Visible and infrared rare-earth-activated electroluminescence from indium tin oxide Schottky diodes to GaN:Er on Si

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(Received 10 August 1998; accepted for publication 27 October 1998)

Visible and infrared rare-earth-activated electroluminescence (EL) has been obtained from Schottky barrier diodes consisting of indium tin oxide (ITO) contacts on an Er-doped GaN layer grown on Si. The GaN was grown by molecular beam epitaxy on Si substrates using solid sources for Ga, Mg, and Er and a plasma source for N_2. RF-sputtered ITO was used for both diode electrodes. The EL spectrum shows two peaks at 537 and 558 nm along with several peaks clustered around 1550 nm. These emission lines correspond to atomic Er transitions to the $^4I_{15/2}$ ground level and have narrow linewidths. The optical power varies linearly with reverse bias current. The external quantum and power efficiencies of GaN:Er visible light-emitting diodes have been measured, with values of 0.026% and 0.001%, respectively. Significantly higher performance is expected from improvements in the growth process, device design, and packaging. *© 1999 American Institute of Physics.* [S0003-6951(99)01002-5]

Green light emission from semiconductor light-emitting diodes (LEDs) is more difficult to achieve than red or infrared (IR) light because of the lack of semiconductors with direct band gap in the range of 2.2–2.4 eV. GaP, which has an indirect band gap of 2.27 eV, has been utilized[1] for green LEDs, but after years of development still has rather inefficient external quantum efficiencies in the range of 0.1%–1%. Nakamura and co-workers[2,3] have demonstrated efficient green emission (2%–6% external quantum efficiency) with InGaN alloys and quantum well structures, but at the price of a highly complicated device structure and, hence, highly complicated processing. At the same time, progress is being made using II–VI materials (ZnTeSe LEDs with 5.3% external quantum efficiency[4]), but device lifetime remains an issue. Green emitting devices grown on Si substrates would be ideal because of the obvious advantage of Si integrated circuit compatibility. IR electroluminescence (EL) has been demonstrated using Si doped with Er by implantation or during growth.[5–10] The IR photoluminescence (PL)[11–15] and cathodoluminescence[16,17] of Er-doped III–V compound semiconductors have been investigated by several groups. Recently, a review[18] of this subject by Zavada and Zhang indicates that wide-band-gap III–N semiconductors may be the ideal hosts for Er-doped devices. IR EL from Er-implanted GaN (Ref. 19) and from *in situ* Er-doped GaN (Ref. 20) have also been demonstrated, but no visible rare-earth-based light emission was observed.

We have recently reported strong visible (green) rare-earth-activated PL from *in situ* Er-doped GaN grown by molecular beam epitaxy (MBE) on sapphire (Ref. 21) and on Si (Ref. 22) substrates. The same strong green rare-earth-activated emission was also observed[23] in EL from simple Al Schottky diodes on GaN:Er. In this letter, we report on the performance characteristics of Er-doped GaN LEDs emitting in both the visible and IR regions. The GaN:Er LEDs consist of Schottky diodes which use a transparent indium tin oxide (ITO) layer for both positive and negative electrodes. The relative sizes of the electrode dictate the diode behavior of the device. Under reverse bias, the smaller electrode is negative and the larger electrode is positive. The Er-doped GaN was grown using a Riber MBE-32 system on 2 in. *p*-Si (111) substrates. Solid sources were used to supply the Ga, Mg, and Er fluxes, while a STVA radio-frequency (RF) plasma source supplied atomic nitrogen.

Prior to MBE growth, the Si substrate was cleaned in acetone, methanol, and DI water, followed by HF to remove all native oxide. After insertion into the MBE chamber, a thin, low-temperature GaN buffer layer was first grown followed by three GaN layers: ~0.6 μm of undoped GaN, ~0.6 μm of Er-doped GaN, and ~0.6 μm of Mg-doped GaN. The GaN layers were grown at a substrate temperature of 750 °C. The ITO contacts were formed using RF sputtering in conjunction with a lift-off process. The ITO target had a com-

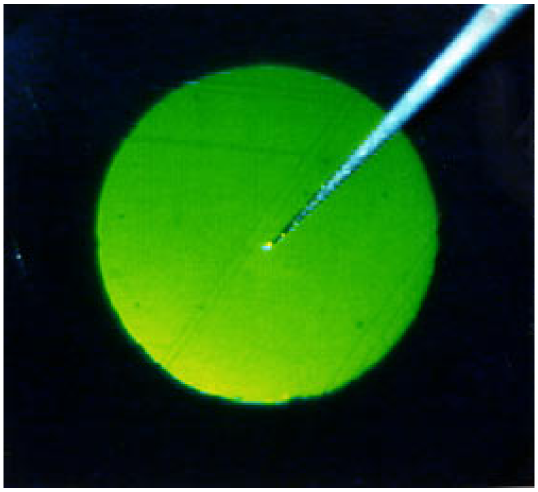

FIG. 1. Photograph of visible rare-earth-activated emission from ITO/GaN:Er Schottky barrier LED (0.125 cm^2 area) operating with 19 mA current.

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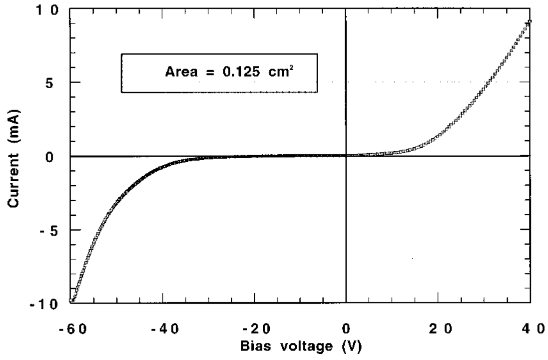

FIG. 2. Current–voltage characteristic of ITO/GaN:Er Schottky barrier diode.

position of 90% In_2O_3 and 10% SnO_2. The sputtering was performed at 8 mTorr with 350 W of RF power, resulting in −526 V of dc bias. Under these conditions, the deposition rate was ~160 Å/min. The ITO film was ~3240 Å thick and had a sheet resistance of 50 Ω/square as deposited. No post-annealing was utilized. The ITO films had a transmission of ~80%–85% for green light and ~85%–90% for near-IR light. Electroluminescence data were collected using an Acton Research spectrometer along with an Ocean Optics fiber-optic spectrometer. Optical power measurements were made using a Newport 1818-SL/CM optical power meter. All measurements reported in this letter were made at room temperature.

Figure 1 shows a photograph of a GaN:Er LED in operation. The powered ITO contact (with a diameter of 4 mm) and a metal electrical probe are clearly visible. In this photograph, negative bias is being applied to the green light-emitting electrode, resulting in a current of 19 mA. The emission intensity and color is fairly uniform across the diode. Some color shift to yellow is observed along the diode edge opposite the probe tip. The emitted light is easily seen in a normally lit room. Figure 2 shows the current–voltage *(I–V)* characteristics of the diode. Hall measurements on the GaN films showed high resistivity, which accounts for the slope of the forward bias region.

The visible EL spectrum of the GaN:Er LED is shown in Fig. 3. The EL peaks at 537 and 558 nm correspond to transitions from the $^2H_{11/2}$ and the $^4S_{3/2}$ to the $^4I_{15/2}$ ground state. The full widths at half maximum (FWHM) of the $^2H_{11/2}$–$^4I_{15/2}$ and $^4S_{3/2}$–$^4I_{15/2}$ lines are 2.56 and 3.0 nm, respectively. By comparison, conventional GaN-based green LEDs have a FWHM ranging from 45 to 90 nm depending on the structure and center wavelength.[2,3] Green LEDs based on II–VI materials (ZnTeSe) have been reported[4] with a FWHM of 52 nm. The IR EL emission spectrum is shown in Fig. 4. Notice that the three peaks are contained in a wavelength range between 1.51 and 1.56 μm, which corresponds very well to the silicate optical fiber attenuation minimum.

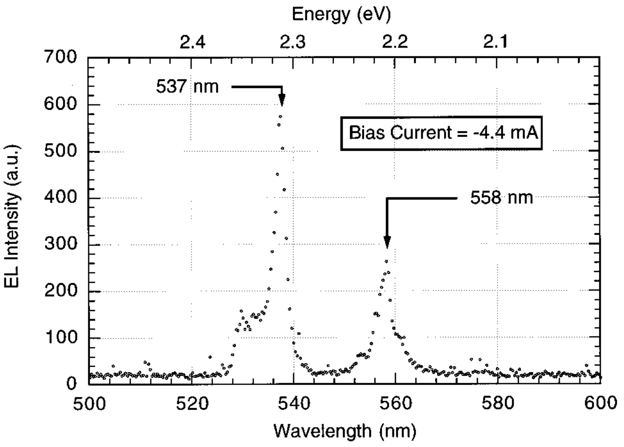

FIG. 3. Rare-earth-activated emission spectrum in the visible range from ITO/GaN:Er Schottky barrier LED reverse biased at 4.4 mA.

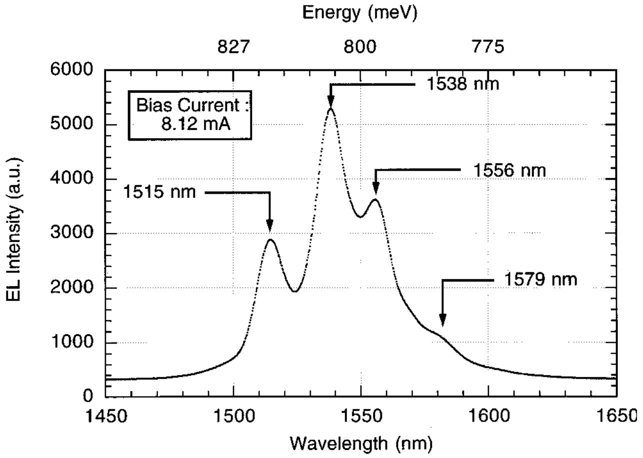

FIG. 4. Rare-earth-activated emission spectrum in the near-IR range from ITO/GaN:Er Schottky barrier LED reverse biased at 8.12 mA.

The visible optical power emitted and detected from a GaN:Er LED is plotted as a function of bias current in Fig. 5. The optical power at the detector increases linearly with current over the measurement range, reaching a maximum of 150 nW at 10 mA. A Si photodetector was placed 2.55 cm above the device during these measurements. Assuming a point source, and hemispherical emission, the optical power generated at the device can be estimated to be 6 μW for 10 mA of applied reverse bias. Under these conditions, the external quantum efficiency is estimated to be 2.6×10^{-4}, and the external power efficiency to be 10^{-5}. It is important to note that all measurements were made at room temperature with no cooling or use of any heat sink applied to the substrate. This indicates a rugged quality of the device given that at 10 mA bias current, 0.6 W of electrical power was applied to the device without causing failure.

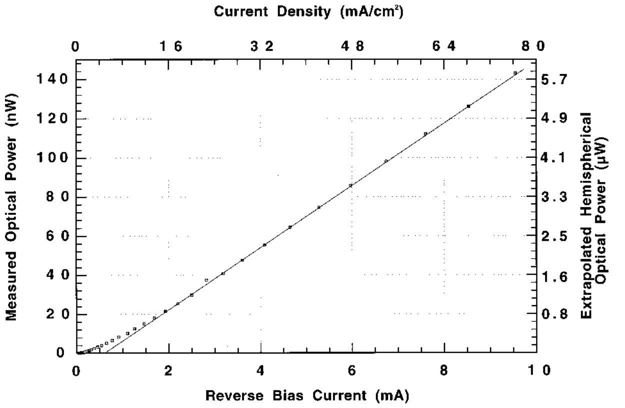

FIG. 5. Visible optical power as a function of bias current.

In summary, we have reported visible and IR rare-earth-activated electroluminescence of Er-doped GaN. The use of ITO as a contact material instead of a conventional metal layer increases the amount of light output from the device. Both IR and visible light EL peaks show narrow linewidths. Further research in contact formation (Ohmic and Schottky) and material quality, along with improved device structure design, are needed to improve the quantum and power efficiencies. However, these early results are encouraging in light of the simple structure and process utilized to achieve them.

This work was supported in part by a BMDO/ARO contract (L. Lome and J. Zavada) and AASERT grants. The authors would like to acknowledge the support and encouragement of J. Zavada. Equipment support was provided by an ARO URI grant and the Ohio Materials Network.

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