

# Flexible Micro Light-Emitting Diodes

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The  $\mu$ LED has been spotlighted as a novel fusion technology of information technology (IT) and nanotechnology (NT) and is proposed as the next-generation light source to solve numerous problems of existing OLED and QLED displays (e.g., afterimage, burn-in effect, heat/water instability, and slow response time).

$\mu$ LED

Internet of Things

bulk LED

## 1. Introduction

With the beginning of the Internet of Things (IoT) era, novel methods for efficient information utilization to handle and share various kinds of information in daily life have been discussed [\[1\]\[2\]\[3\]\[4\]\[5\]\[6\]\[7\]\[8\]\[9\]\[10\]\[11\]\[12\]\[13\]\[14\]](#). According to these requirements, academia and industries are attempting to narrow the physical/psychological distance between users and information, which is expected to be enabled by developing and commercializing various smart devices, including smart watches, home appliances, cell phones, and glasses. In other words, there has been a considerable amount of effort to realize a human–machine interface (HMI) in various aspects [\[15\]\[16\]\[17\]\[18\]\[19\]](#).

Since modern people are accustomed to lots of information, the desire to check their body/disease information in order to easily monitor and treat them has increased. These needs have been directly applied to newly develop smart devices. For example, smart devices can monitor various biometric information, such as pulse, heartbeat, and oxygen saturation, and then analyze living patterns (e.g., exercise and sleep and) in real time, helping to manage personal health [\[20\]\[21\]\[22\]\[23\]\[24\]\[25\]](#). For sustainable health monitoring and treatment, users have to continuously carry or wear the smart device obtaining information. However, these devices still have a critical limitation: huge equipment size, which is due to the intrinsic large volume of components, including batteries, circuits, and displays. In this regard, healthcare devices with a new form factor have been spotlighted, creating competition for the leading position in this fierce industry.

Recently, light-induced monitoring and treatment have attracted a lot of attention because of their biocompatibility, high therapeutic efficiency, and less-invasive process [\[26\]\[27\]\[28\]\[29\]\[30\]](#). Since light-based healthcare devices collect accurate, vital information or efficiently cure physical illnesses without tissue damage, numerous medical teams are actively utilizing lasers or bulk light-emitting diodes (LEDs) as therapeutic equipment. However, this equipment has some drawbacks, such as its huge size, low power efficiency, high cost, and difficulty of frequent uses, as shown in **Figure 1**.

	LASER	Bulk LED	MicroLED
Output power	Proportional to current above threshold	Linearly proportional to current	Linearly proportional to current
Response time	Fast	Slow	Medium
Lifetime	Long	Long	Long
Device Size	Extremely huge	Large	Small
Power efficiency	Low	Medium	High
Cost	Extremely expensive	Cheap	Medium
Ease of Use	Hard	Easy	Easy

**Figure 1.** Comparison of LASER, bulk LED, and  $\mu$ LED as a light source for biomedical applications (red: disadvantages, blue: advantages).

Therefore, several researchers around the world have tried to miniaturize these phototherapy devices to ensure user-friendliness, convenience, and sustainable use. Among various light sources such as organic LEDs (OLEDs), quantum dot (QD)-based LEDs (QLEDs), and bulk LEDs, compound semiconductor-based inorganic microLEDs ( $\mu$ LEDs) have been considered as a next generation novel light source for biomedical applications because of their high brightness, superior power efficiency, fast response time, and excellent stability [7][10][17][31][32][33][34][35]. In particular,  $\mu$ LEDs can be easily manufactured into free form factor optoelectronic devices due to their ultra-small size, showing the advantage of flexibility and the possibility for wearable biomedical applications. According to these advantages, the  $\mu$ LEDs have been applied to various bio-applications such as optogenetics, vital monitoring, and hair loss treatment.

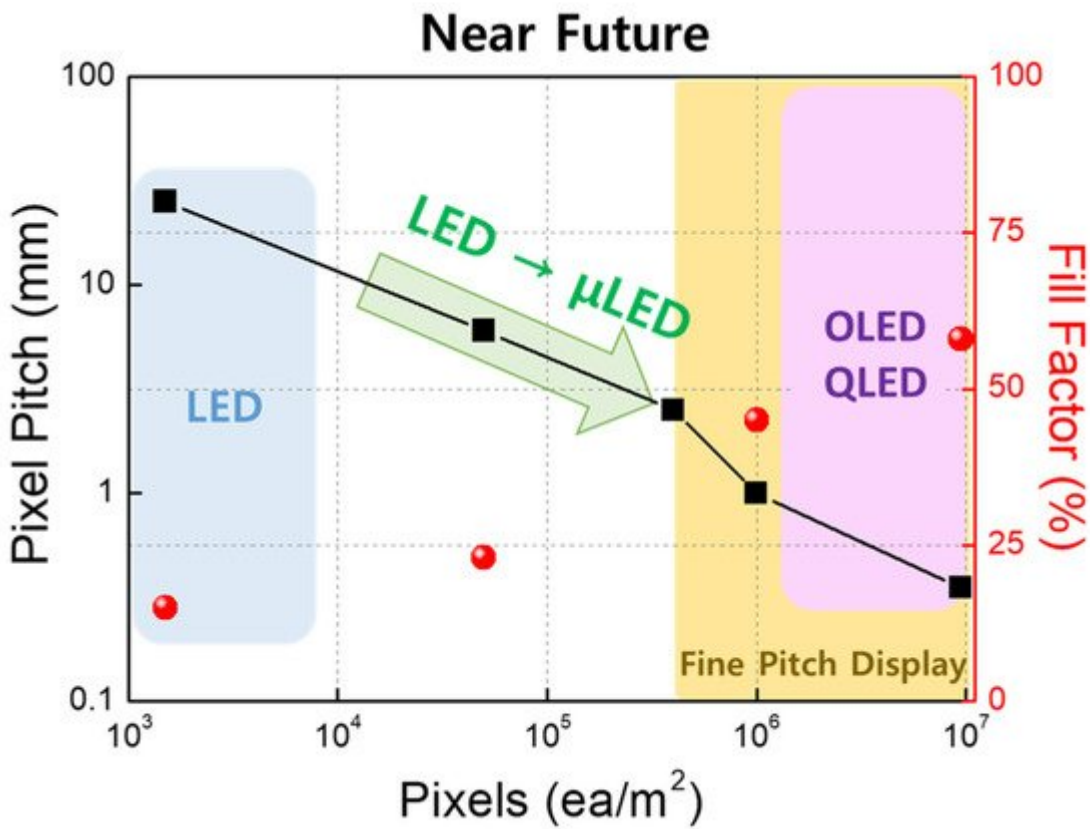
## 2. Flexible Micro Light-Emitting Diodes

The  $\mu$ LED has been spotlighted as a novel fusion technology of information technology (IT) and nanotechnology (NT) and is proposed as the next-generation light source to solve numerous problems of existing OLED and QLED displays (e.g., afterimage, burn-in effect, heat/water instability, and slow response time). **Figure 2** shows a comparison table among QLED, OLED, and  $\mu$ LED displays in terms of their emission type, thickness, optical property, lifetime, and cost. The  $\mu$ LEDs are self-emissive light sources with high brightness and a longer lifetime than OLED and QLED, and display excellent image quality. In particular,  $\mu$ LEDs of extremely small size (width from 10 to 100  $\mu\text{m}$  and thickness under 5  $\mu\text{m}$ ) have superior optical/electrical properties, such as excellent luminescence efficiency over  $100\text{ lm W}^{-1}$ , strong illumination over  $10^5\text{ cd m}^{-2}$ , high color contrast, and superior power efficiency.

	QLED	OLED	MicroLED
Type	Backlight/LED	Self-emissive	Self-emissive
Thickness	Thick	Thin	Thin
Brightness	Medium	Low	High
Contrast ratio	Low	High	High
Lifetime	Medium	Short	Long
Image quality	Low	High	High
Cost	Low	High	High

**Figure 2.** Comparison of QLED, OLED, and  $\mu$ LED display in terms of structure, optical/electrical properties, lifetime, and cost (red: disadvantages, blue: advantages).

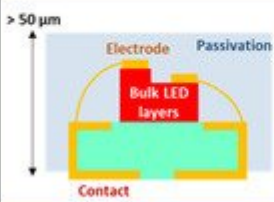
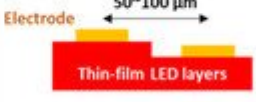

Therefore, in the display industry, it is predicted that high-performance  $\mu$ LEDs will even enter fine-pitch display fields that are dominated by OLEDs and QLEDs, as shown in **Figure 3**. Despite several advantages of  $\mu$ LEDs, there are still some challenges in realizing commercialization, such as efficient packaging, chip structure innovation, and development of a new transfer methodology.



**Figure 3.** Development prospect of light sources as display components.

First, flexible  $\mu$ LEDs are fabricated as follows [11][35][36][37][38][39]: III-V compound semiconductor layers are grown by metalorganic chemical vapor deposition (MOCVD), metalorganic vapor-phase epitaxy (MOVPE), or molecular beam epitaxy (MBE) on the mother substrate (e.g., silicon, GaAs, and sapphire), forming a thin-film LED structure with a p-type material, a multi quantum well (MQW), and an n-type material. The epitaxial layers are etched into numerous microscale chips through micro-electromechanical systems (MEMS) processes. The LEDs on the mother substrate are selectively peeled off and placed into a specific position on a target substrate. Finally, the  $\mu$ LEDs are electrically connected and packaged for passivating the device from environmental stresses.

The  $\mu$ LEDs can typically be divided into three types (Figure 4). There are fully packaged bulk LEDs, as well as lateral- and vertical-structured  $\mu$ LEDs, which are made by III-V or III-N compound semiconductors on epitaxial substrate (e.g., III-V: GaAs; III-N: Si, SiC, and sapphire). They have different characteristics in thermal, electrical, and optical properties, resulting from structural differences of bulk/thin-film and electrode location. Lateral  $\mu$ LEDs have a long current path of about 50~100  $\mu$ m between electrodes, whereas vertical  $\mu$ LEDs have a short current path under 5  $\mu$ m, inducing negligible Joule heating during device operation. Thanks to this structural advantage, vertical-structured microLEDs have various superiorities compared to others, including a small size, a fast/cheap process, superior electrical/thermal properties, and simple wiring. Particularly, vertical-structured  $\mu$ LEDs with low heating are most suitable to realize biomedical applications due to their thermally noninvasive property.

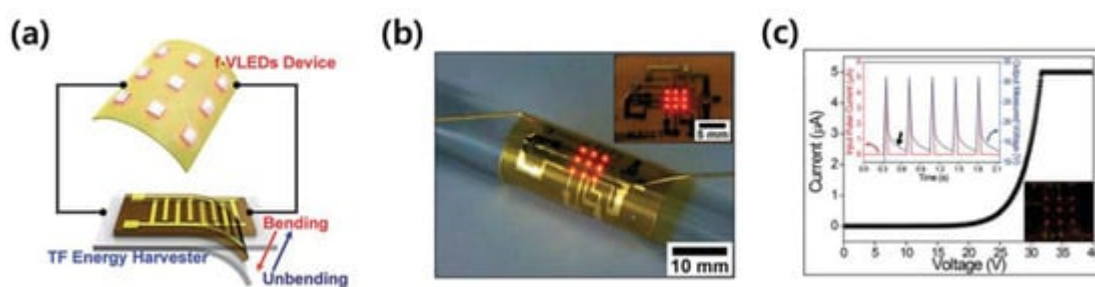
	Bulk LED	Lateral MicroLED	Vertical MicroLED
Material	III-V or III-N compound semiconductor		
Structure			
LED type	Fully-packaged chip	Thin film	Thin film
Size	Height > 50 $\mu$ m	Height < 5 $\mu$ m	Height < 5 $\mu$ m
Process	Slow & Expensive	Fast & Cheap	Fast & Cheap
Power consumption	Low	High	Low
Heating	Low	High	Low
Wiring	Complex	Complex	Simple

**Figure 4.** Comparison of bulk LED, lateral-, and vertical-structured  $\mu$ LEDs; red: disadvantages, blue: advantages).

As mentioned above, the processes, i.e., the transfer technology of numerous  $\mu$ LED chips from the mother wafer to the target substrate, are the most important factors for developing  $\mu$ LED-based electronic systems, such as displays, biomedical therapeutic devices, and healthcare sensors. Since the transfer efficiency is directly related to

the device yield, manufacturing time, and unit cost, several researchers around the world have attempted to transfer thin-film  $\mu$ LED chips through various methods. The polydimethylsiloxane (PDMS)-based pick-and-place method was the most widely used for  $\mu$ LED transfer. The  $\mu$ LED chips were attached to sticky PDMS by van der Waals adhesive force and released onto the adhesive-coated target substrate. Furthermore, although various approaches, such as electrostatic or electromagnetic force-based transfer, were suggested as new transfer methods, they still had many problems, including thermal/electrical damage to the LED layers, slow transfer speed, and difficulty in large-area processing. Recently, novel technology was proposed by using an anisotropic conductive film (ACF) [32][35][40]. Thin-film  $\mu$ LEDs were simultaneously attached and packaged with the target substrate through ACF by applying heat and pressure. The ACF-based transfer was performed with a rapid process speed, high yield, and large-area transfer, enabling electrical connection with complicated electrodes at the same time as the  $\mu$ LED transfer.

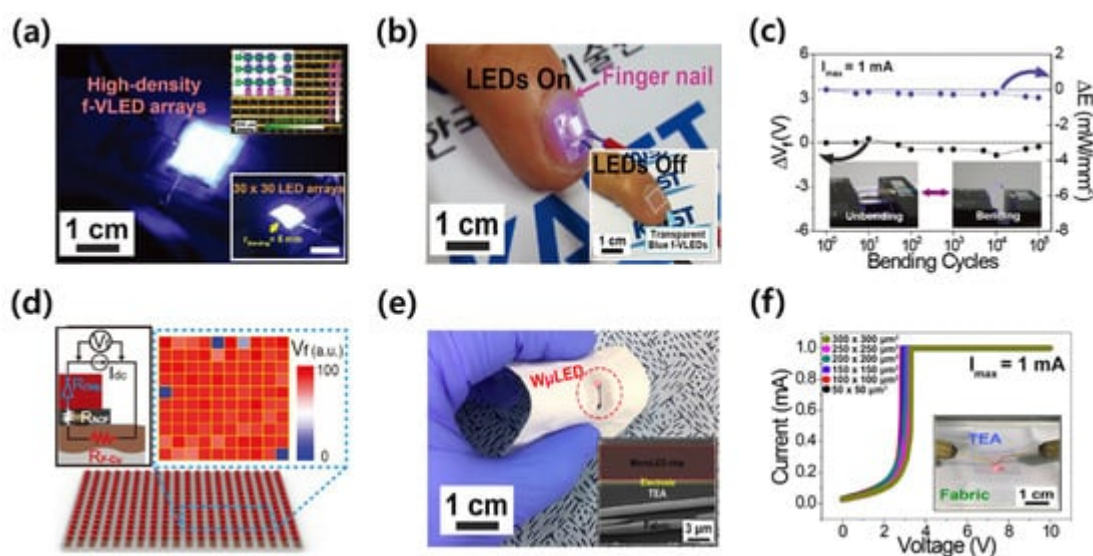
**Figure 5a** shows a self-powered flexible  $\mu$ LED array on a flexible plastic film. Jeong et al. made a flexible  $\mu$ LED array by transferring from a gallium arsenide (GaAs) wafer to a polyimide (PI) substrate by using the ACF transfer/packaging method [32]. Finally,  $\mu$ LEDs were integrated with a flexible piezoelectric energy harvester to complete a self-powered display system. **Figure 5b** indicates a flexible  $3 \times 3$   $\mu$ LED array in a bent state (bending curvature radius of 5 mm) illuminating brilliant light. **Figure 5c** is a luminance–current–voltage (L–I–V) graph of the fabricated flexible  $\mu$ LED. As shown in the bottom inset image, the  $3 \times 3$   $\mu$ LED arrays were driven by a  $\sim 3$  V, emitting red light with a wavelength of 653 nm. When mechanical force was applied to the thin-film piezoelectric material (lead zirconate titanate) of the device, the energy harvester generated an electrical power for operating a flexible  $\mu$ LED array without any external power source. The  $\mu$ LEDs were repeatedly turned on and off by the pulsed electrical power from the energy generator, as depicted in the upper inset graph of **Figure 5c**.



**Figure 5.** (a) Schematic image of self-powered flexible  $\mu$ LEDs that were composed of flexible red  $\mu$ LEDs and a thin-film piezoelectric power generator. (b) Photograph of flexible red  $\mu$ LED array. The inset image is a top view of the device. (c) I–V curve of flexible  $\mu$ LED arrays. The top inset shows output current and voltage from a thin-film energy harvester. The bottom inset indicates flexible red  $\mu$ LEDs, operated by a piezoelectric energy harvester. Reproduced with permission [32]. Copyright 2014, Royal Society of Chemistry.

**Figure 6a** displays a monolithic flexible GaN  $\mu$ LED array with a  $30 \times 30$  passive-matrix circuit [31]. Lee et al. developed the monolithic fabrication process for flexible, vertical-structured  $\mu$ LEDs (f-VLEDs). The GaN  $\mu$ LED array was fabricated on a rigid sapphire wafer and then exfoliated with a laser lift-off process. The freestanding GaN  $\mu$ LED array was isolated with epoxy-based polymer. After the electrical interconnection of  $\mu$ LED chips by a

silver nanowire (AgNW)-based electrode, the device was passivated by the biocompatible parylene-C layer. After flipping over the device, the AgNW top electrode was made on the device. As shown in the inset images of **Figure 6a**, the high-density blue  $\mu$ LED array with passive-matrix structure was operated at a bending curvature radius of 5 mm. Since the device was electrically connected by a transparent AgNW network, the  $\mu$ LEDs in off-state were invisible on the human fingernail (**Figure 6b** and its inset image). According to heat flux simulation, flexible vertical  $\mu$ LEDs had superior thermal stability compared to flexible lateral  $\mu$ LEDs due to efficient heat dissipation through the bottom electrode. The GaN f-VLED displayed excellent mechanical durability during  $10^5$  bending/unbending cycles because its mechanical neutral plane was placed at the center of  $\mu$ LED chips (**Figure 6c**). Furthermore, the device lifetime was expected to last 11.9 years. In accordance with these results, monolithic f-VLEDs are anticipated to commercialize in the display and biomedical device fields.



**Figure 6.** (a) Photograph of monolithic flexible blue  $\mu$ LEDs with  $30 \times 30$  array. The top inset is a magnified optical image of a passive-matrix  $\mu$ LED array. Scale bar: 1 cm. The bottom inset is an optical image of monolithic blue  $\mu$ LEDs in a bent state. (b) Transparent flexible blue  $\mu$ LEDs on human fingernail. The inset image shows fingernail-attached transparent device in off-state. (c) Fatigue test results of monolithic flexible  $\mu$ LEDs during  $10^6$  bending/unbending cycles. Reproduced with permission [31]. Copyright 2018, Wiley-VCH. (d) Normalized forward voltage of  $50 \times 50$   $\mu$ LED arrays with flash-induced Cu electrodes. Reproduced with permission [35]. Copyright 2021, Wiley-VCH. (e) Optical image of wearable red  $\mu$ LED on fabric substrate. The inset is a cross-sectional SEM image of wearable  $\mu$ LED. (f) I-V characteristics of wearable  $\mu$ LEDs with various size. Reproduced with permission [34]. Copyright 2019, Elsevier.

Shin et al. investigated robust Cu electrodes for  $\mu$ LED display applications [35]. Although Cu-based electrodes were spotlighted for application in display circuits due to their cheap price, robustness, and high conductivity, Cu had a critical delamination issue on rigid glass substrate. Shin et al. resolved this issue through flashlight-induced Cu-glass interlocking. By radiating a high-powered flashlight on CuO nanoparticles, the CuO was reduced to a conductive Cu layer, simultaneously forming strong adhesion with glass. The  $50 \times 50$   $\mu$ LED arrays were interconnected with a flash-induced robust Cu electrode by a thermo-compressive ACF bonding process. The

developed device showed thermal/humid stability and high uniformity in large-scale  $\mu$ LED arrays, as shown in **Figure 6d**. Lee et al. developed wearable  $\mu$ LEDs (W $\mu$ LEDs) on a 100% cotton fabric [34]. W $\mu$ LEDs were fabricated using the same protocol with monolithic f-VLED and transferred through transparent elastomeric adhesive by the thermo-compressive process. **Figure 6e** displays W $\mu$ LEDs emitting red light at a bent state. The attachment stability between  $\mu$ LED chips and fabric was sophisticatedly investigated by finite element method (FEM) simulation, tensile tests, peel-off tests, digital image correlation (DIC) analysis, and bending fatigue tests. As shown in **Figure 6f**, W $\mu$ LEDs with various chip sizes were operated at a forward voltage of  $\sim 2.8$  V. The W $\mu$ LEDs showed potential for outdoor application through chemical, thermal, humid, and artificial sunlight tests.

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