Latest developments in phosphorescent OLEDs

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Abstract
We report state-of-the-art phosphorescent organic light emitting diode lifetime and efficiency performances for a range of emission colors. Lifetimes in excess of 100,000hrs have been demonstrated at display luminance levels for saturated red emission. External quantum efficiencies close to the theoretical maximum (e.g. 23% without enhanced optical output coupling) are also demonstrated for devices with lifetimes in excess of 15,000hrs at a display level luminance for both orange- red and green.

1. Introduction
Since the discovery of light from organic materials, organic light emitting diodes[1,2] (OLEDs) today have the potential to corner a larger share of the flat panel display (FPD) market. However, in order to maximize their market potential, improvements in efficiency and lifetime are desirable.

In conventional fluorescent small-molecule OLEDs, light emission occurs as a result of the radiative decay of singlet excitons, and the internal quantum efficiency is limited to approximately 25%. The first demonstration of high efficiency phosphorescent organic light emitting diode (PHOLED™) by Baldo et al. in 1998 generated intense research interest around the world with the potential for 100% internal quantum efficient OLED devices[3]. Shortly afterwards the Princeton group of researchers found by utilizing a green phosphorescent material namely, *fac*-tris(2- phenylpyridine)iridium(III) ($Ir(ppy)_3$), maximum external quantum efficiencies of 19-20%[4] could be achieved. Although the efficiency results were good, the long term stability of these devices was limited to <2,000 hours. Hence work to solve the lifetime issue was launched.

One of the goals of Universal Display Corporation is to develop PHOLED materials and device architectures designed for long lifetime and that can also realize maximum internal quantum efficiencies.
In previous work, we reported state-of-the-art PHOLED performances[5]. These results are summarized in Table 1. Also included in the table is a new sky blue PHOLED device we recently reported with CIE co-ordinates of (0.16, 0.32), a luminous efficiency of 22cd/A (9.5% external quantum efficiency) and a half lifetime of 15,000hrs from an initial luminance of 200cd/m^2. In this work, we report on new materials and device architectures towards next generation display requirements and ongoing work to maximize the efficiency lifetime product of the full-color PHOLED system and in turn increase the commercial prospects for OLED FPDs with PHOLED.

	PHOLED Materials	Color Coordinates CIE [x, y]	Luminous Efficiency [cd/A]	Operational Lifetime [hrs]	Luminance [cd/m^2]
C	RD15	(0.67, 0.33)	12	100,000	500
	RD07	(0.65, 0.35	18	40,000	500
	GD48	(0.32, 0.63)	24	37,000	1000
D	RD61	(0.62, 0.38)	30	40,000	500
	GD107	(0.35, 0.60)	40	under test	1,000
	YD85	(0.41, 0.58)	65	under test	1,000
R	New Green	(0.32, 0.63)	80	15,000	1,000
	Sky Blue	(0.16, 0.37)	22	15,000	200
	New Blue	(0.14, 0.13)	9	under development	200
	New Blue	(0.16, 0.10)	3	under development	200

Table 1: Summary of current commercial (C), development (D) and research (R) stage PHOLED performance.

2. Results and discussion
In this paper we present PHOLED devices with external quantum efficiencies of greater than 20% with lifetimes up to 20,000 hours at display luminance levels. The PHOLEDs presented in this paper were grown on transparent 120nm thick ITO coated soda lime glass. The organic materials were fabricated by sequentially depositing layers of a hole injection layer (HIL), 4,4'-bis[N-(1-napthyl)-N-phenyl-amino] biphenyl (α-NPD) as the hole transport layer (HTL), an emissive layer (EML)

consisting of a host material doped with an electrophosphorescent dopant, where stated a blocking layer and tris-(8-hydroxyquinoline) aluminum (Alq_3) as the electron transport layer (ETL). The structure was completed with a 1 nm layer of lithium fluoride (LiF) and a 100nm layer of aluminum as the cathode contact. The organic and metal layers were thermally deposited at 0.2-4Å/s in a vacuum of <10^{-7}Torr to yield 5mm^2 devices. The PHOLEDs were encapsulated in a dry nitrogen atmosphere (<1ppm H_2O and O_2) using a glass lid and UV cured epoxy edge seal. A CaO getter was added inside the package to react with any byproducts of the epoxy cure and any residual water or oxygen present within the encapsulated volume.

2.1 Devices with >20% EQE

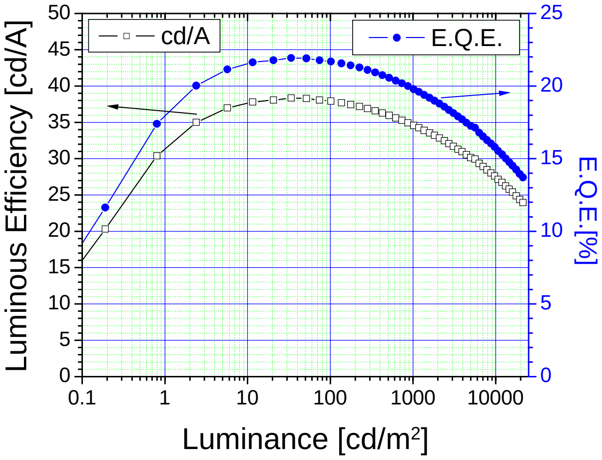

Figure 1. Luminous and external quantum efficiency of an orange PHOLED. The device has CIE co-ordinates of (0.62, 0.38), a peak luminance efficiency of 38cd/A and an external quantum efficiency of 22%.

Figure 1 shows an orange-red PHOLED with CIE coordinates of (0.62, 0.38) that has a peak luminance efficiency of 38cd/A and an external quantum efficiency (EQE) of 22%. The lifetime of this device (Figure 2) is >20,000hrs driven constant current dc from an initial 1000cd/m^2 luminance at room temperature. The device was doped with 6%, by weight, of the electrophosphorescent dopant and incorporated a UDC proprietary blocking material, referred to as BL41, between the EML and ETL. A high conductivity HIL was also used. By using the blocking material and high conductivity HIL the electron and hole recombination can be controlled to maximize efficiency in the luminance range required for active matrix OLED (AMOLED) displays. For example for the device in Figure 1 the efficiency is greater than 19% EQE from 2 to 2000cd/m^2. Even at 20,000cd/m^2 the efficiency is greater than 25cd/A.

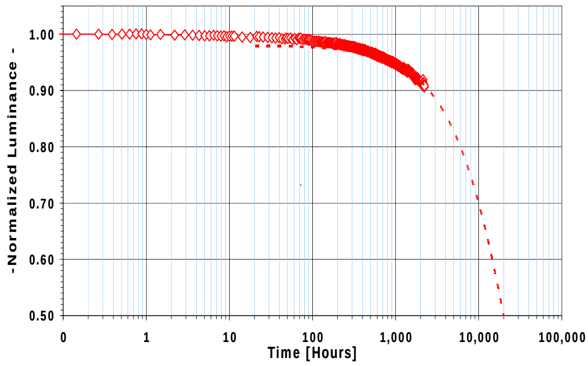

Figure 2. Operational lifetime performance for an orange-red PHOLED operated under constant DC current drive at room temperature. The initial luminance is 1000cd/m^2.The projected lifetime to 50% of initial luminance is >20,000hrs.

Several other phosphorescent devices have also shown >20% external quantum efficiencies with good lifetimes. For example the green PHOLED shown in Figure 3 has CIE co-ordinates of (0.32, 0.63), a peak luminous efficiency of 83cd/A and an external quantum efficiency of 23%. Again the efficiency characteristics of this device were tailored to maximize the efficiency in the luminance range required for AMOLED displays i.e. the external quantum efficiency is greater than 20% from 1 to 4000cd/m^2. This device exhibited a lifetime of >15,000hrs at room temperature driven constant current dc from a starting luminance of 1000cd/m^2 (see Figure 4). The device also incorporated a BL41 blocking layer between the EML and ETL.

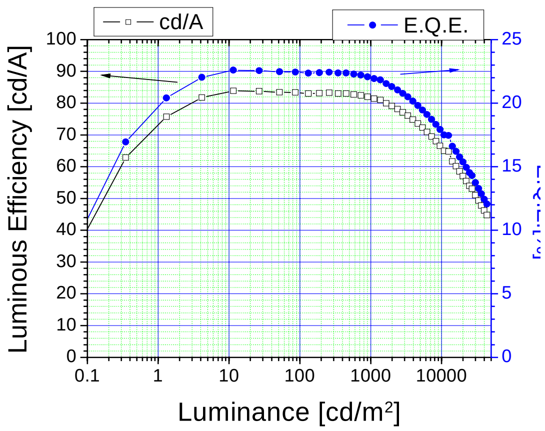

Figure 3. Luminous and external quantum efficiency of a green PHOLED.

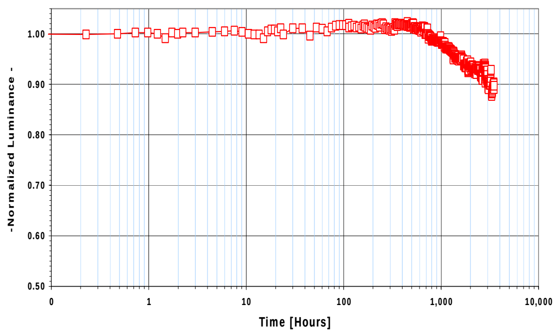

Figure 4. Operational lifetime performance for a 23% EQE green PHOLED operated under constant DC current drive at room temperature. The initial luminance is 1000cd/m^2.

2.2 Devices with ultra-long lifetime

In addition to developing long-lived devices with greater than 20% external quantum efficiencies we also present devices developed for ultra-long lifetime. Figure 5 shows the lifetime of an NTSC (CIE = (0.67, 0.33)) red RD15 PHOLED with a projected lifetime of tens of thousands of hours at an elevated temperature of 60°C (>96%L_0 after 4000hrs). The device did not contain a blocking layer. At room temperature the device has a projected lifetime of >100,000 hours from a starting luminance of 500cd/m^2.

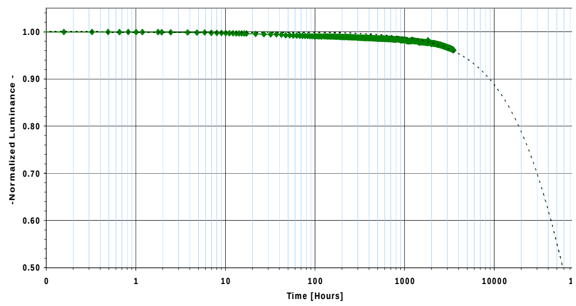

Figure 5. Operational lifetime performance for NTSC red PHOLED RD15 operated under constant DC current drive at an elevated temperature of 60°C. The initial luminance is 500cd/m^2.

The luminous efficiency as a function of luminance of the NTSC standard RD15 red PHOLED is shown in Figure 6. This device has a peak luminous efficiency of 12cd/A (13% EQE).

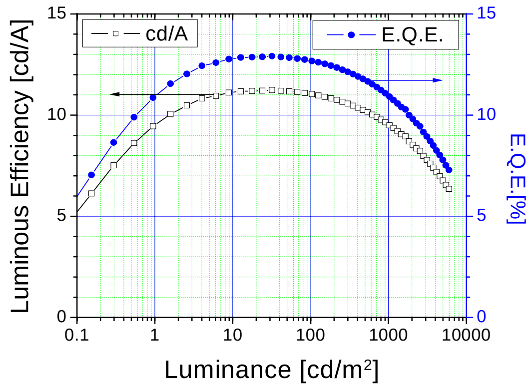

Figure 6. Luminous efficiency and external quantum efficiency as a function of luminance for an NTSC standard RD15 red PHOLED.

3. Summary

The results presented in this paper illustrate the benefit of using PHOLEDs in FPDs today and show their potential for the future. PHOLED devices were fabricated with efficiencies greater than 20% external quantum efficiency and with lifetimes of 15,000 to 20,000hrs at display luminance levels. High efficiency NTSC red devices were also demonstrated with lifetimes in excess of 100,000hrs at display luminance levels. We believe that these devices are of significant interest to the OLED display community and will help OLEDs become the display medium of the future.

4. Acknowledgements

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5. References

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