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Flexible Electronic Devices and Wearable Sensors Based on Liquid Metals

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ABSTRACT

Stretchable electronic devices play a key role in bridging various components, especially in flexible and complex multifunctional logic circuits, as well as in information recognition and transmission systems. The stretchability and stability of solid metal-based stretchable electrodes are still limited due to their intrinsic rigidity. Liquid metals are one of the most popular materials for stretchable electrodes due to their high conductivity, flexibility, and machinability. However, the surface tension of liquid metals is extremely high at room temperature, hindering their applications. In this review, recent developments of liquid metals as conductive fillers in the field of stretchable electrodes are reviewed in detail firstly. Besides, the combination of liquid metals on different substrates according to their types is classified and summarized. Furthermore, the applications of liquid metal-based flexible electronics with single and multiple functions are systematically discussed. A brief perspective for future research is given. We believe that this review would provide a promising path for the future direction and fabrication of functional and high-performance liquid metal-based devices.

1 | Introduction

The emergence of flexible electronics will revolutionize our lives because of their superior adaptability to the environment compared with current rigid devices. Flexible devices can be stretched, bent, and even twisted, with excellent conformal properties. Thus, signals can be transmitted stably in different application scenarios, for example, conformal biosensing [1], intelligent healthcare [2], and image display [3]. Stretchable electrodes play a non-negligible role in connecting different components while maintaining the stability of multifunctional devices under severe environmental conditions.

It is known that solid metals have inherently high electronic conductivity but little flexibility [4]. Recently, stretchable electrodes prepared by evaporating highly conductive metals (e.g., Ag, Au, and Cu) on elastic substrates have been widely studied [5]. The stretchability of these electrodes can be attributed to their ductility [6]. However, due to the rigidity of solid metals, the stretchability is still limited, that is, basically less than 30% [7]. Other strategies were proposed by enhancing the interaction force between conductive metals and substrates, but no more than 100% [7a, 7b, 8] and unstable [9], causing limited application scenarios. Thus, research transforms into blending Au or Ag nanosheets, nanowires, and nanoparticles with different

polymers. However, percolation networks break down easily during stretching due to the insufficient interfacial force between solid metals and polymers [10]. Therefore, modifying the surface of the conductive fillers can partially improve their interfacial force with polymers, but the complicated processes are still unknown to be revealed [11].

Liquid metals demonstrate significant advantages and potential in the field of stretchable electrodes with high conductivity similar to solid metals, excellent machinability, and flexible deformability [1b, 12]. However, the liquid metals are not stretchable when directly attached to substrates with low surface energy because of the high surface tension of liquid metals. Therefore, it is necessary to develop appropriate methods, such as capillary force [13] and surface modification [14], to improve their interfacial force with ubstrates and matrices and thus improve their range of applications.

The development of liquid metals in stretchable electrodes has significantly improved conductivity, flexibility, elasticity, and diversification of application scenarios. In this review, the applications of liquid metals in stretchable electrodes are summarized in detail in four sections, as shown in Figure 1. Section 2 describes how to use liquid metals, including direct usage, shear mixing with polymers, and possessing the liquid metal particles using an ultrasonic cell grinder. The combination of liquid metals with substrates based on different materials, including gels, rubbers, and fibers, is recommended in Section 3. Section 4 introduces the diversified applications of liquid metals in stretchable electrodes, including stretchable electrodes focusing on performance, sensors and heaters focusing on function, multifunctional devices that can simultaneously realize sensing and signal transmission, and applications in elastic sustainable energy devices. We hold the belief that this review will provide a comprehensive and systematic understanding of the applications of liquid metals in flexible electronics.

FIGURE 1 | Summary of this review. Bulk of liquid metals image: Reproduced with permission from Ref. [21] Copyright 2023, Wiley. Shear mixing with polymers image: Reproduced with permission from Ref. [30] Copyright 2020, Wiley. LM particles by ultrasonic image: Reproduced with permission from Ref. [39] Copyright 2019, American Chemical Society. Gels image: Reproduced with permission from Ref. [49] Copyright 2019, American Chemical Society. Fibers image: Reproduced with permission from Ref. [69] Copyright 2022, Nature Publishing Group. Interconnects image: Reproduced with permission from Ref. [5e] Copyright 2021, American Chemical Society. Single-function devices image: Reproduced with permission from Ref. [83] Copyright 2020, American Chemical Society. Multifunction devices image: Reproduced with permission from Ref. [89] Copyright 2022, American Chemical Society. Elastic sustainable energy devices image: Reproduced with permission from Ref. [91] Copyright 2023, Wiley.

2 | Usage Methodology for Liquid Metals

Liquid metals hold immense potential with a melting point close to or below room temperature compared with traditional solid metals. They can be easily molded into different shapes, making them ideal for various applications [12d]. Therefore, the methods of using liquid metals are diverse, mainly including the direct use of bulk liquid metals, blending by shear mixing directly with polymers, and the most common method, ultrasonic vibration of liquid metal particles with different dimensions, that is, millimeters, microns, or even nanoscale.

2.1 | Liquid Metals in Bulk

Bulk liquid metals can combine with numerous materials (e.g., PVA, PDMS, and SEBS) due to their fluid nature and intrinsic high conductivity. As shown in Figure 2A, liquid metals were pumped into the poly(vinyl alcohol) (PVA) thin films within the channels on one side and vacuumed at the other end, and the highest resolution could reach 340 μm. Because of the controllability of the PVA substrates, liquid metal circuits can be prepared in any shape, which significantly enlarges the application scene. In addition, this kind of liquid metal could be recycled because PVA is water soluble, which is a cost-effective approach [15]. Similarly, Ning et al. mixed polyurethane sponge (PUS) with adequate liquid metals sufficiently by vacuuming and then encapsulated the precursor with polydimethylsiloxane (PDMS). This method could improve the stability and prevent leakage of liquid metals (Figure 2B). The conductivity of the PDMS/PUS/LMs composite reached 2.67×10^4 S cm^{-1} and the stretchability can reach 100% when $\Delta R/R_0 < 1$ [16]. Figure 2C shows the microfibers with a polyurethane (PU) shell generated by sequential microfluidic spinning and liquid metal core simultaneously. The microfiber with 250 μm in outer diameter and 210 μm in inner diameter can be stretched to 200%, and the resistance was less than 2.0 Ω [17].

Liquid metals can also be used through vacuum thermal evaporation, which can form centimeter-sized particles, followed by coating with uncured PDMS and heat treatment to cure completely. The liquid metal particles were broken when applying stress and peeling off because the stress has transferred from the polymer to themselves (Figure 2D). The resistance changed by less than 8% at 60% strain due to the liquid metals flowed from the particles that were not completely ruptured to the strain region. Besides, the particles produced by the evaporation process provided a rough surface, which helps to create firm contact with the polymer and directly write on the substrate [18].

The flow characteristic also allows liquid metals to form conductive films by spray coating and direct printing. As shown in Figure 2E, liquid metals were spray coated on the substrate covered by the mask at 14 m/s, where the diameters were around 5 μm. The liquid metals can merge under the pressure of

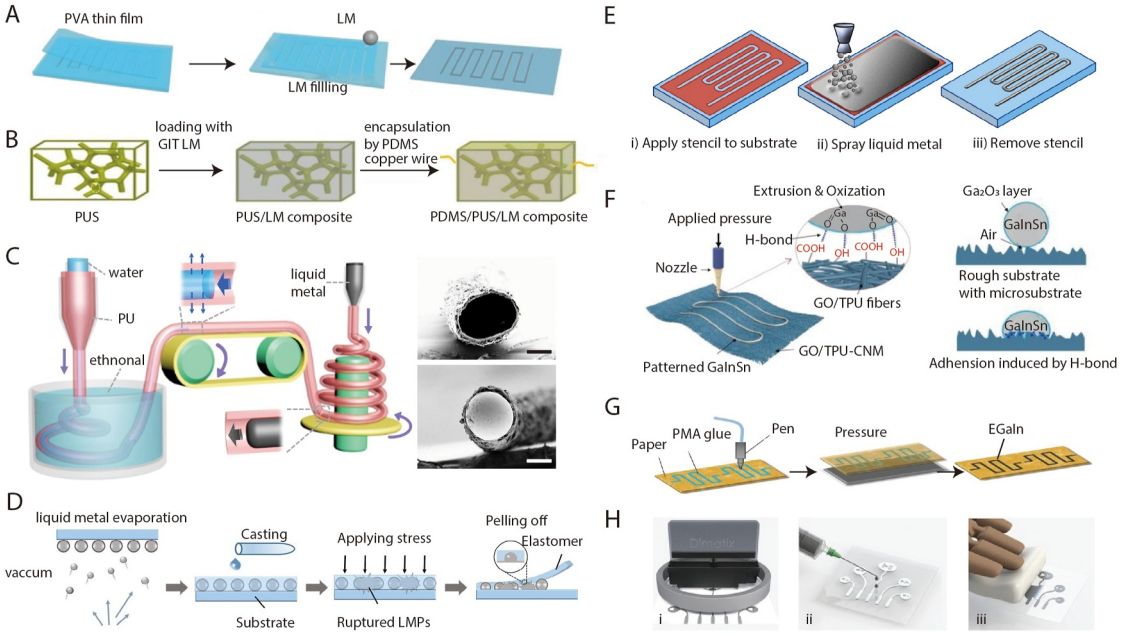

FIGURE 2 | (A) Pumping liquid metals into the PVA thin films within the channels by vacuuming at the other side. Reproduced with permission from Ref. [15] Copyright 2019, Wiley. (B) Liquid metals filling into the PUS porous structure and then encapsulating by PDMS. Reproduced with permission from Ref. [16] Copyright 2019, Elsevier. (C) Injecting liquid metals into the microfiber by sequenced microfluidic spinning. The scale bars are 100 μm. Reproduced with permission from Ref. [17] Copyright 2020, Elsevier. (D) Evaporating liquid metals, casting uncured PDMS, applying stress, and peeling off to get the conductive film. Reproduced with permission from Ref. [18] Copyright 2023, American Chemical Society. (E) Spraying liquid metals on the polymer stencil. Reproduced with permission from Ref. [19] Copyright 2021, MDPI. (F) Direct writing of liquid metals onto an electrospun graphene oxide composite. Reproduced with permission from Ref. [21] Copyright 2021, Wiley. (G) Transfer printing of liquid metals that remain only in the area of the PMA on the PMA-coated paper. Reproduced with permission from Ref. [23] Copyright 2018, Wiley. (H) Dropping liquid metals onto PU substrates with already inkjet printing AgNPs and then erasing the excess. Reproduced with permission from Ref. [25] Copyright 2020, Wiley.

the airflow, and the resolution of the conductive trace was about 300 μm [19]. By spraying the uncured PDMS onto liquid metal, flexible electrodes were prepared.

Moreover, strain sensors with different sensitivities can be produced by designing different patterns. Park et al. printed the liquid metals on the 3D stage with a high resolution of 1.9 μm [20]. Wu et al. directly wrote the liquid metals onto electrospun graphene oxide (GO) composite. Hydrogen bonds were formed between the gallium oxide and GO, which can improve the adhesion and robustness of liquid metals and electrospun films (Figure 2F) simultaneously. As a result, the resistance was less than 10 Ω when strain reached 400% [21].

Blade coating is also a simple way to form liquid metals. Ma et al. obtained stretchable electrodes through blade coating liquid metals onto the styrene-butadiene-styrene (SBS) fiber mats by electrospinning and then further prestretching, which can promote liquid metals to infiltrate into the fiber network and form an infiltrated and wrinkled structure. As a result, the strain of the stretchable electrodes can reach 1800%, and the electrodes can work stably in water [22]. As shown in Figure 2G, Guo et al. fabricated soft electronics by a one-step method, that is, transfer printing the liquid metals on paper realizing a partially patterned structure via polymethacrylate (PMA) glue. Liquid metals were adhered only on the PMA glue instead of on the paper because of the interfacial adhesion heterogeneity [23].

Despite highly adhesive polymers, liquid metals can also adhere to specific metals (e.g., Ag and Cu) [24] by alloying. As shown in Figure 2H, Silva et al. dropped the liquid metals onto PU substrates with inkjet-printed AgNPs and then erased the excess. Ag alloyed with the In from the liquid metals, which enhances the conductivity of the stretchable electrodes, restricts the resistance variation, and fills the cracks while stretching [25].

2.2 | Blend of Liquid Metal With Polymers by Shear Mixing

When the liquid metals are located on the surface of the polymers only, the stretchability of the flexible electrodes is limited by the high surface tension [26] and low viscosity [27], which breaks during stretching and forms discontinuous and uneven conductive traces [28]. Therefore, mixing liquid metals with uncured polymers can improve their stretchability and stability by forming better percolation pathways and a larger contact area between them. At the same time, the liquid metal particles of different sizes can be obtained by controlling the time and speed of the mixing process and maximizing the electronic conductivity.

As shown in Figure 3A, PVA and liquid metals were shear mixed together to get the PVA-LM ink. Liquid metal microparticles coated with gallium oxide were formed during the shearing process. The obtained ink was stable and printable because the O element in gallium oxide formed hydrogen bonds with the hydroxyl group in the PVA. Because of the presence of PVA and the oxide layer, the printed electrode needed to be activated so as to be conductive via an external force, and the activation time was about 1.1 s. In addition, the circuits can be dissolved in water to recycle the liquid metals as mentioned before [29].

When liquid metals are mixed with PVA, its ink must be attached to an elastic substrate to prepare stretchable electrodes. Therefore, directly mixing with elastic substrates is commonly used to

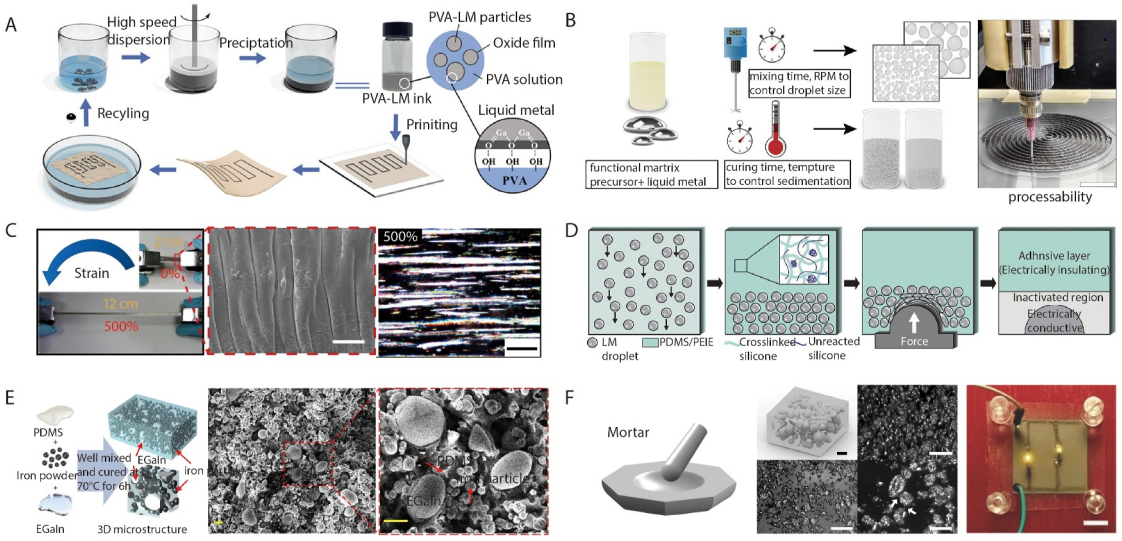

FIGURE 3 | (A) Printing the PVA-LMs ink on the substrates and recycling the liquid metals by dissolving them in the water. Reproduced with permission from Ref. [29] Copyright 2021, American Chemical Society. (B) Shear mixing liquid metals with various uncured polymers and controlling the volume content by controlling the sedimentation. Reproduced with permission from Ref. [30] Copyright 2020, Wiley. (C) Shear mixing liquid metals with TPU. The scale bars are 500 and 20 μm, respectively. Reproduced with permission from Ref. [31] Copyright 2019, Elsevier. (D) Shear mixing liquid metals with uncured PDMS with the addition of PEIE to react with the curing agent. Reproduced with permission from Ref. [32] Copyright 2023, Wiley. (E) Shear mixing liquid metals and Fe microparticles with uncured PDMS. The scale bars are 10 μm. Reproduced with permission from Ref. [33] Copyright 2019, Nature Publishing Group. (F) Mixing liquid metals with uncured polymers in a mortar. The scale bars are 25 μm. Reproduced with permission from Ref. [34] Copyright 2015, Wiley.

obtain stretchable electrodes. Ford et al. obtained printable and self-healing stretchable electrodes by mixing liquid metals with the uncured polymer (including Ecoflex00-30, PDMS, and styrene-ethylene-butylene-styrene (SEBS)). In addition, the composites cured during the particle sedimentation process. Stretchable electrodes with different contents of liquid metal microparticles were obtained by controlling the heating temperature, that is, controlling the sedimentation rates (Figure 3B). It is worth mentioning that the composite still required an external force to become conductive, although liquid metals were in the range of 40–70 vol% after sedimentation. When the volume content was 40%, the activation force was greater than 300 N, whereas when the content rose to 70%, only 50 N was enough. Thus, the stretchability can reach 250% and 600%, respectively [30].

Thermoplastic polyurethane (TPU) is also a mixing carrier (Figure 3C). When the liquid metal content was 5 vol%, the composite was nonconductive until stretched to 350% because the liquid metal microparticles lost their connection to each other. When the content increased to 30 vol%, the stretchability increased to 475% due to polymer fracture [31]. Haque et al. fabricated stretchable electrodes by exploiting the characteristics of liquid metal microparticles settling in uncured polymers, as shown in Figure 3D. By mixing uncured PDMS and liquid metals, the composite (i.e., incompletely cured PDMS on one side and liquid metal microparticles on the other side) was obtained. The adhesion of the composite was improved by adding ethoxylated polyethylenimine (PEIE) to react with the curing agent, that is, PDMS. The composite became conductive after being stimulated by a specific external force and it can be attached to various surfaces in different shapes, significantly improving the scope of application of stretchable electrodes [32].

It can be seen that when polymer matrices were mixed with the liquid metals, the conductivity decreased under stretching due to the reduction of the conductive pathways. Yun et al. added rigid Fe particles about 2–5 μm while mixing PDMS and liquid metals, and the conductivity of the obtained composite improved when deformed (Figure 3E). Because the PDMS was compressed by rigid Fe, the volume of the polymer was reduced, and more connections were formed between Fe and liquid metal microparticles [33]. In addition to planetary shearing and stirring shearing, liquid metals and polymers can also be mixed in mortars (Figure 3F). The obtained composite can form specific conductive paths under the action of a thin-tipped tool to obtain stretchable electrodes [34].

2.3 | Liquid Metal Particles Dispersed by Ultrasonication

More than mixing directly, liquid metals can also form particles with diameters from micrometers to nanometers under ultrasonication while adding surfactants to enable stable dispersion in solution and stable interaction with polymers. Liu et al. produced a double-phase emulsion by ultrasonicating liquid metals in ethanol and then mixing them with PDMS. In the double-phase emulsion, ethanol continuously evaporated, and the PDMS precursor located at the interface of ethanol and liquid metals rapidly cured, forming a stable cross-link with liquid metals (Figure 4A). The PDMS-LM composite is equipped with a high conductivity of 7.7×10^5 S m^{-1} by direct laser writing [35].

Xin et al. ultrasonicated liquid metals in 1,3-diisopropylbenzene (DIB) and then added the mixture to molten sulfur that was prepared by the ring-opening polymerization of elemental sulfur. Molten sulfur contained lots of polysulfide loops and thiol groups, which can form strong bonds with liquid metals, as shown in Figure 4B [36]. Wei et al. dispersed liquid metals in N, N-dimethylformamide (DMF) solvents containing poly(methyl methacrylate)-block-poly(acrylic acid) (PMMA-b-PAA) as a polymeric surfactant. Although shorter PAA chains were anchored to gallium oxide, longer PMMA chains inhibited the coalescence of EGaIn nanodroplets, stabilizing the colloid in the solvent (Figure 4C) [37]. Because of the interaction, the composite obtained self-healing behavior.

Wang et al. dispersed liquid metals in PVA solution grafted by cyclodextrin (CD) and adamantane (AD) groups to form a cross-linked network that provided strong dynamic host–guest interactions (Figure 4D). The printed composites became conductive after being strain-activated [38]. Huang et al. immersed a dopamine-modified polyurethane sponge (PDA-PUS) in an ethanol solution with liquid metals where 3-mercaptopropionic acid was used as a surfactant. Liquid metal nanodroplets can adhere to the surface of PDA-PUS due to the interaction between the sulfhydryl group of 3-mercaptopropionic acid and gallium oxide as well as the hydrogen bond between the hydroxyl group and PDA-PUS, as shown in Figure 4E [39].

Rahim et al. ultrasonicated liquid metals in an ethanol solution of tannic acid (TA) and concentrated it to produce ink that can be written directly, as shown in Figure 4F. TA contains multiple catechol/galliphenol functional groups, which can not only form hydrogen bonds with gallium oxide, but also give rise to the coordinate-driven assembly of TA on liquid metal particles, forming excellent adhesion on different substrates [40]. The writing traces became conductive attributing to the pressure of the ballpoint pen.

By bringing in acrylate ligands on the surface of gallium oxide, Thrasher et al. prepared polymerized liquid metal networks (poly-LMNs) through photo-cross-linking liquid metal particles and 2-hydroxyethyl acrylate (HEA), as shown in Figure 5A. The poly-LMNs were conductive at a strain of 60%–70% due to the rupture of the liquid metal particles, and the R/R_0 was 1.85 at a strain exceeding 700%, which is far less than the theoretical value (the R/R_0 was 50) [41]. Wang et al. mixed liquid metals ultrasonically dispersed in acrylic acid (AA) with PEDS (a mixture of ChCl and AA), and the compound can be polymerized to form a liquid-free ionically conductive elastomer without any initiators and solvents, as shown in Figure 5B. Under the action of an electric field, the elastomers were conductive due to the movement of chloride ions and quaternary ammonium ions [42].

Mou et al. ultrasonicated the liquid metals in an n-decyl alcohol solution of 11-mercaptoundecanoic acid (MUA) to get the MUA-modified liquid metals (LMs@MUA) and then embedded the LMs@MUA into the SBS matrix to obtain stretchable electrodes (SBS&LMs@MUA), as shown in Figure 5C. The strong

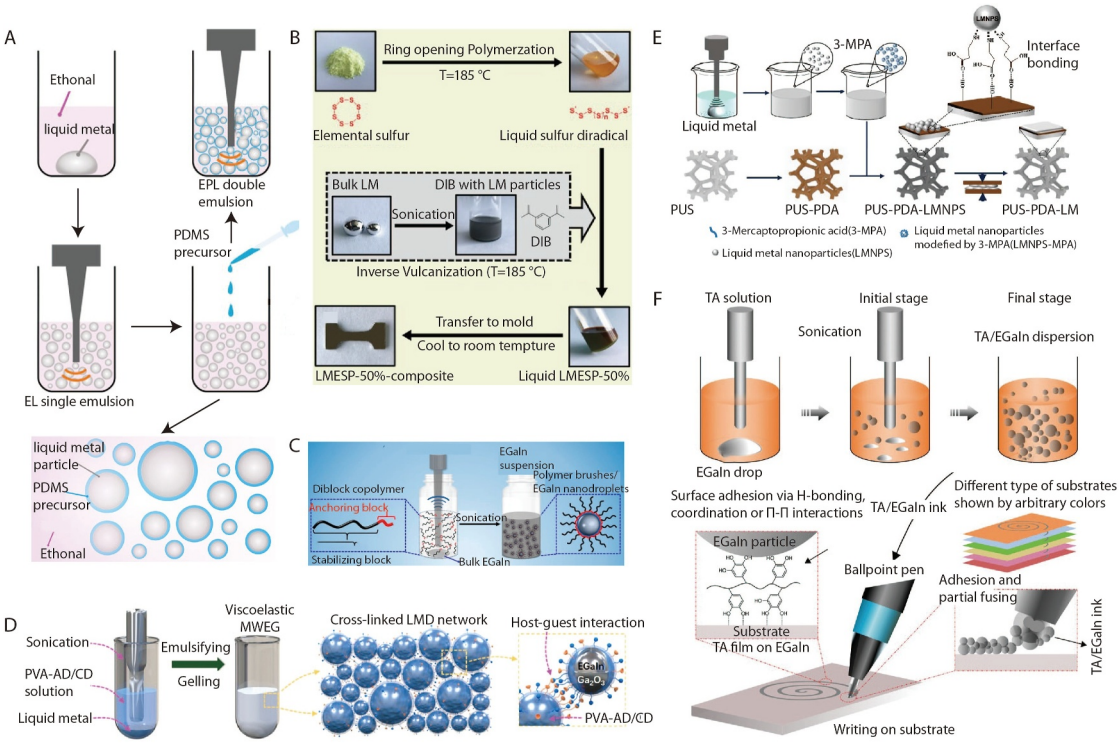

FIGURE 4 | (A) Fabricating and curing the double emulsion. Reproduced with permission from Ref. [35] Copyright 2021, American Chemical Society. (B) Mixing the liquid metal particles in DIB solution with the molten sulfur. Reproduced with permission from Ref. [36] Copyright 2019, Wiley. (C) Dispersing liquid metals in DMF solvents by using PMMA-b-PAA as a polymeric surfactant. Reproduced with permission from Ref. [37] Copyright 2020, American Chemical Society. (D) Cross-linking the liquid metal particles with PVA-AD/CD. Reproduced with permission from Ref. [38] Copyright 2022, American Chemical Society. (E) Adsorbing liquid metal nanoparticles modified by 3-MPA on the PUS-PDA. Reproduced with permission from Ref. [39] Copyright 2019, American Chemical Society. (F) Preparation and writing the ink of TA and liquid metal particles. Reproduced with permission from Ref. [40] Copyright 2020, Wiley.

interaction between the sulfhydryl group and gallium would compete with oxygen for a position on the surface of gallium, thus promoting its conduction. The conductivity of the SBS&LMs@MUA can reach 12,000 S cm^{-1} after being pressed or stretched, and the stretchability was about 800% [43]. Additionally, with a thiolate ligand, Ren et al. dispersed the liquid metals into the ethanol solution of ethyl 3-mercaptopropionate to obtain sulfhydryl-modified liquid metal nanoparticles with a diameter of about 110 nm (Figure 5D), and the stretchable electrodes were prepared by inkjet printing or laser etching [44].

The liquid metal particles can also combine with sulfhydryl-modified liquid rubber (LR), as shown in Figure 5E. Xin et al. mixed the liquid metal droplets in LR-dichloromethane to prepare stretchable electrodes. The disulfide bonds (S-S) and thiol terminal groups of the LR reacted with gallium oxide, which prevents the settling of the liquid metal droplets and stabilizes them [45]. Lee et al. ultrasonically dispersed liquid metals into an ethanol solution containing polysodium-p-styrenesulfonate (PSS) and Pt-modified CNT (CNT@Pt) to produce stable inks for electronic tattoos and stretchable electrodes. As a surfactant, PSS can not only modify gallium oxide but also promote the electrostatic interaction between liquid metal particles and CNT@Pt to improve the stability of inks (Figure 5F). More importantly, the stretchable electrodes were intrinsically conductive without any extra stimulation because of close packing among liquid metal particles by strong electrostatic interactions [46].

3 | Combined With Different Materials of Flexible Substrates

Because of the differences in molecular chain structures, different types of matrix materials exhibit distinct stretchability and processability, where the diverse functional groups result in varying surface bonding forces. Consequently, researchers can select appropriate substrate materials based on specific requirements. These materials are categorized into gels, rubbers, and fibers and are summarized in detail as follows.

3.1 | Gels

Gels are a kind of very popular substrate or matrix material, because they are rich in hydroxyl groups, which can achieve huge strain deformation and swell in solvents to achieve self-healing characteristics. As shown in Figure 6A, Park et al. realized the patterning of liquid metals directly on hydrogel substrates through screen printing. A significant number of hydroxyl groups on the surface of the hydrogel establish hydrogen bonds with the oxide layer on the outer surface of liquid metals, thereby facilitating robust interfacial adhesion. Because of this stable interfacial interaction, the liquid metals underwent elongation during stretching, and the resistance changed no more than three times at 1500% strain. Notably, no obvious delamination occurs during

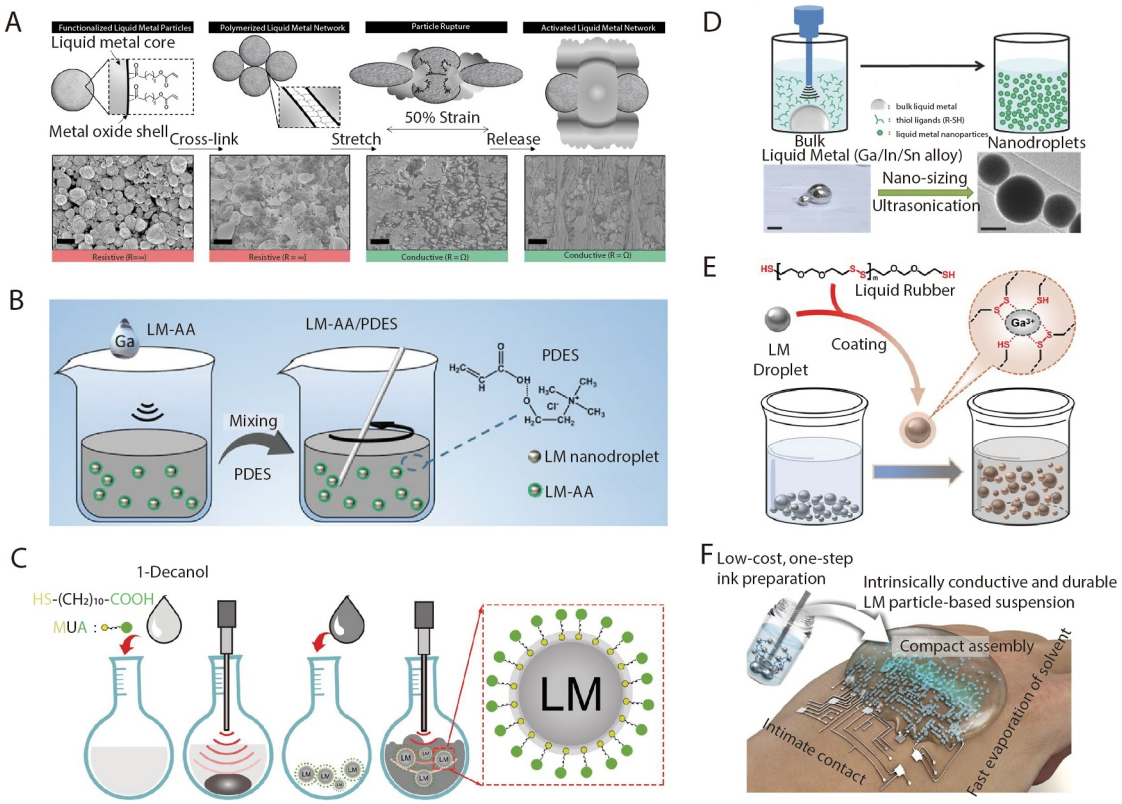

FIGURE 5 | (A) Photo-cross-linking liquid metal particles modified by acrylate ligands with HEA. The scale bars are 10 μm. Reproduced with permission from Ref. [41] Copyright 2020, Wiley. (B) Mixing the liquid metals dispersed AA with PEDS. Reproduced with permission from Ref. [42] Copyright 2021, Wiley. (C) Dispersing the liquid metals in 1-decanol solution with the surfactant of 11-mercaptoundecanoic acid. Reproduced with permission from Ref. [43] Copyright 2020, Wiley. (D) Modifying the liquid metal nanoparticles with ethyl 3-mercaptopropionate in the solution of ethanol. The scale bars are 50 nm. Reproduced with permission from Ref. [44] Copyright 2016, Wiley. (E) Mixing the liquid metal droplets with liquid rubber. Reproduced with permission from Ref. [45] Copyright 2021, Wiley. (F) Assembling liquid metal particles coated with PSS&CNT@Pt. Reproduced with permission from Ref. [46] Copyright 2022, Wiley.

or after stretching [47]. Murakami et al. prepared 3D-stacked wires by utilizing ionic gels with low viscosity and low specific gravity, as shown in Figure 6B. The liquid metals settled in the uncured ionic gel, forming a conductive liquid metal layer in the inner layer and an insulative ionic gel in the upper layer. The presence of an ionic gel insulator prevented leakage of liquid metals, avoiding the short circuit [48].

Hydrogels can be used to prepare circuits that reversibly switch between conductive and nonconductive due to their swelling properties when in contact with water. As shown in Figure 6C, Park et al. used a hard tip to cross the surface of a composite of liquid metals and hydrogel, forming a conductive path that can light the LED. Besides, the hydrogels were swollen when spraying water on the surface, and the conductive paths were wrapped to become insulators [49]. There were abundant covalent bonds, hydrogen bonds, and host–guest interactions in hydrogels to form dynamic cross-linked networks (Figure 6D). Therefore, the hydrogel–liquid metal composite can self-heal to form conductive paths after being cut, and the longer the recovery time is needed, the closer the performance was displaced to the original value [50].

Hydrogels can achieve different swelling degrees by adjusting the composition of the gel material. Hao et al. combined two kinds of hydrogels with different swelling degrees to achieve the construction of 3D electronics, as shown in Figure 6E. Because of the mismatch of the expansion degree after expansion, the layer with a large expansion degree bends in the direction of nonexpansion, which can form 3D conductive wires [51]. By combining tannic acid-modified liquid metals with PVA hydrogels, the composite became extremely tough and could withstand objects more than 2000 times over its own weight, as shown in Figure 6F [52]. Liquid metal–hydrogel composites can also be reshaped because of the dynamic reversibility of the hydrogen bonds between them, as shown in Figure 6G [53].

3.2 | Rubbers

Currently, the elastomers utilized predominantly consist of petro-based elastomers, which possess exceptional elasticity, processability, and broad application scenarios from daily necessities to aerospace domains [54]. In the field of flexible electronics, rubbers are frequently employed as stretchable substrates or matrices for fabricating high-performance stretchable electrodes. The most commonly employed rubbers include PDMS, Ecoflex, SEBS, SBS, styrene-isoprene-styrene (SIS), and TPU [55]. Styrenic block copolymers typically consist of rubber chains with rigid polystyrene

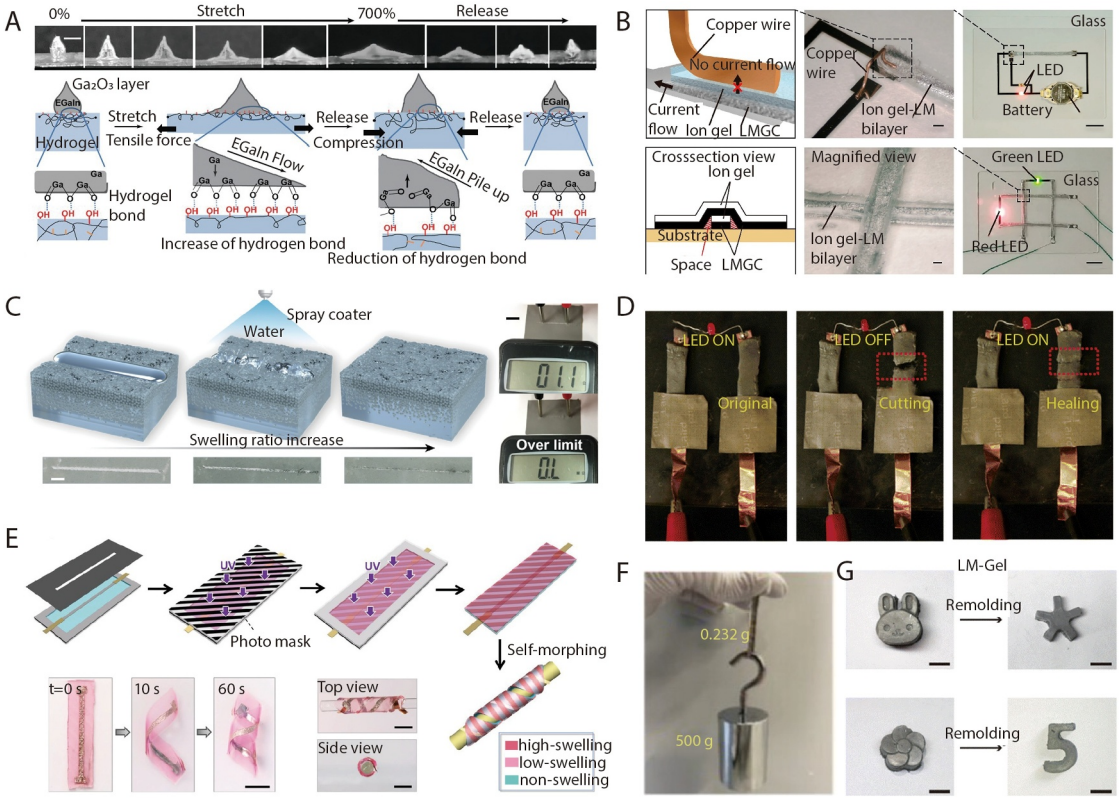

FIGURE 6 | (A) The interaction between gallium oxide and the gel hydroxyl group on the liquid metal surface. Reproduced with permission from Ref. [47] Copyright 2020, Wiley. (B) The liquid metal–gel composite constructing multilayer stacked conductive wires. The scale bars are 1 mm on the left and 10 mm on the right. Reproduced with permission from Ref. [48] Copyright 2023, Nature Publishing Group. (C) The circuit reversibility of the composite depends on the swelling of the hydrogel. Reproduced with permission from Ref. [49] Copyright 2019, American Chemical Society. (D) Self-healing of liquid metal–hydrogel composites. Reproduced with permission from Ref. [50] Copyright 2022, Royal Society of Chemistry. (E) 3D conductive electrodes constructing. The scale bars are 1 cm. Reproduced with permission from Ref. [51] Copyright 2021, Wiley. (F) Superior toughness of liquid metal–gel composites. Reproduced with permission from Ref. [52] Copyright 2023, Wiley. (G) Reshaping of liquid metal–gel composites. The scale bars are 1 cm. Reproduced with permission from Ref. [53] Copyright 2023, Royal Society of Chemistry.

domains that are physically cross-linked [56]. This ensures their recyclability in solvents.

Lopes et al. prepared conductive inks by mixing SIS, LMs, and Ag for stretchable electrodes. Following the placement of the microchip components at specific positions, the ink was exposed to a solvent where SIS underwent partial curing to form a polgel. As a result, the microchip component achieved self-welding and self-coating abilities, significantly advancing the development of elastic circuit boards (Figure 7A) [57]. Tutika et al. blended liquid metals with Ecoflex using shear or ultrasonic methods and obtained elastic dielectric layers with different permittivity by controlling the volume content of liquid metals, as shown in Figure 7B [58].

TPU electrospinning fiber mats are commonly used as substrates for flexible electronics due to their excellent mechanical properties and breathable structure. As shown in Figure 7C, Wang et al. realized the patterning and stable adhesion of liquid metals on TPU nanofiber directly by template printing to manufacture safe and stable flexible displays and sensors with multilayer assembly [59]. In addition, Cao et al. obtained the interlocking structure of liquid metal particles and TPU nanofiber by electrospinning and spraying liquid metal particles simultaneously. The films were conductive after mechanical activation, and the wireless mouse can be achieved through multilayer self-assembly (Figure 7D) [60].

Electrospinning the mixtures of conductive fillers and polymers is extremely difficult because the conductive fillers cause the nanofibers to agglomerate, which affects the unitarity of the nanofibers in the electrostatic field. Ma et al. solved this problem by coaxial electrospinning, as shown in Figure 7E. The inner layer was the mixture of SEBS and liquid metal particles, and the outer layer was SEBS solution, which eliminates the effect of the electric field. The obtained film was encapsulated in Ecoflex and became conductive after being pressed, which can be used for capacitive sensors and actuators [61].

As mentioned above, Ag reacts with EGaIn to form new alloy, that is, AgIn [5e]. Zhuang et al. had taken advantage of this to fabricate stretchable electrodes based on SBS electrospinning nanofibers. A large-area stretchable electrode was obtained by coating Ag on the SBS mat directly [62] (Figure 7F), and a high-resolution stretchable electrode of 2 μm was obtained by pre-patterning Ag [63] (Figure 7G). The latter addressed the limitations of liquid metals in high-resolution wires below 100 μm due to their fluidity and high surface tension. In addition to

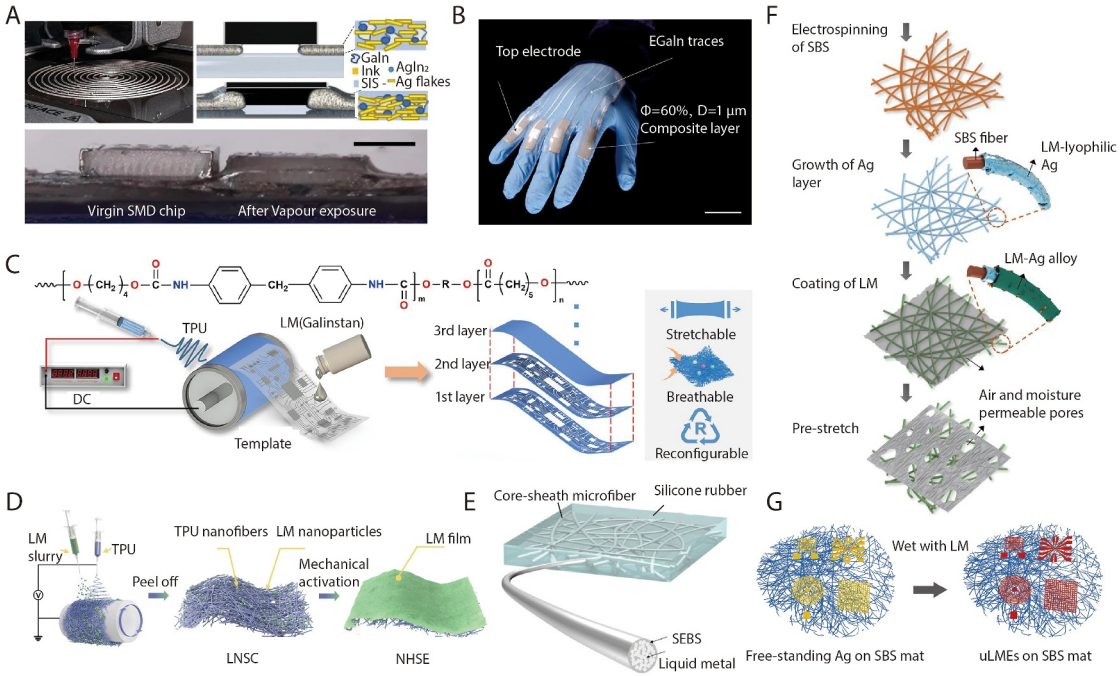

FIGURE 7 | (A) Self-welding of the chip. The scale bars are 1 mm. Reproduced with permission from Ref. [57] Copyright 2021, Nature Publishing Group. (B) Wearable sensing gloves prepared by mixing liquid metal particles and Ecoflex. The scale bars are 50 mm. Reproduced with permission from Ref. [58] Copyright 2019, American Chemical Society. (C) Multilayer electronic devices prepared by stencil printing. Reproduced with permission from Ref. [59] Copyright 2019, American Chemical Society. (D) Stretchable electrodes prepared by electrospinning and spraying liquid metal particles simultaneously. Reproduced with permission from Ref. [60] Copyright 2022, Wiley. (E) Coaxial electrospinning of SEBS and liquid metal solution. Reproduced with permission from Ref. [61] Copyright 2023, Wiley. (F) Conductive composite prepared by electrospinning SBS, growing silver layer, and coating liquid metals. Reproduced with permission from Ref. [62] Copyright 2023, Wiley. (G) Flexible electrodes of patterned liquid metals. Reproduced with permission from Ref. [63] Copyright 2023, American Association for the Advancement of Science.

petro-based elastomers, renewable and sustainable polymers derived from plant species have also been studied to promote sustainable development [54b, 64].

3.3 | Fibers

Fibers, as an important class of polymers, have the advantages of sustainability, recyclability, and being directly worn. Therefore, many researchers strive to combine liquid metals with fiber products, such as fiber fabrics, to accelerate the progress of stretchable electronic products based on liquid metals in the field of wearable flexible electronics [2c, 65].

As shown in Figure 8A, Yang et al. obtained fabrics loaded with liquid metal particles by immersing the fiber fabric in a solution of liquid metal particles directly. The particle loading can be controlled by regulating the number of immersions. Besides, applying pressure within a rationally designed mold can obtain the electrodes in a corresponding shape. The fabric composites could exhibit excellent antibacterial and thermal conductivity [66].

Alginate fibers are well suited for wearable electronics because of their excellent antibacterial and flame-retardant properties [67]. Qi et al. obtained LMs/alginate composite fibers by ultrasonication and then wet spinning (Figure 8B). The composite fibers had excellent mechanical properties, wide-range temperature tolerance, and water and salt resistance. They can also withstand more than 15,000 times their own weight and be capable of degrading in the soil [68].

In addition to contacting the fiber directly, liquid metals can also be attached to the textile indirectly, achieving the fabrication of multifunctional circuits. Fibers with excellent electrical and mechanical properties were obtained by injecting liquid metals into hollow perfluoroalkoxy alkane (PFA) tubing. Then, the fiber and digital embroidery were combined to obtain a variety of patterns, achieving wearable functions such as near-field powering and communication (Figure 8C) [69]. Lee et al. obtained fibers with excellent mechanical stability and electrical conductivity through two steps. Firstly, PSS-modified liquid metal particles were bladed onto the surface of the fiber to obtain the initial conductive fiber. Secondly, CNT@Pt-embedded liquid metal particles were coated to enhance their robustness and conductivity. The fiber can be sutured without any leakage. Similarly, multifunctional circuits can also be fabricated by sewing (Figure 8D) [70].

4 | Application Scenarios of Stretchable Electrodes

Liquid metals are mainly used in the field of flexible electronics due to their high electrical conductivity and processability, initially with stretchable electrodes. However, with the rapid development of research, researchers have developed more

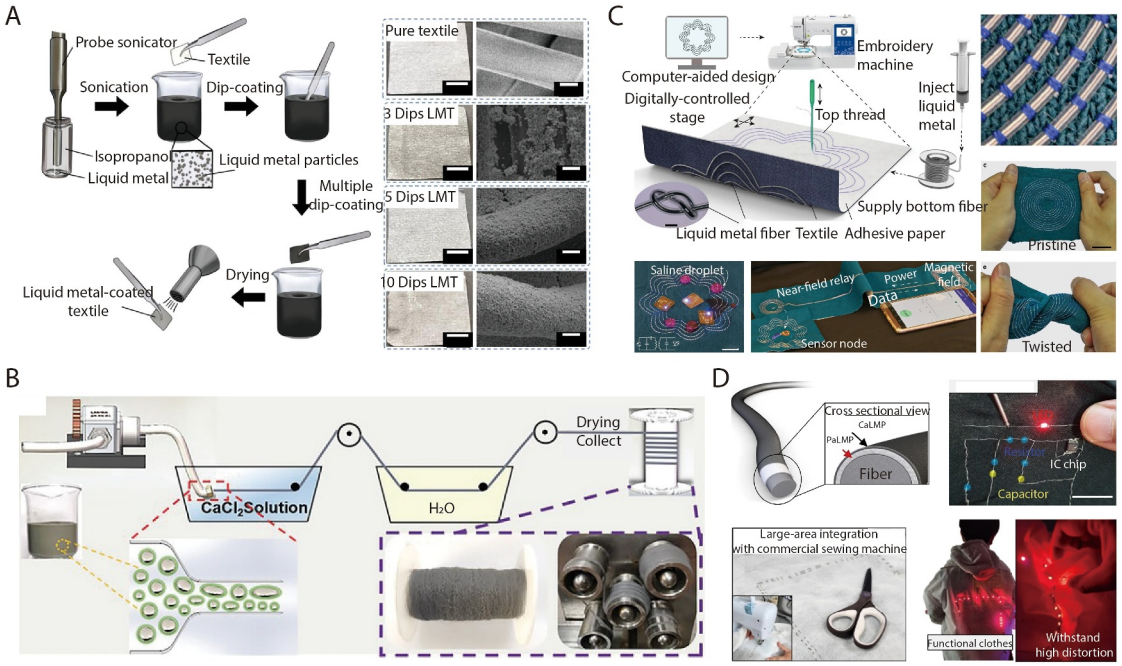

FIGURE 8 | (A) Textiles dip-coated with liquid metal particles. The scale bars are 1 cm on the left and 5 μm on the right. Reproduced with permission from Ref. [66] Copyright 2023, Wiley. (B) LM/alginate composite fibers prepared by wet spinning liquid metal particles and alginate. Reproduced with permission from Ref. [68] Copyright 2023, Wiley. (C) Wearable wireless systems prepared by digitally embroidered of liquid metals fibers. The scale bars are 1 cm. Reproduced with permission from Ref. [69] Copyright 2022, Nature Publishing Group. (D) Illustration of smart clothes. The scale bars are 2 cm. Reproduced with permission from Ref. [70] Copyright 2023, Nature Publishing Group.

extensive and diversified applications of liquid metals in flexible electronics, including wearable sensing, flexible transistors, and energy storage, and gradually evolved from single-function to multifunctional devices, which have been discussed in detail below.

4.1 | Interconnects

In different application scenarios, stretchable electrodes require different properties, such as strain insensitive conductivity, high resolution, and the ability to change signals in response to temperature variation, human movements, and so on. In the current study, the researchers conducted a series of studies that looked at different priorities.

Printing has received significant popularity in the field of stretchable electrodes as a direct patterning method. As shown in Figure 9A, Lopes et al. successfully developed printable inks by incorporating liquid metals into SIS solution and adding silver flakes to disrupt the oxide layer, thereby significantly improving conductivity. This ink can be precisely printed on flexible substrates with a minimum resolution of 140 μm, enabling the creation of fully wireless circuits capable of operating up to 1 m away from the transmitter without electricity [5e].

To obtain strain-insensitive stretchable electrodes, as shown in Figure 9B, Choi et al. designed stretchable electrodes based on kirigami structures by coating liquid metals on silicone rubber with gold acting as the adhesive layer. The electrodes can be stretched to 820% due to the inherent elasticity of silicone rubber as well as the high-density network structure. In addition, the structure can withstand partial damage while maintaining the connection of the circuits, which has an advantage that other electrodes cannot reach [71]. In addition to being attached to elastic substrates, transferable inks are equally important, as application scenarios are increasingly diversified. As shown in Figure 9C, Lopes et al. prepared ink transferable in water by mixing EGaIn and Ag so that the electrodes could be transferred to complex 3D objects to enable multifunctional applications, including tactile manipulators for human–machine interaction [72].

Taking advantage of the fact that the volume of liquid metals changes with temperature, which has hardly been studied, Wang et al. created stretchable electrodes that reversibly transition from insulator to conductor along with temperature by mechanically mixing liquid metals and polymers, as shown in Figure 9D. At 212 K, the polymer becomes thinner and harder, and the liquid metals become solid. The volume expansion causes the particles to contact each other and become conductive, whereas the original insulator recovers when the temperature returns to room temperature. It is worth mentioning that the resistivity changes more than 10^9 times during this process and can withstand about 100 cycles [73].

In addition to flexible wires, Kim et al. obtained a patternable and freestanding liquid metal–silver nanowire (AgNW) thin film by mixing liquid metals and AgNW and then vacuum filtering. The film can fix the electronic patch to the flexible circuit firmly by acting as solder, as shown in Figure 9E [74]. In addition to the conventional top-down method, Han et al. adopted the bottom-up method to obtain a stretchable electrode

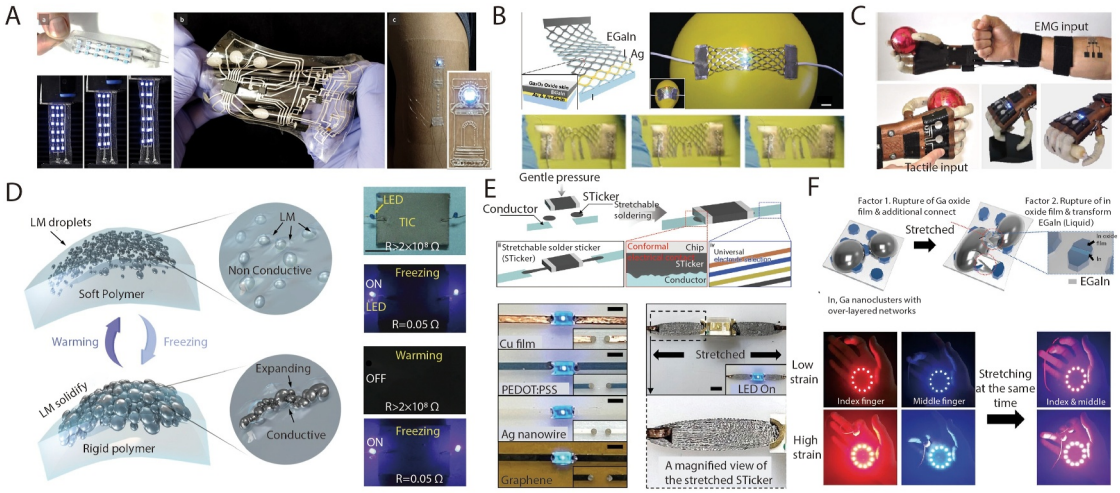

FIGURE 9 | (A) Stretchable electrodes printed on flexible substrates. Reproduced with permission from Ref. [5e] Copyright 2021, American Chemical Society. (B) Stretchable electrodes based on an elastic kirigami structure. Reproduced with permission from Ref. [71] Copyright 2023, Wiley. (C) Transferable liquid metal inks for human–machine interaction. Reproduced with permission from Ref. [72] Copyright 2018, American Chemical Society. (D) Diagram of stretchable electrodes. Reproduced with permission from Ref. [73] Copyright 2019, Wiley. (E) Stretchable soldering stickers supported by the mixture of liquid metals and AgNW. The scale bars are 1 mm on the left and 2 mm on the right. Reproduced with permission from Ref. [74] Copyright 2023, Wiley. (F) Stretchable electrodes prepared by stepwise deposition of In and Ga. Reproduced with permission from Ref. [75] Copyright 2023, Wiley.

whose resistance decreased with deformation by first depositing a seed layer of In and forming oxide layers, and then depositing liquid Ga to form partial EGaIn at the interface. Both the oxide layers of Ga and In were broken when stretching, forming more conductive paths in both horizontal and vertical dimensions, thus reducing resistance (Figure 9F) [75].

In summary, we listed different kinds of liquid metal composites, typical fabrication methods, key features, and emerging applications for the convenience of the readers, as shown in Table 1.

4.2 | Novel Elastic Function Devices

With the development of flexible electronics, more and more electronic devices are gradually changing into flexible in order to meet the needs of wearable applications, including shape memory composites, actuators, sensors, thermoelectric generators, heaters, flexible robots, and transistors. In addition, the development of devices is gradually diversifying to achieve simple manufacturing of single-function devices with multiple functions at the same time. The following are some representative examples to illustrate the application of liquid metals in these fields.

4.2.1 | Single-Function Devices

Gallium with a low melting point (29.8°C) can undergo a phase transition with temperature varying to achieve a change in modulus. Bhuyan et al. prepared shape memory composites by taking advantage of it and combining it with Ecoflex, and the composite responded quickly to the stimulation of temperature, as shown in Figure 10A [13c]. Shu et al. prepared an artificial muscle utilizing liquid Ga whose extremely high surface tension can be reduced to zero by electrochemical control in solution, thus generating force drive by converting electrical energy into mechanical energy (Figure 10B) [80]. Lee et al. obtained an intrinsically conductive patterned electrode array by combining PSS-modified liquid metal particles with photolithography and fabricated the strain-isolated sensors by combining the electrodes with dielectric layers and pyramid microstructures, as shown in Figure 10C [81].

Zhu et al. constructed a thermoelectric generator by connecting commercial n/p Bi_2Te_3 and Sb_2Te_3 TE legs with liquid metals as stretchable interconnects and polyimide as the packaging layer, as shown in Figure 10D. The flexible thermoelectric generators were wearable and could be degraded and recycled, which promotes the sustainable development of flexible electronics [82]. Li et al. designed a skin heater by screen printing ink with suitable viscosity on elastic substrates by mixing liquid metals with Cu and polymer, which can work stably under 60% strain and meet the wearable needs of the human body (Figure 10E) [83]. Guo et al. obtained contactless self-healing, recyclable, and heat transfer-printed electrodes by combining liquid metals with magnetic Fe, as shown in Figure 10F. The electrodes were self-healing after being cut by the noncontact action of a magnet, which has been little studied in the literature [84]. In addition, EGaIn can also be used as the source, drain, and gate electrodes of the flexible transistor directly. As shown in Figure 10G, the performance of the flexible transistors was almost unaffected at 50% strain [85].

4.2.2 | Multifunctional Devices

With the gradual escalation of demand, single-function devices no longer satisfy the requirements, so researchers are increasingly enthusiastic about the research of multifunctional devices. Li

TABLE 1 | The fabrication methods, conductivity, and activation methods of flexible electrodes based on liquid metal.

Materials	Fabrication methods	Activation methods	Conductivity (S/cm)	References
LM on TPU membrane	Printing	Intrinsically conductive	32,000	[59]
BPM on substrates	Mixing and coating	Intrinsically conductive	23,000	[76]
CNT-attached LMP	Coating on fibers	Chemical annealing	22,400	[70]
LMP in polymer	Mixing	Acoustic	21,000	[77]
Supra-LMNs	Cross-linking	Press	16,000	[78]
LMP in SBS polymer	Mixing	Stretch or press	12,000	[43]
LM on electrospun SBS mat	Coating	Stretch	From 100 to 18,000	[22]
LMP@SIS	Mixing and printing	Stretch	5322.7	[79]
Poly-LMNs	Cross-linking	Stretch	2500	[41]
LM@SEBS microfiber coated by silicone rubber	Coaxial emulsion electrospinning	Press	11.1	[61]

Abbreviations: LM: liquid metal; LMP: liquid metal particles; Supra-LMNs: supramolecular LM networks including PBU-COOH, AgNW, and LM.

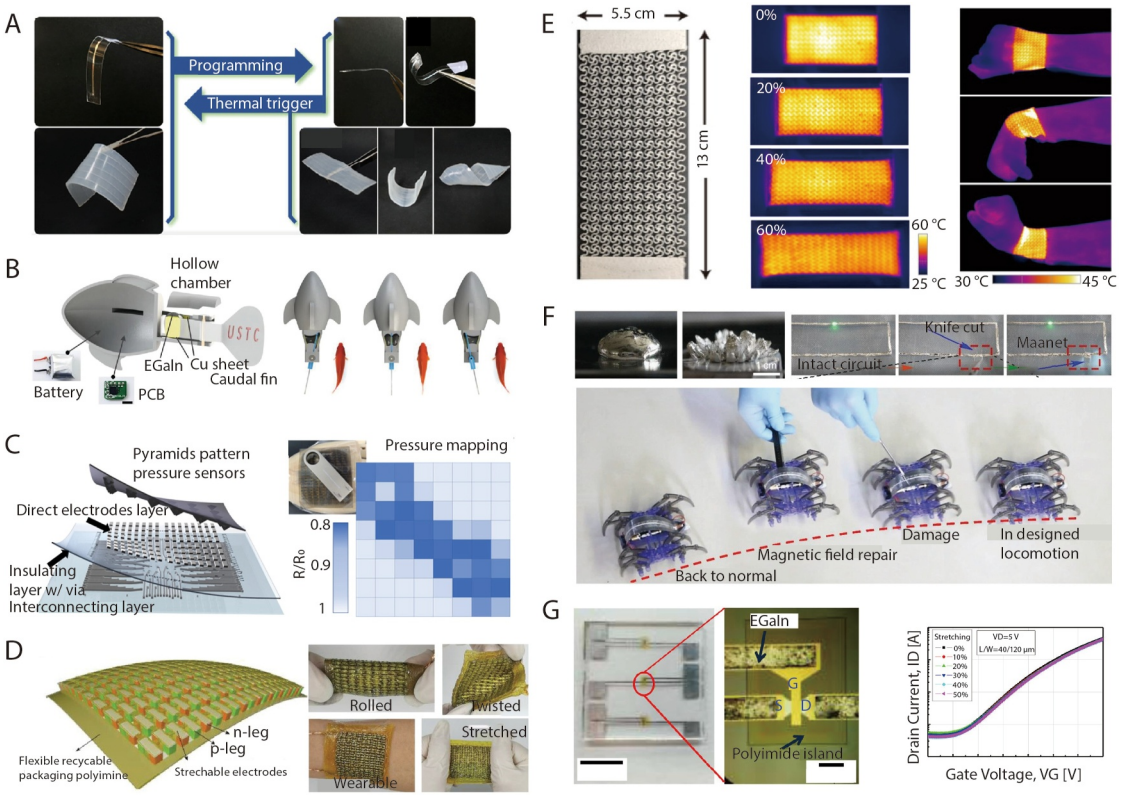

FIGURE 10 | (A) Shape memory composite combining liquid Ga and polymers. Reproduced with permission from Ref. [13c] Copyright 2021, American Chemical Society. (B) Actuator with liquid metals as a power supply. Reproduced with permission from Ref. [80] Copyright 2021, Wiley. (C) Sensor array with liquid metals as electrodes. Reproduced with permission from Ref. [81] Copyright 2023, Elsevier. (D) Thermoelectric generator with liquid metals as a stretchable interconnect. Reproduced with permission from Ref. [82] Copyright 2021, Wiley. (E) Skin heater designed by printing liquid metal inks. Reproduced with permission from Ref. [83] Copyright 2020, American Chemical Society. (F) Magnetic electrodes prepared by mixing liquid metals and Fe. Reproduced with permission from Ref. [84] Copyright 2019, Wiley. (G) Flexible transistor with electrodes of EGaIn. The scale bars are 10 mm on the left and 500 μm on the right. Reproduced with permission from Ref. [85] Copyright 2016, American Chemical Society.

et al. designed a stretchable multifunctional electronic fiber combining the functions of electrodes, data transmission, and biochemical sensing to create artificial neurons. Multifunctional fibers were fabricated by continuously electrospinning SBS on the surface of the PVA as the sacrificial layer, then printing liquid metals on the surface of the fiber with specific templates to prepare the patterned electrodes, followed by electrospinning on the surface once again as the encapsulation layer. The final device is shown in Figure 11A. Note that the multifunctional fiber can light the LEDs and transmit the audio signals that did not change significantly at 300% strain. In addition, the temperature and pressure sensors and detectors were combined to prepare artificial neurons to achieve the simultaneous measurement of temperature and pressure. Importantly, due to the addition of the PVA sacrificial layers, the fiber was more breathable and water permeable than ordinary electrospinning nanofibers, so this work significantly inspired the design of multifunctional devices based on nanofibers [86].

Dong et al. fabricated breathable e-textile electrodes by electrospinning the mixture of phosphor particles and polymer as well as printing the liquid metals as electrodes on the surface. The e-textile electrodes recognized the EMG signals accurately and were comfortable to wear due to their excellent breathability and sweating functions. In addition, combining the signals output from the electrodes with the Arduino microcontroller unit can control the robot and promote the development of the field of human–machine interaction, as shown in Figure 11B [87].

Wu et al. designed a neuromorphic system by integrating touch sensors, synaptic transistors, and flexible wires, where all the parts involved in the electrodes were made of liquid metal, solving the mismatch of modulus and interface between different materials, as shown in Figure 11C. The working mechanism of the neuromorphic system is as follows: the touch sensor transmitted the received signal to the synaptic transistor as the presynaptic signal, where the signal was amplified, and then the signal was transmitted to the synaptic transistors for encoding to identify the tactile information accurately and realize the unified processing of information reception, transmission, and recognition, which significantly promotes the development of the intelligent robot field [88].

Kim et al. optimized the pressure-sensitive transistor by incorporating a three-dimensional liquid metal electrode array, which took advantage of the low modulus and processability of the liquid metals, as shown in Figure 11D. Subsequently, these signals were transmitted to a transistor for signal output and collection. The low modulus of liquid metals, which was different from the traditional solid metal electrodes, enabled the embedded electrodes with minimal impact when placed in organs, facilitating the monitoring of ECG signals and local pressure changes. This multimode sensing enhanced the capability of acquiring and analyzing physiological signals from human organs, thereby promoting the application and development of flexible electronics in the biomedical field [89].

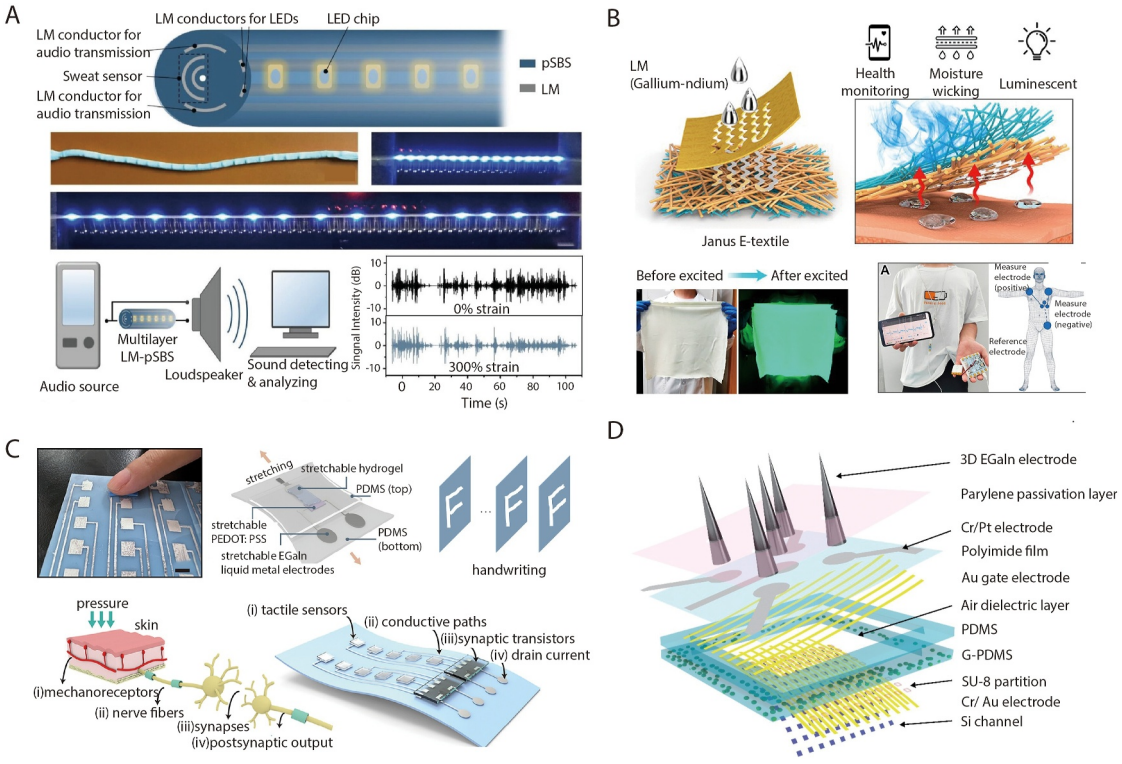

FIGURE 11 | (A) Multifunctional electronic liquid metal fiber. The scale bars are 5 mm. Reproduced with permission from Ref. [86] Copyright 2023, Wiley. (B) Flexible skin electrodes combined with liquid metal electrodes. Reproduced with permission from Ref. [87] Copyright 2022, American Chemical Society. (C) Neuromorphic system by integrating touch sensors, synaptic transistors, and flexible wires. The scale bars are 5 mm. Reproduced with permission from Ref. [88] Copyright 2023, Wiley. (D) Pressure-sensitive transistor incorporating three-dimensional liquid metal electrodes. Reproduced with permission from Ref. [89] Copyright 2022, American Chemical Society.

4.3 | Elastic Sustainable Energy Devices

In order to realize sustained and steady output performances, such stretchable electronics require reliable power supplies that can accommodate such flexibility and stretchability [90], promoting the development of stretchable elastic energy devices. Liquid metals, with a low melting temperature, low toxicity, desirable electrical conductivity, and outstanding stretchability, possess a unique advantage in the production of multifunctional flexible devices, especially soft energy storage devices.

Lithium-ion batteries (LIBs) have been regarded as the dominant player in the power markets due to their high energy density and steady charge–discharge ability. However, current flexible LIBs with an organic electrolyte cannot maintain stable electrochemical performance because of the high sensitivity to moisture and oxygen [90b, 90c]. In order to realize high stability, an LMs-elastomer seal for stretchable organic electrolyte-based LIBs was designed through the integration of EGaIn and polyisobutylene (PIB) (Figure 12A). Benefiting from the hermetic property and low Young's modulus of LMs, the LMs-PIB seal could prevent the inward permeation of moisture/oxygen and the outward permeation of reactive gases. The fabricated LIBs possessed a wide operating voltage range of 2.7–4.1 V, a desirable specific capacity, and stable cycling stability. Moreover, the LED array could also be lit up successfully by the LIBs under stretching (over 30% strain), indicating significant potential in wearable electronics [91].

Considering the safety issues associated with LIBs with organic electrolytes, zinc-ion batteries (ZIBs) have attracted increasing attention, particularly in the field of wearable electronics, due to their high theoretical capacity, good compatibility, and low cost. Nevertheless, the shape memory effect, unstable plating/striping reversibility, and notorious dendrite growth make ZIBs fail to meet the requirements for practical integration into electronic textiles. Absolutely, designing stable and stretchable ZIBs is indeed crucial for providing a steady power supply to electronic textiles. As shown in Figure 12B, Pu et al. reported a unique stretchable fibrous liquid metal@Zn 3D anode for the flexible ZIBs. On the one hand, the induced LMs performed high zincophilicity and low migration energy barriers. On the other hand, they exhibited an alloying effect with Zn, resulting in a homogeneous Zn-ion distribution and dendrite-free Zn deposition. At a strain of 50%, the ZIBs maintained a high capacity of 139.8 mAh cm^{-3} after 300 cycles. Additionally, the fibrous ZIB was perfectly melded with a sensor, Joule heater, and wireless charging device, ensuring consistent and stable power provision for monitoring human signals and managing personal heat conditions [92].

Besides batteries, supercapacitors are also promising mobile energy storage devices because of the fast power supply and long cycling lifespan. Nonetheless, the conventional preparation process makes their use in skin- or body-integrated applications challenging. Consequently, in order to realize all-soft supercapacitors, EGaIn electrodes with integrated oxygen-functionalized CNTs (O-CNTs) were prepared. As presented in Figure 12C, intrinsically soft and metallic conductive EGaIn creates stretchable current collectors and circuits. When chemically incorporated with O-CNTs, it enhances durability, softness, and stretchability. This made them appropriate for use in all-soft supercapacitors [93].

Triboelectric nanogenerators (TENGs) serve as a type of sustainable energy harvester, with the capability to transform mechanical energy into electrical energy [94]. This conversion is achieved through the combined effects of contact electrification and electrostatic induction. These unique properties make TENGs a promising power source for a variety of applications. Compared with the drawbacks of battery-incorporated systems, such as frequent charging and service life limits, TENGs have demonstrated their feasibility in serving as wearable power sources and self-powered sensors owing to the diversified material choices, high efficiency, and low cost.

Zhou et al. reported a robust route to an LMs/polyvinyl alcohol (PVA) hydrogel-based TENG (LP-TENG) through a combination of rational structure, optimized materials, and a synergetic mechanism (Figure 12D). Compared with a previous TENG

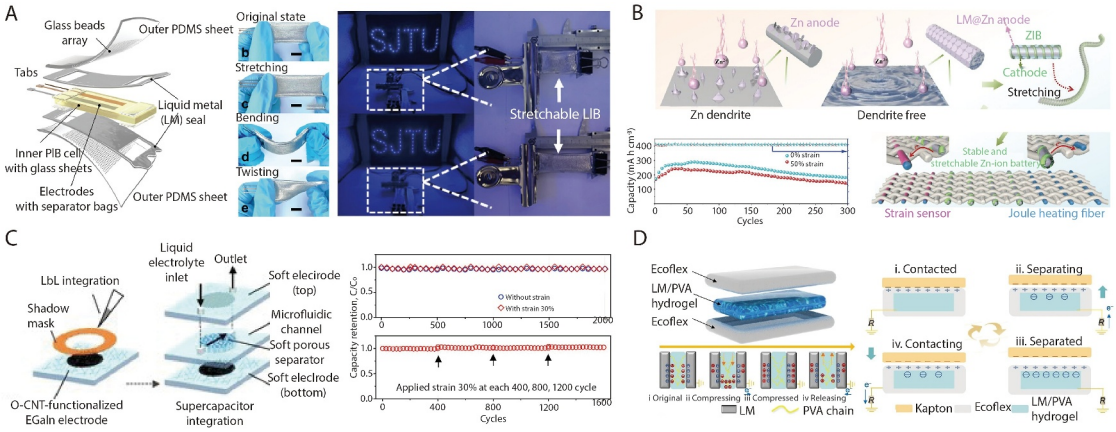

FIGURE 12 | (A) Stretchable organic electrolyte-based LIB. The scale bars are 12 mm. Reproduced with permission from Ref. [91] Copyright 2023, Wiley. (B) A self-powered LM-based electronic textile integrating a ZIB. Reproduced with permission from Ref. [92] Copyright 2023, Wiley. (C) Fabrication process of all-soft supercapacitors and long cycling stability of a soft supercapacitor under stretch strains of 30%. Reproduced with permission from Ref. [93] Copyright 2020, American Chemical Society. (D) Structure and working mechanism of LP-TENG. Reproduced with permission from Ref. [95] Copyright 2023, Nature Publishing Group.

with solid fillers, the adverse internal stress concentration could be resolved due to the introduction of liquid metals. The prepared LP-TENG performed compelling output, superior stability, recyclability, and diverse applications. Indeed, the LP-TENG has been successfully utilized in various applications, such as human motion detection, handwriting recognition, energy collection, message transmission, and even human–machine interaction. This implies that LP-TENG has a broad range of potential uses, especially in the fields of wearable technology and smart devices, where it can contribute significantly to advancements in these areas [95].

5 | Summary and Perspective

In summary, liquid metals have been used in flexible interconnecting circuits, flexible heaters, actuators, transistors, information sensing and transmission systems, and energy equipment due to their high conductivity, low modulus, and excellent machinability. Flexible electrodes based on liquid metals have developed rapidly in these fields, and their application methods and application scenarios are extremely diverse, but the bulk of liquid metals is significantly limited when using due to their high surface tension and low viscosity. However, conductivity will be sacrificed when they are broken into liquid metal particles, so there is still a great deal of research space for flexible electrodes based on liquid metals.

Flexible electrodes fabricated by using bulk liquid metals have high conductivity but poor stability, and liquid metals are prone to oxidation due to their exposure to air. It is possible to package with ultra-thin elastic adhesive layers so that the prepared components can be in conformal contact with the skin while having antioxidant function and promoting the development of wearable flexible electronics.

With the vigorous development of flexible electronics, single devices no longer have the advantage; flexible integrated circuits are the urgent problems to be overcome, but this involves the resolution of flexible interconnecting circuits. Some researchers have indeed attempted to prepare high-resolution interconnecting wires by printing with liquid metals. However, the stretchability of these printed circuits was found to be poor due to the high surface tension of liquid metals. Furthermore, printing machines with high resolution needed for this process are quite costly, making them unsuitable for mass production. It seems that although this method has potential, there are still significant hurdles to overcome for it to become a viable solution.

At present, a feasible way to prepare high-resolution flexible circuits is to break liquid metals into microparticles or even nanoparticles, but conductivity will be sacrificed. The smaller the particles, the more difficult they are to break, which is more difficult to form conductive paths at this time. Based on this, researchers can consider mixing solid metals (such as Ag and Cu) that could alloy with liquid metals so that the solid metal acts as needles to break the liquid metal particles, resulting in quasi-solid circuits.

Additionally, the viscosity of liquid metals is very low; it is difficult to achieve stable adhesion with components or polymers with low surface energy, such as PDMS. However, composites mixed with polymer have low conductivity. Therefore, try to make use of their intrinsic high conductivity, improve their interaction force with substrates, protect liquid metals from oxidation during their usage, and make the devices with excellent abrasion performance to prepare the safer and more comfortable wearable electronics.

In VR and AR, haptic feedback can enhance the user experience. Liquid metal has excellent electrical conductivity and fluidity, so it has significant research space in the field of haptic feedback. When the liquid metal is stimulated by external pressure or touch, its shape or distribution will change, and this change can be converted into electrical signals for transmission and processing. By designing specific structures and circuits, it is possible to convert the deformation of liquid metal into measurable electrical parameters (such as resistance, capacitance, etc.) to realize the perception and feedback of tactile information.

Acknowledgments

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding authors upon request.

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