1.54 μm emitter and optical amplifier based on Er doped InGaN/GaN

R. Dahal*, J. Y. Lin, and H. X. Jiang
Department of Electrical & Computer Engineering, Texas Tech University, Lubbock, TX 79409

J. M. Zavada
Department of Electrical & Computer Engineering, North Carolina State University,

Raleigh, NC 27695-7911

Abstract

Er doped III-nitride semiconductors are a major field of research aiming to achieve photonic devices with multiple functionalities in photonic integrated circuits (PICs), which are not possible with either Er doped silica glasses or narrow band gap semiconductors like InGaAsP. Emitters and optical amplifiers based on Er doped GaN/InGaN operating at 1.54 μm are expected to be electrically pumped, integratable, temperature insensitive and have high signal gain with low noise. These properties are very attractive for next generation optical network systems where multiple amplification steps are required. We will discuss here the metal organic chemical vapor deposition (MOCVD) growth of Er doped GaN/InGaN epilayers. Further, we report on the fabrication of chip size current injected 1.54 μm emitters and optical amplifiers by heterogeneously integrating MOCVD grown Er doped GaN/InGaN with 365 nm nitride light-emitting diodes. The emitted intensity at 1.54 μm varied almost linearly with input forward current. The feasibility of electrically pumped optical amplifiers for PICs with the advantages of both semiconductor optical amplifiers and Er-doped fiber amplifiers will also be discussed.

Key words: Er, GaN, InGaN, PL, PLE, IR emitter, waveguide amplifier, optical gain

1 Introduction

Due to advances in semiconductor photonic device fabrication techniques and design, much research has been devoted to the incorporation of Erbium (Er) into semiconductors aimed at achieving PICs with multiple functionalities [1-2]. It is not possible to attain multiple functionalities from either Er-doped silica glasses or narrow bandgap semiconductor materials such as InGaAsP. Optical sources and amplifiers based on Er-doped semiconductors operating at 1.54 μm, if obtained, will be electrically pumped, integratable, and cost effective and with have the performance benefits of linear gain, temperature insensitivity, and low noise. These characteristics are extremely attractive for local- and wide-area networks, cable TV distribution, and anticipated fiber-to-the-home applications where multiple amplification steps are required.

Although the wavelength of emission is not affected by the solid host, the transition probability (i.e., emission intensity) is affected by the neighboring environment. It has been universally observed that the 1.54 μm emission from Er in small bandgap semiconductors has a low efficiency at room temperature (RT) due to a strong thermal quenching effect. In general, the thermal stability of the Er emission increases with an increase in energy bandgap or crystalline quality in the semiconductor host material [3]. Of the various wide bandgap semiconductor systems, III-nitrides appear to be an excellent host system for Er ions due to their structural and thermal stability as well as their ability to create efficient light emitting devices.

rajendra.dahal@ttu.edu

Optical Components and Materials VII, edited by Shibin Jiang,
Michel J. F. Digonnet, John W. Glesener, J. Christopher Dries, Proc. of SPIE
Vol. 7598, 759819 · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.842325

Until recently, it has been a great challenge to incorporate Er ions into III-nitride materials to produce predominantly 1.54 μm emissions by any growth method. Previous work has been concentrated on the optical property studies of Er dopants with samples doped either by ion implantation or by *in situ* doping using the molecular beam epitaxy (MBE) growth technique [3-12]. GaN and AlGaN epilayers doped with Er ions have shown a highly reduced thermal quenching of the Er luminescence intensity from cryogenic to elevated temperatures when compared to other semiconductor host materials such as Si and GaAs [13]. There have also been reports of Er incorporation into GaN by MBE, leading to 1.54 μm electroluminescent devices [4]. However, all such devices require a high field injection of electrons under reverse bias (several hundred volts) to produce infrared (IR) emission at 1.54 μm (no 1.54 μm emission was observed under forward bias conditions). Under such reverse bias conditions, the excitation of Er ions was through an impact energy transfer mechanism. Furthermore, these devices suffer from strong emission lines in the visible region, severely limiting their prospects for practical devices in optical communication applications. Compared to ion implantation, *in situ* doping provides, in principle, precise control of Er dopants position in the device structure. In contrast to other epitaxial growth techniques, MOCVD is the established growth method in the III-nitride semiconductor industry and almost all commercial III-nitride photonic devices including light emitting diodes (LEDs) and laser diodes (LDs) are grown by MOCVD [14].

Our group has synthesized GaN:Er epilayers that predominantly exhibit the desired optical emission for optical communication at 1.5 μm [15,16]. However, true current-injected 1.5 μm LEDs operating under low forward bias voltages have not been realized. We discuss here the MOCVD growth of GaN:Er and InGaN:Er epilayers which predominantly exhibit the desired 1.5 μm emission and fabrication of current-injected 1.54 μm LEDs by heterogeneous integration of GaN:Er (or InGaN:Er) epilayers with III-nitride LEDs. These 1.54 μm LEDs require only a few volts of bias (determined by the nitride LEDs) for operation and are fully compatible with existing optoelectronic devices for scalable integration.

2 Experiment

2.1 MOCVD Growth of GaN:Er and InGaN:Er

GaN:Er and $In_{0.06}Ga_{0.94}N$:Er epilayers of about 0.5 μm in thickness were grown by MOCVD on (0001) GaN/sapphire templates. Growth of these epilayers began with a thin GaN buffer layer, followed by a GaN epilayer template with a thickness of about 1.2 µm and an Er doped GaN layer. The growth temperature of the GaN template and Er doped GaN layer was 1040 ^{O}C. The Er doped $In_{0.06}Ga_{0.94}N$ sample structure was very similar to that of Er doped GaN. Growth of the epilayer began with a thin GaN buffer layer and a 1.2 µm GaN epi-template followed by an Er doped $In_{0.06}Ga_{0.96}N$ layer grown at 760 ^{O}C. The layer structures of GaN:Er and $In_{0.06}Ga_{0.94}N$:Er employed in this study are shown in Figs.1 (a) and (b), respectively.

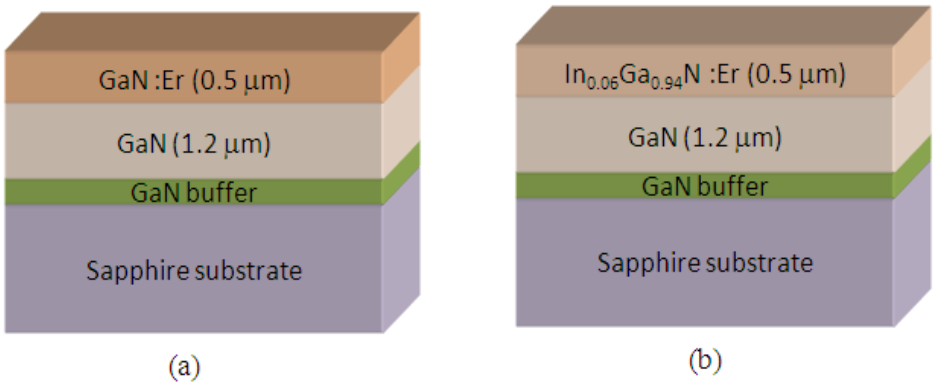

Figure 1 Schematic layer structure of (a) GaN:Er and (b) $In_{0.06}Ga_{0.94}N$: Er epilayers.

3 Results

3.1 Photoluminescence Excitation (PLE) spectroscopy of GaN:Er and InGaN:Er epilayers

In order to design efficient photonic devices, we have measured the photoluminescence excitation (PLE) spectra probed at 1.54 μm and optical absorption spectra of these epilayers to gain further understanding of the mechanisms for obtaining efficient 1.54 μm emission. For PLE spectra measurements, a set of commercially available nitride LEDs was used as the optical pumping sources with the emission wavelengths (352, 362, 371, 378, 381, 398, 411, 450, 470, and 520 nm), ranging from below to above the bandgap of the GaN and InGaN host epilayers. The typical full width at half maximum (FWHM) of each LED was 15–20 nm. For PLE measurements, Er-doped epilayers were mounted on top of nitride LEDs with a distance of about 2 mm from LED's top surface. The IR emission was detected by an InGaAs detector in conjunction with a monochromator, while visible emission was detected by a multichannel plate photomultiplier tube (PMT) in conjunction with another monochromator. The absorption spectra were measured using a deuterium light source in conjunction with a monochromator and PMT.

Figure 2 (a) shows the RT emission spectra of a GaN:Er epilayer under excitation with nitride LEDs of different wavelengths. The emission spectra were taken at a constant current of 20 mA and were normalized to the optical power output of each LED. The emission spectra clearly demonstrate that the emission intensity increases sharply as the excitation energy (E_{exc}) approaches the bandgap of GaN (~3.35 eV or ~370 nm at RT) from below.

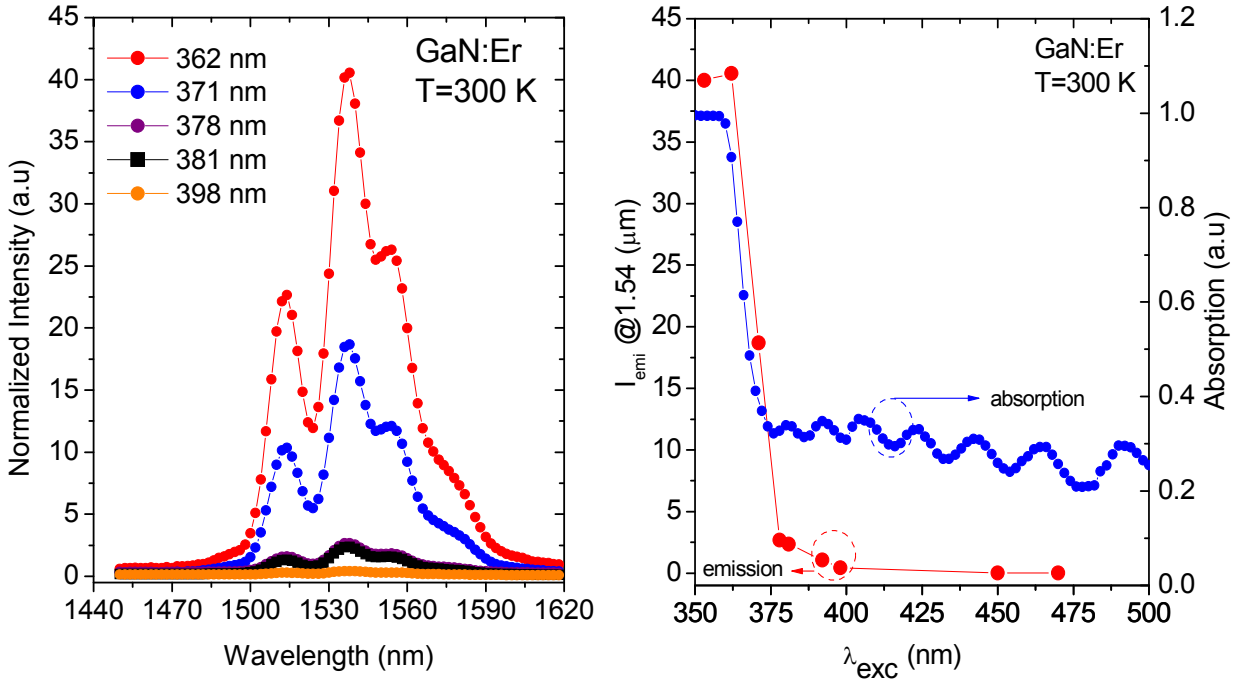

Figure 2 (a) RT emission spectra near 1.54 μm of GaN:Er epilayer with III-nitride LEDs excitation. The excitation wavelengths (λ_{exc}) varies from 362 to 470 nm, corresponding to energies from below to above bandgap of the host GaN and the emission intensities were normalized to the LED optical power outputs, (b) PLE spectrum probed at 1.54 μm (left axis) and optical absorption spectrum (right axis) of GaN:Er. Fringes in the absorption spectrum are due to thin film (GaN:Er) interference effects.

This point is further supported by the PLE and optical absorption spectra shown in Fig. 2 (b). The PLE spectrum probed at 1.54 μm shows that the onset excitation wavelength for obtaining efficient 1.54 μm emission is λ_{exc}<370 nm and the emission intensity at 1.54 μm saturates for λ_{exc}<362 nm. Moreover, there is a little or no emission from excitation for λ_{exc}>400 nm. Comparing the PLE spectrum measured at 1.54 μm and absorption spectrum of GaN:Er, a strong correlation between the two is evident. The two spectra follow exactly the same trend

near the energy bandgap of GaN. These results clearly demonstrate that, in GaN:Er epilayers, excitation of free electrons and holes with above bandgap excitation and the subsequent energy transfer to Er^{3+} ion from electrons and holes is much more efficient compared to below bandgap excitation. These excited Er^{3+} ions emit photons at 1.54 μm due to intra-4*f*-transition of $^4I_{13/2}$ level to the ground state ($^4I_{15/2}$).

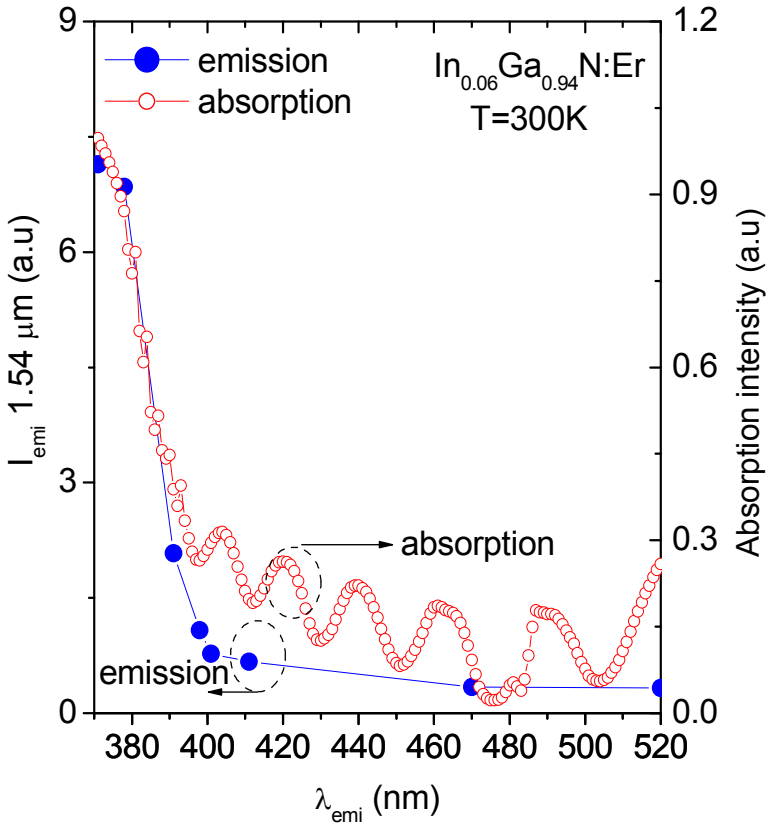

Figure 3 PLE spectrum probed at 1.54 μm (left axis) and absorption spectrum (right axis) of a $In_{0.06}Ga_{0.94}N$:Er epilayer. Emission intensity at 1.54 μm, I_{emi}, increases sharply for excitation energy greater than 3.18 eV (λ_{exc}<390 nm) corresponding to the RT bandgap of $In_{0.06}Ga_{0.94}N$.

To further confirm these results, we have also grown and carried out similar measurements for $In_{0.06}Ga_{0.94}N$:Er epilayers. The relative emission intensity at 1.54 μm in $In_{0.06}Ga_{0.94}N$:Er epilayers is about three times weaker than that in GaN:Er epilayers. The PLE and optical absorption spectra of Er-doped $In_{0.06}Ga_{0.94}N$ epilayers show similar features as those of Er-doped GaN epilayers. The PLE spectrum probed at 1.54 μm and optical absorption spectrum of an $In_{0.06}Ga_{0.94}N$:Er epilayer are plotted in Fig. 3. It is evident that PLE and absorption spectra are again strongly correlated, especially near the energy bandgap of $In_{0.06}Ga_{0.94}N$, which is about 3.18 eV (~390 nm) at RT. In general, $In_{0.06}Ga_{0.94}N$:Er exhibits a similar trend as that observed in GaN:Er shown in Fig. 2 (b), except that the onset excitation energy for obtaining an efficient 1.54 μm emission is reduced because of the smaller bandgap of $In_{0.06}Ga_{0.94}N$ compared to GaN (~3.18 eV for $In_{0.06}Ga_{0.94}N$ versus ~3.35 eV for GaN). The results obtained for $In_{0.06}Ga_{0.94}N$:Er further support the conclusion that the electron and hole energy transfer to Er^{3+} ions is much more effective than below bandgap excitation [17].

3.2 Current injected 1.54 μm emitter based on Er doped GaN

The optical results shown in Figs. 2 and 3 indicate that efficient current-injected 1.54 μm emitters and optical amplifiers could be obtained by monolithically or heterogeneously integrating highly efficient UV/blue/green nitride LEDs or LDs with InGaN:Er or GaN:Er epilayers. Based on the PLE results for obtaining the most efficient 1.54 μm emission, current-injected 1.54 μm emitters were fabricated by heterogeneously integrating GaN:Er (or

InGaN:Er) epilayers with 365 nm nitride LEDs. The integration process started with the back polishing of GaN:Er grown on sapphire wafer down to ~100 μm and then dicing into 500×500 μm^2 chips. The diced chip was then bonded onto a 365 nm nitride LED chip using UV transparent epoxy with GaN:Er surface facing the LED. There

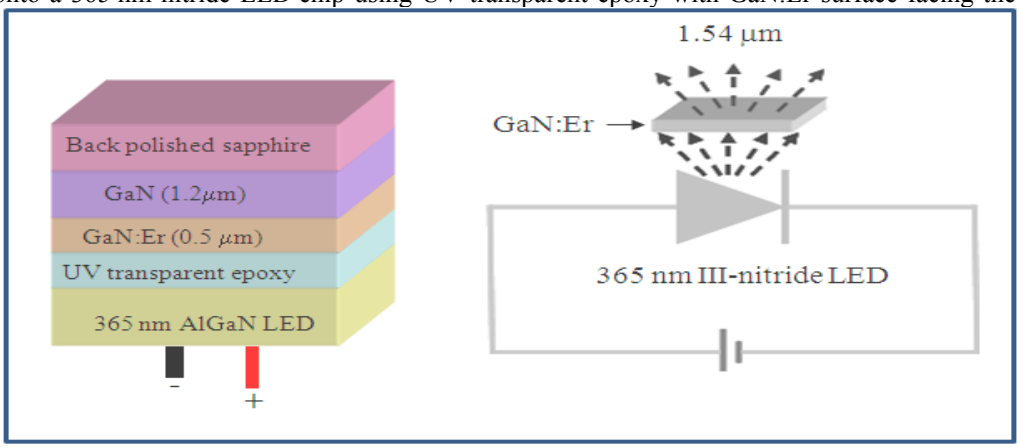

Figure 4 Schematically illustrates that the 1.54 μm LED is fabricated by heterogeneous integration of a GaN:Er epilayer with a 365 nm III-nitride LED.

was a distance of about 0.5 mm between the GaN:Er epilayer and top surface of the LED chip due to the presence of epoxy. A schematic of the heterogeneously integrated device is illustrated in the inset in Fig. 4. These 1.54 μm emitters were characterized in terms of spectral and power emission under different current levels at forward bias. Figure 5 (a) shows the IR emission spectra of a heterogeneously integrated device under different injection current levels at forward bias.

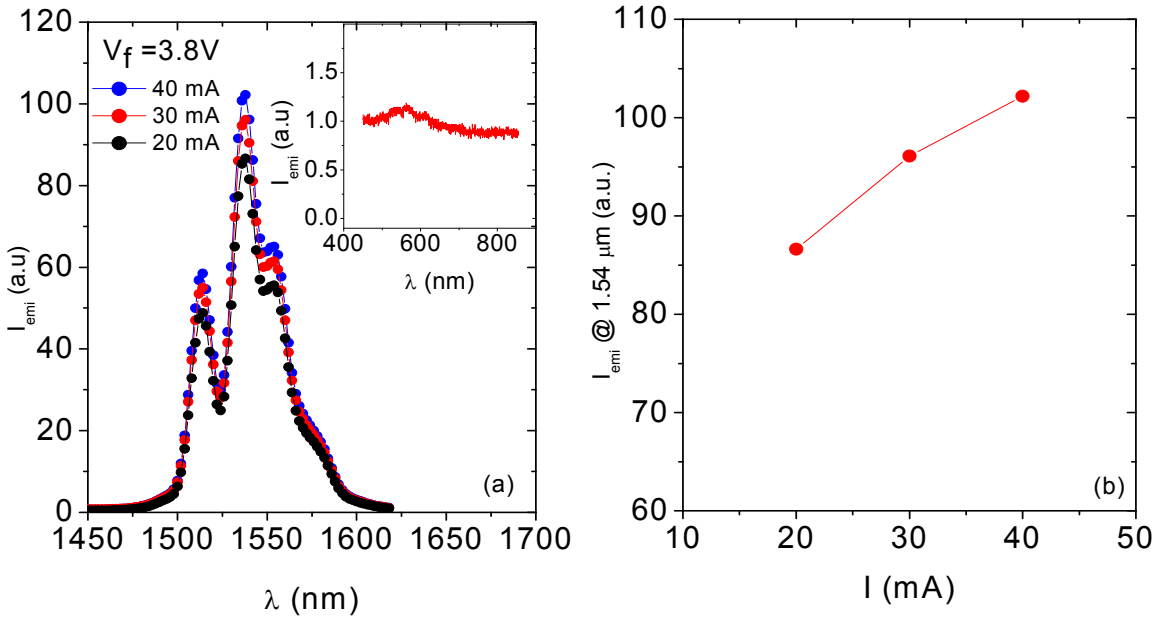

Figure 5 (a) IR emission spectra of a current-injected 1.54 μm LED under different injection current levels. The inset is the visible emission spectrum of the same device, showing virtually no Er-related emission in the spectral range of 430–850 nm. (b) Emission intensity (I_{emi}) of the same 1.54 μm LED as a function of the forward injection current.

The inset in Fig. 5 (a) shows that no Er-related emission in the visible spectral range (between 420 and 850 nm) were observed. The emission intensity at 1.54 μm increases almost linearly with the input current, as shown in Fig. 5 (b).

The attainment of current-injected 1.54 μm emitters by heterogeneous integration suggests that it is highly feasible to directly grow Er-doped nitride layers either on the top or on the back side of the polished sapphire substrate of the UV/blue/green nitride LED structure to achieve monolithic current-injected 1.54 μm optical emitters. It also appears feasible to obtain current-injected optical amplifiers based on a GaN:Er (or InGaN:Er) waveguide layer deposited on top of a completed III-nitride UV (blue) emitter structure or AlGaN/(In)GaN:Er/AlGaN *p-i-n* quantum well (QW) structure [18]. Such a development would require further improvements in GaN:Er and InGaN:Er epilayer quality and device architectures. In particular, it will be a challenging task to obtain highly conductive *p*-type AlGaN (GaN) cladding layers above GaN:Er (InGaN:Er) QW active region.

In summary, we have fabricated current-injected 1.54 μm LEDs based on heterogeneous integration of MOCVD grown Er-doped III-nitride epilayers with III-nitride UV LEDs. The Er emission intensity at 1.54 μm increases significantly as the excitation energy is tuned from below to above the energy bandgap of these epilayers, indicating that the band-to-band excitation of the host material and subsequent electron and hole mediated energy transfer to Er^{3+} ions is a much more effective excitation mechanism for 1.54 μm emission than below bandgap excitation. It was shown that the 1.54 μm emission intensity increases almost linearly with the input forward current. These results open up possibilities for developing next generation IR photonic devices based on Er-doped III-nitride materials such as 1.54 μm emitters and optical amplifiers for optical communications that possess the advantages of both semiconductor optical amplifiers (small size, electrical pumping, ability for photonic integration, etc.) and Er-doped fiber amplifiers (minimal cross-talk between different wavelength channels in wavelength-division multiplexing optical networks).

Acknowledgements

This work is supported by NSF (Grant No: ECCS-0823894) and ARO (Grant No: W911NF-09-1-0277). H. X. Jiang and J. Y. Lin would like to acknowledge the support of Edward Whitacre and Linda Whitacre endowed chairs through the AT&T foundation.

References

1. P. G. Kik and A. Polman, "Erbium-doped optical-waveguide amplifiers in silicon", MRS Bull. **23**, 48 (1998).
2. H. Ennen, J. Schneider, G. Pomrenke, and A. Axmann, "1.54-μm luminescence of erbium-implanted III-V semiconductors and silicon", Appl. Phys. Lett. **43**, 943 (1983).
3. P. N. Favennec, H. L'Haridon, M. Salvi, D. Moutonnet, and Y. Le Guillou, "Luminiscence of erbium implanted in various semiconductors: IV, III-V and II-VI materials", Electron. Lett. **25**, 718 (1989).
4. A. J. Steckl and J. M. Zavada, "Optoelectronic Properties and Applications of Rare-Earth-Doped GaN", MRS Bull. **24**, 33 (1999).
5. J. M. Zavada, S. X. Jin, N. Nepal, J. Y. Lin, H. X. Jiang, P. Chow, and B. Hertog, "Electroluminescent properties of erbium-doped III-N light emitting diodes", Appl. Phys. Lett. **84**, 1061 (2004).
6. S. Kim, S. J. Rhee, X. Li, J. J. Coleman, and S. G. Bishop, "Selective enhancement of 1540 nm Er^{3+} emission centers in Er-implanted GaN by Mg codoping", Appl. Phys. Lett. **76**, 2403 (2000).
7. 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, "Optical and magnetic behavior of erbium-doped GaN epilayers grown by metal-organic chemical vapor deposition", Appl. Phys. Lett. **91**, 054106 (2007).
8. K. P. O'Donnel and B. Hourahine, **"**Rare earth doped III-nitrides for optoelectronics" Eur. Phys. J. Appl. Phys. **36**, 91 (2006).
9. U. Hommerich, M. Thaik, R. N. Schwartz, R. G. Wilson, J. M. Zavada, S. J. Pearton, C. R. Abernathy, and J. D. MacKenzie, " Evaluation of erbium doped III-nitride semiconductors for optoelectronic applications", Proc.-Electrochem. Soc. **2**, 110 (1998).
10. J. T. Torvik, C. H. Qiu, R. J. Feuerstein, J. I. Pankove, and F. Namavar, "Photo-, cathodo-, and electroluminescence from erbium and oxygen co-implanted GaN", J. Appl. Phys. **81**, 6343 (1997).
11. J. T. Seo, U. Hommerich, J. D. MacKenzie, C. R. Abernathy, and J. M. Zavada, "Near-Infrared Luminescent Device and Optical Spectroscopy of Er-doped Gallium Nitride Prepared by Metalorganic Molecular Beam Epitaxy", J. Korean Phys. Soc. **36**, 311 (2000).
12. M. A. J. Klik, I. Izeddin, J. Phillips, and T. Gregorkiewicz, "Excitation paths in RE-doped III–V semiconductors", Mater. Sci. Eng., B **105**, 141 (2003).

13. J. M. Zavada, U. Hommerich, and A. J. Steckl, *III-Nitride Semiconductors: Optical Properties I*, edited by M. O. Manasreh and H. X. Jiang, (Taylor & Francis, New York, 2002).
14. S. Nakamura and G. Fasol, *The Blue Laser Diode: GaN Based Light Emitters and Lasers* (Springer, New York, 1997).
15. C. Ugolini, N. Nepal, J. Y. Lin, H. X. Jiang, and J. M. Zavada, "Erbium-doped GaN epilayers synthesized by metal-organic chemical vapor deposition", Appl. Phys. Lett. **89**, 151903 (2006).
16. C. Ugolini, N. Nepal, J. Y. Lin, H. X. Jiang, and J. M. Zavada, " Excitation dynamics of the 1.54 μm emission in Er doped GaN synthesized by metal organic chemical vapor deposition", Appl. Phys. Lett. **90**, 051110 (2007).
17. R. Dahal, C. Ugolini, J. Y. Lin, H. X. Jiang, and J. M. Zavada," Current-injected 1.54 μm light emitting diodes based on erbium-doped GaN", Appl. Phys. Lett. **93**, 033502 (2008).
18. R. Dahal, C. Ugolini, J. Y. Lin, H. X. Jiang, and J. M. Zavada," Erbium-doped GaN optical amplifiers operating at 1.54 μm", Appl. Phys. Lett. **95**, 111109 (2009).