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Shape-deformable Micro-LEDs for advanced displays and healthcare

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Abstract

Recently, flexible/stretchable micro-scale light-emitting diodes (LEDs), with dimensions significantly smaller than conventional diodes used for illuminations, have emerged for promising applications in areas such as deformable displays, wearable devices for healthcare, *etc*. For such applications, these devices must have some unusual features that common inorganic LEDs do not intrinsically own, including conformability, biocompatibility, mechanical flexibility, *etc*. This Perspective focuses on summarizing the most recent progress in developing such flexible emitters based on inorganic semiconductors, followed by reviewing their potential applications. Finally, major challenges and future research directions of deformable micro-scale LEDs are presented.

Keywords: Micro-LED, conformability, flexibility, healthcare, foldable display

INTRODUCTION

Micro-scale light-emitting diode (Micro-LED) displays made from p-n junctions of III-V inorganic epitaxial semiconductors, such as gallium nitride (GaN) and aluminum gallium indium phosphide (AlGaInP), have stood out as a competing technology over organic LED (OLED) and liquid crystal displays (LCD)[1-7]. Despite the reduced physical dimensions into a regime of a few tens of microns or below, they exhibit unusual properties such as fast switching speed, high brightness, long lifetime, and large current withstanding capability[8], making them particularly suited for low-power consumption and high-resolution display. Indeed, significant progress of Micro-LEDs has been made in areas such as smart watches, VR/AR, and high-resolution TVs. Their huge commercial prospect has been partially confirmed, accompanied by a booming display market worth tens of billions of dollars.

In contrast to the tremendous progress of using planar Micro-LEDs for conventional rigid displays, the development of flexible Micro-LED counterparts is currently actively explored, evidenced by intensive research interest from both academia and industry[9-18]. Benefiting from their extraordinary luminescent property, deformable displays made from inorganic Micro-LEDs can not only significantly improve visual experience of users but also potentially provide more convenience, better portability, and easier connectivity with their surroundings. Furthermore, they allow more versatile design with various forms that are difficult to achieve using conventional planar devices. Examples of such innovations have led to the recent demonstration of distortion-free displays[10], foldable three-dimensional (3D) displays[19], *etc*.

Apart from high-resolution deformable displays, some emerging applications, such as optogenetics[20-28] and smart contact lenses[29-33], also drive the development of highly efficient, biocompatible light sources that can be conformally attachable to skins or implantable inside the human body for healthcare [34]. Micro-LEDs in flexible/stretchable formats are well suited for these purposes. Here, we highlight the recent technology advancements in developing such flexible emitters and then discuss their potential applications for uncommon displays and healthcare. Finally, future research trends of flexible inorganic emitters are also given.

STRATEGIES TOWARD DEFORMABLE MICRO-LEDS

Conventional inorganic semiconductors used for Micro-LEDs have higher conductivities and mobilities, leading to higher brightness and better operation stability. However, high-performance inorganic semiconductors are usually grown on rigid, planar substrates, which means they are not intrinsically flexible. In order to render Micro-LEDs with flexibility, several strategies must be considered, including substrate removal, chip transfer printing, and certain mechanical design for enhanced stretchability [Figure 1].

Substrate removal

Thickness reduction by substrate removal can impart certain flexibility to Micro-LEDs. Two major strategies have been developed to take off the growth substrate: laser lift-off (LLO)[6,35,36] and epitaxial lift-off (ELO)[37-43]. LLO exploits the laser energy absorption at the LED layer/substrate interface, which leads to the release of Micro-LEDs from the substrate due to the high-temperature induced material decomposition at the interface[35] [Figure 1A]. Prior to LLO, the LED wafer is temporarily bonded to a supporting carrier. High-energy laser scanning leads to the transfer of a thin membrane to the supporting substrate. ELO, on the other hand, is a technique based on a modified epitaxial structure, where a sacrificial layer is incorporated in the epi-stack to assist the release of Micro-LEDs grown on the sacrificial layer[38]. Depending on specific release layers, two ELO principles have been established: chemical lift-off (CLO)[43-46] and mechanical lift-off (MLO)[37,38]. In the case of CLO, the sacrificial layer can be removed by chemical solvents, resulting in released thin film Micro-LEDs [Figure 1B]. For MLO, a handling carrier (for instance, a tape) is used to peel off the epi-stack grown on the release layer directly due to the significantly weakened bonding of the epi-layer to the substrate [Figure 1C]. Two-dimensional (2D) material-assisted epitaxy or remote epitaxy has emerged to fulfill this purpose[39-42,47-49]. Growth on voids or porous templates can also lead to successful MLO[50,51]. However, MLO is usually done manually, making it difficult to accurately control the process with good reproducibility. By contrast, CLO is more controllable, which has witnessed commercial success, especially for the fabrication of solar cell modules[52,53].

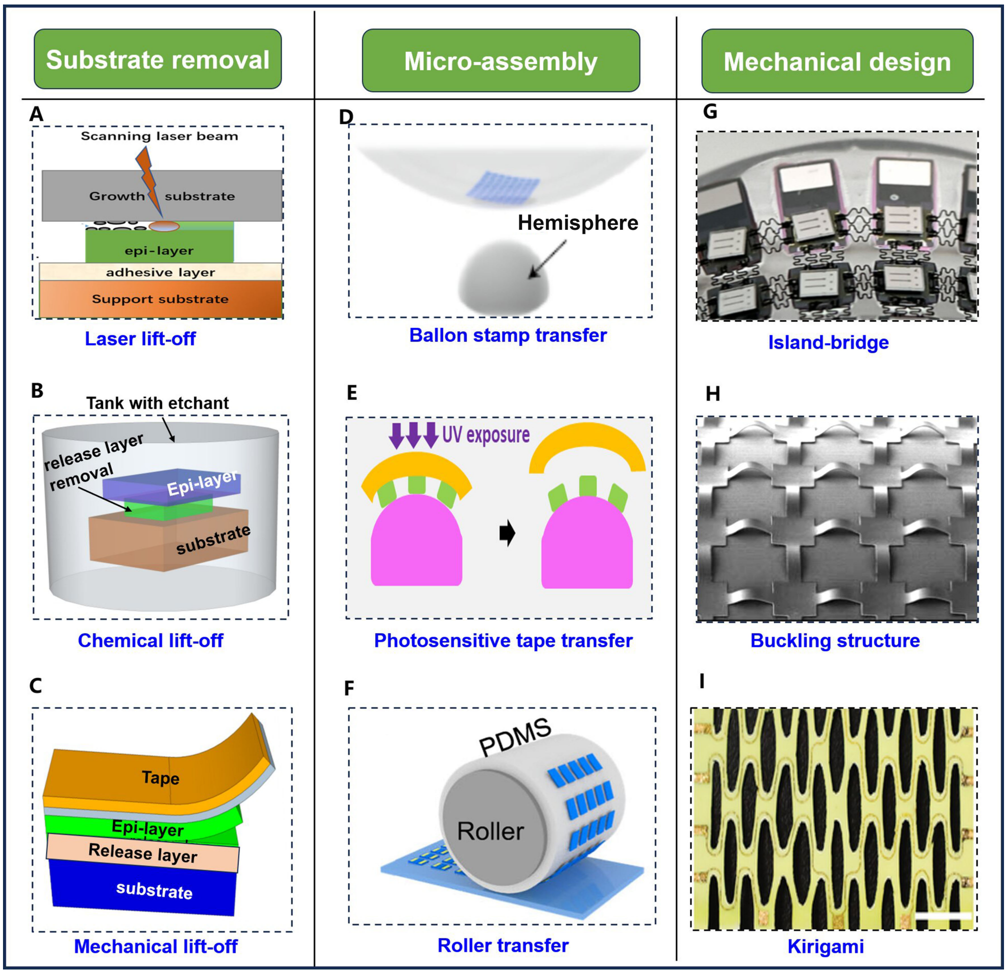

Figure 1. Strategies toward the fabrication of deformable Micro-LEDs, including substrate removal (A-C), micro-assembly (D-F), and mechanical design (E-I). Schematics for the substrate removal methods, including (A) laser lift-off, (B) chemical lift-off, and (C) mechanical lift-off[35]; Representative transfer methods for Micro-LED integration on curvilinear substrates reported recently, including (D) ballon-shaped stamp transfer[60], (E) roller transfer[11], and (F) photosensitive tape-assisted transfer[17]; Typical mechanical structure designs for improved stretchability of Micro-LED devices, including (G) island-bridge design[61], (H) buckling structures[16], and (I) Kirigami structures[9]. Figure 1A-C reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license[35]; Figure 1D adapted with permission from ref.[60]. Copyright 2021 Springer Nature; Figure 1E reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license[11]; Figure 1F reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license[17]; Figure 1G reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license[61]; Figure 1H adapted with permission from ref.[16]. Copyright 2009 AAAS; Figure 1I adapted with permission from ref.[9]. Copyright 2022 Wiley-VCH. Micro-LED: Micro-scale light-emitting diode.

Micro-assembly

System-scale flexibility can be partially enhanced by micro-assembling Micro-LEDs onto soft substrates[35,54-56]. With shrinking the Micro-LED size and thickness into the micro-scale regime, fast and accurate manipulation of Micro-LEDs in a reliable manner becomes a critical challenge. Several micro-assembly techniques have been established to partially address this issue, including the pioneering stamp transfer printing methods[15,16,56,57], where an elastic polydimethylsiloxane (PDMS) stamp picks up the microscale device from the source wafer and then releases it to a receiver. To assist the transfer, Micro-LEDs are commonly patterned in a manner such that they are weakly suspended on the growth substrate by using anchors or undercut microstructures[7]. Other popular methods include laser-based[6,58] or fluid-assisted micro-assembly[55,59], which have competing advantages in terms of the transfer speed. While most of them do work for transfer printing microscale devices to planar surfaces, some present poor combability for integrating Micro-LEDs onto a flexible or curvy substrate, primarily because the conventional planar stamps are difficult to be in conformal contact with the curvy/flexible surface. The issue can be partially alleviated by micro-assembling Micro-LEDs onto a planar soft substrate fixed on a temporary hard substrate. The temporary supporting substrate is then removed, enabling the integration of Micro-LEDs onto soft substrates[6]. Alternatively, several modified micro-assembly methods have been developed to address the challenge of Micro-LED integration onto curved substrates directly [Figure 1D-F]. Rao *et al.* developed a ballon-shaped stamp for printing micro-scale devices onto a curvy surface[60] [Figure 1D]. Hu *et al.* proposed using a roller stamp for flexible Micro-LED integration[11] [Figure 1E]. Guo *et al.* developed a photosensitive polymer adhesive stamp-based method[17] [Figure 1F]. These approaches exhibit excellent capability for micro-assembling micro-scale chips onto both planar and curvilinear surfaces due to the improved conformity with the receiver and adhesion switchability. However, transfer speed, printing yield, and placement accuracy are key factors that need continuous improvement, especially for the device integration onto curvy substrates.

Mechanical structure design

The brittle nature of Micro-LEDs prevents the system (i.e., Micro-LEDs and integrated substrates) from accommodating large strain induced by bending, especially in the localized areas close to Micro-LEDs. Extra mechanical design can provide further room to enhance the system performance and stretchability. Representative strategies toward enhanced deformation of Micro-LEDs include island-bridge[15,61,62], buckling[16,63], and kirigami/origami structures[9,60]. Stretchable Micro-LEDs with the island-bridge configuration have rigid island arrays (where these LEDs are fixed) and meandering metallic interconnects connected to individual islands[61] [Figure 1G]. In this structure, the Micro-LED devices on the rigid islands are hardly affected by external strain, whereas the meandering interconnects, which are commonly patterned into serpentine or noncoplanar arc-shapes, can tolerate most of the strain and geometric deformation. Stretchable Micro-LED devices can also be achieved by incorporating buckled structures[16] [Figure 1H], inspired by the fact that a flexible film on a pre-stretched soft substrate (e.g., PDMS) can turn into periodically wrinkled structures once the pre-stressed substrate is relaxed. Such wrinkle structures can be flattened if the substrate is re-stretched, which allows the flexible devices to be stretched without mechanical failure. Micro-LED integrated onto a substrate with kirigami/origami structures is another smart strategy for fabricating stretchable Micro-LEDs[9] [Figure 1I]. The 2D stress exerted on the Micro-LED device can be significantly reduced via 3D shape transformation induced by the cutting/folding lines, thereby mitigating stress concentrations around the Micro-LED devices.

EMERGING APPLICATIONS

With the above innovations in material epitaxy, chip transfer, device fabrication, and mechanical designs, great progress has been made toward developing advanced deformable Micro-LEDs with expanded functionalities for applications such as advanced displays and healthcare.

Deformable displays

Currently, most display electronics take the rigid, planar shape, but in the future, foldable/flexible displays may become the mainstream products. To this end, Micro-LEDs in deformable formats have undergone intensive research recently due to their higher luminescent efficiency and longer lifetime than their organic counterparts. Industrial research in this field has led to great progress in developing deformable Micro-LED display prototypes with encouraging performances. For instance, AU Optronics successfully demonstrated a 9.4-inch 228-ppi flexible Micro-LED display integrated onto a flexible low-temperature polysilicon thin-film transistor (LTPS-TFT) backplane based on fine-pitch flip-chip bonding, followed by LLO to take off the temporary supporting carrier[12] [Figure 2A]. The display features a high contrast ratio of > 1,000,000:1, a brightness of up to 700 nits, good display uniformity, and minimized color shift at any off-axis viewing angles, revealing its potential for high-resolution flexible automotive applications. Royole Co. demonstrated

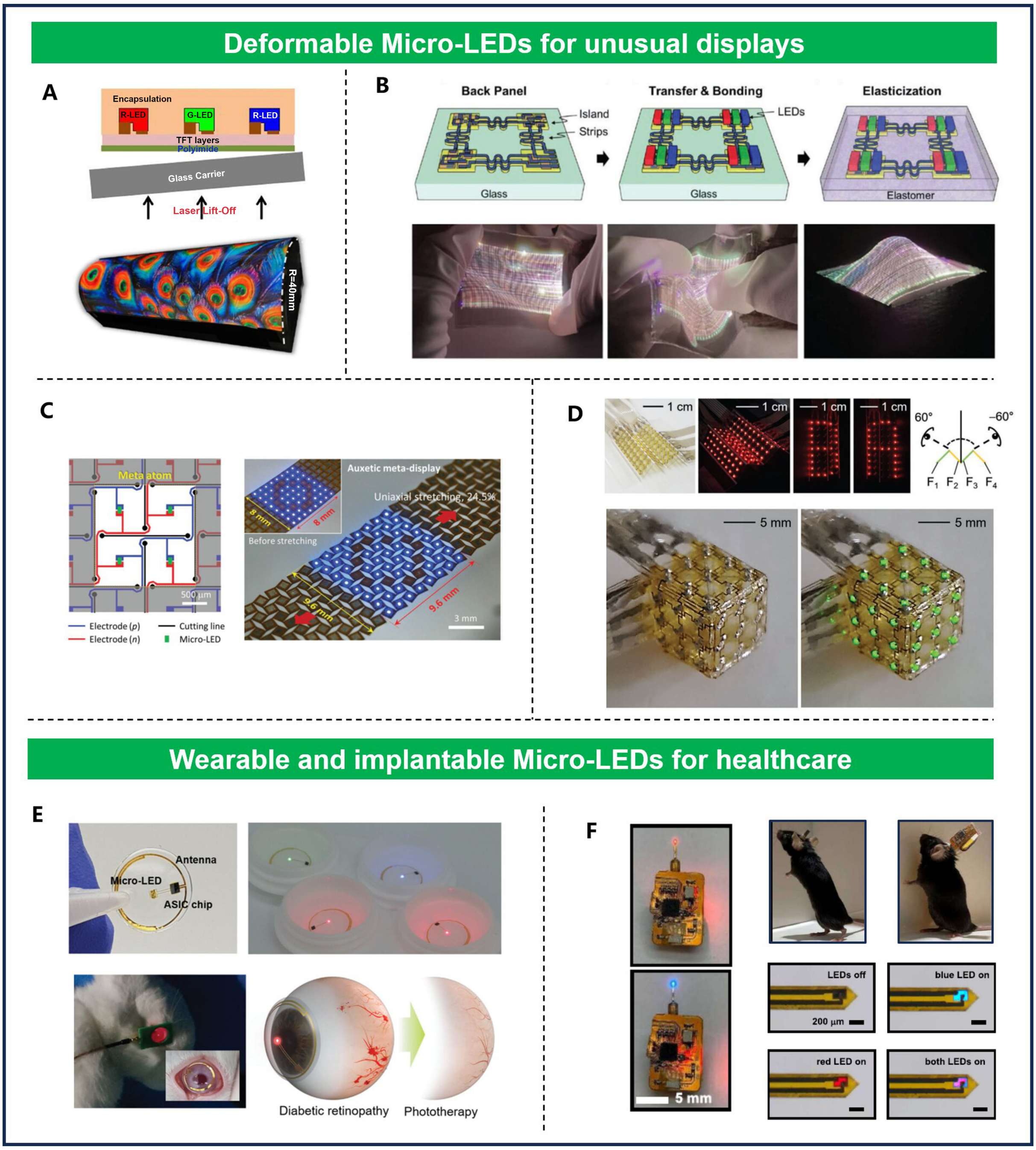

Figure 2. Deformable Micro-LEDs for applications in (A-D) advanced displays and (E and F) healthcare. (A) 4-inch flexible full-color active-matrix display integrated onto TFT backplane by LLO[12]; (B) Stretchable display based on island-bridge structures[64]; (C) Distortion-free stretchable display based on 2D Kirigami structures defined by laser cutting[10]; (D) 3D foldable display based on an origami structure design[19]; (E) Wearable contact lenses for the treatment of diabetic retinopathy[29]; (F) Wirelessly powered, dual-color implantable probes for optogenetics[28]. Figure 2A adapted with permission from ref.[12]. Copyright 2021, Wiley-VCH; Figure 2B adapted with permission from ref.[64]. Copyright 2021, Wiley-VCH; Figure 2C adapted with permission from ref.[10]. Copyright 2022, Wiley-VCH; Figure 2D adapted with permission from ref.[19]. Copyright 2020, Wiley-VCH; Figure 2E reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license [29]; Figure 2F reproduced under the terms of the CC-BY Creative Commons Attribution 4.0 International license[28]. Micro-LED: Micro-scale light-emitting diode; TFT: Thin-film transistor; 2D: two-dimensional; 3D: three-dimensional.

a 2.7-inch 42-PPI stretchable Micro-LED display based on an island-bridge structure in combination with buckling[64] [Figure 2B]. The obtained device panel can be normally operated under biaxial stretching, free-form twisting and poking, revealing its excellent capability for tolerating large deformation.

Academic research, on the other hand, has led to the development of some unusual deformable displays with expanded functionalities that common ones cannot provide. Jang *et al.* demonstrated using Micro-LEDs fabricated on a 2D kirigami electrical circuit board to realize an auxetic distortion-free meta-display with a stretchability of 24.5% and Poisson's ratio of -1 under uniaxial stretching[10] [Figure 2C]. The concept constitutes a remarkable improvement over the common stretchable displays, which can lead to the deterioration of the reduced resolution per unit area and the blurred display image quality when subject to large mechanical stretch. Kim *et al.* demonstrated a hexahedral LED array with general row and column control lines by laminating Micro-LED devices to an acrylonitrile butadiene styrene (ABS) film, followed by selective plasticization and transformation, forming nondisruptive tucking-based origami at the electronics level[19] [Figure 2D]. The novel origami structure and fabrication process, combined with laminated Micro-LEDs, pave the way toward developing 3D foldable displays.

Wearable devices for healthcare

Apart from displays, deformable Micro-LEDs attachable to skins or implantable to human/animal bodies can be used as wearable light sources for healthcare purposes. For instance, Lee *et al.* demonstrated a wirelessly powered smart contact lens based on infrared Micro-LEDs [Figure 2E][29]. The contact lens with integrated Micro-LEDs can be conformally attached to the eyeball, effectively treating diabetic retinopathy that can cause vision loss and blindness in people with diabetes. Li *et al.* developed an implantable, wireless-powered dual-color Micro-LED probe for bidirectional optogenetic modulations[28] [Figure 2F]. The lightweight device has good biocompatibility, reduced dimensions and good portability, constituting remarkable improvements over conventional implantable LEDs driven by external wires and batteries, which restrict the natural motion and social interactions of animals. Self-powered, battery-free flexible Micro-LED-based Optogenetic Systems have also been reported to further reduce the system weight[20,65]. Zhang *et al.* demonstrated a wirelessly powered Micro-LED patch for local tissue oximetry, which allows effective monitoring of the regional tissue oxygenation in animal models[66]. Such a Micro-LED-based tissue oximeter can create many opportunities for studying various O_2-mediated processes in naturally behaving subjects, with implications in biomedical research and clinical practice. Phan *et al.* reported a flexible and wireless Micro-LED patch with an internet of things (IoT) healthcare platform for wound healing applications, which opens tremendous opportunities for remote healthcare with cost-effectiveness in the future[67].

CONCLUSIONS AND REMARKS

Technological advancements in substrate removal, transfer printing and mechanical designs have enabled the fabrication of deformable Micro-LEDs in flexible/stretchable formats. These devices not only reserve their excellent optoelectronic performance but also exhibit substantially improved flexibility and better reliability than rigid counterparts, making them suited for potential application in areas such as unusual deformable displays and wearable devices for healthcare. It is envisioned that deformable Micro-LEDs will lead to a technological revolution in the future display industry.

However, before practical applications of deformable Micro-LEDs, several issues need to be addressed. First, further improving the mechanical properties of Micro-LEDs is urgently required. While some novel mechanical designs, such as island-bridge and buckling structures, can be adopted to enhance the system stretchability, these concepts lead to reduced pixel resolution and compromised filling factors. Innovations in intrinsically stretchable conductors/substrates[68] (for instance, replacing the meandering interconnects using intrinsically stretchable conductors/substrates) and more accurate micro-assembly processes should be considered to simultaneously achieve excellent stretchability and resolution. Vertical stacking of multi-color Micro-LED chips may be another useful strategy toward further enhanced resolution of the flexible device[38]. Second, the long-term operation stability and biocompatibility of such deformable Micro-LEDs in bio-environments needs to be clearly established, especially for healthcare purposes. These devices encapsulated by bio-polymer generally can tolerate harsh environment attacks. However, whether they have any long-term side effects on the skin or human organs needs to be confirmed. It has been known, for example, that wearable devices with poor air permeability can affect the long-term wearing comfort[69]. Bonding failure at the Micro-LED/soft substrate interface is another issue worth future investigation. It may be worthwhile to develop intrinsically stretchable solders that can enhance the interfacial bonding strength. It is also urgently needed to develop flexible Micro-LEDs with full-color emitting capability. Monochromic Micro-LEDs combined with flexible quantum dot patterns[70], for example, may be a practical approach toward full-color wearable displays in the future. Finally, a system-scale, universal fabrication process for wearable Micro-LEDs is required. Currently, most fabrication techniques are only demonstrated at the laboratory, lacking consistent reproducibility. There is still a long way to extend the lab concept to large-scale fabrication.

DECLARATIONS

Authors' contributions

Wrote the original draft: Zou S, Li Y, Gong Z
Supervised, reviewed and revised the manuscript: Gong Z

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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