

Process and design of a multilayer thin film encapsulation of passive matrix OLED displays

L. Moro, T.A. Krajewski, N. M. Rutherford, O. Philips, R.J. Visser*
Vitex Systems, 3047 Orchard Parkway, 95134 San Jose, CA, USA
M. Gross, W. D. Bennett, G. Graff,
Pacific Northwest National Laboratories, Richland, WA, USA

ABSTRACT

Thin film barrier coatings for protecting Organic Light Emitting Diode (OLED) displays against the environment are extremely difficult to fabricate. The coatings must have extremely low water/oxygen permeability, no defects, cover several microns of topography, and be applied at temperatures below 100°C in a process that does not compromise the performance of the display.

Vitex Systems has succeeded in depositing such coatings using an organic/inorganic, thin film multilayer structure termed Barix™ encapsulation. In this paper results on encapsulation of OLED test pixels and passive matrix displays will be shown. Lifetime and permeability tests conducted at high temperature and humidity demonstrate that this thin film coating can meet the necessary performance requirements for commercial OLED displays. Processing parameters, layer architecture and manufacturing techniques are analyzed and discussed. Thin film encapsulated displays are used to demonstrate the utility of the encapsulation technique.

Keywords: OLED, display, thin film encapsulation, water permeability, barrier

1. INTRODUCTION

Thin film encapsulation of OLED displays has been a desirable technological improvement for a number of years. The introduction of this technology would reduce cost, make bottom emitter OLED devices fabricated on glass substrates lighter, and allow the fabrication of more robust OLED's on plastic substrates. Transparent thin film encapsulation is needed for top emitter devices to allow light emission and for devices on plastic to satisfy the requirement of flexibility and light weight. The extremely low water vapor transmission required for successfully encapsulating OLED displays in combination with the restriction of a maximum deposition temperature less than 100°C present serious technical challenges. Moisture diffusion barriers based on vacuum deposited organic/inorganic multi-layer stacks¹ are a promising option for the transparent packaging of OLED devices. Vitex Systems Inc. has developed^{3, 5-6} a commercially available version of this process (Barix™ encapsulation) using the Guardian™ R&D system.

In Barix™ encapsulation the optically transparent organic/inorganic multilayer is applied in a vacuum system using the 'Vacuum Polymer Technology' technique. Polymeric layers are deposited by first evaporating a monomer mixture, followed by condensation on the substrate and then polymerization using UV radiation. The inorganic metal oxide layer is deposited using standard sputtering methods. One of the unique properties of this technique is that the monomer layer is deposited in the liquid phase, resulting in non-conformal surface coverage and extremely good planarization over topological features such as ink jet 'wells' and 'cathode separators'. The inorganic layers are deposited between successive polymer layers and have a very low defect density, thus forming a structure that is an effective diffusion barrier for gaseous species.

In this paper we present results showing Barix™ encapsulation permeability values in the range of 2.2×10^{-6} g/m²/day for water. This permeation was measured using a calcium test to quantify the water transmission coefficient of the barrier layers on planar samples and cathode separator structures. By changing layer thickness and number, the barrier architecture can be tailored to obtain the desired permeation values and final coating properties. The findings of the calcium experiments are then extended to encapsulation of OLED test pixels and passive matrix displays. These findings are then discussed relative to the stricter constraints imposed on the barrier architecture by passive matrix devices.

2. EXPERIMENTAL DETAILS

The proprietary Barix™ encapsulation concept has been described before¹. In synthesis, Barix™ encapsulation (Barix™) is a multilayer coating consisting of a sequence of alternating transparent organic and inorganic layers deposited in vacuum. The inorganic layers are the actual moisture/oxygen penetration barrier and, for the applications shown in the present paper, consist of alumina deposited by reactive sputtering. The polymer layers perform two functions. Whenever the surface presents a pronounced topography (e.g. if cathode separators are present like in passive matrix displays) the first deposited polymer layer(s) planarize the topography on the substrate. In the absence of topography, the polymer layers provide a smooth surface for the deposition of the next inorganic layer, thereby avoiding defects in the oxide introduced by the roughness of the substrate. By decoupling the successive inorganic layers the propagation of defects from layer to layer is stopped, and the final defect density is reduced. The multiple barrier layer approach increases the tortuosity of the path for moisture diffusion through pinholes or nano-defects in the layers. Likewise, the multiplicity of barriers decreases the probability of catastrophic failure due to killer defects.

2.1 Barix™ encapsulation

Device encapsulation (test pixels and displays) was done using a Vitex Guardian™ R&D system. The R&D system is a linear tool that consists of two vacuum chambers: a load-lock chamber that communicates with the rest of the system through a gate valve, and a main deposition chamber with stations for oxide deposition, monomer deposition and monomer cure. Deposition of the Barix™ multilayer stack is done by moving the substrate(s) back and forth between the different stations. The tool interfaces at one end (load-lock side) with a dry box that allows sample loading with no exposure to the ambient environment. On the other end of the tool is a high vacuum (10^{-7} mbar) chamber for Ca or other film evaporation (isolated by a gate valve). The vacuum level in the main deposition chamber is in the low 10^{-5} mbar range, obtained by a turbo molecular pump and LN₂ traps. Alumina layers with typical thickness between 10 and several hundred nm are deposited by DC reactive sputtering of a metallic Al (99.999%) target. Polymer layers are deposited in vacuum by a deposition technique that involves the flash evaporation of liquid monomers. The monomer vapors are condensed on the sample surface in liquid phase and cross linked by UV radiation to form a solid film. A mixture of acrylate monomers is used to give a highly cross-linked acrylic organic film. Typical thicknesses of the organic films vary between 0.25 and several micrometers. The Barix™ barrier properties depend on the number of organic/inorganic layers deposited, with typical coatings consisting of 4-5 pairs. From here on, an organic/inorganic pair may be called a dyad. Barix™ was deposited with no edge seal on most of the sample. Plates as large as 20 cm can be coated in the Vitex Guardian™ R&D system.

2.2 Sample Description

OLED test pixels of different types were received from several display manufactures and coated, however not many details are available on their structures. A typical test pixel size was 2x2 mm². Both small molecule (SM) evaporated devices and polymer-based (PLED) spin coated devices were encapsulated. These samples varied by color (red, blue, green and yellow), type of cathodes (Ca/Al, LiF/Al, Al-Li/Al) and cathode thickness. For the scope of this paper only bottom emitting devices will be covered. Passive matrix PLED glass displays produced by Philips (Philips Mobile Display Systems, PolyLED Group, Heerlen, The Netherlands) were coated and tested.

A majority of samples were transported from the production site to the Vitex laboratories in specially designed air tight metal containers called ‘shippers’. Desiccant was packed in the shipper together with the devices to getter residual or leaked gasses. Test pixels and/or displays were sealed in the shipper in dry box conditions at the production site, and opened inside the Vitex dry box to avoid any environmental exposure.

As a reference, planar Ca test samples were produced by depositing 70 nm thick Ca films in 2.5 cm wide squares located at the center of 5 x 5 cm square glass substrate. The same thickness of Ca was deposited on cathode separator structures to screen the barrier propriety of different Barix™ barrier architectures.

2.3 Sample Testing

The Ca reference samples were measured using the test protocol described before². It is based on the corrosion of thin Ca films. The Ca film, as deposited in vacuum and encapsulated by the barrier film, is initially a metallic layer. By reacting with water and oxygen permeating a leaking barrier, it is progressively transformed into a transparent calcium hydroxide film. By measuring the change in transmission of the film as a function of aging time in accelerated testing, it is possible to calculate the thickness of Ca reacted and therefore the amount of water penetrated through the barrier. Values of

transmission at 633 nm are usually reported. The relative change in transmission, D, is used to quantify and compare barrier performance. D is defined by the formula

$$D (\%) = (T_{ti} - T_{t0}) / T_{t0} (\%)$$

where T_{ti} and T_{t0} are the values of transmission respectively at the aging time and at the initial acquisition after coating.

Device I-V-L curves and pictures were acquired in the dry box before and after encapsulation to evaluate the effect of Barix™ coating on the different OLED and display types. A Keithley 2400 source meter and a luminescence meter (Minolta LS-100) interfaced to a PC computer were used to drive the devices, measure voltage/current and luminance. I-V-L curves were then acquired as a function of accelerated aging. Monitoring of the voltage shift and light output change (in % of the initial value) at a given current in Barix™ coated samples supplied information on the impact of the thin film encapsulation on device performance. Pixel shrinkage that is the reduction in light emitting area due to OLED deterioration by reaction with moisture and black spot growth were also monitored as a function of aging time. Pixel and black spot area were measured from microscope pictures of driven devices by using a standard image analysis program. For each pixel, the percent area remaining (= 100- pixel shrinkage) was calculated using the following formula,

$$A_{ti} (\%) = (\text{lighted area at } t_i / \text{lighted area at } t_0) \%$$

where t_i and t_0 are respectively, the aging time and the initial acquisition after coating.

2.4 Accelerated aging and Thermal Shock Testing

Accelerated life time tests were performed in an oven with controlled relative humidity (Tenney model THJR). Aging conditions were typically 60°C and 90% RH, a standard test condition used in the telecommunication industry. Performance was evaluated as a function of aging time. The performance of different barrier schemes was evaluated at 300 hr, and 500 hr, roughly equivalent respectively to 6000 h and 10000 hours at ambient conditions. An Espec thermal shock chamber (model TSE-11) was used to determine the effect of thermal shock on encapsulated Ca samples and devices. Samples were subjected to a minimum of 100 cycles of -40°C, 15 min / 80°C, 15 min with transition time of 2s.

3. RESULTS AND DISCUSSION

3.1 Ca reference sample encapsulation

Encapsulation of Ca films is used as a test to evaluate and compare barrier performance of different thin-film architectures. Fig. 1 shows the transmission values (filled squares, left axis) as a function of time at 60°C/90% RH for a typical planar reference sample. In the same graph we also show D, the relative change in transmission (open square, right axis). D is defined in section 2.3.

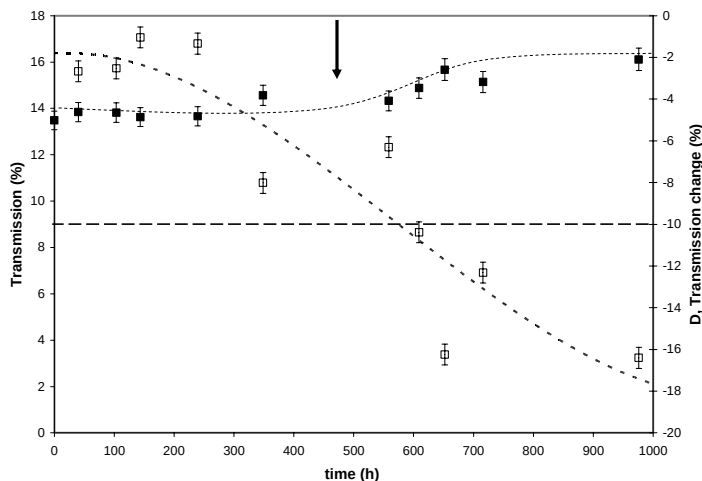


Figure 1: Transmission values (■, left axis) and D, relative change in transmission (□, right axis) as a function of aging time at 60°C/90% RH for a planar sample, the lines between experimental points are fitting with arbitrary mathematical functions. The horizontal dashed line represents the specification limit. The arrow at 500h indicates the onset of a 2-D diffusion front.

A value of D equal to 10% is equivalent to $2.0 \times 10^{-7} \text{ g/cm}^2$ of H_2O permeated through the barrier². Corrected for H_2O partial pressure and temperature² at ambient conditions, this is equivalent to a permeation of about $1 \times 10^{-6} \text{ gr/m}^2/\text{day}$. The arrow at approximately 500h indicates the onset of lateral diffusion of water vapor through the edges of the samples. For aging times longer than 500 h diffusion of H_2O to the Ca film proceeds by lateral penetration through the unsealed edge of the barrier, as well as by penetration through the barrier. 2-D diffusion and its effect on the transmission of Ca films has also been reported in ref. 2 for $t > 500\text{h}$. Water vapor transmission rates (WVTR) of $<8.5 \times 10^{-5} \text{ g/m}^2/\text{day}$ at $20^\circ\text{C}/50\% \text{ RH}$ have been achieved for barrier coated PET, and, more recently, a WVTR of $<2.1 \times 10^{-6} \text{ g/m}^2/\text{day}$ at $20^\circ\text{C}/50\% \text{ RH}$ was reported for thin-film encapsulated Ca test coupons.² These finding clearly demonstrated that the attainment of barrier performance necessary for OLED encapsulation is possible using multi-layer structures.

Recently, efforts have been focused on improving process yield through process control and failure analysis. Barrier performance of the type shown in Fig. 1 is now routinely achieved by encapsulation on the Vitex Guardian™ R&D system. Typical yields are on the order of 70% at over 500 hours (Fig. 2).

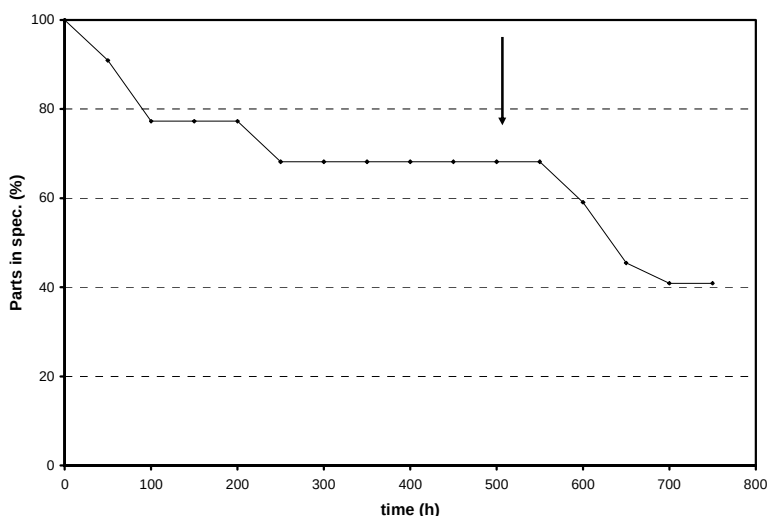


Figure 2: Number of parts out of 25 satisfying the passing criterion versus aging time in $60^\circ\text{C}/90\% \text{ RH}$. The number of parts is normalized to 100% number of parts is reported, rather than the absolute number. The arrow at 500h marks the onset of lateral moisture penetration through the edge of the coating.

Although these results are not yet fully satisfactory, the effort paid to yield improvement has allowed us to identify the causes of premature failure of the barrier. The major catastrophic failure mode was large ($\sim 5\mu\text{m}$ or more) particles (debris) that compromise the thin-film coating. Sources of debris include improper cleaning of the glass substrates, incorrect handling procedures and sample transport issues in the tool. Reduction of particles has been achieved by hardware modification in the Vitex Guardian™ R&D system as well as improved handling protocols. More importantly, extensive experimentation has determined that these large particles are not an intrinsic problem of the Barix™ encapsulation process, and specifically are not introduced by the polymer vacuum deposition process.

3.2 Ca samples with surface topography (in-situ shadow masks or cathode separators)

The planar samples described in the preceding section are a reasonable representation of the topography existing in OLED test pixels, where the maximum feature height is less than $0.5 \mu\text{m}$ with a negligible aspect ratio and step profiles with very gentle positive slopes⁴. The real challenge for a thin film barrier is successful encapsulation over passive-matrix display structures such as the cathode separators. Here the feature slope is not just high (close to 45%), but also negative (see Fig. 11). Planarization on active matrix displays is an easier situation since the step slope is still close to 45%, but positive.

The calcium film was deposited on a glass substrate containing cathode separator structures approximately $4 \mu\text{m}$ in height. Transmission measurements were taken through the entire structure and therefore represent the average of Ca consumption on top of the cathode separators and in the region between them. Observation using optical microscopy shows no preferential corrosion appearing in either of the two regions.

In Fig. 3 D, the relative change in transmission defined in 2.3, is plotted as a function of aging time for three barrier architectures that differ in the total number of dyads. The linear fit of the experimental data is also shown. Though there is some spread in the data, the architectures containing higher numbers of dyads show enhanced performance. The “N+1” and “N+2” structures easily satisfy the < 10% specification (indicated in the graphic by the horizontal dotted line) at 300 h and, by the linear extrapolation, are still within specification near 500 h.

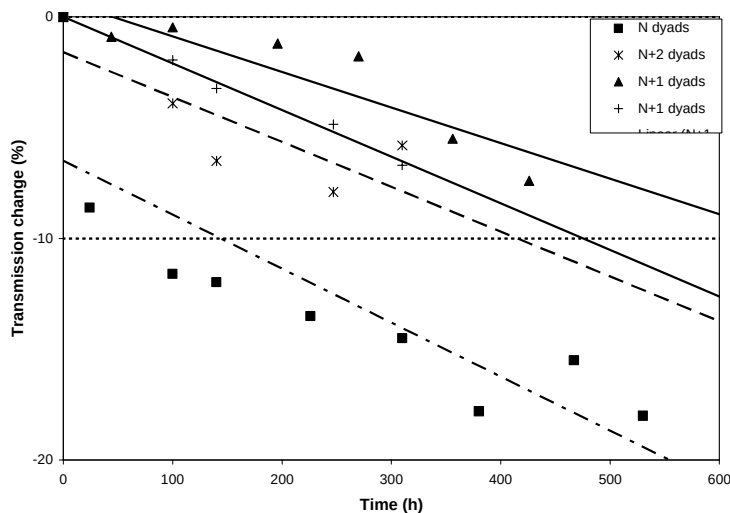


Figure 3: Relative change in transmission D as a function of aging time in 60°C/90% RH for three barrier architectures coated on calcium film deposited on cathode separator structures. The linear fitting of the experimental points is also shown. The horizontal dotted line shows the D= 10% specification.

Absolute and relative thicknesses of oxide and polymer layers were also modified in order to better planarize and successfully encapsulate the significant topography (4 μm) presented by the cathode separators. In Fig. 4, the absolute value of the rate of transmission change, directly correlated to the permeation value of the barrier, is shown as a function of the total thickness of oxide in the structure. The rate of transmission change is calculated by the linear fitting of experimental data like the one's shown in Fig. 3. The general trend is a lower rate of change, and therefore lower moisture permeation, when the sum of the oxide thickness increases in the barrier architecture. Next to the experimental points in Fig. 4 is reported which percentage of samples for a given architecture yields a given rate change. Also in this case the percentage of parts with a lower rate of change is higher for thicker oxides. The statistical significance of this data is limited by the sample size (9 samples per structure) and is also influenced by spurious effects in the experiment, such as the occasional presence of a higher than usual density of particles with size larger than 10 μm .

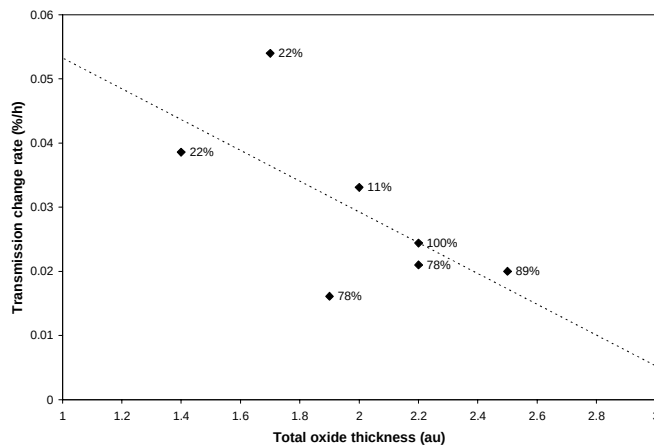


Figure 4: Rate of transmission change calculated by linear fitting of experimental data like those shown in Fig. 3 shown as a function of the total oxide thickness of all AlOx layers in the stack. The percentage of samples for the given rate is shown adjacent to the data point.

Barrier performance comparable to that achieved on planar substrates is obtained with variations in oxide thickness within the 10-100 nm range. These findings show for the first time that the concept of multi-layer barrier encapsulation¹ is applicable to structured substrates.

In Fig. 5, a comparison is made between the H₂O permeation (measured by the Ca transmission method) and the thickness of the first polymer layer in the barrier stack. The moisture permeation is higher at lower polymer thickness, passes through a minimum and increases again for samples with a very thick first polymer layer. The poor performance with thin polymer layers is indicative of incomplete planarization of the surface features (cathode separators). The root cause of increased permeation at high polymer thickness is not well established, but may be related to in-plane diffusion of water vapor.

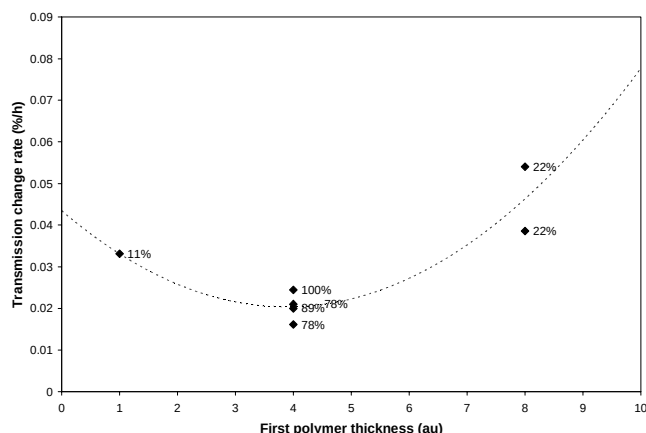


Figure 5: Rate of transmission change calculated by linear fitting of experimental data like those shown in Fig. 3. Shown as a function of first polymer thickness. The polymer thickness is reported in arbitrary units. The percentage of samples the given rate is shown close to the experimental point.

These results clearly demonstrate that the BarixTM thin-film encapsulation process provides acceptable performance on planar and structured (pillared) Ca reference samples. The barrier structures developed in the Ca tests (shown above) served as a starting point for the design of the architecture to be used in encapsulating OLED test pixels and devices.

3.3 Device encapsulation

Many types of test pixels and several PM-OLED devices supplied by industrial collaborators were encapsulated. The results presented and discussed below are restricted to devices with a bottom emitter configuration on glass substrates. Successful encapsulation of test pixels with area shrinkages less than 10% at 500h (60°C/90%RH), and no change in the I-V-L characteristics were generally achieved. In the following sections details on the results of lifetime experiments on test pixels, and preliminary results on encapsulation of displays are reported.

3.3.1 Initial (t_0) device encapsulation damage

A common concern with thin film encapsulation is damage to the electrical and optical emission properties of the devices. The process steps required for BarixTM encapsulation (heat, UV radiation, exposure to plasma, chemical interaction with the polymer, and stress of cured layers) are all potential sources of damage. The effect of the different coating steps has been investigated for all types of devices made available to Vitex. I-V-L characteristics were measured and optical images captured before and after specific process steps. Previously we reported^{3,5} no degradation of performance after thin-film encapsulation. Whereas these findings were accurate for all the devices investigated to that point, recent experiments have shown that certain types of devices are quite sensitive to plasma exposure. Higher turn-on voltages and, in some cases, a loss in light output efficiency was measured after oxide sputtering deposition. This device damage can be minimized, but not always completely eliminated by using optimized process conditions. Process damage can be completely prevented by deposition of a protective, thin-film buffer layer between the device and the barrier structure.

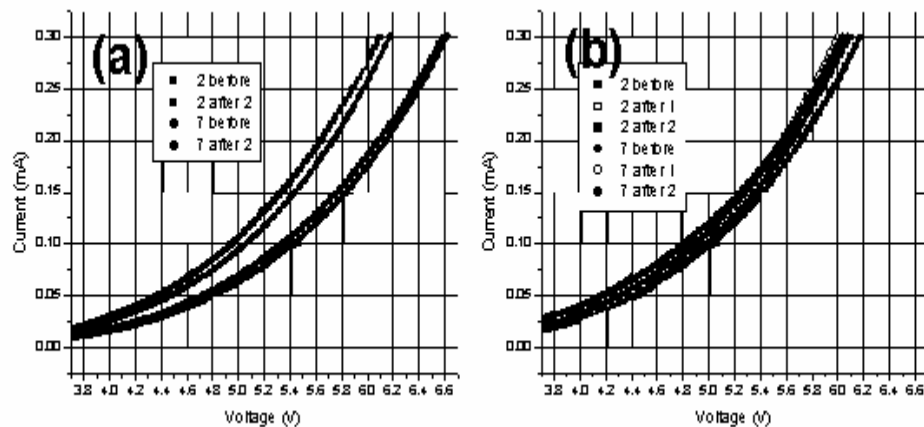


Figure 6: I-V and I-L curves for two devices of the same type, each with two pixels, encapsulated without (a) and with (b) the protective layer. In figure (b) : after 1 = after protective layer deposition, after 2= after plasma exposure.

Fig. 6 shows I-V and I-L curves for two identical devices of the same type, each containing two identical pixels, called respectively 2 and 7, encapsulated with and without the protective (buffer) layer. The voltage shift (about 0.4V at 0.05mA) measured on the encapsulated pixels with no protective layer (Fig. 6(a)) is completely absent in the I-V curve of the device coated with the protective layer (Fig. 6(b)). No deterioration of light output efficiency was measured for these devices. The materials and deposition methods used for the buffer layer are fully compatible with OLED's. The layer is transparent and has excellent adhesion to the under layers present on the device. In addition extensive lifetime testing has shown no adverse effects resulting from deposition of buffer layers on the OLED test structures.

3.3.2 Encapsulation of test pixels

The lifetime of OLED test pixels encapsulated by Barix™ technology was measured using accelerated aging tests at 60°C/90%RH. A 500 h static soak at 60°C/90%RH is considered the equivalent to 10000 hours in an ambient environment. A series of pictures of one representative illuminated pixel is reported in Fig. 7. Evidence of pixel shrinkage and black spot growth is clearly seen only in the picture after 800 h of accelerated testing.

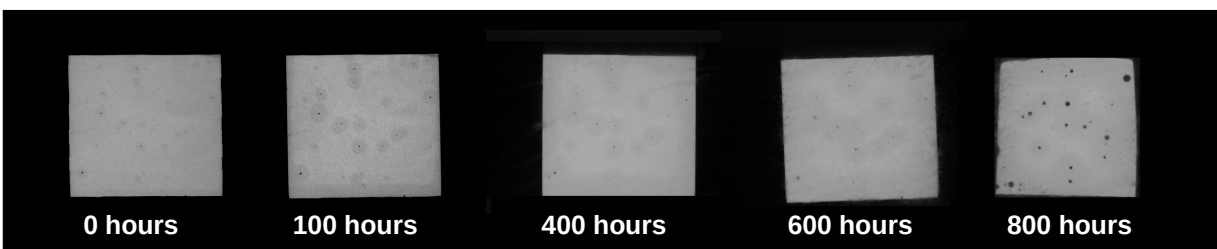


Figure 7: Microscope pictures of a representative illuminated pixel taken at increasing aging times in 60C/90%.

The results are regularly achieved using proper barrier architecture on test pixels. To evaluate the capability of different barrier architectures, the percentage of pixels with a residual area within given limits ($90\% < A_{ti} < 100\%$; $80\% < A_{ti} < 90\%$; $A_{ti} < 80\%$) are compared at fixed intervals of aging time. Figure 8 shows the comparison of three barrier architectures (A, A1, and A2) with common thickness of oxide and polymer, and an increasing number of dyads going from A to A2. At 300 h, as expected, the best and more robust architecture is the one composed of the higher number of dyads. The yield ($A_{300h} > 90\%$) decreases from 80% for structure A2 to 35% for A. At 500 h the performance of the A2-type barrier is unchanged, however there is a drastic drop in yield for the other two structures (25 % for A1 and 5 % for A). This reinforces the concept that the length of the tortuous diffusion path is critical for long term performance.

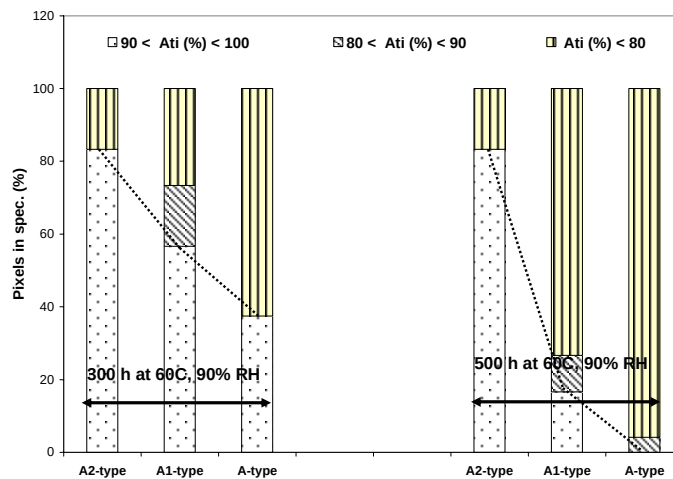


Figure 8: Comparison of three barrier architectures A, A1, and A2 with common thickness of oxide and polymer layers, and increasing number of dyads going from A to A2. The percentage of samples with normalized area within different limits, are shown by different area filling defined in the legend. Yield ($A_{300h} > 90\%$) after aging for 300 h and 500 h at 60°C, 90%RH are reported.

The electrical characteristics (I-V and I-L plots) of Barix™ encapsulated test pixels are substantially unchanged after 500h accelerated aging, when the barrier edge is sealed to prevent water diffusion into the polymer layers. In Fig. 9, the I-V-L characteristics at $t=0$, 300 h and 500 h aging at 60°C/90%RH are shown for a representative OLED pixel encapsulated with an edge seal. On the same type of device without edge sealing, deterioration of the performance is clearly evident after 500h ageing at 60°C/90%RH⁵.

To further evaluate the possibility of stress-induced damage between the barrier coating and fragile OLED devices, thermal shock experiments were conducted. Samples were cycled between -40°C and +80°C with a 2 s transition time. After 500 thermal shock cycles, no premature barrier failure or shift in I-V/I-L curves (Fig. 10) was measured. Similarly, driven tests at room temperature for more than 6000 hours have produced I-V and I-L shifts identical to those seen in glass encapsulated devices.

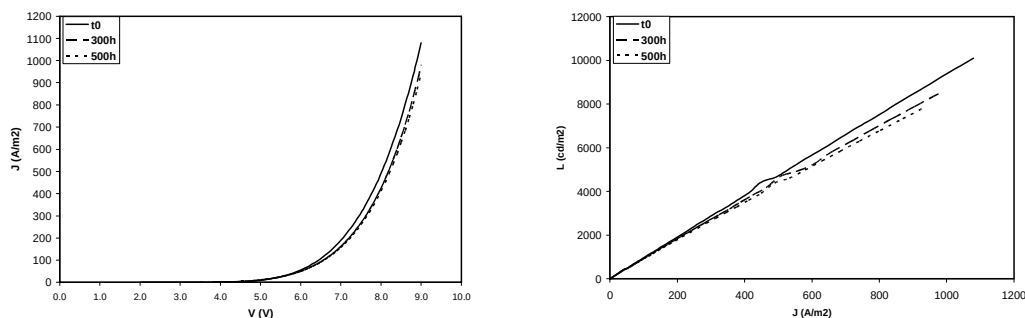


Figure 9: I-V-L characteristic at $t=0$, after 300 h and 500 h aging in 60C/90%RH for a pixel Barix™ encapsulated with an edge seal design.

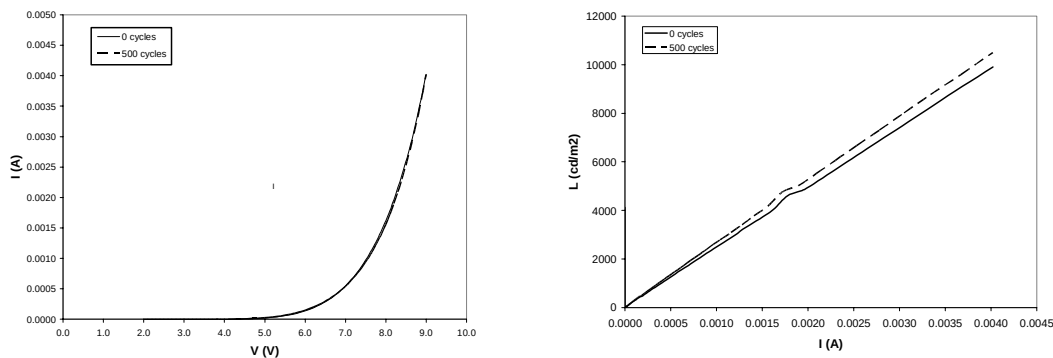


Figure 10: I-V-L characteristic at t_0 and after 500 cycles of thermal shock ($-40\text{ }^{\circ}\text{C}/+80\text{ }^{\circ}\text{C}$) for a pixel Barix™.

3.3.3 Passive Matrix display encapsulation

Barix™ multi-layer thin film structures were used to encapsulate passive matrix displays on glass^{2, 5, 6} and plastic substrates⁷⁻⁹. Demo displays were also shown previously at conferences. The following results were obtained from PM displays on glass only. Several barrier architectures were down-selected from the calcium reference test (see section 3.2). Complete planarization of the cathode separator was achieved by proper choice of polymer layer thickness, and the identical number of oxide-polymer layer pairs as used to successfully encapsulate the planar calcium test coupons. Fig. 11 shows two examples of planarization of the cathode separators.

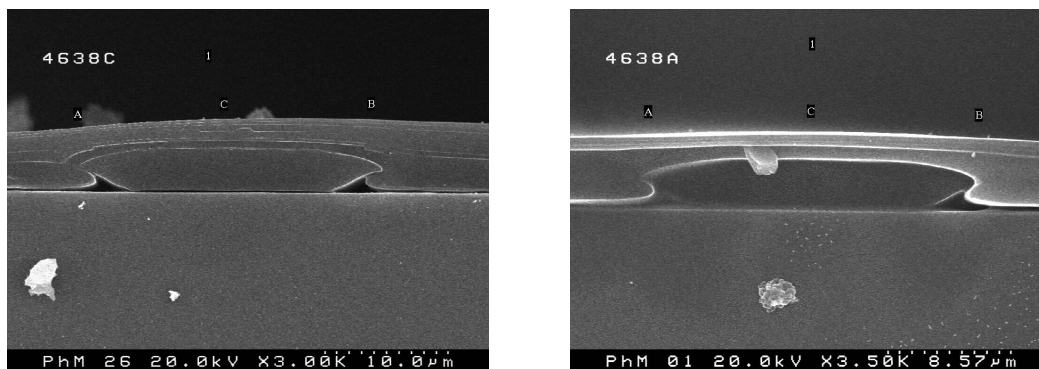


Figure 11: Two examples of Barix™ planarization on cathode separator structures. The thin oxide layers are visible as white lines. The two barrier architectures differ for layer thickness and number of dyads.

These micrographs show that the oxide layers (white lines in the pictures) run continuously over of the cathode separator making the multi-layer coating an effective barrier to moisture penetration. Note that the two differ greatly in thickness and number of layers indicating a wide process window for the planarization. The black areas visible at the bottom of the cathode separator are not voids present in the structure, but artifacts introduced by preferential selective etching of the OLED material during SEM sample preparation.

No evidence of delamination or layer cracking was seen for any of the Barix structures coated on displays, even after accelerated aging tests at $60^{\circ}\text{C}/90\%\text{RH}$ or thermal shock between -40°C and 80°C for up to 500 cycles.

Deposition of varying barrier architectures on PM-OLED displays show that there is an impact of the barrier architecture on the light output of the displays measured immediately after coating. Therefore the barrier and display architecture interaction must be taken into account in the process design.

After encapsulation, displays look uniformly illuminated with no or very few defects or shorts (Fig. 12). Leakage current values measured between cathode/cathode, anode/anode, and cathode/anode are the same as the values recorded for the canned displays.



Figure 12: Encapsulated display.

The first encapsulation runs of spin coated polymer displays clearly demonstrated that the sensitive polymer layers constituting the device (emitting and hole injection layers) needed to be laterally sealed in order to expose the device to accelerated life testing in a high humidity environment. Very rapid diffusion of moisture from the exposed edge outside the encapsulation boundaries, and through these sensitive and hygroscopic layers, made display degradation very rapid and substantially bypassed the presence of the vertical barrier. Encapsulated displays can sustain accelerated testing of up to 300 h with minor changes in the central part of the device. Evidence of moisture penetration through the edges caused by the imperfect seal can be noted. Fig. 13 shows the optical microscope pictures of illuminated pixels near the edge of a display. Only alternating rows and columns were biased during the measurements. The original pixel size can be inferred by looking at the horizontal lines defined by light shining from the back between the spaces coated with aluminum. Pixel deterioration proceeds along the cathode separator from the edges. Further inside pixel shrinkage and black spot growth is limited.



Figure 13: Optical microscope picture of some pixels near the edge of a display aged for 300 h in 60°C/90% RH. Only alternative rows were biased during the measurements.

Little evidence of pixel shrinkage and black spot formation or growth was evident in displays aged in ambient conditions for several months. These preliminary results indicate that although in need of improvement, the BarixTM encapsulation is a viable concept for passive matrix displays. Based on the results illustrated above, further work in the process is needed to improve the barrier performance. Since edge seal is a strong requirement for spin coated devices, it is an active area of development and investigation at Vitex. Other lines of research and development include the better understanding of the mechanism of luminescence loss induced by some barrier architectures, and of their possible repercussions on short and long term performance.

4. CONCLUSIONS

Thin film encapsulation of organic light emitting diode displays presents a very difficult challenge because of the low water and oxygen permeation ($< 5 \times 10^{-6}$ gr/m²/day) required to preserve the integrity of the devices throughout the expected lifetime of 10000 hours. Further, the extreme sensitivity of the organic molecules used in OLED fabrication to

heat, radiation, and aggressive chemicals pose severe requirements on the types of processes that can be used in the film deposition. The Barix™ thin-film encapsulation process meets all these requirements³. The alternating stack of polymer and low temperature inorganic oxide layers produces planarized structures, and oxide layers with a low defect densities, and demonstrated water permeation in the range of 1×10^{-6} gr/m²/day. This level of barrier performance, measured by the change in transmission of encapsulated calcium films, is routinely achieved with process yields that exceed 70% on samples coated by the Vitex Guardian™ R&D system. Similar performance was also measured on calcium evaporated on cathode separator structures.

Results have shown that the Barix™ coating can be deposited with no initial, or long term, damage on OLED test pixels. Certain types of OLED structures are particularly sensitive to plasma exposure, but their degradation in electrical performance can be prevented by the use of a protective “buffer” layer deposited between the OLED device and the barrier structure.

Thin-film encapsulation of test pixels with less than 10% shrinkage after 500 h at 60°C/ 90%RH and no change in I-V-L characteristics has been demonstrated. Passive matrix monochrome displays were also successfully encapsulated. The 4 µm-tall cathode separator structures can be planarized by using different barrier architectures, but the barrier architecture may influence the light output efficiency. After aging at 60°C/90% RH for 300h, limited pixel shrinkage and black spot growth was observed at the center of the device, but edge moisture penetration due to partial edge sealing degrades the outer rows and columns. Work continues to overcome this limitation. Little evidence of degradation was evident in PM-OLED displays operated and aged in ambient conditions for several months.

In conclusion, whereas technological improvements are needed to meet the telecommunication requirements and achieve performances comparable to metal encapsulated displays, Barix™ encapsulation has been proved to be a viable choice for thin film encapsulation of passive matrix displays.

ACKNOWLEDGEMENTS

Fruitful discussions, suggestions and experimental help are gratefully acknowledged to Dr. P. E. Burrows. The contributions of the members of the Viking team at Vitex Systems Inc. and Battelle for the Barix™ encapsulation of samples and maintenance of the Guardian™ R&D systems at Vitex, San Jose and PNNL is also recognized. The display encapsulation program would not exist without the active collaboration of Philips Mobile Display Systems (Heerlen, Netherlands), in particular the contribution of Dr. Tilman Schlenker (Philips Mobile Display Systems, PolyLED Group) and Dr. G. Nisato of Philips Research. The contribution of un-identified Vitex collaborators in supplying OLED test pixels is gratefully acknowledged. The work was partially funded by USDC Contract RFP 01-63 VTX001.

REFERENCES

1. Affinito, J. D., Gross M. E., Coronado C. A., Graff G.L., Greenwell E.N., Martin P.M. , “A new method for fabricating transparent barrier layers , *Thin Solid Film*, **290-291**, 63-67
2. Nisato G., Kuilder M., Piet Bouten, Moro L., Phillips O., Rutherford N., “Thin film Encapsulation for OLEDs: Evaluation of multi-layer barriers using the Ca test”, Society for Information Display, 2003 International Symposium, Digest of Technical Papers, Vol. XXXIV, P-88
3. Moro L., Pagano J.C., Rutherford N., Phillips O., Visser R.J., Graff G.L., Gross M. E., Burrows P.E., “Barrier coatings for organic light emitting Diodes”, presented at “Organic Light Emitting Materials and Devices VI” SPIE annual meeting, 7-11 July 2002, Seattle, Washington, USA
4. The step slope R is given by the ratio of step height and length of the corner. For structure on test pixel this is less 0.3 %
5. R. J. Visser, 3rd International Display Manufacturing Conference, IDMC 2003 Conference, February 18-21, 2003, Taipei, Taiwan
6. Visser R. J., LCD-PDP International 2002 Conference, October 30- November 1, 2002, Pacifico Yokohama, Japan
7. Chwang A. B., M. A Rothman, Sokhanno Y. Mao, R. H. Hewitt, M. S. Weaver, J. A. Silvernail, Kamala Rajan, J. Brown, X. Chu, L. Moro, T. A. Krajewski, N. Rutherford, “Thin film encapsulated flexible OLED displays”, Society for Information Display, 2003 International Symposium, Digest of Technical Papers, Vol. XXXIV, 21.4
8. Chwang A. B., M. A Rothman, Sokhanno Y. Mao, R. H. Hewitt, M. S. Weaver, J. A. Silvernail, Kamala Rajan, J. Brown, X. Chu, L. Moro, T. A. Krajewski, N. Rutherford , submitted to Applied Physics Letter
9. J. Brown , “Recent Progress in Developing Reliable Flexible OLED Displays” FlexElectronics Workshop, March 3-5, 2002, San Francisco, CA
10. Data generated in the frame of the European project FLEXled-IST 2001-34215.