White Paper: Improved Light Extraction For OLED Displays

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OLED display technology is finding its way into the commercial electronics market with new laptops by Lenovo, a line of large panel televisions by LG, the Samsung Galaxy smart phones, and many others.

Introduction

OLED displays have many attractive features including a wide color gamut, a wide viewing angle, high contrast ratio, fast response time, flexibility, and low power consumption. The efficiency of OLED displays has made steady improvement over the last several years, but there are still significant gains to be made. One important area where there is a potential to more than double the efficiency of OLED displays is in light extraction. While there are many known ways to improve light extraction, both the manufacturing process and the requirement to maintain a high quality image severely restrict how light can be extracted. Pixelligent's solution processable high refractive index zirconia materials allow for the creation of high index, transparent, low-haze nanocomposites that can build the necessary light extraction structures.

Efficient OLED Displays

The overall external quantum efficiency for a typical OLED device structure can be described as:

$$\eta_{EQE} = \gamma \eta_{exc} \chi \eta_{coupling}$$

where γ is the electron–hole charge balance factor, η_{exc} is the ratio of radiative to non-radiative recombination of excitons (η_{exc} = 1/4 and 1 for fluorescence and phosphorescence based OLED materials respectively), and χ_p is the intrinsic quantum efficiency for radiative recombination (including both fluorescence and phosphorescence). And $\eta_{coupling}$ is the light extraction efficiency of the device.

Much of the work to improve the efficiency of OLED displays over the last several years has been focused on improving the electro-optical performance of the pixels and not on improving out-coupling. This type of work involves optimizing emitter materials, injection and transport layers, the thickness and interface of the various device layers, etc. The results of this work have been impressive. The display on the Galaxy S6 was 20% more efficient than the S5, consuming 1.2 watts to produce a brightness of ~350 cd/m^2 compared to 1.5 watts for the S5[1]. The S7, while having the same efficiency as the S6 was almost 20% brighter, 414 cd/m^2 compared with 348 cd/m^2 for the S6[2].

Light Extraction for OLED Displays

The root cause of the light loss in the OLED device is the fact that the light is produced in a high index material and has to be transmitted to air with a low index (n0 = 1). When light travels from a material with a high refractive index (n) into a material with low refractive index, if the incident angle is larger than a critical angle, it experiences total internal reflection (TIR), which is the mechanism behind almost all light loss in the device, and the fraction of light that can propagate into air is proportional to $1/n^2$. Because of the large index mismatches and the number of interfaces the total light extraction efficiency for these devices is only ~20% - 30%. The light that undergoes TIR is wasted as heat, reducing the reliability and efficiency of the device.

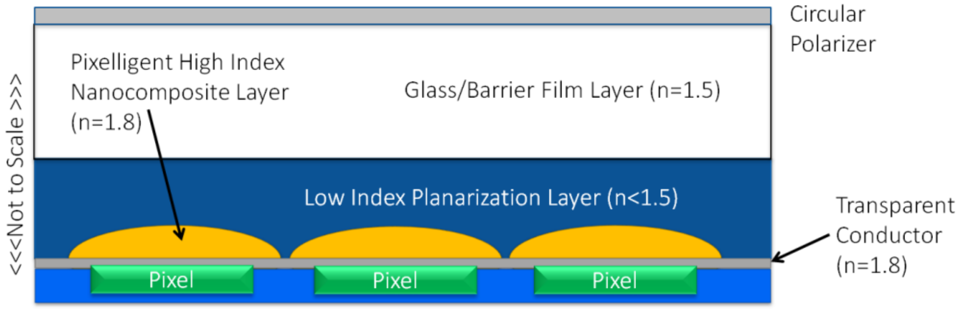
There are a number of approaches that can be used to improve light extraction, all of which involve some variation in redirecting high angle light so that it is not trapped by TIR. Displays impose additional constraints in that any light extraction approach can not interfere with the image quality. The key requirements are:

- Off-State look – The pixels must look black in the off state,
- No crosstalk – Any light extraction features only extract light from a single pixel or sub-pixel
- Large viewing angle, and
- Manufacturing Scalability – The ability to manufacture at large scale with the required cost, uniformity and yield.

Previously, because of these requirements, and the relative immaturity of OLED display manufacturing process, light extraction has not been a priority for the industry. Now that the manufacturing is more mature and many device related opportunities for improvement in efficiencies have been made, many in the industry are starting to look at improved light extraction as the next big opportunity to improve OLED displays.

Light Extraction Structures

While the details will vary significantly depending on the type of display (TV vs cell phone, etc), the basic structure will be a transparent, high index, curved surface very close to the pixel.



The lens has to have a high refractive index so that the curved surface is capable of forward focusing light when embedded in a low index planarization layer, improving the useful brightness of the display as more light is directed towards the common viewing angles[3, 4]. The performance can be engineered through the detailed lens shape and curvature design as well as by co-optimizing the pixel design.

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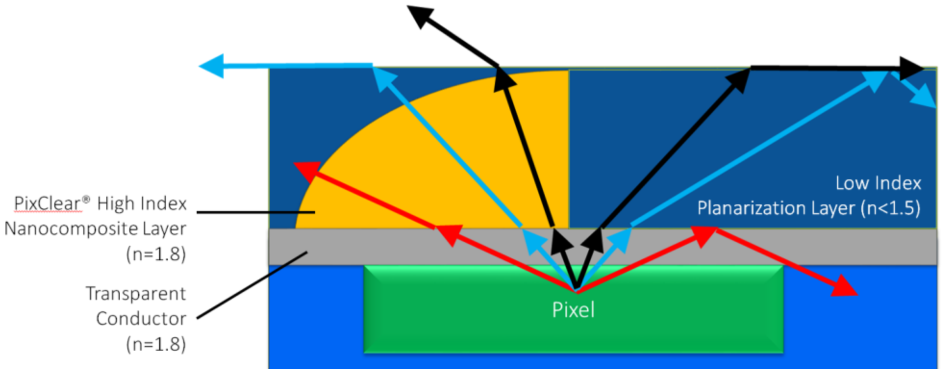
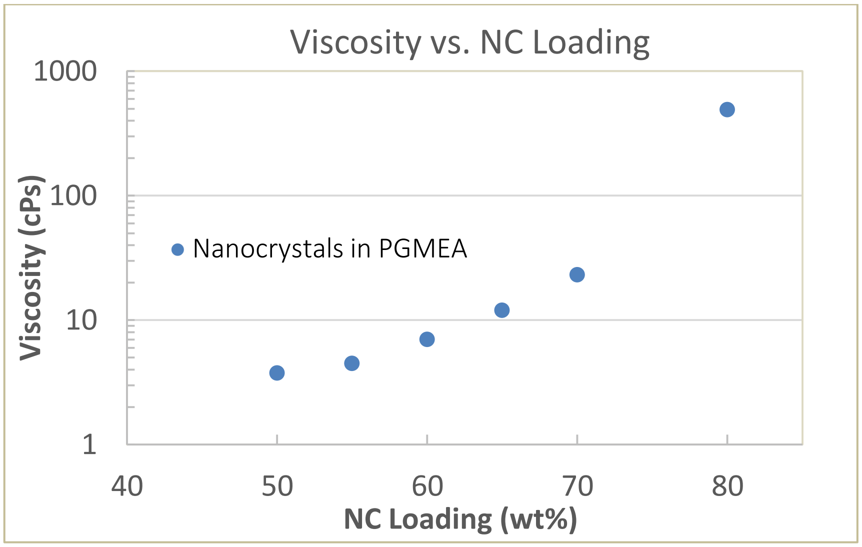


More importantly, the high refractive index layer can match the index of the transparent conducting layer and the light emitting region of the OLED device, minimizing the loss of light due to total internal reflection. Based on a simple optical model we estimate the improvement in light extraction efficiency at 50% to 200%.

Pixelligent's PixClear® series of high refractive index ZrO_2 nanocrystals formulations and nanocomposites are the perfect candidates for creating such high index microlens arrays. With these products, nanocomposites with refractive indices ranging from 1.5 – 1.85 can be created with superb transparency. The formulations are also compatible with most common polymer systems, and their viscosity can be adjusted to be compatible with most printing technologies such as slot-die, screen printing, inkjet, etc. Pixelligent's nanocrystal dispersions are made using a scaled and in-control manufacturing process. And through Pixelligent's similar work in OLED lighting, these materials have been shown to be compatible with OLED manufacturing processes.



Another advantage of Pixelligent's nanocrystal additives is that it is capable of creating gradient index lens through a simple diffusion process. The gradient index provides the extra freedom needed to minimize image blur, reducing the polarization effect, and further improve the light extraction efficiency.

Conclusion

Application of Pixelligent's high refractive index nanocomposites to OLED display has the potential to dramatically improve the light extraction efficiency, and the overall energy efficiency, without sacrificing the image quality. The improved energy efficiency will enable electronic devices to have longer battery life, greater power, and smaller form factors. Because of our world class dispersion technology Pixelligent's PixClear® materials offer the ideal solution for light extraction in displays. First, because of our stable low viscosity dispersions, our materials can be used in formulations that are compatible with OLED display manufacturing such as inkjet, imprint, and photolithography. Second, the cured formulations create nanocomposites with superb properties such as low surface roughness, high refractive index, and excellent transparency.

[1] http://www.displaymate.com/Galaxy_S6_ShootOut_1.htm#Display_Power
[2] http://www.displaymate.com/Galaxy_S7_ShootOut_1.htm#Display_Power
[3] Chen, Kuan-Yu, et al. "Emitter apodization dependent angular luminance enhancement of microlens-array film attached organic light-emitting devices." *Optics express* 18.4 (2010): 3238-3243.
[4] Brütting, Wolfgang, et al. "Device efficiency of organic light-emitting diodes: Progress by improved light outcoupling." *physica status solidi (a)* 210.1 (2013): 44-65.