1.54 μm emitters based on erbium doped InGaN p-i-n junctions

R. Dahal,[1] C. Ugolini,[2] J. Y. Lin,[1] H. X. Jiang,[1,a)] and J. M. Zavada[3]
[1]Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, Texas 79409, USA
[2]Department of Physics, Kansas State University, Manhattan, Kansas 66506-2601, USA
[3]Department of Electrical and Computer Engineering, Polytechnic Institute of New York University, Brooklyn, New York 11201, USA

(Received 19 September 2010; accepted 21 September 2010; published online 8 October 2010)

We present here on the growth, fabrication and electroluminescence (EL) characteristics of light emitting diodes (LEDs) based on Er-doped InGaN active layers. The p-i-n structures were grown using metal organic chemical vapor deposition and processed into 300×300 μm^2 mesa devices. The LEDs exhibit strong emissions at 1.0 and 1.54 μm, due to Er intra-4*f* transitions, under forward bias conditions. The emitted EL intensity increases with applied input current without exhibiting saturation up to 70 mA. The integrated power over the near infrared emission, measured at room temperature from the top of a bare chip, is about 2 μW. The results represent a significant advance in the development of current injected, chip-scale emitters and waveguide amplifiers based on Er doped semiconductors. © *2010 American Institute of Physics*. [doi:10.1063/1.3499654]

Over recent years, the rare earth (RE) doped III-nitride semiconductors have emerged as important materials for applications ranging from optical communication devices with multiple functionalities to full color display systems. Such applications are not possible with either RE doped silica glasses or narrow band gap semiconductors.[1–5] Much of the research work on RE doping into semiconductors has focused on the element, erbium (Er) for potential applications in optical communications. Wide band gap semiconductors, doped with Er, exhibit spectral emissions from the visible to near infrared (IR) region due to the Er intra-4*f* transitions.[6–8] The transition from the first excited level ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) results in ~1.54 μm emission which falls within the minimum loss window of optic fibers for optical communications. It has been shown that the Er excitation cross section under current injection ($\sim10^{-15}$ cm^2) is up to five orders of magnitude higher than the optical excitation cross section in conventional Er-doped fiber amplifiers ($\sim10^{-20}$ cm^2).[9] Of the various wide band gap semiconductor systems, III-nitride semiconductors appear to be excellent host materials for Er ions to achieve room temperature (RT) operation of electrically pumped emitters and amplifiers operating at 1.54 μm. The structural and thermal stability, as well as recent advancements in growth techniques of high-quality III-nitride materials with both n- and p-type conductivities, indicates the potential to create efficient light emitting devices.

Recently, we have succeeded in incorporating Er ions into GaN and InGaN epilayers *in situ* during metal organic chemical vapor deposition (MOCVD) growth.[7,8] The Er doped GaN and InGaN epilayers, synthesized by MOCVD, exhibit a predominant 1.54 μm emission that is highly thermal stable, which opens the possibility of fabricating current injected 1.54 μm emitters and waveguide amplifiers for RT operation.

Previous studies have been concentrated on Er doped III-nitride samples produced either by ion implantation or by *in situ* doping using molecular beam epitaxy (MBE).[10–18] Compared to ion implantation, *in situ* doping provides precise control of Er concentration and dopant position in the thin film. Electroluminescent devices have been fabricated from MBE grown materials and shown to emit at visible and IR wavelengths.[6] However, these Schottky-type devices require applying a high electric field under reverse bias (several hundred volts) to produce emission at 1.54 μm. Light emitting diodes (LEDs) have been fabricated using a combination of MOCVD and MBE techniques and yielded 1.54 μm emission under both reverse and forward bias conditions.[12] Moreover, emission intensity under forward bias was much weaker than that under reverse bias. In both cases, the primary excitation of Er ions in GaN was through an impact energy transfer mechanism.

MOCVD is the established growth method in III-nitride semiconductor industry, and used to produce almost all the commercial III-nitride photonic devices including LEDs and laser diodes (LDs).[19] Recently, we have demonstrated the operation of current injected 1.54 μm LEDs and waveguide amplifiers by heterogeneous integration of Er doped GaN and InGaN epilayers, synthesized by MOCVD, with commercially available III-nitride UV/blue LEDs.[20] In these devices the excitation of Er^{3+} ions is through an optical pumping process and the overall efficiency was low due to poor coupling efficiency. In this letter, we report on the MOCVD growth, fabrication, and electroluminescence (EL) characteristics of Er-doped p-i-n LEDs. The devices showed a dominant EL emission at 1.54 μm under forward bias, making these materials highly promising for on-chip optical communication applications.

The device structure was a p-i-n diode in which the i-layer was a 200 nm thick Er doped $In_{0.05}Ga_{0.95}N$ layer ($Er:In_{0.05}Ga_{0.95}N$). The schematic structure of the fabricated LED is depicted in Fig. 1. The p-i-n diodes were grown on the (0001) sapphire substrates and growth began with a thin GaN buffer layer, followed by a 0.6 μm thick undoped GaN epilayer grown at 1040 °C. Then a 1.5 μm thick Si doped GaN n-contact layer with electron concentration, $n=5\times10^{18}$ cm^{-3}, and mobility $\mu=250$ $cm^2/V\,s$ was deposited. This was followed by a 200 nm thick Er-doped $In_{0.05}Ga_{0.95}N$

a)Electronic mail: hx.jiang@ttu.edu.

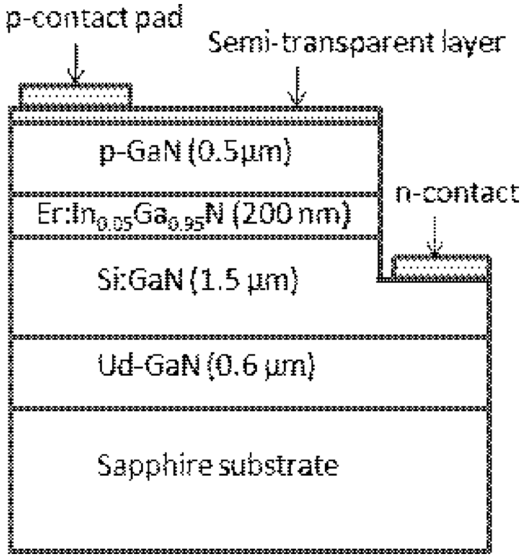

FIG. 1. Schematic of the multilayer structure of the fabricated p-GaN/Er:InGaN/n-GaN LEDs. The active region is a 200 nm thick Er doped $In_{0.05}Ga_{0.95}N$ epilayer [or ($Er:In_{0.05}Ga_{0.95}N$)].

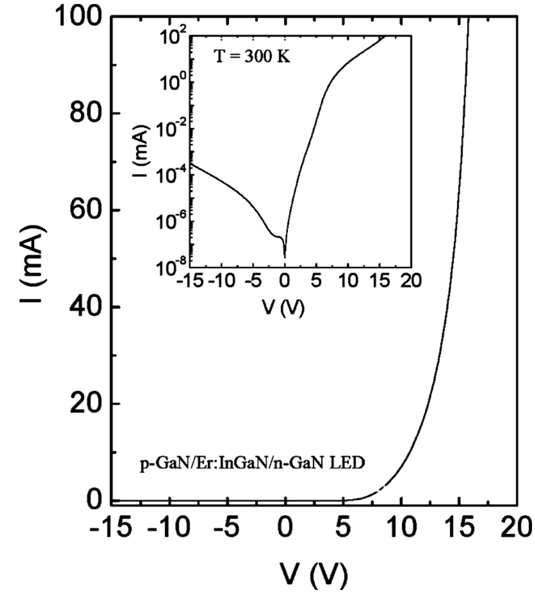

FIG. 2. I-V characteristics of a p-GaN/$In_{0.05}Ga_{0.95}N$:Er/n-GaN LED. The inset shows the same plot on a semilog scale. The leakage current is ~0.2 μm at −15 V bias.

active layer with Er concentration $\sim 2\times 10^{19}$ cm^{-3} and a 0.5 μm thick Mg-doped p-type GaN layer with hole concentration, $p=3\times 10^{17}$ cm^{-3} and mobility, $\mu=10$ cm^2/V s. To activate the Mg acceptors in the p-layers, the structures were annealed in a N_2 ambient at 550 °C for 30 min.

The LED fabrication process started with deposition of a thin semitransparent p-contact layer of Ni/Au (5/10 nm) by e-beam evaporation. Devices with mesa size of 300 ×300 μm^2 were defined by etching down to n-type GaN (0.8 μm deep from top) using chlorine-based inductively coupled plasma technique. Then the semitransparent p-contact was annealed for 30 min in air at 450 °C to obtain the Ohmic behavior. Finally, the n-contact, Ti/Al/Ti/Au (30/100/20/150 nm), and p-contact pad Ni/Au (30/200 nm) were deposited by e-beam evaporation using optical lithography and lift-off techniques. The I-V, EL and total emitted power of these fabricated LEDs were measured using a microprobe station comprised of a source meter (Keithley 2400), and spectrometers for the visible region (Ocean optics 2000 equipped an InGaAs detector) and for the IR region (Bayspec 2020 with a deep cooled InGaAs detector).

Figure 2 shows typical I-V characteristics of a 300 ×300 μm^2 mesa size LED device. The inset shows the same data on a semilog scale. The leakage current, under reverse bias voltage of −15 V, is only about 0.2 μA. Under forward bias condition, the required voltage for 20 mA current injection was about 12.5 V, which is significantly higher than that found in standard multiple quantum wells (MQWs) III-nitride blue/green LEDs. The relatively high forward voltage observed in these LEDs is related to the high series resistance introduced by the 200 nm thick Er doped $In_{0.05}Ga_{0.95}N$ layer, which was not optimized for the conductivity. The forward voltage can be reduced by optimizing the active layer thickness and by employing Si codoping. However, there could be trade-offs among the active layer thickness, Si codoping concentration and EL intensity, which will require further investigations.

Figure 3 depicts the RT EL spectrum in (a) visible and (b) near IR region of the LED under 20 mA current injection at a forward bias of 12.5 V. In contrast to the PL spectrum,[7] which yielded only emission peaks at 1.0 and 1.54 μm, emission lines at wavelengths of 536, 556, and 667 nm were also observed in EL spectrum. These peaks are attributed to the following intra-4f Er transitions; 536 nm ($^2H_{11/2}\rightarrow {}^4I_{15/2}$), 556 nm ($^2S_{3/2}\rightarrow {}^4I_{15/2}$), and 667 nm ($^4F_{9/2}\rightarrow {}^4I_{15/2}$). The appearance of these emissions peaks implies that the excitation process for the p-i-n diode is different than the PL mechanism involving above band gap optical excitation.[7] The emitted power (P_{int}) measured from one side of a bare chip, integrated over both the visible and near IR regions, is shown in Fig. 4 as a function of applied current. Under 20 mA current injection, the integrated power over the near IR region (1.0 and 1.54 μm bands) is about 2 μW, which is about two times larger than the integrated power in the visible region (536, 556, and 667 nm) of about ~1 μW. The total P_{int} montonically increases with applied current up to 60 mA. Although the emitted power of these LEDs is significantly lower than standard MQWs III-nitride blue/green LEDs, the L–I characteristics are similar. The output power from these Er doped InGaN LEDs is comparable to that reported for initial Eu doped GaN LEDs.[21]

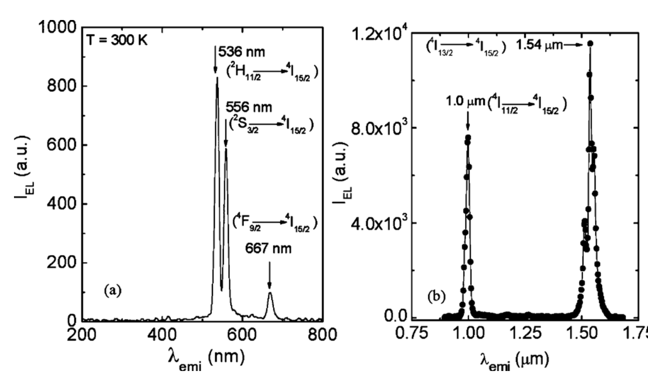

FIG. 3. RT EL spectra of a p-GaN/$Er:In_{0.05}Ga_{0.95}N$/n-GaN LED (a) in visible region, and (b) in near-IR region under a current injection of 20 mA with a forward bias of 12.5 V.

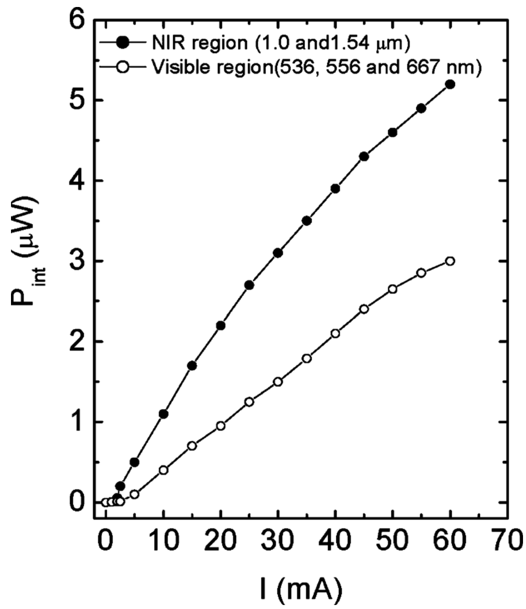

FIG. 4. Integrated optical power, over the visible and near IR regions, of a p-GaN/Er:$In_{0.05}Ga_{0.95}N$/n-GaN LED as a function of input forward current.

Figure 5 shows the EL spectra measured between 900 to 1700 nm with input currents varying from 5 to 70 mA. The intensities of both emission lines (1.0 and 1.54 μm) increase with increasing input currents. At lower values of input currents ($I<30$ mA), the 1.54 μm emission line is stronger than that at 1.0 μm. However, for $I>30$ mA, emission at 1.0 μm is stronger than that at 1.54 μm. The integrated EL intensity of 1.0 and 1.54 μm emission lines as a function of input current is shown in the inset of Fig. 5. This result

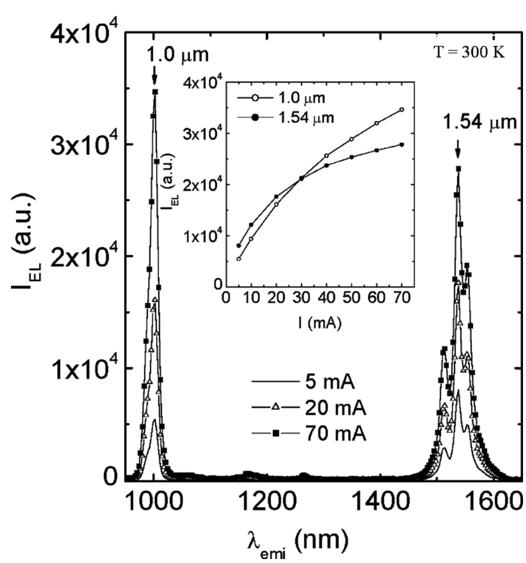

FIG. 5. Near IR EL spectra of a p-GaN/Er:$In_{0.05}Ga_{0.95}N$/n-GaN LED under different levels of injection currents. The inset shows the peak EL intensities of 1.0 and 1.54 μm emissions as functions of injection current.

indicates that the relaxation of electrons to the first excited state ($^4I_{13/2}$) from higher energy levels reduces as the injection current increases.

In summary, Er doped InGaN p-i-n structures were grown by MOCVD and the EL characteristics of fabricated LEDs were probed in the visible and near IR regions. Emission at 1.0 and 1.54 μm was observed under forward bias condition with an output power of ~ 2 μW. These results are very promising for development of Er doped 1.54 μm emitters having very stable RT operation. They also present an important step in the development of current injected chip scale optical amplifiers active in the 1.54 μm wavelength window for future optical communication applications.

The MOCVD growth and device fabrication efforts are supported by ARO (Grant No. W911NF-09-1-0275) and materials characterization effort is supported by NSF (Grant No. ECCS-0854619). Jiang and Lin gratefully acknowledge the support of Ed and Linda Whitacre Endowed Chair positions through the AT & T Foundation.

[1]Y. Q. Wang and A. J. Steckl, Appl. Phys. Lett. **82**, 502 (2003).
[2]P. G. Kik and A. Polman, MRS Bull. **23**, 48 (1998).
[3]H. Ennen, J. Schneider, G. Pomrenke, and A. Axmann, Appl. Phys. Lett. **43**, 943 (1983).
[4]P. N. Favennec, H. L'Haridon, M. Salvi, D. Moutonnet, and Y. Le Guillou, Electron. Lett. **25**, 718 (1989).
[5]R. Dahal, C. Ugolini, J. Y. Lin, H. X. Jiang, and J. M. Zavada, Appl. Phys. Lett. **95**, 111109 (2009).
[6]A. J. Steckl and R. Birkhahn, Appl. Phys. Lett. **73**, 1700 (1998).
[7]C. Ugolini, N. Nepal, J. Y. Lin, H. X. Jiang, and J. M. Zavada, Appl. Phys. Lett. **89**, 151903 (2006).
[8]C. Ugolini, N. Nepal, J. Y. Lin, H. X. Jiang, and J. M. Zavada, Appl. Phys. Lett. **90**, 051110 (2007).
[9]A. Koizumi, Y. Fujiwara, A. Urakami, K. Inoue, T. Yoshikane, and Y. Takeda, Physica B **340–342**, 309 (2003).
[10]K. P. O'Donnell and B. Hourahine, Eur. Phys. J.: Appl. Phys. **36**, 91 (2006).
[11]A. J. Steckl and J. M. Zavada, MRS Bull. **24**, 33 (1999).
[12]J. M. Zavada, S. X. Jin, N. Nepal, J. Y. Lin, H. X. Jiang, P. Chow, and B. Hertog, Appl. Phys. Lett. **84**, 1061 (2004).
[13]S. Kim, S. J. Rhee, X. Li, J. J. Coleman, and S. G. Bishop, Appl. Phys. Lett. **76**, 2403 (2000).
[14]J. M. Zavada, N. Nepal, C. Ugolini, J. Y. Lin, H. X. Jiang, R. Devies, J. Hite, C. R. Abernathy, S. J. Pearton, E. E. Brown, and U. Hommerich, Appl. Phys. Lett. **91**, 054106 (2007).
[15]U. Hommerich, M. Thaik, R. N. Schwartz, R. G. Wilson, J. M. Zavada, S. J. Pearton, C. R. Abernathy, and J. D. MacKenzie, Proc.-Electrochem. Soc. **2**, 110 (1998).
[16]J. T. Torvik, C. H. Qiu, R. J. Feuerstein, J. I. Pankove, and F. Namavar, J. Appl. Phys. **81**, 6343 (1997).
[17]J. T. Seo, U. Hommerich, J. D. MacKenzie, C. R. Abernathy, and J. M. Zavada, J. Korean Phys. Soc. **36**, 311 (2000).
[18]M. A. J. Klik, I. Izeddin, J. Phillips, and T. Gregorkiewicz, Mater. Sci. Eng., B **105**, 141 (2003).
[19]S. Nakamura and G. Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers* (Springer, New York, 1997).
[20]R. Dahal, C. Ugilini, J. Y. Lin, H. X. Jiang, and J. M. Zavada, Appl. Phys. Lett. **93**, 033502 (2008).
[21]A. Nishikawa, T. Kawasaki, N. Furukawa, Y. Terai, and Y. Fujiwara, Appl. Phys. Express **2**, 071004 (2009).