Optical Enhancement Technologies for PLED displays

Abstract

The efficiency of display devices has always been an important criteria and there are many contributing technologies that play a role in the efficiency of polymer organic light emitting diode (P-OLED) displays. They include the printing process and materials development; Thin-Film Transistor (TFT) and Driver technology; large substrate manufacturing as well as device optimisation.

Organic light emitting diodes (OLEDs) have seen much development efforts dedicated to increasing the overall efficiency of devices fabricated from this new electroluminescent technology. In this paper we report how higher efficiency OLED device structures can be achieved by maximising the number of excitons that can emit light and the amount of that light which reaches the viewer.

This paper also focuses on the latest developments in blue LEP-OLED materials. It has achieved high efficiency, low operating voltage and an extrapolated time to half-luminance in excess of 70,000 hours from 100 cd/m2 initial luminance at room temperature.

Introduction

Storage lifetimes of at least five years are typically required by most consumer and business products, and operating lifetimes of more than 20,000 hours are necessary for most applications. In the area of light emitting polymers, significant advances have taken place to improve material lifetimes both through use of materials that are resistant to degredation and through improved encapsulation.

For the past several years, The Dow Chemical Company and CDT have worked closely together to develop improved polyfluorene blue LEP-OLED materials and optimise device structures. Recent results yield an extrapolated time to half-luminance of over 70,000 hours from 100 cd/m2 at room temperature (see figures 2-4). This is a dramatic increase of more than an order of magnitude over the measurements attained two years ago (figure 6).

Material developments have focused on blue polymers consisting of fluorene, hole transporting and emissive moieties which are prepared by Suzuki cross-coupling [1]. Optimisation of the original polymer structure resulted in materials which possessed a higher glass transition temperature (Tg), increased hole mobility [2], improved fluorescence efficiency and exhibited improved time to half-luminance. Improvements in the device fabrication process led to a considerable increase of the device time to half luminance by optimisation of layer deposition and the introduction of annealing stages in the fabrication process [3].

Further, the efficiency of an OLED (whether small molecule, dendrimer or a polymer based PLED) can also be expressed as the product of four terms:

1. The fraction of injected charges which form excitons
2. The fraction of excitons which can radiatively decay
3. The fraction of such excitons which do radiatively decay
4. The fraction of generated light emitted from the device

The first and third terms can be optimised by careful selection of materials and device structure and can approach 100% for more complex device structures. Much work over the past few years has successfully produced higher efficiency OLED device structures by maximising the number of excitons that can emit light, whether through triplet harvesting systems, or by taking advantage of the higher singlet:triplet ratios observed in polymer devices. As a result of these measures, devices have been produced with an internal efficiency (that is, neglecting the last term) approaching 100%. It is the final term, the optical out-coupling efficiency, which has proved the most intractable.

Light trapping occurs due to the high refractive index of the OLED materials. Light within a high refractive index medium arriving at an interface with a low index medium at greater than the critical angle will be totally internally reflected. As shown in figure 1, in an OLED, this results in light trapping both within the device layers (3) and within the substrate (2) with only 20-25% (molecular or dendrimer systems) or 30-40% (polymers) emitted from the device (1).

Device Efficiency and Lifetime

It was discovered that a thin polymer interlayer between the PEDOT:PSS hole-conducting layer and an emissive LEP layer plays an important role in improving significantly the device efficiency and lifetime of RGB LEP-OLEDs. The thin interlayer (only about 10 nm thick) is spin-coated directly on the top of the PEDOT:PSS layer. With the interlayer, blue LEP-OLEDs with an external quantum efficiency above 5.0% have been measured, which is 35% higher than without the interlayer.

This increased efficiency was accompanied by significant increases in both the DC and pulsed driven time to half-luminance of the devices. One possible explanation for the improved performance associated with the interlayer is that it prevents exciton quenching at the PEDOT:PSS/LEP interface, thereby improving the device performance.

Most importantly, this development has made it possible to develop a new range of blue LEP-OLED materials optimised for a simple barium cathode architecture, which is compatible with all colors. The previous generation of materials performed optimally with a lithium fluoride/calcium cathode for blue and a barium (or alternatively calcium) cathode with the red and green polymers – with obvious drawbacks for the manufacturing process. Therefore, the development of the new common cathode architecture is a significant step forward for cost-effective manufacturing of solution-processable LEP-OLED displays.

Diodes based on these new polyfluorene materials show high efficiency (peak 8.9 cd/A), low operating voltages (4.2 V at 100 cd/m2) and an emission spectrum with 1931 CIE co-ordinates (0.17, 0.22). A typical luminance-voltage and efficiency-voltage characteristic is shown in Figure 2.

The devices were driven at constant current from an initial luminance of 800 cd/m2 until the luminance had dropped by 50% (figure 3). The 'new blue' material shows a strong power law dependence of time to half-luminance on initial luminance with an exponent of 1.9 as shown in Figure 4. Using this empirical power law, we can extrapolate the device time to half-luminance from 100 cd/m2 initial luminance to be in excess of 70,000 hours at room temperature.

Device Light Emission

Two approaches can be taken to enhance the light output from a device - extraction of light from trapped optical modes, or modification of the emission profile to prevent emission into these trapped modes. The emission profile is modified through control of the optical modes into which light can be emitted, and the strength of the coupling between the light emission and these modes. This is achieved through design of the optical interfaces surrounding the PLED device.

The simplest modification is produced through a change in device type from substrate emission through the anode, to emission through a transparent cathode known as top-emission. This represents the simplest case of one-dimensional modifications of the optical modes, with other methods including the use of low-index layers (e.g. aerogels), which produce essentially the same effect as cathode emission, and stronger enhancements by forming micro-cavities. These methods can both enhance light output and provide colour tuning. In particular, the combination of a partially reflective cathode on a top-emitting structure is probably the only optical enhancement method so far demonstrated on a display scale. However, light is emitted in three dimensions, not only one, and unless there is particularly strong coupling between the light emission and these cavity-enhanced modes, one-dimensional enhancement cannot produce large increases in total light output.

Through the use of photonic band-gap structures, it is in principle possible to modify the light emission in all three dimensions and in theory, extract almost all light from a device. Indeed, this has been demonstrated successfully in inorganic LEDs. However, to achieve a true photonic band-gap, a structure needs to be formed using two materials with a high refractive index contrast and a feature size of the order of a quarter of the wavelength of the emitted light – very hard to achieve practically in an OLED or PLED device structure. The term 'photonic band-gap' is often misused to refer to structures where no band-gap is formed and are, in essence, 2D Bragg gratings. Indeed, such structures can produce significant enhancements in light output. However, this is not through modification of the emission profile, rather from scattering of light from trapped optical modes.

Device Light Extraction

Broadly speaking, there are two places where light can be scattered from trapped modes – at the substrate-air surface and within the device itself. The first of these seems the most desirable as it is the simplest to implement. However, there is a fundamental problem. Trapped modes propagating in the substrates are, by definition, propagating at shallow angles. To extract these modes the angle of propagation needs to be changed so that this light can escape into air. If this extraction occurs at the surface of a display then this light, due to its angle of propagation, will appear to emanate from a different pixel (label 4, figure 5), thereby blurring the display. A more efficient extraction film will produce more blurring. To enhance light extraction from a display without blurring, this needs to occur as close to the emission as possible.

Within the device structure light scattering has been demonstrated, by laterally patterning one of the device interfaces, using many techniques from direct writing to soft lithography. These techniques have demonstrated substantial increases in optical out-coupling efficiency on single-pixel devices, but have yet to be demonstrated at a display scale.

Conclusions

Eventually, improving the efficiency and stability of PLED materials and devices is essential for the commercial development of PLED technology in flat panel display applications. The results presented in figure 6 show a dramatic increase in device performance of more than one order of magnitude in the last couple of years which was achieved through continuous development of new, more stable materials together with systematic improvement in the device fabrication process and a new device architecture. This approach has enabled the increase of the blue device time to half-luminance to 70,000 hours sufficient for many commercial applications.

Any technique to improve its efficiency must also be low cost, has a low impact on yield, limited negative effects on other performance characteristics and be generally applicable to red, green and blue pixels. A technique to access a substantial quantity of the trapped light and meeting the above criteria, has yet to be found. However, here lies the challenge – access all that trapped light and the PLED screen on your TV could produce light more efficiently than the fluorescent lighting above your head.

References

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3. M. Leadbeater, N. Patel, C. Murphy, M. Roberts, T. Butler, D. Forsythe, R. Archer, N. Phillips, S. Cina, C. Towns. IEEE/LEOS Annual Meeting Conference Proceedings LEOS 2002 volume 1, 243, (2002)

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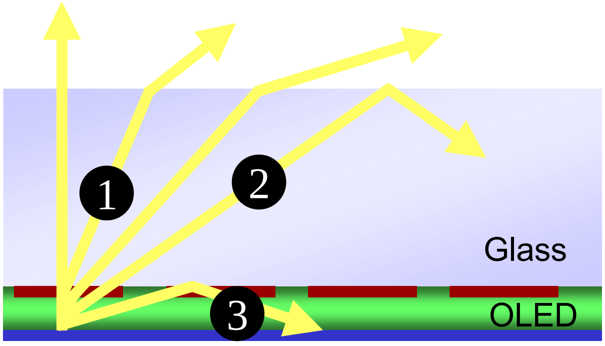


Figure 1 - Light trapping modes in OLEDs

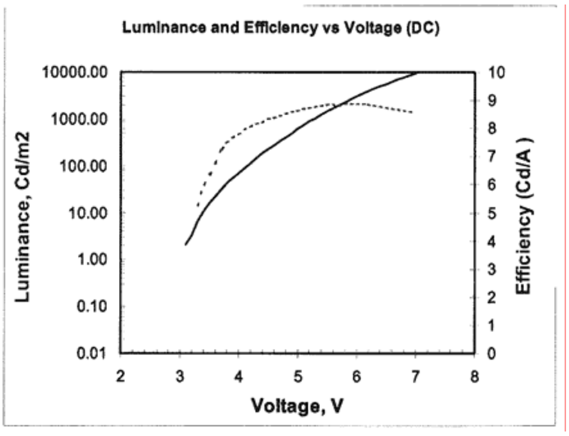
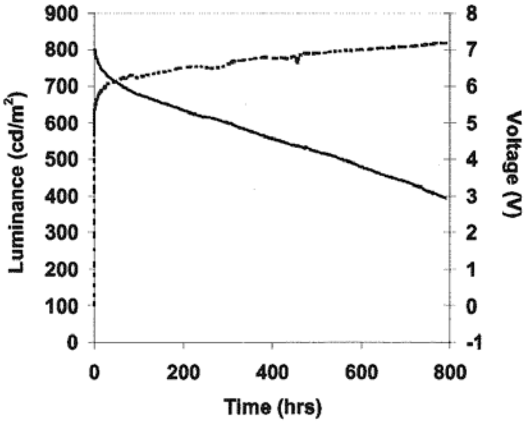


Figure 2. Luminance in cd/m2 (solid line) and efficiency in cd/A (dashed) plotted as a function of applied bias for a device made using the 'new blue'

Figure 3 - Decrease in luminance over time under constant current driving conditions from 800 cd/m2 initial luminance at room temperature



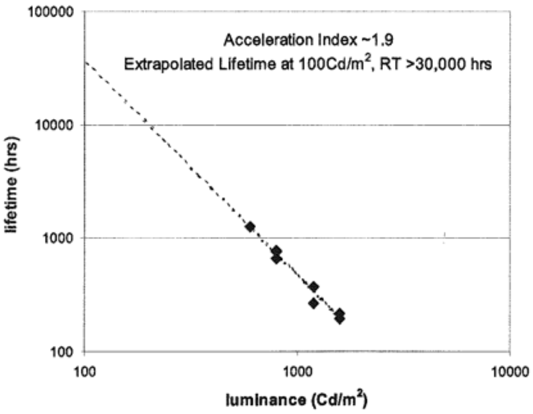


Figure 4 - Time to half-luminance as a function of initial luminance showing power law dependence with an exponent of 1.9 at room temperature

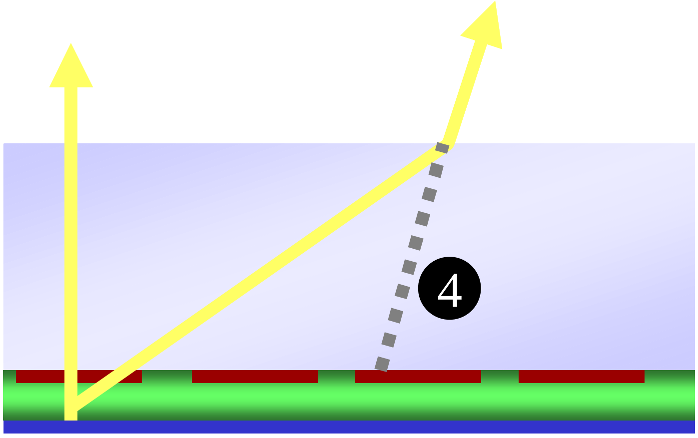


Figure 5 - Blurring of display from light extraction

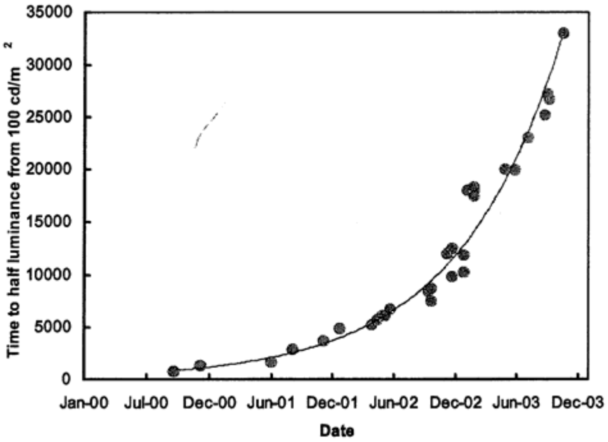


Figure 6 – Improvement in time to half-luminance of blue PLED research devices