Low-voltage GaN:Er green electroluminescent devices

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Green light emission has been measured from Er-doped GaN electroluminescent devices (ELDs) at an applied bias as low as 5 V. The GaN–Er ELDs were grown by solid source molecular beam epitaxy on Si (111) substrates. We have achieved this low-voltage operation (ten-fold reduction in optical turn-on voltage) by using heavily doped (~0.01 Ω cm) Si substrates and by decreasing the GaN–Er layer thickness to several hundred nanometers. A simple device model is presented for the indium tin oxide/GaN–Er/Si/Al ELD. This work demonstrates the voltage excitation efficiency of Er^{3+} luminescent centers and the compatibility of GaN rare earth-doped ELDs with low-voltage drive circuitry. © *2000 American Institute of Physics.* [S0003-6951(00)01511-4]

Rare-earth-(RE)-based electroluminescence (EL) in a matrix of ZnS (or other II–VI compounds) has been the key ingredient[1] in many display technologies, such as electroluminescent devices (ELDs). Recently, significant progress[2] has been made using the wide band gap III–V semiconductor GaN as the host for RE-based photoemission at visible and infrared (IR) wavelengths. In the past two years it has been shown that RE-doped GaN ELDs can produce green[3] (based on Er doping), red (Pr, Eu),[4,5] and blue[6] light (Tm), as well as 1.55 μm IR[7,8] emission (Er). Visible emission from Dy, Er, Tm, Sm, Ho doped GaN has also been achieved through cathodoluminescence,[9,10] which demonstrates the feasibility of GaN:RE for field emission displays.

GaN:RE ELDs hold several promising qualities which are attractive for small- and mid-scale display and lighting. The emission from a GaN:RE ELD is spectrally sharp and requires no color filtering since it arises from atomic RE transitions. The red, green, and blue GaN:RE ELDs utilize a similar device structure and power requirements, which could simplify some critical electrical and material obstacles[11] in multicolor integration of single color devices. GaN is an advantageous host for RE-based ELDs for several reasons: it has excellent high field carrier transport properties which can provide hot carriers for impact excitation[12] of the RE ions (breakdown field ~3 MV/cm); it is transparent to visible RE emission; it is thermally and chemically rugged; the majority of the trivalent RE dopants[13] in GaN is located substitutionally on the cation (Ga) sublattice, unlike the case of II–VI hosts where additional defects are induced due to lack of charge neutrality; unlike Er in other hosts the emission is not appreciably quenched at high temperature[14,15] or high Er concentration.[13] Fabrication of the GaN:RE ELDs is a relatively simple process in terms of the few processing steps involved. With the present device structures, single ELDs have been operated at power densities as high as several hundred W/cm^2 in a stable manner without the usage of a heat sink or active cooling. While this demonstrates the highly desirable temperature independence and ruggedness of the RE emission in GaN, lowering the power requirement would make the GaN:RE devices more appealing in a variety of applications, such as flat panel use. In particular, lowering the typical bias of 50–60 V would greatly simplify the driving circuitry. In this letter we report on reduction of the GaN:Er ELD bias voltage required to observe green emission at 537 and 558 nm. The photoemission is produced by the relaxation of the Er^{3+} $4f$ shell $^2H_{11/2}$ and $^4S_{3/2}$ excited levels, resulting in radiative transitions to the $^4I_{15/2}$ ground state. We report on methods which have reduced the optical turn-on voltage by an order of magnitude, to 5–6 V. We use the term ''optical turn-on'' voltage to signify the ELD bias condition wherein visible emission is first noticeable to the naked eye in normal ambient lighting conditions. A representative low-voltage ELD is shown in operation in Fig. 1. A bias of 7.5 V applied to the ring contact results in bright green emission.

The Er-doped GaN was grown in a Riber MBE-32 system on 2 in. n^+-Si(111) substrates. Ga and Er solid sources were used in conjunction with a radio frequency plasma source supplying atomic nitrogen. Epitaxy for all ELDs was performed at growth rate of ~0.8 μm/h. After growth, n^+ indium tin oxide (ITO) ring contacts of area $7.65 \times 10^{-4}\ cm^2$ were fabricated on the GaN:Er layer. Ohmic contact to the Si substrate was formed by rf sputtering of Al followed by annealing at 450 °C for 2 min. A schematic dia-

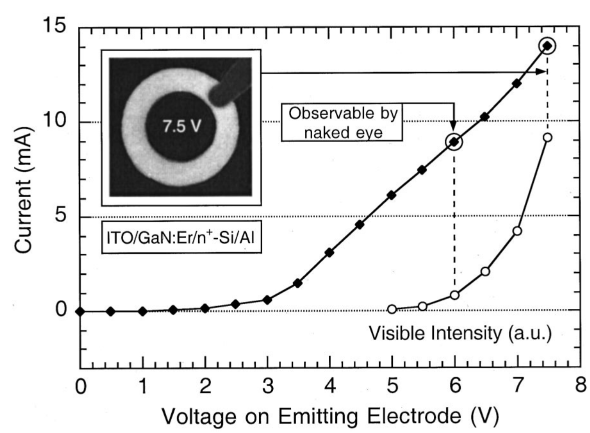

FIG. 1. GaN:Er ELD current and EL intensity as a function of voltage on emitting electrode. A thin (~300 nm) GaN layer and n^+ Si substrate are used to obtain low-voltage optical turn-on at 6 V. The inset is a photograph of green emission under the ITO bias electrode at 7.5 V.

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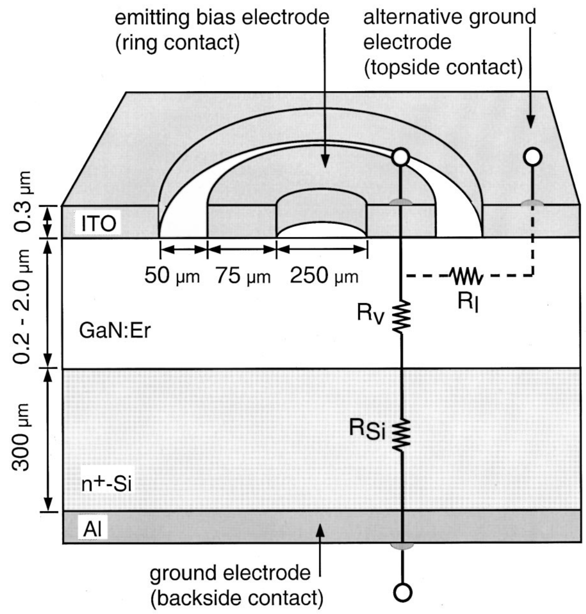

FIG. 2. Schematic diagram of GaN:Er ELD device structure and simple equivalent circuit model. The device area is 7.65×10^{-4} cm^2.

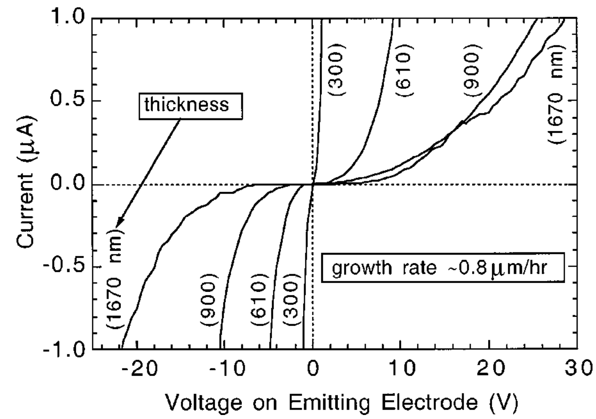

FIG. 3. $I-V$ characteristics of GaN:Er ELDs for different GaN:Er layer thickness. The ITO ring contact is the bias electrode and the backside Al contact is the ground electrode. The data was averaged from four ELDs per GaN:Er layer thickness.

gram of the completed ELD structure is shown in Fig. 2, along with device dimensions. During operation of the ELD the ITO ring contact is always used as the biased electrode. Unless otherwise indicated, the Al backside contact to the Si substrate is used as the ground electrode. An alternative biasing scheme occasionally utilized uses the large area ITO topside contact as the ground electrode.

To achieve a low optical turn-on voltage, the ELD shown in Fig. 1 incorporates two features designed to reduce the electrical resistance of the device: (a) use of a heavily doped n^+-Si substrate, with 0.01 Ω cm resistivity and (b) reduction of the GaN:Er layer to ~300 nm. The current–voltage ($I-V$) characteristic has a low threshold voltage of ~3 V, while the optical turn-on voltage occurs at ~6 V. For the ELD shown in operation in the inset to Fig. 1, a 7.5 V bias drives 14 mA through the device. The low-voltage ELD requires merely 2.5 V for switching the ELD on and off with proper contrast. The ELD discussed here utilizes *n*-type contacts. The GaN layer, which is not intentionally electrically doped, is semi-insulating. The absence of hole injection to complement electron injection precludes the possibility of recombination-induced luminescence. The emitted intensity versus voltage and current indicates that impact excitation[8] is the mechanism behind green emission. Using these $I-V$ characteristics, a low-voltage injection-type device could also be formed utilizing electron-hole recombination mediated Er excitation.

The choice of substrate conductivity is critical to the low-voltage ELDs. In Fig. 2 a device cross section is shown which also depicts the current paths in the device. If insulating substrates are used, such as sapphire, only topside contacts to the GaN:Er layer may be utilized. This would lead to the lateral current path between topside contacts shown in Fig. 2 as the dotted line circuit path with resistance R_L. For most device geometries, R_L will exceed R_V for normal ~1 μm GaN:Er films. Also the current path through R_L results in undesired current crowding at the ITO contact edges. If a conductive substrate is utilized, the solid-line circuit path (R_V+R_{Si}) is the path of least resistance for ELD operation. By utilizing an ohmic Al contact to an n^+-Si(111) substrate R_{Si} is greatly minimized and the resistance of the device decreases proportionally with decreasing GaN:Er thickness. The Si substrates support GaN:Er epitaxy, are easily heavily doped and are of significantly lower cost than either SiC or GaN substrates. It should be noted that making the GaN:Er layer highly conductive is not a good approach for bright low-voltage ELDs since the field strength will be compromised and most carriers will not have enough energy to impact excite the Er atoms regardless of how much current flows through the ELD.

The effect of GaN:Er layer thickness on the $I-V$ characteristics of a low-voltage ELD were investigated with structures grown on n^+-Si. A buffer layer was first grown for 5 min at 600 °C, followed by an initialization layer of undoped GaN grown for 10 min at 800 °C. GaN doped with Er was then grown at 800 °C for four different durations resulting in GaN film thickness' ranging from ~0.3 to 1.67 μm. For each thickness, data taken from four ELDs was averaged, and then plotted as shown in Fig. 3. As the GaN:Er layer thickness is decreased, the $I-V$ characteristic generally follows a trend towards lower turn-on voltage ELDs. Decreasing the GaN:Er thickness results in less voltage being required to reach adequate field strength for hot carrier impact excitation of the Er ions.

For the low-voltage ELD in Fig. 1, a 100 nm buffer layer and 200 nm GaN:Er was grown on n^+-Si. From the graph of intensity versus voltage in Fig. 1, the green emission from the GaN:Er starts to be detected by a photomultiplier tube at 5 V applied bias. The minimum energy required for excitation of Er to the $^2H_{11/2}$ level[16] is approximately ~2.3 eV. The maximum GaN:Er ELD voltage efficiency is then $(2.3\,\mathrm{eV})/(5\,\mathrm{V}\times e^-)$ or ~46%. The voltage efficiency at the optical turn-on voltage of 6 V is 38%.

Figure 4 provides an initial model of ELD operation at the atomic level and gives some insight into its remarkable voltage efficiency. A simplified device structure and bias scheme are shown in Fig. 4(a). Given the $I-V-L$ characteristic shown in Fig. 1, it appears that any hot carriers gener-

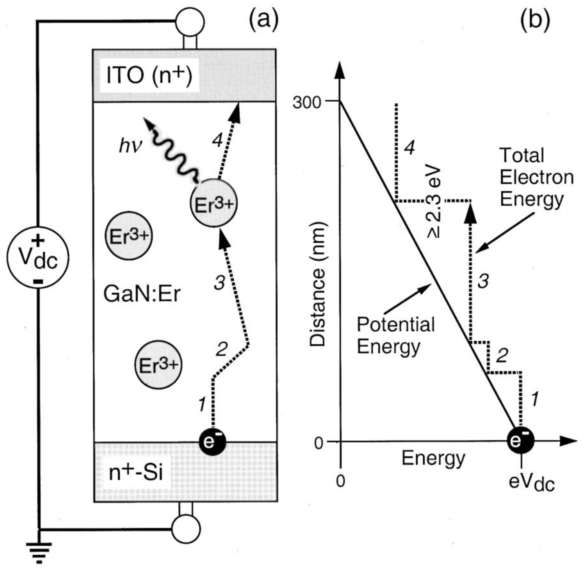

FIG. 4. Simple model of the path of an electron in the GaN:Er excitation process (a) and corresponding energy loss mechanisms (b).

ated through thermionic emission or tunnelling at the interfaces to GaN are not a significant photogeneration source since the optical turn-on requires several volts (and milliamps) above the 3 V electrical turn-on. The differential resistance above the 3 V threshold for the ELD structure shown in Fig. 1 is ~330 Ω, which is much larger than the 0.4 Ω resistance of the Si substrate (R_{Si}). The very low resistivity of the ITO layer ($\sim 10^{-4}\,\Omega$ cm) results in a negligible resistance. It is therefore reasonable to assume that the voltage beyond the electrical turn-on is applied across the GaN:Er layer and produces a fairly uniform electric field. The 330 Ω resistance corresponds to a resistivity of ~8.5 kΩ cm for the GaN:Er layer. To reach the optical turn-on voltage of 6 V requires 3 V beyond the electrical threshold voltage. This minimum voltage drop indicates that the minimum field strength for a GaN:Er ELD with a 300 nm phosphor layer is only ~0.1 MV/cm, which compares very favorably with the 1–2 MV/cm minimum field strength reported for II–VI alternating current-driven ELDs.[12] The current breakdown field of GaN:Er is ~1.5 MV/cm, which allows for a maximum electric field equivalent to ~10× the minimum field for optical turn-on.

As shown in Fig. 4(a), the electrons injected into the GaN:Er layer experience both radiative and nonradiative collisions. The accompanying energy loss is shown in Fig. 4(b). The nonradiative host scattering events 1 and 2 reduce the voltage efficiency of the device. In scattering event 3, an electron gains more than 2.3 eV of kinetic energy and transfers it to an optically active Er atom. Improvements in material quality are being pursued in order to further improve the efficiency of the GaN:RE ELDs. More specifically, the ELDs may be improved by reduction of the frequency of host (GaN) scattering events and by an increase of the impact excitation cross section of RE dopants.

In summary, we have reported on low-voltage GaN:Er ELDs. The optical turn-on voltage has been reduced by an order of magnitude from the previous 50 to 60 V range to the 5–6 V range by utilizing a thinner GaN layer and an n^+-Si substrate. Some brightness of the ELD is sacrificed in a low-voltage device structure since the reduction in GaN:Er layer thickness also reduces the volume of green luminescence. We believe that these results are readily extendable to other GaN:RE (Pr, Eu, Tm) ELDs which we have previously demonstrated.

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