White Paper:

Pixelligent Internal Light Extraction Layer for OLED Lighting

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May 2014

Abstract

Pixelligent has successfully developed a complete internal light extraction layer (ILE) for OLED lighting applications based on titania scatterers and Pixelligent's zirconia nanodispersions. This high-refractive index layer increases light output and can be applied with slot-die coating to provide customers with a single process for an ILE with integrated scatters. The slot-die coating technique is a scalable and low-cost process suitable for large size manufacturing.

Introduction

Organic Light Emitting Diodes (OLEDs) have been successfully commercialized for displays, but are still under development in lighting applications. One of the critical challenges facing market adoption of OLED technology for lighting is the high cost of devices, which is negatively influenced by the low light extraction efficiency of typical OLED lighting devices. The low light extraction efficiency is highlighted in the National Research Council's 2013 Assessment on Solid State Lighting[1].

The relationship between the internal quantum efficiency (IQE) defined as the number of generated photons per injected carrier, and the external quantum efficiency (EQE) defined as the number of photons emitted into the viewing direction per injected carrier, is expressed in the following equation[2]:

$$\eta_{\mathrm{EQE}} = \eta_{\mathrm{IQE}} \times \eta_{\mathrm{OUT}} \qquad (1)$$

where η_{OUT} is the light output coupling efficiency. A large portion of internally generated light can't exit the OLED devices' forward viewing side, due to the total internal reflection at the interface between the air and the transparent device substrate. The light output coupling efficiency determines how much light can escape from the device in the forward viewing direction. For a smooth plane device surface, the η_{OUT} is given by[3]:

$$\eta_{\mathrm{OUT}} = 1 - \frac{3}{4}\left\{\sqrt{1-\frac{1}{n^2}} + \frac{1}{3}\left(1-\frac{1}{n^2}\right)^{\frac{3}{2}}\right\} \approx 0.75n^{-2} \qquad (2)$$

where n is the refractive index of the substrate. Taking the refractive index of the emission layer (n ~ 1.8), the η_{OUT} is only ~25%, meaning that three quarters of the generated light is trapped inside.

Pixelligent has been developing a high refractive index zirconia nanocrystal based internal light extraction layer to substantially improve the light output efficiency of the OLEDs. A common internal light extract layer structure is schematically illustrated in Figure 1. The scatterers are usually inorganic particles with high refractive index and, in order to scatter efficiently, must have a size comparable to the wavelength of visible light. A smoothing layer is used to not only planarize the scatterers, but also match the ITO's refractive index. Therefore, the smoothing layer must have surface roughness less than ~2 nm to avoid a negative impact on yield and reliability. It must also have high refractive index, >1.7, preferably >1.8, close to that of ITO, with high transparency, to avoid index mismatch with ITO and allow the light to be transmitted to the scatterers. The scatterers are needed to redirect the high angle light that would otherwise not escape the device.

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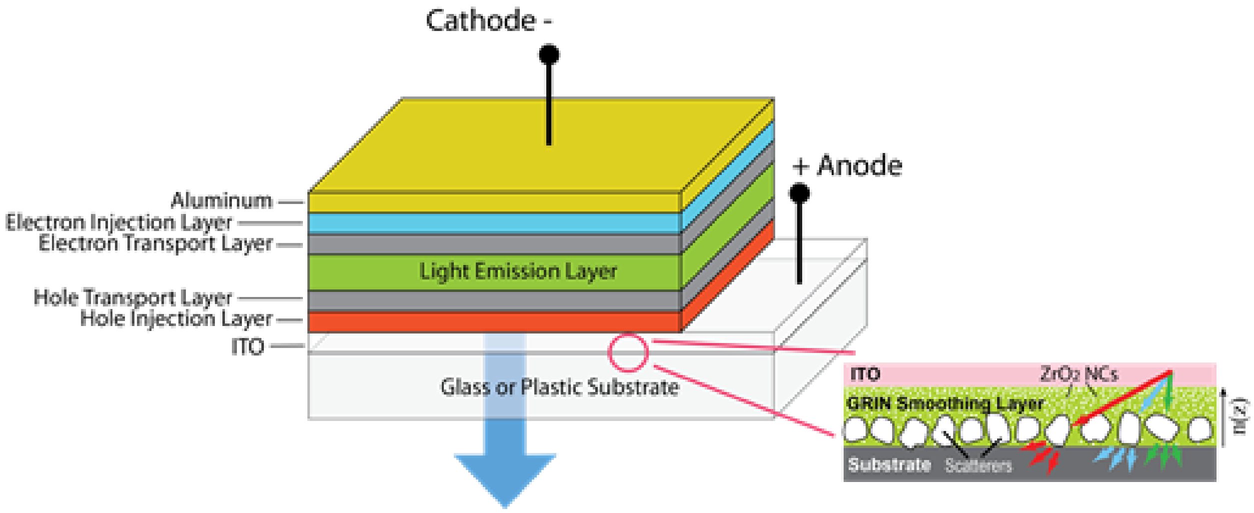
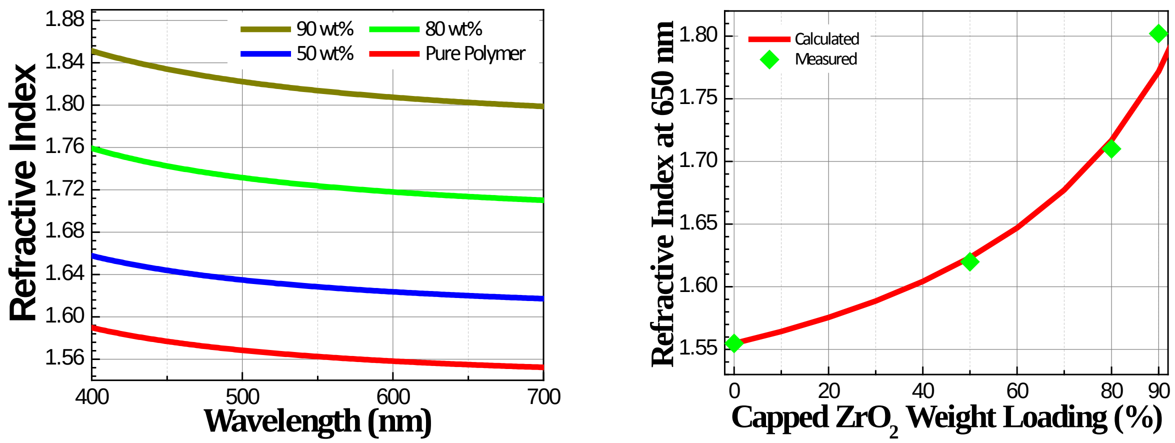


Figure 1: Typical OLED lighting device structure with internal light extraction layer.

Pixelligent Zirconia Nanodispersions

Pixelligent has developed high quality 5 nm ZrO_2 nanocrystals with precisely engineered surface chemistry. The nanocrystals are coated with organic 'capping agents,' which prevent agglomeration and enable compatibility with a broad array of solvents, monomers and polymers. The 5 nm particle size is only about one percent of the wavelength and is comparable to the size of polymer molecules. At this size range, the nanocrystals induce minor, if any, amounts of scattering, even with very high loading and large layer thickness. By loading the ZrO_2 nanocrystals into acrylic polymer matrix, the refraction index of the smoothing layer can be designed to be greater than 1.8 across the whole visible spectrum as shown in Figure 2.



a) b)

Figure 2: a) Refractive indexes of the acrylic/capped ZrO_2 nanocrystal nanocomposite films with different nanocrystal loading as measured with Woollam M2000 ellipsometer; and b) The calculated refractive as a function loading vs. the measure values. The near perfect match also indicated the high quality of the dispersion.

Generation 1: High-RI Smoothing Layer

Previously announced, Pixelligent's first generation material is a high-refractive index smoothing layer. In the OLED lighting panel manufacturing process, the scatterer layer is first deposited onto the glass substrate. Then, the high-refractive index smoothing layer is coated to planarize the rough scatterer layer[4]. Working with our industrial partners, the performance of Pixelligent first generation layer has been

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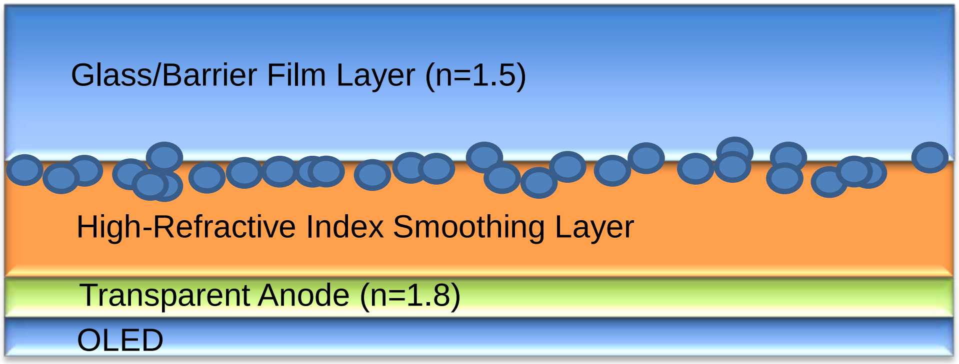

Figure 3: Schematic of the integration of Pixelligent's first generation high-refractive index smoothing layer into an OLED device.

demonstrated on white OLED lighting panels. As shown in Figure 4, Pixelligent's material provides more than 200% light output improvement, and no external light extraction layer is needed, since additional external light extraction layer does not further enhance the light output. However, many customers prefer to use a fully integrated internal light extraction layer, with scatterers already integrated, which led to the development of a second generation product.

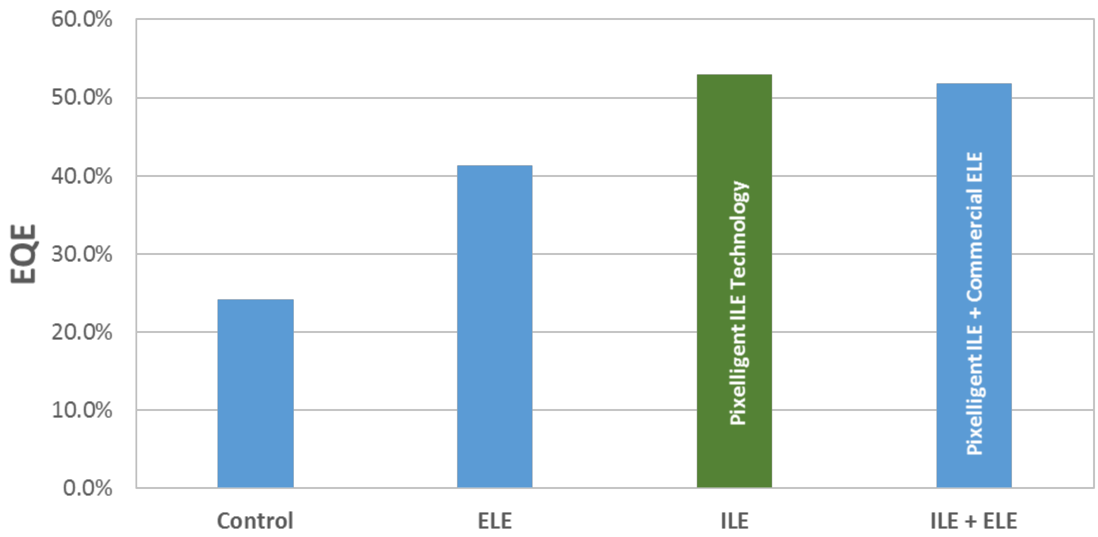

Figure 4. External quantum efficiency of white OLED lighting panels utilizing Pixelligent's first generation materials.

Generation 2: Internal Light Extraction Layer

Under several DOE funded projects, Pixelligent has developed a scatterer-loaded internal light extraction layer to provide a simplified process to customers. Since the scatterers are dispersed into the high refraction index formulation, Pixelligent's second generation material reduces the deposition of the internal light extraction layer from 2-step process to 1-step process. There's no need to coat the scatterer layer prior to the coating of Pixelligent's second generation ILE layer. The simplification of the deposition process will lower down the manufacturing cost of the customers, and allow customers who do not currently use scatters or an ILE to incorporate them. Figure 6 shows a photo of Pixelligent's second generation formulation.

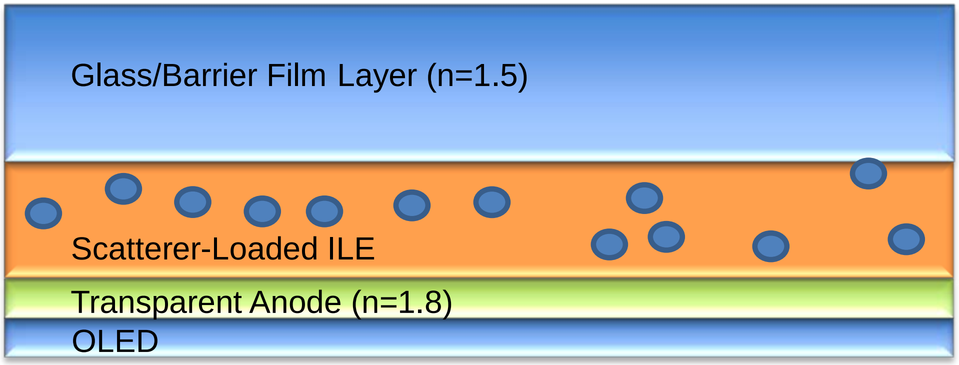

Figure 5: (above) Schematic of the integration of Pixelligent's second generation scatterer loaded high-refractive index layer into an OLED device.

Figure 6. (left) A photo of scatterer-loaded ZrO_2 nanocrystal formulation.

Furthermore, Pixelligent has developed a slot-die coating technique to coat the dispersion onto 4 inch substrates. In addition to having a material utilization of near 90%, slot-die coating is a scalable process which could be easily adopted in the production line with substrate size larger than Gen. 2 (370 mm × 470 mm), as slot-die coating is currently used in LCD manufacturing for Gen. 8 sized glass. Moreover, the slot die coating gap height can be adjusted to accommodate glass substrate waviness or warping, which are common defects in low-cost glass substrates produced in large-scale processes. Coating gap and coating speed in slot die coating can be optimized to deliver a robust coating. Figure 7 schematically illustrates the slot-die coating setup.

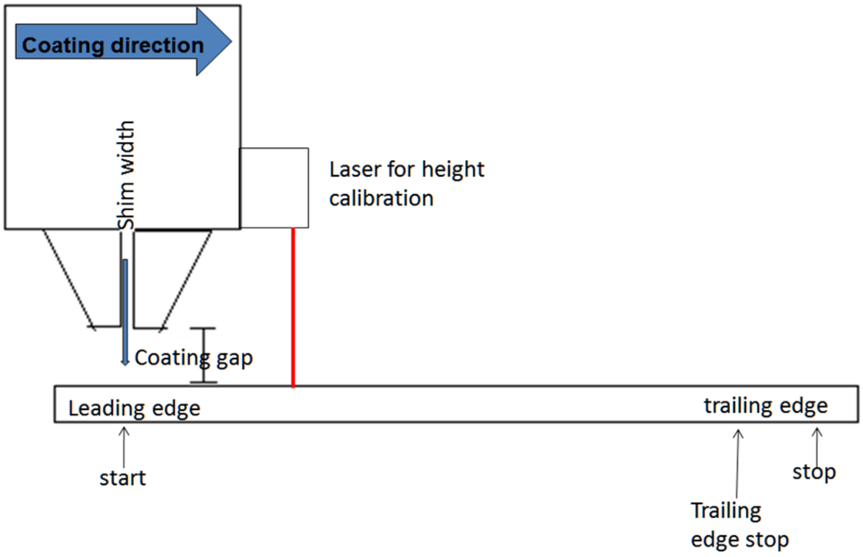

Figure 7. Schematic illustration of the slot-die coating setup.

Figure 8 shows a photo of a scattering film slot-die coated on the 2.5” by 2.5” glass wafer. The ILE layer is highly uniform across the deposition area.

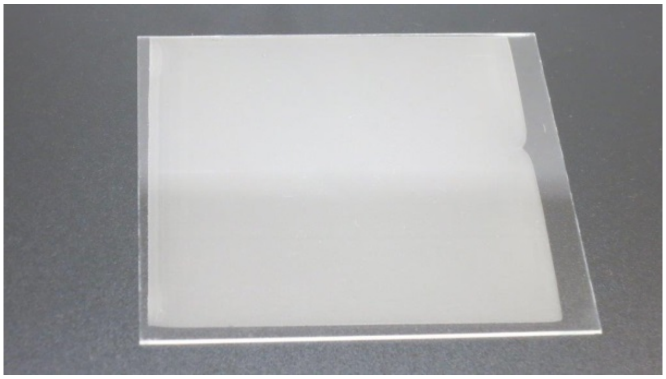

Figure 8. A photo of the scatterer layer slot-die coated on 2.5” by 2.5” glass substrate.

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Summary

Pixelligent has developed high-RI materials for OLED lighting that increase light output up to 200% and has now integrated them into a complete internal light extraction layer. This scatter-loaded material based on Pixelligent's proprietary nanocrystal manufacturing process provides customers with a single process for a high index smoothing layer with integrated scatters and can be deposited with slot-die coating. The accompanying slot-die coating technique is a scalable and low-cost process suitable for large size manufacturing.

Reference:

1. National Research Council, "Assessment of Advanced Solid State Lighting," The National Academics Press, 2013.
2. J. Zhou, N. Ai, L. Wang, H. Zheng, C. Luo, Z. Jiang, Y. Cao, and J. Wang, *Organic Electronics* 12 (2011) 648.
3. J.-S. Kim, P. K. H. Ho, N. C. Greenham, and R. H. Friend, *J. Appl. Phys.* 88 (**2000**) 1073.
4. Z. Chen, "Pixelligent Zirconia Nano-Crystals for OLED Applications", http://www.pixelligent.com/news-events/white-papers/, 2014.