

Intrinsically stretchable and transparent conductors for next-generation soft optoelectronics [Invited]

Ji Su Kim,^{1,2,†} Jinhong Park,^{3,†} Dae Hwan Kim,^{4,5,†} Dogyun Kim,⁶ Dae-hyeong Kim,^{1,2,7} Dong Chan Kim,^{4,5,8} and Gi Doo Cha^{6,9} 

¹Center for Nanoparticle Research, Institute for Basic Science (IBS), Seoul 08826, Republic of Korea

²School of Chemical and Biological Engineering, Institute of Chemical Processes, Seoul National University, Seoul 08826, Republic of Korea

³The Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, TX, 77843, USA

⁴Department of Chemical, Biological, and Battery Engineering, Gachon University, Gyeonggi-do 13120, Republic of Korea

⁵Department of Semiconductor Engineering, Gachon University, Gyeonggi-do 13120, Republic of Korea

⁶Department of Systems Biotechnology, Chung-Ang University, Anseong 17546, Republic of Korea

⁷dkim98@snu.ac.kr

⁸dckim@gachon.ac.kr

⁹cgidoo@cau.ac.kr

[†]These authors equally contributed to this work.

Abstract: The rapid advancement of optoelectronic devices has intensified the demand for materials that are not only functional but also mechanically adaptable to human-centric applications. Conventional transparent conductors, such as indium tin oxide, offer excellent conductivity and optical transparency but fail under mechanical strain, limiting their use in flexible and stretchable systems. This limitation has motivated the development of intrinsically stretchable and transparent conductors capable of maintaining electrical and optical performance under large, repeated deformations. These conductors are typically fabricated by embedding conducting fillers within elastomeric matrices, providing skin-like mechanical compliance without the need for complex geometric patterning and enabling seamless integration with soft, irregular surfaces. Intrinsically stretchable and transparent conductors can be divided into metallic and non-metallic conductors. Each category offers distinct advantages but also presents trade-offs among conductivity, transparency, stretchability, and environmental stability. Therefore, careful material selection and design optimization are essential to balance these competing properties. This review summarizes recent progress in intrinsically stretchable and transparent conductors, with a focus on materials and design strategies for optimizing electrical, optical, and mechanical performance. We further highlight their integration into optoelectronic devices and discuss remaining challenges and potential solutions to advance next-generation soft optoelectronic technologies.

© 2025 Optica Publishing Group under the terms of the [Optica Open Access Publishing Agreement](#)

1. Introduction

Over the past several decades, optoelectronic devices have progressed from bulky components to highly integrated and compact systems with diverse functionalities [1–5]. However, the foundational materials of conventional optoelectronics, such as rigid glass substrates and indium tin oxide (ITO) transparent electrodes, possess intrinsic limitations that hinder their adaptation to human-centric technologies [6–9]. Their brittle and inflexible nature makes them susceptible to mechanical failure under deformation, rendering them incompatible with applications that

demand flexibility, stretchability, and mechanical resilience [10–13]. These constraints have driven a fundamental paradigm shift towards soft optoelectronics, a new class of devices designed to be deformable, adaptive, and robust under dynamic environments [14–16]. By enabling seamless integration with irregular, moving, and biological surfaces, this new generation of devices is opening transformative applications, including wearable energy-harvesting systems, on-skin displays, and implantable optical sensors [16–20].

For soft optoelectronic devices to function reliably, all components must retain performance under large and repeated deformations [21–24]. Among them, conductors, the core current-carrying elements of every optoelectronic system, face the most stringent requirements: they must combine mechanical stretchability with optical transparency to ensure efficient light transmission. In light-emitting diodes, high transmittance is required to facilitate efficient photon outcoupling and maintain uniform emission during operation and deformation. Similarly, transparency in photodetectors and photovoltaic devices is essential to ensure efficient delivery of incident light to reach photoactive layer for high responsivity and power conversion efficiency. For wearable and implantable optoelectronics, transparent conductors enable seamless interfacing with the tissues for accurate sensing, stimulation and therapeutic functions. However, simultaneously achieving high electrical conductivity, optical transparency, and mechanical stretchability is inherently challenging due to trade-offs between those properties [25–27]. For example, conventional transparent conductors such as ITO, while excellent in conductivity and transparency, are intrinsically brittle and fail even under mild strain.

Addressing this fundamental limitation requires innovative strategies that decouple the traditionally antagonistic properties of conductivity, transparency, and stretchability. Recent efforts have introduced significant advances through engineered nanocomposite architectures, hybrid metal-nanomaterial network, geometric design principles, and emerging fabrication methods, collectively pushing the boundaries of soft optoelectronics. These developments can be broadly classified into two main approaches: structural engineering and intrinsic material design. Structural approaches introduce deformability by patterning rigid conductors into serpentine, wrinkled, or origami/kirigami geometries [6,28,29]. While effective, these methods add design complexity and may limit conductivity, scalability, and spatial resolution. In contrast, intrinsically stretchable conductors, typically implemented by embedding conducting fillers within elastomeric matrices, exhibit tissue-like mechanical compliance with electrical functionality and optical transparency, without relying on complex geometries [6,30,31]. This intrinsic approach minimizes mechanical mismatch with soft surfaces and enhances cyclic durability, making it highly promising for next-generation wearable and implantable optoelectronics [32–35].

Intrinsically stretchable and transparent conductors can be broadly classified into two categories based on the type of conductive fillers: metallic and non-metallic (Fig. 1(a)). Metallic conductors include ultrathin metals, metal nanomaterials, and liquid metals. These systems generally provide superior electrical conductivity (10^5 – 10^7 S m⁻¹) [36–38] but often require microstructural engineering, such as patterned meshes, to improve optical uniformity and strain tolerance (5–30%, extendable >100% with mesh design) (Fig. 1(b)) [6,25,39–42]. Non-metallic conductors, including carbon allotropes such as graphene and carbon nanotubes (CNTs), conducting polymers (e.g., poly(3,4-ethylenedioxythiophene) polystyrene sulfonate, PEDOT:PSS), and ionic conductors (e.g., ion gels and hydrogels), offer exceptional mechanical compliance, softness and optical clarity (transmittance >90%) [43–45] but their electrical conductivity (< 10^5 S m⁻¹) remains relatively lower than that of metallic counterparts (Fig. 1(c)) [7,40,44,46–50]. These contrasting characteristics highlight the need for careful engineering to balance conductivity, stretchability, transparency, environmental stability, and interfacial compatibility when designing conductors for soft optoelectronic devices.

In order to achieve the targeted compromise between conductivity, stretchability, transparency, and stability, the careful selection and engineering of the properties for stretchable conducting

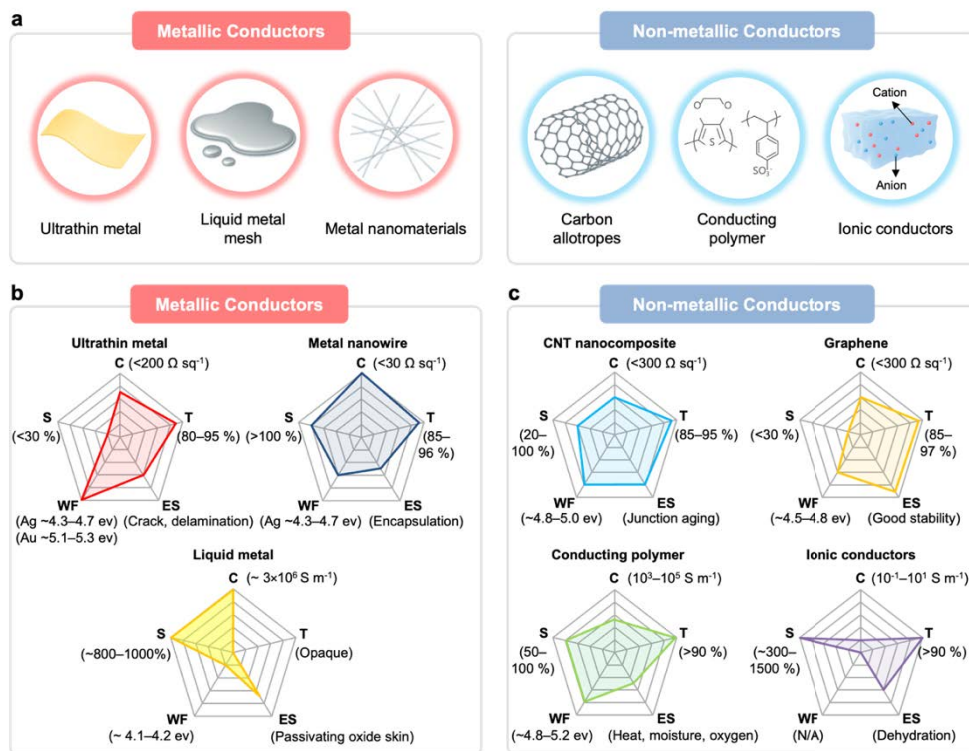


Fig. 1. Intrinsically stretchable and transparent conductors for soft optoelectronics. **a**, Classification of intrinsically stretchable and transparent conductors into metallic and non-metallic categories, with representative structural configurations. **b,c**, Comparative evaluation of metallic (b) and non-metallic (c) conductors across five key parameters: conductivity (C), stretchability (S), transparency (T), environmental stability (ES), and work function (WF). The radial axes are intended to illustrate relative property trends rather than absolute values. Notably, liquid metals are intrinsically opaque but can be engineered for optical transparency through geometric design. Ionic conductors do not possess a defined work function.

material is essential (Fig. 2). Each type of conductor has own distinctive advantages and limitations that must be considered in conjunction with other engineering options. Therefore, it is essential to prioritize specific properties, and synergistically combine complementary materials, such as hybrid electrodes, to maximize their benefits for optimizing desired applications. For instance, light-emitting displays demand high transparency and smooth surface of electrodes, implantable biosensors rely on softness and biocompatibility, and energy-harvesting devices emphasize long-term stability. In this context, careful evaluation provides a practical guideline for selecting conductors, ensuring that material choices are strategically aligned with the functional requirements of diverse soft optoelectronic systems.

This review aims to provide a comprehensive overview of intrinsically stretchable and transparent conductors for soft optoelectronic applications. We first discuss the materials, structural designs, and fundamental design principles that govern their performance, followed by strategies to achieve the demanding balance of high electrical conductivity, optical transparency, and mechanical stretchability. By systematically classifying conductors into metallic and non-metallic categories, we highlight recent breakthroughs and emerging trends that are pushing the performance limits of soft optoelectronic systems. Finally, we outline the key challenges,

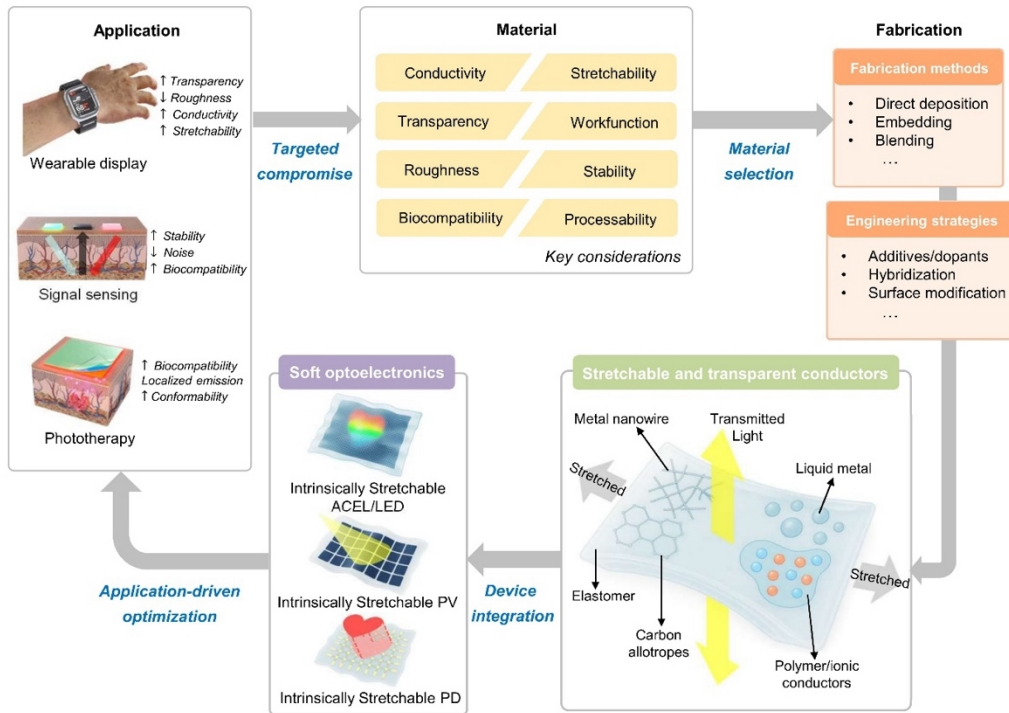


Fig. 2. Schematic overview illustrating how application requirements guide material selection, fabrication strategies, and device integration in the design of stretchable and transparent conductors for soft optoelectronic systems.

such as improving environmental stability, enabling large-scale processability, and ensuring compatibility with scalable manufacturing, which must be addressed to fully realize the potential of human-centric optoelectronic devices, including stretchable light-emitting diodes (LEDs), photodetectors, and photovoltaics.

2. Metallic stretchable transparent conductors

2.1. Ultrathin films

Ultrathin metallic films (Fig. 3(a)) represent one of the earliest strategies for transparent and stretchable conductors, owing to their intrinsically high conductivity and optical transparency. Reducing metals to a nanometer-scale thickness is the simplest route to implement transparent and stretchable electrodes. At this scale, the films retain the intrinsic conductivity of bulk metals while suppressing optical absorption, yielding electrodes with high transparency and low sheet resistance.

The ultrathin film morphology and its mechanical reliability are closely related with the intrinsic properties of the constituent metals [51]. Metals with low surface diffusion barriers and moderate cohesive energy, such as Ag and Au, undergo Volmer-Weber growth, forming dense islands that coalesce into continuous percolation networks. When integrated with elastomeric substrates, these films spontaneously fracture into island-like domains interconnected by percolating cracks (Fig. 3(a)). The resulting island-bridge network accommodates tensile strain through reversible crack opening and closure, thereby preserving electrical continuity during deformation. However, the uncontrolled propagation of cracks could lead to electrical failure under repeated deformation.

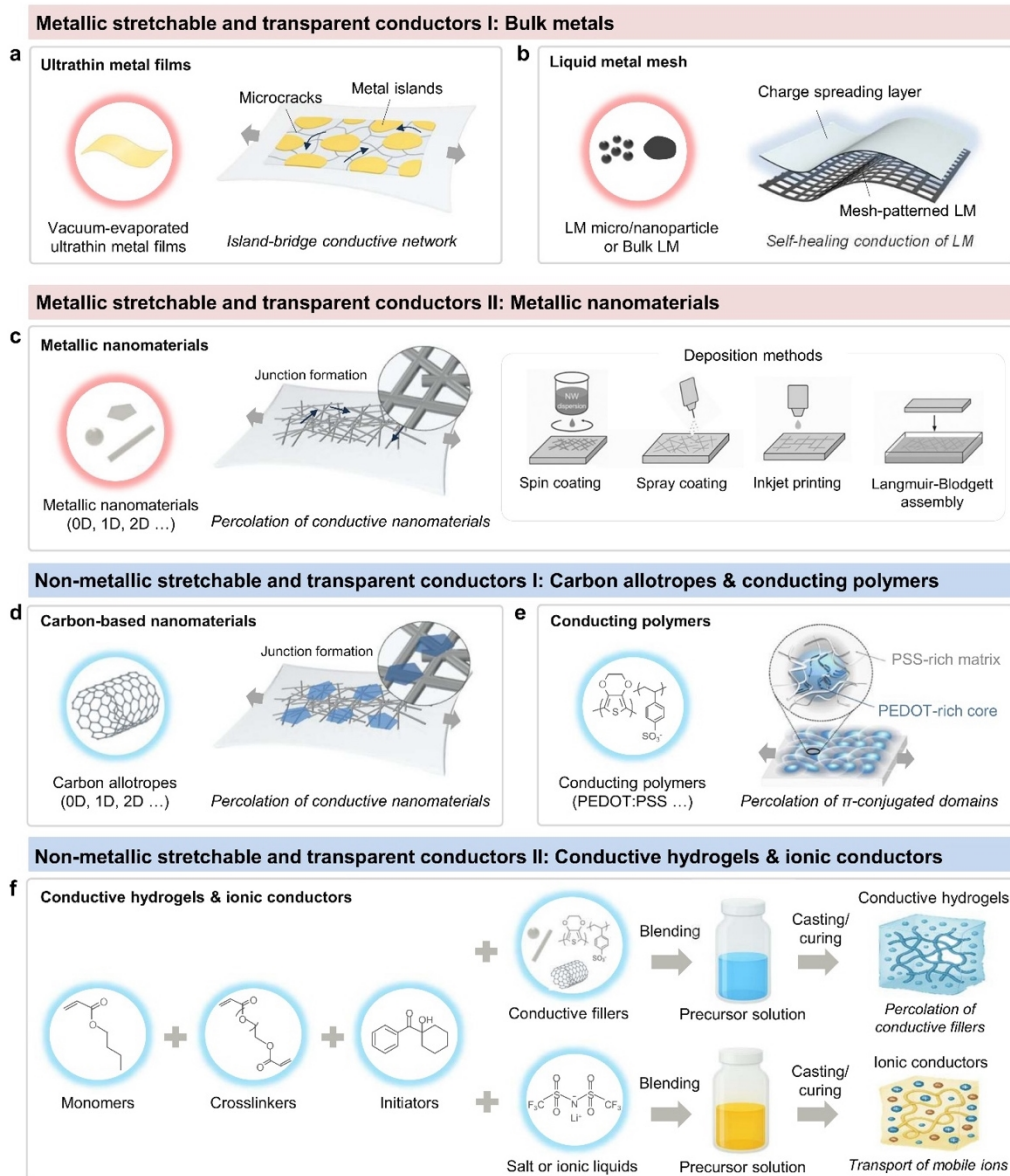


Fig. 3. Material design strategies for stretchable and transparent conductors. **a**, Schematic of ultrathin metallic films (Ag, Au, Cu) on elastomer substrates, forming island-bridge networks. **b**, Schematic of liquid metal (LM microparticle and bulk LM) mesh electrodes integrated with charge spreading layer. **c**, Schematic of percolating AgNW/NP networks embedded in elastomer substrates (left). Schematic of deposition strategies for AgNW networks, including spin coating, spray coating, inkjet printing, and Langmuir-Blodgett assembly (right). **d**, Schematic of percolated carbon networks embedded in elastomer substrates. **e**, Schematic of nanostructured PEDOT:PSS films on elastomer substrates. Reproduced with permission from Ref. [111], Copyright 2019, American Chemical Society. **f**, Synthesis process of the hydrogel and ionic conductor.

In contrast, metals, such as Cu and Al, with higher surface diffusion barriers and stronger substrate interactions, form more rough and discontinuous films with reduced conductive networks. Their high oxidation tendency further compromises electrical and mechanical stability. Other intrinsic properties, including work function, optical transparency, and adhesion energy, are also important factors that lead to distinct electrode morphology and performance across different metals.

In addition to choosing appropriate metals, two complementary strategies including interfacial engineering and deposition control are used to achieve continuous, mechanically stable ultrathin films. Seed or adhesion layers, such as transition metal oxides or organic anchoring molecules, stabilize nucleation, suppress dewetting, and strengthen interfacial bonding [52–54]. Lee et al. [55] demonstrated that the bottom oxide layer significantly impacts the performance of oxide–metal–oxide electrodes. In particular, V_2O_5 enabled better uniform Au nucleation than MoO_3 due to its higher surface energy and stronger interfacial bonding, resulting in continuous films (Fig. 4(a)). XPS analysis showed enhanced charge transfer at the V_2O_5 /Au interface, correlating with the superior film continuity. The electrodes exhibited stable resistance down to 1 mm bending radii and strains exceeding 40% (Fig. 4(e)). Similarly, Qin et al. [56] found that amino acid–based adhesion layers, rich in amine groups, facilitate the adhesion of Ag atoms during evaporation and enable the formation of continuous films as thin as ~ 7 nm (Fig. 4(b)). The electrodes achieved a transmittance of $\sim 98\%$ and a sheet resistance of $\sim 8.7 \Omega \text{ sq}^{-1}$, while maintaining stable conductivity after 500 cycles at 100% strain, thereby outperforming bare Ag films that failed rapidly (Fig. 4(f)).

The precise control of deposition [36] has also proven effective for defining the microstructure and stretchability of ultrathin metallic electrodes. Oh et al. [57] optimized Ag deposition conditions for intrinsically stretchable OLED cathodes, identifying three distinct growth regimes following the Volmer–Weber mechanism: discrete islands with poor conduction, partially connected networks with strain tolerance, and continuous films that are highly conductive yet brittle (Figs. 4(c) and (d)). By adjusting evaporation rate and thickness (Ag 60 nm at $1 \text{ \AA s}^{-1}$), they obtained a morphology that balanced connectivity with crack-mediated flexibility. The optimized electrodes exhibited a sheet resistance of $\sim 6 \Omega \text{ sq}^{-1}$ and a luminance exceeding 2300 cd m^{-2} , with minimal resistance change even under 70% strain. Conductivity was maintained over 200 cycles at 40% strain (Fig. 4(g)), enabled by crack opening and closure within percolated Ag grains (Fig. 4(h)). This study highlights that careful control of deposition parameters, together with interfacial stabilization, allows ultrathin metal electrodes to balance conductivity, transparency, and stretchability.

2.2. Liquid metal mesh

Liquid metals (LMs), such as eutectic gallium-indium (EGaIn) and Galinstan, are intrinsically stretchable conductors (Fig. 3(b)) [58–60]. Unlike solid metals, which fracture and lose conductivity under strain, their fluidic nature allows for deformation without cracking, sustaining conduction even at strains beyond 100%. Their main drawback, however, is opacity, limiting direct use as transparent electrodes. To overcome this, LMs are patterned [61] into defined geometries, such as mesh, grid, or serpentine designs, where transparency is achieved through open apertures while conduction is preserved through narrow LM lines. These meshes are often combined with charge-spreading layers, including conducting polymers or oxides, to distribute current evenly and reduce local crowding.

Various patterning strategies have been developed to realize transparent LM meshes. Inkjet printing directly deposits LM inks with high spatial precision, eliminating the need for masks or etching [62,63]. Fang et al. [64] demonstrated micrometer-scale electrodes with $\sim 90\%$ optical transmittance at 550 nm and a sheet resistance of only a few ohms per square (Fig. 4(i)). The

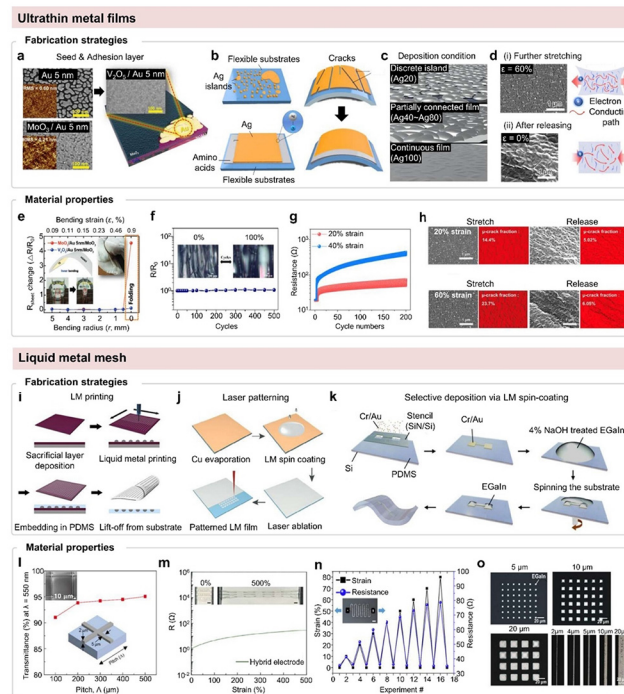


Fig. 4. Metallic stretchable transparent conductors based on ultrathin film and liquid metal meshes. **a**, FE-SEM and AFM images of Au films deposited with or without seed layers (MoO_3 , V_2O_5), showing surface morphologies and roughness values. Reproduced with permission from Ref. [55], Copyright 2023, Wiley-VCH. **b**, Schematic of nucleation and bending of the bare Ag electrodes and amino acid/Ag electrodes. Reproduced with permission from Ref. [56], Copyright 2024, Springer Nature. **c,d**, Schematic of intrinsically stretchable Ag cathode surface morphology at different thicknesses, with SEM images under 60% strain. Reproduced with permission from Ref. [57], Copyright 2024, Springer Nature. **e**, Resistance change of oxide-metal-oxide electrodes with MoO_3 and V_2O_5 seed layers under different bending radii and uniaxial strains, respectively. Reproduced with permission from Ref. [55], Copyright 2023, Wiley-VCH. **f**, Resistance change of the NOA63/amino acid/Ag/HATCN electrodes under repetitive stretching cycles. Inset shows optical images of the microstructures. Reproduced with permission from Ref. [56], Copyright 2024, Springer Nature. **g**, Resistance change of the Ag (60 nm, $1 \text{ \AA s}^{-1}$) cathodes during cyclic stretching at 20% and 40% strain. Reproduced with permission from Ref. [57], Copyright 2024, Springer Nature. **h**, SEM images of Ag cathodes after stretching and release, showing crack-mediated conduction. Reproduced with permission from Ref. [57], Copyright 2024, Springer Nature. **i**, Schematic of LM grid electrodes fabricated by inkjet printing. Reproduced with permission from Ref. [64], Copyright 2022, Elsevier B.V. **j**, Schematic of LM electrodes fabricated by laser ablation. Reproduced with permission from Ref. [66], Copyright 2025, Wiley-VCH. **k**, Schematic of LM patterning using spin coating with selective wetting. Reproduced with permission from Ref. [70], Copyright 2021, American Chemical Society. **l**, Optical transmittance of LM grid electrodes as a function of pitch. Inset shows schematic of the simulated structure and SEM image of embedded EGaln grids. Reproduced with permission from Ref. [64], Copyright 2022, Elsevier B.V. **m**, Resistance-strain characteristics of hybrid LM-INC electrodes. Inset shows optical images of hybrid transparent electrodes under uniaxial tensile deformation. Scale bars: 3 mm. Reproduced with permission from Ref. [66], Copyright 2025, Wiley-VCH. **n**, Resistance change of patterned LM electrodes under tensile cycling. Inset shows the optical image of the sample. Scale bar: $100 \mu\text{m}$. Reproduced with permission from Ref. [70], Copyright 2021, American Chemical Society. **o**, Various EGaln patterns obtained by the proposed process. Patterned EGaln square dot arrays with width from 5 to $20 \mu\text{m}$ and line patterns with width from 2 to $20 \mu\text{m}$. Reproduced with permission from Ref. [70], Copyright 2021, American Chemical Society.

electrodes remained conductive under strains exceeding 200%, while optical simulations further quantified the dependence of transmittance on mesh pitch (Fig. 4 (l)).

Laser ablation [65] offers an alternative approach, in which a continuous LM layer is deposited on an adhesion layer (e.g., Cu or Au) and subsequently patterned by laser irradiation. Sun et al. [66] fabricated LM meshes with linewidths down to tens of micrometers, achieving ultralow sheet resistance and high transparency (Fig. 4(j)). Integration with an ionic nanocomposite overlayer further enhanced charge distribution. The resulting electrodes showed only a moderate increase in resistance from $1.2\ \Omega$ at 0% strain to $25.1\ \Omega$ at 500% strain, while maintaining >96% transmittance in the emitting region (Fig. 4 (m)).

Spin-coating with selective wetting [67–69] has also been explored for LM patterning. In this approach [70], an adhesion metal is pre-patterned (e.g., via stencil mask), followed by LM spin-coating (Fig. 4(k)). The LM selectively wets the patterned metal regions, while the excess material is removed during the spin coating process. This method enables resolution down to $\sim 2\ \mu\text{m}$ and diverse pattern formation on elastomer substrates (Fig. 4(o)), maintaining conductivity under repeated stretching (Fig. 4(n)).

2.3. Metal nanomaterials

Metal nanomaterials [71,72], particularly silver nanowires (AgNWs) and metallic nanoparticles (NPs), represent one of the most widely adopted platforms for stretchable transparent electrodes (Fig. 3(c)). High-aspect-ratio nanowires form percolating networks with low thresholds, simultaneously achieving high conductivity and optical transparency. Nanoparticles can fill the gaps between nanowires and strengthen their junctions, creating additional conduction pathways and improving percolation network. However, excessive loading can lower transmittance. Under strain, nanowire networks accommodate deformation through rotation, junction sliding, and reorientation, delaying electrical failure. Embedding these structures within elastomer matrices further reduces stress at the filler–polymer interface, preventing delamination and ensuring more stable electrical performance under large and repeated strains.

Several deposition strategies [73] have been employed to assemble such networks (Fig. 3(c)), including spin coating, spray coating, inkjet printing, and Langmuir-Blodgett assembly. While these methods differ in scalability and patterning capability, their shared goal is to form percolating networks just above the percolation threshold, ensuring low sheet resistance without sacrificing transparency or stretchability.

Based on these deposition methods, three fabrication strategies have been widely applied. Elastomer embedding [74] involves depositing nanowire film followed by overcoating with curable elastomers such as polyurethane acrylate (PUA), yielding partially embedded networks with high transparency (> 80% at 550 nm), low sheet resistance ($\sim 15\ \Omega\ \text{sq}^{-1}$), and excellent cycling durability (Fig. 5(a)). Polymer blending [75] disperses nanowires or nanoparticles directly into stretchable matrices, producing composites that preserve conductivity even at elongations of 700% (Fig. 5(b)). Self-assembly [76] leverages spontaneous organization of nanomaterials into percolating networks, often yielding partially embedded morphologies that dissipate strain and sustain electrical connectivity under deformations (Fig. 5(c)).

To further enhance performance, several engineering strategies address the intrinsic weaknesses of percolation networks. Junction welding reduces high contact resistance between nanowires. Du et al. [77] introduced a nanowelding process combining Xe-lamp irradiation and pressing process that fuses nanowire junctions into continuous pathways (Fig. 5(d)). This reduced sheet resistance to $\sim 26.5\ \Omega\ \text{sq}^{-1}$ at $\sim 95\%$ transmittance and enabled electrodes to withstand over 1000 bending cycles without degradation (Figs. 5 (g) and h). Jung et al. [78] demonstrated that thiol-based modification promoted adaptive nanowire reorganization under strain, minimizing resistance changes during repeated formations (Figs. 5(e), (i) and (j)). Hybrid fillers provide complementary conduction pathways. Hwang et al. [79] reported AgNW–SWCNT hybrid

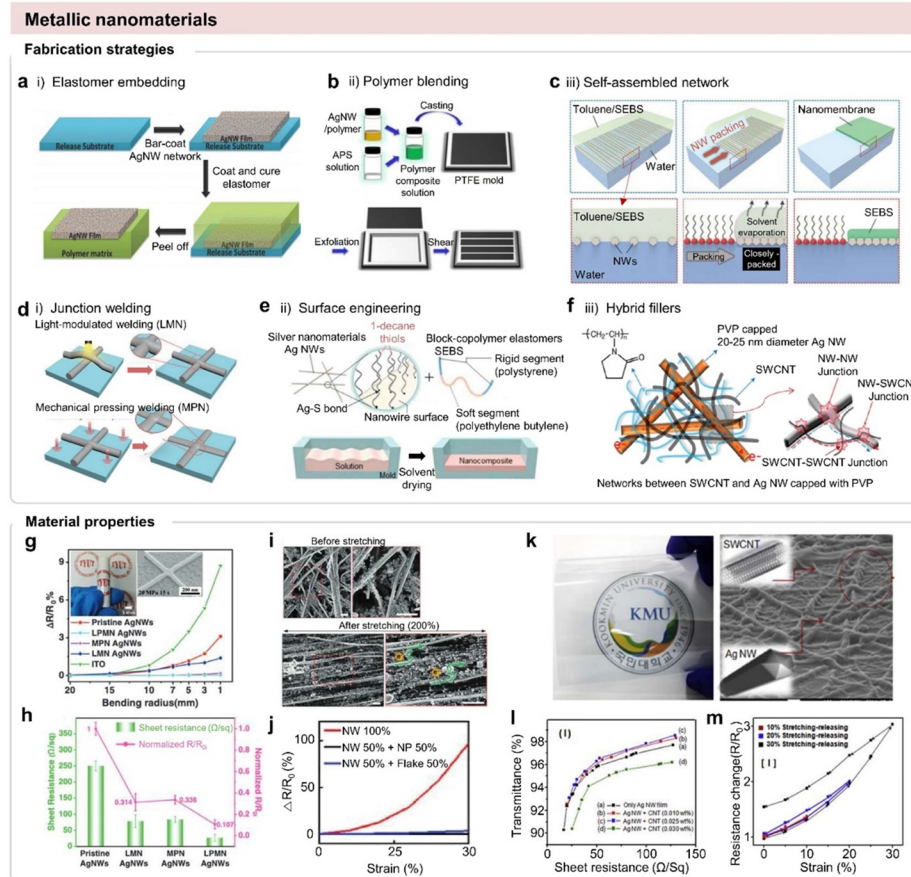


Fig. 5. Metallic stretchable transparent conductors based on metal nanomaterials.

a. Schematic of elastomer embedding process for AgNW-PUA composite electrodes. Reproduced with permission from Ref. [74], Copyright 2013, Springer Nature. **b.** Schematic of polymer blending strategy for AgNW composites. Reproduced with permission from Ref. [75], Copyright 2020, Springer Nature. **c.** Schematic of self-assembled nanomembrane fabrication via float assembly. Reproduced with permission from Ref. [76], Copyright 2021, The American Association for the Advancement of Science. **d.** Schematic illustration of nanowire junction welding by light-modulation (LMN) and mechanical pressing (MPN). Reproduced with permission from Ref. [77], Copyright 2024, Wiley-VCH. **e.** Schematic illustration that shows composition and fabrication of AgNW-SEBS nanocomposite using solution casting and drying. Reproduced with permission from Ref. [78], Copyright 2022, Wiley-VCH. **f.** Schematic of the Ag NW-SWCNT hybrid networks showing conduction pathways. Reproduced with permission from Ref. [79], Copyright 2018, Elsevier B.V. **g,h.** Resistance change of pristine, LMN, MPN, and LPMN treated AgNW electrodes compared with ITO electrodes under bending (top). Inset shows bent transparent electrode (left) and SEM image of welded junctions (right). Bottom shows sheet resistance and normalized R/R_0 of AgNWs with different treatments. Reproduced with permission from Ref. [77], Copyright 2024, Wiley-VCH. **i,j.** SEM images of AgNW-NP nanocomposites before (top) and after (middle) 200% stretching. Bottom shows relative resistance variation under 50% strain. Scale bars: 1 μm . Reproduced with permission from Ref. [78], Copyright 2022, Wiley-VCH. **k.** Photograph and FESEM image of AgNW-SWCNT hybrid composite layer on TPU. **l.** Transmittance-resistance relationship of the hybrid networks. **m.** Hysteresis curves of hybrid film heaters under tensile strain of 10-30%. **k,l,m.** Reproduced with permission from Ref. [79], Copyright 2018, Elsevier B.V.

electrodes in which CNTs bridged nanowire junctions and reinforced the network, achieving a $\sim 95\%$ transmittance, a sheet resistance of $\sim 30 \Omega \text{ sq}^{-1}$, and mechanical stability under a strain of $\sim 20\%$ (Figs. 5(f), (k), (l) and (m)).

3. Non-metallic conductors

3.1. Carbon allotropes

Carbon allotropes (Fig. 3(d)) [80–82], such as graphene and carbon nanotubes (CNT), are attractive candidates for transparent and stretchable conductors due to their atomic thickness, high conductivity, and optical transparency. However, pristine graphene films or CNT sheets are inherently rigid and tend to crack or lose connectivity under strain, limiting their application in deformable systems. To overcome these drawbacks, structural strategies have been developed to reorganize carbon networks under strain and preserve electrical pathways.

One effective approach is intercalation and stacking, where additional carbon nanostructures are inserted between graphene layers to bridge cracks. Liu et al. [83] demonstrated multilayer graphene/graphene-scroll (MGG) electrodes in which graphene scrolls intercalated within the stacks stabilized electrical conduction during stretching (Fig. 6(a)). While introducing CNT or graphene-scroll interlayers slightly reduced transmittance, the MGG electrodes maintained $\sim 90\%$ transparency with low sheet resistance and exhibited minimal resistance change during cyclic stretching (Fig. 6(c)), highlighting the robustness of intercalation strategies across fractured domains.

Beyond stacking, surface modification is another strategy to enhance the stretchability of carbon-based electrodes. Zhou et al. [84] reported two-dimensional contact stretchable electrodes (TCSEs) formed by integrating graphene scrolls with AgNWs, where the scrolls bridged cracks and reinforced interfacial adhesion (Fig. 6(b)). These electrodes maintained $> 80\%$ transmittance while suppressing resistance increase under strain, as confirmed by AFM images that showed scrolls filling fractured domains (Fig. 6(d)). Han et al. [85] introduced a complementary process combining cold-pressing (CP) with solvent-vapor-assisted lamination to planarize AgNW/graphene composites and reinforce cathode surface (Fig. 6(b)). The CP + thermally welded electrodes exhibited significantly lower $\Delta R/R$ values under strain compared to untreated controls (Fig. 6(e)).

3.2. Conducting polymers

Conducting polymers (Fig. 3(e)), particularly PEDOT:PSS, offer unique advantages for soft optoelectronics due to their solution processability and optical transparency. However, pristine PEDOT:PSS films are brittle and exhibit limited conductivity, requiring additional material engineering to meet the demands of deformable devices. Three complementary strategies have been widely adopted to overcome these limitations.

The first approach introduces additives and secondary dopants [86–88] such as ethylene glycol, DMSO, and ionic liquids, which weaken Coulombic interactions between PEDOT and PSS, thereby promoting conformational changes of PEDOT chains and enhancing conductivity and flexibility. Wang et al. [89] introduced ionic liquid-based STEC enhancers into PEDOT:PSS, which softened the PSS-rich domains while promoting PEDOT aggregation and chain alignment under strain (Fig. 6(f)). The films reached $\sim 3100 \text{ S cm}^{-1}$ at 0% strain and $> 4100 \text{ S cm}^{-1}$ at 100% strain, maintaining exceptional stress–strain behavior and durability under cyclic stretching (Fig. 6(j)). More recently [90], the zwitterionic additive ION E was applied in intrinsically stretchable OPVs, where it reinforced interfacial adhesion with polyurethane, delaying crack initiation and propagation (Figs. 6 (g) and (k)).

The second strategy relies on acid post-treatment [91] to remove excess insulating PSS and improve PEDOT crystallinity. For example [92], triblock copolymer (Pluronic P123) was blended

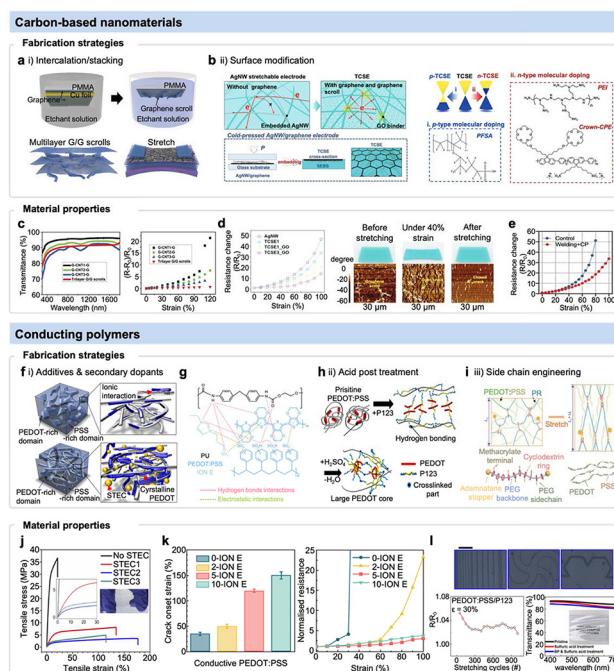


Fig. 6. Non-metallic stretchable transparent conductors based on carbon allotropes and conducting polymers. **a**, Schematic of multilayer graphene/graphene-scroll (MGG) electrode fabrication. Reproduced with permission from Ref. [83], Copyright 2017, The American Association for the Advancement of Science. **b**, Schematic of pristine AgNW and 2D-contact stretchable electrodes (TCSEs, top left). Materials used for molecular doping of TCSEs (right). Reproduced with permission from Ref. [84], Copyright 2022, Wiley-VCH. Cold-pressing method for reducing surface roughness of AgNW/graphene electrodes (bottom left). Reproduced with permission from Ref. [85], Copyright 2023, Wiley-VCH. **c**, Optical transmittances (left) and normalized resistance change under strain (right) of G-CNT-G and trilayer MGG electrodes. Reproduced with permission from Ref. [83], Copyright 2017, The American Association for the Advancement of Science. **d**, Resistance change of AgNW, TCSE, and TCSE with multilayer graphene before and after graphene oxide (GO) treatment (left). AFM phase images of graphene on SEBS under 40% strain (right). Reproduced with permission from Ref. [84], Copyright 2022, Wiley-VCH. **e**, Cyclic stretching tests (40% strain) of the TCSEs without treatment (control) and after thermal welding and cold-pressing. Reproduced with permission from Ref. [85], Copyright 2023, Wiley-VCH. **f**, Schematic morphology of pristine PEDOT:PSS versus stretchable PEDOT films with STEC enhancers. Reproduced with permission from Ref. [89], Copyright 2017, The American Association for the Advancement of Science. **g**, Schematic of interfacial interactions between PEDOT:PSS and polyurethane substrates. Reproduced with permission from Ref. [90], Copyright 2024, Springer Nature. **h**, Schematic of PEDOT:PSS modification with P123 and sulfuric acid post-treatment. Reproduced with permission from Ref. [92], Copyright 2018, American Chemical Society. **i**, Schematic of topological supramolecular network based on polyrotaxane. Reproduced with permission from Ref. [93], Copyright 2022, The American Association for the Advancement of Science. **j**, Stress-strain characteristics of freestanding PEDOT/STEC films. Reproduced with permission from Ref. [89], Copyright 2017, American Association for the Advancement of Science. **k**, Crack onset strain (left) and normalized resistance during elongation (right) of PU/conductive PEDOT:PSS films with varying ION E contents. Reproduced with permission from Ref. [90], Copyright 2024, Springer Nature. **l**, Optical images of patterned PEDOT:PSS films (top). Resistance change under 30% strain during cyclic test (bottom left). Transmittance spectra of PEDOT:PSS films on SEBS substrates (bottom right). Scale bars: 200 μm . Reproduced with permission from Ref. [94], Copyright 2024, Springer Nature.

into PEDOT:PSS and subsequently treated with H_2SO_4 (Fig. 6 (h)). P123 acts as a secondary dopant and a soft matrix, while the acid enhances the PEDOT crystallinity. The resulting electrodes exhibit $\approx 89\%$ transmittance, conductivity of $\sim 1700 \text{ S cm}^{-1}$, and stretchability with $\Delta R/R \approx 4\%$ at 40% strain over 1000 cycles.

The third route is side-chain and topological engineering, which embeds stretchability at the molecular level. Jiang et al. [93] introduced a polyrotaxane-based supramolecular additive (TopoE), in which PEG backbones and sliding cyclodextrin rings prevented crystallization while providing conformational freedom (Fig. 6(i)). This design produced a topological network that decoupled conductivity and stretchability, enabling films with $\sim 2700 \text{ S cm}^{-1}$ conductivity and crack-free elongation up to 150%.

Finally, water-based direct photopatterning has been suggested for integration with high-resolution stretchable devices. A PEDOT:PSS with [94] P123 and benzophenone enabled positive liftoff in water, producing $\sim 20 \mu\text{m}$ patterns that retained transparency and low resistance under strain (Fig. 6 (l)).

3.3. Hydrogel

The hydrogel is formed from a mixture of monomer, crosslinker, and initiator, which is subsequently cured into a gel state on external stimulation (Fig. 3(f)). The resulting water-swallowable polymeric network, established via physical/chemical crosslinking, have distinctive characteristics: ultrahigh soft modulus. This mechanical property minimizes mechanical mismatch with biological tissues, enabling intimate contact with human tissues for bio-applications. Furthermore, the intrinsic deformability of the hydrogel naturally provides stretchability. However, pristine hydrogels typically suffer from low conductivity and opaque properties, necessitating further material engineering strategies to implement transparent and conductive systems (Figs. 7(a) and (b)).

Ji et al. [95] reported transparent conductive hydrogels synthesized from acrylamide, polyethylene glycol, and carboxymethyl cellulose, with alkaline salts (e.g., NaCl, KCl, LiCl; Fig. 7(a)). Such alkaline salts offer ionic conductivity, mechanical toughness, and excellent optical clarity. Among them, hydrogel with NaCl exhibits the most balanced characteristics required for transparent hydrogel sensors, especially for transparency exceeding 99%, and stable resistance under strains up to 400% (Figs. 7(c) and (d)). Consequently, the hydrogel demonstrated sensitive detection human motions ranging from large-scale gestures to subtle physiological signals (Fig. 7(e)). The optimal ion selection additionally contributes to the self-healing ability and tissue adhesion, which underscores the promise of ion-based engineering strategies for hydrogel sensors.

A supramolecular engineering [96] strategy was employed for constructing hydrogel sensors. Cyclodextrin-based hydrogel accompanies topological crosslinking through host-guest reactions by ring structures, and the resulting slide-ring gels have mobile crosslinking points that allow sliding when external strain is applied (Figs. 7(b) and (f)). This effect imparts ultrahigh stretchability to the hydrogel, while the polymeric network inherently features conductivity and transparency. Furthermore, supramolecular inclusion complex confers passive-cooling feature based on light shielding ability (Fig. 7 (g)), while abundant hydroxyl and amine moieties on the polymer endows radical scavenging capability (Fig. 7 (h)). These multifunctionality renders the hydrogel with human-friendly characteristics, broadening its applicability in bioelectronic applications.

3.4. Ionic conductors

Ionic conductors share many structural similarities with hydrogel conductors, differing primarily in the types of solvent used (Fig. 3(f)). Unlike electronic conductors, which rely on delocalized electrons, ionic conductors transport charges through the migration of mobile ions within a

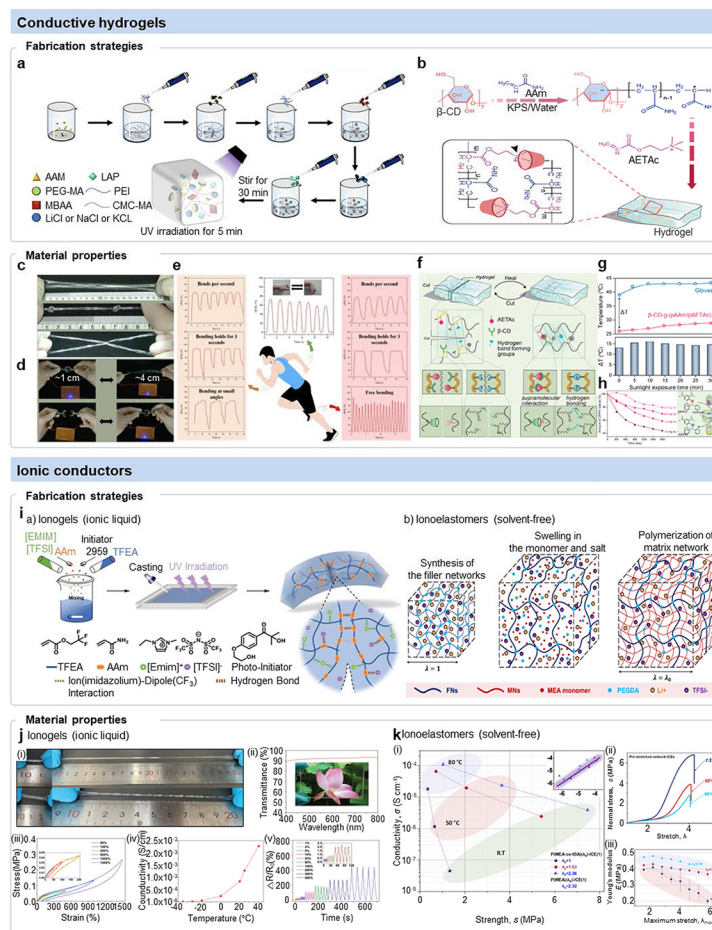


Fig. 7. Non-metallic stretchable transparent conductors based on hydrogels and ionic conductors. **a**, Synthesis process of the ion-mediated hydrogel. Reproduced with permission. [95], Copyright 2025, American Chemical Society. **b**, Synthesis process of the supramolecular grafting hydrogel. Reproduced with permission. [96], Copyright 2024, Wiley-VCH. **c**, Stretchability of the ion-mediated hydrogel. **d**, Demonstration of the conductivity for ion-mediated hydrogel under various deformation. **e**, Measurement of various human motions by ion-mediated hydrogel. Reproduced with permission. [95], Copyright 2025, American Chemical Society. **f**, Change of the hydrogel polymer network at the molecular level during grafting. **g**, Passive-cooling characterization of the supramolecular grafting hydrogel. **h**, Radical-scavenging characterization of the supramolecular grafting hydrogel. Reproduced with permission. [96], Copyright 2024, Wiley-VCH. **i**, Schematic illustration of the fabrication process of ionogels (left). Reproduced with permission. [98], Copyright 2021, Wiley-VCH. Schematic illustration of the representative synthesis steps of ICEs based on multi-network architectures (right). Reproduced with permission. [101], Copyright 2025, Springer Nature. **j**, Key characteristics of ionogels: (i) photographs of ionogels before and after stretching without (top) and with (bottom) twisting; (ii) transmittance spectra of ionogel. The inset shows the photograph of the ionogel over a flower image; (iii) cyclic stress–strain curves under strains ranging from 50% to 1500%. The inset highlights the 0–200% strain range; (iv) ionic conductivity as a function of temperature; and (v) relative resistance under applied strains from 1% to 400%. The inset highlights the 0–120% strain range. Reproduced with permission. [98], Copyright 2021, Wiley-VCH. **k**, Key characteristics of ICEs: (i) ionic conductivity as a function of stress at break (strength, s) measured at different temperature; (ii) stress–strain curves; and (iii) Young's modulus at different applied strains. Reproduced with permission. [102], Copyright 2025, Springer Nature.

polymeric or gel-like medium. This ion-based mechanism decouples conductivity from rigid electronic networks, enabling the design of materials with ultrahigh stretchability, optical clarity, and mechanical softness [47,97]. Broadly, ionic conductors can be categorized into ionic liquid-based ionogels and solvent-free ionically conductive elastomers (ICEs), each offering distinct advantages and challenges (Figs. 7(i), (j) and (k)).

Ionogels are typically fabricated by mixing monomers, crosslinkers, and photoinitiators with an ionic liquid, followed by UV or thermal curing to form a solid-like gel while retaining optical transparency. The ionic liquid provides intrinsic ionic conductivity, negligible volatility, and thermal stability, whereas the polymer network imparts mechanical integrity and processability (Fig. 7(i), (a)) [98]. Typical ionogels generally exhibit conductivities on the order of 10^{-4} – 10^{-3} S cm^{-1} at room temperature, optical transparency exceeding 90%, and elongations often greater than 1000%, depending on the polymer composition (Fig. 7(j)) [98]. However, conventional ionogels are mechanically weak, with a low Young's modulus (< 0.1 MPa) and low fracture strength (< 1 MPa) [99–101]. Recent advances, such as phase-separated architecture, supramolecular crosslinking, and multiple-network strategies, have significantly enhanced their toughness, elasticity, and fatigue resistance without sacrificing transparency and conductivity [101].

To address stability issues inherent to liquid-containing systems, such as leakage and long-term evaporation, solvent-free ICEs have been developed (Fig. 7(i), (b)) [102,103]. In these systems, lithium salts (e.g., LiTFSI) are directly incorporated into elastomeric polymer networks, eliminating volatile solvents while preserving ionic conductivity. A common fabrication strategy involves copolymerizing acrylate-based monomers with crosslinkers and lithium salts under UV curing. More advanced strategies employ multiple network elastomer (MNE) architectures, which integrate a tough primary network with a soft, low- T_g secondary network. This design balances mechanical robustness with ion transport, enabling simultaneous gains in strength, toughness, and ionic conductivity. Representative ICE prepared via MNE architectures exhibit ionic conductivity on the order of 10^{-6} S cm^{-1} at room temperature, fracture strength approaching 7 MPa, and stretchability up to 400–500% (Fig. 7(k)) [102]. While mechanically more robust than ionogels, ICEs still face trade-offs: enhancing toughness via viscoelastic energy dissipation can reduce fatigue resistance and limit long-term durability under cyclic strain.

4. Applications of stretchable and transparent conductors for optoelectronic devices

The recent progress in developing high-performance stretchable and transparent conductors has laid a critical foundation for the fabrication of intrinsically stretchable optoelectronic devices. Unlike structural strategies—such as island–bridge architectures, buckling, or kirigami—that localize strain in predefined regions, intrinsically stretchable systems achieve mechanical compliance directly at the material level. In structural designs, strain is concentrated within serpentine interconnects or buckled regions, while the rigid functional islands remain largely undeformed. This mismatch often results in nonuniform strain distribution, limits device miniaturization, and can lead to mechanical fatigue or delamination at the rigid–soft interfaces. By contrast, intrinsically stretchable devices allow both the active pixels and interconnections to deform uniformly, thereby maintaining a consistent fill factor during stretching. The elimination of rigid islands and fragile interfaces not only improves mechanical reliability under repeated deformation but also simplifies device layouts, enabling higher pixel densities and resolution.

Intrinsically stretchable optoelectronic devices can be broadly categorized into light-emitting devices (e.g., ACEs, and LEDs) and light-harvesting devices (e.g., PDs, and PVs). Fabrication of these devices requires more than substituting electrodes alone; all other components—including charge transport layers, light-emissive/absorption layers, and encapsulation layers—must also be re-engineered or replaced to novel materials to impart stretchability, rather than relying on conventional rigid electronic materials. This transition of materials often entails a persistent

trade-off between mechanical compliance and optoelectronic performance. Furthermore, beyond the electrical and mechanical performance of these materials, multiple factors related to device feasibility must be considered. For example, when employing stretchable, transparent electrodes as the bottom electrode in diode-type devices, in addition to core metrics such as conductivity, optical transmittance, and stretchability, the electrodes often must: (1) tolerate solution-processed fabrication steps; (2) maintain low surface roughness to suppress short circuits; (3) provide appropriate work-function alignment for efficient interfacial charge injection; and (4) support fine patterning of conducting materials. In this regard, such material and process innovations are essential for enabling high-performance intrinsically stretchable optoelectronic systems.

These advances in individual optoelectronics naturally led to the realization of human-centric soft optoelectronics (Fig. 8). The harmonic integration of the intrinsically stretchable optoelectronic devices contributes to implementing a cutting-edge electronic system optimized for each desired application. For example, such devices could be integrated with lens or glasses to provide augmented/virtual reality vision, enabling multimodal interaction and personalized spaces. The optoelectronics could be also implanted into the central nervous system to deliver light to the genetically modified cells, thereby manipulating neural circuits. Wearable textile-based light-emissive systems could enable real-time monitoring of body conditions and mediate light-based therapies in combination with phototherapeutic agents, thus supporting urgent medical interventions. In addition, portable healthcare devices such as X-ray imager by for non-invasive detection of orthopedic abnormalities and electronic skin sensor by multimodal physiological monitoring highlight the translational potential of soft electronics based on stretchable and transparent conductors. Based on the understanding of human factors knowledge, the effective incorporation of devices enabled by human-centered design allows usability, practicality, adaptability, and convenience, which could be applied for next-generation digital healthcare and mobile display.

In order to realize these human-centric optoelectronic applications, it is essential to identify and optimize performance parameters of devices' functional requirement. For example, augmented and virtual reality displays require high resolution, high luminance, and mechanical uniformity for immersive experience. Neural optoelectronic systems, such as deformable micro-LED implants, require accurate optical power delivery and long-term stability for reliable stimulation and monitoring. Wearable phototherapeutic and healthcare devices, including stretchable light-emitting diodes and photodetectors, require durability, biocompatibility, and minimal heat generation for stable and accurate monitoring.

To meet this need, performance and multifunctionality of individual device component should be preceded. In the following sections, we highlight recent advances in intrinsically stretchable light-emitting and light-harvesting devices that utilize stretchable and transparent conductors as electrodes, with particular emphasis on material design, device architecture, performance optimization, and emerging applications.

4.1. *Intrinsically stretchable light-emitting devices*

Intrinsically stretchable light-emitting devices, with the advances in material design and device integration (Table 1), hold significant promise for diverse applications, ranging from next-generation deformable displays to skin-mounted light sources for smart healthcare. As discussed above, these devices can generally be divided into two categories: ACELs and LEDs.

ACELs feature a capacitor-like configuration in which phosphor particles (e.g., ZnS:Cu) are dispersed within an elastomeric dielectric and sandwiched between two stretchable electrodes. Their emission relies on hot-electron injection and impact excitation. When an AC voltage is applied, a strong electric field develops across the dielectric, polarizing the surrounding medium and exciting the embedded phosphors to emit photons. This straightforward structure enables ACELs to maintain light-emission performance under extreme mechanical deformation.

Table 1. Materials and device performance of previously-reported intrinsically stretchable light-emitting devices, including ACELs and LEDs.

Device type	year	Device structure		EL materials	Performance			Ref.
		Bottom electrode (Anode)	Top electrode (Cathode)		Max luminance [Cd m ⁻²]	Max EQE [%]	Stretchability [%]	
Intrinsically stretchable ACEL	2015	Ag NW/PDMS	Ag NW/PDMS	ZnS:Cu	225	-	100	[113]
	2016	Hydrogel (PAM-LiCl)	Hydrogel (PAM-LiCl)	ZnS	-	-	487	[114]
	2016	Hydrogel (PAM-LiCl)	Hydrogel (PAM-LiCl)	ZnS:Cu,Mo,Cl	9.4	-	1500	[115]
	2016	Ionic gel (PMMA-LiClO ₄ in PC/ACN)	Ionic gel (PMMA-LiClO ₄ in PC/ACN)	ZnS:Cu	95	-	700	[116]
	2016	Ag NW/PDMS	Ag NW/PDMS	ZnS:Cu + BaTiO ₃	121	-	30	[117]
	2018	Hydrogel (PVA/PEO)	Hydrogel (PVA/PEO)	ZnS	242	-	800	[118]
	2018	Ag NW/PDMS	Ag NW/PDMS	ZnS:Cu	307	-	80	[119]
	2021	Ionogel (PNN/x-Ch)	Ionogel (PNN/x-Ch)	ZnS:Cu, Cl	647	-	1200	[104]
	2022	Ag/Ecoflex (coplanar electrodes)	Ag/Ecoflex (coplanar electrodes)	ZnS:Cu + BaTiO ₃	80	-	600	[120]
	2022	Cu NW/PDMS	Cu NW/PDMS	ZnS:Cu,Cl	97.6	-	100	[121]
	2023	Hydrogel (PHA/x-CS)	Hydrogel (PHA/x-CS)	ZnS:Mn,Cl(orange), ZnS:Cu,Cl(green), ZnS:Cu,Cl(neon-blue)	395	-	1400	[122]
	2023	Galinstan/Cu-SIS	Hydrogel (PAM-LiCl)	ZnS:Cu	110	-	400	[123]
	2023	Ag NW – PEDOT:PSS/TPU	Ag NW – PEDOT:PSS/TPU	ZnS:Cu + BaTiO ₃	591	-	120	[105]
	2023	Ag NW/TPU	Ag NW/TPU	ZnS:Cu/PVDF-HFP	87	-	50	[124]
	2024	Ag NW/SEBS	Ag NW/SEBS	ZnS core coated with CsPbX ₃ NPs	276	-	400	[106]
Intrinsically stretchable OLED	2011	SWNT/PtBA	SWNT/PtBA	PF-B + PEO-DMA + LiTf	200	-	45	[125]
	2014	GO-Ag NW/PUA	GO-Ag NW/PUA	White light –emitting polymer + OXD-7	1100	-	130	[126]
	2021	Ag NW +Silica Aerogel /PDMS	Ag NW + ZnO +d-PEIE	SY + Triton X	4400	-	80	[127]
	2022	PEDOT: PSS + PR	PEDOT: PSS + PR	Sy + PU	7450	-	100	[107]
	2022	Au	Ag NW/PDMS	L-SY-PPV + PAN	3780	0.69	30	[128]
	2022	Ag NW + Graphene /SEBS + PFSA	Graphene + Ag NW /SEBS + PEI + Crown-CPE	SY + Triton X	2185	-	20	[84]
	2023	PEDOT:PSS (PH1000)	LiF/Al	SBSPy-16	3274	2.08	54	[129]
	2023	Ag NW + Graphene /SEBS + PFSA	Graphene + Ag NW /SEBS + PEI + Crown-CPE	SY + PEO + KCF ₃ SO ₃	1754	-	30	[85]
	2023	Ag NW/TPU/ PDMS	Ag NW/TPU/ PDMS	stretchable TADF polymer	>10 ³	3.3	60	[130]
	2024	Ag NW/PDMS	Ag	SY + Triton X	3151	-	70	[57]
Intrinsically stretchable PELED	2013	Ag NW/PUA	Ag NW/PUA	SY + ETPTA + PEO + LiTF	2200	4	120	[74]
	2017	PEDOT:PSS + PEO	EGaIn	MAPbBr ₃ + PEO	15960	0.62	40	[131]
Intrinsically stretchable QLED	2020	PEDOT:PSS + PEO	Ag NW/PU	CsPbBr ₃ + PEO + PVP	380.5	0.25–0.3	30	[132]
	2024	Ag NW/PUA +PEDOT:PSS (PH1000)	Ag NW + Ag + EGaIn/PUA	CdSe/ZnS + SEBS-g-MA + TFB	15170	1.2	50	[88]

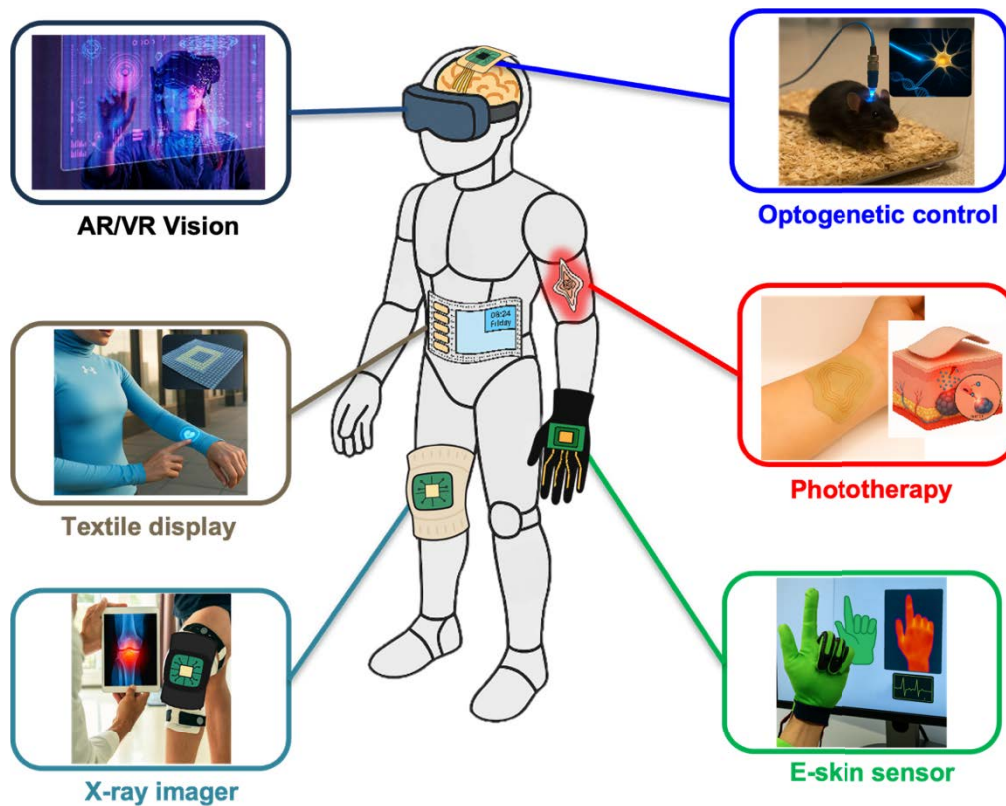


Fig. 8. Perspective on future human-centric applications of stretchable transparent conductor-based soft optoelectronic system. The potential applications include AR/VR vision, optogenetic control system, textile display, phototherapy, X-ray image, and E-skin.

For instance, an intrinsically stretchable ACEL demonstrated by Xuan et al. [104] could withstand strains of up to 1,200% without notable degradation. Importantly, because these devices are field-driven rather than current-driven, a broad range of electrode materials can be employed—including ionic and polymeric conductors with relatively low conductivity—making ACELs highly versatile for transparent and stretchable electrode integration.

Despite their excellent mechanical compliance, ACELs continue to suffer from limited electroluminescent (EL) performance. Typically, high AC electric fields on the order of 10^4 – 10^5 V cm⁻¹ are required to generate noticeable brightness levels (> 100 cd m⁻²), which translates into the need for high operating voltages (> 100 V) and driving frequencies above 0.5 kHz. In addition, scalable high-resolution patterning of both the electrodes and dielectric layers is essential for practical ACEL displays. Consequently, considerable research efforts have focused on improving luminous efficiency and device complexity while preserving stretchability.

For example, Yoo et al. [105] demonstrated high-resolution, high-performance stretchable ACEL displays by employing a transfer-printing approach. In this device, stretchable and transparent electrodes were fabricated from Ag nanowires (AgNWs) and PEDOT:PSS embedded within a thermoplastic polyurethane (TPU) matrix, offering high optical transmittance, mechanical robustness, and stable conductivity under strain (Fig. 9(a)). The emissive composite layer consisted of ZnS:Cu phosphors blended with BaTiO₃ high-k dielectric particles and PDMS. The incorporation of BaTiO₃ increased the dielectric constant of the emissive layer, thereby

boosting device brightness. Moreover, transfer-printing yielded densified, thinner emissive films with enhanced capacitance, which elevated luminance (up to $\sim 600 \text{ cd m}^{-2}$) (Fig. 9(b)). The devices retained stable optical and acoustic performance under strains up to 120% and after more than 5,000 stretching cycles (Fig. 9(c)). Importantly, the transfer-printed strategy allowed high-resolution patterning down to $300 \mu\text{m}$, as demonstrated in multicolor mosaic artworks and multiplexed QR code displays (Fig. 9(d)).

Parallel efforts have also been made to address the limited color reproducibility of ACELS. Conventionally, emission colors were adjusted by varying the dopant metal in ZnS phosphors (e.g., Mn:ZnS or Cu:ZnS). However, these phosphors provide only a narrow color range from orange to blue, with broad emission bandwidths ($\text{FWHM} > 50 \text{ nm}$) and poor color purity. To address this, Chun et al. [106] proposed a core-shell-like design in which Cu:ZnS particles were decorated with perovskite nanocrystals (PeNCs) for color conversion, while stretchable transparent electrodes were realized using AgNW-embedded SEBS (Fig. 9(e)). Photon reabsorption and Förster resonance energy transfer between Cu:ZnS and the surface-decorated PeNCs enabled efficient blue-to-red downconversion. By tuning the emission characteristics of the PeNCs, ACEL devices achieved a broad color gamut spanning 468–694 nm, narrowed linewidths ($\text{FWHM} < 37 \text{ nm}$), high luminance ($> 500 \text{ cd m}^{-2}$), and excellent stretchability up to 400% (Figs. 9(f) and (g)). As a proof of concept, on-skin displays integrated with tactile and temperature sensors were demonstrated, providing real-time visual feedback to users (Fig. 9(h)).

Unlike ACELS, intrinsically stretchable LEDs adopt a multilayer p-i-n configuration consisting of charge transport and emissive layers. Under DC bias, electrons and holes are injected from opposing electrodes and undergo radiative recombination within the emissive layer. These devices deliver superior luminous performance, achieving higher brightness ($10^3\text{--}10^4 \text{ cd m}^{-2}$) at much lower operating voltages ($\sim 10 \text{ V}$). However, their stretchability is generally limited ($< 150\%$) due to the structural complexity of the multilayer architecture. In particular, maintaining efficient current transport requires that the charge transport and emissive layers minimize insulating additives, such as elastomers or surfactants, which in turn constrains mechanical compliance. Consequently, achieving high stretchability in LEDs is more challenging than in ACELS. Nonetheless, their exceptional brightness and compatibility with DC-driven operation—well suited for conventional active-matrix display systems—make intrinsically stretchable LEDs the most promising candidates for next-generation stretchable display technologies.

In the early stages, intrinsically stretchable LEDs featured a simple design with an emissive layer (EML) sandwiched between two stretchable electrodes—similar to ACELS but operated under DC bias. Some reviews classify such devices as light-emitting electrochemical cells (LEECs). More recent studies have demonstrated that incorporating stretchable charge transport layers can markedly enhance device performance. For instance, Zheng et al. [107] developed SY/PU composite EMLs, in which uniformly dispersed SY nanofibers within a polyurethane matrix improved film morphology, reduced trap density, and suppressed nonradiative recombination (Fig. 9(i)). Stretchable transparent electrodes were realized using PEDOT:PSS blended with polyrotaxane (PR), while the device stack included a PEDOT:PSS/Triton X hole injection layer (HIL), PU-blended TFB as the HTL, the stretchable EML, and a PFN-Br/PEIE ETL. This architecture achieved a maximum brightness of 7450 cd m^{-2} at 15 V, maintained performance under 100% strain (Figs. 9(j) and (k)), and was further demonstrated as a skin-attachable LED capable of visualizing cardiovascular signals in real time (Fig. 9(l)).

Inorganic emitters have also been explored to combine stretchability with high optoelectronic quality. Recently, Kim et al. [88] reported a ternary composite EML of CdSe quantum dots (QDs), SEBS-g-MA elastomer, and TFB polymer (Fig. 9(m)). Phase-separated TFB domains facilitated efficient hole injection into QDs, yielding rigid QLEDs with a brightness of $173,171 \text{ cd m}^{-2}$ and current efficiency of 28.4 cd A^{-1} at 8 V. When integrated into intrinsically stretchable QLEDs with AgNW/PEDOT:PSS anodes, ZnO/PFN-Br ETLs, and liquid-metal cathodes, the

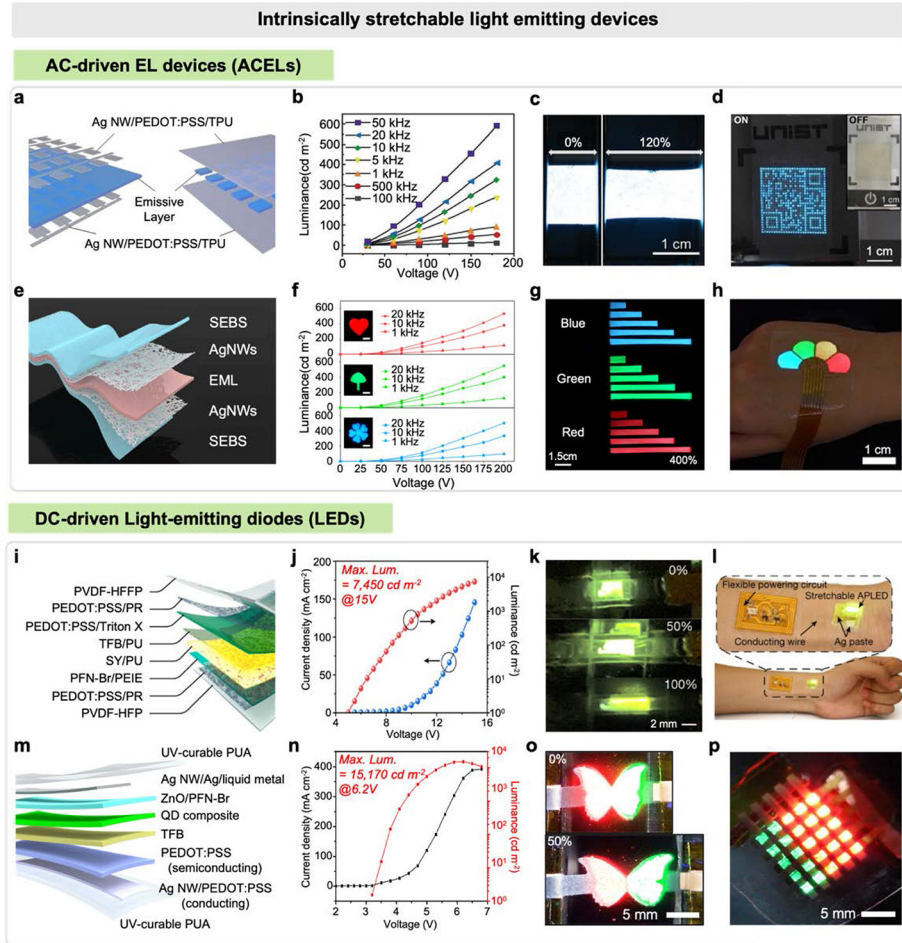


Fig. 9. Intrinsically stretchable light-emitting devices. **a**, Device structure of an intrinsically stretchable ACEL based on AgNW/PEDOT:PSS/TPU electrodes and ZnS:Cu:BaTiO₃/PDMS as emissive layers. **b**, Voltage-luminance (V - L) characteristics of stretchable ACELs under various operation frequency. **c**, Photographs of stretchable ACELs at 0% (left) and 120% strain (right). **d**, Operation of high-resolution ACEL arrays, demonstrating QR code patterns. Reproduced with permission from Ref. [105], Copyright 2023, Wiley-VCH. **e**, Device structure of a multi-color intrinsically stretchable ACEL based on AgNW/SEBS electrodes and PeNC-decorated ZnS phosphors as emissive layers. **f**, V - L characteristics for red, green, and blue ACELs under various operation frequencies. **g**, Photographs of red, green, and blue-emitting stretchable ACELs, stretched up to 400% of strain. **h**, Skin-mounted, multi-color stretchable ACELs integrated with various wearable sensors. Reproduced with permission from Ref. [106], Copyright 2024, Springer Nature. **i**, Device structure of an intrinsically stretchable OLED. **j**, Current density-voltage-luminance (J - V - L) characteristics of stretchable OLEDs. **k**, Photographs of stretchable OLEDs, stretched under 0% (top), 50% (middle) and 100% of strain (bottom). **l**, Wearable displays based on stretchable OLEDs, sensors, and flexible powering circuits. Reproduced with permission from Ref. [107], Copyright 2022, Springer Nature. **m**, Device structure of an intrinsically stretchable QLED. **n**, J - V - L characteristics of stretchable QLEDs. **o**, Photographs of stretchable QLEDs, stretched under 0% (top) and 50% (bottom) of strain. **p**, Photographs of 5×5 passive-matrix operation of multi-color stretchable QLED arrays. Reproduced with permission from Ref. [88], Copyright 2024, Springer Nature.

devices achieved $15,170 \text{ cd m}^{-2}$ at 6.2 V while sustaining stable EL output under 50% strain (Figs. 9(n) and (o)). Moreover, multi-color stretchable QLED arrays were realized via intaglio transfer printing, highlighting the potential for high-resolution, stretchable display applications (Fig. 9(p)).

4.2. Intrinsically stretchable light-harvesting devices

Research on intrinsically stretchable light-harvesting devices has gained significant momentum in recent years. Such devices can be broadly classified into two categories: photodetectors, which convert incident light into electrical signals, and PVs, which transform light energy into electrical power. Meanwhile, photodetectors themselves can be categorized into three types: photoresistors (or photoconductors), photodiodes (PDs), and phototransistors. Photoresistors and phototransistors typically employ horizontal configurations in which the photoactive material directly absorbs incident light. In contrast, PDs operate in a vertical configuration, where incoming light must pass through a transparent or semi-transparent electrode before reaching the photoactive layer.

In this section, we focus on intrinsically stretchable PDs and PVs, as their vertically stacked architectures fundamentally rely on stretchable and transparent electrodes, making optical transparency and mechanical compliance critical to device performance. A summary of materials and device performance metrics reported for intrinsically stretchable light-harvesting devices, including both PDs and PVs, is provided in Table 2.

The key advantage of stretchable photodetectors lies in their ability to enable planar-to-curved image sensor transformations, thereby offering dynamic focal lengths and wide fields of view. Conventional stretchable photodetectors often rely on inorganic photoactive materials to achieve high optoelectronic performance, combined with geometrical designs to isolate the active device regions from applied strains. However, these designs inevitably compromise pixel density and resolution, particularly under stretching, as the spacing between active units increases. In contrast, intrinsically stretchable photodetectors can sustain much higher device densities and resolutions, which is essential for practical applications such as artificial vision systems. The central challenge, however, remains the concurrent realization of high photoresponse sensitivity and robust mechanical durability.

Kang et al. [108] reported a skin-like intrinsically stretchable polymer-based photodiode with an all-polymeric architecture, in which elastomeric photoactive layers were formed by blending elastomers with p- and n-type semiconducting polymers to ensure mechanical compliance under large deformations (Fig. 10(a)). Stretchable transparent electrodes based on the conducting polymer PEDOT:PSS (PH1000) were further engineered with modulated work functions to provide efficient charge injection and extraction while preserving electrical continuity under strain. Specifically, anodic electrodes were fabricated by blending PH1000 with a fluorine-based ionomer to achieve a work function of -5.3 eV , while cathodic electrodes were realized by coating a PEIE overlayer on PH1000, yielding a work function of -4.2 eV . As a result, the devices achieved exceptional optoelectronic performance, with detectivity (D^*) exceeding 10^{13} Jones and a low dark current density of 0.1 nA cm^{-2} , both of which remained stable even under 100% strain (Fig. 10(b)). When applied as skin-conformable photoplethysmography sensors (Fig. 10(c)), the device provided high-quality, reliable pulse signals at the wrist, underscoring their potential for next-generation wearable electronics in optical biometric monitoring and biomedical imaging (Fig. 10(d)).

Similarly, Qin et al. [109] introduced ultrasensitive intrinsically stretchable organic PDs designed for faint near-infrared (NIR) light detection and extendable imaging (Fig. 10(e)). The device employed a spatially modularizable-assembled elastic (SMAE) photoactive film comprising a polymer donor, a non-fullerene small-molecule acceptor, and a SEBS elastomer, which produced uniform bulk heterojunction morphologies and mechanically robust interfaces

Table 2. Materials and device performance of previously-reported intrinsically stretchable light-harvesting devices, including PDs and PVs.

Device type	Year	Device structure		Active layer materials	Performance			Ref.
		Anode	Cathode		Max D* [Jones]	Initial PCE [%]	Stretchability [%]	
Intrinsically stretchable PD	2021	PEDOT:PSS + EG + Capstone/PDMS	EGaIn	P3HT:ICBA:SEBS	5.3×10^{10}		60	[133]
	2023	PEDOT:PSS + PEO/PDMS	EGaIn	P3HT:PCBM:SIS	-		25	[134]
	2023	PPR-M (PR + PEDOT:PSS PH1000 + Capstone, methanol-treated)	SPC (PPR-M + PEIE interfacial modification)	DPP-DTT:PC ₇₀ BM:SEBS	3.09×10^{11}		100	[135]
	2023	PEDOT:PSS + DMSO + Triton X + FI/PDMS	PEDOT:PSS + DMSO + Triton X + PEIE/PDMS	N2200:PTB7-Th:SEBS	3.0×10^{13}		100	[108]
	2024	PEDOT:PSS + D-sorbitol + ionic liquid + FS-30	EGaIn	PM6:Y6:SEBS	$>10^{13}$		100	[109]
Intrinsically stretchable PV	2017	Ag NW + SWNT/PUA	Ag NW + SWNT/PUA	PTB7:PC ₇₁ BM:DIO		3.48	100	[136]
	2021	Ag NW/TPU	EGaIn	PTB7-Th:IEICO-4F:PDMS		10.1	20	[137]
	2021	PH1000 + Al4083	EGaIn	PM6:Y7		11.2	10	[138]
	2022	PH1000 + DMSO + PEG + FS-30	EGaIn	PM6:Y7 + P _{VH}		11.71	20	[139]
	2022	PH1000	EGaIn	PhAm5:Y7		12.73	32	[140]
	2022	PH1000	EGaIn	PM6-OEG5:BTP-eC9		17.74	22	[141]
	2022	PEDOT:PSS	EGaIn	PBDB-T:PYFS-Reg		10.64	36.7	[142]
	2022	PH1000 + GL	EGaIn	PM6:Y6-BAC		13.4	20	[143]
	2023	Ag NW/TPU	AZO + Ag NWs + AZO	PM6:BTP-eC9		10.9	5	[144]
	2023	PH1000 + DMSO + PEG + FS-30 + GOPS	EGaIn	PM6:Y6-BO:N2200		10.2	40	[145]
	2023	PH1000 + DMSO + GOPS + Fluorosurfactant	EGaIn	PM7-Thy10:L8-BO		13.69	43	[146]
	2024	Ag NW/TPU	EGaIn	PBQx-TCI:PYF-IT:N2200		12.6	51	[112]
	2024	PH1000 + EG + ION E	EGaIn	Ter-D18:Y6		14.2	52	[90]
	2024	PH1000 + DMSO + PEG + FS-30	EGaIn@Ag	PTzBI-oF:PYIT:EVA		10.7	>30	[147]
	2024	PH1000	EGaIn	PM6:PM6-HD:N2200		2.28	50	[148]
	2025	Ag NW/TPU	EGaIn	PNTB6-Cl:BTP-Si4		14.6	80	[110]
	2025	PH1000	EGaIn	PBET-TF:MYBO		12.93	50	[149]
	2025	m-PH1000	EGaIn	PM6:eC9:TDY- α (20%)		15.07	9	[150]
	2025	PH1000 + DMSO + FS-30	EGaIn	PM6:L8-BO		14.3	30.6	[151]
	2025	PEDOT:PSS	EGaIn	PM6:DY-FBrL		14.31	23	[152]
	2025	PH1000 + DMSO + PEG + FS-30	EGaIn	PM6-b-PDMS: DYBT:DYPDMS		12.74	40	[153]
	2025	Ag NW/TPU	EGaIn	PM-BO10%:BTP-eC9		14.2	31	[154]
	2025	PH1000	EGaIn	PM6:IDTBT		14.2	~35	[155]

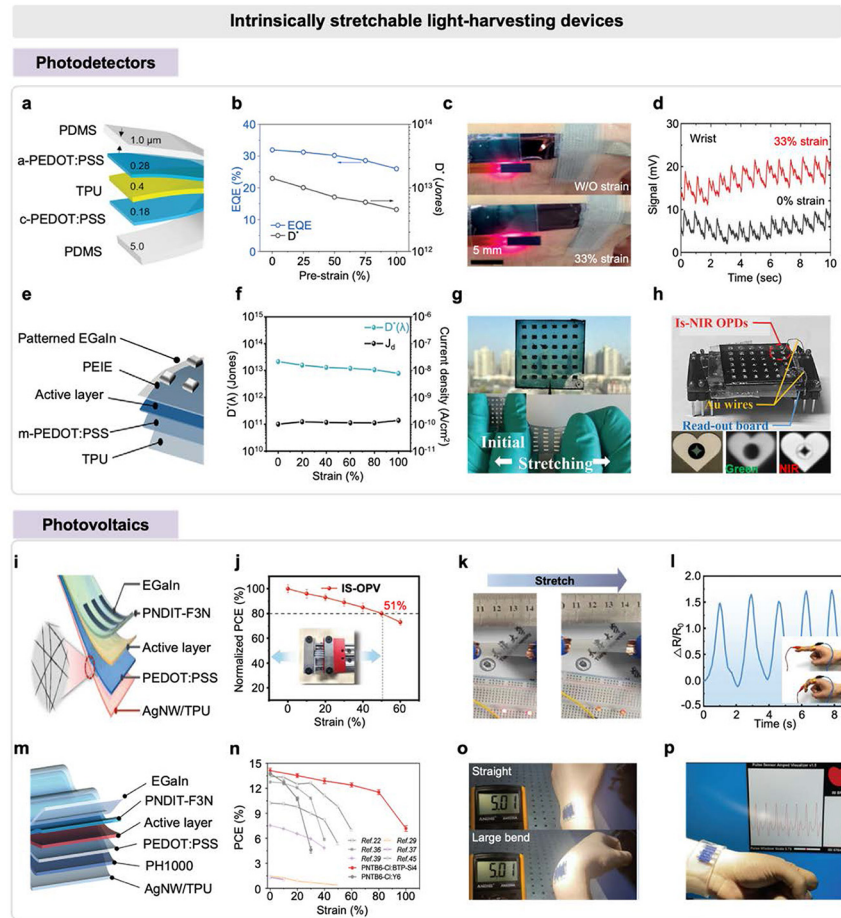


Fig. 10. Intrinsically stretchable light-harvesting devices. **a**, Device structure of an intrinsically stretchable polymer photodiode using elastomeric photoactive blends and work-function-tuned conducting-polymer transparent electrodes. **b**, Detectivity and response stability as functions of pre-strain. **c**, Photographs of an on-skin PPG sensor at 0% and 33% strain. **d**, Wrist-mounted PPG readout showing stable waveforms with increasing strain. Reproduced with permission from Ref. [108], Copyright 2023, Wiley-VCH. **e**, Device structure of a stretchable NIR-OPD featuring a SMAE photoactive layer and a patterned EGaIn top electrode. **f**, Detectivity and noise current versus applied strain. **g**, Photographs of a stretchable NIR-OPD pixel array before and after extension. **h**, Extendable NIR cryptographic imaging, in which encrypted NIR patterns decoded by the OPD array remain legible under tensile extension. Reproduced with permission from Ref. [109], Copyright 2024, Wiley-VCH. **i**, Device structure of an intrinsically stretchable organic PV based on PBQx-TCI:PYF-IT:N2200 as photoactive layer. **j**, Changes of power-conversion efficiency under various tensile strain. **k**, Photographs of a small light bulb driven through the stretchable PVs, showing brightness variation under different strain. **l**, Time-dependent $\Delta R/R_0$ from a finger-mounted stretchable device, showing repeatable resistance modulation during flexion and extension. Reproduced with permission from Ref. [112], Copyright 2024, Wiley-VCH. **m**, Device structure of an intrinsically stretchable PV based on PNTB6-Cl:BTP-Si4 donor-acceptor blend as photoactive layer. **n**, PCE-strain characteristics demonstrating high ultimate strain with strong efficiency retention. **o**, Photographs of stretchable PVs operating under bending and large deformations. **p**, Demonstration of skin-mounted, self-powered health-monitoring system, based on stretchable PVs. Reproduced with permission from Ref. [110], Copyright 2025, The American Association for the Advancement of Science.

under strain. Stretchable transparent electrodes based on PH1000 modified with fluorine-based ionic liquids were integrated to ensure stable carrier injection and collection during deformation, enabling the stretchable organic PDs to achieve both high mechanical compliance and efficient photon-to-charge conversion. This architecture enabled high detectivity over 10^{12} Jones at 850 nm (Fig. 10(f)), along with an ultralow noise current of 4.1×10^{-15} A Hz $^{-1/2}$ and reliable stretchability up to 100% (Fig. 10(g)). Beyond conventional sensing, the photodiodes uniquely demonstrated extendable NIR cryptographic imaging, underscoring their potential in practical applications (Fig. 10(h)).

While stretchable PDs focus on light detection, intrinsically stretchable PVs offer complementary capabilities for energy harvesting. Often referred to as stretchable solar cells, have been extensively investigated as potential power supply devices, mostly for wearable electronic applications. Intrinsically stretchable PVs share a similar multilayer architecture with PDs, but are optimized for energy harvesting. Upon solar illumination, excitons are generated in the photoactive absorber, dissociate at donor–acceptor interfaces, and the resulting free carriers are transported to the electrodes to produce electrical power. While both devices rely on the same fundamental process of photon-to-charge conversion, PDs prioritize responsivity and detectivity, whereas PVs focus on maximizing power conversion efficiency (PCE) under strain.

One demonstration of this approach was presented by Han et al. [100], who introduced a scalable electrode platform, compatible with stretchable PVs. They reported a simple and efficient embedding strategy to fabricate stretchable silver nanowire/thermoplastic elastomer composite electrodes (Strem-AT), which leverage the viscoelasticity and mechanical robustness of elastomers to achieve high extensibility, conductivity, and smooth surface morphology (Fig. 10(i)). These electrodes exhibited excellent tensile properties, low surface roughness, and stable electrical performance, enabling their reliable integration into stretchable sensors and intrinsically stretchable organic PVs. The structure of stretchable organic PV is Strem-AT/PEDOT:PSS/PBQx-TCI:PYF-IT:N2200/PNDIT-F3N/EGaIn. The resulting stretchable PVs delivered a PCE exceeding 12.5% and retained more than 50% of the initial PCE under 80% strain, with 76% of the original performance preserved even after 1000 cycles at 50% strain (Figs. 10(j) and (k)). In addition, when employed as skin-mounted motion sensors, the devices demonstrated remarkable stretchability and stable signal output (Fig. 10(l)). These results underscore the scalability and multifunctionality of Strem-AT electrodes for next-generation wearable sensors and energy-harvesting photovoltaics.

Recently, Zhang et al. [110] developed intrinsically stretchable organic PVs by formulating ductile donor–acceptor blends based on the polymer donor PNTB6-Cl and an organosilane-functionalized small-molecule acceptor (BTP-Si4) (Fig. 10(m)). Unlike conventional non-fullerene acceptors that typically reduce blend ductility, BTP-Si4 offered high miscibility with PNTB6-Cl while retaining sufficient electron mobility, enabling active layers with both mechanical compliance and charge transport. The resulting stretchable PVs achieved PCEs exceeding 16% with ultimate strain above 95%, and maintained over 80% of their initial efficiency under 80% strain (Fig. 10(n)). Even under various deformation states, devices with PCEs above 14% were consistently demonstrated, underscoring the robustness of the donor–acceptor system. As a demonstration, they achieved a self-powered, skin-mounted health-monitoring system by integrating a pulse oximeter with the fabricated stretchable PVs, demonstrating potential for early disease diagnosis and treatment (Figs. 10(o) and (p)).

5. Conclusion

This review organizes the material development of intrinsically stretchable and transparent conductors, classified into metallic (e.g., nanocomposite and liquid metal) and non-metallic ones (CNT, ionic conductor, and PEDOT:PSS). Their respective advantages, characteristics, and design strategies are described in detail. Among these materials, proper candidates could

be selected, engineered, and integrated with other electronic components for the construction of soft optoelectronics. For example, recent research on unconventional devices including light-emitting diodes, photodetectors, and photovoltaic devices has demonstrated enhanced performance and imparted new functionalities when incorporating intrinsically stretchable and transparent conductors. The material development of stretchable transparent conductors and their device integration strategies have revolutionized the field of intrinsically stretchable optoelectronics. These innovations would present a new paradigm of soft electronics toward human-centric applications, ranging from biomedical fields to displays, comprehensively.

However, major challenges remain related to the device performance. For enhancing the device quality, the individual performance of all materials composing the device must be supported. Beyond stretchable conductors, intrinsically stretchable functional materials, including emissive layers, charge-transport polymers, and photoactive materials, are also important in realizing fully deformable optoelectronic systems. These active layers need to maintain their optical and electronic properties under strain, but there still are some limitations in mechanical stretchability, interfacial instability, and unoptimized device architecture. Recent studies, such as elastomer blending, polymer-backbone engineering, and molecular design of active materials have shown promising development, but further advances are needed to overcome the trade-offs between stretchability and optoelectronic performance in intrinsically stretchable devices.

Challenges on other respects also remain: ensuring long-term safety, achieving reliable integration of multiplexed devices, enhancing performance, achieving sustainable operation of the device, and advancing interdisciplinary collaboration with AI technologies. Breakthrough solutions should be proposed for addressing these challenges, which is essential before clinical translation. For example, a dramatic improvement in performance might be possible, with the aid of AI for finding optimal composition ratio of several conductor candidates. While these issues are still unresolved, soft optoelectronics based on stretchable and transparent conductors, particularly when combined with other types of bioelectronics, hold great promise for broadening applicability and enhancing practicality. Continued progress in this field is expected to accelerate the development of next-generation digital healthcare, wearable displays, and other real-world clinical applications, ultimately improving quality of the life.

Funding. Institute for Basic Science (IBS-R006-A1); National Research Foundation of Korea (NRF) (RS-2024-00405381); Basic Science Research Program through the National Research Foundation of Korea (NRF) (RS-2025-25420409).

Acknowledgements. This work was supported by Institute for Basic Science (IBS-R006-A1). This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2024-00405381, RS-2025-25442287). This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (RS-2025-25420409)

Disclosures. The authors declare no conflict of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

1. H. G. Lee, Y. W. Kwon, W. H. Jung, *et al.*, "Supercycle Al-Doped ZnMgO Alloys via Atomic Layer Deposition for Quantum Dot Light-Emitting Diodes," *ACS Appl. Mater. Interfaces* **17**(2), 3597–3607 (2025).
2. W. H. Jung, B. J. Kim, M. Choi, *et al.*, "Spatial Control of Nickel Vacancies in Colloidal NiMgO Nanocrystals for Efficient and Stable All-inorganic Quantum Dot Light-Emitting Diodes," *Adv. Mater.* **36**(46), 2410441 (2024).
3. J. Park, H. Cho, J. Kim, *et al.*, "Efficient and spectrally stable pure blue light-emitting diodes enabled by phosphonate passivated CsPbBr₃ nanoplatelets with conjugated polyelectrolyte-based energy transfer layer," *EcoMat* **6**(10), e12487 (2024).
4. J. Yoo, S. Li, D.-H. Kim, *et al.*, "Materials and design strategies for stretchable electroluminescent devices," *Nanoscale Horiz.* **7**(8), 801–821 (2022).
5. H. Seung, C. Choi, D. C. Kim, *et al.*, "Integration of synaptic phototransistors and quantum dot light-emitting diodes for visualization and recognition of UV patterns," *Sci. Adv.* **8**(41), eabq3101 (2022).
6. S. Chang, J. H. Koo, J. Yoo, *et al.*, "Flexible and stretchable light-emitting diodes and photodetectors for human-centric optoelectronics," *Chem. Rev.* **124**(3), 768–859 (2024).

7. M. Vosgueritchian, D. J. Lipomi, and Z. Bao, "Highly conductive and transparent PEDOT:PSS films with a fluorosurfactant for stretchable and flexible transparent electrodes," *Adv. Funct. Mater.* **22**(2), 421–428 (2012).
8. J.-K. Song, M. S. Kim, S. Yoo, *et al.*, "Materials and devices for flexible and stretchable photodetectors and light-emitting diodes," *Nano Res.* **14**(9), 2919–2937 (2021).
9. J. Park, H. Seung, D. C. Kim, *et al.*, "Unconventional image-sensing and light-emitting devices for extended reality," *Adv. Funct. Mater.* **31**(39), 2009281 (2021).
10. H. Joo, D. Jung, S. H. Sunwoo, *et al.*, "Material design and fabrication strategies for stretchable metallic nanocomposites," *Small* **16**(11), 1906270 (2020).
11. D. C. Kim, H. Yun, J. Kim, *et al.*, "Three-dimensional foldable quantum dot light-emitting diodes," *Nat. Electron.* **4**(9), 671–680 (2021).
12. C. Park, M. S. Kim, H. H. Kim, *et al.*, "Stretchable conductive nanocomposites and their applications in wearable devices," *Appl. Phys. Rev.* **9**(2), 021312 (2022).
13. S. Li, J. H. Jang, W. Chung, *et al.*, "Ultrathin self-powered heavy-metal-free Cu–In–Se quantum dot photodetectors for wearable health monitoring," *ACS Nano* **17**(20), 20013–20023 (2023).
14. G. D. Cha, D.-H. Kim, and D. C. Kim, "Wearable and implantable light-emitting diodes and their biomedical applications," *Korean J. Chem. Eng.* **41**(1), 1–24 (2024).
15. S. Nam, G. D. Cha, S. H. Sunwoo, *et al.*, "Needle-Like Multifunctional Biphasic Microfiber for Minimally Invasive Implantable Bioelectronics," *Adv. Mater.* **36**(36), 2404101 (2024).
16. H. J. Kim, J. H. Koo, S. Lee, *et al.*, "Materials design and integration strategies for soft bioelectronics in digital healthcare," *Nat. Rev. Mater.* **10**(9), 654–673 (2025).
17. M. Yu, Y. Kim, S. Nam, *et al.*, "Integrated implantable bioelectronic system based on intrinsically stretchable and conductive nanocomposites," *Health Nanotechnology* **1**(1), 12 (2025).
18. S. H. Lee, H. J. Lee, S. Lee, *et al.*, "Intrinsically Soft Implantable Electronics for Long-term Biosensing Applications," *Adv. Sensor Res.* **4**(7), 2500002 (2025).
19. J. Park, J. Mok, J. Ha, *et al.*, "Next-Generation Flexible and Stretchable Vision Systems for Advanced Image Acquisition and Processing," *FlexTech* **1**(2), 66–88 (2025).
20. H. J. Kim, S.-H. Sunwoo, J. H. Koo, *et al.*, "Soft implantable bioelectronics for the management of neurological disorders and cardiovascular diseases," *Korean J. Chem. Eng.* **42**(9), 2037–2068 (2025).
21. T.-H. Kim, C.-S. Lee, S. Kim, *et al.*, "Fully stretchable optoelectronic sensors based on colloidal quantum dots for sensing photoplethysmographic signals," *ACS Nano* **11**(6), 5992–6003 (2017).
22. S. Hong, S. Lee, and D.-H. Kim, "Materials and design strategies of stretchable electrodes for electronic skin and its applications," *Proc. IEEE* **107**(10), 2185–2197 (2019).
23. J. Yang, M. K. Choi, U. J. Yang, *et al.*, "Toward full-color electroluminescent quantum dot displays," *Nano Lett.* **21**(1), 26–33 (2021).
24. D. Jung, Y. Kim, H. Lee, *et al.*, "Metal-like stretchable nanocomposite using locally-bundled nanowires for skin-mountable devices," *Adv. Mater.* **35**(44), 2303458 (2023).
25. H. Zhou, K.-N. Kim, M.-J. Sung, *et al.*, "Intrinsically stretchable low-dimensional conductors for wearable organic light-emitting diodes," *Device* **1**(3), 100060 (2023).
26. K. Kim, J. Kim, B. G. Hyun, *et al.*, "Stretchable and transparent electrodes based on in-plane structures," *Nanoscale* **7**(35), 14577–14594 (2015).
27. J. H. Jang, S. Li, D. H. Kim, *et al.*, "Materials, Device Structures, and Applications of Flexible Perovskite Light-Emitting Diodes," *Adv. Electron. Mater.* **9**(9), 2201271 (2023).
28. M. K. Choi, I. Park, D. C. Kim, *et al.*, "Thermally controlled, patterned graphene transfer printing for transparent and wearable electronic/optoelectronic system," *Adv. Funct. Mater.* **25**(46), 7109–7118 (2015).
29. J. K. Song, D. Son, J. Kim, *et al.*, "Wearable force touch sensor array using a flexible and transparent electrode," *Adv. Funct. Mater.* **27**(6), 1605286 (2017).
30. D. C. Kim, M. Karl, K. Lee, *et al.*, "Recent Progress on the Development of Intrinsically Stretchable Electroluminescent Devices," *Small* **21**(37), e05099 (2025).
31. J. H. Koo, H. Yun, W. Lee, *et al.*, "Recent advances in soft electronic materials for intrinsically stretchable optoelectronic systems," *Opto-Electron. Adv.* **5**(8), 210131 (2022).
32. J.-K. Song, J. Kim, J. Yoon, *et al.*, "Stretchable colour-sensitive quantum dot nanocomposites for shape-tunable multiplexed phototransistor arrays," *Nat. Nanotechnol.* **17**(8), 849–856 (2022).
33. J. H. Koo, J. Kang, S. Lee, *et al.*, "A vacuum-deposited polymer dielectric for wafer-scale stretchable electronics," *Nat. Electron.* **6**(2), 137–145 (2023).
34. T. Park, J. S. Kim, D. Ko, *et al.*, "Advances in flexible, foldable, and stretchable quantum dot light-emitting diodes: materials and fabrication strategies," *Korean J. Chem. Eng.* **41**(13), 3517–3543 (2024).
35. K. Kim, D. R. Kim, D. Kim, *et al.*, "Intrinsically-Stretchable and Patternable Quantum Dot Color Conversion Layers for Stretchable Displays in Robotic Skin and Wearable Electronics," *Adv. Mater.* **37**(32), 2420633 (2025).
36. G. Ferrando, C. Mennucci, M. Barelli, *et al.*, "Flexible and Transparent Ultrathin Gold Electrodes via Ion Beam Smoothing," *Small Sci.* **5**(1), 2400272 (2025).
37. Y. Jiang, J. Xi, Z. Wu, *et al.*, "Highly transparent, conductive, flexible resin films embedded with silver nanowires," *Langmuir* **31**(17), 4950–4957 (2015).

38. Z. Zhao, S. Soni, T. Lee, *et al.*, "Smart Eutectic Gallium–Indium: From Properties to Applications," *Adv. Mater.* **35**(1), 2203391 (2023).
39. X. Lu, Y. Zhang, and Z. Zheng, "Metal-based flexible transparent electrodes: challenges and recent advances," *Adv. Electron. Mater.* **7**(5), 2001121 (2021).
40. K. Kim, B. G. Hyun, J. Jang, *et al.*, "Nanomaterial-based stretchable and transparent electrodes," *J. Inf. Disp.* **17**(4), 131–141 (2016).
41. C. Park, Y. Kim, S. Nam, *et al.*, "Liquid metal-based stretchable bioelectronic fiber for electrical stimulation and drug delivery in minimally invasive cardiac therapy," *APL Bioeng.* **9**(2), 026118 (2025).
42. K. Keum, S. Yang, K. S. Kim, *et al.*, "Recent progress of stretchable displays: a comprehensive review of materials, device architectures, and applications," *Soft Science* **4**(4), 34 (2024).
43. Y. Zhou and R. Azumi, "Carbon nanotube based transparent conductive films: progress, challenges, and perspectives," *Sci. Technol. Adv. Mater.* **17**(1), 493–516 (2016).
44. X. Fan, W. Nie, H. Tsai, *et al.*, "PEDOT:PSS for Flexible and Stretchable Electronics Modifications, Strategies, and Applications," *Adv. Sci.* **6**(19), 1900813 (2019).
45. L.-P. Ma, Z. Wu, L. Yin, *et al.*, "Pushing the conductance and transparency limit of monolayer graphene electrodes for flexible organic light-emitting diodes," *Proc. Natl. Acad. Sci.* **117**(42), 25991–25998 (2020).
46. Y. Shin, H. S. Lee, H. Jeong, *et al.*, "Recent advances in conductive hydrogels for soft biointegrated electronics: Materials, properties, and device applications," *Wearable Electronics* **1**, 255–280 (2024).
47. J.-M. Park, S. Lim, and J.-Y. Sun, "Materials development in stretchable iontronics," *Soft Matter* **18**(35), 6487–6510 (2022).
48. J. K. Wassei and R. B. Kaner, "Graphene, a promising transparent conductor," *Mater. Today* **13**(3), 52–59 (2010).
49. S. Wang, L. Yu, S. Wang, *et al.*, "Strong, tough, ionic conductive, and freezing-tolerant all-natural hydrogel enabled by cellulose-bentonite coordination interactions," *Nat. Commun.* **13**(1), 3408 (2022).
50. D. Zhang, K. Ryu, X. Liu, *et al.*, "Transparent, conductive, and flexible carbon nanotube films and their application in organic light-emitting diodes," *Nano Lett.* **6**(9), 1880–1886 (2006).
51. C. Zhang, C. Ji, Y. B. Park, *et al.*, "Thin-metal-film-based transparent conductors: Material preparation, optical design, and device applications," *Adv. Opt. Mater.* **9**(3), 2001298 (2021).
52. L. Shi, Y. Cui, Y. Gao, *et al.*, "High performance ultrathin MoO₃/Ag transparent electrode and its application in semitransparent organic solar cells," *Nanomaterials* **8**(7), 473 (2018).
53. D. Martinez-Cercos, B. Paulillo, R. A. Maniyara, *et al.*, "Ultrathin metals on a transparent seed and application to infrared reflectors," *ACS Appl. Mater. Interfaces* **13**(39), 46990–46997 (2021).
54. D. Li, Y. Pan, H. Liu, *et al.*, "Study on ultrathin silver film transparent electrodes based on aluminum seed layers with different structures," *Nanomaterials* **12**(19), 3540 (2022).
55. C. M. Lee, Y. B. Kim, S. Sarker, *et al.*, "The Role of the Bottom Oxide Layer in Oxide-Metal-Oxide (OMO) Electrode for Stretchable Organic Light-Emitting Diodes," *Adv. Mater. Interfaces* **11**(2), 2300652 (2024).
56. Y. Qin, Y. Wang, X. Wang, *et al.*, "High-performance ultrathin Ag electrodes by chemical bond anchoring Ag atoms for stretchable organic light-emitting devices," *Nano Res.* **17**(8), 7614–7620 (2024).
57. J.-H. Oh, K.-H. Jeon, and J.-W. Park, "Intrinsically stretchable OLEDs with a designed morphology-sustainable layer and stretchable metal cathode," *npj Flex. Electron.* **8**(1), 43 (2024).
58. W. Lee, H. Kim, I. Kang, *et al.*, "Universal assembly of liquid metal particles in polymers enables elastic printed circuit board," *Science* **378**(6620), 637–641 (2022).
59. M. D. Dickey, "Stretchable and soft electronics using liquid metals," *Adv. Mater.* **29**(27), 1606425 (2017).
60. D. Zhong, C. Wu, Y. Jiang, *et al.*, "High-speed and large-scale intrinsically stretchable integrated circuits," *Nature* **627**(8003), 313–320 (2024).
61. M. Kim, H. Lim, and S. H. Ko, "Liquid metal patterning and unique properties for next-generation soft electronics," *Adv. Sci.* **10**(6), 2205795 (2023).
62. Y.-G. Park, H. S. An, J.-Y. Kim, *et al.*, "High-resolution, reconfigurable printing of liquid metals with three-dimensional structures," *Sci. Adv.* **5**(6), eaaw2844 (2019).
63. Y.-G. Park, Y. W. Kwon, C. S. Koh, *et al.*, "In-vivo integration of soft neural probes through high-resolution printing of liquid electronics on the cranium," *Nat. Commun.* **15**(1), 1772 (2024).
64. I. Yun, Y. Lee, Y.-G. Park, *et al.*, "Transferable transparent electrodes of liquid metals for bifacial perovskite solar cells and heaters," *Nano Energy* **93**, 106857 (2022).
65. K.-W. Kim, S. J. Park, S.-J. Park, *et al.*, "Deformable micro-supercapacitor fabricated via laser ablation patterning of Graphene/liquid metal," *npj Flex. Electron.* **8**(1), 18 (2024).
66. T. Fang, J. Zhang, S. Cao, *et al.*, "Hybrid Liquid Metal/Ionic Nanocomposite Transparent Electrodes for Highly Stretchable Electroluminescent Matrix Displays," *Adv. Funct. Mater.* **35**(13), 2417982 (2025).
67. Q. Zhuang, K. Yao, M. Wu, *et al.*, "Wafer-patterned, permeable, and stretchable liquid metal microelectrodes for implantable bioelectronics with chronic biocompatibility," *Sci. Adv.* **9**(22), eadg8602 (2023).
68. H. Zhu, S. Wang, M. Zhang, *et al.*, "Fully solution processed liquid metal features as highly conductive and ultrastretchable conductors," *npj Flex. Electron.* **5**(1), 25 (2021).
69. J.-H. Kim, S. Kim, H. Kim, *et al.*, "Imbibition-induced selective wetting of liquid metal," *Nat. Commun.* **13**(1), 4763 (2022).

70. Y.-C. Sun, G. Boero, and J. Brugger, "Stretchable Conductors Fabricated by Stencil Lithography and Centrifugal Force-Assisted Patterning of Liquid Metal," *ACS Appl. Electron. Mater.* **3**(12), 5423–5432 (2021).
71. Y. Ding, S. Xiong, L. Sun, *et al.*, "Metal nanowire-based transparent electrode for flexible and stretchable optoelectronic devices," *Chem. Soc. Rev.* **53**(15), 7784–7827 (2024).
72. Y. Yang, S. Duan, and H. Zhao, "Advances in constructing silver nanowire-based conductive pathways for flexible and stretchable electronics," *Nanoscale* **14**(32), 11484–11511 (2022).
73. X. Xu, P. Xue, M. Gao, *et al.*, "Assembled one-dimensional nanowires for flexible electronic devices via printing and coating: Techniques, applications, and perspectives," *Adv. Colloid Interface Sci.* **321**, 102987 (2023).
74. J. Liang, L. Li, X. Niu, *et al.*, "Elastomeric polymer light-emitting devices and displays," *Nat. Photonics* **7**(10), 817–824 (2013).
75. Y. Zhang, P. He, M. Luo, *et al.*, "Highly stretchable polymer/silver nanowires composite sensor for human health monitoring," *Nano Res.* **13**(4), 919–926 (2020).
76. D. Jung, C. Lim, H. J. Shim, *et al.*, "Highly conductive and elastic nanomembrane for skin electronics," *Science* **373**(6558), 1022–1026 (2021).
77. M. Du, Z. Yang, Y. Miao, *et al.*, "Facile Nanowelding Process for Silver Nanowire Electrodes Toward High-Performance Large-Area Flexible Organic Light-Emitting Diodes," *Adv. Funct. Mater.* **34**(42), 2404567 (2024).
78. D. Jung, C. Lim, C. Park, *et al.*, "Adaptive self-organization of nanomaterials enables strain-insensitive resistance of stretchable metallic nanocomposites," *Adv. Mater.* **34**(23), 2200980 (2022).
79. B.-Y. Hwang, S.-H. Choi, K.-W. Lee, *et al.*, "Highly stretchable and transparent electrode film based on SWCNT/Silver nanowire hybrid nanocomposite," *Compos. Part B Eng.* **151**, 1–7 (2018).
80. L. Cai, J. Li, P. Luan, *et al.*, "Highly Transparent and Conductive Stretchable Conductors Based on Hierarchical Reticulate Single-Walled Carbon Nanotube Architecture," *Adv. Funct. Mater.* **22**(24), 5238–5244 (2012).
81. P. Wang, Z. Peng, M. Li, *et al.*, "Stretchable Transparent conductive films from long carbon nanotube metals," *Small* **14**(38), 1802625 (2018).
82. M.-S. Lee, K. Lee, S.-Y. Kim, *et al.*, "High-performance, transparent, and stretchable electrodes using graphene–metal nanowire hybrid structures," *Nano Lett.* **13**(6), 2814–2821 (2013).
83. N. Liu, A. Chortos, T. Lei, *et al.*, "Ultratransparent and stretchable graphene electrodes," *Sci. Adv.* **3**(9), e1700159 (2017).
84. H. Zhou, S. J. Han, A. K. Harit, *et al.*, "Graphene-based intrinsically stretchable 2D-contact electrodes for highly efficient organic light-emitting diodes," *Adv. Mater.* **34**(31), 2203040 (2022).
85. S. J. Han, H. Zhou, H. Kwon, *et al.*, "Achieving Low-Voltage Operation of Intrinsically-Stretchable Organic Light-Emitting Diodes," *Adv. Funct. Mater.* **33**(10), 2211150 (2023).
86. Y. Li, Y. Pang, L. Wang, *et al.*, "Boosting the performance of PEDOT:PSS based electronics via ionic liquids," *Adv. Mater.* **36**(13), 2310973 (2024).
87. M. Y. Teo, N. Kim, S. Kee, *et al.*, "Highly stretchable and highly conductive PEDOT:PSS/ionic liquid composite transparent electrodes for solution-processed stretchable electronics," *ACS Appl. Mater. Interfaces* **9**(1), 819–826 (2017).
88. D. C. Kim, H. Seung, J. Yoo, *et al.*, "Intrinsically stretchable quantum dot light-emitting diodes," *Nat. Electron.* **7**(5), 365–374 (2024).
89. Y. Wang, C. Zhu, R. Pfattner, *et al.*, "A highly stretchable, transparent, and conductive polymer," *Sci. Adv.* **3**(3), e1602076 (2017).
90. J. Wang, Y. Ochiai, N. Wu, *et al.*, "Intrinsically stretchable organic photovoltaics by redistributing strain to PEDOT:PSS with enhanced stretchability and interfacial adhesion," *Nat. Commun.* **15**(1), 4902 (2024).
91. N. Kim, H. Kang, J. H. Lee, *et al.*, "Highly conductive all-plastic electrodes fabricated using a novel chemically controlled transfer-printing method," *Adv. Mater.* **27**(14), 2317–2323 (2015).
92. J. H. Lee, Y. R. Jeong, G. Lee, *et al.*, "Highly Conductive, Stretchable, and Transparent PEDOT:PSS Electrodes Fabricated with Triblock Copolymer Additives and Acid Treatment," *ACS Appl. Mater. Interfaces* **10**(33), 28027–28035 (2018).
93. Y. Jiang, Z. Zhang, Y.-X. Wang, *et al.*, "Topological supramolecular network enabled high-conductivity, stretchable organic bioelectronics," *Science* **375**(6587), 1411–1417 (2022).
94. S. J. Yoon, J. Ha, H. Lee, *et al.*, "Water-based direct photopatterning of stretchable PEDOT:PSS using amphiphilic block copolymers," *npj Flex. Electron.* **8**(1), 22 (2024).
95. D.-H. Ji, Y.-F. Ni, C.-Y. Lin, *et al.*, "Transparent and Stretchable Conductive Hydrogel Sensors: Optimizing Ion Selection to Enhance Mechanical and Sensing Performance," *ACS Appl. Electron. Mater.* **7**(2), 874–883 (2025).
96. A. Roy, S. Zenker, S. Jain, *et al.*, "A Highly Stretchable, Conductive, and Transparent Bioadhesive Hydrogel as a Flexible Sensor for Enhanced Real-Time Human Health Monitoring," *Adv. Mater.* **36**(35), 2404225 (2024).
97. C. Keplinger, J.-Y. Sun, C. C. Foo, *et al.*, "Stretchable, transparent, ionic conductors," *Science* **341**(6149), 984–987 (2013).
98. L. Xu, Z. Huang, Z. Deng, *et al.*, "A Transparent, Highly Stretchable, Solvent-Resistant, Recyclable Multifunctional Ionogel with Underwater Self-Healing and Adhesion for Reliable Strain Sensors," *Adv. Mater.* **33**(51), 2105306 (2021).
99. L. Shi, K. Jia, Y. Gao, *et al.*, "Highly Stretchable and Transparent Ionic Conductor with Novel Hydrophobicity and Extreme-Temperature Tolerance," *Research* **2020**, 2505619 (2020).

100. Z. Cao, H. Liu, and L. Jiang, "Transparent, mechanically robust, and ultrastable ionogels enabled by hydrogen bonding between elastomers and ionic liquids," *Mater. Horiz.* **7**(3), 912–918 (2020).
101. M. Wang, J. Hu, and M. D. Dickey, "Tough ionogels: synthesis, toughening mechanisms, and mechanical properties—a perspective," *JACS Au*. **2**(12), 2645–2657 (2022).
102. B. Yiming, S. Hubert, A. Cartier, *et al.*, "Elastic, strong and tough ionically conductive elastomers," *Nat. Commun.* **16**(1), 431 (2025).
103. H. J. Kim, B. Chen, Z. Suo, *et al.*, "Ionoelastomer junctions between polymer networks of fixed anions and cations," *Science* **367**(6479), 773–776 (2020).
104. H. Dinh Xuan, B. Timothy, H. Y. Park, *et al.*, "Super stretchable and durable electroluminescent devices based on double-network ionogels," *Adv. Mater.* **33**(25), 2008849 (2021).
105. J. Yoo, S. Ha, G. H. Lee, *et al.*, "Stretchable High-Resolution User-Interactive Synesthesia Displays for Visual–Acoustic Encryption," *Adv. Funct. Mater.* **33**(48), 2302473 (2023).
106. F. Chun, B. Zhang, Y. Gao, *et al.*, "Multicolour stretchable perovskite electroluminescent devices for user-interactive displays," *Nat. Photonics* **18**(8), 856–863 (2024).
107. Z. Zhang, W. Wang, Y. Jiang, *et al.*, "High-brightness all-polymer stretchable LED with charge-trapping dilution," *Nature* **603**(7902), 624–630 (2022).
108. H. Kang, Y. Lee, G. H. Lee, *et al.*, "Strain-Tolerant, High-Detectivity, and Intrinsically Stretchable All-Polymer Photodiodes," *Adv. Funct. Mater.* **33**(13), 2212219 (2023).
109. M. Qin, Y. Bian, C. Wang, *et al.*, "Intrinsically Stretchable Organic Photodiodes for Faint Near-Infrared Light Detection and Extendable Cryptographic Imaging," *Adv. Funct. Mater.* **34**(40), 2403770 (2024).
110. Z. Wang, D. Zhang, L. Yang, *et al.*, "Mechanically robust and stretchable organic solar cells plasticized by small-molecule acceptors," *Science* **387**(6732), 381–387 (2025).
111. E. Dauzon, A. E. Mansour, M. R. Niazi, *et al.*, "Conducting and Stretchable PEDOT:PSS Electrodes: Role of Additives on Self-Assembly, Morphology, and Transport," *ACS Appl. Mater. Interfaces* **11**(19), 17570–17582 (2019).
112. D. Han, K. Zhou, X. Li, *et al.*, "Intrinsically Stretchable Organic Solar Cells and Sensors Enabled by Extensible Composite Electrodes," *Adv. Funct. Mater.* **34**(44), 2407392 (2024).
113. J. Wang, C. Yan, K. J. Chee, *et al.*, "Highly stretchable and self-deformable alternating current electroluminescent devices," *Adv. Mater.* **27**(18), 2876–2882 (2015).
114. C. Larson, B. Peele, S. Li, *et al.*, "Highly stretchable electroluminescent skin for optical signaling and tactile sensing," *Science* **351**(6277), 1071–1074 (2016).
115. C. H. Yang, B. Chen, J. Zhou, *et al.*, "Electroluminescence of giant stretchability," *Adv. Mater.* **28**(22), 4480–4484 (2016).
116. J. Wang, C. Yan, G. Cai, *et al.*, "Extremely stretchable electroluminescent devices with ionic conductors," *Adv. Mater.* **28**(22), 4490–4496 (2016).
117. F. Stauffer and K. Tybrandt, "Bright stretchable alternating current electroluminescent displays based on high permittivity composites," *Adv. Mater.* **28**(33), 7200–7203 (2016).
118. Z. Zhang, L. Cui, X. Shi, *et al.*, "Textile display for electronic and brain-interfaced communications," *Adv. Mater.* **30**(18), 1800323 (2018).
119. D. Hu, X. Xu, J. Miao, *et al.*, "A stretchable alternating current electroluminescent fiber," *Materials* **11**(2), 184 (2018).
120. B. Yang, Y. Zhao, M. U. Ali, *et al.*, "Asymmetrically Enhanced Coplanar-Electrode Electroluminescence for Information Encryption and Ultrahighly Stretchable Displays," *Adv. Mater.* **34**(31), 2201342 (2022).
121. P. Tran, N.-H. Tran, and J.-H. Lee, "Highly stretchable electroluminescent device based on copper nanowires electrode," *Sci. Rep.* **12**(1), 8967 (2022).
122. Y. Go, H. Y. Park, Y. Zhu, *et al.*, "Optically transparent and mechanically robust ionic hydrogel electrodes for bright electroluminescent devices achieving high stretchability over 1400%," *Adv. Funct. Mater.* **33**(32), 2215193 (2023).
123. S. Gu, Y. Zhou, Y. Li, *et al.*, "Ultrastretchable alternating current electroluminescent panels for arbitrary luminous patterns," *Appl. Mater. Today* **31**, 101764 (2023).
124. H. Lee, D.-h. Kang, S. Cho, *et al.*, "Low-voltage stretchable electroluminescent loudspeakers with synchronous sound and light generation," *ACS Appl. Mater. Interfaces* **15**(12), 16299–16307 (2023).
125. Z. Yu, X. Niu, Z. Liu, *et al.*, "Intrinsically stretchable polymer light-emitting devices using carbon nanotube-polymer composite electrodes," *Adv. Mater.* **23**(34), 3989–3994 (2011).
126. J. Liang, L. Li, K. Tong, *et al.*, "Silver nanowire percolation network soldered with graphene oxide at room temperature and its application for fully stretchable polymer light-emitting diodes," *ACS Nano* **8**(2), 1590–1600 (2014).
127. J.-H. Kim and J.-W. Park, "Intrinsically stretchable organic light-emitting diodes," *Sci. Adv.* **7**(9), eabd9715 (2021).
128. Y. Liu, M. Zhu, J. Sun, *et al.*, "A self-assembled 3D penetrating nanonetwork for high-performance intrinsically stretchable polymer light-emitting diodes," *Adv. Mater.* **34**(27), 2201844 (2022).
129. X. C. Li, L. Yao, W. Song, *et al.*, "Intrinsically Stretchable Electroluminescent Elastomers with Self-Confinement Effect for Highly Efficient Non-Blended Stretchable OLEDs," *Angew. Chem. Int. Ed.* **62**(2), e202213749 (2023).
130. W. Liu, C. Zhang, R. Alessandri, *et al.*, "High-efficiency stretchable light-emitting polymers from thermally activated delayed fluorescence," *Nat. Mater.* **22**(6), 737–745 (2023).

131. S. G. R. Bade, X. Shan, P. T. Hoang, *et al.*, “Stretchable light-emitting diodes with organometal-halide-perovskite-polymer composite emitters,” *Adv. Mater.* **29**(23), 1607053 (2017).
132. D.-H. Jiang, Y.-C. Liao, C.-J. Cho, *et al.*, “Facile fabrication of stretchable touch-responsive perovskite light-emitting diodes using robust stretchable composite electrodes,” *ACS Appl. Mater. Interfaces* **12**(12), 14408–14415 (2020).
133. Y. Park, C. Fuentes-Hernandez, K. Kim, *et al.*, “Skin-like low-noise elastomeric organic photodiodes,” *Sci. Adv.* **7**(51), eabj6565 (2021).
134. P. Mao, H. Li, X. Shan, *et al.*, “Stretchable photodiodes with polymer-engineered semiconductor nanowires for wearable photoplethysmography,” *ACS Appl. Mater. Interfaces* **15**(28), 33797–33808 (2023).
135. F. Chen, Y. Li, Y. Chen, *et al.*, “Supramolecular interface decoration on a polymer conductor for an intrinsically stretchable near-infrared photodiode,” *Chem. Commun.* **59**(80), 11975–11978 (2023).
136. L. Li, J. Liang, H. Gao, *et al.*, “A solid-state intrinsically stretchable polymer solar cell,” *ACS Appl. Mater. Interfaces* **9**(46), 40523–40532 (2017).
137. Z. Wang, M. Xu, Z. Li, *et al.*, “Intrinsically stretchable organic solar cells beyond 10% power conversion efficiency enabled by transfer printing method,” *Adv. Funct. Mater.* **31**(35), 2103534 (2021).
138. J. Noh, G.-U. Kim, S. Han, *et al.*, “Intrinsically stretchable organic solar cells with efficiencies of over 11%,” *ACS Energy Lett.* **6**(7), 2512–2518 (2021).
139. J. W. Lee, G. U. Kim, D. J. Kim, *et al.*, “Intrinsically-stretchable, efficient organic solar cells achieved by high-molecular-weight, electro-active polymer acceptor additives,” *Adv. Energy Mater.* **12**(28), 2200887 (2022).
140. J. W. Lee, S. Seo, S. W. Lee, *et al.*, “Intrinsically stretchable, highly efficient organic solar cells enabled by polymer donors featuring hydrogen-bonding spacers,” *Adv. Mater.* **34**(50), 2207544 (2022).
141. J. W. Lee, C. Lim, S. W. Lee, *et al.*, “Intrinsically stretchable and non-halogenated solvent processed polymer solar cells enabled by hydrophilic spacer-incorporated polymers,” *Adv. Energy Mater.* **12**(46), 2202224 (2022).
142. J.-W. Lee, C. Sun, S.-W. Lee, *et al.*, “Sequentially regular polymer acceptors featuring flexible spacers for high-performance and mechanically robust all-polymer solar cells,” *Energy Environ. Sci.* **15**(11), 4672–4685 (2022).
143. Z. Wang, D. Zhang, M. Xu, *et al.*, “Intrinsically Stretchable Organic Solar Cells with Simultaneously Improved Mechanical Robustness and Morphological Stability Enabled by a Universal Crosslinking Strategy,” *Small* **18**(26), 2201589 (2022).
144. J. Huang, Z. Lu, J. He, *et al.*, “Intrinsically stretchable, semi-transparent organic photovoltaics with high efficiency and mechanical robustness via a full-solution process,” *Energy Environ. Sci.* **16**(3), 1251–1263 (2023).
145. S. Lee, Y. Jeon, S. Y. Lee, *et al.*, “Intrinsically Stretchable Organic Solar Cells without Cracks under 40% Strain,” *Adv. Energy Mater.* **13**(30), 2300533 (2023).
146. Q. Wan, S. Seo, S.-W. Lee, *et al.*, “High-Performance Intrinsically Stretchable Polymer Solar Cell with Record Efficiency and Stretchability Enabled by Thymine-Functionalized Terpolyme,” *J. Am. Chem. Soc.* **145**(22), 11914–11920 (2023).
147. W. Yang, X. Luo, M. Li, *et al.*, “Achieving Efficient Intrinsically Stretchable Organic Photovoltaics with a Conjugated and Elastomeric Dual-Network Morphology,” *Adv. Energy Mater.* **15**(6), 2403259 (2025).
148. X. Li, H. Ke, S. Li, *et al.*, “Intrinsically Stretchable Organic Photovoltaic Cells with Improved Mechanical Durability and Stability via Dual-Donor Polymer Blending,” *Adv. Funct. Mater.* **34**(29), 2400702 (2024).
149. J.-W. Lee, E. S. Oh, S. Lee, *et al.*, “Strain-induced power output enhancement in intrinsically stretchable organic solar cells,” *Joule* **9**(2), 101792 (2025).
150. K. Xian, K. Zhang, T. Zhang, *et al.*, “Simultaneously improving efficiency, stability and intrinsic stretchability of organic photovoltaic films via molecular toughening,” *Energy Environ. Sci.* **18**(5), 2570–2583 (2025).
151. M. Sun, C. Wang, M. Xiao, *et al.*, “Control of Effective Elastomer Density Enables Mechanically Robust and High-Efficiency Intrinsically Stretchable Organic Solar Cells,” *Adv. Mater.*, **2025**, e14031 (2025).
152. Y. Ding, S. Xiong, W. A. Memon, *et al.*, “High-Performance Intrinsically-Stretchable Organic Solar Cells Enabled by Electron Acceptors with Flexible Linkers,” *Angew. Chem. Int. Ed.* **64**(14), e202421430 (2025).
153. J.-W. Lee, T. H.-Q. Nguyen, W. J. Kang, *et al.*, “Simultaneous integration of poly(dimethylsiloxane) elastomer in polymer donor and dimer acceptor enables strain-induced power enhancement in intrinsically-stretchable organic photovoltaics,” *Energy Environ. Sci.* **18**(7), 3325–3340 (2025).
154. D. Zhang, Z. Wang, J. Liu, *et al.*, ““Twisted” Terpolymer Donor Enabling High-Performance Intrinsically Stretchable Organic Solar Cells,” *Angew. Chem. Int. Ed.* **64**(43), e202509160 (2025).
155. L. Pei, D. Han, Y. Wang, *et al.*, “Advancing Intrinsically Stretchable Organic Photovoltaics with a Nearly Amorphous Polymer Semiconductor,” *Adv. Funct. Mater.* **35**(36), 2425892 (2025).