

Intrinsically stretchable large-area pixelated electrochromic displays via direct photopatterning

Received: 30 September 2025

Accepted: 27 April 2026

Published online: 13 May 2026

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Electrochromic displays (ECDs) have gained increasing attention for various stretchable applications, offering voltage-controlled optical modulation with low power consumption. However, realizing ECDs that include stretchability with high-resolution pixelation remains challenging. Here, we present an unprecedented combination of materials and device architectures that enable intrinsically stretchable and highly pixelated ECDs via direct photopatterning. Central to this strategy is a stretchable and photopatternable electrochromic (EC) material, containing acrylate-substituted RGB viologens, that supports direct photopatterning with high mechanical durability. To facilitate more strategic device architecture, a stretchable reactive spacer layer and a pixel-defining layer were introduced, ensuring uniform electrical contact and improving mechanical integrity with minimized crosstalk, respectively. Leveraging the cooperative function of the developed materials and device structures, we implemented a fully stretchable 20×20 passive matrix ECD ($10 \text{ cm} \times 10 \text{ cm}$) that exhibits RGB pixelated coloration and maintains stable electrochromic performance under strains up to 30%, with durability sustained over 1500 mechanical cycles.

The increasing demand for mechanically robust and highly deformable electronics, such as wearable systems and biomedical devices, has accelerated research into 3D free-form display technologies that can seamlessly act as interactive interfaces for dynamic, arbitrarily shaped surfaces^{1–6}. These devices need to be lightweight, energy efficient, and intrinsically stretchable, enabling facile integration with the human body while ensuring reliable optical and mechanical performance^{7–11}.

Electrochromic displays (ECDs), which reversibly modulate color under low-voltage electrical bias, offer a compelling platform for such applications^{12,13}. Their simple architecture, comprising an electrochromic (EC) layer sandwiched between two electrodes, supports low power consumption, broad material compatibility, and scalability to large-area fabrication¹⁴. Accordingly, ECDs have been explored in smart windows^{15–19}, health monitors^{20–22}, flexible displays^{23–29}, and

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adaptive camouflage^{30–32}. Although inorganic ECDs based on tungsten oxide (WO₃) exhibit excellent cycling stability and rapid switching speeds, the intrinsic brittleness of WO₃ presents major limitations for mechanically deformable displays. While hybrid structures incorporating WO₃ with flexible conductors, such as silver nanowires (AgNWs)^{29,33,34}, offer improved durability, further integration with resilient EC materials remains challenging for the realization of full-color and high-resolution stretchable ECDs.

Organic-based ECDs offer a promising alternative due to their inherent flexibility and straightforward device configurations³⁵. Various efforts to develop deformable devices have involved blending electrochromic polymers with elastomers, including those based on thiophene and phenylenevinylene^{18,19,29,30}. Although these materials offer flexibility and durability, their limited patternability remains problematic for highly defined devices and pixelated display applications. As an alternative approach, viologen derivatives, 1,1'-substituted-4,4'-bipyridinium salts, have been incorporated into photocurable polymer matrices to fabricate flexible ECDs with reversible color switching^{25,26,36}. However, these systems often suffer from poor interfacial contact between electrodes and EC layers, resulting in incomplete pixel activation, nonuniform coloration, and limited optical performance. To integrate highly defined ECDs in fully stretchable electronics, the devices must simultaneously exhibit photo-patternability, stretchability, and multicolor capability. Direct photopatterning is essential for achieving pixel-level definition and scalable integration; however, it remains extremely challenging to implement on stretchable, multilayered substrates due to issues such as optical scattering that hinders photopolymerization, mechanical mismatches between layers, and alignment distortions during processing. Recent efforts have advanced large-area flexible ECDs using multifunctional polymers³⁷, MXene-based composites³⁸, and integrated sensing systems³⁹. However, these developments remain largely limited to simple bending, with performance often degrading under complex stretching. Here, we report an intrinsically stretchable SPEC ion-gel system that maintains stable electrochromic operation even under significant strain, overcoming the mechanical limitations of conventional flexible architectures.

Here, we report the strategy for integrating materials and device architectures that enable intrinsically stretchable, highly photopatternable, and large-area pixelated ECDs. One of the key components for this system is a stretchable and photopatternable electrochromic (SPEC) material, developed by incorporating acrylate-substituted viologens into EC gels. The SPEC formulation comprising acrylate-functionalized viologens, an anodic EC component, an ionic liquid, and a photocurable elastomeric matrix, enables red (R), green (G), and blue (B) coloration with sub-micrometre resolution and mechanical resilience. Devices fabricated with SPEC materials demonstrate excellent EC stability, maintaining consistent coloration over 12,000 s of repeated cycling without performance degradation. Fine-patterned pixelation is directly achieved on highly stretchable polyurethane acrylate (PUA) substrates via ultraviolet (UV) irradiation, demonstrating sub-micrometre shapes.

For the facile implementation of fully stretchable ECDs, we further introduce two key architectural components: a stretchable reactive spacer layer (SRSL) with ion-gel and a pixel-definition layer (PDL) to enhance contact between deformable nanomeshed electrodes and the resilient SPEC materials, and structural integrity among the device components and less cross-talk in pixelated ECDs. Thus, the multicolor, pixelated ECDs exhibit stable and uniform color transitions under strains of up to 30%, maintaining durability over 1500 mechanical cycles, and significantly outperform previously reported stretchable electrochromic systems. These findings underscore the synergistic importance of the SPEC material platform and the engineered SRSL and PDL architectures, providing a robust and scalable

route toward high-definition, intrinsically stretchable ECDs that are compatible with standard CMOS processes.

Results

The ECD structure and the constituent components of the SPEC gels are illustrated in Fig. 1a–c. In the stretchable ECD, the photo-patterned SPEC gel, integrated with SRSL and PDL, is sandwiched between two stretchable networked electrodes. Although the bottom electrodes and SPEC layer establish a highly conformal and reliable contact, mainly due to the bottom-up fabrication process, in which the SPEC is spun over the bottom electrodes, the top electrodes contact only the SPEC layer, resulting in poor interfacial contact and weak adhesion. The SRSL and PDL are strategically introduced to ensure both stable electrical properties and mechanical durability of the ECD under extreme operating conditions. As shown in Fig. 1b, the SRSL provides a reliable and uniform electrical contact by eliminating the air gaps between the top electrodes and EC layer, while the PDL, which physically (electrically) separates the pixels, enhances mechanical integrity and prevents electrical crosstalk. The cross-sectional structure of the device is further confirmed by the corresponding images provided in Supplementary Fig. 1. The SPEC gel formulation comprises an acrylate viologen, PUA, diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO), and 1,1'-dimethyl ferrocene (DMFc), combined with acetone, propylene carbonate (PC), and ionic liquids ([EMIM][TFSI] or [BMIM][TFSI]) (Supplementary Fig. 2). As illustrated in the schematic of Fig. 1c, these components are represented by purple ovals (viologens), a green network (cross-linked PUA matrix), and red/blue ovals (ionic liquid cations/anions), with small green dots indicating the photo-initiators (TPO).

The RGB acrylate viologens displayed sufficient solubility in both ionic liquids, highlighting their suitability as media for SPEC gels. The use of ionic liquids was carefully guided through EC performance evaluations (Detailed explanation is provided in Supplementary Figs. 3–5 and Supplementary Note 1–4). PUA and TPO served as a UV-curable polymer matrix and photo-initiators, respectively. DMFc served as an anodic species, effectively suppressing undesired reactions between solvents and electrolytes, thereby reducing the operating voltage of ECDs by facilitating electron transfer during electrochemical reactions.

Red, green, and blue-color SPEC gels were prepared using different acrylate viologen derivatives. The SPEC gel containing red viologen was designated as SPEC-R, and those with green and blue viologens were labelled SPEC-G and SPEC-B, respectively. As shown in Fig. 1d, electrochemical characterization revealed high ionic conductivities of approximately 3.6, 5.05, and 7.2 mS/cm for the SPEC-R, SPEC-G, and SPEC-B, respectively. Also, the Nyquist plots confirm stable charge-transfer kinetics, consistent with their excellent electrochemical performance. A more detailed analysis of the Nyquist plots indicates that the charge-transfer resistance (R_{ct}) varies among the three SPEC gels, reflecting distinct interfacial charge-transfer behaviors. Specifically, the R_{ct} values were approximately 5233 Ohm, 4084 Ohm, and 1945 Ohm for SPEC-R, SPEC-G, and SPEC-B, respectively, with the SPEC-B gel exhibiting the lowest resistance. This trend is highly consistent with the observed ionic conductivity and is attributed to the synergistic effects of color-specific viologen structures and optimized ion-gel compositions, particularly the choice of ionic liquids with different alkyl chain lengths, thereby facilitating efficient charge transport kinetics within the SPEC platform⁴⁰.

Notably, this continuous network is maintained even after 1000 stretching cycles, indicating the robustness of the interfacial bonding. (Supplementary Fig. 6) Such stability is attributed to acrylate-based covalent bonding and an optimized layer-by-layer thickness design, which together preserve interface integrity under mechanical deformation (Fig. 1e).

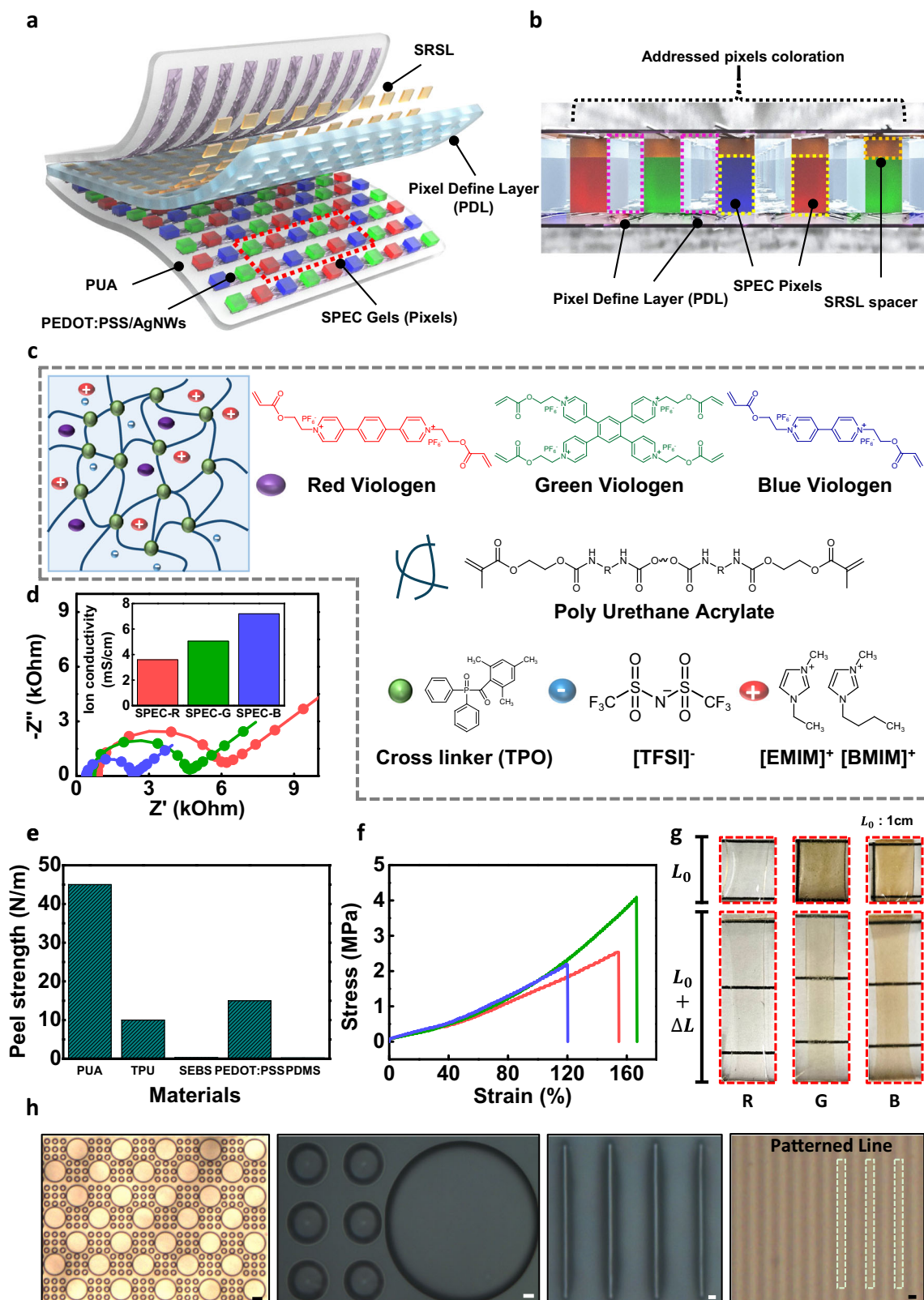


Fig. 1 | Acrylate-substituted viologen-based SPEC gels for stretchable and multi-color ECDs. a Schematic of intrinsically stretchable, photo-patterned multi-color ECDs. **b** Schematic of the cross-section of an intrinsically stretchable multi-color display. **c** Schematic of chemical structure and compositions of SPEC gels. **d** EIS plot and ionic conductivity of SPEC-R, SPEC-G and SPEC-B. **e** Peel strength of

PUA/SPEC, TPU/SPEC, SEBS/SPEC, PEDOT:PSS/SPEC, and PDMS/SPEC. **f** stress-strain curves of red, green, blue-color SPEC gels. **g** photographs of red, green, blue SPEC gels: Initial state (top) and stretched state (bottom). L_0 : 1 cm. **h** Optical microscopy images of photo-patterned SPEC gels. Scale bars: 50 μ m, 10 μ m, 2 μ m and 1 μ m (from left to right).

Following complete photo-curing, the SPEC gels exhibited high stretchability with maximum strain tolerances of 154% (SPEC-R), 169.3% (SPEC-G), and 120.3% (SPEC-B), with corresponding elastic moduli of 2.54 MPa, 2.190 MPa, and 4.12 MPa, respectively (Fig. 1f). The strain-dependent behaviours (Fig. 1g) highlight uniform deformation across all three layers in both relaxed and stretched states, confirming their robust resilience under dynamic conditions.

More importantly, the SPEC layers can be directly patterned onto PUA substrates, as illustrated in Fig. 1h. This compatibility arises from their shared chemical composition, with both materials featuring methyl acrylate terminal groups. Upon UV irradiation, polymerization is initiated, and polymer chain mobility gradually decreases. Residual unsaturated groups facilitate the formation of strong covalent bonds between the two layers, leading to strong interfacial adhesion. To enhance UV patternability and improve chemical compatibility with the PUA-based substrates, acrylate-functionalized viologens were employed. This chemical modification enables rapid, UV-triggered radical polymerization, as confirmed by Fourier transform infrared (FTIR) spectroscopy (Supplementary Fig. 7a–c). The resulting covalent interactions, mediated by polymerized acrylate groups, not only strengthen interfacial bonding but also enable the formation of sub-micrometre resolution patterns. This is achieved by selectively dissolving the unexposed EC gel in dimethyl sulfoxide (DMSO) during development. A more mediated fine-patterning process was carried out using an optimized EC gel thickness of 60 μm , which was determined based on a balance between ionic conductivity and optical modulation, as displayed in Supplementary Tables 1–3 and Supplementary Figs. 8–10.

In the device, the SPEC-R/G/B layers are deposited onto poly(3,4-ethylenedioxythiophene): poly(styrene sulfonate) (PEDOT:PSS)/AgNWs electrodes, where the AgNWs are partially embedded within the PUA matrix. Notably, the PEDOT:PSS network does not completely encapsulate the PUA/AgNWs interface, leaving portions of the methyl acrylate-terminated PUA surface exposed (Supplementary Fig. 11). This residual chemical reactivity enhances intrinsic interfacial cohesion, thereby reinforcing the structural integrity of the layered assembly. To elucidate the nature of interlayer bonding, FTIR spectroscopy was employed to analyze chemical interactions between SPEC and PUA, with a focus on the acrylate functional groups (Supplementary Fig. 11a–c). For the SPEC/PUA sample, the PUA was partially cured to retain acrylate double bonds before deposition and complete curing of the SPEC layer. This sequential curing allowed additional covalent bonding between SPEC and the residual acrylate groups in PUA. FTIR spectra of individual SPEC and PUA layers, compared to the combined SPEC/PUA layer, revealed distinct spectral changes—most notably a peak at 1639 cm^{-1} —indicative of new covalent bonds formed at the interface. This interaction, driven by the shared methyl acrylate, substantially improves the cohesion between the layers. To quantitatively evaluate the adhesive strength of the SPEC layers, peel tests were conducted using various substrate configurations (Supplementary Fig. 11d). Both polydimethylsiloxane (PDMS)- and polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene (SEBS)-based substrates exhibited an initial peel force of 0 N/m at 0 mm displacement, indicating immediate delamination. In contrast, the thermoplastic polyurethane (TPU)-based substrate exhibited an initial peel force of 5 N/m at 0 mm, which increased to 10 N/m at 40 mm, suggesting partial peeling and interfacial recombination, possibly due to hydrogen bonding associated with the acrylate groups. The PEDOT:PSS on PUA substrate demonstrated a peel strength of 20 N/m up to 60 mm displacement, after which a decline was observed, indicating a degree of interfacial adhesion attributed to the partially exposed methyl acrylate terminations. Notably, the PUA substrate exhibited a consistent peel strength of 45 N/m from 0 mm displacement onward, which remained stable with increasing displacement, highlighting the superior bonding strength between SPEC and PUA. Polydimethylsiloxane (PDMS)- and

polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene (SEBS)-based substrates exhibited immediate delamination, whereas thermoplastic polyurethane (TPU) substrates showed partial delamination and possible interfacial recombination via hydrogen bonding. PEDOT:PSS on PUA substrate showed higher adhesion, while PUA substrate exhibited a stable force throughout the displacement range, underscoring the exceptional interfacial bonding between SPEC and PUA. Furthermore, FTIR spectroscopy was used to examine whether methyl acrylate groups facilitate covalent bonding between the electrode and SPEC in the presence of PEDOT:PSS and AgNWs. (Supplementary Fig. 11e–g). The SPEC layer was cured entirely on both AgNWs/PUA and PEDOT:PSS/AgNWs/PUA sides, as evidenced by a reduced band at 1639 cm^{-1} in the FTIR spectra. This result confirms the successful formation of covalent bonds, as the AgNW network, which was well embedded in the PUA, did not interfere with the bonding process. Consequently, the chain-like morphology and thus incomplete encapsulation of PEDOT:PSS are not likely to prevent direct covalent linkage between SPECs and PUA. These results collectively demonstrate that acrylate crosslinking proceeds effectively across the interfaces, enabling the formation of a continuous polymeric network even in the presence of electrodes.

To evaluate the electrochemical properties of SPECs, cyclic voltammetry (CV) was performed using a sandwiched structure with indium tin oxide (ITO) glass electrodes (Fig. 2a–c and Supplementary Note 5). The anodic/cathodic peak currents showed a linear relationship with the square root of the scan rate, indicating a diffusion-controlled mechanism⁴¹. To further verify this, a quantitative analysis of the charge contributions was performed by plotting the peak currents against the square root of the scan rate (Supplementary Fig. 12). The results show a high degree of linearity for all SPEC samples, with SPEC-B exhibiting the highest diffusion coefficient, which supports the efficient ion transport within the optimized ion-gel matrix.

Incorporating ionic liquids improved ionic conductivity, enhancing the redox characteristics and enabling reversible color switching of SPEC-R, SPEC-G, and SPEC-B to reveal red, green, and blue colored states (Supplementary Fig. 13). In spectroelectrochemical analyses, SPEC-R initiated coloration at -1.3 V, exhibiting a prominent absorption peak at 515 nm (Fig. 2d and Supplementary Fig. 8j). The transmittance contrast (ΔT) between bleached and colored states was 85.2% at 470 nm and reached 90.2% at 515 nm. SPEC-G showed coloration starting at -1.4 V, characterized by strong absorption peaks at 620 nm (visible region) and 851 nm (near-infrared (NIR) region) (Fig. 2e and Supplementary Fig. 9j). The corresponding ΔT values were 69% and 82.2%, respectively, showing NIR absorption capability due to the extended absorption range of the four pyridinium groups⁴². SPEC-B demonstrated prominent absorption at 539 nm and 602 nm upon applying -1.3 V, achieving a ΔT of 83% at 602 nm (Fig. 2f and Supplementary Fig. 10j). The color changes of these SPECs were quantitatively analyzed through color coordinates (Fig. 2g, h). In the bleached state, the xy coordinates of SPEC-R, SPEC-G, and SPEC-B were (0.33, 0.35), (0.31, 0.34), and (0.30, 0.36), respectively, corresponding to pale yellow. Upon electrochemical activation by applied voltage, these coordinates shifted to (0.46, 0.34), (0.29, 0.40), and (0.31, 0.27), corresponding to red, green, and blue coloration, respectively.

Alternating voltages of -1.5 V and 0.5 V were applied in 20-s intervals to evaluate the stability and coloration efficiency (CE) of the ECDs (Fig. 2i–k). The CE, a key figure of merit, relates optical modulation to the charge involved in the redox process, and was calculated as

$$CE = \frac{\Delta OD}{Q} \quad (1)$$

$$\Delta OD = \log \frac{T_{\max}}{T_{\min}} \quad (2)$$

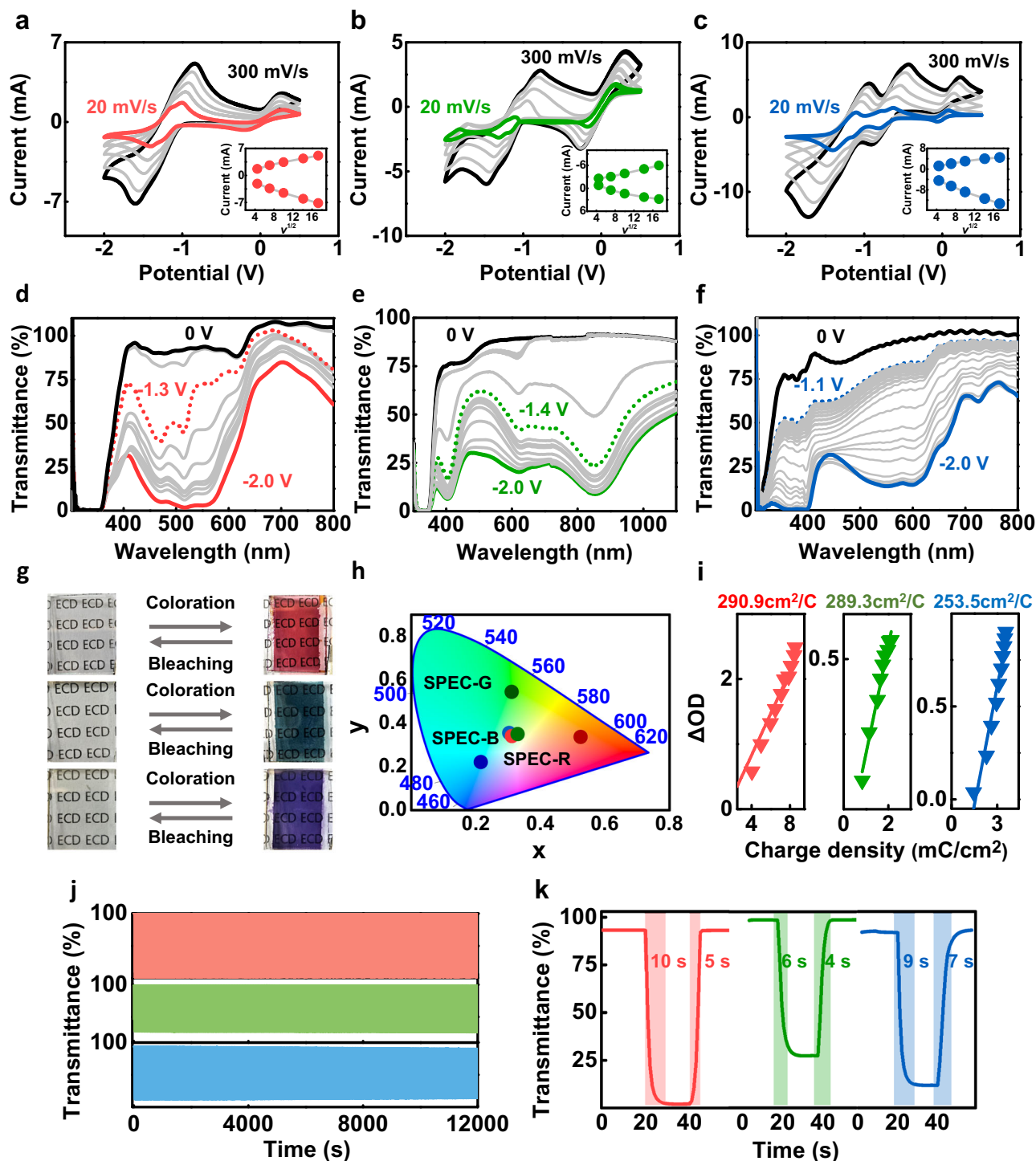


Fig. 2 | Characterization of RGB-color SPEC gels. Cyclic voltammetry curves with different scan rates for the **a** SPEC-R, **b** SPEC-G, and **c** SPEC-B SPEC gels fabricated using ITO electrodes. Inset images show the peak anodic and cathodic current vs. square root of scan rate. The corresponding transmittance change curves with different applied potentials for **d** SPEC-R, **e** SPEC-G, and **f** SPEC-B. **g** Photograph of an operating image of ECD with different colors (SPEC-R(top), SPEC-G(middle), SPEC-B(bottom)). **h** CIE color coordinates of three ECDs at different color states.

i Optical density graph of three ECDs (SPEC-R(left), SPEC-G(middle), SPEC-B(right)) **j** Kinetic stability of three ECDs obtained at different wavelengths corresponding to different colors (SPEC-R(top), SPEC-G(middle), SPEC-B(bottom)). **k** In situ dynamic transmittance responses for the three ECDs obtained at different wavelengths corresponding to different colors (SPEC-R(left), SPEC-G(middle), SPEC-B(right)) under square-wave voltage between -2 and 0.5 V.

where Q is the exchanged charge density, with $T_{\max}$ and $T_{\min}$ denoting transmittance in bleached and colored states.

Initially, SPEC-R demonstrated exceptional electrochemical stability, maintaining a consistently high ΔT of 99.5% throughout the cycling test without any initial degradation. Even after 300 cycles

(12,000 s), the transmittance variation remained remarkably stable, yielding a final ΔT of 98.8% with $T_{\min}$ stabilizing at 1%. Moreover, SPEC-G exhibited a ΔT of 69.2%, which decreased to 54.7% after 300 cycles, corresponding to a CE of $289.3 \text{ cm}^2/\text{C}$ and switching times of 6 s (τ_c) and 4 s (τ_b). Reflecting this superior performance, we further

optimized the switching kinetics by introducing a PEDOT:PSS-based ionic liquid composite as an interfacial buffer layer. As shown in the updated Fig. 2k, this modification significantly enhanced the charge-transfer kinetics, resulting in significantly reduced switching times for SPEC-R (tc: 10 s, tb: 5 s) and SPEC-B (tc: 9 s, tb: 7 s). This improvement is attributed to the optimized ion-transport pathways facilitated by the buffer layer, while maintaining full mechanical stretchability. Detailed comparative data, including the initial switching performance before optimization, are provided in Supplementary Table 5.

To realize large-area, high-resolution pixelated stretchable ECDs, it is essential to develop electrodes that are not only transparent and stretchable but also capable of high-resolution patterning. AgNWs have been widely used as electrode materials that fulfill these requirements; however, they are prone to oxidation during ECD operation, compromising the device performance^{26,43}. To mitigate this challenge, a layer of PEDOT:PSS was introduced onto the AgNW network, effectively preventing oxidation⁴⁴, while maintaining electrical conductivity. The resultant electrode features a bilayer architecture comprising a thin AgNW network embedded within a PUA matrix, which is integrated with PEDOT:PSS to form a composite electrode. The fabrication process for the PEDOT:PSS/AgNWs/PUA composite electrode is depicted in Fig. 3a. After annealing to establish a conductive AgNWs network, an anti-oxidation layer consisting of highly conductive PEDOT:PSS, modified with 5 wt% DMSO, was spun onto the network^{45,46}. Specifically, the PEDOT:PSS-coated AgNW electrodes exhibited significantly enhanced electrochemical stability compared to pristine AgNW electrodes, as evidenced by the stable redox behavior maintained over 1000 cycles without noticeable current degradation. Further investigation through linear sweep voltammetry (LSV) and Tafel polarization analysis (Supplementary Figs. 14 and 15 and Supplementary Table 6) confirmed that the PEDOT:PSS layer functions as an effective electrochemical barrier. This coating not only facilitates ion-to-electron transduction but also fundamentally suppresses the oxidative degradation of the underlying AgNWs by shifting the corrosion potential (E_{corr}) towards a more noble direction and reducing the corrosion current density (I_{corr}).

Scanning electron microscope (SEM) images of the composite electrodes (Fig. 3b) indicate that PEDOT:PSS/AgNWs are partially embedded within the PUA matrix, facilitating robust electrical interconnection and enhanced mechanical stability. Element mapping data further confirms the uniform distribution of AgNWs and PEDOT:PSS (Fig. 3c), demonstrating the successful integration of these components within the PUA matrix. The PEDOT:PSS/AgNWs layer was first patterned via photolithography, followed by wet etching, achieving high-resolution features with various line widths down to 10 μm (Fig. 3d and Supplementary Fig. 16). To minimize electrical crosstalk, ensure effective pixel confinement, and accommodate mechanical deformation in stretchable devices, the electrodes were designed with a pixel width of approximately 1550 μm . For large-area devices, the pixel dimensions were scaled accordingly, with widths of 2400 μm for the 5 cm $\times$ 5 cm device and 3200 μm for the 10 cm $\times$ 10 cm device (Fig. 3f–h). Following photopatterning, a PUA solution was overcoated onto the electrodes, and the patterned structures were subsequently released by immersing them in water, allowing for clean detachment from the underlying substrate. The atomic force microscopy (AFM) measurements revealed a smooth surface with a root-mean-square roughness of 4.53 nm was obtained (Fig. 3e). Furthermore, we assessed more critical properties of the PEDOT:PSS, modified AgNWs electrodes, including durability, transparency, conductivity, and mechanical stability, to ascertain their suitability for stretchable ECDs, which are described more detail in Supplementary Fig. 17.

Figure 4a shows the structure of intrinsically stretchable ECDs composed of SPEC and PEDOT:PSS/AgNWs composite electrodes. The colored and bleached states of SPEC-R, SPEC-G, and SPEC-B at 60 μm SRSL thickness are depicted in Fig. 4b, confirming successful ECD

operation. SRSL thickness was determined based on stable operation and stretchability (Supplementary Fig. 18). To investigate the SPEC properties, the redox behaviors of SPEC-R, SPEC-G, and SPEC-B were evaluated using CV measurement (Supplementary Fig. 19a–c). The observed redox behaviours were comparable to those of ECDs fabricated with ITO electrodes. Coloration for red, green, and blue was initiated at -1.4 V, -1.3 V, and -1.3 V, respectively, with all devices operating at voltages below -2 V. These characteristics suggest favourable compatibility between the stretchable electrodes and SPECs, ensuring reliable voltage delivery and thus stable and energy-efficient EC performance. Additionally, the devices exhibited a linear dependence on the square root of the scan rates for both anodic and cathodic peak currents, consistent with a typical one-electron transfer process described by the Randle-Sevcik equation⁴⁷.

The equivalent circuit of the stretchable ECD is illustrated in Fig. 4c, where R_e represents the resistance of the stretchable electrodes, R_{ct} denotes the charge transfer resistance, Z_w corresponds to the Warburg impedance, and C_{dl} signifies the double-layer capacitance. Under direct-current bias, C_{dl} behaves as an open circuit, allowing the equivalent resistance (R_{eq}) to be expressed as $R_{eq} = 2(R_e + R_{ct} + Z_w)$. Notably, all of these resistive components are highly strain-sensitive. In stretchable electrodes, resistance typically increases in proportion to the square of the applied strain. Similarly, our AgNW-based composite electrodes exhibit a severe increase in resistance with strain, primarily due to the percolation-dependent nature of randomly distributed AgNW networks (Fig. 4c). This increased resistance directly impacts device operation by reducing the voltage drop across the SPEC layer, thereby limiting the effective bias available for electrochromic switching. Such phenomena typically introduce a critical hurdle to implementing strain-resilient, high-performance stretchable ECDs. However, the device architectures we proposed in this research can address these challenges through optimized electrode design and interface engineering, such as PEDOT:PSS integrated AgNWs and SRSL and PDL layers, which mitigate the resistance growth under strain.

EC performance under mechanical deformation was evaluated, as shown in Fig. 4d–f. The transmittance spectra and switching behaviours of red, green, and blue ECDs were measured under strains of up to 50%. In the bleached state, all SPEC films exhibited a slight rise in baseline transmittance with increasing tensile strain, as detailed in Supplementary Fig. 20 and Supplementary Table 7. This optical behavior can be primarily attributed to two structural factors during mechanical deformation: (1) the macroscopic thinning of the polymer layer, and (2) the geometric expansion of the AgNW percolation network, which enlarges the inter-nanowire spacing and permits greater light transmission through the electrode. Notably, despite these strain-induced structural changes, the intrinsic optical modulation capability of the SPEC system remains robust and well preserved, even under substantial mechanical strain.

In the colored state, a comparable increase in transmittance was observed, attributed to a strain-induced increase in resistance, which reduces the effective coloration bias. Despite these optical variations, the devices maintained strong EC functionality. Even at 50% strain, the transmittance differences between the bleached (T_0) and colored (T_{color}) states were 57.77%, 41.53%, and 49.57% for red, green, and blue ECDs, respectively—values that remain comparable to their pristine (0% strain) conditions of 42.35%, 43.54%, 46.85% (Fig. 4g–i). To further validate mechanical robustness, we conducted fatigue tests involving 1500 stretch–relaxation cycles between 0% and 30% strain. The corresponding $T_0 - T_{color}$ values over these cycles are shown in Fig. 4j–l. A slight decline in optical contrast was observed within the first 500 cycles, after which performance remained relatively stable. After 1500 cycles, the $T_0 - T_{color}$ values were retained at 40.36%, 51.40%, and 44.60% for red, green, and blue devices, respectively. These results demonstrate that the current ECDs not only survive but also maintain functional integrity under sustained mechanical strain, highlighting

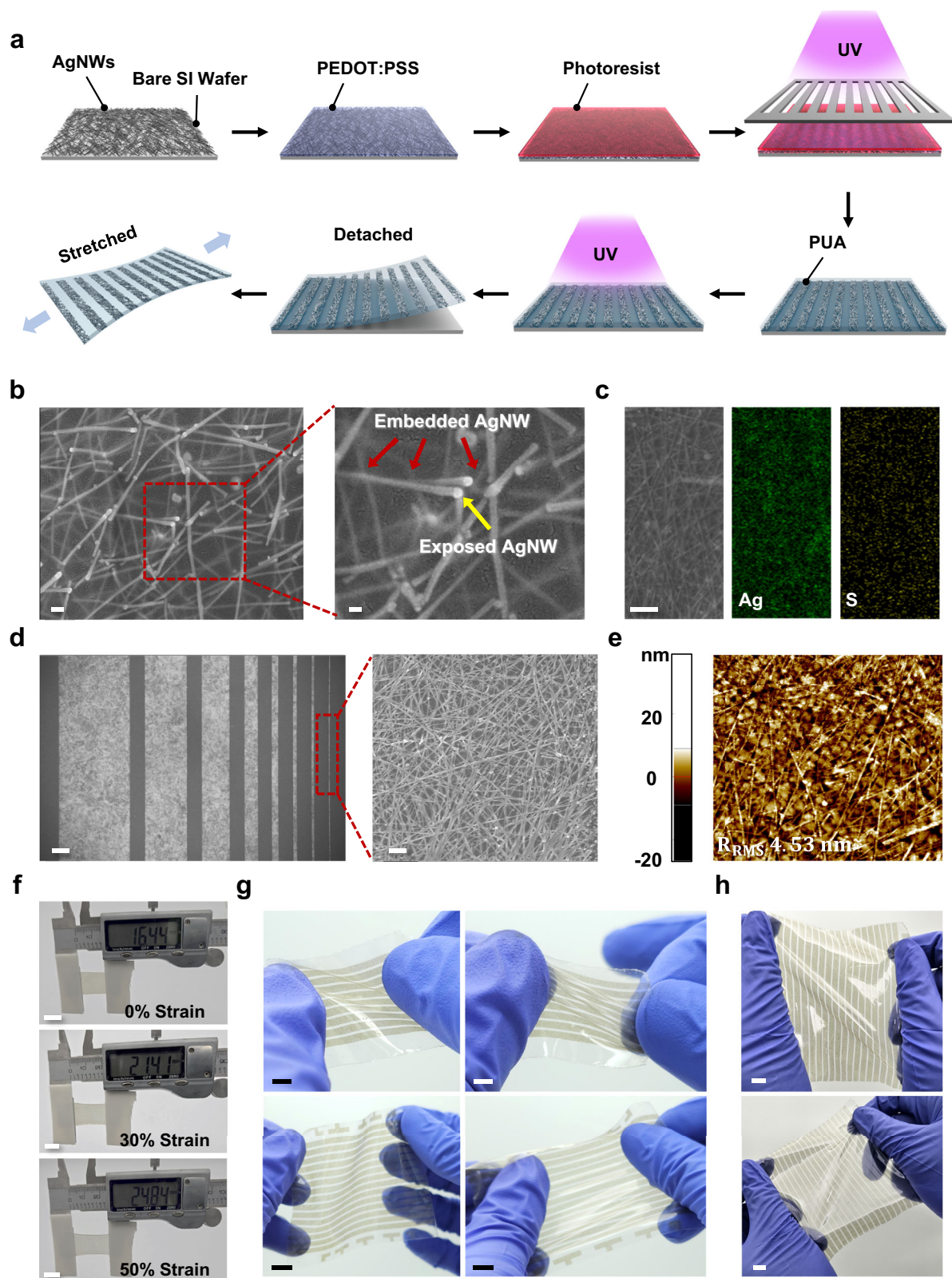


Fig. 3 | PEDOT:PSS/AgNWs/PUA stretchable electrodes. **a** Schematic of the fabrication process for the PEDOT:PSS/AgNWs/PUA stretchable electrode. **b** SEM images of PEDOT:PSS/AgNWs/PUA stretchable electrode. Scale bar: 100 nm. **c** The SEM image (left) and EDS mapping for PEDOT:PSS/AgNWs/PUA: Ag (middle) and sulfur (right). Scale bar: 500 nm. **d** The SEM images of AgNWs patterns with a line width of 10, 20, 30, 50, 100, 200, 250 and 500 μm (left). Scale bar: 100 μm (Left), 300 nm (Right). The high magnification SEM image of the AgNWs line pattern with a

line width of 10 μm (right). **e** AFM image of PEDOT:PSS/AgNWs/PUA stretchable electrode. **f** Photographs of the PEDOT:PSS/AgNWs/PUA electrode under tensile strains of 0%, 30%, and 50%. Scale bar: 1 cm. **g** Photographs of PEDOT:PSS/AgNWs/PUA electrodes: $2.5 \times 2.5 \text{ cm}^2$ (left) and $5 \times 5 \text{ cm}^2$ (right). Scale bar: 0.5 mm ($2.5 \times 2.5 \text{ cm}^2$), 1 cm ($5 \times 5 \text{ cm}^2$). **h** Photograph of a $10 \times 10 \text{ cm}^2$ large-area electrode. Scale bar: 1 cm.

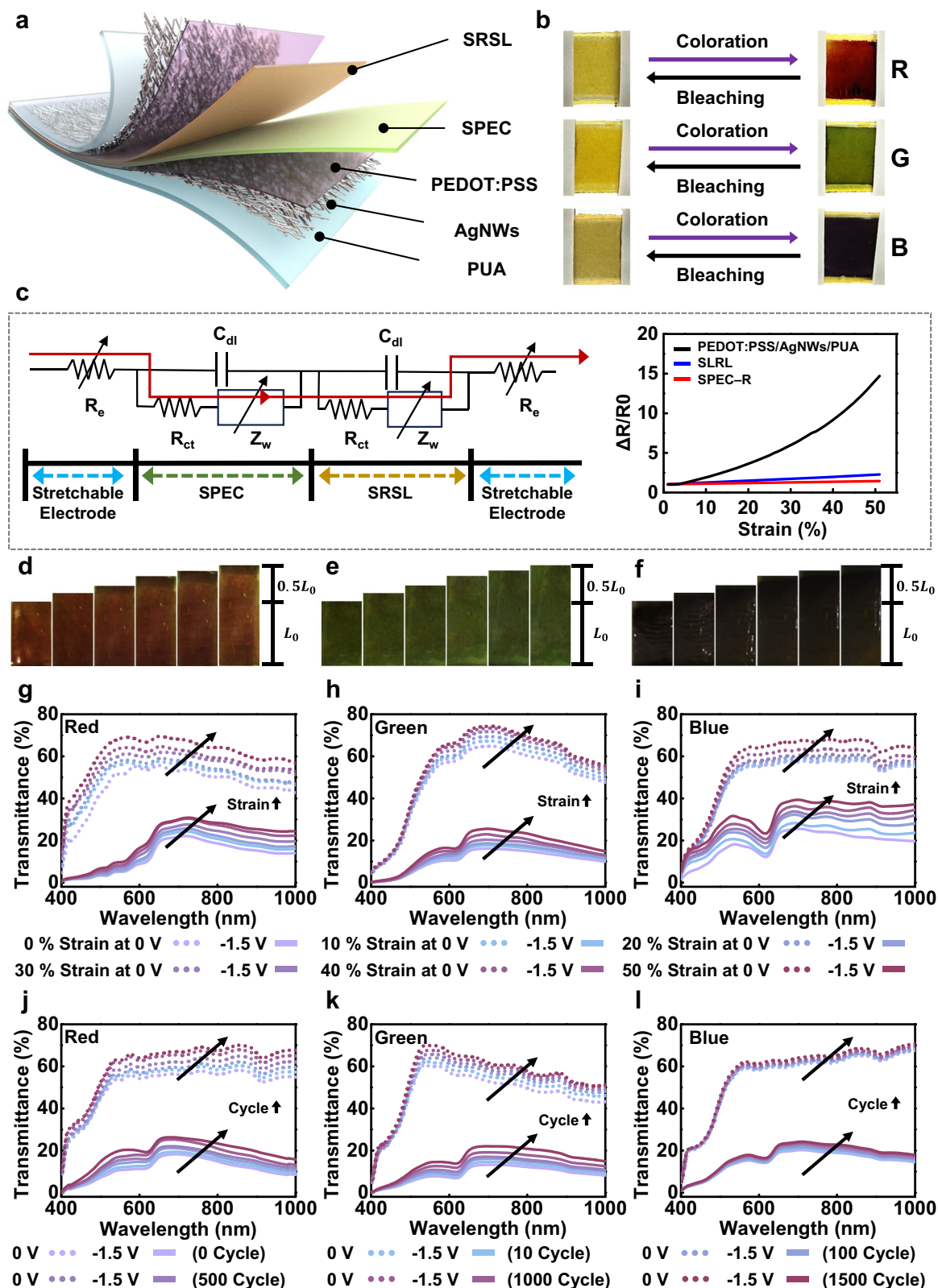


Fig. 4 | Electrochromic properties of an intrinsically stretchable electrochromic ECD. **a** Device structure of the intrinsically stretchable ECD. **b** Photographs of coloration and bleached state of intrinsically stretchable ECD. **c** Schematic of the intrinsically stretchable ECD circuit (left), normalized resistance (R/R_0) under strain up to 50% for EC, SPEC gel, and PEDOT:PSS/AgNWs/PUA

electrodes (right). **d–h** Photographs of intrinsically stretchable ECDs stretched up to 50% for SPEC-R (left), SPEC-G (middle), and SPEC-B (right). Transmittance curves of intrinsically stretchable ECDs for SPEC-R, SPEC-G, and SPEC-B at 0 V and 1.5 V under mechanical strain from 0% to 50% (**g–i**) and after 0, 10, 100, 500, 1000, and 1500 stretching cycles at 30% strain (**j–l**).

the success of material and structural design strategies. Furthermore, we evaluated the electrochemical stability of the SPEC-R, -G, and -B unit cells under repeated bending to verify their mechanical versatility. As shown in Supplementary Fig. 21, the CV curves remained nearly identical even after 1000 bending cycles at a radius of 15 mm, further confirming the superior mechanical durability of intrinsically stretchable ECDs.

To realize highly pixelated stretchable ECDs, three SPEC gel arrays were photo-patterned onto a stretchable electrode substrate. Subpixelated ECDs were fabricated by sequentially patterning the SPEC gels through a drop-casting and UV-curing process, as illustrated in Fig. 5a. A critical consideration during the SPEC gel patterning process is avoiding exposure of the EC solution to oxygen, which inhibits the photopolymerization of acrylate-based resins^{48,49}. Supplementary Figs. 22 and 23 show fabrication details and the PDL with SPEC pixels. The incorporation of PUA in both the SPEC gels and the electrode substrate also significantly enhanced the adhesion of the cured SPEC gels, contributing to robust structural integrity under deformation. The proposed device architecture implies three essential advantages: 1. Enhanced interfacial bonding. The SRSL ensures secure bonding between the top electrode and underlying layers. During UV curing, polymer chains form covalent bonds with adjacent layers, effectively integrating all device components into a cohesive assembly (Fig. 5b). 2. Enhanced electrical connectivity. The SRSL fills the air gaps between the multi-layered SPEC pixels and the top electrode, enabling conformal electrical contact that facilitates efficient ion transport. This design leads to enhanced EC switching behaviours. To suppress signal crosstalk arising from ion diffusion in the SRSL, the PDL provides pixel confinement (Fig. 5c). All functional materials—stretchable electrodes, SPEC layers, SRSL, and PDL—are physically confined within defined pixel areas, eliminating undesired lateral diffusion. The mechanism is schematically illustrated in Fig. 5d. Notably, as shown in Fig. 5e, ECDs fabricated without the SRSL showed low, diminished current densities, indicating ineffective electrochemical contact and switching behaviours. In contrast, SRSL-integrated devices exhibited high and stable current densities, confirming reversible electrochemical reactions facilitated by robust electrical pathways. 3. Mechanical stress release. The SRSL and PDL also serve to redistribute mechanical stress across the device surface. Horizontal and vertical air gaps between SPEC subpixels and between SPEC and electrodes, respectively, can be considered as zero-modulus areas, resulting in significant modulus mismatch and localized stress concentration at pixel boundaries and electrode interfaces. This mismatch is a common cause of cracking or delamination under strain. Therefore, devices without the SRSL fractured immediately upon strain, whereas those with SRSL maintained electrical and mechanical stability up to 50% strain (Supplementary Fig. 19d–i). Finite element simulations (COMSOL) confirmed that placing the SRSL and PDL in these regions effectively redistributes stress, releasing the imposed stresses and thus preventing localized failure (Fig. 5f). This stress-balancing strategy allows the device to maintain structural cohesion and stable coloration performance even under substantial mechanical deformation. To ensure the scalability and practical applicability of the developed SPEC materials and device architecture, we fabricated pixelated passive matrix (PM) stretchable electrochromic devices (ECDs). A 10 × 10 RGB pixel array was implemented within an active area of 2.5 cm × 2.5 cm to validate device performance at the unit-pixel level. To further investigate large-area scalability, the device dimensions were extended to 5 cm × 5 cm (225 pixels) and 10 cm × 10 cm (400 pixels), with independently addressable R, G, and B pixel configurations. Consistent coloration and stable performance were observed for these device sizes, demonstrating the robustness of both the material system and the device architecture. To further evaluate the display quality, we systematically analyzed the spatial color uniformity by measuring the CIE 1931 chromaticity coordinates at multiple pixel locations. The results showed negligible

deviations across the active area, confirming the high structural and functional uniformity of the SPEC gels (Supplementary Fig. 24). Moreover, this uniformity was well-preserved even after 1000 stretching cycles at 30% strain, highlighting the mechanical and electrochemical robustness of our platform in large-area applications. These free-standing, multicolor pixel arrays demonstrated excellent mechanical durability and reliable coloration for 1500 mechanical strain cycles at strains up to 30%. (Fig. 5g–k and Supplementary Fig. 25). Notably, no degradation or crosstalk was observed between adjacent pixels under stretched states. All RGB colored characters and images were implemented, and full-pixel activation of blue arrays was successfully demonstrated.

Discussion

In this article, we presented a general and scalable strategy for realizing highly pixelated, intrinsically stretchable full-color ECDs that outperform the state-of-the-art stretchable counterparts. To address the above requirements, we proposed a novel material design and facile implementation methods based on direct photo-patternable acrylate-substituted viologens and PUA-mediated stretchable electrodes. This approach is further integrated with ion gel-based stretchable components, such as SRSLs and PDLs, to achieve system-level robustness and scalability, thereby validating significantly improved interfacial adhesion and overall device performance via CMOS-compatible processes. These intrinsically stretchable, high-resolution ECDs could be of use for a wide range of applications in large-area skin-worn displays, healthcare monitoring, and professional outdoor platforms, offering a solid foundation for full autonomy in next-generation intrinsically stretchable electronic systems. To advance this technology further, while this study successfully demonstrates the feasibility of intrinsically stretchable ECDs, scaling to even larger areas presents inherent challenges. Through our stepwise approach, we identified the primary hurdles associated with large-area scalability. These include: (i) increased surface tension effects during coating and patterning, (ii) less uniform adhesion between adjacent layers, and (iii) material non-uniformity arising from larger-volume electrochromic (EC) material synthesis. Addressing these factors will be a key focus of our future work. We believe that resolving these engineering challenges will ultimately lead to defect-free pixel arrays, enhanced structural uniformity, and a highly successful scale-up process for practical applications.

Methods

Materials

Raw material, imidazole, triphenylphosphine (PPh₃), bromine, 2-hydroxyethyl acrylate, sodium bicarbonate (NaHCO₃), 1,2,4,5-tetra-bromobenzene, hydroquinone, 1,4-diiodobenzene, ammonium hexa-fluorophosphate (NH₄PF₆), lithium bis(trifluoromethanesulfonyl)imide ([Li][TFSI]), 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([EMIM][TFSI]), 1-butyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([BMIM][TFSI]), diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO), anhydrous dichloromethane, 1,4-dioxane, propylene carbonate were purchased from Sigma aldrich. 4-pyridienboronic acid, Potassium carbonate, Tetrakis(triphenylphosphine)-palladium(0), 4,4-bipyridine, ferrocene (Fc), magnesium sulfate (MgSO₄) were purchased from TCI chemical. Methacrylate-polyhedral oligomeric silsesquioxane (MA-POSS) was purchased from Hybrid Plastics. Dichloromethane, petroleum ether, ethyl acetate, acetonitrile, methanol, dimethylformamide, and dimethyl sulfoxide were purchased from Daejung and used without any purification.

Synthesis of AC-R, AC-G, and AC-B viologens

The details of all synthetic procedures, Synthesis of 4,4'-(1,4-phenylene)bis(1-(2-(acryloyloxy)ethyl)pyridin-1-ium) (AC-R), Synthesis of Synthesis of 4-(2,4,5-tri(pyridine-4-yl)phenyl)-bis(1-(2-(acryloyloxy)

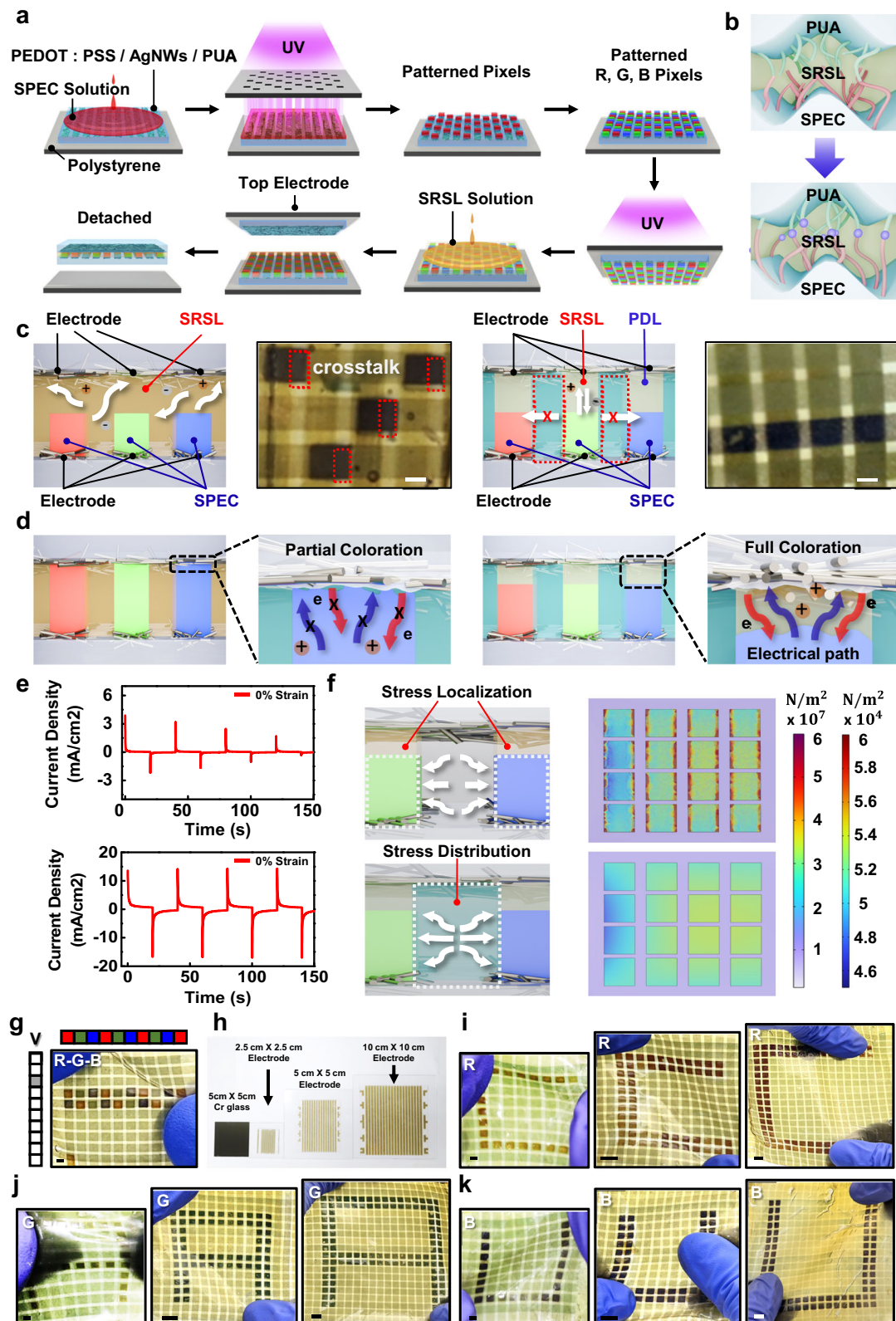


Fig. 5 | Structures and key components for large-area pixelated multicolor stretchable displays. **a** Schematic of the fabrication process of stretchable sub-pixelated multi-color ECDs. **b** Schematic of the bonding process by UV curable SRSL. **c** Schematic and photographs of the ion transport in the EC pixelated display: w/o PDL (left), w/ PDL (right). Scale bars: 1000 μm . **d** Schematic illustration of two stretchable ECDs: w/o SRSL (top), w/ SRSL (bottom). **e** Current density curves of two stretchable ECDs: w/o SRSL (top), w/ SRSL (bottom). **f** Schematic (left) and

COMSOL simulation data at 30% strain (right) of the stress relief effect of PDL and SRSL at 30% strain. **g** Photographs of stretchable sub-pixelated passive matrix ECD arrays RGB sub-pixels. Scale bar: 1000 μm . **h** photographs of Cr glass and stretchable electrodes with sizes of $2.5 \times 2.5 \text{ cm}^2$, $5 \times 5 \text{ cm}^2$ and $10 \times 10 \text{ cm}^2$. **i-k** Photographs of large-area stretchable pixelated PM ECDs. **i** Red (top right), **j** Green (bottom left), **k** Blue (bottom right). $2.5 \times 2.5 \text{ cm}^2$ | $5 \times 5 \text{ cm}^2$ | $10 \times 10 \text{ cm}^2$ (left to right). Scale bar: 1000 μm ($2.5 \times 2.5 \text{ cm}^2$), 0.5 cm ($5 \times 5 \text{ cm}^2$), 0.5 cm ($10 \times 10 \text{ cm}^2$).

ethyl)pyridine (AC-B), Synthesis of 1,1'-bis(2-(acryloyloxy)ethyl)-[4,4'-bipyridine]-1,1'-dium (AC-G) are available in Supplementary Note 1, Supplementary Figs. 1–3, Supplementary Table 4.

Preparation of the polyurethane acrylate precursor

A flask charged with polyol (25 g, 100 mmol) and Methyl ethyl ketone (MEK) (25 mL) was heated at 60 °C until the solution turned clear, after which isophorone diisocyanate (IPDI) (8.33 g, 150.0 mmol) and dibutyltin dilaurate (cat.) were added. This mixture was then heated at 60 °C for 3 h, and after adding HEA (2.9 g, 99.9 mmol), it was stirred for an additional 3 h at 60 °C before cooling to room temperature. It was then mixed with an Irgacure 184 at a ratio of 10:0.36.

Synthesis of SRSL

The polyurethane acrylate (6 g), [BMIM][TFSI] (1.5 g), [Li][TFSI] (1.5 g), ferrocene (Fc) (20 mg), TPO (216 mg), and 2-propanone (1.5 g) were mixed and stirred for 24 hrs at 80 °C.

Synthesis of PDL

The polyurethane acrylate (6 g) and Irgacure 184 (0.36 g) were stirred for 20 min at room temperature.

Fabrication process of stretchable electrodes

A dispersion of AgNWs in water (concentration of 1 mg ml⁻¹) was coated onto bare wafer substrates using a #5 Meyer rod until the sheet resistance was below 30 Ω/□, and then annealed at 120 °C for 1 min. PEDOT:PSS ink was prepared for the electrode solution using PEDOT:PSS (1.3 wt% dispersion in water, Clevios pH 1000) (10 g). Then, DMSO (2.5 g) and glycerol (1 g) were added, and the mixture was stirred at room temperature for 2 h. After that, ethylene glycol (0.5 mL) and DBSA (0.05 mL) were added, and stirred for 15 min. The prepared PEDOT:PSS solution was spin-coated onto the AgNWs layer using a consecutive two-step coating process with different spin speeds (500 rpm, 10 s and 1500 rpm, 20 s) and subsequently annealed at 120 °C. The obtained transparent conductive coating on the wafer substrates was then coated with a PUA solution. The PEDOT:PSS and AgNW layers were patterned by conventional photolithography and wet etching with Cr etchant (ETCR-300). The PUA solution was spin-coated at 300 rpm for 60 s. The coated AgNWs wafer was placed in a convection oven at 80 °C for 1 h to evaporate residual solvent and level the plane, then cured with a UV lamp. After that, the patterned electrodes were heated at 80 °C for 1 h and then immersed in water for 1 h to peel off.

Fabrication of stretchable ECDs

Polystyrene (Sigma-Aldrich, average M_w ~ 350,000) (25 g) and toluene (25 mL) were stirred for 12 h at 80 °C. The polystyrene solution was spin-coated on bare glass at 1000 rpm for 60 s, and then heated at 100 °C for 10 min. Unpatterned PEDOT:PSS-AgNW-PUA composite electrodes were transferred to polystyrene-coated carrier glass. The EC solutions were drop-cast onto the composite electrodes and cured under UV irradiation (350 nm, 145 W) through a PDMS-coated glass, resulting in a final layer thickness of 60 μm. After curing, the PDMS glass was removed. The SRSL solution was drop-cast onto the SPEC gel/electrode surface. The second electrode was then aligned in reverse and placed on top of the SRSL-coated SPEC gel. UV light was applied through the second electrode to cure the SRSL solution in place. After curing, the assembled device was carefully removed from the carrier glass.

Fabrication of multi-colored stretchable ECDs

The SPEC gel solution was drop-cast onto a PEDOT:PSS-AgNW-PUA and cured by UV (352 nm, 15 W) irradiation through a PDMS layer. The UV curing times of red, green, and blue SPEC gels were optimized at 180 s. The uncured SPEC gel, not exposed to the UV light during the

developing process, was developed by washing with acetone and deionized water. Then, the SPEC gels were pixelated onto the stretchable electrode.

The PDL solution was drop-cast onto the pixelated SPEC gels and stretchable electrode, then the structure was flipped and UV-cured through the PDMS layer. After that, the SRSL solution was drop-cast on the resulting substrate. Lastly, the second stretchable electrode was placed on top of the subpixelated SPEC gels. The SRSL solution was sandwiched between two electrodes, the solution is exposed to UV light through the top electrode for 300 s.

Characterization and measurements

The ECD cells were fabricated by placing the prepared SPEC gel on an ITO-coated glass. The ITO-coated glass was sandwiched with a Surlyn film and measured in a two-electrode system using an SP-150 potentiostat (Biologic). Absorption and spectroelectrochemical measurements were performed using a UV-1800 UV-Vis spectrophotometer (Shimadzu). The kinetic stability of the ECDs was measured by applying constant potential steps with a Biologic SP150 potentiostat, and the corresponding change in transmittance was monitored with a UV-Vis spectrophotometer. The percent transmittance (ΔT), the change in the optical density (ΔOD), and the coloration efficiency (CE) were calculated using the following relationships: $\Delta T = T_{max} - T_{min}$, $\Delta OD = \log T_b / T_c$, and $CE = \Delta OD / Q_d$, respectively, where T_b and T_c indicate the bleached and colored transmittance values, respectively, and Q_d is the injected charge per unit area. Tensile properties were also assessed using a Universal testing machine (UTM) in constant strain-rate testing mode. Microstructures and surface morphologies of thin films were investigated by using optical microscopy (OM, BX53 M, Olympus), atomic force microscopy (AFM, NX10, Park-systems), and field emission scanning electron microscopy (FE-SEM, SIGMA 300, Carl Zeiss). Elemental composition profiles of the stretchable electrode were investigated using Energy Dispersive X-ray Spectroscopy (EDS) during the SEM analysis. For the dynamic measurement of the resistance of stretchable electrodes, a measurement system comprising a switch mainframe (Keithley 3706A), a double-channel source meter (Keithley 2636B), and a high-speed reed relay MUX card was used, connected to a data acquisition system (DAQ; SnM).

Finite element simulation

To investigate the stress distribution in the pixels of stretchable subpixelated ECDs and their relevant mechanisms, a numerical stress/strain analysis using FEA (COMSOL Multiphysics 5.3) was carried out. The cubic EC pixels were designed in the actual array size (720 mm [width] × 1 mm [length] × 60 mm [height]).

Data availability

Source data are provided with the paper. Additional data related to this work are available from the corresponding authors upon request. Source data are provided with this paper.

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Acknowledgements

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIP) (No. RS-2024-00347845). This work was supported by the Nano & Material Technology Development Program through the National Research Foundation of Korea (NRF) funded by Ministry of Science and ICT (RS-2023-00281346). This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (RS-2026-25469060). S.K.P. discloses support for the research of this work from the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIP) [grant number RS-2024-00347845] and the Nano & Material Technology Development Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT [grant number RS-2023-00281346]. J.S.P. discloses support for the research of this work from the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) [grant number RS-2026-25469060]. The other authors declare no relevant funding.

Author contributions

S.K.P. and J.S.P. conceived the idea for this work and designed the materials and experiments. K.S.K., S.H.Y. and S.Y.E. synthesized EC materials, implemented intrinsically stretchable ECDs, and characterized all the data. J.-W.J., B. J., M.-J.-L., J.-W.K. and Y.-H.K. provided suggestions for the experiment designs. K.S.K. and R.L. conducted FT-IR analysis and Peel-test. S.H.Y. and F. S. assisted the characterization of materials and device properties. K.S.K. and S.H.Y. conducted COMSOL simulation. K.S.K., S.Y.E., S.H.Y., J.S.P. and S.K.P. wrote the manuscript based on the input from all the authors. S.K.P., J.S.P., Y.H.K. and J.-W.K. reviewed and revised the manuscript. All the authors participated in discussions regarding the findings and collectively endorsed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41467-026-72888-6>.

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Peer review information *Nature Communications* thanks Libu Manjakkal, Kai Zhao, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. A peer review file is available.

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