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FUNDAMENTAL RESEARCH ON GALLIUM-BASED LIQUID METAL FLEXIBLE ROBOTS

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Abstract: This research focuses on the fundamental study of gallium-based liquid metal flexible robots. First, the composition and ratio of the alloy were determined, and a gallium-indium alloy liquid metal suitable for flexible robots was successfully fabricated. The research conducts experimental studies on the morphological changes and movement of liquid metal under electric field control. Quantitative conclusions were drawn, revealing that the deformation speed is proportional to the applied voltage, with a stable deformation region around 40 seconds. Once the electric field is removed, the deformation is reversible, and the recovery speed is consistent. Lastly, qualitative research examined the effects of conductive and non-conductive substrates on liquid metal deformation and movement, considering factors such as charge polarity and the surface oxide film. On non-conductive substrates, the deformation is reversible and moves towards the positive electrode, whereas on conductive substrates, the deformation is irreversible and moves towards the negative electrode.

Keywords: Gallium-based liquid metal; Flexible robots; Electric field control; Substrates; Amoeba-like deformation; Controllable deformation

1 INTRODUCTION

Room-temperature liquid metals refer to metallic alloys or pure metals that exist in a liquid state under ambient temperature conditions. Mercury, gallium, and cesium are naturally occurring room-temperature liquid metals. These materials can exist in a liquid state at room temperature due to their low melting points, making them possess both "metal" and "liquid" properties. However, mercury is highly toxic and volatile, while cesium reacts violently with water and oxygen in the air. Therefore, gallium has become a widely studied and promising room-temperature liquid metal material. In recent years, gallium-based alloys, as a representative of flexible metal materials, have emerged as a promising field of study, drawing significant attention from the international research community. It is believed that this new class of materials could potentially revolutionize many critical sectors, including energy, chemical engineering, electronics, advanced manufacturing, defense, and medical biotechnology[1-3].

The main properties of gallium-based liquid metals are their excellent electrical and thermal conductivity, low melting point, high boiling point, good fluidity, and shape recovery. They also exhibit high surface tension, extremely low toxicity, and low vapor pressure, posing minimal harm to the human body. Research utilizing these characteristics has already yielded significant advancements in various fields such as additive manufacturing, electronics printing, circuit components, sensors, and biomedical applications. Specifically, in flexible actuators, research has been conducted on controlling the interfacial tension of gallium-based liquid metals in electrolyte solutions, manipulating the directional flow of the droplet-solution interface to drive droplet movement[4-6].

Among the many control methods for gallium-based liquid metals, the use of electric fields has become the preferred driving mechanism for liquid metal droplets due to its high precision, flexibility, and wide range of output speeds. This makes electric field control an ideal choice for manipulating gallium-based liquid metals in a variety of applications.

The experiments on the morphological changes and movements of gallium-based liquid metals, including quantitative measurements of controlled deformation and movement under direct current electric fields, and qualitative studies on the effects of conductive and non-conductive substrates on liquid metal deformation and motion, are of significant research importance and scientific value. These studies will contribute to the expansion of gallium-based liquid metals' applications in diverse fields, potentially leading to breakthroughs in soft robotics, smart materials, and flexible electronics. Moreover, exploring the interactions between these materials and external forces, such as electric fields, will enhance our ability to control liquid metal dynamics with greater precision, further opening up possibilities for the next generation of advanced materials with transformative capabilities[7-8].

The ongoing research on gallium-based liquid metals is expected to drive innovations in multiple industries, advancing technologies that require precise control of material properties and unprecedented flexibility. As these materials continue to evolve, they hold the potential to impact sectors ranging from microelectronics to healthcare, offering new solutions for challenges in energy efficiency, manufacturing processes, and biocompatible technologies[9-11].

2 GALLIUM-BASED LIQUID METAL ELECTRIC FIELD CONTROL THEORY

2.1 Basic Physicochemical Properties of Gallium-based Liquid Metals

Room-temperature liquid metals refer to a class of metals or alloys that have a melting point below 30°C. In recent years, room-temperature liquid metal alloys based on low-melting-point metals, such as gallium (with a melting point of 29.8°C and a boiling point of 2204°C), have attracted widespread attention due to their relatively stable physical properties. Gallium-based liquid metals are typically formed by combining gallium with other metals such as indium, tin, and zinc.

Currently, the most commonly used gallium-based liquid metals in laboratory environments are gallium-indium alloys (GaIn, with 75% Ga and 25% In) and gallium-indium-tin alloys (Galinstan, with 68% Ga, 22% In, and 10% Sn). These alloys are favored for their low toxicity, high fluidity, and excellent conductivity, making them ideal for various applications, including flexible electronics, cooling systems, and soft robotics.

At room temperature (25°C), gallium-based liquid metals appear as silvery-white liquids. In an oxygen-free environment or NaOH solution, due to the high surface tension inherent in the liquid metal, it forms a hemispherical shape when placed on a flat surface under the influence of gravity. However, in air, oxidation occurs, which reduces the surface tension, making it more difficult for the liquid metal droplet to maintain its hemispherical shape.

Figures 1 (a) and (b) show the side view of a 800 μL droplet of gallium-based liquid metal in these two conditions. It can be seen that, under the same volume conditions, the decrease in surface tension due to the oxide layer causes a noticeable difference in the height of the liquid metal droplet. Figure 1 (c) compares the shapes of gallium-based liquid metal on glass substrate and graphite substrate.

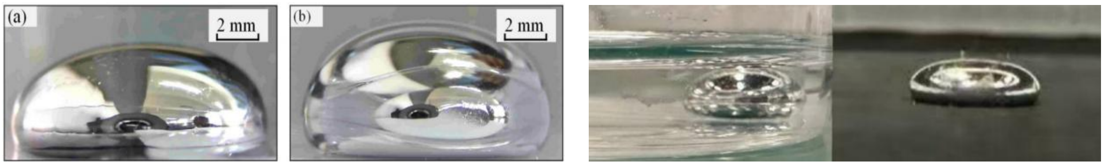

Figure 1 Side view of Gallium-based Liquid Metal in Different Environments. (a) In air; (b) In 1 mol/L NaOH solution; (c) Comparison of Gallium-based Liquid Metal Shapes on Different Substrates

In addition, gallium-based liquid metals also possess excellent properties such as low viscosity, high thermal conductivity, electrical conductivity, and fluidity. A comparison of some physical property parameters of gallium-based liquid metal, mercury, and water is shown in Table 1.

Table 1 Melting Points and Other Physical Properties of Liquid Metal Materials with Different Mixing Ratios

	mercury	gallium	$GaIn_{24.5}$	$Ga_{68.5}In_{21.5}Sn_{10}$	$Ga_{67}In_{25}Sn_{18}Zn_{1}$	water
melting point /°C	-38.8	29.8	15.5	10.5	7.6	0
boiling point /°C	357	2204	2000	1300	900	100
Density/[1000kg·m-3]	1.353	6.08	6.28	6.36	6.5	1.0
viscosity/[10-7 m2·s-1]	13.5	3.24	2.7	2.98	0.71	11.2
surface tension [N/m]/[N·m-1]	0.5	0.72	0.624	0.533	0.5	0.07
thermal conductivity [106 sm-1]	1	3.7	3.4	3.1	2.8	10-10
thermal conductivity*m·k*/[w-1]	8.34	29.4	42.2	44.8	48.2	0.55
water compatibility	compatibility	incompatibility	incompatibility	incompatibility	incompatibility	—

2.2 Electrochemical Oxidation-Reduction Reactions of Gallium-based Liquid Metals

When gallium-indium (Ga-In) alloy droplets are exposed to the atmospheric environment, as shown in Figure 2(a), a thin oxide film (on the micron scale) forms on the metal surface. The viscosity of the droplet is high, making it difficult for the droplet to slide on the substrate surface, and the droplet shape is irregular. This irregularity does not change over time. Figure 2(b) shows the morphology of the Ga-In alloy in distilled water. Due to the presence of the oxide film, which wraps around the droplet's surface, the viscosity is reduced compared to the air environment, resulting in increased fluidity and a more regular droplet shape. When the Ga-In alloy droplet is placed in a NaOH solution, the oxide film easily dissolves in the solution, causing the viscosity to decrease instantly, increasing the fluidity, and restoring the droplet to an ellipsoidal shape, as shown in Figure 2(c).

The droplet undergoes different changes in different environments. In the air, the oxide film on the droplet's surface is most prominent, making the droplet shape the most irregular. In distilled water, there are no charge-bearing ions to transfer, and no charge accumulation occurs on the droplet surface. Part of the oxide film may dissolve in the distilled water, reducing the viscosity of the droplet. When the liquid metal is placed in a NaOH solution, the oxide film dissolves and reacts with the solution. The viscosity of the droplet decreases rapidly, surface tension increases, and the droplet carries a certain amount of negative charge. Under the influence of an external electric field, ions from the solution gather on the droplet's surface. Due to the electrochemical reaction, the surface tension of the droplet inevitably changes. Therefore, this study uses NaOH solution as the environmental medium to investigate the morphological changes and movement behavior of liquid metal under electric field control.

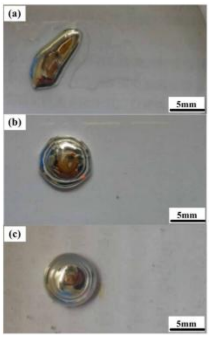

Figure 2 Macroscopic Phenomena of Gallium-Indium Alloy Droplets in Different Environmental Media. (a) Shape exposed to air; (b) Shape in distilled water; (c) Shape in NaOH aqueous solution

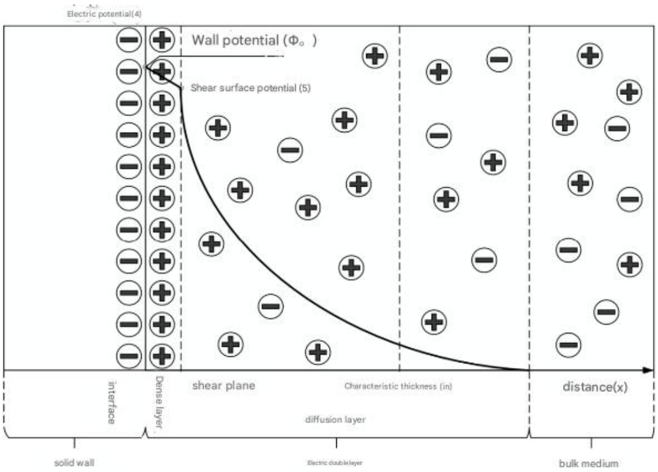

Figure 3 Charge and Potential Distribution within the Double Layer

2.3 Gallium-based Liquid Metal – Double Layer Model of Charged Interfaces in Alkaline Solutions

For a solid immersed in a solution, its surface generally becomes charged due to the dissociation of surface chemical groups or the selective adsorption of specific ions from the solution. This charged surface is referred to as the solid wall. The net charge on the solid wall attracts ions of opposite charge from the solution and repels ions of the same charge. This results in the formation of a thin layer near the solid wall where the net charge density monotonically decreases and eventually becomes zero, as shown in Figure 3. This layer is known as the electric double layer.

Beyond the electric double layer, in the region of the solution that continues to move away from the solid wall, there is no net charge, and this area is referred to as the bulk medium. The electric double layer serves as the theoretical foundation for the study of most electrodynamic phenomena. Within the double layer, the strength of the adsorption effect caused by the charge on the solid wall, which is influenced by distance, allows the double layer to be divided into two regions: the compact layer and the diffuse layer.

The compact layer refers to the single layer of charge that is tightly bound to the solid wall, strongly adsorbed on the interface solution side due to electrostatic forces. Its thickness is generally equivalent to the size of a single ion or charged molecule in the solution. The diffuse layer, on the other hand, lies between the compact layer and the bulk medium, where the net charge density varies monotonically due to electrostatic forces and thermal diffusion effects.

3 MORPHOLOGICAL CHANGES AND MOVEMENT OF GALLIUM-BASED LIQUID METAL UNDER ELECTRIC FIELD CONTROL

3.1.Selection of Gallium-based Liquid Metal

When the temperature is above the melting point, liquid metals exhibit excellent fluidity and flexibility. However, when the temperature drops below the melting point, the liquid metal displays the mechanical strength of solid metals. This unique liquid-to-solid phase transition mechanism allows liquid metals to rapidly form at lower temperatures, making them suitable for manufacturing three-dimensional objects in various shapes. The low melting point of gallium makes it convenient to prepare, store, and use under room temperature conditions. Additionally, the biocompatibility of gallium-indium alloys ensures they do not have significant toxic side effects on humans. Considering these properties of gallium-based liquid metals, the gallium-indium alloy was chosen for the implementation of this study and subsequent experiments.

Typically, metals have much higher electrical conductivity than non-metal materials. Compared to non-metallic conductive materials, liquid metals not only maintain flexibility but also exhibit much higher electrical conductivity

(3.4×10⁶ S/m), far exceeding non-metal materials such as carbon (1.8×10³ S/m) and carbon nanotubes (5.03×10³ S/m).

Table 2 Melting Points of Gallium-Indium Alloy Materials with Different Ratios

Gallium (%)	Indium (%)	Melting (℃)
100	0	29.8
90	10	25
80	20	20
75.5	24.5	15.5
70	30	20
60	40	35
50	50	50
40	60	70
30	70	90
20	80	110
10	90	130
0	100	156.6

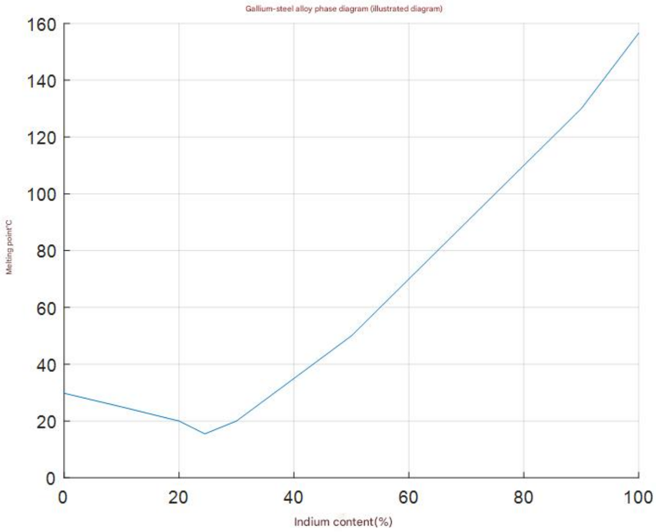

Figure 4 Melting Points of Gallium-Indium Alloys with Different Ratios

The melting point of pure gallium is 29.76°C, and the melting point of pure indium is 156.6°C. The characteristic of the gallium-indium alloy is that its melting point is much lower than those of pure gallium and pure indium, making it a typical eutectic alloy. The melting point of the gallium-indium alloy changes depending on the ratio of gallium to indium. Table 2 lists the melting points of gallium-indium alloys with different ratios.

To provide a more intuitive representation, a graph based on Table 2 is shown in Figure 4. From the graph, we can clearly see the change in the melting point and the position of the lowest eutectic point: as the indium content increases, the melting point of the alloy decreases rapidly. When the indium content reaches approximately 24.5%, the melting point reaches the lowest point of 15.5°C, which is the eutectic point. Beyond the eutectic point, as the indium content further increases, the melting point of the alloy rises again.

Considering that liquid metal flexible robots can conveniently undergo solid-to-liquid phase changes within the room temperature range using high and low temperatures, this experiment selects a gallium-indium alloy with a melting point of 25°C, specifically with gallium and indium contents of 90% and 10%, respectively.

The first experiment is the preparation of gallium-based liquid metal. 1.8 grams of gallium and 0.2 grams of indium are weighed, and the gallium and indium are dropped into a beaker using a dropper. The beaker is then placed in a water bath and heated to 100°C. During heating, a stirring rod is used to continuously stir the liquid metal. Once the liquid metal becomes a uniform alloy, the beaker is removed, and the preparation is complete, resulting in the gallium-indium alloy.

3.2 Amoeba-like Deformation Effect of Gallium-based Liquid Metal

The amoeba-like effect of liquid metal refers to the phenomenon in which liquid metal can self-drive and deform, resembling the behavior of an amoeba. This effect is related to the electric double layer, mainly caused by the interaction between the liquid gallium alloy, aluminum, graphite substrate, and alkaline electrolytes, which leads to changes in the surface tension of the liquid metal.

When a droplet of liquid metal contacts a graphite substrate in a NaOH electrolyte, a thin oxide layer forms on the surface of the droplet. This oxide layer significantly reduces the surface tension of the liquid metal. The oxidation effect of graphite is stronger than the oxide removal capability of NaOH. In the case of aluminum, it initially reacts within the liquid metal droplet and loses electrons, which then flow through the liquid metal to the graphite. This reduction process removes the oxide layer from the surface of the liquid metal.

The oxidation effect of graphite and the reduction effect of aluminum compete and collaborate throughout the deformation process, generating a surface tension gradient. These interactions together lead to dynamic changes and gradients in the surface tension, which in turn drive the deformation and movement of the liquid droplet.

3.3 Controllable Deformation and Movement of Gallium-based Liquid Metal under Electric Field

3.3.1 Study on the controllable deformation of gallium-based liquid metal under electric field

The deformation process of the amoeba-like effect is irreversible and uncontrollable. However, by combining chemical and electrochemical mechanisms, it is possible to achieve controlled and reversible deformation of liquid metal. The study also investigates the impact of different voltages on the controllable and reversible deformation of liquid metal.

In the experiment, sodium hydroxide solution was poured into a petri dish. A small amount of liquid metal was then picked up with a pipette and dropped into the petri dish. The positive electrode wire was inserted into the liquid metal droplet, while the negative electrode wire was immersed in the solution (away from the droplet). The voltage was then sequentially adjusted to 5V, 10V, 15V, and 20V. Upon applying the electric field, the liquid metal spread irregularly, resembling the behavior of an amoeba. After the power was turned off, the liquid metal rapidly contracted back into an almost spherical shape.

Experiments were conducted at four different voltages, with data recorded for each voltage. The area change of the liquid metal was measured every 2 seconds. To smooth the data for better visual comparison, all experimental data were interpolated to a 1-second sampling rate using cubic spline interpolation. This method constructs a smooth curve using piecewise cubic polynomials, ensuring continuity of the second derivative at the nodes, while maintaining high precision and computational efficiency. It is widely used in engineering design and numerical analysis.

Figure 5 shows the relationship between the applied voltage and the area change of the liquid metal, with screenshots taken every 5 seconds. The experimental data, after interpolation, are depicted as a curve representing the relationship between the voltage and area change. Different voltage values are represented by different colors and line styles, with the moment when the voltage was turned off marked at 40 seconds. It is evident that the deformation speed of the liquid metal is proportional to the voltage, with deformation tending to stabilize around 40 seconds. After the electric field is removed, the deformation is reversible, and the recovery speed is almost identical.

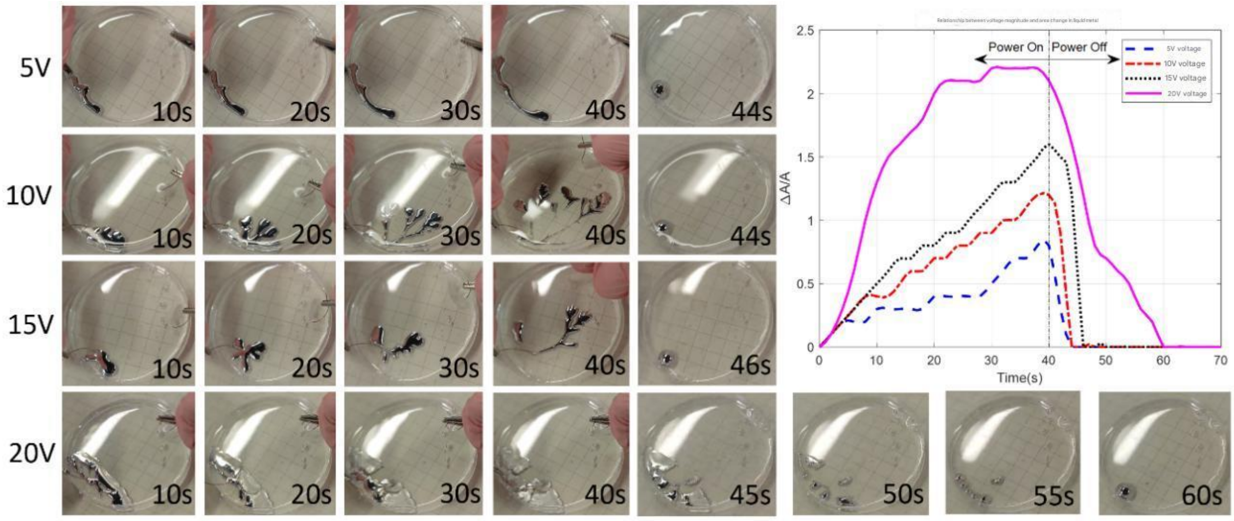

Figure 5 Relationship between Voltage and Area Change of Liquid Metal, Summarized Every 5 Seconds

From the figure, it can be observed that after the electric field is applied, the area of the liquid metal increases. The higher the applied voltage, the faster the area grows, and the larger the maximum area achieved. After the power is turned off, the liquid metal quickly contracts back into an almost spherical shape. Moreover, the higher the voltage applied before turning off the power, the slower the area decreases after the power is removed.

This behavior occurs because, as the applied voltage increases, the reduction in surface tension becomes more significant. The lower the surface tension, the less resistance there is to the spreading of the liquid metal. As a result, the area increases more quickly, and the maximum achievable area becomes larger. After the power is turned off, the larger the area that the liquid metal spreads to, the larger the oxide film formed on the surface. This results in a slower recovery time.

3.3.2 Controllable movement of gallium-based liquid metal under electric field

In this experiment, a sodium hydroxide solution is poured into a water tank, and a droplet of gallium-based liquid metal is introduced into the solution using a pipette. Both the positive and negative electrode wires are inserted into the solution, with the positive electrode positioned in the direction the liquid metal droplet is intended to move. The voltage is then sequentially adjusted to 10V, 20V, and 30V. It is observed that the liquid metal rolls toward the positive electrode wire.

In the experiment, under the influence of the electric field, the liquid metal moves from the negative electrode (cathode) to the positive electrode (anode). This experiment explores how different voltages affect the movement speed of the liquid metal.

The experiment was conducted at three different voltages, and video snapshots are shown in Figure 6, with screenshots taken at 0s, 1s, and 2s, arranged from top to bottom. After the power is applied, it can be observed that the higher the applied voltage, the faster the liquid metal moves. This is because a higher voltage increases the attraction between the negative charge on the liquid metal and the positive electrode, causing the liquid metal to move faster.

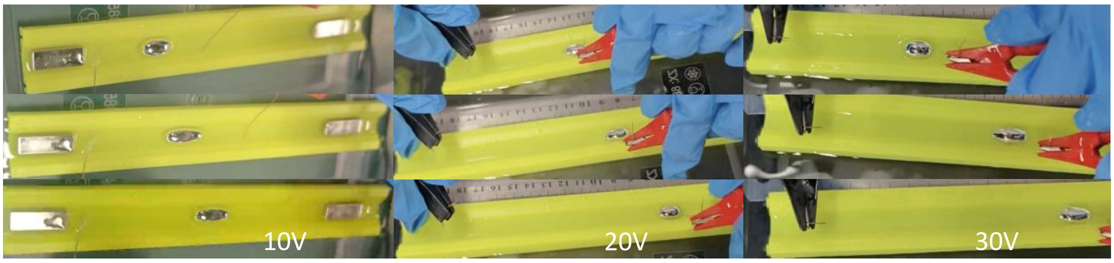

Figure 6 Experiment on the Controllable Movement of Gallium-based Liquid Metal under Electric Field

2.3.3 Gallium-based liquid metal maze experiment

In this experiment, a sodium hydroxide solution is poured into a water tank, and magnets are used to construct the walls of a maze. Once the maze is set up, a droplet of liquid metal is placed at the entrance of the maze using a pipette. The positive electrode wire is inserted into the solution, positioned in front of the direction in which the liquid metal droplet is intended to move. The negative electrode wire is inserted into the solution and placed behind the droplet.

When the power is turned on, the liquid metal moves towards the positive electrode wire. Whenever the liquid metal reaches a dead end or needs to change direction in the maze, the positions of the positive and negative electrodes were adjusted. The positive electrode was relocated to the front of the new desired direction of motion, while the negative electrode was placed behind the droplet. Under the continuously applied electric field, the liquid metal immediately responded to the updated electric field configuration and proceeded to move along the newly defined path.This process is repeated until the liquid metal successfully navigates its way out of the maze.

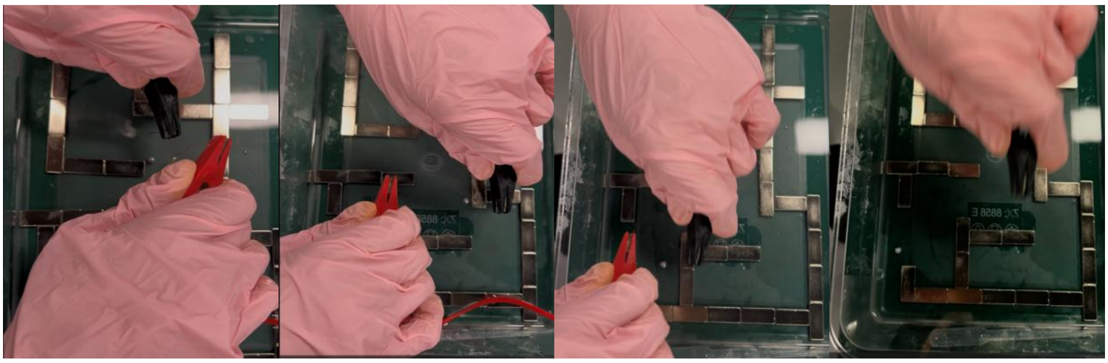

Figure 7 Gallium-based Liquid Metal Maze Experiment

The liquid metal maze experiment demonstrates that gallium-based liquid metal droplets can achieve real-time, reprogrammable, and substrate-dependent navigation in complex confined environments under a dynamically configured electric field. It provides a proof-of-concept that electrically driven liquid metal droplets can function as minimal soft robotic systems capable of path selection and navigation without embedded actuation or control components..

3.4 Controllable Deformation and Movement of Gallium-based Liquid Metal on Graphite Substrate under Electric Field

In an alkaline solution, liquid metal tends to take a spherical shape. However, when the liquid metal droplet is immersed on the surface of a graphite material in the alkaline solution, it spreads out, forming a flat metal disc, and a thin oxide layer forms on the surface. This is due to a chemical reaction in the alkaline solution that causes the surface of the liquid metal to acquire a layer of charge, while the graphite surface becomes positively charged.

When the liquid metal, a good conductor, comes into contact with the graphite, which is also a good conductor, the negative charge of the liquid metal will flow toward the graphite surface in order to reach an equal potential. As a result, the liquid metal becomes oxidized. Consequently, the initially spherical liquid metal droplet transforms into a flattened shape. This behavior is influenced by the interaction between the electrical charges and the material properties of the liquid metal and the graphite substrate.

3.4.1 Gallium-based liquid metal morphology control experiment on graphite substrate

A sodium hydroxide solution is poured into a water tank, and a graphite plate is placed inside the tank. A small amount of gallium-based liquid metal is then taken using a pipette and dropped onto the graphite plate. The positive electrode wire is inserted into the liquid metal droplet, while the negative electrode wire is immersed in the solution (away from the droplet). After applying the electric field, the liquid metal spreads irregularly on the surface, resembling the movement of an amoeba. The cause of this phenomenon has been explained in detail in Section 2.2, and will not be elaborated further here.

Figure 8 Morphological changes of liquid metal on graphite substrates under electric field

The entire experiment at 20V was recorded on video, and video frames were captured every 8 seconds, as shown in Figure 8.

After applying the electric field, the area of the liquid metal increases, similar to its behavior on a glass container. However, once the power is turned off, the liquid metal maintains its current shape and does not revert to its original form. This is because the oxide film on the liquid metal's surface, formed on the graphite substrate, restricts the movement of the liquid metal, preventing it from returning to its previous shape after the electric field is removed.

3.4.2 Gallium-based liquid metal movement experiment on graphite substrate

In the experiment, a graphite substrate was placed in the experimental container, and NaOH solution was added to the container. A droplet of gallium-based liquid metal was then dropped into the NaOH solution. The positive electrode wire was inserted into the solution in front of the liquid metal droplet, while the negative electrode wire was placed in the solution behind the droplet (away from the positive electrode direction). A 10V DC voltage was applied, and the movement of the liquid metal was observed. The movement distance was recorded every second and stored as the project's raw data in tabular form.

It is important to note that in the case of a graphite substrate, the gallium-based liquid metal moves toward the negative electrode direction when a DC electric field is applied in the alkaline solution. This phenomenon is different from the behavior on glass substrates. When the substrate is graphite, because graphite is conductive, a large number of negative charges flow toward the graphite, causing the liquid metal to acquire a positive charge. As a result, on the graphite substrate, the liquid metal moves toward the negative electrode.

The entire experiment of the movement of the gallium-based liquid metal on the graphite substrate was video-recorded. Every 5 seconds, video frames were captured, and the experimental data were also displayed in graphical form, showing the relationship between the liquid metal's movement distance on the graphite substrate and time, as depicted in Figure 9. The entire experiment of the movement of gallium-based liquid metal on the graphite substrate was recorded on video. Every 5 seconds, video frames were captured, and the experimental data were displayed in graphical form, illustrating the relationship between the movement distance and time of the liquid metal on the graphite substrate, as shown in Figure 9. This figure presents the movement behavior of the liquid metal over time, with the recorded data showing how the distance changes as the liquid metal moves along the graphite surface under the influence of an applied electric field. The graph visually captures key moments of the experiment, such as the initial spreading, acceleration, and eventual stabilization of the liquid metal's movement.

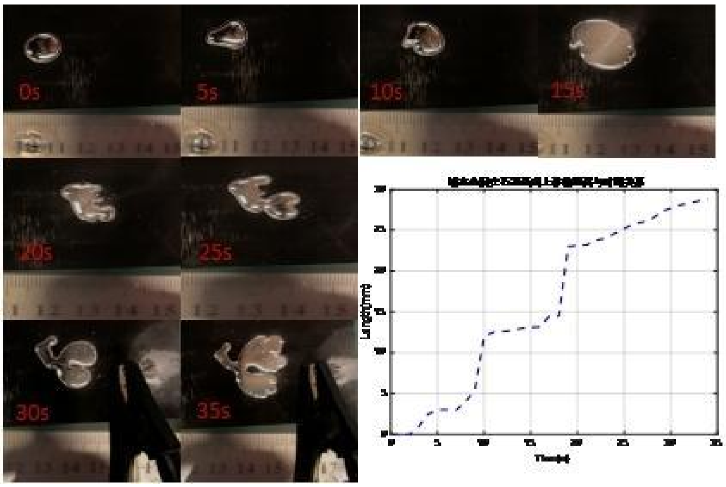

Figure 9 Experiment on the Relationship Between the Movement Distance and Time of Liquid Metal on Graphite Substrate

It can be observed that the movement distance of the liquid metal on the graphite substrate does not follow a linear relationship with time, but rather exhibits a phase-based growth pattern. Within the 35-second experimental time frame, the movement can be roughly divided into four phases: the first phase from 0 to 5 seconds, the second phase from 5 to 10 seconds, the third phase from 10 to 19 seconds, and the fourth phase from 19 seconds onwards.

The first three phases share similar characteristics. In each of these phases, the first half is relatively stable, with a nearly horizontal, linear increase with a very low slope. The duration of the first half of each phase gradually increases. However, in the second half of each phase, there is a noticeable jump in the motion, with the slope approaching 90°. The fourth phase, on the other hand, continues as a linear increase with a low slope, similar to the first half of the previous phases. It can be speculated that if the experiment were extended, the fourth phase might also exhibit the same phenomenon as the previous phases, where the second half would show a jump with a slope approaching a right angle.

From the observation of the experimental data in the first three phases and the experimental video, it is clear that the movement of the liquid metal on the graphite substrate under the influence of the electric field is similar to the movement of a jellyfish. After the electric field is applied, the liquid metal moves forward on the graphite surface in a crawling motion. Initially, the head stretches forward, followed by the tail contracting forward. The overall movement pattern resembles the swimming motion of a jellyfish.

3.4.3 Gallium-based liquid metal crawling experiment on graphite substrate

In the experiment, sodium hydroxide solution is poured into a water tank, and a graphite plate is placed in the tank at a certain angle. A droplet of gallium-based liquid metal is then taken using a pipette and placed on the graphite plate. The negative electrode wire is inserted into the solution and positioned in front of the liquid metal droplet, while the positive electrode wire is inserted into the solution and placed behind the droplet (away from the positive electrode direction), ensuring it does not touch the graphite plate. The power is turned on, and it is observed that the liquid metal slowly crawls upward along the inclined surface of the graphite plate, moving towards the direction of the negative electrode wire. This movement resembles the behavior described in section 2.4.2.

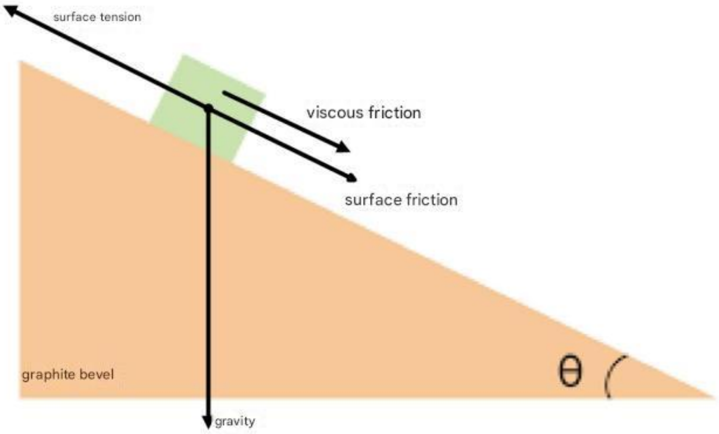

Figure 10 Force Analysis of Gallium-based Liquid Metal Crawling on Graphite Substrate

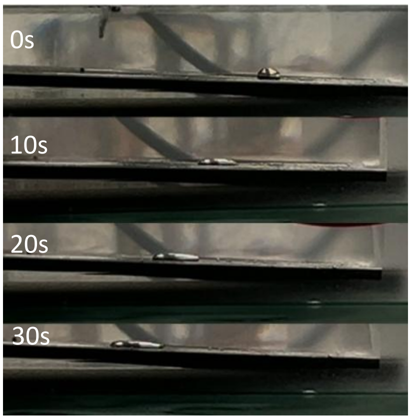

Figure 11 Gallium-based Liquid Metal Crawling Experiment on Graphite Substrate

The force analysis and video snapshots of the gallium-based liquid metal crawling experiment on a graphite substrate are shown in Figures 10 and 11.

From the figures, it can be observed that the movement distance of the gallium-based liquid metal on the graphite slope is approximately linear with respect to time. However, as time increases, the shape of the gallium-based liquid metal gradually transitions from an ellipsoidal form to a flatter shape.

4 CONCLUSION

This study quantitatively measured the controllable deformation and movement of gallium-based liquid metal under electric field control. The results show that the deformation speed is proportional to the applied voltage, with deformation stabilizing around 40 seconds. Once the electric field is removed, the deformation is reversible, and the recovery speed is consistent.

The experiment also qualitatively explored the effects of conductive and non-conductive substrates, along with factors such as charge polarity and surface oxide films, on the deformation and movement of liquid metal. On non-conductive substrates, the deformation is reversible and moves toward the positive electrode, while on conductive substrates, the deformation is irreversible and moves toward the negative electrode. The relationship between the movement distance and time of the liquid metal on the graphite substrate does not follow a linear pattern but instead exhibits phase-based growth. In each phase, the first half is relatively stable with a very low slope, and the duration of the first half of each phase gradually increases. The second half, however, shows a noticeable jump with a slope close to 90°. From the observation of the experimental data and the experimental video, it can be seen that the movement of the liquid metal on the graphite substrate under the influence of the electric field resembles the motion of a jellyfish.

Additionally, a liquid metal maze experiment demonstrated that gallium-based liquid metal droplets could achieve real-time, reprogrammable navigation in complex confined environments through dynamic reconfiguration of the electric field, without the need for embedded actuation or control systems. This behavior provides a proof-of-concept for electrically driven liquid metal droplets functioning as minimal soft robotic systems.

Overall, this research reveals a series of fundamental phenomena regarding the electrochemical control of low-melting-point liquid metals on conductive and non-conductive substrates. These findings offer promising strategies for the development of soft robotics, reconfigurable electronics, and adaptive microfluidic systems based on liquid metal actuation.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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