A Self-Conformable Smart Skin with Sensing and Variable Stiffness Functions

Yu Qiu, Siyuan Ma, Qibing Pei,* and James D. Holbery*

Artificial smart skins that integrate sensing and adaptiveness present a novel platform in wearable electronics on epidermis or next-generation robotics. Herein, a highly sensitive capacitive touch sensor based on a self-conformable bi-stable electroactive polymer (BSEP) is developed. The device combines the properties of conformable polymers and touch sensors, which grants the sensor the ability to conform to the shape of various surfaces and in different working conditions. A spray-coated silver nanowire (AgNW) is selected as the sensor electrode for high-resolution patterning. The unique antenna-shaped electrode pattern results in a capacitance change of 31% when in contact with ground at a baseline of 0.13 pF. The BSEP provides stiffness tunability via an embedded compliant heater. The heater combines interdigitated silver with carbon nanotubes delivering uniform and highly efficient heating to create a tunable device with stiffness between 100s of MPa and tens of kPa, providing a large working flexibility. The efficient resistive heater provides uniform and stable heating over an area of 40 by 40 mm with a rate of 48 °C min⁻¹ at an input voltage as low as 7 V. This research merges intelligent polymeric systems and thin film electronics advancing conformable, skin-like functional electronics.

1. Introduction

Skin provides our body with protection, regulation, sensation, and is highly adaptive.[1,2] As the interface for the outside world, skin can be regarded as an ultra-compliant sensor for our body. It is, thus, inspiring for the engineering field to build compliant sensor skins with apparent simplicity and complex functionalities. The current electronic skin devices have shown the ability of having such long-term intimate contact on skin remains controversial.[14] Soft elastomer-based smart skin electronics are soft, curvilinear, and deformable. The epidermis has an elastic modulus ranging from ten to a few hundred kPa, coinciding with the modulus range of most soft elastomers.[15] The use of a soft elastomer ensures matched form factors and mechanical properties with epidermis resulting in compliant bioelectronic interfaces.[16–18] Soft elastomer electronics act as conformable artificial electronic skins eliminating the concern of leaving a nonremovable trace on epidermis and minimizing irritation caused by contact between the skin and certain metals.[14,19] However, most soft elastomer electronics are difficult to handle due to the soft-adhesive nature of soft materials.[20,21] During transfer or lamination, the soft elastomer membrane, especially a thin film elastomer with thickness under 500 μm, may adhere to other objects or itself, and the printed electrodes or control elements could delaminate by stretching. Increasing the elastomer membrane thickness may ease the concern of crumpling, but it also weakens the compliance of the device. Thus, a material with adjustable stiffness that can be both compliant for conformal lamination and rigid for easy handling, such as variable stiffness polymer (VSP), is desired in the field of conformable thin film electronics.

Phase-changing bi-stable electroactive polymers (BSEPs) emerge as novel VSPs that can adjust the stiffness from rigid to soft state.[22,23] The phase-changing BSEP is a thermal stimulus.
variable stiffness polymer that exhibits stiffness change of three orders of magnitude in a narrow temperature band slightly above the room temperature. In the rigid state, the BSEPs behave like plastics and possess modulus of several hundred of MPa. In the softened state, the modulus decreases to kPa range and the BSEPs can be treated as soft elastomers. The stiffness tunability is realized by reversible crystallization and melting of nanocrystalline phase in the polymer network, which grants the BSEP with compliancy in a controllable manner. Unlike most glass transition shape memory polymers,[24,25] which have a broad transition temperature band of over 30 °C, phase-changing BSEP possesses a sharp phase transition within 10 °C and a tunable inflection point below 50 °C. Such narrow transition band and low inflection point reduces thermal energy consumption during heating and ensures the use of BSEP in human-contact applications.[23]

In this work, we designed and fabricated a self-conformable sensor comprised of a highly sensitive capacitive touch sensor matrix on a stiffness variable BSEP substrate. Compared with other flexible sensors in the literature, our work shows distinct novelty and advantages. To achieve intimate contact to external 3D objects for precise touch location sensing, there are two methods that are commonly used, highly conformal thin membrane[26,27] and transferrable tattoo.[12,13] Fabricating sensors on a extremely thin polymeric membrane substrate is inherently difficult to manipulate due to ease of substrate tearing and wrinkling. Fabricating sensors on a tattoo paper and subsequently transferring them to external 3D structure forms a nonreusable sensor structure. The use of variable stiffness BSEP grants the device the ability of being both soft for conformal lamination and rigid for ease of handling. The embedded, compliant Joule heating electrode controls the device stiffness conforming to nearly any surface topography. The developed sensor has the ability to accommodate irregular surfaces and demonstrates excellent sensing performance in imitate contact to complicated 3D objects. Importantly, the thermally formed BSEP sensor structure can be easily transitioned from 3D skin back to its original 2D sheet form factor. This enables fabricating of a universally reusable 2D device structure that can be applied to different 3D external object surfaces.

2. Results and Discussion

2.1. Device Design and Fabrication

The self-conformable sensor contains an 8 by 8 tactile pixel (taxel) sensor matrix combined with an embedded resistive heater (Figure 1a). The device has an active area of 40 × 40 mm with a thickness of 230 μm. It comprises four main components: 1) top and bottom BSEP layer (thickness, 70 μm); 2) top and bottom silver nanowire (AgNW) sensor electrodes (Rx: receiver and Tx: transmitter); 3) BSEP sensor dielectric layer (thickness, 90 μm); 4) bottom heater electrode comprising an interdigitated-patterned silver combined with carbon nanotubes (ID-Ag/CNT). The bottom heater layer also serves as the ground electrode to

Figure 1. Self-conformable capacitive touch sensor. a) Schematic of the layered structure of the device. b) Finger approaching a pair of antenna-shaped electrodes. The finger reduces capacitance between the sensor electrodes (Cs) by coupling itself with fringing field (Cf increases). c) Representative image of the smart electronic skin with capacitive sensing and shape memory function. d–f) Demonstration of the device’s conformity by wrapping around a finger, laminating to the wall of a cup, and conforming on a sharp edge.
eliminate electrical noises caused by the surface charge on human skin or other electronic devices.

The top sensor electrodes are patterned into antenna-shaped electrodes (ASEs) with 5 mm pitch. The bottom electrodes are in parallel lines with 0.5 mm width and 5 mm pitch, capacitively coupled with ASEs through the BSEP dielectric layer. Fringing fields are generated from the ASE pattern that is coupled with and enable detection of a nearby finger ($C_\text{f}$), herein offering good sensitivity of the device (Table S1 and Figure S2, Supporting Information). As shown in Figure 1b, an approaching finger leads to a reduction of the charge stored between the two adjacent electrodes, resulting in decrease of measured capacitance ($C_S$). Each sensing node is a classic charge-storing capacitor structure that forms fringing fields in-between electrodes. Once being approached by external conductive objects (e.g., finger), the fringing fields are coupled, which results in charge transferring from the node to external objects.[28] The sensing hardware measures amount of charges transferred and classifies touch input event–based preprogrammed threshold. A layer of compliant ID-Ag/CNT Joule heating electrode is formed at the bottom to administrate the stiffness of the BSEP matrix through thermal stimuli. Conductive silver ink is patterned into interdigitated shape to uniformly deliver charge carriers over the active area. Highly compliant CNTs are chosen based on their thermal stability, mechanical compliancy, and chemical resistance.[23] The resulting ASE-patterned sensor combined with ID-Ag/CNT heater can effectively work as a capacitive touch sensor with an ability to adapt to different surfaces (Figure 1c–f).

Phase-changing BSEP was formulated to contain 80 parts (by weight) of stearyl acrylate (SA), 20 parts of urethane diacrylate (UDA), 10 parts of acrylic acid (AA), 0.25 part of 2,2-dimethoxy-2-phenylacetophenone (DMPA), and 0.125 part of benzophenone (BP). This formulation is optimized based on our previous work[23] to achieve high compliancy in the soften state. The use of SA and UDA forms bottlebrush polymer network results in ultralow stiffness of 45 kPa in the softened state. The addition of AA introduces hydrogen bonds to the polymer system, which can help increase the mechanical toughness and electrode bonding.[23,29] The synthetic details are found in the Experimental Section.

Fabrication of self-conformable sensor device comprises three primary steps: 1) fabrication of the sensor; 2) fabrication of the Joule heating electrode (ID-Ag/CNT); 3) alignment of the sensor and heater (Figure 2). The process starts with spray-printing AgNW electrodes ($R_X$ and $T_X$) on shadow-masked glass substrates. The two glass substrates are then stacked together with two stripes of tape as spacers (90 µm thick). The electrode sides

![Figure 2](www.advancedsciencenews.com)
are facing each other and perfectly aligned to form R_x and T_x electrodes. Next, the BSEP prepolymer solution is injected between two glass substrates to encapsulate the AgNWs and cured under UV. The top glass substrate is gently taken off. The BSEP top layer (70 μm) is formed above the R_x electrode using the same stack-inject method. Fabrication of ID-Ag/CNT electrode starts with screen-printing of interdigitated silver on a glass substrate. Then, the CNT solution is blanket-sprayed on top of ID-Ag. The glass substrate is aligned and stacked underneath the sensor structure to form the bottom BSEP layer (70 μm thick). The thin film electronic device can be gently peeled off from the glass substrates and works as a self-conformable capacitive touch sensor. A more detailed fabrication process can be found in the Experimental Section.

2.2. Capacitive Touch Sensor

The rapid growth of capacitive touch sensor in commercial products is mainly attributed to their high working sensitivity, good mechanical robustness, and structural simplicity. A self-conformable smart skin sensor requires not only a deformable dielectric substrate but also compliant electrodes. Low resistance electrodes are desirable in sensor devices to enable fast circuit measuring time and high signal-to-noise ratio. Sliver nanowires with a high length-to-diameter aspect ratio (Figure S1a,b, Supporting Information) have shown promise in low sheet resistance and high compliancy for flexible electronics. We used spray printing to produce high-quality AgNW patterns resulting in a sheet resistance as low as 18 Ω sq⁻¹ (Figure 3a). The AgNW patterns were embedded in the BSEP substrate, physical translation of nanowires is largely prevented during deformation (Figure S1c,d, Supporting Information). Moreover, strong bonding is formed between AgNWs and BSEP substrate due to the existence of large amount of acrylic acid in the polymer system. The combination of AgNWs and BSEP affords a capacitive touch sensor with high compliancy and good sensing performances.

The ANSYS finite element analysis (FEA) was performed to seek and optimize vital structural parameters of the sensor device. The 3D structural model was generated using computer-aided design software SolidWorks. After inputting the model to ANSYS Electronics Desktop suite and assigning corresponding materials properties, ANSYS Q3D analysis module was executed to calculate capacitance between adjacent electrodes. Briefly, the calculation process involves the following steps: 1) set a 1 V potential on one of the conductive bodies and set all other conductive bodies to 0 V (ground); 2) calculate spatial potential using Laplace’s equation; 3) find electrical field from the calculated potential using gradient operation; 4) find total charges between each electrode pair using Gauss’ law; 5) find capacitance value based on C = Q/V; 6) repeat steps 1–5 for all conductive bodies to compute full capacitance matrix. We evaluated influences of electrode pattern design, BSEP layer thickness and simulated human finger on capacitance values, and compared simulation results to experimentally measured values.

![Figure 3. Performances of capacitive touch sensor.](image-url)
As a capacitive touch sensor, one of the most important parameters that impact sensing performance is the thickness of the BSEP dielectric layer between $R_X$ and $T_X$ electrodes. Thus, sensor devices with BSEP thickness varying from 30 to 90 $\mu$m were fabricated; their capacitances were characterized with an multinational inductance (L), capacitance (C), and resistance (R) (LCR) meter (E4980A, Agilent, Technologies, Santa Clara, CA). Figure 3b,c shows the experiment data and simulation results of capacitance baseline ($C_o$) and change in the device capacitance as a function of thickness. Experimental results match the simulation data extremely well. When the ASE is untouched, the $C_o$ decreases with increasing BSEP thickness (t), which can be explained by the less charges shared between $R_X$ and $T_X$ for thicker BSEPs.[28] The sensitivity (−ve $\Delta C/C_o$), however, increases with increasing t. This is due to the amount of charge transferred remaining stable for different t. $C_o$ is inversely proportional to t. Thus, the sensitivity, equal to the change in capacitance divided by the capacitance baseline, increases with increasing t. Theory is verified by the simulation results shown in Figure S3, Supporting Information, in which the changes in capacitance with touch ($C_t$−$C$) of sensors with different BSEP thicknesses are characterized. For different t, the value of $C_o$−$C$ remains constant. Based on the aforementioned results, we have chosen a 90 $\mu$m-thick BSEP layer to fabricate the device. We chose not to increase t for even higher sensitivity due to our desire to ease the Joule heating challenge during the softening process (thermal mass at reasonably small value to achieve fast heating rate). The representative sensor is a highly sensitive device that possesses a $C_o$ of 0.13 pF and a change in capacitance of 31%.

Contactless sensing is important for devices that require remote control. One way to characterize that is through proximity detection. As shown in Figure 3d inset, measurements were carried out by vertically moving the finger through an elevator stage with the sensor at a fixed position with the corresponding device capacitances as a function of BSEP thicknesses recorded. Figure 3d shows the sensitivity as a function of distance between finger and device surface. Sensors with BSEP thicknesses of 70 and 90 $\mu$m demonstrate sensitivity greater than 10% at a hovering distance smaller than 0.5 cm. The changes in capacitances fall off significantly when the finger moves 1 cm further from the surface. As the BSEP thickness increases, the sensitivity increases as well, which corresponds with the previous results shown in Figure 3c. For the 90 $\mu$m BSEP device, the most sensitive of all thicknesses, the change in capacitance is still significant with a value of 10%, even at a 2 cm distance.

As a conformable touch sensor, the device may conform to surfaces with different curvatures, for example, the surface of a cup, a forearm, and a pen. To determine the stability of sensing to bending, we measured the capacitance of the device with different bending radii (Figure 3e). As shown in the inset of Figure 3e, the BSEP sensor was softened and wrapped around metal bars with the radius varying from 10 to 1 mm. Then, the capacitance was recorded after the BSEP cooled down to room temperature. The device displayed a very consistent capacitance and sensitivity curve with various bending radii, which guarantees a reliable performance when conformed to arbitrary surfaces. After the tests, the capacitance perfectly recovered after BSEP returned to its original flat state. Moreover, the Joule heating electrode is used as a ground plane, which shields electrical field coupling between sensor electrode and substrate materials. Therefore, our sensor shows identical properties, which are independent when different substrate material area is used.

A capacitive touch sensor with good sensitivity and reliability, structured as an 8 × 8 matrix, was then fabricated for touch-sensing visualization. The lateral position of a finger can be detected on the basis of the capacitance changes observed in the sensor matrix (as shown in Figure 3f). When a finger approaches the surface of the sensor, the fringing electric field generated from the ASE design is absorbed resulting in capacitance reduction. Such local capacitance change can be measured individually at each taxel. When the finger reaches the interface, it yields up to 30% decrease in capacitance at the taxels being activated (Figure 3f). Video 1, Supporting Information, demonstrates the real-time capacitance change of the sensor with touch input from multiple fingers. The device exhibits fast and stable sensing performance.

### 2.3. Joule Heating Electrode

Uniform heating and stiffness impedance of the Joule heating electrode can affect the compliancy of the smart skin sensor. It is essential to develop a heating electrode that is compliant and can generate uniform heat over a relatively large area. We selected CNT as the main Joule heating electrode material, thanks to the nanotube’s large length-to-diameter aspect ratio that forms highly compliant networks. Traditional blanket-coated Joule heating requires a thick layer of CNT to obtain low surface resistance for low-voltage activation, but a thick coating would induce significant stiffness increase and impede electrode deformation.[18] Serpentine architecture is widely explored as an effective approach to impart electronic device compliance.[17,23] However, in a Joule heating electrode with active area as large as 40 × 40 mm, the total length of the serpentine path may be too long to achieve low resistance for low voltage activation. Moreover, uniform heating often requires a high quality CNT coating that can increase the fabrication difficulty.[15,36] To overcome these issues, we combined the screen-printed interdigitated silver electrode with CNT for low surface resistance, low mechanical impedance, and uniform heating (Figure 4a). The combination of an interdigitated silver electrode with blank-coated CNT largely reduces the difficulty in fabrication and increases reproducibility of the Joule heating electrode to generate uniform heating over a large area.

The electrode pattern design is critical for efficient Joule heating. To achieve uniform and high-efficiency heating with low stiffness constraint, we fabricated the ID-Ag/CNT electrode. Using the silver electrode with interdigitated pattern results in uniform heating over large surface area (Figure 4a). This is due to interdigitated pattern forming a uniform gap between neighboring “fingers” resulting in highly controlled potential difference across each pair. This approach effectively overcomes the current crowding phenomenon that can significantly deteriorate heating uniformity. The screen-printed ID-Ag electrodes contain sharp edges and have uniform and well-defined line widths (Figure 4b). The printed lines were continuous with no voids. The resistances of the ID-Ag electrode from the end of the “rail"
to the end of “fingers” were measured to be relatively consistent with value of 3 ± 0.2 Ω. This value determines uniform heating if the CNT resistance between two adjacent Ag “fingers” is much larger than 3 Ω, which is easily achieved for carbon-based electrode materials.

Robust mechanical bonding between the electrode and BSEP substrate is formed. The reason behind this is two-fold. The Ag and CNT layers are embedded in the polymer membrane, which are mechanically robust during the thermal conforming process. The large amount of acrylic acid in the BSEP system strongly interacts with the Ag and CNT, which further prevents physical translation of the electrode during deformation.[23,29] The scanning electron microscopy (SEM) image of the device cross section, after 100 bending events with 1 cm radius, shows no evidence of structural delamination or other failure mechanisms (Figure S4, Supporting Information). The interdigitated silver may possess anisotropic mechanical stiffness. However, due to the small thickness of ID-Ag/CNT as well as the small difference in anisotropy, it would not have much impact on the device compliance. As demonstrated in Figure 1d–f, the device was conformed on surfaces with different orientations.

A key parameter determining ID-Ag/CNT electrode heating performance is the amount of CNT sprayed on ID-Ag. Thus, electrodes with different CNT concentrations were fabricated, and their Joule heating characteristics under 7 V DC were investigated (Figure 4c). The temperature was recorded as the average temperature of the device active area. During the tests, the voltage was on for 50 s, then turned off. The temperature versus time profiles were captured by IR camera (FLIR T640). As the amount of CNT increases, resistance decreases and the heating rate increases. Based on the temperature profiles, the efficiency of the device heating performance (E) can be calculated as

$$E = \frac{Q_{out}}{W_{in}}$$

where $Q_{out}$ is the thermal energy generated by ID-Ag/CNT, $W_{in}$ is the electrical energy input. The results are shown in Table 1. $Q_{out}$ is defined as

$$Q_{out} = m \times c \times \Delta T$$

where $m$ is the mass of the device (230 μm-thick BSEP with ID-Ag/CNT electrode), $c$ is the specific heat of BSEP, $\Delta T$ is the change in temperature during the heating process. BSEP specific heat was calculated from differential scanning calorimetric
Table 1. Heating performances of ID-Ag/CNT electrodes with different amounts of CNT.

|               | ID-Ag/CNT [2 mL] | ID-Ag/CNT [3 mL] | ID-Ag/CNT [4 mL] | ID-Ag/CNT [5 mL] |
|---------------|------------------|------------------|------------------|------------------|
| R [Ω]         | 46.71            | 34.25            | 26.13            | 15.95            |
| $W_{in}$ [J]  | 53.2             | 73               | 94.7             | 157.1            |
| $T_e$ ['C min$^{-1}$] | 23.7             | 35.3             | 47.7             | 65.3             |
| $Q_{out}$ [J] | 31.7             | 47.6             | 63.6             | 88.1             |
| Efficiency [%] | 59.6             | 65.2             | 67.2             | 56.1             |

(DSC) curves by integrating the area under the endothermic curve (Figure S6, Supporting Information), 3.17 Jg$^{-1}$°C$^{-1}$. The electric energy input $W_{in}$ is calculated by

$$W_{in} = \frac{U^2}{R} \times t$$

(3)

where $U$ is the applied voltage (7 V), $R$ is the resistance of the corresponding ID-Ag/CNT electrode, $t$ is the working time (50 s). Based on the aforementioned calculations, the ID-Ag/CNT (4 mL) demonstrates highest efficiency of 67.2%, so it was chosen to be used in following experiments.

Joule heating characteristics of the ID-Ag/CNT (4 mL) electrode under different voltages were investigated and the results are illustrated in Figure 4d. The electrode appears at a high heating rate, considering the large active area and thick BSEP substrate. During heating, most of the curves (7–9 V) exhibit an inflection point at ≈45°C, the nanocrystalline melting point of BSEP. The complete softening (above 47°C) could be obtained in less than 15 s at voltage as low as 7 V. In the cooling step, an inflection point appears at a similar temperature range for those curves, indicating recrystallization of the BSEP. Stiffening of the device can be completed within 30–40 s depending on the maximum temperature or the activation voltage. We have chosen 7 V to be the activation voltage to drive the device because it is the lowest voltage required to efficiently soften the BSEP while producing a gentle upward-temperature within the comfort of human perception. The Supporting Videos demonstrate the heating performance of ID-Ag/CNT (4 mL) in adjusting BSEP’s stiffness (Video 2, Supporting Information), softening BSEP film to comply on a curved surface (Video 3, Supporting Information) and restoring a deformed BSEP to its original flat state (Video 4, Supporting Information).

The heating uniformity of ID-Ag/CNT was also characterized by recording the temperature profiles of five different spots (1 in the center of device and 4 on device corners) in the active area (Figure 4e). The 5 spots show similar heating profile with negligible differences. The heating and cooling performances of ID-Ag/CNT on BSEP substrate can be seen in Figure 4f and Video 5, Supporting Information, where a live thermal image recording is shown alongside the temperature-time curve. Video 6, Supporting Information, shows the performance of integrated smart skin device with ASE patterned touch sensor and ID-Ag/CNT heater. The device was first softened by the Joule heating electrode at 7 V to conform on a metal bar and rigidified. Then, the real-time capacitance change with multiple touches was recorded by the LCR meter and presented on the laptop through a Labview program. The capacitance showed obvious and consistent changes with touches, demonstrating stable sensing performance with embedded heating element.

3. Conclusion

In summary, a highly sensitive capacitive touch sensor with the ability to self-conform was designed and fabricated. The sensor electrodes comprise highly conductive AgNWs patterned in antenna shape for effective fringing field coupling. The resulting sensor device exhibits large capacitance change of 31% with touch and good proximity detection with 10% of capacitance change at a distance of 2 cm. Due to the strong bonding between AgNW electrodes and BSEP substrate, the device demonstrates stable sensing performance at bend radii to 1 mm. The compliant ID-Ag/CNT Joule heating electrode shows stable and uniform heating over an active area of 40 × 40 mm. The low active voltage of 7 V and fast heating rate of 47.7°C min$^{-1}$ produces an ID-Ag/CNT electrode with efficiencies as high as 67.2%. The developed process demonstrates a low-cost, repeatable, and efficient method of fabricating multi-layer electronics. The integrated multifunctional device mimics the sensing and adaptiveness of human skin and has the potential to be used in areas such as wearable electronics and smart skin for next-generation robotics.

4. Experimental Section

Raw Materials: AgNWs (catalog name: Agnw-L30) were purchased from ACS Material, LLC. The average diameter and length of the AgNWs are 30 nm and 100–200 μm. Urethane diacylate (UDA, catalog name: CN9021) was obtained from SARTOMER and used as received. Stearyl acrylate (SA), acrylic acid (AA), 2,2-dimethoxy-2-phenylacetophenone (DMPA), benzophenone (BP), and isopropyl alcohol (IPA) were purchased from Sigma-Aldrich and used as received. Screen-printable silver ink (catalog name: PE873) was purchased from DUPONT and used as received. Single-walled carbon nanotubes (catalog name: P3-SWNT) were purchased from Carbon Solutions, Inc.

BSEP Prepolymer Solution Preparation and Thin-Film Fabrication: The prepolymer solution was made by mixing 80 parts (by weight) of SA, 20 parts of UDA, 10 parts of AA, 0.25 part of DMPA, and 0.125 part of BP at 50°C. The prepolymer solution was then injected between a pair of glass slides on a hot plate with two strips of tape as spacers, forming a “sandwich” structure. The thickness of the liquid layer was defined by the thickness of the spacers. In the experiments, BSEP film with thickness varied from 30 to 90 μm were fabricated. Next, the prepolymer was cured in a Dymax UV light-curing chamber equipped with ECE 5000 flood-lamp for 1 min. The film can be gently peeled off the glass substrate upon cooling to room temperature.

Capacitive Touch Sensor Fabrication: Sensor electrodes were made by first spray coating a dispersion of AgNW (concentration of 1.5 mg mL$^{-1}$) in IPA on two glass substrates through shadow masks. The shadow masks have antenna-shaped and strip-shaped cutouts formed by laser ablation. The BSEP film was fabricated using the AgNW-patterned glass slides following aforementioned “sandwich” method. In the “sandwich” structure, the AgNW electrodes were facing each other and embedded into the BSEP film.

Joule Heating Electrode Fabrication: The carbon nanotube (CNT) dispersion was made by mixing 5 mg of P3-SWNT powder, 1 mL water, and 20 mL IPA. The mixture was tip sonicated for 40 min to obtain a stable...
dispersion. The solution was then kept overnight to settle large aggregates. The resulting supernatant is then ready for spray coating.

The interdigitated silver electrode (ID-Ag) was obtained by screen printing the silver paste electrode on a glass substrate. Screen-printing tests were performed on a semi-automatic screen printer (Asys E2), and a 12 × 12 inch precision stainless-steel screen mesh (200 mesh count, 40 μm wire diameter, 29 N cm⁻¹ mesh tension, and 15 μm emulsion thickness) purchased from Sefar Inc. The print speed was 100 mm s⁻¹ and printing force 1 N. The printed ID-Ag pattern was annealed at 110 °C for 30 min to evaporate the solvent. Then, a layer of the CNT electrode was blanket-coated on top of silver electrode through spray printing.

Device Assembly: The device can be integrated by first taking off the top glass substrate (the one close to Rx) of the as fabricated sensor “sandwich” structure. The remaining sensor structure was used as the substrate to form another “sandwich” structure with a new glass slide and a new pair of spacers (70 μm thickness) to fabricate the top BSEP layer. The aforementioned process was then repeated to fabricate the bottom BSEP layer (70 μm thickness) by taking off the bottom glass slide (the one close to Tz) and use ID-Ag/CNT patterned glass to form a new “sandwich” structure. The resulting device comprises, from top to bottom, a 70 μm thick BSEP top layer, a Rx sensor electrode, a 90 μm thick BSEP dielectric layer, a Tx sensor electrode, a 70 μm thick BSEP bottom layer, and a Joule heating electrode layer.

Disclaimer: For user finger touch input experiments, informed consent was obtained from volunteers.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

capacitive touch sensors, self-conformable, smart skin, variable stiffness polymers

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