Black and Blue: The Impact of Pigmented Thick Dielectrics for Superior Contrast Inorganic EL Displays

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Abstract

The development of pigmentation processes for high capacitance thick dielectrics allows for robust reduction of display reflectivity and therefore contrast of thick dielectric electroluminescent (EL) panels. We present the recent results on black thick dielectric EL display technology and prototypes. Blue thick dielectrics also show excellent promise for boosting the contrast and luminance of monochrome and full-color EL panels. Black and blue thick dielectrics allow inorganic EL an additional performance advantage over highly reflective display technologies such as plasma display panels.

Rapid Progress in Thick Dielectric EL

The development of thick dielectric EL and efficient blue EL phosphors has rapidly revolutionized[1] the field of inorganic EL with large full-color prototype screens now heading towards an unprecedented 1000 cd/m^2 luminance. Thick dielectric EL has removed the majority of limitations previously associated with traditional thin film EL (TFEL) displays. These limitations in full color luminance and large-size manufacturability have long prevented expansion of inorganic EL technology. However, the transformation of TFEL to thick dielectric EL initially abandoned one of TFEL's strongest performance advantages: built-in contrast enhancement for ~1-2% display reflectivity. In response, Extreme Photonix began development in 2001 of its EL technology with built-in contrast enhancement using black or color pigmented thick dielectrics. The first Extreme Photonix monochrome EL prototypes using a black thick dielectric have now been demonstrated in 2003. Also in 2003, the demonstration of iFire's Color-by-Blue™ approach [2] creates a new high performance role for blue pigmented thick dielectrics. Both black or blue dielectric contrast enhancement for EL (BDEL) renew the superior contrast advantage long-associated with inorganic EL technology.

Black Thick Dielectrics for Monochrome EL

The contrast ratio for highly reflective display technologies is often reported only in terms of dark contrast (pixel on divided by pixel off luminance). A much more accurate representation of display contrast is that of contrast in typical lighting environment. Consider for example a plasma display with 1000:1 dark contrast, 400 cd/m^2 luminance, but with 10% diffuse reflectivity. In a common lighting environment of 500 lux this contrast is reduced to less than 30:1. The same challenge was initially present in thick dielectric EL displays. However, unlike plasma-displays the emissive layer in EL is a transparent thin film. Therefore thick dielectric EL devices can be internally contrasted using a rear light absorbing

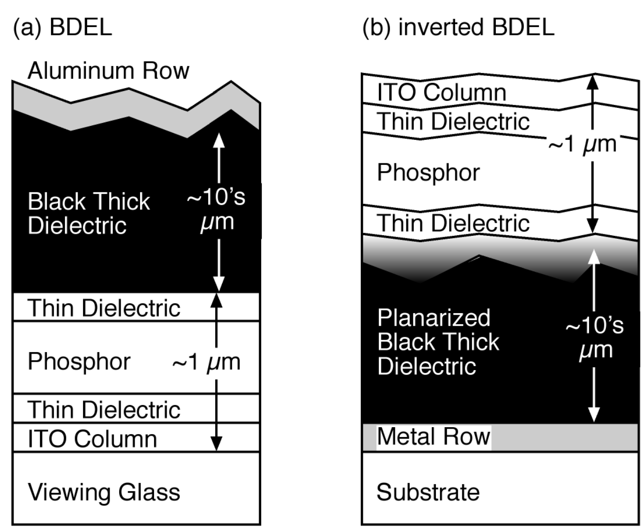

Fig. 1. BDEL device cross-sections.

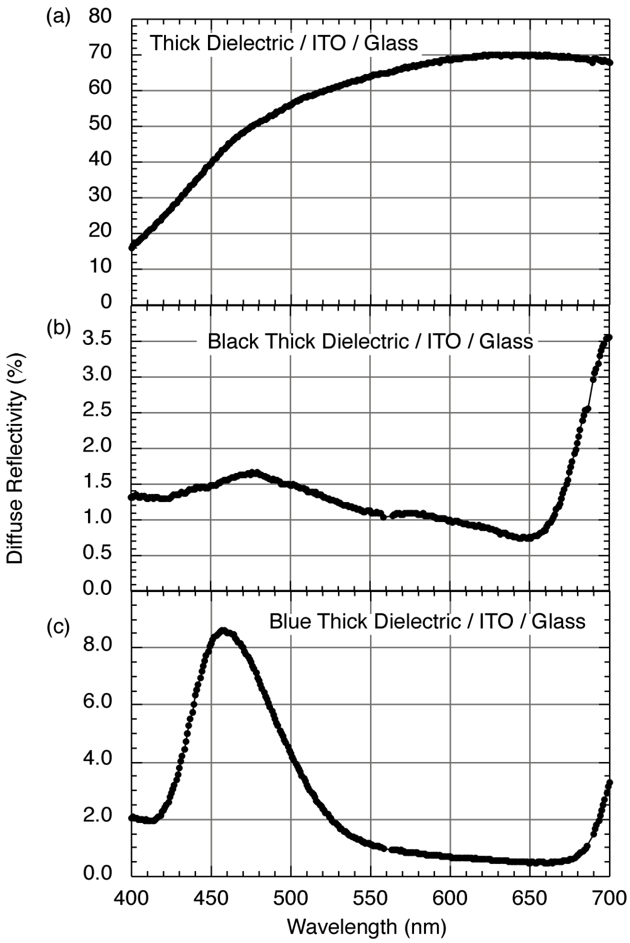

Fig. 2 Diffuse reflectivity for PMN/PT:PZT thick dielectric (a), minimum achievable diffuse reflectivity for black (b) and blue (c) pigmented PMN/PT:PZT thick dielectric.

layer, specifically a black thick dielectric. Inclusion of a black dielectric in non-inverted or inverted EL device structure is shown in Fig. 1. Internal contrast enhancement provides two major advantages over typical use of a front neutral density filter: (1) display diffuse reflectivity can be decreased to well below 10%, (2) there is only slight reduction in luminance with continued decrease in display reflectivity. Elaborating on (2), the luminance in a BDEL display decreases very slowly (asymptotically) as reflectivity is decreased below 10%. On the other hand, the case of a neutral density filter decreases the luminance more strongly, with a square root dependence on reflectivity. Internal contrast enhancement most strongly produces this advantage over external contrast enhancement in cases where low (<5%) reflectivity is advantageous or required (1000 to 100,000 lux). It is important to note that unlike using typical black layers such as carbon-black, narrow-band-gap semiconductors, or oxygen deficient metals oxides, the unique black pigmentation method developed by Extreme Photonix does not alter the very high capacitance (up to 100's nF/cm^2), high breakdown voltage (>300 V), or self-healing breakdown characteristics (when using a thin Al electrode) of the thick dielectric layer. An example of a screen-printable thick dielectric formulation for use in EL is lead magnesium niobate / lead titanate (PMN/PT) with a lead zirconate titanate (PZT) sol-gel derived matrix for low temperature sintering (<700 °C). Using a mixture of PT compositions allows a flat permittivity vs. temperature response for this very high permittivity (10,000's) electrostrictor material system. However, this system, like thick film (powder) systems such as $BaTiO_3$, exhibits a very high diffuse reflectivity (Fig. 2a) which assists in EL emission outcoupling, but which causes low display contrast in bright lighting. The black pigmentation process largely eliminates this diffuse reflection (Fig. 2b) down to a diffuse luminous reflectivity of ~2%.

A summary of available contrast enhancement techniques for monochrome inorganic EL is shown in Table 1. Internal contrast enhancement for TFEL generally utilizes a graded index or optical interference approaches to eliminate specular reflectance from the rear electrode and the thin dielectric layer behind the phosphor layer.

Approach	Reflectance	Luminance
Thin Film EL	(specular)	
Planar ICE™	~1%	Moderate
Luxell Black Layer™	~1%	Moderate
Circular polarizer	~2%	Moderate
Thick Dielectric EL	(diffuse)	
Neutral Density (ND)	~5-20%	High
ND and Color Filter	~2-5%	High
Black Dielectric	~1-3%	High

Table 1. Contrast enhancement for monochrome EL panels.

Generally luminance of TFEL displays is moderate since the dielectric capacitance (phosphor thickness, panel efficiency) and diffuse outcoupling of phosphor emission are both limited by the high voltage requirements for the thin film dielectrics. Thick dielectrics overcome these drawbacks, but thick dielectrics cannot benefit from existing TFEL contrast enhancement techniques which require transparent (and therefore thin) rear dielectrics. This presently leaves the black thick dielectric as the only existing method for internal contrast enhancement of thick dielectric EL panels. It is important to note that the pigmentation process eXp has developed is rapid (minutes / panel) and involves very low cost materials (<$1/m^2 of coverage).

Black Thick Dielectric EL Prototype Displays

Extreme Photonix has demonstrated monochrome BDEL prototypes in 160x80 pixel formats and is now in product-driven development of QVGA BDEL prototypes. The QVGA BDEL displays are being pursued as a higher luminance / lower cost alternative to existing monochrome TFEL display products. Shown in Table 2 is a summary of present BDEL prototypes and expected performance (based on experimental results) of QVGA prototypes in development.

The BDEL prototypes use the device structure shown in Fig. 1a. The prototypes are fabricated using sputter deposition for all thin films and screen printing for all thick films. The electrode patterning is performed using low-cost dry-film

	Demonstrated	In Development
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
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%
Max Contrast[2] 5 klux	3:1	30:1
Power[4] (60-240 Hz)	2.0-7.0 W	2.0-6.0 W

Table 2. BDEL prototype performance.

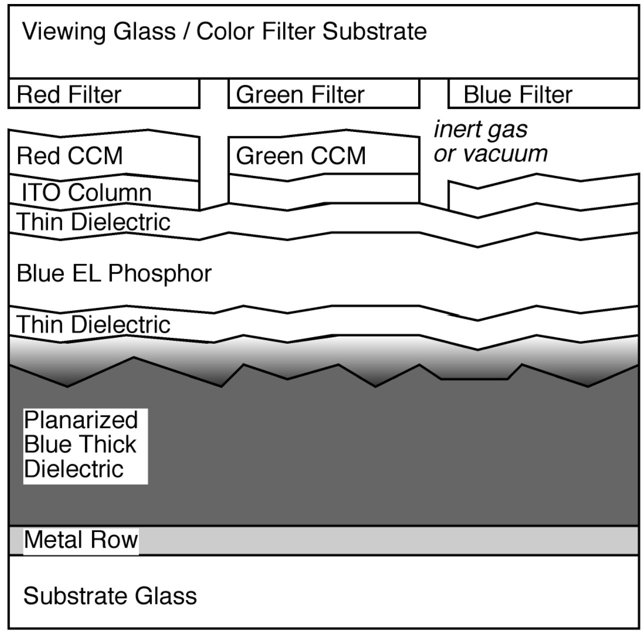

Fig. 3. High contrast blue dielectric EL display concept.

photolithography. Projected equipment cost and production throughput has been improved over traditional EL panel approaches for all layers deposited/patterned in the EL panel production. The thick dielectric is impervious to electrical breakdown at sub-micron defects and allows for flexibility in material choice, deposition technique/rate of thin film layers.

Blue Thick Dielectrics for Full Color EL

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, the most promising color (non-black) dielectric was that of blue for two reasons: (1) blue had a very low photopic reflectivity equivalent for high display contrast in bright lighting; (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 of iFire's Color-by-Blue™ an even more attractive application for a

Approach	Reflectance	% of Original Luminance
Thin Film EL	(specular)	~300 cd/m^2
Planar ICE™	~1% at rear	~50%
Luxell Black Layer™	~1% at rear	~50%
Circular polarizer	<2%	~40%
Thick Dielectric EL	(diffuse)	~1000 cd/m^2
Neutral Density (ND)	~5-20%	~40%
ND and Color Filters	~2-5%	~40%
Blue Dielectric, CCM, and Color Filters	~2%	~60%

Table 3. Theoretical contrast enhancement for full-color EL panels.

blue thick dielectric has now emerged. iFire Color-by-Blue™ is an adaptation of previous pixel emission down-conversion techniques in inorganic EL (UV to visible) and organic EL (blue to red and green). Advantageously, a single blue phosphor (BaMgAlS:Eu) is used in conjunction with an emission down-converting layer common called the color-conversion-medium (CCM) layer. Shown in Fig. 3 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 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. 2a, 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. The big payoff occurs when attaching a standard color-filter plate to the front of the display. 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. The color filters also eliminate the majority of shorter wavelength ambient light excitation of the CCM layers. If this effect is uncorrected, it can lead to a significant reduction in display contrast, especially in high color temperature lighting (fluorescent, sunlight).

Several design aspects are important to this approach. First, the reflectivity characteristics of the blue dielectric can be controlled by adjusting the composition of the pigment and dielectric. This allows for the selection of the reflectivity at blue wavelengths and absorption at red and green wavelengths, leading to optimization of the luminance and contrast trade-off. Other design issues in the Extreme Photonix approach include the design of the CCM layers for >75% emission outcoupling to the viewer.

Shown in Table 3 is a theoretical comparison of various contrast enhancement techniques for full color EL displays. The blue dielectric in combination with CCM layer approach allows for high-contrast without the large sacrifice in display luminance associated with other contrast enhancement techniques. With proper modification, black and blue dielectric technology could also be extendable to applicability in other thick-film display technologies such plasma display panels.

References

[1] J. Heikenfeld and A. J. Steckl, "Inorganic EL Displays at a Cross-Roads", Information Display Magazine, Vol. 19, No. 12, December 2003.

[2] X. Wu, A. Nakua, and D. Cheong, "Color by Blue - A New Method of Achieving Full Color for Inorganic EL", International Display Workshops, invited paper PH3-1, 2003.