

Alternating current thin-film electroluminescence of GaN:Er

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Thin-film electroluminescence has been obtained from GaN:Er deposited directly on amorphous dielectric layers. Electroluminescent device (ELD) structures consisting of metal/dielectric/GaN:Er/dielectric were fabricated on p^+ -Si substrates. In contrast to previous GaN:Er ELDs which used epitaxial growth conditions on crystalline substrates and were operated under direct current bias, these ELDs were operated under alternating current bias. Under bias conditions of 170 peak voltage (V_p) and frequencies of 10 and 100 kHz, the ELDs exhibit a luminance of 50 and 300 cd/m^2 , respectively. The emission spectra, which originate from Er^{3+} $4f-4f$ transitions, consist of dominant green emission at $\sim 537/558$ nm accompanied by violet (415 nm) and infrared ($1.5 \mu\text{m}$) peaks. The violet emission peak indicates that hot carriers can gain up to ~ 3 eV energy for a V_p 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 the visible emission and ~ 8 kHz for the infrared emission. © 2000 American Institute of Physics. [S0003-6951(00)04749-5]

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 electroluminescence¹ (TFEL) of inorganic phosphors. TFEL displays¹⁻³ can provide high brightness ($\sim 150 \text{ cd/m}^2$), outstanding durability and reliability (only 10% brightness loss at $\sim 50\,000$ h). Current inorganic TFEL phosphors are composed of II-VI wide band gap 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 alternating current (ac)-biased dielectric/phosphor/dielectric layered structure⁴ 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 WBGs GaN⁵ has demonstrated high brightness ($500-1000 \text{ cd/m}^2$) direct current (dc) operation of GaN:Er films grown on crystalline Si and sapphire substrates. GaN incorporates very well⁶ the trivalent rare earth ions (Pr, Eu, Er, Tm) and has excellent high field transport characteristics.⁷ In this letter 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 first demonstration of an ‘‘all-nitride’’ ac-TFEL (using Si_3N_4 or AlN dielectric layers, and the GaN phosphor).

The electroluminescent devices (ELD) for this investigation into GaN:RE ac-TFEL utilize the basic structure shown in Fig. 1. The structure consists of a p^+ -Si substrate and the following layers: 300 nm dielectric/600 nm GaN:Er/300 nm dielectric/200 nm metal [indium tin oxide (ITO)]. The dielectrics (Al_2O_3 , AlN, Si_3N_4 , and SiON) evaluated for GaN:Er ac-ELDs have permittivity similar to that of GaN

(~ 8). ELDs with an emitting area of $\sim 1.8 \times 10^{-3} \text{ cm}^2$ had a corresponding operational capacitance of ~ 30 pF. This value is close to what is expected under conditions of electrical breakdown for the GaN:Er layer. The focus in this letter is on a ELD structure which uses ~ 300 nm of radio frequency sputtered Al_2O_3 dielectric layers. The GaN:Er phosphor is deposited by molecular beam epitaxy (MBE) on amorphous insulators under conditions⁸ similar to those previously reported for GaN:Er epitaxy on Si(111) and sapphire. The ac-ELDs were driven with an AVTECH 100 kHz, ± 200 V linear amplifier with 50 k Ω output resistance. The luminance values are measured with a Minolta CS-100 Chroma-Meter and a Newport 1830-C optical power meter.

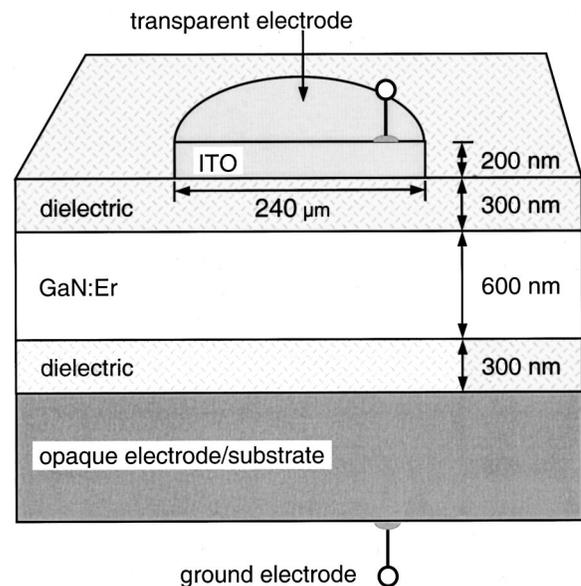


FIG. 1. Diagram of TFEL device structure implemented with polycrystalline GaN:Er as a green emitting phosphor and an ITO dot contact which defines the area ($\sim 1.8 \times 10^{-3} \text{ cm}^2$) of emission. The dielectric layers (ϵ of ~ 8) capacitively couple an alternating voltage to the GaN:Er phosphor layer (ϵ of ~ 8).

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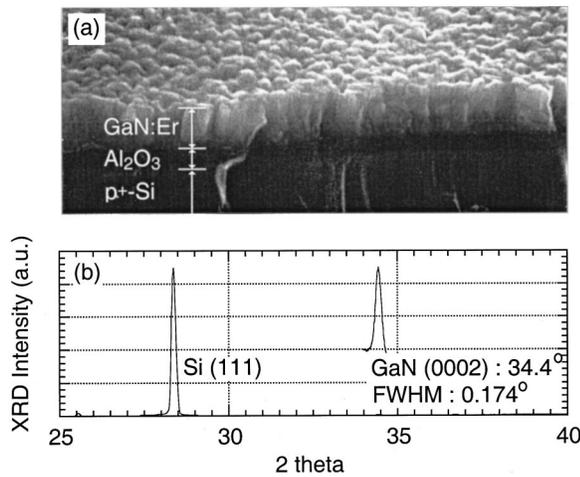


FIG. 2. SEM picture of GaN:Er/Al₂O₃/p⁺-Si structure and corresponding XRD spectrum. The dielectric and GaN:Er layers are marked by white lines. The GaN:Er deposited on the dielectric is generally *c* axis oriented with a (0002) linewidth of 0.174° and exhibits the same green emission witnessed in GaN:Er grown on crystalline Si(111) and sapphire substrates.

The GaN:Er films were deposited at ~700 °C and are polycrystalline with an x-ray diffraction (XRD) linewidth of 0.174° for the (0002) peak. A scanning electron microscopy (SEM) photograph of the Si/Al₂O₃/GaN:Er structure is shown along with the XRD spectrum in Fig. 2. The surface roughness of the GaN:Er film has a strong influence on light outcoupling. Similar to other thin-film ELD structures,⁹ the final Al₂O₃/GaN:Er/Al₂O₃/ITO film stack is subject to significant light piping in the phosphor and dielectrics. Light piping has been reported in similar structures which are opaque at one end (Si) resulting in ~5% outcoupling efficiency.⁹ Improvements in outcoupling efficiency can be achieved by replacing the Si substrate with a mirrored substrate such as Pt-coated alumina.

The GaN:Er ac-ELDs have a strong Er visible emission spectrum as shown in Fig. 3. The spectrum is taken from an ELD operated with a ±180 V, 10 kHz square wave. At 180 peak voltage (*V_p*), the peak field applied to Al₂O₃/GaN:Er/Al₂O₃ layers is ~1.5 MV/cm. The two green emission peaks at ~537/558 nm are essentially identical to

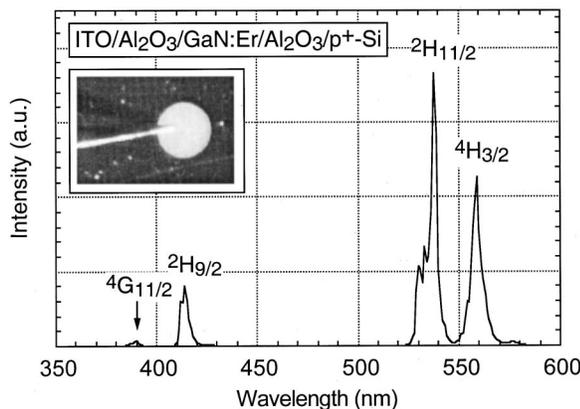


FIG. 3. Electroluminescent spectrum from an ITO/Al₂O₃/GaN:Er/Al₂O₃/p⁺-Si driven by a 180 *V_p* square wave at 10 kHz. All peaks originate from relaxation of Er³⁺ excited states (labeled in plot) to the ⁴I_{15/2} ground state. The Er³⁺ peak at 415 nm indicates hot carriers in the GaN:Er phosphor possess as much as ~3 eV.

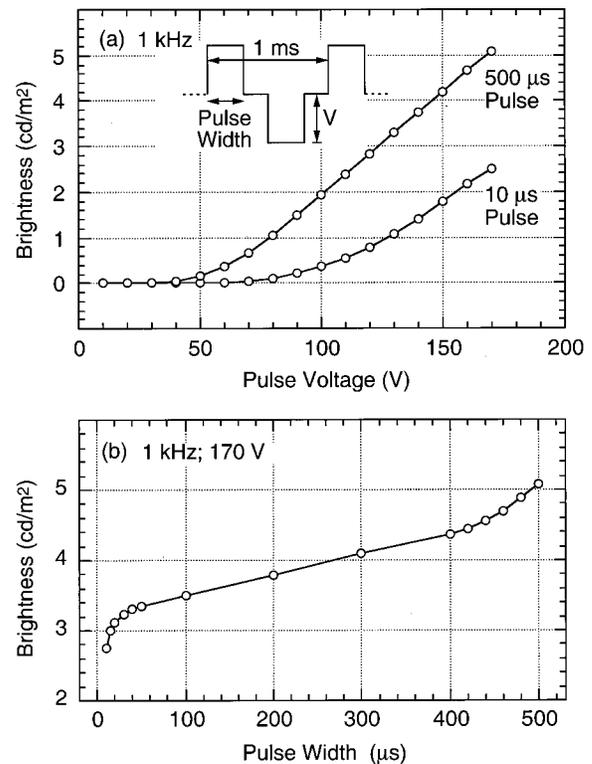


FIG. 4. Brightness (cd/m²) for green (537/558 nm) emission from ac-TFEL operated at 1 kHz as a function of: (a) peak voltage, for 500 μs square wave and for 10 μs bipolar pulse wave form (2% duty ratio); (b) pulse width, for 170 *V_p*.

those reported for epitaxially grown GaN:Er dc-ELDs and originate from the relaxation of the ²H_{11/2} and ⁴H_{3/2} excited states to the ⁴I_{15/2} ground state of Er³⁺. 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}). This 415 nm emission corresponds to an energy of ~3 eV, indicating that the carrier energy distribution is populated to levels exceeding the requirements¹⁰ for a blue TFEL phosphor (~2.6 eV). A similar emission spectrum has been reported¹¹ for AlN:Er ac-ELDs, prompting the investigation of Al_xGa_{1-x}N:RE phosphors.

Luminance-voltage measurements at 1 kHz are plotted in Fig. 4(a) for both square wave (100%) and 10 μs (2% duty ratio) pulse wave forms. A 170 *V_p*, 1 kHz square wave applied to the GaN:Er ac-ELD results in a luminance of 5 cd/m². The effect of wave form pulse width for a fixed frequency on the device brightness is shown in Fig. 4(b). The increase in brightness with pulse width is due to the fact that during most of the pulse duration the electrons are held near the GaN/dielectric interface. When the pulse is off, the electrons which are not trapped at the interface are free to diffuse away. These “wandering” electrons will not be able to achieve full acceleration during the next pulse. By increasing the pulse width, we increase the number of electrons which can reach the necessary energy for impact excitation of the Er ions. The effect of charge trapping can be readily observed by comparing bipolar and monopolar biasing of the device at the same duty ratio. Strong charge trapping leads to a much brighter emission under bipolar biasing. In these preliminary experiments we have observed an increase of 2×

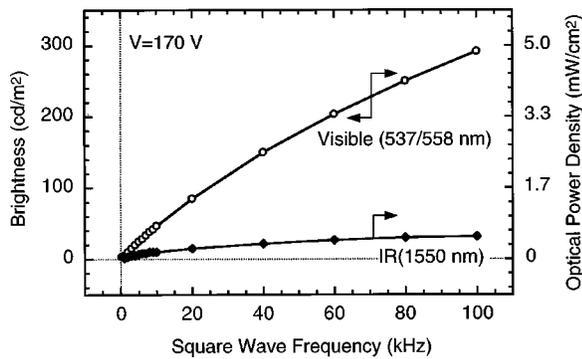


FIG. 5. Brightness (green emission at 537/558 nm) and optical power (green and IR emission at 1550 nm) from ac-TFEL operated at 170 V_p as a function of square wave frequency.

for bipolar versus monopolar operation. This indicates that only a moderate amount of trapping is present.

The frequency dependence of the visible (537/558 nm) and infrared (IR) emission (1550 nm) is shown in Fig. 5 for 170 V_p square wave excitation. At 100 kHz a brightness of 300 cd/m^2 was obtained for the visible emission. The infrared (1550 nm) GaN:Er emission originates from relaxation of the lowest excited Er^{3+} state ($^4I_{13/2}$) and is of interest¹² for optical communications. 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 onset of this saturation process. From the data of Fig. 5(b), we obtain 3 dB frequencies of ~ 65 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 measured¹³ 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 (<1 kHz) an Er atom will have adequate time to radiatively ($\sim 537/558$ nm) relax from higher excited states to the ground state or to nonradiatively relax to the IR level ($^4I_{13/2}$) and then radiatively relax (1.5 μm) to the ground state. Ac-

cording 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 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 at a lower frequency is predicted.

In summary, ac-biased thin-film electroluminescence has been obtained from GaN:Er deposited by MBE on an amorphous dielectric layer. This indicates improved compatibility of phosphors based on the GaN:RE material system with commercial TFEL flat panel display fabrication techniques. It is important to point out that the luminance values obtained for our preliminary device structure can be further increased by incorporating high permittivity ($\epsilon = 20\text{--}1000$'s) dielectrics (Al_2O_3 : TiO_2 , BaTa_2O_6 , BaTiO_3).

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