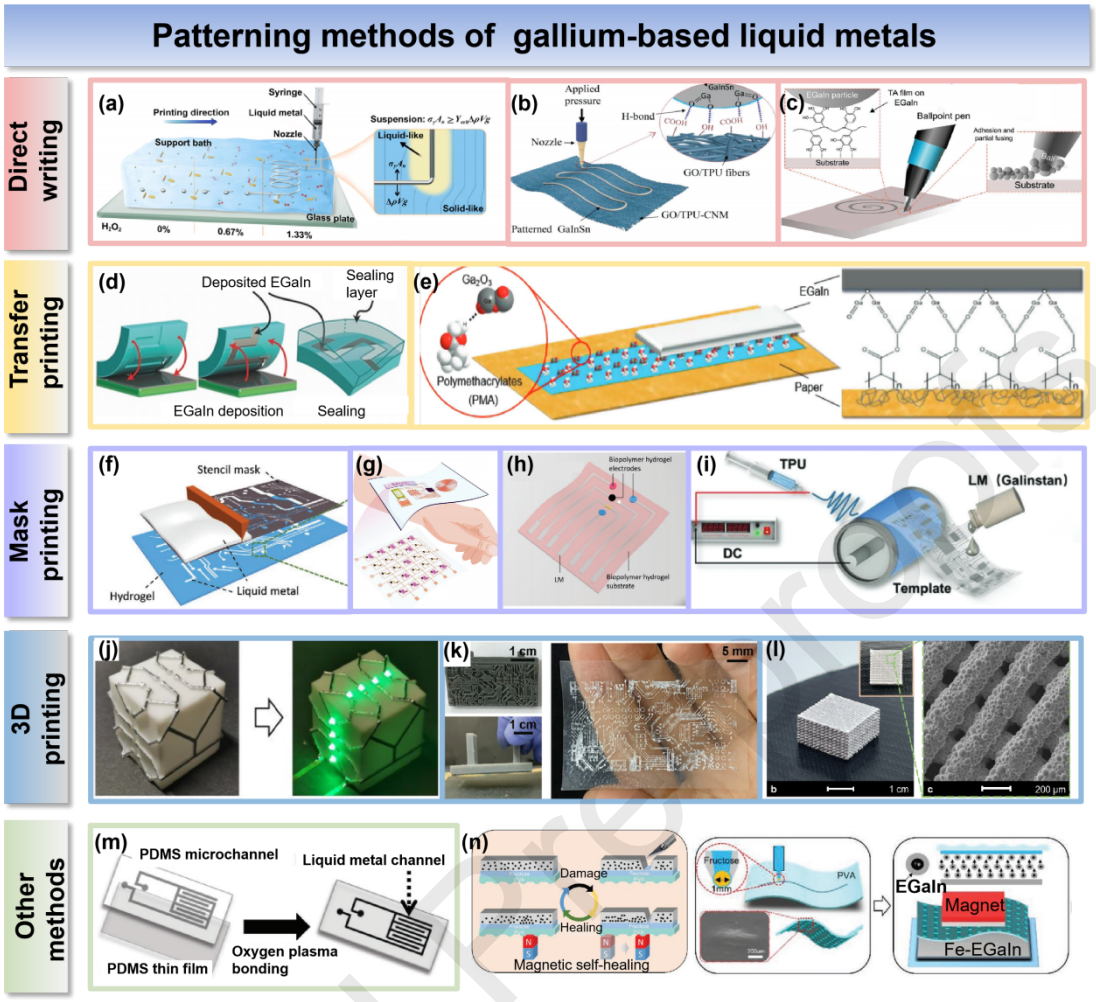


Fig. 8. Patterning methods of Ga-LMs. Direct writing. **(a)** Direct-write deposition of GaInSn eutectic alloy in a hydrogen peroxide-enhanced AAm/nanoclay supporting matrix. Reproduced with permission from Ref. [95]. **Error! Reference source not found.** Copyright 2022, Springer Nature. **(b)** Precision patterning of gallium-indium-tin (GaInSn) ternary alloys on graphene oxide-reinforced thermoplastic polyurethane (GO/TPU) substrates. Reproduced with permission from Ref. [96]. Copyright 2023, Wiley-VCH. **(c)** Ballpoint-assisted micropatterning using tannic acid-functionalized eutectic gallium-indium (TA/EGaIn) composite inks. Reproduced with permission from Ref. [57]. Copyright 2021, Wiley-VCH. Transfer Printing. **(d)** Schematic description of the EGaIn deposition process. Reproduced with permission from Ref. [97]. Copyright 2014, Wiley-VCH. **(e)** Chemical bonding interaction mechanism between polymethyl acrylate (PMA) adhesive and EGaIn alloy surfaces. Reproduced with permission from Ref. [18]. Copyright 2018, Wiley-VCH. Mask printing. **(f)** Hydrogel-integrated soft electronic fabrication via stencil-guided LM patterning. Reproduced with permission from Ref. [91]. Copyright 2021, Wiley-VCH. **(g)** Bilayer liquid-solid conductor architecture development through masked deposition of programmable circuit geometries. Reproduced with permission from Ref. [56]. Copyright 2023, Wiley-VCH. **(h)** Biohybrid electronics platform combining biopolymer gel substrates with embedded LM interconnects. Reproduced with permission from Ref. [98]. Copyright 2022, Wiley-VCH. **(i)** Multilayer assembly strategy employing electrospun TPU matrices with precision-patterned LM

circuitry. Reproduced with permission from Ref. [92]. American Chemical Society. 3D printing. **(j)** Mold-assisted transfer printing process demonstrating: (top) 3D-printed template fabrication, (center) direct hydrogel imprinting, and (right) final micropatterned EGaIn electrode arrays. Reproduced with permission from Ref. [86]. Copyright 2021, Elsevier. **(k)** Structural demonstration of non-dense cubic lattice fabricated via additive manufacturing. Reproduced with permission from Ref. [33].**Error! Reference source not found.** Copyright 2020, Wiley-VCH. **(l)** Electrical characterization of omnidirectionally conductive 3D EGaIn architectures. Reproduced with permission from Ref. [40]. Copyright 2024, Springer Nature. Other methods. **(m)** Silicone-embedded LM microelectrode arrays for electroadhesive applications. Reproduced with permission from Ref. [99]. Copyright 2021, Wiley-VCH. **(n)** Magnetic field enabled printing of ferrofluidic LMs. Reproduced with permission from Ref. [100]. Copyright 2019, Wiley-VCH.

5. Multifunctional closed-loop electronic application of Ga-LMs in HMI technology

5.1 Stretchable and self-healing circuits

The focus of electronic technology is shifting toward integration with the human body rather than just improving processing speed and efficiency. Advances in materials science and fabrication technologies enable stretchable electronics with compliant mechanical properties that can adapt to the dynamic biological surface. Intrinsically stretchable materials offer significant advantages over conventional fabrication approaches to developing advanced stretchable electronics [101]. These materials inherently preserve critical device integration capabilities that are often compromised in traditional techniques, particularly in maintaining: (i) high production yield for scalable manufacturing, (ii) superior device density through seamless integration of functional components, (iii) exceptional uniformity in both mechanical and electrical properties across large-area substrates, and (iv) remarkable optical transparency critical for advancing next-generation wearable optoelectronics and bio-integrated systems. The self-healing mechanism in Ga-LMs based devices refers to the spontaneous and autonomous repair process of mechanical and electronic properties without external intervention. These devices typically incorporate a combination of a flexible and stretchable elastomer framework infused with Ga-LMs, thereby enabling self-healing functionality. For example, the interactions between the hydroxyl groups presented in hydrogels and water molecules, as well as the native gallium oxide layer enable effective droplet wetting behavior. Based on this understanding, Park et al. [37] developed self-healable and super-stretchable EGaIn electrodes directly on hydrogels. The key objective was to ensure a firm interface between the EGaIn and the hydrogel during the deformation of the hydrogel. By maintaining a strong bond between the EGaIn and the hydrogel, the electrodes can deform along with the hydrogel and exhibit self-healing properties. This hypothesis laid the groundwork for the advancement of micropatterned EGaIn electrodes directly onto hydrogels (Fig. 9a). However, the liquid metal present at the interface inevitably slows down the regeneration of the polymer

network. There is a trade-off in healing efficiency between mechanical and electrical properties. For instance, Chen et al. [56] created a bilayer liquid-solid conductor (b-LSC). The bilayer architecture enables spontaneous self-soldering interfaces between the upper liquid metal layer and rigid electronics, achieving ultra-low contact resistance through mechanical pressing-induced embedding of surface-mounted device (SMD) pinouts into the LM matrix. This configuration maintains robust electrical continuity under severe mechanical deformation, sustaining approximately 400% tensile strain (Fig. 9b). Nevertheless, the healed conductor exhibits a significantly reduced fracture strain, likely due to liquid metal leakage. An alternative approach involves electrically self-healing conductors engineered by embedding liquid metal microcapsules within polymer matrices. A representative implementation by the Majidi group employed LM-encapsulated elastomers that required localized pressure activation to form conductive traces. [102] This system demonstrated operational stability in extreme conditions, maintaining functionality in a microcontroller-connected timer display through four-wire LM interconnects despite severe mechanical damage (e.g., cutting and tearing).

5.2 Flexible sensors

Flexible sensors represent a transformative advancement in bridging biological systems with electromechanical technologies and serve as critical interfaces for perceiving both external environments and internal physiological states. In closed-loop electronic systems, flexible sensors act as the pivotal functional element that integrates multimodal sensing capabilities by decoding heterogeneous environmental stimuli (such as strain, temperature, biochemical signals), enabling seamless data transmission across system hierarchy and ensuring dynamic feedback-regulated operations through bidirectional information exchange [103,104]. They demonstrate dual functional significance in human-machine integration. Primarily, these systems serve two essential purposes: (i) continuous physiological monitoring with therapeutic intervention capabilities, and (ii) augmentation of human performance in challenging environments through enhanced environmental adaptability. The primary functionality manifests in healthcare applications, where conformal integration with wearable platforms enables continuous monitoring of multidimensional physiological parameters with real-time feedback [105-109]. In the context of a closed-loop HMI system, the Ga-LMs based sensors described here (e.g., stretch, chemical, e-skins) primarily constitute the input or perception module. Their fundamental role is to transduce external physical, chemical and electrophysiological stimuli (such as motion, touch, pH, or glucose levels) into quantifiable electrical signals. This sensory feedback is the critical first step that initiates the closed-loop operation, completing the perception-decision-action cycle that defines an intelligent, closed-loop HMI.

5.2.1 Physical signal

The primary developmental objective of flexible physical sensors lies in optimizing wearability and metrological precision to facilitate continuous, noninvasive, and clinically validated vital sign monitoring in ambulatory settings [110-112]. Chung et al. [113] fabricated a multifunctional electronic textile integrated with liquid metal-based conductive ink, demonstrating exceptional capabilities in real time monitoring of complex human motions. As illustrated in Fig. 9c, an e-textile glove was developed and each finger was connected with an individual channel to supplement real time detection results [114]. Reproducible, high-amplitude signals were systematically recorded during sequential phalangeal flexion-extension cycles, static grip maintenance, and multi-postural configurations, demonstrating robust cross-motion discriminability. The system permits programmable threshold alerts through the mobile interface when bending angles exceed predetermined limits. This operational principle relies on piezoresistive transduction, where conductor deformation-induced resistance variations provide quantifiable strain-electrical coupling [115,116]. Bai et al. [114] introduced a method employing Ga-LMs to reconfigure conductive networks within mechanically compromised platinum fabric electrode (Fig. 9d). Ga-LMs present as an attractive candidate for stretchable electrodes owing to its intrinsic malleability, strain-independent electrical stability, and tissue-like compliance. Serving as an autonomous electrical healing medium, Ga-LMs enable textile-based strain sensors that achieve conformal epidermal contact for high-fidelity biomechanical monitoring. These advancements provide novel insights for haptic human-machine interfaces and further expand the potential application in next-generation adaptive bioelectronics.

5.2.2 Chemical signal

Chemical biomarkers such as glucose, lactic acid, pH, and cations hold clinical significance for diabetes management, cardiovascular risk stratification, and stress quantification through noninvasive biofluid analysis (urine, saliva, tear) [117]. A representative strategy involves integrating sweat analysis with electrophysiological signal monitoring, which enables synergistic evaluation of exercise-induced physiological responses. Specifically, sweat biomarkers reflect metabolic and hormonal variations during physical exertion, while concurrent electrophysiological measurements capture neuromuscular electrical activity dynamics. This approach concurrently tracks: metabolic flux (e.g., Δ[glucose] = -0.8 mmol L^{-1} min^{-1} during exercise), neuroendocrine signaling (cortisol surge >2 ng mL^{-1} post-exertion), neuromuscular activation (EMG amplitude increase 300% during contraction). Multimodal biosensing platforms offer three distinct advantages versus unimodal systems:

(i) Cross-parameter validation: cross-dimensional biomarker correlation establishes comprehensive physiological profiles through complementary data integration.

(ii) Error compensation: multimodal signal verification improves diagnostic accuracy by compensating for potential technical limitations in individual detection modalities.

(iii) Enhanced sensitivity: this approach enhances detection sensitivity through cross-validation of biological parameters, thereby identifying subtle physiological alterations that might otherwise remain undetected in single-parameter analyses.

Researchers developed a sweat-detecting sensor using LM-based stretchable conductors (Fig. 9e). By repeating the electrospinning and printing processes, they fabricated vertically stacked multilayer electrical circuits that were incorporated into a monolithic elastic mat, which contained three layers of printed EGaIn electrodes for a total thickness of ~1 mm. The three-layer EGaIn electrodes function as an ECG sensor (top layer), a sweat sensor (middle layer) and an electrothermal heater (bottom layer). Such a vertically stacked multilayer architecture is expected to provide multichannel monitoring of human physiological states and electrothermal therapy. Another study described a health monitoring platform with similar integrated capabilities. Researchers engineered a multifunctional sensing platform that integrates thermometric, pulse monitoring, and potassium detection capabilities, supported by a microcontroller-based data processing architecture with wireless Bluetooth transmission components, powered through an embedded rechargeable lithium-ion battery (Fig. 9f). As a crucial development direction for wearable devices, high integration enables simultaneous multi-dimensional and multi-indicator detection, which effectively mitigates random errors and data misinterpretation inherent in single-signal detection systems. Current research advancements encompass multiple sensing modalities: flexible electrochemical sensors for sweat analysis, flexible temperature sensors for body temperature monitoring, and flexible electrophysiological sensors for myoelectric signal acquisition, electrocardiogram (ECG) recording, and pulse waveform detection [9,118,119]. These integrated sensing approaches have been extensively documented in academic literature, demonstrating the effectiveness of Ga-LMs sensors in comprehensive physiological monitoring applications.

5.2.3 Electrophysiological signal

Electrophysiological sensing systems quantify bioelectric potential gradients across anatomically targeted electrodes interfacing with excitable tissues: cardiac (ECG), neural (EEG: electroencephalogram), and musculoskeletal (EMG: electromyogram) systems [120]. These sensors monitor biopotential variations generated during cardiovascular, neurological, and muscular activities. A fundamental challenge in their development lies in engineering epidermal electrodes that achieve three critical characteristics: thinness, conformal adaptability, and biocompatibility, which all essential for minimizing skin-electrode contact impedance. Successful signal acquisition depends critically on optimizing the interface between these flexible

electrodes and biological tissue. Notably, achieving and maintaining intimate electrode-skin contact is the primary determinant for reducing interfacial impedance and ensuring reliable extraction of electrophysiological signals. Ai et al. [27] successfully integrated functional circuits containing electronic components, chips, and PCB boards into polymer and textile substrates, demonstrating promising applications in wearable electronics such as NFC systems, touch panels, and EMG signal detection. As a crucial biomarker for sports training optimization and musculoskeletal health assessment, EMG signals have attracted substantial research attention. The proposed wearable textile-based EMG sensor capitalizes on the superior biocompatibility and electromechanical properties of liquid metal conductors, integrating both rigid and stretchable elements into a cohesive system. Fig. 9g shows a Ga-LM stretchable electrode for wireless EMG transmission, outperforming conventional dry electrodes by achieving a 28% higher SNR and enhanced motion-artifact resistance. These improvements stem from the optimized interfacial contact maintained by the LM-based electrodes' adaptive conformability to skin morphology. Utilizing a strain-insensitive Ga-LMs kirigami electrode (LM-eKE), Choi et al. [121] constructed a wearable EEG system that reliably acquires physiological signals, as demonstrated by the clear recording of eye movements, as illustrated in Fig. 9h. Zhou et al. [51] fabricated an implantable Ga-LMs physiological electrode capable of recording ECoG and ECG signals from soft, curved, and complex intracorporeal organs (Fig. 9i). These strain-insensitive properties make the technology particularly advantageous for applications requiring stable electrical performance in dynamic environments.

5.3 Electronic skins

Ga-LMs epidermal electronics (commonly termed e-skin) constitute ultrathin, conformable systems that enable seamless integration with the cutaneous surface through gentle lamination. Existing in various formulations including adhesive patches, polymeric films, and hydrogel matrices, these devices demonstrate multifunctional capabilities ranging from transdermal pharmacologic delivery to continuous vital sign monitoring and targeted electrotherapy. Crucially, preliminary toxicological assessments indicate that Ga-LMs particles exhibit acceptable biocompatibility profiles at therapeutic concentrations, supporting their potential for human epidermal applications. The operational reliability of e-skin systems hinges on achieving mechanical harmony between the entangled epidermal microstructure and flexible electronics. This conformal integration is essential for maintaining stable interfacial contact while preventing irreversible structural deformation through mismatched strain responses. Silva et al. [122] developed highly stretchable epidermal electrochemical devices through a synergistic integration of liquid metals (LMs) and island-bridge (IB) structural engineering (Fig. 9j). The IB architecture, comprising rigid functional "islands" that are interconnected by serpentine-bridge conductive traces, was creatively combined with LM-enhanced printable inks to achieve exceptional electromechanical performance. The custom Ag-LM hybrid ink formulation incorporates silver flakes as

conductive fillers, eutectic gallium-indium particles (EGaInPs) as dynamic conductive components, and styrenic block copolymers as hyperelastic binders, enabling dual-mode stretchability via both material compliance and structural design. This hierarchical approach combining intrinsic LM conductivity with engineered serpentine interconnects endows the system with unprecedented mechanical robustness (100% strain tolerance), multidirectional deformability, and stable electrochemical functionality under severe mechanical stress. The demonstrated integration of material with bioinspired structural design establishing a new paradigm for developing advanced epidermal electronics with clinical-grade durability and signal fidelity. Ding et al. developed an advanced epidermal electronic system utilizing airbrushed adhesive liquid metal particles (ALMP) via in situ deposition as shown in Fig. 9k. The developed ALMP-based electrodes exhibit remarkable resolution (~80 μm width) while maintaining robust skin adhesion and mechanical durability, even under both micropatterning and mechanical deformation (compression, stretching, twisting). The electromechanical stability originates from a dynamically reconfigurable percolation network, where the dense liquid metal particles maintain conductive pathways through continuous rupture and reconnection under strain, ensuring strain-invariant conductivity. This fabrication methodology integrates mask-assisted micropatterning with airbrush deposition technology, establishing a novel paradigm for next-generation epidermal electronics that combines micron-scale resolution, strain-invariant electrical characteristics, and extended wearable durability. A self-powered epidermal electronic system was developed through integration of a stretchable solar cell array with a flexible circuit board embedded within a conformable PDMS film, as schematically presented in Fig. 9l. The device demonstrates multifunctional capabilities including continuous energy harvesting and multiparameter sensing of body surface temperature, humidity, and ambient light intensity. The solar array exhibited exceptional mechanical resilience (capable of withstanding 300% substrate deformation) combined with reliable skin adhesion, enabling 24-hour operation across varied lighting conditions. The integrated flexible electronics achieved real-time environmental monitoring with 0.1 Hz sampling rate, with potential applications in sports physiology monitoring (preventing hypothermia/sunburn) and wilderness survival. Extended wear tests confirmed stable operation during daily activities, demonstrating autonomous power management and wireless data transmission capabilities without external charging requirements. This energy-autonomous platform represents a significant advancement in durable epidermal electronics for continuous health-environment interaction monitoring. Similarly, an ultrathin skin-conformal system utilizing a liquid metal micro/nano (LMMN) film integrates triboelectric energy harvesting and epidermal sensing [123]. By providing power to electronic devices and leveraging its strain-invariant conductivity for real-time joint angle monitoring, the LMMN-based TENG defines a new paradigm for imperceptible wearables. These platforms concurrently harvest biomechanical energy and monitor physiological motions without

compromising skin conformability, thereby enabling self-sustaining intelligent interfaces for liquid metal-based medical robotics in advanced closed-loop electronics.

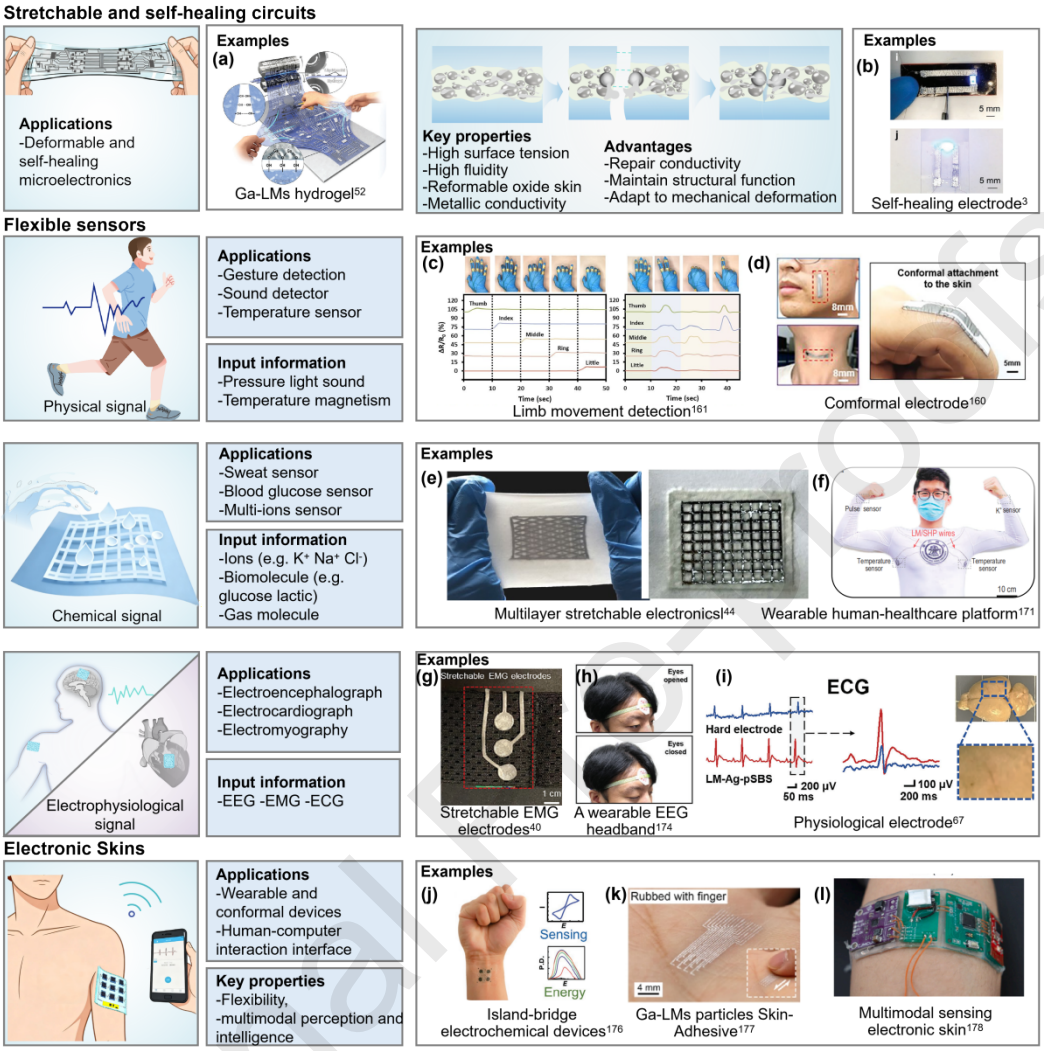


Fig. 9. Bionic Ga-LMs Electronic Skin Integrating Circuitry, Self-Healing and Sensing for Human-Machine Interaction. Stretchable and self-healing circuits **(a)** Self-healing liquid metal electrodes based on hydrogel substrates enables conformal bioelectronic interfaces. Reproduced with permission from Ref. [37]. Copyright 2020, Wiley-VCH. **(b)** The Ga-LMs system demonstrates 190% stretchability after self-healing. Reproduced with permission from Ref. [56]. Copyright 2023, Wiley-VCH. Flexible sensor **(c)** Ga-LMs based e-textiles with integrated circuits demonstrated reliable multifunctional sensing capabilities for monitoring human motions, respiratory patterns, vocal vibrations, and spatial pressure distributions. Reproduced with permission from Ref. [114]. Copyright 2021, Springer Singapore. **(d)** A Ga-LMs flexible strain sensor used for human body motion signal detection. Reproduced with permission from Ref. [113]. Copyright 2021, Springer Singapore. **(e)** The three-layer device based on Ga-LMs electrodes demonstrated multi-modal physiological monitoring capabilities. Reproduced with permission from Ref. [29]. Copyright 2021, Springer Nature. **(f)** An integrated wearable platform for multimodal physiological monitoring. Reproduced with permission from Ref. [124]. Copyright 2024, The

 (g) The Ga-LMs electrode's custom circuit acquires EMG signals upon arm-mounted deployment. Reproduced with permission from Ref. [27]. Copyright 2025, Wiley-VCH. **(h)** Illustrated the Ga-LMs based elastic kirigami electrode architecture and cross-sectional structure. Reproduced with permission from Ref. [121]. Copyright 2023, Wiley-VCH. **(i)** Ga-LMs electrode for customized EMG sensor device. Reproduced with permission from Ref. [51]. Copyright 2024, American Association for the Advancement of Science. Electronic skins **(j)** The all-printed silver-liquid metal island-bridge architecture demonstrates significant potential for wearable electrochemical device applications. Reproduced with permission from Ref. [122]. Copyright 2020, Wiley-VCH. **(k)** Skin-adhesive Ga-LMs particles for electronic skin with stretchability, micropatterning, and epidermal conformality. Reproduced with permission from Ref. [125]. Copyright 2022, American Chemical Society. **(l)** The self-powered electronic skin for multiparameter sensing on human skin. Reproduced with permission from Ref. [126]. Copyright 2024, Elsevier.

5.4 Soft conductive energy systems based on Ga-LMs

Liquid metal batteries (LMBs), defined as energy storage devices containing at least one liquid metal electrode, trace their conceptual origins to early 20th-century electrometallurgical innovations [127,128]. The historical progression begins with the three-liquid-layer Hoopes cell developed in the 1920s for aluminum purification, which establishes the fundamental principle of density-driven liquid phase separation [129,130]. Conventional LMB architectures typically comprise three immiscible layers: a molten salt electrolyte (commonly halide-based) sandwiched between two high-melting-point liquid metal electrodes. These systems traditionally require sustained high-temperature operation (>350 °C) to maintain component liquidity and electrolyte conductivity. Recent developments focus on room-temperature operation (0−40 °C) through the implementation of fusible materials like gallium and its alloys, which combine favorable electrochemical stability with an appropriate operating potential window [131-134]. Current research focuses on high-capacity electrode materials such as tin, silicon anodes, and sulfur cathodes. However, these materials face critical challenges including structural degradation during cycling and dendritic growth at metal anodes (e.g., zinc, lithium), which compromise cycle life and safety [135]. Ga-LMs present unique solutions to these challenges through their phase-transition behavior and interfacial properties. In LIB systems, Ga anodes demonstrate reversible liquid-solid-liquid phase transitions during charge/discharge cycles, effectively mitigating the volume expansion issues that plague conventional alloy anodes (Sn, Si) and sulfur cathodes. The fluid nature of Ga-LMs enables morphological recovery during lithiation/delithiation processes, while their superior wettability facilitates stable electrode/electrolyte interface formation [136-138]. Notably, Ga-LMs coatings show promise in suppressing lithium dendrite formation through surface tension modulation and current distribution optimization. Compared to room-temperature liquid alloys like

Na-K systems proposed as alternative anodes (Fig. 10a), Ga-based solutions offer enhanced safety profiles and broader electrochemical compatibility [139].

Additionally, Fig. 10b exemplifies how Ga-LMs can address the intrinsic challenges of volume variation and solid-electrolyte interphase (SEI) instability in lithium metal battery systems [140]. The anode reaction mechanism in the LFP‖RGO@EGaIn-V-4 full cell during charging demonstrates the unique advantages of gallium-based liquid metal (LMP) composites. During the charging process, lithium ions extracted from the LFP cathode undergo an alloying reaction with the RGO@EGaIn LMP anode, where the Ga-In liquid metal matrix enables homogeneous lithium deposition. Simultaneously, the formation of a stable SEI film is facilitated through controlled interfacial reactions between the RGO@EGaIn composite and the electrolyte. This contrasts sharply with conventional LMP systems, where unmitigated volume expansion (~160%) during lithiation induces continuous SEI layer rupture and particle fracturing, ultimately leading to rapid capacity decay. The RGO encapsulated EGaIn architecture effectively confines the liquid metal within a conductive graphene framework, demonstrating the critical role of gallium in achieving both dynamic lithium alloying capability and exceptional interfacial stability. In contrast to employing Ga-LMs as an auxiliary electrode for battery stability enhancement, their application as primary electrodes offers superior advantages for flexible battery design. As demonstrated by Fig. 10c,**Error! Reference source not found.** a one-dimensional air battery configuration with LM-based anode and flexible carbon fiber cathode maintains stable discharge performance under mechanical deformation, enabling arbitrary bending and stretching. This breakthrough provides a promising approach for integrating multifiber systems in soft batteries that mimic biological organisms. In a parallel development, Fu et al. [129] employed liquid metal alloy as the liquid metal anode to develop a shape-adaptive aqueous secondary battery operable at low temperatures (-19 °C). The GaInSn alloy composition strategically utilizes Ga as the electrochemical active component, while Sn and In synergistically enhance acid resistance and reduce the eutectic point. This battery system combines remarkable electrochemical properties with mechanical robustness, demonstrating significant potential as a deformable power source for low-temperature applications and extreme environmental conditions (Fig. 10d). As electrical-to-mechanical energy conversion devices, such systems warrant further investigation to enhance energy efficiency, particularly through systematic studies on liquid metal-enabled energy generation and harvesting methodologies. Current energy harvesting implementations predominantly utilize four physical principles: (i) triboelectric conversion via contact electrification and electrostatic induction, (ii) piezoelectric conversion via mechanical stress-induced charge separation, (iii) electromagnetic induction through relative motion between conductors and magnetic field, and (iv) thermoelectric conversion based on the Seebeck effect in temperature gradients. These established mechanisms collectively provide foundational solutions for environmental energy extraction in robotic applications [141,142]. Lai et al. [87]**Error! Reference source not found.** developed an elastic multifunctional fiber capable of

simultaneously harvesting mechanical energy from human-body motion and electromagnetic energy from surrounding electrical appliances (Fig. 10e). The mechanical energy harvesting component demonstrated a peak output of -160 V m^{-1} and 360 μW m^{-1} under optimal conditions. Notably, the fiber-based devices maintained full functionality under tensile strain and exhibited no performance degradation after 10,000 stretching cycles. Furthermore, the integrated energy harvesting system successfully demonstrated the feasibility of utilizing dual-mode energy collection to power various wearable electronic devices. This combined energy acquisition approach ensures continuous operation of smart gadgets through complementary energy sources derived from biological motion and ambient electromagnetic fields.

Conventionally, polymers dominate the triboelectric series, exhibiting diverse energy harvesting capabilities. For Ga-LMs based triboelectric nanogenerators, elastomers are the main materials that can be optimized to enhance energy harvesting efficiency. Shao et al. [143] developed a monolithic hybrid triboelectric-piezoelectric-electromagnetic nanogenerator-based electronic skin (TPEG-skin) that combines high efficiency, breathability, and stretchability via a layered architecture. The device features a liquid metal mesh sandwiched between two layers of topological insulator-piezoelectric polymer composite nanofibers, establishing a breakthrough in on-skin/wearable energy harvesting technology. This design successfully addresses the longstanding challenge of achieving simultaneous high efficiency, permeability, and stretchability in hybrid energy harvesters. Beyond capturing biomechanical energy from body motions, the TPEG-skin demonstrates dual functionality by harvesting electromagnetic energy from surrounding electronic devices, as conceptually illustrated in Fig. 10f. The high-frequency electrical output enables rapid charging of low-power portable electronics. Benefiting from the structural configuration, material selection, and fabrication methodology, this work provides a scalable platform for next-generation wearables that integrate multisource energy harvesting capabilities with multifunctional self-powered sensing in a seamless, skin-conforming format.

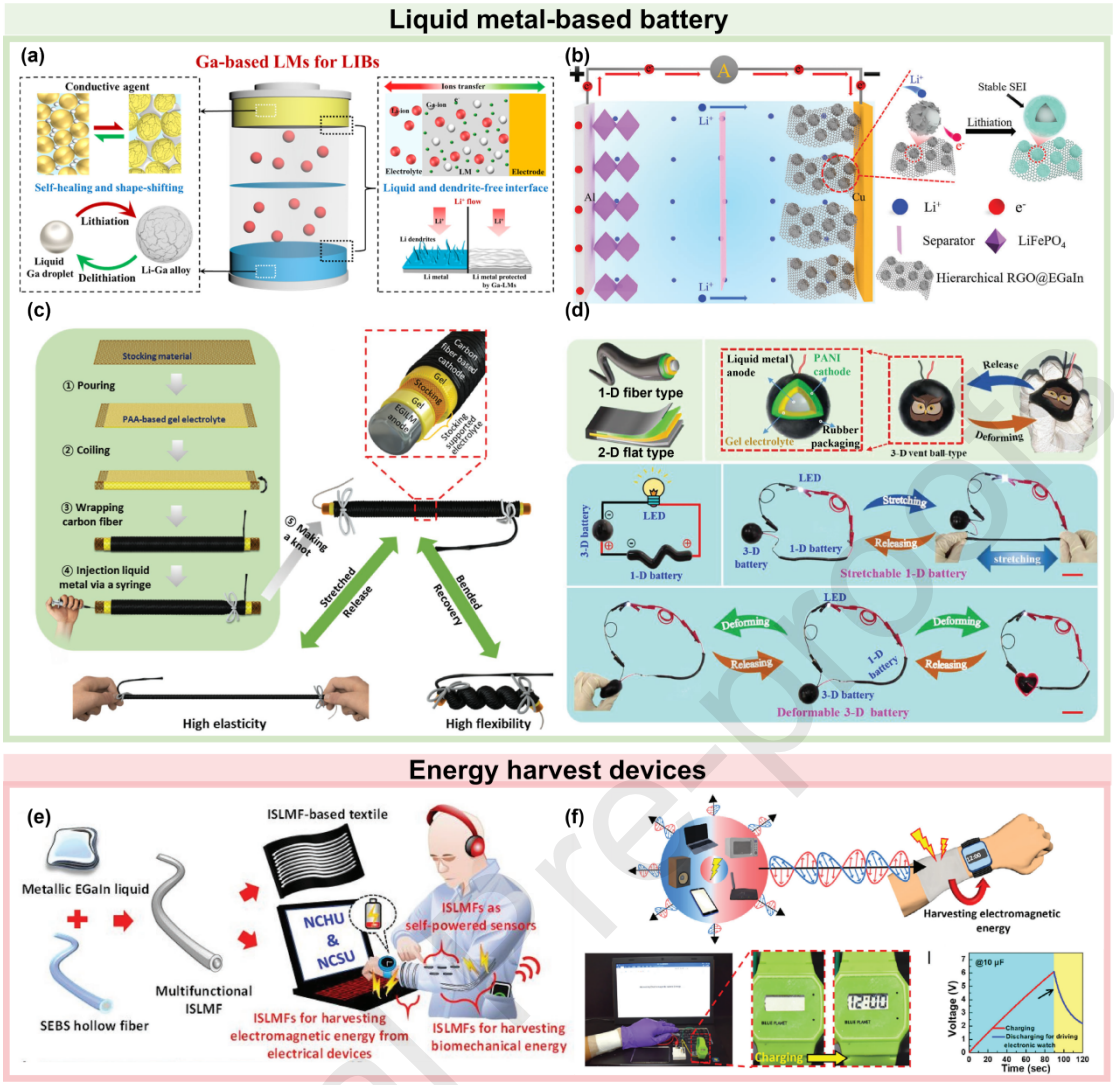


Fig. 10. Liquid Metal-based Battery. **(a)** Schematic illustrations showing the advantages of Ga-LMs toward Li-ion batteries. Reproduced with permission from Ref. [139]. Copyright 2022, The Authors. Interdisciplinary Materials published by Wuhan University of Technology and John Wiley & Sons Australia, Ltd. **(b)** Schematic diagram of the anode reaction during the charging process of the LFP‖RGO@EGaIn-V-4 full cell. Reproduced with permission from Ref. [140]. Copyright 2025, Wiley-VCH. **(c)** Sketch for the cable-shaped eutectic gallium-indium liquid metal-air battery. Reproduced with permission from Ref. [144]. Copyright 2018, Wiley-VCH. **(d)** Schematics of the internal structures of the GaInSn liquid metal–PANI battery with 1-D fiber, 2-D sheet, and 3-D spherical shapes. Reproduced with permission from Ref. [129]. Copyright 2021, Wiley-VCH. Energy harvest devices. **(e)** Multifunctional intrinsically stretchable liquid-metal fiber (ISLMF) for harvesting mechanical energy from human motion and electromagnetic energy from electrical devices and as self-powered sensors. Reproduced with permission from Ref. [143]. Copyright 2021, Wiley-VCH. **(f)** Electrical performance of TPEG-skin by harvesting EM energy. Reproduced with permission from Ref. [145]. Copyright 2024, Wiley-VCH.

5.5 Human body augmentation

Owing to their exceptional biocompatibility, intrinsic conductivity, and adaptive fluidic properties, Ga-LMs demonstrate considerable promise in bio-integrated applications by functioning as actuator modules within closed-loop systems to establish a sense-process-actuate cycle. These materials are emerging as pivotal candidates for advancing bioartificial organs and augmenting human physiological functionalities. The functional integration of Ga-LMs with components (e.g., human muscle fibers), combined with rationally selected supplementary materials presents a promising strategy for advancing the development of biohybrid intelligent systems. For instance, researchers developed an artificial muscle actuator that uses the electronic control characteristics of Ga-LMs surface tension. It can lift heavier objects and be integrated a cargo delivery system through multiple integrations [146]. While native blood vessels efficiently transport oxygen and nutrients while removing carbon dioxide and metabolic waste, they lack the capacity to monitor hemodynamic parameters or enable advanced therapeutic interventions such as gene therapy [147]. In addition, recent breakthroughs in biomimetic ocular devices have demonstrated unprecedented progress through the development of a hemispherical artificial retina array (Fig. 11a). Similarly, Chung et al. [148] reported a 10-μm-thick soft artificial retina integrating flexible ultrathin photosensitive transistors with three-dimensional stimulation electrodes based on Ga-LMs. (Fig. 11b). This bioinspired Ga-LMs paradigm advances beyond conventional approaches by achieving authentic neuromorphic replication and enabling optoelectronic stimulation through Ga-LMs integrated electrodes, heralding transformative advances in next-generation visual prosthetics and human-machine interfaces. In an endeavor to overcome these functional limitations of conventional vascular replacements, Cheng et al. [149]**Error! Reference source not found.** pioneered the use of artificial blood vessels incorporating Ga-LMs architectures to achieve the emulation of native vasculature through dynamic self-adaptation and continuous hemodynamic monitoring, offering unprecedented opportunities for postoperative monitoring and personalized hemodynamic management (Fig. 11c). Remarkably, the researchers engineered a three-dimensional liquid metal-based conductor that seamlessly integrates with bioinspired vascular architectures. This integrated system effectively promotes structural integration between engineered and native vasculature. Experimental validation in rabbit models demonstrated excellent patency and biosafety over a 3-month postoperative period. Extending this paradigm, Ga-LMs enabled neuromorphic architectures offer unprecedented opportunities to replicate biological neural networks. Fig. 11d shows a hippocampal cyborg organoid (cyb-organoid) platform combing a liquid metal-polymer conductor (MPC)-based mesh neuro-interface with hHOs [150]. This system successfully detects neural activities from hHOs via the mMPC in the cyb-organoid. In contrast to conventional two-dimensional platforms, noninvasive coupling enables neural signal acquisition from 3D models. Therefore, the new mMPC exhibited considerable potential for neural signal detection from neural organoids, offering unique opportunities for studying signal transmission in neural tissues.

Emerging evidence suggests that Ga-LMs hold strong promise in neuromorphic computing systems and brain-machine interfaces (BCIs) due to their low modulus, biocompatibility, conformability, and ion-electron hybrid conduction potential, aligning with the biophysical nature of neural communication [147]. Notably, researchers have developed an artificial peripheral nerve using a Ga-LMs conductor. The Ga-LMs cuff electrode was proven capable of transmitting neural stimuli to the peripheral nerve on a long-term basis by triggering clear event-related potentials (ERPs) in both cortical potential and sciatic signal (Fig. 11e). **Error! Reference source not found.** These results demonstrate that the Ga-LMs electrodes fulfill the critical criteria of peripheral nerve signal recording and stimulation for long-term implantation, and have the potential to become a new generation of interfaces that can supplement, enhance, or even replace the real peripheral nerve. Recent advances in BCIs have revolutionized neural activity monitoring, significantly enhancing our comprehension of brain function and enabling transformative diagnostic capabilities. Implantable neural probes now play an increasingly critical role in both fundamental neuroscience research and clinical management of neurological disorders such as epilepsy, Parkinson's disease and depression. However, a persistent challenge remains due to the mechanical mismatch between conventional probes (typically metallic or silicon-based) and compliant neural tissues. To address this limitation, Dong et al. [153] developed flexible neural electrode arrays through screen-printing Ga-LMs conductors on polydimethylsiloxane (PDMS) substrates (Fig. 11f). The resulting stretchable electrode array (SEA) demonstrated exceptional performance in real-time cortical EEG monitoring during rat epileptic seizure studies, successfully capturing distinct electrophysiological signatures across different seizure phases. This breakthrough establishes SEA technology as a promising solution for next-generation diagnostic BCIs, combining tissue-compliant mechanics with high-fidelity neural signal acquisition.

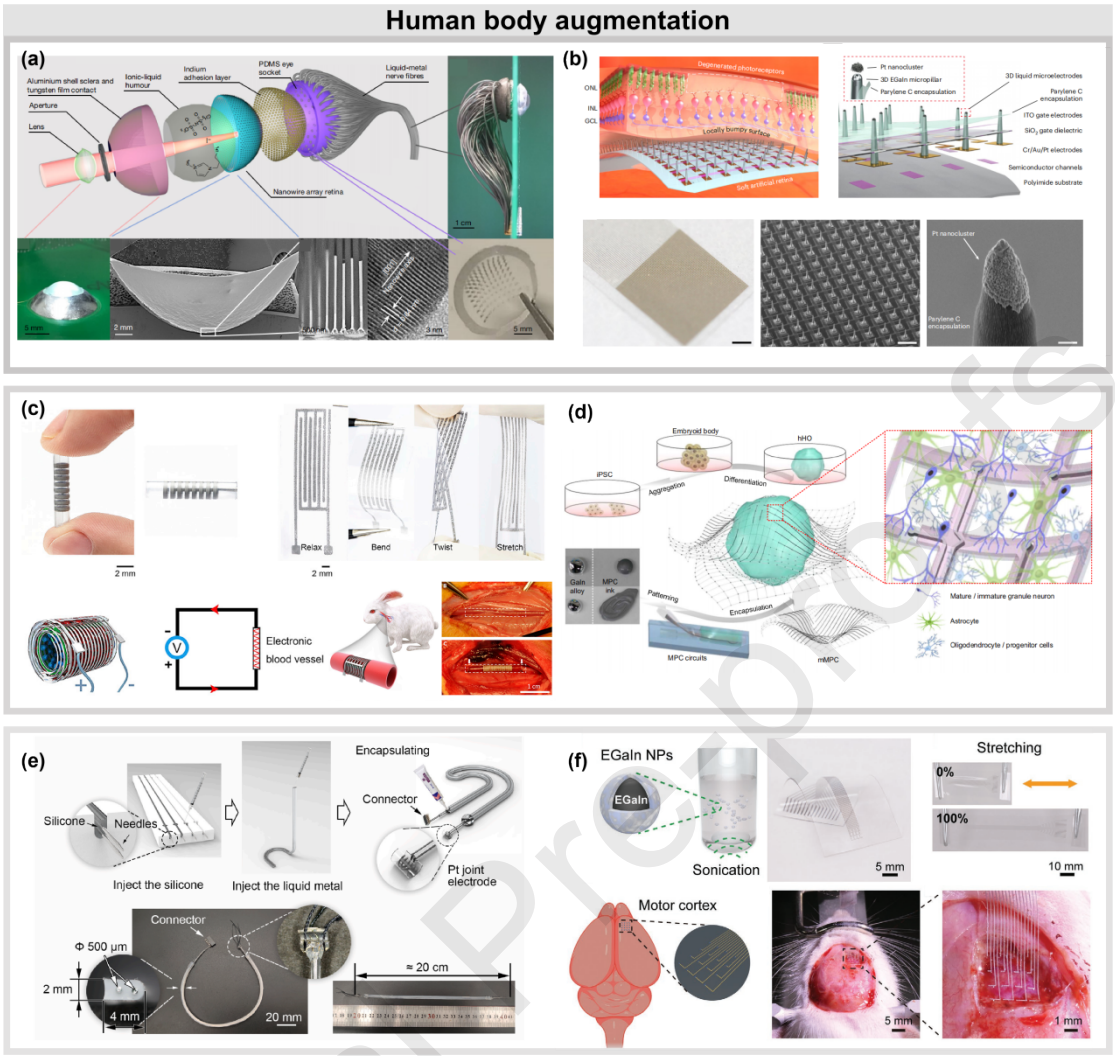


Fig. 11. Human body augmentation based on Ga-LMs. (a) Ga-doped LM neural fibers for biomimetic ocular constructs. Reproduced with permission from Ref. [151]. Copyright 2020, Springer Nature. **(b)** Retinal interface design employing 3D Ga-LMs microelectrodes with conformal contact to degenerated photoreceptor surfaces. Reproduced with permission from Ref. [148]. Copyright 2024, Springer Nature. **(c)** Structural characterization of electronic blood vessel prototypes. Reproduced with permission from Ref. [149].**Error! Reference source not found.** Copyright 2020, Cell Press. **(d)** Three-dimensional neuroelectronic interfaces for human hippocampal organoids using Ga-LMs architectures. Reproduced with permission from Ref. [150]. Copyright 2024, Springer Nature, and **(e)** Long-term neural modulation through optimized Ga-LMs cuff electrode fabrication. Reproduced with permission from Ref. [152]. Copyright 2022, Elsevier. **(f)** Highly stretchable Ga-LMs based neural electrodes Showed excellent performance for neurite growth and long-term implantation. Reproduced with permission from Ref. [153]. Copyright 2021, Wiley-VCH.

6. Challenges and outlooks

The intrinsic fluidity of Ga-LMs enables dynamic conformability to irregular surfaces, making them ideal for wearable electronics and bio-integrated systems that

require seamless interaction with soft biological tissues. The superior electrical performances compared to most flexible polymeric conductors and composite systems, which enables efficient signal transduction in stretchable circuit designs and sensor applications. Furthermore, the biocompatibility of gallium alloys minimizes immune rejection in biomedical applications, such as epidermal electronics and neural interfaces. The self-healing capability of Ga-LMs, driven by their liquid-phase mobility and oxide layer reformation, ensures prolonged durability under mechanical stress, a critical feature for robust HMIs in real-world environments. These properties collectively enable Ga-LMs as a cornerstone for future advanced closed-loop electronic products. Despite their considerable potential for multi-functional integrated HMI systems, it still faces severe critical challenges of Ga-LMs in advanced closed-loop systems.

(i) The comprehensive investigation of oxide layer evolution assumes pivotal significance in interfacial optimization, as oxidative surface dynamics fundamentally dictate adhesion thermodynamics, wetting kinetics, and electrochemical durability. The interfacial properties of liquid metals critically determine their practical applicability, prompting extensive research endeavors to address this fundamental challenge. A representative research focus involves the engineering of native oxide layers through strategic removal, functional modification, or direct utilization of their unique physicochemical characteristics for fabricating advanced electronic devices. Although native oxide matrices confer self-passivation capability and lithographic adaptability, their transient response mechanisms under multi-physical fields (mechanical-thermal-electrochemical) remain inadequately deciphered. Looking forward, tackling the challenges of oxide layer evolution and interfacial compatibility requires targeted strategies. Promising avenues involve the development of in-situ chemical or electrochemical methods to control oxide growth, and the alloying of Ga-LMs with elements that modulate surface energy and oxide properties. Additionally, the design of composite materials with functionalized conductive fillers facilitates the formation of stable interfaces with the LM matrix. Success in these areas will be pivotal for transitioning Ga-LMs from laboratory curiosities into reliable materials for industrial-scale manufacturing.

(ii) The inherently constrained conductivity of Ga-LMs fundamentally restricts their deployment in high-frequency or ultra-low-impedance regimes. Pioneering multiscale hybridization strategies coupling Ga-LMs with conductive nanofillers or core-shell nanostructures demonstrate unprecedented functionality for advanced applications. However, critical challenges exist in optimizing interfacial compatibility and charge transport dynamics, requiring systematic investigation of hybrid component synergies and surface engineering strategies to fully realize their theoretical performance limits.

(iii) The absence of standardized characterization protocols for Ga-LMs-based devices obstructs cross-platform benchmarking and commercial scalability.

Establishing universally recognized evaluation criteria addressing three critical performance metrics - electrical reliability, biostable operation, and fatigue resistance - emerges as a prerequisite for viable technology translation. Industrial adoption demands innovations in autonomous high-throughput manufacturing architectures, particularly precision additive fabrication and microfluidic-guided assembly mechanisms, coupled with standardized protocols to ensure device-to-device reproducibility across digital production platforms. These dual requirements, including robust performance standardization and advanced manufacturing paradigm development, necessitate coordinated advances in both metrological frameworks and production methodologies to bridge the lab-to-fab gap.

(iv) Ga-LMs hold immense potential for implantable and wearable technologies, yet their practical operation requires urgent resolution of interrelated long-term reliability, mechanical durability, and environmental stability challenges. Prolonged exposure to hygrothermal/oxidative stresses drives electrochemical degradation through interfacial oxide nucleation and ionic migration, compromising structural integrity. Under repeated mechanical strain, fatigue-induced cracking of conductive pathways and eventual electrical failure remain a critical issue for durable operation. Furthermore, stability across a range of environmental conditions, including variable temperature, humidity, and chemical exposure, is not yet fully understood or engineered for. Implantable devices are bound to experience device wear and tear during long-term use, while liquid gold metal devices may face the risks of oxide layer degradation or metal leakage. Concurrently, the environmental sustainability of Ga-LM systems demands urgent attention through development of closed-loop recycling protocols, green synthesis methods for LM-polymer hybrids, and systematic evaluation of biological fate for degradation byproducts.

The future of Ga-LMs-based HMIs lies in integrating active components, developing entirely soft material systems, and enabling reconfigurable electronics. Embedding functional additives (e.g., magnetic nanoparticles, stimuli-responsive polymers) could transform passive Ga-LMs into active systems capable of sensing, energy harvesting, or autonomous shape-morphing. Achieving entirely soft materials, combining Ga-LMs with elastomers, hydrogels, and organic semiconductors, will yield HMI that mimic the mechanical compliance of biological tissues, enhancing user comfort and signal fidelity. Additionally, reconfigurable electronics leveraging the reconfigurability of Ga-LMs may enable adaptive circuits that dynamically alter functionality in response to environmental cues or user demands, paving the way for intelligent, context-aware interfaces. To realize these goals, interdisciplinary efforts in materials science, bioengineering, and robotics must address fundamental questions about Ga-LMs fluid dynamics, interfacial chemistry, and biocompatibility under chronic implantation. Ga-LMs hold the potential for bridging the gap between rigid electronics and biological systems (Fig. 12). Overcoming existing challenges through targeted research on Ga-LMs-based HMIs could revolutionize closed-loop

architectures, with transformative potential for next-generation healthcare systems, precision robotics, and intelligent wearable technologies over the next decade.

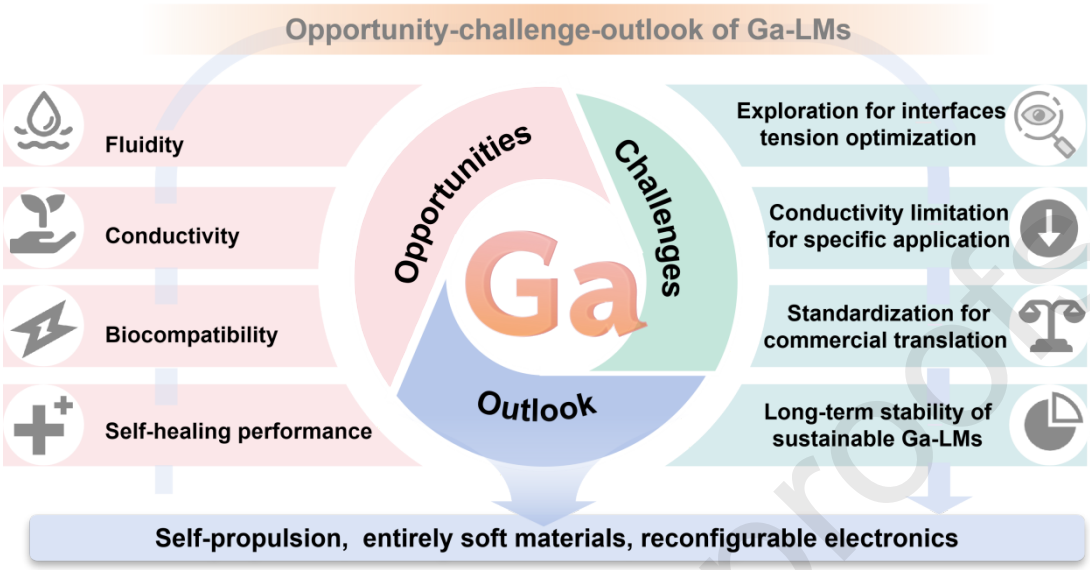


Fig. 12. Opportunity, challenges, and outlook of Ga-LMs for HMI applications.

In summary, Ga-LMs have emerged as revolutionary materials for next-generation human-machine interfaces (HMIs), owing to their unique combination of fluidity, conductivity, biocompatibility, and self-healing performances. By integrating functional modules for energy harvesting, signal sensing, human-machine interaction, AI decision-making, and actuation feedback, liquid-metal-enabled flexible interface architectures hold promise for establishing interconnected frameworks that synergistically unify energy-material-information dimensions. Such systems aim to achieve autonomous, adaptive operation through dynamic bidirectional translation between energy-driven physical processes and algorithm-guided information flows, thereby enabling embedded intelligence for next-generation closed-loop smart interactive platforms.

Conflict of Interest

The authors declare that they have no conflict of interest

Author contribution

Wenqi Wang and Jun Yang carried out the literature search and manuscript preparation. Boya Song, Zhouyang Hu and Fangqing Wang conceptualized the study and led the discussion of the review. Sanwei Hao and Changyou Shao conceived the idea. Peng Fu, Hailin Cong, and Caofeng Pan proposed revisions to the manuscript. All the authors contributed to the preparation of the manuscript.

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