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Electrical and Optoelectronic Performance of a 610 nm OLED for Skin Wellness

Sang-Hyun HWANG[1], Hae-Chang JEONG[2†], Sang-Geon PARK[3†]

1. First Author Researcher, Dept. of Smart Manufacturing Engineering, Changwon National University, Korea. Email: hwang981023@naver.com
2. Corresponding Author Professor, Dept. of Electrical, Electronic, Control Engineering, Changwon National University, Korea. Email: jhchang@changwon.ac.kr
3. Corresponding Author Professor, Dept. of Mechatronics Convergence, Changwon National University, Korea. Email: sgpark@changwon.ac.kr

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Abstract

This study investigates the effects of introducing a self-assembled monolayer with fluorinated terminal groups onto an ITO electrode surface on the interfacial characteristics and optoelectronic device performance of red organic light-emitting diodes (OLEDs). Surface analysis revealed that the contact angle increased from 10.28° for the ITO device to 79.40° for ITO/PFDTES, indicating that the surface became hydrophobic due to the fluorinated terminal groups. UV-Vis spectrophotometry analysis of absorbance and transmittance revealed that the optical transparency of the ITO substrate in the visible region was maintained despite the PFDTES-SAM introduction, with no significant optical loss observed due to the SAM. Analysis of electrical and optical properties revealed that at the same operating voltage, the luminance of the bare ITO device was 1996.4 cd/m², whereas the device incorporating PFDTES-SAM exhibited a high luminance efficiency of 3259.55 cd/m². Furthermore, both current efficiency and power efficiency were confirmed to be approximately doubled compared to bare ITO. This study enhanced the electrical and optical properties of OLED devices by utilizing fluorinated SAM as a hole injection layer, presenting it as a useful interfacial engineering strategy for designing low-power, high-efficiency OLED devices in the fields of phototherapy and wellness.

Keywords : Organic light-emitting diode, Medical Device, Wellness, Phototherapy, Hole injection layer.

JEL Classification Code :I00,I10,I11, L60, L65, L69

1. Introduction

Recent years have seen a continuous rise in societal interest in skin health and well-being. This shift stems from a growing recognition that skin is not merely an aesthetic feature but a crucial indicator of physical health and psychological stability (Kim & Han, 2021; Park & So, 2021; So et al., 2020). Research findings indicate that actual skin care experiences provide psychological healing effects such as stress reduction and emotional stability, and skin wellness is establishing itself as an integrated concept encompassing both physical and mental health. This growing interest in skin wellness is also leading to expanded research into light-based phototherapy technologies (Kim, 2019).

Light therapy has emerged as a promising non-invasive treatment method across various medical conditions and cosmetic skin applications. Among these, PBM (photobiomodulation) stands out as a non-invasive light therapy mechanism that stimulates cellular function. It activates cellular energy metabolism, promotes collagen synthesis, accelerates tissue regeneration, and induces improvements in skin function. PBM primarily utilizes LED (Light Emitting Diode) or OLED (Organic Light Emitting Diode) technology, with red and near-infrared light sources in the 600-900 nm wavelength range being widely used in the fields of skin regeneration and wound healing (Minatel et al., 2009; Barolet et al., 2009).

However, LEDs typically have a point light source structure, limiting their ability to provide uniform illumination and causing localized heating symptoms when applied to the skin. In contrast, OLEDs feature a thin-film-based structure, enabling illumination of large skin areas with uniform light distribution (Tyan, 2011). Their flexible substrate formation significantly enhances skin adhesion. Recent studies have reported that experiments utilizing red and near-infrared OLED devices demonstrated key physiological effects of PBM, including increased collagen production, improved skin microcirculation, and reduced skin pigmentation. This further highlights the potential of OLED devices as next-generation wearable-based skin wellness technology (Zhu et al., 2025).

These technical characteristics are expected to be applicable in the development of personalized skincare, medical, and wellness devices that require portability and stability. In this study, red OLED devices were fabricated on ITO substrates, and the surface characteristics of the ITO electrodes were precisely controlled by improving the Hole injection layer. Energy alignment and charge injection efficiency are key factors determining the performance of OLED-based devices, making an interfacial engineering approach essential for their optimization (Li & Lu, 2020).

Therefore, this study aims to improve the injection barrier with the hole transport layer by adjusting the work function of the ITO surface using self-assembled monolayers. The red OLED device realized based on this interfacial control can reduce the operating voltage and enhance luminance and current density efficiency as a function of voltage. This demonstrates its potential for use as a next-generation phototherapy platform for skin wellness and skin regeneration applications.

2. Literature Review

2.1. The Operating Mechanism of OLEDs

OLEDs feature a multilayer organic thin-film structure comprising a hole injection layer, hole transport layer, emissive layer, electron transport layer, and electron injection layer between the anode and cathode. Holes injected from the anode and electrons injected from the cathode travel through the transport layers before recombining in the emissive layer to form excitons. The generated excitons undergo radiative decay, emitting energy as photons to produce light. This structure, combined with the advantages of a thin structure, enables flexible fabrication and offers benefits of thinness and lightness. OLED-based phototherapy devices are gaining attention as a promising alternative (Tankelevičiūtė et al., 2024).

2.2. Self-assembled Monolayer

Self-Assembled Monolayers (SAMs) are organic materials that spontaneously form regular monolayers on substrate surfaces. Typically, SAM molecules consist of a head group that chemically bonds to the substrate, an alkyl chain that induces molecular alignment, and a terminal functional group that determines surface properties. These molecules form stable monolayers on the substrate surface through hydrolysis and condensation reactions. Research on enhancing OLED performance using SAMs is actively underway, with particular focus on their introduction onto ITO cathode surfaces to serve as hole injection layers. Among these, fluorinated organic compound-based SAMs can effectively modulate the work function of the electrode due to the large electric dipole moment of fluorine atoms. Consequently, they are reported to improve hole injection characteristics and contribute to enhancing the driving characteristics and efficiency of OLED devices (Batdelger et al., 2023)

2.3. Phototherapy Effects in the Red Wavelength

Phototherapy is generally known to exhibit increased scattering within tissue as light wavelength decreases, while longer wavelengths penetrate deeper into skin tissue (Stewart et al., 2013). Light in the red wavelength range that penetrates the skin activates mitochondria to regulate the concentration of reactive oxygen species (ROS), which has been reported to promote fibroblast proliferation. This ROS regulation effect and cell proliferation promotion play a key role in skin regeneration and therapeutic effects, and are considered the primary mechanism of action for red wavelength phototherapy (Wunsch & Matuschka, 2014). Specifically, the wavelength bands in the red and near-infrared regions are known to promote wound healing and activate cellular regeneration processes, thereby aiding in the regeneration of skin tissue. They are primarily utilized for various medical applications, including treatment and diagnosis, and promote efficient therapeutic effects by irradiating light of specific wavelengths (Kim et al., 2010).

3. Research Methods and Materials

3.1. Materials

The ITO substrates used in this study were purchased from AMG (Gyeonggi-do, Republic of Korea) and had a sheet resistance of 10 Ω/sq. The hole injection layer material, 1H,1H,2H,2H-perfluorooctyltriethoxysilane (PFDTES), was obtained from Gelest (Bucks County, PA, USA) and used as received. The TmPyPB (98% purity) used as the reference layer was purchased from Angene and used without further purification.

3.2. Cleaning and Preparation of ITO Substrates

The ITO substrate was cleaned through a pretreatment process prior to use. Ultrasonic cleaning was performed for 5 minutes each in acetone, DI water, and IPA solutions. Subsequently, the substrate was dried for 5 minutes on a hot plate set to 150 °C. To enhance the work function of the ITO surface and remove contaminants, an additional 20 minutes of UV–ozone treatment was conducted.

3.3. Deposition of PFDTES-SAM on ITO substrates

PEDTES-SAM was formed on the ITO substrate via a gas-phase deposition process for 20 minutes in a dry oven set at 160 °C. After deposition, the substrate was cleaned in an IPA solution for 5 minutes to remove any non-adsorbed molecules and contaminants that might remain on the surface. Subsequently, a drying process was performed on a hot plate at 150 °C for 5 minutes.

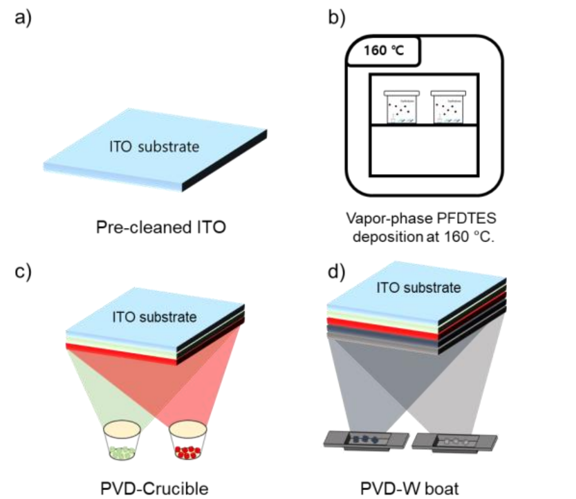

Figure 1: Schematic of the experiment process (a) Pre-cleaned ITO, (b) Vapor-phase PFDTES depostition at 160 °C, (c) NPB and $Ir(pq)_2(acac)$ deposition on ITO/PFDTES through crucible cell, (d) LiF and Al deposition on ITO/PFDETS/NPB/$Ir(pq)_2(acac)$.

4. Results and Discussion

4.1. Surface Wettability Analysis

The wettability of the ITO surface was evaluated by measuring the water contact angle on bare ITO substrates and ITO substrates modified with PFDTES-SAM, as shown in Figure 2. The bare ITO substrate exhibited a low contact angle of approximately 10° due to UV-ozone treatment, indicating a hydrophilic surface characteristic. In contrast, the surface with PFDTES-SAM introduced onto the ITO substrate exhibited a contact angle of approximately 79°, a significant increase compared to bare ITO, confirming a shift in surface characteristics from hydrophilic to hydrophobic. This improvement in contact angle suggests that a dense and stable fluorine-based SAM(PFDTES) has formed on the ITO surface (Weinstein et al., 2003), indicating that surface modification has been effectively achieved.

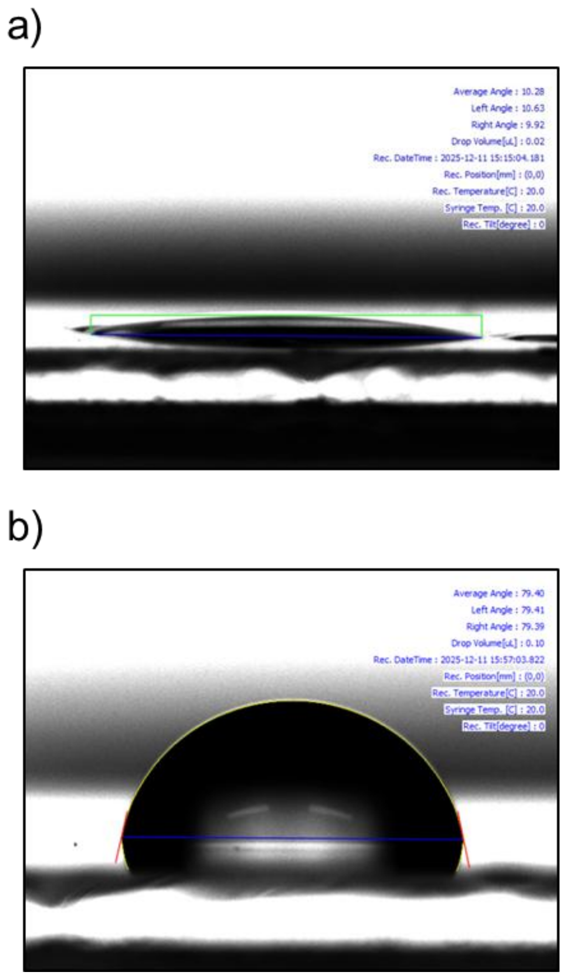

Figure 2: Water contact angle measurement of (a) bare ITO, (b) ITO/PFDTES-SAM.

4.2. Optical Properties of Thin Films

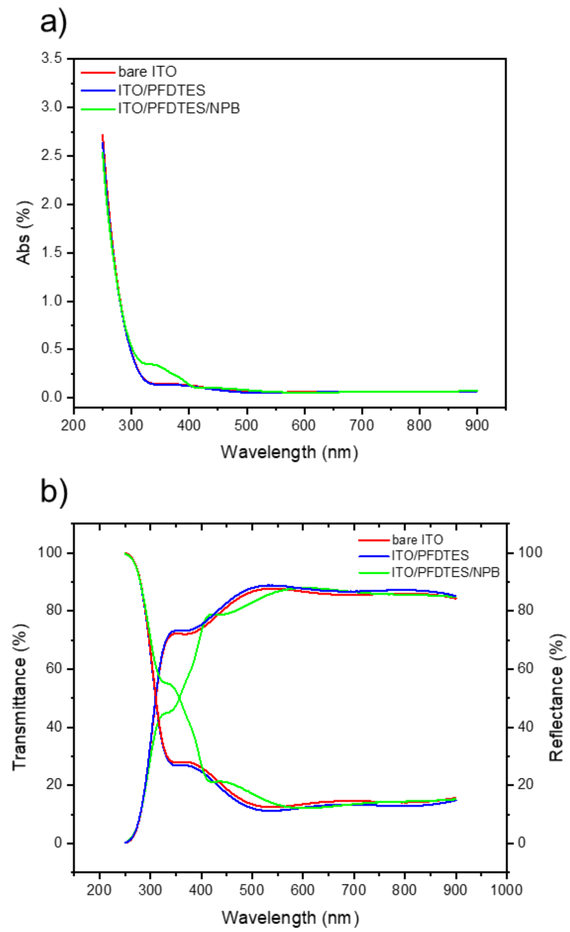

Figure 3: UV-Vis measurement of (a) Absorbance spectra (b) transmittance and reflectance spectra for bare ITO, ITO/PFDTES-SAM, and ITO/PFDTES-SAM/NPB structures.

The bare ITO and PFDTES-SAM-modified ITO substrates exhibited very low absorbance, with no significant absorption observed due to SAM modification. This indicates that the PFDTES-SAM was formed at an extremely thin thickness, preserving the substrate's optical properties. In contrast, the ITO/PFDTES-SAM/NPB structure exhibited a tendency toward relatively increased absorbance in the 300–400 nm range, which is interpreted as being due to the intrinsic light-absorption characteristics of the NPB organic layer.

Figure 3(b) shows the transmittance and reflectance spectra of the same specimens. The bare ITO and ITO/PFDTES-SAM substrates exhibited similar transmittance, confirming that the optical transmittance characteristics of the substrate remained largely unchanged despite the introduction of the SAM. This suggests that the PFDTES-SAM acted as an optically transparent interface modification layer. In contrast, the structure incorporating the hole transport layer NPB exhibited a slight decrease in transmittance. This is judged to be a result of the typical light-absorbing properties of hole transport layers. Consequently, the introduction of PFDTES-SAM did not significantly affect the optical absorption and transmittance characteristics of the ITO substrate, confirming that interfacial modification occurred without compromising optical performance.

4.3. Fabrication of Optoelectronic Devices

To evaluate the effect of modified ITO substrates on device performance, red OLED devices were fabricated and analyzed. Figure 7(a) shows the emission wavelength spectrum of the optoelectronic device, revealing a peak center wavelength of 610 ± 5 nm at the same voltage of 6 V. This wavelength band corresponds to the spectral region utilized in phototherapy and wellness applications. Figure 7(b) shows the current density-voltage-luminance (J-V-L) characteristics of the fabricated red light emitting device. Both the bare ITO device and the ITO/PFDTES device exhibited a similar turn-on voltage of approximately 3 V. However, at 6 V, the maximum luminance value relative to voltage was 1996.4 cd/m² for bare ITO, whereas the device incorporating PFDTES-SAM exhibited a luminance characteristic of 3259.55 cd/m^2. Compared to bare ITO devices, the introduction of a fluorinated SAM (PFDTES) significantly increased luminance at the same voltage. This indicates that PFDTE enhances hole injection efficiency, resulting in improved hole mobility and injection characteristics. Figures 7(c) and (d) show the current efficiency (CE)-luminance and power efficiency (PE)-luminance curves, respectively. Compared to bare ITO, the introduction of PFDTES-SAM resulted in a slight improvement in maximum current efficiency (CE_{max}) from 0.24 to 0.59 Cd/A and maximum power efficiency (PE_{max}) from 0.27 to 0.54 lm/W.

Table 1 summarizes the performance of the optoelectronic device. Devices incorporating PFDTES-SAM demonstrated overall improved performance compared to bare ITO in terms of current density, luminance, and efficiency. This enhanced performance is attributed to the introduction of the SAM-based hole injection layer, which mitigates the hole injection barrier at the ITO/organic layer interface, thereby improving charge injection balance within the device.

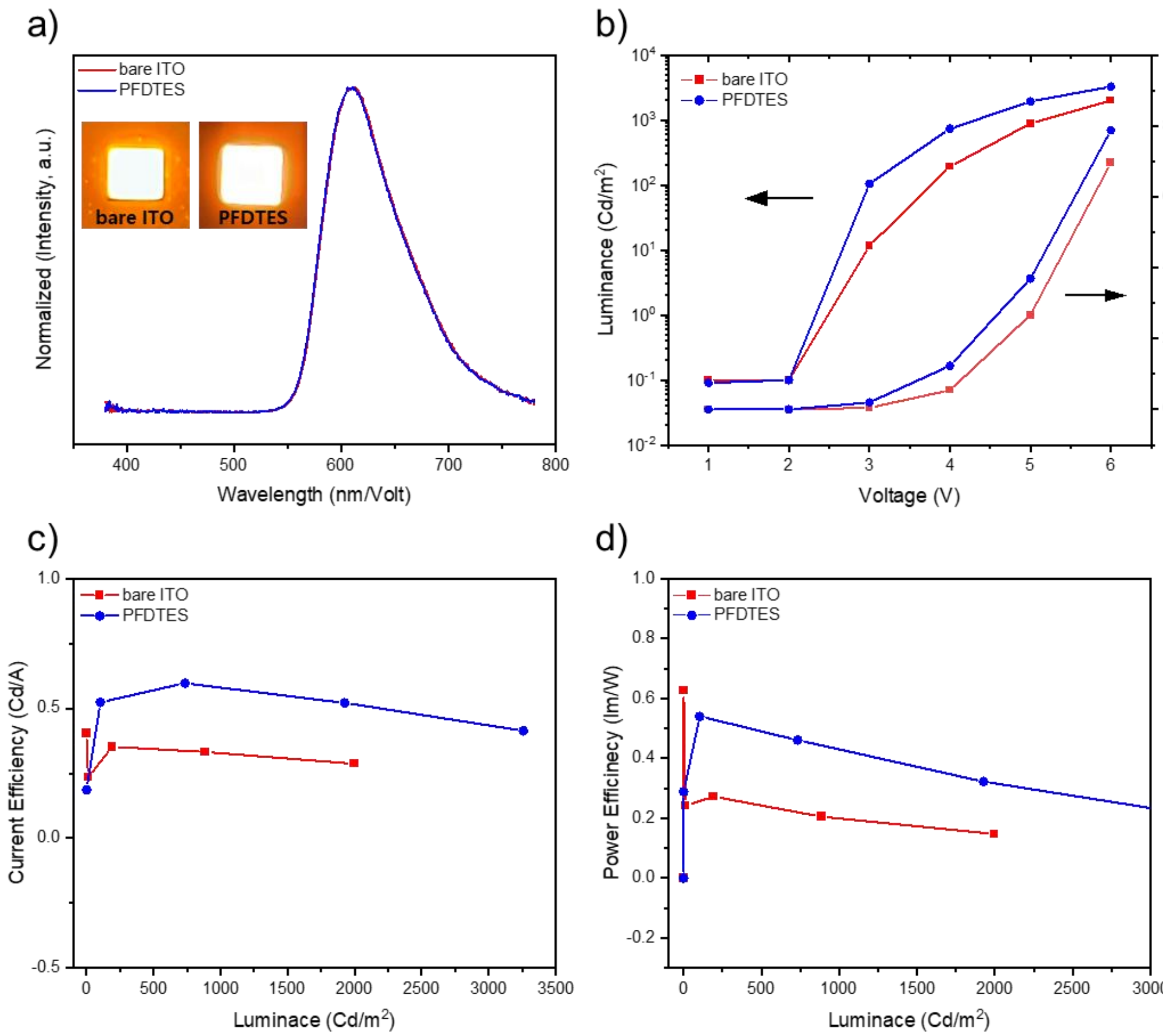

Figure 4: (a) Figure 7. (a) EL wavelength spectrum (610 ± 5 nm) and photograph of bare ITO and PFDTES-SAM-modified

optoelectronic devices. (b) Current density-voltage (J-V) and luminance-voltage (L-V) characteristics of the optoelectronic device. (c) Current efficiency-luminance curve of the optoelectronic device. (d) Power efficiency-luminance curve of the optoelectronic device.

Table 1: Performance of optoelectronic devices

	V_{on} (V)	L_s (Cd/m^2)	L_{max} (Cd/m^2)	CE_{max} (Cd/A)	PE_{max} (lm/W)	λ_{EL} (nm)
Bare ITO	3 V	11.58	1996.4	0.24	0.27	610
ITO/PFDTES	3 V	104.52	3259.55	0.59	0.54	610

5. Conclusions

In this study, we systematically analyzed the effects of introducing PFDTES self-assembled monolayers (SAMs) with fluorinated terminal groups onto ITO electrode surfaces on the interfacial characteristics and device performance of red OLEDs. Contact angle analysis revealed that the ITO surface modified with PFDTES-SAM exhibited a significantly increased contact angle compared to bare ITO, indicating a shift in surface characteristics from hydrophilic to hydrophobic. This result, attributed to the low polarity of the fluorinated terminal groups and the reduction in surface free energy, suggests that the PFDTES-SAM was formed densely and stably on the ITO surface. To confirm the interference caused by PFDTES-SAM from an optical perspective, UV-Vis absorbance and transmittance were analyzed. It was confirmed that the optical transparency of the ITO substrate in the visible light region was maintained despite the introduction of PFDTES-SAM. These results demonstrate that PFDTES-SAM acts as an optically non-interfering interfacial modification layer. In the electrical characteristic analysis, the bare ITO device exhibited a luminance of 1996.4 cd/m² at 6 V, whereas the device incorporating PFDTES-SAM demonstrated a luminance of 3259.55 cd/m² at the same voltage of 6 V. It showed improved luminance, current efficiency, and power efficiency compared to the bare device at the same voltage. This performance improvement is interpreted as resulting from the introduction of the SAM-based hole injection layer, which mitigates the hole injection barrier at the ITO/organic layer interface, thereby improving charge injection balance within the device. This study analyzed the electrical and optical properties of red devices by utilizing fluorinated SAM (PFDTES) as a Hole Injection layer to modify the ITO surface interface. This characterization approach is expected to serve as foundational research in surface modification interface engineering for future phototherapy and wellness applications.

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