Skin-inspired electronic devices

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Electronic devices that mimic the properties of skin have potential important applications in advanced robotics, prosthetics, and health monitoring technologies. Methods for measuring tactile and temperature signals have progressed rapidly due to innovations in materials and processing methods. Imparting skin-like stretchability to electronic devices can be accomplished by patterning traditional electronic materials or developing new materials that are intrinsically stretchable. The incorporation of sensing methods with transistors facilitates large-area sensor arrays. While sensor arrays have surpassed the properties of human skin in terms of sensitivity, time response, and device density, many opportunities remain for future development.

Introduction

Human skin exhibits a remarkable range of properties. It is sensitive enough to detect a gentle breeze and distinguish subtle differences in the texture of materials, while simultaneously being robust enough to protect our bodies against damage from external objects and harmful biological entities. As our interface with the outside world, skin provides complex tactile sensing functionality that facilitates many of our essential activities. For example, normal force measurements facilitate grasp control, while proprioception (monitoring body movements) is important for most body movements [1,2]. Additionally, skin provides temperature sensing capabilities that help us understand our surroundings and avoid damaging temperatures. While an electronic version of skin (e-skin) provides the opportunity to incorporate additional functionalities such as chemical sensors [3] and energy generation [4], this review will focus on strategies used to mimic the mechanical properties and tactile- and temperature-sensing properties of human skin.

E-skin provides the promise of facilitating important advancements in the fields of robotics and medical devices. Since their inception, robots have been restricted to highly repetitive tasks in a structured environment. However, with the ability to collect complex information about their surroundings using e-skins, robots could succeed in more dynamic and variable tasks, such as rescue missions or caring for the elderly [5]. Used in prosthetics, synthetic skin could provide the ability to sense touch and temperature for amputees and individuals with nerve damage. Sensor skins are also capable of monitoring health parameters such as pulse waveforms [6] and temperature distributions [7]. The following section reviews strategies for mimicking the mechanical properties of skin. The fundamentals of commonly used sensing methods are subsequently summarized, and the paper is concludes with a survey of recent e-skin devices.

E-skin mechanics

A remarkable property of skin is its ability to accommodate body movements while maintaining its sensing functionalities, which requires exceptional flexibility and the capability to stretch to ~30% strain [8]. The strain at the surface of a bent material depends on the thickness (t) and the radius of curvature (r) according to Eq. (1):

$$\varepsilon = \frac{t}{2r} \quad (1)$$

For thin devices on a flexible substrate, the strain experienced by the device is equal to the bending-induced strain at the surface of the substrate [9]. Two methods of producing highly flexible devices have commonly been pursued. The first is to reduce the thickness of the substrate to lower the bending-induced...

Strains [10]. The second is to position the active components of the device within the materials stack at a position that does not experience strain during bending, referred to as the neutral mechanical plane (NMP) [7,11].

Compared to flexibility, imparting stretchability generally requires more substantial changes to the device fabrication process [12,13]. The two general strategies for making e-skin devices stretchable are: (1) shape engineering of traditional (non-stretchable) electronic materials, and (2) implementation of intrinsically stretchable components. These two strategies can be used separately or in combination [14].

Processing conventional electronic materials such as gold, silicon, and pentacene into mechanically compliant forms can be achieved using patterning in 2 or 3 dimensions and on different length scales. Imparting stretchability to coplanar (2D) structures involves patterning discontinuous structures. Networks of low-dimensional materials such as nanowires [15–17], nanoplates [18], or carbon nanotubes [19] deposited on stretchable substrates can extend to large strain values (Fig. 1a). A high aspect ratio is important in order for nanostructures to maintain a percolating network during extension. Alternatively, strain-induced cracks can be formed in a continuous thin film of active material while maintaining a percolating pathway (Fig. 1b) [20–22]. Rational control of the crack formation process can improve the stretchability to values as large as 100% in gold films [23], and the use of very compliant materials can allow stretching to 170% [24]. Deliberate patterning into optimized 'horseshoe' [25] or ‘serpentine’ [26] structures can further extend stretchability up to 300% (Fig. 1c) [27]. A related strategy is to pattern the substrate to allow flexing out of the plane of the strain (Fig. 1d) [28,29].

Three-dimensional (non-coplanar) patterning involves ‘buckling’ a material by depositing a high-modulus material on a prestretched elastomer, followed by releasing the prestrain, which results in the formation of wavy structures (Fig. 1e)
Consequently, the strain in the active material is limited to the bending-induced strain caused by the buckles, which is dramatically lower than the strain applied to the substrate. Selective adhesion of a thin film to a substrate results in ‘pop-up’ structures that can more effectively accommodate strain [33,34]. A common strategy for making stretchable arrays of devices is to connect non-stretchable device islands with stretchable electrical connections [33,35–37]. This approach is advantageous in that it allows the utilization of currently available high-performance devices.

Devices composed of intrinsically stretchable materials have seen slower implementation because of the necessity for new materials development [38–43]. Intrinsically stretchable devices are attractive in applications when coplanar devices are needed and where buckling strategies could compromise performance, such as optoelectronic applications [44,45]. Intrinsic stretchability is compatible with some organic semiconductors [4,46], which may have a cost advantage over traditional inorganic semiconductors like silicon. Intrinsically stretchable electronic devices require stretchable conductors, semiconductors, and dielectrics. Stretchable conductors are often created by impregnating an elastomeric matrix with conductive materials, such as carbon nanotubes [37], organic conductors [47], or metal particles [48]. The limited amount of research into intrinsically stretchable semiconductors has so far focused on neat organic semiconductors [46,49]. However, an impregnation strategy similar to that used for stretchable conductors could be expected to be similarly successful. Work on dielectric elastomers for actuators has provided substantial insight into the properties of stretchable dielectrics [50,51].

**Sensing mechanisms**

The tactile sensing capabilities of biological skin include measurements of pressure, strain, shear forces, and vibrations. Measurement of pressure and shear forces are important for grasp control, while strain detection is essential for proprioception. Vibrations give information about the texture of objects. Widely used methods for converting these tactile stimuli into electrical signals include changes in resistance or capacitance and the production of a voltage using piezoelectric components. Other transduction methods, such as optical sensors [52–54], are covered in several thorough reviews [1,4,55]. Traditional sensing technologies typically possess considerable drawbacks, and recent improvements in device performance have resulted from the incorporation of nano- and microtechnologies, several of which are highlighted in the following section.

**Piezoresistive tactile sensing**

Resistance-based pressure and strain sensors transduce a change in strain state into a change in resistance by modifying the resistivity of a conductive component or the contact resistance between conductive components [56,57]. Elastomers with embedded conductive fillers have been widely used because of their ready availability and low cost [57]. Traditional pressure-sensitive rubbers use carbon black as the conductive filler. However, these materials typically exhibit low sensitivity, large hysteresis, and large temperature dependence [4].

Sensitivity can be improved by using low-density structures such as carbon nanotube aerogels that have very low elastic moduli [58]. Alternatively, newly implemented conductive fillers with sharp features, such as microstructured Ni particles, can improve the sensitivity by concentrating the electric field at sharp tips, enhancing the dependence of tunneling current on the strain state of the material [56]. By incorporating microstructured Ni particles into a self-healing polymer, our group was able to demonstrate the first self-healing conductor that could function as a pressure and flexion sensor (Fig. 2) [59]. The temperature dependence of pressure sensitive rubbers containing CNTs and graphene depends on the concentration [60] and type of filler [61]. For example, a CNT-filled rubber exhibited decreasing resistance with increasing temperature, while graphene-filled rubber displayed the opposite tendency. By co-dispersing both CNTs and graphene in an elastomer and optimizing the concentrations, Luo et al. eliminated the temperature sensitivity of the composite resistivity [61].

Sensors for tensile strain are frequently based on resistive mechanisms. Traditional strain sensors composed of Si or metals are effective at low strain values (<5%). However, human skin can tolerate strains up to 30% [8]. Consequently, new concepts and materials have recently been implemented to measure large strain values. Manandhar et al. developed a stretchable conductive hydrogel that sensed strain based on a change in the dimensions of...
the active element. The material exhibited excellent reproducibility over a range of measurement conditions, and showed no hysteresis [62]. The modification of contact resistance between CNTs in an aligned film was demonstrated as an effective sensor for strains up to 280% (Fig. 3a) [63]. Alignment of the CNTs was a key enabling characteristic; random network films stretched to only a few percent. Contact resistance between conductive materials embedded in or deposited on polymeric fibers has provided excellent performance in strain sensors up to 50% (Fig. 3b) [64].

**Capacitive tactile sensing**

The capacitance of a dielectric depends on the distance between the conducting plates (d), area of the device (A) and the dielectric constant (ε) of the material according to Eq. (2):

$$C = \frac{\varepsilon A}{d}$$

Changes in \(d\) and \(A\) have commonly been used to measure normal forces [65], shear forces [66], and strain [19]. High compressibility of the dielectric leads to higher sensitivity. Consequently, air gap devices have commonly been used [66,67]. Advantages of capacitive devices include high sensitivity and no inherent temperature sensitivity. However, devices are susceptible to interference from external objects that modify the fringe fields of the capacitor [68].

Thin, solid dielectrics exhibit slow response times caused by the viscoelastic properties of the materials. On the other hand, air gap devices require air gaps that are relatively large, resulting in low capacitance values and impaired sensitivities. By microstructuring the dielectric into pyramid shapes, we avoided the viscous properties of bulk elastomers (resulting in a fast time response) while achieving very small dielectric thicknesses. The high capacitance accompanying the small dielectric thickness enabled the fabrication of highly pressure-sensitive transistors [65].

**Piezoelectric tactile sensing**

The production of a voltage in response to strain is referred to as piezoelectricity, which is derived from oriented, permanent dipoles in the material [69]. Sensors based on piezoelectric transduction methods can very effectively sense vibrations and changes in force on small timescales, but have inaccurate static pressure sensing characteristics. Furthermore, piezoelectric materials also respond to temperature changes, compromising the selectivity for the tactile signal [4]. Piezoelectric devices are based on a similar mechanism, but the dipoles are formed by long-lasting charges within the pores of a low-density material. Advantages of piezoelectrets over piezoelectric materials include their higher electromechanical transduction coefficients \((d_{33})\) and smaller temperature dependence [70].

Piezoelectric ceramics can have very large \(d_{33}\) coefficients, while piezoelectric polymers are flexible. Lee and coworkers developed a composite incorporating both qualities by dispersing piezoelectric ceramic nanoparticles in a piezoelectric polymer [71]. To overcome the temperature sensitivity of piezoelectric materials, Graz et al. developed composites of a piezoelectric polymer and ceramic that could be controlled to be sensitive to either temperature or...
pressure based on the preparation method [72]. New form factors, such as nanowires or nanoribbons, have been shown to produce stretchable [73] or ultra-sensitive devices [74]. For example, Rogers and coworkers developed vertical arrays of piezoelectric polymer nanowires that could sense pressures as low as 0.1 Pa [74].

**Temperature sensing**

A common method of transducing temperature data is to rely on the temperature-sensitive resistivity of metals (called temperature coefficient of resistance, TCR) [7,75,76]. However, measuring the small change in resistance with temperature requires complicated readout circuitry [77]. The use of semiconductor p–n junctions for temperature sensing possesses the advantages of higher sensitivity and rectifying properties that can facilitate more effective multiplexing [7,28,78]. Conductive polymer composites exhibit large changes in conductivity near the melting point of the polymer matrix [79]. However, two component mixtures (polymer matrix and conductor) exhibit a lack of reproducibility with cycling [80]. Our group developed composites composed of one high melting point (T_m) polymer, one polymer with T_m in the temperature range of interest, and a conductive filler. The composites exhibited good reproducibility with cycling, and exceptionally high sensitivity that enabled wireless readout of the signal [77].

**E-skin devices**

The capabilities of e-skin systems have been advancing rapidly. While there are still many opportunities for innovation, recent devices have already surpassed the capabilities of biological skin in terms of sensitivity, spatial resolution, and stretchability. This section will first describe a selection of directly or passively addressed devices with notable properties (multiple functionalities, stretchability, sensitivity) followed by a summary of sensing devices integrated with transistors for active matrix readout.

Engel et al. developed a flexible skin sensor that is notable for the range of different stimuli that it could measure. The system could detect normal forces as well as strain, temperature, thermal conductivity, and hardness. Hardness was elucidated using a pixel consisting of two normal force sensors with different compliances. The thermal conductivity of an object could be discriminated using a microheater and temperature sensor at a fixed distance apart [76].

Our group developed a skin-like stretchable array of sensors based on electrodes composed of spray-coated CNTs sandwiching an ultrasoft silicone dielectric. The resistance of the CNT films could be programmed straining the system to a particular value. Subsequently, the resistance was constant within the strain range lower than the programmed strain. A crossbar architecture provided passive matrix multiplexing for pressure and strain measurements (Fig. 4a) [19].

A system based on the contact resistance between metal-coated interlocking micropillars was reported by Pang et al. The micropillar structure provided multifunctional sensing of normal, shear, and torsion strains with different gauge factors (Fig. 4b). Ultrathin substrates allowed the device to be very flexible [81].

‘Epidermal electronics’ that can be applied to skin like a temporary tattoo have been developed by Rogers and coworkers. The ability to conformally adhere to the rough surface of the skin through van der Waals forces required an ultrathin device structure with a very low modulus. Compatibility with a range of active components was demonstrated, including sensors for temperature and strain and supporting electronics such as transistors, ring
oscillators, and radio frequency inductors that could be used to condition and read out the sensors’ signals. Patterning the components into serpentine structures allowed stretching and flexing to accommodate movements (Fig. 5a) [82]. Arrays of highly sensitive temperature sensors were developed using the temperature-dependent resistivity (TCR) of gold conductors and the temperature-dependent properties of silicon PIN diodes. The rectifying behavior of the diode-based devices allowed multiplexing that facilitated an array size of 8 × 8. The devices could map temperature distributions on the skin with high fidelity (Fig. 5b,c). The highly compliant nature of the devices allowed them to be worn imperceptibly by the user for long periods of time, enabling long-term monitoring that could give information about heart conditions and track diseases [7].

The abovementioned devices were addressed using direct or passive matrix addressing methods. While passive matrices are a simple way to multiplex sensor arrays, their disadvantages include interference between pixels and large power dissipation. Active matrix arrays incorporate transistors in order to turn on and address sensors in a manner that allows faster scan rates and fewer interactions between pixels. Consequently, integration of pressure sensing capabilities with transistors has been a subject attracting considerable attention.

The response of organic transistors to tactile stimuli has been studied in depth by several research groups [83–85]. The mobility and on current of devices typically increases with normal pressure, possibly caused by a modification of trap states at the interface of the electrodes and semiconductor. The pressure-dependent characteristics depend on the grain structure of the semiconductor, with smaller grains associated with higher sensitivity. While the reported sensitivities are adequate, slow time response (>10 s) may limit applications. Printed, flexible arrays have suggested the potential for cost effective coverage of large areas [86,87].

Someya and coworkers have developed an e-skin platform based on high-performance organic transistor active matrices that were fabricated using traditional evaporation technologies [88]. The source of the transistors was coupled in series with a commercially available pressure sensitive rubber. When the transistor was off,
the current through the device was limited by the resistance of the channel. When the transistor was on, the current was limited by the resistance of the pressure-sensitive component, and increased with pressure [89]. Thermal sensing abilities were incorporated using the same active matrix technology; a temperature-sensitive organic diode was placed in series with the source of the transistor (Fig. 6a). The two active matrices were laminated together to sense temperature and pressure simultaneously. In both sensor matrices, the relative resistance of the transistor channel and sensing component are important. For example, in the on state, the resistance through the transistor channel must be smaller than the resistance through the pressure-sensitive material in the desired pressure range [28]. While patterning the flexible substrate permitted extension to 25% [28], stretchability was further improved by implementing stretchable conductive interconnects composed of carbon nanotubes and an ionic liquid dispersed in a fluorinated polymer. This allowed biaxial stretching to 70% strain with insignificant changes in the device performance [37]. The incorporation of non-volatile memory capabilities affords a range of new functions. During the array scanning process, some transient features of the pressure distribution could be missed. Memory allows an instantaneous pressure distribution to be captured for later readout (Fig. 6b,c) [90]. As part of an international team, Someya and coworkers developed pressure sensitive active matrix arrays on ultra-thin substrates (Fig. 6d,e). When bonded to a prestretched elastomer, the resulting buckled devices could be stretched to 230% [10].

Javey and coworkers have developed processes to fabricate arrays of active matrix pressure sensors using transistors based on inorganic nanowires and CNTs (Fig. 7a). The processing methods were developed to be compatible with roll-to-roll fabrication, with the aim of producing large area devices at low cost. Low-voltage operation also suggests compatibility with large area, low power devices [91]. Moderate stretchability (~11.5%) was included by patterning the substrate to allow deflection out of the plane of the strain. The high mobility of the 1D conductor-based devices (30 cm²/V·s) means that the transistors respond to a gate voltage within 1 ms. However, the pressure response time is limited by the piezoresistive element to approximately 100 ms [29]. This observation illustrates the opportunities for device improvement through the development of new tactile transduction materials. The pressure-sensitive transistor matrices were laminated with flexible organic light emitting diodes (LEDs) (Fig. 7c). The brightness of the LED was controlled by the application of force, allowing the pressure to be detected visually (Fig. 7d) [92].

Our work on highly compressible dielectrics has been applied to the fabrication of pressure-sensitive transistors with exceptional sensitivity and time response. When a pyramid-structured dielectric layer was laminated onto a single crystal organic semiconductor transistor, the change in current through the device increased proportionally to the increase in capacitance caused by compressing the dielectric [65]. Further development employed polymeric semiconductors to make flexible devices (Fig. 8a). The pyramid structures in the dielectric layer were instrumental in providing sensing characteristics with a response time of ~10 ms. This compares favorably with the response time of human skin and the response time of ~100 ms obtained with commercial piezoresistive materials used in several other e-skins [28,91]. The devices
exhibited an exceptional sensitivity of 8.4 kPa⁻¹, many times higher than biological skin. The fast response time and exceptional sensitivity allowed this flexible device to resolve the detailed shape of the pulse wave (Fig. 8b,c), which can give information about the stiffness and health of a person’s arteries. An array of 4 × 4 pixels suggests the possibility of scaling up to skin-sized areas [6].

Bauer and coworkers coupled a ferroelectret to the gate of a flexible amorphous Si transistor. Spatial separation of the sensing element (ferroelectret) and the readout transistor allowed the two components to be optimized independently (Fig. 9a). Using the ferroelectret as a capacitor allowed measurement of static pressures, while using the piezoelectric properties of the ferroelectret provided high-sensitivity measurements of oscillating pressures such as sound [94]. Alternatively, piezoelectric materials can be incorporated as the gate of a transistor [71,95–98], reducing the area of the device. Tien et al. developed a method to separate the temperature dependence of the device from the pressure or strain dependence using a combination of DC and AC biasing. The resulting devices could measure multiple inputs with a compact device structure (Fig. 9b) [71,98].

While active addressing of pixels is important for improving signal collection effectiveness, the incorporation of three-terminal transistors complicates patterning processes and device fabrication. Wang and coworkers developed two-terminal transistors based on a vertical array of piezoelectric ZnO nanowires (Fig. 9c). The gating effect was provided by the piezoelectric nature of the ZnO nanowires; applied pressure caused a buildup of charge at the ends of the wires, reducing the injection barrier and increasing the current. Arrays were fabricated with a density of 8464 cm⁻², more than 30 times higher than the density of mechanoreceptors in biological skin [99]. Further studies demonstrated that the nanowires could be operated as pressure-dependent light emitters [100]. Table 1 compares the characteristics of several transistor-integrated pressure sensing devices.

**Summary and outlook**

Recent advancements in materials, integration, and processing methods have enabled dramatic advancements in the capabilities of systems that mimic the function of biological skin. Technologies for fabricating flexible devices are well developed, and
(a) Device structure for a ferroelectret coupled to the gate of a flexible transistor. Reproduced with permission [94]. Copyright (2006) AIP Publishing LLC.

(b) Depiction of a transistor with a gate dielectric composed of a pressure- and temperature-sensitive composite. The biasing method allows discrimination of temperature and pressure. Reproduced with permission [98]. Copyright (2014) WILEY-VCH.

(c) 92 × 92 pixel array of two-terminal transistors gated by the piezoelectric properties of the nanowires. Reproduced with permission [99]. Copyright (2013) AAAS.
strategies for making stretchable systems using shape engineering of brittle active materials are approaching maturity. Because of the need for extensible materials development, intrinsically stretchable devices have seen slower implementation, but several potential advantages provide motivation for future development. Transduction methods for tactile and temperature information has benefited greatly from the implementation of nano- and microtechnologies. Two important trends in e-skin systems are: (1) sensing multiple stimuli, and (2) integration with transistors in order to realize active matrix addressing and signal amplification. Despite impressive examples of devices that surpass the characteristics of human skin, there are many opportunities for improvement, including response time, cost, and integration of multiple functionalities (e.g. shear and vibration sensing). Overall, the rapid rate of advancements suggests a bright future for the field.

References