Inkjet-Printed Iontronics for Transparent, Elastic, and Strain-Insensitive Touch Sensing Matrix

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Next-generation soft electronics are expected to be intrinsically stretchable, skin conformable, and fully integrated with diverse receptive modules to facilitate bidirectional human–machine interactions. Receptive touch sensors, in particular, should provide stable touch sensing outputs without being affected by external force-induced strains. Herein, the design and fabrication of an iontronic touch sensing matrix, based on the fringe-field capacitive mechanism, are introduced for robust touch mapping under large deformation. Enabled by our well-formulated ink, ionic gel electrodes are directly inkjet printed onto elastomeric substrate to impart superior transparency and elasticity, and hybridized with a customized electronic circuitry through electrical double layers (EDLs) for the multiplexing and transduction of capacitive signals. Notably, the coplanar “interlocking-diamond” electrode layout in a stretchable modality is adopted for the first time, which helps to boost touch sensitivity and suppress strain-induced artifacts under static/dynamic deformations. For practical applications, the iontronic matrix demonstrates the capabilities of proximity sensing, multitouch detection, and gesture communication in real time, leading to a robust touch sensing interface that captures high-fidelity signals during complex human–machine interactions.

1. Introduction

Taxel-addressable touch sensors endowed with transparency and softness are critical inventive components for future intelligent systems, such as stretchable displays, soft robotics, prosthetics, and epidermal bioelectronic devices. In this regard, deformable sensors that exploit diverse tactile/touch sensing mechanisms[1–4] have been demonstrated, wherein various stretchable conductors, including liquid metal,[5–7] graphene,[8–10] silver nanowire (AgNW),[11–13] and carbon nanotube (CNT) percolation networks,[14,15] are utilized as sensing electrodes to detect touch-induced signal variation. Despite the multivariate strategies being developed, the implementation of stretchable touch sensors in real-world setting still encounters two major challenges. First, existing electronic conductor-based soft sensors are incapable of delivering ultrahigh visual transmittance and sufficient stretchability simultaneously, which hinders their integration with soft optoelectronic devices. In addition, these initial demonstrators are prone to cross-sensitivities induced by simultaneous physical input such as tensile or compressive strain, making it difficult to achieve strain-independent touch sensitivity.

Ionic conductors, including but not limited to ionic liquid,[16] gel polymer electrolyte,[17] ionic hydrogels,[18–21] and ionicogels,[22,23] are considered promising candidates to address the first issue because they can render nearly 100% average transmittance in a visible light region while maintaining superior compliance to deformation.[19] The endeavor to incorporate ionic conductors into functional devices has inspired the research field of iontronics,[18,24] where ionic and electronic components are hybridized through electrical double layer (EDL) for achieving novel functionalities that are unattainable in pure electronics. In a typical stretchable iontronic device, ionic and electronic conductors are integrated with dielectric elastomer substrates or matrices to form a heterogeneous system, in which ionic conductors play the role of transparent and compliant electrodes for signal transmission[2,23–27] or energy coupling,[17,19,28,29] whereas circuitry functions of electronics are harnessed for device operation and signal analysis. Recent work conducted by Kim et al.[21] introduced an iontronic touch panel by adopting the surface capacitive sensing mechanism. The panel consists of an intact piece of ionic hydrogel with four corner platinum electrodes, and the magnitudes of current through these electrodes are measured to determine touch location. Although the device is simple in structure and easy to fabricate, it is limited to single touch detection and is prone to positional mapping distortion under stretched states. As an alternative, the fringe-field capacitive sensing system[30] was used by Sarwar et al.[31] to devise iontronic touch sensors that detect multitouch input. Inspired by microfluidics, ionic hydrogel precursor is injected and cross-linked in the molded
polydimethylsiloxane (PDMS) channels to create an array of capacitors sensitive to touch. However, the unavoidable molding process makes it burdensome to alter device design from batch to batch, and the sensor only demonstrates touch detection under 7% tensile strain with obvious signal fluctuation in baseline capacitance, which leads to a poor signal-to-noise ratio (SNR) in touch sensing. Consequently, we envisaged that the ability to directly pattern ion conductors onto elastomers with higher resolution is imperative to enable rapid prototyping of stretchable iontronic systems; more importantly, a robust readout strategy that prohibits the cross-sensitivity to strain should be developed to improve the SNR in stretchable capacitive touch sensors.

Compared with processes that require masks or molds,\textsuperscript{[29,31]} direct ink writing (DIW) techniques can readily pattern active materials from digital graphics in a maskless, additive, and noncontact manner. Extrusion printing has been used to deposit conductive hydrogel onto elastomer substrates,\textsuperscript{[32,33]} but the submillimeter resolution and undesirable patterning accuracy as demonstrated is insufficient to create precise features. Herein, we adopt the strategy of another class of DIW techniques, namely, drop-on-demand (DOD) inkjet printing, to directly pattern ion conductors on PDMS at a feature resolution of 40 \textmu m. Unlike extrusion printing systems that extrude continuous filaments, DOD inkjet printers eject picoliter volumes of ink drop by drop, leading to a better positional control in material deposition. Based on this platform, we demonstrate an iontronic touch sensing matrix with epidermal conformability and over 94% visible transmittance. Given the flexibility to design and pattern ionic conductors in arbitrary 2D geometries, we unprecedentedly incorporate a coplanar electrode layout in our stretchable capacitive touch sensor to enhance vertical projection of fringe field, and concomitantly endow it with immunity to strain-induced noises. As a result, the iontronic matrix delivers a long proximity sensing distance, a record touch sensitivity of 47.3% under 40% uniaxial tensile strain, and a high SNR of 19 dB against dynamic noises. As a result, the pregel ink exhibits a desirable shelf-life: after storing in ambient environment for 12 months, it remained transparent and stable without any aggregation or precipitation being observed (Figure 1a).

The counterbalance between inertial force, capillary force, and the fluid/air interfacial tension controls the dynamics of droplet generation in DOD printer head.\textsuperscript{[34]} These underlying physical effects can be revealed by several dimensionless groups of physical constants, including Weber (We) and Reynold (Re) numbers (Table S1, Supporting Information).

\[
W_e = \frac{\rho v^3 a}{\gamma} \quad \text{Re} = \frac{\rho v a}{\eta}
\]  

where the values depend on ink density (\(\rho\)), viscosity (\(\eta\)), surface tension (\(\gamma\)), jetting velocity (\(v\)), and nozzle aperture (\(a\)). We investigated the rheological property of the ink by varying the mass fraction of PVA (6–14 wt\%) while fixing the load of other compositions in the ink. The apparent viscosity–shear rate (\(\eta - \gamma\)) plots in Figure 1b indicate a shear-thinning (pseudoplastic) behavior for all inks at low shear rate (<20 s\(^{-1}\)), the trend of which can be interpreted according to Ostwald–De Waele power law: \(\eta = k\gamma^n\), where \(k\) and \(n\) are the flow consistency and flow behavior index, respectively (Table S1, Supporting Information); at higher shear rates, the viscosities become stable and exhibit a positive correlation with the weight percentage of PVA. In addition, the inclusion of 0.02 wt\% polymeric surfactant can regulate the inks’ surface tension to \(\approx 32\text{ mN m}^{-1}\) despite the variant polymer concentrations (Figure 1c). The parameter \(Z = \text{Re}/\sqrt{W_e}\) serves as a figure of merit to evaluate the viability of droplet formation,\textsuperscript{[34,36]} whereby a rational range of \(1 < Z < 10\) can be mapped into the We–Re coordinate space to determine if an ink is inkjet printable or not. Based on the aforementioned characterizations (Table S2, Supporting Information), we find a printable ink has an upper limit of 10 wt\% in PVA concentration, above which the viscous dissipation will prevent fluid ejection (Figure 1d). The ink with 6 wt\% PVA loading is selected for the following studies due to the low voltage required to achieve consistent jetting performance (see the customized jetting waveform in Figure S1, Supporting Information).

After droplet ejection, a moderate ink wetting on target substrate is crucial to form stable, uniform, and high-resolution material deposition. Considering the surface energy of pristine PDMS is fairly low (\(\approx 21\text{ mN m}^{-1}\)),\textsuperscript{[37]} we improve its...
hydrophilicity by oxygen plasma to convert the superficial methyl groups into silanol groups. As a result, the advancing contact angle of the ink on PDMS can be reduced from 81° to 26° (Figure S2a, Supporting Information) by stringently controlling the plasma strength and activation period. DOD inkjet printing is conducted under ambient condition without any postprocessing (Figure 1e, printer setting is available in Section 4). Gelation occurs as the ink partially dehydrates post-printing (Figure S2b, Supporting Information), during which PVA chains in the binary solvent concentrate and form a polymeric network via physical entanglement and hydrogen bonds. Solvent content in the equilibrated gel is estimated to be ≈78 wt%, in which the solvated LiCl provides an ionic conductivity of $3.2 \times 10^{-3}$ S cm$^{-1}$ (Figure S2c, Supporting Information). In addition, the gel shows great compliance and adhesion to the plasma-treated PDMS substrates because water and PVA can effectively bind with silanol groups and suppress hydrophobic recovery through the formation of hydrogen bonds. The resolution of our patterning process is determined by the minimum feature size it creates, that is, the contact diameter of an individual dot gelated from a single droplet ($\approx 10$ pl) of the pregel ink. As shown in Figure 1f, the dots array printed on plasma-treated PDMS exhibits good uniformity in footprints, dictating an approximately 40 μm patterning resolution. Coalescence behavior between adjacent ink droplets was further studied to pattern continuous features. We performed line printing at various drop-spacings and found that 25 μm is optimal for creating parallel-sided lines. The droplets cannot properly merge at higher drop-spacing (e.g., 30 μm), while printing them even closer (e.g., 20 μm) will lead to periodical bulges along the line direction. Topographical information of representative dot and parallel line was obtained from confocal microscope. The results reveal that both features render a smooth contour without the appearance of coffee ring effect (see cross-sectional profiles in Figure S3, Supporting Information). To demonstrate the versatility and accuracy of our inkjet printing protocol, a gel pattern with microscopic precision was successfully printed on activated PDMS, as shown in Figure 1g. A macroscopic gel–elastomer complex was also used to demonstrate the potential applications of our inkjet printing protocol for soft robotics.
complex was also fabricated to showcase the stretchability of the complex system (Figure 1h).

2.2. Iontronic Touch Sensing Matrix: Device Structure and Sensing Mechanism

Harnessing the aforementioned high-resolution DIW protocol, we use a coplanar electrode layout, specifically “interlocking-diamond,”[30] to fabricate our iontronic taxel matrix. In this design, two sets of ionic electrodes are perpendicularly patterned on 600 μm-thick PDMS substrate via inkjet printing, wherein each electrode consists of aligned diamonds on a 45° angle with two corners connected by bridges. While all the diamonds are allocated on the same surface, intersected bridges are isolated by PDMS separators; therefore, the row and column electrodes are physically coplanar yet ionically insulated. PDMS separators could be deposited either manually or automatically via extrusion 3D printing to achieve favorable reproducibility and lateral patterning precision (Figure S4, Supporting Information). The diagonal length of diamond, the width of bridge, and the interval between parallel electrodes are 5.5, 0.9, and 7 mm, respectively (Figure S5, Supporting Information). Benefited from the high degree of automation throughout the fabricating process, we can further scale down the taxel around one magnitude smaller, as shown in Figure S6, Supporting Information. Ionic/electronic contact is established at the end of each ionic electrode using a stretchable Ag-eutectic gallium indium particle (EGalnP) conductor,[42] and all the features described earlier are protected with a 200 μm-thick PDMS encapsulation layer. The general device fabrication flow is shown in Figure 2a and elaborated in Section 4. The as-fabricated sensor array shows intimate conformability to human skin and over 94% optical transparency to visible light (Figure 2b). Ionic conductors embedded in PDMS are invisible attributing to their ultrathin thickness and negligible light scattering at the edges.

Our iontronic touch sensor functions on the basis of fringe-field capacitive sensing mechanism, where touch sensation is realized by electric field disturbance instead of physical deformation. In the 4 × 4 matrix demonstrated here, each intersection represents a unique touch sensing coordinate, and the four adjacent diamonds substantially constitute a taxel capacitor. Figure 2c depicts a transient moment when a pair of column and row electrodes is activated by alternating current (AC), with the column being positively charged. The simplified equivalent circuit contains three capacitors in series, which are two EDL capacitance (C_{EDL}) formed at ionic/electronic interfaces, and one mutual capacitance (C_M) coupled within the ionic taxel. The equivalent capacitance C is determined by \( C = \frac{1}{C_{EDL}} + \frac{1}{C_M} \). As ions and electrons are only separated by a few nanometers at the EDL interface,[20] C_{EDL} is several orders of magnitude larger than C_M with a relationship of \( C_{EDL}/C_M \approx 10^5 \), thereby C_M can be estimated by directly measuring the equivalent capacitance as \( C_M \approx C \). When a conductive and grounded object, such as human finger, approaches an activated coplanar taxel, the strongly projected fringe field will be distorted and diverted (Figure 2d), attenuating the density of mutually coupled ions in the ionic electrodes. Figure 2e shows the capacitance change of a coplanar taxel responding to periodical and gentle finger touch. It decreases from an initial value \( C_0 = 1.40 \) pF down to...

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Iontronics-based touch sensing matrix. a) Fabrication process flow of the fringe-field capacitive touch sensing matrix with an interlocking-diamond electrode layout. b) UV–vis transmission spectrum of the touch sensing matrix in the visible light regime. Transmittance at 550 nm is 94.6%. The inset photograph shows a 4 × 4 matrix attached conformably to inner forearm. c) Schematic illustration and equivalent circuit of an activated touch sensing taxel. d) Sensing mechanism of a coplanar fringe-field capacitive taxel. The charges coupled between electrodes are reduced by the approaching finger. e) Mutual capacitance change of a taxel responding to periodical finger touch. f) Touch sensitivity mapping at each taxel coordinate in the 4 × 4 matrix.
C = 0.77 pF upon finger contact. The response time is characterized to be below 40 ms (Figure S7a, Supporting Information), and the taxel matrix exhibits a uniform touch sensitivity \((-\Delta C/C_0)\) distribution of 47.3 ± 2.1% (Figure 2f).

For fringe-field capacitive touch sensors, a well-designed and finely patterned electrode layout is crucial to enhance touch sensitivity. Due to the lack of high-resolution DIW techniques, previously reported stretchable prototypes have to assign the column and row electrodes in two separated layers, which results in the formation of parallel-plate capacitors with limited field projection capability. To confirm that the coplanar interlocking-diamond layout (ID taxel) possesses superior touch sensitivity than the parallel-plate configuration (PP taxel), we fabricated individual taxel devices in both formats as shown in Figure 3a, wherein the effective electrode areas in both geometries are designed to be identical (≈32 mm²). Touch sensing performances were characterized in proximity (noncontact) and contact modes. Here, we simulated a human finger with a grounded metal probe for better distance control in vertical translation (Figure 3b). The ID taxel exhibited a long-range non-contact sensitivity of 2% at a distance of 60 mm (Figure S7b, Supporting Information), whereas the PP taxel detected 2% capacitance drop when the probe head was only 10 mm away from the sensor surface. Proximity sensing performances at 10, 1, and 0.1 mm proximity as well as in contact are shown in Figure 3d. The result clearly indicates that a coplanar ID taxel always exhibits 3 times higher touch sensitivity than a PP taxel at any detecting distance. In addition, finite element analysis (FEA) was performed to investigate electric field distribution in both capacitors (Figure 3e,f). The simulation results (cross-sectional views) reveal that PP taxel encompasses a uniform electric field in between top and bottom electrodes with limited field projection; in contrast, the large fraction of the fringe field in ID taxel significantly protrudes outward beyond its encapsulation layer owing to the open geometry of coplanar electrodes. We further extracted the lateral profile of electric field strength along the surface of both sensors. For ID taxel, the fringe field concentrates at the borders where the oppositely charged electrodes meet, which represents the region with predominant touch sensitivity.

2.3. Reliable Capacitive Touch Sensing against Cross-Sensitivity

While breakthroughs are being made in the preparation of elastic conductors with stabilized conductivity against stretch, little effort has been spent to suppress strain-induced capacitance change in capacitors. It is impractical to reject strain-induced

![Figure 3](image-url)

Figure 3. Proximity sensing characterization and fringe field distribution analysis. a) Schematic illustrations showing top and cross-sectional views of ID and PP taxels, respectively. b) Photographs displaying proximity (left) and contact (right) testing modes. c) Continuously recorded capacitance changes in both ID and PP taxels as the grounded metal probe approached the device surface at a constant speed of 10 mm min⁻¹. d) Comparison of proximity/touch sensing sensitivities between ID and PP taxels at representative sensing distances (error bars, n = 3). e,f) Simulation of electric field distribution in ID and PP taxels. Profiles of normalized electric field strength are examined along (e2, f2) the cross section and (e3, f3) the upper surface of the devices. Scale bars, 2 mm.
errors in a PP taxel because the applied compression or stretch will introduce contraction in dielectric thickness and expansion in electrodes area due to Poisson effect (Figure S8a, Supporting Information), leading to an inevitable variation in its baseline capacitance. In contrast, a coplanar capacitor possesses a remarkably different electrode configuration in which charges are predominantly coupled through fringe field rather than the field enclosed between parallel plates. Therefore, ID taxel should display a disparate capacitance–strain relationship compared with PP taxel in view of that capacitance derived from fringe field is weakly correlated to shape change in dielectric and electrodes.\textsuperscript{[46]}

It should be noted that both ID and PP taxels possess low sensitivity to normal pressure due to the usage of dielectric with relatively high compressive modulus. Details about touch sensing performance under pressure are shown in Figure S8, Supporting Information. To characterize the reliability of the touch sensors under stretched conditions, we prepared ID and PP taxels in a rectangular form factor (Figure 4a), exposed them to dynamic or static uniaxial extensions as shown in Figure 4b, and recorded the corresponding responses in capacitance change. Here, ID taxels are patterned with either its diagonal (ID-A) or edge (ID-B) parallel to the tensile axis so as to study if the anisotropic electrode geometry will lead to different capacitive response upon variant stretch directions. In an ideal situation where the silicone elastomer is isotropic and incompressible, a PP taxel being uniaxially elongated to $\lambda$ times of its initial length will concurrently contract in width and thickness by a factor of $\sqrt{\lambda}$. Providing the ionic electrodes is compliant with the Poisson deformation of the silicone elastomer, the capacitance of the stretched PP taxel will scale following $C = \lambda C_0$, leading to a theoretical capacitive gauge factor of $(\Delta C / C_0) / \epsilon = 1$,\textsuperscript{[47]} where $\epsilon$ is the tensile strain defined as

Figure 4. Reliable touch detection under static and dynamic stretch. a) Geometries of rectangular individual taxel devices prepared for uniaxial stretching. b) Photographs of a rectangular-shaped taxel under 0%, 20%, and 40% strains. c) Relative capacitance changes of PP, ID-A, and ID-B taxels while being continuously stretched up to 40% strain. d,e) Relative capacitance changes of (d) a PP taxel and (e) an ID taxel under a series of tensile strains with and without finger touch ($n = 5$). f) Detection of proximity and touch by an ID taxel under dynamic stretch. g) Cycling stability of an ID taxel-based touch sensor: capacitance values with and without touch are recorded against number of cycles. h) Photograph displaying a taxel being stretched along orthogonal directions by the biaxial stretcher. i) Theoretical prediction and measured relative capacitance changes of PP and ID taxels subjected to biaxial tensile stretches.
\( \varepsilon = \lambda - 1 \). Figure 4c shows the representative capacitive responses of all sensors upon being uniaxially stretched up to \( \lambda = 1.4 \) at a constant strain rate of 0.5 min \(^{-1}\). The experimental data of a PP taxel agreed well with the theoretical model at low strain regime \( (\varepsilon < 0.1) \), above which the observed deviation may stem from inadequate shrinkage in dielectric width and variation in the permittivity of PDMS. Capacitance of ID taxels also increased linearly during the test, attributing to the linear areal expansion in their coplanar electrodes. The capacitance-stretch responses of ID-A and ID-B showed great consistency and both led to a gauge factor around 0.25, implying that the strain sensitivity of ID taxel is fourfold lower than that of PP taxel, and its capacitance–strain relationship is independent of either strain direction or strain rate in a range from 0.2 to 2 min \(^{-1}\) (Figure S9, Supporting Information). Consequently, the strain-sensitive, yet touch-insensitive attribute of PP taxel always leads to ambiguity in signal interpretation (Figure 4d) because the amplitude of noise exceeds that of touch when the applied uniaxial strain is above 15%. In contrast, an ID taxel offers a desirable capability to distinguish touch from stretch. As shown in Figure 4e, the ID taxel retained a relatively stable baseline capacitance under a ramp of static strains; meanwhile the touch-induced capacitance drop from baseline was significant enough to be unambiguously captured. We further applied dynamic stretch to the ID taxel with a maximum strain of 20% and a period of 25 s. Although tensile strain-induced signal fluctuation cannot be completely eliminated, the proximity and touch of a finger at around 145 and 170 s were evidently detected without being interfered by the background noise (Figure 4f), and the SNR of contact touch sensing against 20% strain was calculated to be 19 dB according to 
\[ \text{SNR} = 10 \log \left( \frac{S}{N} \right)^2, \]
where \( S \) and \( N \) are the amplitudes of touch and noise signal, respectively. Moreover, the durability of our touch sensors was investigated by exposing it to 10,000 cycles of stretch loading–unloading following the waveform in Figure 4f. After the cyclic test, the ID taxel continued to function normally without any appreciable declination in touch sensitivity (Figure 4g), and with no noticeable delamination between PDMS substrate and encapsulation layer.

In real-life applications, a stretchable device will encounter not only uniaxial but also biaxial stresses during operation. When an equibiaxial force deforms a PP taxel by elongating it \( \lambda \) times in two perpendicular directions, the capacitance of the taxel will scale according to \( C = \lambda^2 C_0 \). We customized a biaxial stretcher to pull the touch sensors along two perpendicular axes (Figure 4h). The as-measured capacitances of the PP taxel were somewhat lower than the predicted values, which is reasonable because the biaxial stretching condition provided by our stretcher is not ideally equibiaxial. Similarly, the capacitance increments in ID taxel were always 3 times smaller than that of PP taxel (Figure 4i). Although an ID taxel is susceptible to noise at high biaxial stretches, a SNR of 12 dB is still achievable while the sensor is sustaining a biaxial stretch of \( \lambda = 1.2 \).

### 2.4. Real-Time Mapping of Touch Information

The touch sensing matrix was fully functionalized when a customized readout circuitry (Figure 5a, see details in Section 4) was incorporated into the iontronic system. By scanning each combination of column and row electrodes in sequence, capacitance variations at all taxels were multiplexed to create a real-time spatial mapping of touch locations. Ascribing to the fringe-field capacitive sensing mechanism, our stretchable sensor can detect not only single but also multiple touch coordinates (Figure 5b; Movie S1, Supporting Information). In addition, it can capture simple gestures like finger swipe, which is a commonly applied human–machine interaction mode in consumer electronics. As shown in Figure 5c and Movie S2, Supporting Information, the translation of fingertip from (1,2) to (1,4) was clearly recorded. As the fringe-field capacitive sensing mechanism does not require pressure for touch detection, there is no need to press while swiping, which minimizes friction between skin and PDMS and makes the interaction much smoother and faster. Recognition of complex gestures is feasible if the panel is scaled up to include more taxels. The device’s reliability under dynamic deformations was also investigated (Movie S3, Supporting Information). We subjected the taxel matrix to a periodical stretch along its diagonal up to 10% strain, during which the device remained functional and capable of recognizing touch input without any spatial distortion (Figure 5d). As discussed before, noise signal induced by 10% strain is around 2.5%, therefore the noise can be easily filtered by a signal stabilizing program. Similarly, dynamic bending caused no detrimental effect to the accuracy of touch mapping (Figure 5e). We folded the sensor to a flexed state with \( \approx 1 \) cm \(^{-1} \) curvature, under which condition the panel was touched with the profile of capacitance change plotted. The immunity to bending is also evidently achieved. As the coplanar electrodes are merely 200 \( \mu \)m away from the neutral axis, only 2% strain in the electrode layer is generated upon 0.94 cm \(^{-1} \) curvature bending (Figure S10, Supporting Information).

### 3. Conclusions

In summary, we devised an iontronic touch sensing matrix with remarkable compliance, transparency, and strain insensitivity. First, a high-resolution inkjet printing protocol was established to directly deposit ionic conductors on elastomer substrates. This platform led to the design and patterning of a coplanar electrode configuration that endows the sensor array with outstanding touch sensitivity and strain noise suppression capability, which in synergy contributes to a superior touch sensing SNR against mechanical deformation. Future iterations on the capacitive sensing interface would benefit from the tunable taxel size, so that much smaller or larger lateral resolutions can be yielded to cater for different application scenarios. With flexible displays having been commercialized in foldable phones, and with stretchable light emitting devices and logic circuits continuously emerging, our iontronic touch sensor can be readily integrated with other stretchable modules seamlessly to make future electronics soft, interactive, and reliable in touch sensation under deformed conditions.

### 4. Experimental Section

**Materials Preparation:** To prepare the pregel ink, deionized water and DMSO (D5879; Sigma-Aldrich) were first mixed by 4:1 volume ratio to form a binary solvent. Then different amount (6–14 wt%) of PVA
Mw 9000–10 000, 360 627; Sigma-Aldrich) and 2 wt% LiCl (310 468; Sigma-Aldrich) were dissolved in the solvent with 70 °C water bath and magnetic stirring for 1 h. Subsequently, 0.02 wt% polyether modified siloxane surfactant (BYK-348, BYK Additives & Instruments) was added into the solution at room temperature. The as-prepared ink was filtered through a polytetrafluoroethylene (PTFE) syringe filter (0.45 μm pore size; C2008S1, Ossila) to remove impurities. PDMS (Sylgard 184, Dow Corning) was mixed with cross-linker in a 10:1 weight ratio, degassed for 20 min, and cured in an 80 °C oven for 1 h to form 600 μm-thick PDMS film. The film was further blade cut into target dimensions for use. Hydrophilicity modification of PDMS surface was achieved by oxygen plasma under the condition of 500 mTorr vacuum chamber pressure, 25 sccm oxygen flow, and 20 W radio frequency power for 30 s.

**Inkjet Printing Conditions**: DOD Inkjet printing was performed by a Dimatix Materials Printer (DMP-2800, Fuji film). The cartridge head contains 16 parallel nozzles (diameter: 21.5 μm) that eject fluid droplets. Printing frequency was set as 5 kHz, whereas driving voltage at each nozzle was individually controlled (around 16 V) to ensure that all droplets have an identical drop velocity of 8 m s⁻¹. Jetting waveform customized for the pregel ink is available in Figure S1, Supporting Information. All 16 nozzles were used when patterning ionic conductor electrodes, whereas only one nozzle was in use for dot and line printing.

**Materials Characterization**: Apparent viscosity and surface tension of the pregel ink was characterized under ambient condition using a rheometer (MCR 501, Anton-Paar) and a microtensiometer (EZ-Pi plus, Kibron), respectively. Advancing contact angles of the pregel ink on pristine and plasma-treated PDMS surfaces were measured by a contact angle measuring system (OCA 15 Pro, Dataphysics). Ionic conductivity of the ionic gel was obtained through electrochemical impedance spectroscopy (EIS) characterization, which was conducted by a potentiostat (Autolab PCSTAT302, Metrohm). 3D topographies of the printed gel dots and lines were examined by an optical confocal microscope (Smartproof5, ZEISS).

**Device Fabrication**: Column electrodes of the matrix were first patterned onto a plasma-activated PDMS substrate (thickness: 600 μm) via inkjet printing, and then kept at ambient environment over 6 h for polymer gelation. The mixture of PDMS base and cross-linker was precured at 60 °C for 15 min, and then deposited either manually or by 3D printing to cover all the bridge area of column electrodes. 3D printing of PDMS was performed using an extrusion-based 3D printer (Hyrel 3D, System 30M). Further curing at room temperature for 24 h will lead to the formation of PDMS dielectric separators. Row electrodes were subsequently printed perpendicularly to column electrodes, before which plasma treatment was performed again to activate the pristine PDMS separators and the substrate whose hydrophilicity had degraded over time. A stretchable silver paste[42] was utilized to attach a copper wire (diameter: 0.1 mm) to the end of each electrode for external circuitry connection. The device was finally encapsulated with PDMS. Polyimide (PI) tape with 200 μm thickness was used as spacer, and then precured PDMS liquid was casted, pressed by a piece of glass, and cured at room temperature. Individual taxel sensors were fabricated via the same method. For PP taxels, top and bottom electrodes were patterned on opposite sides of the 600 μm-thick PDMS substrate, and then encapsulated by 200 μm-thick PDMS, respectively. Electrode layouts of all devices were designed using AutoCAD 2018 (education version), and then exported as bitmap files for the printer to read. Original bitmap graphics of electrodes design are available in Figure S11, Supporting Information.
Device Characterization: Light transmittance of the matrix was measured by a ultraviolet-visible–near infrared (UV-vis-NIR) spectrophotometer (Lambda 950, PerkinElmer). Capacitance measurement of the sensors was conducted using an LCR meter (Agilent E4980A, Keysight Technologies) under the condition of 1 V, 10 kHz. A motorized test stand (ESM303, Mark-10) was used to control proximity distance, exert compressive loads, and apply static and dynamic stretches to the sensors. In the compression tests, a force gauge (M7-025, Mark 10) with 0.2 mN force resolution was used to record loads. The contact areas of the metal probe (circle of 1.2 cm diameter) and the dielectric column (1 cm × 1 cm square) are both large enough to fully cover the taxel area.

FEA: FEA was conducted using a commercial finite element software (Comsol Multiphysics) in its AC/DC-Electrostatics module. Geometries of the ID and PP taxels were built identical to real devices. Free tetrahedral element was adopted to build meshes across the electrodes and the dielectrics. Boundary conditions include having one electrode biased to 1 V and the other electrode grounded.

Readout Circuitry Design: Touch signal acquisition and visualization were realized by a hardware group in combination with a graphical user interface (GUI). In this setup, two multiplexers (MAX4518, Maxim Integrated) were utilized to cycle through the 16 taxels, and the detected capacitance values were converted to digital signal through a capacitance-to-digital converter (CDC) chip (AD7746, Analog Devices) with a conversion time of 40 ms. A microcontroller (Arduino Uno) was used to control the aforementioned electronics and interface with a computer for data transmission. Capacitance changes at all taxels could be calculated and finally presented in the GUI by Python.

The experiments involving human subject have been performed with the full, informed consent of the volunteer and approved by the university (ref. no. IRB-2017-08-038).

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.

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