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Effects of Mg dopant on the degradation of InGaN multiple quantum wells in AlInGaN-based light emitting devices

**Sung-Nam Lee · H. S. Paek · J. K. Son · H. Kim ·
K. K. Kim · K. H. Ha · O. H. Nam · Y. Park**

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Abstract We investigated the effects of Mg dopant on the degradation of AlInGaN-based light emitting diodes (LEDs) and laser diodes (LDs) with InGaN multi-quantum wells (MQWs). Photoluminescence (PL) intensity of InGaN MQWs was significantly decreased with increasing the Mg intentional doping process in InGaN active region, indicating that Mg dopant could degrade the optical quality of InGaN MQWs. From secondary ion mass spectroscopy (SIMS) analysis of AlInGaN-based LDs grown on GaN/sapphire and GaN substrate with different dislocation densities, we found that Mg concentration of LD on GaN/sapphire was higher than that of LD on GaN substrate at the InGaN MQWs regions. Additionally, we observed that Mg atoms were significantly diffused from p-type layer to InGaN MQWs region in the LD structure after aging evaluation. From these results, we could conclude that Mg diffusion along threading dislocations is one of the major gradual degradation mechanisms of AlInGaN-based LD/LEDs during the device operation under high voltage condition.

Keywords GaN · LD · LED · Degradation

1 Introduction

Generally, the epitaxial growth of III-nitrides has focused on the improvement of optical and crystal qualities of InGaN multi-quantum wells (MQWs) since they are used as active medium of AlInGaN-based laser diodes (LDs) as a lighting source for optical storage system and mobile display systems [1–7]. Recently, although the reliability of AlInGaN-based LDs has been drastically improved by the introduction of GaN substrate with low dislocation density, there are some reliability problems in the AlInGaN-based LD/LEDs [1]. The reliability of device is determined by the weakest part of the device and depends on factors ranging from material properties to processing technologies. Generally, the failure modes of optical device can be roughly divided into three categories: sudden, rapid, and gradual degradation [8]. Among various degradations, the gradual degradation can be mainly occurred by increasing the point defects at the hetero-interface in the epilayers [8].

In the GaN-based LD/LEDs, since Mg dopant must be heavily doped on GaN epilayer to obtain a sufficient carrier density due to the high activation energy of Mg dopant [3], there are some problems in GaN-based optical device, such as Mg dopant diffusion and Mg-related optical loss [2, 4]. Therefore, one of the most important issues is how to control the Mg doping profile and concentration to improve the performance and the reliability of LED/LDs [2, 5]. Additional issue is the high dislocation density in GaN epilayer due to the large lattice mismatch between GaN-based material and sapphire substrate [9]. However, the degradation of GaN-based LD/LEDs is not responsible for the multiplications of the dislocation motions that is usually

S.-N. Lee (✉) · H. S. Paek · J. K. Son · H. Kim · Y. Park
OS Laboratory, Central R&D Institute,
Samsung Electro-Mechanics Co. Ltd.,
Suwon, Korea
e-mail: snlee@samsung.com

K. K. Kim · K. H. Ha
Semiconductor Device Laboratory,
Samsung Advanced Institute of Technology,
Suwon, Korea

O. H. Nam
Department of Nano-Optical Engineering,
Korea Polytechnic University,
Siheung, Korea

observed in zincblende structure-based LDs [10]. From the dependence on dislocation density of life time of GaN-based LDs, it has been believed that one of degradation mechanisms is the dislocation-related diffusion process [11, 12]. However, the degradation mechanism of these devices has not been clearly understood yet. In this study, we systematically report on the effect of Mg dopant on the optical degradation of InGaN active layer and the evidence of Mg diffusion through the dislocation from p-layer to InGaN active layer during the device operation.

2 Experimental

AlInGaN-based LD structures with InGaN/InGaN multiple quantum wells were grown on a sapphire (0001) and a GaN substrate by low pressure metalorganic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAl), bis-cyclopentadienyl magnesium (Cp_2Mg) and ammonia (NH_3) were used as precursors for Ga, In, Al, Mg, and N sources, respectively. A Si-doped GaN layer was grown on GaN/sapphire template and GaN substrate with dislocation density of 1.0×10^9 cm^{-2} and 5.0×10^6 cm^{-2}, followed by growth of the LD structures, including the active layers of InGaN/InGaN multi-quantum well, electron blocking layer (EBL), waveguide layer of doped GaN layer, cladding layers of doped AlGaN, and Mg-doped GaN p-type contact layer [12]. The InGaN/InGaN multiple quantum well structure consists of three-period MQWs with 3-nm-thick InGaN wells and 10-nm-thick Si-doped InGaN barriers.

To investigate the effect of Mg dopant for the InGaN MQWs, we intentionally doped Mg atoms in the InGaN MQWs regions and added the preflow steps of Cp_2Mg gas before growing p-type AlGaN EBL. The Mg preflow time was varied from 0 to 50 s. Each sample was characterized by photoluminescence (PL) and electroluminescence (EL). The secondary ion mass spectroscopy (SIMS) measurements were carried out to analyze the Mg behaviors in the LD structure. Unfortunately, since the beam diameter (100 μm) of SIMS is larger than the ridge width (~2 μm) of LDs, for SIMS analysis, we fabricated LEDs with size of 300×300 μm^2 using LD epi-wafers and carried out the aging test for LEDs at high temperature (75°C) and high current density condition (0.3 kA/cm^2) using ACC mode. This current density corresponds to about one tenth of LD operation condition.

3 Results and discussion

Figure 1 shows the room temperature PL spectra of intentional Mg-doped InGaN MQWs with different Mg doping concentrations. Undoped InGaN MQWs exhibits the strong PL emission of 2.79 eV, while Mg-doped InGaN MQWs shows the weak PL emission of 2.76 eV. For p-type GaN, it is well known from PL studies, the Mg dopant (>1.0×10^{19} cm^{-3}) in GaN forms acceptor levels (~3.27 eV) as well as deep level (~2.88 eV) [3]. However, we could not observe any Mg-related acceptor peaks due to a low Mg doping concentration below 1.0×10^{18} cm^{-3} as shown in Fig. 1. The PL intensities of Mg doped InGaN MQWs were significantly reduced with increasing Mg doping concentration, indicating the increase of the Mg-related non-radiative recombination centers (NRCs). These NRCs may be caused by the Mg-related point defect such as Mg-H, Mg interstitials, or Mg-related complexes, etc. [11]. Additionally, the emission peak of InGaN MQWs was slightly red-shifted from 2.79 to 2.76 eV with increasing Mg doping concentration. The PL peak redshift of Mg-doped InGaN MQWs may be caused by the donor–acceptor pair (DAP) or the band tail effect due to the increase of composition fluctuation [13].

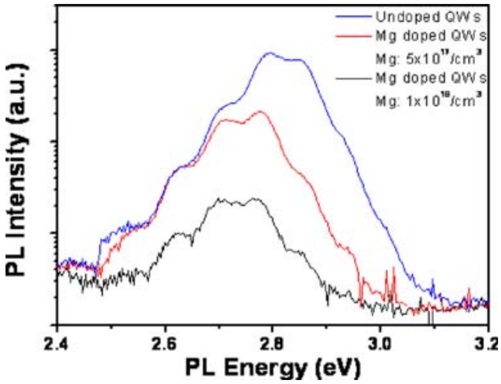

Fig. 1 The room temperature PL spectra of Mg doped InGaN MQWs with different Mg doping concentrations

Figure 2 shows the EL intensity of AlInGaN-based LDs structure as a function of the preflow time of Cp_2Mg gas in the MOCVD reactor before growing the high temperature p-type layer after the growth of InGaN MQWs. The EL intensity of AlInGaN-based LD structure was significantly decreased with increasing the preflow time of Cp_2Mg. From SIMS analysis, we could observe the evidence of Mg diffusion profile into InGaN MQWs by introducing the Mg preflow process not shown here. It indicated that Mg atoms adsorbed at the surface of InGaN during the Mg preflow process and diffused into InGaN MQWs during the growth of high temperature p-type layer. Therefore, one can see that the drastic reduction of EL intensity was ascribed to the diffusion of Mg atoms and the generation of the Mg-related NRCs in InGaN active layer.

It has been reported that dislocations are strongly related with diffusion of Mg atoms and non-radiative recombination sources [14]. To investigate Mg diffusion path, SIMS analyses were conducted for InGaN MQWs LD

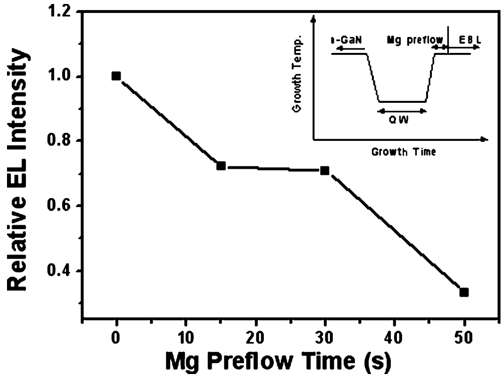

Fig. 2 The electroluminescence intensities of AlInGaN-based laser diode structures as a function of the preflow times of Cp_2Mg gas before the growth of p-type AlGaN EBL

structures grown on GaN/sapphire and free-standing GaN substrates with different dislocation density of 1×10^9 and 5.0×10^6 cm^{-2}, respectively. As shown in Fig. 3., SIMS analyses showed that the Mg concentration profiles of both sample were same at p-type regions, while the Mg concentration of LD on GaN/sapphire substrate was much higher than that of LD on free-standing GaN substrate at n-type region. For the LD on GaN substrate with low dislocation density, the Mg concentration profile was very abrupt at the interface between the active region and EBL and was near detection limit at the n-type region. It implied that there is no significant diffusion of Mg atoms in LD structure on GaN substrate with low dislocation density. On the contrary, Mg concentration profile of LD on GaN/sapphire template was tailed from p-type to n-type region, indicating the Mg dopants diffused from p-type to n-type region. Since both samples were grown at the same time, the significant difference between both samples was only dislocation density in the epitaxial layer. From the difference of Mg profile for both samples at n-type region, we could suggest that major diffusion path of Mg atoms was dislocation rather than vacancy in GaN epitaxial layer.

Although a few groups reported the possible degradation mechanism of the AlInGaN-based LD/LEDs [8–12, 15–17], it has not been fully understood yet. We proposed the degradation possibility of Mg dopant diffusion into the InGaN active layer by applied voltage [15]. Takeya et al. also reported the possibility that the accumulated point defects such as vacancy, Mg interstitials or their complexes diffuse into and accumulate at the InGaN active layer [11]. However, these reports did not show any direct evidence for the diffusion of Mg-related NRCs. If Mg diffusion is closely related with the degradation of LD/LEDs, SIMS analysis can be used for the verification of the diffusion of Mg atoms. We fabricated LEDs with 300×300 μm^2 by using LD on GaN epi-wafer. In the aging evaluation of LEDs, the light output intensity of LEDs was exponentially decreased with aging time. SIMS analyses showed the Mg profile difference between LED samples before and after aging test, as shown in Fig. 4. This result indicated that Mg diffusion into InGaN active layer occurred in the degraded sample. Therefore, we could suggest that Mg diffusion and accumulation at the active layer is probably major gradual degradation mechanism in AlInGaN-based LD/LEDs. From our results, we could also conclude that the dislocations are detrimental defect as the diffusion path of Mg atoms which can generate Mg-related NRCs in the InGaN active layer. Accordingly, we should minimize the dislocation density to achieve the high performance of blue-violet LD/LEDs with long lifetime.

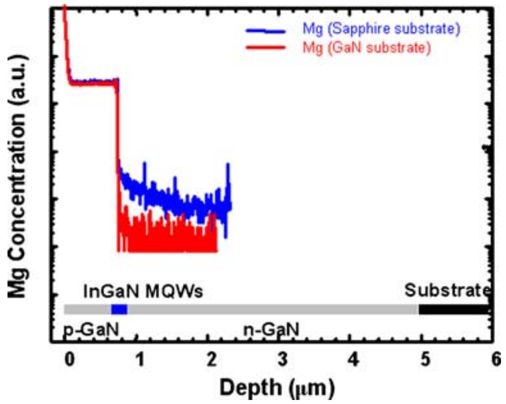

Fig. 3 SIMS depth profiles of Mg dopant for InGaN MQWs LD structures grown on sapphire and free-standing substrate with different dislocation density of 1×10^9 and 5.0×10^6 cm^{-2}, respectively

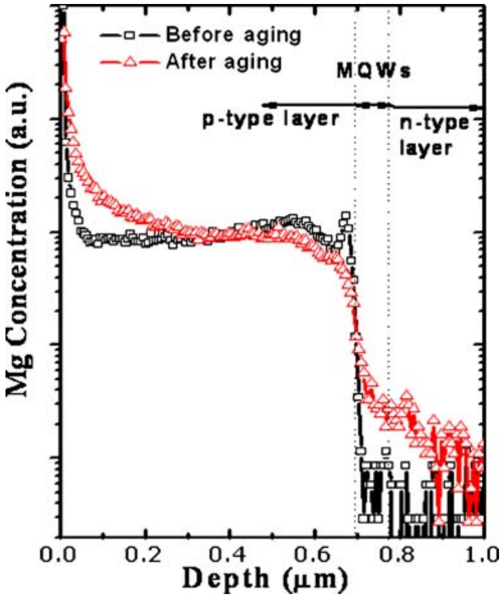

Fig. 4 SIMS depth profiles of Mg dopant for AlInGaN-based LEDs samples before and after aging test

4 Conclusion

The PL intensity of InGaN QWs was significantly decreased with increase the intentional Mg doping concentration in the InGaN QWs regions. Additionally, the EL intensity of AlInGaN-based LDs with InGaN QWs was also decreased with increasing the preflow time of Cp_2Mg before the growth of p-type layers. It indicated that the Mg atoms was one of NRCs in the InGaN QWs and could be easily diffused from surface to QWs region during the growth of high temperature p-type layers. From SIMS analyses, we observed the higher Mg concentration of LD on GaN/sapphire than that of LD on free-standing GaN substrate at the n-type regions. After current aging test, SIMS analyses indicated that Mg diffusion into active layer occurred in the degraded sample. From these results, we could suggest that the dislocation diffusion of Mg atoms and the generation of Mg-related NRCs in the active layer is one of major gradual degradation mechanism in the AlInGaN-based LD/LEDs.

References

1. P. Prystawko, R. Czernetzki, L. Gorczyca, G. Targowski, P. Wisniewski, P. Perlin, M. Zielinski, T. Suski, M. Leszczynski, I. Grzegory, S. Porowski, J. Cryst. Growth **272**, 274 (2004)
2. N. Kuroda, C. Sasaoka, A. Kimura, A. Usui, Y. Mochizuki, J. Cryst. Growth **189/190**, 551 (1998)
3. S.N. Lee, J.L. Son, T. Sakong, W. Lee, H.S. Peak, E. Yoon, J.Y. Kim, Y.H. Cho, O.H. Nam, Y. Park, J. Cryst. Growth **272**, 455 (2004)
4. J.K. Son, J.S. Hwang, S.N. Lee, T. Sakong, H. Paek, S. Chae, H. K. Kim, O.H. Nam, J.Y. Kim, Y.H. Cho, Y. Park, Phys. Stat. Sol. (c) **3**, 2178 (2006)
5. J. Ran, X. Wang, G. Hu, J. Wang, J. Li, C. Wang, Y. Zeng, J. Li, Mircoelectronics J. **37**, 583 (2006)
6. Y.S. Yoon, H.K. Kim, J. Electroceramics **17**, 277 (2006)
7. J.M. Lee, B.I. Kim, S.J. Park, J. Electroceramics **17**, 227 (2006)
8. M. Fukuda, *Optical Semiconductor Devices* (Wiley, New York, 1999), p. 326
9. S.N. Lee, J.K. Son, H.S.H.S. Paek, T. Sakong, W. Lee, K.H. Kim, S.S. Kim, Y.J. Lee, D.Y. Noh, E. Yoon, O.H. Nam, Y. Park, Phys. Stat. Sol (c) **1**, 2458 (2004)
10. S. Tomiya, S. Goto, M. Takeya, M. Ikeda, Phys. Stat. Sol. (a) **200**, 139 (2003)
11. M. Takeya, T. Mizuno, T. Sasaki, S. Ikeda, T. Fugimoto, Y. Ohfuji, K. Oikawa, Y. Yabuki, S. Uchida, M. Ikeda, Phys. Stat. Sol (c) **0**, 2092 (2003)
12. O.H. Nam, K.H. Ha, J.S. Kwak, S.N. Lee, K.K. Choi, T.H. Chang, S.H. Chae, W.S. Lee, Y.J. Sung, J.H. Chae, T. Sakong, J. K. Son, H.Y. Ryu, Y.H. Kim, Y. Park, Phys. Stat. Sol. (a) **201**, 2717 (2004)
13. B. Han, M.P. Ulmer, B.W. Wessels, Physica B **340–342**, 470 (2003)
14. T. Hino, S. Tomiya, T. Miyajima, K. Yanashima, S. Hashimoto, M. Ikeda, Appl. Phys. Lett. **76**, 3421 (2000)
15. O.H. Nam, K.H. Ha, J.S. Kwak, S.N. Lee, K.K. Choi, T.H. Chang, S.H. Chae, W.S. Lee, Y.J. Sung, H.S. Paek, J.H. Chae, T. Sakong, Y. Park, Phys. Stat. Sol. (c) **0**, 2278 (2003)
16. T. Schoedl, U.T. Schwarz, S. Miller, A. Leber, M. Furitsch, A. Lell, V. Harle, Phys. Stat. Sol. (a) **201**, 2278 (2003)
17. V. Kummler, G. Bruderl, S. Bader, S. Miller, A. Weimar, A. Lell, V. Harle, U.T. Schwarz, N. Gmeinwieser, W. Wegscheider, Phys. Stat. Sol. (a) **194**, 419 (2002)