# Development of a Novel p-Dopant for OLED and Its Combination with HTL to Reduce Leakage Current

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## Abstract

***This study focuses on two recently developed p-Dopant materials, PD-1 and PD-2, and their combinations with various hole transport layers (HTLs) to reduce leakage current in organic light-emitting diodes (OLEDs). By comparing these new p-Dopants with reference p-Dopants PD-0 and 1,4,5,8,9,11-hexaazatriphenylene-hexacarbonitrile (HATCN), we demonstrate significant improvements in electrical performance and lateral conductivity reduction with the optimal device properties. In addition, our new p-Dopants have an optical advantage due to their low absorption. Our findings highlight the potential of optimized p-Dopant selection in enhancing OLED efficiency and stability while addressing critical challenges associated with lateral leakage current.***

## Author Keywords

OLEDs, p-Dopant, LUMO, Lateral conductivity, Absorption, Doping concentration

## 1. Introduction

Organic Light Emitting Diodes (OLEDs) have emerged as a leading technology in the display industries due to their high efficiency, flexibility, and color quality [1]. Ensuring the reliability of OLED panels remains a challenge, particularly due to the issue of lateral leakage current. Lateral leakage current, which occurs when charge carriers move laterally across the device, can lead to white color distortion, reduced operational efficiency, and poor display quality. Addressing this issue is crucial for the long-term reliability and performance of OLED panels. To accurately measure and address lateral leakage current, it is essential to focus on reducing lateral conductivity within the OLED structure. Lateral conductivity refers to the ease with which charge carriers can move laterally across the device, contributing to leakage currents. By minimizing lateral conductivity, we can effectively reduce lateral leakage current, thereby enhancing the overall reliability and efficiency of OLED panels. Researchers have explored various strategies to investigate p-dopants and hole transport layers (HTLs) [2-3]. Another study designed new anchored p-dopants that significantly enhance power efficiency in OLEDs [4]. Additionally, the research results of various types of p-Dopant materials, including 1,4,5,8,9,11 -hexaazatriphenylene -hexacarbonitrile (HATCN) indicate that they have an important impact on the charge carrier characteristics of OLEDs [5-7]. In addition, the point group of organic electronic materials play a role in determining their electrical properties and directionality. Studies have shown that the manipulation of point group can lead to changes in the electrical characteristics of these materials, thereby influencing their performance in devices [8]. Understanding and optimizing these properties is essential for the development of high-performance OLEDs and other organic electronic devices. Recent studies have also focused on improving lateral current characteristics. Studies of lateral diffusion of holes in the anode buffer layer show that lateral diffusion can reduce hole build-up and improve device stability [9]. Additionally, research on the electrical crosstalk effect between pixels in high-resolution OLED displays highlighted the importance of managing lateral leakage current to enhance device performance [10].

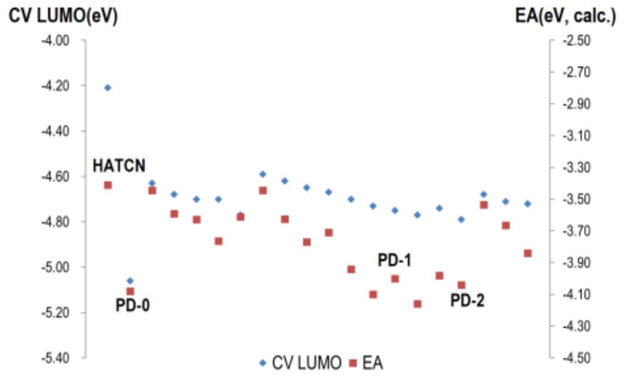

**Figure 1.** p-Dopant materials with various types of LUMO levels and electron affinity

In this study, we introduce two newly developed p-Dopants, PD-1 and PD-2, which possess shallower LUMO levels compared to the reference p-Dopant PD-0, while exhibiting deep LUMO levels that contribute to excellent device characteristics. PD-1 and PD-2 also have significant lower optical absorption in the blue region, which can positively affect its performance in color displays. On the other hand, HATCN has very low optical absorption but features much shallower LUMO levels, resulting in poorer device performance.

PD-1 and PD-2 have LUMO levels that are shallower than PD-0 but deeper than HATCN, placing them in an optimal range where they achieve device characteristics comparable to those of PD-0 while exhibiting lower blue region absorption than PD-0 and higher absorption than HATCN. This balance makes PD-1 and PD-2 superior candidates as OLED p-Dopants in terms of both electrical and optical properties.

A significant structural difference exists between the reference p-Dopants PD-0 and HATCN, which both contain radialene structures, and the newly developed p-Dopants PD-1 and PD-2, which feature non-radialene structures. This structural distinction provides PD-1 and PD-2 with the potential for varied electrical behavior depending on the direction of charge transport. The non-radialene structure may facilitate improved charge mobility along certain pathways, enhancing vertical current contributions in the device. Our research has confirmed that single carrier device measurements show superior J-V characteristics for PD-1 and PD-2, while simultaneously demonstrating reduced lateral current contributions, as indicated by lower conductivity values. This structural advantage suggests that PD-1 and PD-2 not only mitigate lateral leakage current effectively but also ensure robust vertical current performance, ultimately leading to enhanced device efficiency.

Our findings reveal that the incorporation of PD-1 and PD-2 leads to a notable reduction in lateral conductivity of the films, confirming their effectiveness in mitigating lateral leakage current while ensuring that vertical current characteristics remain comparable to those achieved with reference p-Dopants. Furthermore, under optimal thickness and doping ratio conditions, these new p-Dopants maintain sufficiently favorable driving voltages, demonstrating stable vertical current performance. This results in a significant reduction of lateral current, ensuring reliable operation of the OLED devices.

## 2. Experiment

The new p-Dopants PD-1 and PD-2 were synthesized and characterized. Reference p-Dopants PD-0 and HATCN were obtained from commercial sources. The energy levels of p-dopants used in this research, are summarized in Table 1. Computational LUMO of p-Dopants were calculated value by Gaussian TD-DFT (time-dependent density functional theory. Experimental LUMO of p-Dopants were measured by cyclic voltammetry. The energy levels of HTL were experimental values measured by AC3 for HOMO, and LUMO was calculated from film absorption edge of photoluminescence data measured by JASCO FP-8600.

**Table 1.** LUMO levels and point group (symmetry labels) of p-Dopant materials

| p-Dopant | Computational LUMO (eV) | Experimental LUMO (eV) | Point Group |
|---|---|---|---|
| PD-2 | 5.12 | 4.80 | C2 |
| PD-1 | 5.11 | 4.79 | C2 |
| PD-0 | 5.20 | 5.06 | D3 |
| HATCN | 4.62 | 4.21 | D6 |

**Table 2.** LUMO levels and symmetry labels of p-Dopant materials

| HTL | Experimental HOMO/ LUMO (eV) |
|---|---|
| HTL-A | 5.65/ 2.52 |
| HTL-B | 5.55/ 2.46 |
| HTL-C | 5.51/ 2.42 |

In addition, the point group was specified in consideration of the three-dimensional structure of the molecule for each material of p-dopants. Based on the review of the degree of symmetry, it can be confirmed that the PD-1 and PD-2 have reduced molecular symmetry compared to PD-0. Therefore, it can be expected that the preference direction for current flow can be distinguished, which is expected to ultimately contribute to the improvement of lateral leakage current. To increase the reliability and verify the reproducibility of the experiment, three types of HTL materials were selected and conducted. OLED devices were fabricated using a standard structure: an indium tin oxide (ITO) anode, followed by the HTL, Blue emissive layer, and cathode. The specific combinations of the new p-Dopants with HTLs were systematically varied.

Device performance, the current density-voltage-luminance (J-V-L) characteristics were measured simultaneously with a programmable Keithly 2635B power source and a PhotoResearch PR 670. In order to measure conductivity, the van der pauw method was used to measure the electrical conductivity. Keithley 6430 was used as SMU and the conductivity measuring device deposited organic materials on four electrodes in the form of square. Optical performance, UV absorption was measured by JASCO V-770 in 100 nm film on bare glass.

## 3. Results and discussion

The electrical performance of OLED devices incorporating the newly developed p-Dopants PD-1 and PD-2 was evaluated. First, as shown in Figure 2, the conductivity was measured by doping three types of HTLs with the same concentration (10wt%) according to their HOMO levels. It was found that the conductivity of PD-0 increased dependently on the HOMO level of the HTL. In contrast, PD-1 and PD-2 showed weaker dependence on the HOMO level of the HTL compared to PD-0. In HTL-A with a deep HOMO level, the electrical conductivity difference between PD-0 and PD-1, PD-2 is 1.5 orders, whereas in HTL-C with a relatively shallow HOMO level, the electrical conductivity difference is about 2.5 orders, showing a larger difference.

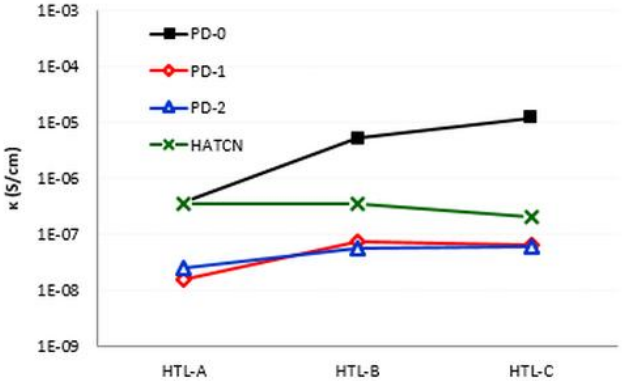

**Figure 2.** Electrical conductivity with HTL and p-Dopant combination. (Films with 10wt% of doping concentration)

Additionally, as shown in Figure. 3, the electrical conductivity was measured while increasing the doping concentration of PD in HTL-A. The results confirmed that PD-1 and PD-2 exhibited lower conductivity compared to PD-0 at all doping concentrations.

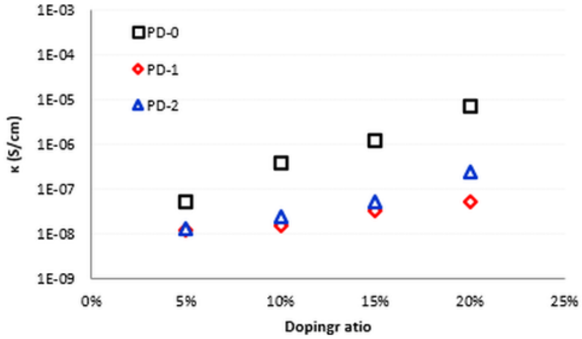

**Figure 3.** Electrical conductivity by doping concentration of p-Dopant in HTL-A

Figure 4 shows the comparison of J-V characteristics by fabricating a hole-only device to verify the hole injection characteristics in OLED devices. In the experiment, HTL-A with PD-0, PD-1, and

PD-2 was deposited at the same concentration (10wt%) to a thickness of 10nm on an ITO electrode. An undoped region was then deposited to a thickness of 90 nm, followed by the construction of the cathode to compare the J-V characteristics.

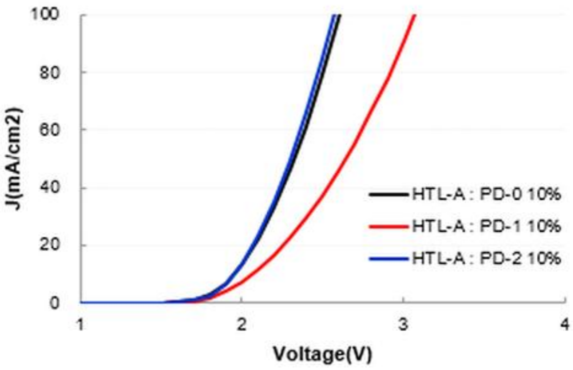

**Figure 4.** Comparison of J-V characteristics of hole only device by p-Dopant type in HTL-A

The results show that while PD-0 and PD-1 exhibited reduced hole injection characteristics, PD-2 demonstrated injection characteristics equivalent to those of PD-0. This indicates that PD-2 is more efficient in hole injection than PD-1 due to its lower LUMO energy

The reduced molecular symmetry of PD-2 results in a preferred current flow. At the same doping concentration (10wt%), it has 1.5 orders lower electrical conductivity in the horizontal direction compared to PD-0 but maintains equivalent hole injection characteristics in vertical OLED devices. This could have significant implications for the design and optimization of materials in electronic devices.

The following are the results of Blue OLED devices using HTL-A and PD-0, PD-1, PD-2. As with the hole-only device, the device was constructed by sequentially depositing HIL, HTL, Blue EML, ETL, EIL, and Cathode. When PD-0, PD-1, and PD-2 were applied at the same concentration (10wt%), the increase in delta voltage during device lifetime measurement was significant. Therefore, in Table 3, the results of PD-0 at 10wt% were compared with those of PD-1 and PD-2 at 15wt%. It was found that the voltage and efficiency levels at a current density of 10mA/cm² were equivalent under all three conditions.

**Table 3.** Comparison of device performances with optimal conditions of doping concentration.

| Conditions | OP.V | Cd/A | lm/W | EQE | CIE-x | CIE-y |
|---|---|---|---|---|---|---|
| HTL-A<br>PD-0 (10wt%) | 3.70 | 5.68 | 4.82 | 8.55 | 0.132 | 0.080 |
| HTL-A<br>PD-1 (15wt%) | 3.73 | 5.69 | 4.79 | 8.62 | 0.132 | 0.079 |
| HTL-A<br>PD-2 (15wt%) | 3.67 | 5.67 | 4.86 | 8.59 | 0.132 | 0.080 |

For the lifetime characteristics (Figure 5), PD-1 at 15wt% shows a rising in luminance and delta voltage due to ITO/Organic interface characteristics, whereas PD-2 exhibits equivalent luminance lifetime and voltage changes to PD-0.

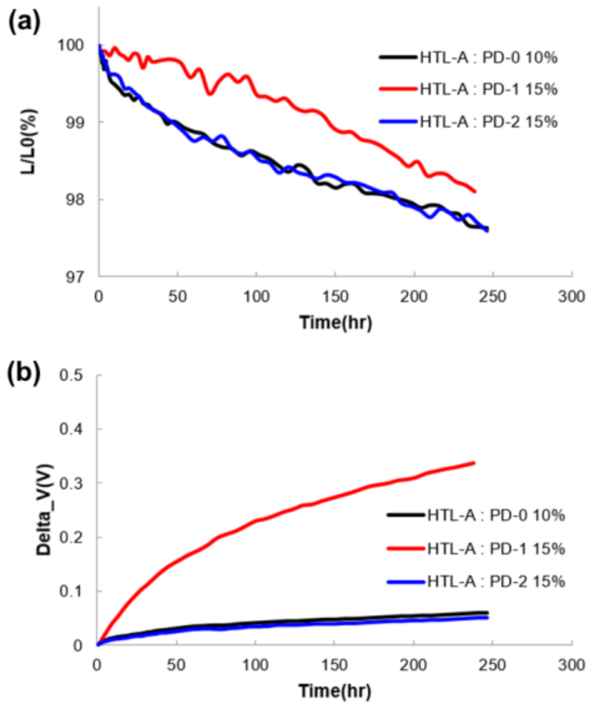

**Figure 5.** (a) Operational lifetime of the devices with optimal conditions of doping concentration. (b) Driving voltage as a function of the operational time for devices.

Photoluminescence and electroluminescence measurements further confirmed that the new p-Dopants did not adversely affect the emissive efficiency of the devices. In fact, the optical absorption characteristics of PD-1 and PD-2 provide a favorable balance, allowing for improved visibility and color accuracy in OLED displays. The ability of PD-1 and PD-2 to absorb less in the blue region compared to PD-0 while still maintaining adequate absorption relative to HATCN contributes to their enhanced performance.

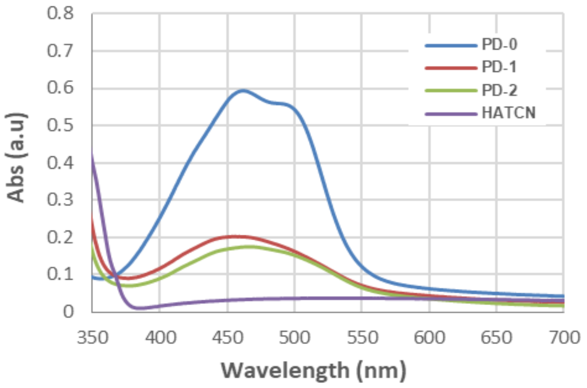

**Figure 6.** Comparison of UV absorption by p-Dopant type

The observed reduction in lateral leakage current and conductivity can be attributed to several factors. The improved energy level alignment facilitated by the new p-Dopants enhances hole mobility, which is vital for efficient charge transport. The non-radialene structure of PD-1 and PD-2 allows for varied electrical behavior depending on the direction of charge transport, which may contribute to better vertical current contributions while minimizing lateral currents.

The optimal thickness and doping ratio conditions employed in the study ensure that the lateral conductivity is minimized without sacrificing vertical current stability. This balance is critical for maintaining reliable device operation, demonstrating that the strategic combination of p-Dopants and HTLs can lead to significant improvements in OLED performance.

## 4. Conclusion

In conclusion, this study illustrates that the newly developed p-Dopants PD-1 and PD-2, when combined with appropriate HTLs, significantly reduce lateral leakage current in OLEDs while maintaining vertical current characteristics comparable to those achieved with the reference p-Dopant PD-0. The results indicate that both PD-1 and PD-2 are effective in mitigating lateral leakage, which is crucial for preserving brightness and color accuracy in OLED displays.

Importantly, the conductivity measurements revealed that PD-1 and PD-2 consistently exhibit lower values across all doping ratios compared to PD-0. While PD-1 requires a higher doping concentration to achieve optimal lifetime characteristics, PD-2 demonstrates lower leakage current (1 order) and equivalent driving voltage and lifetime characteristics even at 1.5 times higher doping ratios compared to PD-0. This distinction highlights PD-2 as a particularly advantageous choice for OLED applications, as it not only reduces material costs but also enhances the efficiency of the device.

Overall, the integration of PD-1 and PD-2 into the OLED architecture provides significant advancements in addressing lateral leakage currents while ensuring robust vertical current performance. The findings underscore the importance of optimizing p-Dopant selection and HTL combinations in the design of high-performance OLED devices. Future research will focus on long-term stability assessments and further optimizations of p-Dopant and HTL combinations to maximize device performance and reliability.

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