AC Operation of GaN:Er Thin Film Electroluminescent Display Devices

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ABSTRACT

Thin-film electroluminescence has been obtained from GaN:Er deposited directly on amorphous dielectric layers. Electroluminescent device (ELD) structures consisting of a dielectric/GaN/dielectric were formed on p^+-Si substrates. In contrast to previous GaN:Er ELDs which used epitaxial growth conditions on crystalline substrates and were operated under DC bias, these ELDs were operated under AC bias. A maximum luminance value of 300, 60, and 15 cd/m^2 has been achieved from GaN:Er and AlGaN:Er AC-ELDs biased at 180 V and 100, 10, and 1 kHz, respectively. The emission spectra, which originate from Er^{3+} 4*f*-4*f* transitions, consist of dominant visible emission at ~537/558 nm and infra-red (IR) emission at 1.5 μm. A violet emission peak at 415 nm indicates that hot carriers can gain up to ~3 eV energy for an applied voltage corresponding to 1.5 MV/cm applied field. The emitted intensity initially increases linearly with frequency, followed by a trend towards saturation. The frequency for 3 dB reduction from the linear relation is at ~65 kHz for visible emission and ~8 kHz for infrared emission. The saturation trends can be explained in terms of the spontaneous emission lifetimes of the visible (~10 μs) and IR (~1ms) Er^{3+} emissions.

INTRODUCTION

The next generation of flat panel displays (FPDs) is seeking to provide advances in brightness, efficiency, color purity, resolution, scalability, reliability, and reduced cost. One such technology is thin-film electroluminescence[1] (TFEL) of inorganic phosphors. TFEL displays[2,3] can provide high brightness (~150 cd/m^2), outstanding durability and reliability (only 10% brightness loss at ~50,000 hrs). Current inorganic TFEL phosphors are composed of II-VI wide bandgap semiconductor (WBGS) hosts (ZnS, SrS) which provide hot carriers (>2 eV) which impact excite luminescent centers (Mn, Tb, Ce, Cu). Sufficient hot carrier generation requires high field strengths (>1 MV/cm) exceeding the breakdown field of the phosphor thin film. An AC-biased dielectric/phosphor/dielectric layered structure[4] allows reliable high field operation by current-limiting the electrical breakdown of the phosphor layer. Recently, a new full-color TFEL phosphor system based on rare earth (RE) elements incorporated into the III-V wide-bandgap semiconductor (WBGS) GaN[5] has demonstrated high brightness (500-1000 cd/m^2) DC operation of GaN:Er films grown on crystalline Si and sapphire substrates. GaN incorporates very well[6] the trivalent RE ions (Pr, Eu, Er, Tm) and has excellent high field transport characteristics[7]. In this work we demonstrate AC-TFEL of a dielectric/GaN:RE/dielectric structure. We also report on the deposition of GaN:RE on amorphous substrates and on the demonstration of an “all-nitride” AC-ELD (using Si_3N_4 or AlN dielectric layers, and GaN:RE or AlGaN:RE phosphor).

DEVICE STRUCTURE

AC-biased GaN:Er electroluminescent devices[8] utilize the basic structure shown in Fig. 1b. In contrast to previous GaN:Er ELDs (Fig. 1a) which used epitaxial growth conditions on crystalline substrates and were operated under DC bias, these ELDs were operated under AC bias. For a DC-ELD bias current increases with applied voltage (and therefore field) until catastrophic electrical breakdown of the GaN:Er phosphor layer occurs. For an AC-ELD the maximum applied field is determined not by the breakdown field of the GaN:Er phosphor layer but by the dielectric layers. With proper choice of dielectric layers with high breakdown field (MV/cm) and/or high permittivity ($\varepsilon>8$) the maximum applied field can exceed the breakdown field of the phosphor layer. The operational current in an AC-ELD is primarily determined by the combined capacitance of the dielectric layers. GaN:Er AC-ELDs also inherently allow high-field biasing without saturation of the emission intensity. Most *4f-4f* RE^{3+} emissions have long lifetimes since the RE^{3+} transitions are partially forbidden by the parity selection rule. Therefore pulsed excitation (AC-biasing) at a frequency lower than the inverse of the emission lifetime is necessary in order to efficiently operate a GaN:RE ELD. Results on bias frequency saturation of emission from GaN:Er AC-ELDs are discussed later in this paper.

AC-ELD structures were formed on p$^+$-Si substrates and represent an inverted TFEL structure which emits light away from the substrate. These inverted devices have the advantage of Si integration. The substrate temperature during MBE deposition[9] of the GaN:Er was held at ~600-700 °C. Compatibility with standard glass substrates is envisioned for GaN:Er since 500-600°C temperatures are required for poly-Si processing in active-matrix LCD manufacturing. Dielectric layers used for demonstration of these preliminary AC-ELDs are Al_2O_3, AlN, Si_3N_4, SiON, $BaTa_2O_6$, and $BaTiO_3$. AlN, deposited by MBE, is often used as the lower insulator dielectric (closest to substrate) because it has both the advantage of high-temperature stability during GaN:Er deposition and it can be used as buffer layer in order to promote GaN:Er grain growth. The GaN:Er layer thickness ranges from 0.5 to 1 μm. The dielectric layer thickness (>200 nm) and permittivity ($\varepsilon>8$) are such that the AC-ELDs operate reliably and the majority

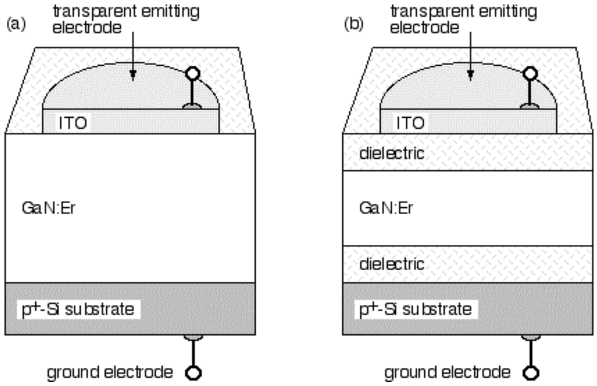

Figure 1. *Basic device structures for DC- (a) and AC-biased GaN:Er ELDs(b) formed on Si substrates.*

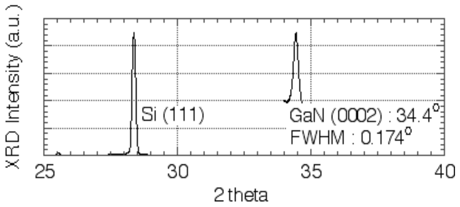

***Figure 2**. XRD spectrum for polycrystalline GaN:Er (600 nm) deposited on amorphous Al_2O_3 (300 nm) on <111> oriented Si.*

of the applied voltage is coupled to the phosphor layer. The surface roughness of the AC-ELD thin films has a strong influence on light outcoupling. The case of polished opaque substrates (Si) with RF sputtered dielectrics/conductors subjects the AC-ELDs to significant light piping (guiding) within the phosphor layer. Light piping has been reported[10] in similar structures resulting in ~5% out-coupling efficiency. Significant improvements in out-coupling efficiency can be achieved by roughening the substrate on which the thin films are deposited on. Although substrate roughness improves the diffuse out-coupling of light, surface roughness on the order of the dielectric layer thickness degrades the reliability of the AC-ELD. If the surface is too rough high-field points are created at surface ‘peaks’ which can result in premature electrical breakdown of the insulating dielectric layers.

The GaN:Er films are polycrystalline with an x-ray diffraction (XRD) linewidth of 0.174° for the (0002) peak (see Fig. 2). An efficient GaN:RE layer requires RE incorporation on the Ga sublattice and reduction of point defects which can significantly cool the hot-electron distribution through non-radiative scattering events [11]. The intense light emission from GaN:RE ELDs can be partially attributed to the ability of GaN to incorporate large concentrations of optically active RE species. In other semiconductor hosts[5] (such as Si, GaAs), high RE concentrations result in quenching of the emission due to degradation of the host material and or RE precipitation. This ability to incorporate large RE concentrations in GaN is surprising when considering the size mismatch between RE ions and the Ga^{3+} cation, which is larger than in II-VI hosts. For comparison some relevant effective ionic radii[12,13] are listed for Er-doped GaN, Si, ZnS, and AlN in Table 1. An X-ray absorption study[6] of GaN:Er reveals that even at high Er concentrations (>0.1 at. %) the great majority of Er ions sit substitutionally on the Ga sublattice.

***Table 1**. Effective ionic radii and coordination number (CN) for Er doped GaN, Si, ZnS, and AlN.*

Ga^{3+}	*0.47*	N^{3-}	*1.44*	Er^{3+}	*0.78*	(CN=4)
Si	*1.18*			Er^{3+}	*1.76*	(CN=10)
Zn^{2+}	*0.60*	S^{2-}	*no data*	Er^{3+}	*0.78*	(CN=4)
Al^{3+}	*0.39*	N^{3-}	*1.44*	Er^{3+}	*0.78*	(CN=4)

EXPERIMENTAL RESULTS

The AC-ELDs were driven with an AVTECH 100 kHz, ±200 V linear amplifier with 50 kΩ output resistance. The luminance values are measured with a Minolta CS-100 Chroma-Meter and a Newport 1830-C optical power meter. The GaN:Er AC-ELDs have a strong Er visible emission spectrum as shown at the top of Fig. 3. The spectrum is taken from an ELD operated with a ±180 V, 10 kHz square wave. At 180 V peak voltage, the peak field applied to the GaN:Er layer in a Al_2O_3/GaN:Er/Al_2O_3 AC-ELD is ~1.5 MV/cm. The infrared (~1550 nm) and two green emission peaks (~537/558 nm) are similar to those reported for epitaxially grown GaN:Er DC-ELDs and originate from the relaxation of the $^4I_{13/2}$ and $^2H_{11/2}$/$^4H_{3/2}$ excited states to the $^4I_{15/2}$ ground state of Er^{3+}, respectively. The infrared (1550 nm) GaN:Er emission originates from relaxation of the lowest excited Er^3 state ($^4I_{13/2}$) and is of interest[14] for optical communications. The spectrum also contains a strong violet peak at ~415 nm ($^2H_{9/2}$) and a weaker ultraviolet peak at 389 nm ($^4G_{11/2}$). TFEL hosts must provide hot carriers with greater than 2 eV energy at an applied field of ~1-2 MV/cm in order to impact excite the luminescent RE dopants. The 415 nm emission corresponds to an energy of ~3 eV, indicating that the carrier energy distribution at 1.5 MV/cm is populated to levels exceeding the requirements[15] for a blue TFEL phosphor (~2.6 eV). At the bottom of Fig. 3 is a qualitative plot of electron energy distribution in GaN at several applied field strengths. The pictured electron distributions are presented accurately in average energy only, as taken from Monte Carlo calculations[7] of high field transport in GaN. The calculations show that at ~2 MV/cm applied field the average carrier energy is equal to that required for exciting blue (2.6 eV) emission. Also plotted in Fig. 3 is an approximate curve for the Er impact excitation cross-section of the $^2H_{11/2}$ level which results in green (~2.3 eV) emission.

The frequency dependence of the visible (537/558 nm) and infra-red (IR) emission (1550 nm) from a GaN:Er AC-ELD is shown in Fig. 4 for 170 V square wave excitation. At low frequency (< 1 kHz) the expected linear relation between frequency and visible and IR emission intensity is observed, with roughly as many photons emitted in the IR as in the green. As the frequency increases beyond 1 kHz there is a clear saturation of the IR intensity. The visible emission intensity also increases sub-linearly with frequency at higher frequencies. One can use the frequency for which a 3 dB reduction from the linear relation occurs as an indicator of the

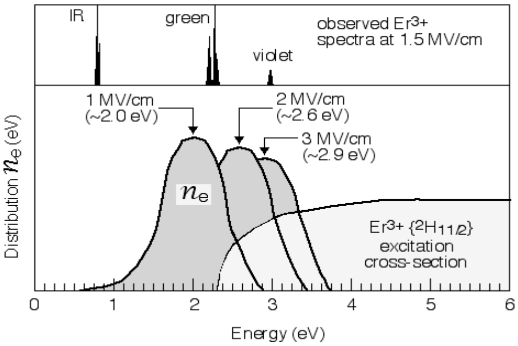

Figure 3 *Qualitative plot of electron energy distribution for 1, 2, and 3 MV/cm fields applied to GaN. The pictured electron distributions are estimated based on average energy only, as determined from Monte Carlo calculations[7] of high field transport in GaN. Also shown is an approximate curve for the Er impact excitation cross-section of the* $^2H_{11/2}$ *level which results in green (~2.3 eV) emission. A corresponding emission spectrum(intensity vs. photon energy) from a GaN:Er AC-ELD biased at 1.5 MV/cm is shown at top. The intensities of the visible and IR peaks are not comparable, while green and violet peaks are directly comparable in intensity.*

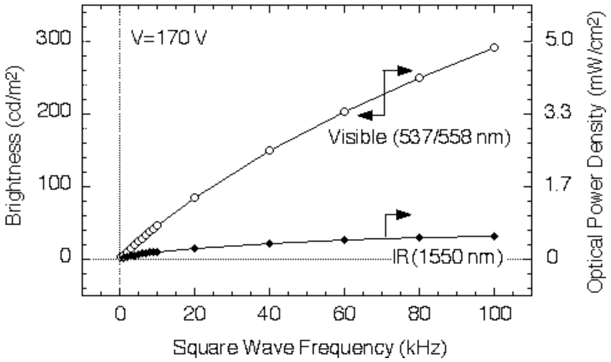

Figure 4 *Brightness and optical power from a GaN:Er AC-ELD vs. square wave frequency.*

onset of this saturation process. From the data of Fig. 4, we obtain 3 dB frequencies of ~65 kHz and ~8 kHz for the visible and IR emission intensities, respectively. The frequency saturation process can be related to the GaN:Er excited state lifetime of each particular transition, which in our case have been measured[16] to be on the order of ~10 µs for the visible green emission and ~1 ms for the 1.5 µm IR emission. At low frequency (<1kHz) an Er atom will have adequate time to radiatively (~537/558 nm) relax from higher excited states to the ground state or to non-radiatively relax to the IR level ($^4I_{13/2}$) and then radiatively relax (1.5 µm) to the ground state. According to this argument the emission intensity will saturate as the frequency exceeds the inverse of the corresponding excited state lifetime. Based on the lifetime argument, saturation in the IR signal should be noticeable at ~1 kHz and at ~100 kHz for the visible signal. The agreement with the 3 dB frequency is fairly good in the case of the visible signal, but not for the IR signal where saturation is observed at higher frequency than predicted.

Luminance-voltage measurements at 1 kHz square wave excitation for $Al_xGa_{1-x}N$ phosphor layers of different Al concentration are plotted in Fig. 5. At 160 V a GaN:Er AC-ELD with no Al content exhibits a luminance of 10 cd/m^2. Introducing 20% Al ($Al_{0.2}Ga_{0.8}N$:Er) improves the device brightness to 12 cd/m^2 and results in a steeper brightness-voltage slope. The

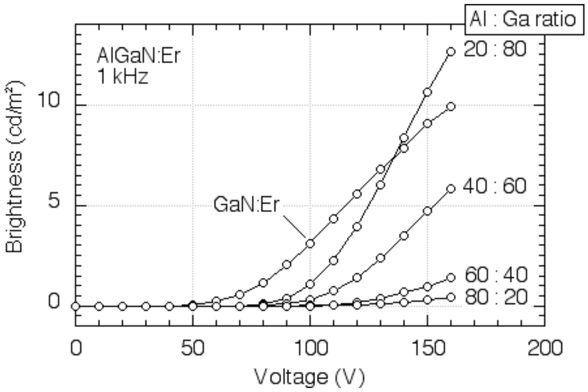

Figure 5 *Brightness vs. square wave voltage for a GaN:Er AC-ELD and AlGaN:Er AC-ELDs. The approximate Al:Ga ratio is calculated from molecular beam partial pressures used during MBE deposition.*

ratio of Al to Ga was calculated from the molecular beam partial pressures of the Al and Ga sources used during MBE deposition. AlGaN:Er has a wider bandgap than GaN:Er and prevents charge flow until fields are at levels high enough (~1 MV/cm) for efficient generation of hot carriers (~2.3 eV). Promising results with green light emission from AlN:Er AC-ELDs[17] has prompted this investigation of $Al_xGa_{1-x}N$:RE phosphors. The lower brightness values observed for the higher Al content (> 40%) samples is partly due to the increase in phosphor breakdown field. If the high Al content AC-ELD is to operate at standard AC-TFEL voltages (120-220 Vp) a thinner AlGaN:Er phosphor layer should be implemented in order to increase the brightness.

CONCLUSION/ACKNOWLEDGEMENT

In this work we have demonstrated AC-TFEL of a dielectric/GaN:Er/dielectric structure. We envision significant improvements in device brightness by improving the GaN-based phosphor and electrical incoupling/optical outcoupling efficiency of the AC-TFEL structure. The authors would to thank P. D. Rack of RIT for many useful discussions on AC-TFEL and M. Garter and D. S. Lee of the UC NanoLab on GaN:Er growth and device operation. This work was supported in part by ARO contract #DAA D19-99-1-0348.

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