REVIEW ARTICLE

https://doi.org/10.21608/fpmpeb.2025.377784.1014

Vol. 2, No 2/2025

Liquid Metals Characteristics, Applications and Innovative Biomedical uses of Eutectic Alloys

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Abstract

Liquid metals is a group of metallic elements with melting points less than 300 °C. Liquid metals in particular, the post-transition metals used for synthesizing a class of alloys known as eutectic alloys, which melt temperatures T_m are lower than their components. Eutectic alloys, along with eutectic composites, eutectic salts and deep eutectic solvents constitute eutectic material systems which have many advanced applications. Gallium forms unique eutectic alloys with low toxicity, rheological properties, electrical and thermal conductivity, rendering them ideal for biomedical applications. Medical Applications includes eliminating cancer cells and repairing damaged nerves, thus representing a new class of promising materials for technological and biological applications. In this review paper we appraise eutectic materials and emphasize their applications with a focus on medical and biological applications.

Keywords: Liquid metals; Eutectic alloys; Ga-based alloys; Medical applications.

1. Introduction

Seeking effective innovations, learning the advanced chemical properties and behaviour of materials, contributed to the development of new materials with desirable properties for use in diverse applications from advanced electronics to medicine. Among the 118 elements, metals constitute the most dominant elements (77%) and have distinctive chemical, physical and mechanical properties that make metals the backbone of many industries [1]. Liquid metals (LMs) refer to a group of metals with low melting points below 300 °C [2] that combine metals and fluids [3]. Low melting points combined with properties such as high surface tension [4], low viscosity and low vapour pressure [5], plasticity and self-healing open the door to a wide range of applications [6]. Mercury (Hg) is the most recognised example of a liquid metal; it is the only metal that is liquid at room temperature due to its extremely low melting point (-38.8 °C), unlike the rest of the transition metal group [7]. In addition to mercury, liquid metals include a number of metals, such as Gallium (Ga), Indium (In), Cadmium (Cd), Lithium (Li), Tin (Sn), Francium (Fr), and Lead (Pb), divided into three classes of metals (Table 1) that share with mercury the criterion for defining them as liquid metals, namely low melting points [8-9].

The phase transition in liquid metals is easier to accomplish than in metals with high melting points such as Iron (1538 °C), Copper (1084 °C), Nickel (1455 °C) and Chromium (1907 °C). This transition leads to designing and controlling the properties of liquid metal-based materials [10]. Additionally, eutectic refers to a low melting point class of alloys (Table 2), even lower melting points than the melting points of their individual components [11]. Melting point assessment of liquid metals, combined with multi-element matrix evaluation, determines the practical use of a liquid metal. While the five liquid metals with melting points below 40 °C were determined to be mercury, Gallium, Rubidium, Cesium, and Francium Rubidium tendency to explode when exposed to air prevents its practical use in medical applications [9].

While Cesium oxidation is accompanied with explosive reactions when in contact with water [12], francium is considered a rare radioactive element [13]. Another liquid metal, Mercury has been used in some applications, such as thermometers and electrodes in electrochemistry; its high toxicity limits its use in further applications [14-15]. Gallium stands out as a suitable example of use; although it did not receive enough attention for a long time, Gallium and its based materials soon showed advantages that allowed their widespread use. The low toxicity and vapour pressure are factors that allow its use in various applications in a safer way [16-17]. Integrating liquid metals with other materials such as nanomaterials or polymers improves their properties. In this review, we will explain the properties of liquid metals and their applications to shed light on Gallium and its derivative materials.

Table 1: Melting point (°C), type of metal and electrical resistivity at melting point (ρ_{MP}) of liquid metals [8]

Element	Symbol	Atomic Number	Melting Point	ρ_{MP} [Ω.cm]
Alkali metal				
Lithium	Li	3	180.5	2.5×10^{-5}
Sodium	Na	11	97.8	9.6×10^{-6}
Rubidium	Rb	37	39.3	2.2×10^{-5}
Cesium	Cs	55	28.4	3.6×10^{-5}
Transition metal				
Cadmium	Cd	48	321.1	3.37×10^{-5}
Mercury	Hg	80	-38.8	9.5×10^{-5}
Post-transition metal				
Gallium	Ga	31	29.8	2.58×10^{-5}
Indium	In	49	156.6	3.31×10^{-5}
Tin	Sn	50	231.9	4.8×10^{-5}
Thallium	TI	81	304.0	7.31×10^{-5}
Lead	Pb	82	327.5	9.5×10^{-5}
Bismuth	Bi	83	271.4	1.28×10^{-4}

2. Eutectic material systems

Eutectic material falls into four categories including eutectic metals (alloys), eutectic composites, eutectic salts and deep eutectic solvents (DESs) [11, 17].

2.1. Eutectic metals (Alloys)

Until recently, bronze was considered a eutectic alloy system composed of copper and tin in a 3:1 weight ratio. However, this understanding has been revised based on modern interpretations of eutectic behavior. Bronze serves as a classic example of how the solid–liquid phase transition temperature in an alloy system can be significantly reduced—from the melting point of pure copper (1085 °C) to approximately 800 °C. Additionally, the Cu–Sn alloy is known for its excellent chemical stability and corrosion resistance [18-20].

2.2. Eutectic Composite

The composite effect strategy involves combining liquid metal with other materials to achieve maximum performance minimize defects thereby avoiding the expected shortcomings of liquid metals. The application of this strategy resulted in the emergence of a new class of materials, namely LM-Composite. This composite includes two or more materials in which liquid metals constitute a basic component in their chemical composition. LM-Composite is categorized three sub-sections, namely LM-core/shell composite, LM-polymer composite, and LM-particle composite, all of which fall within the micro/nano size range [17].

2.2.1 LM-core/shell composite

The LM-composite is a core/shell nanostructure that is created by different forms of boundary force such as chemical bonds allowing integration of properties of the incorporated materials [21]. Gallium-based materials exposure to air causes the formation of the oxide layer that modify the rheological properties of the material, which in turn affects its potential application. Modifying these materials improves stability of the composite. For instance, stability was crucial for preparing the two-dimensional semiconductors [22] and for production of micro-wires by injecting LM-materials into microfluidic channels [3]. Material studies have revealed that while, the surface oxide layer reduces the flow of the liquid metal-based material, modifying the composition of the shell affects the flow rate. For instance, coating the core with a layer of Nickel (Ni) controlled the flow by applying an external magnetic field. This was attributed to the Marangoni effect whereby coating Nickle created surface tension, which contributed to the development of non-adhesive materials used for microfluidic channels [23-24]. LM-core/shell composites were used for medical applications class, whereby drugs loaded onto the surface of the shell and released to treat target tissues or cells [25-28]. In pharmaceutical applications, LM-core/shell composite was loaded with doxorubicin to target breast and bladder tumors [29]. A notable application includes the use of LM–core/shell composites loaded with doxorubicin for the targeted treatment of breast and bladder tumors [29]. One of the most effective shell materials that forms a stable bilayer ideal for encapsulation is is 1,2-distearoyl-sn-glycero-3-phosphocholine (DSPC), a phospholipid characterized by a hydrophilic head group (~1.5 nm) and hydrophobic alkyl chains (~2.0 nm) [30]. The LM-core/shell composite was synthesized by exposing a solution of liquid metal and DSPC to sonication, when LM-core/shell composite particles are exposed to physical stimuli as light or temperature a deformity occurred, releasing the drug with 50% efficiency resulting in cancer cells apoptosis [17].

2.2.2. LM-polymers composite

LM-polymer composite is a new material form that consists of a polymer matrix supported by liquid metals. These composite effect strategies combine the flexibility of polymer with the advanced properties of the liquid metal, such as low cytotoxicity, high electrical and thermal conductivity, in addition to low temperature of phase transitions. Polymers are generally used in electronic applications by integrating electrically conductive materials, however this type of metal-polymer integration could be compromised by the negative effect on mechanical performance. By incorporating LM as an alternative to conventional metals, it is possible to improve the mechanical performance of LM-polymer composites and their deformations tolerance [31-34]. Biocompatibility of this integration, represented by low cytotoxicity, flexibility, self-healing and high electrical conductivity, encourages its applications in biology and biomedicine. LM-polymer composite biocompatibility combined with self-healing and electrical conductivity, render them useful as an artificial neural connector [35-36]**.** A predominantly notable example is the development of self-healing circuits based on LM–polymer composites, capable of restoring functionality in under 1 millisecond after damage [37]. Furthermore, LM alloys such as EGaInSn have been successfully applied in repairing sciatic nerve injuries in animal models, including bullfrogs and mice [38], further validating the biomedical potential of these materials.

Table 2: Alloys based on liquid metals, the elements that make up their composition, and the values of their melting points

Alloy	Number of elements (n)	Melting point (°C)	ρ[Ω.cm]
GaIn	2	15.5	2.94×10^{-5}
GaInSn (Galinstan)	3	13.2	2.89×10^{-5}
GaInSnZn	4	7.6	3.57×10^{-5}

2.2.3 LM-particle composite

The LM-particle composite class is created by incorporating nanoparticles of Copper, Silver, Gold or Carbon nanotubes in tiny amounts within the liquid metal. These particles are homogeneously distributed within the liquid metal matrix controlling structure and thermal conductivity [39-40]. LM-Fe particle composite treated with acid removed the oxide layer resulting in development of materials that are strongly affected by magnetic fields [41]. Likewise, LM-Ni particle showed similar magnetic properties to LM-Fe [42]. Many LM-Mg particle composite class has been modulated for biomedical applications to treat skin cancer by photothermal stimulation [29]. The Mg_2Ga_5 is created with surface properties that enhance the photothermal effect with low cytotoxicity. This LM-particle composite can also be maximized through synergism with other types of treatment [17].

2.3. Eutectic salts

Under the specific criterion of the eutectic concept, the term eutectic salt refers to a group of inorganic compounds with melting points lower than the melting points of their components. The application trends of eutectic salts revolve around energy storage and conversion [43-44], starting in the mid-twentieth century with the use of Glauber's salt ($Na_2SO_4.10H_2O$) to store and convert solar energy into other forms [45]. In LiF-LiCl-LiBr based systems, according to the rules of thermodynamics, the salts play their role in the electrolytes in the batteries [46-48].

2.3. Deep eutectic solvents (DESs)

Deep eutectic solvents (DESs) are new class of eutectic material systems that, in addition to their low melting point, are thermally stable, less volatile, low in toxicity, and biodegradable class of materials. Furthermore, they are also tunable for a wide range of applications, and their low manufacturing costs make them an economically preferable class [49-51]. Researchers have modulated DESs for advanced biotechnology and biomedicine applications [52-55]. DESs were mixed with complexes of renewable biological origin, such as amino acids, alcohols, and organic acids, resulting in natural deep eutectic solvents (NADESs) with the ability to be biosynthesised and biodegraded [56-62]. These products were promoted as an alternative to organic solvents that can be used for purification of active biochemical materials [63]. It has been used for polysaccharides, proteins, polyphenols, phenolic acids and flavonoids extraction and purification [64-67]. In biomedical applications, deep therapeutic eutectic solvents (THEDES), have shown antibacterial, fungal and viral pathogen effects [68]. Due to the similarity in properties between the materials of eutectic systems, this review will focus on discussing eutectic alloys based on liquid metals and their applications and uses in biomedicine in some detail in the following sections.

3. Basic Features of Eutectic Alloys

In metals-based applications, researchers pay significant attention to mechanical performance indicators such as stress and strain [69], as well as the metal tolerance to withstand elevated temperature [70]. because the classical idea of Despite this common belief about metals, some of them deviate from these properties, particularly those with low melting temperature (Tm). This led to identification of a distinctive metal category known as liquid metals, with unconventional yet valuable physicochemical characteristics [71].

3.1. Melting point

All LMs members share the low melting point physical common feature for. This significant reduction in the melting point arises from the exclusive physicochemical behavior of the atoms of these metals. For instance elements in the zinc group; Zn [Ar] $3d^{10}$ $4s^2$, Cd [Kr] $4d^{10}$ $5s^2$ and Hg [Xe] $4f^{14}$ $5d^{10}$ $6s^2$ represented weak metallic bonds. This low melting points are largely attributed to sharing only two electrons of the s subshell in bonding, resulting in a weak cohesion and low phase transition temperature [72]. Conversely, the alkali liquid metals like Li, Na, K, Rb, and Cs have simple electronic configuration and expanded atomic leading weak metallic bond and low phase transition temperatures [10]. Gallium, a representative of post-transition metal with electron configuration Ga [Ar] $3d^{10}$ $4s^2$ $4p^1$, is characterized by a completely filled d subshell, and unpaired p subshell. This electron configuration supports the formation of metallic and covalent bonds, resulting in low melting point of 29.8 °C [12]. Among gallium's various allotropes, αGa is the most stable [73] (Table 3). with a crystalline structure and strong covalent bonds Ga-Ga. These bonds are responsible for the high boiling temperature (2478 °C), despite the low melting point, giving it an exceptionally wide liquid temperature range [73-74]. Furthermore, post-transition metals such as gallium can form alloys with low melting points. Likewise, Eutectic binary alloys such as $Ga_{78.6}In_{21.4}$ (EGaIn), made of gallium and indium, show extraordinary thermal behavior as it melts at 15.4 °C, which is far below the melting points of its individual components (29.8 °C and 156.6 °C, respectively) [17]. Furthermore, eutectic ternary alloys like $Ga_{68.5}In_{21.5}Sn_{10}$ (Galinstan), which contains Gallium and Indium, with Tin added to them, the melting points drops further 13.2 °C compared to the melting points of its components [75].

The thermal properties of eutectic materials are not limited to the melting point as a physical feature, but thermodynamic features under a constant temperature and pressure (eq. 1) play a role in shaping and explaining the melting point and the behavior of the material in this regard.

$$\Delta G = \Delta H - T\Delta S \quad (1)$$

Entropy according to the rules of thermodynamics is a measure of the disorder in the system when mixing the components of the eutectic alloy at the phase transition of the two states that exist together in a state of equilibrium (solid ⇌ liquid), consequently $\Delta G = 0$

$$T_m = \frac{\Delta H_{fus}}{\Delta S_{fus}} \quad (2)$$

During the melting process and the associated phase transition, the melting temperature (T_m) decreases as a result of increased entropy ($\Delta S > 0$), as shown in Equation 2. Although simplified, this explanation offers a foundational understanding of the melting point depression observed in eutectic material systems [11].

3.2. Rheological Characteristics

Rheological properties describe the response of a material to forces such as stress and pressure particularly in terms of flow and deformation. From a rheological perspective, very low melting temperature metals such as mercury and gallium/gallium-based alloys behave as liquids under standard temperature and pressure and conditions. These metals high fluidity is due to their notably low viscosity, namely for 1.55×10^{-3} Pa·s for mercury, 2.04×10^{-3} Pa·s for gallium, 1.69×10^{-3} Pa·s for indium, and 1.99×10^{-3} Pa·s for the eutectic alloy EGaIn [72, 76–77]. EGaIn exhibits elasticity when subjected to critical surface pressure or stress a property shared with Mercury. Alongside low viscosity, the elasticity characteristic enhances the metallic liquid flows **[3].** The capability of liquid metal to flow under pressure or surface stress enables their injection into microfluidic channels. These microfluidic channels, primarily designed for the study of microfluidics, [9] are made of polymer as polydimethylsitoxane (PDMS), include inlet and outlet channels 400 μm in diameter connected by a 20 μm micro-channel. This configuration allows the construction of fine structures essential for electronic device fabrication [3]. To assess the effect of pressure induced flow, different pressures were applied to both EGaIn and Mercury. Applying a pressure of less than 85 kPa to EGaIn filled only the wider parts of the microfluidic channel in less than one second yet failed to penetrate the narrowest segment [78]. Similarly, Mercury demonstrated the same behavior but at a lower threshold pressure of 54 kPa. Upon increasing the applied pressure to 57 kPa for Mercury and 89 kPa for EGaIn, both metals crossed the narrow part of the channeland fully fill the microfluidic structure [79]. Thus, both Mercury and EGaIn show similar behavior at different pressures, which can be attributed, to some extent, to the effect of viscosity. Despite the similar viscosities EGaIn and Mercury can be assumed that viscosity plays a major role in explaining this behavior. Injected mercury adopts unstable structures manifested by spontaneous withdrawal from microfluidic channels once the driving forces or pressure reduced or removed. In contrast, Ga/Ga-based alloys form stable structures post injection [80]. This stability is largely due to Gallium tendency to stick to the thin surface oxide layer (Ga_2O_3), with a thickness of no more than 3 nm, which hinders flow and prevent spontaneous withdrawal [81-84]. EGaIn residues adhering to channel surfaces can be removed from the inner surfaces of the channels by acids or fluid sliding layers [85]. Although the phenomenon of EGaIn adhesion to its native oxide laye constitutes an obstacle when applying injection into microfluidic channels, it proves beneficial when applying EGaIn droplets to the surfaces of PDMS substrate during electronic components manufacturing [80]. Consequently, Gallium and its alloys are superior to Mercury in rheological properties, supporting the construction of stable liquid metal structures with conductive and mechanical properties suitable for many applications. The combination of electrical conductivity and low viscosity properties of liquid metals in Gallium and Gallium-based liquid metals enabled the development of flexible electronic components through printing liquid metals on flexible substrates [86-90]. Nevertheless, the advancement of printing techniques used to manufacture electronic device components, the high surface tension as one of the factors affecting the rheological properties [91]. High surface tension of alloys like EGaIn and Galinstan may negatively affects the printing methods causing them to form spherical shapes instead of flowing and covering the surface of the substrate. Although PDMS [92] are suitable and suitable for Ga-eutectic alloys, the limited availability of these substrates represented an obstacle for researchers [93]. To avoid this problem and its effect on printing liquid metals the surface tension of EGaIn droplets was modified **[91]** by mixing EGaIn with nanoparticles of Iron **[94]**, Copper **[39,95]**, Silver **[96]**, Gadolinium **[97]**, in addition to micro and nanoparticles of Nickel **[98-99].** Mixing EGaIn with these metal nanoparticles formed a kind of paste that decreased the surface tension and expanded the range of substrates used in printing **[93].**

3.2. Self-healing Properties

Self-healing materials are a group of smart materials that can fully or partially restore their lost or impaired functions. This concept was inspired by the natural healing mechanism of living organisms [100]. In biological systems both plants and animals possess their own self-healing strategies. Living organisms repair damage to their structural parts such as trunks and bones with high elastic modulus under normal temperature conditions (20-40 °C). Comparing the self-healing of metals with their counterparts in biological systems Gallium and its based materials are particularly promising. Thus, the possibility of expanding the scope of its applications in biology and biomedicine are supported by attributes such as biocompatibility such as low toxicity, flexibility, stretchability, stress tolerance, and signal transmission [101-104]. Self-healing materials include a broad spectrum of materials including polymers [105-106], ceramics and metals specifically liquid metals [107, 108]. Among these, flexible organometallic polymers composed of N-heterocyclic carbenes and transition metals, after casting them on silicon wafers substrates, producing electrical conductors with conductivity in the range of 10-3 S/cm. While these classes of polymers demonstrate self-healing peoperities, they require relatively high temperatures (200 °C) to activate the healing process, unlike liquid metals that heal at room temperature [36]. Flexible Electronic materials meet the conductivity and mechanical properties requirements for developing a wide range of applications such as biomedicine, antennas, conductors, semiconductors, as well as environmental studies [109-111]. This exceptional stability, stretching, imposes the high requirements of self-healing materials. This efficiency is limited by their need for high temperature recovery, as previously indicated, which makes liquid metals the most effective choice due to their rheological and electrical properties [100, 112-113]. Flexible self-healing metal-based wires have recently emerged as an essential in the electronics industry. These wires are manufactured by injecting liquid metal such as Gallium and its alloys into microfluidic channels [114]. Flexible liquid metal wires self-repair arises from the rheological properties such as low viscosity and high surface tension. While Low viscosity facilitates the flow of the metal, high surface tension encourages the surfaces of damaged parts to expand and fill cracks and fractures. These exclusive rheological properties enhance the dynamics of molecules within the metal matrix at the damaged parts, which increases the efficiency of self-healing [1]. Gallium-based materials introduced a promising approach for self-healing electronic components capable of repairing conductive paths such as EGaIn [115-116]. For instance, an integrated circuit of LED constructed of EGaInSn metal was healed spontaneously when the conductive paths were cut [117]. Recently, scientists developed a conductive sponge-like macro-porous composite hydrogel made of liquid metals (LM-MCH) with excellent sensing properties. These materials, as acrylic acid has displayed a beneficial sensing throughout converting physical effects such as mechanical deformation and temperature changes into electrical signals.

The biocompatibility of LM-MCH has played a role in promising opportunities to produce artificial limbs and wearable prosthetic electronics that mimic and exceed the capabilities of biological sensors such as natural skin. The self-healing properties of LM-MCH and low toxicity of these metal boost its using in biomedicine and other applications in other biological fields [118-122]. The conventional deliberate cutting test ensued the self-healing ability of the liquid metal gel material poly(acrylic acid)–LM/reduced graphene oxide (PAA-LM/rGO) need about 24 hours to achieve self-healing. Self-healing depends on time, as the ability to heal improves with increasing time. Using PAA-LM20/RGO-25, the mechanical and electrical self-healing efficiency was 87% and 92% respectively, but it remains lower than the efficiency of electrically stimulated self-healing 100%. The molecular dynamics at the damage areas initiates the ionic bonds between the COO^- group in PAA and the Gallium ion Ga^{3+}, which drives the Gallium-based gel material to heal by restoring the damage areas at the molecular level [123].

3.3. Electrical Conductivity

The electrical resistivity of metals (Fig 1) occupied the attention of researchers to formulate models that explain the behavior of metals as good electrical conductors [124-126]. According to the theory of electrical conductivity of metals, the resistivity of a metal is a function of temperature $\rho(T)$ it increases with increasing temperature; Bloch-Grüneisen formula (eq. 3), gives accurate solutions for the effect of temperature on resistivity,

$$\rho(T) = A\left(\frac{T}{\Theta}\right)^n \int_0^{\Theta/T} \frac{x^n}{(e^x - 1)(1 - e^{-x})} dx \qquad (3)$$

A is a characteristic constant of the metal that depends on its resistivity, x is a dimensionless variable $x = \frac{\hbar\omega}{k_B T}$ that represents the frequency of phonons around the equilibrium positions in the crystal lattice, Θ is a characteristic temperature approximately equal to the Debye temperature $\Theta \cong \Theta_D$ [127-129]. Theoretically, according to the dependence of electrical resistivity on temperature, $\rho(T)$ collapses and disappears at absolute zero (-273.15 °C), but since it is practically impossible to reach absolute zero, the resistivity does not disappear completely, but rather reaches its lowest levels at the limits of absolute zero, so the metal changes from normal conductivity to superconductivity at a temperature that distinguishes each metal, and upon reaching transformation in behavior [130].

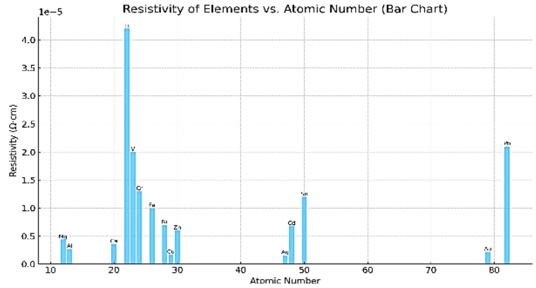

Figure 1. Resistivity vs Atomic Number of metallic elements

The dependence of electrical resistivity on temperature is not the only factor. Impurities in the metal matrix play a role in electrical resistivity, even assuming of reaching absolute zero, a non-zero electrical resistivity (residual resistivity ρ_R) appears (eq. 4), although it is negligible because it is infinitesimal [131].

$$\rho = \rho_T + \rho_R \quad (4)$$

Liquid metals do not deviate from the general behaviour of metals in their electrical conductivity; likewise, gallium showed a linear relationship between it and temperature (Fig. 2), which is consistent with the general behaviour of metal sections [132].

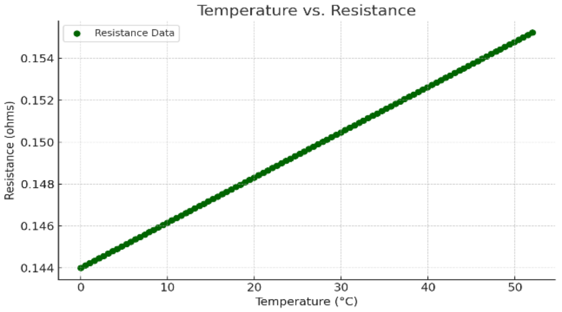

Figure 2. the linear relationship between R (Ω) and temperature (°C) of Gallium [132].

The resistivity of elemental Gallium (1.49×10^{-5} Ω.cm) and Gallium-based materials (Table 3) such as EGaInSn (2.98×10^{-5} Ω.cm) is higher than that of Copper (1.54×10^{-6} Ω.cm). The electrical conductivity of Gallium also varies according to the phase, as it is higher in the liquid phase than its conductivity in the solid phase. Overall, Gallium and its based materials exhibit metallic conductivity at normal temperatures close to room temperature [1]. A novel kind of reversible flexible antenna was developed to support the rapidly expanding wireless communications and remote sensing industries [133].

Table 3: Crystallography of αGa

α**Ga**		
Symmetry	Lattice parameter	Cell density
Orthorhombic	a = 4.519 b = 7.660 c = 4.525	0.43

Although copper has a lower resistance than gallium, gallium and materials based on it are more flexible, making them the ideal material for creating flexible conductors. For example, standard antennas are made of copper and are operationally useful, but the breakdown of copper is irreversible, unlike gallium and its based materials, which are distinguish by their great flexibility and the ability to be readily reshaped at normal temperatures.[134]. Materials classified as superconductors have nearly zero specific resistance, no considerable losses, and no quantum effects when they cross the Tc, which is the crucial point that separates a metal's normal behaviors from superconductor behavior. Researchers in material chemistry and engineering have been drawn to these characteristics to create micro/nano devices like micro-magnetic resonance and remote sensing devices. However, one of the biggest issues with traditional superconductors like copper is their fragility, which naturally makes it difficult to produce flexible electronic components for potentially innovative applications. [135-137]. Gallium and Mercury are exceptional metals with a superconductors T_C these metals expectations arose for wide range of use in the field of flexible electronics, but the ceiling of expectations decreased for a number of reasons. First, the toxicity of mercury and the high cost of manufacturing combined to limit progress; however, this did not stop some breakthroughs through nanoprinting techniques and the resultant production of flexible nanoelectronics components. Secondly, the TC of gallium (-272.06 °C) is lower than the liquefaction point of helium (-268.95 °C) and is the lowest temperature for practical application in the field of manufacturing nanoelectronics in general. These drawbacks did not prevent breakthroughs through nonprinting and the production of flexible nanoelectronics components [138]. Lead ρ_{Pb} specific resistivity dramatically increases at T_C = -265.96 °C and decrease significantly to less than 10^{-23} Ω.cm at T_C = -268.95 °C, which corresponds to the gas-liquid phase transformation temperature of Helium [130]. Expanding the range of applications using liquid metals as superconductors is closely related to the phase transition temperature of Helium. Limited contributions have been made by adjusting the T_C of the EGaInSn (Galinstan) alloy by changing the proportions of its components to prepare nanoscale particles. Furthermore, T_C of these alloys was raised to suit the desired goal of expanding the range of applications for superconductors based on the rheological properties of liquid metals such as low viscosity and self-healing. One of these contributions was the preparation of inks from nanoscale liquid metals to print electronic components on suitable substrates [138].

4. Applications of Eutectic Alloys

Liquid materials stand out as multifunctional materials, attracting the attention of the scientific community for sensors fabrication (Table 4), soft electronics (Table 5), wearable devices, superconductors, catalysis (Table 6), energy storage, environmental monitoring and support of sustainable chemical processes as key areas driving technological innovation [139-150].

Table 4: LM-based sensors and their applications

Application Area	Key Materials	Mechanism/Properties	Uses
Pressure and Motion Sensing	LM/polymer composites, LM-based rubber foam, Galinstan adhesives, LM gel nanocomposites	Positive piezoreductivity (increased conductivity upon strain), capacitance change under deformation	Wearable strain sensors (e.g., gloves), pressure/touch sensors, pressure-sensitive adhesives
Electromagnetic Sensing	EGaIn with iron/nickel microparticles in PDMS, LM-based magnetic elastomers	Magnetic susceptibility, magneto-thermal response, alignment of magnetic particles with fields	Magnetic field sensors, stretchable magnetic conductors
LM-Based Antennas	LM injected into elastomers, LM nanodroplets in microchannels	Reversible deformability, self-healing, frequency tunability, remote strain sensing	Stretchable, tunable, and self-healing antennas
Gas and Vapor Sensing	Ga_2O_3 thin films, Galinstan droplets, GaIn/GaSn/GaZn nanodroplets, EGaIn/WO_3 nanocomposites	Chemisorption (high-temp), physical adsorption (low-temp), heterostructure formation, nano-alloy conversion	NO_2, NH_3, CH_4, H_2 sensors; selective chemical sensors with Ga-based nanomaterials

Table 5: Applications of soft, flexible and self-healable LM electronics [140-141, 143-144]

Application Area	Key Materials	Mechanism/Properties	Uses
Catalysis (General)	Liquid Metals (LMs), Liquid Ga	Dynamic interfaces, resistance to coking and morphological changes	Broad catalytic applications
Photocatalysis	LMs (bulk/nano) + Nano oxide particles	Co-contribution for enhanced photocatalytic activity	Degradation of organic dyes
Sonochemical Catalysis	LM micro/nanodroplets	In situ synthesis, sonochemical activity	Degradation of organic dyes
CO_2 Electro-reduction	Liquid Ga, Galinstan, Ce nanoparticles	Low van der Waals forces at liquid interface, coking resistance	Electro-reduction of CO_2 to solid carbon products
CO_2 Reduction (Mechanically Induced)	Ga nanodroplets + Ag/Ga intermetallic nanorods	Mechanical induction at room temperature	Reduction of CO_2 to solid carbonaceous products and O_2
Methanol & Ethanol Oxidation	GaPt nanoparticles	Galvanic replacement synthesis	Oxidation of methanol and ethanol
Propane Dehydrogenation	GaPt catalytic system on alumina matrix	Galvanic replacement of Pt salts on Ga	Dehydrogenation of propane at 350–450°C
Organic Compound Dehydrogenation	Pd with Ga support	High-temperature dehydrogenation	Dehydrogenation of organic compounds
Photocatalysis & CO_2 Reduction	Eutectic BiSn nanoalloys	Controllable polycrystallinity, grain size, surface oxide decoration	Degradation of organic dyes, CO_2 reduction reaction
Photocatalysis (Nanoflakes)	Hexagonal α-Ga_2O_3 nanoflakes	Sonication of liquid Ga followed by annealing	Photocatalytic degradation of pollutants
Photocatalysis (Nanocomposites)	EGaIn/MnO_2 nanocomposites	High photocatalytic activity due to composite synergy	Degradation of organic dyes

Table 6: Applications of LMs in the catalyst industry

Application Area	Key Materials	Properties	Uses
Soft Junctions & Contacts	LM marbles with semiconducting particles, LM nanotips	Soft contacts, flexible electronic interfaces	LM–semiconductor junctions, surface electrical characterization
Stretchable Conductive Wires	LM/CNTs nanocomposites, LM nanodroplet inks	Enhanced electrical conductivity, stretchability	3D printed wires, flexible circuits
Flexible Electronics	EGaIn, Galinstan nanodroplets, LM-polymer nanocomposites	High stretchability (up to 1200% strain), deformability	Wearable devices, soft robotics
Self-Healing Circuits	Encapsulated EGaIn microdroplets, functionalized LM nanodroplets	Self-healing after mechanical damage	Restoring conductivity in gold circuits, elastomers with self-repair capabilities
Energy Harvesting	LM/PDMS triboelectric nanogenerators, thermoelectric composites	Conversion of mechanical energy to electrical energy	Body motion energy harvesting, stretchable thermoelectric devices
Reversible Conductors	EGaIn droplets in polymer matrix	Insulating above melting point, conducting upon freezing (percolation path formation)	Temperature-responsive circuits
Printable Electronics	LM nanodroplet inks with polymers (e.g., tannic acid, polysaccharides)	Inkjet printing, spray coating for conductive paths	Flexible sensors, soft electronic patterns
Antennas for Wireless Comms	EGaIn slurries in microchannels	Tunable frequency through selective merging of LM nanodroplets	Wireless communication antennas
Nanostructured Conductive Traces	Biphasic LM/solid nanocomposites, LM/photoresist nanodispersions	Enhanced stability, mechanical activation for conductivity	Maskless UV photolithography, direct laser writing
Recyclable Electronics	LM-based soft circuits with dissolvable polymer matrices	Mechanical agitation for LM recovery	Recyclable soft electronic components
Microscale Patterning	Sub-micron EGaIn patterns, mechanically activated LM inks	High-resolution pattern formation using lithography and mechanical processes	Microelectronics, nano-patterned conductive paths
Stress-Resistant Devices	LM additives in polymers	Redirection of stress away from cracks, preventing tear propagation	Crack-resistant flexible electronics
Soft Sensors	LM/polymer composites with conductive traces	Damage detection via changes in conductivity during mechanical strain	Mechanical damage sensors
Liquid Microwires	Aligned EGaIn nanodroplets in silicone matrix	Dielectrophoresis for alignment and sintering before curing	Stretchable electronics with reduced LM loading

5. Biomedical Applications of Eutectic Alloys

Eutectic alloys' suitability for application in biological and medical systems is referred to as their biocompatibility. It is a wide notion that encompasses several features that serve as benchmarks for assessing a material's appropriateness for its intended use. In addition to electrical conductivity, these requirements cover toxicity, melting point, high flexibility, and stress endurance [1, 7]. Among their numerous medicinal applications, liquid metals offer raw materials for treating tumours [149] and having antimicrobial properties [151, 152].

5.1. Safe doses and Toxicity Studies

Gallium meets biosafety requirements as it has low cytotoxicity, many studies have been conducted to evaluate the toxicity of Gallium and its alloys, which has increased confidence in its use in biological systems [150]. In order to verify the toxicity of Ga and In, the viability of cells was tested using EGaIn alloy on two groups of cell cultures, in which the cells showed very positive indicators, as the cells remained 100% viable even after 48 hours of application [153, 154]. Although Gallium has generally low cytotoxicity, Ga complexes have had negative effects on cells, raising concerns that they may pose a threat to human health [155]. The high toxicity level of EGaIn alloy was associated with the release of Ga^{3+} and In^{3+} into human cells [156]. Factors that stimulate the release of Ga^{3+} ions included the metabolic wastes of cells that decrease the pH to the point that allows the release of more ions

[157-158]. In biological systems, physical stimuli also contribute to EGaIn toxicity. Ga^{3+} and In^{3+} concentrations are comparable when mechanical stimulation is triggered by ultrasonic waves, therefore the elevated degree of toxicity is not only caused by the rise in Ga concentration; rather, the similarity between In and Ga concentrations is a key factor in this respect [159-161]. Other studies supported the principle of linking increased toxicity with increased concentration by injecting a group of mice with Gallium nanorods at relatively high concentrations, which led to the death of 75% of the individuals in the tested group after 20 days of injection [162-164]. Toxicity studies revealed that dose of Gallium for biological purposes should not exceed 700 mg/kg [25].

5.2. Antimicrobial and Anticancer Liquid Metals

When liquid metals undergo oxidation under acidic and basic chemical stimulation, they release Ga3+ ions, which have an antibacterial impact by altering cell membranes [155, 165-167]. Pathogenic microorganisms that have demonstrated antibiotic resistance are eliminated by gallium compounds. [168-169]. Furthermore, magnetic stimulation transforms Galinstan nanodroplets into sharp-edged nanoparticles and when liquid metal nanodroplets are exposed to a magnetic field, they behave lethally to pathogenic bacteria [170]. Radiation and chemical methods have undesirable side effects. Despite their therapeutic ability, they harm healthy tissues or weaken the patient's immune system [1, 10]. considering their unique characteristics, liquid metals have played a significant role in the development of novel treatment approaches, such as flexible patches and amorphous electrodes. $Ga(NO_3)_3$ might be utilized as an approved cancer treatment regime [7]. Liquid metals fine particles destroy cancer cells when cooled to freezing point by forming ice around and inside cells. Reducing the size of liquid metals particles and injecting them directly into the tumor, the particles enter the cell vesicles, causing morphological changes, accompanied by a change in phase from liquid to solid and killing cancer cells. However, the treatment was not 100% effective, as residues of tumors remain after treatment [171-174]. Alternatively, induction by sound and electromagnetic waves (optical - thermal) Gallium oxidation to the nanorods form and cancer cells killing [175].

5.3. Drug Delivery using Liquid Metals

Inorganic nanoparticles have shown the ability to deliver drugs [175-176]. Despite this important role played by these particles, there are factors that limit the use of many of them, such as toxicity and lack of biodegradability [25]. The factors that reduce the possibility of using nanoparticles in transporting drugs can be avoided by using Gallium and its alloys to achieve the conditions of use, as they are low-toxic and biodegradable in low-pH cellular environments [1]. Under the effects of chemical and physical stimuli, either alone or by combining them, a decrease in pH or physical stimulation by thermal radiation, electromagnetic waves, sound waves or ultrasound increases the efficiency of drug delivery performance [25, 28, 177-178]. Changes in physical stimuli have an effect on the delivery of the drug to the target areas inside the body. In studying the effect of changing the temperature, it was proven that increasing the temperature in the vicinity of the droplets EGaIn nanoparticles exposed to NIR affect the performance efficiency [7]. EGaIn nanodroplets coated with a thiolated polymer capable of carrying drug molecules [25]. The drug molecules are attached to the surfaces of EGaIn through two thiolated ligands, namely 2-hydroxy propyl-b-cyclodextrine (MUA-CD) and thiolated hyaluronic acid (m-HA), stimulated by sound waves at room temperature. These compounds play a dual role: the first is to protect the EGaIn nanoparticles and the second is to bind and carry the drug molecules on CD and HA, forming a three-part complex EGaIn core-CD-HA, abbreviated as LM-NP/L, which, upon reaching the target part inside the body, is biologically dissolved in the acidic medium of the cellular system, releasing the drug molecules [25, 179].

5.4. Damaged Nerves Repair by Liquid Metals

Nerve damages may happen due exposure to an accident or neurological disorders such as peripheral nerve disorders that many patients suffer [180-183]. Modern surgeries techniques are set to repair nerve damage [181, 184]. Nerve damage such as cuts, for example, can be repaired surgically by reconnecting the nerve endings in the case of small gaps, while in the case of large gaps treatment requires transferring nerves from the donor to the patient using grafting [185-186]. Liquid metals has been promoted in this field due to their electrical and mechanical properties, which increase their suitability for application by employing them as flexible, low-toxic conductors for nerve signals across the nerve network [187]. EGaIn alloy, remarked for its electrical conductivity, has shown good biocompatibility when used in the form of electrodes nerve damage repair [188]. Liquid metal microelectrodes were used as a prosthetic nerve connection to replace damaged nerves with successful long-term biocompatibility for hippocampal nerves [7]. EGaInSn (Galinstan) electrodes was used as a prosthetic nerve for the sciatic nerve of the bullfrog indicated that nerve signals in the LM-nerve system flow normally through this system [38, 187]. Experimental studies showed successful nerve signal flow upon replacement of a severed part of the sciatic nerve by injecting Ga into silicone tubes with the ends of the tube fixed to the terminals of healthy nerves, [189].

5.4. Bones and Wound Repair using Liquid Metals

Metals often used in orthopaedics, such as titanium, have a high melting point [190]. In contrast, liquid metals with low melting temperatures and phase transitions (solid liquid) at normal temperature provide enough flexibility in orthopaedics. This has aided in constructing artificial joints from EBiInSn, since their phase transitions provide desirable features like durability and flexibility of movement. [191]. Removal of a tumor from the bones or other medical causes leads to skeletal disorders accompanied by acute or chronic pain with negative effects on the patient's general health. Amputation was replaced by bone cement that gained interest with some limitations, bone cement based on low-toxic liquid metals has also been promoted [192]. One of the materials recommended for usage was BiInSnZn alloy bone cement, which may be used to cure bone deformities via local injection [193]. In contrast to typical bandages, bandages made from liquid metals give external structural support by demonstrating a high capacity to endure minor stresses associated with movement. Also, altering the hardness of liquid metal bandages involves modifying their components and adapting to the nature of the desired performance [194]. Double-layer bandages were also created, with the interior soaked with soft Al-NaOH-EGaIn to prevent injury to the contact region, and the exterior containing BiInSn by exposing the inner portion to deionised water. (DI) A specific amount of heat is produced, causing the BiInSn to transition from solid to liquid, achieving a degree of flexibility ideal for the curves of the wounded person's body; when the BiInSn solidifies, it gives the proper amount of support [195].

6. Conclusion

In this review, the properties of liquid metals and the suitability of these properties for a wide range of applications were shown. The main feature shared by members of this group of elements is their low melting points, which do not exceed 300 °C, which has a significant impact on phase transitions at low temperatures. This is a property that has a positive impact on potential applications. However, it is not the only property of these metals that is important. The low toxicity of some members of this group is a priority when applied. Gallium and materials based on it are characterized by their significantly low toxicity, which made them a promising material in medical applications. Despite the possibility of using materials based on Gallium in the manufacture of flexible electronics due to their excellent electrical and rheological properties and the role they can play in sensors, catalysts and other applications that guarantee a better level of well-being for humans, preserving life itself comes at the top of the priorities, which made interest in research in medical applications in particular a point of attraction for researchers. Positive indicators appeared in the treatment of a number of health problems that can affect humans. Cancerous tumors and nerve damage are problems for which liquid metal-based technologies have offered a glimmer of hope. Although research on this topic has not yet gone beyond the scope of research, researchers are seeking to apply it in a way that guarantees the survival of patients and provides better health care in the near future.

7. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

8. Acknowledgement

The authors gratefully acknowledge the support and facilities provided by the Study Abroad Program (SAP), Gujarat University, Ahmedabad, Gujarat 380009, India, which significantly contributed to the successful completion of this research work.

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Timeline of Publication

Received Date:	12 April	2025
Revised Date:	20 May	2025
Accepted Date:	2 June	2025
Published Date:	20 June	2025