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Current injection 1.54 µm light-emitting devices based on Er-doped GaN/AlGaN multiple quantum wells

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Abstract: We report on the growth, fabrication and electroluminescence (EL) characteristics of light-emitting diodes (LEDs) based on Er-doped GaN (GaN:Er) and GaN/AlGaN multiple quantum well (MQW:Er) active layers. The LED structures were grown using metal organic chemical vapor deposition and processed into 300x300 µm^2 mesa devices. The LEDs exhibit emission at 1.54 µm, due to Er intra-4*f* transitions, under forward bias conditions. The 1.54 µm emission properties from LEDs with MQWs:Er and GaN:Er active layers were probed. The LEDs fabricated using MQWs:Er exhibited improved performance as evidenced by a factor of 4 enhancement in the optical power output as compared to conventional GaN:Er based LEDs. The results demonstrate a significant advance in the development of current injected, chip-scale emitters and waveguide amplifiers based on Er doped semiconductors.

OCIS codes: (160.5690) Rare-earth-doped materials; (250.5590) Quantum-well devices.

References and links

1. 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**(10), 943 (1983).
2. P. N. Favennec, H. L'Halidon, M. Salvi, D. Moutonnet, and Y. Le Guillou, "Luminescence of erbium implanted in various semiconductors: IV, III-V and II-VI materials," Electron. Lett. **25**(11), 718–719 (1989).
3. P. G. Kik and A. Polman, "Erbium-Doped Optical-Waveguide Amplifiers on Silicon," MRS Bull. **23**(04), 48–54 (1998).
4. T. M. Al tahtamouni, X. Du, J. Li, J. Lin, and H. Jiang, "Erbium-doped a-plane GaN epilayers synthesized by metal-organic chemical vapor deposition," Opt. Mater. Express **5**(2), 274 (2015).
5. 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**(11), 111109 (2009).
6. R. Dahal, C. Ugolini, J. Y. Lin, H. X. Jiang, and J. M. Zavada, "1.54 µm emitters based on erbium doped InGaN p-i-n junctions," Appl. Phys. Lett. **97**(14), 141109 (2010).
7. P. N. Favennec, H. L'Haridon, D. Moutonnet, M. Salvi, and M. Gauneau, "Optical Activation of Er^{3+} Implanted in Silicon by Oxygen Impurities," Jpn. J. Appl. Phys. **29**(Part 2), L524–L526 (1990).
8. R. G. Wilson, R. N. Schwartz, C. R. Abernathy, S. J. Pearton, N. Newman, M. Rubin, T. Fu, and J. M. Zavada, "1.54-µm photoluminescence from Er-implanted GaN and AlN," Appl. Phys. Lett. **65**(8), 992 (1994).
9. C. H. Qiu, M. W. Leksono, J. I. Pankove, J. T. Torvik, R. J. Feurstein, and F. Namavar, "Cathodoluminescence study of erbium and oxygen coimplanted gallium nitride thin films on sapphire substrates," Appl. Phys. Lett. **66**(5), 562 (1995).
10. S. Kim, S. J. Rhee, D. A. Turnbull, X. Li, J. J. Coleman, S. G. Bishop, and P. B. Klein, "Trap-mediated excitation of Er^{3+} photoluminescence in Er-implanted GaN," Appl. Phys. Lett. **71**(18), 2662–2664 (1997).
11. J. T. Torvik, C. H. Qiu, R. J. Feurstein, J. I. Pankove, and F. Namavar, "Photo-, cathodo-, and electroluminescence from erbium and oxygen co-implanted GaN," J. Appl. Phys. **81**(9), 6343 (1997).
12. D. M. Hansen, R. Zhang, N. R. Perkins, S. Safvi, L. Zhang, K. L. Bray, and T. F. Kuech, "Photoluminescence of erbium-implanted GaN and in situ-doped GaN:Er," Appl. Phys. Lett. **72**(10), 1244 (1998).
13. H. J. Lozykowski, W. M. Jadwisienczak, and I. Brown, "Photoluminescence and cathodoluminescence of GaN doped with Pr," J. Appl. Phys. **88**(1), 210 (2000).
14. J. D. MacKenzie, C. R. Abernathy, S. J. Pearton, U. Hommerich, J. T. Seo, R. G. Wilson, and J. M. Zavada, "Er doping of GaN during growth by metalorganic molecular beam epitaxy," Appl. Phys. Lett. **72**(21), 2710–2712 (1998).
15. A. J. Steckl, M. Garter, R. Birkhahn, and J. Scofield, "Green electroluminescence from Er-doped GaN Schottky barrier diodes," Appl. Phys. Lett. **73**(17), 2450 (1998).

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Optical Materials EXPRESS

16. M. Garter, J. Scofield, R. Birkhahn, and A. J. Steckl, "Visible and infrared rare-earth-activated electroluminescence from indium tin oxide Schottky diodes to GaN:Er on Si," Appl. Phys. Lett. **74**(2), 182 (1999).
17. R. H. Birkhahn, R. Hudgins, D. S. Lee, B. K. Lee, A. J. Steckl, A. Saleh, R. G. Wilson, and J. M. Zavada, "Optical and structural properties of Er^{3+}-doped GaN grown by MBE," MRS Internet J. Nitride Semicond. Res. **4S1**, **537**, 80 (1999).
18. A. J. Steckl, J. Heikenfeld, M. Garter, R. Birkhahn, and D. S. Lee, "Rare earth doped gallium nitride — light emission from ultraviolet to infrared," Compd. Semicond. **6**(1), 48–52 (2000).
19. S. Son, S. Kim, Y. H. Kim, I. K. Han, Y. T. Kim, A. Wakahara, I. H. Choi, and H. C. Lopez, "Photoluminescence of Er-implanted GaN," J. Korean Phys. Soc. **45**, 955 (2004).
20. X. Wu, U. Hommerich, J. D. MacKenzie, C. R. Abernathy, S. J. Pearton, R. Schwartz, R. G. Wilson, and J. M. Zavada, "Direct and indirect excitation of Er^{3+} ions in Er: AIN," Appl. Phys. Lett. **70**(16), 2126 (1997).
21. 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**(15), 151903 (2006).
22. T. M. Al tahtamouni, X. Du, J. Lin, and H. Jiang, "Erbium-doped AlN epilayers synthesized by metal-organic chemical vapor deposition," Opt. Mater. Express **5**(3), 648 (2015).
23. J. M. Zavada, S. X. Jin, N. Nepal, H. X. Jiang, J. Y. Lin, P. Chow, and B. Hertog, "Electroluminescent properties of erbium-doped III–N light-emitting diodes," Appl. Phys. Lett. **84**(7), 1061–1063 (2004).
24. I. W. Feng, J. Li, A. Sedhain, J. Y. Lin, H. X. Jiang, and J. Zavada, "Enhancing erbium emission by strain engineering in GaN heteroepitaxial layers," Appl. Phys. Lett. **96**(3), 031908 (2010).
25. T. Ishiyama, S. Yoneyama, Y. Yamashita, Y. Kamiura, T. Date, T. Hasegawa, K. Inoue, and K. Okuno, "Enhancement of photoluminescence at 1.54 µm from Er in strained Si and SiGe," Physica B **376-377**, 122–125 (2006).
26. T. M. Al tahtamouni, M. Stachowicz, J. Li, J. Y. Lin, and H. X. Jiang, "Dramatic enhancement of 1.54 µm emission in Er doped GaN quantum well structures," Appl. Phys. Lett. **106**(12), 121106 (2015).
27. K. Iida, T. Kawashima, A. Miyake, M. Iwaya, S. Kamiyama, H. Amano, and I. Akasaki, "Laser diode of 350.9 nm wavelength grown on sapphire substrate by MOVPE," J. Cryst. Growth **272**(1-4), 270–273 (2004).
28. T. Arai, D. Timmerman, R. Wakamatsu, D. Lee, A. Koizumi, and Y. Fujiwara, "Enhanced excitation efficiency of Eu ions in Eu-doped GaN/AlGaN multiple quantum well structures grown by organometallic vapor phase epitaxy," J. Lumin. **158**, 70–74 (2015).

1. Introduction

Rare earth (RE) doped III-nitride semiconductors have attracted a lot of interest for applications in full color display systems to optical communication devices with multiple functionalities. Such functionalities are not possible to obtain from either Er-doped silica glasses or narrow bandgap semiconductors [1–5]. Erbium (Er) has been the main RE element under investigation in these semiconductors, due to the importance of the 1.54 µm emission resulting from the intra-4f transition from the first excited manifold ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$) in Er^{3+} ions for telecommunications. 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]. The 1.54 µm emission lies in the minimum loss region of silica fibers used in optical communications. It is well established that the thermal quenching of the Er^{3+} emission intensity depends strongly on the band gap of the host semiconductor and is dramatically reduced in wide band-gap semiconductors [7]. Er doped III–nitride semiconductors are of great interest for applications in light-emitting diodes (LEDs) operating at 1.54 µm, because of their temperature insensitive, sharp and stable emission and an ease of current injection. 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, provides the opportunity to create efficient light-emitting devices [6].

Er doped III-nitride materials have been investigated using different growth methods such as ion implantation [8–13], *in situ* metal-organic molecular beam epitaxy [14–20], and *in situ* metal organic chemical vapor deposition (MOCVD) [21,22]. 1.54 µm emission from Er doped GaN (GaN:Er) and Er doped InGaN (InGaN:Er) based LEDs under current injection were reported [6,23]. However, the light output power of these devices still suffer from a low quantum efficiency. There is a continued need to exploring effective mechanisms to further improve the quantum efficiency (QE) of the 1.54 µm emission in Er-doped III-nitrides.

To improve the quantum efficiency of the GaN:Er based LEDs, the excitation efficiency of the Er ions has to be improved. Using quantum well (QW) architecture is expected to

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enhance both the spatial confinement and density of states of carriers within the well layers leading to an increase in the carrier density and energy transfer from carriers to Er^{3+} ions. Furthermore, the use of the QW architecture allows the flexibility in strain engineering which was shown to be an effective means in optimizing the emission characteristics of Er doped semiconductors [24,25]. Recently, we have demonstrated through photoluminescence (PL) spectroscopy that Er doped GaN/AlN multiple QWs(MQWs:Er) structure is an effective means for dramatically enhancing the quantum efficiency of the 1.54 µm emission in Er doped GaN via quantum confinement [26].

In this letter, we report on MOCVD synthesis and fabrication of Er-doped GaN p-i-n LEDs based on AlGaN/GaN multiple quantum wells (MQWs). The electroluminescence (EL) spectra, current-voltage (I–V) characteristics, and light emission characteristics (L-I) of fabricated LEDs were measured and discussed. The characteristics of the LEDs with MQWs:Er have been studied and compared to LEDs incorporating GaN:Er epilayer as the active layer. The devices showed a dominant EL emission at 1.54 µm under forward bias. The performance of the LEDs fabricated using MQWs:Er was significantly improved, as manifested by enhanced electroluminescence (EL) intensity and integrated optical power over the near IR regions. However, the turn-on voltage for LEDs fabricated using MQWs:Er is higher than that of LEDs using GaN:Er.

2. Experimental details

The device structure was a p-i-n diode for which the i-layer was Er doped GaN/AlGaN multiple quantum wells (MQWs:Er). The p-i-n structures were grown on GaN/sapphire templates by MOCVD. The metalorganic sources used were trimethylaluminum, trimethylgallium, and biscyclopentadienylmagnesium, for aluminum, gallium, and magnesium, respectively. Trisisopropylcyclopentadienylerbium was used for the *in situ* Er doping. Blue ammonia and silane (SiH_4) were used as nitrogen and silicon sources, respectively. Hydrogen was the carrier gas. The growth was initiated by a thin low temperature (550 °C) GaN buffer layer grown on sapphire (0001) substrate, followed by undoped GaN template with a thickness of about 1.0 µm grown at 1050 °C. This was then followed by the growth of a 2.5 µm Si-doped GaN epilayer at 1060 °C. The targeted electron concentration was around $5x10^{18}$ cm^{-3}. It was then followed by the growth of the MQWs:Er structure with 40 periods of 2 nm Er doped GaN well and 10 nm undoped $Al_{0.1}Ga_{0.9}N$ barrier. The growth temperature and pressure were 1020 °C and 30 mbar, respectively. The targeted Er concentration in the QW layer was $2x10^{19}$ cm^{-3}. The structure was then completed with a 0.3 µm thick p-GaN contact layer. The targeted hole concentration was around $3x10^{17}$ cm^{-3}. For comparison, LEDs incorporating 80 nm thick GaN:Er layer as an active region, providing the same thickness of Er doped layer as in MQWs:Er, was also fabricated.

The LED fabrication process was identical to that of a blue/green LED and started from the deposition of Ni/Au semitransparent layer and mesa etching to expose the n-type GaN, followed by Ti/Al/Ti/Au metal deposition for the n-contact and Ni/Au for p-contact with a rapid thermal annealing at 450 °C for 30 min. LEDs with different mesa disk sizes were then diced into single devices, flip-chip bonded with Au bumps onto ceramic AlN submount, and finally mounted on TO headers. The EL, I-V, and total emitted power of the fabricated LEDs were measured using a microprobe station comprised of a source meter (Keithley 2400), and spectrometer for the IR region (Bayspec 2020 with a deep cooled InGaAs detector).

3. Results and discussion

Figure 1(a) shows the entire temperature profile of complete growth process. Figure 1(b) shows the trace of *in situ* optical reflectivity with monitoring wavelength of 670 nm during the LED structure growth. GaN layers and MQW:Er growths exhibit different oscillation periods in the Fig. due to their reflectivity differences at the growth temperature. No damping

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of the oscillation amplitude with increase of the thickness indicates a two-dimensional growth mode and good surface morphology.

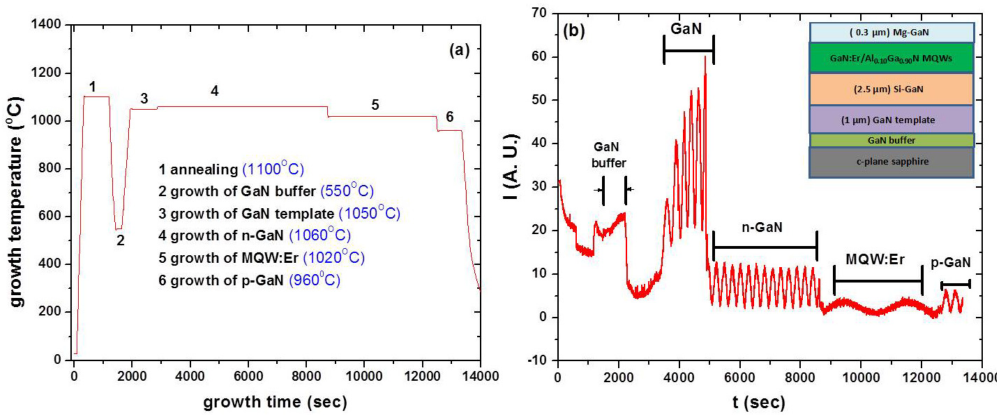

Fig. 1. (a) The growth temperature sequence and (b) In situ optical reflection curve in the whole growth process of 1.54 μm LED structure incorporating MQWs:Er as active layer. Inset: Schematic layer structure of 1.54 μm LED.

The device layer structure employed in this study is schematically shown in Fig. 2(a), which utilizes MQWs:Er structure as an active layer. Figure 2 (b) shows the optical microscopy image of a fabricated device with a size of 300 x 300 μm^2.

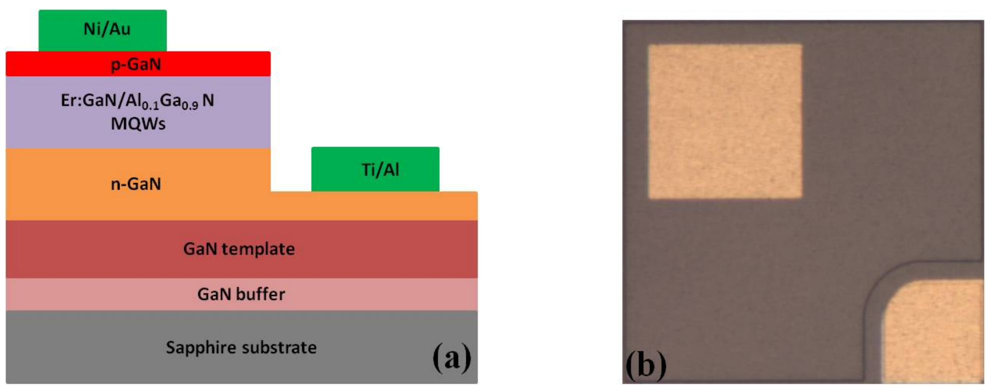

Fig. 2. (a) Device layer structure employed in this study and (b) the optical microscopy image of a fabricated device of size 300 x 300 μm^2.

Electroluminescence properties of MQWs:Er and GaN:Er based LED structures were measured at room temperature. Infrared spectra shown in Fig. 3 were detected at 20 mA current injection from MQWs:Er and GaN:Er based LED structures. Both devices exhibit emission peak at 1.54 μm (~0.81 eV), corresponding to the intra-4f Er^{3+} transitions from the first excited state ($^4I_{13/2}$) to the ground state ($^4I_{15/2}$). The intensity of the 1.54 μm emission peak from the device utilizing MQWs:Er is 4 times higher than that from the device utilizing GaN:Er epilayer with a comparable Er active layer thickness. This large enhancement indicates that the MQW architecture significantly enhances the excitation efficiency of Er^{3+} owing to the enhanced carrier density in quantum wells [26].

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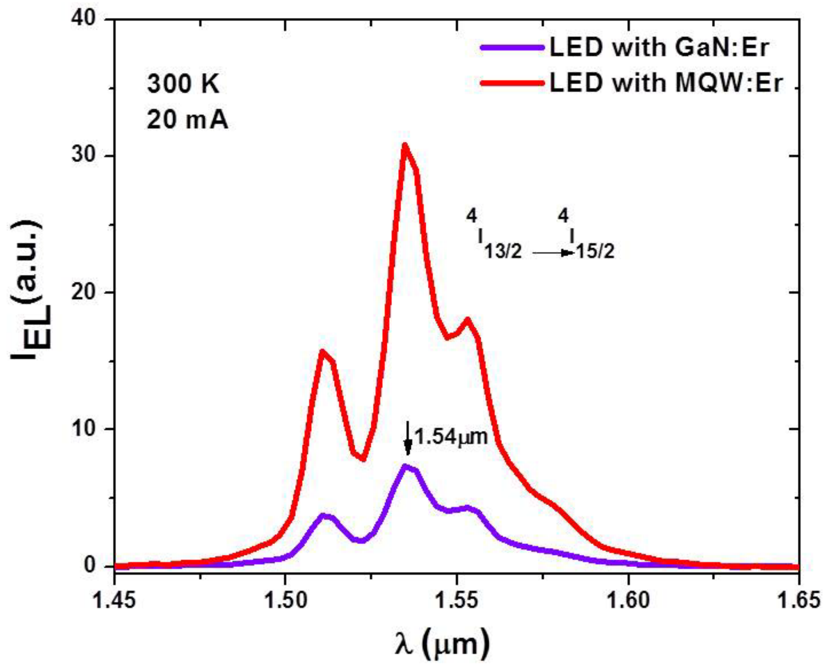

Fig. 3. EL spectra from MQW:Er and GaN:Er based LED structures in near Infrared region under a current injection of 20 mA.

The light emission characteristics of the 1.54 µm LEDs were estimated by comparing the intensity change with increasing current, as shown in Fig. 4. The light output of the 1.54 µm LED with MQWs:Er active layer is 4 times higher than that of the 1.54 µm LED with GaN:Er active layer at I > 20 mA. A three times enhancement was reported for MQW:Eu structures [28]. The light output is significantly enhanced when replacing GaN:Er active layer with MQWs:Er active layer. The cause for the superiority of 1.54 µm LED with MQWs:Er active layer is the enhancement of the quantum efficiency of the 1.54 µm emission via quantum confinement [26].

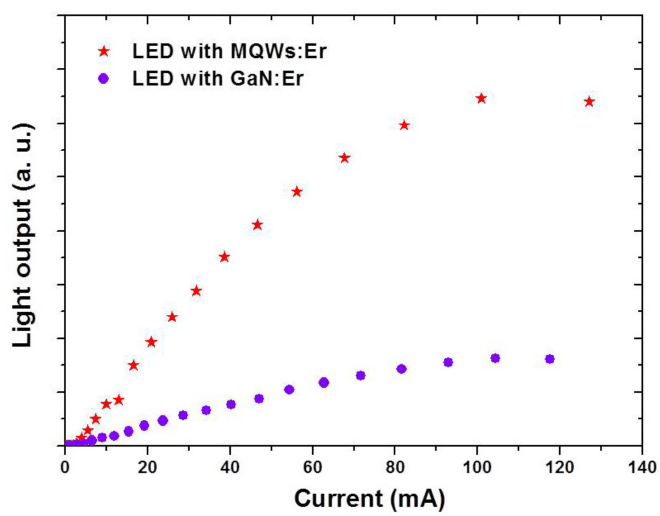

Fig. 4. Light output vs current (L-I) characteristics of 1.54 µm LEDs with MQWs:Er active layer and GaN:Er active layer under wafer probe.

The forward I-V characteristics of a 300 x 300 μm^2 mesa size MQW:Er and GaN:Er based LED devices are shown in Fig. 5. The forward voltage at 20 mA for the LED with MQWs:Er (13.5 V) is higher than that of LED with GaN:Er (8.6 V). The relatively high forward voltage observed in the MQWs:Er LED is related to the high series resistance introduced by the high resistivity of the $Al_{0.10}Ga_{0.90}N$ barriers [27,28].

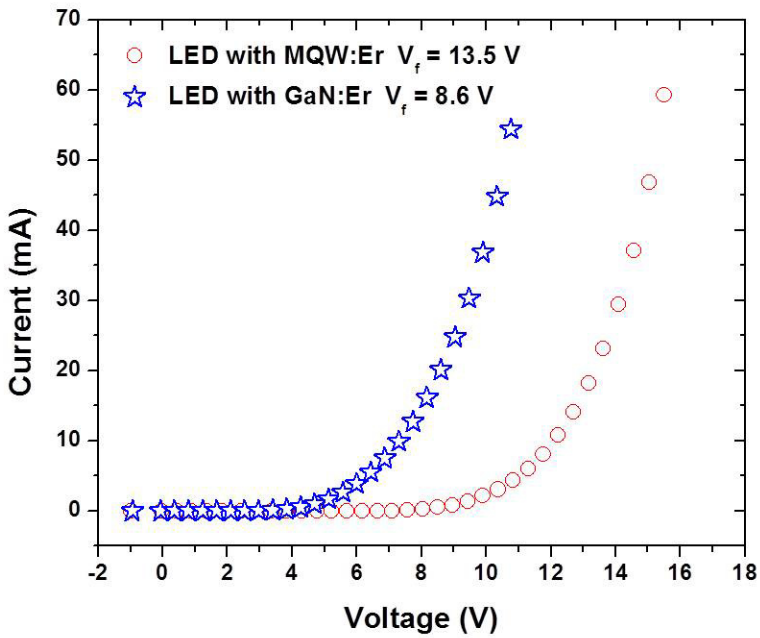

Fig. 5. Current-voltage (I – V) characteristics for 1.54 μm LEDs with MQWs:Er active layer and GaN:Er active layer under wafer probe.

4. Summary

We have fabricated GaN/AlGaN MQW:Er and GaN:Er 1.54μm LED devices. It was shown that the use of MWQs:Er structures as an active layer in the 1.54μm LED structures is an effective way to improve the performance of these 1.54μm LEDs. A significant enhancement of the EL intensity and light output in 1.54μm LEDs with MWQs:Er active layers over similar LEDs with GaN:Er active layer was demonstrated. These results provide useful insights to guide the development of Er doped 1.54 μm emitters having stable room temperature 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.

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