Fabrication and performance characteristics of black-dielectric electroluminescent 160 × 80-pixel displays

J. Heikenfeld
A. J. Steckl

Abstract — We report on recent technological progress in black-dielectric electroluminescent (BDEL) displays. Fabrication of the first monochrome BDEL 160 × 80-pixel 4-in. displays driven with commercial low-power (<5 W) drive circuitry is presented. Preliminary results on blue-dielectric EL full-color displays are also reported. Improvements in both BDEL display performance and display manufacturability underscore the recent development path.

Keywords — *Electroluminescence, black dielectric, thin-film EL.*

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 160 × 80-pixel format have now been demonstrated just 2 years after the BDEL device concept was first realized[4] at the University of Cincinnati. Shown in Fig. 1 is a first-generation 4-in.-diagonal 160 × 80-pixel eXp prototype. First-generation monochrome prototypes have exhibited display luminance values greater than 100 cd/m^2 with an off-state luminance of less than 1 cd/m^2. A proprietary blue-dielectric approach for high-contrast full-color EL displays is also in development. Second-generation prototypes will have a QVGA format, and their projected monochrome and full-color luminance is expected to exceed 500 cd/m^2.

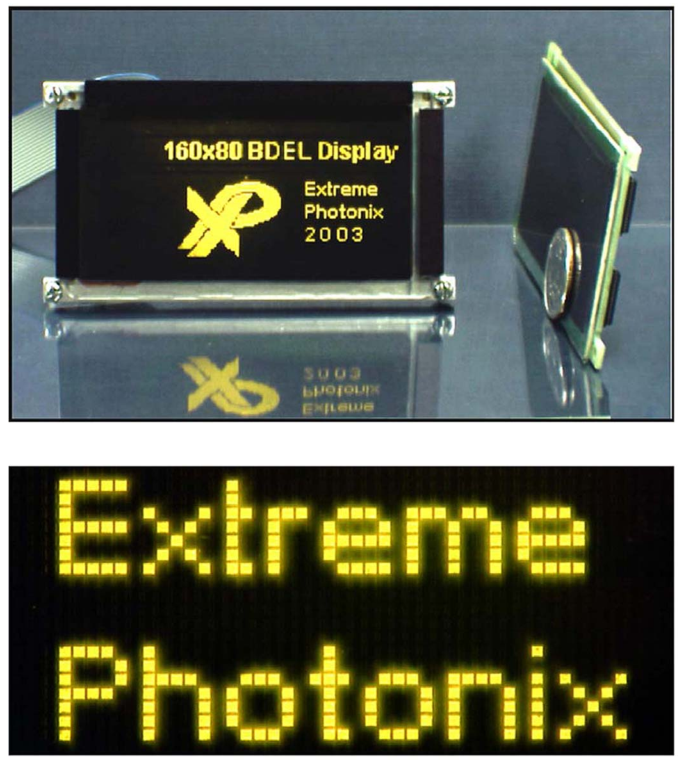

FIGURE 1 — 160 × 80-pixel BDEL display (top) and zoom-in photo (bottom).

2 An advantageous 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 that can be manufactured directly onto low-cost viewing glass.[3]

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The authors are with Extreme Photonix, 3130 Highland Ave., Ste. 3225, Cincinnati, OH 45219-2374; telephone 513/475-6615, fax 513/221-1891, e-mail: jheikenf.extremephotonix@biostart.org; a.steckl@uc.edu.

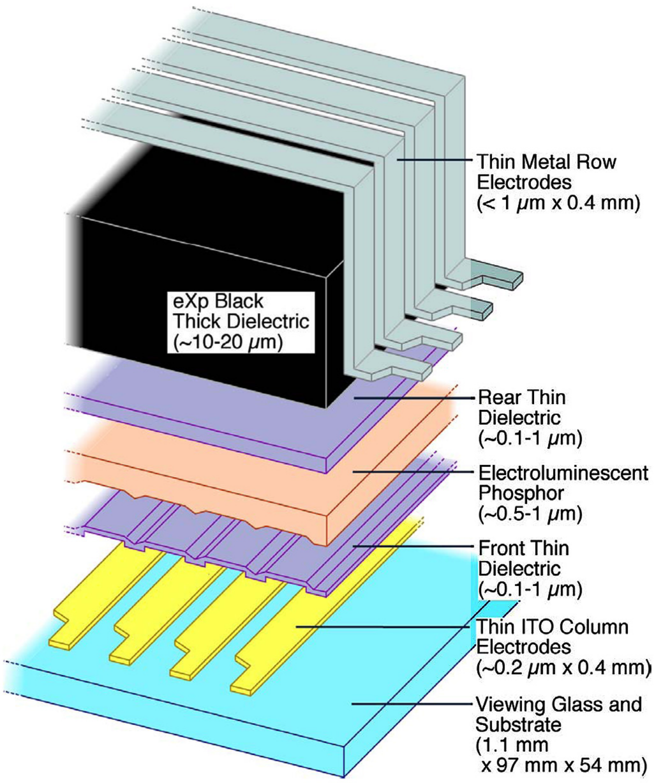

FIGURE 2 — BDEL passive-matrix-display structure.

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 dry-film photolithography, which is the low-cost process most often used for printed-circuit-board manufacturing. eXp has also developed an even simpler process using screen-print patterning. This screen-print 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)

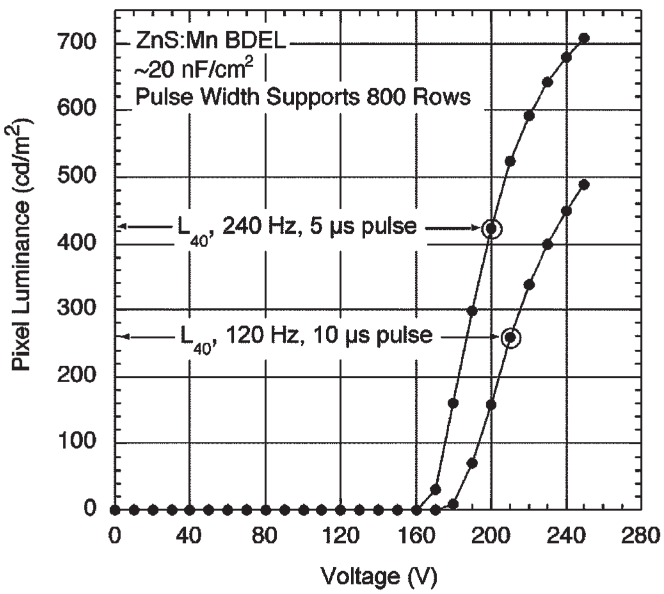

FIGURE 3 — Pixel luminance *vs.* voltage for ZnS:Mn BDEL 160 × 80-pixel arrays. Luminance plots for both 120-Hz and 240-Hz bipolar pulse excitation are shown.

pulse drive compatibility, charge-injection response compatible with the maximum row scan rate (~10 μsec); (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 caused by electrical breakdown. Effectively, these thin-film dielectrics in a BDEL display are large-area coatings that have 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 160 × 80 BDEL technology has now been demonstrated using 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 hours for GaN phosphors in unsealed BDEL devices. For 160 × 80 prototype compatibility, the scale-up of GaN phosphors to deposition on 4-in.-diagonal glass is now in progress.

The first BDEL 160 × 80 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 160 × 80 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

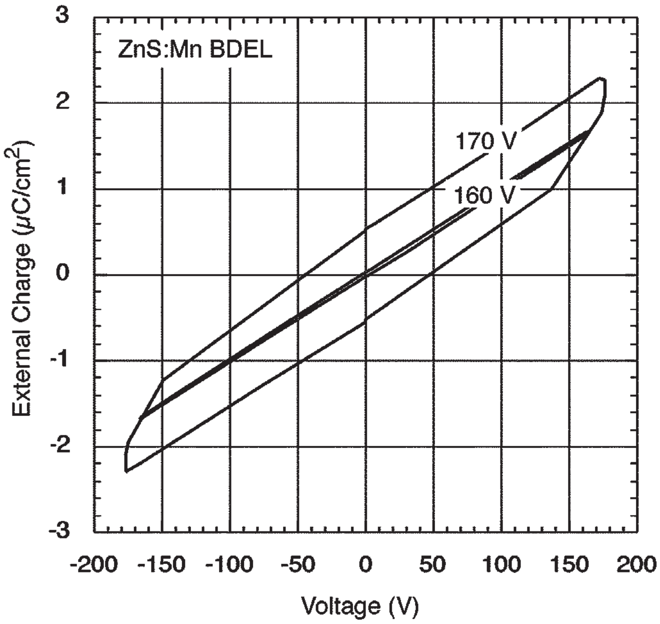

FIGURE 4 — Externally measured charge *vs.* voltage for a ZnS:Mn device at a maximum applied voltage of +/– 160 V and +/– 170 V.

drive circuitry (compatible with ~20-nF/cm^2 dielectric capacitance). These high-luminance results are obtained from a composite ZnS/MnS sputtering target. Increased luminance will result from optimization of phosphor composition, deposition, and 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-κ-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 160 × 80 BDEL prototypes utilize an improved thick dielectric that approximately doubles the luminance with only a 10–20% increase in thick-dielectric capacitance. The new thick dielectric incorporates a much higher κ material in place of the low κ 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 μsec. Furthermore, this new thick dielectric provides superior electric-field homogeneity across the phosphor layer. Electric-field homogeneity is a reliability requirement for TFEL technology, but is not required for reliability in thick-dielectric EL technology. As shown in Fig. 4, the new thick dielectric exhibits TFEL-like charge–voltage (*Q–V*) behavior.[5] The electric-field homogeneity (reduction of high/low-field points) at the phosphor/dielectric interface results in a steep ~0.5 μC/cm^2 increase in charge injection over only 10 V of modulation above threshold. The hysteresis of the *Q–V* loop is also indicative of the strong and homogeneous charge trapping provided by thin film dielectrics flanking the phosphor layer. The charge injection increases several fold from that shown in Fig. 4, for the case of higher capacitance (40–100 nF/cm^2) thick dielectrics.

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 a patented eXp pigmentation process that transforms a standard thick-dielectric layer into a black dielectric. Pigmentation for a blue (or other color) dielectric is also possible as discussed in a later section. The black dielectric exhibits a luminous reflectivity of only ~2.5% without the use of filters (neutral density, color, or polarizing). The black-dielectric reflectivity is primarily diffuse, which therefore is independent of viewing 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 indicies (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-display applications.

A 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 2, 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 display burn-in

A sputtered thin-film Al metal electrode is patterned using the simple screen-printing technique which can also be 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 that results in complete pixel burnout and/or row-column termination. Unlike the case when 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. The excellent high-voltage reliability and self-healing breakdown of the thick dielectric/Al allows virgin BDEL displays to be instantaneously operated at their full operating voltage. This provides BDEL a throughput advantage over TFEL manufacturing which generally uses a meticulous voltage step-up sequence to full operating voltage in order to allow self-healing passivation of thin-film-dielectric defects.

2.6 Simple hermetic seal

The display is sealed using simple silicone oil and epoxied float-glass seal 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 a getter. Including the sealing step, the majority of the display fabrication is conducted in air, with only the phosphor layer formation requiring a vacuum for deposition and a vacuum or inert atmosphere for annealing.

3 The first-generation BDEL display

The 160 × 80 BDEL display-performance specifications, shown in the left-hand column of Table 1, are representative of BDEL performance at ~6 months into 160 × 80-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 that provides video data, logic (5 V), and power voltage (12 V). The Amulet controller board allows for rapid prototyping using straightforward HTML programming of the display graphics and a serial download to onboard memory.

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 row driver is discussed in the next section. The early 160 × 80 prototype 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 and (2) process ramp-up for these first video-rate 160 × 80 prototypes has required involvement of less than 1000 man-hours. Furthermore, the entire display fabrication requires only a single multi-cathode sputtering system, screen printer, and furnace. Repeatable 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 (~msec) and wide temperature operating range. Aging analysis is under way and it is fully expected that perfected BDEL prototypes will achieve typical inorganic EL display lifetimes that exceed 30,000–50,000 hours. The total performance benefit projected for ZnS:Mn phosphor optimization and the next generation of higher-capacitance dielectrics optimization is reflected in the middle column of Table 1. The form factor for this next generation of BDEL prototypes is QVGA and is now in development.

4 Reaching the ultimate potential of BDEL

In addition to achieving sub-1% display reflectivity, improvement paths are available for a major increase in

TABLE 1 - Performance of currently demonstrated prototypes, performance goals for prototypes in development, and performance goals for full-color blue-dielectric EL-display research.

	Prototoypes Demonstrated	Prototypes In Process Development	Full Color Displays Research w/ Blue Dielectric
Pixel Count	160x80 (12,800)	320x240 (76,800)	320(x3)x240 (76,800)
Pixel Pitch / Fill Factor	0.5 mm / >50%	0.36 mm / >64%	>80%
Color	Mono (amber)	Mono (amber or green)	Multi Color, Full Color
Luminance			
Maximum (L_{50})	>100 cd/m^2	>500 cd/m^2	>500 cd/m^2
Typical (L_{50})	~30-50 cd/m^2	>300 cd/m^2	>300 cd/m^2
Best Uniformity	10%	<5%	<5%
Typical Uniformity	10-50%	<5-25%	<5-10%
Max Contrast 500 lux	20:1 over >160°	300:1 over >160°	150:1 over >160°
Max Contrast 5000 lux	3:1 over >160°	30:1 over >160°	15:1 over >160°
Operating Temp.	0-55 °C	-40-65 °C	-40-65 °C
Power (varied pixel on %)	2.0-7.0 W	2.0-6.0 W	4.0-12.0 W

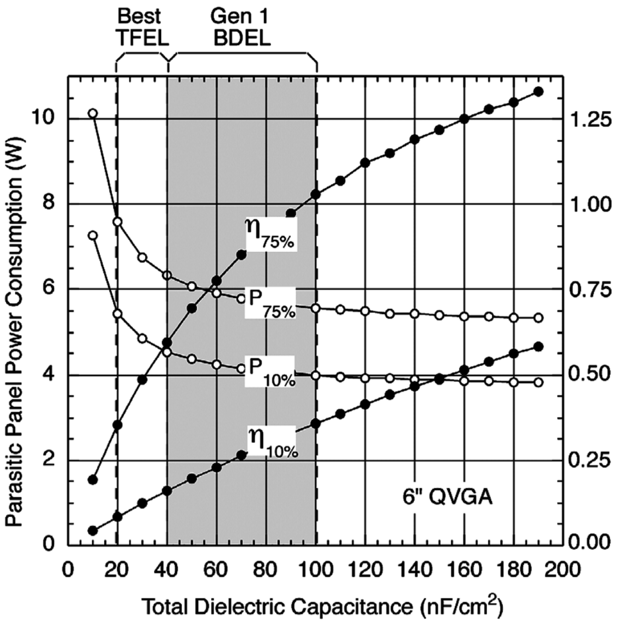

FIGURE 5 — A 6-in. QVGA modeling of parasitic panel power consumption (P, in W) and panel efficiency (η, in lm/W) at 10% and 75% of pixels lit *vs.* total dielectric capacitance.

BDEL display luminance. Such paths clearly lead to record levels of display legibility in bright lighting, procured from a low-cost manufacturing process. This primarily involves phosphor and dielectric optimization (composition, process). Display luminance and contrast can also be improved by increasing emission outcoupling, decreasing parasitic power consumption, and implementing novel contrast enhancement well-suited to full-color BDEL displays.

4.1 Emission outcoupling

A several-fold increase in luminance can be obtained through diffuse emission outcoupling (film roughness). Common EL phosphors such as ZnS posses a very high refractive index of ~2.4. For perfectly specular ZnS films on glass, ~45% of the emitted-light waveguides within the EL stack and another ~45% of the emitted-light waveguides within the EL stack and substrate glass.[6] This leaves only 10% out-coupling of light for EL devices with a reflective back electrode. 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 is applicable to BDEL due to the same advantage that allows for low-cost manufacturing: inclusion of a thick-film dielectric that is high-field-point tolerant.

4.2 Increased panel efficiency and luminance

Figure 5 details a display-efficiency trend that strongly supports the use of high-κ thick dielectrics. Simply stated, in a well-designed EL panel increased dielectric capacitance leads to increased panel efficiency. The efficiency shown in

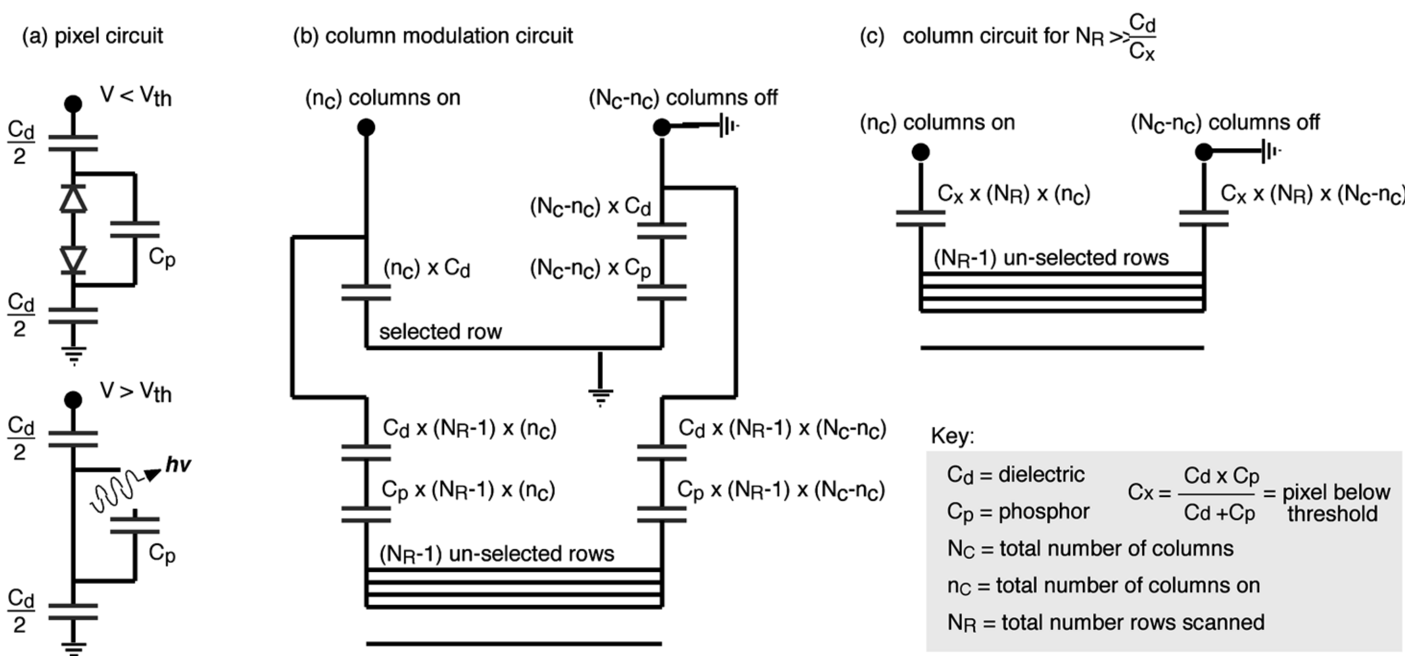

FIGURE 6 — Simple circuit model of (a) a single-pixel above and below EL threshold, (b) the parasitic capacitive load between columns in the ON and OFF states, and (c) an approximated version of (b) for the case of a large number of rows.

Fig. 5 does not include previously mentioned luminance increases, which would further increase overall BDEL panel efficiency. The modeling in Fig. 5 is based on the display circuit model shown in Fig. 6. The calculations assume a symmetric drive 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. The row driver provides voltages (~160–200 V) near the EL emission threshold and the column drivers provide voltage (~40 V) which modulates pixel luminance above threshold. Parasitic power consumption for a given row scan is largely due to capacitance between columns with lit and unlit pixels. This parasitic power consumption is repeated for each row as it is scanned. Given the case of hundreds of rows per frame and 60–240 frames/sec, the parasitic power consumption can dominate display power consumption. Parasitic capacitance does not increase significantly with dielectric capacitance since it is dominated by the series capacitance of a low-capacitance phosphor layer and a high-capacitance dielectric. Using the simplified model of Fig. 6(c), the dominant portion of parasitic power consumption, which is due to modulation voltage applied to the columns, can be approximated as

$$f \times N_R^2 \times V_M^2 \times C_x \frac{n_C \times (N_C - n_C)}{N_C} (W), \tag{1}$$

where the parameters are defined in the key of Fig. 6, V_M represents the modulation voltage above the threshold voltage, and f represents the frame rate. With higher dielectric capacitance, voltage is more efficiently coupled to the phosphor and the column (V_M) voltage is reduced. According to Eq. (1), this reduced modulation voltage then 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. 5. In order to fully capitalize on this ideal model for panel efficiency, factors such as row-driver current, panel refresh rate, modulation voltage, and phosphor layer thickness must be optimized while keeping in mind luminance saturation effects.

There is also an additional technique related to dielectric capacitance and phosphor thickness that can markedly improve display luminance. Generally, phosphors deposited using high-volume low-cost techniques such as in-line sputtering have a fixed dead layer (non-emitting) thickness of >100 nm. By increasing dielectric capacitance, the phosphor layer thickness, and therefore the emitting percentage of the phosphor layer, can be increased (to ~1 μm) without a comparable increase in drive voltage. Alleviating the increase in drive voltage with increasing phosphor thickness can also be achieved through strong avalanching breakdown characteristics for the phosphor layer and slight electric-field inhomogeneity which reduces the threshold field for EL emission. The pixel capacitance below threshold [C_x in Eq. (1)] is approximately inversely proportional to phosphor thickness (since $C_d >> C_p$). Therefore, for increasing phosphor layer thickness, the power consumption increase with increased applied voltage is partially offset by the reduced parasitic capacitance that is proportional to C_x. It is clear from these results that the push towards higher-capacitance dielectrics is critical for higher EL panel luminance. It should also be noted that additional energy-recovery techniques exist which can recover a large portion (~50%) of the parasitic power consumption.[7]

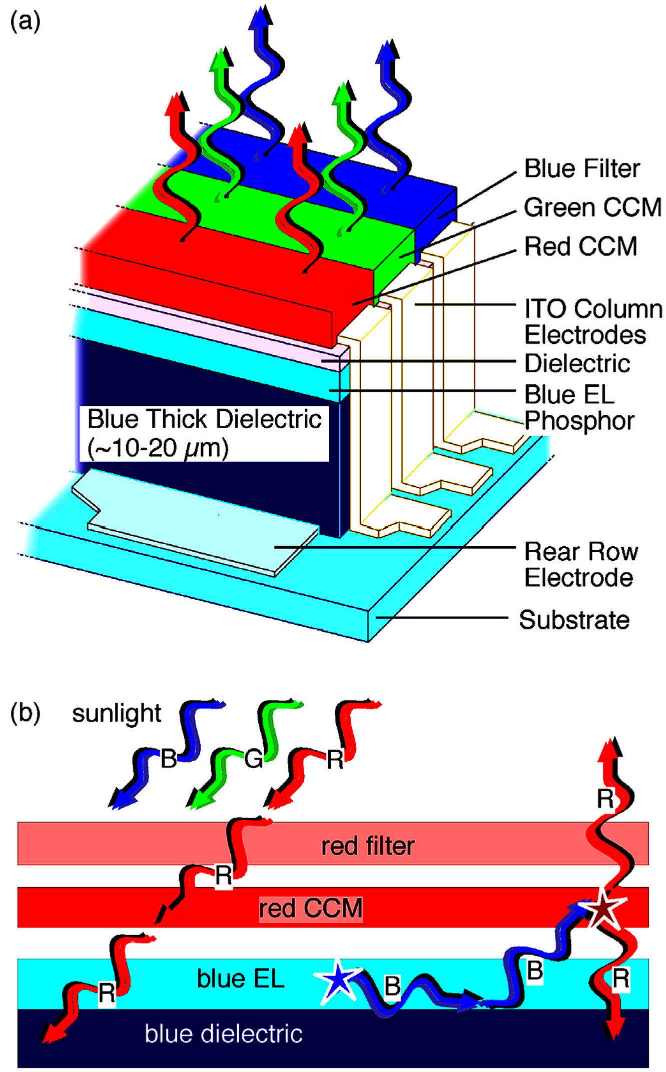

FIGURE 7 — High-contrast blue-dielectric EL-display concept device. (a) Structure; (b) operation.

4.3 High contrast without sacrifice in luminance

The original invention for the pigmentation of the black-thick-dielectric layer included the concept of pigmentation for a color-dielectric layer as well. From early on, blue was clearly the most promising color (non-black) version of the thick dielectric for two reasons: (1) blue has a very low photopic reflectivity equivalent for high display contrast in bright lighting and (2) the blue background also allows for superb color contrast when used in conjunction with a

ZnS:Mn yellow phosphor for the pixel emission. The end result is a highly attractive monochrome display with vivid at-a-glance legibility.

With the recent demonstration[8] of full-color inorganic EL panels using conversion by color-changing media (CCM), an even more attractive application for a blue thick dielectric has now emerged. In this technique, a single efficient blue phosphor, such as BaAlS:Eu[9] or SrS:Cu,[10] may be used in conjunction with a CCM layer which down-converts (with ~50% efficiency) blue emission to green or red emission. Shown in Fig. 7(a) is a CCM-based thick-dielectric EL device. The significance of the blue thick dielectric in this device structure is the elimination of the majority of display reflection, while preserving the majority of the display luminance achieved before contrast enhancement.

Organic versions of CCM layers are transparent (lightly colored) and therefore reveal the reflectivity of the thick-dielectric layer. Unlike powder phosphor down converters, these CCM layers are most often composed of ~90% peak-quantum-efficient fluorescent perylene or coumarin or other dyes in a PMMA or other polymer matrix. As shown specifically for PMN/PT in Fig. 8(a), the majority of thick-film dielectrics reflect most strongly in the high-photopic-response green and red regions, which reduces the display contrast in bright lighting. Therefore, it is advantageous to eliminate the red and green reflection and preserve the blue reflection through blue pigmentation of the thick-dielectric layer. The low photopic reflection equivalent for a blue dielectric layer alone leads to a strong reduction in display reflectivity without significant decrease in luminance [Fig. 8(c)]. The big payoff occurs when attaching a standard color-filter plate to the front of the display [Fig. 7(b)]. Ambient light passing through the red and green pixels is absorbed by the blue dielectric. The blue pixel still reflects blue light, but it is of a low photopic equivalent. This ideal combination of blue emitter and blue dielectric therefore should result in both high luminance and high contrast. Of course, ~50% of the red or green CCM emission is absorbed by the blue dielectric and the sub-pixel area must be adjusted accordingly. None the less, the theoretical maximum improvement in luminance and contrast is significant. Assuming a panel white luminance of 1000 cd/m^2 before contrast enhancement, with the panel exhibiting ~80% diffuse reflectivity from the rear thick dielectric, the addition of a 40% neutral density filter results in ~13% diffuse luminous reflectivity and 400-cd/m^2 luminance. Implementation of a blue thick dielectric without any color filters would result in an ~9% luminous reflectivity and 600 cd/m^2. The most powerful embodiment would be a blue dielectric, red and green color filters on top of the CCM (which also prevents ambient fluorescence of the CCM), resulting in a luminous reflectivity of ~2%, and a luminance of 600 cd/m^2 for a full-color contrast ratio of ~100:1 in 1000 lux and 3:1 in 50,000 lux. In HDTV applications, this result would lend inorganic EL an additional advantage in very-high-contrast performance over PDPs. The projected performance of full-color blue-dielectric EL displays using CCM conversion is reflected in the right-hand column of Table 1.

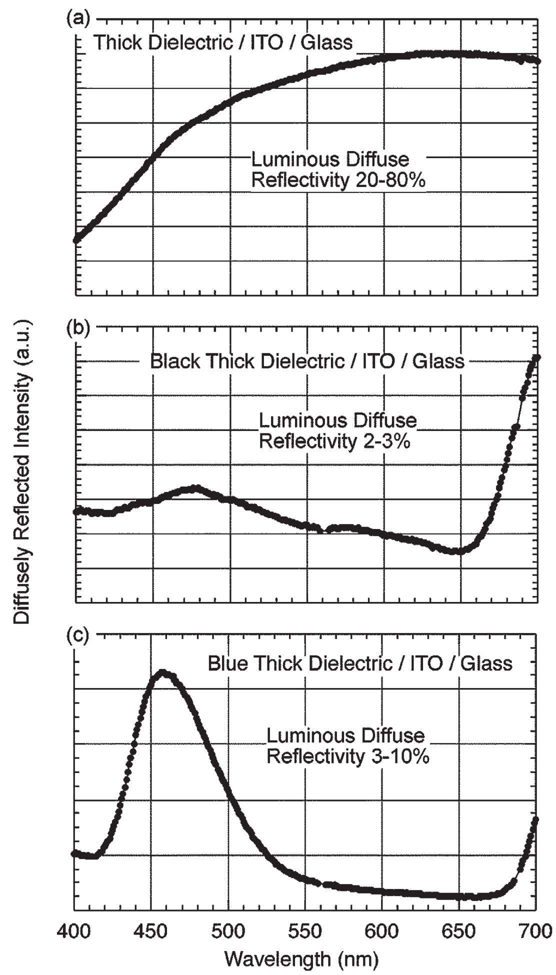

FIGURE 8 — (a) Diffuse reflectivity for PMN/PT:PZT thick dielectric. Minimum achievable diffuse reflectivity for (b) black- and (c) blue-pigmented PMN/PT:PZT thick dielectric.

4.4 The future promise of BDEL

When the present results with BDEL prototypes are combined with performance enhancements offered through optimization of material composition, process, and morphology, the total result lends strong promise to performance advantages that can be offered by BDEL displays. QVGA BDEL prototyping is now in development, and full-color R&D is advancing the role of the blue dielectric. Both black- and blue-dielectric EL technologies offer expanded applicability for inorganic EL technology.

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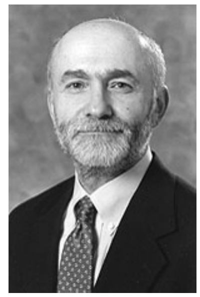
Jason Heikenfeld received the B.S. and Ph.D. degrees from the University of Cincinnati in 1998 and 2001, respectively. His major was in electrical engineering with minors in both photonics and physics. Dr. Heikenfeld is now a research scientist at Extreme Photonix Corp., Cincinnati, OH. His main duties at Extreme Photonix involve leading the research and development of electroluminescent displays. He has authored and co-authored over 80 publications in refereed journals, conference proceedings, and a book chapter. He is an inventor on one granted and two pending U.S. patents. He is a member of the Institute for Electrical and Electronics Engineers and the Society for Information Display.



Andrew J. Steckl received his B.S.E. degree in electrical engineering from Princeton University, Princeton, NJ, in 1968, and his M.Sc. and Ph.D. degrees from the University of Rochester, Rochester, NY, in 1970 and 1973, respectively. In 1972, Dr. Steckl joined the Honeywell Radiation Center, Lexington, MA, as a Senior Research Engineer, where he worked on new concepts and devices in the area of infrared detection. In 1973, he joined the Technical Staff of the Electronics Research Division of Rockwell International, Anaheim, CA. At Rockwell, he was primarily involved in research on charge-coupled devices. In 1976, Dr. Steckl joined the Electrical, Computer and Systems Engineering Department at Rensselaer Polytechnic Institute in Troy, NY, where he developed a research program in microfabrication of Si devices. In 1981, he founded the Center for Integrated Electronics, a multi-disciplinary academic center focused on VLSI research and teaching, and served as its director until 1986. In 1988, Dr. Steckl joined the Electrical and Computer Engineering Department of the University of Cincinnati as Ohio Eminent Scholar and Gieringer Professor of Solid-State Microelectronics. At Cincinnati, he has developed the Nanoelectronics Laboratory with research activities in semiconductor materials and devices for photonics: SiC and GaN thin-film growth by CVD and MBE; focused-ion-beam fabrication of photonic components and circuits; and rare-earth-doped luminescent devices for flat-panel displays and communications. His research has resulted in over 300 publications and 310 conference and seminar presentations. In 2000, Dr. Steckl started Extreme Photonix with the goal of commercializing novel flat-panel displays based on the technology pioneered at the NanoLab.