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REVIEW PAPER

Role of Liquid Metal in Flexible Electronics and Envisage with the Aid of Patent Landscape: A Conspicuous Review

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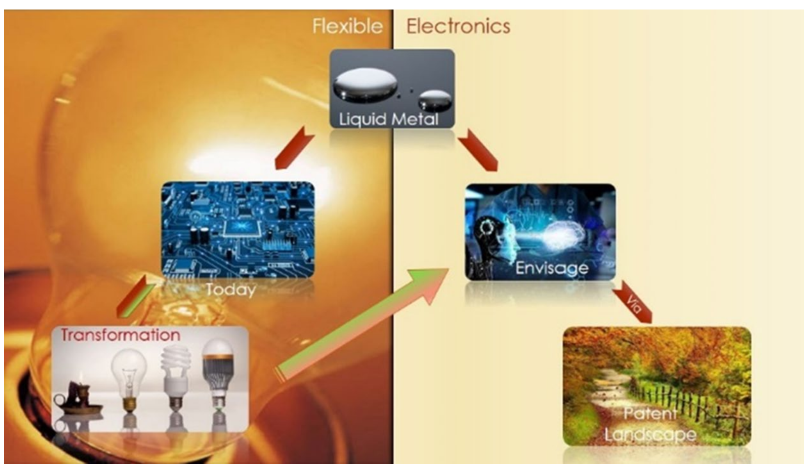
Abstract
Wearable's become most widely used in the medical field to assess and monitor human body conditions even from remote locations. So, it should be weightless as well as functional at various temperature ranges. It is mandated that it should be functional with ultra-sensitiveness. The proper selection of conductive elements should be part of the measuring device. Based on these criteria, this review article is articulated. The effect conductor is metal, but metal is heavier, wearable should be slick thereby, the best material is liquid metal. So, the scope and implications of the liquid metal in flexible electronics are consolidated. Furthermore, the future scope of the wearable is assessed with the aid of patent landscape analysis, as a known fact is updated faster than other databases. As well-identified few technologies that have been applied as patents, it might have better growth owing to its technological advancements.

Graphical Abstract



Keywords Wearable · Flexible electronics · Patent landscape · Liquid metal

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1 Introduction

There is a surge of attention to flexible electronics due to various about their wide range of implementations in wearable devices [1–4], healthcare [5–7], antennas [8–10], portable equipment [11–13], and sensors [14–16]. Flexible conductors but also many other exceptional stretchable, as well as deformable components, have played a key function in soft electronics [11, 17, 18]. For example, silver, copper, as well as aluminum are high-conductivity metals that can withstand recurring bending, warping, or stretching but are just not very long-lived. Gallium (Ga) as well as Ga-depend metal alloys, on the other hand, are typically liquid at room temperature and then have the additional benefits of high conductivity as well as strong ductility, excellent flexibility, and also nontoxicity [19–23]. Ga-based liquid metals have outstanding mechanical as well as electrical characteristics that make them ideal replacements for conventional metal conductors in wearable electronics [24–28]. Liquid Ga-based metal alloys, on the other hand, are commonly covered in a thin oxide shell, which severely limits their successful applicability [29, 30]. For this reason, the casing of the molten material is more likely than other materials to adhere strongly to a solid surface. To prepare Ga-based microelectronic devices, it is hard to eliminate the rigidly adhere liquid metal because of the metal residues. Oxidation can eliminate the unwanted oxide shell, but the oxide coating quickly regenerates again when the liquid alloys come into interaction with air [31–34]. The acid/alkaline solutions commonly being used to remove the oxide shell are also corrosive, making them unsuitable for microelectronic gadgets [35]. Without removing the oxide shell, a new technique for reducing the adhesion between liquid metal as well as the solid surface has been established using the liquid–metal-repellent microstructure [36–40]. A liquid–metal repellent surface has been fabricated based on the remarkably liquid–metal-repellent substrates that are constructed by the combination of surface microstructure as well as chemical composition. Carbon nanotubes can be deposited on a polydimethylsiloxane (PDMS) surface, for example, by Kim et al. CA hysteresis of something like a liquid galinstan drop of water on the surface has been greater than 155°, as well as the CA hysteresis of the galinstan droplet has been 19°. Low-surface-energy silica nanoparticles have been encased onto a glass surface by Jiang et al. [41] as an outcome, EGaIn did not wet a glass surface (85.8 percent Ga, 14.2 percent In). By preferentially as well as partially having removed the nanoparticle coating, we were capable of achieving a more complex wetting/dewetting sequence to liquid metal. A "never-wet" path for EGaIn was created by Joshipura et al. using a superhydrophobic spray-coating process [42]. Presently, superhydrophobic sealants are used to achieve liquid–metal repellence, but a Ga-based liquid puddle on something like a harsh solid substrate has a wettability that differs greatly from a water droplet. Ga-based liquid metal's wettability, as well as the design concept for liquid–metal-repellent surfaces, have not yet been fully understood. It is also necessary in most cases to wet/de-wet micro-shaped surfaces to liquid metals when using them in soft microelectronic devices. Liquid–metal repellent-shaped surfaces, on the other hand, are usually prepared using expensive masks on complex substrates, as well as the concocted patterns are also insufficient for real-world applications [14, 17, 18, 43]. A one-step and flexible approach to achieving durable as well as patternable liquid–metal-repellent surfaces is difficult. It is possible to create patterns on solid surfaces using FDW—Femtosecond Laser Direct Writing [44–52].

2 Laser Printing of Liquid Metal

Liquid metal is an outstanding material for fabricating flexible electronics because of its fluidity as well as elevated electrical conductivity. We've developed a technique for making 3D flexible electronics using a common laser-printing technique. We were able to selectively adhere liquid metal to the constructed configuration using digital fabrication of fluid alloy-philic gentle toner on fluid alloy-phobic harsh surfaces. An unequal, as well as, deformable Ecoflex outer layer can be used to transfer the fluid metal circuit into a 3D circuit. The printing mechanism of fluid metal on just a surface to chosen adhesion has been simulated using computational fluid dynamics. There are many possibilities for office but also home use of flexible electronics now that this technique can produce such high-quality products. Our technique not just saves money as well as time in preparation but also recognizes favorable opportunities for the fully developed laser-printing company to enhance next-generation flexible electronics manufacturing by making significant use of laser printers. The manufacturing and testing are shown in Fig. 1 [53].

3 Laser Sintering

To transfer power as well as data but also detect dynamic postures in next-gen wearable, soft robotic systems, as well as biocompatible devices wherein, it also needs to be soft, flexible, but also stretchable electronics. Although liquid metal has arisen as a good potential substance for such implementations due to its elevated conductivity as well as liquid state at room temperature, the outer-layer

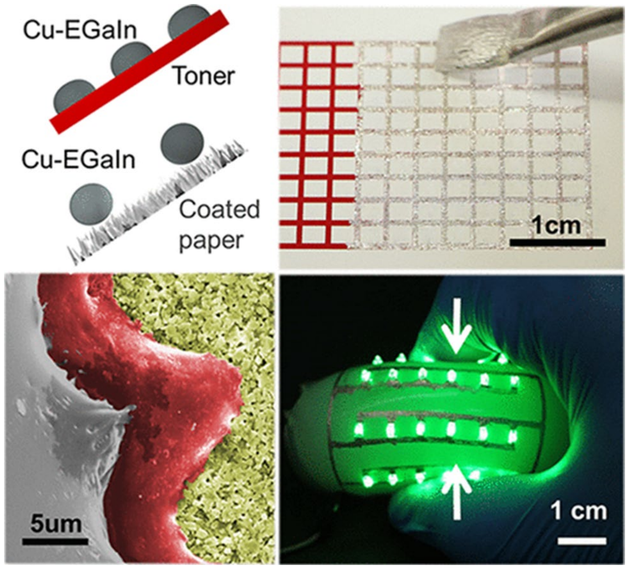


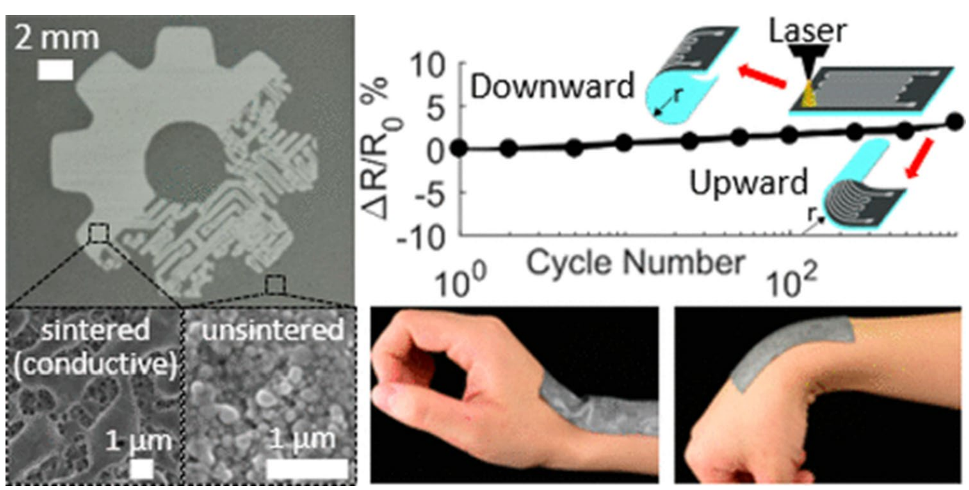
Fig. 1 Manufacturing and testing of flexible electronics [53]

oxidation of liquefied metal provides it unique behavior that is often inconsistent with configurable manufacturing techniques. This report outlines a fast as well as a scalable method for making flexible as well as soft electronic devices out of liquid metals. When tried compared to other liquefied metal patterning methods, this technique seems to have the benefits of being able to work with a wide range of substrates and is easily scaled. Laser sintering of non-conductive liquid metal nanoparticle films creates electrically conductive structures by breaking and abating the oxide shells of the nanoparticles and allowing their liquid metal cores to emerge as well as coalesce. Comparing laser sintering with concentrated ion beams and analyzing the consequences of thermodynamic transmission in sintered films are used to examine the concept. Sintered films are tested for their resistance to chemical and mechanical damage. Laser-patterning liquefied metal marks under flexing, multi-layer circuits, as well as intricate geometric circuits have been used to illustrate their electrical stability. Using lasers and fluid conductors on elastic surfaces, this research demonstrates significant advances forward in the commercial production of smooth electronics [54]. Figure 2—reveals the processes of laser sintering.

4 Transfer Printing

Flexible electronics can be made using room-temperature liquid metal alloys (LMs), which are soft conductive substances with elevated liquid fluidity. The alloy's greater surface tension, as well as poor wettability with several substrates, have so far hampered the development of techniques for patterning LMs. Mass manufacturing depending on LMs that print quickly and efficiently on the intended point still faces enormous challenges that have yet to be solved. In this article, a one-step liquid metal transfer printing technique with a diverse variety of substrate abilities to adapt is presented, including a polymer-based adhesive glue, its ability to print machine, and liquid metal ink. On substrates with low LM wettability, the LM transfer printing can still be used to create multilayer circuitry, complex geometries, along with large-area conductive designs with outstanding transfer efficacy, an easy production method, along with phenomenal electrical reliability, wherein it would be advantageous to rapidly build wearable electronics as well as 3D folding conductive structures as well as flexible actuator and soft robots, among other things. Self-healing, as well as recyclable quality, make the tactic feasible to make preparations for reconfigurable circuits as well as further decrease fabrication costs and pollution. Liquid metal soft workable electronics could benefit greatly from this research. Figure 3 reveals the process of transfer printing with testing [55].

Fig. 2 Manufactured by laser sintering [54]



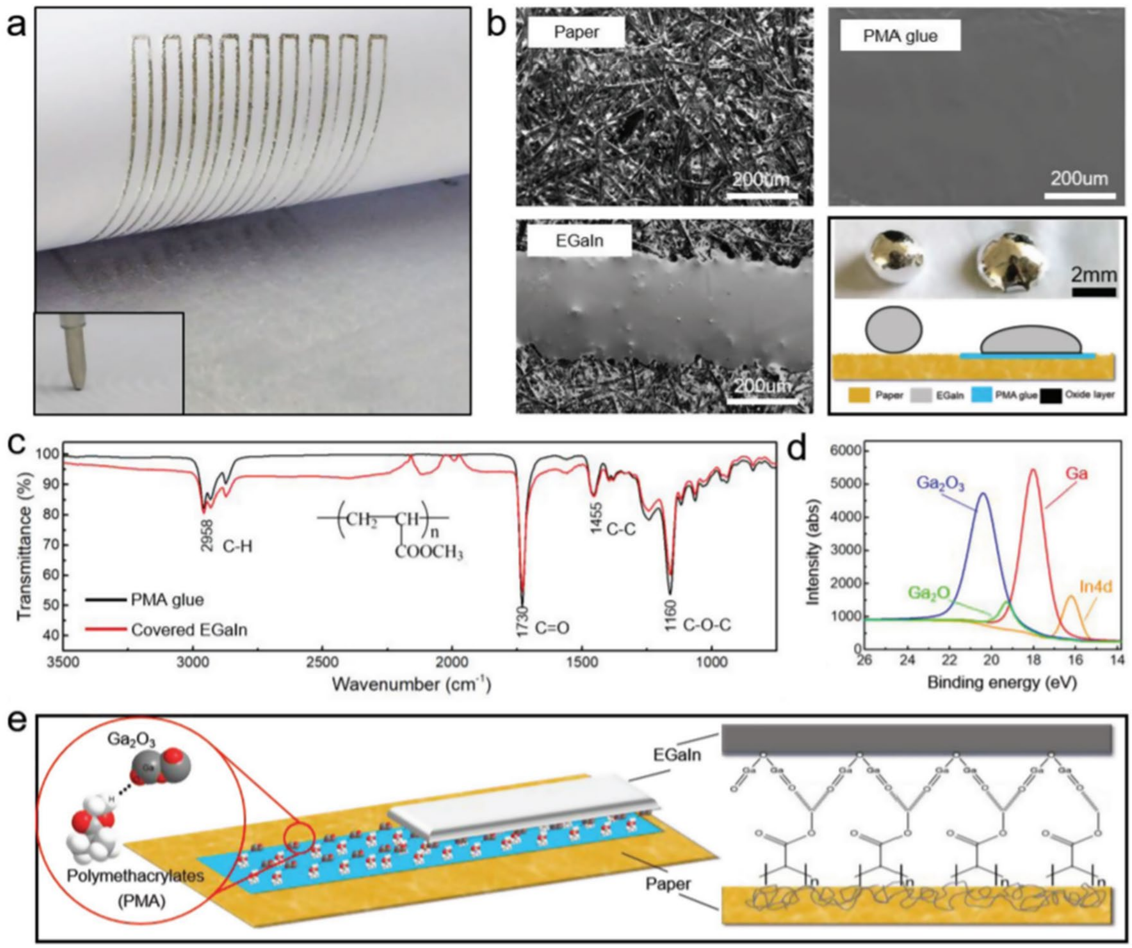


Fig. 3 Adhesion technique of EGaIn on the PMA glue over paper. **a** The photo of ball-point pen writing, **b** The SEM images and EGaIn droplets over the paper as well as over PMA glue. **c** The infrared spectroscopy of PMA, **d** Ga 2*p* fitted XPS spectra of the EGaIn. **e** Chemical interaction [55]

5 Recyclable Electronics

The ease and comfort with which flexible electronics can be used greatly improve the quality of human life. The elevated surface tension, as well as poor surface wettability of liquid metals, make them excellent candidates for flexible devices. Poly (vinyl alcohol) plus LM (PVA-LM) were combined to create a printable as well as recyclable ink to address these issues. The materials have been designed taking into account the compatibility between PVA as well as the liquid metal, as well as the composite theory was used to evaluate the component proportions. Three-dimensional printing technology has been selected to improvise the use of the substance because the advanced composites enhanced the liquid metal's surface wettability on various substrates. In addition, the conductivity of the PVA-LM ink had been excellent, allowing for the configuration of alarm systems as well as to object locators. With this ink, flexible sensors with high sensitivity as well as a super-stable signal generation can be produced even after 200 cycles of use. In their capacity as strain sensors, built composites were extremely sensitive to human movement monitoring. Alkaline recycling is an option for liquid metals in printed products has been shown in Fig. 4. This research paves the way for a new era of environmentally friendly, stretchable electronic devices in the future [56].

6 Repairable Paper

Electronic circuits can be created by printing liquid metals like gallium as well as its alloys on a variety of substrates. However, only a few techniques exist for writing liquid metals directly onto common printed paper. Addition of metal powder to gallium alloy results in a new and improved conductor. Electrical connections can be made with the proposed material because it has low viscosity, outstanding plasticity, as well as significantly improved adhesion to

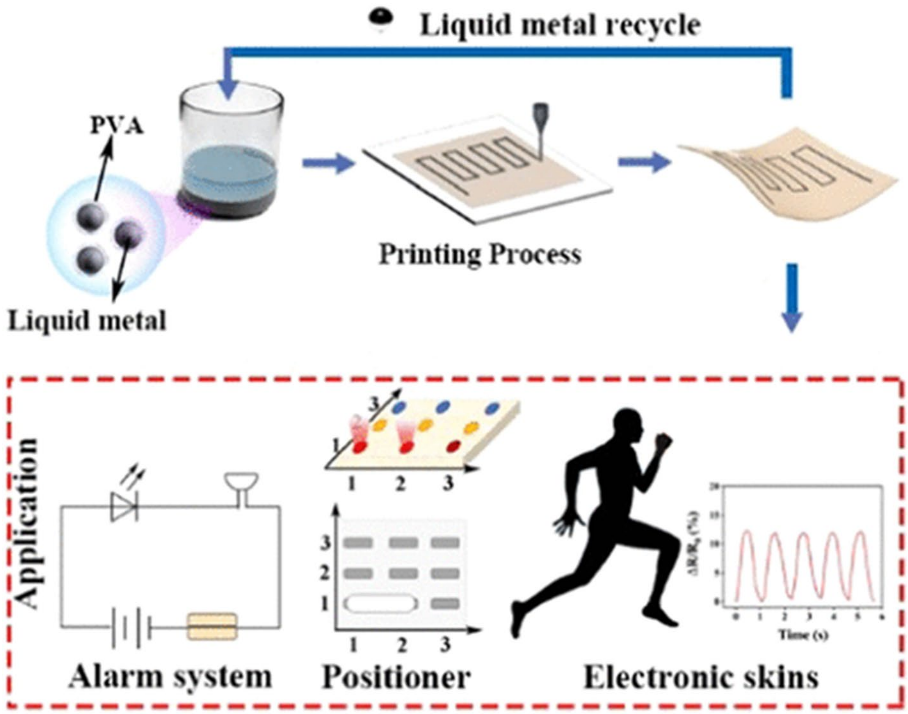


Fig. 4 Manufacturing of electronic skins [56]

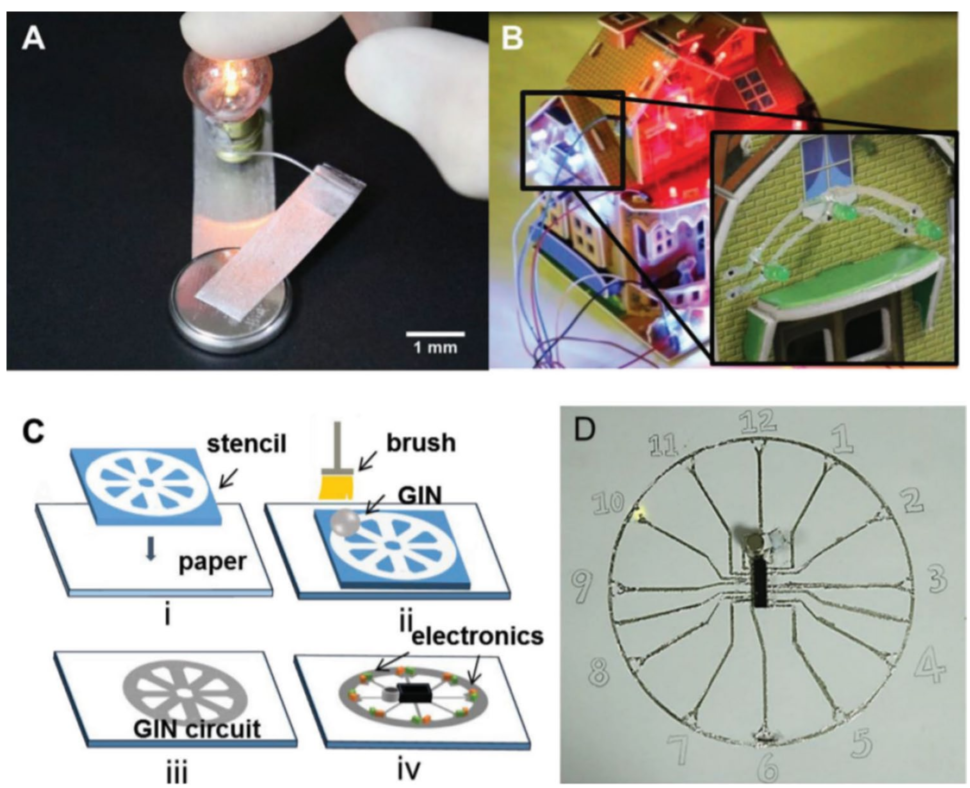


Fig. 5 Applying GIN for making electronics [57]

paper substrates. A skeleton of oxidation products is formed by the oxide film that covers the nickel powder, making it more adherent to paper. To illustrate the practicality and repair-ability of this material, several paper-based electronic applications are being shown in Fig. 5. An easy method for making paper electronics is now possible thanks to the results of this research [57].

7 LM Role in Flexible Electronics

Some of the variants of liquid metal-based flexible electronics (LMBFE) are discussed in the above section. The following Table 1 reveals the consolidated various LMBFE.

8 Future Envision

In general, envisioning the future scope of flexible electronics can be done in a few ways including assessing journal articles, industrial bulletins, and the patent landscape. In this article, it is accomplished with the aid of patent landscape owing to the update of the patent database is quite faster than others. It is revealed in Table 2.

The total count is 209 as per the record for the keyword ("liquid metal" "flexible electronics") and the entity selected is "English ALL (ENG_ALL), with "single-family member", which means the same patent filed in different countries is omitted and considered as one patent. The following Fig. 6 reveals the dominant entities are highlighted.

The USA is the dominant player in using liquid metal in flexible electronics followed by China. As a known fact the USA has quite remarkable growth in the medical first which always stands first, so the same trend is being followed in the flexible electronics as well owing to the application of flexible electronics is much high in the medical field. The dominant applicant is the "Institute of flexible electronics tech of thu Zhejiang", herein it reveals that the universities are quite competitive in the industry, rather than the vice-versa. In the top 10 list universities are higher than the industries, it resembles university research laboratories are focusing more on a flexible wearable. The next entity to be considered is International Patent Classification (IPC) code, the following two are quite dominative that is H05K and H01L, IPC codes. H05K is specifically for printed circuits as well as more particularly it deals with the electric apparatus constructional features or casing. So, most the flexible electronics components act as a printed circuits as well as receive input and deliver the output in the form of the electric pulse. H01L is specifically for semiconductor devices and more particularly for a solid-state electric devices. So, the flexible electronic device most commonly acts as a semiconductor as well as a solid-state electric device. While researchers looking for the patent database they can very well look for these two IPCs for printed circuits and semiconductor-based devices. In case they look for other combinations for liquid metal-based they have to add on the other IPCs. It is very easy to consolidate the domain-specific data. It is one of appreciable consolidation given in the patent database as well it is followed throughout the globe. In the case of year-wide count is a concern, it has gradual growth in their numbers and is quite dominative in the year 2020, but there isn't much surge in the years 2021 and 2022 by count. It further reveals that the growth in this domain is much higher in the near future too.

8.1 Ecoflex Liquid Metal Electronics

This technique disclosure is to provide a liquid metal-based flexible electron device and a preparation method. According to the method of this disclosure, a micro channel is quickly constructed in a flexible Ecoflex (silica gel) substrate, and liquid metal is then injected into the microchannel, and thereby a flexible electronic device is fabricated, without the construction of the microchannel by traditional lithography process, which greatly simplifies the operations and reduces the cost.

To achieve the above object of this technique disclosure provides the following technical solutions. This technique disclosure provides a method for preparing a liquid metal-based flexible electronic device, comprising: preparing an ABS (Acrylonitrile Butadiene Styrene) plastic model by a 3D printing according to a circuit pattern; performing an ion sputtering on a surface of the ABS plastic model to form a gold film, to obtain a gold-plated ABS circuit; introducing Ecoflex into a mold, suspending the gold-plated ABS circuit inside the mold such that the gold-plated ABS circuit does not contact the mold, and curing Ecoflex, to obtain a cured model; immersing the cured model in acetone to dissolve the ABS plastic model, to obtain a microchannel with a gold plating on an inner wall of the microchannel in the Ecoflex substrate; and injecting a gallium-indium eutectic into the microchannel with a gold plating on the inner wall, inserting a copper wire into the liquid metal at both ends of the microchannel with a gold plating on the inner wall, and applying Ecoflex to a port of the microchannel with a gold plating on the inner wall and curing Ecoflex such that the circuit is encapsulated, to obtain the liquid metal-based flexible electronic device is shown in Fig. 7.

The parameters are listed below,

- The ion sputtering is performed for 60–100 s.
- Curing eco-flex is performed independently for 2 to 4 h.
- Immersing the cured model in acetone is performed for 12–24 h.

Table 1 Consolidation of various LMBFE

S. no.	Liquid metal (LM)	Technique adopted	Properties observed	References
1	LM	Soldering	130% of elongation	[63]
2	LM with LAPONITE	Spontaneous sintering	Rigid, soft, and fragile	[64]
3	LM	Electro-spinning	Reconfigurable and Recyclable	[65]
4	Oxide-free Eutectic Gallium Indium (EGaIn) alloy along with a high-surface-energy gold	Intermetallic wetting	Outstanding stability during the deformation mechanically	[66]
5	LM	Coupling of the mask along with plasma treatment	Fast self-healing, Extreme reliability, and complete recyclability	[67]
6	LM with graphene oxide, poly (3,4-ethylene dioxythiophene) polystyrene sulfonate	Facile solution-process	Better electrical contact	[68]
7	LM with Silicone inks	Direct ink writing	The revelation of great resistance to damage	[69]
8	AlGaN/GaN	Phase transition technique	Heat dissipation is 2.33 times greater than a high electron mobility transistor	[70]
9	Eutectic gallium indium (EGaIn)	Direct-writing	Reconciles firmness as well as biocompatible	[71]
10	Nanocellulose—based LM	Evaporation-induced transfer printing	Renewable	[72]
11	LM	Solution-depend process	Outstanding electrical conductivity, ultrahigh stretch-ability (1000 percentage of tensile strain), mechanical durability	[73]
12	Gallium alloy	Solid–liquid phase transition and plastic deformation	Highly integrated 3D circuits	[74]
13	LM	Stimulation model	Flexible bio-electrode	[75]
14	LM nanoparticles	Polyurethane (PU) matrix	Outstanding stretch-ability along with permittivity	[76]
15	Eutectic gallium indium (EGaIn)	Manual hand lay-up method	Flexible thermoelectric generator	[77]
16	Gallium	Uniform coating technique	Sintering-free LM ink	[78]
17	Copper-gallium oxide	Interfacial engineering approach	High thermal conductivity as well as stability of composite	[79]
18	LM, Silicon carbide, may or may not be coated with silver	Mechanical compression	Averting LM de-wetting	[80]
19	EGaIn film	Ultrafast photonic sintering	Excellent electrical conductivity	[81]
20	Galinstan along with silicone rubber	Sterilization methods	Flexible body implants	[82]
21	LM and shape-morphing liquid crystal networks	Ultrasonication	Greater adhesion as well as photothermal conversion	[83]
22	LM	Sequential oxidation strategy	Working under the very low temperature of minus 196 degrees Celsius	[84]
23	LM nanoparticles	Grinding technology	Stable for around 90 days	[85]
24	LM with Diels–Alder (DA) bond crosslinked polyurethane	Mechano-training	Durable as well as recyclable	[86]
25	Magnetic LM	Laser ablation	A flexible tensile sensor is fabricated	[87]
26	LM	Stack sandwich method	Faster fabrication with erasable display	[88]
27	LM with thermoplastic polyurethane	Mechanical injection	Stretchable electrode	[89]
28	LM with hydrogel	Stencil printing	Self-shaping ability	[90]
29	LM with silver and Silicone oil	Compression	Thermal applications	[91]
30	LM	3D printing	Tactile sensor	[92]
31	LM with acrylic acid	Manual method	Strain sensitivity around 400 percent, self-healable	[93]
32	Semi-LM	Adhesion-selection enabled rolling and transfer (SMART) printing	Fabrication is completely automatic	[94]

Table 1 (continued)

S. no.	Liquid metal (LM)	Technique adopted	Properties observed	References
33	LM is filled polymer micro lattice metamaterial	micro-stereolithography additive manufacturing	Shape memory effect	[95]
34	LM	Direct patterning	Patterning LM over the non-planar surface	[96]
35	LM micro droplets	Strong impulse	Shape morphing	[97]
36	LM	Transfer printing	Flexible electronics	[98]
37	Fe-EGaIn	Thermal transfer printing	Remote auto-healing	[99]
38	LM	Vacuuming	Super-high electrical (Approx.104 S per cm) and thermal conductivities (17.6 W per mK)	[100]
39	LM particle coated with Ga_2O_3	Screen printing	Exceptional stability along with durability (R by R_0 is less than 1.65 beyond 10,000 bending cycles of the radius of 0.5 mm)	[101]
40	LM	Additive manufacturing	Escalation in fluidic elastic modulus along with the yield stress	[102]
41	Indium tin oxide	Direct depositiontechnique	Material resistance as less as 5.4 kilo-ohms /square	[103]
42	Ferromagnetic LM	Homogenously mixing	Polarity reconfigurable	[104]
43	LM	Printing	Repairable and reconfigurable	[105]
44	LM	Direct patterning	Super-metallophobic	[106]
45	Non-toxic LMs	Chemical vapor deposition (CVD)	96 percent of yield from the manufactured transistors	[107]
46	Gallium alloys in Colloidal LM	Press—rolling	Conductive in circuit tracks and self-healing ability	[108]
47	LM	Facile fabrication	Recyclable and recoverable	[109]
48	Elastomer LM	3D printing	Elastomeric electronics	[110]
49	LM based hydrogel	Friction pen-based printing	Rewriteable	[111]
50	Surfactant-less Ga-In LM	Physical vapor deposition	Gradually grew	[112]
51	LM with bismuth telluride nano-wires	Inkjet-printed	Thermoelectric-generators	[113]
52	LM	Printed and stretched	Cascade phase change mediated	[114]
53	LM droplets	Evaporation-induced sintering	Responsive actuation	[115]
54	LM micro-particle	Physical vapor deposition	Soft motors	[116]
55	LM nano-composite	Direct writing	Robustness	[117]
56	Oxide-free EGaIn alloy along with gold	Direct writing	The functional circuit acts as a resistive sensor	[66]
57	α-thioctic acid along with butyl acrylate	Plasma treatment along with coupling	Instant bionic self-healing material	[118]
58	Carbon nanotube (CNT) composite	Coating of LM over CNT using ultra-high conductivity	Droplets LM which are extremely stable	[119]
59	Indium tin oxide	Interface phase separation	The flexible electrode is fabricated	[120]
60	Ga-LM	Laser	Rapid fabrication is possible due to laser	[121]
61	LM elastomer composite	3D Printing and liquid injection	Recognition of magnetic field and compressive force	[122]
62	Gallium based LM	Direct writing	As batteries	[123]
63	LM micro-gel	3D Printing	Smart clothes	[124]
64	LM based nano-composite	Ultrasound	Biomedical	[125]
65	Nickel LM ink	Shear mixing	As repairable paper	[57]
66	LM based nano-composite	Nebulization	Functional as well as stable	[126]
67	LM based nano-composite	Surface rolling coating	Greater elasticity, portability along with robust mechanically	[127]
68	PDMS with LM electrodes	Soft-lithography	As a sensor for skin	[128]
69	LM	Laser screen printing	Glucose detection in sweat	[129]

Table 1 (continued)

S. no.	Liquid metal (LM)	Technique adopted	Properties observed	References
70	EGaIn	Electro-wetting is evaluated numerically, empirically, and through simulation	Electrical control over droplet bouncing study used for versatile applications	[130]
71	GaIn	Direct writing	Better bio-compability	[131]
72	EGaIn oxide-free	Intermetallic wetting	Act as a resistive motion sensor	[132]
73	Polydimethylsiloxane	Femtosecond laser direct writing	Micro-heater, micro-strip are fabricated	[133]
74	Polycaprolactone with LM	Filtration and rolling	Act as a weight, sound and breathing sensor	[134]
75	Gallium based LM	Direct writing	In soft robotics	[135]
76	Aerogel silicone composite with LM	Double side tape and pouring	Act as a flexible thermoelectric generator, converts human body heat into electricity	[136]
77	EGaIn nanoparticles with CNT and polystyrene sulfonate	Tip sonication	Electronic tattoo for bio electronics	[137]
78	EGaIn nanoparticles with polystyrene sulfonate and acetic acid	Tip sonication	Stable printing of LM for stretchable electronics	[138]

Table 2 Patent landscape for the liquid metal in flexible electronics [62]

S. no.	Country	Count	Applicants	Count	IPC* code	Count	Year	Count
1	USA	83	Institute of flexible electronics tech of thu Zhejiang	19	H05K	52	2013	3
2	PCT**	65	Tsinghua university	15	H01L	49	2014	18
3	China	56	Ellinger Carolyn R	8	H01B	27	2015	11
4	Republic of Korea	2	Levy David H	8	B29C	19	2016	6
5	Australia	1	Nelson Shelby F	8	A61B	17	2017	19
6	Canada	1	Beijing dream ink tech co. Ltd	7	C09D	13	2018	22
7	India	1	Elwha LLC	7	G01L	12	2019	28
8			Iowa state university research foundation Inc	7	H01R	12	2020	35
9			President and Fellows of Harvard college	7	B33Y	11	2021	31
10			Ningbo Institute of materials tech and engineering Chinese academy of sciences	6	G01N	9	2022	7

**Patent cooperation treaty—PCT

*International patent classification code—IPC

- The gallium-indium eutectic has a Ga content of 74.5 weight percentage and In the content of 25.5 weight percentage.
- The copper wire has a length of 50–70 mm.

It also provides the use of the liquid metal-based flexible electronic device as described in the above technical solutions in the fields of smart furniture, smart wear, electronic skin, flexible sensing, radio frequency antennas, biomedicine, and aerospace. It provides a method for preparing a liquid metal-based flexible electron device, comprising the following steps: preparing an ABS plastic model by a 3D printing according to a circuit pattern; performing an ion sputtering on a surface of the ABS plastic model to form a gold film, to obtain a gold-plated ABS circuit; introducing Ecoflex into a mold, suspending the gold-plated ABS circuit inside the mold such that the gold-plated ABS circuit does not contact the mold, and curing Ecoflex, to obtain a cured model; immersing the cured model in acetone to dissolve the ABS plastic model, to obtain a microchannel with a gold plating on an inner wall of the microchannel in the Ecoflex substrate; injecting a gallium-indium eutectic into the microchannel with a gold plating on the inner wall, inserting a copper wire into the liquid metal at both ends of the microchannel with a gold plating on the inner wall, and applying Ecoflex to a port of the microchannel with a gold plating on the inner wall and curing Ecoflex such that the circuit is encapsulated, to obtain the liquid metal-based flexible electronic device. In the present disclosure, 3D printing and the characteristic that ABS plastic can be dissolved by acetone were utilized, and a microchannel is quickly constructed in the flexible substrate of Ecoflex, and liquid metal is then

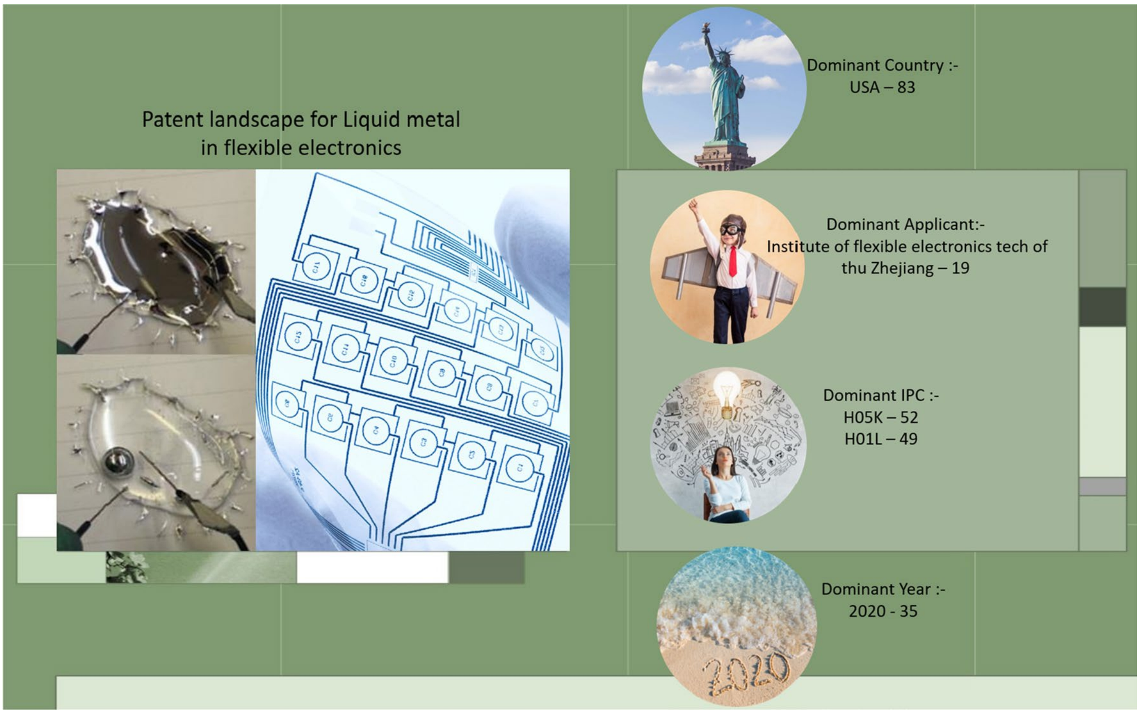


Fig. 6 Landscape dominant entities are highlighted [62]

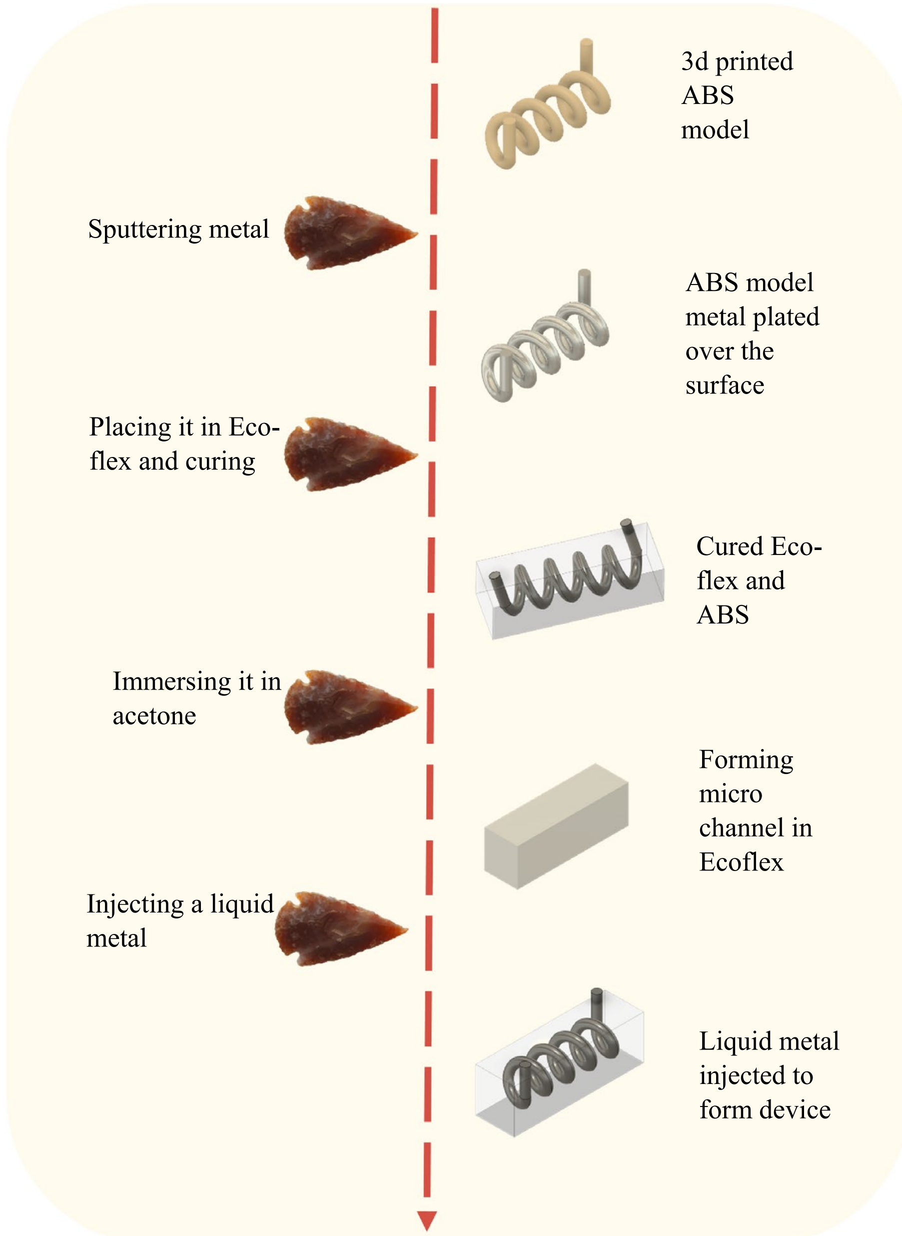
injected into the microchannel to complete the manufacturing of a flexible electronic device. In the inventive method, the construction of the microchannel by a traditional lithography process is not needed, which could greatly simplify the operation steps and reduce the cost.

It also provides a liquid metal-based flexible electron device prepared by the method described in the above technical solutions. In the present disclosure, the gold film on the surface of ABS is transferred to the surface of a flexible Ecoflex substrate, which improves the wettability of liquid metal within the microchannel, thereby facilitating the subsequent liquid metal-injection operation. The prepared flexible liquid metal circuit has high elasticity, could meet the needs of various deformations, and has stable electrical properties during service. The adhesion work of micro channels at different stages was calculated according to the Young Dupre equation. The adhesion work after plating gold increases from 110 (before plating gold) to 200 mJ/m^2, which is increased by nearly twice, thereby significantly improving the wettability. The obtained liquid metal-based flexible electronic devices could be stretched to a strain of 600%, bent 180°, and twisted 360°, and when being subjected to 1,000-cycle tensile tests with a strain of 100%, exhibit stable peaks and valleys in the resistance curve [58].

8.2 Recyclable, Self-repairable Liquid Metal Electronics

The invention provides a self-repairing liquid metal flexible electronic material capable of being completely recycled, and a preparation method and application thereof, and belongs to the technical field of electronic materials. The self-repairing liquid metal flexible electronic material has a three-layer structure, the lower layer and the upper layer are made of a base material, the middle layer is a liquid metal, and the base material is a self-repairing polymer containing a disulfide bond. According to the electronic material, the interaction between liquid metal and the flexible base material is achieved through the plasma surface treatment technology, and dual repairing of acting force, mechanical performance, and electrical performance is achieved. Meanwhile, the self-repairing liquid metal flexible electronic material and an electronic device prepared from the self-repairing liquid metal flexible electronic material are low in cost and simple and convenient to operate; in addition, the electronic material disclosed by the invention has complete recoverability and is green and environment-friendly. The self-repairing liquid metal flexible electronic material and the electronic device prepared from the self-repairing liquid metal flexible electronic material are easy to popularize and apply on a large scale and have a good application prospect [59].

Fig. 7 Ecoflex wire [58]



8.3 Reconfigurable, Wearable Liquid Metal Electronics

In one aspect, the present disclosure relates to an electronic device comprising: a plurality of electronic chip components; a plurality of liquid metal (LM) electrical interconnects coupled to the plurality of electronic chips, and a polyimide film encapsulating the plurality of electronic chip components and the plurality of LM electrical interconnects. In some embodiments, the polyimide film comprises the product of the polymerization reaction between terephthaldehyde, 3,3diamino-N-methyldipropylamine, and tris (2-aminoethyl) amine. In another aspect, the present disclosure relates to a method for manufacturing an electronic device, the method comprising: disposing of a volume of LM on a polyimide substrate to form a plurality of electrical interconnects; disposing of a plurality of electronic chip components onto the polyimide substrate and in contact with the plurality of electrical interconnects; and applying a layer of polyimide onto the polyimide substrate, the plurality of electrical interconnects, and the plurality of electronic chip components [60].

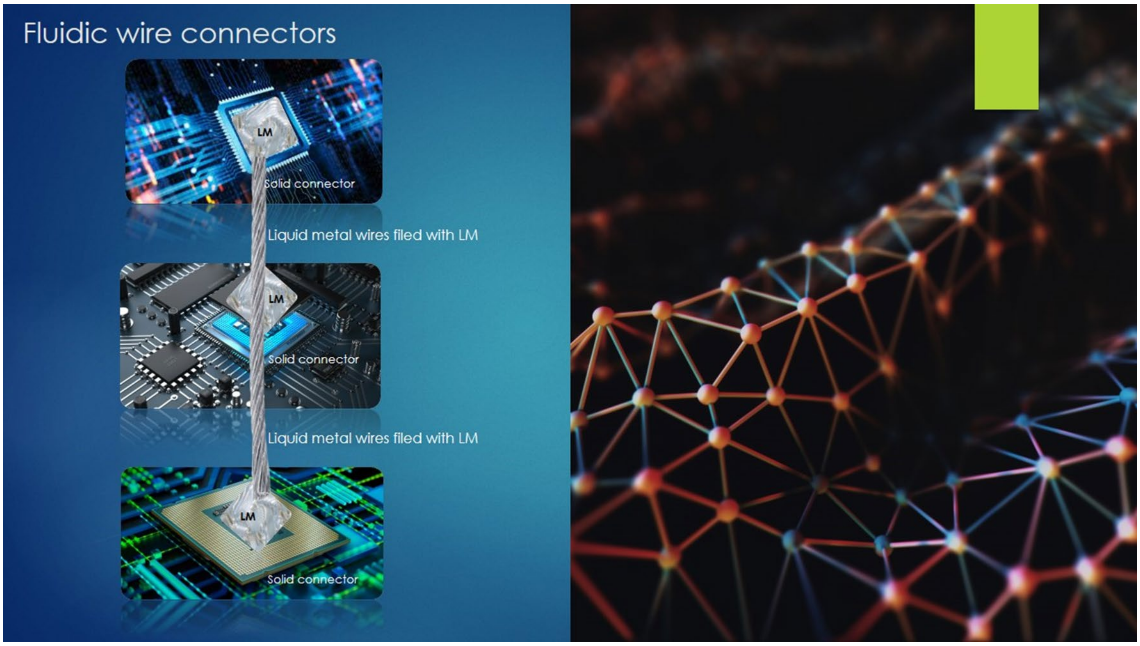


Fig. 8 Fluidic connector—[Redrawn from patent Ref. [61]]

8.4 Flexible Wire Based on Fluids Acts as a Connectors

A reservoir containing a solid alloy conductor is included in a link for connecting to a fluid metal wire. The conduit is hollow to link to a cylindrical wire casing. Liquid metal will be pumped into the reservoir until it reaches the tubular wire casing, at which point the reservoir will be filled. The fluid metal wire is formed when the tubular wire enclosure is stuffed with the liquefied metal is shown in Fig. 8 [61].

The patent specification mentioned above is a potential identity to grow because a common understanding is that these are more technologically advanced than the existing inventions. Besides this, the methodology for producing flexible electronics is a better and simpler way. Let us assess individually, an eco-flex method provides a 3d printed mold for the metal wire thereby, the flexibility is enormous in terms of size and sophistication is limitless. The next one, self-healable flexible electronics has the widest application scope in wearable, thereby the next one is reconfigurable. The final one is fluidic connectors, as a known fact, it provides the best connectivity between the components.

9 Conclusion

This review article is articulated based on a few existing technologies including laser printing of liquid metal, laser sintering, transfer printing, recyclable electronics, and repairable paper are contributed so far to the manufacturing of liquid metal flexible electronics. The major assessment is the future scope of this method of fabricating the flexible electronics wherein it is assessed with the patent landscape. From the consolidation of the growth over 10 years, found to be quite a reasonable acceleration has been realized. So, to emphasize further specific technique which leads a way to the next generation are identified based on the potential filing in the year 2022 are discussed. The techniques include eco-flex liquid metal electronics, recyclable, self-repairable liquid metal electronics, reconfigurable, wearable liquid metal electronics, and flexible wire based on fluids that act as connectors. The potential technique might be fluidic connectors owing to its flexibility over a wider range of operations including temperature changes, impact loads, and vibrations.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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