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Recent progress of stretchable displays: a comprehensive review of materials, device architectures, and applications

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Abstract

Recently, mechanically deformable displays, such as flexible, foldable, rollable, and stretchable displays, have received considerable attention due to their broad range of applications across various electronic systems. Among the various types of deformable displays, stretchable displays represent the most advanced form factor. The stretchable displays require a sophisticated integration of components, including stretchable conducting, insulating, and semiconducting materials, intricate geometrical patterns, and multiple electronic elements. This comprehensive review explores the recent progress in stretchable displays, emphasizing the critical developments in materials, device architectures, and practical applications. Key innovations in stretchable electrodes and interconnections, light-emitting materials, transistors, circuitry, and deformable substrates are explored, highlighting their contributions to enhancing durability and stretchability. Also, the review highlights the latest research on achieving stretchability using intrinsically elastic materials or through structural engineering with rigid materials. Additionally, we introduce innovative applications of stretchable displays in various emerging electronic systems.

Keywords: Stretchable displays, structure engineering, intrinsic stretchability, conductors, semiconductors, light-emitting layers, substrates

INTRODUCTION

Displays are indispensable in our daily lives, playing a critical role in human-machine interaction by visualizing information as prominent electronic devices. Over the past decade, significant progress has been made in miniaturization, the development of new luminescent materials, and enhancing display resolution[1-3]. Apart from the conventional rigid-type displays based on glass or wafer substrates, stretchable displays can mechanically deform to accommodate dynamic shapes and withstand mechanical strain without image distortion[4,5]. This unique flexibility can open up countless possibilities in various areas such as wearable devices[6], medical/healthcare monitoring systems[7], and the next-generation Internet of Things[8]. According to data obtained from a literature search, a keyword search for “stretchable displays” reveals a consistent increase in research activity over the past decade. The number of publications has grown approximately tenfold, from just 17 in 2014 to 197 in 2023. Notably, there was a sharp increase in the number of publications between 2018 and 2019 [Figure 1]. In particular, as technology progresses beyond the development stage, companies have developed various forms of stretchable displays for mass industrial production. For instance, various stretchable displays have been reported including a 9.1-inch bidirectional stretchable low-temperature polycrystalline silicon (LTPS)-based active-matrix organic light-emitting diode (AMOLED) display[9], a 14.1-inch stretchable 3D AMOLED display for freeform applications[10], and a full-color stretchable AMOLED display capable of withstanding both tensile and compressive deformations[11].

The development of stretchable displays continues to advance through materials engineering, device engineering, and manufacturing processes[12]. Key challenges include the achievement of high optical clarity, electrical conductivity, and mechanical robustness in stretchable substrates and electrodes simultaneously. Over the past decade, significant progress has been made in designing and manufacturing stretchable materials, including elastomers, polymers, and nano-material-based conductors, essential for achieving durable and efficient stretchable displays[12-15]. Exploration in materials engineering for stretchable displays focuses on identifying and synthesizing materials that exhibit excellent mechanical properties while maintaining optical clarity and electrical conductivity. Elastomers and polymers play critical roles as substrates, providing the flexibility necessary to accommodate bending and stretching without compromising the integrity of integrated electronic components[16]. Simultaneously, conductive materials such as carbon nanotubes (CNTs), graphene, and metal nano-particles are investigated for their ability to maintain electrical pathways during deformation, enabling reliable functionality across various deformations[14,17]. In complementing these advancements, pattern engineering emerges as a crucial field in optimizing the performance and durability of stretchable displays. By strategically designing the layout and architecture of stretchable circuits and electrodes, engineers can mitigate the stress concentrations and enhance overall mechanical robustness. Techniques such as serpentine designs, fractal patterns, and hierarchical architectures have shown promising results in dispersing strain and improving the lifespan of stretchable electronic products[18,19]. Figure 2 schematically summarizes the essential components for achieving the flexibility in display devices, emphasized in this review. This review aims to provide a comprehensive overview by focusing on recent research and technological innovations in stretchable display technology, exploring various approaches to manufacturing stretchable displays, from the basic components such as luminescent layers to thin-film transistors (TFTs) and integrated circuits, as well as electrodes and interconnects for accommodating mechanical deformations. Additionally, the review provides detailed discussions of recent research achievements from material and structural engineering perspectives, necessary for successful realization of the stretchable displays. Finally, we discuss promising applications such as wearable physical sensors for electronic skin applications, neuromorphic systems mimicking biological functions, and next-generation robotics, highlighting the unique advantages and potential of stretchable displays to expand the boundaries and future development directions for electronic devices.

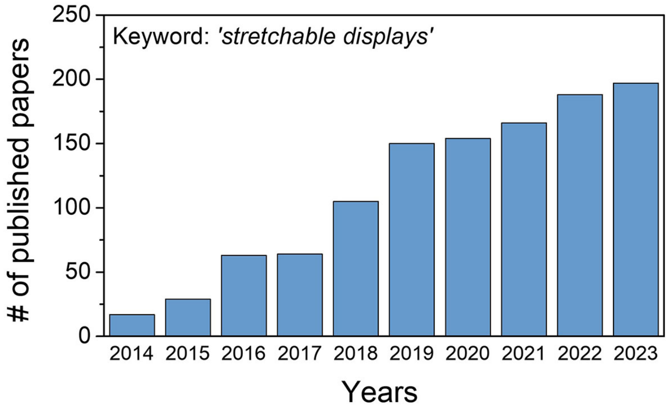

Figure 1. The number of published papers on stretchable displays by year based on the "Web of Science".

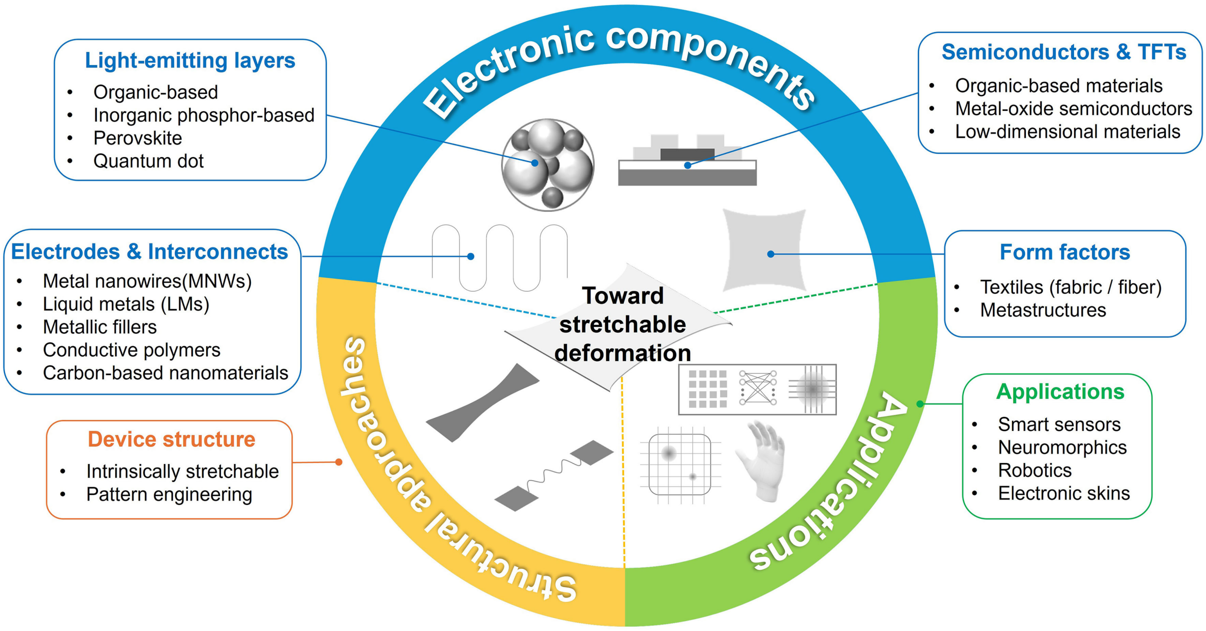

Figure 2. An overview of stretchable displays comprising electronic components, structural approaches for imparting stretchability to devices, and the next-generation applications of stretchable displays.

STRETCHABLE ELECTRODES AND INTERCONNECTS

Electrodes and interconnects are the key components that connect the light-emitting devices, TFTs, and the driving circuitry[20]. To achieve high-performance stretchable electrodes and interconnects, low electrical resistance and excellent mechanical stability should be achieved even under stretched conditions. For stretchable electrodes or interconnects, which are crucial components in the successful realization of stretchable displays, it is essential to maintain electrical connections between each component of the system even at a tensile strain (ε) of 100%[17]. However, enhancing the upper limit of the maximum tensile strain can contribute to improving mechanical reliability at lower deformation, making it desirable to achieve a strain of well over 100% for electrodes or interconnects to ensure practical applicability[17]. To satisfy this, intrinsically stretchable materials or designs of two-dimensional (2D) or 3D structure patterns can be applied to minimize mechanical stress and secure conductivity during stretching. In this section, various research in the areas of materials and structural designs for stretchable electrodes and interconnects is introduced. For display applications, highly conductive electrodes and interconnection are required to suppress the RC delay effect[21]. Therefore, electrode materials with an electrical resistivity of several μΩ-cm are typically used for active-matrix (AM) displays. Specifically, electrodes and interconnects utilizing metal nanowires (MNWs)[22-27], metallic particles (nano- or micro-scale)[28-33], liquid metals (LMs)[34-38], inorganic/organic-based composites[39], carbon-based nanomaterials[40], and hybrid-type conductive materials[41-44] are discussed. Figure 3 shows comparisons of different stretchable interconnect material types in terms of stretchability, transparency, conductivity, cost competitiveness, and processing scalability[17]. Additionally, stretchable electrodes/interconnects obtained through 2D or 3D structural pattern designs are also introduced, which typically utilize rigid inorganic or organic-based materials.

MNWs

Table 1 lists representative stretchable electrodes and interconnects reported recently, comparing the stretchability, electrical conductivity (or sheet resistance), materials, and applications. Among various types of conducting components, MNWs are the representative 1D-type nanomaterials that can exhibit low sheet resistance and high optical transparency owing to their percolating network structure and high aspect ratios[22]. The percolating network of 1D metallic nanomaterials is advantageous for maintaining electrical conductivity even under deformation conditions. Among them, silver nanowires (AgNWs) are most widely used due to their superior sheet resistance (< 10 $\Omega \cdot sq^{-1}$), high optical transparency (≥ 89%), low-cost fabrication, and ease of patterning[14]. Due to these unique properties, AgNWs have been utilized for deformable electrodes in solar cells, sensors, and displays by depositing or coating them on flexible or stretchable substrates[24]. In this context, Cai *et al.* reported a stretchable electroluminescent (EL) display using printed AgNW patterns as the electrodes[24] [Figure 4A(i)]. The AgNW ink was patterned on a biaxially pre-stretched polydimethylsiloxane (PDMS) substrate using a direct printing method. The fabricated stretchable conductor could maintain the electrical conductivity up to 156% of the stretching state. A stretchable EL device was demonstrated with parallelly printed AgNW electrodes assembled with a phosphor composite in a crossbar structure. The fabricated EL display could operate under a 20% stretching state [Figure 4A(ii)]. Similarly, Lin *et al.* reported high-resolution AgNW patterning into a PDMS substrate using the screen printing method[26]. The AgNW electrodes were patterned with high resolution (~50 μm) and utilized in a large-size stretchable circuit and light-emitting diode (LED) array. Additionally, other types of 1D-type nanomaterials, such as Au nanofibers[45], Cu meshes[46], and Cu nanowires[27], have also been reported for use as stretchable electrodes and interconnects in functional electronic devices.

LMs

LMs are also considered as one of the most impressive candidates for stretchable conductors due to their intrinsic characteristics of high electrical conductivity, extreme mechanical deformability, and possibility of large-area patterning[34,37]. In the case of using LMs as interconnecting materials, issues such as relatively low electrical conductivity and limited patternability should be resolved to implement in commercial-level display panels. Additionally, LMs are typically deposited using solution-based fabrication methods; therefore, appropriate process design is further required. As an example, Park *et al.* demonstrated a 4 × 4 stretchable AM micro-LED display using the LM-based interconnects[37] [Figure 4B]. The display pixel islands consisted of oxide TFTs and micro-LEDs. They fabricated oxide TFTs on a flexible polyimide (PI) substrate and bonded the micro-LEDs onto the TFT backplane. Afterward, the pixel islands were transferred onto a stretchable PDMS substrate and LM interconnect patterns were printed using a lift-off process. The micro-LED displays using the LM interconnection were able to function under stretching up to 24% without noticeable performance degradation. Furthermore, Liu *et al.* introduced a printable solid-liquid biphasic Ga-In (BGaIn) that maintains a near-constant resistance under stretching states[35]. The BGaIn was produced by thermally treating eutectic gallium-indium (EGaIn) nano-particles to form a liquid-

Table 1. Comparison of stretchability, electrical conductivity (or sheet resistance), conductive materials, and the applications of stretchable electrodes and interconnects

Year	Type	Stretchability	Sheet resistance/Conductivity	Materials	Applications	Ref.
2019	Conductive Polymers	100%	7×10^4 S·m^{-1} 75 Ω·sq^{-1}	PEDOT:PSS	Solar cell, OLED, electrochemical sensor	[39]
2018	Carbon-based Nanomaterials	60%	N/A 72 S·m^{-1}	Porous GHC/PDMS	Stretchable LED	[40]
2023	Organic/inorganic hybrid type	50%	N/A 2.2×10^6 S·m^{-1}	PSS-attached eutectic gallium-indium	Stretchable LED, pressure sensing systems for artificial finger	[42]
2022	1D/2D hybrid type	40%	24 Ω·sq^{-1} N/A	AgNW/graphene	Stretchable optoelectronics	[44]
2022	Organic/inorganic hybrid	30%	N/A	PVP-treated AgNW mesh and Au film	Strain and temperature sensing electrodes, antennas	[41]
2023	Liquid metal	24%	N/A 3×10^6 S·m^{-1}	EGaIn	Stretchable 4 × 4 micro-LED pixel array	[37]
2021	Liquid metal	1,000%	N/A 2.06×10^6 S·m^{-1}	BGaIn	Multilayer LED display, amplifier circuit, signal conditioning board	[35]
2022	1D metal nanofibers	100%	6.9 Ω·sq^{-1} N/A	CuNWs	ACEL display	[27]
2022	1D metal nanowires	30%	1.4 Ω·sq^{-1} N/A	Ag/Au core-shell nanowires	Breathable nanomesh devices	[25]
2023	Metal particles	30%	N/A 5.94×10^5 S·m^{-1}	Metallic particle fillers/PDMS	Stretchable wireless pressure sensors, passive matrix LED array	[31]
2023	Metal particles	200%	1.54×10^6 S·m^{-1} 0.65 Ω·sq^{-1}	AgNPs	Powering LED in flexible electronic systems	[29]

PEDOT:PSS: Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate; PSS: polystyrene sulfonate; OLED: organic light-emitting diode; N/A: not available; GHC: graphene honeycomb; PDMS: polydimethylsiloxane; AgNW: silver nanowires; EGaIn: eutectic gallium-indium; PVP: polyvinylpyrrolidone; BGaIn: biphasic gallium-indium; CuNWs: copper nanowires; ACEL: alternative current electroluminescence; AgNPs: silver nano-particles.

crystalline solid mixture. The BGaIn electrode exhibited a high electrical conductivity of 2.06×10^6 S·m^{-1}, stretchability of over 1,000%, and mechanical durability of up to 1,500 cycles. By utilizing a transfer-printing process, it was possible to realize various stretchable circuits, including a multilayer structured LED device, an amplifier circuit, and a signal monitoring board which can be applied to wearable sensing applications. Furthermore, alternative LMs besides the EGaIn are also actively developed to improve the printing characteristics and enhance bonding properties with substrates[36].

Metallic micro- and nano-particles

Additionally, stretchable conductive composites can be fabricated with conducting fillers such as metal flakes, micro- and nano-particles, and LM particles (LMPs) embedded in stretchable elastomer materials. One of the distinguished characteristics of these stretchable conductive composites is their function of maintaining electrical conductivity under extreme stretching conditions, mainly due to the percolation networks formed by the conducting fillers[31]. Song *et al.* have developed photothermal lithography-patterned stretchable conductors using Ag flake-based nanocomposites[31]. The fabricated nanocomposite conductor exhibited a high electrical conductivity of 5,940 S·cm^{-1} and negligible resistance change ($R/R_0 = 40$) under a 5,000 stretching cyclic test (30% strain). For the direct patterning, they used infrared (IR) nanosecond pulsed lasers and stacked them into a multilayered circuit [Figure 4C(i)]. It is explained that because of the different transmittance between Ag flakes and PDMS under IR irradiation, it was possible to induce photothermal conduction curing of Ag flakes in selective areas of the nanocomposite. By utilizing the stretchable nanocomposite as electrodes, a stretchable passive-matrix LED array was

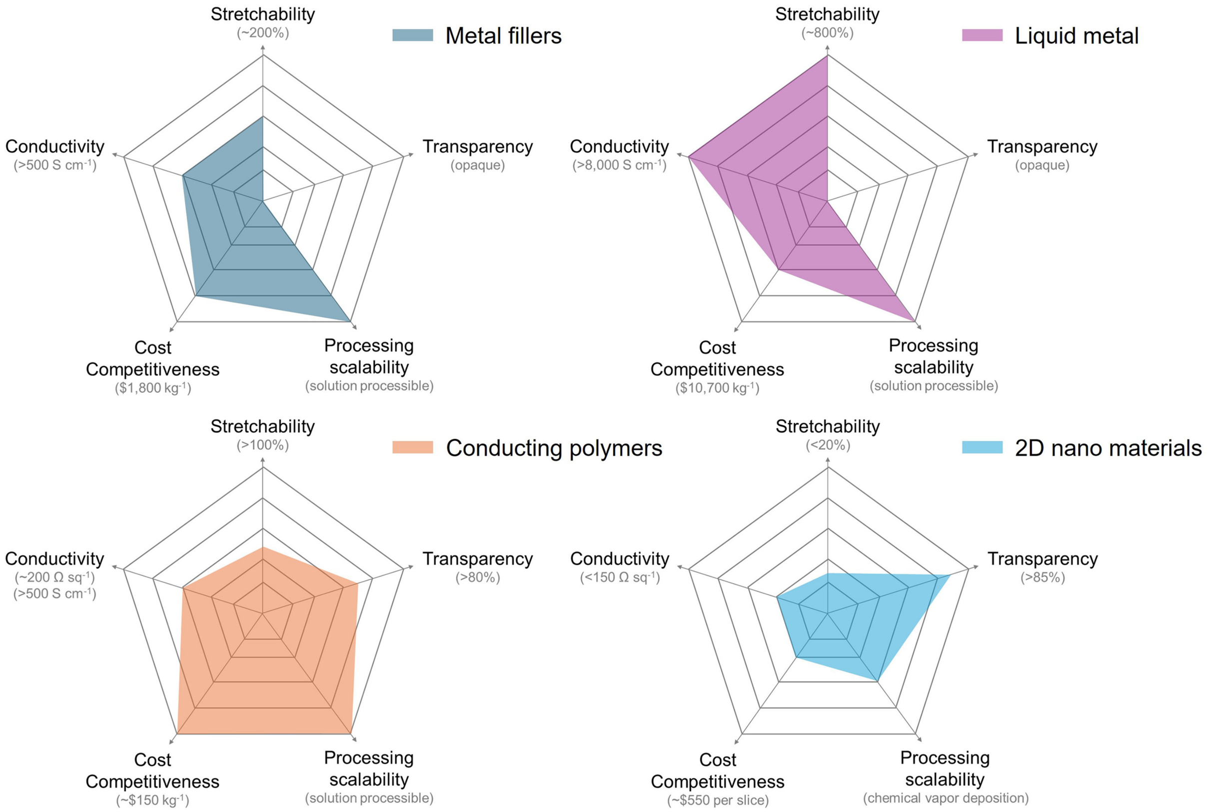

Figure 3. Comparisons of different stretchable interconnect material types in terms of stretchability, transparency, conductivity, cost competitiveness, and processing scalability[17]. Copyright 2023, Elsevier.

demonstrated, which could maintain the light emission even under a stretching state [Figure 4C(ii)]. Among the types of metallic particles, LMs, as mentioned above, could also be used for stretchable conductors. For instance, dispersion of LMPs in an elastomer is a representative approach for creating a long-range conducting network in composites[28,32]. Lee *et al.* reported a universal assembly process for mechanically tough LMP-based stretchable conductors[28]. By applying an acoustic field to the LMPs (EGaIn alloy, average size of 2-3 μm) in a polymer matrix, cavitation effect could be induced, forming the LM nanoparticles (LMP_{nano}, average size of 100 nm) at the LMP surface. The LMP_{nano} formed on the LMP surface were interconnected with the LMPs to compose a long-range assembled conducting network. As a composite undergoes stretching, the micrometer scale LMPs deform into ellipsoidal structures. In contrast, the LMP_{nano} interconnects remain unchanged, resembling solid particles. This structural stability allows for the maintenance of particle-to-particle contact even under large strains of up to 4,000%, thereby preserving electrical conductivity.

Conductive composites containing various conducting fillers such as conductive polymers or metal fillers mixed with a polymer matrix can offer the advantages such as large-area printing and patterning. In addition to the conductive fillers, the polymer matrix is also a key component that must be considered in obtaining high stretchability. Another important consideration is reconstructing the conducting pathway while maintaining high conductivity. In this regard, regulation of the conductive filler microstructure is one of the key approaches[33]. Wang *et al.* reported a processing of reorganizing Ag flake-based conductive filler inside a viscoelastic polymer matrix, developed for stretchable LED arrays[33]. It is explained that a self-orientation reorganization phenomenon inside a viscoelastic polymer matrix is induced by uniaxial cyclic

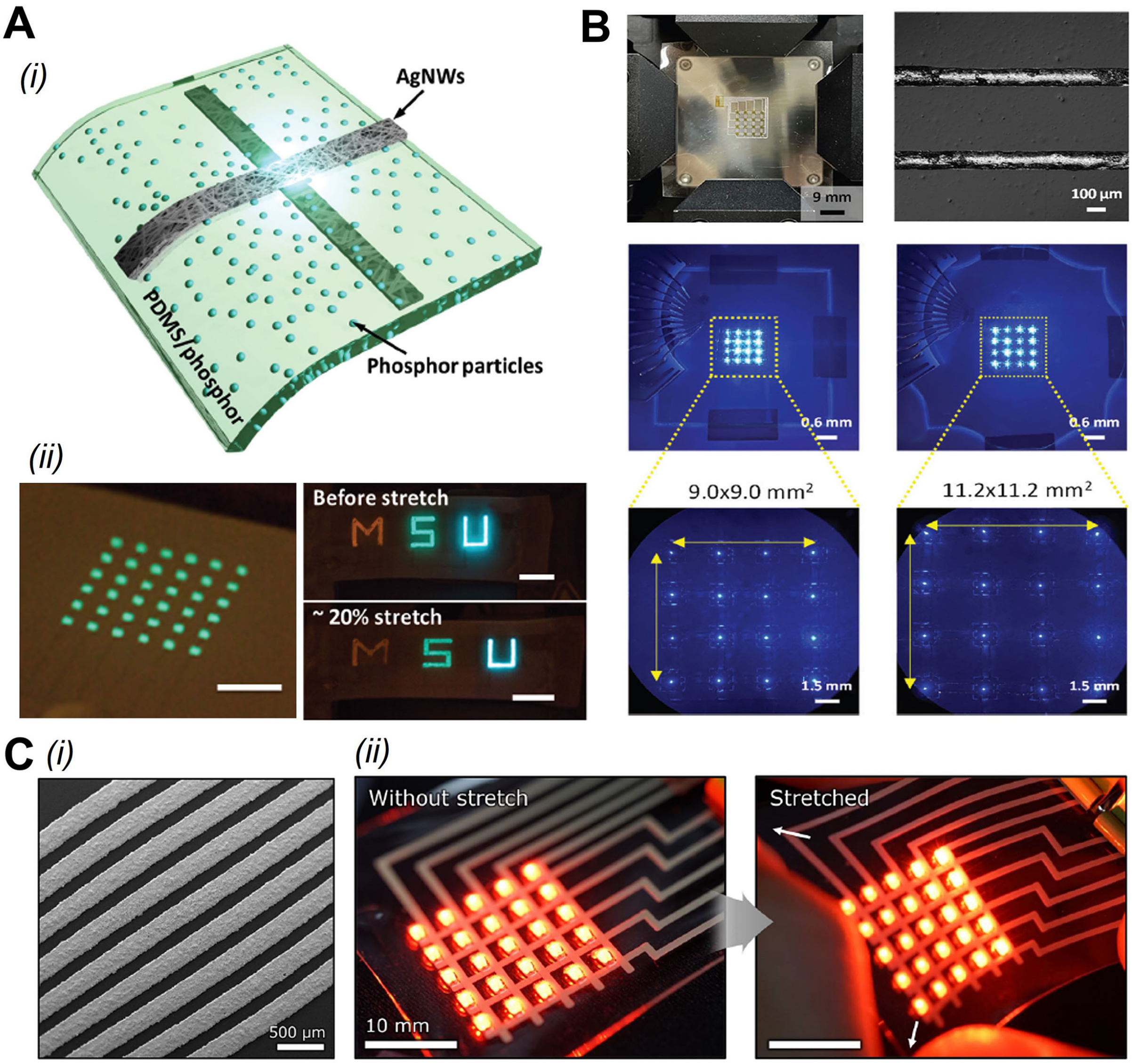

Figure 4. Metal-based electrodes and interconnects for stretchable display applications. (A) (i) A stretchable conductor structure using patterned AgNW layers, and (ii) LED array using AgNW stretchable electrodes and PDMS/phosphor substrates[24]. Copyright 2017, Wiley-VCH; (B) Optical images of LM-based interconnects and stretchable 4 × 4 micro-LED array. The micro-LED array function under 24% biaxial stretching[37]. Copyright 2023, Wiley-VCH; (C) (i) Image of photothermal-patterned stretchable Ag flake-PDMS composite. (ii) Operation of a passive matrix LED array fabricated using Ag-flake/PDMS interconnects[31]. Copyright 2023, ACS Publications. AgNW: Silver nanowire; LED: light-emitting diode; PDMS: polydimethylsiloxane; LM: liquid metal.

stretching. In detail, most of Ag flakes (~80%) were redistributed and aggregated near the top and bottom surfaces of the composite, leading to the formation of highly conductive pathways. Consequently, the electrical conductivity of ~10^4 S·cm^{-1} could be achieved. Moreover, the stretchable conductor exhibited good cycle durability under 1,000% stretching.

Conductive polymers

Another material candidate for stretchable electrodes and interconnects is the intrinsically stretchable conducting polymers. MNWs with high aspect ratios and metal micro- and nano-particles/flakes capable of self-organization upon deformation are promising fillers for stretchable devices. However, the percolationdependent conductivity is highly sensitive to mechanical deformation, and improvements in mechanical cycling stability would be required[47,48]. Therefore, utilizing intrinsically stretchable conductors is desirable for the fabrication of highly conductive stretchable devices. In particular, conductive polymers offer the flexibility of adjusting molecular structure and electrical/mechanical properties, and their solution processability provides advantages for the mass production of flexible electronic devices[47]. As an example, poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) has been reported as a promising conducting polymer[44]. PEDOT:PSS exhibits excellent coating uniformity and relatively low processing costs, along with desirable properties such as low sheet resistance (~46 $\Omega \cdot sq^{-1}$) and high transmittance (~82%)[49]. Moreover, it is amenable to various processing techniques, such as inkjet printing, photolithography, and screen printing, facilitating strategic patterning[50]. For the realization of stretchable interconnects and electrodes, the patterning process is a crucial part. Kraft *et al.* reported inkjet-printed stretchable interconnects based on conductive composites consisting of PEDOT:PSS, ionic additives, and surfactants[39]. The printed interconnects showed a maximum conductivity and sheet resistance of 7×10^4 $S \cdot m^{-1}$ and 75 $\Omega \cdot sq^{-1}$, respectively. The stretchable interconnects sustained strains above 100% and showed mechanical stability of up to 1,000 cyclic tests. As a potential application, the developed stretchable interconnects were utilized in stretchable circuits and interconnection of micro-LEDs [Figure 5A]. However, for polymer-based conducting materials, they have relatively lower electrical conductivity compared to typically metallic materials. They also can suffer from thermal instability, leading to performance degradation in high-temperature and air-ambient environments. Therefore, future research will involve addressing these challenges.

Carbon-based nanomaterials

Similar to metallic particle fillers, carbon-based nanomaterials such as 0D-shape carbon black (CB), 1D-shape CNTs, and 2D-shape graphene can be utilized as conductive fillers in stretchable composites due to their relatively low production cost and good mechanical properties[13]. The formation of percolation networks depends on the size and shape of carbon-based nanomaterials, which significantly impacts the preservation of electrical properties under stretching. Due to their high aspect ratio, 1D-structured CNTs are widely utilized as conductive fillers in stretchable composites. For instance, Gong *et al.* reported a method to fabricate stretchable electrodes by forming anisotropic CNT wrinkle films coated on latex balloon substrates, achieving up to 500% tensile strain and maintaining a gauge factor of ~0.09 with resistance change within 200% strain[51]. Wang *et al.* demonstrated the fabrication of conductive and stretchable graphene honeycomb (GHC) with a porous structure using a 3D-printing process[40] [Figure 5B(i)]. It was demonstrated that the GHCs exhibit density and electrical conductivity of 3.25 $mg \cdot cm^{-3}$ and 72 $S \cdot m^{-1}$, respectively. In addition, the porous structure of the GHC enabled low resistance changes and mechanical stability in stretching conditions up to 60%. By utilizing the GHCs sandwich as the interconnect circuits, stretchable LED displays as pixel-type structures were demonstrated [Figure 5B(ii)].

Hybrid materials

To further enhance the performance and stability of intrinsically stretchable materials, a combination of various conductive materials can be a feasible pathway. This approach has the advantages such as the facile development of high-performance stretchable materials by combining and mixing different materials to complement their limitations, in terms of mechanical durability and electrical properties. For example, a mixture of inorganic- (*cf.* LM EGaIn) and organic-based (*cf.* conductive polymer) materials can be adopted. In the case of EGaIn, which is frequently used as a stretchable electrode, realizing high-performance stretchable electrodes or interconnects can be limited due to the fluidity, high surface tension, surface oxide film formation, and conductivity change during stretching[42,52]. Lee *et al.* presented a wafer-scale conductive film with enhanced chemical/mechanical durability by encapsulating PSS on particulate EGaIn using a photolithography process[42] [Figure 5C(i)]. They successfully demonstrated a large area multilayer

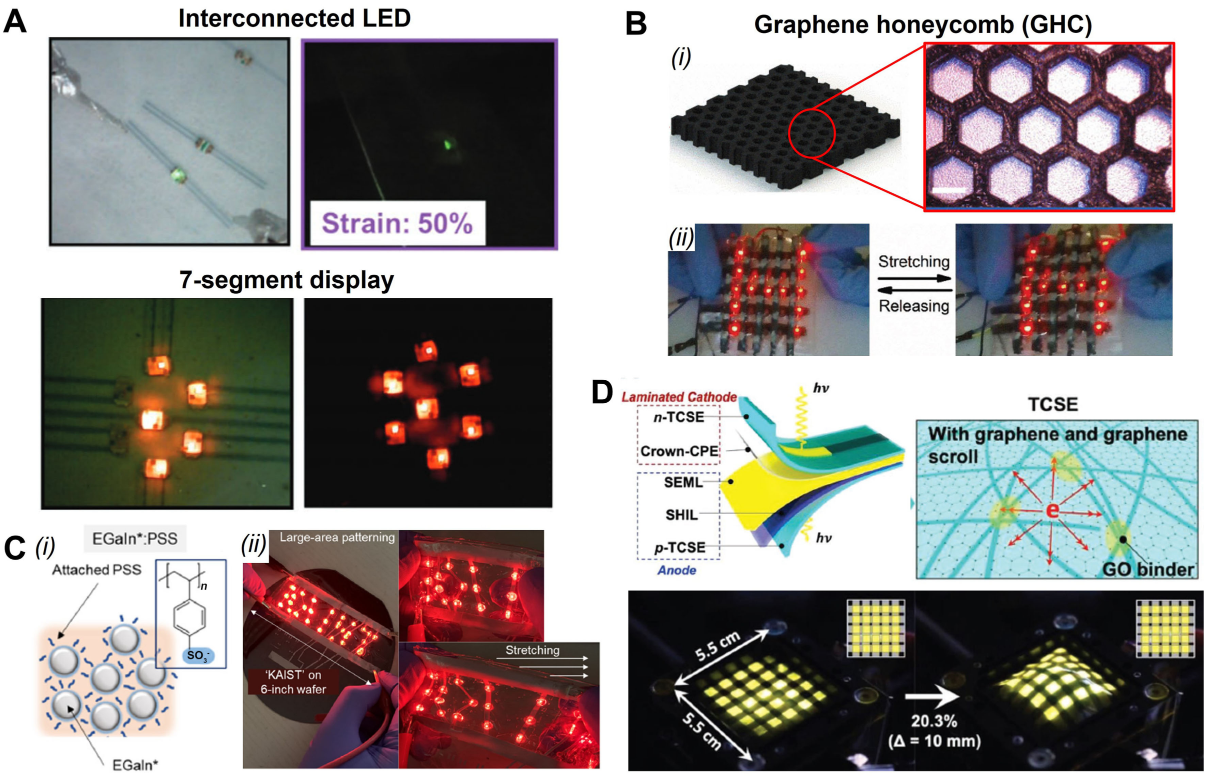

Figure 5. Various stretchable electrodes and interconnects for stretchable LED displays. (A) Interconnection of micro-LEDs using printed PEDOT:PSS and demonstration of a 7-segment display unit[39]. Copyright 2019, Wiley-VCH; (B) (i) Optical images of a porous GHC/PDMS composite. (ii) Operation images of a stretchable display constructed using GHC[40]. Copyright 2018, Wiley-VCH; (C) (i) Schematic illustration of PSS attached EGaIn particles. (ii) Operation of a LED display with EGaIn/PSS interconnects[42]. Copyright 2023, Elsevier; (D) Conceptual illustration of 2D-contact stretchable electrodes and a 5 × 5 passive matrix ISOLED[44]. Copyright 2022, Wiley-VCH. LED: Light-emitting diode; PEDOT:PSS: poly(3,4-ethylenedioxythiophene) polystyrene sulfonate; GHC: graphene honeycomb; PDMS: polydimethylsiloxane; 2D: two-dimensional.

structured PSS attached EGaIn thin-film on various substrates through the photolithography process and used as an interconnect to implement multifunctional soft electronic devices such as 6-inch stretchable LED displays [Figure 5C(ii)]. As another example, Zhou *et al.* reported graphene-based 2D-contact stretchable electrodes (TCSEs) that incorporate a layer of graphene on top of embedded AgNWs networks in the styrene-ethylene-butadiene-styrene (SEBS) elastomer matrix[44] [Figure 5D]. The researchers improved the mechanical stability and charge injection by using the mixture of 2D structure graphene layer and the 1D structure AgNWs. The assessment of low work function due to the induced interfacial dipole is explained as the underlying mechanism. Based on the fabricated electrode, an intrinsically stretchable organic LED (OLED) display was demonstrated to have a current efficiency of 20.3 cd·A^{-1}. Furthermore, by utilizing the TCSEs, they successfully implemented a stretchable 3-inch 5 × 5 passive matrix OLED array [Figure 5D].

Mechanical pattern design or microstructure engineering

This section introduces several approaches to improve the durability during stretching by optimizing the structural design. Generally, when applying mechanically brittle semiconductors or conducting materials to stretchable devices, designing the macro-scale (extrinsically stretchable components) and the micro-scale (intrinsically stretchable materials) can be a critical component including geometrical design engineering such as wrinkled structures (pre-stretching approaches), island-bridge structures, microstructures, and stretchable platforms[15]. Zhu *et al.* designed both mechanically interlocking structures and chemical adhesive polymers to assemble individual soft devices onto soft patternable circuits toward multifunctional electronics [Figure 6A][53]. Specifically, the stretchable interconnections were fabricated with elastic Au thin-film-coated PDMS microbridges and an adhesive polymer, poly[(dopamine methacrylamide)-co-(acrylic acid)]. As a result, stretchability of up to 35% strain ($R/R_0 \le 5$) could be obtained. As a proof-of-concept, a stretchable strain sensor and stretchable supercapacitor interconnected in soft circuits were successfully fabricated. Furthermore, utilizing a stretchable platform structure can be another way to facilitate the integration of soft electronic devices and interconnects. Composite fibers comprised of polymers and conductive nanomaterials can maintain the conductivity under bending or stretching deformation. Kwon *et al.* demonstrated surface-enriched Ag nano-particles (AgNPs)/polyurethane (PU) hybrid conductive fiber which is encapsulated by tough self-healing polymers (T-SHPs), as a fiber-based durable interconnects[54] [Figure 6B]. The T-SHP layer improved the electrical and mechanical durability. Due to the stability of electrical pathways in the Ag-rich shells, the stretchable conducting fiber exhibited 30,485 $S{\cdot}cm^{-1}$ of conductivity under 300% of stretching. Additionally, Lee *et al.* developed a 3D stretchable display that can maintain pixel density and image quality under 100% strain state[55]. They utilized 3D structures inspired by the origami and kirigami structures, which are structural engineering techniques that impart stretchability by optimizing stress distribution in rigid materials. Also, they provided detailed materials design of Au with graphene to improve the mechanical durability. As a potential application, a 7 × 7 GaN micro-LED pixel array was demonstrated, which maintained the image quality and pixel density uniformly even up to 100% strain state [Figure 6C]. In a similar approach, interconnect patterns connecting the LED pixels can be designed to endow with variability to inorganic-based LED displays. For instance, Kim *et al.* used a double-layer modular design to pattern PI/Cu interconnects and incorporated them with 256 AlGaInP LED pixels[56] [Figure 6D]. Using this process, the researchers reported that the area coverage, which is the ratio of the LED pixel's light emitting area to the total display area, was improved by up to 77%, while maintaining the stretchability of the display of up to 10%. This approach can be considered as a solution to improve the relatively low area coverage while maintaining proper elasticity in inorganic-based stretchable LED displays. As another example of a unique design that implements stretchable rigid interconnect structures, Lee *et al.* proposed a 3D architecture for stretchable displays that considers the geometric fill factors which is defined as the ratio of the active area to the total area under tensile strain[57]. The researchers replaced conventional serpentine interconnectors, commonly used in rigid stretchable interconnectors, with an ultrathin hidden active area to achieve a unique design for compensation of loss of fill factor loss. Specifically, they proposed a solution where the interconnects are folded with a very narrow bending radius along the negative z-axis between adjacent active islands in a 3D rigid island array. These folded sections remain invisible under normal states but emerge to the surface when stretched, mitigating the rapid decrease in fill factor during stretching. To ensure precise technical implementation, the researchers adopted a quadaxial stretching method instead of the traditional biaxial approach. This allowed them to minimize deformation in the 3D island array, as well as in the encapsulation layer and electrodes of the OLED. As a result, the fabricated stretchable OLED successfully maintained an initial fill factor of 97% in the unstretched state and retained 87% of the fill factor under 30% biaxial stretching. This structural approach demonstrates the potential of advanced stretchable displays by enabling the entire system to stretch while maintaining the primary active area, with the interconnects serving as secondary active areas that emerge upon stretching to minimize fill factor loss.

STRETCHABLE SEMICONDUCTORS AND TRANSISTORS

TFTs and their constituent semiconductor materials are the essential components for constructing physical/chemical sensors, memory devices, multifunctional circuits, and displays[58]. Unlike typical flat structure electronics, realizing flexible or stretchable TFTs presents various technical challenges. These include unexpected performance degradation due to mechanical stress, poor mechanical durability, low power efficiency, and high fabrication costs due to process complexity[59]. In this section, we introduce TFTs for

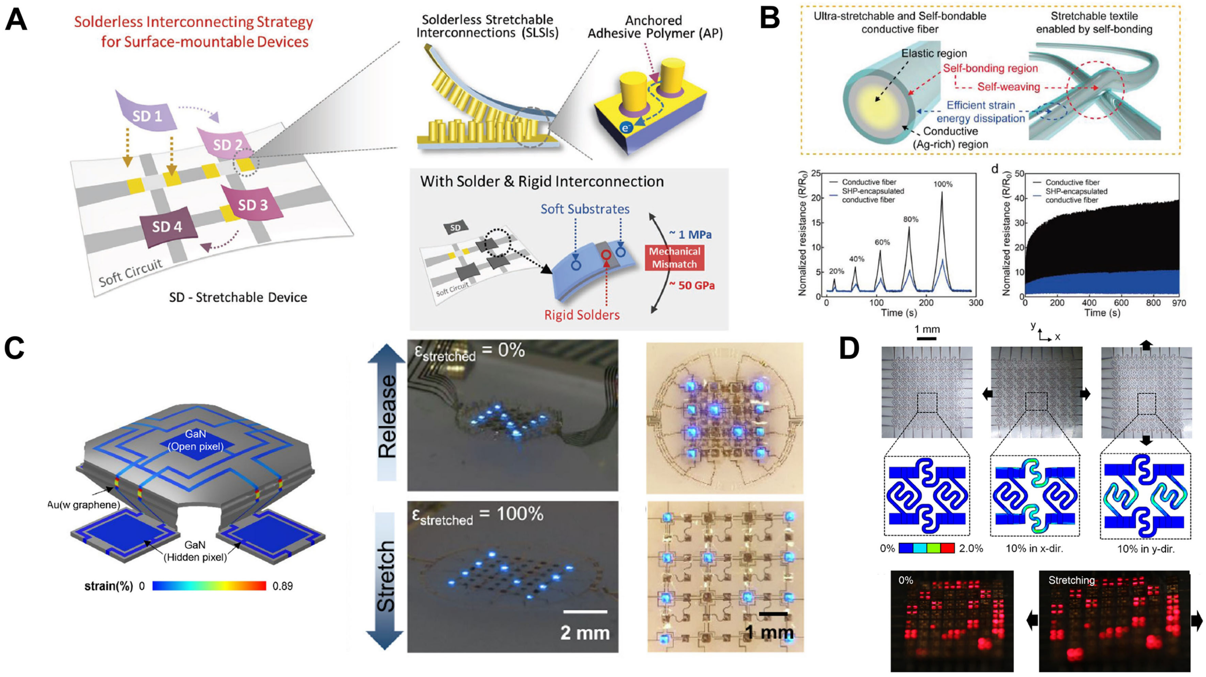

Figure 6. Structural engineering of interconnects for stretchable displays. (A) An all-stretchable platform with solderless stretchable interconnection. Flexible interconnects via mechanically interlocked conductive microbridges and optionally anchored adhesive polymers[53]. Copyright 2022, Wiley-VCH; (B) Schematic illustrations of a T-SHP-encapsulated conductive fiber and strain test results of conductive fiber (black) and T-SHP-encapsulated conductive fiber (blue)[54]. Copyright 2020, Wiley-VCH; (C) Optical image of micro-LED integrated into a 3D geometry structure utilizing Au with graphene interconnects on a supporting plastic film[55]. Copyright 2022, Elsevier; (D) High fill factor stretchable inorganic LED display using double layer interconnect design[56]. Copyright 2022, ACS Publications. T-SHP: Tough self-healing polymer; LED: light-emitting diode.

implementing stretchable displays and their core components, semiconductors materials, categorized into polymer-based (organic)[60-71], metal-oxide (inorganic)[72-81], and low-dimensional materials[82-86]. Additionally, we discuss recent research trends in the manufacturing and synthesis of intrinsically stretchable semiconductors, as well as structural designs that impart stretchability. We also explore the multifaceted approaches to implement stretchable TFTs and semiconductors. Table 2 lists previous research on stretchable TFTs utilizing various active channel layers, comparing their mechanical stretchability, carrier mobility or subthreshold swing (SS) characteristics.

Organic-based intrinsically stretchable semiconductors

Intrinsically stretchable polymer-based semiconductors have advantages such as low cost for fabrication, suitability for large-area patterning, and ease of manufacturing for high-density devices[62]. However, it is essential to improve the electronic properties under mechanical stress and the environmental stability[62,70]. The development of intrinsically stretchable semiconductors faces several challenges. For example, research was performed to realize low-power operation and improvement of transconductance of stretchable organic thin film transistors (OTFTs) with low threshold voltage (V_{th}). Kim *et al.* introduced intrinsically stretchable OTFTs based on nanoconfined poly-[2,5-bis(2-octyldodecyl)-3,6-di(thiophen-2-yl) pyrrolo [3,4-c]pyrrole-1,4(2H,5H)-dionel-alt-thieno [3,2-b]thiophene] (DPPT-TT) active layer in SEBS matrix [Figure 7A(i)][71]. The transfer characteristics, SS, and trap density (N_t) of the device are shown in [Figure 7A(ii)]. The device showed a relatively low trap density of 1.5×10^{11} $cm^{-2} \cdot eV$. Additionally, Liu *et al.* demonstrated a stretchable AM-driven organic light-emitting electrochemical cell (AMOLEC) array to realize a skin-applicable stretchable display[61]. They assembled the stretchable light emitting layer in a sandwich structure using

Table 2. Comparison of stretchability, carrier mobility, SS, active materials, and the applications of stretchable TFTs

Year	Type	Stretchability	Mobility ($cm^2 \cdot V^{-1} \cdot s^{-1}$) SS ($mV \cdot dec^{-1}$)	On/Off ratio	Active materials (Channel layer)	Applications	Ref.
2021	Intrinsically stretchable OTFT	100%	1.81 N/A	N/A	PIDTBT	Stretchable OTFTs	[64]
2022	Intrinsically stretchable OTFT	620%	0.6 500	1.0×10^5	PDPP-TT	Stretchable amplifier circuits	[68]
2022	Intrinsically stretchable OTFT	25%	1 N/A	4.5×10^4	PDPP-C4Ph	Stretchable OTFTs	[66]
2022	Intrinsically stretchable OTFT	120%	1.28 N/A	N/A	PU(DPP)/PDPP3T	Stretchable OTFTs	[67]
2021	Intrinsically stretchable OTFT	50%	1 N/A	N/A	*In-situ* rubber matrix semiconductor	Stretchable OTFTs	[65]
2023	Low-dimensional channel	40%	12.52 252	2.31×10^5	CNTs	Logic gate circuits	[85]
2021	Low-dimensional channel	100%	24 > 1,000	1.1×10^5	CNTs	Stretchable CNT-TFTs	[82]
2021	Low-dimensional channel	50%	32.4 N/A	1.0×10^8	MoS_2	Optoelectronics	[84]
2024	Rigid island structure	50%	12.7 117	1.0×10^7	IGZO	Logic gate circuits	[80]
2022	Serpentine string structure	100%	56.2 N/A	N/A	ITO	Stretchable large-scale integration	[78]
2022	Rigid island structure	50%	30 N/A	1.0×10^8	ITZO	Stretchable metal-oxide TFT	[77]

SS: Subthreshold swing; TFT: thin-film transistor; OTFT: organic thin film transistor; N/A: not available; PIDTBT: indacenodithiophene-co-benzothiadiazole; PDPP-TT: poly(3,6-di(2-thien-5-yl)-2,5-di(2-octyldodecyl)-pyrrolo[3,4-c]pyrrole-1,4-dione) with thieno[3,2-b]thiophene; PDPP-C4Ph: poly(3,6-di(2-thien-5-yl)-2,5-di(2-octyldodecyl)-pyrrolo[3,4-c]pyrrole-1,4-dione) with alkylphenyl (C4Ph); PU: polyurethane; PDPP3T: poly(diketopyrrolopyrrole-terthiophene); CNTs: carbon nanotubes; MoS_2: molybdenum disulfide; IGZO: indium gallium zinc oxide; ITO: indium tin oxide; ITZO: indium tin zinc oxide.

polyurethane acrylate (PUA)-coated with AgNWs as an electrode and PEDOT:PSS as a hole injection layer to fabricate a vertically integrated stretchable AMOLEC array. The stretchable emissive layer was fabricated by mixing the super yellow luminescent polymers, ion conductive polymers, ethoxylated trimethylopropane triacrylate (ETT-15) and lithium trifluoromethane sulfonate (LiTf). The developed AMOLEC array could stably operate under variation deformation conditions [Figure 7B].

Organic-based stretchable semiconductors with structural engineering

Another pathway to obtain stretchability in organic-based semiconductor materials is to provide durability against mechanical stress through the structural engineering of device components. For example, it is possible to control the crack formation and the stress distribution by inserting an interlayer between the soft substrate and the semiconductor, or by applying a pattern to the semiconductor film. Li *et al.* showed a strategy for soft interlayer designs that can significantly improve the elasticity of the active layers on substrates which have lower elastic modulus by using relatively high modulus stretchable materials [Figure 7C][87]. They designed a soft interlayer structure consisting of SEBS to overcome the large difference in moduli across the interface based on the fracture mechanism[88-90] of the film formed on the elastomer substrate. The soft interlayer has an intermediate Young's modulus (2.83 MPa) between the semiconductor films (DPPT-TT, modulus: 19.4 MPa) and the substrate [polyacrylamide (PAAm), modulus: 55 kPa], providing sufficient adhesion on both sides. The fabricated stretchable OTFTs on the PAAm substrate with SEBS soft interlayer structure have an effective Young's modulus of 5.2 kPa, which is 2-3 times softer than the conventional elastomer-based stretchable device. Also, Kim *et al.* fabricated polymer semiconductor

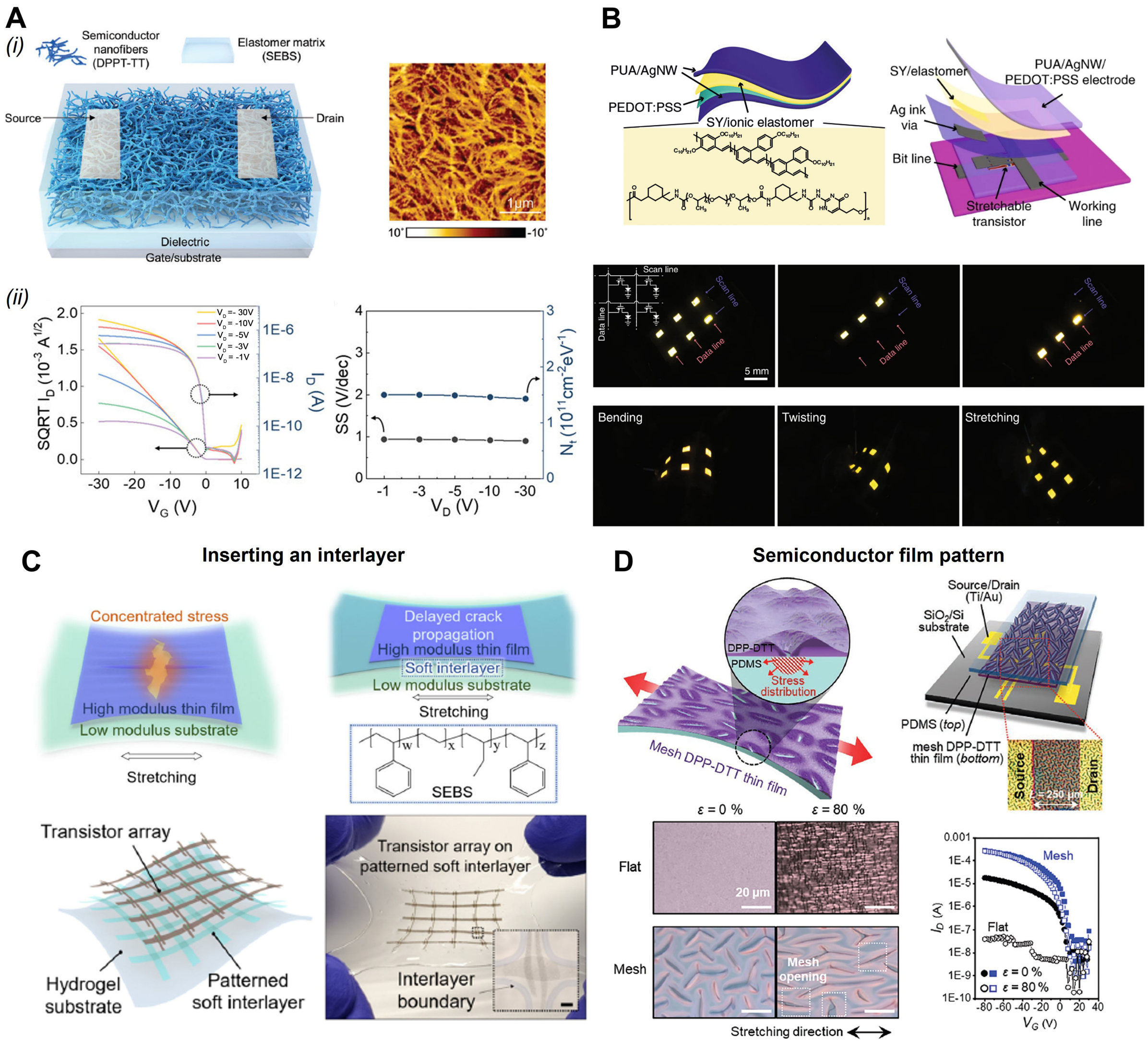

Figure 7. Stretchable semiconducting films and TFTs based on organic semiconductors. (A) (i) Schematic illustration of nanofiber-structured DPPT-TT OTFTs and atomic force microscope image of the semiconducting layer. (ii) Electrical characteristics of nanofiber-structured OTFT[71]. Copyright 2023, Wiley-VCH; (B) Structure of stretchable AMOLEC array and photographs of AMOLEC display pixels[61]. Copyright 2020, Springer Nature; (C) Concept of inserting a stress-relief interlayer between the semiconductor and substrate[87]. Copyright 2023, Springer Nature; (D) Schematic illustration and optical microscope images of a micro-wrinkle pattern semiconductor film and the electrical performance of OTFTs[91]. Copyright 2021, Wiley-VCH. TFT: Thin-film transistor; DPPT-TT: poly-[2,5-bis(2-octyldodecyl)–3,6-di(thiophen-2-yl) pyrrolo [3,4-c]pyrrole-1,4(2H,5H)-dionel-alt-thieno [3,2-b]thiophene]; OTFT: organic thin film transistor; AMOLEC: AM-driven organic light-emitting electrochemical cell.

films in the form of a mesh-like pattern to control the stress distribution and to improve the stretchability and charge transport properties[91]. The stretchable polymer semiconductor film was fabricated by spin-coating π-conjugated polymer, poly[2,5-(2-octyldodecyl)-3,6-diketopyrrolopyrrole-alt-5,5-(2,5-di(thien-2-yl)thieno [3,2-b]-thiophene)] (DPP-DTT), onto a PDMS substrate [Figure 7D]. The mesh-like patterns were formed by controlling the ultraviolet (UV)/ozone treatment time and elastic modulus of PDMS (optimizing the ratio of the PDMS prepolymer and crosslinker) before the spin coating. The formed mesh-like pattern consists of vacant regions in the deep part of the wrinkles and polymer aggregated crystal regions where the percolation paths are formed. It is reported that the vacant regions of the mesh wrinkle are responsible for the stress distribution which contributes to preventing the performance degradation during stretching. As a demonstration, OTFTs were fabricated using the mesh-like polymer semiconductor films. In this case, the initial mobility increased compared to the flat-type OTFTs due to the improved charge transport performance caused by the crystal regions of wrinkles, and the electrical performance degradation was not significant even up to 80% stretched condition [Figure 7D].

Metal-oxide stretchable TFTs

Amorphous oxide semiconductors (AOSs) have great potential in various electronic applications due to their high uniformity, good stability, low leakage current, and high field-effect mobility[92,93]. However, there are significant limitations in implementing the AOS TFTs in stretchable displays due to their brittle nature. Nevertheless, AOS-based stretchable TFTs have been extensively studied by numerous researchers through structural design and deformation engineering, including rigid island structures, wavy-like string structures, and application of stress-relieving dielectric materials[81]. In this section, recent studies and achievements of AOS-based stretchable TFTs are discussed.

Figure 8A shows stretchable InGaZnO (IGZO) TFTs and circuitry with large-area scalability utilizing a rigid-island structure reported by Kang *et al.*[81]. Their strategy was to adopt a dual-island structure on molecular-tailored elastomeric substrates [soft PUA substrate and rigid polyepoxy acrylate (PEA) island] to improve the mechanical properties and maintain the electrical properties at stretched conditions. Also, in consideration of large area and mass production, a bottom-up photolithography-based patterning approach was adopted. It is suggested that the adhesion between PUA substrate and PEA island was improved by forming strong covalent bonds on the two polymer interfaces using the acrylic functional groups derived from a soft PUA substrate and rigid PEA island. Consequently, they successfully demonstrated stretchable (strain up to 50%) 7 × 7 TFT arrays including various circuits such as logic gates and 7-stage ring oscillators. Another example of the stretchable oxide TFTs utilizing rigid-island structures was conducted by Miyakawa *et al.*[78]. A large strain deformation occurs at the interface between the stretching region (soft substrate) and the non-stretching region (rigid island) in the stretchable device. Therefore, strong interfacial adhesion between the rigid island region and the soft substrate is required to secure stable operation under stretching. As shown in Figure 8B, an acrylic adhesive layer was utilized to provide strong adhesion between the PI rigid island and the soft substrate, enabling stable switching characteristics with a field-effect mobility of 30 $cm^2 \cdot V^{-1} \cdot s^{-1}$ without significant performance degradation even at 50% tensile stretching.

Another approach to achieving stretchability is structural engineering. Oh *et al.* reported fabrication of IGZO TFTs on a serpentine string structure to overcome the trade-off between device integration density and stretchability [Figure 8C][79]. Particularly, to obtain mechanical stretchability, the TFT devices were fabricated directly on the serpentine structure PI strings. After fabricating the TFTs, the devices were coated with a second PI layer to place the TFT devices near the center of the PI cladding. The cladded TFT devices were transferred to a stretchable substrate by using a lift-off process. This unique structural approach enabled a maximum integration density of > 30,000 transistors/cm^2, and the stress could be minimized even at 100% strain, maintaining the electrical properties. Another recent attempt was reported to improve the mechanical robustness of TFT devices while maintaining their electrical performance by applying a combination of organic/inorganic materials to the stress relief buffer layers and dielectric layers. As shown in [Figure 8D], Kim *et al.* reported the utilization of organic-inorganic hybrid gate insulators and buffer layers to fabricate metal oxide-based stretchable TFTs[73]. An indium-gallium-tin-oxide (IGTO) channel layer was used because the film formation could be performed at a relatively lower temperature compared to IGZO (~150 °C). Also, the hybrid film was fabricated by the combination of 1,6-bis(trimethoxysilyl)hexane (BTMSH) organic crosslinking agent and zirconium oxide (ZrO_x). The IGTO TFTs fabricated on a PI-coated glass substrate were separated from the glass substrate and transferred onto a stretchable substrate (polyethylene, PE) in a similar process shown in [Figure 8C]. The stretchable IGTO TFTs on PI/PE

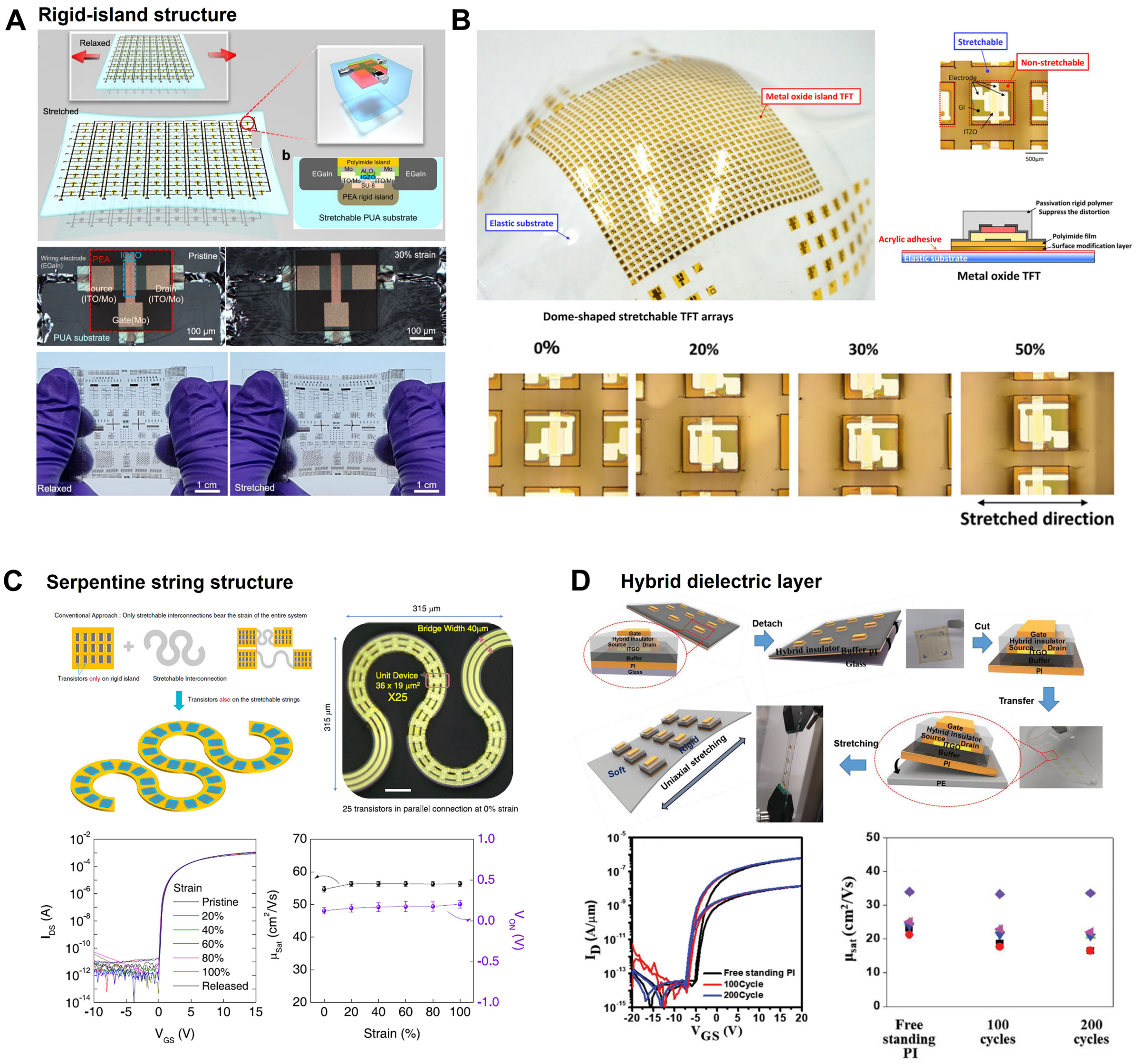

Figure 8. Stretchable metal-oxide TFTs employing structural designs and deformation engineering. (A) Large-area scalable stretchable IGZO TFTs and circuitry using a dual-island structure on molecular-tailored elastomeric substrates[81]. Copyright 2024, Springer Nature; (B) Rigid island structure ITZO TFTs utilizing an acrylic adhesive layer to provide strong adhesion between PI rigid island and soft substrate[78]. Copyright 2022, Wiley-VCH; (C) IGZO TFTs cladded onto a serpentine-structured PI film[79]. Copyright 2022, Springer Nature; (D) Stretchable IGTO TFTs composed of a stress-relief buffer layer and a dielectric layer combining organic/inorganic hybrid materials[73]. Copyright 2020, Wiley-VCH. TFT: thin-film transistor; IGZO: InGaZnO; ITZO: indium tin zinc oxide; PI: polyimide.

substrate exhibited a carrier mobility of ~21.7 $cm^2 \cdot V^{-1} \cdot s^{-1}$, SS of 0.68 $V \cdot decade^{-1}$, and on/off ratio of ~2.0×10^7 even under 300% stretching and 200 cyclic tests.

Low-dimensional semiconducting materials

In recent years, in addition to the above-described organic and metal oxide semiconductors, carbon-based nanomaterials and 2D materials have been actively researched for stretchable TFTs[82-86]. In particular, CNT-based channels have been applied to various stretchable electronics owing to their inherent elasticity and excellent carrier mobility[13]. The inherent nature of stretchability is attributed to the formation of percolation networks which is a unique characteristic of 1D materials[94-96]. Also, Nishio *et al.* reported parylene-C-coated CNT TFTs using a room temperature chemical-vapor deposition process, resulting in stretchable TFTs maintaining the drain current level at a maximum strain of 35% without degradation[84] [Figure 9A]. They explained that the high Young's modulus of parylene-C (about 3.2 GPa) enabled effective suppression of stress distribution applied to the channel region in the TFTs. The fabricated stretchable TFTs could be operated at a low voltage of ~0.7 V and had robust stability even under biaxial stretching. In addition, they successfully demonstrated various stretchable circuits such as inverters and ring oscillators[84].

Additionally, 2D MoS_2 semiconductors have been popularly researched due to their functionality in a wide range of optoelectronic devices[85]. Recently, numerous efforts have been made to enhance the deformability of 2D semiconductors, aimed at expanding their application in device technology. MoS_2 films, known for their lamellar structure, typically exhibit limited deformability due to the strong covalent bonds within their layers. However, Zhang *et al.* proposed an innovative strategy for fabricating stretchable MoS_2 thin films using multilayer structures[85]. It was demonstrated that a 10-layer MoS_2 film on an elastic SEBS substrate can withstand approximately 50% tensile strain, overwhelming the monolayer MoS_2. Molecular dynamics simulation was performed to analyze the strain distribution between MoS_2 tetralayers and the substrate. Figure 9B shows the strain distribution cloud map on tetralayer MoS_2 under applied strain. The color gradient from blue to red indicates increasing strain. The cloud map reveals that as strain progressively increases, strain distribution gradually mitigates towards the top layers of MoS_2. Researchers have corroborated experimental results with simulation and demonstrated that multilayer MoS_2 could withstand greater mechanical deformation than monolayer MoS_2, while maintaining photoelectronic performance, attributed to interlayer sliding between adjacent layers of multilayer MoS_2 compared to monolayer MoS_2. As limitations of these materials, in the case of using CNTs for channel materials, it is challenging to secure high uniformity and/or alignment of CNTs. Furthermore, mass production and process compatibility with conventional TFT fabrication also need to be considered. In the case of 2D semiconductors such as MoS_2, achieving large-area uniformity with controlled layer thickness might be a critical issue. In this regard, chemical vapor deposition methods with large-area processability should be further developed.

LIGHT-EMITTING AND LUMINESCENCE LAYERS

The light-emitting layer, one of the important core components in constructing the display, could be classified into various types, depending on the light-emitting materials applied, such as organic-based LEDs[97-102], inorganic-based phosphors[103-111], perovskites[112-115], and quantum dots (QDs)[116-119]. In the case of organic-based emissive materials, it is challenging to maintain stable performance over extended periods. Appropriate passivation or encapsulation materials should be developed which have high mechanical stretchability. Perovskite and QD-based light-emitting materials are also vulnerable to moisture and oxygen. Therefore, to ensure high operational stability, sufficient passivation layers are required. Additionally, light-emitting materials with high luminous efficiency should be further developed. The important performance indicators in stretchable light-emitting layers are mechanical durability and appropriate retention of light-emitting intensity during stretching. This section introduces several studies that demonstrate stretchable luminescence layers using various light-emitting materials mentioned above. Similar to the electrode and interconnect sections, intrinsically stretchable light-emitting materials and the approach of geometrical structure design to obtain the deformability are discussed in detail.

Organic-based emissive materials

Organic-based emissive materials have been widely used as the emissive layer for stretchable displays, particularly the polymer-type LEDs (PLEDs). Among these, conjugated polymers (CPs), primarily used in polymer-based emissive layers, are notable candidates due to their capability for solution processing, facilitating large-area coverage and patterning. Moreover, their chemical synthesis and blending processes enable facile tuning of material properties, making them suitable candidates for flexible applications[99,120-122].

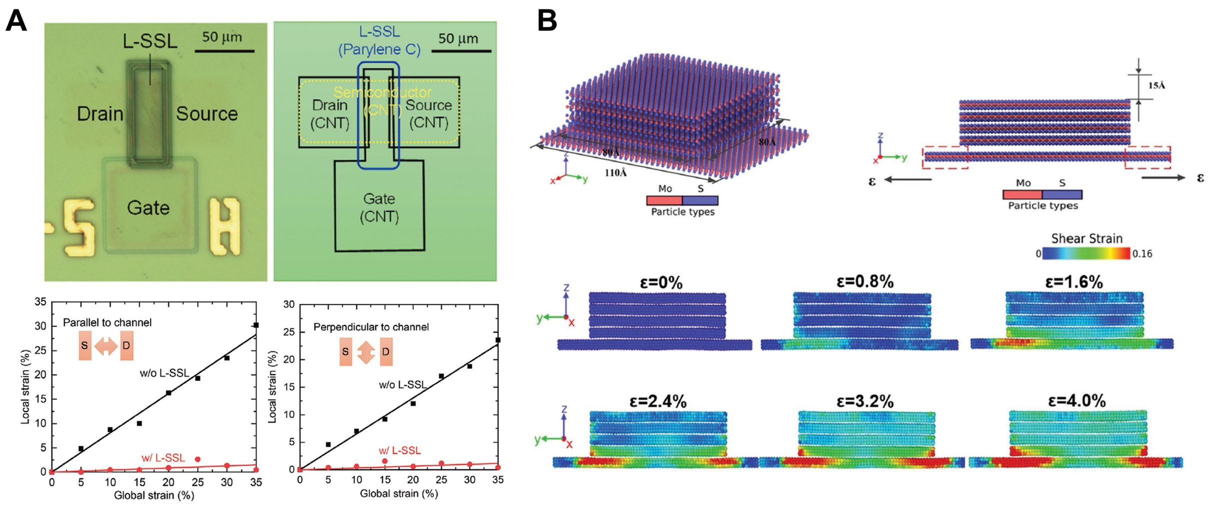

Figure 9. (A) Stretchable CNT TFTs coated with high Young's modulus parylene-C layers that act as stress relief layers in the channel region[84]. Copyright 2020, Wiley-VCH; (B) Molecular dynamic simulation of tetralayer MoS_2 under strain. The simulation cloud map indicates that when strain is applied, stress distribution is alleviated towards the top layers[85]. Copyright 2021, Wiley-VCH. CNT: Carbon nanotube; TFT: thin-film transistor.

Recently, Jeon and Park introduced stretchable emissive layers by mixing PDY-132 emissive polymer (named super yellow) with polystyrene-block-polybutadiene-block-polystyrene (SBS) elastomer[99]. The PLED devices fabricated using this emissive material showed that the emissive performance can be maintained up to 50% of maximum brightness even when stretched up to 60% [Figure 10A]. To achieve the highest performance in terms of luminous efficiency and stretchability, they compared PDY-132 with four different blending elastomers, analyzing their mechanical and optical properties to establish the relationships. Among these, they noted that PDY-132 dispersed most homogeneously in the morphology of small phase domains within the SBS matrix, resulting in superior PLED performance. The design of molecular structures can be another strategy for the development of intrinsically stretchable luminophores. Liu *et al*. introduced a molecular design strategy for stretchable thermally activated delayed fluorescence (TADF) polymers[101]. They synthesized a stretchable TADF polymer by incorporating soft alkyl chains between the TADF units in the polymer backbone to form a linear alkyl linker. This stretchable TADF polymer maintained external quantum efficiency (EQE) of up to 10% under a strain of up to 125%. Furthermore, they developed a device structure utilizing these stretchable TADF polymers that demonstrated EQE of 3.3%, current efficiency of 10.2 cd·A^{-1}, turn-on voltage of 4.75 V, and 60% skin-like stretchability. This indicates that the developed stretchable TADF polymer holds technical potential for realizing fully stretchable OLED devices. Gel-type form factors (hydrogels or ion-gels) are particularly advantageous for applications in stretchable displays by combining optical emissive properties and unique mechanical characteristics of the gels. Specifically, ion-gels and composite materials based on ionic liquids (ILs) are actively researched in related fields for their excellent ion conductivity, thermal stability, and non-volatile characteristics. As a representative example of research, Figure 10B shows a schematic illustration of the material components of the luminescent ion-gel synthesized by Hao *et al.*[123]. As shown in Figure 10B, a luminescent ion-gel has been fabricated by photopolymerization of a blended solution of acrylic acid (AA), IL [1-ethyl-3-methylimidazolium diethylphosphate, $EMIM(EtO)_2PO_2$] and crosslinker (zinc dimethacrylate, ZDMA). They explained that the synthesized ion-gel emits red, green, and blue light depending on various excitation wavelengths due to the unique dynamic coordination interactions between Zn^{2+} in ZDMA and -COO$^-$ in poly(acrylic acid) (PAA) chains (termed as crosslink-enhanced emission or CEE effect). In addition, the crosslinking networks feature robust dynamic coordination bonds and hydrogen bond

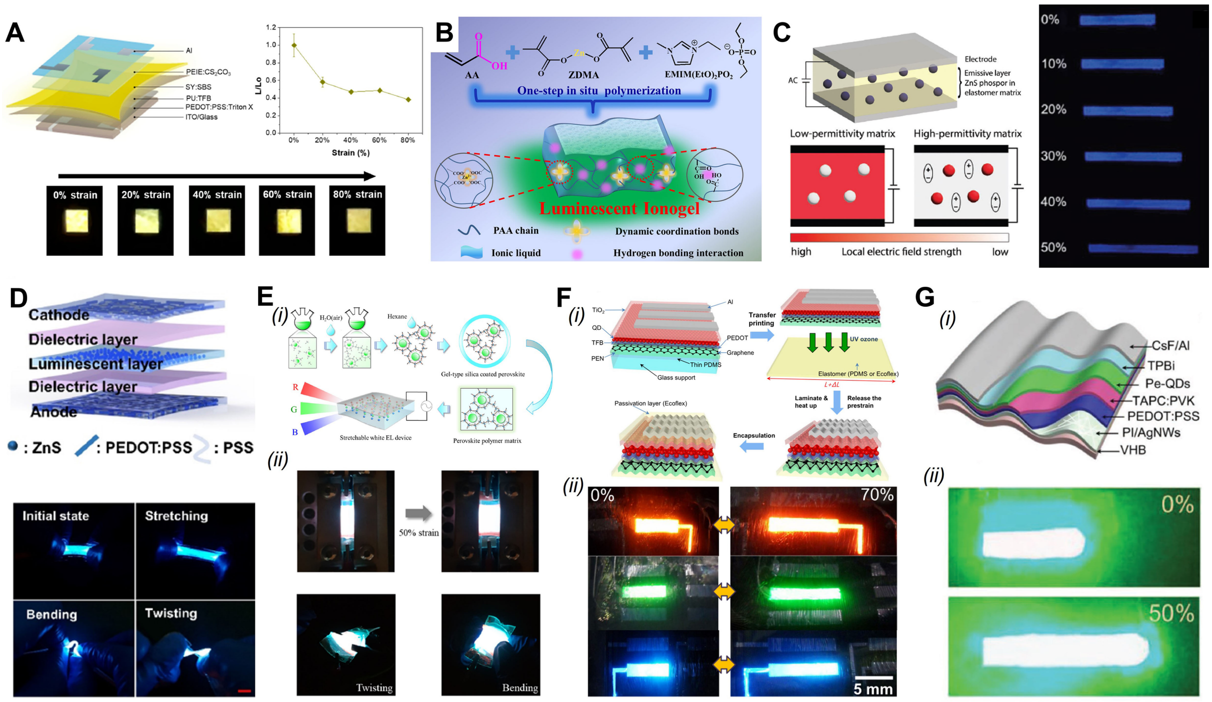

Figure 10. Various emissive materials for stretchable displays. (A) Stretchable PLED emission layers fabricated by blending emitting polymer with elastomers[99]. Copyright 2022, ACS Publications; (B) Stretchable luminescent ion-gel with dynamic coordination and hydrogen bond[123]. Copyright 2023, ACS Publications; (C) Stretchable ACEL fabricated by blending high-permittivity elastomers and inorganic phosphors[111]. Copyright 2024, Wiley-VCH; (D) Inorganic ZnS phosphor-based stretchable EL device integrating PEDOT:PSS-PAAm hydrogel and insulating elastomers[107]. Copyright 2021, ACS Publications; (E) (i) Surface modification process of $CsPbBr_3$ perovskite with silica, and (ii) fabricated perovskite-based stretchable luminescent devices[115]. Copyright 2021, Elsevier; (F) (i) Fabrication process of stretchable QLED devices, and (ii) operation at strain of 0% and 70%[125]. Copyright 2017, ACS Publications; (G) (i) Structure of stretchable Pe-QD LED, and (ii) operation at strain of 0% and 50%[126]. Copyright 2019, Wiley-VCH. PLED: Polymer-type light-emitting diode; ACEL: alternative current electroluminescence; EL: electroluminescent; PEDOT:PSS: poly(3,4-ethylenedioxythiophene) polystyrene sulfonate; PAAm: polyacrylamide; QLED: quantum dot light-emitting diode.

interactions, thereby imparting stretchable properties to the ion-gels.

Inorganic phosphor-based emissive materials

Stretchable alternative current electroluminescence (ACEL) based on inorganic phosphors is a promising component for wearable electronic devices and soft robotics. von Szczepanski *et al.* aimed to improve the high operating voltage of ACEL by increasing the relative permittivity of the elastomer in the emissive layer[111]. They synthesized a polysiloxane dielectric elastomer with cyanopropyl side groups and incorporated inorganic ZnS phosphors to fabricate the ACEL device. The synthesized polar elastomer exhibited a dielectric constant (~11.5) four times higher than commercial PDMS. The ACEL device fabricated using this elastomer showed a maximum luminance of 790 ± 31 cd·m^{-2} at an electric field of 2.5 V·μm^{-1} and a frequency of 60 kHz. Additionally, by utilizing AgNW-based stretchable electrodes, uniform light emission was maintained even under strain up to 50% [Figure 10C]. Similarly, as another example of a stretchable electroluminescence (EL) device based on ZnS phosphors, Zhu *et al.* proposed a 3D printing technique that integrates PEDOT:PSS-PAAm hydrogel and poly(2-hydroxyethyl acrylate) (PHEA) insulating elastomer without additional assembly processes[107]. They reported the development of an EL device by incorporating ZnS phosphor particles into the fabricated elastomer matrix. The fabricated EL device achieved an operating electric field threshold of 1.5 V·μm^{-1} at a frequency of 1 kHz and the maximum luminance of ~35 cd·m^{-2} was achieved at 3.5 V·μm^{-1} beyond the operating threshold. Additionally, the incomplete polymerization at the interface between the hydrogel and PHEA dielectric elastomer layers resulted in strong covalent crosslinking, providing stable mechanical robustness. This ensured the luminescent functionality was maintained under various mechanical deformations [Figure 10D].

Perovskite and QD materials

In general, perovskites have been utilized as optically superior emissive materials due to their high photoluminescence quantum yield and narrow full width at half maximum, along with the ease of tuning the quantum confinement effect[115]. However, perovskites possess high elastic modulus, making them unsuitable for stretchable devices. Therefore, to impart the elasticity, a method of integration with a polymer matrix can be applied, similar to the fabrication process of stretchable inorganic ZnS phosphor-based devices. However, due to their unique ionic structure, perovskites are prone to structural deformation when mixed with polymers, which can lead to instability in the optical properties[115]. Lee *et al.* chemically modified the surface of $CsPbBr_3$ nanocrystals with silica using (3-aminopropyl) triethoxysilane with hexane as a sacrificial solvent, aiming to improve the polymer dispersibility and chemical stability of $CsPbBr_3$ perovskite[115] [Figure 10E(i)]. They fabricated a perovskite stretchable EL device using PDMS substrates and AgNW electrodes and reported that the luminescent properties were maintained even under 50% tensile strain and various mechanical deformations [Figure 10E(ii)]. QD LEDs (QLEDs) are also being actively researched as next-generation display emitters due to their unique advantages, such as wide color gamut, high color purity, relatively high brightness at low operating voltages, and applicability in thin-film form factors[124]. Kim *et al.* integrated a thin-film QLED fabricated on a polyethylene naphthalate/graphene substrate and pre-strained (70%) Ecoflex elastomer to obtain stretchability through spontaneously formed buckled structures[125] [Figure 10F(i)]. The fabricated stretchable QLED maintained stable luminescent performance even under 70% strain [Figure 10F(ii)]. This is a representative achievement in the implementation of stretchable QLEDs, utilizing the QLEDs in an ultra-thin form factor. Recently, Kim *et al.* successfully demonstrated an intrinsically stretchable QLED by utilizing a mechanically soft and stretchable light-emitting layer composed of a ternary nanocomposite of colloidal CdSe/ZnS QDs, elastomer matrix [polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene-graft-maleic anhydride, SEBS-g-MA], and hole transport polymers (poly(9,9-dioctylfluorene-alt-N-(4-sec-butylphenyl)-diphenylamine))[119]. The polymer-rich charge transport region provides a hole transport pathway to the embedded QDs, and the addition of the elastomer at a concentration of 10 wt% of the QD weight in the emissive layer contributes to maintaining a consistent interparticle distance between the embedded QDs, ensuring durability under tensile strain. The fabricated QLED device achieved mechanical stretchability up to 50% without cracks and exhibited a maximum luminance of 15,170 $cd \cdot m^{-2}$ at 6.2 V (turn-on voltage of 3.2 V). In addition, other studies have reported the use of hybrid emissive layers fabricated by mixing QDs and perovskites. Li *et al.* fabricated a thin-film perovskite-QLED (Pe-QLED) by assembling a flexible transparent electrode made of PI/AgNWs and a pre-stretched adhesive elastomer film[126] [Figure 10G(i)]. The surface of the Pe-QLED fabricated on the pre-stretched elastomer film formed a wrinkled pattern when the pre-stretching is released. The fabricated Pe-QLED operated at a threshold electric field of 3.2 V and exhibits a maximum luminance of 3187 $cd \cdot m^{-2}$ at 9 V. Additionally, it maintained the optical performance under mechanical stretching up to 50% [Figure 10G(ii)]. Table 3 provides a brief comparison of light-emitting types, emitting layer materials, stretchability, maximum brightness, and turn-on voltages.

Geometrical structure design of emissive layers

The proposed methods for implementing the aforementioned stretchable emissive layers, whether using intrinsically stretchable emissive materials or integrating thin-film LED devices on pre-deformed elastomer substrates, may have limitations in the availability of high-performance emissive materials or optical clarity[127]. To resolve these issues, Kim *et al.* developed stretchable OLED interconnecting SU-8 rigid island arrays, where the OLED is located, using serpentine bridges formed on a bilayer elastomer substrate[127] [Figure 11A(i)]. This structural design enabled the luminescent performance to be maintained even when

Table 3. Comparison of light-emitting types, colors, stretchability, maximum brightness, and turn-on voltage of stretchable light-emitting devices

Light-emitting type	EML materials (color)	Stretchability (%)	Max. Brightness (cd/m^2)	Turn-on voltage (V)	Ref.
PLED	PDY-132 (yellow)	100%	7,450	-	[99]
OLED	PTrz-tBuCz/TPA-AQ (red) PDKCD (green) PTrz-tBuCz (blue)	125%	2,175	4.75	[101]
PLED	Spiro-red/SEBS (red) Spiro-green/SEBS (green) PFO/SEBS (blue)	100%	1,000	5	[97]
OLED	PVK/Hex-Ir(phq)$_3$ (red) PVK/Ir(ppy)$_3$ (green) PVK/Flrpic (blue)	100%	5,400	-	[100]
QLED	CdSe/ZnS QDs (red, green, and blue)	50%	15,170	3.2	[119]
Pe-QD LED	MAPbBr$_3$ QDs (green)	50%	3,187	3.2	[126]

EML: Emitting layer; SS: subthreshold swing; PLED: polymer-type light-emitting diode; PDY-132: Super Yellow (SY); OLED: organic light-emitting diode; PTrz-tBuCz/TPA-AQ, PDKCD, PTrz-tBuCz: thermally activated delayed fluorescence (TADF) polymers; SEBS: styrene-ethylene-butylene-styrene; PFO: poly(9,9-di-n-octylfluorenyl-2,7-diyl); PVK: poly(9-vinyl carbazole); Flrpic: bis[2-(4,6-difluorophenyl)pyridinato-C2,N]-(picolinato)iridium(III); Hex-Ir(phq)$_3$: tris[2-(4-n-hexylphenyl)-quinoline]iridium(III); Ir(ppy)$_3$: tris(2-phenylpyridine)iridium(III); QD: quantum dot.

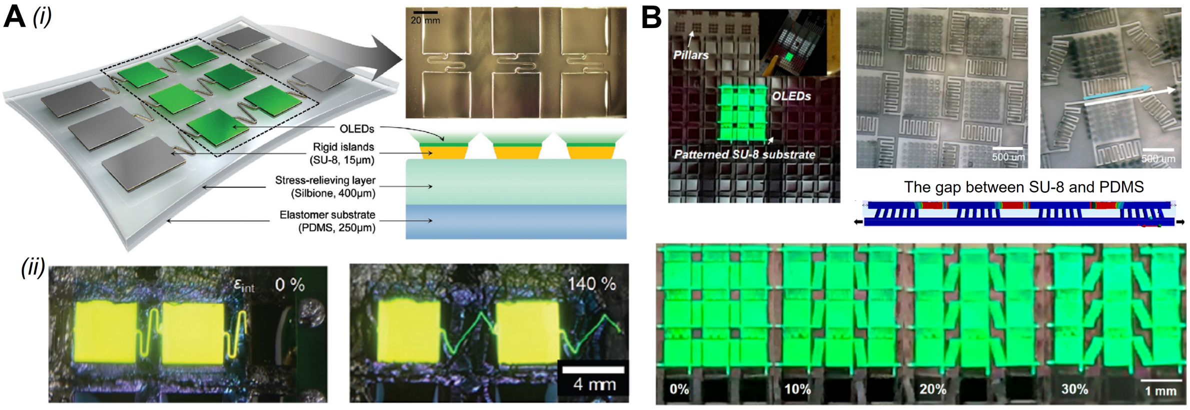

Figure 11. Geometrical structure design approach of LED interconnects for stretchable emissive layers. (A) (i) Schematic illustrations of a stretchable OLED platform composed of SU-8 rigid islands and serpentine structure interconnectors, and (ii) OLED operation under strain of 0 and 140%[127]. Copyright 2020, Wiley-VCH; (B) Biaxially stretchable OLED device utilizing elastic pillars to alleviate stress during tensile deformation[128]. Copyright 2020, ACS Publications. LED: Light-emitting diode; QLED: quantum dot light-emitting diode.

the bridges were stretched up to 140% [Figure 11A(ii)]. This approach is similar to the interconnect design shown in [Figure 6C] and the structural approach for fabricating rigid island stretchable TFTs described in Figure 8A and B. In their proposed bilayer elastomer substrate, the upper layer was composed of a relatively soft Silbione having a low elastic modulus of approximately 0.9 kPa, serving as a stress-relieving layer that significantly mitigates the stress applied to the rigid islands and the interconnects where the OLED devices are located. The bottom PDMS substrate determined the overall stretchability characteristics of the device. Additionally, Lim *et al*. reported a unique geometric approach for implementing stretchable OLED devices by adopting a stretchable PDMS substrate with an array of pillars and SU-8 bridge structures to create a biaxially stretchable substrate[128] [Figure 11B]. The patterned bridges allow the rigid parts of the substrate to be extended, while the PDMS elastic pillars arranged beneath the substrate help mitigate the stress applied to the SU-8 during stretching. Through structural simulations, the researchers analyzed the stress behavior between the elastic pillars and bridges during stretching and reported that improving the layout of the bridge interconnects or the elastic pillars could further enhance the mechanical stability. They also explained that their unique structural approach is not limited to displays but can impart stretchability to various electronics, including semiconductors, circuits, and electrodes.

SUBSTRATE FORM FACTORS

Further, one of the important components for obtaining the stretchability is the development of a deformable substrate. Previously, various rigid LED devices on conventional wafer or glass substrates have been developed, and achieved remarkable advances in pixel resolution, brightness, and device lifespan[129,130]. Similar to the technological advancements in rigid-type displays, achieving advancements in various technical performances of stretchable displays, particularly in deformable substrates and emissive layers, is expected to facilitate their application as next-generation technologies including electronic skin-based displays, soft robotics applications, and hybrid electronic devices with integrated displays. In this section, we introduce various display form factors to provide stretchability by expanding from conventional rigid-based substrates. This section includes textile-based displays based on fibers or fabrics[8,131-136] and unique meta-structured displays[137-140].

Textile-based stretchable displays

Fibers or textiles, with their inherent softness and highly deformable properties, are materials of interest in the wearable electronics as the electronic textiles (e-textiles). In the e-textile displays, a key consideration is the integration of electronic devices while maintaining the intrinsic advantages of the textile materials[141]. Textile-based form factors, composed of fabrics and fibers, inherently possess stretchability due to their unique woven and knitted structures[142]. When integrated with light-emitting layers, textile displays could offer distinctive advantages such as breathability, wearability, and comfortability, making them highly promising for next-generation wearable and stretchable display applications. Recently, there have been numerous attempts to combine OLEDs, which are advantageous in terms of miniaturization and integration, with textile form factors from both material and process technology perspectives. Ma *et al.* fabricated a ZnS phosphor-based textile ACEL display using poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) with high permittivity as a dielectric matrix on an elastic fabric and incorporating barium titanate ($BaTiO_3$) nano-particles into the composite[131]. Stretchable AgNW bottom electrodes, emissive layers, and PVDF-HFP dielectric films were sequentially printed using a screen printing process on a thermoplastic polyurethane (TPU) film interface layer positioned on the fabric, and the AgNW top electrode was formed by spray coating. They reported that the fabricated ACEL display exhibited mechanically robust properties, with only a 5.62% decrease in luminous efficiency when stretched up to 80%, as well as stability under high temperature, humidity, and repeated washing. Additionally, it was explained that it can be produced over a large area using a roll-to-roll (R2R) process [Figure 12A]. There are also research examples of stretchable textile-based displays that adopt different engineering approaches, utilizing 1D fiber-type structures instead of directly deposition of emissive layers and electrodes on the fabrics. Song *et al.* developed a fiber-type OLED device with a patterned emission area[134]. By arranging the fiber OLED devices in a woven structure together with conductive fibers, a 2D textile display was realized that could operate in a pixel matrix format [Figure 12B]. They deposited the constituent layers of a phosphorescent green OLED, which has high brightness (~4,300 $cd \cdot m^{-2}$ at 5 V) and high efficiency (~46 $cd \cdot A^{-1}$, ~58 $lm \cdot W^{-1}$), onto a rectangular indium-tin-oxide/polyethylene terephthalate fiber with patterned PU side barriers. This process was performed to create an interconnected luminescent fiber composed of a 1D OLED pixel array. In addition, a robust and conductive encapsulation system, designed to mitigate oxygen/water permeability and mechanical damages while allowing electrical current flow, was achieved using a combination of Al base pad/molybdenum trioxide (MoO_3) pre-barrier/PU top barrier/Al contact pad. This system preserved the EL performance of the interconnected OLED fiber. The woven

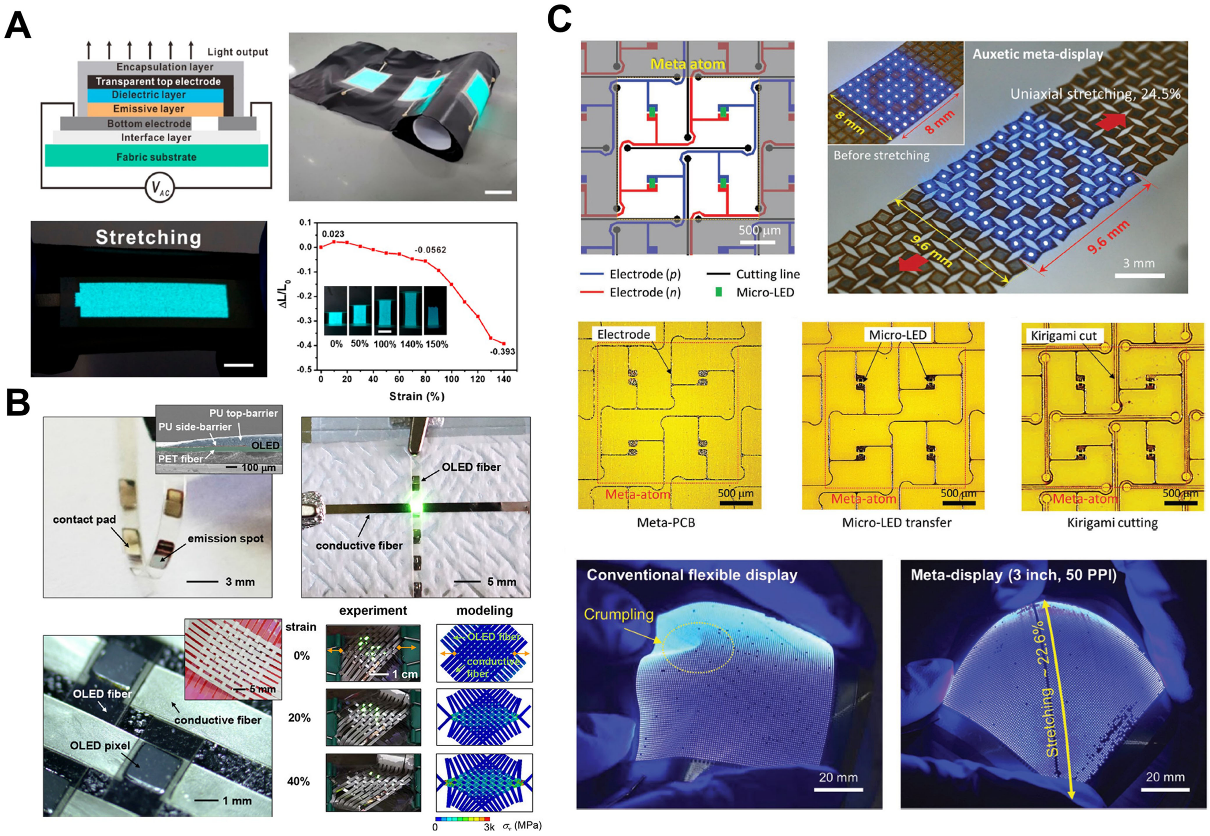

Figure 12. Stretchable displays using various substrate structures. (A) Textile-type large-area stretchable EL device fabricated by printing process on an elastic fabric[131]. Copyright 2021, ACS Publications; (B) Fiber-type OLED devices with a patterned emission area and a 2D textile display weaved with OLED fibers and conductive fibers[134]. Copyright 2020, ACS Publications; (C) Meta-structure stretchable displays with negative Poisson's ratio, inspired by kirigami design[137]. Copyright 2022, Wiley-VCH. EL: Electroluminescent; QLED: quantum dot light-emitting diode; 2D: two-dimensional.

network consisting of interconnected OLED fibers and vertically aligned conductive fibers was operated through a passive matrix driving scheme. The passivated OLED fiber networks were able to operate stably for up to 7 h underwater or under unidirectional tensile stretching along the diagonal axis up to 20% strain.

Meta-structured stretchable displays

As the diversity of display form factors increases, it is necessary to improve the resolution and optical degradation issues that could arise in conventional buckling or kirigami structure designs. Recently, stretchable electronic devices utilizing innovative metamaterials or meta-structures have been reported. To impart the flexibility or stretchable rigid materials, regular patterns or exotic geometric engineering inspired by kirigami or kagome structures can be applied. Through this approach, characteristics such as Poisson's ratio tunability, stiffness modulation, and 2D-to-3D transformability of the device can be adjusted[138,139]. Jang *et al.* have adjusted the mechanical properties of a PI-based printed-circuit-board substrate with a kirigami structure to achieve a negative Poisson's ratio of -1 by forming a meta-structure based on finite element methods[137]. They successfully developed a meta-display with up to 24.5% stretchability without image distortion by integrating with micro-LEDs [Figure 12C]. Additionally, the high Poisson's ratio of elastomers leads to unintended image quality distortion under tensile strain. To address these challenges, Choi *et al.* developed a meta-elastomer substrate with zero Poisson's ratio by integrating a self-deformable soft metamaterial frame[143]. By embedding a self-deformable, compliant mechanical metamaterial frame within the elastomer matrix, they fabricated a stretchable substrate that maintains zero Poisson's ratio in both x-axis and y-axis directions, withstands over 180% strain, and remains durable through 10,000 cycles. This novel approach mitigates the limitations caused by image quality degradation in stretchable displays, which is often a consequence of the high Poisson's ratio of elastomer substrates.

ADVANCED APPLICATIONS OF STRETCHABLE DISPLAY

The stretchable and compact multifunctional displays, capable of versatile deformation, are garnering significant attention as a next-generation application of human-machine interfaces, surpassing its primary role of information displays. Figure 13A shows the stretchable synaesthesia visual-acoustic encryption display capabilities using a high-resolution mosaic image with a dot pattern of 300 μm[144]. As shown in Figure 13A, both visual and acoustic information were used as input signals for decoding during the display operation. By utilizing variable sound signals to create multiplex QR codes, the applicability of the display could extend to the next-generation authentication devices and security systems[144]. As another example of utilizing information displays, Yang *et al.* reported an asymmetrically enhanced coplanar-electrode (AECE) EL device that operates based on impedance adjustment strategy[145]. The reported AECE EL device increases the brightness of one region at the sacrifice of another region, allowing the brighter region to serve as a display and can be easily designed various shape pattern. The contrast between the bright and dark regions of the display can be adjusted by varying the input voltage, frequency, relative area ratio of the electrodes, thickness, and composition of the luminescent layer. The AECE was successfully implemented on a soft substrate along with the luminescent layer to fabricate a stretchable ACEL display. Benefiting from a similarity with the conventional sandwich structure, the AECE EL performed encryption/decryption display applications as a patterned display. Stretchable displays offer versatile shape morphing capabilities, making them promising candidates for next-generation displays by providing enhanced visual information as 3D displays. Oh *et al.* developed a 3D display by integrating a low melting point alloy (LMPA)-graphene nanoplatelet (GNP)-elastomer composite with a stretchable EL device[6]. In this composite, LMPA imparts shape memory properties, while GNP establishes conductive pathways. The 2D morphing display transformed into complex 3D structures through electrothermal activation. They successfully demonstrated applications such as 3D touch-sensing automotive displays, deformable wearable displays, and 3D art displays and highlighted the potential of advanced next-generation visual-tactile interfaces. Figure 13B shows the results of an ionic sensor application by incorporating an IL, ([EMI][TFSI]) and electrochemiluminescent (ECL) luminophore [$Ru(bpy)_3(PF_6)_2$] into a porous poly(ethyl acrylate-*ran*-styrene-*ran*-divinylbenzene) (PEA-*r*-PS-*r*-PDVB) foam[146]. When pressure is applied to the porous ionic gel foam, the bulk resistance decreases, leading to luminescence caused by the ECL annihilation reaction[146-149]. The ECL ion-gel exhibited a proportional increase in the intensity with higher applied pressure. This result demonstrates the successful integration of a deformable physical sensor device and a luminophore, highlighting the application potential of skin displays in the wearable electronics. Moreover, Kim *et al.* proposed an artificial stretchable sensory-neuromorphic system inspired by biological sensory nerve systems, comprising a stretchable capacitive pressure sensor (artificial mechanoreceptor), resistive random-access memory (artificial synapse), and QLED array (epidermal photon actuator) [Figure 13C][150]. In this system, the role of the display array is to visualize the feedback through luminescence in response to electrical feedback that is sensed as stimuli, processed, and inferred through memory. This demonstrates that stretchable displays can be utilized in the emerging field of neuromorphic systems, which mimic the structure and functions of the human brain. The deformable characteristics of the sensory-neuromorphic system suggest the application direction towards the smart skin prosthetic systems. Furthermore, stretchable displays are driving innovations in the field of soft robotics. As shown in Figure 13D, Zhang *et al.* demonstrate successful integration of ZnS phosphor-based elastomer stretchable EL devices with a pneumatic soft robot, fabricated using a self-extrusion multi-materials 3D printing process that enhances the material's flowability and printability to provide mechanical robustness of EL devices. This self-adaptive

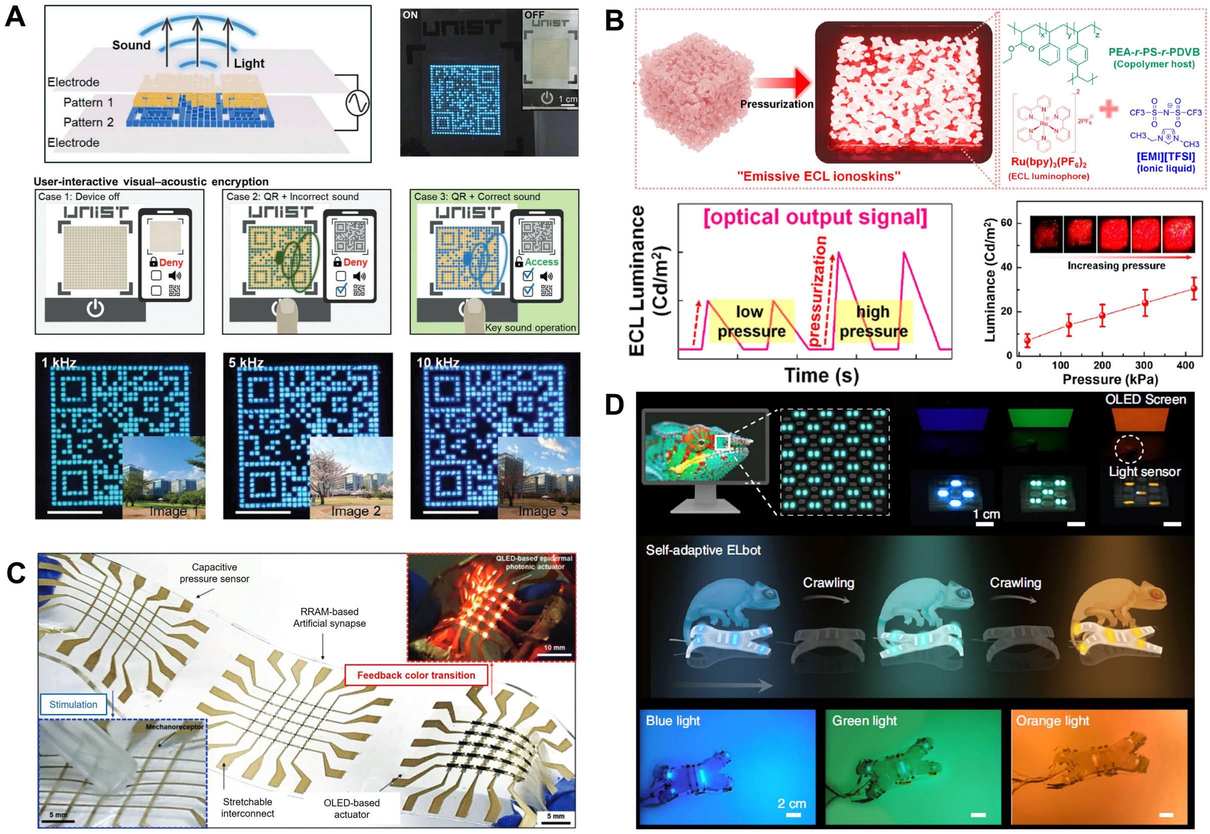

Figure 13. Emerging applications of stretchable displays. (A) High-resolution stretchable synesthesia display and its applications as an input device for user-interactive visual-acoustic encryption and multiplex QR code[144]. Copyright 2023, Wiley-VCH; (B) An emissive ionic sensor incorporating electrochemiluminescence in an ion-gel pressure sensor[146]. Copyright 2021, ACS Publications; (C) A bio-inspired sensory-neuromorphic system with stretchable QLED arrays. In the system, the QLEDs provide feedback by emitting light in response to signals transmitted as a result of training/inferencing[150]. Copyright 2021, Wiley-VCH; (D) Self-adaptive background color-matching EL display in a soft robot[151]. Copyright 2022, Springer Nature. QLED: quantum dot light-emitting diode.

soft robot with an EL device could emit different colors to match the surrounding environment by utilizing an integrated external circuit with a commercial light sensor and microcontroller unit[151].

FABRICATION METHODS FOR STRETCHABLE DISPLAYS

In the final approach, fabrication methods have been investigated by diving into two parts: the deposition and casting of intrinsically stretchable materials, and the printing and patterning process for the geometric structural engineering. To successfully fabricate stretchable electrodes, interconnects, and emissive layers, deposition or printing onto flexible and stretchable substrates is required. One representative solution-based printing process that can address these limitations is inkjet printing. Unlike traditional casting processes such as drop casting, spin coating, and doctor blading, which are commonly used on rigid substrates, inkjet printing allows precise deposition of inks or solutions directly onto soft substrates. This process is non-contact, mask unnecessary, and enables large-area fabrication, making it desirable for the implementation of high-resolution and microscale LED arrays[39,152]. For instance, Zhao *et al.* fabricated halide perovskite LED arrays using inkjet printing for all device layers, including both bottom and top electrodes, highlighting the scalability and significant reduction in manufacturing time achieved through this process[152]. The R2R printing process offers the potential to manufacture large-area LEDs by printing in a continuous roll format, thereby reducing production time and manufacturing costs. Given an adequate supply of materials, the R2R process allows the fabrication of devices in almost endless ways[153]. Transfer printing, a similar assembly technique, utilizes a soft polymer stamp to transfer functional elements fabricated on rigid substrates onto other stretchable substrates. This approach is promising for combining and integrating multi-scale and diverse types of organic and inorganic materials as needed[154]. The transfer printing technique can handle a large number of components, making it particularly valuable for developing advanced display systems, such as stretchable micro-LEDs, through the heterogeneous integration of inorganic materials with soft elastomers[155]. Lastly, by utilizing a photoresist layer, it is possible to achieve precise patterning at the microscale, enabling the fabrication of stretchable electrodes and interconnects, which can serve as the foundation for stretchable TFTs and functional circuits. This simple and efficient process involves patterning interconnect materials, such as LMs, by selectively removing the photoresist layer to form robust liquid patterns, similar to the photolithography and lift-off process used for solid metal thin films[38,81]. This novel approach plays a significant role in realizing highly integrated circuits and effective stretchable platforms that require high-resolution and precise patterning of stretchable materials.

CONCLUSION AND OUTLOOK

In summary, this review explored recent research trends in functional materials and structural designs for stretchable displays. Over the past few years, stretchable display technology has seen significant progress in various areas of stretchable LED devices, driven by material and structural innovations in electrodes, interconnects, luminescent materials, and semiconductors [Figure 14]. However, challenges remain in terms of materials and manufacturing processing in stretchable electronics fields. To provide stretchability in displays, it is crucial to simultaneously achieve high optical clarity, electrical conductivity, high carrier mobility, and mechanical robustness. Stretchable displays represent a significant departure from traditional display technologies by enabling free-form shape changes. However, this flexibility introduces substantial technical challenges. Despite various morphological and structural engineering strategies demonstrating the feasibility of stretchable displays, they are still considered as a future-oriented technology due to numerous limitations. Therefore, the current research in stretchable display technology should focus on the following key aspects:

1. Development of stretchable substrates with zero or negative Poisson's ratio: To mitigate image distortion during stretching, it is crucial to enhance the fill factor of the active area while applying substrates with zero or negative Poisson's ratio. Achieving this will likely require the incorporation of innovative and unique materials in the substrate form factor, or the utilization of diverse structural approaches, including meta-structures or 3D-shape structures.

2. Advancement in fabrication techniques for stretchable electronic components: In the fabrication of stretchable electrodes, interconnects, semiconductors, and emissive layers, improving yield and scalability is essential. To facilitate large-area and mass production, various printing processes should be explored. These techniques must ensure high yield and productivity to make stretchable displays commercially viable.

In response to these requirements, diverse in-depth research has been performed by numerous researchers in the areas of electrode/interconnect design, emissive layers, and TFTs for integrated circuits. Also, various material engineering including organic/inorganic-based materials, low-dimensional nanomaterials, and stretchable substrates has been performed to apply in the stretchable displays. These findings have spurred attempts to apply the technology to promising fields such as skin-like displays that integrate sensors and displays for the next-generation electronic skin applications, neuromorphic systems mimicking the biological functions, and soft robotics. Despite the remarkable advancements in stretchable display technology, challenges remain, including environmental stability, relatively low resolution and image

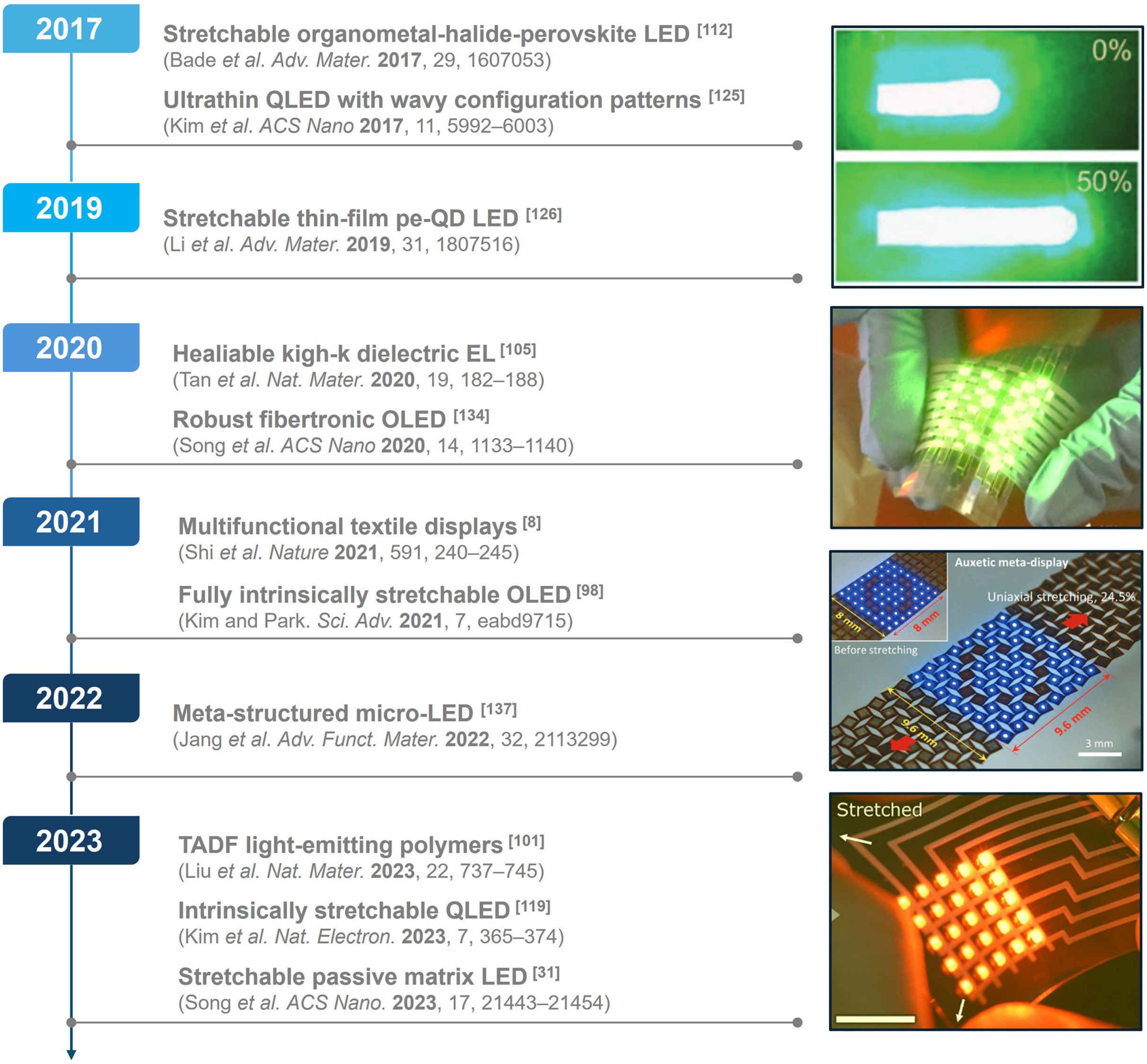

Figure 14. A brief chronology listing the achievements of stretchable LED devices over the past few years. Image reproduced with permission; Stretchable Pe-QD LED[126]. Copyright 2019, Wiley-VCH., Robust fibertronic OLED[134]. Copyright 2020, ACS Publications, Meta-structured micro-LED[137]. Copyright 2022, Wiley-VCH., Stretchable passive matrix LED array[31]. Copyright 2023, ACS Publications. LED: Light-emitting diode; QD: quantum dot; OLED: quantum dot light-emitting diode.

distortion upon stretching, and technical commercialization for practical applications. With continued research and advancements in processing technology, stretchable displays are expected to present more innovative and creative applications and paradigms in the next-generation smart display field.

DECLARATIONS

Authors' contributions

Conceptualization, writing original draft: Keum K, Yang S, Park SK, Kim YH
Revising the manuscript: Park SK, Kim YH
Figure editing, investigation: Keum K, Yang S, Kim KS

Project administration, supervision, review, and editing: Kim YH

Availability of data and materials

Not applicable.

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Conflicts of interest

Park SK is the guest editor of the special issue, while the other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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