Stretchable Conductors Fabricated by Stencil Lithography and Centrifugal Force-Assisted Patterning of Liquid Metal

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ABSTRACT: Embedding liquid metals (LMs) into an elastomer is emerging as a promising strategy for stretchable conductors. Existing manufacturing techniques are struggling between spatial resolution and process complexity and are limited to chemically resistant substrates. Here, we report on a hybrid process combining stencil lithography and centrifugal force-assisted patterning of liquid metal for the development of LM-based stretchable conductors. The selective wetting behavior of oxide-removed eutectic gallium−indium (EGaIn) on metal patterns defined by stencil lithography enables micrometer scale LM patterns on an elastomeric substrate. Stencil lithography allows for defining metal regions without harsh chemical treatments, making it suitable for a wide range of substrates. Microscale LM patterns are achieved by efficiently removing the excess material by the centrifugal forces experienced from spinning the substrate. The proposed approach allows for the creation of LM patterns with a line width as small as 2 μm on a stretchable poly(dimethylsiloxane) (PDMS) substrate. The electrical measurement results show that the fabricated EGaIn devices can endure 40% mechanical strain over several thousands of cycles. Furthermore, a stencil design using microbridges is proposed to address the mechanical stability issue in stencil lithography. An EGaIn conductor with a serpentine structure and an interdigitated capacitor are fabricated and characterized. The results demonstrate that the patterned serpentine conductors retain their functionality with applied mechanical strain up to 80%. The performance of the interdigitated capacitors upon applied strain is in good agreement with the theoretical estimation. Finally, we demonstrate our approach also on poly(octamethylene maleate (anhydride) citrate) (POMaC) substrates to broaden the use of the proposed method to not only flexible and stretchable but also biodegradable substrates, opening a way for in vivo transient microsystem engineering. The work presented here provides a versatile and reliable approach for manufacturing stretchable conductors.

KEYWORDS: liquid metal, poly(dimethylsiloxane) (PDMS), stencil, stretchable conductors, centrifugal force, spinning

INTRODUCTION

Flexible electronics are circuits and electronic components that can afford bending while maintaining their electrical functionality. Significant efforts have been devoted to the development of paper electronics1 and flexible displays.2 As an extension of flexible electronics, stretchable electronics can be elongated to be conformably attached on the soft human skin and tissue and follow body motion. For example, epidermal electronics attached on the human skin allow for electrophysiological recording,3 and soft neural implants enable neuroprosthetic applications.4 Some wearable applications require circuits and electronic components with the capability to monitor large strains. For instance, the bending of human fingers and wrists experience strain up to 30%.5,6 Among all the essential elements for wearable devices, stretchable conductors are particularly important because they address the problem of the mechanical mismatch between the soft tissue and the more rigid functional devices by eliminating stress concentration. To perform this function, stretchable conductors must remain mechanically intact and electrically conductive under mechanical deformation.

The engineering of structures and materials has been intensively studied to enable stretchable conductors. Structuring a rigid metal film into deterministic fractal motifs in 2D7,8 or 3D form9,10 has enabled the extension of the strain limit of rigid metal films. For example, a stretchability of 80% has been demonstrated by shaping thin Ag film into meanders.8 A thin Au film has been shown to be able to endure over 100% strain with 3D helical design.10 However, the stretchability of

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structured metal conductors is mainly dominated by the rigid metal patterns, which decrease the usable density of the electronic components because it consumes a large portion of spaces with meander or helical wiring routing. The immobilization of an ionic conducting liquid into a polymer matrix offers an excellent stretchability and high transparency, which attracts interest for the development of stretchable conductors. A stretchable electroluminescent device using an ionic conductor that shows stable device performance under stretching to 400% strain over 1000 cycles has been demonstrated. However, its high electrical resistivity (in the order of $10^5 \Omega \cdot \mu m$) limits their applications as electrical conductors. Embedding nonstretchable conductive nanomaterials into stretchable insulating polymer matrix provides another design strategy, which is working with the principle of percolation of the conductive nanomaterials. The solid state material is not stretched but displaced so it provides a good stretchability and an acceptable electrical resistivity. Stretchable conductors produced by spray-coating CNTs on PDMS surfaces via a shadow mask enables the realization of stretchable transistors that can sustain strain up to 100% for at least 1000 stretching cycles. Nevertheless, the most commonly used manufacturing method for this type of conductor is spray-coating, which results in a relatively low resolution in the order of tens of micrometers due to the size of the spray nozzles. The relatively low resolution limits their use in high density electronic devices. However, liquid metals (LMs) provide an excellent opportunity for use as stretchable conductors due to the lower electrical resistivity ranging from 0.29 $\Omega \cdot \mu m$ (eutectic gallium–indium) to 1 $\Omega \cdot \mu m$ (Hg) compared to the above-mentioned materials and an intrinsically unlimited strain limit without the need of complex wire routing.

Among the liquid metal candidates for stretchable conductors, the alloy of eutectic gallium–indium (EGaIn, 75 wt % of Ga and 25 wt % of In) and gallium–indium–tin (Galinstan, 68.5 wt % of Ga, 21.5 wt % of In, and 10.0 wt % of Sn) are particularly attractive because of their nontoxicity, low electrical resistivity, negligible vapor pressure, and low melting temperature. For example, EGaIn has a melting temperature of 15.5 °C and an electrical resistivity of 0.29 $\Omega \cdot \mu m$ at room temperature, i.e., in liquid state. The electrical resistivity of EGaIn is one order of magnitude higher than bulk Cu but one order of magnitude lower than nanomaterial-embedded composites (e.g., AgNW) and eight orders lower than ionic gels, which makes EGaIn an excellent candidate for stretchable conductors. One of the promising strategies for the use of liquid gallium alloy is to embed it into an elastomeric polymer. Being liquid at room temperature, the liquid gallium alloy can deform into the shape of the microchannel and remain electrically conducting. These properties make liquid gallium alloy suitable for wearable applications. The rigid thin oxide skin (~1–3 nm), formed on the surface of liquid gallium alloy when exposed to oxygen in the environment, allows for shape retention at the micrometer scale and form stable free-standing structures. A broad range of manufacturing methods have been developed for structuring liquid gallium alloys at micrometer or submicrometer scale by taking advantage of its moldability. For example, liquid gallium alloys can be structured at the micrometer scale by using picosecond laser ablation, printing directly on substrates via nozzles, injecting into microfluidic chan-
the pattern definition. Producing the corrugated membrane requires another fabrication process, which increases the overall stencil fabrication time and costs. Furthermore, a long serpentine or interdigitated structure has not been demonstrated yet by using the reported corrugated membrane. Incorporating with thicker (3 μm) electroplated Cu as the stencil membrane has enabled an interdigitated structure. However, the pattern resolution is limited to few tens of micrometer due to the use of the thicker membrane. In short, a process capable of producing a complex pattern structure in the micrometer scale by SL without additional stencil fabrication steps has not yet been reported.

For facile and reliable patterning, the selective deposition of materials utilizing the centrifugal force experienced from spinning the substrate is a well-established approach. It is normally used to create uniform films on substrate by spinning off excess materials from the surface. Selective deposition of materials can be achieved by controlling interfacial interactions between the substrate and the deposited material. Patterns can be achieved by efficiently removing the excess materials by the well-controlled centrifugal force experienced from spinning the substrates. This approach provides a way for high-resolution and size-scalable manufacturing of patterned liquid structures.

In this paper, we describe a hybrid process combining stencil lithography and centrifugal force-assisted patterning of LM to provide a simple but reliable method to shape LM on an elastomer surface at the micrometer scale. It allows for the creation of microscale EGaIn features on a stretchable poly(dimethylsiloxane) (PDMS) substrate. We also propose a new stencil design using microbridges to address the mechanical stability issue in SL and to further enlarge its applicability of complex design patterns, such as long meanders and interdigitated electrodes. The EGaIn resistors with straight line and serpentine shapes are both fabricated on PDMS to demonstrate the electrical and electromechanical performances. Furthermore, we demonstrate the possibility to extend this approach to a stretchable and biodegradable poly(octamethylene maleate (anhydride) citrate) (POMaC) substrate. This represents an important enabling step toward its use in applications such as recyclable electronics.

## RESULTS AND DISCUSSION

### Microfabrication Based on a Hybrid Process

The fabrication process based on SL and centrifugal force-assisted patterning of LM to shape EGaIn at the micrometer scale is illustrated in Figure 1a. The substrate is composed of a soft PDMS layer having a thickness of 1 mm with a lateral size of 30 × 15 mm² on a 525 μm thick silicon wafer, which is coated with a self-assembled trimethylsilyl chloride silane (TMCS) (Sigma-Aldrich) layer to enable the peeling of PDMS in the last step. The stencil mask used here consists of 500 nm thick low-stress silicon nitride (LS-SiN) membranes supported by a silicon frame. The stencils are fabricated by patterning the apertures on LS-SiN membranes, followed by the etching of...
the backside silicon carrier to release the nitride membranes. First, the fabricated stencil is brought into contact with the substrate and then 4 nm thick Cr and 60 nm thick Au are locally sputter deposited on the substrate via the aperture of the SiN stencil mask. The deposition is performed using DC sputtering with powers of 350 and 250 W for Cr and Au, respectively. Here, Cr is used as an adhesion layer for Au on PDMS, and Au is used to have a selective wetting contrast with EGaIn. After the sputter deposition, the stencil mask is removed from the PDMS substrate by immersing the sample in isopropyl alcohol (IPA). Due to the sticky property of PDMS, we use IPA to assist the removal of the stencil without damaging it. IPA swells PDMS, which increases the strain at the interface of the stencil and the PDMS, resulting in the PDMS film to peel off. In a second experiment, we performed this method on a flexible POMaC substrate to validate the possibility of extending this approach on a biodegradable substrates. On POMaC substrate, the stencil can be released directly after sputter deposition without the use of IPA. After the creation of the Cr/Au pattern and the removal of the stencil mask, 20 μL of 4% NaOH treated EGaIn is dropcasted onto the substrate to cover the entire Cr/Au patterns, followed by spinning the substrate. Here, 4% NaOH is applied to remove the native oxide of EGaIn (Ga2O3) so that it can selectively wet on the patterned Au surfaces. The spinning starts with 100 rpm for 5 s, followed by 500 rpm for 7 s to remove the excess material. At the end, the substrate slows down to 0 rpm in about 2 s. During the spinning, EGaIn wets the metal traces and the excess material is removed from the substrate by the centrifugal force. The EGaIn confinement on the metal traces is attributed to the wetting contrast between PDMS and metal, and the pinning effect on the metal mesa edge. The competition between the adhesion forces between EGaIn and Au, the cohesion forces within EGaIn, and the centrifugal force determines the geometry of the obtained EGaIn structures. Compared to the existing fabrication methods using a roller or manual shaking to remove excess materials, centrifugal force-assisted patterning of EGaIn with microscale wetting contrast patterns provides a way to efficiently remove the excess material in a controllable manner and is scale-able for large area manufacturing. Furthermore, the removed excess EGaIn remains in the spin-coater as a droplet, which allows to be simply recollected for further use (Figure S1, Supporting Information, SI). After the spinning, the device is rinsed in DI water to remove unwanted NaOH residues. Finally, the patterned LM device is sealed with a 1 mm thick layer of PDMS obtained by gently pouring a self-curing liquid PDMS solution over the device to protect LM patterns for further stretching test. At the end, the encapsulated device is peeled off from the silicon carrier. The developed hybrid process enables the creation of EGaIn patterns on the substrate with minimal exposure to harsh chemicals. Only a few seconds of exposure to 4% NaOH and DI water is needed in the process, which allows the process to be extended on a wide range of substrates. To elucidate the resolution limit, we have created on a PDMS substrate squares with a minimum side of 5 μm and lines with a minimum width of 2 μm (Figure 1b). Arrays of lines and narrow lines with large contact pads with a width of 2 μm are also successfully fabricated by the same method (Figure S2, SI). Furthermore, arbitrary patterns can be produced, such as the EPFL logo (Figure 1b(iii)). It is noted that in the stencil design, the letter “P” is connected with bridges because the suspended membrane in the stencil limits the production of a close-loop structure, as known as the “Doughnut problem”. To solve this challenge, we report in a later section a solution utilizing the blurring effect to achieve complex and continuous LM patterns. The fabricated line patterns on a flexible and biodegradable POMaC substrate (Figure S3, SI) demonstrates the possibility to apply the proposed approach on a wide range of substrates.

To assess the geometry of the fabricated EGaIn patterns on a PDMS substrate, confocal microscopy (S neox, Sensofar) is used to measure the profile of the patterned EGaIn square dots having different side widths (Figure 2). As expected, the height of each square pattern increases with its width (Figure 2a). The same result has been shown by using spin-coating to selectively deposit polymer thin film on a heterogeneous substrate. Furthermore, a linear relationship can be obtained between the patterned EGaIn width and height (Figure 2b).

Figure 2. Geometrical analysis of the patterned EGaIn on a PDMS substrate. (a) Profile of the patterned EGaIn square dots with different widths. The inset shows the optical image of the sample. Scale bar: 50 μm. (b) Relationship between patterned EGaIn width and height and its linear fitting curve. The width and height values are taken from the stencil aperture size and the measured profile, respectively. Each data point contains measurement results from three random samples. The error bar represents the standard deviation.
The error bar shows the spread of data from three random samples, with each sample produced from a single 20 μL NaOH treated EGaIn droplet. The process is performed under the same spinning parameters for all samples. Next, to study the effect of the spinning speed, which leads to different centrifugal forces on the geometry of the obtained EGaIn structure, geometrical analysis is carried out on samples fabricated with different spinning speed. Five spinning speeds ranging from 250 to 4000 rpm are used to create EGaIn square array patterns, which consists of square patterns with side widths of 5, 10, and 20 μm, respectively. The results (Figure S4, SI) show a maximum standard deviation in heights of about 20% when applying different spinning speeds. This demonstrates that using centrifugal force experienced from spinning the substrate to structure LM provides not only promising results but also a large process window for reproducible manufacturing. Furthermore, it shows the possibility to extend the presented method to the full wafer scale by adapting a well-established full wafer stencil.  

Electrical Characterization of the Patterned EGaIn. Next we evaluate the electrical performance of the patterned EGaIn on a PDMS substrate (Figure 3). The devices used for resistance measurement contain lines with lengths of 50, 100, and 150 μm, and widths of 2, 5, and 10 μm, and are connected by two square electrical pads having a width of 100 μm at their terminal ends. After patterning EGaIn with the method described above, the electrical measurements are performed before encapsulating the devices. The parasitic resistance, which consists of the resistance of the probes and the contact resistance between the probes and droplets, are quantified and...
Figure 4. The use of a microbridge stencil for patterning EGaIn and the fabrication results (a) Schematic drawings showing the concept of microbridge stencil (i) and fabrication processes (ii–iv). (ii) A microbridge stencil is attached above the Si/PDMS substrate with a certain gap distance (70 μm) and fixed with Kapton tape. (iii) Cr (4 nm) and Au (150 nm) are evaporation deposited on the substrate. (iv) The EGaIn is structured by using the process mentioned in Figure 1. (b) Optical images of the sample during the fabrication steps: (i) Deposited continuous Cr/Au pattern after removing the stencil mask. (ii) Patterned EGaIn serpentine structure and its zoom-in view (iii). (c) Electromechanical characterization results of the patterned LM structures with a microbridge stencil. The inset shows the optical image of the tested sample. Scale bar: 100 μm. (d) Relative resistance change as a function of the applied strain. Error bar shows the standard deviation of the measured two samples. (e) An optical image of the fabricated microbridge stencil with interdigitated apertures. (f) Measured and computed relative capacitance change as a function of the applied mechanical strain. The inset shows the optical image of the tested sample. Scale bar: 100 μm. Error bar shows the standard deviation of the measured two samples.
subtracted from the measured total resistance. The parasitic resistance is measured by inserting two probes into the same droplet whereby the measured values varied between 5 to 10 Ω. The expected resistances of patterned EGaIn are calculated from a parallel circuit formed by the underneath adhesive Au layer and EGaIn structure. Here, because the thickness of Cr (4 nm) is ten times thinner than Au (60 nm) and Cr is six times more resistive than Au (0.12 Ω·μm for Cr and 0.02 Ω·μm for Au), the contribution of Cr to the electrical conductance is neglected. The resistivity of the adhesive Au layer is characterized by measuring the resistance of the sample before patterning EGaIn. The result shows a resistivity of 0.31 Ω·μm for the sputter deposited Au by using a stencil mask (Figure S5, SI). The measured resistivity of a sputtered Au thin film is more than ten times of the value of bulk Au, which is attributed to random cracks and surface wrinkles in the Au film formed during the sputtering process.48,49 To calculate the resistivity of patterned EGaIn, the resistance is plotted as a function of the inverse of the EGaIn cross-section area for different lengths (Figure 3a). The cross-section area of each device is calculated by integrating the profile measured by confocal microscopy (S neox, Sensofar) and subtracted from the area of the underneath adhesive layer. We observe variations in the cross-section area among different samples having the same device geometry. The variations can be explained by the resulting height differences of the patterned structures (Figure 2). The measured resistivity of EGaIn is 0.39 ± 0.02 Ω·μm (Figure 3b), which is close to the reported resistivity of bulk EGaIn (0.29 Ω·μm).15 It is important to note that the calculation is based on a parallel circuit model without considering the occurring cracks on the Au film. If the cracks are filled with EGaIn, then the effective resistivity of the Au film that contributes to the conduction is reduced. Therefore, the presence of such cracks would result in an underestimation of the calculated resistivity of EGaIn.

In order to verify the suitability of the fabricated EGaIn structures as stretchable conductors, the measurement of the maximum operation current is performed. After patterning EGaIn on a PDMS substrate with the presented method, the terminal droplets are administered on the large electrical pads at the ends of the tested EGaIn wire. The terminal droplets allow the copper wire to be added on to perform electrical measurements. The device is encapsulated by gently pouring a self-curing liquid PDMS solution on the device and curing it at room temperature for 48 h. The experiment on the maximum operation current is conducted by measuring the electrical resistance with increased input currents. We observe that, at currents below 7 mA, no permanent modification of the device resistance is introduced. The resistance increases as a function of applied currents due to Joule heating but recover to its initial value once the current is reduced (Figure 3c). The measured resistance change indicates a temperature increase of around 65 °C based on the equation \( \Delta T = \Delta R/(\alpha R) \), where \( \Delta R \) is the resistance, and \( \alpha \) the temperature coefficient of resistivity of EGaIn (~10⁻³ °C⁻¹).50,51 The result shows that LM conductors fabricated by the presented method could meet the requirements for wearable devices operating at least in a temperature range between 20 and 85 °C. At larger currents (7.5 mA), the resistance starts to gradually increase as a function of time and a permanent modification of the device resistance is observed. The phenomena is tentatively attributed to the void formation inside the embedded EGaIn channel when the device is heated up to a certain temperature.50,51 The maximum operation current for the fabricated EGaIn sample is around 7 mA, which corresponds to a current density of around 2 × 10⁹ A/m². The measured current density is about 4 orders of magnitude higher than the values for stretchable conductors based on the percolation of conductive silver nanowires.52 Next, the electrical characterization of a EGaIn resistor under applied uniaxial deformation is performed. It shows an excellent electrical stability over 1000 cycles with 40% maximum applied strain in a sample with 10 μm in width and 100 μm in length (Figure 3d). The electrical resistance increases from about 17 Ω to 45 Ω in the first 100 cycles and then remains constant up to at least 1300 cycles (8.6 h). The mechanism of the observed phenomenon is not clear. In previous literature,53 the initial increase of the electrical resistance is tentatively attributed to the deformation and reformation of the oxide skin. Because PDMS is permeable to oxygen,54 oxygen might permeate inside the PDMS channel and results in the reoxidation process, which forms a different amount of Ga₂O₃ within the wire.53 Another possible explanation for the observed phenomenon is the increased crack density of the underneath Au during stretching.48 In the first few cycles of stretching, EGaIn fills in the cracks produced on the Au film and the entire metal structures are stabilized afterward. After 1300 cycles of stretching in 8.6 h, the device is released to its original shape. To further study the stability of the fabricated device, three additional cycle tests are performed with different interval breaks. The second cycle test is performed after 15 h from the first cycle test. The results of the second cycle indicates that there is no significant change in electrical resistance. The third and the fourth cycle tests are performed after 10 min and 1 h from the second and the third cycles, respectively. No significant electrical resistance variations are observed. It can be concluded that after a certain number of stretching cycles, the electrical resistance of the fabricated device is no more affected by the subsequent stretching cycle. The calculated gauge factor of the fabricated device is 1.3 within the applied strain range from 0% to 40% (the inset in Figure 3d) due to the geometrical change of the embedded liquid conductor, which is in agreement with previously reported values.21 As an example for an application of the proposed process, we show the stretchable connection to a commercial LED chip. The connection to the LED chip can withstand bending and twisting and remains functional (Figure S6, SI). These measurements demonstrate that the bilayer conductive pattern (Au/EGaIn) produced with the method proposed in this work has excellent and stable electrical properties and can be used to fabricate stretchable conductors.

**Microbridge Stencil for More Complex Patterns.** Although stencil lithography has been demonstrated to enable the deposition of materials on a variety of substrates, the low mechanical robustness of the suspended thin SiN membrane limits its use for more complex patterns. To enable a wider variety of structures, in this work we propose a microbridge stencil to enable geometries such as long serpentine and interdigitated structures. The proposed microbridge stencil consists of several bridges with a width of 1 μm uniformly distributed across the entire structure to stabilize the suspended SiN membrane (Figure 4a(i)). The applied microbridges result in a significant reduction of the membrane bending due to stresses and enable the realization of fragile serpentine structure (Figure S7, SI). By lifting the microbridge stencil at a certain gap distance above the substrate surface, the
line-of-sight evaporation results in material blurring and fills the shadowed bridge region (Figure 4a(ii,iii) and Figure S8, S1). In the last, EGaIn is formed on the stencil-patterned metal trace by spinning the excess EGaIn off the substrate. (Figure 4a(iv)). The blurring effect causes pattern enlargement of the evaporated adhesive Au layer and consequently also of the final LM structure. For example, we observe LM pattern enlargement of 2.5 μm per side when using a 70 μm gap stencil-substrate distance. The result indicates that the best resolution of using microbridge stencil to pattern LM is around 6 μm, which results from the 1 μm aperture opening plus the 5 μm pattern enlargement. The optical images of the sample taken during the process indicate that the blurring underneath the microbridges in the stencil allows for a continuous metal pattern on the substrate surface (Figure 4b(i)) and enable a continuous LM pattern across the entire serpentine structure (Figure 4b(ii,iii)). Compared to the reported strategy of using a corrugated SiN or an electroplated Cu membrane to increase its mechanical robustness, the proposed microbridge stencil enables a wider variety of designs in the micrometer scale without introducing additional processes.

The electromechanical characterization is performed on EGaIn resistors patterned with a microbridge stencil on a PDMS substrate. The serpentine EGaIn resistor is characterized by stretching the device up to 80% strain with a step of 10% strain. After each measurement, the device is released to its original shape. The results indicate that the resistance of the LM follows a logarithmic function that returns to its initial value even after stretching to 80% strain. A relative resistance change along with the applied strain shows a maximum relative resistance change of 106% with an applied strain of 80% (Figure 4d). In addition to meander shaped resistors, the proposed microbridge stencil also enables interdigitated structures in the suspended membrane (Figure 4e). The confocal image shows a greatly reduced membrane bending in the stencil (Figure S9, SI) and thus allows the realization of an interdigitated capacitor. The measured initial capacitance is around 0.3 pF, and the relative capacitance change shows a linear relationship with the applied strain having a slope of ~0.9, which agrees well with the theoretical model derived by Fassler and Majidi (Figure 4f). The equation used for the theoretical estimation is given in Equation S1 in the SI.

### CONCLUSIONS

The results reported in this work demonstrate an original process that combines stencil lithography and centrifugal force-assisted patterning of liquid metal for the realization of EGaIn-based stretchable conductors. Using the selective wetting property of oxide-removed EGaIn, micrometer patterns with resolution down to 2 μm can be obtained with micrometer scale wetting contrast patterns. Stencil lithography allows patterning metal traces, that EGaIn wets without harsh chemical treatments and can thus be also applied to soft, biodegradable polymer materials. The stencil can thus be used several times to reduce fabrication costs. The centrifugal force experienced from spinning the substrate allows for the removal of excess materials in a highly controllable manner, and thus enables micrometer EGaIn patterns. The patterned EGaIn on a flexible and biodegradable POMaC substrate demonstrates its suitability for a wider range of substrates. The presented method enables shaping EGaIn into a variety of patterns. Furthermore, the fabricated EGaIn patterns show low electrical resistivity (0.39 Ω·μm) and excellent electromechanical response under large uniaxial deformation. In particular, it can endure an applied strain of 40% over thousands of cycles without significant change in its electrical performance. Furthermore, the proposed microbridge stencil broadens the design flexibility of stencil lithography. With a microbridge stencil, an EGaIn resistor with a serpentine structure and an interdigitated capacitor are demonstrated. The fabricated meander resistor can be stretched up to 80% strain and recovered to its original shape without significant change in its electrical resistance. The performance of the fabricated interdigitated capacitor under the applied strain agrees well with theoretical calculation. Comparing to the reported selective wetting process for patterning liquid gallium alloy, the presented work shows an improved pattern resolution without harsh chemical treatments and thus enables extending the method to a wide range of substrate materials such as biodegradable polymer materials (Table S1, SI). The work presented here provides a simple and versatile method to fabricate liquid metal-based stretchable conductors.

### EXPERIMENTAL SECTION

#### Stencil Fabrication

First, a 500 nm low-stress silicon nitride films is grown on both sides of a bare silicon wafer by low pressure chemical vapor deposition (LPCVD). Second, a photolithography step is performed: 1 μm thick photoresist (AZ ECI 3007, MicroChemicals GmbH) is spin-coated on the wafer and patterned by direct laser writer, followed by the development of the resist (AZ 726 MIF, MicroChemicals GmbH). Reactive ion etching (RIE) is then performed to etch LS-SiN with a mixture of He, H2, and C4F8 gases. The photoresist is then removed with oxygen plasma. Third, by the same method, a photolithography step is performed on the backside of the wafer but with a 8 μm thick photoresist (AZ 10XT, MicroChemicals GmbH), followed by etching the backside LS-SiN film with RIE. Last, the Bosch process is used to etch ~400 μm of the silicon bulk, and KOH is used to etch the remaining silicon. At the end, the wafer is cleaved into 10 × 10 mm² chips.

#### PDMS Substrate Preparation

First, a 4 in. silicon wafer is cleaved into 30 × 15 mm² chips. The chips are exposed to oxygen plasma with 1000 W for 1 min. Then, a self-assembled layer of trimethylsilyl chloride silane (TMCS) (Sigma-Aldrich) is coated on the chips in a desiccator. The polystyrylene (PDSMS) solution is prepared by mixing prepolymer and cross-linker with a mass ratio of 10:1 (Sylgard 184, Dow Corning) and poured on the chips. Later, the chips are placed in a desiccator for degassing. At the end, they are cured in an oven at 80 °C for 2 h.

#### Spinning Procedure

The chip is first attached on a vacuum sample holder in a spin-coater. Then 20 μL of 4% NaOH and EGaIn (Eutectic Gallium–Indium, ≥ 99.99%, Sigma-Aldrich) are drop-casted on the chip using a pipet, followed by spinning the chip.

#### Uniaxial Electromechanical Characterization

The sample chip with size of 30 mm by 15 mm is peeled from the silicon carrier and mounted on a commercial tensile testing stage (TST350, Linkam Scientific) with an in-built controller to actuate one of the two clamps moving along the horizontal plane. The electrical resistance is measured using a two-point probe method (2400 source-meter, Keithley) controlled by a LabVIEW program. The resistances are measured with an applied current of 1 mA. The capacitance is measured using a LCR meter (4285A, HP) with an applied voltage of 500 mV and a frequency of 500 kHz.
**ASSOCIATED CONTENT**

**Supporting Information**

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsaelm.1c00884.

Equation S1, relative capacitance change with applied strain; Table S1, comparison of the reported selective wetting process; Figure S1, recollection of the removed excess EGaIn after spinning; Figure S2, high resolution EGaIn patterns fabricated by the present method; Figure S3, patterned EGaIn on POMAC; Figure S4, measured heights of the EGaIn square patterns fabricated with different spinning speeds: Figure S5, electrical characterization of the sputter deposited Au structures on a PDMS substrate; Figure S6, LED chip connected with EGaIn/Au stretchable conductors; Figure S7, optical and confocal images of stencils with and without microbridges; Figure S8, schematic drawings showing the blurring effect; Figure S9, optical and confocal images of the stencil with interdigitated apertures; and additional references (PDF).

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**Notes**

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