Stretchable electronics for wearable and high-current applications

Daniel Hilbich*[a,b], Lesley Shannon[b], Bonnie L. Gray[a]
[a]Microinstrumentation Lab, School of Engineering Science, Simon Fraser University, Burnaby, Canada V5A 1S6; [b]Reconfigurable Computing Lab, School of Engineering Science, Simon Fraser University, Burnaby, Canada V5A 1S6

ABSTRACT

Advances in the development of novel materials and fabrication processes are resulting in an increased number of flexible and stretchable electronics applications. This evolving technology enables new devices that are not readily fabricated using traditional silicon processes, and has the potential to transform many industries, including personalized healthcare, consumer electronics, and communication. Fabrication of stretchable devices is typically achieved through the use of stretchable polymer-based conductors, or more rigid conductors, such as metals, with patterned geometries that can accommodate stretching. Although the application space for stretchable electronics is extensive, the practicality of these devices can be severely limited by power consumption and cost. Moreover, strict process flows can impede innovation that would otherwise enable new applications. In an effort to overcome these impediments, we present two modified approaches and applications based on a newly developed process for stretchable and flexible electronics fabrication. This includes the development of a metallization pattern stamping process allowing for 1) stretchable interconnects to be directly integrated with stretchable/wearable fabrics, and 2) a process variation enabling aligned multi-layer devices with integrated ferromagnetic nanocomposite polymer components enabling a fully-flexible electromagnetic microactuator for large-magnitude magnetic field generation. The wearable interconnects are measured, showing high conductivity, and can accommodate over 20% strain before experiencing conductive failure. The electromagnetic actuators have been fabricated and initial measurements show well-aligned, highly conductive, isolated metal layers. These two applications demonstrate the versatility of the newly developed process and suggest potential for its furthered use in stretchable electronics and MEMS applications.

Keywords: stretchable electronics, microfabrication, wearable electronics, electromagnetic actuator, MEMS

1. INTRODUCTION

Flexible and stretchable electronics are active areas of research due to the number of challenges that cannot be overcome with rigid silicon-based devices. Example applications in this area include stretchable, foldable integrated circuits[1], waterproof optoelectronics and stretchable displays[2][3], stretchable organic solar cells[4], and a wide variety of bio-integrated devices[5]. The growing number of applications suggests an unmet need for conformal electronic devices, calling for innovative new fabrication processes and techniques that are adaptable to a wide range of applications. With this goal in mind, we have previously developed a new thick-film PDMS metallization process in order to reduce fabrication complexity and cost, while increasing device conductivity for low-power, high-current applications[6]. In the present study, we propose new process variants that allow the fabrication of aligned multi-layer devices and the metallization of unconventional substrates through a stamping technique. This stamping technique is easily adaptable to a wide range of target substrates, which we demonstrate by stamping metallized patterns onto stretchable fabrics for wearable devices.

Wearable electronics, a subset of stretchable electronics, represents an attempt to seamlessly integrate sensing, actuating, communicating and computing components with the human body[7]. Such components can be practical for day-to-activities. For example, fiber-based devices can be used as generators to power personal electronics, or to provide wearable body temperature sensors[8]. More specialized components have also been developed and include cardiovascular monitors for portable healthcare[9], and even wearable computers to aid astronauts during extravehicular activities (space walks)[10]. One of the main challenges in integrating electronics with fabrics is the fact that fabrics are typically not suitable as substrates in traditional fabrication processes. Some approaches to overcome this challenge include using conductive fibers, and conductive patterns screen printed on fabric[11]. However, while fibers and screen printable inks are conductive, their conductivity has not been shown to match that of metals, which is important for low power and highly portable applications. Another approach enables metal patterns to be stamped directly onto the skin,

Nanosensors, Biosensors, and Info-Tech Sensors and Systems 2016,
edited by Vijay K. Varadan, Proc. of SPIE Vol. 9802, 98020R · © 2016
SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2219284

resulting in well-adhered metallization layers imposing minimal mechanical constraints on the skin[12]. This is achieved by electron beam evaporation of thin gold layers on an oxidized silicon substrate, followed by an oxide etching step using hydrofluoric acid, and transferring the printed layer to a layer of water-soluble polymer. This stamp can then transfer the pattern to the skin by applying an adhesive spray to the skin, placing the stamp on the adhesive spray, and dissolving the stamp substrate with water. The final product is an impressive achievement, and has inspired our work to develop a similar process that eliminates some of the process complexities such as specialized deposition equipment and the use of strong acids during the transfer process. We also wish to enable high-current, low-power applications by producing thick film metallization layers, and to improve adhesion by integrating the metal-polymer stamp directly with the target fabric rather than placing it on top of an adhesive layer. We demonstrate this using a simple, new stamping technique for thick-film metallization that integrates the polymer substrate directly with fabrics.

Along with a process variant for stamping on stretchable fabrics, we also explore the fabrication of multiple aligned metallization layers. We demonstrate this via a multi-layer electromagnetic actuator, incorporating an integrated Fe-PDMS core along with stacked and aligned coils. Such multi-layer devices offer many advantages compared to their single layer counterparts. In particular, they can accommodate more current, which is important for applications such as electromagnetic actuators; they enable increased functionality, as some devices are inherently three dimensional, such as semiconducting devices; and, they increase overall device density by extending a fixed two-dimensional area vertically. Similar three-dimensional polymer microstructures are found in multilayer SU-8 tissue scaffolds[13] or three-dimensional PDMS channels for microfluidics[14]. While these applications stack and align polymer layers, they do not do so with integrated conductors. One method of stacking conductors onto PDMS is through a micropattern transfer process whereby patterned CNT-based conductive inks are transferred onto PDMS layers successively[15]. However, it is difficult to align layers using this method, and conductive inks do not conduct as well as metals. An alternative approach that incorporates metal involves the formation of three-dimensional PDMS microfluidic channels (similar to[14]) followed by the injection of liquid solder before cooling and solidifying[16]. This is a creative solution; however, injecting liquid metal into microfluidic channels requires high temperatures during processing and can be especially difficult over large areas. An approach quite similar to what we desire is seen in the fabrication of multi-layer electrode arrays in PDMS for neural stimulation [17], where metal foils are deposited onto PDMS and selectively patterned using a serial laser etching process. The process is repeated to achieve multi-layer devices. Again, multi-layer alignment is difficult, but more importantly, the etching process is serial and thus undesirably time-consuming. Our proposed solution is to modify the stamping process introduced earlier by incorporating alignment features within the stamp substrate, and with corresponding alignment features patterned and deposited onto the target before transfer. One benefit of this technique is that the alignment features can incorporate functional materials. In the electromagnetic actuator presented in this study, the alignment posts are composed of a ferromagnetic Fe-PDMS nanocomposite polymer (NCP), potentially allowing for increased magnetic field generation in the multi-layer coils. A single metallization layer in the actuator fabricated in this study has a finned coil design, which has been studied in high-magnitude pulsed currents in planar coils for short duration, high magnitude magnetic fields[20][21][22]. A detailed characterization of both the wearable application and electromagnetic actuator are beyond the scope of this paper, and will be presented in-depth in future studies. The main contribution in this study is a demonstration of the process variants for wearable electronics and aligned multi-layer devices with integrated ferromagnetic NCP, with sufficient testing and characterization to ensure device functionality.

2. DESIGN AND FABRICATION

2.1 Base metallization process

The process modifications and applications in this study are based off of a low-cost, large-scale, micropattern transfer process recently developed by our group[6]. A simplified description of the 'base' process is shown in Figure 1. A clear transparency film designed for high temperature applications is used as a substrate for an electrically conductive copper paint seed layer, which is deposited using an airbrush (a). Dry film photoresist is laminated on top and patterned using standard lithographic techniques (b). Copper is electroplated through the photoresist mask and the remaining photoresist is stripped, resulting in copper metal microstructures on top of the conductive seed (c). The copper films are 70µm thick. The metal transfer step (d) is distinguished by an infrared assisted transfer process, with the copper structures initially embedded in uncured PDMS. After heating, the PDMS is cured and the copper structures are delaminated from the seed, remaining embedded in the PDMS. This method does not require chemical processing. However, if unwanted seed layer residue is transferred to the copper, it can be rinsed away with methanol if desired. This process, as is shown in the following sections, can be modified to be used as a stamping process and in applications requiring aligned layers and integration with NCPs.

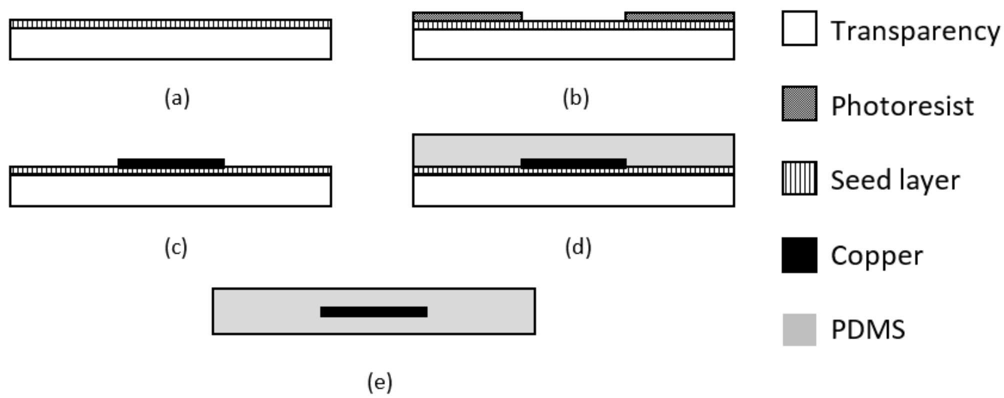

Figure 1. Base fabrication process. A transparency film is airbrushed with a conductive copper paint layer (a) before photoresist is deposited and patterned (b). Copper is electroplated through the photoresist, which is then stripped before liquid PDMS is poured over the assembly (d). A baking procedure transfers the copper to PDMS and a PDMS encapsulation layer is added (e).

2.2 Modified process: stamping on stretchable fabric

In order to deposit metal layers onto unconventional surfaces, the role of PDMS is converted from that of a substrate to an adhesive layer. In this manner, copper patterns can be 'stamped' onto the target substrate with PDMS acting to facilitate delamination from the seed and deposition onto the substrate. This modified process is shown in Figure 2. In (a), the electroplated copper is shown on the sacrificial seed layer, the same as in Figure 1 (c). The difference is in (b), where a thin layer of PDMS, thick enough to encapsulate the electroplated copper, is deposited onto the stamp. Then, the copper stamp is placed on top of the target substrate (c) and the infrared assisted transfer proceeds as before. The result is a copper pattern deposited directly onto the fabric (d). During the transfer and before the PDMS is fully cured, liquid PDMS seeps into the voids of the fabric creating a fully integrated PDMS-fabric hybrid layer with exceptional adhesion.

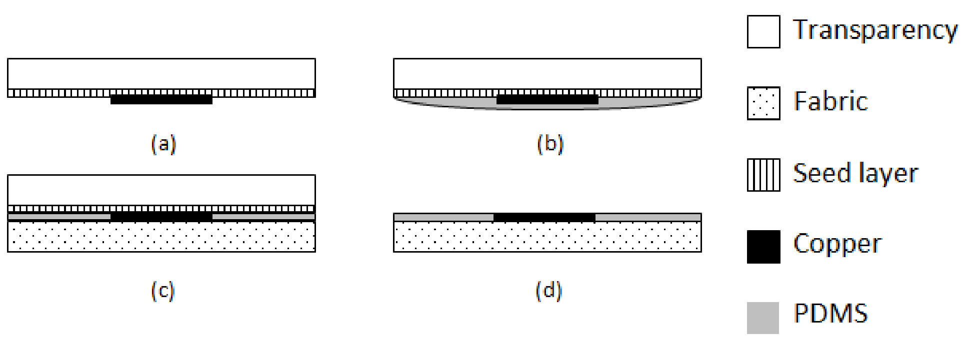

Figure 2. A modified process for stamping conductive layers onto wearable fabrics. A thin layer of PDMS is deposited onto a metal pattern stamp (a, b) before being placed on top of the target fabric (c). A baking procedure releases the metal into the PDMS, and cures the PDMS as it integrates with the fabric.

In this study, the target substrate is the stretchable fabric known as Luon™, produced by Lululemon Athletica. This fabric is used due to its popularity and well-known stretchable properties. The deposited curvilinear pattern shown in Figure 3 has been studied previously by our group in stretchable applications, and accommodates the most strain among all tested structures[23]. Each segment in the curve has a 300µm trace width, an arc angle of 270º, and a radius of curvature of 1.37mm.

Figure 3. A stretchable interconnect for wearable electronics fabricated using a new stamping process with PDMS integrated directly into the fabric substrate.

2.3 Modified process: aligned layers and NCP integration

The process is further modified to demonstrate the ability to produce aligned and stacked metallization layers and the incorporation of NCPs. This stacking and alignment process is demonstrated in Figure 4. In (a) and (b), an Fe-PDMS NCP post is fabricated on a PDMS substrate using a micromolding process[24]. In (c) and (d), the electroplated copper stamp (discussed in the previous section) is modified with an alignment hole to facilitate alignment between layers using the corresponding Fe-PDMS alignment post. This alignment hole is laser etched before electroplating the metallization layer. The stamping of a single layer using the alignment post is illustrated in (e) and (f), while (g) shows the result of stacking four aligned metal layers.

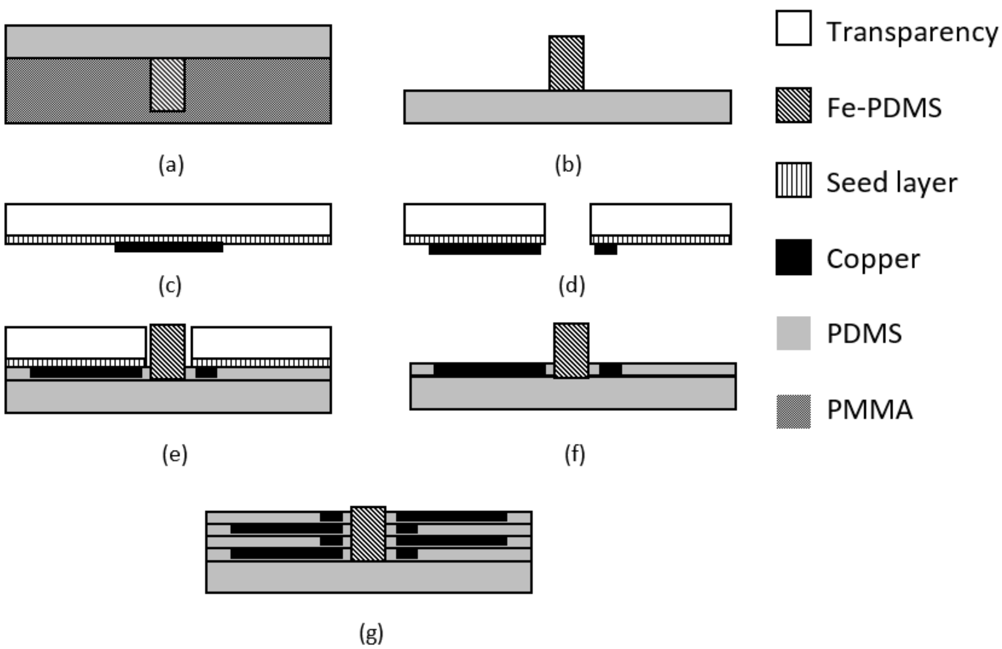

Figure 4. A process for fabricating aligned metallization layer with an integrated NCP feature. The Fe-PDMS NCP alignment post is fabricated via micromolding (a, b), and the metallized stamp is laser etched with a corresponding alignment hole (c, d). A single layer is transferred and aligned via stamping (e, f), which results in a multi-layer device when repeated with successive stamping layers (g).

As mentioned earlier, a single coil in this actuator incorporates finned features to improve heat dissipation and allow for larger currents and magnetic field generation. This design is shown in Figure 5. The trace width, *w,* and spacing between fins are both 500µm, while the radius, *r*, is 2.3mm. A relatively large 500µm trace width is chosen in order to reduce the mechanical stress in the coil during magnetic field generation[20], while the radius is calculated according to the radius-to-trace width ratio that is used in our previous study[23]. The laser-etched alignment hole in the transparency substrate must have a slightly smaller radius than the electroplated coil (Figure 4(d)), and is designed with 80% of the coil radius to allow a degree of tolerance. The corresponding Fe-PDMS post (Figure 4(b)) must similarly have a smaller radius than the alignment hole, and is also designed to be 80% smaller than the alignment hole.

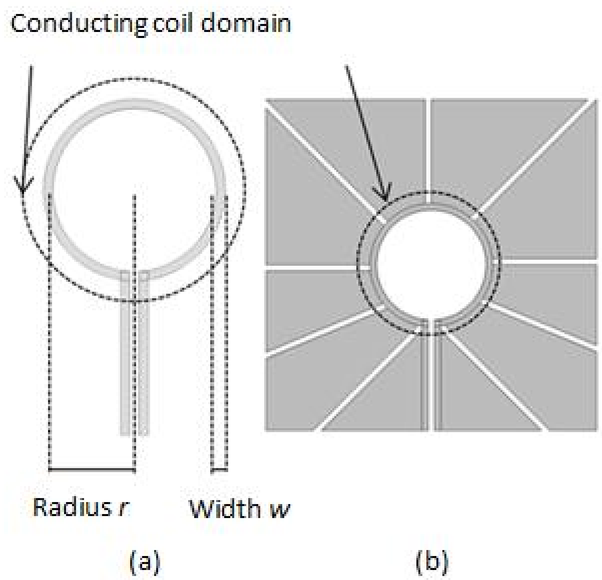

Figure 5. Single layer planar coils for magnetic field generation. A 'clean' design (a) in contrast with a 'finned' design (b) that has incorporated heat sinking features to accommodate larger currents, thus enabling increased magnetic field generation

The completed electromagnetic actuator has four metallization layers and is shown in Figure 6. Note that successive layers are rotated 180˚ to minimize asymmetries in the design. During the transfer step (Figure 4(e)), pressure is applied to the stamp via a 130g mass placed on top of the stamp during the transfer. Before testing, it is not known what the resulting thickness of PDMS will be between layers, or if electrical isolation is maintained between layers.

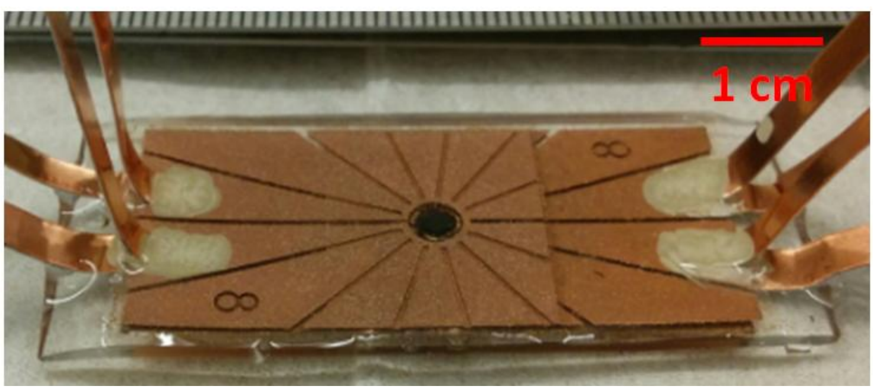

Figure 6. A four-layer electromagnetic actuator incorporating an Fe-PDMS NCP post for increased magnetic field generation and to facilitate alignment between layers.

3. RESULTS AND DISCUSSION

In this section, we provide preliminary results demonstrating the successful fabrication of a wearable electronics application and an aligned multi-layer electromagnetic actuator fabricated using the proposed base process modifications. A full characterization of each device is beyond the scope of this study, and will be provided in future work.

3.1 Stamping on stretchable fabric for wearable electronics

After fabricating the wearable device in Figure 3, electrical connections are established via copper tape with a conductive adhesive backing prior to testing. The connections are reinforced with a silver-based paint to ensure reliable contact. Before stretching, the structure is confirmed to be highly conductive and has a measured resistance of 1.1Ω. Stretching measurements are collected using a hand-operated stretching apparatus capable of stretching in 250μm increments. In this case, a strain of 21.9% is applied before the device experiences conductive failure. This is comparable to the previous result of 18.3% +/- 3% strain before failure found using the same structure with the base process[23].

In addition to testing with Luon™, we deposit the metal patterns onto various fabrics including a stretchable crepe fabric (95% polyester, 5% spandex), two non-stretchable drapery linings (100% cotton, and 70% cotton-30% polyester, respectively), and a stretchable constellation knit (100% mixed fibers). This success is promising, and suggests that the process will succeed in many wearable fabrics with ease. These experiments demonstrate a versatile new method for stamping metal layers onto unconventional substrates such as stretchable fabrics, with initial results indicating that this process is well-suited to stretchable and wearable electronics. Conductive patterns are transferred directly to wearable fabrics without losing integrity or becoming less effective compared to those fabricated using the base process.

3.2 Aligned and stacked layers for a high current electromagnetic actuator

Before fabricating the multi-layer actuator, we first simulate the finned and clean coil designs from Figure 5 to confirm that the fins effectively dissipate heat and allow for larger currents, and therefore, larger induced magnetic fields. Previous studies have shown that this approach is indeed effective[20][21][22], however our goal is to determine the effect on the geometry used in this study. We simulate nine different single-layer coil geometries, with coil conductor widths ranging from 100μm to 300μm and an inner radius ranging from 0.866mm to 2.66mm. Each of the nine geometries is given an increasing applied voltage in a series of steady-state simulations until the maximum temperature within the conductor reaches the melting point of copper. This signals device failure, and the maximum applied voltage for the geometry has been reached. This series of simulations is performed for both the clean and the finned designs. The average increase in applied voltage that the finned designs are able to accommodate is found to be 3.49 times that of the clean designs, thus confirming the enhanced performance in finned designs. An example of the resulting current densities found during simulation is shown in Figure 7, where the finned design (b) is able to accommodate a 0.05V voltage input compared to 0.016V in the clean design (a), resulting in an average current density of 3.6×10^8 A/m^2 compared to 1.3×10^8 A/m^2.

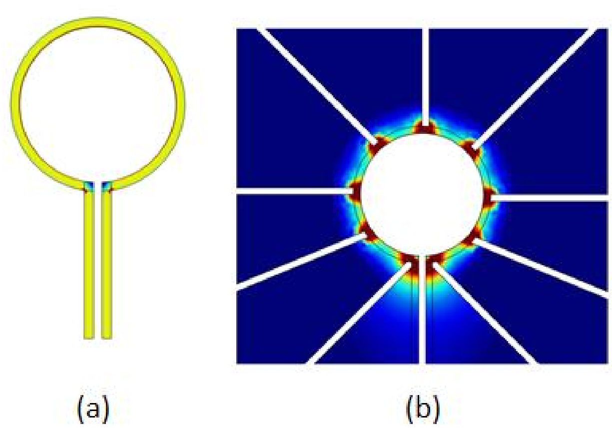

Figure 7. Typical current density distribution at steady state for two designs of an example coil geometry (r = 0.886mm, w = 100μm). Within the conducting coil domain, the fin design (b) shows an average current density of 3.6×10^8 A/m^2 at 0.05V applied, while the clean design (a) shows an average current density of 1.3×10^8 A/m^2 at 0.016V applied.

After simulating the performance of a single layer, we fabricate the multi-layer device as described earlier. To assess the success of the fabrication process, we first test the conductivity of each coil layer and confirm electrical isolation between layers using handheld digital multimeter (DMM). Each layer is found to be effectively isolated, with an open circuit load detected when measuring across different layers. Within the same layer, a resistance of 0.0Ω is measured end to end. The metallization layers are, therefore, well-isolated and highly conductive, and the resistance cannot be measured effectively with the DMM.

We also verify the effectiveness of the alignment method used in this process. Figure 8 shows a single-layer stamp and alignment hole (a), the Fe-PDMS alignment post (b), and the gap g_1 between the top metallization layer and the alignment hole in the assembled device (c). This gap is easily identified because of the residual traces of seed layer that have been transferred to the PDMS during the curing process. This residual seed layer is undesired, but is found to be effectively non-conducive and does not result in electrical shorts across conducting patterns, even between traces spaced as near as 50µm. The gap between the Fe-PDMS alignment post and the stamp alignment hole, g_2, is also easily visible (c). Both gaps are relatively even around the alignment features, indicating an effective alignment process.

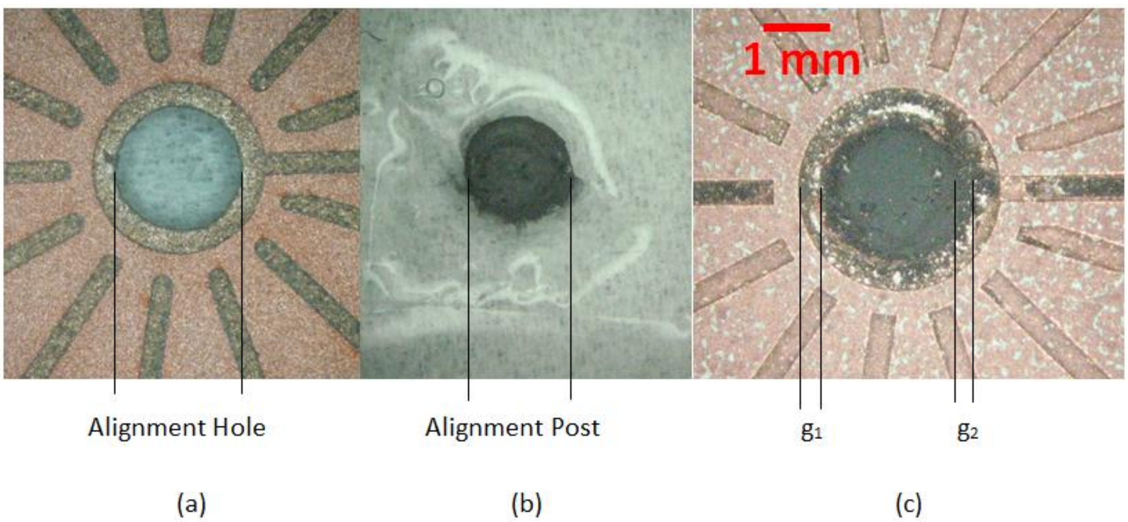

Figure 8. A single-layer stamp with alignment hole (a) and Fe-PDMS alignment post (b). The single-layer stamps are transferred successively to create a well-aligned multi-layer device (c). The gap between the top metallization layer and the alignment hole, g_1, and the gap between the Fe-PDMS alignment post and the stamp alignment hole, g_2, are labelled (c).

Finally, as mentioned earlier, we place a 130g mass on top of the stamp during the transfer step in the fabrication process, which results in an unknown PDMS thickness between metallization layers. In order to determine the PDMS thickness, we measure the height of the Fe-PDMS substrate before transferring any metallization layers and after all four layers have been transferred. The resulting average PDMS thickness between layers is found to be 246µm. Ideally, this thickness would be reduced in order to keep the conductive layers as close as possible while maintaining electrical isolation. This would result in stronger magnetic field generation above the conductor, as the intensity of the magnetic field decreases as the distance to the coil increases.

4. FUTURE WORK

A full characterization of each of the applications that have been fabricated using the newly developed process modifications remains to be completed. For the wearable device, at least three samples need to be tested (stretched until failure) in order to quantify the structure's stretchability using statistics. For the electromagnetic actuator, the remaining work is more extensive. First, a multi-layer actuator with Fe-PDMS core should be constructed in COMSOL using the geometric parameter values that have been measured in this study. This device can then be simulated to find the maximum steady-state magnetic field that can be produced above the coil center. The actual magnetic field produced by the coil will be measured and compared to simulation. In addition, we wish to explore the effectiveness of using high-magnitude pulsed currents rather than steady-state currents in deflecting magnetic cantilevers for use in MEMS and microfluidic applications such as microvalves and pumps. Aside from simulation, the ability to deflect MEMS cantilevers will also be carried out experimentally and characterized. Finally, we hope to demonstrate a bi-stable MEMS electromagnetic microactuator using this design.

5. CONCLUSION

In this study, we present two modified approaches and applications based on a newly developed process for stretchable and flexible electronics fabrication. The first modification is used to demonstrate a versatile new method for 'stamping' metal layers onto unconventional substrates such as stretchable fabrics for wearable electronics applications. A stretchable pattern fabricated using this process is found to adhere effectively to fabrics of various types and materials. During initial stretching experiments, this device is found to stretch up to 20% under an applied strain before conductive failure, thus demonstrating an effective process for fabricating wearable interconnects. The second modification is used to demonstrate a multi-layer electromagnetic actuator through an enhanced process utilizing stacked, aligned coils and an integrated Fe-PDMS core. The fabricated device demonstrates highly conducive layers with effective electrical isolation between layers. Each layer is well-aligned using the new fabrication scheme, demonstrating the effectiveness of the process modification in fabricating aligned polymer metallization layers.

ACKNOWLEDGEMENTS

The authors would like to thank the Canadian National Science and Engineering Research Council (NSERC), the Canadian Foundation for Innovation (CFI), and CMC Microsystems for funding, equipment, and software, which made this research possible.

REFERENCES

[1] Kim, D.-H., Ahn, J.-H., Choi, W.M., Kim, H.-S., Kim, T.-H., Song, J., Huang, Y.Y., Liu, Z., Lu, C., Rogers, J.A., "Stretchable and foldable silicon integrated circuits," Science 320, 507-511 (2008)

[2] Kim, R.-H., Kim, D.-H., Xiao, J., Kim, B.H., Park, S.-I., Panilaitis, B., Ghaffari, R., Yao, J., Li, M., Liu, Z., Malyarchuk, V., Kim, D.G., Le, A.-P., Nuzzo, R.G., Kaplan, D.L., Omenetto, F.G., Huang, Y., Kang, Z., Rogers, J.A., "Waterproof AlInGaP optoelectronics on stretchable substrates with applications in biomedicine and robotics," Nat. Mater. 9, 929–937 (2010)

[3] Sekitani, T., Nakajima, H., Maeda, H., Fukushima, T., Aida, T., Hata, K., Someya, T., "Stretchable active-matrix organic light-emitting diode display using printable elastic conductors," Nat. Mater., 8 (6), 494-499 (2009)

[4] Lipomi, D.J., Tee, B.C.-K., Vosgueritchian, M., Bao, Z., "Stretchable organic solar cells," Adv. Mater. 23, 1771–1775 (2011)

[5] Kim, D.-H., Ghaffari, R., Lu, N., Rogers, J.A., "Flexible and stretchable electronics for biointegrated devices," Annu. Rev. Biomed. Eng. 14, 113-128 (2012)

[6] Hilbich, D., Khosla, A., Shannon, L., Gray, B.L., "A new low-cost, thick-film metallization transfer process onto PDMS using a sacrificial copper seed," Proc. SPIE 9060, Nanosensors, Biosensors, and Info-Tech Sensors and Systems, 906007 (2014)

[7] Zeng, W., Shu, L., Li, Q., Chen, S., Wang,, F., Tao, X.M., "Fiber-based wearable electronics: a review of materials, fabrication, devices, and applications," Adv. Mater. 26(31), 5310–5336 (2014)

[8] Zhong, J., Zhang, Y., Zhong, Q., Hu, Q., Hu, B., Wang, Z.L., Zhou, J., "Fiber-based generator for wearable electronics and mobile medication," ACS Nano 8(6), 6273–6280 (2014)

[9] Shyamkumar, P., Rai, P., Oh , S., Ramasamy, M., Harbaugh, R.E., Varadan, V., "Wearable wireless cardiovascular monitoring using textile-based nanosensor and nanomaterial systems," Electronics 3(3), 504-520 (2014)

[10] Carr, C.E., Schwartz, S.J., Rosenberg, I., "A wearable computer for support of astronaut extravehicular activity," Proceedings of the 6th International Symposium on Wearable Computers, 23-30 (2002)
[11] Jost, K., Stenger, D., Perez, C.R., McDonough, J.K., Lian, K., Gogotsi, Y., Dion, G., "Knitted and screen printed carbon-fiber supercapacitors for applications in wearable electronics," Energy Environ. Sci. 6, 2698-2705 (2013)
[12] Yeo, W.H., Kim, Y.-S., Lee, J., Ameen, A., Shi, L., Li, M., Wang, S., Ma, R., Jin, S.H., Kang, Z., Huang, Y., Rogers, J.A., "Multifunctional epidermal electronics printed directly onto the skin," Adv. Mater. 25, 2773–2778 (2013)
[13] Mata, A., Fleischman, A.J., Roy, S., "Fabrication of multi-layer SU-8 microstructures," J. Micromech. Microeng. 16, 276–284 (2006)
[14] Zhang, M., Wu, J., Wang, L., Xiao, K., Wen, W., "A simple method for fabricating multi-layer PDMS structures for 3D microfluidic chips," Lab Chip 10, 1199–1203 (2010)
[15] Liu, C.-X., Choi, J.-W., "Patterning conductive PDMS nanocomposite in an elastomer using microcontact printing," J. Micromech. Microeng. 19, 085019-085026 (2009)
[16] Siegel, A.C., Bruzewicz, D. A., Weibel, D. B., Whitesides, G. M., "Microsolidics: Fabrication of Three-Dimensional Metallic Microstructures in Poly(dimethylsiloxane)," Adv. Mater. 19, 727–733 (2007)
[17] Suaning, G.J., Schuettler, M., Ordonez, J.S., Lovell, N.H., "Fabrication of multi-layer, high-density micro-electrode arrays for neural stimulation and bio-signal recording," Proceedings of the 3rd International IEEE EMBS Conference on Neural Engineering, 5-8 (2007)
[18] Park, J.H., Ko, J.M., Parka, O.O., "Carbon nanotube/RuO_2 nanocomposite electrodes for supercapacitors," J. Electrochem. Soc. 150 (7), A864-A867 (2003)
[19] Chung, D., Khosla, A., Gray, B. L., "Screen printable flexible conductive nanocomposite polymer with applications to wearable sensors," Proc. SPIE 9060, Nanosensors, Biosensors, and Info-Tech Sensors and Systems, 90600U (2014)
[20] Mackay, K., Bonfim, M., Givord, D., and Fontaine, A., "50 T pulsed magnetic fields in microcoils," J. Appl. Phys. 87, 1996-2002 (2000)
[21] Podaru, G., Ogden, S., Baxter, A., Shrestha, T., Ren, S., Thapa, P., Kumar Dani, R., Wang, H., Basel, M.T., Prakash, P., Bossmann, S.H., and Chikan, V., "Pulsed Magnetic Field Induced Fast Drug Release from Magneto Liposomes via Ultrasound Generation," J. Phys. Chem. B 118, 11715 −11722 (2014)
[22] Wolf Cruz, R.R., Dias, A.L.B., Bonfim, M.J.C, "20 T portable bipolar magnetic pulser," Rev. of Scientific Inst. 81, 064705-064708 (2010)
[23] Hilbich, D., Yu, G., Shannon, L., Gray, B.L., "Characterization of stretchable interconnects fabricated using a low cost metallization transfer process onto PDMS," ECS J. Solid State Sci. Technol., 4(10), S3030-S3033 (2015)
[24] Khosla, A., Gray, B.L., "Micropatternable multifunctional nanocomposite polymers for flexible soft NEMS and MEMS applications," ECS Trans. 45(3), 477-494 (2012)