Chapter 9
Sensor Skins: An Overview

Jennifer Case, Michelle Yuen, Mohammed Mohammed and Rebecca Kramer

Abstract Sensor skins can be broadly defined as distributed sensors over a surface to provide proprioceptive, tactile, and environmental feedback. This chapter focuses on sensors and sensor networks that can achieve strains on the same order as elastomers and human skin, which makes these sensors compatible with emerging wearable technologies. A combination of material choices, processing limitations, and design must be considered in order to achieve multimodal, biocompatible sensor skins capable of operating on objects and bodies with complex geometries and dynamic functionalities. This chapter overviews the commonly used materials, fabrication techniques, structures and designs of stretchable sensor skins, and also highlights the current challenges and future opportunities of such sensors.

Keywords Sensor skins · Wearables · Soft robotics · Stretchable sensors · Pressure sensors · Liquid metals · Sensor fabrication · Flexible materials · Ionic liquids · Conductive ink · Conductive composites · Microchannels

9.1 Introduction

With growing interest in soft systems and wearable technology comes a need to develop deformable sensing components. Traditional sensors and electrical components are often rigid and are best suited to well-defined systems that have discrete motions and confined trajectories. In contrast, soft structures generally have more degrees of freedom than rigid systems. These degrees of freedom come from the deformability of the soft structures themselves. State information of these soft systems may be obtained by populating the surface of the structure with sensor skins, which are stretchable planar structures with embedded sensing components.

J. Case · M. Yuen · M. Mohammed · R. Kramer (✉)
Purdue University, West Lafayette, IN, USA
e-mail: rebeccakramer@purdue.edu

J.A. Rogers et al. (eds.), *Stretchable Bioelectronics for Medical Devices and Systems*, Microsystems and Nanosystems,
DOI 10.1007/978-3-319-28694-5_9

The design of these highly deformable sensory skins has been guided by the flexible and stretchable characteristics of elastomers and human skin.

Let us define what we mean by sensor skins and wearable systems. There are a number of different ways that we can limit our definition of a sensor skin by including stipulations like stretchability, placement on a flexible host, proprioceptive feedback, etc.; however, in this chapter, we will discuss sensor skins that are mechanically compatible with human skin, meaning that they can undergo at least 20 % strain. Wearable systems will be defined here as systems designed to be worn by a human, but we will focus on wearable technology that targets efficient interaction with the host. Other reviews on flexible sensors that do not match this criteria are available for further reading [1–3].

Figure 9.1 shows examples of sensor skins used in different applications. Figure 9.1a (http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7352295) is a sensor skin module containing three resistance-based strain gauges capable of measuring deformation. Multiple modules can be combined into an array to measure the state of deformation of a host. Figure 9.1b shows an example of a tactile sensor skin used in a surgical environment. This device is composed of an array of pressure sensors to probe the environment without damaging tissues during neuroendoscopy and gives the surgeon another tool to help operate safely on a patient [4]. Two examples of wearable sensor skins can be seen in Fig. 9.1c, d. These sensors can detect pose of the lower limbs (Fig. 9.1c) [5] and of the hand (Fig. 9.1d) [6].

In the following sections, we discuss the materials and processing approaches of substrates and conductors, the structures and designs of elements, the systems used in sensor skins, and conclude with potential future directions of sensor skins.

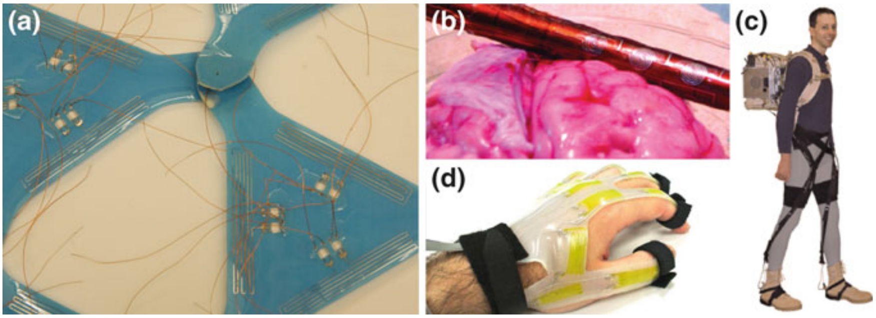

Fig. 9.1 Examples of sensors skins. **a** Sensor skin modules composed of silicone elastomer with three embedded liquid metal sensing strain gauges each. **b** Sensor skin composed of liquid metal pressure sensors for detecting tissue damage [4]. **c** Wearable system with liquid metal strain sensors for detecting pose [5]; and **d** wearable system with ionic liquid strain sensors for detecting hand pose [6]. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=7352295

9.2 Materials and Processing

Sensor skins are generally composed of at least two types of materials: substrates and conductors. These materials give the skins stretchability as well as the ability to interact in some capacity with itself or a host. This section overviews common substrates and conductors that have been used in sensor skin fabrication and their processing techniques.

9.2.1 Substrate

A sensor skin is, in essence, a substrate onto which or into which sensors are integrated. Substrates can be defined in terms of attributes such as stretchability, breathability, toughness, tear resistance, weight, and compatibility with the host or existing manufacturing techniques. Due to the wide range of substrates available and the complex interactions between the substrate and the host, the substrate should be carefully chosen so that it matches the target properties of the sensor and the fabrication process. Furthermore, in some wearable applications there is a need to use two substrates: the sensor substrate and the garment that is meant to be worn. The integration of two substrates into a single device adds another layer of complexity, since the compatibility between substrate materials must be considered in addition to the substrate–host compatibility.

In the following subsections, we discuss two common types of substrate materials: elastomers and woven fabrics.

9.2.1.1 Elastomers

Elastomers are the most common substrates in soft sensor applications. They are capable of supporting structures and encasing functional elements. In addition, elastomers are compatible with other types of substrates, such as woven fabrics [7–9]. There are many commercially available low-cost elastomers with a wide range of stretchability (from 40 % [10] up to 700 % [11]). Because elastomers are highly stretchable, they are conformable to human skin, which can strain up to 30 %, and thus are less likely to limit natural motion than nonstretchable substrates. However, this high flexibility and stretchability comes at a cost; elastomers are subject to viscoelastic behaviors, such as the Mullins effect [12], creep, and stress relaxation [13, 14].

Commercial elastomers usually are sold as two parts (free chains and crosslinker). Polymerization starts by mixing both parts at a specific ratio, and can be triggered by heating [10] or exposure to UV light [15]. Uncured elastomer can be easily cast in a pre-made mold, which is convenient for creating specific geometries for different part functions and material properties. Researchers use different techniques to fabricate molds such as lithography [16] and 3D printing [17].

It is possible to use methods to shape the elastomer other than replica molding, such as spin coating or other coating methods to make thin films. For example, elastomer films cast onto polyethylene terephthalate (PET) sheets can be integrated into roll-to-roll machines. Elastomers can be both physically and chemically altered through processes such as laser ablation [18] and plasma treatment [19].

Elastomers were originally used to coat and support the structure of conductive solid substrates [20–23]. However, the concept of building microchannels into elastomers [24] allowed researchers to build sensor components by filling elastomeric microchannels with functional materials, such as liquid metals [4, 16, 18, 25–37] or ionic liquids [6, 38, 39].

9.2.1.2 Woven Fabrics

Woven fabric is most recognizable as the material of which our garments are comprised. More generally, woven fabrics are composed of two sets of fibers interlaced together. This construction gives rise to the tensile strength and tear resistance of fabrics. Properties of the fabric such as the elasticity, stiffness, chemical resistance, and thermal properties can be tuned based on the choice of the constituent fibers and the pattern with which they are woven.

The first attempts to integrate sensors and fabrics were by means of simple attachment, such as sewing. This concept was improved upon by the invention of conductive fibers that can be woven the same way as conventional fibers and act as sensory elements without additional components [40]. Woven fabrics using conductive threads and fibers have been employed as strain, pressure, respiratory, heart rate, and electrochemical sensors, as well as gesture-input devices [41–43]. Conductive threads woven with a known spacing can act as capacitive pressure sensors by measuring the change in capacitance between fibers due to thread shifting from applied pressure. Conductive fibers can act as resistive sensors when they are woven as single or multiple threads that gain contact with each other and reduce resistance when strain or pressure is applied to them [43, 44].

Woven skin sensors can achieve higher strains by sewing the components onto pre-wrinkled fabrics. This technique allows the devices to be stretched beyond the stretch limit of the fabric itself [45]. Alternately, conductive coatings can be applied to the same pre-wrinkled construct to form stretchable electronics-compatible fabrics [46, 47].

9.2.2 Conductor

A conductor is a material that allows the flow of electrons or ions through it. In sensor skins, conductors have two major functions: conveying information (i.e. a trace on a circuit board) and collecting information (i.e. a sensor). In many cases, conductors can be used for both purposes. The stability of the conductor and its conformal contact with the interface are essential to ensure efficient sensor performance. In wearable applications, it is also important to consider the biocompatibility (i.e. toxicity) of a sensor.

The conductors that we highlight in this section are thin metal films, liquid metals, ionic liquids, conductive polymers, and conductive inks.

9.2.2.1 Thin Metal Films

Conductive materials are, in most cases, rigid. They show flexible behavior when they are shaped as thin films. The first attempt to use thin metal films in flexible electronics was in 1967 to produce the first flexible solar cell [48, 49]. Advanced electronics typically consist of insulators, conductors, and semiconductors, and it is possible to use processes like roll-to-roll to produce electronics at larger scales [50]. Metallic thin films have been fabricated to accommodate moderate strains using clever geometries (waves and nets) made from both highly conductive metals (such as gold, silver, copper, and aluminum) and semiconductors (such as silicon) [51]. Thin-film electronics enable other applications such as displays [9, 52, 53], electrodes [54, 55], LEDs [56] and wearable electronics [57–59].

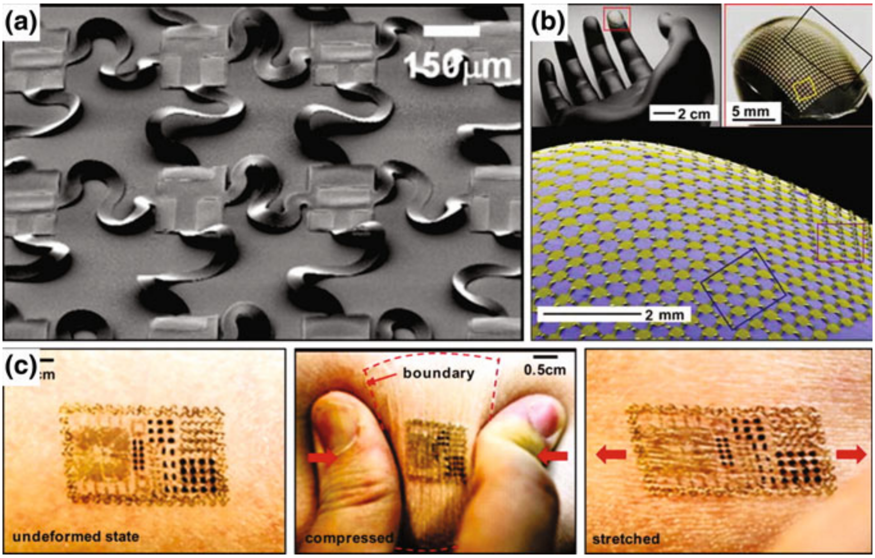

Fig. 9.2 **a** Extremely stretchable metal films with serpentine-design bridges [51]. **b** Stretchable circuit with noncoplanar metal films on a model finger tip [63]. **c** A multifunctional epidermal electronic circuit mounted on human skin in undeformed, compressed, and stretched states [69]

The devices fabricated using thin metal films are flexible. However, they lack stretchability due to the very low fracture strain of most metals. Researchers have used geometry to cause this nonstretchable material to behave elastically. For instance, curved and wavy metal films can undergo strains that are impossible to achieve using flat films [21–23, 60–64]. Figure 9.2a, b shows two examples of thin film structures. This approach enables stretchable interconnects [65, 66], integrated circuits [67], batteries [68] and epidermal electronics (Fig. 9.2c) [69, 70]. With proper engineering design, the devices fabricated using this technique can be strained up to 200 % [71].

Devices fabricated using metal films or wires deform plastically with prolonged use leading to permanent deformation that reduces the device efficiency or totally disconnects the circuit [72–75]. Other conductors, such as liquid metals and ionic liquids, have been recently used as alternatives that do not suffer from this limitation.

9.2.2.2 Liquid Metal

There is a growing interest in using liquid metals in flexible electronics as alternatives to conventional metals. The most famous liquid metals are eutectic alloys such as eutectic gallium-indium (eGaIn) and eutectic gallium-indium-tin (Galinstan). They have high metallic conductivity ($\approx 3.4 \times 10^6\,\Omega^{-1} \cdot \mathrm{m}^{-1}$ for EGaIn and $\approx 3.1 \times 10^6\,\Omega^{-1} \cdot \mathrm{m}^{-1}$ for Galinstan [76]) and form a thin gallium-oxide skin that allows them to form stable nonspherical structures despite their high surface tension [77, 78]. In contrast to mercury, gallium-indium alloys are non-toxic and therefore have potential applications in biocompatible sensors. Gallium-indium alloys can be injected into microchannels due to their low viscosity [16, 25, 26, 32, 37, 79], and their liquid nature allows them to take the shape of the microchannel even at very high strains (up to 700 %) without failure [11].

Researchers have developed fabrication techniques that are more automated than manual injection [80]. For instance, a microtip wet with the liquid metal can transfer patterns on a substrate by direct contact [81]. The tip can be replaced by a syringe needle that continuously extrudes the liquid metal and directly writes onto a surface [28, 78]. Liquid metal can selectively wet parts of a substrate using a predesigned mask [82, 83], or by treating the substrate surfaces such that liquid metal self-assembles into the desired areas [33, 84–86]. Liquid metals are not suitable for inkjet printing due to the high surface tension, its corrosive nature to most other metals and the presence of surface oxide. However, a dispersion of liquid metal nanoparticles in a volatile solvent can be inkjet printed since the dispersion properties are dictated by the carrier solvent rather than the liquid metal [87]. Finally, liquid metal films maybe subtractively patterned by selective laser ablation [88].

The various patterning techniques have enabled the fabrication of different types of liquid metal-based sensors, such as capacitive pressure sensors [35–37], resistive strain sensors [18, 28, 33, 87], resistive pressure sensors [4, 26, 27, 31, 32, 79, 89], curvature sensors [16, 25] and shear sensors [89]. Examples of other liquid metal-based devices are antennas [90–92], soft wires [6, 39], self-healing wires [93], diodes [94], and capacitors [81].

9.2.2.3 Ionic Liquids and Solutions

Ionic liquids and salt solutions can also be used in sensor skins. Ionic liquids are molten salts while salt solutions are salts dissolved in a solvent, typically water. These solutions are capable of reflowing and are typically used within an elastomer substrate, where preformed microchannels are filled with the conductive solutions by injection [6, 29, 39] or vacuum [95].

The most familiar form of a salt solution is a sodium chloride (NaCl) solution, which has been used to make sensors [95] and sensor arrays [96]. Researchers have also demonstrated the use of potassium chloride solution (KCl), sodium hydroxide (NaOH), and hydrogen chloride (HCl) in their sensors, but found that both NaOH and HCl were corrosive to the sensor interface and that NaCl had a better range than KCl [95]. An example of an ionic liquid is 1-ethyl-3-methylimidazolium ethyl sulfate [6, 29, 38]. Ionic liquids and salt solutions have been used in fabricating tactile sensors [29, 95, 96], strain sensors [39], curvature sensors [38], diodes [94] and wearable devices [6].

The major drawback of using salt solutions is that popular substrates, like elastomers, are gas permeable, which means that water will slowly evaporate and leave a salt residue in the substrate. Water evaporation can be slowed down by adding glycerol to the solution [39, 97].

9.2.2.4 Conductive Inks

A conductive ink is a solvent that contains a suspension of conductive particles, such as metallic nanoparticles, organometallic compounds, carbon nanotubes and graphene [98–100]. Volatile organic solvents (ethanol, toluene, etc.) are commonly used and leave behind the conductive particles on the substrate as they evaporate. Additives are often used to keep particles suspended, increase adhesion onto the surface, or reduce surface tension. In some cases, a means of coalescing or sintering is necessary to bridge gaps between nanoparticles and ensure conductivity [87, 101, 102].

The flow properties of the ink are dictated by the properties of the carrier solvent, therefore conductive inks have a lower viscosity relative to many of the previously described liquid conductors. Hence, conductive inks are compatible with inkjet printing [87, 103–105], screen-printing (polymer thick film) [99, 106] and direct-writing [101, 107, 108]. Researchers invented conductive silver inks that can be directly written on different surfaces using rollerball pens [109, 110]. As previously mentioned, liquid metal dispersion inks have also been developed, which bridge the gap between liquid metal conductors and conductive inks using liquid metal nanoparticles suspended in a carried solvent [87].

9.2.2.5 Conductive Polymer Composites

Conductive polymer composites generally consist of a polymer mixed with a conductive material that is packed tightly enough in the polymer to maintain conductivity. Example conductive materials include silver nanoparticles [111–113], graphite [112, 114], graphene [115, 116], carbon black [114, 117], carbon nanotubes [114, 116, 118, 119] and liquid metals [120]. Different polymers can be used, such as polydimethylsiloxane [114, 116, 119, 120], polyisoprene [117], polyvinylidene fluoride [112], rubber fibers [113], and a number of other polymers [115]. Conductive polymers have been used to create tactile sensors [114, 117–119] and strain sensors [47, 117, 118, 120].

It is possible to pattern the conductive polymer using different techniques such as extrusion [119], screen printing [111], spray deposition [118] and hot-rolling [112]. The flow properties of the polymer composite affect the patterning process; therefore, it is common to add thinners to the composite in order to reduce its viscosity. Examples of thinners are reverse micelle solution, which also controls the hardness of the final conductive polymer [119], and cyclohexane [114]. Researchers have developed a novel composite material by embedding liquid metal nanoparticles in elastomer. Initially, the composite is not conductive due to the absence of a conductive path between the nanoparticles; however, applying local pressure on the composite breaks the boundaries between the nanoparticles and creates a conductive path within the composite [120, 121].

9.3 Structures and Designs

It is important to choose the proper materials to fabricate the sensor to ensure stability of the structure and compatibility with the host under representative operating conditions. Therefore, the designer should be aware of different structures and design approaches in order to fabricate a properly functioning device. This section highlights the common features and systems of sensor skins.

9.3.1 Features

There are several features of sensor skins that affect how sensor elements function. These features include microchannels containing liquid conductors (which we discussed in Sect. 9.2.2) and interfaces within the sensor skins. Examples of the latter include interfaces between two different conductors, between substrates, between the sensor skin and external electronics, and, in the case of wearables, between the sensor skin and the human.

9.3.1.1 Microchannels

Microchannels are defined as flow passages with dimensions on the order of tens to hundreds of microns [24, 122]. In sensor skins, these microchannels can be used for sensing or as communication pathways. Chossat et al. demonstrated both of these uses in a wearable glove, where microchannels filled with an ionic liquid serve as the sensing component and microchannels filled with liquid metal serve as a communication pathway [6].

Elastomeric substrates deform under the influence of pressure or strain, therefore changing the dimensions of the embedded microchannels filled with the conductive liquid. This is important for resistive sensors, where the resistance of the channel is guided by $R = \rho L/A$, where R is the resistance, ρ is the resistivity, L is the length and A is the cross-sectional area of the sensor. This is the operational concept behind the variety of liquid-embedded sensors and devices described in Sects. 9.2.2.2 and 9.2.2.3.

Replica molding, subtractive and additive manufacturing are the common techniques used to manufacture microchannels in elastomeric matrices. Molds can be made via 3D printing [26, 27, 89], photolithography [123], patterning films [16] or laser engraving [39]. Microchannels can also be made by subtractively removing material via laser ablation [18] or by adding material via direct printing [28, 119]. The choice of the mold fabrication technique depends on the required resolution of the mold, available time and equipment. For instance, fabricating molds using photolithography produces small features with high resolution, but it is a time-consuming process [124, 125]. 3D printing is a fully automated process; however, the feature sizes of the mold are limited by the nozzle size of the printer. Laser ablation is also capable of achieving small feature sizes, but has less control over channel geometry than 3D printing [126].

9.3.1.2 Interfaces

At physical interfaces within devices, the change in stiffness from a highly deformable substrate to a rigid component or interconnect is a common cause of device failure. As the device is flexed or stretched, rigid parts are unable to follow the change in conformation of more flexible parts. For example, in Fig. 9.1a, while the silicone elastomer substrate is capable of withstanding strains up to 150 %, the electrical interface between the liquid metal and the copper wire limits the usable strain to 50 %. Beyond this limit, the copper wires lose contact with the liquid metal and fail to deliver strain data out of the sensor. This often also results in permanent failure of the device, as the wires contacting the liquid metal in this device will pull out of the channels, thus breaking the path from the sensing element to the rest of the system.

Researchers have addressed this deficiency in interfacing with liquid metal-based sensors using a variety of methods. For instance, copper wires can be replaced by ionic liquids to detect strain signals, which are transferred to external control circuit using liquid metal wires [6, 29]. Other approaches include using stretchable interconnects [127, 128], stretchable wires [11] and stretchable metal films [129, 130]. Uniaxially conductive polymer composites serve as a signal transmitter between the liquid metal circuit and the skin [131].

In addition to interfaces within the device, the interface between the human and the device greatly affects the device performance efficiency. Though elastomers are biocompatible and useful for wearable electronics, in reality, elastomer devices are difficult to secure onto the skin. Researchers have used skin adhesives to adhere electronic devices to the skin [61, 132]. With regard to garments, sensors have been held in place around joints via straps to create sensory suits [5]. Researchers ensured that the interface between the sensor and the strap was robust during motion by creating a stiffness gradient that transitions from the relatively stiff strap to the much softer sensor.

9.3.2 Systems

Moving beyond our discussion of the individual components and fabrication techniques for soft sensor skins, we can start looking at examples and applications. In this section, we focus on sensor skins for robotics and wearables as they fit with the scope of this chapter.

9.3.2.1 Sensor Skins for Robotics

Most traditional robotic systems have very fine tuned position control and can operate very quickly and efficiently. However, they generally lack any knowledge of their environment, which poses a potential safety risk for robots working alongside humans. Applying sensor skins to robots would provide environmental information and increase their awareness with their surroundings [133]. Tactile sensors tend to either use capacitive [30, 35–37, 111, 118, 134, 135] or resistive [4, 26, 31, 32, 38, 79, 117, 136] means of measuring pressure or normal force on the surface. Work has also been done to sense shear forces as well as normal forces on a surface [89]. While a lot of these works are on single sensors, these sensors can be arrayed into a sensor skin.

Soft robots need proprioceptive feedback through soft sensors that are mechanically compatible with the bulk of their structure. This proprioceptive feedback can come from strain sensors [6, 18, 26, 28, 34, 39, 47, 87, 97, 117, 120] or curvature sensors [16, 25, 137]. Yuen et al. demonstrated a robotic fabric skin which included a strain sensor that could differentiate between bending and compressing motion [138]. Resistive strain and pressure sensors have also been combined with existing pneumatic actuators to provide data about current state [139, 140]. A modular capacitive sensor skin has been developed to provide tactile information to existing robots [141].

9.3.2.2 Wearables

Many wearable sensor skin applications are designed for proprioception on conformal interfaces. Proprioceptive devices are used to estimate the state or pose of part of the human body. This can be applied on a smaller scale to measure the state of various joints on the fingers [16, 25] and across the entire hand and wrist [6, 142]. On a larger scale, exosuits have been developed to determine the pose of the lower body [5, 8, 143]. These devices are all composed primarily of elastomers with embedded liquid conductors injected into molded microchannels within the elastomer [144, 145]. Alternate designs rely upon direct adhesion of the strain sensor to the skin [61, 146]. These devices leverage thin film mechanics to measure strain due to skin stretch during joint flexion. The principles used to gather proprioceptive information can also be used to develop user interface devices, such as a wearable keypad [32, 119, 147].

9.4 Frontier and Outlook

The previous sections covered much of the published research in the field of stretchable skin sensors. Here, we discuss a few examples of the ongoing research and look at future opportunities.

Current research focuses on using new materials and novel fabrication strategies to develop sensors that can do multiple sensing tasks, have higher sensitivity and better mechanical properties, in addition to having a long lifetime. There is a need to develop methods to integrate these devices in a larger soft-bodied system, or to design the sensor as a built-in part of it. Such improvements will have a tremendous influence on the future sensor skins applications. An example of an integrated system is the exosuit that we discussed in Sect. 9.3.2.2. In the current state, exosuits require large power supplies or power cables, which is a significant drawback that needs to be addressed in order to make these devices practical.

Biocompatible soft sensors have significant potential in surgical robots. Integrating soft sensors in surgical tools will not only allow sensing of the force exerted on the surface but also determine the type of tissue onto which the force is being applied. Furthermore, the developing field of soft robotics holds the promise of creating new soft surgical tools that are mechanically compatible with soft tissue.

9.5 Conclusion

This chapter gives an overview of the current research on sensor skins. Sensor skins are sensor-embedded substrates that have the ability to flex, bend or stretch. Sensor skins are used to estimate large-deformation motions and changes in system states. There is a growing interest in applying sensor skins to human skin and tissues, since most of the materials used are biocompatible.

Sensor skins are generally made of two components: a conductive material which is the sensing and/or signal transmitting element, and a stretchable encasing substrate. The wide variety of materials that have been used in skin sensors provide a diverse foundation for researchers to develop new devices, fabrication techniques and designs. Within the current state-of-the-art, we are able to control the shape and dimensions of the devices and therefore the resulting sensing and mechanical properties. However, it is important to ensure both compatibility and stability of the sensor skin with the target host of the device in order to meet performance goals. Much of the current research in this field is aimed at integrating multiple sensing elements together into complex sensor skins. This poses new challenges in signal processing and networks that do not exist at the single element level. Major challenges that researchers are working to overcome include a lack of highly scalable manufacturing techniques for soft materials and integration of miniaturized electronics. Together, solving these challenges will significantly improve the utility of sensor skins outside of a laboratory environment.

References

1. C.M.A. Ashruf, Thin flexible pressure sensors. Sens. Rev. **22**(4), 322–327 (2002)
2. C. Pang, C. Lee, K.Y. Suh, Recent advances in flexible sensors for wearable and implantable devices. J. Appl. Polym. Sci. **130**(3), 1429–1441 (2013)
3. S. Khan, L. Lorenzelli, R.S. Dahiya, Technologies for printing sensors and electronics over large flexible substrates: a review. IEEE Sens. J. **15**(6), 3164–3185 (2015)
4. Patrick J. Codd, Arabagi Veaceslav, Andrew H. Gosline, Pierre E. Dupont, Novel pressure-sensing skin for detecting impending tissue damage during neuroendoscopy. J. Neurosurg.: Pediatr. **13**(1), 114–121 (2013)
5. A.T. Asbeck, S.M.M. De Rossi, K.G. Holt, C.J. Walsh, A biologically inspired soft exosuit for walking assistance. Int. J. Robot. Res. 0278364914562476 (2015)
6. J.-B. Chossat, Y. Tao, V. Duchaine, Y.L. Park, Wearable soft artificial skin for hand motion detection with embedded microfluidic strain sensing, in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2568–2573, May 2015
7. K.C. Galloway, P. Polygerinos, C.J. Walsh, R.J. Wood, Mechanically programmable bend radius for fiber-reinforced soft actuators, in *2013 16th International Conference on Advanced Robotics (ICAR)*, pp. 1–6, Nov 2013
8. M. Wehner, B. Quinlivan, P.M. Aubin, E. Martinez-Villalpando, M. Baumann, L. Stirling, K. Holt, R. Wood, C. Walsh, A lightweight soft exosuit for gait assistance, in *2013 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3362–3369, May 2013

9. D.H. Kim, Y.S. Kim, J. Wu, Z. Liu, J. Song, H.S. Kim, Y.Y. Huang, K.C. Hwang, J.A. Rogers, Ultrathin silicon circuits with strain-isolation layers and mesh layouts for high-performance electronics on fabric, vinyl, leather, and paper. Adv. Mater. **21**(36), 3703–3707 (2009)
10. J.C. McDonald, G.M. Whitesides, Poly(dimethylsiloxane) as a material for fabricating microfluidic devices. Acc. Chem. Res. **35**(7), 491–499 (2002)
11. S. Zhu, J.-H. So, R.L. Mays, S. Desai, W.R. Barnes, B. Pourdeyhimi, M.D. Dickey, Ultrastretchable fibers with metallic conductivity using a liquid metal alloy core. Adv. Fun. Mat. **32**(18), 2308–2314 (2013)
12. L. Mullins, Effect of stretching on the properties of rubber. Rubber Chem. Technol. **21**(2), 281–300 (1948)
13. W.N. Findley, F.A. Davis, *Creep and Relaxation of Nonlinear Viscoelastic Materials*. Courier Corporation (2013)
14. N.G. McCrum, C.P. Buckley, C.B. Bucknall, *Principles of Polymer Engineering*. Oxford University Press (1997)
15. A. Bratov, J. Muñoz, C. Dominguez, J. Bartroli, Photocurable polymers applied as encapsulating materials for ISFET production. Sens. Actuators, B: Chem. **25**(13), 823–825 (1995)
16. R.K. Kramer, C. Majidi, R. Sahai, R.J. Wood. Soft curvature sensors for joint angle proprioception, in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1919–1926, 2011
17. R.F. Shepherd, F. Ilievski, W. Choi, S.A. Morin, A.A. Stokes, A.D. Mazzeo, X. Chen, M. Wang, G.M. Whitesides, Multigait soft robot. Proc. Natl. Acad. Sci. **108**(51), 20400–20403 (2011)
18. J.C. Case, E.L. White, R.K. Kramer, Soft material characterization for robotic applications. Soft Robot. **2**(2), 80–87 (2015)
19. M.A. Eddings, M.A. Johnson, B.K. Gale, Determining the optimal PDMSPDMS bonding technique for microfluidic devices. J. Micromech. Microeng. **18**(6), 067001 (2008)
20. D.H. Kim, Z. Liu, Y.S. Kim, J. Wu, J. Song, H.S. Kim, Y. Huang, K.C. Hwang, Y. Zhang, J. A. Rogers, Optimized structural designs for stretchable silicon integrated circuits. Small **5**(24), 2841–2847 (2009)
21. D.Y. Khang, H. Jiang, Y. Huang, J.A. Rogers, A stretchable form of single-crystal silicon for high-performance electronics on rubber substrates. Science **311**(5758), 208–212 (2006)
22. D.H. Kim, J.A. Rogers, Stretchable electronics: materials strategies and devices. Adv. Mater. **20**(24), 4887–4892 (2008)
23. J.A. Fan, W.H. Yeo, Y. Su, Y. Hattori, W. Lee, S.Y. Jung, Y. Zhang, Z. Liu, H. Cheng, L. Falgout, M. Bajema, T. Coleman, D. Gregoire, R.J. Larsen, Y. Huang, J.A. Rogers, Fractal design concepts for stretchable electronics. Nat. Commun. **5** (2014)
24. G.M. Whitesides, The origins and the future of microfluidics. Nature **442**(7101), 368–373 (2006)
25. C. Majidi, R. Kramer, R.J. Wood, A non-differential elastomer curvature sensor for softer-than-skin electronics. Smart Mater. Struct. **20**(10), 105017 (2011)
26. Y.L. Park, B.R. Chen, R.J. Wood, Design and fabrication of soft artificial skin using embedded microchannels and liquid conductors. IEEE Sens. J. **12**(8), 2711–2718 (2012)
27. A. Anderson, Y. Menguc, R.J. Wood, D. Newman, Development of the polipo pressure sensing system for dynamic space-suited motion. IEEE Sens. J. **15**(11), 6229–6237 (2015)
28. J.W. Boley, E.L. White, G.T.-C. Chiu, R.K. Kramer, Direct writing of gallium-indium alloy for stretchable electronics. Adv. Funct. Mater. **24**(23), 3501–3507 (2014)
29. J.B. Chossat, H.S. Shin, Y.L. Park, V. Duchaine, Soft tactile skin using an embedded ionic liquid and tomographic imaging. J. Mech. Rob. **7**(2), 021008 (2015)
30. A.P. Gerratt, H.O. Michaud, S.P. Lacour, Elastomeric electronic skin for prosthetic tactile sensation. Adv. Funct. Mater. **25**(15), 2287–2295 (2015)

31. F.L. Hammond, R.K. Kramer, Q. Wan, R.D. Howe, R.J. Wood, Soft tactile sensor arrays for micromanipulation, in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 25–32, Oct 2012
32. R.K. Kramer, C.Majidi, R.J. Wood, Wearable tactile keypad with stretchable artificial skin, in *2011 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1103–1107 (2011)
33. R. Matsuzaki, K. Tabayashi, Highly stretchable, global, and distributed local strain sensing line using GaInSn electrodes for wearable electronics. Adv. Funct. Mater. **25**(25), 3806–3813 (2015)
34. J.T.B. Overvelde, Y. Mengüç, P. Polygerinos, Y. Wang, Z. Wang, C.J. Walsh, R.J. Wood, K. Bertoldi, Mechanical and electrical numerical analysis of soft liquid-embedded deformation sensors analysis. Extreme Mech. Lett. **1**, 42–46 (2014)
35. J. Choi, S. Kim, J. Lee, B. Choi, Improved capacitive pressure sensors based on liquid alloy and silicone elastomer. IEEE Sens. J. **15**(8), 4180–4181 (2015)
36. S. Baek, D.J. Won, J.G. Kim, J. Kim, Development and analysis of a capacitive touch sensor using a liquid metal droplet. J. Micromech. Microeng. **25**(9), 095015 (2015)
37. D. Ruben, P. Wong, J.D. Posner, V.J. Santos, Flexible microfluidic normal force sensor skin for tactile feedback. Sens. Actuators, A **179**, 62–69 (2012)
38. K. Noda, E. Iwase, K. Matsumoto, I. Shimoyama, Stretchable liquid tactile sensor for robot-joints, in *2010 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 4212–4217, May 2010
39. J.-B. Chossat, Y.-L. Park, R.J. Wood, V. Duchaine, A soft strain sensor based on ionic and metal liquids. IEEE Sens. J. **13**(9), 3405–3414 (2013)
40. C.R. Merritt, H.T. Nagle, E. Grant, Textile-based capacitive sensors for respiration monitoring. IEEE Sens. J. **9**(1), 71–78 (2009)
41. M. Stoppa, A. Chiolerio, Wearable electronics and smart textiles: a critical review. Sensors **14**(7), 11957–11992 (2014)
42. C. Mattmann, F. Clemens, G. Trster, Sensor for measuring strain in textile. Sensors **8**(6), 3719–3732 (2008)
43. L.M. Castano, A.B. Flatau, Smart fabric sensors and e-textile technologies: a review. Smart Mater. Struct. **23**(5), 053001 (2014)
44. L. Capineri, Resistive sensors with smart textiles for wearable technology: from fabrication processes to integration with electronics. Procedia Eng. **87**, 724–727 (2014)
45. R. Xu, K.I. Jang, Y. Ma, H.N. Jung, Y. Yang, M. Cho, Y. Zhang, Y. Huang, J.A. Rogers, Fabric-based stretchable electronics with mechanically optimized designs and prestrained composite substrates. Extreme Mech. Lett. (2014)
46. L. Hu, M. Pasta, F.L. Mantia, L.F. Cui, S. Jeong, H.D. Deshazer, J.W. Choi, S.M. Han, Y. Cui, Stretchable, porous, and conductive energy textiles. Nano Lett. **10**(2), 708–714 (2010)
47. C. Cochrane, V. Koncar, M. Lewandowski, C. Dufour, Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite. Sensors **7**(4), 473–492 (2007)
48. R.L. Crabb, F.C. Treble, Thin silicon solar cells for large flexible arrays. Nature **213**(5082), 1223–1224 (1967)
49. K.A. Ray, Flexible solar cell arrays for increased space power. IEEE Trans. Aerosp. Electron. Syst. **AES-3**(1), 107–115 (1967)
50. K. Jain, M. Klosner, M. Zemel, S. Raghunandan, Flexible electronics and displays: high-resolution, roll-to-roll, projection lithography and photoablation processing technologies for high-throughput production. Proc. IEEE **93**(8), 1500–1510 (2005)
51. D.H. Kim, J. Song, W.M. Choi, H.S. Kim, R.H. Kim, Z. Liu, Z. Liu, Y.Y. Huang, K.C. Hwang, Y.W. Zhang, J.A. Rogers, Materials and noncoplanar mesh designs for integrated circuits with linear elastic responses to extreme mechanical deformations. PNAS **105**(48), 18675–18680 (2008)

52. G.H. Gelinck, H.E.A. Huitema, E. van Veenendaal, E. Cantatore, L. Schrijnemakers, J.B.P. H. van der Putten, T.C.T. Geuns, M. Beenhakkers, J.B. Giesbers, B.H. Huisman, E.J. Meijer, E.M. Benito, F.J. Touwslager, A.W. Marsman, B.J. E. van Rens, D.M. de Leeuw, Flexible active-matrix displays and shift registers based on solution-processed organic transistors. Nat. Mater. **3**(2), 106–110 (2004)
53. J.A. Rogers, Z. Bao, K. Baldwin, A. Dodabalapur, B. Crone, V.R. Raju, V. Kuck, H. Katz, K. Amundson, J. Ewing, P. Drzaic, Paper-like electronic displays: large-area rubber-stamped plastic sheets of electronics and microencapsulated electrophoretic inks. Proc. Nat. Acad. Sci. U.S.A. **98**(9), 4835–4840 (2001) (ArticleType: research-article/Full publication date: Apr. 24, 2001/Copyright 2001 National Academy of Sciences)
54. C. Wang, G.G. Wallace, Flexible electrodes and electrolytes for energy storage. Electrochimica Acta (2015)
55. S.D. Perera, B. Patel, N. Nijem, K. Roodenko, O. Seitz, J.P. Ferraris, Y.J. Chabal, K. J. Balkus, Vanadium oxide nanowire carbon nanotube binder-free flexible electrodes for supercapacitors. Adv. Energy Mater. **1**(5), 936–945 (2011)
56. S.I. Park, Y. Xiong, R.H. Kim, P. Elvikis, M. Meitl, D.H. Kim, J. Wu, J. Yoon, C.J. Yu, Z. Liu, Y. Huang, K.C. Hwang, P. Ferreira, X. Li, K. Choquette, J.A. Rogers, Printed assemblies of inorganic light-emitting diodes for deformable and semitransparent displays. Science **325**(5943), 977–981 (2009)
57. P. Salonen, M. Keskilammi, J. Rantanen, L. Sydanheimo, A novel Bluetooth antenna on flexible substrate for smart clothing, in *2001 IEEE International Conference on Systems, Man, and Cybernetics*, vol. 2, pp. 789–794, 2001
58. C. Cibin, P. Leuchtmann, M. Gimersky, R. Vahldieck, S. Moscibroda, A flexible wearable antenna, in *IEEE Antennas and Propagation Society International Symposium, 2004*, vol. 4, pp. 3589–3592, June 2004
59. J.C.G. Matthews, G. Pettitt, Development of flexible, wearable antennas, in *3rd European Conference on Antennas and Propagation, 2009. EuCAP 2009*, pp. 273–277, March 2009
60. A.J. Baca, J.H. Ahn, Y. Sun, M.A. Meitl, E. Menard, H.S. Kim, W.M. Choi, D.H. Kim, Y. Huang, J.A. Rogers, Semiconductor wires and ribbons for high-performance flexible electronics. Angew. Chem. Int. Ed. **47**(30), 5524–5542 (2008)
61. J.A. Rogers, T. Someya, Y. Huang, Materials and mechanics for stretchable electronics. Science **327**(5973), 1603–1607 (2010)
62. H.C. Ko, G. Shin, S. Wang, M.P. Stoykovich, J.W. Lee, D.H. Kim, J.S. Ha, Y. Huang, K.C. Hwang, J.A. Rogers, Curvilinear electronics formed using silicon membrane circuits and elastomeric transfer elements. Small **5**(23), 2703–2709 (2009)
63. D.H. Kim, J. Xiao, J. Song, Y. Huang, J.A. Rogers, Stretchable, curvilinear electronics based on inorganic materials. Adv. Mater. **22**(19), 2108–2124 (2010)
64. D.H. Kim, N. Lu, Y. Huang, J.A. Rogers, Materials for stretchable electronics in bioinspired and biointegrated devices. MRS Bull. **37**(03), 226–235 (2012)
65. P.J. Hung, K. Jeong, G.L. Liu, L.P. Lee, Microfabricated suspensions for electrical connections on the tunable elastomer membrane. Appl. Phys. Lett. **85**(24), 6051–6053 (2004)
66. S.P. Lacour, J. Jones, S. Wagner, T. Li, Z. Suo. Stretchable interconnects for elastic electronic surfaces. Proc. IEEE **93**(8), 1459–1467 (2005)
67. D.H. Kim, J.H. Ahn, W.M. Choi, H.S. Kim, T.H. Kim, J. Song, Y.Y. Huang, Z. Liu, C. Lu, J.A. Rogers, Stretchable and foldable silicon integrated circuits. Science **320**(5875), 507–511 (2008)
68. S. Xu, Y. Zhang, J. Cho, J. Lee, X. Huang, L. Jia, J.A. Fan, Y. Su, J. Su, H. Zhang, H. Cheng, B. Lu, C. Yu, C. Chuang, T. Kim, T. Song, K. Shigeta, S. Kang, C. Dagdeviren, I. Petrov, P.V. Braun, Y. Huang, U. Paik, J.A. Rogers, Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems. Nat. Commun. **4**, 1543 (2013)

69. D.H. Kim, N. Lu, R. Ma, Y.S. Kim, R.H. Kim, S. Wang, J. Wu, S.M. Won, H. Tao, A. Islam, K.J. Yu, T. Kim, R. Chowdhury, M. Ying, L. Xu, M. Li, H.-J. Chung, H. Keum, M. McCormick, P. Liu, Y.-W. Zhang, F.G. Omenetto, Y. Huang, T. Coleman, J.A. Rogers. Epidermal electronics. Science **333**(6044), 838–843 (2011)
70. J. Kim, A. Banks, H. Cheng, Z. Xie, S. Xu, K.I. Jang, J.W. Lee, Z. Liu, P. Gutruf, X. Huang, P. Wei, F. Liu, K. Li, M. Dalal, R. Ghaffari, X. Feng, Y. Huang, S. Gupta, U. Paik, J.A. Rogers, Epidermal electronics with advanced capabilities in near-field communication. Small **11**(8), 906–912 (2015)
71. X. Hu, P. Krull, de B. Graff, K. Dowling, J.A. Rogers, W.J. Arora, Stretchable inorganic-semiconductor electronic systems. Adv. Mater. **23**(26), 2933–2936 (2011)
72. D.S. Gray, J. Tien, C.S. Chen, High-conductivity elastomeric electronics. Adv. Mater. **16**(5), 393–397 (2004)
73. Y.Y. Hsu, B. Dimcic, M. Gonzalez, F. Bossuyt, J. Vanfleteren, de I. Wolf, Reliability assessment of stretchable interconnects, in *2010 5th International Microsystems Packaging Assembly and Circuits Technology Conference (IMPACT)*, pp. 1–4, Oct 2010
74. F. Bossuyt, J. Guenther, T. Lher, M. Seckel, T. Sterken, J. de Vries, Cyclic endurance reliability of stretchable electronic substrates. Microelectron. Reliab. **51**(3), 628–635 (2011)
75. S.P. Lacour, D. Chan, S. Wagner, T. Li, Z. Suo, Mechanisms of reversible stretchability of thin metal films on elastomeric substrates. Appl. Phys. Lett. **88**(20), 204103–204103-3 (2006)
76. N.B. Morley, J. Burris, L.C. Cadwallader, M.D. Nornberg, GaInSn usage in the research laboratory. Rev. Sci. Instrum. **79**(5), 056107 (2008)
77. M.D. Dickey, R.C. Chiechi, R.J. Larsen, E.A. Weiss, D.A. Weitz, G.M. Whitesides, Eutectic gallium-indium (EGaIn): a liquid metal alloy for the formation of stable structures in microchannels at room temperature. Adv. Funct. Mater. **18**(7), 1097–1104 (2008)
78. C. Ladd, J.H. So, J. Muth, M.D. Dickey, 3d Printing of free standing liquid metal microstructures. Adv. Mater. **25**(36), 5081–5085 (2013)
79. Y.L. Park, C. Majidi, R. Kramer, P. Brard, R.J. Wood, Hyperelastic pressure sensing with a liquid-embedded elastomer. J. Micromech. Microeng. **20**(12), 125029 (2010)
80. M.D. Dickey, Emerging applications of liquid metals featuring surface oxides. ACS Appl. Mater. Interfaces (2014)
81. A. Tabatabai, A. Fassler, C. Usiak, C. Majidi, Liquid-phase gallium indium alloy electronics with microcontact printing. Langmuir **29**(20), 6194–6200 (2013)
82. J. Wissman, T. Lu, C. Majidi, Soft-matter electronics with stencil lithography, in *2013 IEEE Sensors*, pp. 1–4, 2013
83. Q. Zhang, Y. Gao, J. Liu, Atomized spraying of liquid metal droplets on desired substrate surfaces as a generalized way for ubiquitous printed electronics. Appl. Phys. A 1–7 (2013)
84. D. Kim, D.W. Lee, W. Choi, Jeong-Bong Lee, A super-lyophobic 3-D PDMS channel as a novel microfluidic platform to manipulate oxidized galinstan. J. Microelectromech. Syst. **22**(6), 1267–1275 (2013)
85. R.K. Kramer, J. William Boley, H.A. Stone, J.C. Weaver, R.J. Wood, Effect of microtextured surface topography on the wetting behavior of eutectic gallium indium alloys. *Langmuir* **30**(2), 533–539 (2014)
86. G. Li, X. Wu, D.W. Lee, Selectively plated stretchable liquid metal wires for transparent electronics. Sens. Actuators B: Chem. **221**, 1114–1119 (2015)
87. J.W. Boley, E.L. White, R.K. Kramer, Mechanically sintered gallium indium nanoparticles. Adv. Mater. **27**(14), 2355–2360 (2015)
88. T. Lu, L. Finkenauer, J. Wissman, C. Majidi, Rapid prototyping for soft-matter electronics. Adv. Funct. Mater. (2014)
89. D.M. Vogt, Y.L. Park, R.J. Wood, Design and characterization of a soft multi-axis force sensor using embedded microfluidic channels. IEEE Sens. J. **13**(10), 4056–4064 (2013)
90. J.H. So, J. Thelen, A. Qusba, G.J. Hayes, G. Lazzi, M.D. Dickey, Reversibly deformable and mechanically tunable fluidic antennas. Adv. Funct. Mater. **19**(22), 3632–3637 (2009)

91. M. Kubo, X. Li, C. Kim, M. Hashimoto, B.J. Wiley, D. Ham, G.M .Whitesides, Stretchable microfluidic radiofrequency antennas. Adv. Mater. **22**(25), 2749–2752 (2010)
92. Z. Wu, Microfluidic stretchable radio frequency devices, in *Proceedings of the IEEE*, 2015
93. E. Palleau, S. Reece, S.C. Desai, M.E. Smith, M.D. Dickey, Self-healing stretchable wires for reconfigurable circuit wiring and 3d microfluidics. Adv. Mater. **25**(11), 1589–1592 (2013)
94. J.H. So, H.J. Koo, M.D. Dickey, O.D. Velev, Ionic current rectification in soft-matter diodes with liquid-metal electrodes. Adv. Funct. Mater. **22**(3), 625–631 (2012)
95. W.-Y. Tseng, J.S. Fisher, J.L. Prieto, K. Rinaldi, G. Alapati, A.P. Lee, A slow-adapting microfluidic-based tactile sensor. J. Micromech. Microeng. **19**(8), 085002 (2009)
96. N. Wettels, V.J. Santos, R.S. Johansson, G.E. Loeb, Biomimetic tactile sensor array. Adv. Robot. **22**(8), 829–849 (2008)
97. Y.N. Cheung, Y. Zhu, C.H. Cheng, C. Chao, W.W.F. Leung, A novel fluidic strain sensor for large strain measurement. Sens. Actuators, A **147**(2), 401–408 (2008)
98. G. Cummins, M.P.Y. Desmulliez, Inkjet printing of conductive materials: a review. Circuit World **38**(4), 193–213 (2012)
99. Y. Zhang, P. Zhu, G. Li, T. Zhao, X. Fu, R. Sun, F. Zhou, C.P. Wong, Facile preparation of monodisperse, impurity-free, and antioxidation copper nanoparticles on a large scale for application in conductive ink. ACS Appl. Mater. Interfaces **6**(1), 560–567 (2014)
100. S. Merilampi, T. Laine-Ma, P. Ruuskanen, The characterization of electrically conductive silver ink patterns on flexible substrates. Microelectron. Reliab. **49**(7), 782–790 (2009)
101. S. Hong, J. Yeo, G. Kim, D. Kim, H. Lee, J. Kwon, H. Lee, P. Lee, S.H. Ko, Nonvacuum, maskless fabrication of a flexible metal grid transparent conductor by low-temperature selective laser sintering of nanoparticle ink. ACS Nano **7**(6), 5024–5031 (2013)
102. M. Grouchko, A. Kamyshny, C.F. Mihailescu, D.F. Anghel, S. Magdassi, Conductive inks with a built-in mechanism that enables sintering at room temperature. ACS Nano **5**(4), 3354–3359 (2011)
103. A. Kamyshny, M. Ben-Moshe, S. Aviezer, S. Magdassi, Ink-jet printing of metallic nanoparticles and microemulsions. Macromol. Rapid Commun. **26**(4), 281–288 (2005)
104. F. Loffredo, A. De Girolamo Del Mauro, G. Burrasca, V. La Ferrara, L. Quercia, E. Massera, G. Di Francia, D. Della Sala, Ink-jet printing technique in polymer/carbon black sensing device fabrication. Sens. Actuators B: Chem. **143**(1), 421–429 (2009)
105. S.M. Bidoki, D.M. Lewis, M. Clark, A. Vakorov, P.A. Millner, D. McGorman, Ink-jet fabrication of electronic components. J. Micromech. Microeng. **17**(5), 967 (2007)
106. T.H. Kang, C. Merritt, B. Karaguzel, J. Wilson, P.D. Franzon, B. Pourdeyhimi, E. Grant, T. Nagle, Sensors on textile substrates for home-based healthcare monitoring, in *Proceedings of the 1st Transdisciplinary Conference on Distributed Diagnosis and Home Healthcare (D2H206)*, pp. 5–7, 2006
107. Y.L. Tai, Z.G. Yang, Fabrication of paper-based conductive patterns for flexible electronics by direct-writing. J. Mater. Chem. **21**(16), 5938 (2011)
108. H.T. Wang, O.A. Nafday, J.R. Haaheim, E. Tevaarwerk, N.A. Amro, R.G. Sanedrin, C.Y. Chang, F. Ren, S.J. Pearton, Toward conductive traces: dip pen nanolithography of silver nanoparticle-based inks. Appl. Phys. Lett. **93**(14), 143105 (2008)
109. A. Russo, B.Y. Ahn, J.J. Adams, E.B. Duoss, J.T. Bernhard, J.A. Lewis, Pen-on-paper flexible electronics. Adv. Mater. **23**(30), 3426–3430 (2011)
110. L.Y. Xu, G.Y. Yang, H.Y. Jing, J. Wei, Y.D. Han, Aggraphene hybrid conductive ink for writing electronics. Nanotechnology **25**(5), 055201 (2014)
111. S. Khan, L. Lorenzelli, R.S. Dahiya, Screen printed flexible pressure sensors skin, in *2014 25th Annual SEMI on Advanced Semiconductor Manufacturing Conference (ASMC)*, pp. 219–224, May 2014
112. K.Y. Chun, Y. Oh, J. Rho, J.H. Ahn, Y.J. Kim, H.R. Choi, S. Baik, Highly conductive, printable and stretchable composite films of carbon nanotubes and silver. Nat. Nanotechnol. **5**(12), 853–857 (2010)

113. M. Park, J. Im, M. Shin, Y. Min, J. Park, H. Cho, S. Park, M.B. Shim, S. Jeon, D.Y. Chung, J. Bae, J. Park, U. Jeong, K. Kim, Highly stretchable electric circuits from a composite material of silver nanoparticles and elastomeric fibres. Nat. Nanotechnol. **7**(12), 803–809 (2012)
114. Y.J. Yang, M.Y. Cheng, W.Y. Chang, L.C. Tsao, S.A. Yang, W.P. Shih, F.Y. Chang, S.H. Chang, K.C. Fan, An integrated flexible temperature and tactile sensing array using PI-copper films. Sens. Actuators, A **143**(1), 143–153 (2008)
115. R. Verdejo, M.M. Bernal, L.J. Romasanta, M.A. Lopez-Manchado, Graphene filled polymer nanocomposites. J. Mater. Chem. **21**(10), 3301–3310 (2011)
116. M. Chen, T. Tao, L. Zhang, W. Gao, C. Li, Highly conductive and stretchable polymer composites based on graphene/MWCNT network. Chem. Commun. **49**(16), 1612 (2013)
117. M. Knite, V. Teteris, A. Kiploka, J. Kaupuzs, Polyisoprene-carbon black nanocomposites as tensile strain and pressure sensor materials. Sens. Actuators, A **110**(13), 142–149 (2004)
118. D.J. Lipomi, M. Vosgueritchian, B.C.K. Tee, S.L. Hellstrom, J.A. Lee, C.H. Fox, Z. Bao, Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. Nat. Nano **6**(12), 788–792 (2011)
119. S. Jung, J.H. Kim, J. Kim, S. Choi, J. Lee, I. Park, T. Hyeon, D.H. Kim, Reverse-micelle-induced porous pressure-sensitive rubber for wearable human machine interfaces. Adv. Mater. **26**(28), 4825–4830 (2014)
120. A. Fassler, C. Majidi, Liquid-phase metal inclusions for a conductive polymer composite. Adv. Mater. **27**(11), 1928–1932 (2015)
121. Y. Lin, C. Cooper, M. Wang, J.J. Adams, J. Genzer, M.D. Dickey, Handwritten, soft circuit boards and antennas using liquid metal nanoparticles. Small (2015)
122. S.G. Kandlikar, W.J. Grande, Evolution of microchannel flow passages thermohydraulic performance and fabrication technology. Heat Transfer Eng. **24**(1), 3–17 (2003)
123. Y. Xia, G.M. Whitesides, Soft lithography. Annu. Rev. Mater. Sci. **28**(1), 153–184 (1998)
124. L. Geppert, Semiconductor lithography for the next millennium. IEEE Spectr. **33**(4), 33–38 (1996)
125. S. Okazaki, Resolution limits of optical lithography. J. Vac. Sci. Technol., B **9**(6), 2829–2833 (1991)
126. E.A. Waddell, Laser ablation as a fabrication technique for microfluidic devices, in *Microfluidic Techniques*, ed. by S.D. Minteer, Number 321 in Methods In Molecular Biology (Humana Press, Totowa, 2006), pp. 27–38. doi:10.1385/1-59259-997-4:27
127. H.J. Kim, T. Maleki, P. Wei, B. Ziaie, A biaxial stretchable interconnect with liquid-alloy-covered joints on elastomeric substrate. J. Microelectromech. Syst. **18**(1), 138–146 (2009)
128. H.J. Kim, C. Son, B. Ziaie, A multiaxial stretchable interconnect using liquid-alloy-filled elastomeric microchannels. Appl. Phys. Lett. **92**(1), 011904–011904-3 (2008)
129. T. Li, Z. Huang, Z. Suo, S.P. Lacour, S. Wagner, Stretchability of thin metal films on elastomer substrates. Appl. Phys. Lett. **85**(16), 3435–3437 (2004)
130. Y. Arafat, I. Dutta, R. Panat, Super-stretchable metallic interconnects on polymer with a linear strain of up to 100 %. Appl. Phys. Lett. **107**(8), 081906 (2015)
131. T. Lu, J. Wissman, F.N.U. Ruthika, C. Majidi, Soft anisotropic conductors as electric vias for Ga-based liquid metal circuits. ACS Appl. Mater. Interfaces (2015)
132. Y.L. Zheng, X.R. Ding, C.C.Y. Poon, B.P.L. Lo, H. Zhang, X.L. Zhou, G.Z. Yang, N. Zhao, Y.T. Zhang, Unobtrusive sensing and wearable devices for health informatics. IEEE Trans. Biomed. Eng. **61**(5), 1538–1554 (2014)
133. N. Lu, D.H. Kim, Flexible and stretchable electronics paving the way for soft robotics. Soft Rob. **1**(1), 53–62 (2014)
134. H.K. Lee, S.I. Chang, E. Yoon, A flexible polymer tactile sensor: fabrication and modular expandability for large area deployment. J. Microelectromech. Syst. **15**(6), 1681–1686 (2006)

135. I.M. Koo, K. Jung, J.C. Koo, J.D. Nam, Y.K. Lee, H.R. Choi, Development of soft-actuator-based wearable tactile display. IEEE Trans. Rob. **24**(3), 549–558 (2008)
136. J. Engel, J. Chen, C. Liu, Development of polyimide flexible tactile sensor skin. J. Micromech. Microeng. **13**(3), 359 (2003)
137. J.K. Paik, R.K. Kramer, R.J. Wood, Stretchable circuits and sensors for robotic origami, in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 414–420, 2011
138. M. Yuen, A. Cherian, J.C. Case, J. Seipel, R.K. Kramer, Conformable actuation and sensing with robotic fabric, in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2014)*, pp. 580–586. IEEE, 2014
139. Y.L. Park, B.R. Chen, C. Majidi, R.J. Wood, R. Nagpal, E. Goldfield, Active modular elastomer sleeve for soft wearable assistance robots, in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 1595–1602, 2012
140. Y.L. Park, R.J. Wood, Smart pneumatic artificial muscle actuator with embedded microfluidic sensing, in *2013 IEEE Sensors*, pp. 1–4, 2013
141. G. Berselli (ed.), *Smart Actuation and Sensing Systems—Recent Advances and Future Challenges* (InTech, Rijeka, 2012)
142. P. Polygerinos, K.C. Galloway, E. Savage, M. Herman, K. O'Donnell, C.J. Walsh, Soft robotic glove for hand rehabilitation and task specific training, in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2913–2919, May 2015
143. A.T. Asbeck, K. Schmidt, I. Galiana, D. Wagner, C.J. Walsh, Multi-joint soft exosuit for gait assistance, in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 6197–6204, May 2015
144. A. Asbeck, S. De Rossi, I. Galiana, Y. Ding, C. Walsh, Stronger, smarter, softer: next-generation wearable robots. IEEE Robot. Autom. Mag. **21**(4), 22–33 (2014)
145. Y. Menguc, Y.L. Park, E. Martinez-Villalpando, P. Aubin, M. Zisook, L. Stirling, R. J. Wood, C.J. Walsh, Soft wearable motion sensing suit for lower limb biomechanics measurements, in *2013 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5309–5316, May 2013
146. N. Lu, C. Lu, S. Yang, J. Rogers, Highly sensitive skin-mountable strain gauges based entirely on elastomers. Adv. Funct. Mater. **22**(19), 4044–4050 (2012)
147. F. Gemperle, N. Ota, D. Siewiorek. Design of a wearable tactile display, in *Proceedings of the Fifth International Symposium on Wearable Computers, 2001*, pp. 5–12, 2001