Flexible Organic LED Displays

M.S. Weaver, S.Y. Mao, J.K. Mahon, L.A. Michalski, T. Ngo, K. Rajan, M.A. Rothman, J.A. Silvernail, and J.J. Brown, Universal Display Corporation, Ewing, NJ; and W.E. Bennett, C. Bonham, P.E. Burrows, G.L. Graff, M.E. Gross, M. Hall, P.M. Martin, and E. Mast, BattellePacific Northwest Laboratory, Richland, WA

Key Words: Display; Organic LED (OLED); Flexible; Moisture permeation

ABSTRACT

The technology of organic light emitting devices (OLEDs) has recently demonstrated excellent performance for use in flat panel display (FPD) applications. OLED displays emit bright, colorful light with excellent power efficiency, wide viewing angle and video response rates; OLEDs are also demonstrating the requisite environmental robustness for a wide variety of applications. Moreover, OLED technology is, perhaps, the first FPD technology with the potential to be highly functional and durable in a flexible format. Particularly for handheld, portable applications, the use of plastic and other flexible substrate materials offers numerous advantages over commonly used glass substrates. These include impact resistance, light weight, thinness and conformability. In addition, this approach has the potential for adaptation to high-volume, roll-to-roll process manufacturing.

In order to realize flexible OLEDs (FOLEDs), the substrates must possess a number of important performance characteristics. These include low oxygen and moisture transmission rates; smooth surface morphology; chemical and thermal resistance; and optical clarity and transparency. This paper discusses the status and challenges associated with commercializing FOLED technology as well as some of its advantages and opportunities for portable electronics and optical applications.

INTRODUCTION

Just as the liquid crystal display (LCD) enabled the birth of the laptop computer and proliferation of myriad portable electronic products, OLED [1, 2] technology is poised to penetrate many existing flat panel display applications, thereby engendering a whole new family of electronic products. As emissive devices, OLEDs can provide an excellent visual performance that surpasses the capabilities of today's LCDs. OLEDs are low voltage devices and have demonstrated efficiencies > 40 lm/W [3, 4, 5]. They also offer some novel characteristics that create new design features and product opportunities. These include OLED displays fabricated on flexible substrates [6, 7]. The plastic-based OLED display shown in Figure 1 is lightweight, thin and conformable creating the opportunity to integrate displays onto curved surfaces and into places where glass-based displays would otherwise be considered impossible, impractical or unsafe.

Figure 1: A 128 x 64 FOLED passive matrix display fabricated on a 0.175 mm polyethylene terephthalate substrate (PET) shown being driven at a video rate of 60 Hz and an average display brightness of 200 cd/m^2. Each pixel is 400 x 500 μm in size.

FOLEDs

The simplest FOLED consists of a plastic substrate coated with a transparent conductor such as indium tin oxide (ITO) that acts as the hole injecting anode. A multi-layer stack of organic layers is then deposited by vacuum sublimation or other vapor deposition techniques onto the substrate surface. The total organic stack thickness is on the order of 150 nm. The various organic layers are chosen for their respective functionality (e.g. charge carrier mobility, charge injection characteristics and light emission properties). The FOLED is completed with a metal coating on the organic stack, which acts as the electron injecting cathode contact.

The device operates by injecting electrons and holes from the cathode and anode electrodes, respectively. An external applied voltage drives these carriers into the recombination zone where they form a neutral bound state, or exciton. Two types of excitons are formed, namely singlet and triplet. Light is emitted from the OLED by the radiative decay of excitons. In a conventional fluorescent OLED emission is derived from

44th Annual Technical Conference Proceedings—Philadelphia, April 21–26, 2001 ISSN 0737-5921

the singlet excitons only. The triplet state in fluorescent materials is non-radiative. UDC and its research partners at Princeton University and the University of Southern California have developed a new class of high efficiency OLEDs based on triplet exciton emission. Due to quantum mechanical spin statistics there are approximately 3 triplet states formed for every singlet excited state. Electro-phosphorescent materials therefore have the potential to be four times as efficient as conventional fluorescent materials. In electro-phosphorescent materials the triplet state is allowed. This high efficiency triplet emission technology is our baseline FOLED structure. A device cross-section is shown in Figure 2.

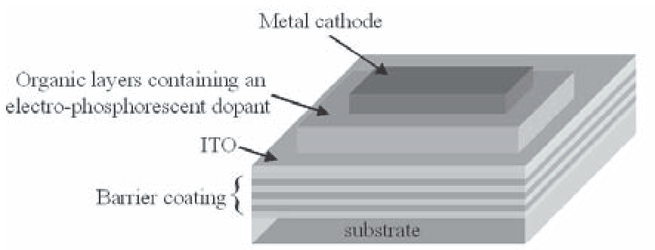

Figure 2: A typical cross sectional view of a FOLED device fabricated on a barrier coated flexible substrate material.

Flexible Substrates

To be effective in OLED applications, flexible films must demonstrate a number of performance characteristics. These include:

- Low permeation rates to oxygen and moisture
- Smooth and uniform surface morphology
- Optical clarity and transparency (for OLED architectures requiring light transmission through the substrate)
- Scratch resistance
- Cost that is comparable to or lower than FPD glass substrates

In addition to these basic requirements there are a number of issues that must be addressed during cleaning and patterning of the substrate architectures in order to successfully produce robust long-lived FOLED displays.

i) Chemical Stability

The flexible material and permeation barrier coatings must be able to withstand typical lithographic cleaning and etching solvents and acids used in the construction of OLED displays. Typical chemicals that the substrate might encounter during processing include various alcohols, water, photoresist, photoresist developers and acid mixtures.

ii) Mechanical Stability

The substrate and device architectures demand mechanical integrity when flexed during display usage and manufacturing. Issues that need to be addressed include connecting to the display and the barrier performance during stress.

iii) Thermal Stability

The thermal stability of the flexible substrate is extremely important. The material must not deform or expand beyond certain limits during manufacture and the displays use. The higher the glass transition temperature (T_g) of the material, the greater the compatibility with conventional FPD processing techniques. Also the higher the T_g of the material the earlier entry to market for flexible active matrix displays. This is due to the present temperature limitations when growing low temperature poly-silicon or amorphous silicon thin film transistor (TFT) elements.

While a number of flexible substrates can be found in the market place, most commercially available transparent plastic films have limitations in FPD applications. Specifically, untreated polyethylene terephthalate (PET) has a low T_g at 78°C that limits its use in standard FPD processing and display applications. Other higher temperature stable flexible materials compatible with roll to roll web coating technology are being explored, e.g. poly-ethersulphone (PES). PES is yellowish in color but has a higher T_g. So too does polyimide (PI) but it is also yellowish in color and highly birefringent.

Several leading chemical companies are developing higher temperature plastic substrates. These new materials under development aim to address deficiencies of present materials but, as yet, are not commercially available. Moreover, these new materials are projected to be more costly than PET and glass substrates. In addition to developing better substrate materials, coatings that can be applied to existing PET and other base substrates to provide the desired properties are also under development. Two of the most critical properties that coated systems need to address are barrier performance and surface morphology.

ADDRESSING THE LIFETIME ISSUE

The electronic properties of OLEDs degrade rapidly when exposed to water or oxygen. The failure mechanisms include delamination of the metal cathode as well as chemical changes within the organic layers. When using glass substrates, the conventional solution is to seal the display in a dry inert environment such as a nitrogen glove box, using a glass (or metal) lid fixed in place by an ultraviolet (UV)-cured epoxy resin. A ‘getter’ material is often also incorporated within the package in order to eliminate any residual water and oxygen that may be left within the encapsulated space. In this approach, the glass behaves as a perfect moisture and air barrier and the only method of ingress into the OLED package is through the epoxy edge seal. Compared to the characteristics of glass, commercially available plastic substrate materials do not have sufficient barrier properties to meet the commercial display lifetime requirement of > 10,000 hours continuous operation at video brightness. Typical materials such as PET are very poor barriers to the diffusion of water and oxygen due to their low density.

The barrier performance required to achieve the lifetime requirements of OLED displays is unclear since the mechanism of long-term degradation is still the subject of debate. However if in order to achieve product lifetimes of 10,000 hours, an estimated package permeability [8] of less than 10^{-6} g/m^2/day at 25°C for water. Typical plastic substrate materials have a permeability of 100 to 10^{-1} g/m^2/day at 25°C, which renders them unsuitable for a commercial OLED product.

One approach to overcome this issue is to use thin film coatings of dense dielectric materials to inhibit diffusion. However, such a film has to be near defect free in terms of pinholes and grain boundaries within the inorganic layer in order to be effective.

A different solution being explored is the use of a multi-layer barrier coating [8, 9], on the plastic substrate and OLED. We are working with Vitex Systems Inc., a Battelle company, under a DARPA contract to apply their multilayer Barix™ coatings to package FOLEDs. This composite barrier consists of alternating layers of vacuum-deposited polymer films and high density vapor barrier layers (e.g. SiO_2, Si_3N_4, Al_2O_3), effectively decoupling each barrier material. Commercially available heat stabilized PET substrates have surface asperities greater than 150 nm. These surface features can protrude through the conformal ITO anode and yield shorting paths through the OLED. In the Barix™ architecture, the applied polymer layer acts to planarize the substrate (or OLED) surface. The polymer is deposited and crosslinked in a vacuum to form a non-conformal polyacrylate film. A dielectric film is then deposited onto the polymer layer as a barrier to the diffusion of water and oxygen (Figure 2).

Substrate barrier properties can be tailored by varying the total number and composition of polymer and inorganic layers in the thin-film coating. Using this technique, the effect of multiple barrier layers is additive. Oxygen and water permeation rates of < 0.005 cc/m^2/day and < 0.005 g/m^2/day, respectively have been achieved at 38ºC. This measurement is limited by the sensitivity of the MOCON measurement technique, which directly measures the molar quantity of oxygen or moisture diffusing across an edge-sealed membrane of material. The barrier structure is then terminated with an ITO layer that serves as the OLED anode. The complete substrate has a transparency of > 80% across the visible spectrum and a sheet resistance of < 40 ohms per square.

Our development work on these plastic substrates shows that the typical current voltage luminance curve from an OLED grown on a plastic substrate compares favorably with an identical device grown on a glass substrate (see Figure 3).

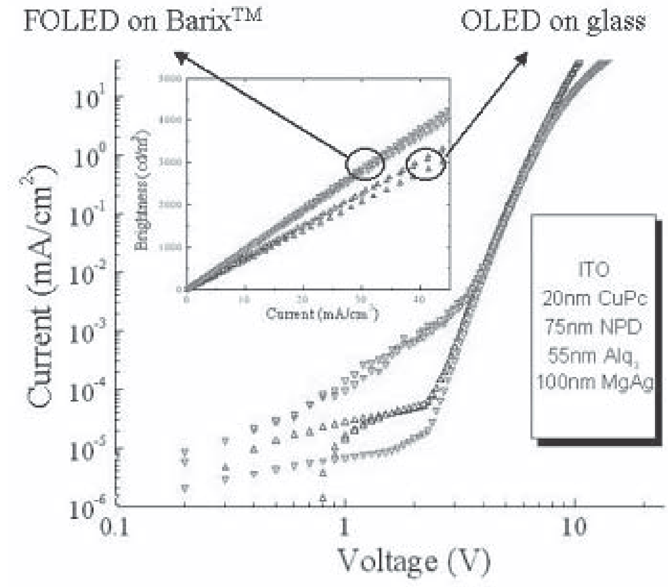

Figure 3: Comparison of the current-voltage-luminance (I-V-L) characteristics of OLEDs on glass and plastic substrates.

Magnified views of identical pixels on the two substrates demonstrate how similar they are (see Figure 4). This evidence suggests that OLEDs can be grown on barrier coated flexible substrates with optical performance that is comparable or superior to similar OLED devices fabricated on conventional glass substrates.

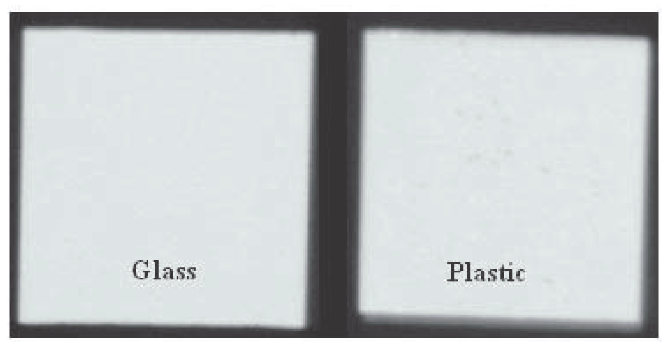

Figure 4: This is a magnified view of green emission OLED pixels grown on glass (on the left) and plastic (on the right) substrates.

Work is underway to use this same barrier coating technique to encapsulate the display. Preliminary results show increased lifetimes and indicate that this approach holds promise to achieve lifetimes comparable to a glass-based system.

FOLED DISPLAYS

In order to fabricate a FOLED display, UDC had to develop new process technology to build the prototype. Figure 1 showed an example of a 60 dpi passive matrix display fabricated in UDC's pilot line facility.

A magnified top view of an 80 dpi FOLED patterned substrate prior to organic deposition is shown in Figure 5. In this particular architecture, a metal bus line has also been added to lower the column resistance of the display. This significantly reduces the power losses incurred by the ITO electrodes and improves the scalability of the display to larger areas.

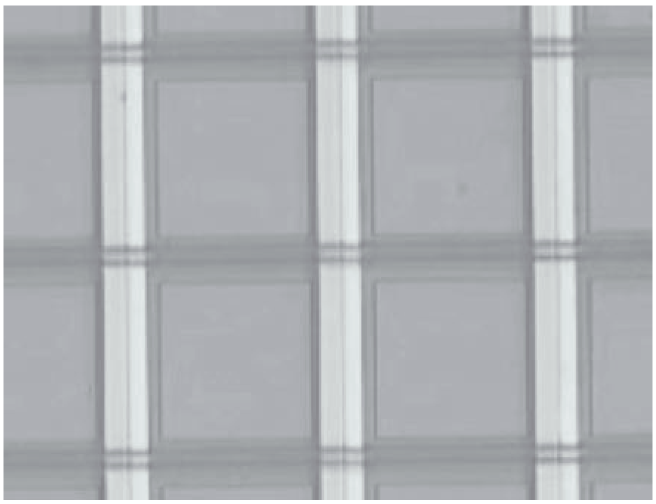

Figure 5: This is a magnified view of a patterned flexible substrate. The pixel pitch is for an 80 dpi resolution display. The active pixel area is defined by each square.

The Future

Ultimately, one would like to be able to make active matrix backplanes on a flexible substrate. A great deal of research is being conducted in this area to reduce the processing temperatures of poly-silicon or amorphous silicon TFTs and increase the thermal stability of suitable plastic materials. However, the fill factor on active matrix backplanes can still be a limiting issue even on glass or silicon. One solution to this problem is to use a transparent cathode or top emission OLEDs (or TOLEDs) [10] that can be grown directly on top of TFTs and bus lines. If desired, this design can achieve a display fill factor close to 100%. TOLED device architectures have previously been fabricated on conventional glass substrates; UDC has demonstrated a 128 x 64 (80 dpi) TOLED passive matrix test display with 64 gray levels. In a TOLED device, a transparent cathode is used which is composed of a thin metal injecting contact less than 10 nm thick, capped with ITO. We demonstrate a flexible TOLED in Figure 6. Here a single flexible TOLED pixel — 5 mm^2 in area is shown wrapped around a pen with a curvature radius of approximately 5 mm.

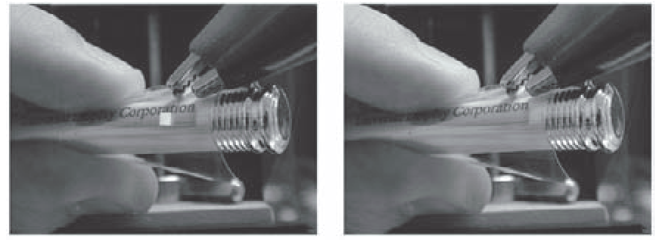

Figure 6: A flexible TOLED is shown here in both its on (left) and off (right) states. The substrate has a radius of curvature of 5 mm.

The combination of flexible TOLEDs with active matrix backplanes opens the way for next-generation commercial products such as low power roll-up and conformable displays. In turn, this can open up a whole new world of flat panel display product designs.

ACKNOWLEDGMENTS

The authors thank Professors Stephen Forrest and Mark Thompson for numerous useful conversations. We also thank DARPA and Vitex Systems for support of this work. N.B. Pacific Northwest National Laboratory is operated for the DOE by Battelle Memorial Institute under contract OE-AC06-76RLO 1850.

REFERENCES

1. C.W. Tang and S.A. VanSlyke, "Organic Electroluminescent Diodes," *Appl. Phys. Lett*., 51, 913, 1987.

2. A.J. Hudson and M.S. Weaver, "Organic Electroluminescence," *Functional Organic Materials*, ed. T.H. Richardson, p.365, John Wiley & Sons, London, 2000.

3. M.A. Baldo, S. Lamansky, P.E. Burrows, M.E. Thompson, and S.R. Forrest, "Very high-efficiency green organic light-emitting devices based on electro-phosphorescence," *Appl. Phys. Lett*., 75, 4, 1999.

4. C. Adachi, M.A. Baldo, S.R. Forrest, and M.E. Thompson, "High-efficiency organic phosphorescent devices with tris(2-phenylpyridine)Iridium doped into electron-transporting materials," *Appl. Phys. Lett*., 77, 6, 904, 2000.

5. C. Adachi, M.A. Baldo, S.R. Forrest, S. Lamansky, M.E. Thompson and R.C. Kwong, "High-efficiency Red Electrophosphorescence Device," *Appl. Phys. Lett*., 78, 11, 1622, 2001.

6. G. Gu, P.E. Burrows, S. Venkatesh, and S.R. Forrest, "Vacuum-Deposited, Non-Polymeric Flexible Organic Light Emitting Devices," *Optics Lett*., 22,172, 1997.

7. G. Gu, P.E. Burrows, and S.R. Forrest, U.S. Patent No. 5,844,363, "Vacuum Deposited, Non-polymeric Flexible Light Emitting Devices," December 1, 1998.

8. P.E. Burrows, G.L. Graff, M.E. Gross, P.M. Martin, M. Hall, E. Mast, C. Bonham, W. Bennett, L. Michalski, M. Weaver, J.J. Brown, D. Fogarty, and L.S. Sapochak, "Gas Permeation and Lifetime Tests On Polymer-Based Barrier Coatings," *SPIE proc*., 4105, 75, 2000.

9. J.D. Affinito, M.E. Gross, P.A. Mournier, M.K. Shi, and G.L. Graff, "Ultrahigh rate, wide area, plasma polymerized films from high molecular weight/low vapor pressure liquid or solid monomer precursors," *J. Vac. Sci. Technol*., A 17, 1974, 1999.

10. V. Bulovic, G. Gu, P.E. Burrows, M.E. Thompson, and S.R. Forrest, "Transparent Organic Light Emitting Devices," *Nature* 380, 29, 1996.