ALL-SOFT PHYSICAL AND CHEMICAL MICROSYSTEMS BASED ON LIQUID METAL FOR WEARABLE ELECTRONICS APPLICATIONS

Min-gu Kim, Hommood Alrowais, and Oliver Brand
School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA
Institute for Electronics and Nanotechnology, Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT

This paper introduces all-soft physical and chemical sensing systems for wearable electronics applications comprising soft microsensors and soft functional circuits using gallium-based liquid metal (eutectic gallium-indium alloy, EGaIn) and poly(dimethylsiloxane) (PDMS). An advanced EGaIn thin-line patterning technique enables size-scalable, high density, and residue-free liquid metal structures that form the base for the demonstrated physical microsystem for strain measurement and liquid-phase chemical sensing platform. The stretchable strain sensor consists of a soft Wheatstone bridge circuit, which exhibits a linear output voltage response for applied uniaxial strain up to 28%. The liquid-phase chemical sensor is comprised of a microfluidic capacitive sensor vertically integrated with a spiral inductor to form an LC resonance circuit. Its resonance frequency changes in response to the relative permittivity of the liquid solvent.

INTRODUCTION

Flexible and stretchable electronics implementations have gained significant attention with possible wearable applications for human motion and health monitoring [1, 2]. One major technical challenge in current flexible and stretchable electronics is the mechanical mismatch between soft biological materials, such as human skin, and conventional rigid electronic materials, such as silicon and solid conductors [3]. To achieve flexible and stretchable characteristics, two primary approaches have been introduced: the first approach is to fabricate highly elastic conductors by mixing conductive materials with a soft elastomer [4, 5], while the second approach is to create wave-like metal patterns on a soft substrate that can endure large mechanical deformation [6, 7].

An alternative approach to realize flexible and stretchable electronics is to use conducting liquids [8-10]. Thereby, the use of liquid-phase conductors, such as eutectic gallium-indium alloy (EGaIn), instead of conventional solid conductors could open the path for all-soft electronics, because of favorable electrical (electrical conductivity (σ) = 3.4×10^6 S/m) and mechanical properties [9, 10]. However, fabrication challenges particularly in terms of minimum feature sizes, size-scalability, and residue-free surfaces have thus far limited the demonstration of highly integrated, all-soft functional circuits and sensing systems [9, 10]. Moreover, although single sensing elements have been investigated, they typically still require rigid components or PCB boards [11], which limits their ultimate usability in wearable electronics applications.

This paper presents all-soft, integrated microsystems composed of soft microsensors and soft functional circuits for physical and chemical sensing applications. Our previous work [12, 13] has demonstrated an advanced EGaIn thin-line patterning process that addresses above fabrication challenges, resulting in size-scalable EGaIn patterns without residues. Building on our work [12-14], a physical microsystem for strain measurement and a chemical sensing platform for liquid-phase chemical sensing are demonstrated based on all-soft electronic passive components.

DESIGN AND FABRICATION

Figure 1 shows the concept of EGaIn-based electronic passive components embedded in a soft poly(dimethylsiloxane) (PDMS) substrate to establish all-soft microsystems. Thereby, resistors, interdigitated capacitors, and planar inductors are fabricated using an advanced EGaIn thin-line patterning process and vertically integrated using soft through-PDMS vias.

The advanced EGaIn patterning process [12, 13] consists of four steps as shown in Figure 2. The fabrication process starts with selective chemical surface modification of a PDMS mold with embedded channels for selective wetting. The PDMS mold is pressed onto a donor PDMS substrate coated with the EGaIn film and separated from it, filling the channels with EGaIn. In the next step, EGaIn residues on the PDMS surface outside the channel areas are transferred to a sacrificial PDMS substrate by reverse stamping. Because of the reduced surface energy of the surface-modified PDMS mold, EGaIn residues outside of the channel areas can be effectively transferred to the non-modified sacrificial PDMS substrate. Finally, the EGaIn-patterned PDMS mold is covered with an additional PDMS layer and vertically interconnected using soft vias.

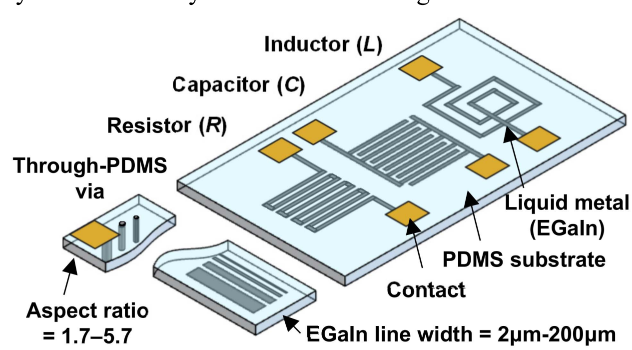

Figure 1: Concept of all-soft electronic passive components using gallium-based liquid metal (eutectic gallium-indium alloy, EGaIn) and PDMS (polydimethylsiloxane) for physical and chemical sensing components and functional circuits.

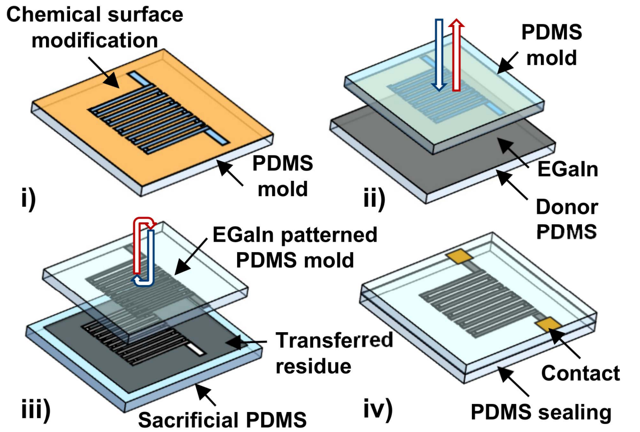

Figure 2: Advanced liquid metal (EGaIn) thin-line patterning process [12-14]: i) chemical surface modification of PDMS mold surface, ii) microtransfer molding of EGaIn, iii) residue transfer, and iv) PDMS sealing and vertical interconnection using soft vias.

Figure 3 (a)-(b) show the EGaIn fabrication results to highlight high resolution and size-scalability with line widths ranging from 2 µm to 200 µm, and high-density capability using the example of an interdigitated capacitor with 74 electrodes. Figure 3 (c) compares patterned EGaIn lines with and without the chemical surface modification and residue transfer technique. Using the surface modification and residue transfer technique, all EGaIn residue formed on the outside of the channel surface can be effectively transferred, and the patterned EGaIn lines show smooth surfaces and uniform thickness inside the PDMS mold.

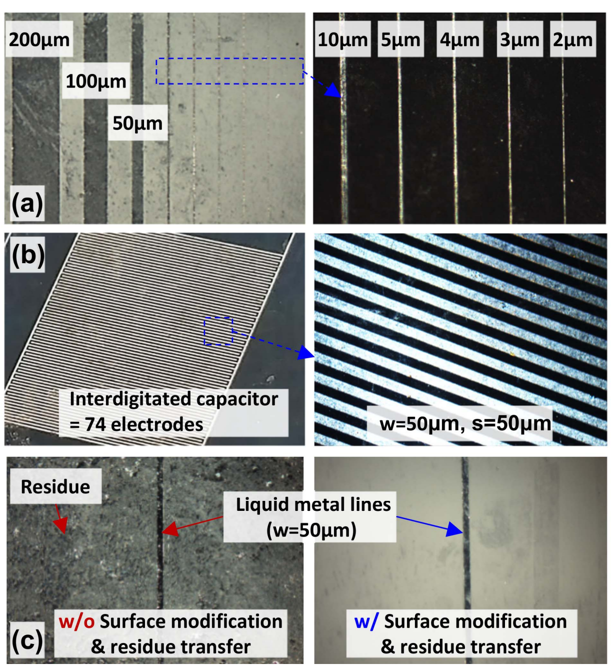

Figure 3: Fabricated liquid metal patterns to highlight (a) size scalability and high resolution, (b) high density, and (c) residue-free surfaces with (w/) and without (w/o) chemical surface modification and residue transfer process.

RESULTS AND DISCUSSION

By employing the advanced EGaIn patterning technique to fabricate all-soft electronic passive components, we designed, fabricated and tested soft microsensors and soft functional circuits to demonstrate a physical microsystem for strain measurement and a liquid-phase chemical sensing system.

All-Soft Physical Microsystems

As a physical microsystem demonstrator, a strain sensor based on a Wheatstone bridge circuit was investigated. Figure 4 shows the fabricated all-soft Wheatstone bridge and its equivalent circuit model. The soft circuit has three resistors in series (R_1 - R_3 = 0.6 ± 0.07 kΩ), with a single soft strain sensor being electrically connected to the soft circuit (R_{sens} ~ 0.6 kΩ).

In the first step, the electrical characteristics of the soft Wheatstone bridge circuit, i.e. its output voltage as a function of the applied sensor resistance R_{sens}, was investigated with and without bending deformation of the soft circuit (Figure 4(b)) and compared with calculated values from Equation (1).

$$V_{out} = V_{in}\left(\frac{R_{sens}}{R_3 + R_{sens}} - \frac{R_2}{R_1 + R_2}\right) \tag{1}$$

Here, V_{out} and V_{in} are the output and input (1 V) voltages, R_1 - R_3 are the resistors embedded in the soft Wheatstone bridge circuit, and R_{sens} is the external sensing resistance.

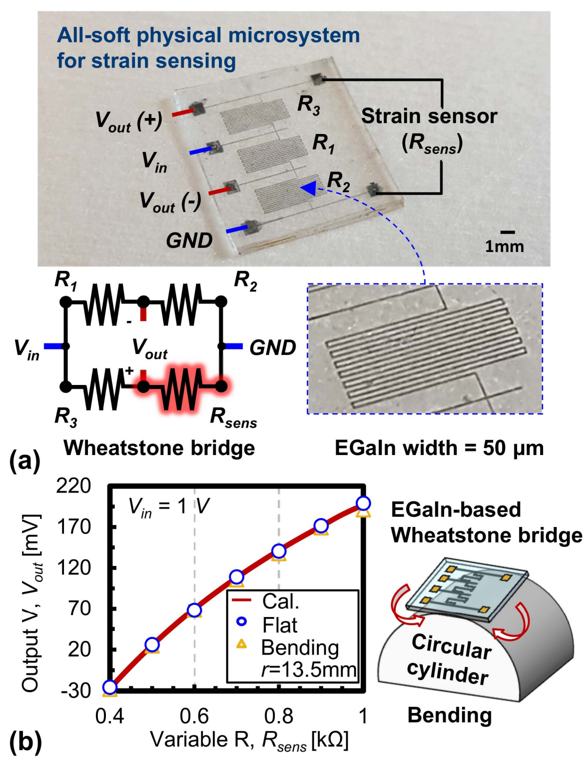

Figure 4: (a) Fabricated soft Wheatstone bridge circuit and equivalent circuit model and (b) measured output voltage as a function of an external, variable sensing resistance for flat and bent (bending radius of 13.5 mm) microsystem in comparison with calculated values.

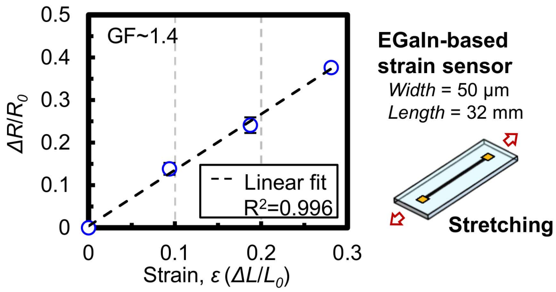

Figure 5: Measured relative resistance change ($\Delta R/R_0$) of an EGaIn-based all-soft strain sensor as a function of applied uniaxial strain up to ~30%.

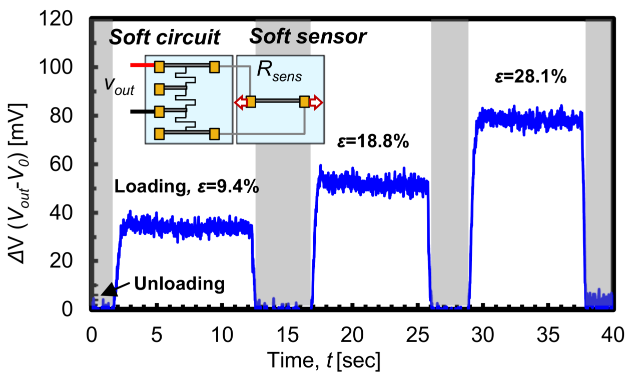

Figure 6: Output voltage of all-soft physical microsystem composed of a soft Wheatstone bridge circuit (biased at V_{in} = 1 V) with a stretchable strain sensor upon different applied strains.

The measured output voltage under flat conditions matches well with the calculated values with <2.1% deviation. When the soft Wheatstone bridge circuit is attached to the surface of a cylinder with a radius of 13.5 mm, a small output voltage change is observed, with <3.7% deviation compared to the voltages measured for the flat circuit. This change can be explained by the increase of the resistances R_1 through R_3 upon bending, i.e. stretching the resistors.

Next, an EGaIn-based soft strain sensor was investigated for wearable strain measurements. Figure 5 shows the measured relative resistance change ($\Delta R/R_0$) of the 32 mm long and 50 µm wide EGaIn resistor as a function of the applied uniaxial strain in the resistor's length direction. The soft strain sensor was stretched up to ~30% and shows a linear relative resistance change with a gauge factor (GF) of 1.4. The resistance change can be explained by the effect of geometry changes on the resistance ($R=\rho L/A$, where ρ is the resistivity of the conductive material (EGaIn), L is the length of the conductor, and A is the cross-sectional area of the conductor) [15].

Finally, the soft strain sensor was electrically connected to the soft Wheatstone bridge circuit, and the output voltage was measured by applying uniaxial strains to the soft strain sensor at 1 *V* input voltage. As expected, the measured output voltage linearly increased with the applied strain. Figure 6 shows the output voltage change with applied strain up to 28% under loading and unloading conditions.

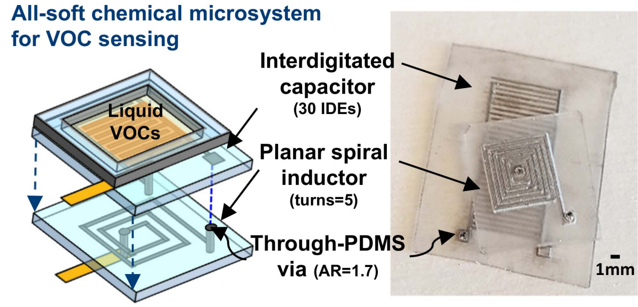

Figure 7: Schematic of and fabricated vertically integrated all-soft chemical microsystem composed of a microfluidic capacitive sensor and a planar spiral inductor to form an LC circuit.

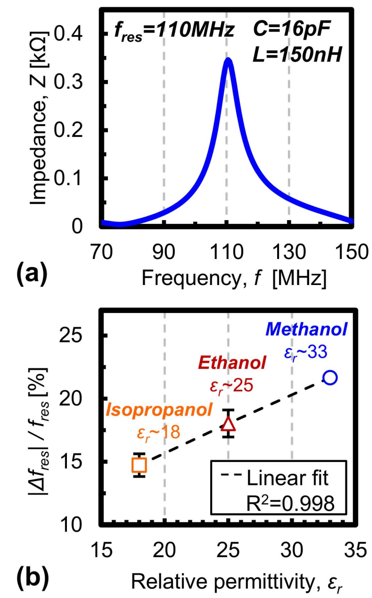

Figure 8: (a) Measured impedance around resonance frequency without fluid and (b) measured resonance frequency changes as a function of fluid permittivity.

All-Soft Chemical Microsystems

As an example for a chemical microsystem, a microfluidic LC resonance sensing platform is investigated for liquid-phase detection of different solvents. In our previous work [13, 14], we have demonstrated an all-soft sensing platform, which consists of a soft capacitive sensor and a PDMS microfluidic reservoir having 136.5 mm^3 fluid capacity. Here, the microfluidic interdigitated capacitive sensor (16 pF) is vertically integrated with a planar spiral inductor (150 nH) using a soft through-PDMS via as shown in Figure 7 to form an all-soft LC resonance sensing platform.

Different liquid-phase solvents, such as isopropanol (ε_r ~ 18 at room temperature and 1kHz probing frequency), ethanol (ε_r ~ 25), and methanol (ε_r ~ 33) were applied to the PDMS microfluidic reservoir. The measured capacitance increases linearly as a function of the relative permittivity of solvents, enabling selective detection of the liquid by its relative permittivity. Figure 8 (a) shows the measured impedance of the integrated LC resonator as a function of frequency without fluid as a reference. The measured resonance frequency was 110MHz, with <7% deviation from the calculated value obtained by Equation (2):

$$f_{res} = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

Here, f_{res} is the resonance frequency, ω_0 is the angular frequency, L is the inductance, and C is the capacitance.

Applying different solvents, in the present example different alcohols, to the microfluidic reservoir decreases the resonance frequency. Over the range of tested alcohols, the magnitude of the resonance frequency change increases almost linearly with the dielectric constant of the solvents, as shown in Figure 8 (b).

CONCLUSION

This paper demonstrates all-soft physical and chemical sensing systems for wearable electronics applications comprising soft microsensors and soft functional circuits using EGaIn and PDMS. An advanced EGaIn thin-line patterning technique enables size-scalable, high density, and residue-free liquid metal patterns, that form the base for the demonstrated physical microsystem for strain measurement and microfluidic chemical sensing platform for liquid-phase sensing. The strain sensor is based on a soft Wheatstone bridge circuit, which shows a linear voltage response as a function of applied uniaxial strain up to 28%. The chemical sensor is based on a microfluidic capacitive sensor, which is vertically integrated with a spiral inductor to form an LC resonance circuit and shows a decrease in resonance frequency with increasing fluid dielectric constant.

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CONTACT

* M. Kim, e-mail: mgk@gatech.edu and
O. Brand, e-mail: oliver.brand@ece.gate.edu