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Integrating Soft Sensor Systems Using Conductive Thread

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Abstract

We are part of a growing community of researchers who are developing a new class of soft machines. By using mechanically soft materials (MPa Modulus) we can design systems which overcome the bulk-mechanical mismatches between soft biological systems and hard engineered components. To develop fully integrated soft machines—which include power, communications, and control sub-systems—the research community requires methods for interconnecting between soft and hard electronics.

Sensors based upon eutectic gallium alloys in microfluidic channels can be used to measure normal and strain forces, but integrating these sensors into systems of heterogeneous Young's Modulus is difficult due the complexity of finding a material which is electrically conductive, mechanically flexible, and stable over prolonged periods of time. Many existing gallium-based liquid alloy sensors are not mechanically or electrically robust, and have poor stability over time.

We present the design and fabrication of a high-resolution pressure-sensor soft system that can transduce normal force into a digital output. In this soft system, which is built on a monolithic silicone substrate, a galinstan-based microfluidic pressure sensor is integrated with a flexible printed circuit board. We used conductive thread as

interconnect and found that this method alleviates problems arising due to the mechanical mismatch between conventional metal wires and soft or liquid materials.

Conductive thread is low-cost, it is readily wetted by the liquid metal, it produces little bending moment into the microfluidic channel, and it can be connected directly onto the copper bond-pads of the flexible printed circuit board. We built a bridge-system to provide stable readings from the galinstan pressure sensor. This system gives linear measurement results between 500Pa-3500Pa of applied pressure.

We anticipate that integrated systems of this type will find utility in soft-robotic systems as used for wearable technologies like virtual reality, or in soft-medical devices such as exoskeletal rehabilitation robots.

1. Introduction

1.1. Why do we need integrate liquid-metal microfluidic devices with conventional electronic systems?

Soft systems research is a burgeoning field which includes research into components such as sensors and actuators, as well as the integrations of these components to make, for example, locomoting robots and wearable exoskeletons. These devices are built from soft materials including silicone elastomers and hydrogels [1,2]. These materials have bulk-properties such as low Young's Modulus and low hysteresis elasticity. These properties mean that the soft systems show great potential for a wide variety of applications, such as: compliant robotic grippers [3], locomoting soft robots that can navigate through narrow spaces [4], artificial skin with multidimensional sensors [5], skin-like large-area strain and pressure sensor [6], graphene–ZnO nanofiber for UV sensing [7],soft curvature sensors for joint angle proprioception [8,9], deformable and mechanically tuneable fluidic antennas [10], and many more.

The community is striding toward integrating more functionality into complex systems which include soft-components. Integrated circuit (IC) microelectronics packages—such as microcontrollers, amplifiers, voltage regulators—are made from hard materials such as epoxy and high-modulus metals. These ICs provide a means for delivering practical functionality to soft-systems, including: i) procedural control; ii) amplification and feedback; and iii) digital communications. The ability to deliver robust, integrated, soft electronics systems will make an important step in the evolution of soft devices.

1.2. Challenges in integrating Gallium-based microfluidic devices into electronic systems

Gallium-based microfluidic electronic devices usually consist of a soft silicone substrate with embedded liquid metal channels formed using soft-lithography. Conventional copper wires, which are commonly used to connect sub components in hard electronic devices by soldering, are not suitable for interconnecting eutectic liquid-metal microfluidic devices. Copper wires have a high bending moment, meaning that any mechanical reaction force acting upon the surrounding soft material can cause delamination, and device failure. Figure 1(a) provides a schematic of the mechanical displacement of a copper wire inside the fluidic channel. Delamination of the silicone, or movement of the wire, can cause a poor and unstable connection or a leak of eutectic liquid metal from the channels. Gallium-based liquid alloys are covered by a thin film of gallium-oxide [11] . This oxide forms a solid oxide 'skin' which affects the wetting dynamics of this complex fluid [12]. Gallium-oxide film is a semiconducting material [13] which means if a wire does not connect to the bulk-liquid, but is in-contact with the surface of the liquid, it is is likely to form a rectifying junction. Figure 1(d) shows the condition when a metal wire is inserted into a micro-channel and is wetted by highly conductive Galinstan, this configuration results in a stable connection. Figure 1(c) shows an unstable connection between the metal wire and the Galinstan, where the displaced wire only makes electrical-contact with the gallium-oxide skin. The displacement shown by Figure 1(c) is often irreversible due to the surface tension of the oxide. In summary, single-core copper-wire is a poor material for making strong-and-stable connections between printed circuit boards and eutectic liquid-metal sub-systems. Therefore, there is a need of a material used for connections with high conductivity and mechanical flexibility.

Several studies have been focused on making soft microfluidic sensors, but little work has been conducted into finding suitable materials for making robust interconnect. In 2015, Lessing et al. [14] proposed a solution to the interconnect problem by using a composite of metal wool embedded in a silicone elastomer. Metal-wools usually have centimetre-scale size and need to be soaked in the pre-polymer and degassed. Due to the amorphous structure of the steel-wool, and the soaking step, it is difficult to imagine how one would use this interconnect system to integrate a sensor with a small form-factor microcontroller, for example.

Park et al. designed a soft artificial skin [15] which uses multiple layers of microfluidic channels embedded in an elastomeric substrate. These channels are filled with eutectic gallium indium (eGaIn). The system is used to detect multi-axial strain and normal pressure. The researchers used thin single-core copper wire as interconnect to an external data-logger. Similar connection methods have also been used other research work, such as (Vogt et al. 2013)[16], (Tabatabai et al. 2013) [17], (Y. L. Park et al. 2012) [18], (Majidi et al. 2011) [9], and (Kubo et al. 2010) [19]. Zhang et al. reported on a novel method for integrating solid-state ICs directly eGaIn microfluidics in an elastomer package, by including the package at the casting-step [20]. Zhang et al. used steel needles to inject the eGaIn into the microchannels and then left these needles in-place to act as the external electrical-connection. Each of these systems has drawbacks in the interconnection to other devices, and these limitations hinder the uptake of the soft-sensor devices into integrated systems.

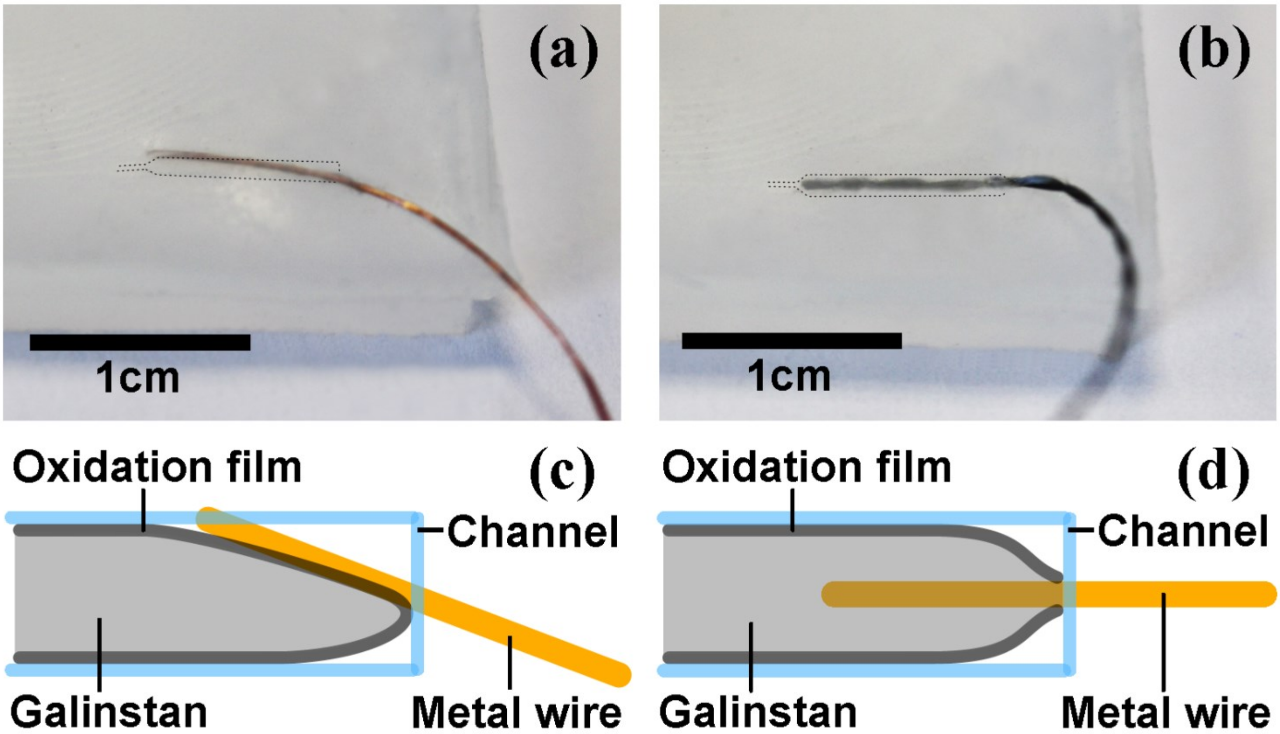

Figure 1. (a) A single-core copper wire inserted into a microfluidic channel in an Ecoflex substrate. Due to the high-bending moment and rigidity of the wire, when the external part of the wire moves it causes movement inside the channel. This movement can lead to delamination and degradation of the device. (b) When conductive thread is inserted into a microfluidic channel in an Ecoflex substrate then external movement doesn't affect the position of the wire inside the channel. (c) Schematic showing a poor connection between the wire and the liquid metal. The copper wire has moved out of the bulk-liquid and only touches the semi-conducting gallium-oxide film. (d) Schematic showing a good connection between the liquid-metal and a wire. The wire is wetted by the eutectic, and makes an electrical connection to the conductive bulk-liquid.

1.3. Conductive thread can be used as an interconnect material for integrated soft systems

Our approach to solve the interconnection-problem is to use conductive thread. This thread is a low-cost commodity material made of steel fibre which is commonly used to make electrically conductive smart-textiles. We used this material to fabricate interconnect for an integrated electronics system. Figure 2 shows the integrated system which contains a sensor, interconnect, and a flexible printed circuit board. The printed circuit board provides a bridge, an amplifier, a microcontroller and LED outputs. The conductive thread lies in a serpentine shape (shown by figure 2b) and form a mechanically, and electrically, robust connection between the soft microfluidic pressure sensor and the flexible printed circuit board (PCB). We made the pressure sensor via soft-lithograpy using a silicone substrate (Ecoflex 00-50), and we filled the channel with a gallium-indium-tin eutectic alloy (Galinstan) that contains 68.5% gallium, 21.5% indium, and 10% tin. We made this alloy from the constituent metals, and we chose the proportions to ensure that the eutectic was liquid at room temperature, it has a melting point of -19°C [11]. The PCB is 18μm (0.5 Oz) copper based on a 200μm flexible FR4 substrate.

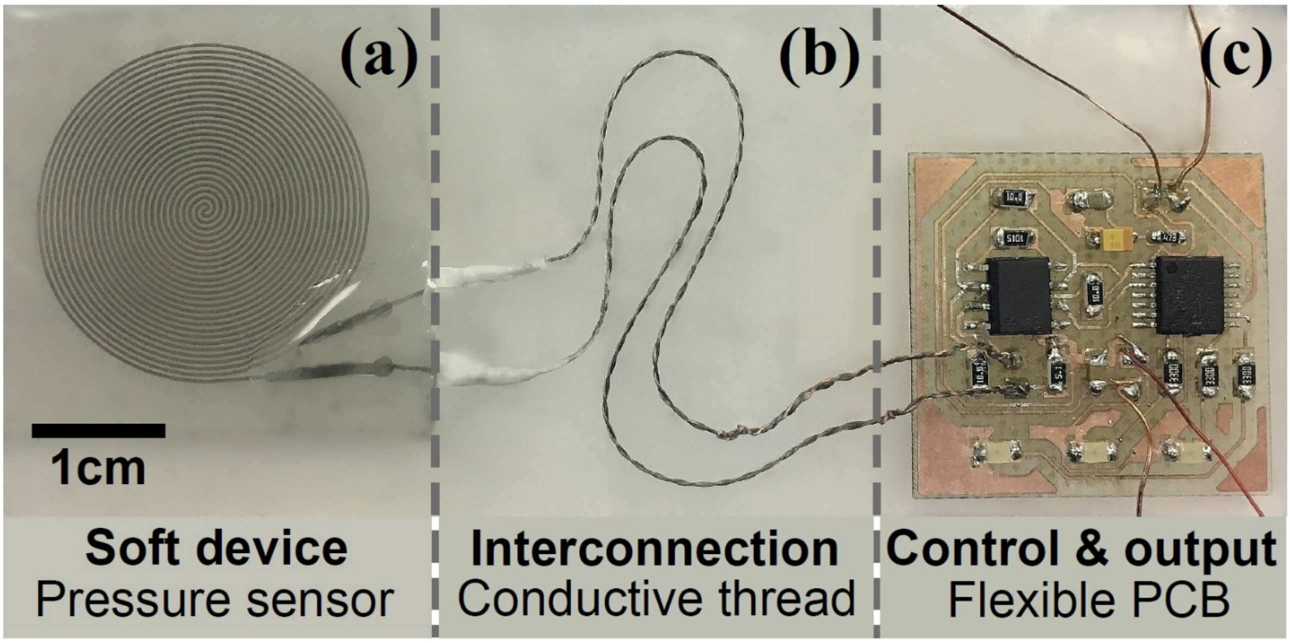

Figure 2. Top view of the integrated soft pressure sensing system. (a) Normal-force pressure sensor made with a Galinstan-filled microfluidic-channel encapsulated in an Ecoflex substrate. (b) Conductive thread is used as interconnection between the pressure sensor and the flexible PCB. The serpentine shape provides strain-relief. (c) A flexible PCB consisting of hard electronic components, including a bridge circuit, an amplifier, a microcontroller, and LEDs.

We chose conductive thread as the best candidate for the connection between the pressure sensor and the flexible PCB due to the combination of its electrical and mechanical properties. Conductive thread can provide an electrically conductive path axially along the fibre bundle as well as it is flexible out-of-plane. As shown in figure 1, conductive thread presents mechanical stability within the channels when moved or deformed, providing a robust electrical connection.

We inserted one piece of conductive thread and one piece of copper wire (each of the same diameter) into two equal-volume droplets of galinstan. We observed the deformation of the complex-liquid surface as we withdrew the wires from the droplets. Figure 3 provides photographs taken immediately before the wires detached from the droplets. This figure shows that conductive thread (3a) is wetted more than the copper (3b).

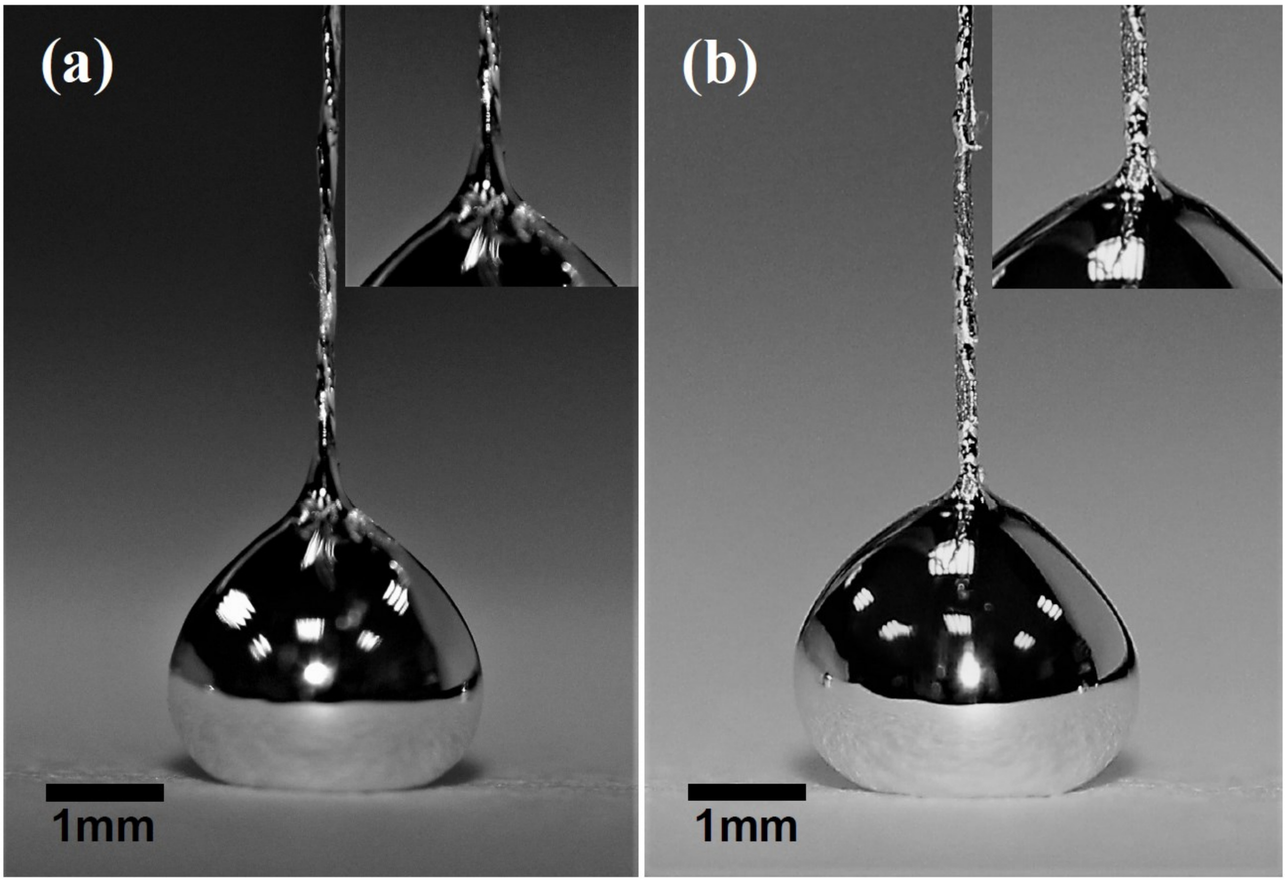

Figure 3. Photographs showing the withdrawal of (a) conductive thread and (b) copper wire from a galinstan droplet. The galinstan wets more onto the conductive thread than the copper wire.

2. Methods

2.1. Design and fabrication

2.1.1. Design of a rapid-prototyping technique for soft-lithography moulds

We developed a novel, rapid, and reliable way of making soft-lithography masters. Figure 4 illustrates the fabrication process: (i) We applied a piece of self-adhesive vinyl (Brand: d-c-fix®, model number: CRAFTPK20) onto the surface of a 2mm-thick acrylic board (2mm Acrylic Cast, AMARI), and removed bubbles using a roller;

(ii) We used an LPKF Protolaser U3 laser micromachining to cut out the designed channel profile on vinyl. The profile of the channels can be cut precisely since the laser system has an error rate less than 5%; (iii) We weeded out the unwanted parts of vinyl and no residue remained on the surface as this vinyl is designed to be removed without leaving residue; (iv) We glued another 2mm-think acrylic frame onto the acrylic substrate as the final step of making a mould for soft-lithograpy.

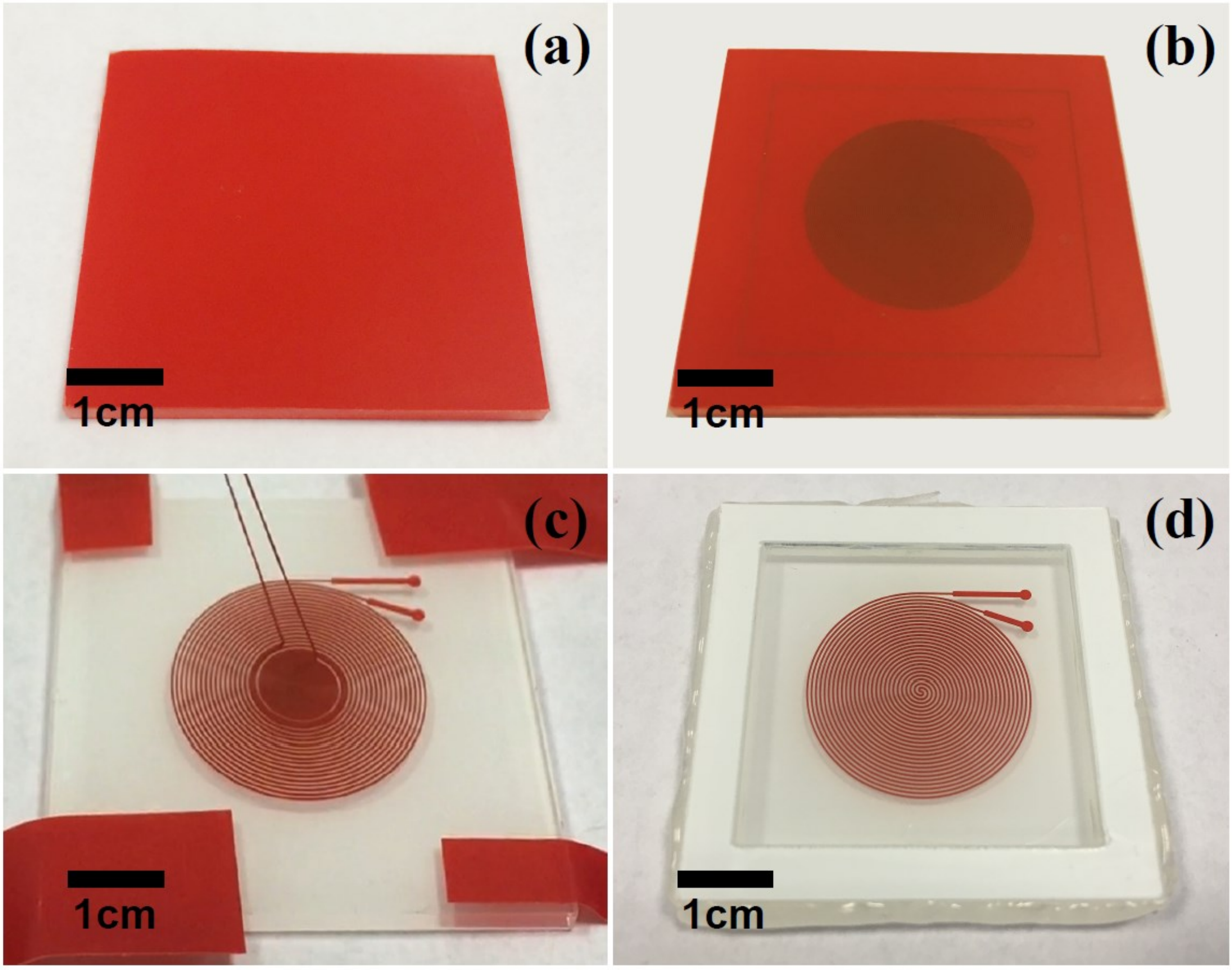

Figure 4. Illustration of fabrication process of the soft-lithography mould. (a) We stuck a piece of 0.15mm thick self-adhesive vinyl onto an acrylic substrate; (b) We cut the vinyl using a laser micro-machining system. The channel width and the gap-width between channels are both 200μm; (c) We weeded out the unwanted vinyl; (d) Finally we glued a 2mm-think acrylic frame onto the substrate to form a mould for soft-lithography.

Using this new method, we can fabricate a custom-designed microscale soft lithography mould in just a few minutes. The smallest channel-width that we achieved using this method is 100μm. The smallest linewidth that the laser micro-machining system can produce is 30μm and the minimum distance between lines is 70μm. Theoretically, we can fabricate any 2D structure with the fabrication procedure we proposed, as long as size of the design can fit the laser machine. When we produce a soft-lithography master with vinyl, we tend to get stable and reliable production results when the line width and space width are both equal or greater than 200μm. This limit of 200μm is limited by the physical removal of the vinyl, not the resolution of the laser system. This type of soft-lithography mould we fabricated can be used approximately 10 times before the vinyl loses adhesion to the acrylic substrate. This method is rapid and convenient for miocrofluidics and soft-systems researchers.

2.1.2. Design and fabrication of the microfluidic pressure sensor

The eutectic alloy we used consists of 68.5% gallium, 21.5% indium, and 10% tin, its bulk-resistance is $4.3 \times 10^{-6}\Omega/\mathrm{cm}$. We used this resistance value and the known dimensions of the vinyl film mould to design the length of the channel in the pressure sensor to be 10Ω.

Figure 5 shows the fabrication process for this microfluidic pressure sensor. (i) We mixed a 1:1 volume ratio of Part A and Part B Ecoflex 00-50 (Reynolds Advanced materials), degassed the pre-polymer, poured the liquid into in the soft-lithography mould, and then placed the filled-mould into a convection oven at 65℃ for 20 minutes. (ii) We bonded another 2mm-thick blank piece of Ecoflex to the casted piece of Ecoflex. We used a cannula to insert the conductive thread into the channels in the Ecoflex substrate. The resistance of the conductive thread is $27\Omega/\mathrm{m}$ (Smooth conductive stainless-steel thread bobbin, Sparkfun Electronics). (iii) We injected galinstan into the channels using a syringe and a needle, and we inserted a second needle into the outlet of the channel to vent air. To ensure that the conductive thread is fully wetted, we injected the galinstan 1cm further into the channel than the protrusion of the embedded conductive thread. Finally, we used silicone epoxy to seal the holes that we created during the injection process. This seal prevents the wire being pulled out and prevents liquid metal-alloy leaks when the sensor is pressed.

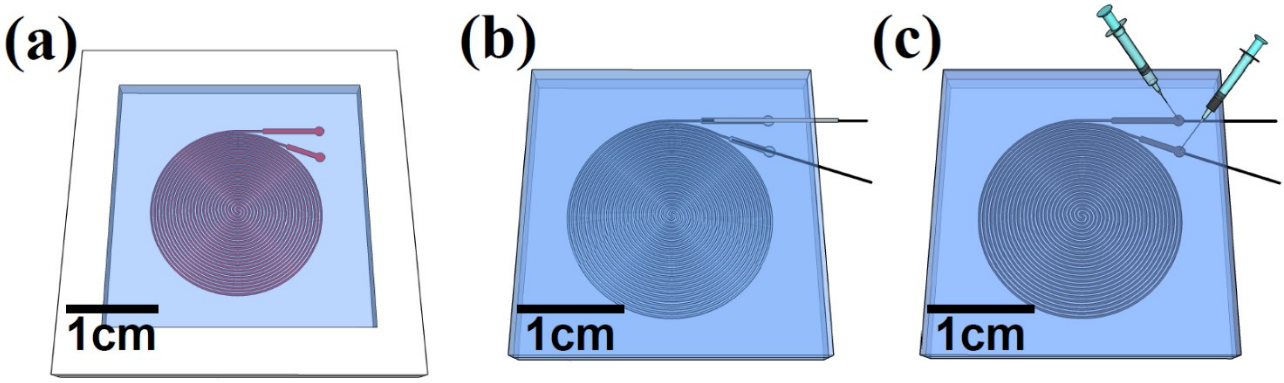

Figure 5. Fabrication process of the microfluidic pressure sensor. (a) We poured uncured Ecoflex into the soft-lithography mould; (b) We bonded another 2mm blank piece of Ecoflex on to the patterned Ecoflex to seal the channel. We used a cannula to insert the conductive thread into the channels; (c) We injected galinstan into the channel with two needles, one to fill and one to vent. The syringes are not shown to scale.

2.1.3. Design of the electronic system

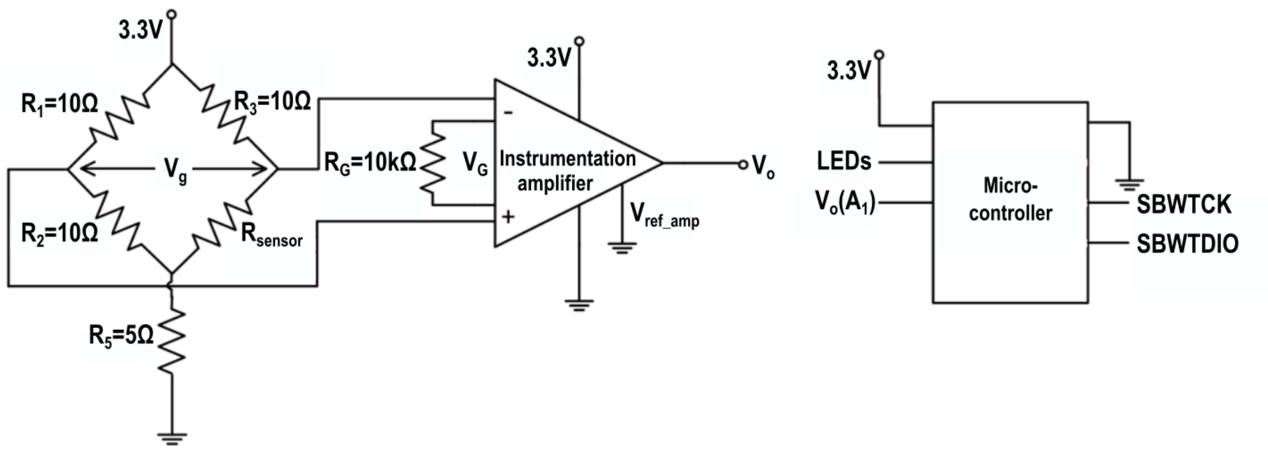

Figure 6. Circuit schematic of the system on the flexible PCB. The pressure sensor is a variable-resistance in the Wheatstone bridge network. The voltage output (V_0) from the instrumentation amplifier is the voltage input to the analog-to-digital (ADC) converter in the microcontroller (12-bit ADC on the Atmel SAM3X8E ARM Cortex-M3 or 10-bit ADC on the MSP430F2012 MCU). The MCU is programmed using 2-wire JTAG via SBWTCK (Spy-Bi-Wire Test Clock) and SBWTDIO (Spy-Bi-Wire Test Digital IO). The MCU outputs to three LEDs which light in-proportion to the applied normal pressure.

Figure 2c shows a top view of PCB in the integrated soft electronic system. In this flexible PCB, there is a Wheatstone bridge, an instrumentation amplifier, a microcontroller, and three LEDs as output. Figure 6 shows the circuit design of the flexible PCB. The Wheatstone bridge is used to measure the variable resistance of the pressure sensor, and the instrumentation amplifier (INA 128, Texas Instruments®) is used to amplify the voltage difference from the bridge circuit. The output from the instrumentation amplifier is fed to the 10-bit analog-to-digital converter (ADC) in the microcontroller. The relationship between the resistance of the microfluidic sensor and the ADC value is shown by formulas 1-4. In these formulas, v_{ADC} is the ADC value measured by the microcontroller and V_{A1} is the voltage on pin A1 of the microcontroller, N is the number of bits in the ADC, and V_{ref_MCU} is the reference voltage of the ADC (3.3V in this circuit). The bridge circuit consists of four resistors, R_1, R_2, R_3 and R_x, which is resistance of the microfluidic sensor. When the sensor is pressed, the cross-sectional area of the channel changes accordingly, and so does the value of R_x. The gain of the instrumentation amplifier is G, and this value depends on R_G in the circuit. Increasing the value of R_G can enhance the measurement sensitivity of the system while decreasing the value of R_G can improve measurement range of the system.

$$v_{ADC} = \frac{V_{A1}}{2^N} \times V_{ref\_MCU} \qquad (1)$$

$$V_{A1} = V_g \times G \qquad (2)$$

$$V_g = \left(\frac{R_x}{R_3+R_x} - \frac{R_2}{R_1+R_2}\right) \times V_s \qquad (3)$$

$$\mathrm{G} = 1 + \frac{50k\Omega}{R_G} \qquad (4)$$

Many of the previously reported soft-sensors have been evaluated using external instrumentation such as a digital-multimeter, an LCR meter or four-point probes [18,21,22]. Including the Wheatstone bridge as an integral part of the system offers the following benefits: 1) The system can be powered with a low-voltage supply or even a 3.3V button battery. 2) The Wheatstone bridge is based on the concept of a differential measurement which can be extremely accurate[23] and provides robustness to thermal-drift.

We used the MSP430F2012 microcontroller in this system as it offers a 10-bit ADC and is capable of low-power modes. We used three LEDs to visually demonstrate compression of the pressure sensor.

2.2 Design of the experimental system and tests

To test the physical limitation of the pressure sensor and the mechanical robustness of the proposed conductive thread connection, we performed: i) A tensile test on three batches of samples at a strain rate of 100mm/min using an INSTRON 3367; ii) A tensile test on two batches of samples with copper and conductive thread connections at a strain rate of 100mm/min using an INSTRON 3367.

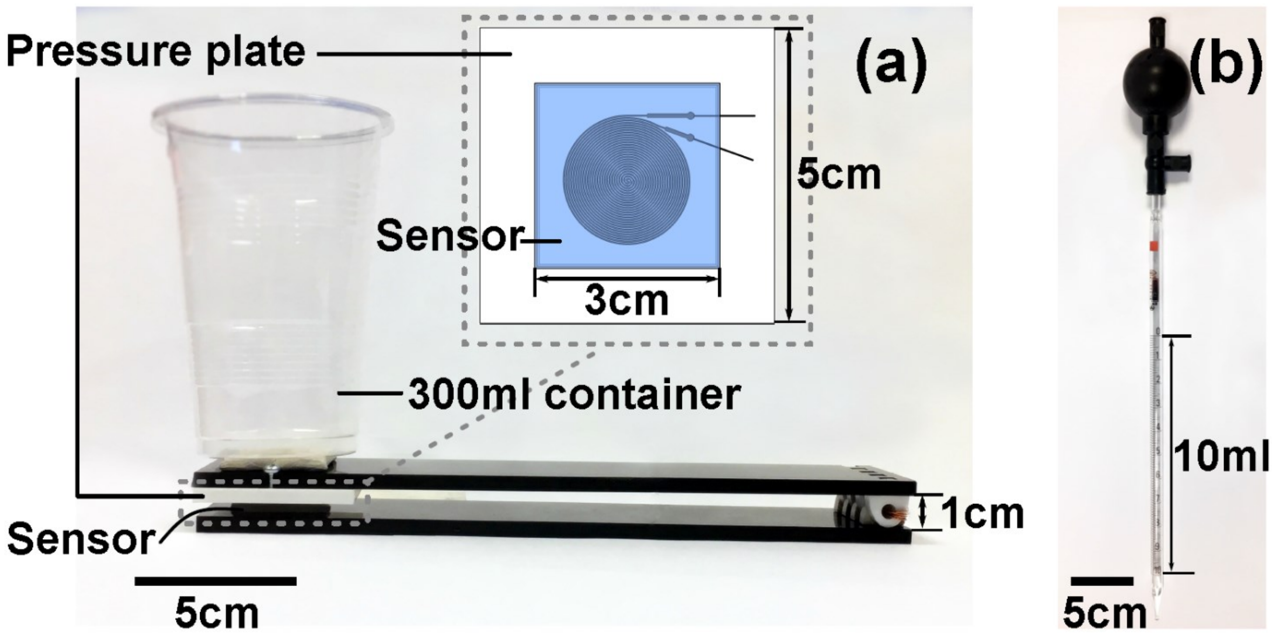

Figure 7. Experimental set-up. (a) A system for applying uniform pressure over the surface of the pressure sensor. The thickness of the pressure-plate is 6mm and the thickness of the sensor is 4mm, by designing the hinge to be 1cm the plates are kept parallel; (b) We used a 10ml-size pipette to dispense accurate volumes of water into the container shown in (a). We found this volumetric approach to be a convenient way to refine the increments of weight applied to the sensor.

Figure 7 shows a photograph of the system we used to apply pressure for the pressure sensing system. In order to apply pressure uniformly, we made a flat clip with a pressure-plate which fully overlapped the sensor. As shown in figure 7(a), we placed the sensor at the centre of the pressure plate. We placed a 300ml container on the top of the indenter. We used a pipette as shown in figure 7(b) to fill the container, and this volumetric approach allowed us to refine the applied weight in varying increments. At 25°C, the weight of 1ml water is 1g, so 10ml water results in a weight of 10g, i.e., about 9.8N on the pressure sensor. The distance between the parallel-plates of the clip is 1cm, which is the sum of thickness of the pressure plate and the pressure sensor. The area of the pressure-plate is 5×5cm^2, and the area of the sensor is 3×3cm^2, which is the effective pressing area.

We designed five experiments using this system, to improve the resolution when characterising the pressure sensor we used a 12-bit ADC on an Atmel SAM3X8E ARM Cortex-M3 rather than the 10-bit ADC on the final integrated device, which used an MSP430F2012 MCU.

Experiment-1.) To test the sensitivity and resolution of the pressure sensing system, we measured the change in the ADC value (Δ ADC) when we varied the weight on the sensor from 0g to 300g with a step-size of 10g.

Experiment-2.) To test the hysteresis properties of the pressure sensor we increased the weight from 0g to 300g and then back from 300g to 0g.

Experiment-3.) To measure the full-range, and get a calibration curve we increased the weight from 0g to1080g using weights.

Experiment-4.) To test the reliability of the sensing system we powered on the sensing system at zero-applied load and recorded the change in the ADC value.

Demonstration.) To visually display the high resolution of our pressure sensing system we used coins as weights to press the sensor. The LEDs on the PCB were used to visually display the number of coins on the sensor.

3. Results

In order to investigate the mechanical properties of our system, a tensile testing was carried out using an INSTRON 3367 fitted with a 250N load cell at a strain rate of 100mm/min. We fabricated three sets of samples with the following dimensions: 50×30×4mm. Each set of samples were tested up to a strain of 500%, including neat Ecoflex, Ecoflex with empty microchannels and Ecoflex with microchannels filled of Galistan. Figure S1 in the supplemental information shows photographs in process of this experiment. Stress and strain curves of the three sets of samples were plotted as shown in Figure 8.

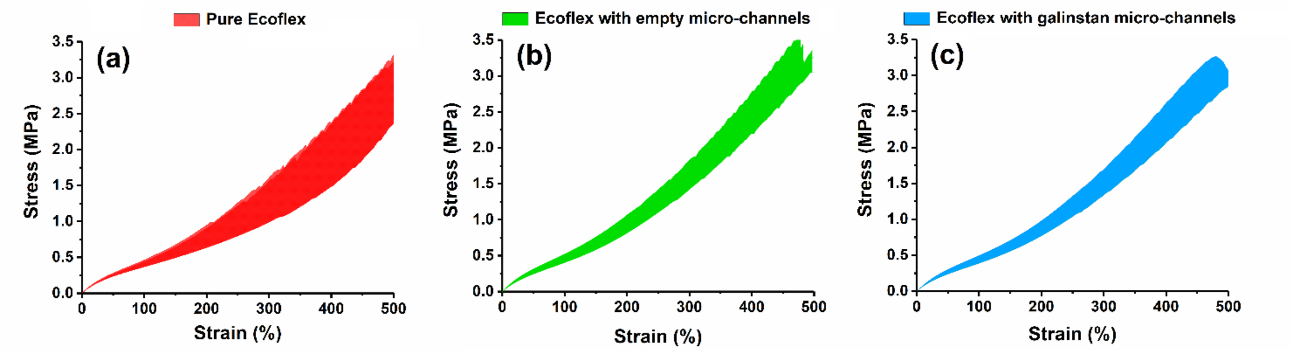

Figure 8. Stress vs strain curves of (a) pure Ecoflex; (b) Ecoflex with empty microchannels; and (c) Ecoflex with microchannels filled with Galistan. The red, green, and blue areas represent range of stress vs strain curves of four samples in each batch.

In the results, the stress and strain curves of the three batches of samples don't show meaningful difference. The microchannel and the gallistan does not affect the overall mechanical behaviour in comparison to the pure Ecoflex. This might be due to the small size of the microchannel comparing to the thickness of the samples as well as the small amount of conductive-liquid within. In addition, each sample can be stretched to a strain up to 500% without failure. When the strain was higher than 500%, the samples slipped out from the clamps during the test. However, according to the datasheet of Ecoflex, elongation at break of Ecoflex 00-50 is 980% (tested with ASTM D-412). Therefore, we believe that the stretchability of the sensor is enough for our pressure sensing system.

An additional test was carried out in order to evaluate the mechanical robustness of the proposed connection. We fabricated two sets of samples. In each sample, copper wire or conductive thread was inserted into Ecoflex with a dimension of 30×20×4mm and then sealed with sil-epoxy, as shown in figure S2. In this experiment, the Ecoflex were clamped from the bottom and the thread or copper wire was clamped from the top. We used INSTRON 3367 fitted with a 250N load cell to stretch the thread or copper wire at a strain rate of 100mm/min until it detached. The minimum load and extension required to detach the thread/wire are shown in Table 1.

As shown in table 1, although the fabrication errors may affect the experimental results, the conductive thread needs more load and extension to be pulled out of Ecoflex substrate than copper wire in general. An average minimum load of 1.40 ± 0.37 N and 1.13 ± 0.12 N is needed in order to detach the conductive thread and copper wire connections from the channel respectively. We believe this test demonstrates that the conductive thread exhibits a higher mechanical robustness than using a copper wire for our system.

	Threads		**Copper**	
	Extension	**Load**	**Extension**	**Load**
	(mm)	**(N)**	**(mm)**	**(N)**
1	10.00323	1.50569	8.67	1.12497
2	10.17	1.34725	7.83669	1.00257
3	14.16996	1.8146	9.5033	1.10632
4	7.17011	0.93495	9.83657	1.30265

Table 1. Values of minimum load required to lose connection (detached wire/thread from the channel).

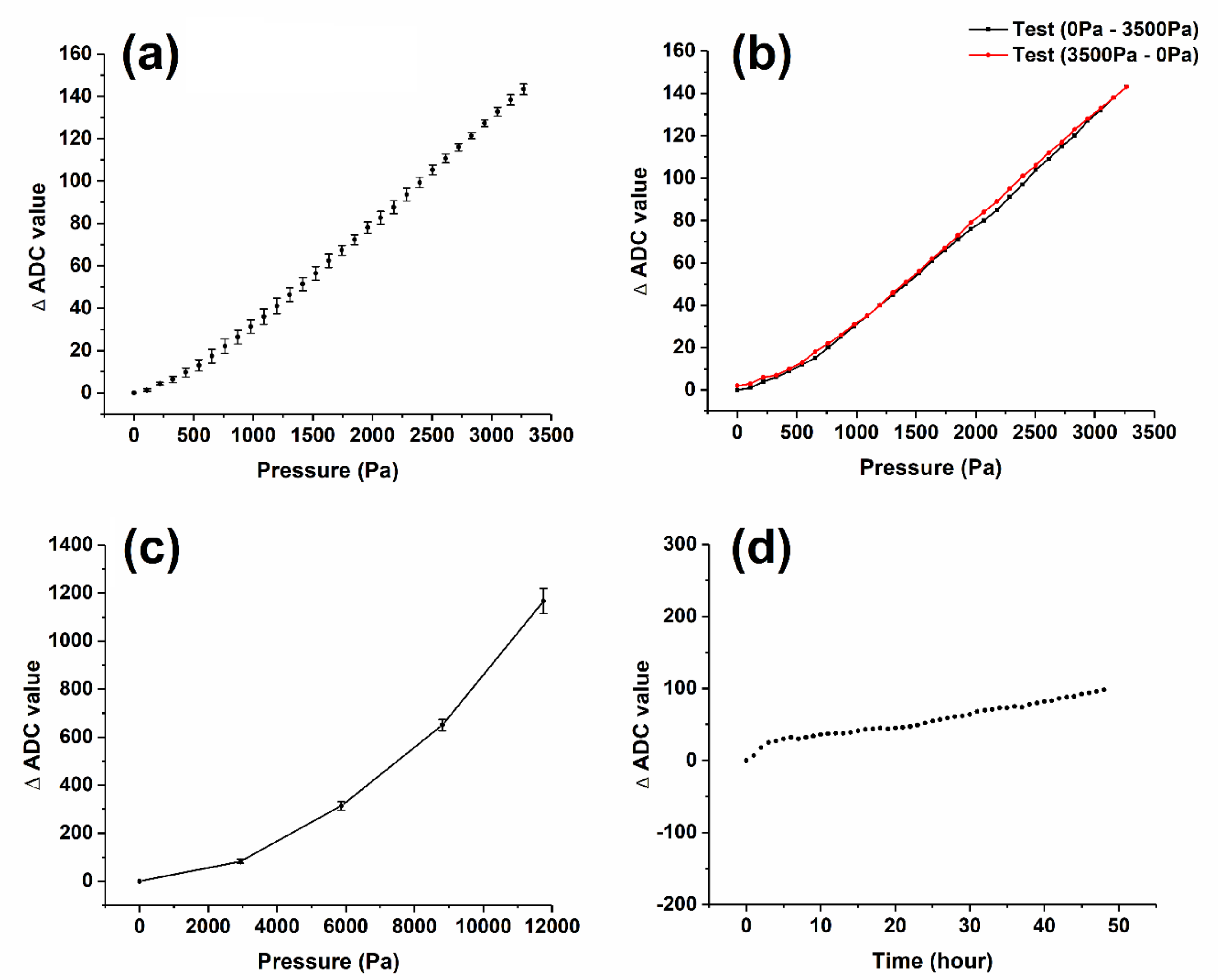

Figure 9. Results of four experiments to characterise the pressure sensor: (a) Sensitivity and resolution test over a pressure range of 0Pa-3500Pa, with an increment of around 100Pa. Points show the mean values of Δ ADC

and the error bar on the Y-axis shows one standard deviation n=7; (b) Hysteresis test. We increased the pressure on the sensor from 0Pa to 3500Pa (black curve) then decreased it from 3500Pa to 0Pa (red curve); (c) Calibration curve of Δ ADC when we increased the weight over a large range from 0Pa to 12kPa, using multiple 270g weights; (d) Reliability test. This curve shows the baseline change of the ADC from sample 1 at t=0 to 48 hours. This drift can be corrected by tracking the baseline value and taking the instantaneous Δ ADC.

Results from the four experiments that carried with the pressure applying system are shown by Figure 9. From the perspective of an electronic system, it is the most intuitive to show the relationship between the value of the ADC read by the microprocessor and the pressure on the sensor. Therefore, ΔADC was used in our results instead of ΔR.

Figure 9 (a) shows the sensitivity and resolution of the system by tracking the variation of the 12-bit ADC output—ΔADC—in the 0Pa-300Pa pressure range, with a step of ~100Pa. Good linearity is observed when the load above 500Pa and when the pressure is spread evenly. In the measured range, the value of the 12-bit ADC increased by 143 units. This experiment was conducted three times and the standard deviation of each point on the curve is less than 4.

Figure 9 (b) shows the result of the hysteresis test. In this experiment, we increased (in ~100Pa increments) the pressure on the pressure sensor from 0Pa to 3500Pa and then decreased it back to 0Pa. The results show that the sensor is has little to zero hysteresis.

We tested a high-load range from 0Pa to 12kPa and the results are shown by figure 9 (c). We conducted this experiment seven times. In the measured range, the value of the 12-bit ADC increased by around 1166 units. The results show that the larger loads give more spread in the data; the largest standard deviation is 52 at the last data point. The sensor shows a quadratic relationship between applied force and electronic output. The sensitivity increases as more pressure is added and this may warrant future investigation for a design with enhanced sensitivity.

We conducted an investigation into baseline-drift over a long period of time. Figure 9 (d) shows the reliability test that we conducted for 48 hours. The 12-bit ADC value in the no-load sensing system increased by 100 units in a linear fashion, but this drift is mitigated in the measurement system by taking instantaneous differential measurements.

To show, visually, the high sensitivity of our integrated pressure sensing system using the MSP430F2012 MCU: we used coins (UK £1) to weigh down the sensor. Figure 10 (a-d) illustrates that when there was no weight on the sensor, no LED lights up, two coins lights one LED and four coins lights two LEDs. The weight of one-pound coin is 9.5g, the diameter of the coin is 22.55mm. Two coins, therefore, creates 0.18N force and ~200Pa on the sensor.

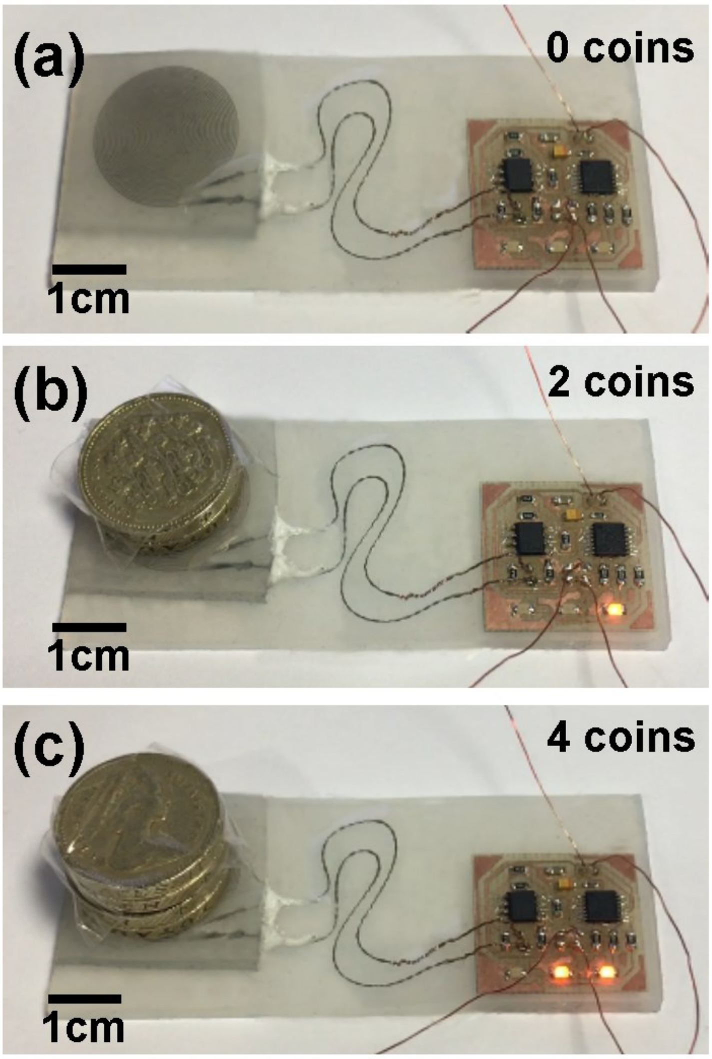

Figure 10. Demonstrating the sensitivity of the integrated soft system. We programmed the system to light

LEDs in proportion to the applied force (a) no coins applied (b) 2 coins applied (c) 4 coins applied.

4. Discussion

Our results clearly show that the proposed pressure sensing system has a high sensitivity in the low-Newtons of force range. Within the pressure range of 500Pa – 3500Pa, the relationship between the 12-bit ADC value in the system and the weight on the sensor shows a linear relationship. Every 100Pa increment in pressure causes an increment of five units in the 12-bit ADC value. After repeating three times the hysteresis experiment, we found out that the largest standard deviation is not higher than four (with a maximum 12-bit ADC variation of 143). However, when applying a high-load (12kPa), the largest standard deviation goes up to 52 (with a maximum 12-bit ADC value of 1166). In 7 repeats of the high-load (12kPa) experiment (with a maximum 12-bit ADC value of 1166) then the largest standard deviation is 52. These results show a good reliability and feasibility of our system. As show in figure 9 (b), this pressure sensing system exhibits a low hysteresis. The test in figure 9 (b) has proved this pressure sensing system has low hysteresis. In summary, we used conductive thread to integrate, robustly, a microfluidic sensor into an electronic system. This integration means that the resulting soft electronic system benefits from the functionality of conventional solid-state electronic system and exhibits the mechanical properties of soft and flexible materials.

We used a Wheatstone bridge and instrumentation amplifier in this system, the voltage that is measured by the microcontroller depends on both the voltage output of the Wheatstone bridge, and on the gain of the instrumentation amplifier. The gain of the amplifier depends on the choice of R_G. We do not discuss the influence of R_G to the sensing system as this is basic background electronics theory; increasing the gain of the instrumentation amplifier can give the sensing system higher resolution but will reduce the corresponding measurement range, and vice versa. The system we presented in the paper is supplied by 3.3V, which means the instrument amplifier that connected to the bridge circuit has a maximum output of 3.3V. When output voltage of the instrument amplifier reaches 3.3V, even resistance of the sensor keeps increasing, the voltage output won't change. In conclusion, ADC value which can represent voltage at the analogue I/O port in the microcontroller, will increase when the sensor is pressed, then remain the same at its maximum value when the pressure reaches a boundary.

In the 48-hour stability test, the ADC value in the system slightly and gradually increased. This increment indicates that the resistance of the microfluidic sensor was increasing. The resistance increase may be a result of temperature increase due to joule-heating or may be due to further oxidation of galinstan in the channel. To mitigate this drift, in future work, we could use a resistor which has ten or hundred times higher resistance than the microfluidic sensor before matching the Wheatstone bridge. This method will reduce the resolution in the system as it will reduce the current passing though the galinstan microfluidic pressure sensor.

5. Conclusions

In this study, we found that conductive thread is a good replacement for conventional metal wires to be used as interconnect in soft sensing systems based on liquid-metal microfluidic devices. We also presented a rapid and reliable method for fabricating soft-lithography moulds in the research laboratory. We built a pressure sensing system using conductive thread as the interconnection between microfluidic sensor and flexible PCB populated with solid-state electronic components. Using this integrated electronic system we demonstrated its ability to sense pressure with high resolution. Using these methods we hope that more researchers will be able to integrate soft devices with electronic systems. By enabling strong-and-stable electrical connections we hope to enable the community to be one-step-closer to developing fully integrated soft robotic, or wearable systems.

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Supplemental Information

In order to investigate the mechanical properties of our system, a tensile testing was carried out using an INSTRON 3367 fitted with a 250N load cell at a strain rate of 100mm/min. Figure S1 and video2 in the supplemental information shows photographs in experimental process. All the samples we used in this tensile test has a dimension of 50×30×4mm.

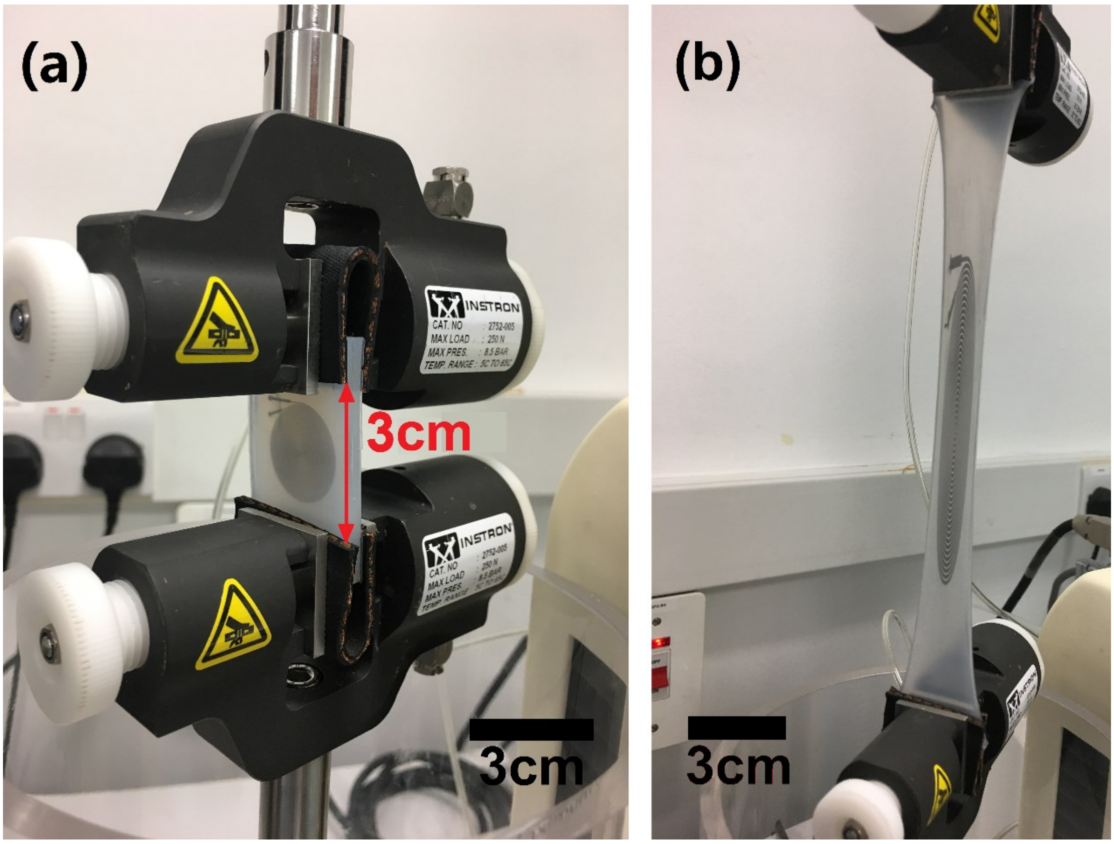

Figure S1. A 50×30×4mm Ecoflex substrate with micro-channels filled of Galinstan was under a tensile test with an INSTRON 3367 fitted with a 250N load cell.

In order to evaluate the mechanical robustness of the proposed connection, we fabricated two sets of samples. In each sample, copper wire or conductive thread was inserted 1cm into Ecoflex with a dimension of 30×20×4mm and then sealed with sil-epoxy, as shown in figure S2.

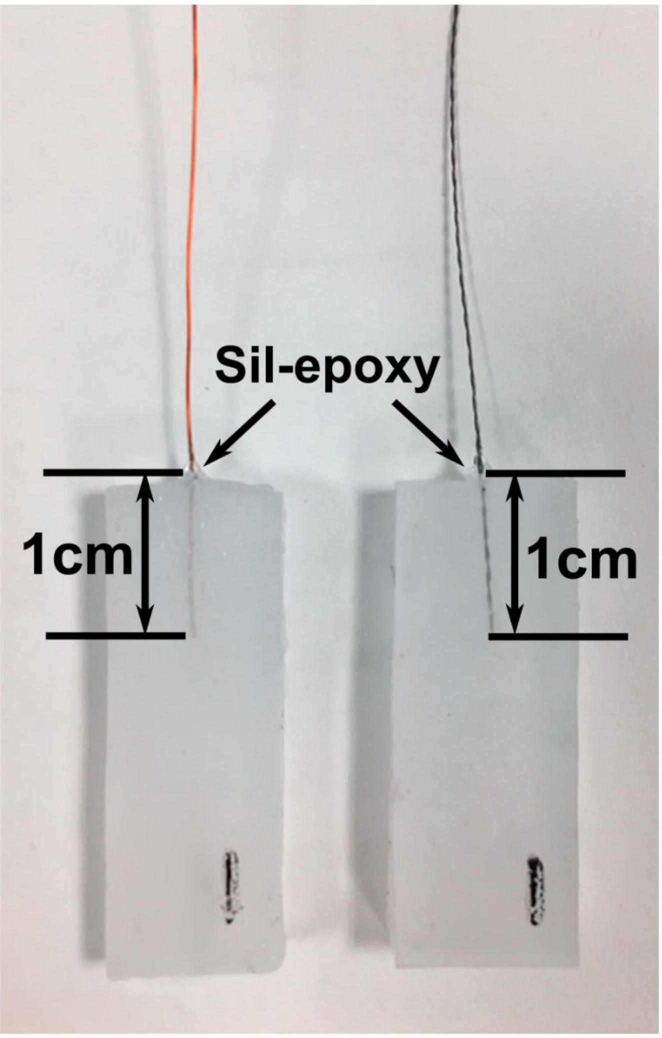

Figure S2. Samples used to test mechanical robustness of the connection between Ecoflex substrate and copper wire or conductive thread.