# *Rare-Earth-Doped GaN Phosphors for Electroluminescent Displays*

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Thin film electroluminescent (TFEL) flat panel displays (FPDs) using inorganic phosphors can provide[1,2,3] high brightness, outstanding durability and long lifetime. Semiconductor-based TFEL FPDs are solid-state devices which do not incorporate vacuum, gases, or liquids in the device structure. After the discovery[4] of extrinsic visible (green) emission from the III-V compound semiconductor GaN doped with Er, pure red[5] and blue[6] light emission have been obtained from EL devices (ELD's) using rare earth (Eu and Tm)-doped GaN. The direct, wide bandgap semiconductor GaN has been found[7] to be surprisingly optically robust, being able to efficiently emit intrinsic radiation under defect conditions which would normally prohibit it in other semiconductors. Together with related alloys with AlN and InN, GaN is aggressively being pursued as intrinsic light emitters for high brightness point sources (e.g. LEDs and laser diodes). We have previously reviewed the basic optoelectronic properties[8] of RE-doped GaN, the wide spectral range[9] possible with this material system and related multiple color applications[10]. In this paper, we discuss the development of full color TFEL using rare-earth-doped GaN devices which combine the robust GaN semiconductor host with the sharp spectral emission of rare earths.

The RE-doped GaN is grown by MBE using Knudsen-type sources for Ga and the RE's and plasma-activated $N_2$ source. While the growth temperature of GaN by MBE is normally 600-800°C, we have obtained[11] visible emission even from room-temperature-grown GaN:RE ELD's. A preliminary model of the GaN:RE structure is shown in Fig.1. The $RE^{3+}$ ions are located[12] preferentially on substitutional sites on the

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Ga sublattice, which results in no change in the local charge distribution. In the case of GaN:Er, the Er-N bond has been found[13] to be unusually short thus minimizing the Ga-Er mismatch. The strong bonding in GaN, in conjunction with substitutional incorporation, allows high RE doping concentrations ( ~10%) without precipitation. The optimum concentration in terms of both materials properties and device performance (shown in Fig. 2) is found[14] at ~ 1%.

Spectra from Tm-, Er-, and Eu-doped GaN ELD are shown in Fig. 3. Ideal for a full-color FPD, GaN:RE ELDs exhibit very narrow emission line-widths which are well aligned with red, green, and blue color display requirements. The main emission mechanism in RE-doped GaN electroluminescence takes place by hot carrier excitation of intra-$4f^n$ transitions in the RE ions. As shown in Fig. 4, GaN:Eu ELDs emitting red light at 622 nm have C.I.E chromaticity coordinates of (x=0.69, y=0.31), GaN:Er emitting green at 537/558 nm (x=0.30, y=0.69), and GaN:Tm blue at 477 nm (x=0.10, y= 0.10). ELDs have also been developed with multiple RE doping in either a single layer to provide specific intermediate colors (such as turquoise, yellow and orange) or with two phosphor layers each doped with a different RE. These devices have the capability[15] of generating red, orange, yellow or green light by varying only the electrical bias conditions on a single electrode.

Visible (and infrared) emission has been obtained from GaN:RE AC-ELD devices fabricated[16] on various types of substrates, including Si, sapphire and glass, as shown in Fig. 5. We have demonstrated GaN:RE phosphors deposited at temperatures < 600 °C, making these phosphors compatible with industry standard FPD glass substrates. We have developed a novel AC-ELD structure and fabrication technique which results in low-cost, high-yield, and high-capacitance (performance) devices on glass substrates. Red-, green-, and blue-emitting thick dielectric electroluminescent (TDEL) display structures made possible by the high-temperature and chemically stability of rare-earth-doped GaN phosphors are shown in Fig. 6.

As shown in Fig. 7, the GaN:RE AC-ELDs exhibit a brightness of ~30-50 cd/m$^2$ at 1 kHz and a voltage of 200-250 V. Alloying the GaN:RE phosphor with a small amount of AlN was shown to further improve the device brightness by >30%. For phosphors with short emission lifetimes such as 537/538 nm emission from GaN:Er (~10 μs), the brightness increases linearly with frequency up to 10's of kHz. The GaN:RE phosphor is much more chemically stable (moisture resistant) than commercial ZnS-based phosphors. The GaN:RE phosphors exhibit optical turn-on voltages (<100 V) which are significantly lower than that of other chemically stable (oxide-based) phosphors (>200 V).

Unlike organic light emitting diodes and liquid crystal display technology, EL phosphors emit light in instantaneous light bursts. The result is high-end video frame rates without the need for costly active

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matrix addressing. Another advantage of EL FPD is the inherently wide view angle. We have measured greater than 90% brightness at viewing angles of ±70°. We have developed a proprietary contrast enhancement technique for sunlight readable displays. Contrast ratios >40:1 in bright lighting are projected for the TDEL device structure. Initial AC-ELD devices operated in a 40% humidity environment have exhibited only a 5% loss in brightness after 1000 hours. Due to the chemical stability of the phosphor, GaN:RE AC-ELDs have the potential for extremely long operational lifetimes (> 50,000 hrs). Furthermore, the use of ultra-stable oxide and nitride materials, and the absence of polymeric materials, vacuum, or gases allow operation in harsh environments, such as vehicular displays, airplanes, hospitals, factories. The expected operational temperature range of –45 to 85°C is determined only by the limitations of the driver electronics. Using the robust, wide bandgap GaN as the host for RE-doped ELDs has resulted in several attractive properties: a very simple device structure, excellent emission chromaticity, high brightness and contrast, low turn-on voltage. A schematic of a full-color GaN:RE TDEL display is shown in Fig. 8. The use of robust materials and an all solid-state structure have the potential for producing the longest lifetime FPD technology.

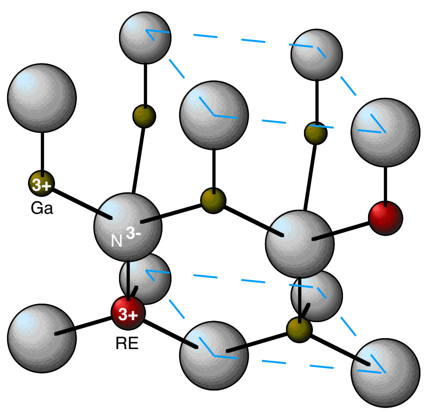


Fig. 1 Simple model of GaN:RE crystal structure.

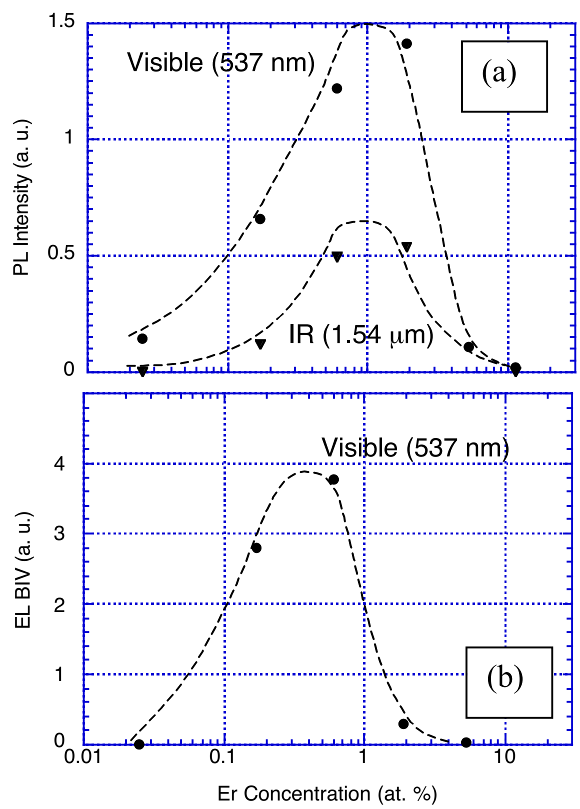


Fig. 2 PL and EL intensity vs. Er concentration: (a) visible and IR PL intensity; (b) current normalized visible EL (BIV).

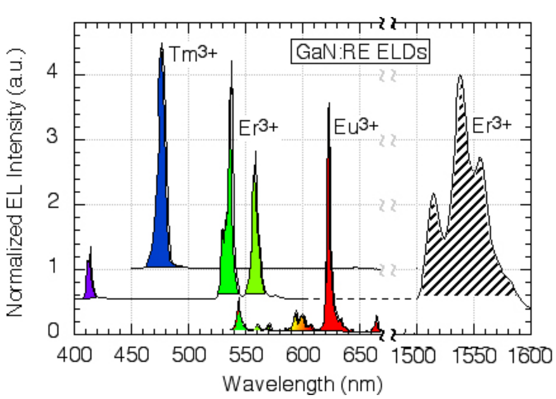


Fig. 3 The emission spectra of Tm-, Er-, and Eu-doped GaN ELDs showing the visible and IR wavelengths of interest.

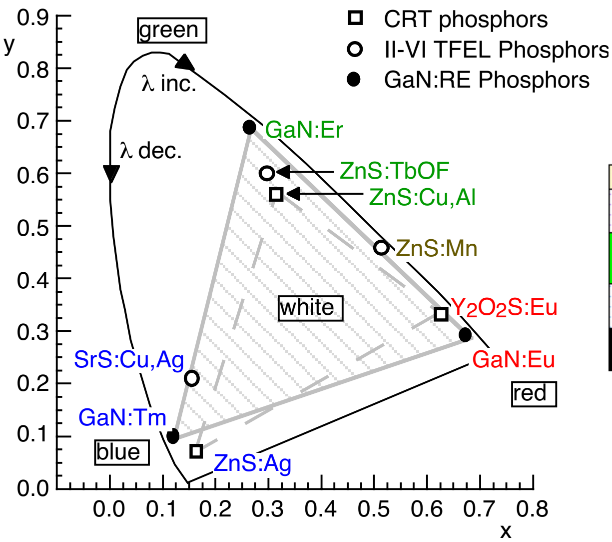


Fig. 4 CIE diagram of GaN:RE & other phosphors.

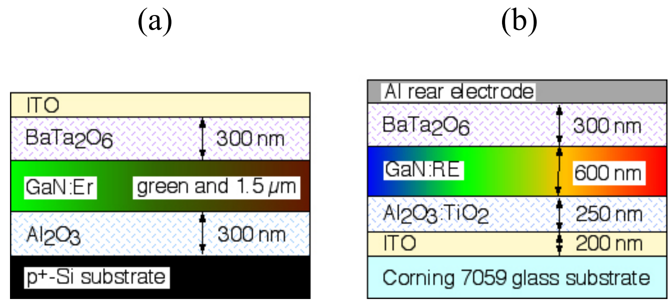


Fig. 5 Schematic diagrams of example AC-ELDs formed on Si substrates (a) and glass substrates (b). The device in (a) can also be utilized as a 1.5 µm emitter on Si.

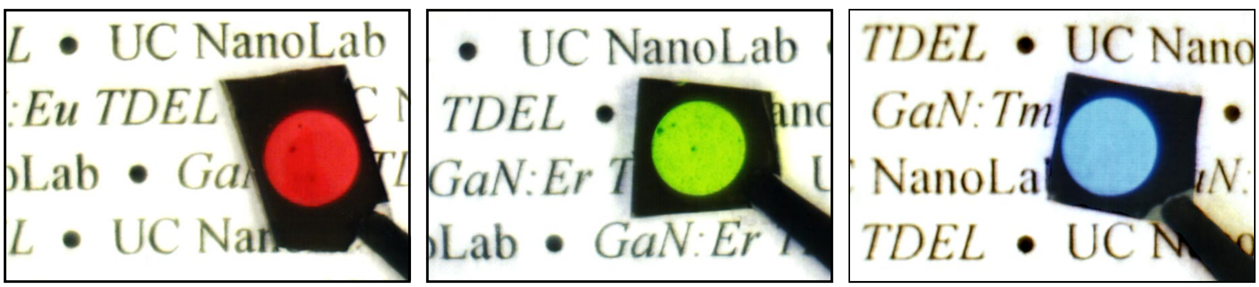


Fig. 6 Single color red, green, and blue GaN:RE TDEL devices.

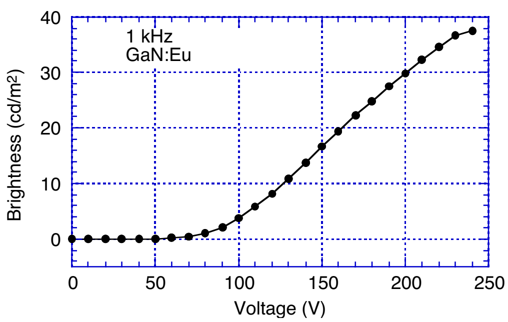


Fig. 7 Brightness characteristics of GaN:Eu TDEL as a function of voltage.

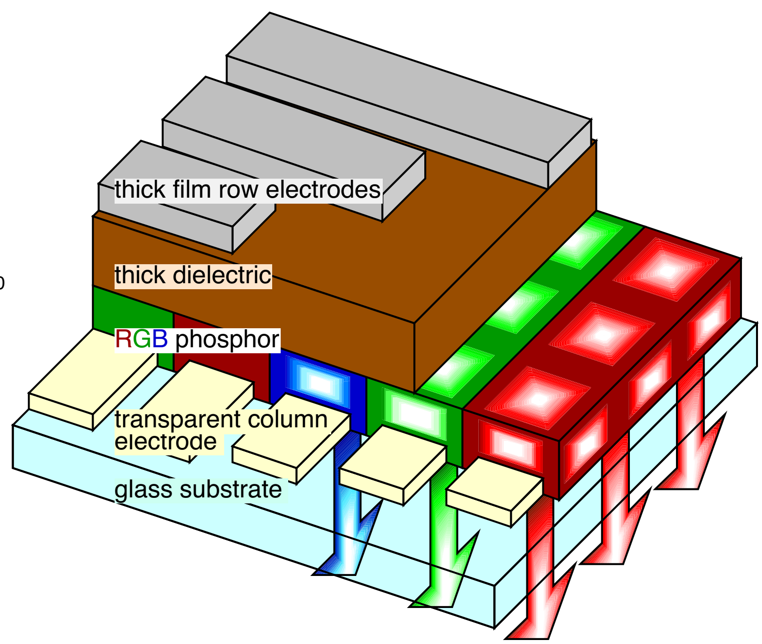


Fig. 8 Schematic of full-color TDEL display structure.