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2018

Ankit., Tiwari, N., Rajput, M., Chien, N. A., & Mathews, N. (2018). Highly transparent and integrable surface texture change device for localized tactile feedback. *Small*, 14(1), 1702312-. doi:10.1002/sml.201702312

<https://hdl.handle.net/10356/138837>

<https://doi.org/10.1002/sml.201702312>

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Highly transparent and integrable surface texture change device for localized tactile feedback

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Keywords: electroactive polymers, dielectric elastomers, soft actuators, transparent electrodes, tactile feedback.

Human-machine haptic interaction is typically detected by variations in friction, roughness, hardness, and temperature; which combines to create sensation of surface texture change. Most of the current technologies work to simulate changes in tactile perception (via electrostatic, lateral force fields, vibration motors etc) without creating actual topographical transformations. This makes it challenging to provide localized feedback. Here, we demonstrate a new concept for on-demand surface texture augmentation that is capable of physically forming local topographic features in any pre-designed pattern. The transparent, flexible, integrable device comprises of a hybrid electrode system with conductive hydrogel, silver nanowires and conductive polymers with acrylic elastomer as the dielectric layer. Desired surface textures can be controlled by pre-designed pattern of electrodes, which operates as independent or interconnected actuators. Surface features with up to a height of 0.155 mm can be achieved with a transformation time of less than a second for a device area of 18 cm². High transparency levels of 76% were achieved due to the judicious choice of the electrode and the active elastomer layer. The capability of localized and controlled deformations, make this system highly useful for applications such as display touchscreens, touchpads, braille displays, on-demand buttons and microfluidic devices.

1. Introduction

The subject of tactile perception has always enjoyed widespread attention; driven by an ensemble of factors like evolution of sense of touch in robotics, tactile perception in virtual and augmented reality, remote sensing and enhancing the quality of human-machine interaction for touch sensitive consumer products such as smartphones and touch-pads. ^[1] Tactile interfaces can communicate information and recreate authentic sensations. ^[2] A human hand can feel variations in friction (moist to dry, sticky to slippery), hardness (soft and hard), temperature (cold and warm) and roughness (unevenness and smoothness) and perceive them as textures of the surface. ^[3] Several technologies such as electrostatic (tactile sensation as a result of pronounced friction and vibration due to the electrostatic forces between the finger and the electrodes), piezoelectric, Peltier elements, surface acoustic waves, air jets and pneumatic valves aim to simulate the perception of texture change via sensory manipulation for tactile feedback. ^[4-10] On the other hand, technologies like microfluidics and electroactive polymers create actual topographical changes on the surface for haptics. ^[11-13] Among these, actuators based on electroactive polymers (EAPs), and dielectric elastomer actuators (DEAs) in particular, provide an attractive alternative as they can directly induce topographical changes on the surface that can be felt by touch and are electrically controllable.

EAPs are polymers that respond to electrical stimuli (voltage or current) by changing size or shape. ^[14] They possess the advantage of being easily made into applications of various sizes due to simple processing and relatively low material costs. ^[15] EAPs are generally classified into 2 subcategories; ionic EAPs, in which actuation is driven by mobility of ions, and electronic EAPs, in which the response is driven by electric fields or Coulomb's forces. ^[14] DEAs, which belong to the family of electronic EAPs, are known to produce high actuation strains; and are made by sandwiching an EAP layer between two compliant electrodes. ^[15] They work on the principle of Maxwell stresses, which is induction of stress due to electric field pressure from the free charges on the surface of insulating material. ^[15] The induced

Maxwell stresses depend on external stimulus like applied electric fields, thickness and area of the sandwiched region; and intrinsic material property like relative permittivity. The layout of a DEA bears a very close resemblance to a parallel plate capacitor, and has a thin insulating elastomeric film sandwiched between compliant electrodes, as shown in **Figure 1 a**.^[15] Compliancy of electrodes (the ability of conducting material to stretch out with elastomeric film while maintaining the conductivity) is extremely critical for the performance of DEAs.^[16] The elastomeric area which overlaps the compliant electrodes is referred to as the active area and the surrounding area is the nonactive area.^[17] Under applied electric field, the active area experiences compressive Maxwell stresses forcing the sandwiched elastomeric film to stretch out, hence providing in-plane deformation (**Figure 1 b**).^[15] The effective Maxwell stress (p) acting on the material is given by

$$p = \epsilon_o \epsilon_r E^2 \quad \dots (1)$$

where, ϵ_o is the permittivity of the free space (8.85×10^{-12} F/m), ϵ_r is the relative permittivity of the material and E is the applied electric field(V/m).^[15]

DEAs have been investigated for applications in tactile and vibrotactile feedback devices via different approaches.^[12-13, 18-23] Since the deformation produced in the active DEA layer can be small, appropriate coupling is required for out-of-plane deformation. Hydrostatic coupling utilising an incompressible fluid in conjunction with a DEA has been shown for refreshable braille displays.^[12] Coupling DEAs with rigid mechanical components allows for an amplification of fine deformations.^[18, 19] Other approaches to “amplify” tactile feedback included coupling DEAs with vibrational simulation via variations in amplitude, frequency or pulse-time combinations.^[19, 20] These systems are single, discrete actuators and need to be arranged in an array for conveying multiple information. Additionally, these systems still suffer from the issue of fabrication complexity, rigid frames for free standing films and opaqueness. Assembling large arrays of discrete actuators is prohibitive in terms of cost, actuator density and fabrication complexity.^[21] This problem can be addressed by making use

of the thickness mode actuation of dielectric elastomers, in which a soft passive layer is integrated on the DEA and capture the changes in the underlying active layer to produce desirable surface patterns. ^[21, 22] Specific topographical changes can be achieved by straightforward patterning of electrodes, resulting in deformations as desired. ^[21, 22]

Figure 1. (a) General configuration of Dielectric elastomer actuators (DEAs). An elastomeric, insulating thin film is sandwiched between compliant electrodes. (b) When the voltage is applied at the compliant electrodes, the elastomer film in the active region deforms, providing the in-plane actuation. (c) Schematic of elastomer getting squeezed between compliant electrodes upon application of voltage. (d) The elastomer lying between the adjacent compliant electrodes experiences shear stress. (e) Schematic showing the deformation of the soft passive layer upon actuation of the underlying DEA.

The thickness mode actuation of DEAs for obtaining out-of-plane deformations on a soft passive layer under the application of the electric field is illustrated in **Figure 1**. ^[22] On the application of an electric field, the elastomer in the active region experiences electrostatic attracting forces, squeezing the elastomer (**Figure 1 c**). ^[15] Thus there is a reduction in the thickness of the elastomer in the active area. At the same time, the elastomer in the non-active region experiences a shear stress caused by the expansion of the active area (**Figure 1 d**). ^[21] The soft passive layer integrated atop the DEA captures these strains produced in the active

layer and displays out-of- plane deformation (**Figure 1 e**).^[21] Due to the strong interaction between the top soft layer and the underlying layers, the soft layer over the active region experiences a reduction in thickness whereas the soft layer over the non-active region bulges out of the plane. The net effect of reduction in thickness at certain locations and increase in thickness at different locations creates a texture change on a flat smooth surface.

Since there are large mechanical strains associated with the operation of DEAs, the electrode materials need to be compliant and robust to accommodate the deformation of EAP.^[23] Carbon powder and conductive carbon pastes have proven to be excellent as compliant electrodes for DEAs.^[14-16, 23] Carbon based devices suffer from the issue of opaqueness, which renders them highly impractical to be integrated with display screens and touch panels. Recently, transparent conductive materials have also been investigated as compliant electrodes in DEAs.^[24-28] Single-walled Carbon nanotubes (SWCNTs), Silver nanowires (AgNWs) and Graphene have been shown to work well as transparent compliant electrodes in applications such as tunable lenses, soft robotic grippers and multilayer actuators.^[25-28] A significant breakthrough in stretchable and conducting electrodes was the development of conducting hydrogels with transparency nearing 100% in the visible region of the spectrum.^[29, 30] These conducting hydrogels work on the principle of ionic conductivity and owe its stretchability to covalently crosslinked networks, and have enabled applications like transparent loudspeakers.^[29, 31, 32] Though utilised in free standing DEAs, none of these transparent electrodes have been employed in tactile devices. Tactile systems necessitate the need for the users to touch the naked conducting electrodes, which poses a risk of high electrical shock in case of electrical breakdown. The thickness mode actuation of DEAs is more suitable for tactile applications as the soft insulating layer on top of the electrically active layer provides the user with additional safety.

We demonstrate here a transparent device to provide unobstructed topographic texture change. We use an all transparent system based on thickness mode actuation of DEA; with the

elastomeric layer, compliant electrodes and the soft passive layer as all transparent materials. The transparent electrode based tactile devices have equivalent performance compared to the conventional carbon powder based devices in thickness mode actuation with high reliability. The device has a high actuation performance with vertical deformation of 0.155 mm and good cyclability. The overall transparency of the device is high in the visible region, with an optical transmittance of 76 percent at 550 nm. To the best of our knowledge, this is first of its kind device architecture which enables integration of DEAs onto a wide variety of substrates to enable tactile feedback.

2. Results and Discussion

2.1. Device Architecture

Figure 2 a shows the cross sectional schematic of the complete device architecture with all the layers in the device. As mentioned previously, the compliancy of electrodes is extremely critical for reliability and performance of DEAs. ^[16] For generating predetermined surface texture changes in thickness mode actuation, patterning of these compliant electrodes is essential. ^[21] The patterning of electrodes on both the top and bottom sides makes it challenging for DEAs to be integrated onto hard substrates. This is because the non-active region adheres to the substrate constraining the deformation of the elastomer in the active region, resulting in no actuation under applied voltage. Hence, we adopt a strategy which does not require the patterning of the electrodes on both sides. The bottom electrode covers the predetermined area of the elastomer and is unpatterned. The predetermined area of the bottom blank electrode is greater than the overall coverage of the top patterned electrodes. **Figure 2 b** shows the area of bottom blank electrodes highlighted in red box and the region of top patterned electrodes demarcated in blue dotted box. Since most of the metallic and non-metallic transparent electrodes exist in the form of nanoparticles and nanowires, they cannot be used for bottom blank electrodes as they will render regions of the elastomer uncovered,

susceptible to sticking to the underlying substrate (Figure S1, Supporting Information). We can clearly see regions of elastomer uncovered by the nanowire network susceptible to adhesion with the substrate. Using conductive nanostructures on both the sides of elastomer will also compromise the transparency of the device. Thus a conducting hydrogel layer was utilised for the bottom electrodes, rendering the elastomeric layer free to stretch in the active region and enabling high transparency. The overall high transparency of the device is also visible from the images of the device taken on top of text and video on a computer display screen in **Figure 2 c** and **Figure 2 d** respectively.

Figure 2. (a) Cross-sectional schematic of the overall device architecture. (b) The coverage of bottom blank electrode (conducting hydrogel) demarcated by the red box and the overall area of the top patterned electrodes shown bounded by the blue dotted box. Transparency of the device on text on display screen (c) and on video on display screen (d). (Device inside the red dotted square)

Although the use of conducting hydrogels as top patterned electrodes would be attractive, it is impractical for scalability due to the cumbersome laser patterning processes required to pattern them to small dimensions. Patterned uniform AgNW networks have been shown to be facilely fabricated by spray coating of AgNWs over physical masks.^[33-35] However high junction resistances at AgNW-AgNW junctions can create high localized electric fields

leading to electrical breakdown. ^[36] One approach to homogenise the electric fields is to coat it with a transparent conducting polymer, which also improves the surface roughness of the nanowire network. ^[37] We make use of sprayed PEDOT: PSS (poly-(4,3-ethylene dioxythiophene): poly(styrene-sulfonate)) as the transparent conducting polymer on the AgNW network. The conducting polymer layer functions as a filler within the AgNW network to give a uniform conductivity over the elastomer surface and prevent electrical breakdown while also potentially improving mechanical properties. ^[38, 39]

Commercially available acrylic tapes (VHB 4910) consisting of mixtures of aliphatic acrylates have excellent transparency and have been known to produce largest actuation strains in the family of elastomeric matrices in DEA configurations. ^[15, 23] Prestretching the film biaxially reduces the thickness; which in turn leads to reduction of the required electric field for actuation. Biaxial prestretching has also been known to increase the breakdown electric field and improve the actuation performance, however necessitates the use of rigid frames to retain the pre-stretch. ^[15, 23] Polydimethylsiloxane (PDMS) elastomer serves as the soft top layer on the top of the active DEA layer due to its low elastic modulus. ^[23] It additionally serves as a protective layer against atmospheric oxidation of top patterned AgNW electrodes. ^[40]

2.2. Physical Characterization

A dense AgNW network is essential to form the top patterned compliant electrodes as they experience high strains and need to stretch out while remaining conductive at the same time. Higher densities will ensure sufficient overlap between the AgNWs even under high strain. Uniform coverage of the substrate is achieved for all concentrations by spray deposition of AgNWs, as seen in **Figure 3** a (i-iv). At 28 mg/cm² (**Figure 3** a (iii)) and 35 mg/cm² (**Figure 3** a (iv)), the density of the AgNW network is highest on the surface with good interconnectivity of the nanowires. Intuitively, the sheet resistance of the network decreases

with the increasing concentration of silver nanowires (**Figure 3 b**).^[41] For 35 mg/cm², the sheet resistance is lowest at 11 $\Omega/\square$ whereas the concentration of 14 mg/cm² gives a sheet resistance of 367 $\Omega/\square$. Optical transmission spectrum for varying concentrations of AgNWs in the visible light region is shown in **Figure 3 c**. As expected, the transparency of the nanowire coating decreases with increasing nanowire concentration. The optical transmittance in the visible region (at 550 nm) drops from approximately 85 % (for 14 mg/cm²) to 68 % (for 35 mg/cm²) as the concentration increases due to increased light scattering.^[33] At lower nanowire densities, the feasible actuation is limited by the interruption of the electrically percolative network.^[24] Compliancy is compromised when the percolative network is disrupted and efficient distribution of charge homogeneously on the elastomer cannot take place.^[24] This leads to local discontinuities and premature failure due to high localized electric fields by electrical breakdown.^[24] Hence, for our device fabrication, we have used concentration of AgNWs as 28 mg/cm², which provides a dense nanowire network required for the intended device performance. The assembled tactile device primarily suffers from transparency losses due to the top patterned electrodes (sprayed silver nanowires+ PEDOT:PSS) (**Figure 3 d**), with the diluted PEDOT: PSS layer playing a minor role. It was also observed that although the sheet resistance varied with stretching, the patterned AgNW electrodes still remained very conductive, in agreement with previous reported works.^[42, 43] **Figure 3 e** shows the setup for measuring the variation in sheet resistance of AgNWs with stretching, and the red arrow shows the direction of the strain. It can be observed from the plot in **Figure 3 f** that the sheet resistance varies from 13.8 $\Omega/\square$ to 45.6 $\Omega/\square$ for 20 % stretching, and proves the continuity of the network at high strains as well.

Figure 3. (a) Scanning electron microscope images for AgNW network at different concentrations (i) 14mg/cm², (ii) 21 mg/cm², (iii) 28 mg/cm² and (iv) 35 mg/cm². (b) Change in Sheet resistance versus with increasing concentration of AgNWs. (c) Variation in percentage transmittance with varying concentration of AgNWs (350 nm – 750 nm). (d) Plot of transmittance vs wavelength in visible region of spectra for AgNW & AgNW+ PEDOT: PSS hybrid. (e) Image showing the configuration used for measuring variation in sheet resistance with stretching shown in the plot (f); Red arrow showing the direction of stretch.

In our previous work, we have also studied the effect of design parameters on the actuation performance of these tactile devices. ^[22] The surface deformations are directly proportional to

the width of active region, when the width of the non-active region is kept constant; and surface deformations are indirectly proportional to width of the non-active region keeping the active region constant. ^[22] Based on this and the miniaturization of device, we chose the width of active region as 6 mm and the width of non-active region as 4mm for our current study.

2.3. Actuation Performance

Carbon powder based devices can be considered as a standard in the field of DEAs owing to the extensive use of carbon powder in fabrication of actuators and generators. We compare the performance of transparent electrode devices and carbon powder electrode devices at 3 different applied electric field values, with the thickness of the soft layer maintained at 1 mm for both the devices. The change in thickness of the soft passive under the application of applied electric field depends directly on the magnitude of the applied electric field. ^[21] Hence, we observe an increase in the change in thickness of the top layer with increase in the applied electric field in both the transparent electrode devices and carbon powder electrode devices as shown in **Figure 4 a**. The device performance for transparent electrodes is comparable with carbon powder electrodes at all the 3 applied electric fields; with the maximum attainable surface deformation being 155 microns for transparent electrodes and 160 microns for carbon powder electrodes at an applied electric field of 21.4 V/ μm . Peer-reviewed reports mention the threshold displacement detection values as 30 – 100 microns for slow adapting receptors (Merkel cells) and 17 microns for fast adapting receptors (Meissner's corpuscles), which are distributed closer to the skin and contribute to the feel of touch. The deformations achieved by our device (up to 0.16 mm out-of-the plane deformations) are significant enough to be easily detected by fingers; as they are much higher than the threshold values for the spatial recognition by receptors in the fingertips. ^[18, 44, 45] At higher applied electric fields, the Maxwell stresses are higher, consequently leading to higher shear strains and reduced thickness of active elastomer layer and electrical breakdown. At lower electric fields, similar

magnitudes of surface deformation were measured for both the devices. Transparent electrode devices showed a deformation of 78 microns and 106 microns compared to the 80 microns and 119 microns in the carbon powder electrode devices at an applied field of 14.3 V/ μm and 17.9 V/ μm respectively. The passive soft layer has no electric field applied to it and all the active properties of the laminate are derived from the underlying elastomer layer. ^[21, 22] These transparent electrode devices also show a consistent performance when tested over several cycles (Movie 1, Cyclic performance, Supporting Information). It can be seen from **Figure 4** c that the device performance remains nearly the same; with the device retaining 91 % of surface deformation after 250 cycles of operation within 20 minutes at an applied electric field of 17.9 V/ μm .

Figure 4. (a) Plot and comparison of out-of-plane surface deformations produced on the soft passive layer with varying electric field in transparent electrode devices and carbon powder electrode devices. (b) Profile of surface change upon application of electric field showed in the inset (Transparent electrode based surface texture device, applied electric field – 17.9 V/ μm). (c) Device actuation performance in terms of vertical deformation produced over 250 cycles of operation. (d) Blocked force from transparent electrode devices against applied

electric fields (DC). (e) Blocked force from transparent electrode devices against applied electric field at different frequencies (Square waveform). (f) Blocked force from transparent electrode device at 21.4 V/ μm and 10 Hz frequency.

Corresponding voltages and Power consumption for the applied electric fields have been mentioned in Table S2 (Electric field Vs Voltage and Power, Supporting Information); and although the voltages seem high (4kV – 6kV), the current drawn (1.2 μA – 11 μA) and the peak power consumption (4.8mW – 66mW) remains very low.

The blocked force measurement for the transparent electrode devices revealed a maximum of 47 mN at 21.4 V/ μm and the force output reduced with lowering the applied electric field as shown in **Figure 4 d**. These forces are large enough to be detected by the Slow adapting and Fast adapting receptors in our fingers. ^[18] To measure the response time and frequency bandwidth of the device, blocked force was measured as a function of frequency at 21.4 V/ μm . As seen in **Figure 4 e**, the device retains its performance at lower frequencies but the performance starts to reduce at higher frequencies. At 20 Hz frequency, the device provides a force output of 43 mN as compared to 47 mN at static fields. The force output starts decreasing, reaching 22 mN at 1000 Hz frequency and the device is not functional at even higher frequencies. Device maintains 50 % of the maximum force output over the frequency range of 0 Hz to 1000 Hz. The bandwidth of the actuator may be limited by a number of factors. ^[46] It may be attributed to the latency in the electronic circuit, electrode materials, and most importantly, the viscoelastic nature of acrylic tape. ^[46] Transparent electrode based tactile devices have similar amplitude of blocked force till the frequency of 20 Hz; and it decreases and reaches 50 % of its maximum performance at 1000 Hz, from which the response time of these devices can be said to be as low as 1 milli-second. ^[47] The estimated RC time constant for the circuit was is in the range of microseconds (μs); significantly lower than the current limit of actuation frequency of the device (kilohertz, millisecond range). Thus

the viscoelasticity of the dielectric polymer is suggested to be the primary reason for the bandwidth limitations of the device (Figure S3, Table S4, Supporting Information).

As explained previously, when an electric field is applied by switching on the voltage, opposite charges build up on the facing sides of the sandwiched elastomer layer creating Maxwell stresses and causing in-plane deformation of the elastomer.^[15] This in-plane actuation in transparent hybrid system of electrodes in our device can be seen in Movie 2 (In-plane deformation by hybrid transparent electrode system, Supporting Information). The images of the transparent and carbon powder electrode devices used for comparison are shown in **Figure 5 a** and **Figure 5 b** respectively. The dimension of the active and the non-active areas have been kept nearly the same for comparison of the lateral and areal strain. The width of the patterned electrodes can be used for lateral strain comparison. Transparent electrode devices produced an areal strain of 8.3 % compared to 15.87 % in carbon powder electrode devices(**Figure 5 c**). The difference in the lateral strains produced is significantly lower with the transparent electrode devices showing a lateral strain of 9.5 % in comparison to 13.5 % observed in carbon powder electrode devices. Although there is a difference between the lateral and areal strains between the transparent and carbon powder electrode devices, there is no significant difference in the intended actuation performance (out-of-the-plane surface deformations). It can also be inferred that the stress on the nanowire networks is relatively small for producing a similar kind of vertical deformation, which in turn helps in better cyclability of the device.

Figure 5. (a) Image of Hybrid transparent electrode DEA with dimensions of the active and the non-active region. (b) Image of Carbon powder based DEA showing the dimensions taken for device fabrication. (c) Comparison of Areal strain and Lateral strain for the transparent electrode devices and carbon powder electrode devices. The applied electric field for all the measurements was 21.4 V/ μm .

2.4. Localized, Patterned and Flexible tactile feedback on surfaces

A unique advantage enabled by our patterned DEA device is the ability to provide local feedback. Typically, smartphones provide a feedback for the users through the sense of vibration, which does not differentiate between the various locations on the interaction surface. We have demonstrated here, with our device, localized feedback on the surface through actual topographical changes as can be seen in Movie 3 (Localized tactile feedback, Supporting Information). Although these changes are easy to observe by the naked eye, capturing them by a camera is a difficult task. These sub-millimeter level deformations can be easily felt by fingers through touch. Under no applied electric field, the surface remains completely smooth. Upon first actuation, the surface texture changes on the left side of the device while the right side remains smooth. The vice versa holds true as well. **Figure 6 a** shows unprotected fingers probing the surface under the actuated condition indicating that the surfaces are electrically

insulating and safe to touch. 1mm thick soft insulating layer on the top provides insulation from direct contact of fingers with electrodes. **Figure 6 b** shows a pattern different to the one shown in **Figure 6 a**. The actuation of these patterned deformations can be clearly seen in Movie 4 (Deformable Patterns, Supporting Information). We also demonstrate the flexibility of these devices by integrating it onto a flexible substrate as shown in **Figure 6 c**. Working of flexible devices has been demonstrated in Movie 5 (Flexible tactile devices, Supporting Information). DEAs conventionally require rigid frames to retain the pre-stretched state of the elastomer, critical for device performance. ^[15, 23] We have clearly demonstrated a concept that does not require such rigid frames enabling facile integration.

Figure 6. (a) Image showing the safe operation of devices and can be touched by naked hand. (b) The surface deformations are not limited to straight ridges and difficult patterns can be generated on the surface. (c) Device fabrication on a flexible substrate (i) and surface transformation from (ii) smooth to deformed on a flexible substrate upon application of electric voltage.

3. Conclusion

In summary, we have demonstrated a transparent surface texture change device for tactile feedback. The device can produce physical surface deformations easily detectable by touch. It is observed that the actuation performance in terms of surface deformation for transparent electrode devices agrees well with the standard carbon powder based electrode surface texture change devices. We have also demonstrated a device architecture, first of its kind, which lends DEAs much more practicability and applicability, allowing the lamination and integration with surfaces without the need of rigid frames. The transparency of the system is excellent; achieved by making use of hybrid system of electrodes – conducting hydrogel as bottom electrodes and silver nanowire – PEDOT: PSS as top electrodes, transparent acrylic elastomer as active layer and transparent PDMS as soft passive layer. The patterning of the deformations has been demonstrated, along with the flexibility and the reliability of operation. Localized tactile feedback demonstrated using these devices, opens up applications in tactile touchpads, braille displays and on-demand buttons.

4. Experimental Section

Device Architecture

The architecture for transparent surface texture change device has been explained in Figure S5 (Supporting Information). We make use of an all transparent material system for our device fabrication; glass slide acting as the hard surface and PET as the flexible substrate, conducting hydrogel as the bottom transparent electrode, Acrylic tape (3M, VHB 4910) as the active elastomer, Silver nanowire – PEDOT: PSS hybrid electrode as the top electrode, and PDMS (Dow Corning, Sylgard 184) as the top soft passive layer. Conducting hydrogel of desired thickness is cured on the top of the cleaned glass substrate (Figure S5 a, b, Supporting Information). Acrylic tape was pre-stretched (300 % biaxially) on a rigid frame. The

elastomer membrane was then laminated on top of the conducting hydrogel layer, ensuring no air bubble is present between the two layers (Figure S5 c, Supporting Information). The pre-stretched film is prevented from falling back by sticking the edges of the tape to the substrate. Top electrodes (Figure S5 d, Supporting Information) were patterned by spray-coating process and using appropriate wax paper masks (Parafilm). Parafilm masks helps to create well-defined patterns and are found to be very convenient to remove after use. Creating thick PDMS layers is quite difficult on planar surfaces having no boundary. Although PDMS can be cured separately and placed on the device, this does not ensure proper pairing of the two layers. Hence, soft passive PDMS layer (Figure S5 e, Supporting Information) was cured directly on the top of the device by creating a 1 mm high boundary around the circumference of the device. PDMS was prepared by mixing elastomer base and curing agent in the ratio of 10:1 (by weight), followed by degasification using vacuum desiccator (Cole Palmer) and cured for 24 hours at room temperature.

Bottom Electrodes

Acrylamide (AAm) – Sodium Chloride (NaCl) conductive hydrogel for bottom electrodes was synthesized following the reported procedure.^[29] 2.2 M of AAm (Sigma-Aldrich, A8887) and 3 M of NaCl (Sigma-Aldrich, 746398) were dissolved in deionized water (DI H₂O). Crosslinking agent *N*, *N*' – methylenebisacrylamide (MBAA, Sigma-Aldrich, M7279) (0.0009 times the weight of AAm), photo-initiator Ammonium persulfate (AP, Sigma-Aldrich, 248614) (0.0017 times the weight of AAm) and crosslinking accelerator *N*, *N*, *N*', *N*' – tetramethylethylenediamine (TEMED, Sigma-Aldrich, T9281) (0.0025 times the weight of AAm) were added to the solution in the same order as listed here.^[29] The conducting hydrogel solution was kept for degassing for 5 minutes. Glass substrate was prepared by ultrasonication 10 minutes in DI water and 15 minutes in ethanol, followed by plasma exposure for 10 minutes. The method used for fabrication has been shown in the schematic image in

Figure S6 (Supporting Information). Commercially available acrylic foam tape (VHB F9473PC, 250 microns, 3M) was used to form a boundary for determining the lateral dimensions and thickness of the hydrogel layer. Conducting hydrogel solution was poured and a 3 mm thick glass slide was placed on top. This prevents the wrinkling on the hydrogel surface. Curing of the gel was done using an ultraviolet light source (Heraeus Noblelight Fusion UV Inc, Incident Power 16 mW/cm²) and exposing the sample for 8 minutes. Cover glass slide and foam tapes were removed; and the cured hydrogel film was washed with DI water to remove unreacted chemicals before purging is done by Nitrogen gas.

Top Electrodes

Silver Nanowire (Sigma- Aldrich, diameter - 115nm, length - 20-50um, 0.5% in IPA) dispersion was prepared by further dilution of the as-received AgNW in isopropyl alcohol (IPA), mixed in a ratio of 1:4 by volume and ultrasonicated (Thermo Fischer Scientific, FB15055) for 20 mins.. AgNW dispersions in IPA have been found to be very stable and uniform. ^[33, 34] Patterning of AgNWs was done by automated spray pyrolysis (HOLMARC Model HO-TH-04) with dry nitrogen gas as a carrier (flow pressure of 15 psi), substrate distance of 11cm from spraying nozzle and hot plate temperature maintained at 50 °C; making use of wax paper masks. Samples were annealed in oven (Mettler, UFE 500) at 70 °C for 5 minutes. Stock PEDOT: PSS (Heraeus, Clevious PH1000) solution was filtered through a PVDF filter (0.45 um pore, Membrane Solutions) and the filtered solution was further diluted in IPA in a ratio of 1:8 by volume. A fine layer of PEDOT: PSS was deposited on top of AgNW network, again by the automatic spray pyrolysis machine, with 4 cycles of coating over an area of 18 cm². Finally the samples were annealed at 70 °C for 5 minutes inside the oven.

Physical characterization and Actuation performance

For sheet resistance and transparency measurement, spray coated samples were made on top of pre-stretched acrylic films, which were stacked on cleaned glass slides. Sheet resistance was calculated from two-probe measurements. Optical transmittance was measured by UV-Vis spectroscopy (Shimadzu UV-3600 and Agilent Cary 5000). Silver nanowires were spray coated directly on cleaned glass slides for analyzing the variation in density of nanowire network by varying the sprayed AgNW concentration by scanning electron microscopy images (JOEL JSM-7600F).

Electric field was applied to the devices by controlling the step-up transformer (XP Power, CB101), which received the input voltage and monitor voltage by a DC voltage supply (Aim-TTi, MX100TP) as shown in Figure S7 (Supporting Information). Strain measurements were done by capturing images (SONY, DSC-WX350) and analyzing by Image J (FIJI) image processing software. Height profile and thickness measurements were done by a surface profilometer (Alpha-Step IQ) and laser deflection system (Keyence, LK-H022K). Blocked force measurement and frequency response of the device was measured using Force Gauge (Mark 10, Figure S8, Supporting Information) and square waveform input was given by Function generator (Tektronix AFG3000C) and High voltage amplifier (Trek 610 B) as shown in Figure S9 (Supporting Information).

Supporting Information

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

Acknowledgements

The authors would like to acknowledge the funding from NTU-A*STAR Silicon Technologies Centre of Excellence under the program grant no. 112 3510 0003 and MOE Tier 1 grant RG184/14, RG166/16 , MOE Tier 2 grant (MOE2016-T2-1-100).

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Supporting Information

Highly transparent and integrable surface texture change device for localized tactile feedback

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Figure S1. Scanning electron micrograph of silver nanowire network on stretched out acrylic elastomer. Rectangular regions highlighted in blue show regions where AgNW networks do not cover the sticky acrylic film and pose the risk of the film getting adhered to the substrate.

Table S2. Corresponding voltages and power to the applied Electric field. Power consumed is calculated from the voltage applied across the device and measuring the current (in series) drawn by the device.

Applied Electric Field (V/ μm)	Voltage (kV)	Current (μA)	Peak Power Consumption (mWatts)
14.3	4	1.2	4.8
17.9	5	3.1	15.5
21.4	6	11	66

Estimation of RC time constant

As already mentioned, DEAs are variable capacitors and the equivalent circuit model is shown in Figure S3 (Supporting Information), based on previous reports (Smart Materials and Structures 2015, 24, 105025). The resistance can be derived from the leakage current through the elastomer and is represented by a parallel resistor R_C to the capacitor C . R_C values were estimated in the range of mega-ohms. Resistance of the compliant electrodes represented by R_{SR} were calculated in the range of kilo-ohms as shown in Table S4 (Supporting Information). Silver nanowire network has much lower resistance than the conducting hydrogel layer, hence can be neglected from R_{SR} calculations. Capacitance C was measured using a HP4284 LCR meter. Time constant (τ) of the device is estimated by formula (2) and results are shown in Table S4.

$$\tau = (R_{SR} \times R_C \times C) / (R_{SR} + R_C) \quad \dots (2)$$

Figure S3. Modeling a DEA as a variable capacitor.

Table S4. Estimation of RC time constant of the device.

R_{SR} (Ohms)	R_C (Ohms)	C (F)	τ (sec)
23.3×10^3	5.4×10^5	2.9×10^{-10}	6.6×10^{-6}

Figure S5. Step-by-step schematic of the device architecture showing the chronological order in which the various layers of the device are fabricated. (a) Glass substrate, (b) Hydrogel, (c) Pre-stretched Acrylic tape, (d) Silver nanowire – PEDOT: PSS, and (e) PDMS.

Figure S6. Schematic for sequential procedure for curing conducting hydrogel on top of the glass substrate of required thickness. This is done for the fabrication of bottom electrodes for the transparent surface texture change device.

Figure S7. Setup for measuring the surface deformations on the left. On the right, schematic for the application of electric field to the sample. The step-up transformer receives 2 outputs from the DC voltage supply, one acting as an Input voltage and the other acting as the monitor or the control voltage.

Figure S8. Setup for measuring the blocked force output from the transparent tactile devices. Non-active region of the device is kept in contact with the tip of the force gauge. Electric field is applied by the step-up transformer, which receives the input from the DC power supply. The measurement is carried out on a vibration isolation table; and the sample is held in place using double sided foam tape (3M VHB 4910 Acrylic tape).

Figure S9. Setup for measuring the frequency response of the transparent tactile devices. Non-active region of the device is kept in contact with the tip of the force gauge. Square wave pattern is fed by function generator the high voltage amplifier, which in turn amplifies the input signal and provides a frequency dependent input to the sample. The measurement is carried out on a vibration isolation table; and the sample is held in place using double sided foam tape (3M VHB 4910 Acrylic tape).