Flexible and Printed Electronics

Tactile sensing and computing on a random network of conducting fluid channels

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Abstract

Liquid electronic sensors are typically based on regular arrays of channels filled with a conductive liquid. We propose that a random planar network of conducting liquid allows us for a wider spectrum of electrical responses and localisation of tactile stimuli. We also speculate that a computation protocol can be implemented on such a network, featuring mechanical inputs and electrical outputs. Our results pave a way towards future developments on sensing and computing wearables with disordered sensing networks structure.

1. Introduction

Liquid electronics [1–4] employs conductive liquids as wires [5], transistors [6, 7], capacitors [8–11] and memristors [12–17]. The advantages of the liquid designs is that they can be implemented inside an insulating polymer sheet in the networks of channels and thus become stretchable and foldable [18–26]. This approach represents a fundamental step towards new paradigms of functional, active and explorative robotics [27]. Another application domain of liquid electronics is electronic skin [28–30], the flexible material with embedded electronics capable of tactile sensing [31–34], low level perception [35, 36], and, ideally, energy autonomous [37]. The notable designs usually use thin-film transistor and pressure sensors integrated in a plastic substrate [26], micro-patterned polydimethylsiloxane with carbon nanotube ultrathin films [38, 39], a large-area film synthesized by sulfuration of a tungsten film [40], multilayer graphene [41], platinumb ribbons [30], PET based silver electrodes [42]. Most published designs are based on regular arrangements of liquid electronic elements. This is advantageous in terms of controllability and repeatability of the results, yet might be disadvantageous in terms of fault tolerance.

Therefore in the present study we consider a proximity graph, the Delaunay triangulation, constructed on the random planar set. Given a planar finite set $V$ the Delaunay triangulation $\mathcal{D}(V) = (V, E)$ is a graph subdividing the space onto triangles with vertices in $V$ and edges in $E$ where the circumcircle of any triangle contains no points of $V$ other than its vertices.

Neighbours of a node $v \in V$ are nodes from $V$ connected with $v$ by edges from $E$.

Why do we use a random Delaunay triangulation? This triangulation gives us a sufficient yet economical (in terms of edges) coverage of a random planar set thus becoming a good candidate for tactile image recognition. In fact results on fingerprint indexing based on Delaunay triangulation [44, 45], including cancellable fingerprint templates for low resolution wearable devices [46], show the full perspective of the triangulation. Moreover, disordered structures show a high degree of scale invariance [47]. As has been demonstrated in [48], the scale invariance could improve a performance of these devices via increased robustness to accidental errors and the fragility to targeted errors. With regards to sensor networks, randomized coverage of space by sensors allows for substantial raw materials and energy saving while meeting constraints of coverage and connectivity, the coverage intensity can be dynamically adjusted and the data reading is resilient to time asynchrony [49].

We use PEDOT:PSS as a liquid conductor. This conductive polymer is proved to work sufficiently well in electrodes for stretchable electronics and have been proposed in [50], piezoresistive pulse sensor [51], PEDOT cellulose conductive paper [52], sulfonated lignin based PEDOT sensor [53], pressure sensor [54], humidity sensor [55], PEDOT:PSS and ionic liquid composites for thermal electronics [56], and is considered to be future corner stone of bioelectronics [57].

Furthermore it is less sensitive to temperature variations in comparison to liquid metals, where the
liquid state is lost when the environment is sufficiently cold (typically below 283 K), and a better conductor and less chemically aggressive than ionic liquids.

The paper is structured as follows. Section 2 introduces experimental techniques. Spatio-temporal resolution of the network is analysed in section 3. As highlighted in electronic skin overview [28], in situ, local, information processing is important because it dramatically reduces bandwidth in communication with central processing unit and increase fault tolerance. Therefore, in section 4 we outline a path towards mechano-electrical computing with the network.

2. Experimental

The flexible sensing and computing skin circuit stack is structured as follows: from bottom, a wedge-shaped polydimethylsiloxane skin (PDMS, R10PRO and R30PRO from RESCHIMICA, Via Borromini, 50 Tavarnelle Val di Pesa 50 028 Firenze, Italy) containing Delaunay triangulation channels, liquid rubber sealant (Gomma Liquida, UHU Bostik SpA Via G.B. Pirelli,19 20 124 Milano, Italy), transparent rigid polyethylene terephthalate membrane (PET, 0.2 mm thickness). The skin measures 20 × 16 cm and has a thickness ranging from 10 to 2 mm, linearly thinning from top to bottom; carved channels have a length comprised between 1.5 and 14 cm, a width of 4 mm and a depth of 2 mm. The PET membrane measures 18 × 16 cm and is printed with a checker-board (1 cm-side squares) to support the correct stimulus application. Channels are first hand-carved into a Linoleum block (MasterCut from Essdee, Educational Art & Craft Supplies Limited Frederick Road, Hoo Farm Industrial Estate, Kidderminster, U.K., 300 × 200 × 4 mm), then PDMS two components are mixed and poured onto the linoleum in a rectangular container. When PDMS is cured, the skin is detached from the linoleum master and liquid rubber is painted on top of the area surrounding the channels, finally PET foil with printed grid is positioned on top of the skin. Curing liquid rubber requires 1 week and some air circulation, granted by holes across PET foil done in five specific positions (see figure 1). The channel connection nodes positions are shown in black, holes across PET for filling Poly(3,4-ethylenedioxythiophene)poly(styrenesulfonate) (PEDOT:PSS) and inserting needle electrodes are shown in violet. PEDOT:PSS (CleviosTM PH 1000, Aqueous PEDOT/PSS dispersion, Heraeus Holding GmbH, Heraeusstraße 12-14, D-63 450 Hanau, Germany) was injected using a lab syringe, filling the channels requires careful extraction of air bubbles, slightly facilitated by the wedge, and an overall volume of 10 ml of conductive liquid. Two needle electrodes (MN4022D10S subdermal electrodes from SPES MEDICA SRL Via Buccari 21 16 153 GENOVA, Italy, 0.4 mm diameter, 22 mm in length) were inserted in holes to contact directly the conductive liquid, and connected to a Keithley 2635A multimeter (for DC characterization) and an Agilent E4980A precision LCR meter (for AC characterization, in the range from 20 Hz up to 2 MHz).

3. Sensing and spatio-temporal resolution

The choice of performing our experiments with an artificial skin approximately the size of an A5 paper is done to create a system compliant with the human skin, where tactile resolution is not that high (1 millimeter or less [58]) in reason of the elastic properties of the skin itself. Nonetheless room for scaling down (as well as up) the system is there, introducing photolithography / digital printing technologies to fabricate the channels pattern. Of course, going micro-metric requires another set of experiments, because below a certain channel width, surface friction and liquid viscosity hinder conductive fluid motion and make less relevant the use of a liquid conductor. Two PDMS skins were prepared using different polydimethylsiloxanes: R10PRO having Shore hardness 10 (soft) and R30PRO having Shore hardness 30 (hard). For each skin only two electrodes were connected through the upper layer in contact with PEDOT:PSS filled channels: 1) center and bottom left (CBL), 2) top right and bottom left (TRBL). We have found that the choice of electrodes is not fundamental in preserving random network properties: 1) spatio-temporal resolved pressure sensing capabilities and 2) computational capabilities. The IV and impedance characteristic measured show that the system can be modelled as a LCR circuit (see figure 2).

In order to evaluate the spatio-temporal resolution of sensing skin, applying over each box in the
Figure 2. IV curve (panel a) in the range [-10, +10] V and impedance curve (panels b and c) measured in the range between 20 Hz and 20 MHz. Measurements were taken by contacting PEDOT:PSS random network channel soft skin, where no mechanical stimulus was applied (at rest).

Figure 3. Sketch showing the spatiotemporal sequence of application of mechanical stimuli, superimposed over the soft skin random network. The range of square boxes that underwent activation has been specified.

The output generated by pressure applied in each position of the chessboard is clearly distinguishable, both reading resistance and reactance (real and imaginary components). All peaks have been labelled as shown in the figure 4. Therefore spatial resolution of 1 cm and temporal resolution in the order of 1 s were achieved. By looking at the details of the electronic response to the stimuli (figure 5) we can sort the curves into four families (red curve is a resistance, blue curve is a reactance). The first family (RED square) shows a dip in resistance as consequence of applied pressure (while the reactance might show either a peak or a more complex shape); the second family (blue square) shows a peak in the reactance as consequence of applied pressure; the third family (gradient square) belongs to the previous group but shows also a marked peak in resistance; the fourth and last family (green square) shows a dip in reactance (and no features in resistance).

By plotting such responses against the map of the Delaunay triangulation and the electrode location, we see a geometrical correspondence (figure 6). RED output occurs in boxes which are between electrodes’ projections, meaning that applied pressure creates a deformation able to slightly reduce the distance covered by PEDOT:PSS between electrodes, therefore provoking a major effect on the real part of

chessboard a fixed weight of 100 g was repeated, lifting the weight to move to the next slot after 5 s. During this procedure, impedance was acquired at a fixed frequency by submitting a sinusoidal signal of fixed amplitude of 100 mV, using electrodes in a fixed position. The sequence of boxes where pressure was applied is shown in figure 3.
impedance (resistance). Green output occurs where slots intercept a duct and therefore a pumping effect is possible. External pressure initiates PEDOT:PSS movement and volumetric rearrangements inside the circuit whose effect is that of reducing reactance with almost no changes in resistance. The system can be conceived as a parallel RLC circuit, where around 100 Hz capacitive component prevails, and around 1 MHz inductive component prevails (see figure 2). Therefore our stimulus either at 1 or 5 kHz is such that both capacitive and inductive effects are measured. Pumping through applied pressure the fluid in the channels increases the inductive behaviour, like expanding the radiating area of an antenna. It does not happen while crossing channel G13-I11, which is a very short one connecting two major central hubs, and channel I11-M16, which is under the influence of the central electrode. GRADIENT output occurs when the stimulus is applied in between the two actively measuring electrodes: the pressure squeezes the conductive channel, reducing eventually the section of the duct and creating a layered structure where the two polymers are closer, increasing associated capacitance. Blue output occurs in every other situation, meaning that the leading effect is a contraction of the conductive area and a consequent reduction of inductance.

4. Multi-touch experiments for implementing computation and skin hardness effect

In the second experiment we implemented a multi-touch protocol: three couples of boxes were identified, regardless of skin hardness and of the positioning of electrodes. For each couple, two pressure stimuli were applied:

(a) pressure on slot number 1 kept until phase (c);
(b) pressure on slot number 2 kept until phase (d);
(c) relieving pressure from slot number 1;
(d) relieving pressure from slot number 2.

Electrical output was recorded in real-time during all this process, with a temporal resolution of 200 ms. Figure 7 shows the location of selected stimuli boxes. The identification of each stimulus can be based on...
reactance in most of the cases. Also resistance, impedance modulus and impedance phase are shown for completeness in figure 8.

Here we show how it is possible to associate four different output levels to the four combinations of two inputs:

- 00: no stimuli are applied, both before and after experiment;
- 01: first stimulus is removed, second is kept;
- 10: first stimulus is applied;
- 11: the two stimuli are applied.

The differential reactance, measured on electrodes BL and C, shows that the inputs are separable. The following values of the reactance are recorded: input \((xy) = (00)\) output \(O_{00} = -1.03 \pm 0.05\Omega\), input \((xy) = (01)\) output \(O_{01} = +5.79 \pm 0.04\Omega\), input \((xy) = (10)\) output \(O_{10} = +0.13 \pm 0.03\Omega\), input \((xy) = (11)\) output \(O_{11} = +8.03 \pm 0.04\Omega\). To convert the reactance outputs to binary values, \(x \times y \xrightarrow{f} z\), where \(x, y, z \in [0, 1]\) we can impose a cutoff threshold \(T\). If \(O_{xy} > T\) then \(f(x, y) = 1\) otherwise \(f(x, y) = 0\). Thus, for \(T = 0.13\) we have \(f(x, y) = y\) and for \(T = 5.79\) we have \(f(x, y) = xy\).

The impact of skin hardness over sensing capabilities was assessed by comparing impedance measured on both the soft and hard skins submitted to the same input pattern described in the multi-touch approach. In figure 9 the two curves (light colours for the soft, darker colours for the hard skin), separated in the real and imaginary components of impedance, have been shown. A softer skin provides a more efficient mechanism for the transduction of the pressure stimuli, resulting in a broader dynamics of the electronic response, both in terms of amplitude of variations and in terms of duration of the effects.
Liquid pumping effect and deformation of the random network are enhanced, creating an electronic echo that makes the use as sensor as well as computing system more subject to nonlinearities. By analysing resistance dips and peaks and fitting with standard exponentially decaying curves, it is possible to estimate that the electrical relaxation times for the soft and hard skins are $3.2 \pm 0.1$ s and $0.6 \pm 0.1$ s, respectively. Relaxation times represent the fingerprint of a complex viscoelastic response, only partially connected to the Shore hardness parameter, that is statically evaluated on the polymers during measurements.

5. Discussion

Our interpretation of the network responses to tactile stimulation in a framework of logical gates echoes and enriches previous designs of mechano-electrical information processing. Thus, a range of logical circuits has been proposed in [59] based on the feature that slime mould *Physarum polycephalum* halts peristaltic movement and transfer of cytoplasm when its protoplasmic tube is stimulated mechanically. A piezo-phototronic binary circuit made of cadmium sulfide nanowire networks, where inputs are optical and mechanical, is demonstrated in [60]. Neuromorphic flexible circuits, including memory arrays and synapse-like devices, are discussed in [61]: the electronic advanced interconnection and packaging technology devices are integrated into on a single plastic substrate. Other neuromorphic devices based on silver nanoparticles have shown the same plasticity typical of liquids [62], even though their aggregation state is solid, with a mechanoelectric coupling that can even be exploited to create actuators [63]. One of the comparative advantages of the device proposed by us is its potentially self-healing ability: a bulk of the conductive material is in liquid phase, thus it is capable for restoring its shape in case of any mechanical damage, assuming, indeed that channel walls remain intact or repaired. In this sense our design organically complements prototypes of self-healing wires.
with liquid metal [5], electric field trapping of gold nanoparticles by a dielectrophoresis force [64], sheets of carbon nanotubes wrapped around polymer fibers [65] and graphene oxide polymer composites [66].

Indeed, to be a proper computing circuit, the network of channels with conductive polymer must be such that both inputs and outputs share the same physical nature and the individual gates should be cascadable. Cascading of the gates could be realised due to the networks of channels being connected: if a pressure is increased on one channel the amount of conductive polymer in its neighbouring channels will increase. Two other fundamental aspects of computation are represented by data relay (transmission and reception, beyond the computing skin itself) and data storage. Transmission of information can be assured by standard wiring of the skin, by means of technologies compliant with flexible and stretchable materials, such as digital printing of conductive inks [67], or by means of wireless channels. Storage of information can be performed through distributed reactions (electrochemical, phase-change, chemical reaction [27]) or through functional particles dispersed within the conductive liquid [17], featuring functionalities such as resistive switching capabilities or even integrated memories embedded in the flexible skin. Some recent studies have demonstrated the capabilities to fabricate flexible and stretchable memory elements, eventually embedded in the texture of a textile [68].

6. Conclusion

We demonstrated that a network of channels hosted by a soft polymeric matrix, being a proximity graph constructed on a random planar set, filled with conductive polymer, can act as a precise and reliable reporter of the tactile stimuli applied. We have also shown that it is possible to implement Boolean gates, where inputs are represented by positions and strength of mechanistic stimuli. Further studies can go into the direction of complete fusion between sensing and computing, where a stretchable and flexible network of conductive polymers makes decision about its response to a complex patterns of dynamic stimuli. The experiments done so far have not yet focused on a practical implementation close to market, where endurance and ageing are required, and where automated testing machines can easily reproduce the stimuli pattern over a long timescale, evidencing a gap that must also be addressed in the near future.

References

[1] Gao Y, Haiyan Li and Liu J 2012 Direct writing of flexible electronics through room temperature liquid metal ink PlOS One 7 e45485
[2] Liu S, Yuen M C and Kramer-Bottiglio R 2019 Reconfigurable electronic devices enabled by laser-sintered liquid metal nanoparticles Flexible and Printed Electronics 4 015004
[3] Nathan A et al 2012 Flexible electronics: the next ubiquitous platform Proc. IEEE 100 1486–1517
[4] Dickey M D 2017 Stretchable and soft electronics using liquid metals Adv. Mater. 29 1606425
[5] Palleau E, Reece S, Desai S C, Smith M E and Dickey M D 2013 Self-healing stretchable wires for reconfigurable circuit wiring and 3D microfluidics Adv. Mater. 25 1589–92
[6] Gkoupidenis P, Schaefer N, Garlan B and Malliaras G G 2015 Neuro morphic functions in PEDO/PSS organic electrochemical transistors Adv. Mater. 27 7176–80
[7] Erokhin V, Rezina T and Fontana M F 2005 Hybrid electronic device based on polyaniline-polyethylene oxide junction J. Appl. Phys. 97 064501
[8] Okuzaki H, Takagi S, Hishiki F and Tanigawa R 2014 Ionic liquid/polyurethane/pedot: PSS composites for electro-active polymer actuators Sensors Actuators Actuators 194 59–63
[9] Shi J, Chen X, Gengfei Li, Na Sun H, Jiang D B, Xie L, Peng M, Liu Y and Wen Z. et al 2019 A liquid pedot: Pss electrode-based stretchable triboelectric nanogenerator for a portable self-charging power source Nanoscale 11 7513–9
[10] Elschner A, Kirchmeyer S, Lovenich W, Merker U and Reuter K 2010 Pedot: Principles and Applications of an Intrinsically Conductive Polymer (Boca Raton, FL: CRC Press)
[11] Scott M J, Zou J, Wang K, Chen C, Su M and Chen L 2013 A gallium nitride switched-capacitor circuit using synchronous rectification IEEE Trans. Ind. Appl. 49 1383–91
[12] Xiao Z and Huang J 2016 Energy-efficient hybrid perovskite memristors and synaptic devices Advanced Electronic Materials 2 680004
[13] Chen Y, Liu G, Wang C, Zhang W, Run-Wei Li and Luxing W 2014 Polymer memristor for information storage and neuromorphic applications Mater. Horizons 1 489–506
[14] Battistoni S, Dimonte A and Erokhin V 2017 Organic memristor based elements for bio-inspired computing Advances in Unconventional Computing (Berlin: Springer) pp 469–496
[15] Koo H-J, Ju-Hee S, Dickey M D and Velev O D 2011 Towards all-soft matter circuits: Prototypes of quasi-liquid devices with memristor characteristics Adv. Mater. 23 3559–64
[16] Sheng Q, Xie Y, Jun Li, Wang X and Xue J 2017 Transporting anionic-liquid/water mixture in a conical nanochannel: a nanofluidic memristor Chemical Communications 53 6125–7
[17] Chiolero A, Roppolo I, Bejtka K, Asvarov A and Pirri C F 2016 Resistive hysteresis in flexible nanocomposites and colloidal suspensions: interfacial coupling mechanism unveiled RSC Adv. 6 56661–7
[18] Rogers J A, Someya T and Huang Y 2010 Materials and mechanics for stretchable electronics Science 327 1603–7
[19] Wagner S and Bauer S 2012 Materials for stretchable electronics MRS Bull. 37 207–13
[20] Fan J A et al 2014 Fractal design concepts for stretchable electronics Nat. Commun. 5 3266
[21] Kim D-H, Ghaffari R, Nanshu L and Rogers J A 2012 Flexible and stretchable electronics for biointegrated devices Ann. Rev. Biomed. Eng. 14 113–28
[22] Ahn J-H and Jung Ho J 2012 Stretchable electronics: materials, architectures and integrations J. Phys. D: Appl. Phys. 45 103001
[23] Yang C, Hongwei G, Lin W, Yuen M M, Wong C P, Xiong M and Gao B 2011 Silver nanowires: from scalable synthesis to recyclable foldable electronics Adv. Mater. 23 3052–6

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[24] Nanshu L and Kim D-H 2014 Flexible and stretchable electronics paving the way for soft robotics Soft Robotics 1 53–62
[25] Siegel A C, Phillips S T, Dickey M D, Nanshu L, Suo Z and Whitesides G M 2010 Foldable printed circuit boards on paper substrates Adv. Funct. Mater. 20 28–35
[26] Wang C, Hwang D, Zhilin Y, Takai K, Park J, Chen T, Biwu M and Javey A 2013 User-interactive electronic skin for instantaneous pressure visualization Nat. Mater. 12 899–904
[27] Chioleiro A and Quadrelli M B 2017 Smart uid systems: the advent of autonomous liquid robotics Advanced Science 4 1700036
[28] Soni M and Dahiya R 2020 Soft eSkin: distributed touch sensing with harmonized energy and computing Philosophical Trans. of the Royal Society A 378 20190136
[29] Mingyuan M, Zhang Z, Liao Q, Fang Y, Han L, Zhang G, Liu S, Liao X and Zhang Y 2017 Self-powered electronic skin for high-resolution pressure sensing Nano Energy 32 389–96
[30] Zhao S and Zhu R 2017 Electronic skin with multifunction sensors based on thermosensation Adv. Mater. 29 1600151
[31] Chou H-H et al 2015 A chameleon-inspired stretchable electronic skin with interactive colour changing controlled by tactile sensing Nat. Commun. 6 1–10
[32] Yang T, Wang W, Zhang H, Xinning Li, Shi J, Yijia H, Zheng Q-shui, Zhihong Li and Zhu H 2015 Tactile sensing system based on arrays of graphene woven microfabrics: electromechanical behavior and electronic skin application ACS nano 9 10867–75
[33] Wang X, Dong L, Zhang H, Ruomeng Y, Pan C and Wang Z L 2015 Recent progress in electronic skin Advanced Science 2 1500169
[34] Xiong P, Liu M, Chen X, Sun J, Chunhua D, Zhang Y, Zhai J, Weigu H and Wang Z L 2017 Ultrastretchable, transparent triboelectric nanogenerator as electronic skin for biomechanical energy harvesting and tactile sensing Science advances 3 e1700015
[35] Chortos A, Liu J and Bao Z 2016 Pursuing prosthetic electronic skin Nat. Mater. 15 937–50
[36] Park S et al 2014 Stretchable energy-harvesting tactile electronic skin capable of differentiating multiple mechanical stimuli modes Adv. Mater. 26 7324–32
[37] Núñez C, Gia, Manjakakkal L and Dahiya R 2019 Energy autonomous electronic skin npj Flexible Electronics 3 1–24
[38] Wang X, Yang G, Xiong Z, Cui Z and Zhang T 2014 Silk-molded flexible, ultrasensitive and highly stable electronic skin for monitoring human physiological signals Adv. Mater. 26 1336–42
[39] Sekitani T and Someya T 2012 Stretchable organic integrated circuits for large-area electronic skin surfaces MRS Bull. 37 236–45
[40] Guo H, Lan C, Zhou Z, Sun P, Wei D and Chun Li 2017 Transparent, flexible and stretchable ws 2 based humidity sensors for electronic skin Nanoscale 9 6246–53
[41] Qiao Y et al 2018 Multilayer graphene epidermal electronic skin ACS nano 12 8839–46
[42] Zhao X, Hua Q, Ruomeng Y, Zhang Y and Pan C 2015 Flexible, stretchable and wearable multifunctional sensor array as artificial electronic skin for static and dynamic strain mapping Advanced Electronic Materials 1 1500142
[43] Delaunay B et al 1934 Sur la sphere vide Izv. Akad. Nauk SSSR, Otdelenie Matematicheskaya Nauk 7 1–2
[44] Bebis G, Deaconu T and Georgiopoulos M 1999 Fingerprint identification using delaunay triangulation Proc. 1999 Int. Conf. on Information Intelligence and Systems (Cat. No. PR00446) (IEEE) pp 452–9
[45] Wang C and Gavrilova M L 2006 Delaunay triangulation algorithm for fingerprint matching 2006 3rd Int. Symp. on Voronoi Diagrams in Science and Engineering (IEEE) pp 208–16
[46] Lee S and Jeong I R 2019 A cancelable template for the low-quality fingerprints from wearable devices Security and Communication Networks 2019 4202671
[47] Lesne A and Lagués M 2011 Scale Invariance: From Phase Transitions to Turbulence (Berlin: Springer)
[48] Sunkyu Y, Piao X and Park N 2020 Machine learning identifies scale-free properties in disordered materials (https://www.researchgate.net/publication/339972021_Machine_learning_identifies_scale-free_properties_in_disordered_materials)
[49] Liu C, Kui Wu , Xiao Y and Sun B 2006 Random coverage with guaranteed connectivity: Joint scheduling for wireless sensor networks IEEE Trans. Parallel Distrib. Syst. 17 562–75
[50] Gang Li et al 2019 PEDOT: PSS/grafted-PDMS electrodes for fully organic and intrinsically stretchable skin-like electronics ACS Appl. Mater. Interfaces 11 10373–9
[51] Jang H-H, Park J-S and Choi B 2019 Flexible piezoresistive sensor using biomimetic PDMS mold replicated negatively from shark skin and PEDOT:PSS thin film sensors and Actuators A: Physical 286 1500169
[52] Xiaou F, Wang J K, Ramirez-Perez A C, Choong C and Lisak G 2020 Flexible conducting polymer-based cellulose substrates for on-skin applications Mater. Sci. Eng. C 108 110392
[53] Wang Q, Pan X, Lin C, Lin D, Yonghao N, Chen L, Huang L, Cao S and Xiaojuan M 2019 Biocompatible, self-wrinkled, antifreezing and stretchable hydrogel-based wearable sensor with PEDOT: sulfonated lignin as conductive materials Chem. Eng. J. 379 10199–47
[54] Chegini E and Hossein-Babaei F 2019 Ti/PEDOT:PSS/Ti pressure sensor 2019 27th Conf. on Electrical Engineering (ICEE) (IEEE) pp 348–351
[55] Kang T-G, Park J-K, Yun G-H, Choi H H, Lee H-J and Yook J-G 2019 A real-time humidity sensor based on a microwave oscillator with conducting polymer pedot: Pss film Sensors Actuators 282 145–51
[56] Kee S, Kim H, Paleti S, Liao X and Zhang Y 2017 Self-powered artificial electronic skin for high-resolution pressure sensing Nano Energy 38 9–6
[57] Donahue M J, Sanchez-Sanchez A, Inal S, Jing Q, Owens R M, Mecerreyes D, Malliaras G G and Martin D C 2020 Tailoring PEDOT properties for applications in bioelectronics Mater. Sci. Eng. B: Rep. 140 105046
[58] Chioleiro A et al 2013 Effect of the fabrication method on the functional properties of batio3: Pvd nanocomposites J. Mater. Sci. 48 6943–51
[59] Adamatzky A and Schubert T 2014 Slime mold microfluidic logical gates Mater. Today 17 86–91
[60] Ruomeng Y, Wenzhuo W, Pan C, Wang Z, Ding Y and Wang Z L 2015 Pizio-photoronic boolean logic and computation using photon and strain dual-gated nanowire transitors Adv. Mater. 27 940–7
[61] Lee H E, Park J H, Kim T J, Doyoung I, Shin J H, Kim D H, Mohammad B, Kang I-S and Lee K J 2018 Novel electronics for flexible and neuromorphic computing Adv. Funct. Mater. 28 1801690
[62] Rajan R M 2016 Ionic liquid-enhanced soft resistive switching devices RSC Adv. 6 94128–38
[63] Chioleiro A et al 2019 Nanoparticle reshaping and ion migration in nanocomposite ultrafast ionic actuators: the converse Piezo–electro–kinetic effect Adv. Funct. Mater. 29 1902941
[64] Koshi T and Iwase E 2015 Self-healing metal wire using electric field trapping of metal nanoparticles Japan. J. Appl. Phys. 54 06FP03
[65] Sun H, You X, Jiang Y, Guan G, Fang X, Deng J, Chen P, Luo Y and Peng H 2014 Self-healable electrically conducting wires for wearable microelectronics Angewandte Chemie Int. edn 53 9526–31
[66] Chinke S L and Alegaonkar P S 2020 Self-Healing Aspects of Graphene Oxide/Polymer Nanocomposites Self-Healing Composite Materials (Amsterdam: Elsevier) pp 285–312
[67] Chiolerio A, Vescovo L and Sangermano M 2010 Conductive uv-cured acrylic inks for resistor fabrication: Models for their electrical properties Macromolecular Chemistry and Physics 211 2008–16
[68] Rajan K, Garofalo E and Chiolerio A 2018 Wearable intrinsically soft, stretchable, flexible devices for memories and computing Sensors 18 367