Design and Evaluation of a Highly Stretchable and Conductive Thin Film for Tactile Sensors

Yuhang Sun[a], Debao Zhou[b], Jing Bai[a], Haopeng Wang[c], and Jianguo Cao[c]

[a]Department of Electrical Engineering, University of Minnesota, Duluth, MN, 55812, USA
[b]Dept. of Mechanical and Industrial Engineering, University of Minnesota, Duluth, MN, 55812, USA
[c]School of Mechanical Engineering, University of Science and Technology Beijing, China 100083

ABSTRACT

Keeping good conductivity at high stretching strain is one of the main requirements for the design of flexible electronic devices. The elastic nature of siloxane-based elastomers enables many innovative designs in wearable sensor devices and non-invasive insert instruments. Over the last few years, Poly-di-methyl-siloxane (PDMS) thin films have been heavily used as the substrates in the fabrication of tactile sensing devices due to their high sensitivity, good elasticity and outstanding biocompatibility. However, these kinds of conductors usually suffer poor tearing property and insufficient compliance to curved surfaces, which greatly limited their applications. Currently no three-dimensionally mountable sensor arrays have been reported. In this work, we developed an excellent mechanically compliant skin-like conductors by patterning silver nano wire traces in Dragon Skin® substrate instead of PDMS substrate, high cross-link quality was achieved then. Moreover, to further enhance the conductivity, a thin gold layer was coated on the AgNWs strips, 4 different fabrication routines was designed and conducted. Thanks to the intrinsically outstanding physical property of Dragon Skin and the uniform embedment built in fabrication process, the AgNWs/Dragon Skin layer showed convincible advantage over AgNWs/PDMS layer both in mechanical capability and conductive stability.

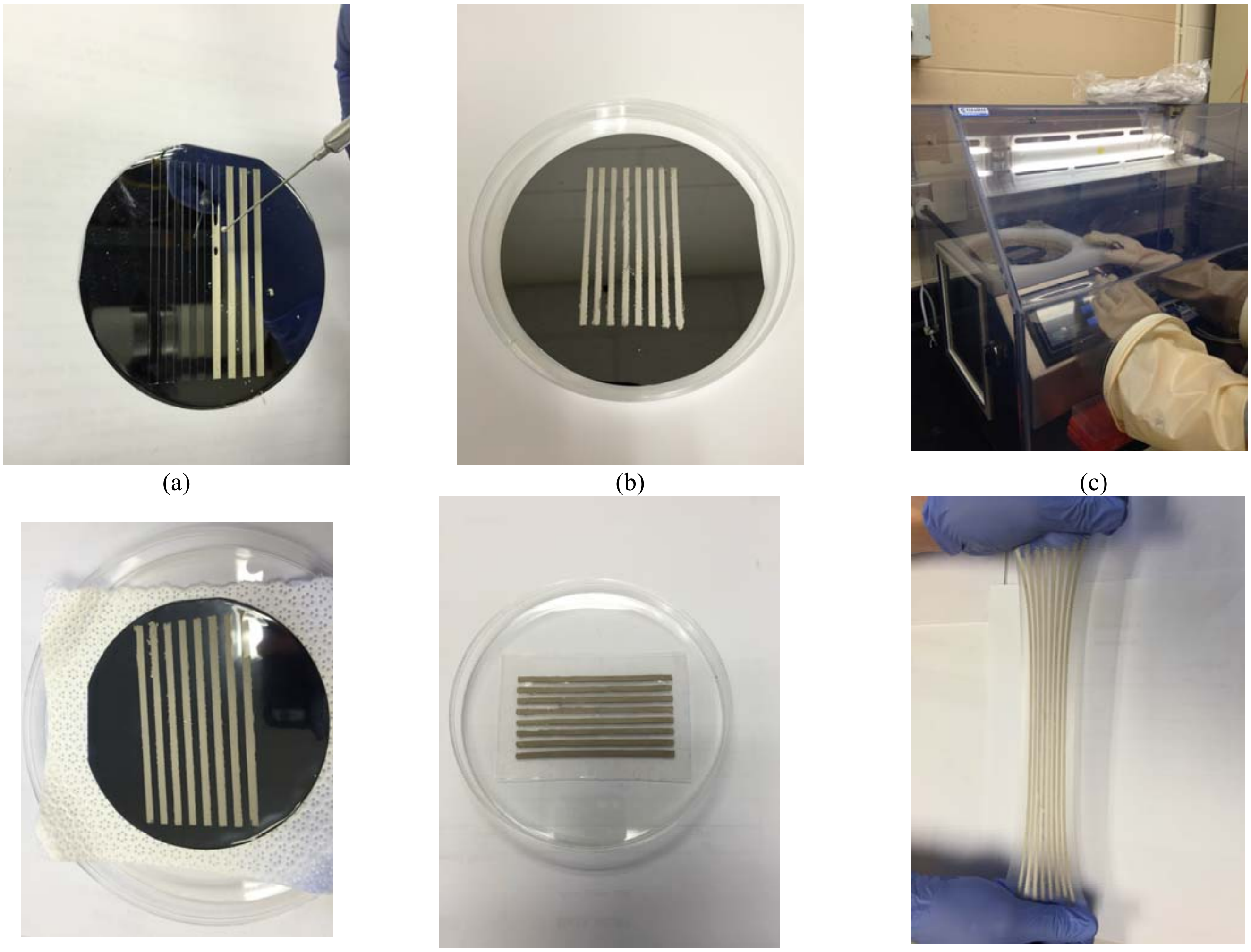
Keywords: electronic sensor, stretchability, PDMS, Dragon Skin, conductivity

1 INTRODUCTION

Imitating human sense using electronic methods is a popular and magnificent topic in past few years, many researchers have been working on flexible electronic sensors. Artificial skin sensors will help bring in extraordinary advanced intelligence. For example, robots equipped with these kind of sensors may greatly extend their applications to some interactive tasks such as caring for kids and elders, applying sensor skins on embedded medical devices will provide an unprecedented level of diagnostic and detection capability. Compared to the sense of heat [1], light [2], sound [3] and taste [4], the sense of touch is more difficult to mimic, since it requires a kind of relatively large-sized, high spatial resolution, high sensitivity and fast response tactile sensing array [5], while any of these prerequisites has yet to be fulfilled. Tactile sensors should be able to accommodate deformation while keeping their sensing capability [6]. Some of these tasks require more than 30% stretching strain [7]. Among the various possible solutions, one strategy is to make the artificial skin with intrinsic flexible and biocompatible substrates and stretchable conductors [8]. There are quite a few candidates to make stretchable conductors. Conducting polymers was used to be one fo the most popular solutions. However, the lack of simple methods to maintain low cost made conducting polymers unfavorable afterwards [9]. Carbon nanotubes [10] and graphene films [11] have high intrinsic conductivity and can be produced at low cost, but they suffered the large tube-to-tube junction resistance [12]. Most recent studies have shown that the AgNWs based electrodes is a good candidate for flexible sensor structures, the interpenetrating networks of AgNWs fits the crosslinked polymer substrate very well [13]. Hu et *al*. demonstrated that the AgNWs/polymer matrix electrodes only get a small increase of sheet resistance after multiple times of stretching [14]. For the flexible substrate, polydimethylsiloxane (PDMS) is currently one of the most favorable choices in deformable sensor fabrication, thanks to its good biocompatibility, flexibility and good processing ability. Most conducting materials can be embedded in a PDMS structure to work in mechanically deformable environment [15]. However, PDMS based sensors are not complaint enough for mounting on a three-dimensionally curved surface. Yang et *al*. designed a highly twistable 8×8 sensor array with PDMS as substrate and demonstrated good three-dimensional stretchability [16], but the structure is too thick to be implemented on diagnostic medical equipment, and also the sensor elements uniformity would be deteriorated after several twists. Basically, it's proved that PDMS substrate can provide sufficient planer stretchability[17], but it's not good enough to work for fully conformable requirements owing to its considerable rigidity and low toughness [18].

In this paper, a high performance silicone rubber, named Dragon Skin by Smooth-On Inc, is firstly used as the substrate to fabricate stretchable electrodes. Dragon Skin has been widely used in prosthetics and cushioning applications and showed good conformability to human bone and skins. Then, both PDMS/AgNWs and Dragon Skin/AgNWs conducting electrodes are fabricated for stretchability comparison. To further enhance their

 TechConnect Briefs 2015, TechConnect.org, ISBN 978-1-4987-4730-1



(a) (b) (c) (d) (e) (f)

Fig.1, (a) Pattern AgNWs conduction strip in a removable PDMS mold; (b) The parallel patterned AgNWs; (c) Mixed PDMS/Dragon Skin dispersed on AgNWs by spin coating in a glove box; (d) Thin and uniform electrode layer after spinning coating; (e) The electrode layer peelled off from silicon wafer; (f) The whole Dragon Skin based electrode layer can be stretched over 150%.

conductivity, two most popular types of PVD processes, sputtering and electronic beam evaporation are applied to coat a gold layer on the electrode strips. In addition, the adhesion effects of different interlayers (Titanium and Chrome) were studied as well.

2 FABRICATION OF STRETCHABLE CONDUCTING ELECTRODES

The following steps were used to fabricate the proposed stretchable electrode:

#1: Some liquid PDMS (Dow Corning Sylgard 184, ratio of base to crosslinker is 10:1 by mass) was dispersed on 5 inch silicon wafers by spin coating (spin parameters are shown in Table 1), and was thermally cured in an oven at 65 ℃ for 12 hours to make molds for AgNWs networks of the electrode.

#2: AgNWs (Blue Nano, SLV-NW-90 ETH, 10mg/ml) were dried in these PDMS mold on the silicon wafers by a syringe, forming the eight parallel strips of AgNWs networks (Fig.1a).

Table 1: Parameters for spin coatin in Steps #1 and #4

Process Steps	Parameters		
	Acceleration	**Speed**	**Time**
Spread	200rpm/s	800rpm	10s
Spin	250rpm/s	1000rpm	30s

#3: As the AgNWs dried, the PDMS mold was removed (Fig.1b) and left the AgNWs strips are patterned.

#4: Some liquid PDMS//Dragon Skin (Smooth-On. Inc) was mixed, degassed and poured over the AgNWs strips, and dispersed by spin coating again (Fig.1d).

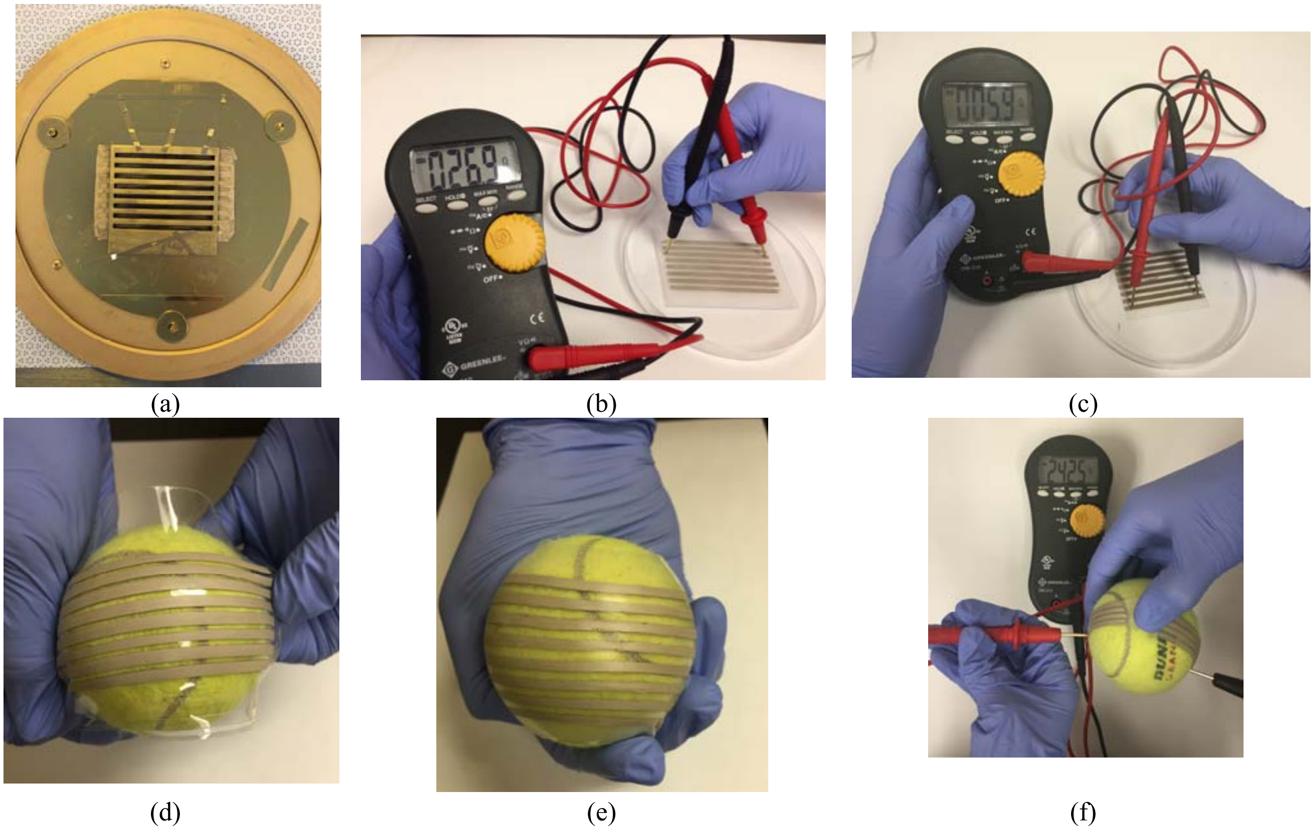


Fig.2, (a) Stretchable electrodes flipped under a mask on a sample holder for PVD processes; (b) Resistance of a 110mm AgNWs conducting strip is about 25~28Ω; (c) Resistance of a 80mm AgNWs/Cr/Au(E-beam deposited) conducting strip is below 6Ω; (d) A tennis ball is wrapped by an AgNWs/PDMS electrode; (e) A tennis ball is tightly wrapped by an AgNWs/Dragon Skin electrode; (f) Rhe AgNWs/Dragon Skin electrode layer can keep quite low resistance under large 3D deformation.

#5: Finally, the whole structure was thermally cured for 12 hours, after this, the PDMS/Dragon Skin thin film electrode was peeled off from the silicon wafer carefully (Fig.1e).

3 RESISTANCE MEASUREMENT AND STRETCHABILITY COMPARISON

Following the fabrication process, the stretchable electrodes were catogized into 4 groups for futher metalization, AJA sputtering system and CHA evaporation system were utilized here to coat a thin gold layer on the AgNWs conducting strips separately, titanium and chrome are applied as the interlayer for each kind of deposition. Detailed parameters are shown in table 2.

The measurements for stretchable electrodes are shown in Fig.2b and Fig.2c, resistances of each group are listed in Table 3, at least 16 different conduting strips are measured for each PVD process to get the realiable values.

From data in Table 3, it's noted that after coating a 50nm gold thin flim with chrome as interlayer by E-beam, the resistance of conducting strips dropped more than 3 times compared to AgNWs conduting strips. The reason is that the chrome has higher inter-diffusion rate with AgNWs, and provides better adhesion force in these samples. In addition, the E-beam evaporation permits more direct energy transfer to the source during heating than sputtering, and due to the higher vacuum degree achieved, the E-beam can get purer evaporated material to substrate, so that electrode processed by E-beam showed better conductivity than those by sputtering accordingly.

On the other hand, from Fig. 2d and Fig. 2e, it is observed that although the PDMS based electrode layer is thin, it cannot able to mount on a curved surface well, while the Dragon Skin based electrode layers could be wrapped around a tennis ball tightly and nicely. In Fig. 2f, a 80mm long AgNWs/Dragon Skin electrode can be wrapped around a tennis (r = 33mm) with elongation of nearly 160% and still keep a resistance of 2.2Ω/1mm , which is in the top level of any kinds of stretchable electrodes under large deformation.

Table 2: Parameters for different PVD processes

Group No.	CVD Process	Metalized layer	Parameters		
			Chamber Pressure	Deposition Rate	Total Time
#1	E-beam evaporation	Ti(10nm)+ Au(50nm)	1.5×10^{-6} Tor	0.2nm/s	300s
#2		Cr(10nm)+ Au(50nm)			
#3	Sputtering	Ti(10nm)+ Au(50nm)	1.0×10^{-5} Tor	0.25nm/s	240s
#4		Cr(10nm)+ Au(50nm)			

Table 3: Resistances of the stretchable eletrodes after different metalization routines

Group No.	Conductor Strip	Resistance (Ω/1mm)
#0	AgNWs	0.269
#1	AgNWs/Ti/Au by E-beam	0.125
#2	AgNWs/Cr/Au by E-beam	0.084
#3	AgNWs/Ti/Au by sputtering	0.157
#4	AgNWs/Cr/Au by sputtering	0.103

4 CONCLUSION

Flexible electrodes with both high conductivity and good stretchabillty will greatly help optimize the design and fabrication of flexible skin-like sensors. In this paper, a new type of high stretchable silicone, Dragon Skin is applied for fabricating conduting electrodes, it showed much better comformability to curved surface and capability to withstand extremly large 3D deformation than the commonly used PDMS flexible electrodes. To further enhance the conductivity of the stretchable electrodes, a comparison of different PVD routines was conducted. The results indicated that by coating a thin gold film with chrome as interlayer by electronic-beam evaporation, the Dragon Skin/AgNWs electrode can achieve much better behavior in conductivity under stretching.

REFERENCES

[1] Webb, R.C., et al., *Ultrathin conformal devices for precise and continuous thermal characterization of human skin (vol 12, pg 938, 2013).* Nature Materials, 2013. **12**(11): p. 1078-1078.

[2] Zhang, C., et al., *Room temperature nitrogen dioxide sensors based on N719-dye sensitized amorphous zinc oxide sensors performed under visible-light illumination.* Sensors and Actuators B-Chemical, 2015. **209**: p. 69-77.

[3] Habukawa, C., et al., *Evaluation of airflow limitation using a new modality of lung sound analysis in asthmatic children.* Allergology International, 2015. **64**(1): p. 84-89.

[4] Ha, D., et al., *Recent achievements in electronic tongue and bioelectronic tongue as taste sensors.* Sensors and Actuators B-Chemical, 2015. **207**: p. 1136-1146.

[5] Pan, C.F., et al., *High-resolution electroluminescent imaging of pressure distribution using a piezoelectric nanowire LED array.* Nature Photonics, 2013. **7**(9): p. 752-758.

[6] Sokhanvar, S., M. Packirisamy, and J. Dargahi, *A multifunctional PVDF-based tactile sensor for minimally invasive surgery.* Smart Materials & Structures, 2007. **16**(4): p. 989-998.

[7] Arumugam, V., M.D. Naresh, and R. Sanjeevi, *EFFECT OF STRAIN-RATE ON THE FRACTURE-BEHAVIOR OF SKIN.* Journal of Biosciences, 1994. **19**(3): p. 307-313.

[8] Chortos, A. and Z.N. Bao, *Skin-inspired electronic devices.* Materials Today, 2014. **17**(7): p. 321-331.

[9] Costello, B., R. Mayne, and A. Adamatzky, *Conducting polymer-coated Physarum polycephalum towards the synthesis of bio-hybrid electronic devices.* International Journal of General Systems, 2015. **44**(3): p. 409-420.

[10]De, S., et al., *Flexible, Transparent, Conducting Films of Randomly Stacked Graphene from Surfactant-Stabilized, Oxide-Free Graphene Dispersions.* Small, 2010. **6**(3): p. 458-464.

[11]Kim, T., et al., *Uniformly Interconnected Silver-Nanowire Networks for Transparent Film Heaters.* Advanced Functional Materials, 2013. **23**(10): p. 1250-1255.

[12]Vosgueritchian, M., D.J. Lipomi, and Z.A. Bao, *Highly Conductive and Transparent PEDOT:PSS Films with a Fluorosurfactant for Stretchable and Flexible Transparent Electrodes.* Advanced Functional Materials, 2012. **22**(2): p. 421-428.

[13]Song, C.H., et al., *Intense-pulsed-light irradiation of Ag nanowire-based transparent electrodes for use in flexible organic light emitting diodes.* Organic Electronics, 2015. **17**: p. 208-215.

[14]Hu, W.L., et al., *Intrinsically stretchable transparent electrodes based on silver-nanowire-crosslinked-polyacrylate composites.* Nanotechnology, 2012. **23**(34): p. 9.

[15]Pang, C., et al., *A flexible and highly sensitive strain-gauge sensor using reversible interlocking of nanofibres.* Nature Materials, 2012. **11**(9): p. 795-801.

[16]Cheng, M.Y., et al., *The development of a highly twistable tactile sensing array with stretchable helical electrodes.* Sensors and Actuators a-Physical, 2011. **166**(2): p. 226-233.

[17]Li, Y.Q., Y.A. Samad, and K. Liao, *From cotton to wearable pressure sensor.* Journal of Materials Chemistry A, 2015. **3**(5): p. 2181-2187.

[18] Johnston, I.D., et al., *Mechanical characterization of bulk Sylgard 184 for microfluidics and microengineering.* Journal of Micromechanics and Microengineering, 2014. **24**(3): p. 7.