Wearable Tactile Keypad with Stretchable Artificial Skin

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***Abstract*— A hyperelastic, thin, transparent pressure sensitive keypad is fabricated by embedding a silicone rubber film with conductive liquid-filled microchannels. Applying pressure to the surface of the elastomer deforms the cross-section of underlying microchannels and changes the electrical resistance across the affected channels. Perpendicular conductive channels form a quasi-planar network within an elastomeric matrix that registers the location, intensity and duration of applied pressure. Pressing channel intersections of the keypad triggers one of twelve keys, allowing the user to write any combination of alphabetic letters. A 5% change in channel output voltage must be achieved to trigger a key. It is found that approximately 100 kPa of pressure is necessary to produce a 5% change in voltage across a conductive microchannel that is 20 microns in height and 200 microns in width. Sensitivity of the keypad is tunable via channel geometry and choice of elastomeric material.**

I. INTRODUCTION

Recent developments in wearable computing [1], as well as flexible pressure sensors and circuits [2], [3], have brought the robotics community closer towards the realization of skin-like tactile sensing. Flexibility and stretchability will significantly expand the scope of applications of sensors, particularly towards wearable sensing for which surfaces are arbitrary and dynamic. Pressure sensors and tactile interfaces for wearable electronics and soft robots must be elastically soft and remain functional when stretched to several times their natural length.

Stretchable capacitive pressure sensors for tactile sensing and humanoid robots have recently been demonstrated with elastic insulator layered between conductive fabric [4], [5], [6] and a silicone rubber sheet embedded with thin gold film [7]. Such sensors also operate by continuously supplying electrostatic charge and measuring the electrostatic induction induced by surface pressure [8]. Other recent efforts include resistive sensors composed of elastomer embedded with conductive microparticle filler [9], [10], [11] and ionic liquid [12].

Various types of highly conductive stretchable materials have been developed for stretchable electronic applications. Many exploit structures such as waves and nets, as in the case of wavy thin metals [13], [14], [15], [16], [17], [18], graphene films [19], and single-walled carbon nanotubes [20]. Stretchable electronics consisting of elastomers embedded with channels of conductive liquid have also been investigated [21], [22], [23], [24]. Liquid conductors eliminate the need for rigid electronics and preserve the natural hyperelasticity of the embedded elastomer. Thus, this technology offers a vast range of applications for which large deformations and pressures might be sustained.

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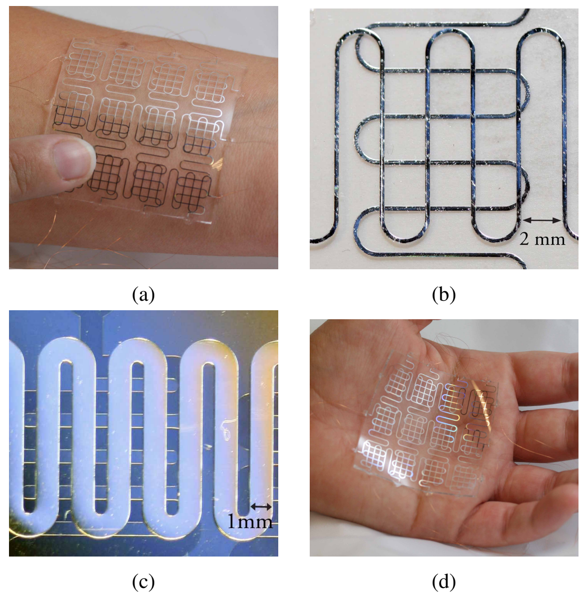


Fig. 1. Thin sheets of polydimethylsiloxane (PDMS) silicon rubber embedded with conductive liquid-filled (eGaIn) microchannels for pressure sensing applications. (a) A twelve-key keypad resting on a wrist. The channels are 20 microns in height and 200 microns in width. The entire device thickness is approximately 700 microns. (b) A single key of the keypad shown in subfigure(a). (c) Conductive liquid-filled channels with dimensions of 10 microns in height and 1000 microns in width, for a channel aspect ratio equal to 0.01. (d) A twelve-key keypad resting in the palm of a hand, demonstrating its conformability.

In this work, we present the application of a thin, transparent elastomeric sheet embedded with conductive liquid microchannels to an all-compliant and stretchable pressure sensing keypad. A functional keypad comprising of twelve keys is fabricated and can be seen in Figure 1. The keypad is composed of a polydimethylsiloxane (PDMS) matrix sheet embedded with conductive liquid microchannels of non-toxic Eutectic Gallium-Indium (eGaIn, BASF) and is approximately 700 microns in total thickness. Applying pressure to the surface of the elastomeric sheet deforms the cross-section of nearby channels and changes the electrical resistance of the channels. The relative change in the electrical resistance of all of the channels within the network yields the location and intensity of applied pressure. Here, serpentine-patterned channels are overlaid perpendicularly, such that the locations of the channel intersections behave as 'buttons'. The serpentine-like pattern allows the highly compliant and stretchable sensors to sense pressure over a larger area. Keypads are rapidly fabricated via a maskless photolithography technique. Enhanced sensitivity of the keypad can be achieved through reduction of the microchannel aspect ratio and increased density of the channel network. Moreover, the elastomeric sheet may be easily integrated with wearable electronics, human-computer interactions or robotic systems for soft and stretchable sensing functionality.

II. FABRICATION

Tactile keypad devices are fabricated by means of a photolithography process, which is detailed in Figure 2. Choice of photoresist and spin-rate determine the subsequent depth of the patterned features. Photoresist (SU-8 2050) is spun onto a clean wafer at 500 rpm for 10 seconds (spread), followed by 4000 rpm for 30 seconds (spin). The wafer is then placed on a hot plate at 65 °C for 3 minute and 95 °C for 6 minutes. The coated wafer is then patterned via a maskless, direct-write laser exposure utilizing a diode-pumped solid-state (DPSS) 355nm laser micromachining system. This method of exposure enables channels as small as 25 microns in width and has produced networks with channels edges only 50 microns separated, thus introducing the potential for densly packed fine features. After exposure, the wafer is post-baked for 1 minute at 65 °C and 6 minutes at 95 °C and finally developed in SU-8 developer for 5 minutes.

Silicon wafers patterned with photoresist are used to mold three PDMS layers that result in the keypad device. A hydrophobic monolayer is introduced by vapor deposition to discourage adhesion between the silicon molds and subsequently cured PDMS. The wafers are placed in an evacuated chamber ($\sim$20 mTorr) with an open vessel containing a few drops of Trichloro(1H,1H,2H,2H-perfluorooctyl)silane (Aldrich) for $\geq$3 hours. PDMS (Sylgard 184; Dow Corning, Midland, MI) is spin-coated in liquid form (10:1 mass ratio of elastomer base to curing agent) onto a silicon mold to result in a thin elastomer film of tunable thickness.

The device shown in Figure 1 is comprised of two patterned PDMS layers with a thickness of approximately 250 microns, which corresponds to a spin-coating speed of 300 rpm. The third and bottom layer of the device is unpatterned and approximately 200 microns in thickness, which is fabricated by spin-casting PDMS on a blank silanized wafer at 400 rpm. Each of the PDMS layers are cross-linked in the molds by oven-curing at ~ 60 °C for 30-40 minutes. Layers are manually removed from the molds and bonded together via oxygen plasma surface treatment, conducted at 65 watts for 30 seconds. Patterned layers are bonded together first, overlaying the channel patterns with the desired alignment.

In order to accommodate subsequent filling of the channels within such a thin device using conventional tubing and syringe dispensing, small blocks of PDMS are adhered to the device inlet and outlet locations on top of the cured PDMS. Adhesion is achieved by heating the cured PDMS on a hot plate at 100 °C, applying a small amount of uncured PDMS onto the inlet and outlet locations, and then pressing the PDMS blocks into the uncured droplets. These blocks are then allowed to fully cure on the hotplate for approximately 30 minutes. Lastly, small holes are introduced to the adhered

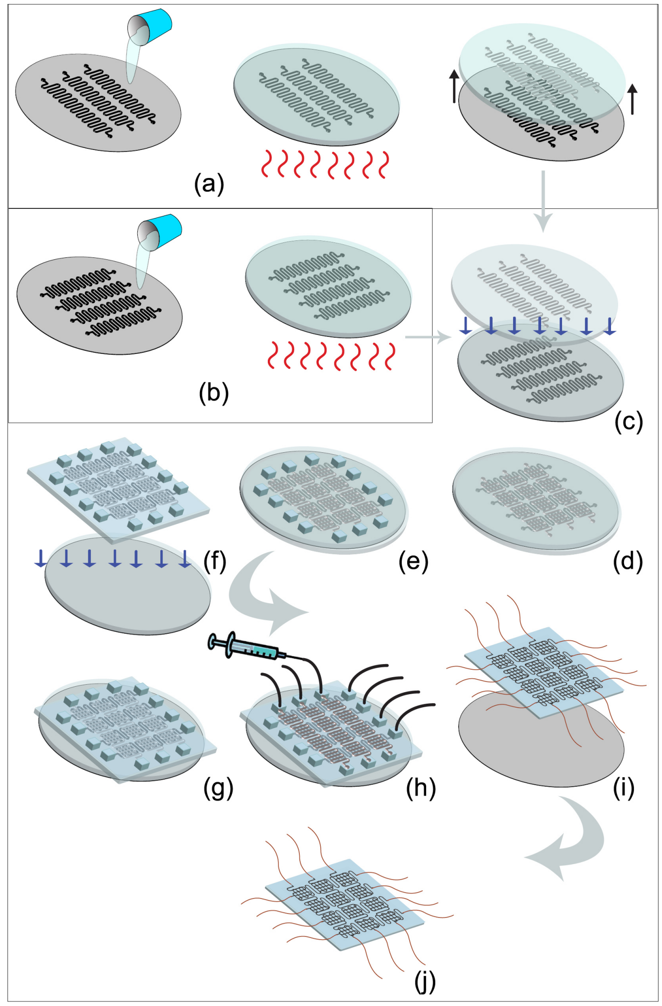


Fig. 2. Keypad fabrication process. Silicon wafer positive reliefs are obtained with a maskless, direct-write laser exposure photolithography process. (a) A thin film of PDMS (250 μm) is spin-coated (300 rpm) onto a patterned silicon mold, thermally cross-linked, and manually peeled from the silicon master. (b) A thin film of PDMS is spin-coated onto a second silicon mold and thermally cured. (c-d) The existing PDMS layers are thoroughly bonded via oxygen plasma treatment. (e) Small blocks of PDMS are adhered to the channel pattern inlet and outlet locations on top of the cured PDMS. (f-g) The existing structures are manually cut and peeled from the silicon wafer, and holes are stamped through the PDMS blocks at the channel inlets and outlets. The channels are then bonded to a final, unpatterned PDMS film by means of oxygen plasma treatment. The unpatterned film is 200 μm in thickness and is achieved by spin-coating PDMS onto a blank, unpatterned wafer at 400 rpm. (h) Conventional microfluidic tubing is connected at the channel inlet locations, and a syringe is used to fill the microchannels with conductive liquid eGaIn. (i) The PDMS blocks are cut and removed from the device, and conductive wires are introduced into the channel ends. The channels are sealed and wires are held in place with a final coating of PDMS. (j) The final device is peeled from the silicon wafer and ready for use.

inlet and outlet blocks, and the thin films are bonded to the unpatterned layer. Sealed microchannels are filled with eGaIn and the filling blocks are manually cut off. This step is largely enabled by the high surface energy of eGaIn, which allows a channel to be filled and remain in tact even if the channel inlet and outlet are exposed (assuming no external pressure is applied). The eGaIn-filled channels are then wired and re-sealed with a final coating of PDMS. The final device thickness is approximately 700 microns.

III. EXPERIMENTAL SETUP

The keypad design tested in this work (shown in Figure 1) is a display of perpendicular serpentine channels for which the feature height is 20 microns and the width of the channels is 200 microns, yielding an aspect ratio of AR = 0.1. The serpentine pattern was chosen to increase the effective width of the sensing channels, hence allowing a change in local pressure to be detected over a larger area. As discussed by Park, et al. [24], pressure sensitivity of conductive liquid microchannels embedded in a silicon elastomer matrix is determined by the elastic modulus of the matrix and the aspect ratio of the channels. That is, the lower the aspect ratio of a rectangular microchannel, the greater the sensitivity of the pressure sensor. In the experimental keypad device tested here, a channel height of 20 microns was chosen to increase repeatability of the fabrication process, and a channel width of 200 microns increases transparency and overall aesthetics of the device.

The ends of the eGaIn filled channels are wired to a DAQ breadboard (Measurement Computing USB-1208LS) for keypad device usage. As shown in Figure 3, the experimental circuit is composed of voltage dividers, where the applied voltage is 2 V and the initial voltage read by the DAQ is 0.9-1.1 V (depending on the channel). Because each of the conductive channels, or sensors, are in series with a 10 Ohm resistor, it is implied that the sensors start out with a resistance of approximately 10 Ohm.

Pressing each sensor increases the output voltage, V_{out}, across that channel. In order to eliminate noise in the voltage signal, a threshold of 5% was set, such that when the output voltage of the channel increases by 5% the key is interpreted to have been pressed. For example, for an initial voltage readout of 1 V, the key gets triggered when the voltage increases to 1.05 V or greater. According to this example and the governing equation of a voltage divider,

$$V_{out} = \frac{R_{out}}{R_{initial} + R_{out}} \cdot V_{initial} \tag{1}$$

a 5% increase in voltage corresponds to approximately a 10% increase in resistance.

An experimental code was developed with the Data Acquisition Toolbox in MATLAB R2010a (The Mathworks). In this setup, the twelve-key keypad was made to perform similarly to a mobile phone keypad. The functionality of the keypad is shown in Figure 4. By putting pressure on a key, two perpendicular channels each output a change in resistance, thus registering that the key was pressed and displaying the corresponding letter on a computer screen. Keys were able to produce multiple letters; by either holding down a key or pressing it in succession ($\leq$2 seconds) one could toggle through the available letter options. By waiting for a period greater than two seconds, a new letter could be inscribed.

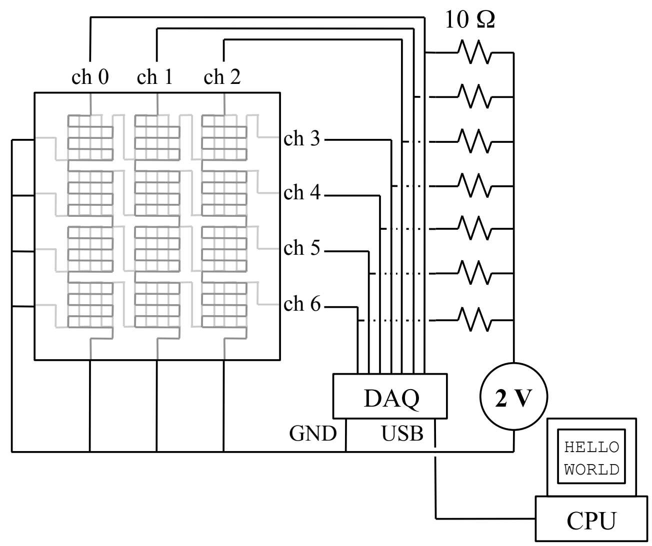


Fig. 3. Wiring schematic for experimental testing of the twelve-key keypad.

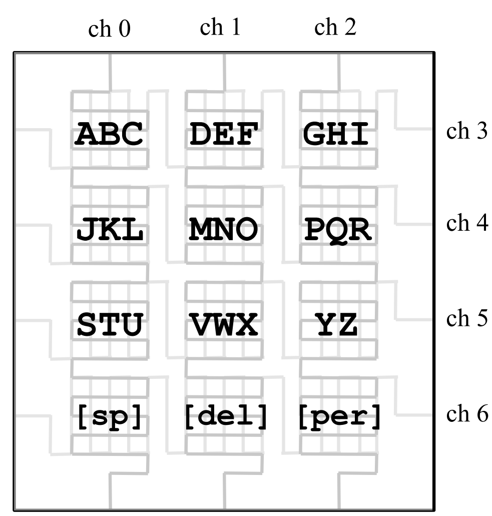


Fig. 4. Schematic demonstrating the functionality of the keypad device (similar to a mobile-phone keypad). Each of the upper nine keys has the ability to toggle between three alphabetic letters. Sustaining pressure on a key, or pressing the key in succession, will toggle to the next letter. If the key is not pressed for a duration of two seconds, a new letter placeholder is realized.

IV. RESULTS AND DISCUSSION

Changes in electrical resistance and output voltage of the embedded, liquid-filled conductive microchannels was sensed and registered, resulting in real-time display of an alphabetic message on a computer monitor. One representative experiment is shown in Figure 5. In Figure 5, the base voltage of each channel was normalized after data

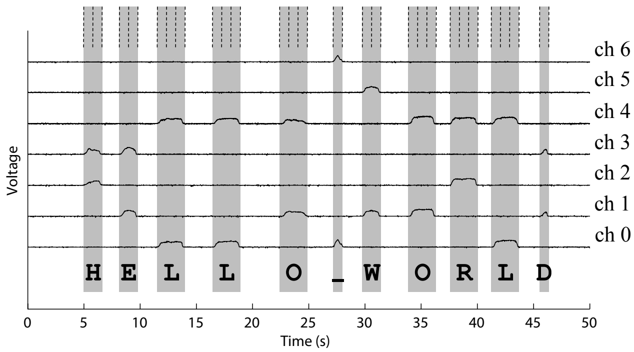


Fig. 5. Representative results displaying signal as a function of time for each channel in the keypad device. Base voltage for each channel was normalized after data collection. A change in voltage denotes that a key has been pressed. Given the location and duration of pressure, the message 'HELLO WORLD' was typed using the keypad.

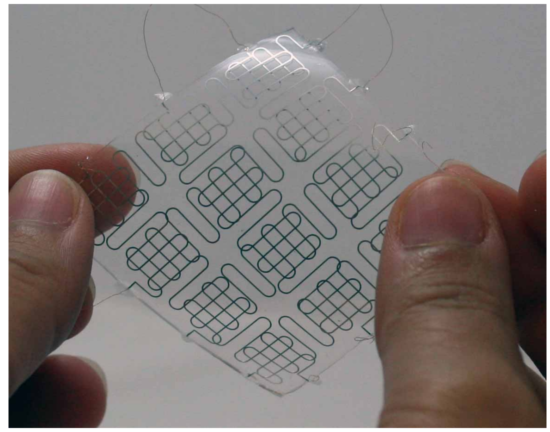
collection, such that only a relative change in voltage is relevant to the plot. The keypad was used in this trial to type the phrase 'HELLO WORLD'. One should note that the change in voltage, and hence applied pressure, lasts over varying durations and denotes the toggling of letters specific to the key being pressed. For example, to achieve the letter 'L', which is the third letter for a key as seen in Figure 4, pressure must be maintained on the key for approximately three seconds. Alternatively, to obtain the letter 'D', which is the first letter for a key, the pressure duration is less than one second.

Using a scale (ScoutPRO 6000g, OHAUS), we measured that about 10 N of force is necessary to increase V_{out} by 5%-10% and trigger a key. A typical fingerprint area is $\sim$1 cm^2, and thus the total necessary pressure to be applied is approximately 100 kPa. In contrast, normal keyboard typing is on the order of 5 - 10 kPa [25]. Trigger pressure, or the pressure required to change the output voltage of a channel by 5%, can be reduced by decreasing the aspect ratio of the channels or implementing softer materials. For example, EcoFlex silicon rubber (0030, SmoothOn) has an elastic modulus of $\sim$125 kPa, as opposed to 1 to 2 MPa for PDMS. Alternatively, the threshold value may be decreased based on the signal/noise ratio of the sensors and the resolution of the analog/digital converter used during experimentation.

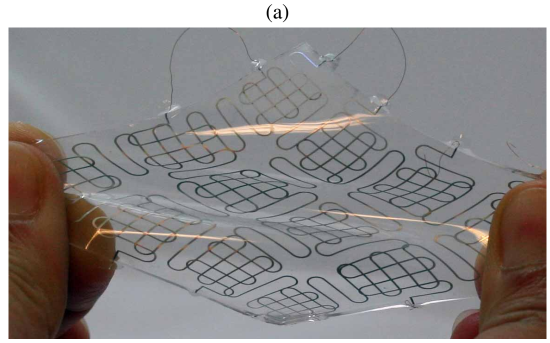
Figure 1(c) displays a microchannel with a height of 10 microns and a channel width of 1000 microns, yeilding an aspect ratio of 0.01. Park, et al. [24], derived that for a channel embedded near the surface of the elastomer,

$$\frac{\Delta R}{R_0} = \frac{1}{(1-2(1-\nu^2)\frac{p}{p'})} - 1 \tag{2}$$

where ν is Poisson's ratio, p is the applied pressure, p' is a characteristic pressure defined by $p' = Eh/w$, E is Young's modulus, h/w is the aspect ratio of the channel, and $\Delta R/R_0$ is the percent change in electrical resistance of the microchannel. By reducing the aspect ratio by an order of magnitude (i.e. from 0.1 to 0.01) it can be found that the relative change in electrical resistance is nearly 300%. Thus,



(a)



(b)

Fig. 6. (a) An elastomeric keypad at a minimum energy configuration. (b) An elastomeric keypad under tensile deformation.

it is clear that a lower aspect ratio increases the sensitivity of the channels' pressure sensing capabilities dramatically.

The mechanical limits of stretchability for both functionality and failure of the keypad were also investigated. The keypad device was stretched with pure tensile loading using an Instron Materials Testing System (model 5544A) in tensile extension mode. Functionality was considered to be maintained as long as all of the channels remained conductive. By this standard, the keypad was found to fail mechanically before failing in functionality. In fact, sensors became slightly more responsive to pressure under the stretched condition. Lastly, the keypad device was stretched to greater than 350% before mechanical failure.

V. CONCLUSIONS AND FUTURE WORK

A transparent, all-compliant, pressure sensing keypad with embedded conductive liquid-filled microchannels is presented. The keypad is comprised of twelve keys and is approximately 700 microns in total thickness. Embedded rectangular microchannels are 20 microns in height and 200 microns in width, yielding an aspect ratio of 0.1. Applying pressure to the channels changes the electrical resistance across the channels, hence pressing the channels allows the location, intensity and duration of the pressure to be registered. Perpendicularly overlaid serpentine patterned channels allow the channel intersections to act as keys on a keypad. According to the location and duration of pressure, an alphabetic letter is output from the keypad and displayed on a computer monitor in real-time. The output voltage through a channel must increase by at least 5% for a key to be triggered, which corresponds to a pressure of approximately 100 kPa. Sensitivity of the pressure sensing keypad is tunable via a reduction in channel aspect ratio and choice of softer materials.

The stretchable sensors and fabrication technology used in this study may be applied to create other types of functional electronics and sensing. A pressure sensitive keypad is only one of many applications for this all-compliant sensing technology. Future efforts may be focused on further integration of hyperelastic pressure sensors with soft robotics, artificial skin, soft orthotics and integrated circuitry. Such efforts may also take advantage of the 25 micron resolution of the laser photolithography process, which allows sensing elements and electrical connections to be further miniaturized.

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