Recent Progress in Stretchable OLED Design and Applications

Xuesong Hu[1, *] and Zixin Yang[2]

[1]Shanghai Weiyu international school, Shanghai, 200231, China

[2]Ulink College Guangzhou, Guangzhou, 511458, China

*Corresponding author: w19947931721@163.com

Abstract. With the recently rapid development of flexible electronics, stretchable OLEDs has become a significant direction to study because of its strong potential, like its ultra-thin structure, self-emissive nature, bendability, and stretchability. This new technology not only overcomes the limitations of traditional rigid screens, but also provides new opportunities in developing other fields, for example healthcare and human-computer interaction. From this perspective, the existing technology of OLED and its applications in different fields deserve attention. Firstly, it introduces the laser programming Buckling Process, three different island-bridge structures, Fold Bridge and Curved Bridge, Serpentine Bridge and Fractal Bridge, and talks about the Intrinsically stretchable materials. It then gives a few examples of applications in different fields, including Heart rate and blood oxygen monitoring, Variable-size screens and wearable devices and Phototherapy. This article not only makes a conclusion of current technological achievements and challenges of stretchable OLEDs but also makes a foundation for the future development of this field.

Keywords: Stretchable OLED; recent advance; wearable devices; phototherapy.

1. Introduction

Nowadays, the two major types of displays used in daily life are LCD (Liquid Crystal Display) displays and OLED (Organic Light-Emitting Diode) displays. The LCD displays use Backlight Units as the light source, and their colors are controlled by the deflection of liquid crystals and RGB pixels. This makes their contrast weaker than that of OLED displays, and they cannot be stretched. In contrast, OLED displays are composed of small, individual light-emitting diodes made from organic compounds—these compounds emit light in response to an electric current. This enables OLED displays to show pure black simply by not applying an electric current to the diodes. Additionally, it eliminates the need for a backlight unit, simplifying its structure and resulting in a thinner profile that saves space and reduces power consumption. Without a backlight unit, OLED displays also produce softer light and enable stretchability [1]. Thus, this stretchable potential makes them highly demanded in wearable devices and the healthcare field.

Wearable devices leverage stretchable OLED displays by shaping them into various forms, which enhances wearing comfort and increases the display area. What's more, extensibility also allows these displays to be used in more scenarios—they no longer need a fixed shape and can even be designed as spheres or cylinders. Another advantage of OLED displays lies in their healthcare applications: their flexibility allows them to adhere more closely to the skin, enabling more accurate data collection and a more comfortable wearing experience [2]. This is particularly useful for pulse rate monitoring, pulse oximetry, and biosignal visualization. Additionally, stretchable OLEDs can also be applied in medical phototherapy.

At the current research stage, there are mainly three solutions to achieve stretchability in OLED displays: (1) Laser-Programmed Buckling Process: A technique that uses laser patterning to allow OLEDs to bend locally, instead of stretching or compressing globally; (2) 3D Height-Alternating Island Structure: A special design where display components (arranged as "islands") are placed at alternating heights and connected by stretchable materials; (3) Intrinsically Stretchable Materials: A method where all components of the OLED display are made from stretchable materials.

This review summarizes the latest developments in stretchable OLEDs. The three main solutions for stretchable OLED are highlighted, describing how each solution achieves stretchability, its advantages, as well as the main limitations and challenges currently faced [3]. In addition, the application of stretchable OLEDs will be studied, and the requirements of these applications will be compared with the capabilities of current technology. By delving into these aspects, detailed comparisons can be made between different technologies, and future prospects can be outlined by emphasizing the main challenges currently faced by researchers [4].

2. Overview of Stretchable OLED Background and Existing Technologies

2.1. Laser Programming Buckling Process

This solution was proposed by a research group from Jilin University in China [5]. In their study, they presented a technique for fabricating highly stretchable OLEDs that exhibit both high efficiency and mechanical durability. This OLED is manufactured via a laser-programmable buckling process, which enables the OLED to form an ordered buckling profile—this profile supports controlled stretch-and-release cycles. From their experimental data, they demonstrated that the device achieved a maximum efficiency of 72.5, 68.5, and 70.0 cd A^{-1} at a mechanical strain of 0%, 40%, and 70%, respectively [5]. The OLEDs can withstand a tensile strain of up to 100% and exhibit only minor fluctuations in performance over 15,000 stretch-release cycles. In addition, this method also features ease of application and low cost, which makes it stand out among all existing solutions. The process is shown in Fig. 1.

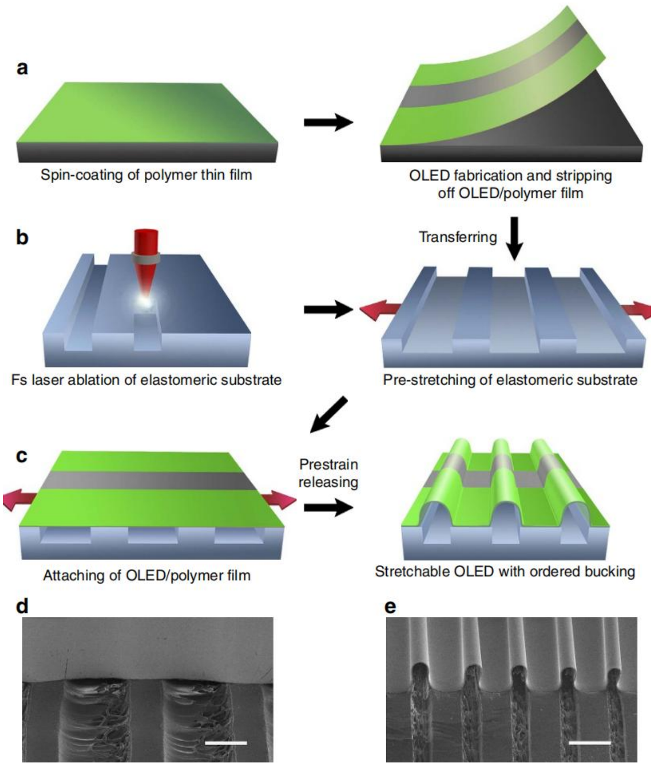

Fig. 1 The process of Laser Programming Buckling [5]

Researchers used femtosecond laser ablation to create a one-dimensional grating with a 570 μm period in the elastomeric layer (3M VHB 4905). They then used an ultra-thin OLED/polymer (~10 μm thick) film in a “pre-stretch-attach-release” strategy to achieve ordered buckling—particularly on top of the grooves of the one-dimensional grating—rather than random wrinkling. These stretchable displays could be stretched up to 70% strain with a 120% pre-strain; by increasing the pre-strain to 200%, a maximum stretch of 100% could be achieved [6]. Even when attached to a bending finger joint (experiencing ~55–60% strain), the devices’ buckles remained ordered, demonstrating great application value in wearable electronics. This is because the ordered layout of both electrodes ensured that the devices’ conductivity did not change significantly even under maximum strain.

Benefiting from the ultra-smooth polymer substrates (surface roughness: 0.35 nm), researchers deposited small-molecule materials via thermal evaporation—with the emissive layer using $Ir(ppy)_3$—and developed highly flexible OLEDs with efficiency exceeding all previously reported levels. Notably, after fabricating these OLEDs on elastomeric substrates, they could emit light even when stretched from 0–100%. At a driving voltage of 4 V, the Current Efficiency (CE) remained high across the entire stretch range: 72.5 cd/A at 0% strain, 68.5 cd/A at 40% strain, and 70 cd/A at 70% strain. This performance exceeded that of the reference planar device (fabricated on silicon wafers), which had a CE of ~71 cd/A (the same as the stretchable device at the corresponding strain). Importantly, the stretchable OLEDs' performance was much higher than any reported data to date. Finally, in long-term tests, the devices showed excellent endurance: after over 15,000 stretch/release cycles in a 0–20% strain range, only ~16% luminance loss was observed; even in a higher-strain range (0–40%), only 25% luminance loss occurred after ~6,000 cycles. In fact, the current efficiency increased slightly, likely due to lower current density resulting from the ordered layout.

This work showed that the maximum tensile strain of the devices could be precisely tuned by laser-programming both the groove width and line width of the gratings [7]. For a fixed line width (400 μm), the maximum strain increased with groove width. Controlling the grooves revealed that increasing the groove width reduced the buckling frequency and the area required for failure; however, the maximum strain of the structures decreased with increasing groove width and increased with increasing line width. For a fixed groove width (170 μm), the maximum strain decreased as the line width increased. Strain was mainly concentrated in the grooves, enabling "on-demand design" of the buckling behavior and ultimate stretching capability of the devices.

To fabricate these OLEDs, a commercial femtosecond laser microfabrication system (wavelength: 800 nm, pulse width: 100 fs, repetition rate: 1 kHz) was used to create one-dimensional grating structures on the surface of 3M VHB 4905 elastomeric substrates. A laser fluence of 6,000 W/cm^2 was selected, and different scanning paths were used to create regular 4 × 4 cm^2 groove arrays with a 570 μm period. The key effect of the laser process was removing surface adhesion in the groove regions without affecting the high surface adhesion in the grating line regions (90° peel strength: 21 N/cm) [8]. This enabled subsequent selective adhesion of the devices.

Next, a 10 μm flexible thin-film device was fabricated by spin-coating photosensitive NOA43 onto an ultra-smooth silicon wafer (surface roughness: 0.35 nm) followed by UV curing. The functional layer stack—Ag anode (80 nm)/MoO_3 hole injection layer (3 nm)/NPB hole transport layer (40 nm)/mCP:$Ir(ppy)_3$ (6%, 20 nm) emissive layer/TPBi electron transport layer (35 nm)/Ca/Ag cathode (3/18 nm)—was then deposited via thermal evaporation. The fully completed functional stack could be freely delaminated from the rigid silicon substrate to form free-standing ultrathin light-emitting OLED films.

Second, the patterned elastomeric substrates were pre-stretched to 120–200% strain using a precision stretching stage, causing the grating period to increase accordingly. The prepared ultrathin OLED devices were then transferred onto the surface of the stretched elastomeric substrates. Using the difference in adhesion between the substrates and devices, the devices bonded to the grating line regions but remained suspended over the groove regions. When the initial pre-strain was released, the elastomeric substrates experienced compressive strain, resulting in ordered buckling and forming a three-dimensional wavy morphology of the light-emitting regions (suspended in the grooves). Deformable eutectic gallium-indium (EGaIn) liquid metal connections were used to maintain stable electrical transmission while the devices were stretched [9]. EGaIn is a eutectic mixture of gallium and indium with good stretchability, low resistivity (29.4×10^{-6} Ω·cm), and low toxicity—making it safe for use as a connecting electrode in stretchable and wearable electronics.

2.2. Island-Bridge Structure

In the island-bridge structure, for non-stretchable sensor components, the luminescent parts are regarded as "islands". These islands serve functions such as sensing or computing. The "bridges" refer to stretchable wire segments that connect the islands. These lines link all the luminescent parts and transmit signals. A key feature of the island-bridge structure is that it enables the lines to function like elastic iron wires: when the lines are under stress, they can stretch and bend without being damaged or broken. The "islands" remain unaffected and suffer almost no damage. Such islands can well provide a stable foundation for integrating today's OLEDs into flexible electronic devices. There are different types of islands, and common bridge designs include folded bridges, bending bridges, fractal bridges, and serpentine bridges.

2.2.1 Fold bridge and curved bridge

Folded bridges and curved bridges are similar to each other, with comparable mechanisms for withstanding mechanical stress and exhibiting elasticity. The wires are attached to the bottom of each non-stretchable component, which are the "islands". When pressure is applied to the devices, the bridges undergo compression. This process is reversible, so waves form on the bridges while the wires remain undamaged [10]. The difference between folded bridges and curved bridges is that curved bridges are fully attached to the substrate, whereas folded bridges are only attached to the "islands" at both ends, as shown in Fig. 2. These two types of interconnecting bridges have the advantages of simple fabrication and the ability to withstand relatively high mechanical stress. However, they also have shortcomings: they cannot be used in large-sized devices and cannot be mass-produced.

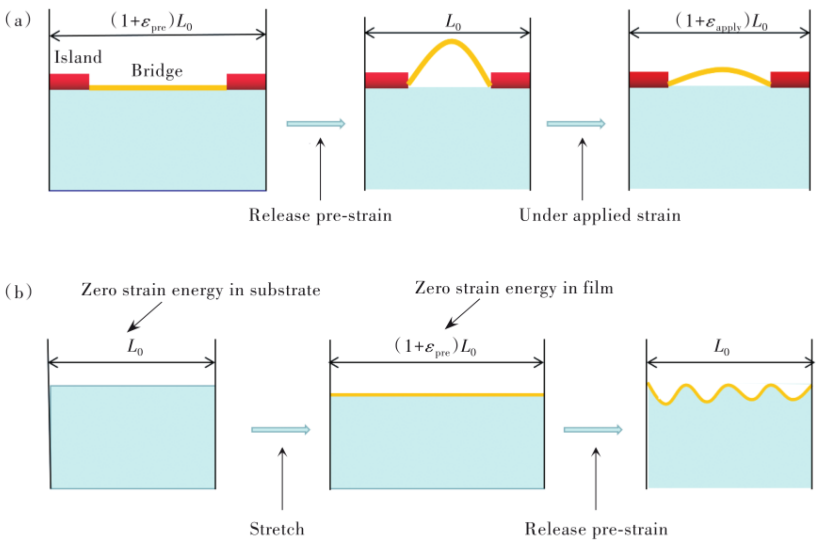

Fig.2 (a) Schematic diagram of arc bridge (b) Schematic diagram of wrinkled bridge [11]

2.2.2 Serpentine bridge.

Serpentine bridges are more stretchable in comparison with the other two types of bridges, making them the most common type of bridge. A serpentine bridge can either be fully attached to the substrate or only attached to the "islands" at the two ends—this design allows it to change its shape freely between the two ends. When the mechanical stress applied to the bridge is small, the bridge's arched structure gradually unfolds and straightens. When the mechanical stress applied to the bridge increases, the arched structure begins to fold. Its deformation from 2D to 3D enables the bridge to easily withstand greater mechanical stress.

2.2.3 Fractal bridge

To form this type of bridge (note: typically referring to "fractal bridges" based on context), wires and non-stretchable components are combined to form a complex geometric pattern. It is similar to serpentine bridges but offers more efficient space utilization, as it can unfold in multiple directions. Mechanical stress is distributed more evenly across it, allowing it to withstand higher levels of mechanical stress than serpentine bridges. However, it has shortcomings: its complex structure makes it difficult to design and fabricate.

3. Intrinsically Stretchable Materials

Existing methods—such as incorporating rigid nanostructures or engineering deformations in elastomers—allow for stretching but often result in degraded device performance or resolution. Research has focused on electroluminescent layers (EMLs), where stretchability is improved by blending polymers, adding additives (e.g., Triton X-100), or modifying molecular structures. However, relatively little attention has been paid to other functional layers and the overall device fabrication process.

In intrinsically stretchable solution-processed organic light-emitting diodes (is-OLEDs), solvent incompatibility is a major challenge, as it can disrupt the morphological structure of underlying layers. Lamination techniques are often used to address this issue, but this approach leads to orientation errors, spacing issues, and poor durability under repeated stretching. Electrodes represent another bottleneck: metals like silver (Ag) and aluminum (Al) have excellent conductivity but lack stretchability, while alternative materials (e.g., silver nanowires, graphene, or PEDOT:PSS) require complex transfer steps and exhibit lower conductivity. Therefore, there is an urgent need to develop intrinsically stretchable OLEDs with improved transport layers and electrodes, as well as simplified preparation processes. The research team led by Professor Jionghui Wu at Nanjing University has achieved a latest breakthrough in this field. In their study, an intrinsically stretchable OLED (is-OLED) was developed using a systematic fabrication process: (1) The light-emitting layer (LEL) was prepared by mixing the commercial polymer Super Yellow (SY) with the surfactant Triton X-100 (TX); (2) The hole transport layer (HTL) was fabricated by mixing poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) with isopropanol and TX; (3) The electron transport layer (ETL) consisted of polyfluoroalkylbenzene bromide (PFN-Br) and poly(ethyleneimine ethoxylated) (PEIE); TX was added to preserve the morphology of the underlying ETL. (4) Additionally, a top ETL of PEIE doped with cesium carbonate (denoted as d-PEIE) was introduced to enhance electron injection efficiency [12].

For device fabrication, elastomeric polydimethylsiloxane (PDMS) was used as the substrate. After plasma treatment, each organic layer was coated sequentially. The mechanical properties of the layers were evaluated via crack onset strain (COS) testing [13]. Three device configurations were prepared for testing: (1) A rigid OLED with indium tin oxide (ITO) as the anode; (2) An electron-dominant device with silver as the anode and aluminum as the cathode; (3) A fully stretchable OLED—with silver nanowires (NWs) integrated into PDMS as the anode and aluminum as the cathode.

For the fully stretchable device, the PDMS substrate (with integrated Ag NWs as the anode) was sequentially coated with the positive organic layer (HTL), emissive organic layer (EML), and top organic layer (ETL). A silver cathode was then formed over the entire device via vacuum evaporation, followed by the deposition of a thin d-PEIE layer on top of the cathode.

This unique hybrid fabrication method—combining solution coating of device layers with controlled metal evaporation—enables layer-by-layer analysis of morphology, deformation behavior, and optoelectronic properties, laying the foundation for manufacturing high-performance intrinsically stretchable OLEDs. The process also provides a practical approach to obtaining conductive metal materials without complex and costly procedures [14]. Here, low-resistance, low-cost, highly conductive, and stable silver is achieved, retaining key metallic properties—including contributing to the ultra-long lifetime of the stretchable OLEDs. Furthermore, due to its unique adaptability to mechanical deformation, this OLED retains at least 75% of its initial brightness after 300 cycles under high-d eformation conditions, making it a promising candidate for potential applications. The schematics and images of the key device fabrication steps in this study are consistent with those described above.

4. Application

With the development and popularization of OLED, it began to involve into many different fields, such as healthcare, biomedicine, and portable devices.

4.1. Heart Rate and Blood Oxygen Monitoring

Heart rate is detected by measuring changes in blood vessel volume. A heart rate monitor emits light into the human skin; this light is then reflected or transmitted by the blood vessels and received by a light receiver. When the heart beats, it contracts and relaxes, which is followed by a change in the volume of blood vessels. This causes the reflected light detected by the receiver to start changing—thus, heart rate can be determined by analyzing this light signal. OLEDs, as superior light sources, can provide more stable and efficient light. Additionally, they are more flexible, making them relatively ideal light sources for application in heart rate monitors.

Previous researchers have made numerous innovations and improvements in this field. For example, one research team added a polarizer to OLEDs: when the light emitted by the OLEDs passes through the polarizer, it becomes polarized light. The receiver then only detects this polarized light, so no interfering light is received by the receiver. This improvement aims to reduce interference and improve detection efficiency.

4.2. Variable-Size Screens and Wearable Devices

Organic Light-Emitting Diodes (OLEDs) hold great promise for the next generation of wearable displays, whether integrated into fibres, fabrics, or attached to human skin. (1) Via techniques such as direct thermal evaporation on rotating fibres and solution dip-coating, OLED fibres were woven into textiles and integrated into garments for illumination. By optimizing the structure of the "monorail" anode, good performance was achieved—for example, a current efficiency of up to 70.89 cd/A; (2) Using techniques like template stripping to create smooth surfaces on rough fabrics enables the fabrication of highly flexible OLEDs with excellent light confinement (e.g., an external quantum efficiency (EQE) of ~78%). These OLEDs can withstand repeated folding and feature water- and moisture-resistant encapsulation; (3) Flexible, bendable display panels that conform to human skin are ultra-thin (~3 μm thick) and have low stiffness, allowing them to fit comfortably on stretchable skin. They can utilize either clickable or inherently deformable structures. These panels can withstand deformations of up to 20% and are suitable for precision applications such as health monitoring and biosensing, as they can move in sync with the body.

4.3. Phototherapy

Organic Light Emitting Diode (OLED) phototherapy technology offers innovative applications in the medical field, mainly in photodynamic therapy (PDT) and photobiomodulation therapy (PBM) [15]. In photodynamic therapy, OLED light sources can be used to activate photosensitisers that produce cytotoxic substances specifically targeting cancer cells or microbes. For example, flexible red organic light-emitting diode patches have been used to treat skin cancer with comparable efficacy to conventional methods, but with less pain and ease of use. A new generation of parallel array organic light-emitting diodes (PAOLEDs) with a power density of even more than 100 mW/cm^2 can effectively suppress melanoma. Even implantable wireless active light-emitting diodes have been developed for metabolic photodynamic therapy of deep organs through continuous low-intensity light.

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In photodynamic therapy, OLED light sources can activate photosensitizers, which produce cytotoxic substances that specifically target cancer cells or microbes. For example, flexible red OLED patches have been used to treat skin cancer, with efficacy comparable to conventional methods but with less pain and greater ease of use. A new generation of parallel array OLEDs (PAOLEDs) with a power density exceeding 100 mW/cm^2 can effectively inhibit melanoma growth. Researchers have even developed implantable wireless OLEDs for metabolic photodynamic therapy of deep organs, using continuous low-intensity light.

In PBM, OLEDs show potential for promoting tissue repair and enhancing cellular activity. Red OLEDs accelerate wound healing and fibroblast proliferation, with effects comparable to laser light. Ultra-thin conformable OLEDs (~10 μm thick) are ideally suited for at-home skin treatment; studies have shown that light at a wavelength of 670 nm is particularly effective in promoting cell migration and proliferation. Additionally, OLED applications are being expanded to specialized therapeutic areas—for instance, blue OLEDs for treating neonatal jaundice (by photodegrading bilirubin) and red OLEDs (which have been shown to significantly promote hair growth by stimulating hair follicle stem cells and improving local microcirculation).

Owing to their thin profile, flexibility, low heat generation, and biocompatibility, OLEDs are well-suited for developing portable phototherapy devices that conform to the human body's curved surfaces. This provides a new technical direction for at-home and emergency medical treatments.

5. Conclusion

Stretchable OLED technology is a key advancement in the field of flexible electronics, offering revolutionary potential for wearable electronics and biomedical applications. This study focuses on three main strategies to achieve stretchability: laser-induced buckling structures, island-bridge structures, and intrinsically stretchable materials. Each approach has its advantages and limitations: (1) The laser-programmed buckling technique is characterized by high efficiency (over 70 cd/A) and mechanical durability—it can withstand over 15,000 stretch cycles with minimal performance degradation. Additionally, it is cost-effective and enables high-precision deformation control. However, the femtosecond laser-based preparation process is complex and not suitable for mass production; (2) Island-bridge structures enable efficient system stretching by combining rigid functional elements ("islands") with stretchable connecting wires ("bridges"). Among these, serpentine and fractal structures excel in stretchability and space utilization. However, this structure results in large pixel pitches, leading to poor luminance uniformity and making it difficult to fabricate high-resolution, large area displays; (3) Strategies using intrinsically stretchable materials aim to render all functional layers (including electrodes and transport layers) flexible. Thanks to recent research, devices can maintain 75% of their initial brightness at 40% deformation by integrating a ternary transport layer with an optimized metal cathode. The biggest challenge, however, lies in simultaneously achieving high conductivity and excellent mechanical elasticity; additionally, solvent compatibility issues in multilayer solution processing persist.

In terms of applications, stretchable OLED technology is directly driving the development of next-generation portable medical devices. It offers significant advantages for continuous health monitoring (e.g., heart rate and blood oxygen monitoring), where motion artifacts can be effectively reduced, and signal accuracy improved by conforming to the body. Meanwhile, the field of phototherapy—such as photodynamic therapy (PDT) for cancer treatment and photobiomodulation (PBM) for wound healing and hair growth therapy—also holds great potential to extend treatments from clinical settings to portable home care.

Moving forward, the development of stretchable OLEDs will continue to focus on balancing performance, durability, and mass production. Key research priorities include developing new materials with both high carrier mobility and good ductility; advancing mass production processes such as roll-to-roll printing; and developing flexible packaging technologies that can effectively block water and oxygen while withstanding repeated deformation. As these core technologies continue to mature, stretchable OLEDs are expected to become a critical component of next-generation portable devices and exert a profound impact on key fields such as interactive textiles, foldable screens, and even personalized medicine.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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