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Thin film encapsulated flexible organic electroluminescent displays

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We describe encapsulated passive matrix, video rate organic light-emitting diode (OLED) displays on flexible plastic substrates using a multilayer barrier encapsulation technology. The flexible OLED (FOLEDTM) displays are based on highly efficient electrophosphorescent OLED (PHOLEDTM) technology deposited on barrier coated plastic (Flexible GlassTM substrate) and are hermetically sealed with an optically transmissive multilayer barrier coating (BarixTM encapsulation). Preliminary lifetime to half initial luminance ($L_0 \sim 100 \text{ cd/m}^2$) of order 200 h is achieved on the passive matrix driven encapsulated 80 dpi displays; 2500 h lifetime is achieved on a dc tested encapsulated 5 mm² FOLED test pixel. The encapsulated displays are flexed 1000 times around a 1 in. diameter cylinder and show minimal damage. © 2003 American Institute of Physics.
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Organic light-emitting device (OLED) technology is rapidly gaining momentum as the technology of choice for future flat panel display applications where low power consumption, low cost, and superior viewing ability are desired.¹ The flexibility of both small molecule² and polymer³ OLEDs further enables the use of these materials in flexible displays.⁴ OLED displays on flexible plastic substrates have been demonstrated;^{4,5} the principal limitation of OLED displays on plastic, however, is their lifetime. The materials currently used in OLEDs are very sensitive to moisture and oxygen, and plastic substrates are generally too permeable to both to be suitable for OLEDs.⁵ Development of a long-lived flexible OLED (FOLED) display on plastic therefore poses two major challenges: preventing moisture and oxygen diffusion into the display area from the bottom/substrate and also from the top [see Fig. 1(a)].

Phosphorescent OLEDs (PHOLEDs)⁶ on barrier coated polyethyleneterephthalate (PET) substrates with operating lifetimes approaching that of PHOLEDs on glass have been demonstrated.⁷ However, those devices were encapsulated using a glass lid and perimeter epoxy seal. Here, we report PHOLED displays on plastic with a monolithic, thin film encapsulant. The displays are passive matrix with 80 dpi resolution and grown on 178- μm -thick barrier coated PET. After OLED deposition, the displays are encapsulated with an optically transmissive multilayer barrier coating. The thin film encapsulation process includes deposition of Al_2O_3 layers, which are reactively sputtered onto the display via an energetic plasma, in between polyacrylate layers, which are deposited via flash evaporation of the monomer followed by UV curing.⁷ The entire process is carried out in an integrated vacuum tool. The alternating layers of inorganic oxide and polyacrylate protect the OLEDs from moisture and oxygen [Fig. 1(a)]. The inorganic oxide layers act as diffusion barriers to water/oxygen while the polymer layers decouple de-

fects in the oxide as well as allow for greater flexibility in an otherwise rigid coating.

Figure 1(b) shows lifetime data for a 5 mm² thin film encapsulated PHOLED test pixel on barrier coated PET. Included for comparison are data for a glass based PHOLED with glass lid and desiccant as well as a thin film encapsulated PHOLED test pixel on glass. The PHOLEDs are based

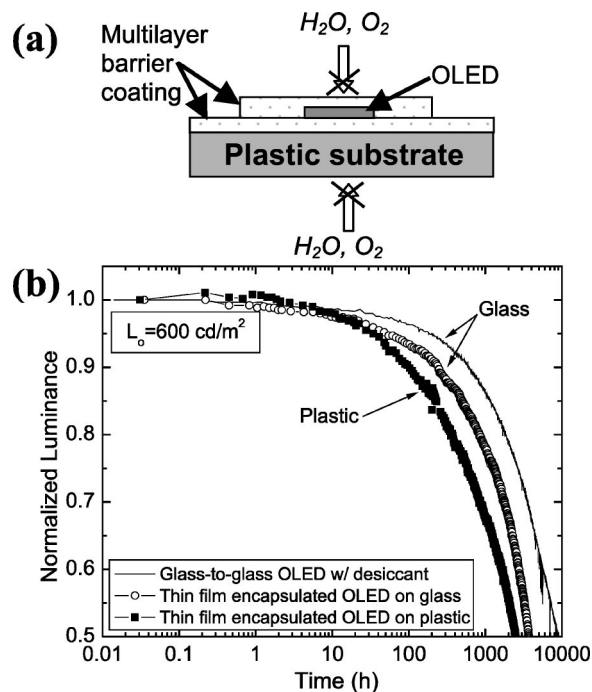


FIG. 1. (a) Schematic diagram of a thin film encapsulated OLED on barrier coated plastic. The multilayer barrier coatings on the substrate and OLED protect the OLED from water and oxygen. (b) Normalized lifetime data under dc drive for a PHOLED on glass packaged with a glass lid and desiccant (solid line), thin film encapsulated PHOLED on glass (open circles), and thin film encapsulated PHOLED on plastic (solid squares). Starting luminance for all 5 mm² devices was 600 cd/m². Half lives of the devices are 9000, 3700, and 2500 h, respectively.

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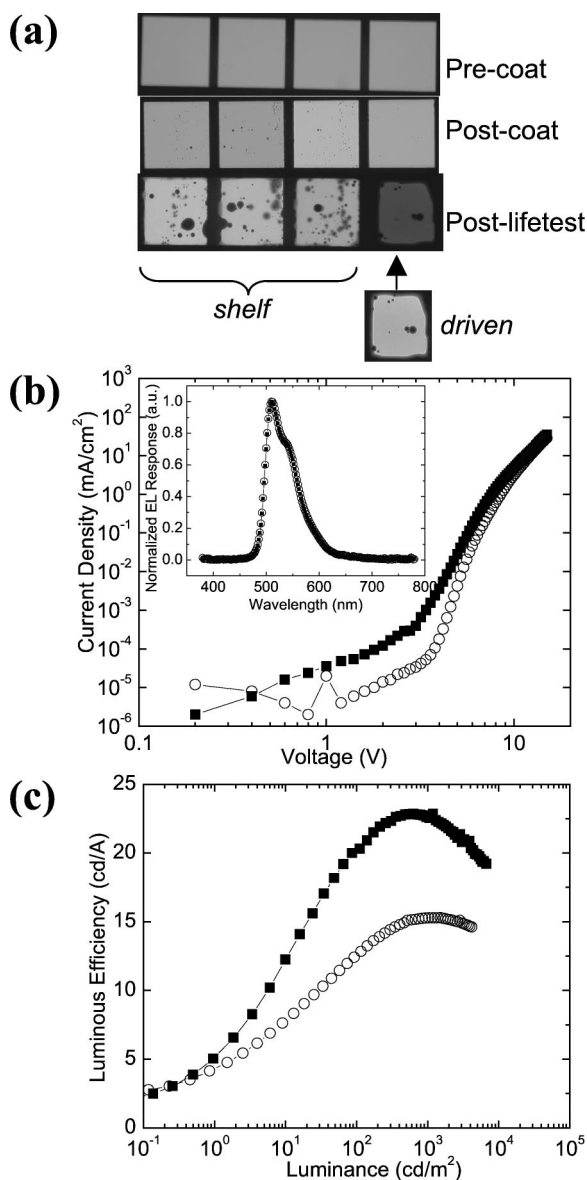


FIG. 2. (a) Pictures of a set of PHOLEDs before and after thin film encapsulation and lifetest. The first three pixels at the bottom of Fig. 2(a) were shelf tested, i.e., not driven, at room temperature. The fourth pixel was dc tested at room temperature with initial luminance of 600 cd/m². Electroluminescent spectra [(b), inset], current density–voltage characteristics (b), and luminous efficiencies (c) of the dc tested thin film encapsulated PHOLED of Fig. 2(a) before (filled squares) and after (open circles) lifetest.

on the green electrophosphorescent dopant *fac* tris(2-phenylpyridine) iridium [Ir(ppy)₃].⁸ Device structure of the OLEDs, grown by vacuum thermal deposition, is 100–400 Å CuPc/300 Å α -NPD/300 Å CBP:Ir(ppy)₃ (6 wt %)/100 Å BAlq/400 Å Alq₃/LiF/Al.⁷ The devices were lifetested at room temperature and ambient pressure under dc drive and constant current conditions. Starting luminance for all devices was 600 cd/m². The multilayer coating on the thin film encapsulated PHOLEDs consists of 4–5 pairs of alternating Al₂O₃ and polyacrylate; the total thickness of the multilayer thin film coating is 5–7 μ m. While the 2500 h half life of the thin film encapsulated PHOLED on plastic is not as long as the 10 000 h half life of the glass-to-glass device, this lifetime represents a significant achievement considering that an unencapsulated PHOLED on glass typically decays to half luminance in less than 600 h. Figure 1(b) also shows that



FIG. 3. Thin film encapsulated PHOLED display on 178 μ m barrier coated PET. The encapsulation is comprised of five alternating pairs of Al₂O₃ and polyacrylate; total thickness of the multilayer barrier stack is 5–7 μ m. The 64 $\times$ 240 display is passive matrix and capable of full motion video.

thin film encapsulation using a multilayer barrier stack has significant potential as a packaging option for plastic and glass OLEDs as the lifetime of the thin film encapsulated glass sample was extended to 3700 h.

Electroluminescent spectra, current density–voltage (*J*–*V*) characteristics, and luminous efficiencies of a thin film encapsulated PHOLED test pixel on plastic before and after lifetest characterization are presented in Fig. 2. Spectra were measured using a PhotoResearch SpectraScan 705 radiance meter. The *J*–*V* characteristics and luminous efficiencies were measured with a Keithley 236 source-measure unit and a Keithley 2400 source meter in combination with a calibrated Hamamatsu S3584-08 photodiode to measure light output. Also shown in Fig. 2(a) are pictures of the PHOLED before and after encapsulation and after driven lifetest at room temperature (dc, constant current). Included in Fig. 2(a) are pictures of the adjacent pixels on the substrate which were shelf tested, i.e., not driven. The normalized electroluminescence spectra of the bottom right driven PHOLED in Fig. 2(a) are presented in the inset of Fig. 2(b) and are characteristic of the green phosphorescent emitter Ir(ppy)₃ used in these devices. That the spectrum does not change after the driven lifetest indicates that as the device decays, the electron-hole recombination zone is still confined to the Ir(ppy)₃ doped region. Figures 2(b) and 2(c) illustrate that the decayed PHOLED has a higher voltage and lower luminous efficiency for a given current density or luminance. This is a typical observation of aged OLEDs, plastic or glass based. The dark spot growth observed in all four devices is illustrated in Fig. 2(a). Close examination of Fig. 2(a) reveals that the dark spots were present after encapsulation at the beginning of the lifetest, i.e., no new dark spots formed as the devices aged, but the ones which were present grew larger. The initial formation of dark spots are believed to be due to unintentional exposure of the OLEDs to particulates, oxygen and/or H₂O immediately prior to encapsulation. The observed dark spot growth is attributed to exposure of the OLED to oxygen and H₂O in the environment due to unoptimized barrier coatings on the PET substrate and on top of the OLED.⁹

The multilayer, thin film barrier coating of the test pixels in Figs. 1 and 2 can be extended to displays. Figure 3 shows a video rate 64 $\times$ 240, 80 dpi, passive matrix PHOLED display on barrier coated PET after encapsulation with five alternating pairs of Al₂O₃ and polyacrylate.

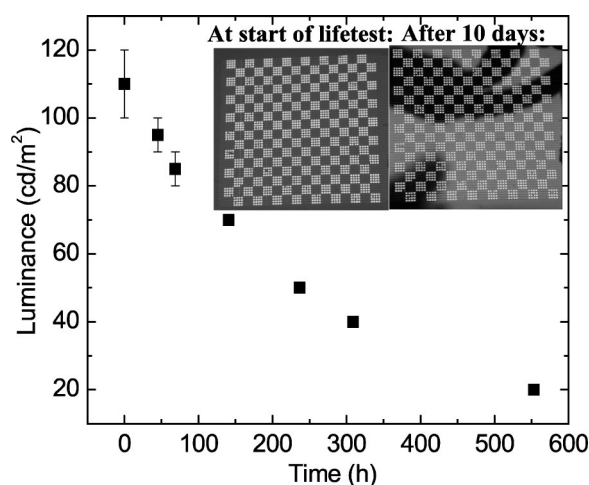


FIG. 4. Luminance vs time of the thin film encapsulated 64×64 passive matrix PHOLED display in the inset showing time to half luminance of >200 h. The encapsulation is comprised of five alternating pairs of Al_2O_3 and polyacrylate with total thickness $5\text{--}7\ \mu\text{m}$.

Figure 4 shows lifetime data for a similarly encapsulated 64×64 , 80 dpi display with a 50% fill factor. The passive matrix driven display was lifetested with a starting luminance of $110\ \text{cd/m}^2$ (duty cycle = $1/64$). Display luminance was measured using a handheld luminance meter (Minolta LS-100). As seen in Fig. 4, the lifetime to half luminance of the encapsulated display on barrier coated PET was over 200 h. We note that the shelf life of a similarly encapsulated PHOLED display on barrier coated PET is approximately 700 h.

The discrepancy between the thin film encapsulated FOLED pixel (2500 h) and display (200 h) lifetimes may be partially explained by the relatively high current drive of the pixels in the display and the presence of an organic grid surrounding each pixel, neither of which are particular to PHOLED displays. For example, to achieve a display luminance of $100\ \text{cd/m}^2$, each pixel in the 64×64 display must be driven to at least $6400\ \text{cd/m}^2$. The actual luminance of a driven pixel will be higher due to the 50% fill factor. Each display pixel is therefore pulsed an order of magnitude higher in current density than an individual (nondisplay) test pixel, which can lead to faster decay. Moreover, the organic grid used in the FOLED display to electrically insulate each pixel from adjacent pixels is made of photoresist material. Normally this material is sufficiently baked to remove any harmful solvents and/or moisture that would lead to premature degradation of the OLED. However, a compromised bake due to the temperature limitations of the plastic substrate may result in incomplete outgassing or curing of the photoresist which would negatively affect OLED lifetime. A higher T_g barrier substrate would alleviate this problem, as would a grid that does not require high temperature processing.

A display with the same device structure and encapsulation as that in Fig. 4 was also flex tested. The display was flexed along the rows and under tensile stress 1000 times around a cylinder of 1 in. diameter at a rate of approximately 12 flexes/min. After 100 flexes, the display showed no damage. After 500 flexes, two additional defects (cathode breaks) that led to two partial row-outs were observed that had not

been observed before the test. Finally, after 1000 flexes, three additional partial row-outs were observed, also due to cracks in the cathode (five total). While further flex testing is required to determine the ruggedness of the encapsulated display under alternative flexing conditions, e.g., along the columns, under compression, in two dimensions, etc., these early results are promising.

In summary, we have demonstrated hermetically sealed, thin film encapsulated PHOLED displays on barrier coated PET with preliminary operating lifetimes of >200 h (passive matrix drive). Operating lifetime of 2500 h was achieved on a thin film encapsulated PHOLED test pixel on barrier coated PET. Initial flex test results indicate that the thin film encapsulated displays suffer some damage after being flexed under tensile stress around a 1 in. diameter cylinder. We note that the thin film, multilayer barrier stack encapsulant has not yet been optimized for either barrier properties or flexibility and that such optimization, in addition to a higher T_g substrate, should improve display lifetime (and flexibility). While further optimization and testing of the encapsulation and substrate are required, the achievement of a functional, thin film encapsulated PHOLED display on plastic with extended lifetime represents a significant step towards fulfillment of advanced communication devices with roll-out, flexible emissive displays.

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