Performance and Applications of High Efficiency Phosphorescent OLED Technology

M. Hack, M.H. Lu, R. Kwong, M.S. Weaver, Y.-J. Tung, A. Chwang and J.J. Brown
Universal Display Corporation, 375 Phillips Blvd., Ewing, NJ 08618, USA

Abstract

Universal Display Corporation (UDC), together with its University partners at Princeton University and the University of Southern California, are developing high-efficiency electrophosphorescent OLED devices, based on triplet emission. Recent results show both excellent device efficiencies and good lifetimes for the commercialization of low power consumption, full-color, passive and active-matrix OLED displays. We also show that phosphorescent devices may be driven by low cost amorphous silicon backplanes, and discuss the benefits of using our proprietary top emission OLED device architecture.

Introduction

Low power consumption is a key display requirement for mobile applications. The first efficient OLED devices were invented by Tang et al from Kodak in the 1980뭘 and in these conventional fluorescent small-molecule OLEDs [1] light emission occurs as a result of the recombination of singlet excitons, and the internal quantum efficiency is limited to approximately 25%. Based on the inventions of its University partners at Princeton University and University of Southern California [2,3], UDC is developing the next generation of high efficiency phosphorescent OLED (PHOLED? devices.

EL Color	Red	Green	Blue
Peak wavelength	620 nm	510 nm	460 nm
CIE – (x, y)	(0.65,0.35)	(0.30,0.63)	(0.14,0.23)
Luminance η @ 1 mA/cm^2	14 cd/A	27 cd/A	10 cd/A
Lifetime (hours)	15,000@ 300 cd/m^2	>15,000 @ 600 cd/m^2	Under development

Table 1- Performance of a selection of UDC PHOLEDs

In the phosphorescent system, all excitons may be converted into triplet states through inter-system crossing around a heavy metal atom. These triplet states emit radiatively, enabling the extremely high efficiencies shown in Table 1. Work on further stability improvements and deep blue phosphorescent emission is ongoing. Given the threefold increase in efficiency that organic phosphorescent devices offer over their fluorescent counterparts, these new OLEDs provide improved performance for applications from simple icon monochrome displays, to full color passive matrix displays [4], and high resolution, full-color active matrix displays [5].

The high conversion efficiency of PHOLED devices may also enable amorphous silicon (a-Si:H) TFTs to provide the backplane for an active matrix OLED (AMOLED) display [6]. Using our PHOLEDs, the maximum AMOLED pixel current is approximately 1-2μA, well within the capability of an a-Si:H TFT. For commercialization, it is also important to demonstrate display uniformity, especially after extended periods of operation. In this paper we present results showing that the high efficiency of our phosphorescent devices enables them to be driven by a-Si:H TFTs operating at low gate to source voltages, a prerequisite for good TFT stability. Finally we discuss the benefits of AMOLED displays using a top emission device architecture.

RESULTS

Phosphorescent device Performance for Passive and Active Matrix Applications

Many manufacturers are planning to launch full color passive and active matrix OLED displays in the 2003-2004 timeframe. Passive matrix architecture provides a simpler and lower cost solution for small, relatively low resolution displays for cell phone applications. Active matrix drive is required for higher information content displays exceeding approximately 200 row lines or greater than 3? size.

Electrophosphorescent dopants enable small molecule OLEDs to have internal quantum efficiencies approaching 100% [7], as compared to an approximate 25% maximum for conventional fluorescent devices. Figure 1 shows the luminous efficiency versus luminance of our baseline green phosphorescent device (GD29 dopant) along with a recent higher efficiency and longer lifetime device (GD33 dopant). For active matrix displays, typical green sub-pixel luminances will be in the 100 – 1,000 cd/m^2 , and for passive matrix applications 10,000 to 50,000 cd/m^2.

It is a characteristic of all OLEDs that their efficiency decreases at high luminances. This has been attributed to several possible mechanisms, such as polaron-exciton quenching [8], exciton dissociation under high electric fields [9], or heating. In a previous paper [4] we showed that the decrease in efficiency (roll-off) of phosphorescent (PHOLED) devices is very comparable with that observed in fluorescent OLED devices. Table 1 also shows the very good lifetimes [10] that now have been achieved using our green and red PHOLED devices.

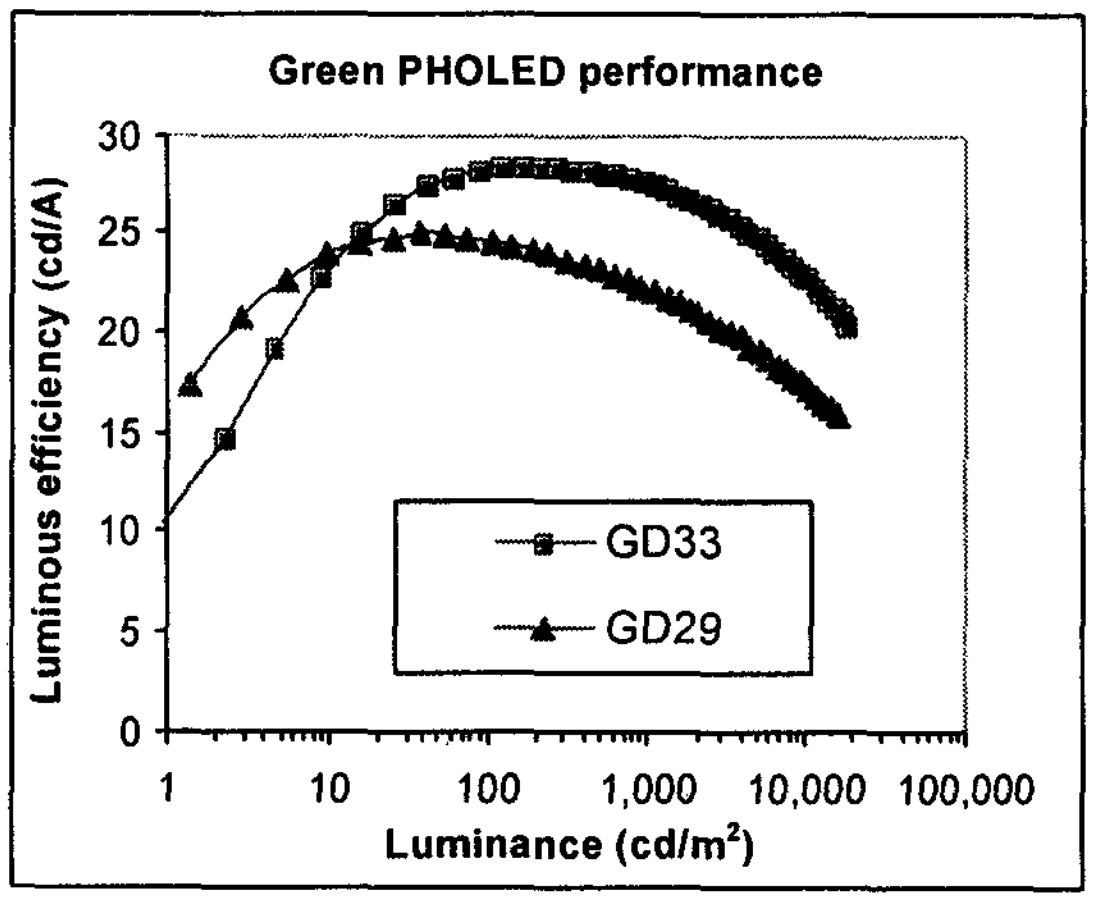

Figure 1 – Luminous efficiency (cd/A) versus luminance (cd/m^2) for green PHOLED devices (CIE = (0.30, 0.63) for two phosphorescent dopants.

Our baseline long lived GD29 based device exhibits 22-24 cd/A for active matrix applications and 13-17 cd/A for passive matrix displays. As can be seen, our newer GD33 based devices show improved performance with 28 cd/A for active-matrix applications and 18 – 22 cd/A for passive-matrix displays. This contrasts with the performance of fluorescent devices in the range of 7 – 15 cd/A in active-matrix applications [11,12], with lower performances at passive matrix peak luminances.

Figure 2 shows the luminous efficiency versus luminance for two of our red long lived phosphorescent devices. In fluorescent displays, the red sub-pixel generally consumes the most power, and for this reason we have developed a series of extremely high efficiency red phosphorescent dopants [17]. Our saturated red (RD07) has a luminance efficiency of approx 14 cd/A for active-matrix displays and 8 – 10 cd/A for passive-matrix applications. To further reduce power consumption of full-color displays we have developed a less saturated red PHOLED dopant (RD61) with active-matrix efficiencies of 22-24 cd/A and passive-matrix efficiencies of 15-20 cd/A. These high efficiencies are to be compared with the best red fluorescent devices of only 2-5 cd/A for active-matrix displays [13].

Not only do these phosphorescent devices exhibit excellent efficiencies, but to date we have also observed very good operational lifetimes for both green and red PHOLEDs.

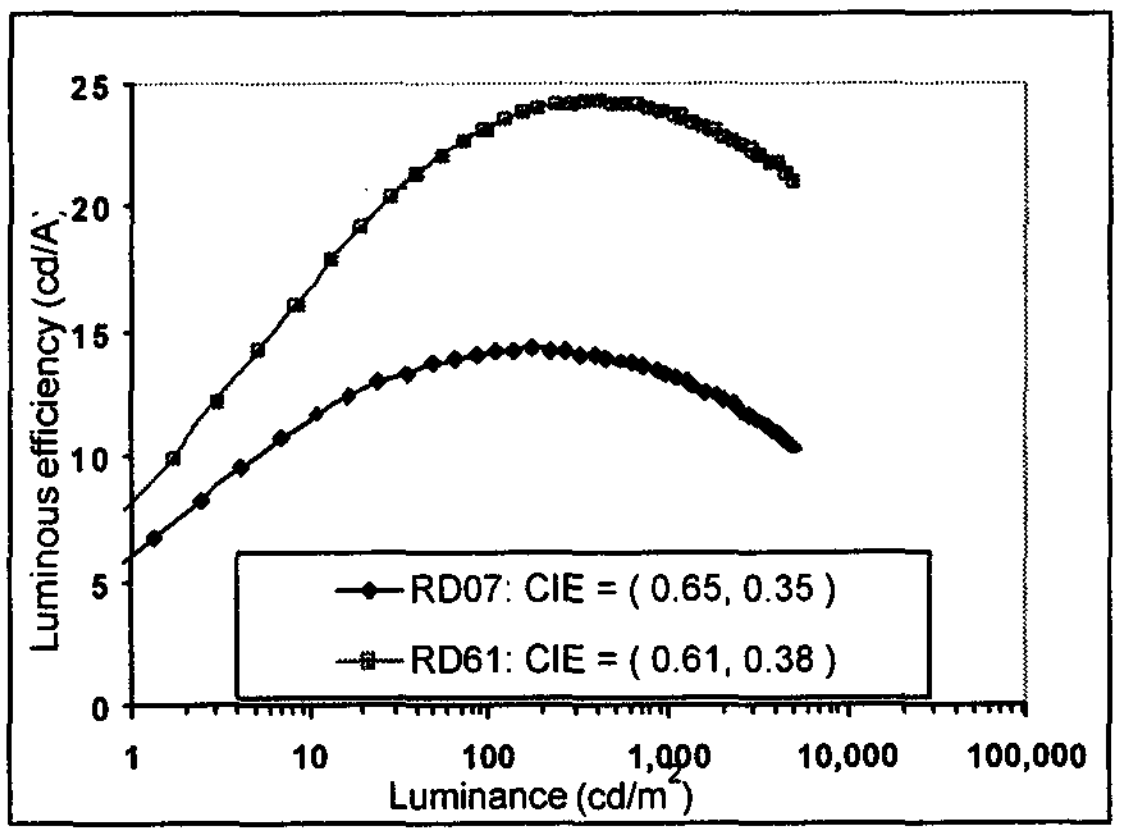

Figure 2 – Luminous efficiency (cd/A) versus luminance (cd/m^2) for two red phosphorescent devices.

Figure 3 shows the improvement in lifetime of our new GD33 dopant system over the previous GD29 PHOLED devices. As can be seen from the data, this new dopant offers the expectation of room temperature device lifetimes to half brightness of greater than 20,000 hours for an initial luminance of 600 cd/m^2.

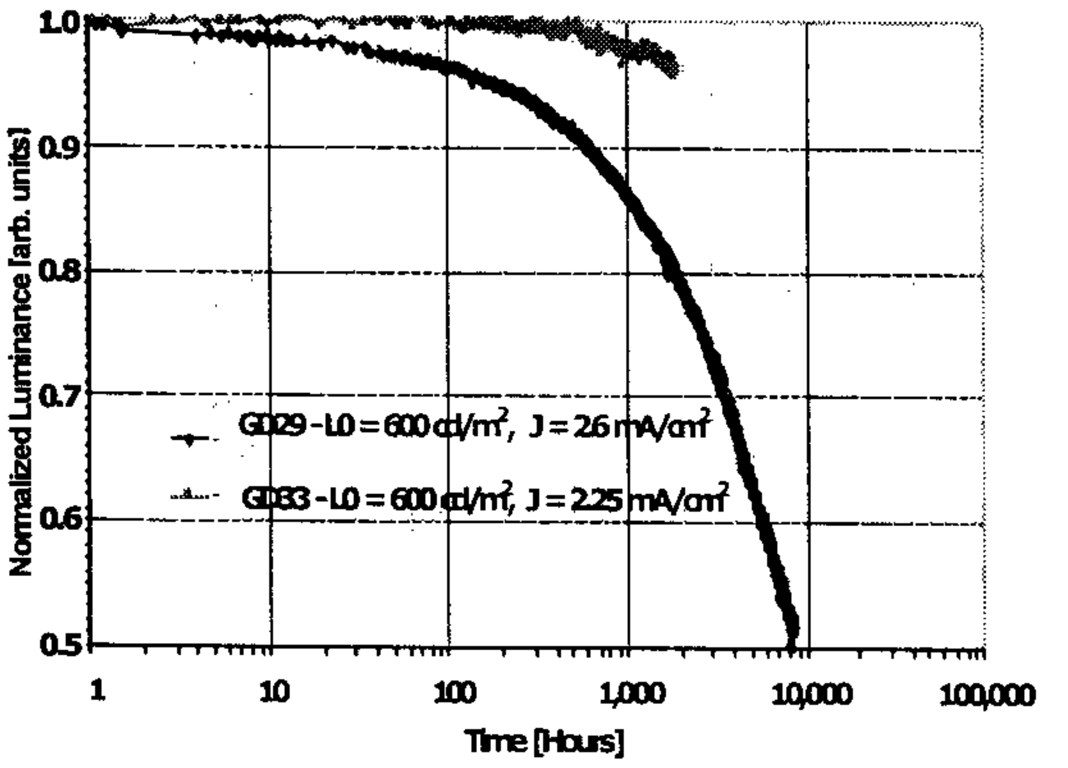

Figure 3 – Room temperature luminance versus lifetime for two green PHOLED devices, GD29 and GD33. Initial luminance = 600 cd/m^2.

To demonstrate the performance of our high efficiency material system, Figure 4 shows simulations of the power consumption for 2 diagonal active-matrix IMT-2000 resolution full-color display for UDC뮐 phosphorescent small molecule OLED materials (AM-PHOLED), fluorescent small molecule materials (AMOLED (F)), polymer light emitting diodes (PLED), and a backlit AMLCD. For the three OLED displays we assume a 50% efficient circular polarizer, and that 30% of the pixels are illuminated. While both the fluorescent OLED displays have similar power consumption to an AMLCD backlight, our phosphorescent OLED devices show over a factor of two less power consumption, significantly extending battery life for mobile devices. The lower current drive also lowers the line resistance requirements for larger AMOLED backplanes.

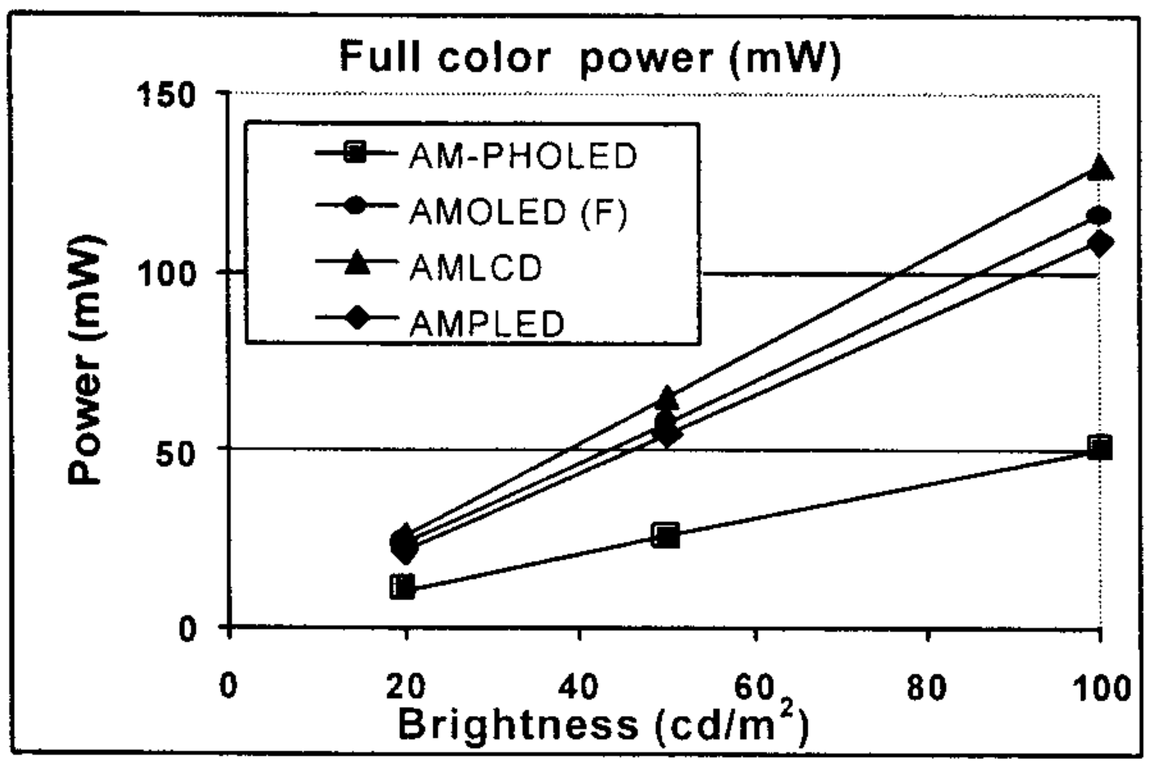

Figure 4 – Simulated power consumption for a 2? IMT-2000 cell phone display using phosphorescent OLEDs (PHOLED), fluorescent OLEDs (OLED (F)) and polymer OLEDs (PLED), compared to an AMLCD backlight

Backplane Technologies for AMOLEDs

While poly-Si is proving itself to be a viable candidate for the backplane technology to drive AMOLEDs, the high efficiency of our phosphorescent material system may enable the use of amorphous silicon backplanes. There is now considerable interest in fabricating AMOLED displays using a-Si backplanes as they could lower manufacturing costs as a result of a lower mask count fabrication process, and the ability to leverage off the large a-Si:H TFT manufacturing base that already serves the AMLCD industry and can be easily adapted for AMOLEDs.

Having already demonstrated that a-Si:H TFTs can supply the drive currents for our PHOLED devices [6], their viability to drive PHOLEDs depends on their ability to ensure display image uniformity. Using poly-Si TFT backplanes, variations in TFT threshold voltages (V_{th}) can cause significant variations in image intensity across a display, and many groups are developing advanced multi-TFT pixel circuits to provide uniformity correction. For a-Si:H TFTs, while the as-deposited threshold voltages are usually in a relatively narrow range, gate bias stressing causes V_{th} to shift during operation, and at low positive gate voltages, this is attributed to defect creation in the a-Si:H TFT channel. From reference [14], the change in V_{th} during positive bias gate stressing ΔV_{th} is given by

$$\Delta V_{th} = A\, V_{gs}^{\beta} t^{\gamma} \exp(-E_a/kT) \qquad ?\ 1)$$

퀠

where E_a is the activation energy, V_{gs} the TFT gate to source voltage, and A, β, and γ are constants. For the low gate voltages applicable to an AMOLED pixel, β is in the range of 1 – 2.

Display Size (ins)	Resolution	Max. Pixel current	Driver TFT W/L for V_{gs}-V_{th} = 4V
2	160x120x3	0.53μA	10.1
5	320x240x3	0.82μA	15.6
10	800x600x3	0.53μA	10.1
20	1024x768x3	1.29μA	24.6

Table 2 – Maximum pixel currents for varying AMOLED displays at 300 cd/m^2 for phosphorescent materials shown in Table 1, together with driver TFT size to minimize TFT gate bias stressing.

Table 2 shows calculations of the required W/L ratio for the driver TFT to provide the largest pixel current (red pixel) for a series of AMOLEDs of varying sizes and resolutions, fabricated using our PHOLED devices, for a TFT operating 4 Volts above threshold, where V_{th}, = 1V. The maximum pixel current is just above 1μA, and even for a 5V gate to source voltage for the driver TFT, the largest required W/L is only approximately 25.

These calculations are supported by preliminary results in Figure 5 [15] showing the current versus data voltage through an 10^{-3} cm^2 phosphorescent OLED, for a conventional 2 TFT pixel circuit. The PHOLED had a luminous efficiency of 20 cd/A, and the TFT aspect ratio (W/L) was 8:1. As can be seen from Fig. 5, a brightness of 200 cd/m^2 can be achieved for V_{data} = 16V. As V_{data} is equal to the sum of the voltage drop across the OLED (8V) and the driver TFT gate to source voltage (V_{gs}), for this circuit V_{gs} = 8V. As V_{th} = 2V, the driver TFT being driven just 6 Volts above threshold, demonstrating that an a-Si:H TFT only requires a very low gate stress to drive phosphorescent OLEDs.

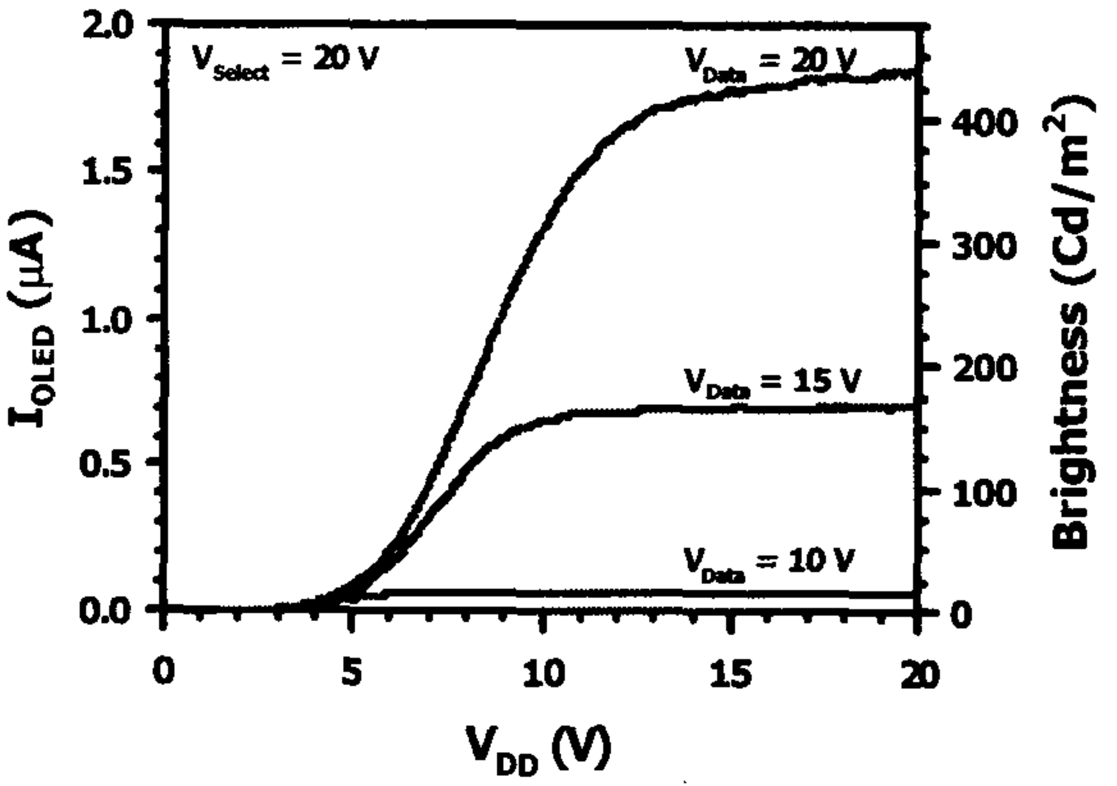

Figure 5 - Current voltage data from an a-Si:H TFT driving a phosphorescent OLED.

This work has now been extended to the fabrication of a full color AMOLED based on combining an amorphous silicon backplane with phosphorescent OLEDs [16].

The incorporation of just red phosphorescent OLED pixels (with green and blue fluorescent) reduced power consumption by 42% compared to the equivalent all fluorescent device, enabling a 4? full color AMOLED to operate at 300 cd/m^2, consuming only 670 mW under video mode conditions (30% pixels illuminated). This compares very favorably with an equivalent LCD backlight which would consume 1.8W [16].

For conventional fluorescent and polymer systems, most of the power is consumed in the red pixels, whereas our high efficiency phosphorescent red materials [17] lead to power being consumed more equally amongst the three primary colors. The lower current requirements of the phosphorescent devices also reduces power losses in the TFT backplane. These results are shown in Figure 6 which shows a comparison of the power consumed in an all fluorescent AMOLED compared to one with a phosphorescent red pixel [16].

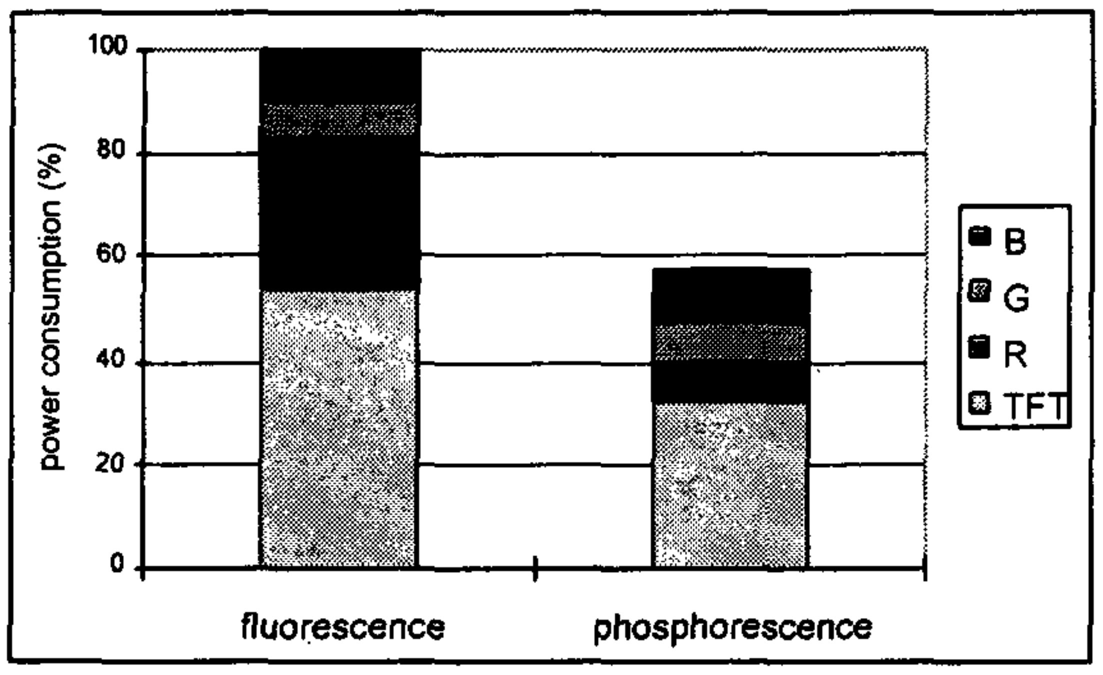

Figure 6 – Power consumption of blue, red and green OLED pixels, together with a-Si TFTs, for an all fluorescent AMOLED compared to one with a phosphorescent red OLED pixel.

Top Emission AMOLEDs

In previous sections we have shown that amorphous silicon TFTs may be viable as a backplane technology to drive our high efficiency PHOLED devices. In most cases the TFT circuit will occupy a significant fraction of each sub-pixel, reducing the pixel aperture ratio, particularly if for threshold voltage compensation, more complex 4 or 5 TFT pixel circuits are employed. Using our proprietary compound cathode consisting of a thin layer of metal (e.g. MgAg) and a conductive oxide (e.g. ITO) [18], in Figure 7 we present data showing a higher luminous output from a top emission OLED (TOLED? as compared to an equivalent conventional bottom emission OLED. At 10 mA/cm^2 the TOLED has a 15% greater luminance (2310 cd/m^2) than the conventional bottom emission device (2030 cd/m^2), resulting in a potential lifetime improvement on account of the lower current density to achieve any given luminance.

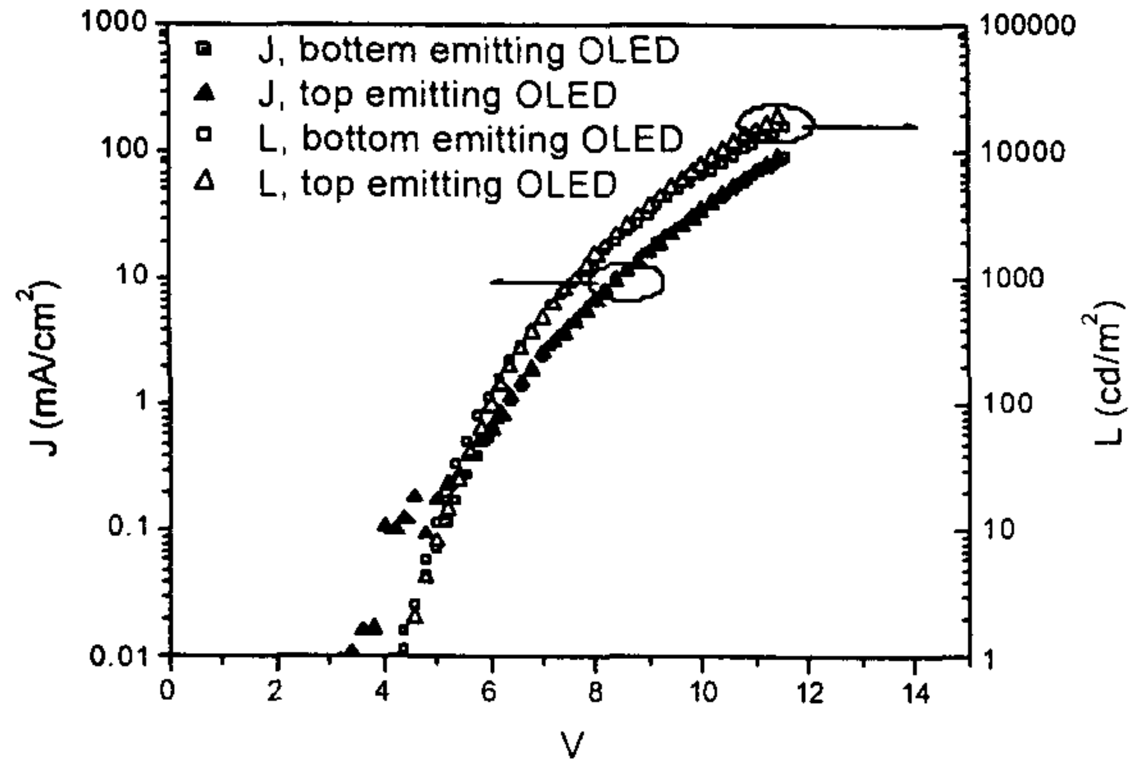

Figure 7 J-V-L of a TOLED compared to a bottom-emitting OLED. The luminance of the TOLED is measured through the coverglass.

Conclusions

We have shown that our proprietary phosphorescent OLED devices allow for the production of AMOLED displays with much lower power consumption than using fluorescent OLED material systems, as well as less power than a backlit AMLCD. We have demonstrated that the high efficiency of our PHOLEDs enables them to be driven by a-Si:H TFTs operating at low gate to source voltages, a prerequisite for good stability, and also shown the benefits of fabricating top emission AMOLED pixels.

Acknowledgements

The authors wish to convey their deep thanks and appreciation to their University partners, Professor Stephen Forrest at Princeton University and Professor Mark Thompson at the University of Southern California, the entire UDC team, and their colleagues at PPG Industries. The authors also wish to thank ARL (Contract #_DAAD19-02-2-0019) for their partial support of this work.

References

[1] C.W. Tang and S.A. VanSlyke, Appl. Phys. Lett. 51, 913 (1987)
[2] M.A. Baldo, D.F. O뭤rien, Y.You, A. Shoustikov, S. Sibley, M.E. Thompson and S.R. Forrest, Nature 395, 151 (1998).
[3] D.F. O뭤rien, M.A. Baldo, M.E. Thompson and S.R. Forrest, Appl. Phys. Lett. 74, 442 (1999).
[4] R.C. Kwong, M.R. Nugent, L. Michalski, T. Ngo, K. Rajan, Y.J. Tung, M.S. Weaver, T.X. Zhou, M. Hack and J.J. Brown, 멒isplay Properties of High-efficiency Electrophosphorescent Diodes? Proceedings of the Society for Information Display, Digest of Technical Papers, Vol. 33, No. 2, pp. 1365-1367, (2002)
[5] S.H. Ju, S.H. Yu, J.H. Kwon, H.D. Kim, B.H. Kim, S.C. Kim, H.K. Chung, M.S. Weaver, M.H. Lu, M. Hack and J.J. Brown, 븠igh Performance 2.2? QCIF Full Color AMOLED Displays based on Electrophosphorescence? Proceedings of the Society for Information Display, Vol. 33, No. 2, pp 1096-1099, (2002)
[6] M. Hack, J.J. Brown, J.K. Mahon, R. Kwong and R. Hewitt, 밯erformance of High Efficiency AMOLED Displays? Journal of Society for Information Display, vol. 9, #3, pp 191-195 (2001)
[7] C. Adachi, M.A. Baldo, M.E. Thompson, and S.R. Forrest, J. Appl. Phys. Vol. 90, No. 10, 5048-5051, November (2001)
[8] Young et al., Appl. Phys. Lett. 80, 874 (2002).
[9] Szmytkowski et al., Appl. Phys. Lett. 80, 1465 (2002)
[10] Raymond C. Kwong, Lech Michalski, Tan Ngo, Matthew R. Nugent, Kamala Rajan, Michael S. Weaver, Theodore X. Zhou, Michael Hack, and Julie J. Brown, Appl. Phys. Lett. 81, 162 (2002)
[11] G. Rajeswaran, Proceedings of OLEDs 2001 Intertech Conference, San Diego, November 2001
[12]S. Hough, Proceedings of Stanford Resources 18th Annual Flat Information Displays Conference, Monterey, CA, Dec 2001
[13] H.K. Chung Proceedings of Ninth International Display Workshops IDW ? 2, Hiroshima, Japan pp. 1107-1110 (2002)
[14] M.J. Powell, Appl. Phys. Lett. 43, 597-599 (1983)
[15] J.A. Nichols, T.N. Jackson, M.H. Lu and M. Hack, 멉 morphous Si TFT Active-Matrix Phosphorescent OLED Pixel? Proceedings of the Society for Information Display, Vol. 33, No. 2, pp. 1368-1371, (2002)
[16] J.J. Lih, C.F. Sung, M.S. Weaver, M. Hack and J.J. Brown, 븜 Phosphoresecent Active-Matrix OLED Display Driven by Amorphous Silicon Backplane? Proceedings of the Society for Information Display, Digest of Technical Papers, Vol. XXXIV, No. 1, pp. 14 - 17, (2003)
[17] R. C. Kwong et al., The 21st International Display Workshop, Nagoya, Oct 16-19, 2001
[18] M.H. Lu, M.S. Weaver, T.X. Zhou, M. Rothman, R.C. Kwong, M. Hack and J.J. Brown, Appl. Phys. Lett. **81**, 3921 (2002)