35.2: Black Dielectric Electroluminescent 160x80 Pixel Display

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Abstract

We report on recent technological progress in black dielectric electroluminescent (BDEL) displays. Fabrication of the first BDEL 160x80 pixel 4" displays driven with commercial low power (<5W) drive circuitry is presented. Improvements in both BDEL display performance and display manufacturability underscore the recent development path.

1. Introduction

In recent years inorganic electroluminescence (EL) has been progressing towards its full potential at a rate unseen since thin film EL (TFEL) research and commercialization breakthroughs in the 1970's and 1980's. The development of low-cost scalable thick film dielectric EL (TDEL) manufacturing [1] and long-awaited breakthroughs in full color phosphors [1, 2] have driven potential EL display applicability beyond the stable niche markets captured by monochrome high-contrast TFEL displays.

However, some of the most attractive advantages to TFEL (contrast) and TDEL (scalability, higher luminance) technology have been mutually exclusive. In response, Extreme Photonix (eXp) has developed black dielectric EL (BDEL) display technology[3]. The eXp BDEL approach uniquely provides high display contrast in bright ambient lighting and low-cost scalable display fabrication. Furthermore, since BDEL displays are non-inverted (fabricated directly onto low-cost viewing glass), this new approach is readily compatible with several decades of commercial advancement in non-inverted TFEL displays.

The first eXp displays in a commercially viable 160x80 pixel format have now been demonstrated just two years after the BDEL device concept was first realized[4] at the University of Cincinnati. Shown in Fig. 1, is a first generation 4" diagonal 160x80 pixel eXp prototype. First generation prototypes have exhibited display luminance values greater than 100 cd/m^2 with an off state luminance of less than 1 cd/m^2.

2. An Advantaged EL Display Fabrication Route

Of the major display technologies only organic and inorganic EL displays have the advantage of complete pixel fabrication and viewing on a single substrate. BDEL further exploits this advantage, as the only thin/thick-film EL technology which can be manufactured directly onto low cost viewing glass[3].

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2.1 Simple Front ITO Column Electrode

The eXp BDEL fabrication approach (Fig. 2) begins with indium-tin-oxide (ITO) column electrode formation on low-cost industrial grade Corning 1737 glass. ITO columns are defined using a novel screen printing / sputtering / lift-off process which requires half the steps of a comparable photolithography process. eXp has already extended this ultra-simple process to metal row electrode patterning. This process, which is stable to >600 °C, also has potential for full-color phosphor patterning. Rounding of the ITO column edges is not required since the thick/thin film hybrid EL stack is impervious to catastrophic electrical breakdown at thin-film high field points. To improve column electrode contact to the driver circuitry, self-aligning non-oxidizing metal contact pads are deposited at the ends of the column electrodes.

2.2 High Performance Thin Dielectrics

Following ITO column electrode fabrication, the first of two thin film dielectrics is sputter deposited. It is well known that the EL phosphor/dielectric interface strongly affects the luminance-voltage characteristics of an EL device. Specifically, the thin film dielectrics in the BDEL device structure are chosen/implemented for the purposes of: (1) *reliability*, symmetric bipolar EL emission and aging; (2) *high luminance*, a high density of energetically homogeneous electron traps at the phosphor/dielectric interface; (3) *pulse drive compatibility*, charge injection response compatible with the maximum row scan rate (~10 μs); (4) *thin/thick film coupling*, electric field dispersion and thick film adhesion. Due to the later application of the thick film dielectric, these thin film dielectrics are not required to prevent pixel burnout due to electrical breakdown. Effectively, these thin film dielectrics in a BDEL display are large area coatings which have

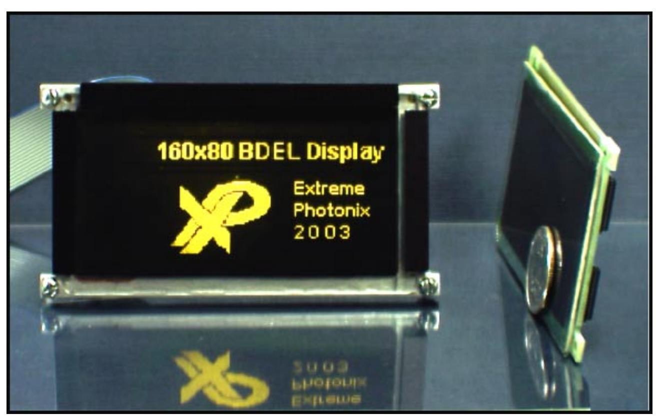

Figure 1. 160x80 pixel BDEL display.

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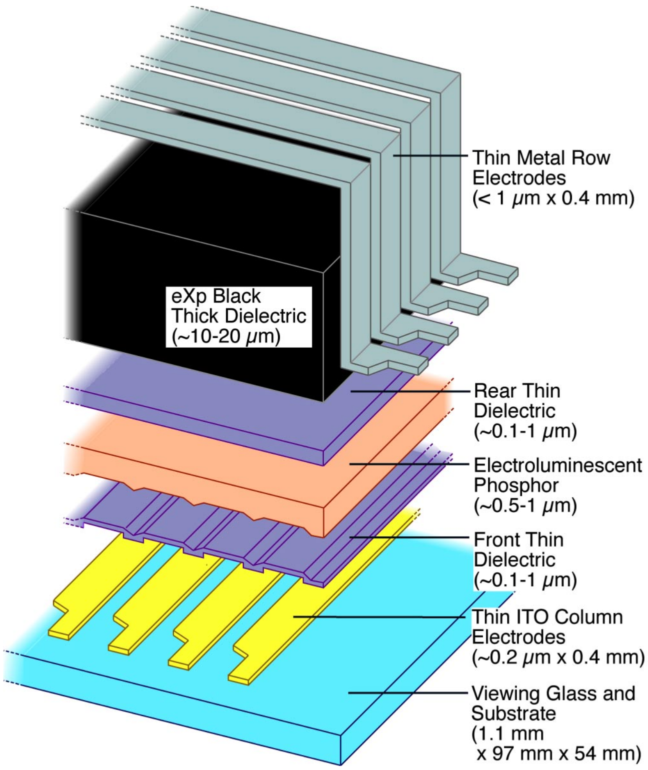

Figure 2. BDEL passive-matrix display structure.

the primary purpose of boosting display performance (similar to MgO in plasma displays). A doubling of BDEL luminance has resulted from implementation of the present set of thin film dielectrics (ε_r ~20-30, E_{br} >2 MV/cm).

2.3 Full-Color Nitride, Oxide, or Sulfide EL Phosphors

eXp 160x80 BDEL technology has now been demonstrated using eXp nitride, oxide, and sulfide phosphors. eXp GaN phosphor[3] technology combines the excellent electron-impact excitation properties of GaN with the pure emission colors achieved with luminescent activators such as rare-earth atoms. In addition to the potential for an ultra-wide color gamut and efficient phosphor operation, GaN phosphors are extremely rugged. Operational lifetimes[3] extrapolate to >50,000 hrs for GaN phosphors in *unsealed* BDEL devices. For 160x80 prototype compatibility, GaN phosphor scale-up to deposition on 4" diagonal glass is now in progress.

The first BDEL 160x80 display prototypes presented here utilize a sputter-deposited ~0.5-1 μm thick ZnS:Mn phosphor layer. As shown in Fig. 3, the first generation ZnS:Mn 160x80 BDEL displays have already achieved pixel luminance values of >250 cd/m^2 at 40 V above threshold, 120 Hz, (240 Hz refresh), and with use of low current drive circuitry (~20 nF/cm^2 dielectric compatible). These high-luminance results are obtained from a composite ZnS/MnS sputtering target. Increased luminance will result from optimization of phosphor composition, deposition, and

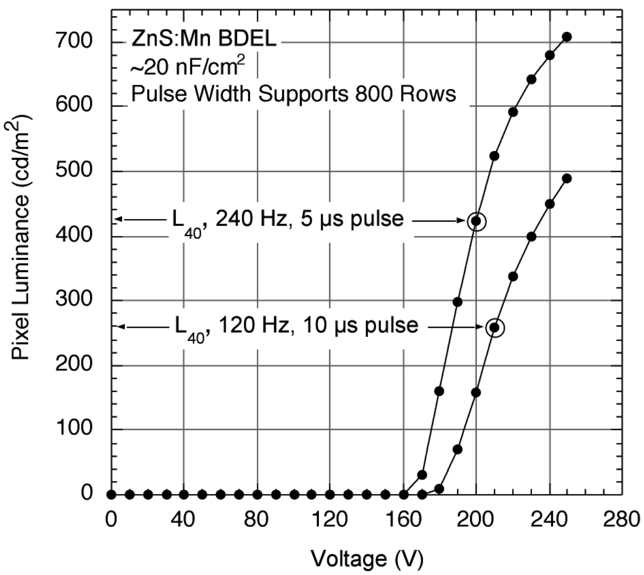

Figure 3. Pixel luminance vs. voltage for ZnS:Mn BDEL 160x80 pixel arrays. Luminance plots for both 120 Hz and 240 Hz bipolar pulse excitation are shown.

anneal parameters. The high luminance provided by BDEL is critical for multi and full color capability, especially for blue phosphors which generally provide ~0.5 lm/W efficiency.

2.4 The Black Thick Dielectric Layer

eXp BDEL is the first display-glass-compatible, thick film high-k dielectric based EL display. As reported[3] at SID '02, eXp has developed a thick dielectric (~20-60 nF/cm^2) screen printing and sintering sequence currently implemented at <650 °C for display glass compatibility. The 160x80 BDEL prototypes utilize an improved thick dielectric which approximately doubles the luminance with only a 10-20% increase in thick dielectric capacitance. The new thick dielectric incorporates a much higher k material in place of the low k glass frit conventionally used for low temperature thick film sintering. This new dielectric composition also has a much faster response than the previous formulation, resulting in high luminance values (see Fig. 3) for the very short pulse width of <10 μs.

In addition to providing high-luminance, scalability, and thin film defect tolerant fabrication, the thick dielectric provides excellent contrast enhancement. Contrast enhancement is achieved through an eXp proprietary pigmentation process which transforms a standard thick dielectric layer into a *black* dielectric. This black dielectric exhibits a luminous reflectivity of only ~2.5 % without use of filters (neutral density, color, or polarizing). The black dielectric reflectivity is primarily diffuse, which therefore is independent of view angle, quenches unwanted pixel blooming, and provides built-in display glare reduction. After application of an anti-reflective film to the front of the viewing glass, the only significant reflection component remaining in a BDEL display is specular reflection between layers of material with varied refractive index (Δn ~0.1-0.4). Fortunately, the thin film dielectric thickness and refractive indices can be implemented such that specular reflection is reduced via index matching and/or optical interference effects through modified dielectric thickness and index. Full freedom in thin film dielectric design is unique to BDEL, since the black dielectric fully provides the high voltage reliability, capacitance, and low reflectance required by EL displays.

A candidate higher capacitance (40-100 nF/cm^2) black dielectric material/fabrication process is under development. Early EL device results with this next generation black dielectric show a tripling of luminance, a reduction in reflectivity by a factor of two, both achieved at an even lower dielectric sintering temperature. The black dielectric approach is now poised to meet the goal of higher luminance EL displays without a sacrifice in reliability or bright light contrast.

2.5 Rear Electrode and Simple Sealant

A sputtered thin film Al metal electrode is patterned using the same simple screen printing technique used for ITO patterning (no photolithography or etching required). This technique is particularly well-suited to BDEL rear electrode patterning since it takes place on the rough top surface of the thick film dielectric layer. In addition to providing high current capability, the rear electrode in a TFEL device can have a strong effect on display manufacturing yield/reliability. A major roadblock to utilizing high capacitance thin or thick film dielectrics has been the tendency towards propagating dielectric breakdown which results in complete pixel burnout and/or row-column termination. Unlike the case of using thick-film electrodes (Au, Ag pastes), the eXp thin film Al row electrode/thick film dielectric combination exhibits *highly self-healing breakdown*. Use of a low-cost thin film Al contact to the thick film dielectric is made possible by using a non-inverted device structure. Furthermore, self-healing is more easily achieved in the non-inverted structure since the self-healing Al electrode is not buried between the substrate and dielectric layer.

5. Simple Hermetic Seal

The display is sealed using a simple silicone oil and polyimide laminate to prevent significant moisture absorption by the hydrophilic thick-film dielectric layer. This technique is much simpler than that used for many competing display technologies which require vacuum sealing and insertion of an oxygen getter.

3. The First Generation BDEL Display

The display performance specifications shown in Table 1 are representative of BDEL performance at ~6 months into 160x80 pixel prototype development. The BDEL display panel is mounted to a Planar EL160.80.50 display driver via Zebra flexible mounting strips. The driver is connected through a ribbon cable to an Amulet CB-GT570 controller board which provides video data, logic (5V) and power voltage (12V). The Amulet controller board allows for rapid prototyping using straight-forward HTML programming of the display graphics and a serial download to onboard memory.

Table 1. Present and future generation eXp BDEL prototype display characteristics.

	Present Gen.	Future Gen.
Pixel Count	160x80 (12,800)	320x240 (76,800)
Pixel Pitch / Fill Factor	0.5 mm / >50%	0.36 mm / >64%
Color	Mono (amber)	Mono, *Multi, Full*
Luminance		
Maximum (L_{50})	>100 cd/m^2	>500 cd/m^2
Typical (L_{50})	~30-50 cd/m^2	>300 cd/m^2
Best Uniformity	10%	<5%
Typical Uniformity[1]	10-50%	<5-25%
Working Column %	100%	100%
Working Row %	95-100%	100%
Max Contrast[2] 500 lux	20:1 over >160°	300:1 over >160°
Max Contrast[2] 5000 lux	3:1 over >160°	30:1 over >160°
Operating Temp.[3]	0-55 °C	-40-65 °C
Power[4] (60-240 Hz)	2.0-7.0 W	2.0-6.0 W

[1] due to non-uniform temperature during phosphor deposition
[2] primarily diffuse reflection measurement
[3] driver circuitry limited
[4] per Planar operation manual OM100-02

BDEL prototypes are now exhibiting luminance values comparable to most commercial TFEL products (50-150 cd/m^2). It is very important to note that these BDEL luminance values are achieved using dielectric capacitance (~20-30 nF/cm^2) compatible with existing TFEL drivers. The benefit of implementing a higher capacitance black dielectric and requisite higher current display driver is discussed in the next section. These early displays exhibit fair to good luminance uniformity which will be dramatically improved by switching to a radiant heat absorption scheme during the temperature sensitive phosphor deposition process. The luminance and row/column yields are very good considering that: (1) the BDEL prototypes are manually fabricated in a laboratory environment of class >10,000; (2) process ramp-up for these first video-rate 160x80 prototypes has required involvement of less than 1,000 man hours. Furthermore, the *entire* display fabrication requires only a single multi-cathode sputtering system, screen printer, and furnace. 100% row yields are expected by simply switching to an improved black thick dielectric composition. The displays exhibit good contrast in bright lighting at all view angles, due to the highly absorbing matte appearance of the black dielectric. The displays also share traits common to other inorganic EL displays such as fast response time (~ms) and wide temperature operating range. Aging analysis is underway and it is fully expected that perfected BDEL prototypes will achieve typical inorganic EL display lifetimes which exceed 30,000-50,000 hrs.

4. Reaching the Ultimate Potential of BDEL

In addition to achieving sub-1% display reflectivity, improvement paths are available for a major increase in BDEL display luminance. Such paths clearly lead to record levels of display legibility in bright lighting, procured from a low-cost manufacturing process. This includes phosphor and dielectric optimization (composition, process) and diffuse emission outcoupling (film roughness) for a several fold improvement in luminance. There is a ceiling imposed on organic EL and TFEL diffuse out-coupling due to high field points which reduce *thin-*film breakdown voltages below the intrinsic level, resulting in pixel burnout. This can similarly limit the maximum TFEL phosphor anneal temperature, and therefore luminance, due to the appearance of additional roughness at the rear phosphor surface. *Neither* of these limitations are applicable to BDEL due to the same advantage which allows for low cost manufacturing: inclusion of a thick-film dielectric which is high-field point tolerant.

Fig. 4 details display efficiency trends which strongly support use of a high-k thick dielectric. Simply stated, in a well-designed EL panel increased dielectric capacitance leads to increased panel efficiency. The efficiency shown in Fig. 4 does not include previously mentioned luminance increases, which would further increase overall BDEL panel efficiency. The calculations assume a symmetric driver scheme and a constant peak field applied to the phosphor. The constant peak field allows for reduced row and column voltages (V) as the dielectric capacitance increases. Parasitic power consumption ($\sim C_P \bullet \Delta V^2$) is largely due to capacitance between columns with lit and unlit pixels. Parasitic capacitance (C_P) does not increase significantly with dielectric capacitance since it represents the series capacitance of a low capacitance phosphor layer and a high capacitance dielectric. Therefore, the reduced row and column voltage with increasing dielectric capacitance reduces the parasitic panel power consumption. Advantageously, the power coupled directly into EL light emission, increases proportionally with dielectric capacitance. The result is the panel efficiency boost shown in Fig. 4. In order to fully capitalize on this ideal model for panel efficiency, factors such as row-driver current, panel refresh rate,

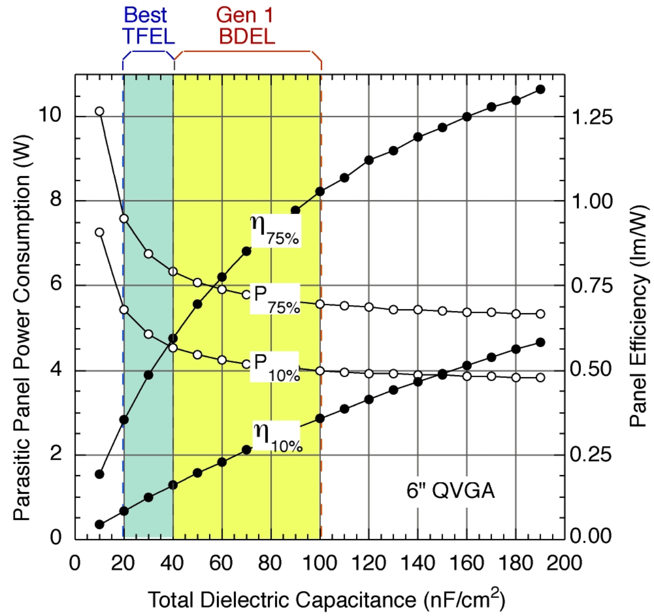

Figure 4. 6" QVGA modeling of parasitic panel power consumption (P, in W) and panel efficiency (η, in lm/W) at 10% and 75% of pixels lit vs. total dielectric capacitance.

modulation voltage, and phosphor layer thickness must be optimized while keeping in mind luminance saturation effects. When combined with performance enhancements offered through optimization of material composition, process, and morphology, the total result lends strong promise to the ultimate performance of BDEL and inorganic EL in general.

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