Electroluminescent Devices Using a High-Temperature Stable GaN-Based Phosphor and Thick-Film Dielectric Layer

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Abstract—Red, green, and blue light emission has been obtained from electroluminescent devices on glass using a high-temperature stable (HTS) GaN-based phosphor doped with rare earths (Eu, Er, Tm) and a screen-printed thick-film dielectric layer. The thick-dielectric electroluminescent (TDEL) structure consists of metal/dielectric/GaN/indium-tin-oxide/Corning 1737 glass. The $BaTiO_3$-based $\sim$20–40 μm thick-film dielectric layer has a dielectric constant of $\varepsilon_r \sim$ 500–1000 and breakdown voltage >300 V. Despite the granularity of the dielectric layer, the emission is uniform to well-below pixel dimensions (<10 μm). Red GaN:Eu TDEL operated at 240 V and 1 kHz exhibits a luminance of 35–40 cd/m^2. Under 140 lux illumination, the TDEL device structure exhibits a contrast ratio of 5:1 at 120 V, 1 kHz biasing, without the assistance of contrast-enhancement techniques. Accelerated aging tests of TDEL devices show 60 Hz operating lifetimes exceeding 1000 h at >95% brightness. The TDEL structure has several advantages over current thin-film and thick-dielectric electroluminescent structures in flat panel display applications.

Index Terms—Electroluminescence, GaN, phosphor, thick dielectric, thin-film electroluminescence (TFEL), display.

Fig. 1. Photographs of light emission from GaN:RE TDEL devices: (a) red GaN:Eu at 621 nm; (b) green GaN:Er at $537/558$ nm; and (c) blue GaN:Tm at 477 nm. The transparency of the metal/GaN:Er/ITO/glass substrate structure is revealed in the absence of the thick-film dielectric layer (d). The emitting area measures 5 mm in diameter, and the paper background uses 8 pt. Times New Roman font.

I. INTRODUCTION

FLAT panel displays (FPD) based on thin-film electroluminescence [1] (TFEL) of inorganic phosphors such as ZnS:Mn/SrS:Ce can provide high white brightness [2] ($\sim$150 cd/m^2) along with outstanding reliability [3] (only 10% brightness loss at $\sim$50 000 hrs) and good efficiency ($\sim$5 lm/W). Fabrication of a TFEL structure is inherently less complex than that of other large screen FPD technologies such as liquid crystal, plasma, and field emission displays. TFEL devices utilize structures which consist of a sequence of materials: metal/dielectric/phosphor/dielectric/indium-tin oxide (ITO)/glass substrate. Large area (1–10 in^2) capacitive TFEL devices with loads up to 100's of nF can be biased with inexpensive ($\sim$\$2 US) high voltage CMOS drivers which supply high bipolar voltages ($\pm$120–240 V$_p$) at low current (100–1000 Hz). The photographs contained in Fig. 1 show EL devices which use rare earth-doped GaN phosphors [4] on glass substrates. The three primary colors are obtained from GaN:Eu for red, GaN:Er for green, and GaN:Tm for blue emission.

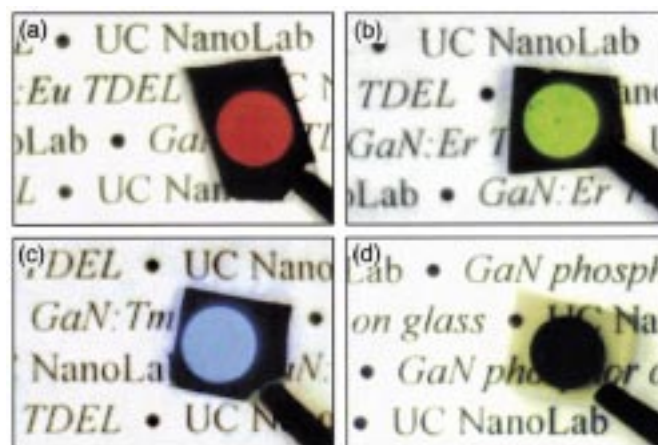Efficient coupling of voltage and, therefore, electric field (1–2 MV/cm) to the phosphor layer in a standard TFEL device [Fig. 2(a), (b)] requires the difficult task of depositing dielectrics that are free of pinholes and other defects and exhibit a high dielectric constant ($\varepsilon_r \sim$ 20–30) and/or high breakdown field (4–7 MV/cm). Furthermore, use of these thin-film dielectrics places constraints on the substrate/film surface roughness since sharp peaks create high-field points that can catastrophically break down the dielectric layers. Therefore, diffuse outcoupling [5] (scattering) of light is limited if reliability is to be preserved. Recently, a new EL structure [Fig. 2(c)] has been developed [2], [6], which provides improved light outcoupling, high-voltage reliability (300–500 V), high capacitance ($\varepsilon_r \sim$ 1000's for dielectric layer), and simple high-yield screen-printing processing of a thick-film (10's μm) dielectric layer. This *inverted* thick-film dielectric EL device (I-TDEL) is structurally superior to TFEL in diffuse light outcoupling, capacitance, ease of large area fabrication, and is being strongly pursued for applications such as flat display high-definition television. However, I-TDEL requires formation of the opaque thick-film dielectric layer *before* a ZnS:Mn/SrS:Ce phosphor layer is deposited. This is because the ZnS:Mn/SrS:Ce phosphor is incompatible with the temperature required (800–900 °C) and byproducts produced during the firing cycle [7] of the thick-film dielectric layer. Since the thick-film dielectric layer is semitransparent at best, the advantage of light emission through a glass substrate is
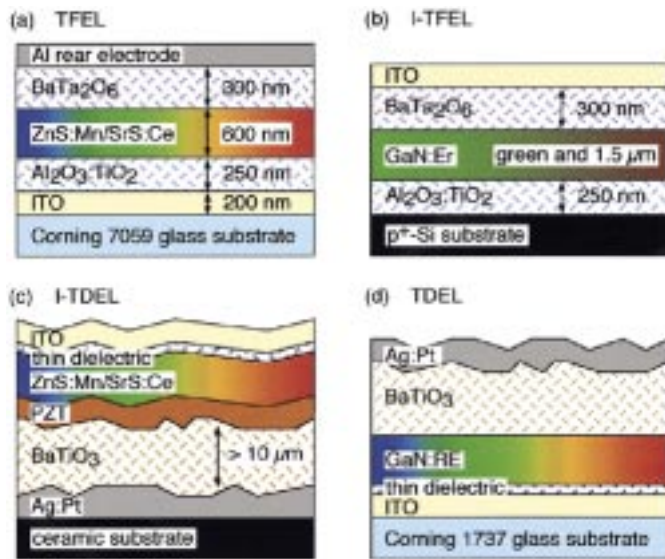
Fig. 2.   Schematic diagrams of example EL structures: (a) TFEL; (b) I-TFEL; (c) I-TDEL; and (d) TDEL. All devices are operated with an alternating voltage source and can be used for display applications while (b) can also be utilized as a 1.5 μm emitter integrated on Si. The thin (<100 nm) dielectric layers of (c) and (d) are optional in the device structure.

not available (hence, the inverted structure). Also presenting difficulty, the surface roughness (~ 1 μm) of the thick-film dielectric layer is inadequately smooth for thin-film (~ 1 μm) phosphor layer deposition. Therefore, prior to phosphor deposition the surface must be smoothed by an additional planarization layer. This usually takes the form of sol-gel dip-coating applications [8] of thin-film dielectric ($\varepsilon_r \sim 1000$) layers such as lead-zirconate-titanate (PZT). In this paper we present a *noninverted* thick-film dielectric electroluminescent (TDEL) structure formed on glass substrates which is rendered possible by implementing a high-temperature and chemically stable (HTS) rare-earth-doped GaN phosphor [4], [9] [Figs. 1, 2(d)]. The structure shown in Fig. 1(d) reveals the transparency of the GaN:Er/ITO/glass substrate structure in the absence of the opaque thick-film dielectric layer. The TDEL approach combines key advantages unique to TFEL and I-TDEL into a single FPD device. This structure is a continuation of our pursuit [9], [10] of FPDs and 1.5 μm (Er) emitters based on GaN-based phosphors.

II. FABRICATION

The TDEL structures were formed on Corning 1737 glass substrates which have a thermal strain point of 666 °C, sufficiently above the ~ 600 °C substrate temperature used during GaN phosphor deposition. The GaN:RE film quality was similar to that reported [10] for p-GaN:Er/a-Al$_2$O$_3$/c-Si. Corning 1737 is a widely utilized display glass [11] due to its compatibility with low temperature (500–600 °C) poly-Si processing used for active-matrix liquid crystal displays. The thick dielectric can tolerate slight substrate surface defects. Therefore, the TDEL structures are fabricated on industrial grade 1737 glass, which is $\sim 1/3$ the cost of display grade 1737. Approximately 1 μm thick GaN HTS phosphor films were

deposited by solid-source molecular beam epitaxy (MBE) onto ~ 300 nm ITO-coated 1737 glass substrates. MBE is utilized as a phosphor layer research tool for the TDEL device because of its flexibility. Future large area deposition can be carried out by evaporation, sputtering, or plasma-enhanced CVD. For example, undoped GaN deposition by reactive plasma excitation on glass substrates has been previously reported [12]. Following phosphor deposition, one or two layers of Dupont 5540 dielectric paste [7] were screen printed through a 200 lines/in, 2.1 mm diameter wire mesh. The 5540 paste contains BaTiO$_3$ along with fluxing agents that facilitate low temperature (<900 °C) sintering of the dielectric. In order to preserve compatibility with the glass substrate, a special printing/firing sequence was implemented in order to significantly reduce substrate shrinkage/warpage while maintaining high capacitance. The resulting dielectric layer had a thickness of 20 or 40 μm (1 or 2 prints), breakdown strength >300 V, and a dielectric constant of $\varepsilon_r \sim 500$–1000. The thickness of the dielectric layer can be reduced by screen printing through a 1.1 mil wire diameter mesh with higher mesh count.

Thick-film back electrodes can be screen printed with a resolution limit of less than 100 μm. Use of a single firing cycle *after* the final thick-film back electrode is deposited on a densified (but not fully sintered) dielectric layer eliminates shrinkage/warpage difficulties with pattern alignment and vacuum chucking in an automated fabrication line. Video rate operation is inherent to passive matrix addressed AC-EL displays. Since the very small thin film features associated with active matrix technology need not be utilized, issues with glass substrate shrinkage are greatly reduced. With development of lower firing temperature dielectrics, much higher dielectric constant ($\varepsilon_r > 1000$) and/or reduced substrate shrinkage/warpage are envisioned. The thick-film dielectric layer could also be formed by multiple coatings (up to ~ 10 μm) of PZT sol-gel [8], which requires a final firing temperature of ~ 700 °C in order to achieve a dielectric constant of ~ 1000. A reduced dielectric firing temperature would also allow for compatibility with a larger variety of HTS phosphors. During high temperature firing of the dielectric layer, a HTS phosphor should be chemically and structurally stable, or at least structurally stable with implementation of a diffusion barrier. Other inert oxide [13] and nitride [14] phosphor systems such as green-emitting Ga$_2$O$_3$:Mn (1.7 lm/W) are likely to be compatible with the high-temperature firing cycle of dielectric layer.

III. STRUCTURE CHARACTERIZATION

An SEM photograph of a BaTiO$_3$/GaN:Er/ITO/glass substrate structure is shown in Fig. 3(a). The sintered thick-film dielectric layer is granular with high porosity. As the firing temperature and/or duration is increased, the individual granules decrease in number, increase in size, the layer further densifies, and the dielectric constant increases. The GaN/ITO layers are structurally intact after firing the dielectric layer [Fig. 3(b)]. No emission spatial variation due to the granular nature of the thick-film dielectric layer was observed. However, this is not the case for an inverted structure [Fig. 1(c) without PZT layer] where spatial variation of emission greatly decreases
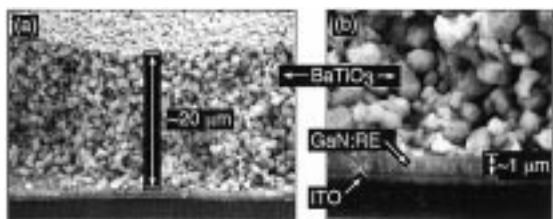
Fig. 3. (a) SEM photograph of a BaTiO$_3$/GaN:Er/ITO/glass substrate structure and (b) close-up of the BaTiO$_3$/GaN:Er/ITO interface .
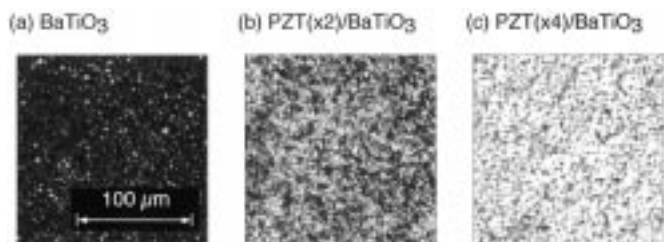

Fig. 4. High-resolution photographs of (a) white-light illuminated (normal incidence) thick BaTiO$_3$ film, (b) BaTiO$_3$ with two sol-gel coatings of PZT, and (c) BaTiO$_3$ with four sol-gel coatings of PZT. The increased reflectivity with an increasing number of PZT layers is a measure of increasing surface smoothness.
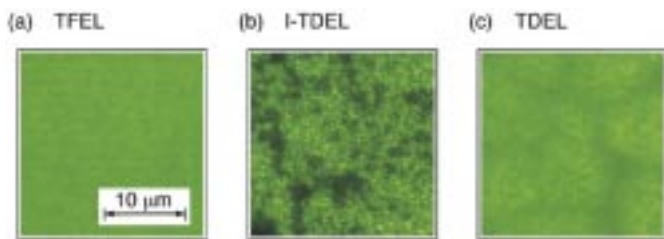

Fig. 5. High-resolution photographs of emission from GaN:Er EL structures: (a) TFEL; (b) I-TDEL; and (c) TDEL. For the I-TDEL structure, the PZT planarization layer was intentionally not included in order to reveal the poor luminance performance of the phosphor layer when directly deposited on the granular thick-film dielectric layer.

device brightness. Therefore, for the I-TDEL structure the thick dielectric must be smoothed by additional processing. This usually takes the form of sol-gel dip-coating applications. The effect of smoothing the rough thick-film dielectric layer by application of several PZT solgel spin coatings is shown in Fig. 4. Up to 4 PZT layers were applied. Each PZT layer was applied by spin coating at 3000 rpm and rapid firing at 600 °C, followed by a final 700 °C firing of the resulting stack of PZT layers. With four PZT coatings the surface roughness was reduced by an order of magnitude and the surface normal reflectivity increased as shown in Fig. 4. We observed that the sequential firing required for formation of the PZT layers can reduce high voltage device reliability (<100 V) due to formation of cracks in the thick film dielectric layer. The TDEL device we present here requires no such additional thick dielectric surface processing in order to achieve spatially uniform phosphor light emission. As shown in Fig. 5, the green GaN:Er EL emission from the TDEL device is highly uniform, nearly as good as that of a TFEL structure and much superior to that of a I-TDEL structure without the planarization layer.

Dielectric	ε_d	$E_{d,br}$ (MV/cm)	t_d (μm)	ε_d / t_d	$\varepsilon_o \varepsilon_d E_{d,br}$ (μC/cm^2)	V_{th} [a] (V)
SiO$_2$	4	8	0.2 (x2)	10	3	125
BaTa$_2$O$_6$	23	4	0.3 (x2)	38	8	71
Al$_2$O$_3$:TiO$_2$	18	6.0	0.2 (x2)	45	10	68
BaTiO$_3$ [b]	2000	~0.1	30	67	19	62
BaTiO$_3$ [c]	1000	~0.1	20	50	10	66

[a] for $E_{p,br}$ = 1 MV/cm, t_p = 0.5 μm, ε_p = 8
[b] for I-TDEL of Fig. 2c
[c] for TDEL of Fig. 2d

IV. THIN VERSUS THICK FILM DIELECTRICS

A comparison of dielectric constant and breakdown strength for various thin and thick film dielectrics is shown in Table I. The thick dielectric results are typical values achieved in our lab with I-TDEL and TDEL GaN:RE devices, whereas the thin film dielectric results are for general TFEL devices. Shown in Table I are example layer thickness values (for high voltage reliability), dielectric constant/thickness ratio (capacitance per unit area), theoretical maximum charge capacity, and voltage required in order to apply 1MV/cm field to an EL device with a 500 nm GaN:RE phosphor layer ($\varepsilon_p \sim 8$). An increased dielectric constant/thickness ratio correlates with increased current flow in the device and a resulting increase in EL brightness. The threshold voltage for light emission from the EL device occurs when there is electrical breakdown of the phosphor layer, typically at an electric field of the order of $\sim$1 MV/cm. The threshold voltage in a TFEL device is determined primarily by the dielectric layer capacitance and by the density and binding energy of electron traps at the dielectric/phosphor interface. Lowering of the threshold voltage reduces complexity of electrical driving circuitry. Considering dielectric layer capacitance only, the threshold voltage can be calculated from constant electric flux density (product of electric field intensity and dielectric constant) across dielectric (ε_d) and phosphor (ε_p) layers, and voltage across each layer as the product of electric field and layer thickness (t_d or t_p). The resulting relation for threshold voltage is then

$$V_{\text{th}} = [1 + (\varepsilon_p t_d)/(\varepsilon_d t_p)]E_{\text{th}}t_p \qquad (1)$$

with $E_{\text{th}} = 1$ MV/cm, $t_p = 500$ nm, $\varepsilon_p = 8$ used for the examples in Table I. The BaTiO$_3$ dielectric constant and layer thickness listed in Table I are exemplary for I-TDEL and TDEL devices of Fig. 2(c) and (d), respectively. BaTiO$_3$ in TDEL will have a lower dielectric constant since it must be fired at reduced temperature in order to maintain compatibility with the glass substrate. However, for TDEL a thinner dielectric may be used

due to increased dielectric layer uniformity when printed on a smooth surface. With our GaN:RE I-TDEL devices, forming a thick film dielectric layer on a rough thick film metal electrode and multi-step processing after thick dielectric firing requires an increased dielectric thickness in order to maintain high voltage reliability. Both thick-film dielectric formats (I-TDEL and TDEL) possess clear electrical advantages over the widely utilized thin-film dielectrics. Beyond threshold voltage and capacitance, thick dielectrics possess strong advantages in display panel fabrication. Scaling thick film dielectric screen printing and oven firing to large panels ($>17''$) is more easily achieved than large-area sputtering of $BaTa_2O_5$ or atomic layer epitaxy deposition of Al_2O_3:TiO_2. Furthermore, formation of thick-film dielectrics does not require clean room conditions (or vacuum chamber for that matter) due to insensitivity to normal particulates which would cause premature breakdown in thin film dielectrics. There is a tradeoff between dielectric firing temperature and resulting dielectric constant. For example, thick film dielectrics with $\varepsilon_d > 30$ can be processed at low temperature on plastic substrates (for powder EL devices), whereas using high-temperature stable ceramic substrates allows for very high capacitance ($\varepsilon_d \sim 1000$–$20\,000$) thick dielectric films. With improvements in $BaTiO_3$ paste composition, high dielectric constant ($\varepsilon_d = 2000$) could be achieved at firing temperatures compatible with glass substrates. This would result in improved TDEL $BaTiO_3$ performance ($\varepsilon_d/t_d = 100, V_{th} = 58$ V, $\varepsilon_d\varepsilon_d E_{d,br} = 20 \ \mu C/cm^2$). A dielectric constant increase to $\sim$2000 in conjunction with lower firing temperature is ideally desired. An increase in dielectric constant can also be achieved through use of higher firing temperature if higher thermal strain point sheet drawn glasses [15] are used such as Corning 1729 (800 °C). It should be noted that most EL phosphors benefit in luminous efficiency from higher phosphor annealing temperatures allowed by high thermal strain point glass. However, utilizing a reduced firing temperature dielectric is likely the best avenue of improvement if display manufacturing costs are considered.

V. ELECTRO-OPTIC CHARACTERISTICS

The luminance versus voltage characteristic is plotted for TDEL with a $\sim$1 μm-thick GaN:Eu phosphor in Fig. 6(a). GaN:Eu TDEL has shown maximum brightness values of 37 cd/m^2 at 240 V and 1 kHz and an excellent red chromaticity with 1931 Commission Internationale d'Eclairage (CIE) coordinates $x = 0.69, y = 0.31$. A thinner $\sim$500 nm GaN:Eu phosphor layer exhibits $\sim$25 cd/m^2 at a much reduced peak voltage of 120 V. Luminance-frequency plots are shown for GaN:Er and GaN:Eu TDEL devices in Fig. 6(b). The onset of frequency saturation for GaN:Eu emission above 1 kHz confirms that the GaN:Eu emission lifetime is very long ($\sim$200 μs). The shorter lifetime GaN:Er ($\sim$5–10 μs) emission follows a saturation trend similar to that previously reported [10]. The Eu-, Er-, and Tm-doped GaN phosphors have not yet been fully optimized and we expect the maximum luminance from the phosphor set to increase significantly and allow standard electrical biasing at $\sim$60–240 Hz. This is based on several potential improvements, such as reduced scattering of
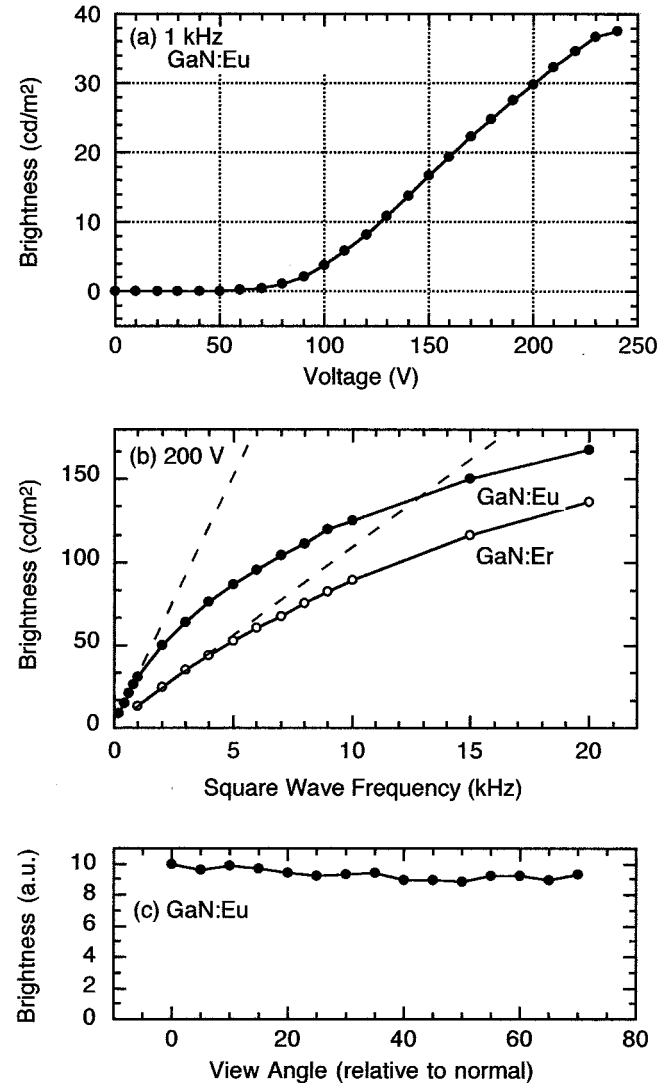

Fig. 6. Brightness characteristics of GaN:RE TDELs: (a) square wave voltage dependence at 1 kHz; (b) square wave frequency dependence at a constant peak voltage of 200 V for GaN:Eu and GaN:Er TDEL; (c) view angle dependence for GaN:Eu TDEL at 200 V, 1 kHz. For (b), the dotted lines represent the expected linear increase in luminance without frequency saturation effects.

hot electrons at GaN point defects. Further luminance increases are also envisioned through doping a GaN phosphor layer with luminescent activators (Mn, Tb, Cu) possessing stronger oscillator strengths. The low luminance-voltage slope [10] shown in Fig. 6(a) is not favorable for row-column multiplexing [1] in display operation. Possible solutions for increasing the luminance-voltage slope include modifying the charge trapping characteristics at the GaN:RE/dielectric interface or using a ZnS buffer layer between the GaN:RE phosphor and dielectric. A steep luminance-voltage slope coupled with low threshold voltage would be ideal for a multiplexed address scheme. However, it should be noted that in order to achieve gray-scale capability the luminance-voltage slope should not be too steep for adequate brightness modulation by the display drive circuitry.

Unlike light subtractive liquid crystal displays, light emissive displays inherently possess wide view angles. As shown in Fig. 6(c) TDEL also possesses a wide view angle. A minor
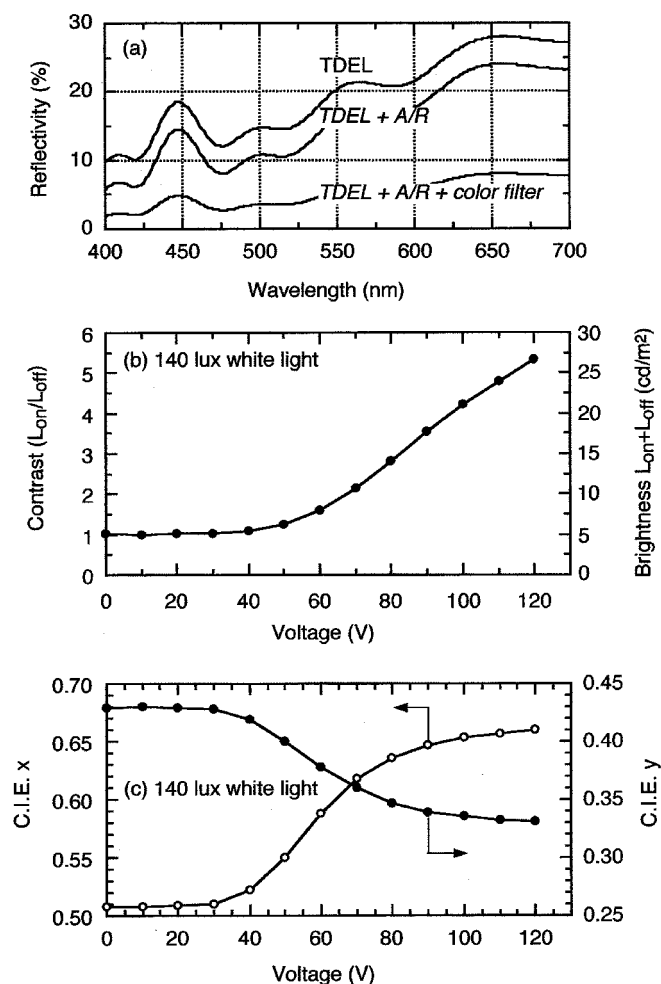
Fig. 7. Reflectivity versus wavelength (light incident normal to the surface) of a TDEL and expected reflectivity of a TDEL device with contrast enhancement techniques (a). GaN:Eu TDEL contrast versus applied voltage at a bias frequency of 1 kHz in a white light illuminance of 140 lux (b). Color saturation (C.I.E. chromaticity coordinates) versus applied voltage at a bias frequency of 1 kHz in a white light illuminance of 140 lux (c).

oscillation in brightness with view angle is due to thin film interference effects within the EL stack. Interference effects are more easily observable for spectrally narrow light emission (full width at half maximum of ~6 nm for GaN:Eu) but are reduced through slight roughening of the thin film layers.

VI. DEVICE CONTRAST

Since the thin film layers and substrate are transparent to visible light, the thick film dielectric layer determines the color background of the TDEL device. With increasing firing temperature and/or firing duration the thick dielectric layer color progresses from light brown, to dark brown, to dark gray after complete sintering. The reflectivity of ambient light from the thick dielectric layer determines the device contrast ratio (emitted brightness/brightness reflected from ambient light). Reflectivity versus wavelength at surface-normal light incidence for a TDEL device is shown in Fig. 7(a). The calculated reflectivity with additional contrast enhancement techniques is also shown in Fig. 8(a). Use of a commercial anti-reflective (A/R) film such as
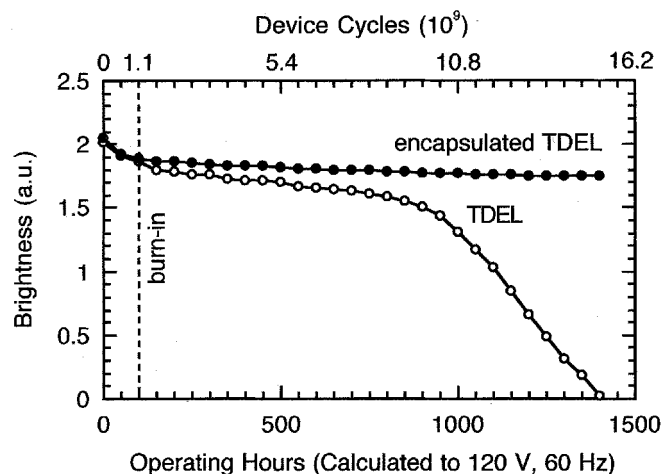

Fig. 8. Brightness versus operating hours at 60 Hz excitation. The accelerated testing results were extrapolated from high-frequency excitation to 60 Hz excitation. Accelerated tests were performed on a TDEL device in 40% relative humidity with and without use of a hermetic encapsulant.

MgF on the front glass surface would eliminate much of the 4% Fresnel reflection. Color filters would decrease reflectivity to ~1/3 of its original value. Color filters allow only a narrow band of wavelengths to pass (such as red, green, or blue band). The filter would be chosen to match the phosphor emission wavelength so that device emission brightness is not sacrificed while a significant portion (~2/3) of ambient light is absorbed. Device contrast for TDEL was measured and plotted in Fig. 7(b) as a function of applied voltage. The measurements were performed under the normal ambient fluorescent lighting of our laboratory. The illuminance incident on the device (measured in lux or lumen (lm) per m^2) was measured with a 99.9% diffuse (Lambertian) reflection standard which reflected a luminance of ~45 cd/m^2. Assuming perfectly diffuse reflection, the measured luminance in cd/m^2 (lm/m^2/steradian) is translated to illuminance in lux (lm/m^2) by multiplying by π. As shown in Fig. 7(b), even without implementation of any contrast enhancement techniques, a TDEL device with a ~500 nm GaN:Eu phosphor layer and under 140 lux illumination exhibits a contrast ratio of 5:1 at 120 V and 1 kHz biasing. Efforts are underway to increase contrast several fold through modification of the thick film dielectric and adjacent thin film layers. As shown in Fig. 7(c), within the same voltage range up to 120 V, the GaN:Eu TDEL chromaticity saturates to red.

Diffuse outcoupling (scattering) of light should increase the device brightness as the surface roughness is increased for either the thin-film phosphor, the transparent electrode, or the glass substrate. Unlike the situation for TFEL, in a TDEL structure the surface roughness can be adjusted to an optimum value without concerns of catastrophic breakdown of the dielectric layer(s) at high field points. However, due to diffuse reflection, increased diffuse outcoupling will at some point result in an unwanted reduction of device contrast in bright lighting conditions. For the TFEL devices of Fig. 2(a) and (b), this is generally not a problem. For the I-TDEL device of Fig. 2(c), this is a potential problem since vacuum deposited (after PZT layer) thin film layers reproduce the roughness of the surface they are deposited on. Without proper planarization by the PZT layer, the

combination of diffuse reflectance from the rough thick dielectric layer and rough thin film layers can result in large diffuse reflectivity and poor I-TDEL device contrast in bright ambient lighting. In the TDEL device of Fig. 2(d), the ITO, and thin film dielectric, and phosphor layers can be as smooth as those of TFEL devices resulting in diffuse reflection from only the thick film dielectric.

VII. ISSUES FOR DISPLAY USAGE

Some further issues toward practicality of TDEL devices for commercial flat panel displays are discussed. Accelerated TDEL aging tests are plotted in Fig. 8. TDEL devices operated in 40% humidity without a hermitic encapsulant have shown 60 Hz operation in excess of 1000 hrs at $>$50% initial brightness. Also shown in Fig. 8, preliminary results with a hermetic encapsulant have shown 60 Hz operation in excess of 1000 hours at $>$95% initial brightness. For the TDEL devices, rapid brightness reduction of the TDEL device occurs due to degradation of electrical contact between device layers. Once electrical contact degradation is corrected, operational lifetimes extend to $>$10 000 hrs at $\sim$50% brightness. With device structure improvements we envision that GaN-based TDEL can meet or exceed the operational lifetimes ($>$50 000 hrs) shown for ZnS:Mn since GaN is a very stable host and the thick film dielectric is reliable up to 300–500 V. In terms of pixel resolution, TDEL has the capability to be fabricated with resolutions appropriate for high definition television (HDTV) or high resolution monitors. Given an HDTV display (1400×800) with a $34''$ diagonal and $\sim$16:9 aspect ratio ($W \times H$), a pixel fill factor (pixel area/pixel separation area) of > 80% can theoretically be achieved by metal electrode screen printing through high resolution screen and emulsion. This assumes row-column matrix addressing and red, green, and blue subpixels, which are located within ITO (column) electrode dimensions. Even higher resolutions are possible using photo-patternable thick-film materials [16] such as DuPont Fodel composition, which has been shown to achieve $\sim$40 μm metal lines. Maintaining standard drive circuitry and reducing power consumption for large panels could be achieved by driving a single panel with two or four submatrices of row-column electrodes.

VIII. CONCLUSION

In summary, the TDEL approach possesses some clear advantages over TFEL and I-TDEL structures. Improved viability of TDEL should result from the development of lower firing temperature ($\sim$600–700 °C), screen-printable thick-film dielectric pastes. Nitride- and oxide-based phosphors are most compatible with the TDEL structure reported here. We envision that nitride and/or oxide phosphor TDEL could replace some sulfide phosphor TFEL applications if adequate luminance performance ($\sim$1 lm/W) can be achieved at acceptable phosphor deposition (< 600 °C) or annealing (< 800 °C) temperatures. Particularly exciting is the prospect of a TDEL device structure with 1

lm/W efficiency and vacuum-free fabrication (sol-gel thin film and screen-printed thick-film). Similar to the potential [2] of I-TDEL, with such advances, TDEL could be strongly considered for applications such as flat TVs.

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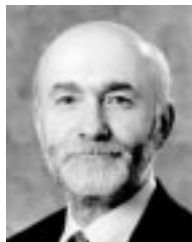
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