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Titao Jing

jingtt@mail.sysu.edu.cn

Sun Yat-sen University https://orcid.org/0000-0001-6819-046X

Zupeng Liu

Sun Yat-sen University

Xia Lei

Sun Yat-sen University

Di Tan

The Education University of Hong Kong

Zhao Liu

Swinburne University of Technology

Zugan Zou

Sun Yat-sen University

Yujue Yang

yujue1031.yang@connect.polyu.hk

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Ultra-Bright Stretchable Electroluminescent Devices at Low Driving Fields Enabled by a High-Permittivity Elastomer

Zupeng Liu,[a] Xia Lei,[a] Di Tan,[b] Zhao Liu,[c] Zugan Zou,[a] Yujue Yang,[a]* Titao Jing[a]*

[a] School of Chemical Engineering and Technology, Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Sun Yat-sen University, Zhuhai 519082, China;

[b] Department of Mathematics and Information Technology, The Education University of Hong Kong, 999077, Hong Kong, China;

[c] Centre for Quantum Technology Theory, Swinburne University of Technology, Melbourne 3122, Australia;

* Corresponding author, E-mail: yujue1031.yang@connect.polyu.hk, jingtt@mail.sysu.edu.cn,

Abstract:

As a crucial interface for human-machine interaction, displays are expected to be stretchable to keep pace with the evolution of next-generation electronics. Intrinsically stretchable alternating current electroluminescence (ACEL) devices are promising for this purpose but are plagued by high driving fields and frequencies due to low-permittivity elastomers. Herein, we incorporated polar vinylethylene carbonate into polyacrylate to boost permittivity up to an exceptional value of 19.6, and maintains high transparency (91%) and large loading capacity that are essential for high-luminance

devices. Moreover, the vinylethylene carbonate simultaneously improves the stretchability of the elastomer, avoiding the undesirable rigidification typically induced by strong intermolecular interactions among polar group. The stretchable ACEL devices based on the elastomer thus achieves a record luminance of 2117.6 $cd \cdot m^{-2}$ under a low electric field of 3.0 $V \cdot \mu m^{-1}$ at 1 kHz, marking a breakthrough for low-field operation. The device performs effectively at a maximum elongation of up to 500% and a cyclical elongation of 200%. We further employ fluorescent electrodes to realize multi-color displays that can vividly convert sensor signals into colorful information, and demonstrate an 8×16-pixel device for dynamic display. These findings represent a considerable advancement in stretchable displays, highlighting their transformative potential for next-generation electronics.

Keywords: Electroluminescent devices, Stretchable display, Transparent and high-permittivity elastomers, High luminance.

1. Introduction

Stretchable displays have become a pivotal component of next-generation electronics, poised to reshape human society through a wide range of transformative applications, including visual read-outs, interactive recognition, optical communication, neurostimulation, and soft robotics.[1, 2, 3, 4, 5, 6] Light-emitting diode (LED) displays have achieved remarkable success over the past decades owing to their high brightness and ability to produce multiple colors for traditional rigid displays.[7, 8, 9] However, despite

notable advances in recent years, the fabrication of stretchable LEDs remains constrained by stringent material and assembly requirements for balanced charge injection, which present significant challenges to achieving high stretchability and scalable production.[2, 6, 10, 11, 12] In contrast, alternating current electroluminescent (ACEL) devices have gained renewed attention in the era of stretchable electronics because they offer inherent advantages for realizing intrinsic stretchability.[1, 6, 11, 13, 14, 15, 16, 17] Furthermore, the structure of ACEL devices is considerably simpler than that of LEDs, typically comprising a light-emitting layer sandwiched between electrodes with low interface requirements between functional layers.[2, 18, 19] These advantages make ACEL devices highly suitable for producing stretchable displays in diverse forms, from films and fibers to textiles, which are adaptable to variable application scenarios for next-generation electronics.[1, 5, 20, 21, 22, 23]

However, stretchable ACEL devices usually require high alternating electric fields (**E**) and frequencies to achieve good brightness.[13, 18, 22, 24, 25] This raises concerns regarding the driving source and severely limits their applications in next-generation electronics.[2, 6, 13, 22, 26] In principle, to achieve good stretchability for ACEL devices, researchers must employ elastomers embedded with ZnS phosphors as stretchable light-emitting layers.[18, 22, 25] Elastomers typically exhibit a permittivity below 10, which significantly weakens the effective electric fields acting on ZnS phosphors, leading to insufficient excitation of the phosphors for high brightness.[18, 27, 28] Hence, researchers have made great efforts to explore elastomers with high permittivity to address this key

challenge of stretchable ACEL devices in next-generation electronics.[13, 22, 25, 29, 30] A notable advance was reported in 2019. Tan et al. demonstrated a stretchable ACEL device with a maximum luminance of 1459.7 cd·m^{-2} at a sinusoidal **E** =2.5 V·μm^{-1}of a frequency = 1 kHz, using a plasticized fluoroelastomer-based emitting layer with a thickness of 1500 μm; this device is recognized as having record-breaking performance under sinusoidal **E** in recent years.[22] However, the device can only achieve a cyclical strain of 20% and is difficult to recover after larger elongation. As recently as 2025, we reported a dielectric gel-based device (emitting layer thickness of 800 μm) with a maximum luminance of 1823.5 cd·m^{-2} at a square-wave **E**·=2.5 ·μm^{-1} of 1 kHz.[31] These two works serve as the benchmarks for addressing the low-driving-field, high-luminance challenges of stretchable ACEL devices.

In this work, we developed a polyacrylate elastomer with a high permittivity of 19.6 based on the copolymerization of methyl acrylate (MA) and highly polar vinylethylene carbonate (VEC), which enables stretchable ACEL devices with a record luminance of 2117.6 ± 121.4 cd·m^{-2} under low driving fields, as shown in Figure 1. Notably, under comparable conditions, **E** = 2.5 V·μm^{-1} at 1 kHz and emitting layer thickness = 500 μm, the luminance of the devices significantly exceeds that of previous records: 719.2 cd·m^{-2} (this work) *versus* 221.0 cd·m^{-2} (plasticized fluoroelastomer-based devices) at sinusoidal **E**, and 1548.8 cd·m^{-2} (this work) *versus* 952.2 cd·m^{-2} (dielectric gel-based devices) at square-wave **E**.[22, 31] This demonstrates a considerable achievement in stretchable electroluminescent devices for display applications.

Moreover, rigid, highly polar VEC improves the elastomer's stretchability conversely, eliminating polymer stiffening caused by ordinary high-polarity functional groups. The assembled ACEL devices thus can achieve an elongation of up to 500% and a cyclical strain of 200% during operation. Subsequently, colorful devices with vivid colors were assembled, which can emit even brighter light. These colorful devices were integrated with a strain sensor to visualize sensor signals as colorful information. Finally, we demonstrated a wearable 8×16-pixel device with rich colors that can realize the dynamic real-time display of information, indicating a promising platform for information transmission in wearable electronics.

2. Results and discussion

2.1 High-permittivity elastomer PMV with the high transparency and good elasticity for ACEL devices

High permittivity of the matrix for loading ZnS phosphors is a well-established principle in preparing brighter ACEL devices. Nevertheless, high transparency to enable light penetration from phosphors, good elasticity for recoverable deformation, and sufficient space for phosphor loading are also critical to stretchable ACEL devices with high luminance. These comprehensive requirements pose a significant challenge for elastomers, as it is difficult for them to achieve excellent performance in all aspects. For instance, ferroelectric or plasticized polymers (e.g., fluoroelastomers) have very good permittivity, but their transparency and recoverable stretchability are not ideal.[22, 24, 32] Doped elastomer composites are also limited by opacity and insufficient ZnS

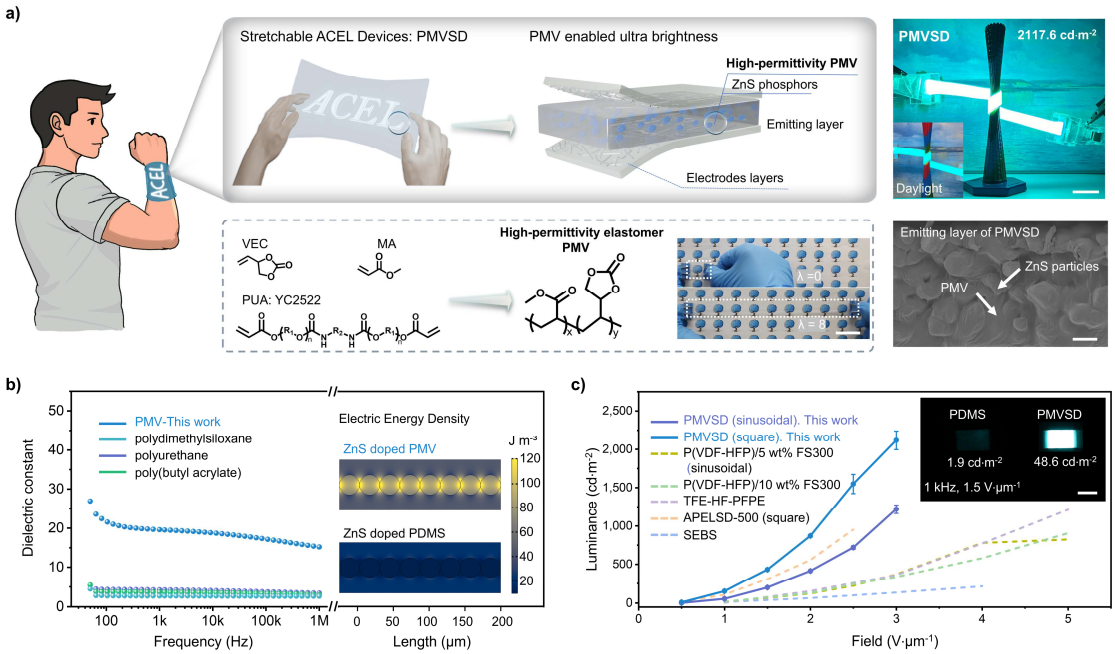


Figure 1. **a)** Structure of the ultra-bright ACEL device (PMVSD) enabled by high-permittivity elastomer PMV, along with its digital photos in twisted and stretched states under 3.0 V·μm^{-1} at 1 kHz, scale bar: 3 cm. The chemical structure of high-permittivity PMV, which also possess good transparency and stretchability, is also illustrated, scale bar: 3 cm. The SEM image of the emitting layer, ZnS particle-doped PMV, is presented in the lower right, scale bar: 25 μm. **b)** Permittivity of PMV and other commonly used matrices for stretchable ACEL devices. COMSOL simulations of ZnS doped polydimethylsiloxane (PDMS) and PMV are also displayed. **c)** Luminance comparison between PMVSD and other previously reported stretchable ACEL devices at their corresponding electric fields. The inset images show PMVSD and the PDMS-based device with a 100 μm emitting layer in the dark, scale bar: 1 cm.

loading space.[29, 33, 34, 35] Our group and Li et.al. proposed dielectric gels for high-permittivity matrix; in particular, we set previous luminance records for stretchable ACEL devices.[13, 31] However, the swollen liquid in dielectric gel easily interacts with other highly stretchable gel electrodes, requiring a more complicated structure for high stretchability. Moreover, although the luminance is favorable under ultra-low electric field, the luminance of these dielectric gel-based devices at moderate or higher electric field fails to meet our expectations based on its ultrahigh permittivity. This is most likely attributed to the high mobility of swollen liquid, especially under an applied electric field.

Using highly polar monomers is a widely adopted strategy for increasing elastomer permittivity. Unfortunately, strong intermolecular forces of polar groups lead to stiffness, making it difficult to balance high permittivity and stretchability toward stretchable ACEL devices. As depicted in Figure 1a and S1a, we prepared an elastomer with high permittivity in this work via a crosslinked polyacrylate copolymer (denoted as PMV) of MA and VEC. VEC possesses a large dipole moment of 5.58 D (Figure S1b), which can significantly enhance the permittivity to 19.6 at 1 kHz. This permittivity value is very high compared with that of commercial elastomers (ranging from 3 to 10), thus ensuring a much higher effective electric field for ZnS phosphor excitation and the corresponding light emission, Figure 1b–c. In fact, we have identified the potential of VEC to boost permittivity within the selection of gel framework in our previous work.[31] Nevertheless, VEC is a typical highly polar and rigid monomer, rendering the polymers too stiff for stretchable devices. Herein, we copolymerize the soft monomer MA together with a polyurethane macro-crosslinker to fabricate soft elastomers. Encouragingly, the copolymer of MA and VEC does not become increasingly rigid with rising VEC ratio. In contrast, elevating the VEC ratio from 1:0 to 1:0.8 increases permittivity from 6.3 to 19.6, while the elongation at break gradually rises from 501% to 861%, as presented in Figure 2a-b and S1c. This unexpected softening behavior is both intriguing and puzzling for high-permittivity elastomers. We investigate the polymerization of MA and VEC, finding that the number-average molecular weight of the main chains (linear copolymer of MA and VEC without

crosslinker) decreases from 110 kDa to 29 kDa with the increase in VEC ratio, Figure S1d. The lower mainchain molecular weight thus results in reduced chain entanglement in PMV, and an abnormal softening effect emerges. Besides, PMV possesses excellent transparency of 91%, Figure 2c. Its loading capacity is also comparable to that of commercial elastomers, as no additional fillers are present to compete for space. In general, PMV exhibits comprehensively excellent performance in all four key aspects required for ACEL devices (i.e., high permittivity, good elasticity, high transparency, and sufficient space for phosphor loading), as illustrated in Figure 1. PMV with a monomer ratio of 1:0.8(at higher ratio, the VEC cannot be fully reacted) was thus selected as the matrix for loading ZnS phosphors to fabricate the light-emitting layers in this study.

2.2 Stretchable ACEL devices with high luminance achieved by the high-permittivity elastomer PMV

A stretchable ACEL device (denoted as PMVSD) was further assembled using stretchable electrodes composed of AgNWs-coated polydimethylsiloxane (PDMS)—a classical transparent and stretchable electrode (Figure S2). As shown in the electric field simulation of Figure 1b, the effective electric fields acting on ZnS phosphors are enhanced by the permittivity of the matrix. Accordingly, PMVSD with a high-permittivity PMV matrix emits very bright light, which is attributed to the more efficient excitation of phosphors. We fabricated PMVSD devices with three different thicknesses of the light-emitting layer, designated as PMVSD-X (where X μm represents the thickness of the light-emitting layer). As illustrated in Figure 2d–h and

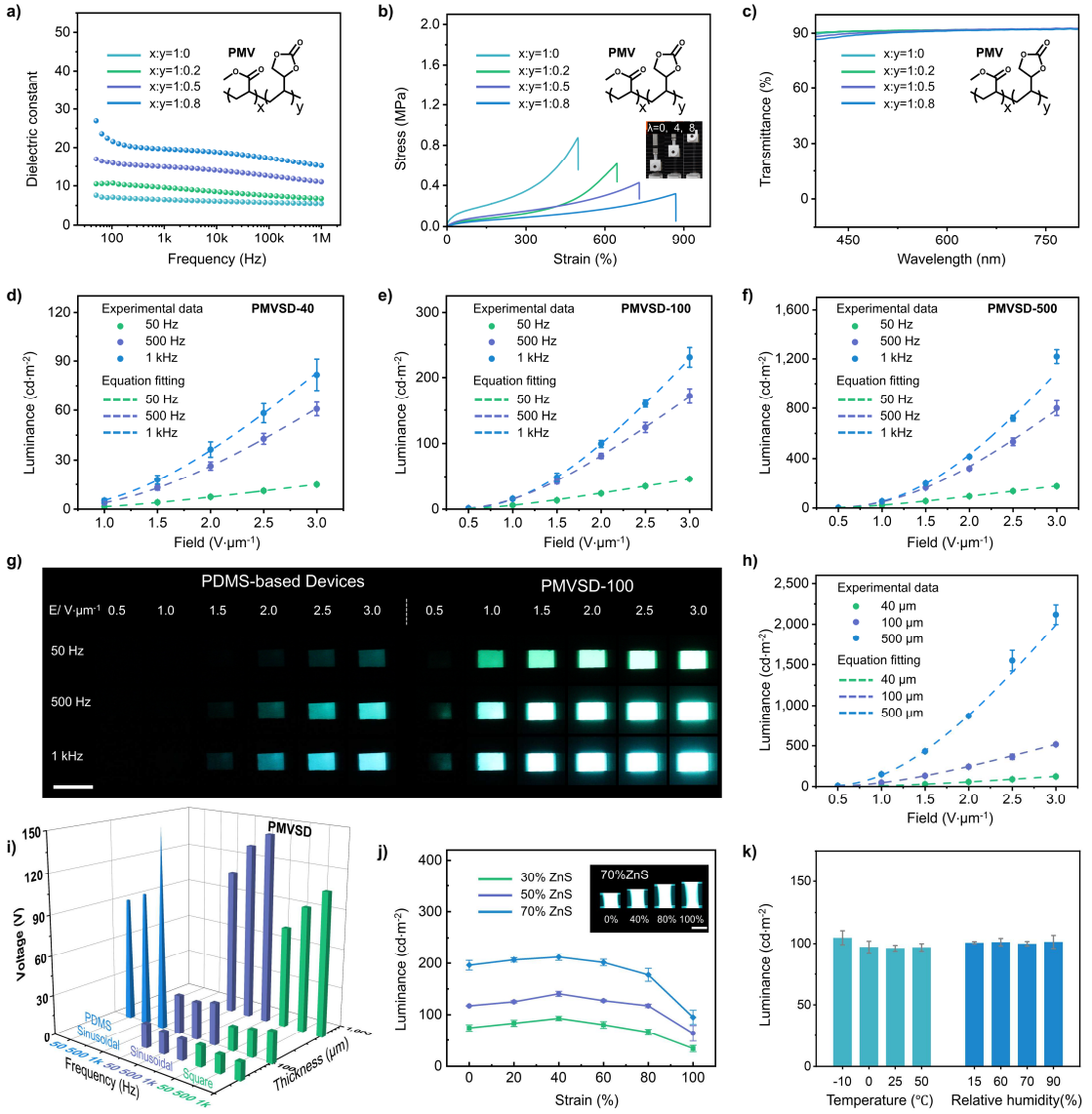


Figure 2. **a)** Permittivities, **b)** stress-strain curves, and **c)** transmittances of PMV with different structural unit ratios. Luminance of **d)** PMVSD-40, **e)** PMVSD-100, and **f)** PMVSD-500 under different sinusoidal electric fields. **g)** Digital photos of PMVSD-100 and PDMS-based devices under different sinusoidal electric fields, scale bar: 2 cm. **h)** Luminance of PMVSD with different thicknesses under different square-wave electric fields at 1 kHz. The dashed lines in these luminance figures are the fitting lines of $L = Aexp(-(b/E)^{0.5})$, where L and E represent luminance and driving electric field, respectively, and A and b are constants. **i)** Turn-on voltages of PMVSD and PDMS-based devices. **j)** Luminance of stretched PMVSD with different ZnS particle contents. Inset images are digital photos, scale bar: 1 cm. **k)** Luminance of PMVSD-100 under different environmental conditions.

Figure S3, the luminance of PMVSD increases with the thickness of the light-emitting layer. PMVSD-500 can reach a luminance of 1218.7 ± 55.5 cd·m^{-2} under a sinusoidal **E** of 3.0 V·μm^{-1} at a low frequency of 1 kHz (unless otherwise specified, the applied

electric field is sinusoidal, consistent with that of the power grid), which is far superior to devices based on PDMS (Figure 2g and S4), a widely used elastomeric dielectric. Notably, this luminance is 3 times higher than that of the previous record based on plasticized fluoroelastomer (369.4 $cd \cdot m^{-2}$) under the same conditions, representing a substantial advancement in stretchable ACEL devices.[22] Furthermore, the luminance of PMVSD-500 is higher when using a square-wave electric field, achieving 2117.6 ± 121.4 $cd \cdot m^{-2}$ at $\mathbf{E} = 3.0\ V \cdot \mu m^{-1}$ and 1 kHz. This performance is also significantly higher than that of gel-based devices reported in our previous work under square-wave **E**, even with a much thinner emitting layer, as shown in Figure 1c and Supplementary Table S1 for comparison.[31]

The turn-on threshold voltage/**E** is widely regarded as the key parameter to evaluate the lighting ability of ACEL devices, which is defined as the required voltage/**E** for reaching 0.1 $cd \cdot m^{-2}$. Owing to the high permittivity of the used elastomers, PMVSD showcases very low turn-on voltages, as described in Figure 2i. The minimum turn-on threshold voltage of this work is 15 V (square-wave **E**) or 18 V (sinusoidal **E**) at 50 Hz, which is achieved by PMVSD-40. At sinusoidal **E**, the threshold voltage is significantly lower than the previous record of 23 V at 50 Hz using a plasticized fluoroelastomer with a permittivity of 18.[22] Moreover, under similar conditions (emitting layer thickness = 100 μm, sinusoidal **E** of 1 kHz), the turn-on threshold voltage/**E** of PMVSD-100 is obviously lower than that of plasticized fluoroelastomer-based devices: 31 V/0.31 $V \cdot \mu m^{-1}$ (this work) *versus* 40 V/0.40 $V \cdot \mu m^{-1}$ (plasticized

fluoroelastomer-based devices).[22] Meanwhile, the PDMS-based devices exhibit a much higher turn-on voltage/**E** of 92 V/ 0.92 V·μm^{-1} due to the very low permittivity of PDMS. At square-wave **E**, the turn-on voltage of PMVSD-40 is also comparable to the previous record achieved by dielectric gel-based devices: 15 V (this work) *versus* 13 V (dielectric gel-based devices).[31] Besides, the minimum turn-on threshold **E** could be as low as 0.15 V·μm^{-1} at 50 Hz achieved by PMVSD-500. These data all illustrate the outstanding emitting ability at low driving source.

The content of ZnS phosphors is also critical to the luminance. As shown in Figure S5a, PMVSD-100 becomes increasingly bright as the phosphor content is adjusted to 30 wt%, 50 wt%, and 70 wt%. For the elastomer matrix, 70 wt% is the optimal content for maximum brightness, because the light emitted by the phosphors would be obscured by the phosphors themselves at higher contents. Traditionally, doped composites are a well-established method for enhancing the permittivity of commercial elastomers. However, fillers inevitably occupy the space available for ZnS phosphors and block light transmission, making it difficult for doped composites to achieve high phosphor loading.[29, 33] In this work, the high permittivity of PMV is inherently achieved without the need for additional fillers, thereby enabling a phosphor content of 70 wt% for high luminance (all contents are 70 wt% unless otherwise specified). Additionally, we evaluated the luminance change of devices with PMV matrices prepared at lower VEC monomer ratios (1:0.5, 1:0.2, 1:0), as shown in Figure S5b–h. As expected, the reduced permittivity of the elastomers weakens the effective electric fields acting on the

phosphors, which in turn results in lower device luminance with decreasing VEC monomer ratios.

The stretchability of PMVSD is demonstrated in Figure 2j, Figure S6a–c and SI video-1. PMVSD functions well at a strain of 80%, but exhibits decreased luminance when the strain is further increased to 100%. Furthermore, the operational stretchability of PMVSD is limited by the AgNWs-coated PDMS electrode, whereas the light-emitting layer (ZnS-doped elastomer) can achieve a much higher elongation of up to 600%. As demonstrated in later sections, PMVSD is expected to exhibit greater operational elongation with a more robust electrode. The stability of PMVSD under different conditions, including temperatures ranging from -10 °C to 50 °C, and humidity levels ranging from 15% to 90%, and different deformations, is presented in Figure 2k and S6d. No obvious changes in the luminance of the devices are observed under these conditions, confirming the excellent stability of PMVSD.

2.3 Colorful devices with higher luminance based on fluorescent electrodes

On the basis of the highly bright devices, we further fabricated a series of colorful ACEL devices for advanced display applications based on our previous work.[36] As illustrated in the mechanism diagram of Figure 3a and S7, the front stretchable electrodes are incorporated with fluorescent particles. These particles can absorb the emitted light from ZnS phosphors excited by an electric field and convert it into desired colors (yellow, green, and red). The electrodes thus integrate a light-converting function, eliminating the need for additional layers and resulting in a simplified structure for colorful ACEL devices. As shown in Figure 3b, the color coordinates of the front side

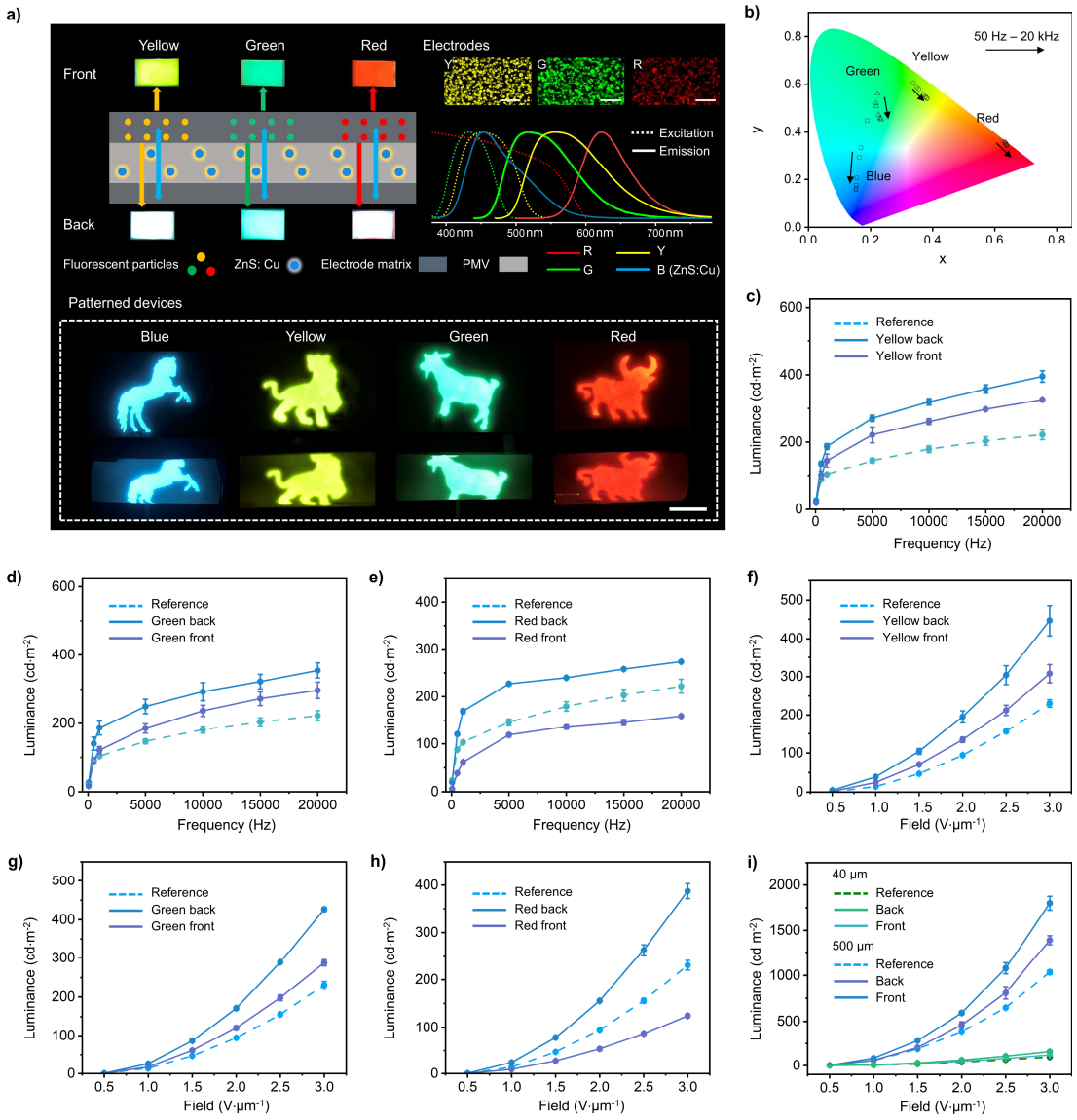


Figure 3. **a)** Structure and mechanism of stretchable PMVSD with fluorescent electrodes, along with excitation spectra, emission spectra, and microscopic images of fluorescent particles in the electrodes, scale bar: 100 μm. Bottom digital photos show patterned PMVSD devices fabricated with fluorescent electrodes, displaying a blue horse, yellow tiger, green goat, and red bull under a driving frequency of 1 kHz, scale bar: 2 cm. **b)** CIE color coordinates of the front side of PMVSD with fluorescent electrodes over a driving frequency range of 50 Hz–20 kHz. Luminance of PMVSD-100 with **c)** Yellow, **d)** Green, and **e)** Red electrodes, respectively, as a function of driving frequency at an electric field of 2 $V \cdot \mu m^{-1}$. Luminance of PMVSD-100 with **f)** Yellow, **g)** Green, and **h)** Red electrodes, respectively, as a function of electric field at a driving frequency of 1 kHz. **i)** Luminance of PMVSD-40 and PMVSD-500 with yellow electrodes as a function of electric field. The dashed lines represent the corresponding PMVSD with non-fluorescent electrodes as references in these luminance figures.

are as follows: yellow (Y: 0.355, 0.578), green (G: 0.218, 0.505), and red (R: 0.635, 0.354) at a frequency of 1 kHz. At a higher frequency of 5 kHz, these coordinates shift

to yellow (Y: 0.370, 0.555), green (G: 0.226, 0.471), and red (R: 0.638, 0.349), respectively. The coordinate shift is attributed to the frequency change-induced light variations of ZnS phosphors.[36] For the back side, the colors also vary because they are generated by the mixed light of photoluminescence from the front electrode and blue light from the light-emitting layer, Figure S8a. These colorful devices can provide rich visual information for displays. In a demonstration experiment, we fabricated patterned devices to showcase their potential in Figure 3a. These patterns including those shaped like a blue horse, yellow tiger, are function well under deformation states.

Moreover, this structure enhances PMVSD's luminance, particularly on the back side, as presented in Figure 3c-h, S7 and S8. Back-side light is a mixture of photoluminescence from the front electrode and blue light from the light-emitting layer, resulting in a brighter device. For example, under the same conditions (3.0 $V \cdot \mu m^{-1}$, 1 kHz), PMVSD-100 exhibits a back-side luminance of 446.8 $cd \cdot m^{-2}$ with the yellow electrode, compared to 230.0 $cd \cdot m^{-2}$ without it. With a thicker light-emitting layer, PMVSD-500, the maximum back-side luminance reaches 1391.6 ± 48.9 $cd \cdot m^{-2}$, slightly brighter than the devices without a fluorescent electrode, as exhibited in Figure 3i. On the front side, yellow electrodes can even provide PMVSD-500 with a maximum front-side luminance of 1798.2 ± 76.0 $cd \cdot m^{-2}$ (3.0 $V \cdot \mu m^{-1}$, 1 kHz), which is accounted for by the well overlapping of their excitation spectrum and the emission spectrum of the emitting layer.

2.4 Gel electrodes-based ACEL devices with larger stretchability

As mentioned earlier, the highly stretchable PMV elastomer enables ACEL devices to achieve superior stretchability. In our previous work, the high-permittivity dielectric gel was used as a matrix for emitting layer, whereas the swollen liquid in the dielectric gel easily interacts with other highly stretchable gel electrodes, requiring additional inserted layers to separate emitting layers and gel electrodes.[31] A complicated structure and thicker devices are inevitable, which induces a higher voltage at same electric fields. In contrast, the PMV is a solid elastomer that can be easily integrated with other electrodes without complicated structures. A conductive deep eutectic solvent (DES) gel electrode with an elongation around 800% and a transmittance of 91% was used to replace the AgNWs electrodes (Figure 4a, S9) for demonstration. The adhesion strength between the gel electrode and the light-emitting layer reaches over 4 $N \cdot m^{-1}$, which is sufficient to ensure structural reliability during deformation, as shown in Figure 4b–e). Therefore, the operational elongation of PMVSD with 70 wt% ZnS content is extended to 150% for the gel-based devices. The operational elongation could be further extended. The gel-based devices achieve a maximum operational elongation of 500% when the ZnS content in the elastomer is 30 wt% (Figure 4d and SI video-2). Moreover, owing to the large elasticity of the dielectric layer, the devices also emit stably over 1000 cyclical stretches at 200% strain (Figure 4e, S10a, and SI video-3). In the previous milestone for stretchable ACEL devices reported by Tan, the cyclic strain was limited to 20%.[22] This is because the plasticized polymers used to achieve high

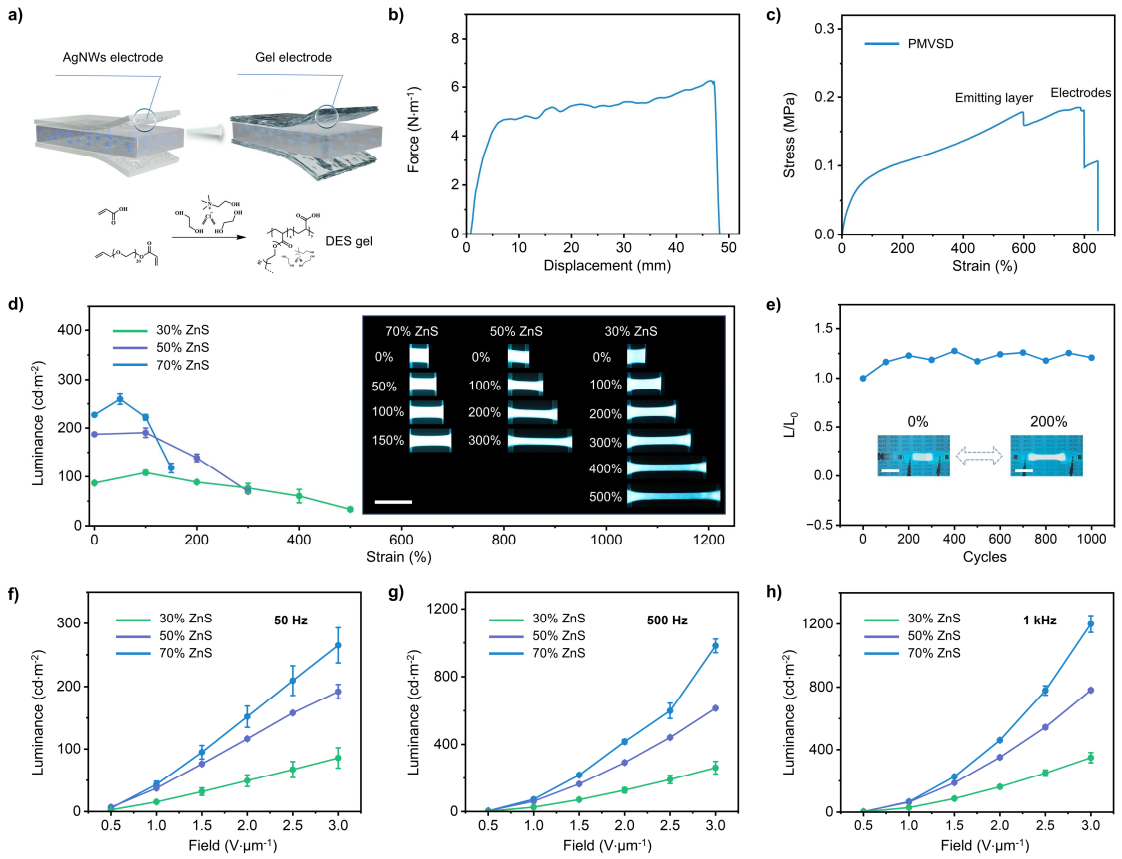


Figure 4. **a)** Gel electrodes endow PMVSD with enhanced stretchability. **b**) Adhesion strength between gel electrodes and emitting layers. **c**) Stress-strain curve of gel electrode-based PMVSD. **d**) The luminance changes at stretching states of gel electrode-based PMVSD-500 with different ratios of ZnS particles. The photos at stretching states are also inserted, scale bar: 3 cm. **e**) L/L_0 for cyclical strain of 200% of the gel electrode-based PMVSD-500 with a ZnS content of 30 wt% in emitting layer, scale bar: 3.5 cm. The luminance of gel electrode-based PMVSD under different electric fields at **f**) 50 Hz, **g**) 500 Hz, and **h**) 1 kHz.

permittivity in those devices exhibit very low recoverable deformation. Furthermore, the gel-based devices also exhibit high luminance. These devices can emit a maximum luminance of 1199.9 ± 53.3 cd·m^{-2} at 3.0 V·μm^{-1} (Figure 4f-h and S10b–c), which is close to that of AgNWs electrode-based PMVSD and significantly exceeds previous records under similar conditions (369.4 cd·m^{-2}).[22]

2.5 Visualization of sensor information and dynamic colorful display with an 8×16 pixels array

Sensors for the body are very important because they can provide valuable physiological information for medicine, sports monitoring, and many other applications.[37] Electroluminescent devices can be integrated with human body sensors to visualize signals for direct observation.[11, 16] As a demonstration, a resistance sensor for monitoring strain was bonded to a finger and integrated with patterned devices, as presented in Figure 5a and S11. The resistance of the sensor increased as the finger bent, which stepwise turned on the corresponding areas of the electroluminescent devices with different colors. In this way, the resistance changes of the sensors can be converted into visual information in real time, which is more intuitive.

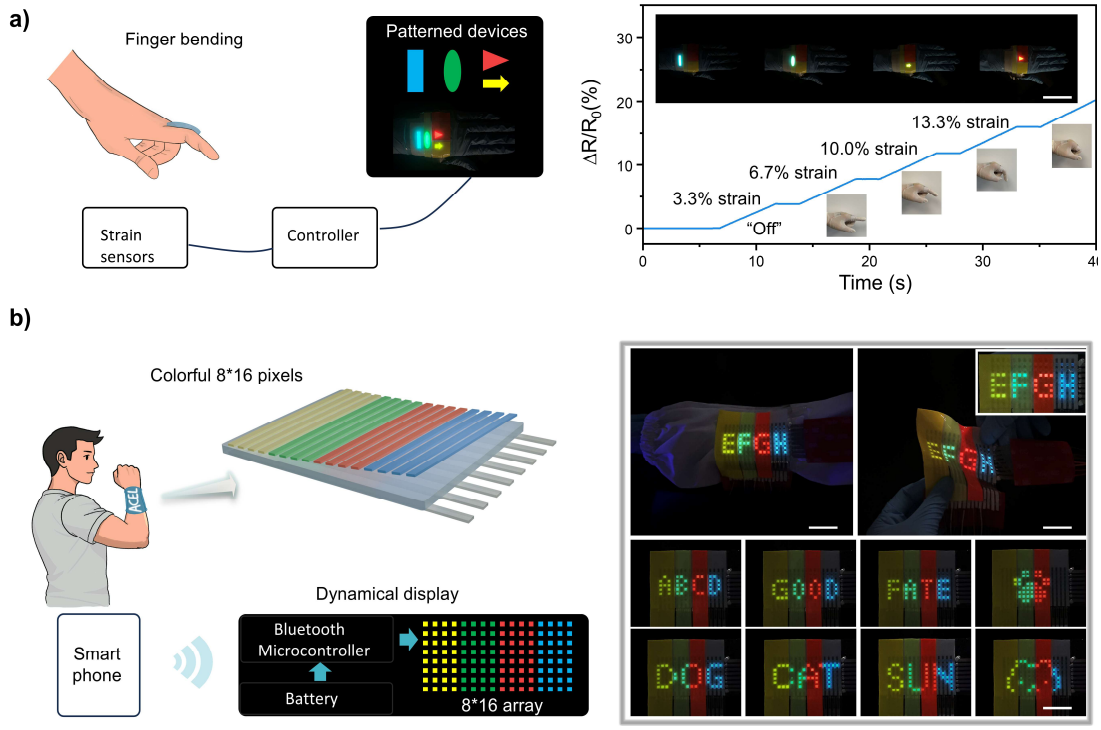


Figure 5. **a)** Patterned devices for visualizing strain sensor signals acquired from finger bending. Scale bar = 7 cm. **b)** Structure and information display mechanism of a 128-pixel full-color device via wireless communication. Digital photos show information transmitted by a smartphone. Scale bars = 3 cm.

A 128-pixel colorful device was further fabricated to demonstrate its potential for dynamic information displays. The device's pixels are formed by vertically arranged front electrodes (16 stripes) and back electrodes (8 stripes). The front electrodes are fluorescent, enabling the device to display colorful content (yellow, red, blue, and green). This device can showcase information transmitted wirelessly from a smartphone. By controlling pixel combinations, it achieves dynamic information display rather than presenting fixed, specific content. As shown in Figure 5b and SI video-4, various types of information, including "ABCD", "EFGH", "GOOD", and patterns, are accurately displayed on the device in real time. The device also operates stably under bending conditions for wearable applications. This colorful device exemplifies a practical wearable display technology for efficient information interaction, laying a foundation for future integrated flexible electronic systems.

3. Conclusion

In conclusion, we demonstrate breakthrough brightness for stretchable ACEL devices at low electric fields and frequencies, achieved using a high-permittivity elastomer. The stretchable ACEL device exhibits a maximum luminance of 1218.7cd·m^{-2} under a sinusoidal $\mathbf{E}$ = 3.0 V·μm^{-1} at 1 kHz, and a higher luminance of 2117.6 cd·m^{-2} under a square-wave electric field. PMVSD also demonstrates excellent stretchability: it can achieve a maximum operational strain of 500% and maintain stable luminance under 200% cyclical strain. The high performance of PMVSD stems from

the elastomer's comprehensive properties, which are ideal for stretchable ACEL devices—including a high permittivity of 19.6, a good transmittance of 91% @ 550 nm, a large stretchability of 861%, and a high ZnS loading capacity. We further integrated fluorescent electrodes to develop full-color devices (red, yellow, green) for rich information display. Finally, we fabricated a colorful stretchable display capable of dynamically presenting information in real time via wireless communication. This work represents a significant breakthrough in achieving high brightness for stretchable ACEL devices at low voltage and frequency, substantially surpassing previous records and paving the way for the development of stretchable optoelectronic devices and next-generation electronics.

4. Experimental section

Materials and Characterization

Choline chloride, ethylene glycol, acrylic acid (AA), 4-vinyl-1,3-dioxolan-2-one (VEC), poly(ethylene glycol) diacrylate (PEGDA, M_n = 1,000), 2-hydroxy-2-methylpropiophenone (photoinitiator 1173), and AgNWs (outer diameter: < 2 nm, length: 5–30 μm, isopropyl alcohol suspension) were purchased from Shanghai Macklin Biochemical Technology Co., Ltd. Methyl acrylate (MA), octadecyltrichlorosilane (OTS), 1-hydroxycyclohexyl phenyl ketone (photoinitiator 184), I2959,), bis(trifluoromethylsulfonyl imide) ([BMIM]TFSI), and N,N'-methylene diacrylamide (MBAA) were products of Shanghai Aladdin Bio-Chem Technology Co.,

Ltd. Polydimethylsiloxane (PDMS, Sylgard 184) was supplied by Dow Corning. Electroluminescent phosphor (ZnS: Cu) microparticles were acquired from Shanghai KPT Co., Ltd. Fluorescent particles (YAG:Ce, yellow, YG-45M; YAG:Ga, green, GG-520B; Nitride 1113, red, HR-629H) were obtained from Grirem Advanced Materials Co., Ltd. The crosslinker for the high-permittivity elastomer was a urethane acrylate oligomer (YC2511), procured from Shanghai Yinchang Co., Ltd. The AgNWs suspension was diluted in isopropanol (IPA) to a concentration of 0.3 $mg \cdot mL^{-1}$ and sonicated for 90 min prior to use. All chemicals were used as received without further purification.

The dielectric properties were measured using a LCR meter (Keysight E4980AL). The mechanical properties were tested on a universal testing machine (HZ-1007C, Dongguan Lixian Instrument Technology Co., Ltd.) at a crosshead speed of 50 mm/min. The FTIR spectra were acquired with a Nicolet iS50-Nicolet RaptIR spectrometer (Thermo Scientific). Confocal White Laser Scanning Microscopy (Leica STELLARIS 5) was used to characterize the fluorescent electrodes. The optical transmittance of the materials was measured using a spectrophotometer (UH-5700, Hitachi). The vacuum laminator employed in the experiments was model JKD-LH18F (Shenzhen Jingke Machinery & Electronic Equipment Co., Ltd.). The applied alternating current electric fields were generated by a waveform generator (Keysight 33509B) coupled with high-voltage amplifiers (Aigtek ATA-2081 or EEL EEL1102.05). A luminance meter (Everfine SRC-200M) was used to determine the luminance, emission spectra, and CIE

color coordinates of the ACEL devices. The excitation and emission spectra were recorded using a photoluminescence spectrometer (Edinburgh Instruments FLS1000). The stretchable display was controlled by a microcontroller-based drive system (Arduino, STM32) integrated with a Bluetooth module, and powered by a 5 V lithium battery (Jiangmen Baofengli New Energy Technology Co., Ltd.).

Preparation of elastomers（PMV）and light-emitting layer

The high-permittivity elastomers were synthesized using monomers of MA and VEC mixed at predetermined monomer ratios (1:0.8, 1:0.5, 1:0.2, and 1:0). The crosslinker YC2511 and photoinitiator 184 were then added, accounting for 20 wt% and 1.5 wt% of the total monomer mass, respectively. The resulting precursor solution was poured into a custom-designed mold with a preset thickness and cured under irradiation from a broadband light source (covering the ultraviolet to visible range, peak wavelength: 420 nm, power: 50 W) for 15 minutes. For the light-emitting layer, ZnS:Cu phosphor was dispersed into the elastomer precursor at specified mass ratios prior to UV-visible curing. Unless otherwise specified, a monomer ratio of 1:0.8 and a phosphor content of 70 wt% were adopted as the standard formulation for the light-emitting layer.

Preparation of electrodes and ACEL devices, PMVSD

For AgNWs-based electrodes, AgNWs were first sprayed onto OTS-modified glass at an areal density of approximately 20 μg/cm². Subsequently, a PDMS layer (0.5 mm thick) was cured on the glass surface. The AgNWs were thereby transferred onto the PDMS surface, yielding the AgNWs-coated PDMS electrodes. Fluorescent

electrodes were fabricated by replacing the transparent PDMS with fluorescent PDMS. The latter was prepared by blending PDMS precursor solution with photoluminescent phosphor microparticles at the corresponding mass fractions. PMVSD devices were further assembled via lamination (60 kPa for 5 minutes), with the light-emitting layer sandwiched between two AgNWs electrodes.

The gel electrodes consisted of a conventional DES gel. Choline chloride and ethylene glycol were mixed at a 1:2 molar ratio and stirred at 80 °C to form a transparent DES. Monomer AA and DES were then mixed at a 50:50 mass ratio. Crosslinker PEGDA and photoinitiator 1173 were further added to the solution, accounting for 0.09 mol% and 0.5 mol% of the monomer, respectively. The mixture was poured into a transparent mold and exposed to light for 5 min to obtain the DES gel. For gel-based ACEL devices, the gel precursor was in situ cured on the surface of the light-emitting layers to form a robust interface. The gel layer had a thickness of 0.5 mm.

Preparation of strain sensor array and with 8×16 pixels

The sensor was fabricated by UV polymerization of BA and [BMIM]TFSI with a weight ratio of 4: 1 in a PTFE mold. The crosslinker and initiator were MBAA, 0.5 wt%, and I2959, 1 wt%, respectively.

The 8×16-pixel array display was fabricated using a procedure similar to that for PMVSD. However, the electrodes were patterned into parallel, equally spaced stripes via a shadow mask (with 8 or 16 channels). The front electrodes were fluorescent and composed of 16 stripes, where each color was assigned to four electrode stripes.

Through a layer-by-layer assembly process followed by lamination at 60 kPa for 5 min, the 100-μm-thick light-emitting layer and electrode layers were integrated to construct the 8*16-pixel devices.

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Declaration of interests

The authors declare no competing interests.

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