Solution-based processes enhance organic light-emitting diode stacks

Jing Wang and Neetu Chopra

A cost-effective ink and materials system replacing vapor thermal evaporation refines hole injection and transport layer technology, improving organic light-emitting diode production and performance.

Organic light-emitting diode (OLED) displays, especially active-matrix OLED displays (AMOLEDs), are widely used in smartphones today. As AMOLEDs enable larger sizes and higher resolution, the incentive to use them in large-area televisions is gaining momentum among mainstream companies owing to their performance advantages over liquid crystal displays (LCDs). Compared with LCDs, OLEDs render richer colors, deeper blacks, and wider viewing angles. In addition, they use less power and are brighter and thinner. The simplicity of OLED engineering also eliminates the need for a backlight unit, polarizer, and potentially color filters.

Currently, AMOLEDs are manufactured using vapor thermal evaporation (VTE), which despite its high material consumption has low material use and thus leads to significant wastage. It is also limited to smaller substrate sizes due to the complexity of the production process. As a result, it has become apparent that producing OLEDs cost-effectively requires a transition from VTE-based manufacturing to a solution-based printing process.

To help meet this need, we have developed and manufactured solution-processed materials and ink systems with a focus on applying hole injection layers (HILs) and hole transport layers (HTLs) to enable the commercialization of solution-processed OLED stacks (see Figure 1). Our Plexcore OC HIL product encompasses a p-doped conductive polymer-based technology in which we formulate both water-based (AQ) and solvent-based (NQ) inks. This technique delivers high hole injection efficiency and a wide range of film and electrical properties for leading OLED emitter stack technologies.

An OLED HIL plays a central role in enhancing performance and production efficiency by improving the yield of device manufacturing. It not only minimizes injection barriers at the anode and HTL interfaces but also allows for passivation of any defects present on the anode/indium tin oxide (ITO) surface through its conformal coating capabilities (see Figure 2). Owing to their low vertical resistance, our HILs, even at high thicknesses, facilitate low-voltage performance in OLED devices. This enables optical microcavity tuning by changing the location of the recombination zone within the device. The energy required to inject charges from the HIL to the HTL is minimized both by ensuring the use of high-electron-affinity dopants and energy level alignment between the HIL and HTL layers, and by maximizing the surface density of charge injection functionality at the interface of the HIL and the HTL. Our results show that the measured injection efficiencies for our various HIL inks are at least equal to and typically exceed the injection efficiency of two of the commonly known vapor-based HILs: hexaazatriphenylene-hexacarbonitrile and molybdenum oxide.

![Figure 1. Typical organic light-emitting diode (OLED) device structure and Plexcore OC product lines. V: Vapor. AQ: Water-based. NQ: Solvent-based. HT: Hole transport. ETL: Electron transport layer. EML: Emission layer. HTL: Hole transport layer. HIL: Hole injection layer.](image)

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Table 1. Key HTL properties and value for OLEDs. RMS: Root mean square. AFM: Atomic force microscopy. Tg: Glass transition temperature. TGA: Thermogravimetric analysis. eV: Electron volts. NPB: N,N'-di-[(1-naphthyl)-N,N'-diphenyl]-1,1'-biphenyl)-4,4'-diamine.

<table>
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<tr>
<th>HTL features</th>
<th>Target properties</th>
<th>Value for OLED</th>
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<tr>
<td>High-quality thin films</td>
<td>Up to 100nm films with:</td>
<td>Repeatability and reliability of performance. Uniform non-textured emission</td>
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<td></td>
<td>- 100% thickness retention after toluene spin wash</td>
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<td></td>
<td>- &lt;3nm RMS (via AFM)</td>
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<td>- &gt;90% transmission at 400–800nm</td>
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<td>High mobility</td>
<td>Equal or greater than NPB (&lt;0.1eV increase for every 10nm increase)</td>
<td>Low drive voltage</td>
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<td>Electronics grade purity</td>
<td>&gt;99% organic purity &lt;10ppm key metals and halogens</td>
<td>Enable long lifetimes</td>
</tr>
<tr>
<td>High thermal stability</td>
<td>Tg&gt;99°C TGA &gt;250°C for 5% loss</td>
<td>Enable long lifetimes</td>
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<tr>
<td>Triplet energy</td>
<td>2.4–2.8eV</td>
<td>Enable higher efficiency and longer lifetimes</td>
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Figure 2. This schematic describes the role of hole injection layers in a device stack as a passivation and injection layer. E: Electric field. A: Vertical resistance. B: Energy barrier (\(\Delta E\)) between HIL and HTL. C: Location of the recombination zone.

(see Figure 3). Solution-based HILs also planarize the roughness of the underlying ITO substrates, reducing device shorts and thus improving device yield$^2$ (see Figure 4).

The HTL not only helps lower the injection barrier from the HIL to the emission layer (EML), but it may also block any exciton/electron leakage from the EML into the HIL and minimize losses such as any quenching from the HIL/anode. The combination of HIL and HTL can effectively tune the charge balance and the recombination zone in the device, thus improving its overall efficiency and lifetime. Promising results have been reported comparing our HTL with a vapor-deposited N,N'-di-[(1-naphthyl)-N,N'-diphenyl]-1,1'-biphenyl)-4,4'-diamine HTL in a white OLED stack.$^3$

We are currently pairing solution-processed HTLs with our HIL to deliver a balanced charge in OLED devices while

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enabling all-solution-processed device stacks. A key feature of our HTLs is their ability to maintain film thickness and improve device performance when they are exposed to common EML solvents such as toluene and o-xylene. In our work, we are developing HTLs that address both the processing constraints of today’s vapor HTLs as well as the performance gaps seen with solution HTLs. The key features of our HTLs under development are detailed in Table 1.

Our products address market needs for flat OLED panel displays by providing solution-processed hole injection and transport layers that demonstrate comparable or better hole injection efficiency than vapor-deposited HILs. Planarization also enables them to improve device yield by reducing shorts. Plextronics strives to enable the broad adoption of its conductive polymer inks in emerging organic electronics applications. In future, we plan to explore additional materials to improve the performance of state-of-the-art device stacks.

Author Information

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Jing Wang has a PhD in organic chemistry and has been working as a material scientist at Plextronics since 2007. She is a team leader for the development of materials and inks for hole transport layers in OLED applications.

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References