# Maximizing Blue OLED Power Efficiency Using Ultra-Strong p-Dopants

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## Abstract

***Blue phosphorescent emitters significantly boost current efficiency in organic light-emitting diode (OLED) displays but require host materials with high triplet energy and large bandgaps. Consequently, conventional hole-transport layers create large hole-injection barriers. We show that combining deep-HOMO hole-transport materials with our recently developed ultra-strong p-dopants effectively reduces these barriers, paving the way for blue OLEDs with maximum power efficiency and enhanced lifetime.***

## Author Keywords

OLED materials; p-dopant; phosphorescent blue.

## 1. Introduction

The optimal use of highly efficient blue emitter technologies, such as phosphorescence or thermally activated delayed fluorescence (TADF), necessitates a comprehensive redesign of the organic light-emitting diode (OLED) stack. While most scientific studies focus on the emitting layer and adjacent blocking layers to enhance quantum efficiency, color purity, and operational lifetime—achieving remarkable progress in recent years (1-3)—it is equally critical to reduce the operating voltage to maximize power efficiency. Achieving this requires careful adaptation of the charge transport and injection layers.

Figure 1a presents a schematic energy-level diagram of a state-of-the-art blue phosphorescent OLED (adapted from Reference 1). To confine the high-energy triplet states of deep-blue phosphorescent emitters, host materials with even higher triplet energy levels are essential. These hosts must possess a wide bandgap and a deep highest occupied molecular orbital (HOMO) level. However, this often leads to significant hole-injection barriers (>0.3 eV) due to the mismatch with typical hole-transport layers (HTLs), which generally have HOMO levels in the range of -5.0 to -5.2 eV.

Reducing this barrier can be achieved by employing hole-transport materials (HTMs) with deeper HOMO levels, as illustrated in Figure 1b. Simultaneously, efficient hole injection from the ITO electrode must be ensured. This calls for the use of p-dopants with deeper lowest occupied molecular orbital (LUMO) levels, i.e., with a high doping strength, to enhance hole injection and transport effectively.

CREDOXYS has developed a novel class of p-dopants based on Ce complexes, designed to overcome previous limitations in OLED stack design by offering exceptionally high doping strength. Due to their unique metal-organic structure, CREDOXYS p-dopants provide a rare combination of high tunability, excellent optical transparency, and outstanding thermal stability. Notably, the low parasitic absorption of Ce-based p-dopants enables the design of organic optoelectronic devices with significantly enhanced quantum efficiency, as recently demonstrated in NIR organic photodetectors (4). In this work, we demonstrate how the exceptionally high doping strength of these novel p-dopants can be leveraged in phosphorescent blue OLEDs to reduce driving voltage, thereby enhancing power efficiency, and even extending device lifetime.

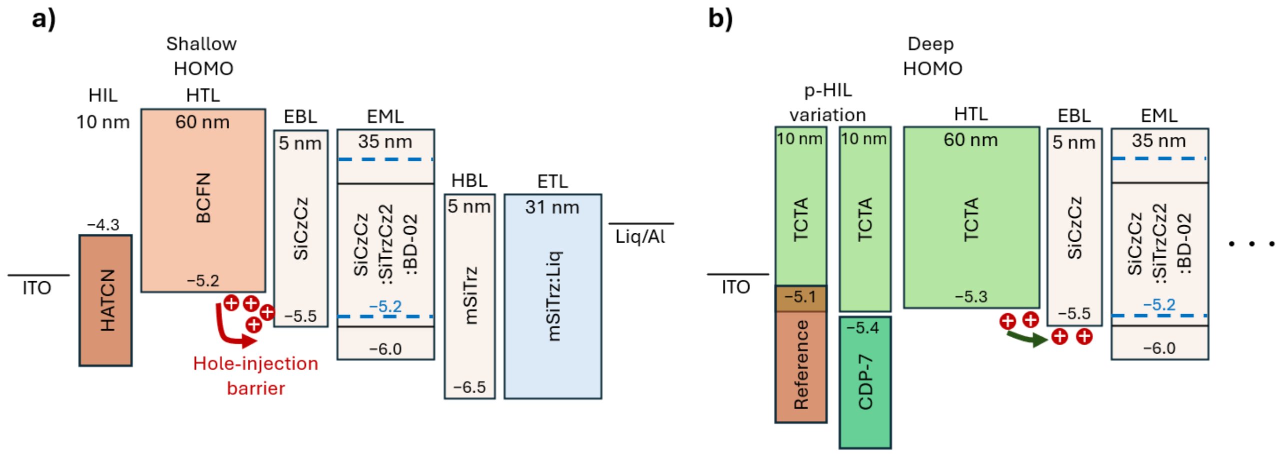

**Figure 1.** a) Schematic energy-level diagram of a blue phosphorescent OLED (adapted from Reference 1), illustrating how a large hole-injection barrier between the hole-transport layer (HTL) and the electron-blocking layer (EBL) leads to hole accumulation and increased operating voltage. b) The diagram demonstrates a reduced hole-injection barrier, achieved by incorporating a deep-HOMO HTM in combination with a market-relevant p-doped hole injection layer (HIL) instead of conventional HATCN. The figure compares two p-dopants used in the hole injection layer (HIL). Dopant CDP-7 is more suitable for the deep-HOMO HTMs due to improved energy level alignment. HOMO levels for the emitting layers (EMLs), electron and hole blocking layers (EBL and HBL), and an electron-transport layer (ETL) are taken from Reference 1 (measured by differential pulse voltammetry), while HOMO and LUMO values for the HIL and HTL materials, including p-dopants, were measured by cyclic voltammetry (CV).

ISSN 0097-996X/25/5601-0247-$1.00 © 2025

## 2. Results and Discussion

To identify the strongest p-dopants within the Ce-based material class, we measured the lateral conductivity of several p-doped HTM layers using the transmission line method on interdigitated ITO electrodes. CDP-1 and CDP-7 are CREDOXYS proprietary p-dopants that can be vacuum sublimed at around 110°C and 180°C, respectively, and have a high thermostability, which makes them suitable for OLED mass production. We compare them to a market-relevant organic reference p-dopant.

Table 1 summarizes the results at a dopant concentration of 10 wt%. The data reveal that, while all three p-dopants are well suited to dope BCFN (N-([1,1′-biphenyl]-4-yl)-9,9-dimethyl-N-(4-(9-phenyl-9H-carbazol-3-yl)phenyl)-9H-fluoren-2-amine) with a shallow HOMO level, both CDP-1 and the reference dopant are insufficient for doping HTMs with deeper HOMO levels similar to TCTA (4,4',4"-Tris(carbazol-9-yl)triphenylamine) or below. In contrast, CDP-7 leads to conductivities in the range of $10^{-5}$ S/cm, meeting the threshold for OLED operation. This result correlates well to the relative position of the LUMO of the p-dopants and the HOMO of the HTMs (as measured by CV). The higher conductivity of p-doped HTM-A (a commercial deep-HOMO HTM) as compared to TCTA is likely due to a higher hole mobility.

**Table 1.** Conductivity of deep-HOMO HTMs in S/cm$^2$ at 10 wt% dopant concentration. HTM-A is a commercial deep-HOMO hole-transport material. For comparison, data obtained with a market-relevant organic p-dopant are included. The LUMO of CDP-7 was estimated from a soluble derivative.

| p-HTM | HOMO CV (eV) | CDP-1 | CDP-7 | Reference |
|---|---|---|---|---|
| BCFN | -5.15 | $4\cdot10^{-5}$ | $2\cdot10^{-4}$ | $1\cdot10^{-4}$ |
| TCTA | -5.28 | $5\cdot10^{-7}$ | $1\cdot10^{-5}$ | $1\cdot10^{-7}$ |
| HTM-A | -5.36 | $2\cdot10^{-6}$ | $3\cdot10^{-5}$ | $5\cdot10^{-7}$ |
| LUMO (eV) by CV | | -5.16 | -5.35 | -5.05 |

Thus, CDP-7 was selected to investigate the potential of stronger p-dopants in phosphorescent blue OLEDs. Bottom-emitting devices were fabricated on ITO substrates, utilizing a layer structure similar to that shown in Figure 1: p-HIL (10 nm)/HTL (60 nm)/HH (5 nm)/HH:EH:BD (56:38:6 vol%, 35 nm)/EH (5 nm)/ETM:Liq (1:1, 31 nm)/Liq (0.5 nm), where HH, EH, BD and ETM represent commercial hole-transporting host, electron-transporting host, blue phosphorescent dopant, and electron-transport materials, respectively. To evaluate the impact of hole-transport materials, four devices were compared with p-HILs as follows: TCTA doped with 8 vol% of CDP-7 (Device B1), TCTA doped with 8 vol% of the reference dopant (Device B2), HTM-A doped with 6 vol% of CDP-7 (Device C1), and HTM-A doped with 6 vol% of the reference dopant. (Device C2). The HTL consists of the same material as the HTM in the p-HIL. For comparison, the OLED device with conventional HIL consisting of HATCN and BCFN as HTM (Device A) was also tested.

The electro-optical performance and lifetime of the investigated OLEDs are summarized in Table 2. Utilizing the deep-HOMO materials like TCTA and HTM-A in combination with the novel p-dopant CDP-7 decreases the operating voltage and enhances power efficiency. Remarkably, device lifetime also improves significantly when using a deep-HOMO HTL. This improvement is attributed to a lower energy barrier at the HTL/EBL interface. Figure 1b suggests that the combination of a deep-HOMO HTM with the strong p-dopant CDP-7 enhances performance through improved energy level alignment compared to the reference dopant or a conventional HATCN HIL structure (Figure 1a).

**Table 2.** Electro-optical performance of a blue phosphorescent OLED measured at 10 mA/cm$^2$.

| Device | V (V) | L (cd/m$^2$) | EQE (%) | PE (lm/W) | CIE x/y | LT70 (h) |
|---|---|---|---|---|---|---|
| A1 | 5.5 | 1914 | 14.5 | 12.7 | 0.16/0.20 | 30 |
| B1 | 5.2 | 2004 | 15.0 | 14.6 | 0.16/0.22 | 50 |
| B2 | 6.2 | 1926 | 15.0 | 12.0 | 0.16/0.22 | 41 |
| C1 | 5.1 | 1916 | 14.7 | 13.9 | 0.15/0.19 | 42 |
| C2 | 5.6 | 1873 | 14.8 | 12.4 | 0.15/0.19 | 42 |

A recent study has demonstrated that a higher energy barrier at the HTL/EBL interface shifts the recombination profile in the EML toward the EBL/EML interface due to the limited injection of holes into the EML (5). This shift increases bimolecular annihilation processes, such as exciton-polaron quenching and triplet-triplet annihilation, within the EML bulk. Other studies have shown that an energy barrier at the HTL/EBL interface leads to reduced efficiency and lower device stability due to charge accumulation at the interface (6, 7). Our results demonstrate that operating voltage, efficiency and lifetime improve when deep-HOMO HTMs and CDP-7 are used. In contrast, the organic reference dopant fails to achieve this enhancement due to its shallower LUMO level, which hinders efficient charge injection into deep-HOMO HTMs.

Alongside the power efficiency and lifetime, color purity is a crucial characteristic of an OLED, especially in blue phosphorescent OLEDs. Notably, while devices with TCTA exhibited enhanced efficiency and lifetime, they also showed a slight undesirable color shift (increase in CIEy). However, this effect can be mitigated—or even improved—by using HTM-A, which simultaneously enhances operating voltage, efficiency, and lifetime, when combined with a sufficiently strong p-dopant as CDP-7.

## 3. Conclusion

Maximizing the performance and stability of phosphorescent blue OLEDs requires optimization beyond the emitting layer, extending to the charge transport layers. This work demonstrates that ultra-strong p-dopants enable the integration of deep-HOMO hole-transport materials, leading to substantial improvements in operating voltage, power efficiency, and device lifetime. Specifically, using a deep-HOMO HTM-A doped with CDP-7 increased power efficiency by ~10% compared to the conventional HATCN HIL structure, while also enhancing lifetime by 40% and improving color purity. These results highlight the potential of Ce-based p-dopants to unlock even greater performance gains, particularly when combined with deeper blue emitters and wider-bandgap host materials. By providing greater flexibility in stack design, this novel dopant class paves the way for the next generation of high-performance blue OLEDs.

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