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High luminance and efficient GaN:Eu inorganic EL devices for monochromatic display applications

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Abstract

In this paper we report GaN:Eu AC-TDEL devices with high luminance and high efficiency levels obtained through optimized phosphor growth techniques and device structure. The GaN:Eu phosphor is grown using *interrupted growth epitaxy (IGE™)*. An improved thick dielectric layer for inorganic electroluminescent EL display devices has been achieved through a composite high-κ dielectric sol-gel/powder route. The reduction in thick dielectric porosity has improved the homogeneity of the electric field applied to the phosphor layer, resulting in a steeper luminance-voltage slope with a maximum luminance of ~1,000 cd/m^2. Furthermore, the reduction in porosity has also decreased the diffuse reflection of the thick dielectric, which when pigmented, exhibits a diffuse reflectivity of <2% resulting in high display contrast.

Introduction

Inorganic electroluminescent devices (ELDs) have traditionally utilized thin film dielectrics (TFELs) to provide the electrical isolation and high electric field across the phosphor layer. The use of thick dielectric layer[1] (TDEL) has eliminated the stringent fabrication conditions needed by TFELs to prevent premature device breakdown caused by high field points in thin insulating layers. Furthermore, the TDEL devices have demonstrated much higher contrast levels compared to TFEL devices.

The luminous intensity, efficiency of the emission process, and chromaticity of the emission are the primary characteristics of ELDs. The luminance, a measurement of power, is frequently translated by the human vision sensitivity. The measurement and the interpretation of efficiency is more complex and fundamentally can be considered to be the combination of three factors: excitation, radiative and out-coupling efficiency[2].

GaN:Eu TDEL Devices

The feasibility of GaN:RE phosphor for AC-TDEL devices in display applications has been demonstrated[3]. Recently, we have been successful in enhancing both the luminance and efficiency of GaN:Eu TDELs (figure 1). Thin (~100nm) strontium titanate (STO; ε_r~140) films were used as charge trapping thin dielectrics. Research has led to the utilization of sol-gel based lead zirconate titanate (PZT) ceramic layers with high dielectric constant (ε_r~500) and high breakdown field (>0.3 MV/cm) as thick dielectric layer (previously, barium titanate layers were used). The PZT thick dielectric, along with the other thin film layers, has enabled a significantly higher charge (>3μC/cm^2) transport across the phosphor.

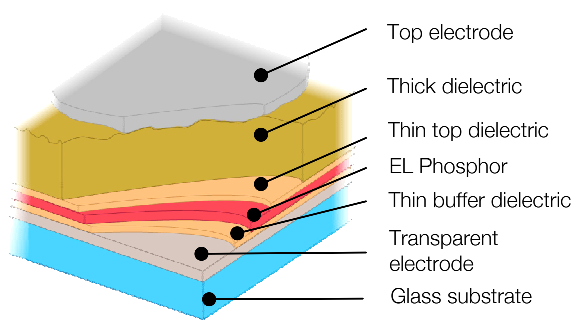

Figure 1. AC-TDEL device structure on glass substrates with PZT based thick dielectric layer.

A novel process is utilized for thick dielectric deposition. Figure 2 contains the SEM photomicrograph of the AC-TDEL device. The thick dielectric layer takes up most of the device cross-section. The thick dielectric layer is deposited using a composite sol-gel technique whereby PZT (PZ26, Ferroperm) ceramic powder was mixed with a sol (metal organic PZT precursor) and a dispersant (KR55, Kenrich Petrochemicals) to yield a slurry, which was deposited on the substrate. Subsequent firing converted the sol to an oxide ceramic, which bound the ceramic powder together and to the substrate.

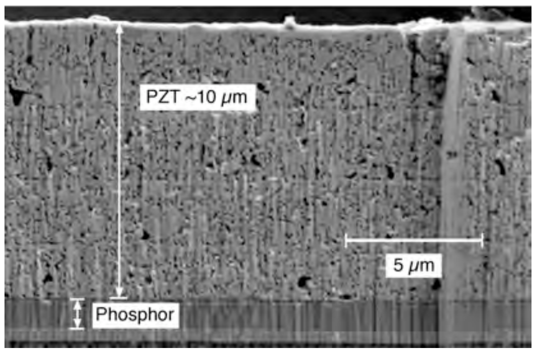

Figure 2. SEM photomicrograph of AC-TDEL device.

GaN:Eu Phosphor Optimization

Solid source MBE system with RF nitrogen plasma source is used for the GaN:RE growth. A new phosphor material growth method, namely, *interrupted growth epitaxy (IGE™)* is used for GaN: RE growth. It is important to point out that the IGE process is a hybrid between conventional MBE and migration enhanced epitaxy (MEE) semiconductor growth techniques. In MBE, all molecular beams are incident upon the growth surface simultaneously throughout the entire growth period, whereas in MEE each individual beam is incident consecutively on to the substrate for rather short periods. In IGE, the growth consists of cycles during which part of the time all beams are incident on to the substrate followed by periods where only selected beams are incident. Furthermore, the cycling times are relatively longer than that used in the MEE.

The key hypothesis that led to the IGE growth technique for GaN:RE material is that in conventional MBE growth the group V material incorporation into the film is much less than that of group III, which in turn can result in a low III/V ratio in the film. In order to eliminate this anomaly, during IGE the film is temporarily nitridized in periodic cycles. The growth is done in a periodic fashion and the shutters of the group III elements are open for a part of the cycle and closed during the rest of the cycle. The optimum conditions for GaN:Eu on glass substrates were found to be 20 min interval with both group III and V are incident followed by a 5 min nitridation. For the results shown in this paper growth cycle was repeated three times.

GaN:Eu TDEL Optical Properties

The $^5D_0$-$^7F_2$ transition in GaN:Eu results in a sharp optical emission around 621nm, with a narrow spectrum width (FWHM ~3nm). We have compared the GaN:Eu phosphor with ZnS:Mn,

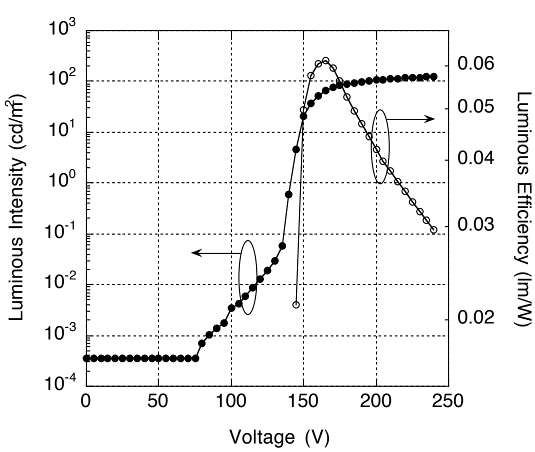

Figure 3. Luminance and luminous efficiency of *Red filtered* ZnS:Mn AC-TDEL

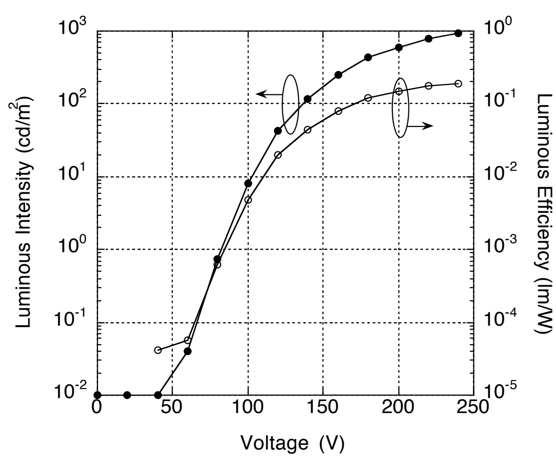

Figure 4. Luminance and luminous efficiency of GaN:Eu AC-TDEL

the industrial standard for TFEL devices, for luminance and device luminous efficiency as a red emitter. ZnS:Mn possesses an EL spectrum with peak around 580nm and FWHM ~91nm. Integrated luminous intensity of ZnS:Mn in the range of 619-625nm (to match spectral emission in GaN:Eu) was considered for comparison.

We have fabricated GaN:Eu and ZnS:Mn devices with the same dielectric layers and thicknesses. The resulting device characteristics (luminance and efficiency) are shown in Fig. 3 and 4. In a direct comparison with ZnS:Mn (red filtered), GaN:Eu clearly demonstrates its superiority as a red emitter. We have measured a maximum red luminance of ~1,000 cd/m^2 for GaN:Eu, whereas only 125 cd/m^2 was obtained from ZnS:Mn filtered red luminance under the same exact conditions. The GaN:Eu luminous efficiency as calculated from the optical measurements peaked at ~0.2 lm/W, while the ZnS:Mn red emission reached a maximum of 0.062 lm/W. The activated lumophore concentration in the GaN:Eu as calculated from the optical characteristics is ~6.2x10^{17} cm^{-3} at ~1,000 cd/m^2. This activated concentration is ~ 0.1% of the total lumophor concentration of ~8x10^{20} cm^{-3}, which in turn provides more latitude to improve in the future. The CIE coordinates for the GaN:Eu red monochrome displays stand well within the industrial standards (x= 0.68, y= 0.31). The high luminance level of GaN:Eu facilitates display applications that require high definition halftones (gray scale). The luminance, efficiency and chromaticity values of the GaN:Eu compared with other leading EL technologies (Table 1) proves that it is an excellent candidate for mono-chrome EL displays.

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EL Phosphor	Red Luminance (cd/m^2)	Red Estimated Efficiency (lm/W)	Organization
ZnS:Mn (*filtered*)	Max. ~350 [1]	*Not Available*	*iFire Technologies*
ZnS:Mn (*filtered*)	L_{50}~97 [4]	η_{max}~ 0.8 [5]	*Planar Int. Ltd.*
CaSSe:Eu (*filtered*)	L_{40}~25 [5]	η_{max}~ 0.2 [5]	*Planar Int. Ltd.*
ZnS:Mn (*filtered*)	L_{40}~90 Max. ~125	η_{40}~ 0.045 η_{max} ~0.06	*UC NanoLab*
GaN:Eu	L_{40}~150 Max. ~1000	η_{40}~ 0.08 η_{max} ~0.2	*UC NanoLab*

Table 1. Red inorganic EL phosphor comparison

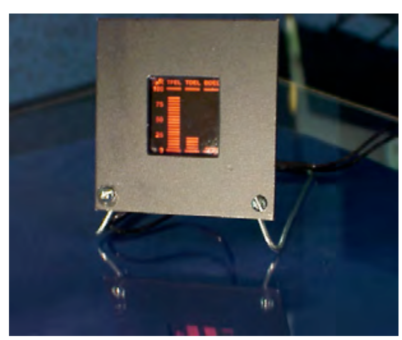

Figure 5. GaN:Eu display prototype.

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