Contrast-Enhancement in Black Dielectric Electroluminescent Devices

Jason Heikenfeld, *Member, IEEE*, and Andrew J. Steckl, *Fellow, IEEE*

***Abstract*—A high contrast electroluminescent (EL) device structure is presented. The diffuse luminous reflectivity from the metal/dielectric/phosphor/indium-tin-oxide/glass EL device structure is $\sim 3\%$. A Eu-doped GaN phosphor is used to demonstrate the contrast-enhanced operation. Low reflectivity is achieved by inserting a light-absorbing black thick-film $BaTiO_3$ layer between the phosphor and the rear metal electrode. In addition to providing contrast enhancement, the opaque thick dielectric film exhibits capacitance and high voltage reliability (40 nF/cm^2, dielectric constant $\varepsilon_d \sim 500$–1000, breakdown field $E_{d,br} \sim 0.1$–0.4 MV/cm) similar to that of the highest performance transparent thin-film dielectrics. An EL device luminance of only 20 cd/m^2 is sufficient for a display contrast ratio of $\sim$10:1 under 140 lux indoor ambient lighting (illumination). Under sunlight illumination of 100 000 lux, a display contrast ratio of >3:1 is expected with application of additional contrast enhancement techniques.**

***Index Terms*—Black dielectric, contrast, display, electroluminescence, GaN, reflectivity.**

I. Introduction

LIGHT emissive technologies currently being investigated for flat panel displays [1] (FPDs) include: field emission display (FED), plasma display panel (PDP), inorganic thin-film electroluminescence (TFEL), and organic light emitting diode (OLED). ZnS:Mn TFEL [2], [3] flat panel displays are well known for their superior readability and durability. Such readability is due to an excellent view angle and very high display contrast. In a dark operating environment, display dark contrast is the ratio of maximum pixel luminance ($L_{\max}$) to minimum pixel luminance ($L_{\min}$). Pixel blooming (emission that appears outside the pixel area) is one effect that can reduce dark contrast. Most display applications, however, must take into account the reflected luminance (L_{ambient}) from ambient light (illumination). This true measure of display contrast [4], or contrast ratio (CR), is defined for a Lambertian emitter/reflector as

$$CR = \frac{L_{\max} + L_{\text{ambient}}}{L_{\min} + L_{\text{ambient}}}, \text{ with } L_{\text{ambient}} = R_L \frac{E_{\text{ambient}}}{\pi}. \tag{1}$$

R_L is the diffuse luminous reflectance of the ambient illumination (E_{ambient}). R_L is the absolute reflectivity weighted against the spectral (photopic) response of the human eye versus wavelength. The diffusely reflected surface luminance of the display (L_{ambient} in lm/m^2/sr) is calculated as $R_L E_{\text{ambient}}/\pi$. A display with 50% diffuse reflection under an ambient illuminance (E_{ambient} in lm/m^2 or lux) of 100 lux for office lighting will reflect a luminance of 16 cd/m^2. Operation in direct sunlight at 100 000 lux results in a reflected luminance of 16 000 cd/m^2. For long life display operation and low power consumption it is clear that low reflectivity, not higher brightness, is the best approach for high display contrast. We have recently developed a thick-film dielectric electroluminescent (TDEL) structure [5] on glass substrates. The TDEL devices were demonstrated using a novel phosphor which we have developed, namely rare-earth-doped GaN [6], [7]. In this paper, we report on the contrast enhancement obtained with a black dielectric TDEL (B-TDEL) device structure. This increase in contrast is seen in Fig. 1 which compares GaN:Eu TDEL and B-TDEL devices operating at 1 kHz and 0, 80, and 120 V. The Eu emission wavelength is 621 nm. It is quite apparent that the B-TDEL approach allows for increased legibility and saturated emission chromaticity.

II. Comparison to Existing Approaches

Existing high contrast TFEL device structures are shown in Fig. 2(a)–(c). The oxidized metal TFEL (OM-TFEL) structure [8] in Fig. 2(a) uses a low reflectivity, graded Al_2O_3-to-Al rear electrode in order to achieve readability in 10 000 lux lighting. The absorbing substrate [9] TFEL (AS-TFEL) structure in Fig. 2(b) uses a light absorbing Si substrate as a rear electrode. For the optical interference [10] TFEL (OI-TFEL) structure in Fig. 2(c), the light reflected from the partially reflective Iconel (low corrosion metal alloy) layer experiences destructive optical interference with light reflected from the Al electrode. All other layers in the structure of Fig. 2(c) are also modified for low reflectivity. For OI-TFEL, the reflectance is a strong function of view angle. OI-TFEL is difficult to use in multi-viewer or full color displays due to a narrow high-contrast view angle and emission color shift with view angle, respectively. By comparison, the B-TDEL structure in Fig. 2(d) uses a black diffuse dielectric surface to absorb light. While these contrast enhancement techniques (as shown in Fig. 2) are readily applicable to inorganic display technologies, they could also apply with some modification in design to direct current supply from a rear metal electrode (OLED).

III. Fabrication

B-TDEL display devices were fabricated [5] in a manner similar to TDEL devices. Indium-tin-oxide (ITO) thin transparent electrodes ($\sim$200 nm) are sputtered onto Corning 1737 glass.

Manuscript received December 19, 2001; revised April 24, 2002. This work was funded in part by ARO contract DAA D19-99-1-0348. The review of this paper was arranged by Editor J. Hynecek.

The authors are with the Nanoelectronics Laboratory, University of Cincinnati, Cincinnati, OH 45221-0030 USA (e-mail: a.steckl@uc.edu).

Publisher Item Identifier 10.1109/TED.2002.801298.

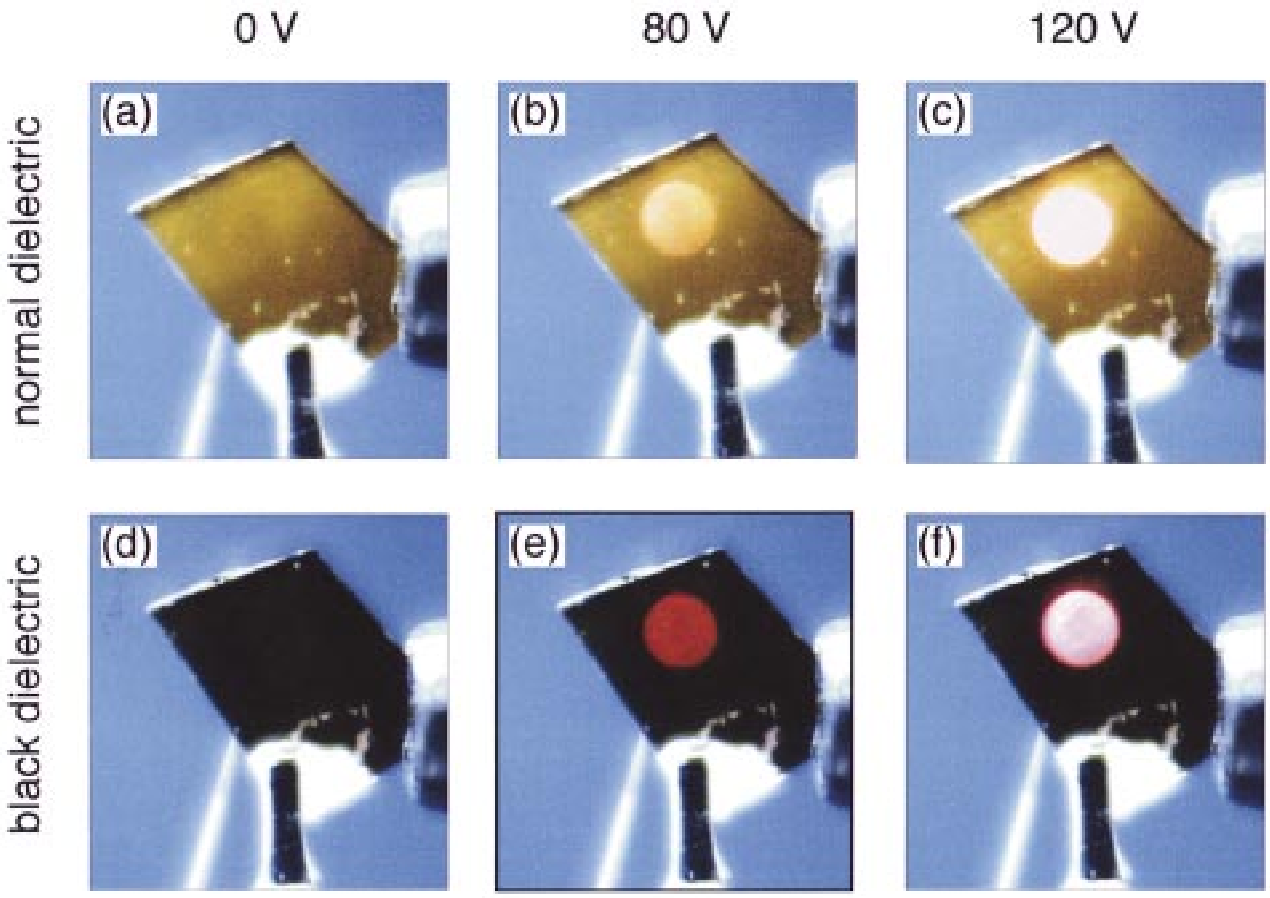


Fig. 1. Photographs of operating GaN:Eu EL devices taken in ambient lighting of 140 lux. The TDEL (a, b, c) and B-TDEL (d, e, f) devices were operated at 1 kHz frequency and biased at 0, 80, and 120 V, respectively. The pictures were taken in an ambient lighting of 140 lux.

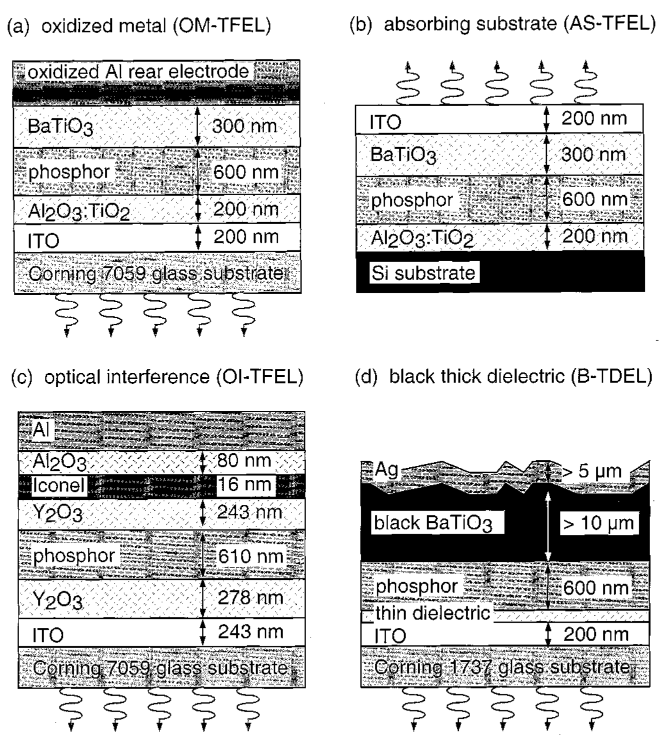


Fig. 2. Approaches for high contrast EL devices: (a) oxidized metal (OM)-TFEL; (b) absorbing substrate (AS)-TFEL; (c) optical interference (OI)-TFEL; and (d) black thick dielectric (B)-TDEL.

Following ITO deposition, an AlN thin dielectric ($\sim$50 nm) and a $\sim$ 500 nm GaN:Eu phosphor layer were deposited by solid-source molecular beam epitaxy. Alternative GaN phosphor deposition means (sputtering, reactive evaporation) and/or other phosphor (ZnS:Mn) and dielectric layers (Al_2O_3) are envisioned for the B-TDEL structure. One of the key advantages of the B-TDEL device is use of a thick film dielectric. The screen printed thick film dielectric layer determines the high voltage reliability of the device and is beneficial for high yield fabrication. Unlike thin-film dielectrics used in TFEL, thick film dielectrics are easily scaleable to large display sizes ($>17''$) with vacuum-free processing, and can tolerate μm-sized film defects, surface roughness (high-field points), or even small particulate contamination. The figure of merit [3] (FOM) for dielectrics is given by the maximum charge capacity ($Q_{\max}$, μC/cm^2) prior to dielectric breakdown ($E_{d,br}$)

$$Q_{\max} = \frac{\varepsilon_o \varepsilon_d}{t_d} E_{d,br} t_d \text{ or } Q_{\max} = \varepsilon_o \varepsilon_d E_{d,br} \qquad (2)$$

where t_d and ε_d are the dielectric film thickness and relative permittivity (dielectric constant). The $BaTiO_3$ thick-film dielectric implemented in TDEL devices exhibits an excellent FOM of $Q_{\max} \sim$ 10–20 μC/cm^2 ($\varepsilon_o = 8.85 \times 10^{-14}$ F/cm, $\varepsilon_d \sim$ 500–1000, $E_{d,br} \sim$ 0.1–0.4 MV/cm). The FOM for thick-film ($\sim$20 μm) $BaTiO_3$ allows for efficient and reliable ($>$300 V) coupling of voltage to the phosphor layer which emits light by

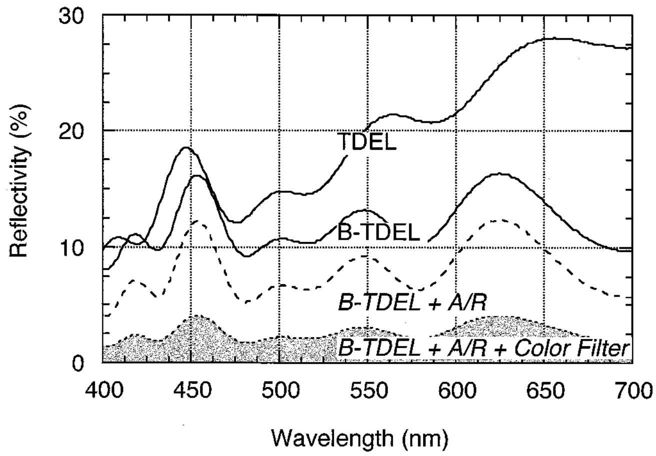


Fig. 3. Measured reflectivity spectra for surface-normal light incidence of TDEL and B-TDEL structures. Also shown is the projected (calculated) reflectivity spectrum for B-TDEL with antireflective (A/R) and with color filter contrast enhancement.

undergoing reversible (current limited) electrical breakdown. The FOM for screen printed $BaTiO_3$ is of the same level as that of the high performance TFEL dielectric [2], Al_2O_3:TiO_2, which is deposited by atomic layer epitaxy.

In the fabrication process of B-TDEL devices, a pigmentation process is used to coat the numerous cavities found in the porous microstructure of the thick-film dielectric. The black pigment, which is thermally stable, is delivered by a solvent which is volatilized at $\sim$ 200 °C after delivery. This black thick dielectric layer is then capable of absorbing $>$90% of the incident light. It is important to note that the high voltage reliability and high capacitance of the thick dielectric layer are not compromised by the pigmentation process. The black dielectric approach also appears applicable to inverted TDEL (I-TDEL) flat television displays [11], which are formed on ceramic substrates.

IV. Reflectance Characteristics

The spectral reflectance characteristics were measured under surface normal incidence in an integrating sphere. The reflectivity of TDEL and B-TDEL device structures are shown in Fig. 3 as a function of wavelength. Thin-film interference effects are obvious. The largest component of reflectivity for the TDEL device is in the red and green (20–25%), corresponding to the brown appearance of the TDEL device background (thick dielectric layer). Using the black dielectric reduces the total reflectivity to $\sim$10–15%. A large portion of this reflectivity is due to Fresnel (specular) reflection [12] between adjacent layers $(i, i+1)$ with different indices of refraction (n_i)

$$F_i = \frac{(n_i - n_{i+1})^2}{(n_i + n_{i+1})^2} \tag{3}$$

where n_i takes the appropriate value of the five layers shown in Fig. 4. For the glass ($n_1 \sim$ 1.5 at 550 nm)/air $(n_0 = 1.0)$ interface this specular reflection is large ($\sim$4%), but can be nearly eliminated through use of an antireflective (A/R) coating. Use of such an A/R coating would result in the spectral reflectance characteristic shown as the dashed line curve in Fig. 3. The specular Fresnel reflection from the other layers in the structures is calculated using (2) to be $\sim$3%. This calculation does not take into account thin-film interference effects. This remaining reflection can be further reduced by exploiting thin-film interference effects similar to those used in OI-TFEL. In addition, color filter technology can also be used to reduce reflectance from the device and improve contrast without decreasing the emitted luminance. The color filter is chosen to match the device emission wavelength and absorb all other visible light wavelengths. For a red, green, and blue (RGB) emitting full color display, the overall reflection would be reduced to approximately 1/3 its original value. This averaged effect of RGB color filters is approximated as a 3$\times$ reduction in B-TDEL device reflectivity and is shown as the dotted-line and shaded curve of Fig. 3. The summation of these further contrast enhancements would result in a total reflectance of $\sim$3% which is composed of $\sim$2% specular and $\sim$1% diffuse reflection. With 1% diffuse reflection and 60 cd/m^2 device luminance, a 3:1 contrast ratio is expected for 10 000 lux ambient lighting.

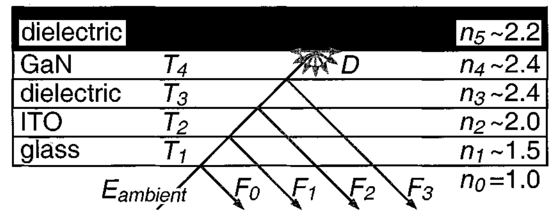


Fig. 4. Diagram of specular (F) and diffuse (D) light reflection and transmission (T) components in a B-TDEL device.

All thin-film layers in the B-TDEL stack are transparent ($>$90%). The total reflectance (R) decrease associated with light absorption in the thin-film layers, without thin-film interference, can be calculated as

$$R = \sum_{i=0}^{3} \left(F_i \prod_{j=0}^{j=i} T_j^2 \right) + D \prod_{i=0}^{4} T_i^2 \tag{4}$$

where T_i is the transmittance of each layer (i), and D is the diffuse reflection from the rear thick dielectric layer. Fig. 4 diagrams the multiple reflection components according to (4). To reach sub-1% diffuse reflectance and sunlight legibility (100 000 lux illumination), one can insert an additional absorbing layer between the phosphor layer and black dielectric. This is an effective method to decrease the reflectance because of the double pass of diffusely reflected light through the absorbing layer. Unlike use of dark front glass, use of an absorbing layer between phosphor layer and black dielectric can enhance contrast without reducing the device luminance. To achieve such contrast enhancement, an oxygen deficient dielectric (Al_2O_3:Al) or a narrow-gap ($<$2 eV) semiconductor layer (InN) could be embedded in a insulating thin dielectric layer. The absorbing film should be chosen such that its refractive index matches that of the dielectrics. Otherwise, refractive index mismatch will result in strong specular reflection. For example, the use of an a-Si ($n_{\mathrm{Si}} \sim$ 4.2) layer [Fig. 2(b)] for this purpose would result in $\sim$10% specular reflection [see (3)]. Once properly chosen, an absorbing layer with 40% transmittance would reduce the diffuse reflectivity of the B-TDEL

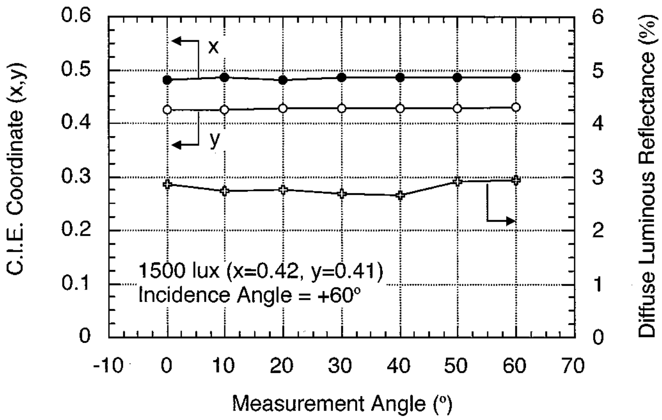


Fig. 5. CIE chromaticity (x, y) and diffuse luminous reflectance versus measurement (view) angle for a B-TDEL device with 1500 lux luminance incident at $+60°$. Diffuse reflection of 1% corresponds to ~5 cd/m^2 surface luminance.

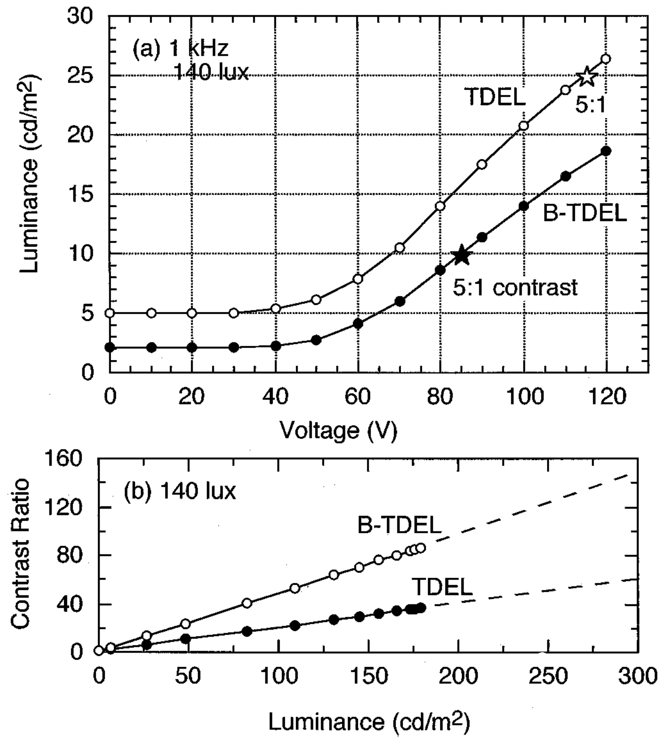


Fig. 6. TDEL and B-TDEL device luminance and contrast as a function of operating parameters and 140 lux ambient lighting: (a) applied peak voltage at 1 kHz and (b) contrast ratio for different device luminance levels (obtained by increasing the bias frequency).

device by a factor of six $[1/(0.4)^2]$. For an original diffuse reflectance of $\sim 3\%$, this absorbing layer would reduce the reflectance to 0.5%. Under 100 000 lux illumination, this would result in a (diffusively) reflected brightness of ~150 cd/m^2, requiring a device luminance of ~300 cd/m^3 for a contrast ratio of 3:1. This value is achieved without use of a color filter(s), which if implemented, would further reduce the luminance requirement for sunlight legibility.

V. Additional Display Usage Issues

The chromaticity and luminance of the B-TDEL reflectance is shown in Fig. 5 as a function of view angle for a 1500 lux light source with 1931 Commission Internationale d'Eclairage (CIE) coordinates of $x = 0.42$, $y = 0.41$. The color of reflected light is nearly constant with view angle (CIE coordinates of $x = 0.49, y = 0.43$). The intensity of reflected light from the B-TDEL structure is also insensitive to view angle (constant luminous reflectance of $\sim 3\%$, equivalent to a reflected luminance of 14 cd/m^2). This is very important for multiviewer applications since display contrast must be consistently high at all view angles. Since the black dielectric layer is a diffuse reflector, the B-TDEL device has built-in display glare reduction. Unlike the OI-TFEL device, the B-TDEL device is ideal for a full color display since emitted and reflected chromaticity will not significantly vary with view angle. Total luminance (emitted + reflected) and contrast ratio as a function of applied voltage and emission brightness are shown in Fig. 6 under office lighting conditions (140 lux). The B-TDEL device exhibits twice the contrast of the TDEL device at 120 V bias. At a bias frequency of 1 kHz, a useable contrast ratio of 5:1 is achieved at a device luminance of 25 cd/m^2 for the TDEL structure while requiring only 8 cd/m^2 device luminance for the B-TDEL structure [Fig. 6(a)]. By increasing the bias frequency, the device luminance and contrast ratio for B-TDEL are further increased [Fig. 6(b)].

The pigmentation process used in the fabrication of the black dielectric layer is highly flexible. Shown in Fig. 7 is a photograph of an alternate embodiment of TDEL contrast enhancement using a colored thick dielectric. In order to achieve strong color saturation a lightly colored (semitransparent) lead niobate thick film dielectric layer (region "a") is printed, fired, and then pigmented either red ("b"), green ("c"), blue ("d"), or black ("e"). The dark circles seen in the pigment-free dielectric regions ("a") are due to reflection from the rear metal electrodes. This technique can be utilized to create strongly contrasting color combinations (such as blue backgound, yellow emission) for novelty display applications.

VI. Conclusions

In conclusion, we have demonstrated contrast enhancement using a black thick dielectric in an electroluminescent device structure. In addition to providing contrast enhancement, the opaque thick dielectric film exhibits capacitance and high voltage reliability (40 nF/cm^2, $\varepsilon_d \sim$ 500–1000, $E_{d,br} \sim$ 0.1–0.4 MV/cm) similar to that of the highest performance transparent thin-film dielectrics. For medium to large size displays and in a variety of lighting conditions (100–1000 lux), the B-TDEL device approach greatly reduces the complexity associated with contrast enhancement, thin-film defects, and scalability issues in TFEL display devices. Furthermore, the B-TDEL approach does not suffer from the angular variation of emitted and reflected intensity associated with contrast enhancement using optical interference. Invariance of emission/reflected color with view angle is critically important for wide-view angle full-color displays. With additional contrast enhancement such as antireflective film, color

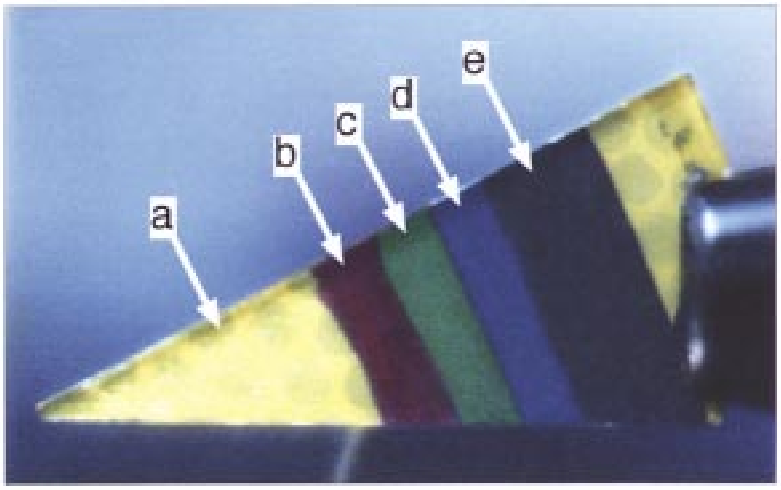


Fig. 7. Photograph of TDEL contrast enhancement using a colored thick dielectric. The lightly colored (semitransparent) lead niobate thick film dielectric layer (region "a") is printed, fired, and then pigmented either red ("b"), green ("c"), blue ("d"), or black ("e").

filtering, and/or a light absorbing layer, the B-TDEL device would be legible under sunlight ambient lighting conditions of 100 000 lux.

ACKNOWLEDGMENT

The authors would like to thank D. S. Lee and other members of the University of Cincinnati Nanoelectronics Laboratory for many useful discussions. The support of M. Gerhold and J. Zavada is gratefully acknowledged.

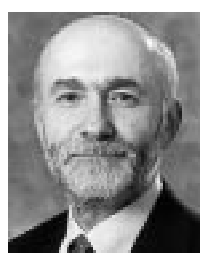
REFERENCES

[1] K. R. Sarma and T. Akinwande, "Flat panel displays for portable systems," *J. VLSI Signal Process. Syst.*, vol. 13, pp. 165–190, 1996.
[2] R. Mueller-Mach and G. O. Mueller, "Thin film electroluminescence," in *Electroluminescence II*, G. O. Meuller, Ed. San Diego: Academic, 2000, vol. 65, Semiconductors and Semimetals, ch. 2.
[3] M. Leskelä, W. Li, and M. Ritala, "Thin film electroluminescent devices," in *Electroluminescence II*, G. O. Meuller, Ed. San Diego: Academic, 2000, vol. 65, Semiconductors and Semimetals, ch. 3.
[4] M. Ylilammi, "Optical properties of ACTFEL displays," *J. Soc. Inform. Display*, vol. 3/2, pp. 59–66, 1995.
[5] J. Heikenfeld and A. J. Steckl, "Electroluminescent devices using a high-temperature stable GaN-based phosphor and thick-film dielectric layer," *IEEE Trans. Electron Devices*, vol. 49, pp. 557–563, Apr. 2002.
[6] A. J. Steckl and R. Birkhahn, "Visible emission from Er-doped GaN grown by solid source molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 73, no. 12, pp. 1700–1702, 1998.
[7] A. J. Steckl and J. M. Zavada, "Optoelectronic properties and applications of rare-earth doped GaN," *Mat. Res. Soc. Bull.*, vol. 24, no. 9, pp. 33–38, 1999.
[8] E. Dickey, "Black electrode TFEL display," U.S. Patent 5 504 389, 1996.
[9] J. Heikenfeld and A. J. Steckl, "Alternating current thin-film electroluminescence of GaN:Er," *Appl. Phys. Lett.*, vol. 77, no. 22, pp. 3520–3522, 2000.
[10] J. A. Dobrowolski, B. T. Sullivan, and R. C. Bajcar, "Optical interference, contrast-enhanced electroluminescent device," *Appl. Opt.*, vol. 31, no. 28, pp. 5988–5996, 1992.
[11] J. Virginia, "iFire's development path to large, inexpensive FPDs for television," *Inform. Display*, vol. 17, no. 5&6, pp. 16–20, 2001.
[12] E. Hecht, *Optics*, B. Spatz, Ed. Reading, MA: Addison-Wesley, 1974.

Jason Heikenfeld (M'99) recieved the B.S. and Ph.D. degrees from the University of Cincinnati, Cincinnati, OH, in 1998 and 2001, respectively. His major was electrical engineering with minors in both photonics and physics. His doctoral study was supported by the University of Cincinnati Distinguished Graduate Assistantship. His doctoral research concentrated on novel inorganic electroluminescent display devices based on rare earth-doped GaN.

He is now a Research Scientist with Extreme Photonix Corp., Cincinnati. His main duties at Extreme Photonix involve leading the development of electroluminescent devices for flat panel displays. He has authored and coauthored 20 publications in refereed journals, conference proceedings, and a book chapter. He is an inventor on three pending U.S. patents.

Dr. Heikenfeld is a member of the Society for Information Display, the Materials Research Society, and the American Society for Engineering Education.



Andrew J. Steckl (S'70–M'73–SM'79–F'99) received the B.S.E. degree in electrical engineering from Princeton University, Princeton, NJ, in 1968, and the M.Sc. and Ph.D. Degrees from the University of Rochester, Rochester, NY, in 1970 and 1973, respectively.

In 1972, he 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, he joined the Electrical, Computer and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, NY, where he developed a research program in microfabrication of Si devices. In 1981, he founded the Center for Integrated Electronics, a multidisciplinary academic center focused on VLSI research and teaching, and served as its director until 1986. In 1988, he joined the Electrical and Computer Engineering Department, University of Cincinnati, Cincinnati, OH, as Ohio Eminent Scholar and Gieringer Professor of Solid-State Microelectronics. At Cincinnati, he has built 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 280 publications and over 300 conferences and seminar presentations.