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# Flexible Bifacial OLEDs-based Photomedicine for User-friendly Healthcare Platforms

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## Abstract

This paper proposes a user-friendly phototherapy platform using vertically stacked and parallel-connected organic light-emitting diodes (OLEDs). Bifacial OLEDs can be individually operated and are multifunctional, enabling simultaneous phototherapy and display functionality. It was confirmed that this platform achieved electro-optical performance, flexibility, and reliability suitable for phototherapy and demonstrated a wound-healing effect.

## Author Keywords

Flexible electronics, Bifacial OLEDs, Photomedicine, User-friendly electronics, Wound healing, Healthcare application

## 1. Introduction

With advancements in science and technology, wearable

healthcare devices are being developed to meet the increasing demand and interest in healthcare and medical management. Flexible and wearable healthcare electronics can be applied to manage or treat people's health without time and space constraints. They enable measure bio-signals such as heart rate and blood pressure, and treat using light or ultrasonic stimulation, which are being developed as personal, ubiquitous medical devices. (1–3)

Phototherapy promotes cell migration and growth beneath the skin through low-level light irradiation, demonstrating therapeutic effects. It offers non-invasive and effective treatment without side effects. Light stimulates cellular metabolism, leading to the production of NO, ATP, and ROS, which promote tissue healing and regeneration. Therefore, phototherapy is considered a promising method for wound healing. (4,5)

OLEDs are in the form of a surface light source, which is

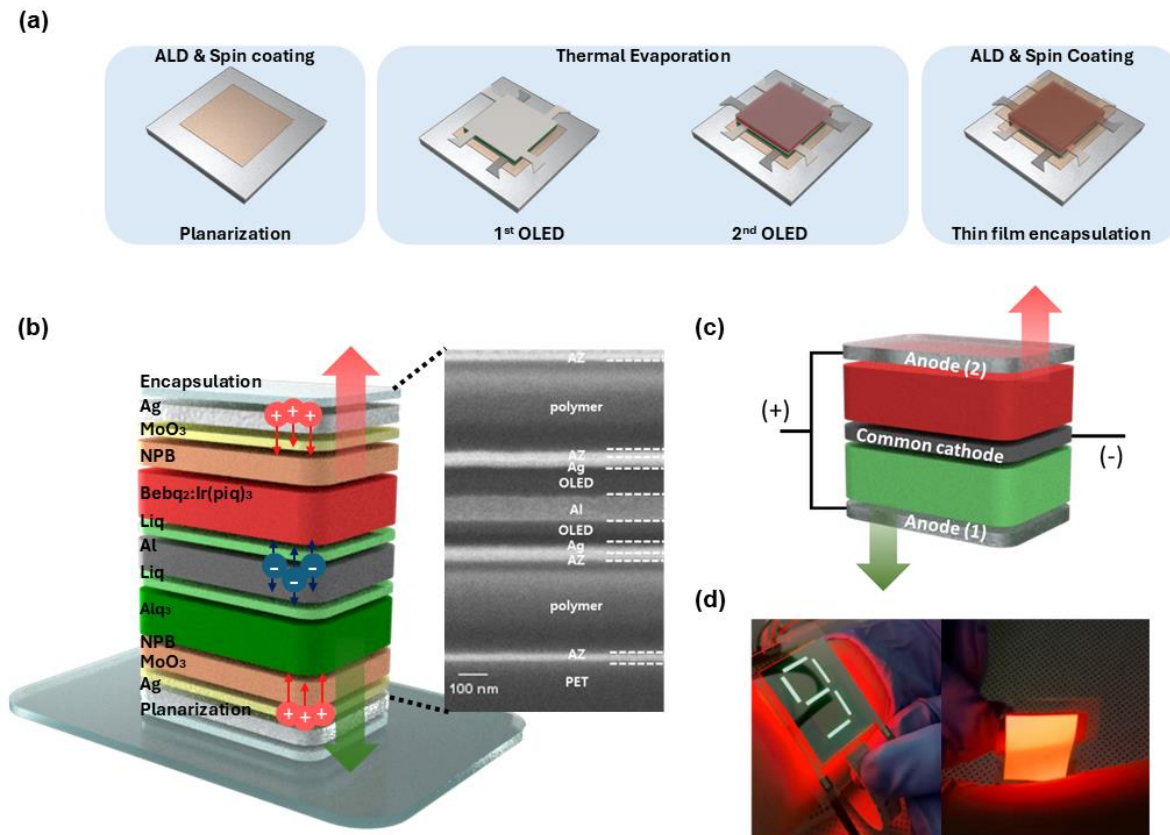
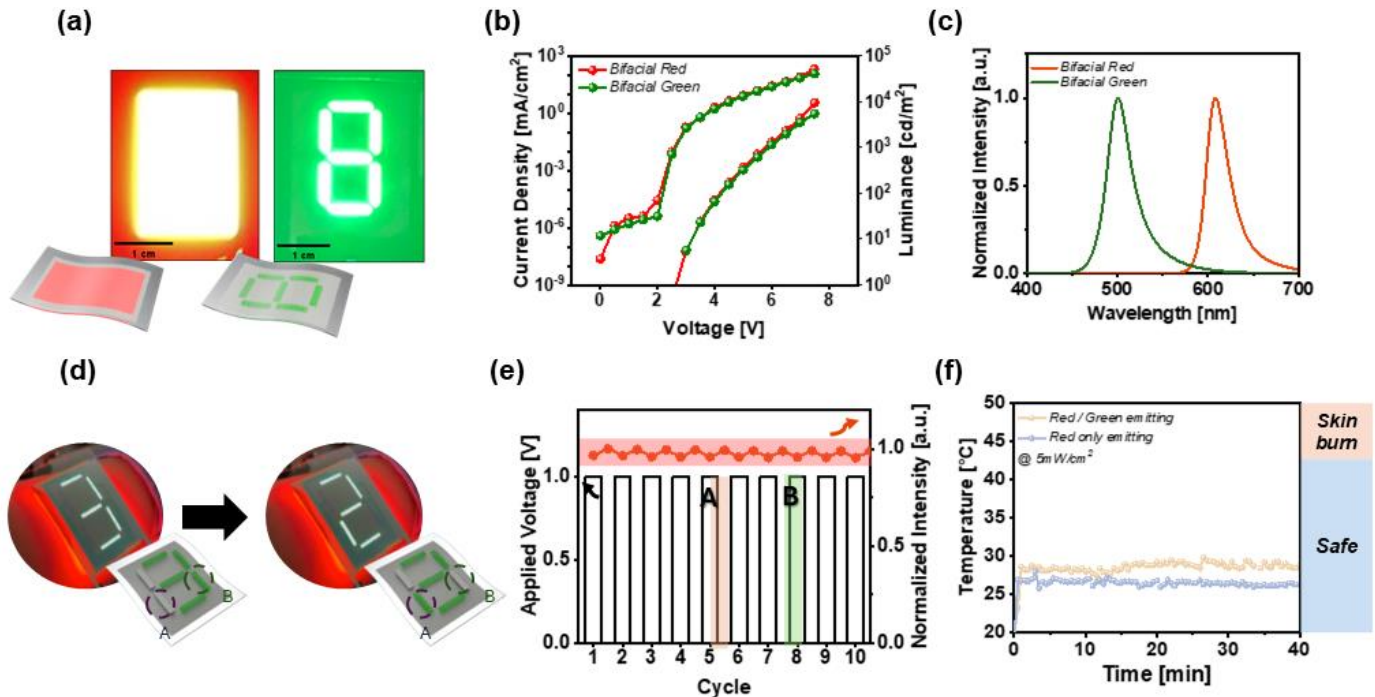


Figure 1. Schematic of Bifacial OLEDs (a) Fabrication process (b) Vertical stacked and (c) Parallel-connected structure (d) Application for phototherapy platform



**Figure 2. Characteristics of Bifacial OLEDs (a) Operating photograph, (b) Voltage-current density-Luminance (c) EL spectrum, (d) Photograph and (e) Intensity for Individual operating reliability, (f) Thermal stability with operating temperature**

um-scale thin, light and flexible. In addition, they can be manufactured on bandages, patches, and fabric substrates using transfer or planarization process. Wearable phototherapy platforms can be applied as a human body-attached/wearable medical electronics. OLED-based phototherapy has been shown to provide various therapeutic effects including wound healing, skin rejuvenation, and neonatal jaundice treatment. OLEDs have high flexibility, process-compatibility, and scalability, but their form factor lacks user-friendly functions for interaction and convenience required in wearable healthcare electronics. Therefore, there is a need for an OLED structure capable of simultaneously performing phototherapy and a user-friendly function. (6–8)

In this study, the structure of bifacial OLEDs (Bi-OLEDs) is proposed, which are connected in parallel, and stacked vertically. It enhances manufacturing compatibility and scalability, and multi-functionality, and could be performed by applying each to a display module and a phototherapy module. Additionally, the improvement of cell migration was confirmed through red OLED light irradiation, validating the wound healing effect.

## 2. Experiments and Results

Bi-OLEDs were designed based on PAOLEDs (parallel-stacked OLEDs) with high power intensity, as previously reported by our group. Unlike PAOLEDs, which emit light in the same direction, Bi-OLEDs can serve as multifunctional devices by emitting light in different directions. (9) The structure of Bi-OLEDs was designed to take advantage of both vertical stacking and parallel connection.

The Bi-OLEDs were fabricated as shown in Figure 1a: a planarization process was carried out on a PET substrate using

ALD and spin-coating. Subsequently, a bottom-emitting OLED was deposited, followed by the deposition of a top-emitting OLED on the cathode of the bottom-emitting OLED. Finally, an encapsulation process was performed using ALD and spin-coating.

Bi-OLEDs present two primary benefits, stemming from their vertical stacked structure and parallel connection. The vertical stacked structure can manufacture a more facile fabrication process and compact electronics with multi-functionality. In addition, the electrical parallel connection allows each function to be driven individually. This feature supports dual functionality at lower voltages, providing a more user-friendly phototherapy.

Bi-OLEDs are manufactured in the structure shown in Figure 1b, where two OLEDs are vertically stacked. After depositing a planarization layer on the flexible substrate, a bottom-emitting OLED with a green fluorescent emitting layer (EML) and a top-emitting OLED with a red phosphorescent EML are sequentially deposited. Since the two OLEDs can be deposited vertically, additional processes such as planarization and encapsulation are not required, enabling a simplified fabrication process. Moreover, the two OLEDs are electrically connected in parallel through the common cathode, aluminum (Al). (Figure 1c) When two OLEDs are manufactured through a vertically stacked process, they can be electrically connected either in series or in parallel. In a single circuit diagram, a series connection does not allow individual operation of each OLED, whereas a parallel connection enables independent operation with the same voltage applied to each device. By applying the same voltage to the devices, a parallel connection allows for lower voltage operation compared to a series connection, making it possible to use smaller-capacity

batteries. Parallel-connected Bi-OLEDs can emit light independently in both upward and downward directions. As shown in Figure 1d, the red light and green light emitted by Bi-OLEDs can be utilized for phototherapy and as a timer or display for light therapy, respectively. Consequently, Bi-OLEDs offer a user-friendly light therapy platform, providing phototherapy in an accessible and convenient manner.

As shown in Figure 2a, the phototherapy light from Bi-OLEDs features a red light-emitting surface light source for uniform light irradiation, while the green OLED is designed in a seven-segment shape for the display module. For phototherapy applications, the bidirectional OLED light source should have sufficient electro-optical performance, flexibility, and reliability. (5,7) Bi-OLEDs demonstrated electrically stable operation. (figure 2b) They achieve the luminance of 4000 nits, corresponding to an intensity of 5 mW/cm<sup>2</sup>, which is commonly used in low-level light therapy, indicating sufficient power intensity. Since the therapeutic effect varies depending on the wavelength of light, the light emission wavelength characteristics of light are also important. (5) When both light sources emit simultaneously, there is no interference between the emissions, and the EL spectrum remains identical to that of a conventional OLED with a single EML. (Figure 2c)

To assign individual functions to each bidirectional output OLED, it is essential to ensure stable and independent operation of each device. (Figure 2d) When a pulse signal was applied to the green region, the emission intensity of the red OLED was measured. It was observed that the optical properties of the red OLED remained at a similar level regardless of whether the voltage was applied to the green region, confirming the feasibility of stable and independent operation. (Figure 2e)

OLED light sources used in phototherapy, located close to the human body, must be thermally stable, especially at temperatures below 42 °C to prevent low-temperature burns. When the red light from Bi-OLEDs was emitted at an intensity of 5 mW/cm<sup>2</sup>, the operating temperature saturated at 31 °C regardless of the operation of the green OLED, confirming the thermal reliability of the Bi-OLED light source (Figure 2f).

As shown in Figure 1a, the Bi-OLEDs structure consists of 1.5 dyads, with alternating Al<sub>2</sub>O<sub>3</sub> and ZnO layers forming an AZ stack of 30 nm, and a 300 nm silane-based elastomer for top encapsulation and bottom planarization. This encapsulation effectively protects the device, maintaining sufficient stability even in a flexible environment. (10,11) A cyclic bending test was performed at a bending radius of 20 mm with a strain of 0.188% for 1,000 cycles to compare the performance before and after the test. Both bidirectional OLEDs maintained the same performance as the initial OLED. The red-emitting OLED demonstrated an intensity of 5 mW/cm<sup>2</sup>, sufficient for light therapy, while the green-emitting OLED achieved brightness exceeding 1,000 nits, making it suitable for outdoor display applications. It demonstrates the flexibility required for human attachment (Figure 3).

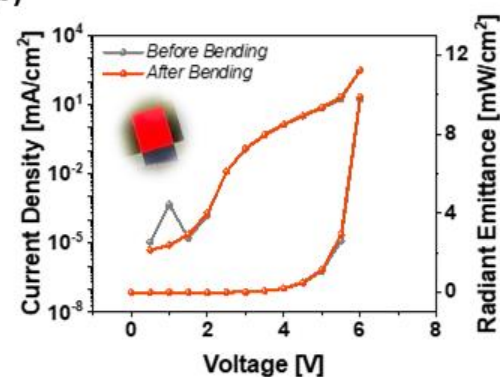
To investigate the effects on a wound healing model, a cell migration experiment was conducted using the scratch-assay method. Promoting cell migration is essential for effective wound healing. A scratch was artificially made at the center of a cell culture using a tip, followed by light irradiation, and changes in the closure of the scratched area were observed over 72 hours. The scratch closure was measured and analyzed using ImageJ. By evaluating the degree of closure around the scratch, the

improvement in cell mobility due to light irradiation was quantified. The wound treatment effect was assessed by irradiating the red OLED, emitting light at 630 nm, for 20 minutes.

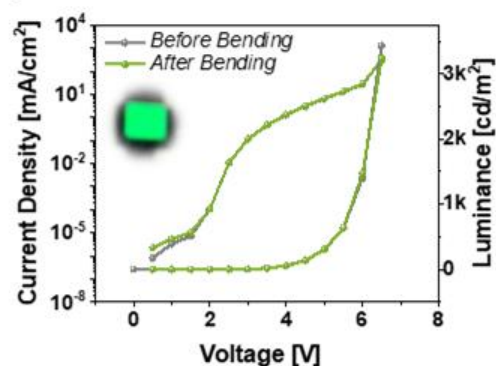
(a)



(b)

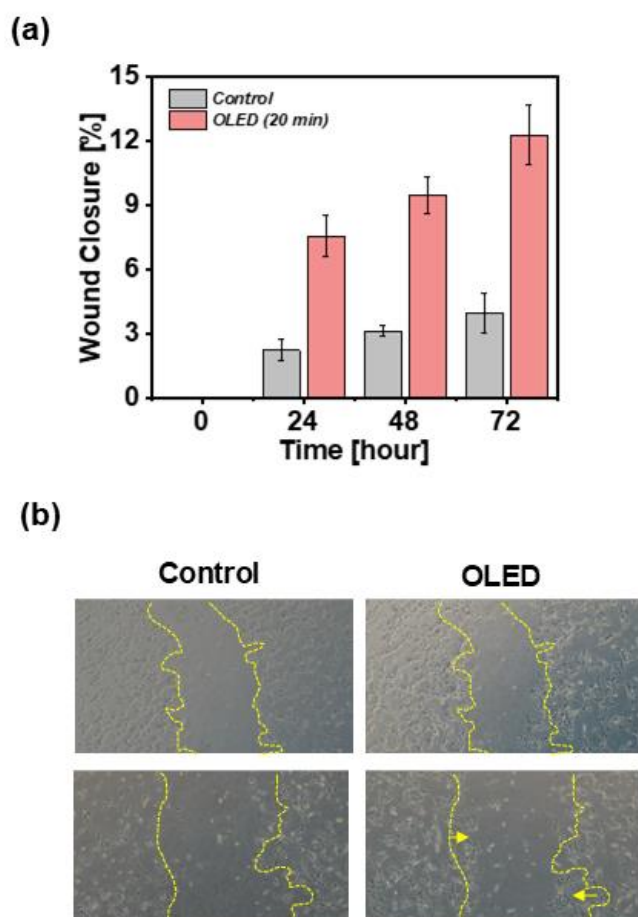


(c)



**Figure 3 Flexibility with cyclic bending test (a) Photograph of bending test. (b) Red OLED in Bifacial OLEDs, (c) Green OLED in Bifacial-OLEDs electrical-optical characteristics**

In the control group, 2.2%, 3.2%, and 4.0% of the wounds closed after 24, 48, and 72 hours, respectively. In contrast, after OLED light irradiation, 7.6%, 9.5%, and 12.3% of the wounds closed over the same time periods. With OLED light irradiation for 20 minutes, it was confirmed that cell migration improved by 8.3% compared to the control group. These experimental results show that OLED photomedicine has the potential to accelerate cell migration and promote wound healing.



**Figure 4. Wound healing validation using cell migration test (a) Cell migration measurement, (b) Cell migration images**

### 3. Impacts

In this study, Bi-OLEDs with the characteristics of vertical stacking and parallel connection was presented as a compact light source capable of performing phototherapy and display module, and the wound healing effect was confirmed using the red OLED light. Therefore, Bi-OLEDs can be used as an all-in one phototherapy platform that can provide not only light therapy but also user-friendliness.

### 4. Acknowledgement

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