

Mg가 첨가된 GaN:Er 발광 현상에 관한 연구

Photoluminescence and Photoluminescence Excitation Spectra of Mg-codoped GaN:Er

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Abstract

The ~ 1540 nm Er^{3+} photoluminescence (PL) and photoluminescence excitation (PLE) spectra of Er-implanted Mg-codoped GaN (GaN:Er+Mg) exhibit that the excitation efficiency of a specific Er^{3+} center among different Er^{3+} centers existing in Er-implanted GaN is selectively enhanced, compared to Er-implanted undoped GaN (GaN:Er). In GaN:Er+Mg, the 1540 nm PL peaks characteristic of the so-called "violet-pumped" Er^{3+} center and the ~ 2.8 - 3.4 eV (violet) PLE band are significantly strengthened by the Mg-doping. The intra-f absorption PLE bands associated with this "violet-pumped" center are also enhanced by this doping. The 1540 nm PL peaks originating from the violet-pumped center dominate the above-gap-excited Er^{3+} PL spectrum of GaN:Er+Mg, whereas it was unobservable under above-gap excitation in GaN:Er. All of these results indicate that Mg doping increases the efficiency of trap-mediated excitation of Er^{3+} emission in Er-implanted GaN.

Key Wards : Mg, GaN:Er, 발광, PLE

1. Introduction

The thermal quenching of Er^{3+} emission in Er-doped semiconductors decreases with increasing bandgap of the host semiconductor [1,2]. This fact has stimulated studies of Er-doped GaN, because of its wide-bandgap (3.5 eV at 300 K) [3,4]. Recent photoluminescence (PL) and photoluminescence excitation (PLE) studies of Er-implanted GaN (GaN:Er) have detected several different Er^{3+} emission centers existing in this material [5,6], and have revealed that a specific Er^{3+} center being excited efficiently by direct intra-4f-shell absorption represents over 99% of the optically active Er atoms. However, this center is not strongly pumped by above-gap light.

The recent Er^{3+} PL studies show also that less than 1% of the Er atoms involved in the Er-defect/impurity complexes mediate the excitation of the Er^{3+} emission spectra pumped by above-gap absorption [5,6]. These previous observations suggest that appropriate co-dopants should be identified to improve the efficiency of above-gap optical or electrical excitation of Er^{3+} in GaN.

In this paper we report a significant enhancement of the so-called "violet-pumped" Er^{3+} center-associated PL and PLE bands in Er-implanted GaN by Mg-codoping as well as the domination of the "violet-pumped" Er^{3+} center-associated PL peaks in the above-gap pumped Er^{3+} PL spectrum of Mg-codoped GaN:Er

(GaN:Er+Mg). In this work, we show that Mg is one of appropriate co-dopants increasing the efficiency of trap-mediated above-gap excitation of Er^{3+} emission in Er-implanted GaN.

II. Experimental procedure

Mg-doped ($0.7\mu\text{m}$ thick) GaN films were grown on (0001) sapphire by atmospheric pressure metal-organic chemical vapor deposition (MOCVD). Undoped GaN films grown on (0001) sapphire by MOCVD were also prepared for reference samples. The concentration of electrically active Mg dopants was $\sim 5 \times 10^{19} \text{ cm}^{-3}$ before the Er implantation. The Mg-doped and undoped GaN films were implanted with a dosage of $4 \times 10^{13} \text{ Er ions/cm}^2$, with the projected range for the 280-keV Er ions estimated to be approximately $0.05\mu\text{m}$ [5,7]. The implanted samples were annealed at 900°C for 90 minutes under a continuous flow of nitrogen gas.

The Er^{3+} PL spectra were excited by a variety of sources. These include the 325 nm line from a HeCd laser, 404 nm light from a Xe lamp, the 458 nm line from an Ar ion laser, and the 633 nm line from a HeNe laser. The broad band PLE spectra were obtained with a Xe lamp dispersed by a double grating monochromator, and the high-resolution sharp-line $\sim 810 \text{ nm}$ 4f band PLE spectra were scanned with a tunable titanium-doped sapphire laser. All of the Er^{3+} PLE spectra were corrected for the spectral response of the tunable excitation systems. Luminescence was analyzed by a 1-m single grating monochromator and detected by a cooled Ge PIN detector. The Er-implanted GaN samples were mounted in a Janis Superveritemp liquid helium cryostat, and the PLE and PL spectroscopies were carried out at 6 K.

III. Results and discussion

Fig. 1 compares the six Er^{3+} PL spectra. We describe first the five different Er^{3+} PL spectra of the GaN:Er material for convenience, before dealing with the above-gap excited Er^{3+} PL

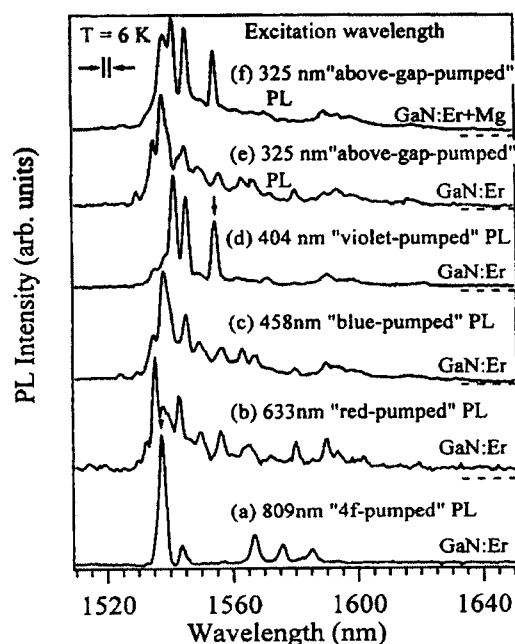


그림 1. Comparison of the above-gap pumped Er^{3+} PL spectrum of GaN:Er+Mg with the five different PL spectra of GaN:Er.

spectrum of the GaN:Er+Mg. For GaN:Er, the 4f-pumped PL spectrum (Fig. 1(a)) was excited by the direct $\text{Er}^{3+} 4I_{15/2} \rightarrow 4I_{9/2}$ 4f shell PLE absorption peaks, and the red-pumped, blue-pumped, and violet-pumped PL spectra (Figs. 1(b)-(d)) were excited by 633, 458, and 404 nm light, respectively, of which wavelengths were chosen to coincide with the below-gap PLE absorption bands described in detail in Ref. 6. Each of these four PL spectra contains sets of prominent peaks being dominant in its spectrum. The spectral difference in the PL spectra is due to the existence of four different Er centers existing in GaN:Er.

Our previous study suggested that the simple-structured, 4f-pumped PL spectrum originate from an isolated Er^{3+} ion on a Ga site and showed that this so-called 4f-pumped Er center represents 99% of the optically active Er^{3+} centers present in GaN:Er [5,6]. The excitation process of the 4f-pumped center is direct-4f shell excitation. On the contrary, the excitation

process of the other Er^{3+} centers corresponds to trap-mediated excitation mechanism in which absorption by the defects is followed by efficient, nonradiative transfer of the excitation energy to neighboring Er^{3+} ions [8]. This implies that the other three Er centers are complex of Er^{3+} ions with nearby defects.

While below-gap excitation that consists of the direct-4f shell and trap-mediated excitations is a useful tool in identifying the origin of Er^{3+} centers, above-gap excitation is of practical importance since this excitation emulates electrical excitation by which light-emitting diodes and laser devices operate. The analysis of the above-gap-pumped PL spectrum provides the practically important information that which of the four Er^{3+} centers can be electrically pumped. Fig. 1(e) shows the above-gap-pumped PL spectrum excited by 325 nm light of which energy is higher than the bandgap of GaN. A careful comparison of this PL spectrum with the four below-gap-pumped PL spectra (Figs. 1(a)-(d)) reveals that the above-gap-pumped PL spectrum is a mixture of the red-pumped and blue-pumped PL spectra, but that any of the PL peaks in the 4f-pumped and violet-pumped PL spectra are not seen in above-gap-pumped PL spectrum. In other words, the above-gap pumped PL spectra from GaN:Er represent the superposition of emissions from two different Er^{3+} centers that are trap-mediatedly excitable, and the 4f-pumped and violet-pumped Er^{3+} centers are not pumped efficiently by above gap light. From the practical viewpoint, this is the discouraging information. The implication of the information is that 99% of the optically active Er^{3+} centers existing in GaN:Er are not electrically excitable.

Now we turn our attention to the above-gap-pumped PL spectrum from GaN:Er+Mg (Fig. 1(f)). This above-gap-pumped PL spectrum is very different from that of GaN:Er in that it is dominated by the strong, distinctive PL peaks characterizing the violet-pumped Er^{3+} PL spectrum shown in Fig. 1(e). A comparison between the above-gap pumped PL spectra of the GaN:Mg+Er and GaN:Er samples clearly

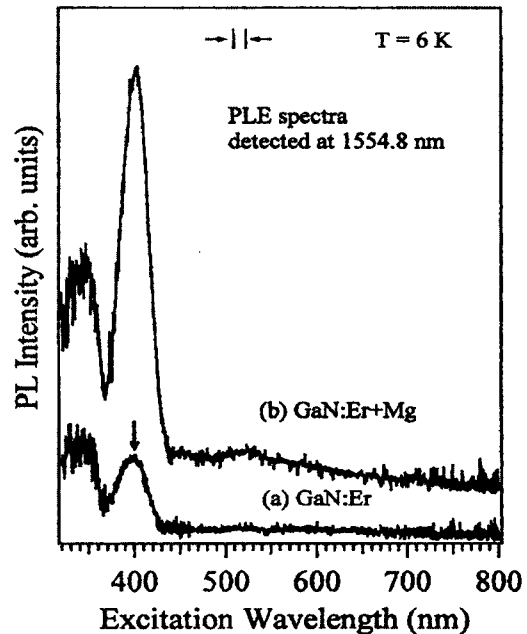


그림 2. Broadband PLE spectra detected at the 1554.8 nm peak of the violet-pumped PL in (a) GaN:Er, and (b) GaN:Er+Mg.

reveals the dramatic effect of the Mg-doping upon the Er^{3+} emission. Thus the Mg-doping has had the effect of making the violet-pumped centers the dominant contributors to the above-gap pumped Er^{3+} PL spectrum of GaN:Er+Mg, whereas they are undetectable in the above-gap pumped PL spectrum of GaN:Er.

The violet-pumped center is originally named for the well-defined violet PLE band peaking at 404 nm just below the GaN band gap, shown in the PLE spectra of Fig. 2. The PLE spectra of Fig. 2 were detected at the distinctive 1554.8 nm peak indicated by an arrow in the violet-pumped PL spectrum of Fig. 1(d). A comparison between the above-gap pumped PL spectra of the GaN:Mg+Er and GaN:Er samples illuminates that the broadband PLE spectra of Fig. 2 also provide direct evidence for the enhancement of the violet-pumped centers in Mg-doped material. The intensity of the distinctive violet PLE band peaking at ~ 404 nm is enhanced by a

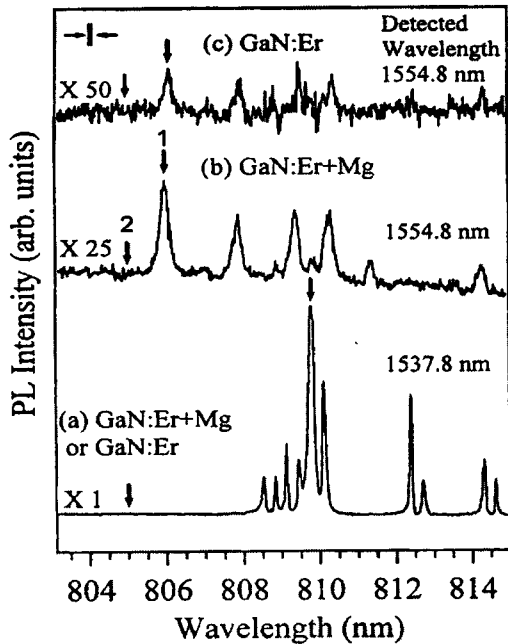


그림 3. The high-resolution ${}^4I_{15/2} \rightarrow {}^4I_{9/2}$ 4f shell PLE spectra obtained from GaN:Er and GaN:Er+Mg. The PLE spectrum (a), generated by detecting at 1537.8 nm, exhibits the sharpline PLE speaks characteristic of the 4f-pumped Er^{3+} center. Both the PLE spectra of (b) GaN:Er+Mg and (c) GaN:Er, detected at the 1554.8 nm, originate from the violet-pumped centers.

factor of approximately five in the Mg-doped GaN:Er PLE spectrum for Fig. 2b relative to that obtained from undoped GaN:Er shown in Fig. 2(a). Fig. 3 compares the sharpline 4f PLE spectra taken under different spectral conditions. Fig. 3(a) shows the strong, sharpline 4f PLE spectrum in the $\sim 808\text{--}815$ nm spectral range, which was detected at 1537.8 nm (marked by an arrow in Fig. 1(a)). This 4f PLE spectrum is attributed to the 4f-pumped center that is present at a large enough concentration to manifest a sharpline 4f PLE. Figs. 3(b) and 3(c) show the high resolution PLE spectra obtained from GaN:Er+Mg and GaN:Er while detecting the Er^{3+} emission at 1554.8 nm (marked by arrows in Figs. 1(d), 4(a) and

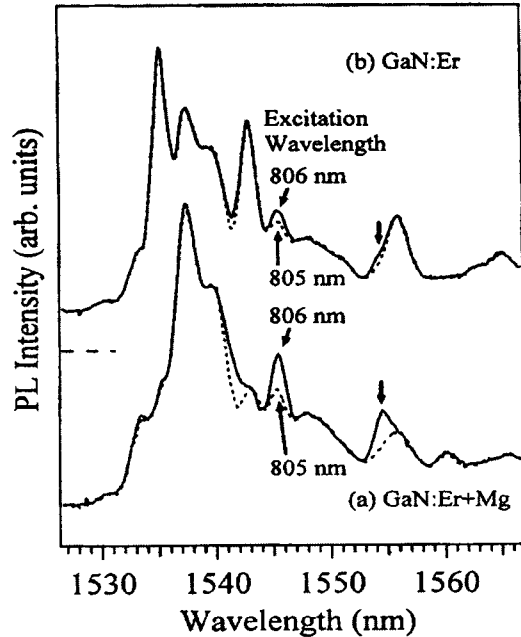


그림 4. The PL spectra excited at 805 and 806 nm for (a) GaN:Er+Mg and (b) GaN:Er.

4(b)). These PLE spectra exhibit the different 4f PLE peaks from those seen in the PLE spectrum in Fig. 3(a). These PLE peaks were previously undetected in our earlier work [6].

A careful examination of the 4f PLE spectrum of Fig. 4(b) is now made to identify Er^{3+} centers responsible for the sharpline 4f PLE peaks in this PLE spectrum. The sharp 4f PLE peaks are superposed on the broad, defect PLE bands so that the PL spectrum excited at the wavelength of any of the sharp PLE peaks consists of the PL spectrum excited by only the sharp PLE peak absorption and the PL spectrum excited by the broad PLE band absorption. The procedure described below was followed to obtain the Er^{3+} PL spectrum excited by only the sharpline 4f PLE peaks. Fig. 5 exhibits the PL spectrum (drawn by a thin solid line) excited at 806 nm (indicated by the arrow 1 in Fig. 3(b)). As mentioned above, this PL spectrum consists of the PL spectrum excited by the sharp PLE peak absorption and the PL spectrum excited by the broad PLE band

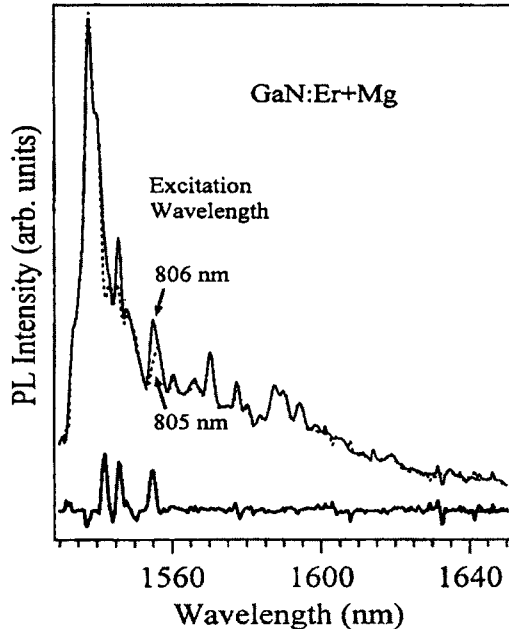


그림 5. The PL spectra excited at 805 and 806 nm and the difference between these two PL spectra. The spectral difference (plotted as a thick solid line) corresponds to the same as the violet-pumped PL spectrum.

absorption at the wavelength of the sharp PLE peak. Since the PL spectrum excited by the broad PLE band absorption is the same as the PL spectrum (drawn by a dashed line) excited at 805 nm (indicated by the arrow 2 in Fig. 3(b)), the difference between the two PL spectra excited at 805 and 806 nm corresponds to the Er^{3+} PL spectrum excited by only the sharpline 4f PLE peak. This difference (plotted as a thick solid line in Fig. 5 turns out to be the same as the violet-pumped PL spectrum, so that the PL spectrum excited specifically by the sharp intra-f band absorption of the Er^{3+} ion is the violet-pumped PL spectrum. The violet-pumped Er center is therefore responsible for the sharpline 4f PLE peaks in this PLE spectrum.

The same procedure as described above was applied to the case of GaN:Er. For this only Er-implanted GaN material, the difference between the PL spectra of Fig. 4(b) is seen at the same

wavelengths as the violet-pumped PL spectrum. And the same sharp intra-f absorption PLE bands as those observed for GaN:Er+Mg are seen in the PLE spectrum of Fig. 3(c). The intensity of the PLE peaks is much weaker than that for GaN:Er+Mg. The comparison of the PLE spectra of GaN:Er and GaN:Er+Mg illustrates that the Mg-doping has increased the concentration of the violet-pumped Er^{3+} center sufficiently to manifest its own characteristic sharpline 4f PLE.

The fact that the violet-pumped Er^{3+} PL and PLE spectra in GaN:Er+Mg material have increased intensities seems to indicate that the concentration of the violet-pumped center has increased relative to the other Er^{3+} PL centers. And our observation that the Mg doping increases the concentration of the violet-pumped centers suggests that Mg impurities be directly involved in the formation of complexes with the implanted Er^{3+} ions.

IV. Conclusion

Er implantation into Mg-doped GaN produces an enhancement of the PL and PLE spectra of a particular, trap-mediated Er^{3+} emission center. The violet-pumped PL center dominates the above-gap excited Er^{3+} PL spectrum of GaN:Er+Mg, whereas it was unobservable under above-gap excitation in GaN:Er. The observation that the violet-pumped Er^{3+} PL and PLE spectra in the Mg-doped material have increased intensities leads to the indication of the increase in the concentration of this center relative to the other Er^{3+} PL centers.

References

- [1] A. J. Neuhalfen and B. W. Wessels, Appl. Phys. Lett. **60**, 2657 (1992).
- [2] J. H. Shin, H.-S Han, S. Y Seo, and W. H Lee, J. Korean Phys. Soc., **34**, S16 (1999).
- [3] J. T. Torvik, C. H. Qiu, R. J. Feuerstein, J. I. Pankove, and F. Namavar, J. Appl. Phys. **81**, 6343 (1997).

- [4] A. J. Steckl and R. Birkhahn, Appl. Phys. Lett. **73**, 1700 (1998).
- [5] S. Kim, S. J. Rhee, D. A. Turnbull, E. E. Reuter, X. Li, J. J. Coleman, and S. G. Bishop, Appl. Phys. Lett. **71**, 231 (1997).
- [6] S. Kim, S. J. Rhee, X. Li, J. J. Coleman, and S. G. Bishop, J. Electron. Mater., **28**, 266 (1999).
- [7] X. Li, S. Gu, E. R. Reuter, J. T. Verdeyen, S. G. Bishop, and J. J. Coleman, J. Appl. Phys. **80**, 2687 (1996).
- [8] D. L. Dexter, J. Chem. Phys. **21**, 836 (1953).